# Final Technical Report summarizing Purdue research activities as part of the DOE JET Topical Collaboration

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## 1 Executive summary

Purdue has received support for 1/2 graduate student (Deke Sun) from the Collaboration for three years. This facilitated extension of the group's research profile to include high-$p_T$ physics topics. In particular we focused on radiative energy loss in the Gyulassy-Levai-Vitev (GLV) and Djordjevic-Gyulassy-Levai-Vitev (DGLV) formulations using realistic bulk medium evolution.

We first used transport solutions from our MPC/Cascade parton cascade code for the bulk and investigated the influence of fluctuations in scattering location on medium induced GLV energy loss. Specifically, we looked at two observables: the nuclear suppression factor $R_{AA}(p_T)$ and differential elliptic flow $v_2(p_T)$ of pions. While there was noticeable effect on the medium opacity required to match experimental data, the opacity difference could be largely absorbed into a modest adjustment of the strong coupling constant $\alpha_s$ used in the calculation. We did find, however, that contrary to earlier expectation the transverse expansion of the medium reduced elliptic flow by nearly a half, and therefore GLV energy loss fails to simultaneously describe $R_{AA}$ and $v_2$ (so called "$v_2$ puzzle"). Our main focus, thereafter, was on understanding and corroborating this surprising result, especially because the JET Collaboration group at Columbia University soon claimed that the $v_2$ puzzle disappears if GLV energy loss is used with bulk medium from hydrodynamics.

We proceeded with investigating four different bulk evolution scenarios from hydrodynamics, and demonstrated that the suppression of elliptic flow due to transverse expansion is a general feature of GLV energy loss. On the other hand, the equation of state of the medium significantly affects high-$p_T$ observables, and the $v_2$ puzzle indeed disappears for the unrealistic "bag model" equation of state used by that other group. Through this study we also realized that the typical formulation of GLV energy loss in media with hydrodynamic flow violates Lorentz covariance, and therefore derived a Lorentz covariant formulation for GLV energy loss. Our covariant formulation exhibits a novel interplay between the jet direction and medium flow, which we showed tends to enhance elliptic flow and thereby alleviate the $v_2$ puzzle. This work was followed by a covariant formulation DGLV energy loss for heavy quarks. We found that DGLV also leads to a similar $v_2$ suppression for $D$ and $B$ mesons when transverse expansion of the medium is included, but the reduction in $v_2$ is again largely compensated by the covariant treatment.

Near the end of the JET project we turned our attention to energy loss signatures in small p+A systems. This is an especially interesting area because, shockingly, these systems also seem to behave hydrodynamically.

Participation in the JET Collaboration also lead to the extension of Molnar's Program Collection (MPC) with a new MPC/Eloss package, which implements our covariant GLV and DGLV energy loss and facilitates calculations with arbitrary (currently 2+1D boost invariant) medium evolution. This code will be released on the Open Source Codes And Routines (OSCAR) archive. Our covariant formulation of GLV energy loss was also implemented in the CUJET-3 code by the Columbia group.

## 2 Purdue research as part of DOE JET Collaboration

The Section below summarizes research done by the Purdue group as part of the DOE JET Topical Collaboration (DOE grant DE-AC02-05CH11231). The group received support for 1/2 graduate student, Deke Sun, for 3 years (total cost of about $75,000). This support was used to extend the research profile of the group with investigations in the area of high-$p_T$ parton energy loss. Overlapping with the JET Collaboration, the group was also conducting research on bulk evolution models and collective observables in relativistic heavy ion collisions, mainly radiative $ggg \leftrightarrow gg$ parton transport and self-consistent conversion of dissipative fluids to particles, funded under a DOE Early Career Research Award (grant DE-PS02-09ER41665). Only the JET Collaboration funded activities are summarized in this report.

### 2.1 GLV energy loss with realistic medium evolution from transport

Understanding parton energy loss in ultrarelativistic heavy-ion reactions has been the focus of considerable recent theoretical effort. A variety of phenomenological approaches (e.g., [1, 2, 3]) formulate the problem deterministically, in terms of a local energy loss rate $dE/dL = -f(E(L), T(L), L)$ that depends on local temperature, position, and parton energy along the Eikonal (straight-line) parton trajectory. In the weak-coupling regime, more rigorous treatment is possible based on perturbative QCD[4, 5, 6]. This includes quantum interference such as the Landau-Pomeranchuk-Migdal (LPM) effect and also fluctuations; i.e., energy loss for a given jet becomes a stochastic variable that is a function of the scattering and emission history of the jet.

A critical step in computing heavy-ion observables from any energy loss model is spatial and temporal averaging over the bulk medium formed in the collision. Purdue started out with investigating the Gyulassy-Levai-Vitev (GLV) framework[6] in which a high-energy parton loses energy through gluon radiation induced by interactions with static Yukawa scatterers in the medium. It was natural to combine GLV with our MPC/Cascade code (originally called Molnar's Parton Cascade[7]) because in MPC the bulk medium consists of a "cloud" of partons that then serve as the scattering centers for GLV. Regarding the energy loss model, our approach was similar to then recent works such as [8] or CUJET-1.0 by the Columbia group [9]. Unlike CUJET-1.0, our initial focus was on light partons, and we did not include multiple gluon radiation, elastic energy loss, or energy loss fluctuations due to variations in radiated gluon momentum. However, we did, for the first time, compute GLV energy loss with realistic 3D medium evolution, with both longitudinal and transverse expansion, which turned out to crucially influence elliptic flow $v_2$ and also affect the nuclear suppression factor $R_{AA}$. We also studied how differences between the commonly used deterministic (medium averaged) energy loss and stochastic energy loss, which fluctuates depending on where the jet parton interacts with the medium, impact these two observables. This was especially timely because a then recent assessment by the PHENIX Collaboration[10] highlighted the difficulty many parton energy loss frameworks have with reproducing the azimuthal angle dependent nuclear suppression at RHIC, $R_{AA}(\phi)$, which essentially carries the same information[1] as azimuthally averaged $R_{AA}$ and elliptic flow $v_2$, but GLV calculations were absent from that analysis.

#### 2.1.1 GLV energy loss to first order in opacity

In the Gyulassy-Levai-Vitev (GLV) formulation of energy loss[6] for a gluon or light quark jet, the spectrum of gluons radiated by the jet parton is obtained as an expansion in the total number of scatterings $n$ the jet and the radiated gluon experience with the medium as they travel through it.

[1] Roughly speaking, $R_{AA} \approx [R_{AA}(\phi{=}0) + R_{AA}(\phi{=}\pi/2)]/2$, while $v_2 \approx [R_{AA}(\phi{=}0) - R_{AA}(\phi{=}\pi/2)]/(4R_{AA})$.

The dominant contribution is given by the leading $n = 1$ (single scattering) term

$$x\frac{dN^{(1)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\chi\int d^2\mathbf{q}\,\frac{\mu^2(z)}{\pi[\mathbf{q}^2+\mu^2(z)]^2}\,\frac{2\mathbf{k}\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\times\left(1-\cos\frac{(\mathbf{k}-\mathbf{q})^2 z}{2xE}\right) . \qquad (1)$$

Here, $x$ and $\mathbf{k}$ are the light-cone momentum fraction and transverse momentum of the radiated gluon, the jet energy is $E$, the original hard scattering is at $z = 0$, the jet is moving in the $z$ direction and rescatters once at position $z$, $\mu(z)$ is the local Debye screening mass, $\chi = \int dz\,\rho\,\sigma$ is the opacity for *gluon* jets (irrespectively of the jet Casimir $C_R$), and $\sigma = 9\pi\alpha_s^2/(2\mu^2)$ is the (screened) total $gg \to gg$ scattering cross section provided the medium is made of gluons. The result was obtained for a medium of static Yukawa scatterers that are well-separated with mean distance $d \gg 1/\mu$, the radiated gluon is assumed to be soft ($x \ll 1$), and the calculation was done at tree level. Higher-order terms in number of scatterings have been systematically investigated[11], up to at least $n = 9$, and were found to give modest corrections to the $n = 1$ result for the observables studied here.

Integrating the spectrum (1) numerically, one obtains a momentum-averaged energy loss

$$\Delta E^{(1)}(z) = \int dx\,d^2\mathbf{k}\,Ex\,\frac{dN^{(1)}}{dx\,d^2\mathbf{k}} \qquad (2)$$

for *fixed* $z$; i.e., $\Delta E^{(1)}(z)$ retains energy loss fluctuations due to variations in $z$ only. The probability for the scattering to occur at $z$ is

$$p(z) = \frac{\rho(z)\sigma(z)}{\chi} . \qquad (3)$$

Integrating over $z$ as well yields the deterministic average energy loss

$$\langle\Delta E^{(1)}\rangle = \int dz\,p(z)\,\Delta E^{(1)}(z) . \qquad (4)$$

For asymptotic jet energies, the average energy loss (4) is given by what we termed the GLV "pocket formula" [12]

$$\langle\Delta E^{(1)}\rangle \approx \frac{9\pi C_R\alpha_s^3}{4}\int dz\,z\,\rho(z)\ln\frac{2E}{\mu^2 z} . \qquad (5)$$

Though this remarkably compact expression (and its even simpler cousin without the $\ln[2E/(\mu^2 z)]$ factor) has motivated workers in the past, it is unreliable in practice even for qualitative conclusions. Basic constraints that i) the radiated gluon energy does not exceed the energy of the parent jet, ii) momentum transfer in scattering off a thermal particle in the medium has *on average* an upper bound given by the center-of-mass energy available, and iii) the radiated gluon energy must exceed the plasma frequency for the gluon to propagate in the medium, translate into kinematic bounds

$$k < xE\ , \quad q < \sqrt{6ET}\ , \quad xE \gtrsim \mu\ , \qquad (6)$$

and after suitable variable substitution lead to [26]

$$\Delta E^{(1)}(z) = \frac{2C_R\alpha_s}{\pi}\,E\,\chi\,I\left(b = \frac{z}{\tau(z)}, \epsilon = \frac{E}{\mu(z)}\right) , \qquad (7)$$

where $\tau(z) = 2E/\mu^2(z)$ is a characteristic formation time, and the function $I$ is determined by the integral (1). Only for small $b \to 0$ and large $E/\mu \to \infty$ one does recover (5). In actual calculations we use a precalculated 2D table for $I$ and obtain $I(b,\epsilon)$ values via interpolation.

Note that we only considered radiative energy loss as encoded in (1). There are significant additional contributions from collisional energy loss[13]. Recoil of scattering centers in scattering also enhances[14] energy loss because it effectively changes the denominator $(\mathbf{q}^2+\mu^2)^2$ in (1) to $\mathbf{q}^2(\mathbf{q}^2+\mu^2)$ (see Sec. 2.3.2). One also expects potentially large higher-order corrections in the strong coupling constant $\alpha_s$ that are yet to be computed. In the approach here all these effects were roughly incorporated into the parameter $\alpha_s$ when the calculation was calibrated to reproduce $R_{AA}$ in central collisions (through $\Delta E \sim \alpha_s^3$).

#### 2.1.2 Coupling to bulk medium

Coupling energy loss to bulk medium evolution involves several open questions and assumptions (see, e.g., [15] and references therein for a detailed discussion). First, the GLV result (1) was derived for a medium of *static* scattering centers whereas in a heavy-ion collision the density changes rapidly with time. Unfortunately, the formulation has not been extended yet to time-dependent background color fields. Therefore, as is customary in practice, for *non-static* media we reinterpret $\rho(z)$ in the GLV formula as the local density $\rho(z, t=t_0+z)$ along the parton trajectory.

Second, it is nontrivial to apply perturbative energy loss unless the medium is also perturbative. For example, questions arise whether the scatterers are quark- or gluon-like quasiparticles or some other field configurations, and whether the key parameter in (1), the local Debye mass $\mu \sim gT$, is computed from the temperature ($\sim T$), local energy density ($\sim e^{1/4}$), or some other thermodynamic quantity. For simplicity, we will consider here the medium to be a system of massless gluons that thermalize to a large degree by Bjorken proper time $\tau_0 = 0.6$ fm. The local $\mu(z)$ is then determined along the straight-line jet path from the local temperature, which we calculate using tabulated density evolution $n(\vec{x}_\perp, \eta=0, \tau)$ from the bulk dynamics model. For our gluon gas, $n \approx 2T^3$ and $\mu = gT \approx 2T$ (similar expressions have been used in [12]). We set aside the interesting question of quark chemical equilibration, namely, how quark/antiquark abundances build up after the early gluon-dominated stage of the collision. At fixed parton density, quarks would significantly lower the opacity because of their smaller Casimir $C_2$. (On the other hand, the Debye mass would only be affected by $\sim 10\%$ based on perturbation theory[2].)

Another open question is energy loss prior to the assumed thermalization time $\tau_0$. Reference [9] found GLV energy loss to be quite sensitive to whether density for $\tau < \tau_0$ was taken to be constant, or rising linearly with $\tau$, or zero. However, differences in early density evolution were largely compensated by slightly different values of $\alpha_s$ when the calculation was calibrated to experimental data. We assumed at early times $\tau < \tau_0$ a linear density build-up $\rho(\vec{x}_\perp, \eta, \tau) = \tau\rho(\vec{x}_\perp, \eta, \tau_0)/\tau_0$.

One also has to address energy loss in the low-temperature (hadronic) regime, where the isolated Yukawa scattering center assumption in GLV clearly breaks down. The calculation here did not include hadronic energy loss, and simply set vanishing $\Delta E(z) = 0$ for jet path sections where $\mu < \Lambda_{QCD}$, with cutoff $\Lambda_{QCD} = 0.2$ GeV. Though one expects qualitative conclusions to be robust, it would be interesting to vary the assumptions above in the future.

#### 2.1.3 Jet initial conditions and fragmentation

We obtained initial jet momentum distributions in p+p, Au+Au and Pb+Pb from leading-order (LO) perturbative QCD with one-loop running coupling $\alpha_s(Q^2)$, using CTEQ5L parton distribution

[2] Boldly applying at temperatures $T \sim 150-700$ MeV accessible at RHIC and the LHC perturbative quark-gluon plasma expressions for density and Debye mass,

$$\frac{n}{T^3} = (16+9N_f)\frac{\zeta(3)}{\pi^2}, \qquad \frac{\mu}{gT} = \sqrt{1+\frac{N_f}{6}}\ ,$$

$\mu(T(n))$ in a pure gluon plasma ($N_f = 0$) is not that different from a plasma with light quarks ($N_f \approx 2-3$) because the $N_f$ dependences largely compensate each other.

function parameterizations[16] with $Q^2 = p^2_{T,parton}$. Nuclear effects such as shadowing were ignored but isospin (proton-neutron difference) was included. We considered jets produced at midrapidity both in coordinate and momentum space, i.e., $y = \eta = 0$, where $y$ and $\eta$ are the coordinate and momentum rapidity[3]. The jet transverse momentum distribution was generated uniformly in azimuth, while the transverse density distribution follows the binary collision distribution for two Woods-Saxon distributions $\rho_A(r)$. I.e., for collisions with impact parameter $b$ we used the transverse profile

$$\frac{dN(\mathbf{b})}{d^2\mathbf{x}_\perp} = const \times T_A\!\left(\mathbf{x}_\perp + \frac{\mathbf{b}}{2}\right) T_A\!\left(\mathbf{x}_\perp - \frac{\mathbf{b}}{2}\right) \quad , \tag{8}$$

where $T_A(\mathbf{b}) \equiv \int dz \rho_A(\sqrt{z^2 + \mathbf{b}^2})$ is the nuclear thickness function. Woods-Saxon parameters for gold and lead nuclei were taken from HIJING[17]. To enhance statistics at high $p_T$, we generated uniform jet $p_T$ in the intervals $[2, 80]$ GeV for RHIC and $[2, 300]$ GeV for LHC, and then appropriately reweighted contributions to reflect the real jet spectrum.

The density evolution of scatterers was calculated from parton transport as discussed in the next Section. After energy loss, jets were fragmented independently using LO BKK95 fragmentation function parameterizations[18] with scale factor $Q^2 = p^2_{T,hadron}$, and we take $\pi_0 = (\pi^+ + \pi^-)/2$ for the neutral pion yield. This procedure reproduces high-$p_T$ $\pi_0$ and charged particle spectra in p+p at RHIC and LHC with a modest $K$-factor $K_{NLO} \approx 2.5$ to account for higher-order contributions.

#### 2.1.4 Bulk medium evolution for $\tau > \tau_0$

For medium evolution *without* transverse expansion, we used the initial conditions discussed later in this Section but kept the transverse profile "frozen", i.e., as in [9, 8], the local density was assumed to undergo longitudinal Bjorken expansion $\rho(\vec{x}_\perp, \eta, \tau) = \rho(\vec{x}_\perp, \eta, \tau_0)\tau_0/\tau$.

For medium evolution *with* transverse expansion, we employed covariant transport theory in the same spirit as Refs. [19, 20] to model the collective expansion of a causal, relativistic, low-viscosity bulk medium. We evolved a system of massless "gluons" with $2 \to 2$ interactions via MPC/Cascade[7] (the closest-approach based Boltzmann solver from Molnar's Program Collection), i.e., solved

$$p_1^\mu \partial_\mu f_1 \quad = \quad S(x, \vec{p}_1) + \iiint_{234} (f_3 f_4 - f_1 f_2)\, W_{12\to 34}\; \delta^4(p_1 + p_2 - p_3 - p_4) \ . \tag{9}$$

Here the integrals are shorthands for $\int_i \equiv \int d^3p_i/(2E_i)$, and $f_j \equiv f(x, \vec{p}_j)$ is the phase space density. The source function $S$ specifies the initial conditions, while $W = (1/\pi)s^2 d\sigma/dt$ controls the local scattering rate.

We used isotropic $d\sigma/dt = 2\sigma_{tot}/s$, for simplicity, with $\sigma_{tot}(\tau) = \sigma_0(\tau/\tau_0)^{2/3}$ growing with time in order to keep the shear viscosity to entropy ratio $\eta/s$ approximately constant[21, 20]. To generate substantial elliptic flow $v_2(p_T \approx 3 \text{ GeV}) \sim 0.25$ in collisions with $b = 8$ fm impact parameter at RHIC and LHC, we set $\sigma_0 = 8$ mb and 4.5 mb respectively.

Initial conditions for Au+Au at $\sqrt{s_{NN}} = 200$ GeV and Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV with impact parameter $b = 3$ and 8 fm (about 0-10% and 30% centrality, respectively) were constructed as follows. As in [19], we started at proper time $\tau_0 = 0.6$ fm with a locally thermalized system at

[3]With the $z$ axis along the beam direction,

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z} \ , \qquad \eta = \frac{1}{2}\ln\frac{t+z}{t-z}$$

temperature $T = 0.385$ GeV. Because we were only interested in observables at midrapidity, we set up longitudinally boost invariant conditions in a wide coordinate rapidity window $|\eta| < 5$, with rapidity densities $dN(b)/d\eta \propto N_{part}(b)$ proportional to the number of participants ("wounded" nucleons)

$$N_{part}(b) = \int d^2\mathbf{x}_\perp \, [T_A(\mathbf{x}_\perp + \mathbf{b}) + T_A(\mathbf{x}_\perp - \mathbf{b})] \, \left(1 - e^{-\sigma_{NN} T_A(\mathbf{x}_\perp)}\right) \, . \tag{10}$$

Here the inelastic nucleon-nucleon cross section is $\sigma_{NN} = 42$ mb at $\sqrt{s_{NN}} = 200$ GeV (RHIC) and 70 mb at $\sqrt{s_{NN}} = 2.76$ TeV (LHC), and we matched the "gluon" multiplicity $dN/d\eta$ to the observed charge particle $dN/dy$ via setting $dN(b = 0)/d\eta = 1100$ (Au+Au) and 2400 (Pb+Pb). For the transverse density *profile*, on the other hand, we used the same binary collision distributions as for jets. This choice is motivated by a classical Yang-Mills ("color glass condensate") calculation[22] that found eccentricities at early times to be much closer to binary collision eccentricities than to wounded nucleon eccentricities.

The initial conditions above are more general than they may appear at first sight. Due to scalings[23] of the transport equation (9), a single transport solution contains the answer to a whole class of *equivalent* problems with scaled initial conditions, cross sections, and particle properties. For example, one can freely increase the initial density provided cross sections are reduced in inverse proportion to keep the mean free path the same. The initial temperature can also be rescaled together with particle masses (in fact for our massless quanta, $T_0$ does not influence the density evolution at all).

Though in principle the transport provides an ensemble of evolving scattering centers, here we solely use density information to calculate energy loss. Technically this is very similar to employing ideal or viscous hydrodynamics for the medium evolution, which we also pursued later.

#### 2.1.5 Effect of bulk dynamics on nuclear suppression and elliptic flow

We focused on two basic high-$p_T$ observables for neutral pions at midrapidity, the nuclear suppression factor $R_{AA}$ and the momentum anisotropy (elliptic flow) $v_2 = \langle \cos 2\phi \rangle_{p_T}$. Only energy loss was considered, i.e., contributions by the radiated gluons to the final spectrum and feedback on the bulk medium due to the jet were ignored. This is a good approximation at sufficiently high $p_T$. We considered **four scenarios** based on i) whether the medium was only undergoing Bjorken expansion ("1D" as in [9, 8]) or transverse expansion as well ("3D"); and ii) whether average energy loss $\langle \Delta E \rangle$ was used or the stochastic $\Delta E(z)$.

Results from this calculation were first presented at the Hard Probes 2012 conference.

#### Nuclear suppression in Au+Au at RHIC

Figure 1 shows our results for neutral pion $R_{AA}$ at RHIC, for fixed $\alpha_s = 0.29$ for all four scenarios. With stochastic energy loss the suppression is noticeably weaker, as expected for "upward curving" parton spectra at high $p_T$. Quite interestingly, realistic transverse expansion significantly enhances jet quenching. This is a generic feature of GLV energy loss coming from the $(1 - \cos)$ interference term in (1). Scatterings at large $z$ induce larger energy loss because the LPM suppression is weaker, and with a transversely expanding density profile there is higher chance to scatter further away from the production point than in the transversely frozen case.

Unfortunately, without precise control over $\alpha_s$, $R_{AA}$ alone cannot differentiate between our four scenarios. As shown in Fig. 2, after a slight tuning of $\alpha_s$ to reproduce the suppression in central collisions, differences in $R_{AA}$ largely disappear. We need $\sim 10 - 20\%$ higher $\alpha_s$ with fluctuating

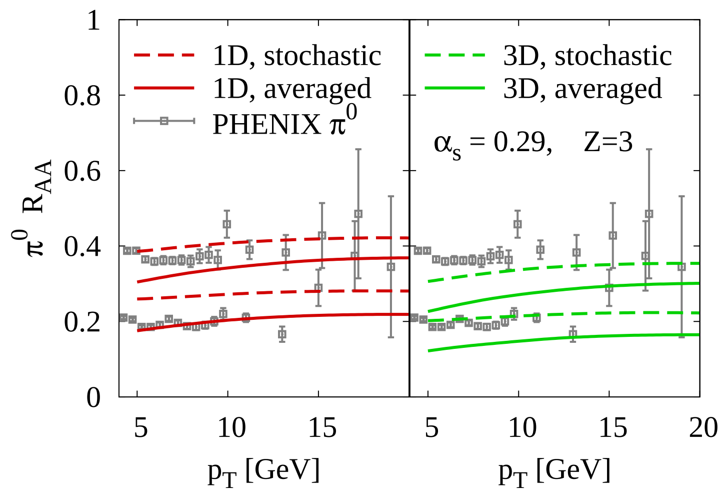


Figure 1: Neutral pion $R_{AA}$ in $Au+Au$ at $\sqrt{s_{NN}} = 200$ GeV at RHIC with impact parameters $b = 3$ fm and 8 fm (lower pair of lines vs upper pair of lines, respectively, in both panels) calculated in four different scenarios with GLV energy loss (see text). *Left panel:* transversely frozen density profiles. *Right panel:* realistic transverse expansion modeled with parton transport MPC[7]. *Dashed curves* were obtained with fluctuating energy loss, while *solid curves* with averaged energy loss along the jet path. Data[24] from PHENIX (boxes) are also shown for comparable centralities 0-10% and $\approx 30\%$ to guide the eye. (Figure taken from Ref. [26].)

energy loss than with the path-averaged one, while $\sim 10-15\%$ lower $\alpha_s$ with transverse expansion than without it.

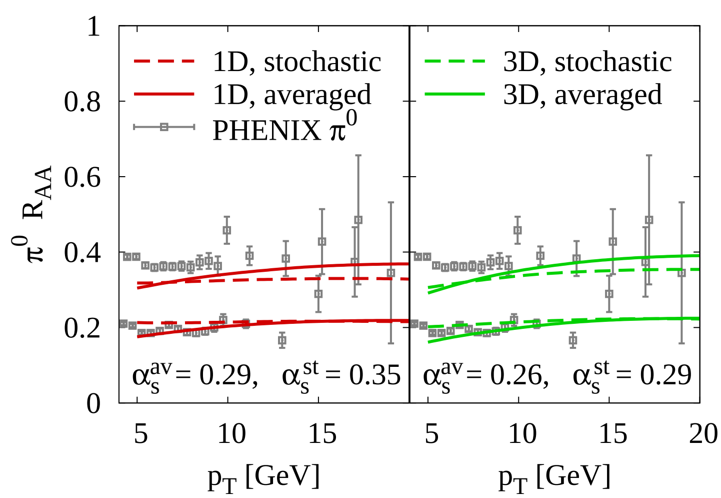


Figure 2: Same as Fig. 1 but with $\alpha_s$ tuned in all four scenarios to reproduce $R_{AA}$ in nearly central ($b = 3$ fm) collisions. (Figure taken from Ref. [26].)

### Elliptic flow in Au+Au at RHIC

Luckily, $p_T$-differential elliptic flow turns out to be a much more sensitive probe of the medium evolution and energy loss treatment. Figure 3 shows our results for neutral pion $v_2(p_T)$ in $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV at RHIC, for fixed $\alpha_s = 0.29$ in all four scenarios. We find that, especially in more peripheral $b = 8$ fm collisions, stochastic energy loss gives smaller elliptic flow both with and without transverse expansion than average energy loss. This is in line with the weaker nuclear suppression for the stochastic case shown in Fig. 1.

On the other hand, transverse expansion *reduces* elliptic flow, and at the same time also gives *smaller* smaller $R_{AA}$ as we have seen in the previous Section. This may seem counter-intuitive at first, but it is also a feature of GLV energy loss. Because the interference term in (1) biases against early scattering in the medium, a jet parton loses more energy if it scatters further away from the production point, which also means the scattering is later in time. Compared to the transversely "frozen" 1D scenario, transverse expansion gives at later times higher densities away from the center, so there is more quenching, but at the same time the medium also rapidly becomes more azimuthally symmetric, so the elliptic flow response is weaker.

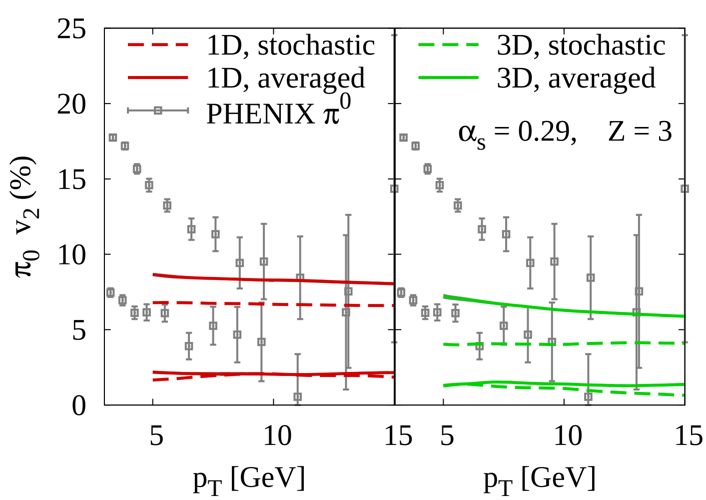


Figure 3: Neutral pion $v_2$ in $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV at RHIC with impact parameters $b = 3$ fm and 8 fm (lower pair of lines vs upper pair of lines, respectively, in both panels) calculated in four different scenarios with GLV energy loss (see text). *Left panel:* transversely frozen density profiles. *Right panel:* realistic transverse expansion modeled with parton transport MPC[7]. *Dashed curves* were obtained with fluctuating energy loss, while *solid curves* with averaged energy loss along the jet path. Data[25] from PHENIX (boxes) are also shown for comparable centralities 0-10% and $\approx 30\%$ to guide the eye. (Figure taken from Ref. [26].)

The reduction of $v_2$ in the 3D case is manifest even after $\alpha_s$ is tuned to reproduce $R_{AA}$ in central collision, as shown in Fig. 4. For both averaged energy and stochastic energy loss, $v_2$ is reduced by $\approx 40\%$ (nearly half!) at high $p_T \sim 10 - 15$ GeV due to transverse expansion. In the more realistic "3D" scenario with both transverse and longitudinal expansion, both averaged and stochastic energy loss give about the same $v_2(p_T)$ at high $p_T$ for both centralities we studied.

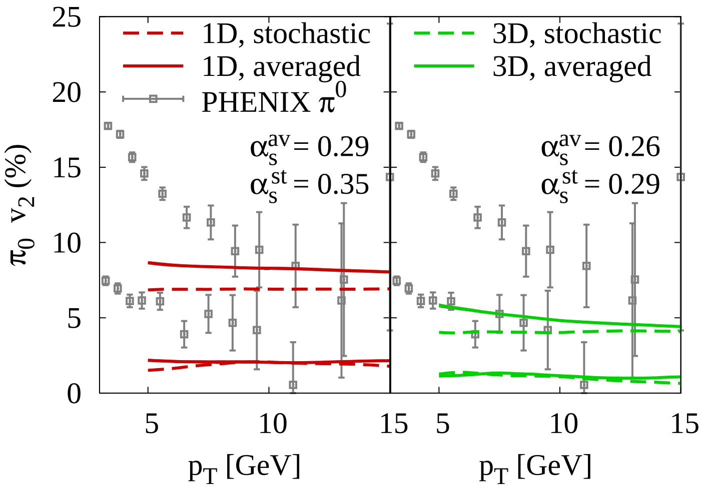


Figure 4: Same as Fig. 3 but with $\alpha_s$ tuned in all four scenarios to reproduce $R_{AA}$ in nearly central ($b = 3$ fm) collisions. (Figure taken from Ref. [26].)

**Nuclear suppression and elliptic flow in Pb+Pb at the LHC**

For brevity we omit here our results (see Ref. [26]) for the nuclear suppression and elliptic flow in Pb+Pb at LHC energies ($\sqrt{s}_{NN} = 2.76$ TeV). The influence of transverse expansion was qualitatively the same as for collisions at RHIC energies. In fact, the reduction of elliptic flow was even somewhat more pronounced than at RHIC.

### 2.1.6 Conclusions

Our most striking and therefore most interesting finding was that with Gyulassy-Levai-Vitev (GLV) energy loss, at both RHIC and LHC energies, realistic transverse expansion strongly suppressed elliptic flow at high $p_T$ compared to calculations with longitudinal Bjorken expansion only (so-called "$v_2$ puzzle"). We identified that this is a generic feature of GLV energy loss, coming from interference bias against early rescattering in the medium.

We also found that transverse expansion enhances high-$p_T$ suppression, while energy loss fluctuations for the stochastic ensemble of scattering centers provided by the transport lead to weaker suppression and smaller elliptic flow. However, unlike the strong reduction of elliptic flow with transverse expansion, these latter effects were less interesting because they almost completely disappeared once calculations were adjusted to reproduce $R_{AA}$ in central collisions. Therefore, we decided to focus on the "$v_2$ puzzle" instead.

Though this calculation lacked a few other effects such as elastic energy loss and multi-gluon emission, the results did indicate a difficulty with the simultaneous description of nuclear suppression and elliptic flow at RHIC and the LHC using GLV energy loss.

## 2.2 Sensitivity to the bulk evolution model

Our result that transverse expansion affected observables strongly was initially received with unexpected scepticism. This was because an earlier estimate in Ref. [12] concluded that GLV energy loss was insensitive to transverse expansion (this was inferred from Fig. 2 therein, which figure, however, has rather large uncertainties), and also new work [27] from the Columbia group claimed simultaneous reproduction of nuclear suppression and elliptic flow with simple pQCD-motivated energy loss formulas and hydrodynamics for the medium. We therefore proceeded to track down the origin of the apparent discrepancy, and demonstrated that the findings of Ref. [27] are largely due to the hydrodynamic solutions used in that calculation for bulk medium evolution that employed unphysical "bag-model" equation of state for the quark-gluon plasma. In addition, we also showed that covariant treatment of GLV energy loss introduces an interplay between jet direction and hydrodynamic flow of the medium, which significantly affects elliptic flow (see Section 2.3).

Results from these calculations were first presented at the Hard Probes 2013 conference.

#### 2.2.1 Comparison using different bulk medium models

For our detailed comparisons we considered two energy loss models. One was GLV as described in Section 2.1.1. The other model was the same parameterized $dE/dL = \kappa\, E^a L^b T^c$ energy loss per path length as in Ref. [27], with their "pQCD-like" set of exponents $a = 1/3$, $b = 1$, and $c = 2 - a + b = 8/3$ ($\kappa$ is then dimensionless). Here $E$ is the jet energy, $T$ is temperature of the medium, and $L$ is the path length traveled by the jet.

To study the sensitivity to the bulk medium evolution, we investigated both GLV and the $dE/dL$ model in **five different dynamical evolution scenarios** for Au+Au at $\sqrt{s_{NN}} = 200$ GeV at RHIC, impact parameter $b \approx 7.5$ fm. Four of these were solutions of boost-invariant 2+1D hydrodynamics using the VISH2+1 code[28], which are available in tabulated form from the TECHQM Collaboration website [29] in two data sets. Set 1 was for a "bag-model" like equation of state (EoS), "fKLN" initial profile motivated by the color glass condensate model, with zero viscosity or constant shear viscosity to entropy density ratio $\eta/s = 0.08$ [30]. The ideal and viscous versions of this set were practically identical for observables studied here, so we only show results for "ideal-fKLN", which was the evolution used in Ref. [27]. Set 2 from TECHQM is a later calculation with more realistic lattice QCD EoS, constant $\eta/s = 0.08$, for fKLN or Glauber initial profile [31]. The fifth model was the same covariant transport evolution as in Section 2.1, computed using MPC/Cascade [7]. The main difference compared to the hydro solutions is that the transport has a massless $e = 3p$ EoS. The transport can also handle far-from-equilibrium dissipative effects that cannot be well captured through viscosity. In the case of GLV energy loss with bulk medium from hydrodynamics, we took for parton density in the fluid rest frame $n = e/3T$, where $e$ is the energy density in the fluid rest frame.

Figure 5 shows the neutral pion $R_{AA}$ (left plot) and $v_2$ (right plot) in $Au+Au$ at RHIC for these scenarios from the $dE/dL$ energy loss model. $R_{AA}$ was essentially the same for all cases because $\kappa$ was dialed to obtain the same suppression at high $p_T$. In all scenarios, elliptic flow was reduced to $\sim 4-5\%$ at high $p_T$, much the same value as what we had found earlier with GLV energy loss[26], *except* for the "ideal-fKLN" evolution studied by Columbia. Thus, we confirmed their result, but also demonstrated that transverse expansion suppresses $v_2$ for a hydrodynamic medium as well if one includes a realistic equation of state.

To test how well the power-law $dE/dL \propto E^a L^b T^c$ formula captures perturbative QCD parton energy loss in the GLV formalism, we repeated the same comparison with GLV energy loss as well. Figure 6 shows neutral pion $R_{AA}$ and $v_2$ for the different bulk medium scenarios. Qualitatively the results are very similar to those in Fig. 5, confirming that the "pQCD-like" exponents in Ref. [27] are a reasonable approximation to GLV energy loss. After fixing $R_{AA} \sim 0.4$ at high $p_T$ (left plot), a residual sensitivity to the bulk evolution still remained in elliptic flow (right plot). The "ideal-fKLN" evolution used in Ref. [27] gave largest $v_2$, almost as large as the results with transversely frozen dynamics in Ref. [26] (solid line). Hydrodynamic solutions with lattice QCD

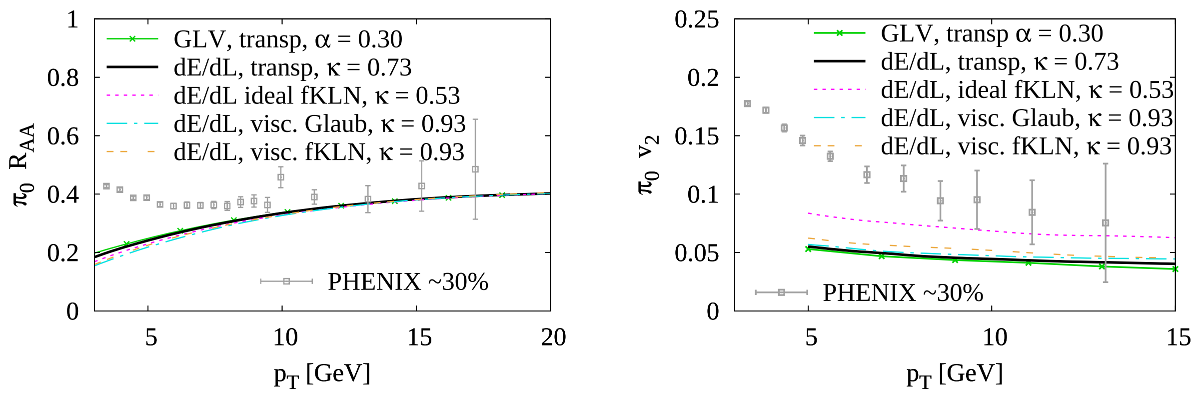


Figure 5: Neutral pion suppression factor $R_{AA}$ (left) and differential elliptic flow $v_2(p_T)$ (right) at midrapidity in mid-peripheral ($b \approx 7.5 fm$) Au+Au at $\sqrt{s_{NN}} = 200$ GeV, calculated using parton energy loss parameterization[27] $dE/dL = \kappa E^{1/3} L^1 T^{8/3}$. Results for four different bulk medium models are plotted (see text): i) ideal hydrodynamics with fKLN initial profile from "Set 1" (dotted); ii) viscous hydrodynamics with $\eta/s = 0.08$ and fKLN initial profile (dashed-dotted); iii) viscous hydrodynamics with $\eta/s = 0.08$ and Glauber initial profile from "Set 2" (double short dashes); and iv) covariant parton transport MPC as in Ref. [26] (solid lines). For comparison, results from Ref. [26] using MPC and GLV energy loss are also shown (solid lines with crosses). In all cases energy loss is scaled to set a fixed $R_{AA} \sim 0.4$ at $p_T \sim 15 - 20$ GeV. As in Ref. [26], data[24, 25] from PHENIX (boxes) are shown to guide the eye. (Figure taken from Ref. [32].)

EoS, on the other hand, gave smaller $v_2$. There was a modest $\sim 15\%$ difference between fKLN and Glauber profiles with viscous hydrodynamics (fKLN is higher), which may help constrain the initial geometry.

### 2.2.2 Conclusions

We investigated the consistency between high-$p_T$ nuclear suppression ($R_{AA}$) and elliptic flow ($v_2$) using Gyulassy-Levai-Vitev (GLV) energy loss or a simpler power-law $dE/dL$ formula, for a variety of bulk evolution models. The results generally confirmed our earlier work [26] that found suppressed elliptic flow for transversely expanding media. However, one exception was the set of hydrodynamic solutions used in Ref. [27] by the Columbia group, which give significantly higher $v_2$ but unfortunately assume unrealistic bag-model equation of state.

## 2.3 Covariant (D)GLV energy loss

During the investigation of the $dE/dL$ model we realized, however, that none of the above calculations, in fact no prior GLV calculation either, observes proper Lorentz covariance because both $dE/dL \propto E^a L^b T^c$ and the energy loss Eq. (1) from GLV give frame dependent results. For example, Ref. [27] evaluated $dE/dL$ using $E$ and $L$ in the laboratory frame of the collision, which was an arbitrary choice. We therefore proceeded with formulating a frame-independent expression of energy loss, based on the requirement that energy loss should reduce to the naive expression in the frame where the fluid is locally static along the path (LR frame).

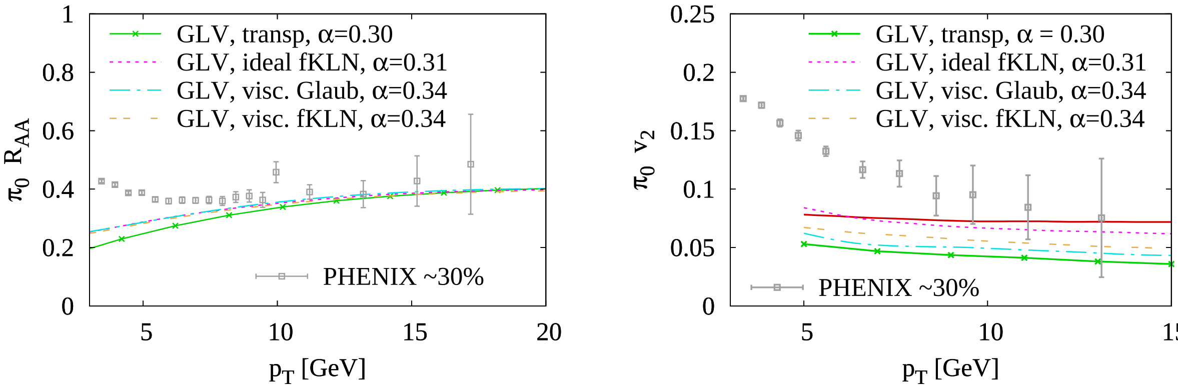


Figure 6: The same as Fig. 5, except calculated using GLV energy loss.The solid line (without crosses) in the right plot now shows $v_2$ from Ref. [26] for transversely frozen, boost-invariant 0+1D medium evolution. (Figure taken from Ref. [32].)

### 2.3.1 Covariant energy loss in massless limit (GLV and $dE/dL$)

For massless partons produced at spacetime point $(0, \vec{0})$, scattering occurs at $L(1, \vec{v})$, which transforms the same way as the four-momentum $E(1, \vec{v})$. Therefore, in the massless case $dE/dL$ is a Lorentz scalar, which means that for the $dE/dL$ model one should have

$$\frac{dE}{dL} = \frac{dE_{LR}}{dL_{LR}} = \kappa\, E^a_{LR}\, L^b_{LR} T^c = \kappa \left[\gamma_F (1 - \vec{v}\vec{v}_F)\right]^{a+b} E^a L^b T^c \;, \tag{11}$$

while for GLV

$$dL_{LR}\, \rho_{LR}\, \sigma = dL\, \rho_{LR}\, \sigma\, \gamma_F (1 - \vec{v}\vec{v}_F) = dL\, \rho\, \sigma\, (1 - \vec{v}\vec{v}_F) \;. \tag{12}$$

Here, $\vec{v}_F$ is the local three-velocity of fluid flow, while $\gamma_F \equiv (1 - v_F^2)^{-1/2}$. In both cases, a new factor appears that couples the motion of the jet to that of the fluid. For GLV this is very similar to the term introduced in Ref. [33], however, in contrast to the results there we find that jet-medium flow coupling has significant effect on observables.

Figure 7 shows neutral pion $R_{AA}$ and $v_2$ in Au+Au at RHIC with $b \approx 7.5$ fm, calculated using covariant $dE/dL$ energy loss. Two features are noticeable immediately. First, with covariant energy loss one needs higher scaling factors $\kappa$ to obtain the same $R_{AA}$. Second, even after setting $\kappa$ to $R_{AA}$ at high $p_T$, $v_2$ is larger with covariant energy loss and shows strong dependence on bulk dynamics. Qualitatively the reason is that jet-medium flow coupling reduces energy loss for jets moving in the same direction as the medium flow, the more the larger the flow velocity. For jets that move in-plane (short direction), flow tends to be larger, so the reduction is stronger. The resulting $v_2$ enhancement largely cancels out the flow suppression due to transverse expansion found in Ref. [26]. We find the largest $v_2$ for the "ideal-fKLN" profile used in Ref. [27].

Very similar results followed with covariant GLV energy loss, as shown in Figure 8. Elliptic flow was a little bit smaller than for the covariant $dE/dL$ model but otherwise it shows the same ordering between the various scenarios.

The covariant GLV and $dE/dL$ results here were first presented at the Hard Probes 2013 conference.

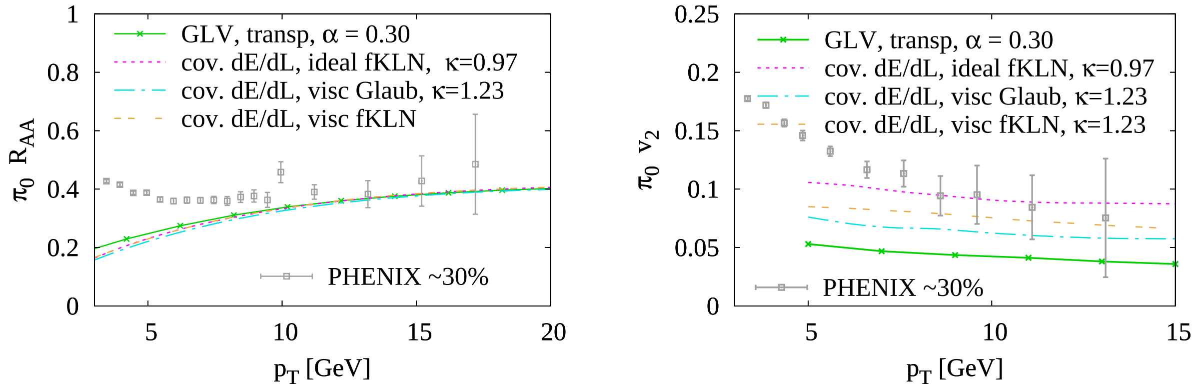


Figure 7: The same as Fig. 5, except for a covariant $dE/dL$ calculation using Eq. (11). (Figure taken from Ref. [32].)

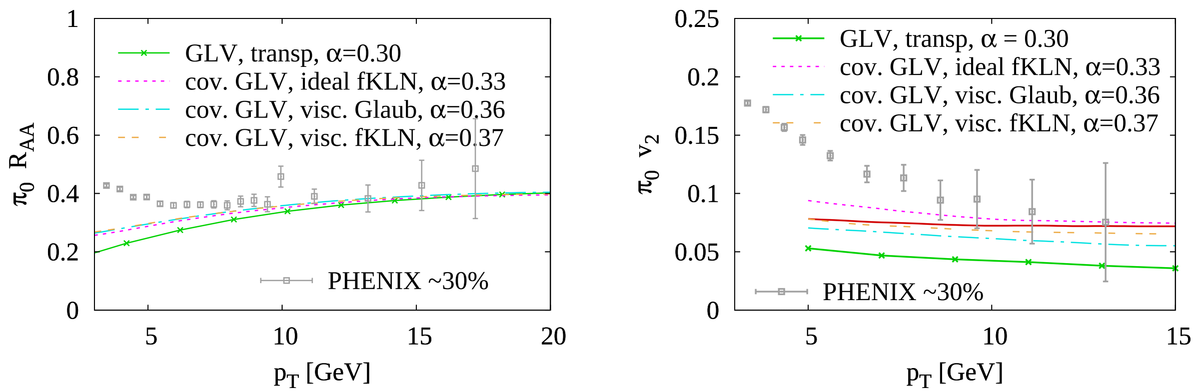


Figure 8: The same as Fig. 6, except with the covariant opacity factor Eq. (11) in the GLV energy loss formula Eq. (1). (Figure taken from Ref. [32].)

### 2.3.2 Covariant DGLV energy loss (massive quarks)

Having realized the importance of medium expansion and covariance in GLV energy loss, it was natural to continue this line of research and include heavy quarks. Heavy quarks provide a stringent cross-check for energy loss theory because, perturbatively at least, the quark mass dependence of energy loss is calculable and, therefore, all model parameters are completely fixed by light hadron observables (there are no free parameters left to dial to match heavy quark observables).

The GLV formalism applies to gluons and light quarks only because it assumes massless partons. An extension to heavy quarks is provided by the Djordjevic-Gyulassy-Levai-Vitev (DGLV) formalism[34, 14]. Even when realistic recoil of medium partons included[14], the result for the spectrum of medium induced gluon radiation at first order in opacity has a form quite similar to the original GLV expression (1):

$$x\frac{dN^{(1)}_{DGLV}}{dx\,d\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\chi\frac{x}{x_+}J\int\frac{d\mathbf{q}}{\pi}\,\frac{\mu^2}{\mathbf{q}^2(\mathbf{q}^2+\mu^2)}\frac{2\mathbf{Q}}{\mathbf{Q}^2+X}\left(\frac{\mathbf{Q}}{\mathbf{Q}^2+X}-\frac{\mathbf{k}}{\mathbf{k}^2+X}\right)(1-\cos\omega z)\ , \quad (13)$$

where

$$\omega\equiv\frac{\mathbf{Q}^2+X}{2Ex}\ ,\quad \mathbf{Q}\equiv\mathbf{k}+\mathbf{q}\ ,\quad X\equiv x_+^2M^2+\frac{(1-x_+)\mu^2}{2}\approx x_+^2M^2\ ,\quad J\equiv\partial x_+/\partial x\ . \quad (14)$$

Here $x_+\equiv(k^0+k^z)/2E$ is the positive fractional light cone momentum of the radiative gluon, and $J$ is a Jacobian between fractional light cone momentum $x_+$ and fractional energy $x$ (see Refs. [34, 38] for more detail). We drop the last term in $X$ so that the massless $M\to 0$ limit reproduces the GLV result (1) apart from the replacement of the strongly screened Yukawa potential term $1/(\mathbf{q}^2+\mu^2)^2$ with the weaker "dynamically screened" form $1/\mathbf{q}^2(\mathbf{q}^2+\mu^2)$ (the $\mathbf{q}\to\mathbf{0}$ limit and integral in (13) are still finite).

After similar averaging over radiated momenta as in Sec. 2.1.1, we write the average radiative DGLV energy loss for scattering at $z$ as

$$\Delta E^{(1)}_{DGLV}(z)=\frac{2C_R\alpha_s}{\pi}\,E\,\chi\,I\left(b=\frac{z}{\tau(z)},\epsilon=\frac{E}{\mu(z)},m\equiv\frac{M}{\mu(z)}\right)\ . \quad (15)$$

The function $I$ is now three dimensional but we can still tabulate it and obtain $I(b,\epsilon,m)$ values via interpolation without major computational challenge.

The energy loss (15) is not covariant because the DGLV result (13) was derived for a medium at rest. Using the same principle as for the massless case we next obtained a covariant DGLV formulation via demanding that (15) applies in the rest frame of the fluid element at the point of scattering $z$. This leads to a similar interplay between medium flow and jet velocity as for massless partons (Sec. 2.3.1). However, the massive case is more involved because the boosts cannot be explicitly calculated in a practical, compact form (e.g., in $dE/dL$ energy loss $dE$ and $dL$ transform differently and their ratio does not stay invariant). Instead, for each line element (12) in the opacity integral (4), the quark momentum has to be boosted numerically to the fluid rest frame, where the DGLV energy loss (15) is evaluated, with which one computes the final quark momentum after energy loss in the fluid rest frame, and then boosts the final quark momentum back to the laboratory frame.

The first results from the covariant DGLV formulation here were presented by graduate student Deke Sun at the 2015 Winter Workshop on Nuclear Dynamics (WWND2015). Figure 9 shows the nuclear suppression and differential elliptic flow for $D$ mesons in Au+Au at RHIC, calculated using DGLV energy loss for charm quarks ($M=1.5$ GeV) followed by independent fragmentation using Peterson fragmentation functions[39] with $\epsilon_c=0.06$ as in Ref. [38]. Three scenarios are contrasted: i) "1D" - medium with longitudinal Bjorken expansion only using original DGLV energy loss (dashed); ii) "3D" - viscous hydrodynamics with both longitudinal and transverse expansion, $\eta/s=0.08$, fKLN initial profile, using original DGLV energy loss (dotted); and iii) "3D covariant" - the same medium as in the "3D" case but using covariant DGLV energy loss (solid lines). In all cases $\alpha_s$ was set to reproduce neutral pion $R_{AA}$ data (after which no free parameters remain). We found negligible difference for $D$ meson $R_{AA}$ between the three scenarios, while the effect on $v_2$ was qualitatively similar to what we found earlier for neutral pions: transverse expansion does reduce elliptic flow for heavy quarks as well, while covariant energy loss increases elliptic flow. Albeit quantitatively both effects were much smaller (only $\sim 10-20\%$) than for neutral pions (nearly factor of 2).

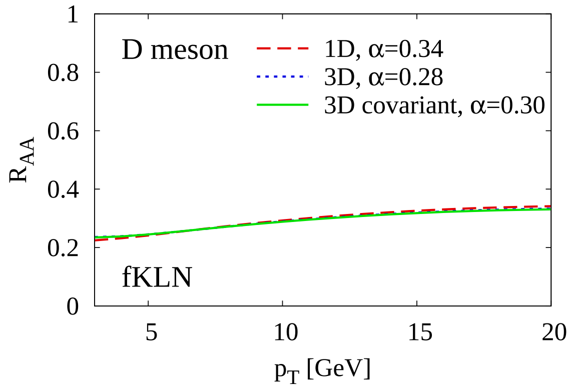


Figure 9: $D$ meson suppression factor $R_{AA}$ (left) and differential elliptic flow $v_2(p_T)$ (right) at midrapidity in mid-peripheral ($b \approx 7.5fm$) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC, calculated using DGLV parton energy loss. Results for three different scenarios are plotted: i) "1D" - medium with longitudinal expansion only, ii) "3D" - original DGLV energy loss with medium expanding both transversely and longitudinally (viscous hydrodynamics, $\eta/s = 0.08$, fKLN profile, same as one of the scenarios in Ref. [26]), and iii) "3D covariant" - same as "3D" but with covariant DGLV energy loss. In all cases $\alpha_s$ is set to reproduce neutral pion $R_{AA}$ data (there are no free parameters left).

The situation for $B$ mesons at RHIC is slightly different as shown in Fig. 10. These results are from an analogous calculation but with quark mass $M = 4.5$ GeV and Peterson parameter $\epsilon_b = 0.006$. There is notable influence of transverse expansion and covariance already in $B$ meson $R_{AA}$ at the 5-10% level up to moderately high $p_T \sim 10$ GeV. The effect on elliptic flow is also much more pronounced. At high $p_T$ we found significant $v_2$ suppression due to transverse expansion, which was nearly fully compensated by the covariant treatment. At low $p_T$, however, the $v_2$ increase due to covariance was much smaller.

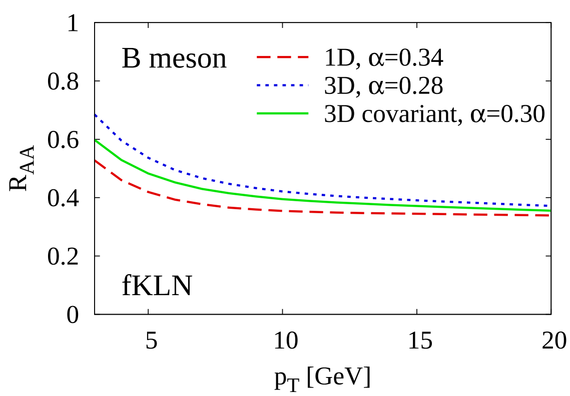


Figure 10: Same as Fig. 9 but for $B$ mesons.

#### 2.3.3 Running coupling

Following the Columbia group [38], we also went beyond fixed coupling calculations and included one-loop running QCD coupling via

$$\alpha_s(Q^2) = \begin{cases} \alpha_{max} & , \quad \text{for } Q < Q_{min} \\ \dfrac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2)} & , \quad \text{for } Q \geq Q_{min} \end{cases} \tag{16}$$

with $\beta_0 = 11 - 2N_f/3 = 9$ (for three light flavors) and $Q_{min} = \Lambda \exp(2\pi/\alpha_{max}\beta_0)$. Here the value $\alpha_{max}$ in the nonperturbative limit is a parameter that replaces the role of the constant $\alpha_s$ value in the fixed coupling treatment, and we set $\Lambda_{QCD} = 0.2$ GeV. As Ref. [38], we use different scales for the three powers of $\alpha_s$ in the DGLV energy loss; namely $\alpha_s^3 \to \alpha_s^2(Q_1^2)\,\alpha_s(Q_2^2)$ with $Q_1^2 = q^2$ for the jet-medium vertices and $Q_2^2 \approx k^2/x_+(1-x_+)$ for the gluon radiation vertex. First results with running coupling were presented by graduate student Deke Sun at the 2015 Winter Workshop on Nuclear Dynamics (WWND2015).

Figure 11 compares neutral pion observables in Au+Au at RHIC from covariant GLV energy loss with (solid lines) and without (dashed) running coupling. For completeness, running coupling effects for the original non-covariant GLV calculation (Sec. 2.1) are also shown (dotted). While $\alpha_{max}$ and $\alpha_s$ were adjusted to best match the $R_{AA}$ data, running coupling had practically no effect on the shape of pion $R_{AA}$ vs $p_T$, and it only reduced $v_2$ by an almost negligible amount. The nuclear suppression and elliptic flow of $D$ and $B$ mesons showed even less dependence on whether running coupling or fixed coupling was used (figures omitted for brevity).

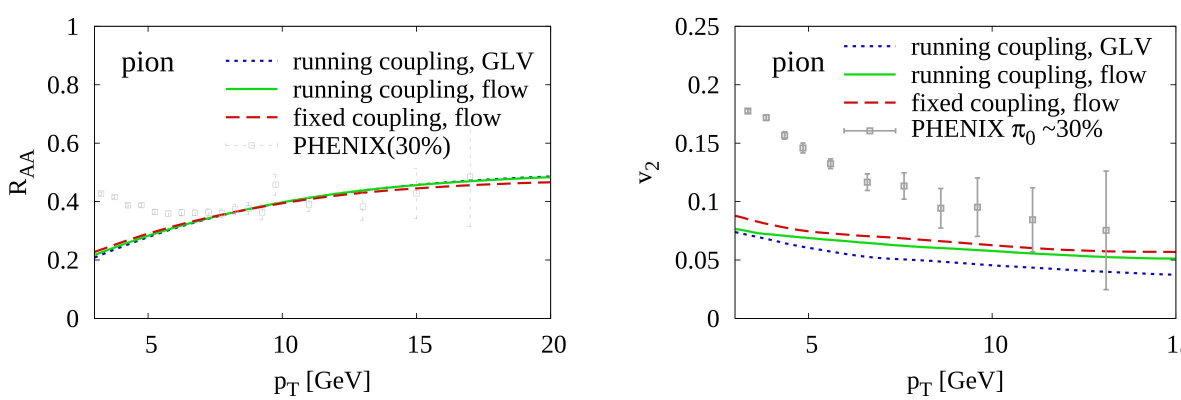


Figure 11: Neutral pion suppression factor $R_{AA}$ (left) and differential elliptic flow $v_2(p_T)$ (right) at midrapidity in mid-peripheral ($b \approx 7.5 fm$) Au+Au at $\sqrt{s_{NN}} = 200$ GeV, calculated using DGLV parton energy loss. For the medium viscous hydrodynamics is used with $\eta/s = 0.08$ and fKLN initial profile (the same medium was also studied in Ref. [26]). Results for three different scenarios are plotted: i) "running coupling, GLV" - the original non-covariant GLV energy loss but with running coupling (dotted); ii) "running coupling, flow" - covariant GLV energy loss with running coupling (solid lines); and iii) "fixed coupling, flow" - covariant GLV energy loss with fixed coupling (dashed). With parameters set to reproduce pion $R_{AA}$ data, $\alpha_{max} = 0.276$ and 0.3 for scenarios i) and ii), respectively. As in Ref. [26], data[24, 25] from PHENIX (boxes) are shown to guide the eye.

At LHC energies the situation was much the same. As shown in Fig. 12, we found negligible running coupling effects for neutral pions in Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV, and similarly no effect from DGLV energy loss on the basic $D$ and $B$ meson observables we studied (latter are not shown for brevity). The main benefit of using running coupling is a reduction in the difference between the coupling values needed to match RHIC and LHC data, albeit we still could not reproduce data sets at both energies using the same $\alpha_{max}$ value. This may be because elastic energy loss was not included (needs to be investigated).

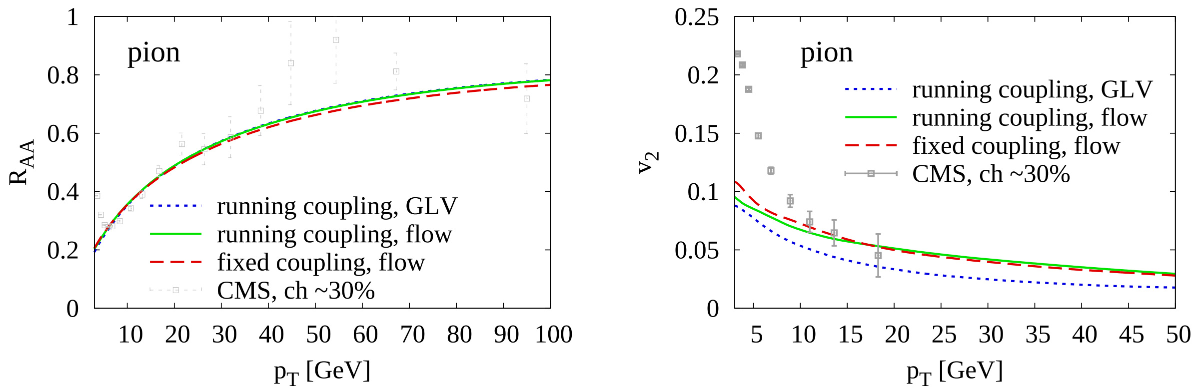


Figure 12: Same as Fig. 11 but for Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV, with viscous hydrodynamic evolution from [40], and CMS data [42, 43] to guide the eye. Parameter values for the running coupling calculations were $\alpha_{max} = 0.21$ (non-covariant GLV) and $\alpha_{max} = 0.23$ (covariant GLV).

#### 2.3.4 Conclusions

Covariant treatment of GLV and DGLV energy loss introduces an interplay between jet direction and hydrodynamic flow of the medium. This largely compensates for the elliptic flow suppression due to transverse expansion we found earlier (Sections 2.1 and 2.2), provided $p_T \gg M$. For charm quarks, transverse expansion and covariance matter less than for neutral pions. For bottom quarks, on the other hand, at low $p_T$ transverse expansion strongly suppresses $v_2$ even when covariant energy loss is used.

We also studied the influence of running coupling in radiative (D)GLV energy loss and found only very small difference between fixed coupling and running coupling calculations at both RHIC and LHC energies on the $R_{AA}$ and $v_2$ of neutral pions, and $D/B$ mesons, once the coupling parameter was calibrated to pion $R_{AA}$ data.

Our results on covariant (D)GLV energy loss also spurred the inclusion of covariance effects in the CUJET-3.0 model by the Columbia group.

### 2.4 Energy loss in small p+A systems

Near the very end of the 5-year period we turned our attention to energy loss in small systems formed in proton-nucleus (p+A) and deuteron-nucleus (d+A) collisions. These are interesting because, shockingly, very central p+Pb events appear to behave hydrodynamically[44] at the LHC at $\sqrt{s_{NN}} = 5.02$ TeV despite the small transverse size. If thermalization occurs because of high opacities, energy loss signatures may be measurable and, thus, provide independent cross-checks of the hydrodynamic interpretation.

Very first results for p+Pb at LHC with covariant (D)GLV energy loss were presented at the April 2015 DNP GHP meeting. Following Ref. [44] we used a small ensemble of fluctuating initial conditions generated via the GLISSANDO package[45], which were then evolved with ideal hydrodynamics using our 2+1D Bjorken boost invariant solver MPC/Hydro. Geometric fluctuations arise because nuclei contain a finite number of nucleons, and also because particle production in an individual nucleon-nucleon collision is a stochastic process. For the 3.4% most central p+Pb events, we found the nuclear suppression factor noticeably below unity (e.g., $R_{AA}$ at 10 GeV is $\sim 0.9$). Whereas harmonic flow coefficients $v_2$ and $v_3$ were nonzero but small at moderately high $p_T \sim 5 - 10$ GeV, less than 1% in magnitude even when geometry fluctuations were included.

## 2.5 Other investigations

In a set of calculations similar to those in Sec. 2.1, we also analyzed event-by-event harmonic flow $v_n \equiv |\langle e^{in\phi} \rangle|$ in 570 simulated Pb+Pb events at $\sqrt{s}_{NN} = 2.76$ TeV at the LHC. These were in fact our most challenging calculations numerically because of the $\mathcal{O}(10^3)$ different geometries involved (the JET Collaboration grant provided only manpower but not computing resources). For bulk medium evolution, our covariant transport solver MPC/Cascade was used with interactions set to model a low viscosity system with $\eta/s \approx 0.1$. This study was interesting because data[46] from ATLAS indicated that harmonic flow coefficients $v_n$ in momentum space strongly follow the corresponding coordinate space Fourier coefficient $\varepsilon_n = |\langle r^2 e^{in\varphi_x} \rangle|$ of the initial geometry in the event, and similar features had been seen in hydrodynamic calculations as well.

Results from the fluctuating initial condition calculation were presented at the Strange Quark Matter 2013 conference. We found (see Fig. 13) that normalized $v_n$ distributions of both low-$p_T$ particles in the bulk medium from the transport and high-$p_T$ pions from GLV energy loss match well, within statistical uncertainties, the event-by-event distribution of the corresponding $\varepsilon_n$ geometry coefficient, for $n = 2$, 3, and 4. This occurred despite the very large fluctuations in the initial geometry with strong "spikes" in initial density that cannot be considered small linear, perturbations over a smooth background.

For $n = 2$ and 3, we also saw strong correlation between the orientation of the harmonic planes in final momentum space and initial coordinate space (phases of $\langle e^{in\phi} \rangle$ and $\langle r^2 e^{in\varphi_x} \rangle$). [The corresponding figures are omitted for brevity.]

The reason these results were not pushed for publication is that these were all obtained using non-covariant GLV energy loss, and shortly afterwards we realized the importance of the covariant treatment. We plan to redo this study with covariant energy loss by the end of the year.

## 2.6 MPC/Eloss package

A major practical outcome of the Purdue work is a numerical jet energy loss package MPC/Eloss, written in C++, which is part of Molnar's Program Collection[4] (MPC). The main executable in the package calculates radiative jet energy loss in the GLV or DGLV approach, with or without covariance, with running or fixed coupling, for an evolving bulk medium (longitudinal Bjorken boost invariance is currently assumed). The medium evolution can be passed to the package as hydrodynamic or transport output (AZHYDRO, VISH2+1, and MPC formats) or, instead,

[4]Historically MPC referred to Molnar's Parton Cascade, but Molnar's Program Collection is now more appropriate because MPC includes two covariant transport solvers MPC/Cascade and MPC/Grid, 2+1D ideal and viscous hydrodynamic solvers MPC/Hydro, a jet energy loss package MPC/Eloss, and other useful heavy-ion physics tools.

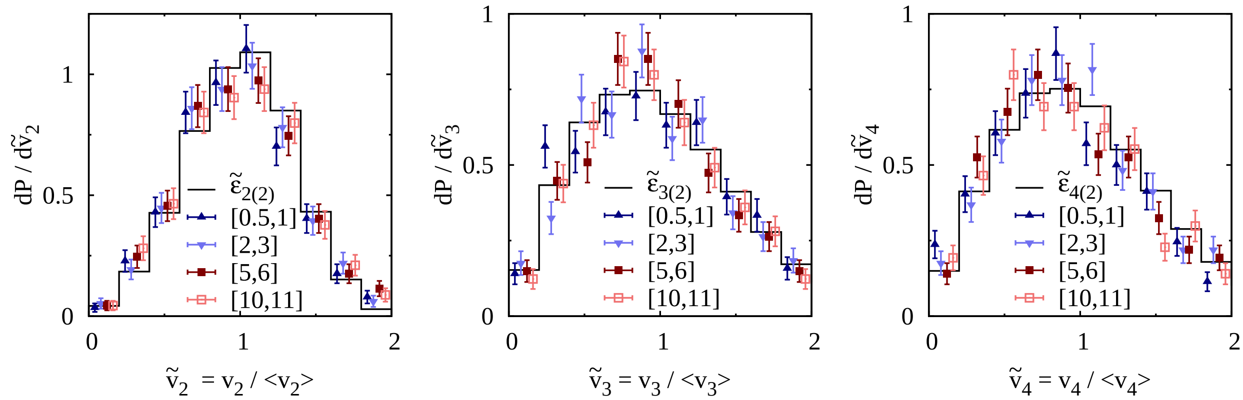


Figure 13: Event-by-event probability distributions of neutral pion $v_2$ (left), $v_3$ (center), and $v_4$ (right) in Au+Au at $\sqrt{s_{NN}} = 200$ GeV with $b = 8$ fm. Distributions for normalized $\tilde{v}_n \equiv v_n/\langle v_n \rangle$ are shown in transverse momentum intervals $0.5 < p_T < 1$ GeV (up-pointing triangles) and $2 < p_T < 3$ GeV (down-pointing triangles) for the bulk medium from covariant transport, and $5 < p_T < 6$ GeV (filled boxes) and $10 < p_T < 11$ GeV (open boxes) for jet fragments from GLV radiative energy loss. Black solid line shows the probability distribution of analogously normalized spatial harmonic coefficients $\varepsilon_{n,2} = \langle x_T^2 \, e^{in\varphi_x} \rangle$.

parameterizations such as expanding Gaussians can be used as in early analytic studies by the Columbia group. The package also contains executables to generate energy loss tables (the $I$ functions), and tools to compute $R_{AA}$ and harmonic flow $v_n$ observables for pions and $D$ and $B$ mesons.

We plan to release the MPC/Eloss package around Labor Day on the Open Standard Codes And Routines (OSCAR) archive maintained by Purdue at http://karman.physics.purdue.edu/OSCAR .

## 2.7 Presentations and publications

Refereed publications and presentations of Purdue research activities funded by the JET Collaboration are listed below. The works on covariant DGLV energy loss and energy loss in small systems are currently being prepared for publication.

**Conferences/workshops:**

1) talk - Denes Molnar & Deke Sun, "Realistic medium averaging in GLV energy loss", Hard Probes, May 27 - Jun 1, 2012, Cagliari, Italy

2) poster - Deke Sun & Denes Molnar, "Realistic medium-averaging in radiative energy loss", Quark Matter, Aug 12-18, Washington DC

3) invited talk - Denes Molnar & Deke Sun, "GLV energy loss in realistic expanding medium", 8th International Workshop on High pT Physics at the LHC, Oct 21-24, 2012 Central China Normal University, Wuhan, China

4) talk - Denes Molnar & Deke Sun, "Hard and soft responses from parton transport", Workshop on Jet Quenching at RHIC vs LHC in Light of Recent dAu vs pPb controls, Apr 15-17, Brookhaven National Laboratory, Upton, NY

5) talk - Denes Molnar & Deke Sun, "Event-by-event correlation between medium and jet flow", Strange Quark Matter, Jul 21-27, 2013, Birmingham, UK

6) talk - Denes Molnar & Deke Sun, "Interplay between bulk medium evolution and (D)GLV energy loss", Hard Probes, Nov 4-8, 2013, Stellenbosch, South Africa

7) poster - Deke Sun & Denes Molnar, "Frame independent formulation of energy loss in evolving bulk medium", Quark Matter, May 19-24, 2014, Darmstadt, Germany

8) invited talk - Denes Molnar, "Jet energy loss and fluid dynamics", Workshop on Jet Modification in the RHIC and LHC Era, Aug 18-20, 2014, Wayne State University, Detroit, Michigan

9) talk - Deke Sun & Denes Molnar, "Interplay between bulk medium evolution and covariant (D)GLV energy loss", 31st Winter Workshop on Nuclear Dynamics (WWND2015), Jan 26-31, 2015, Keystone, Colorado

10) invited talk - Denes Molnar, "Jet quenching and fluid dynamics", 12th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2015), May 19-24, Vail, Colorado

**Seminars:**

1) Denes Molnar, Columbia University, Feb 2, 2013, New York, NY

2) Denes Molnar, Brookhaven National Laboratory, Oct 18, 2014, Upton, NY

**JET Collaboration related publications:**

1) D. Molnar and D. Sun, "Realistic medium-averaging in radiative energy loss," Nucl. Phys. A **910-911**, 486 (2013) [arXiv:1209.2430 [nucl-th)]].

2) D. Molnar and D. Sun, "High-pT suppression and elliptic flow from radiative energy loss with realistic bulk medium expansion," arXiv:1305.1046 [nucl-th], to appear in Phys. Rev. C

3) D. Molnar and D. Sun, "Interplay between bulk medium evolution and (D)GLV energy loss," Nucl. Phys. A **932**, 140 (2014) [arXiv:1405.4848 [nucl-th]].

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# Final Report (2010-2015)

# for the Topical Collaboration on

# Quantitative Jet and Electromagnetic Tomography (JET) of Extreme Phases of Matter in Heavy-ion Collisions

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## Executive Summary

Jet and electromagnetic tomography of QCD matter is based on the principle that the interaction between hard partons and the medium is calculable within perturbative QCD (pQCD) and can be used to probe properties of the strongly coupled quark-gluon plasma (sQGP) in heavy-ion collisions at the relativistic heavy-ion collider (RHIC) and the large hadron collider (LHC). The Topical Collaboration on the Quantitative Jet and Electromagnetic Tomography (JET) of Extreme Phases of Matter in Heavy-ion Collisions (JET Collaboration) funded by DOE during 2010-2015 aims to combine pQCD calculations of parton energy loss, model implementations and realistic 3+1D models of the bulk matter evolution to develop tools that can be used for phenomenological analyses of the experimental data.

During the 5-year funding period (2010-2015), the JET Collaboration carried out a comprehensive research program with coordinated efforts involving all PI members and external associated members according to the plan and milestones outlined in the approved JET proposal. We identified important issues in the study of parton energy loss and made significant progress toward NLO calculations; advanced event-by-event hydrodynamic simulations of bulk matter evolution; developed Monte Carlo tools that combine different parton energy loss approaches, hydrodynamic models and parton recombination model for jet hadronization; and carried out the first comprehensive phenomenological study to extract the jet transport parameter. Specifically, our major achievements during the last 5 years are:

- **Parton energy loss**: We completed a comparative study of modified fragmentation functions from four different approaches to parton energy loss and identified the main source of discrepancy as the collinear approximation in the treatment of gluon radiation. Within the soft-collinear effective theory (SCET), we derived the medium-induced splitting kernels beyond the soft-gluon approximation. We carried out the first complete NLO pQCD calculation of the transverse momentum weighted cross section of semi-inclusive deeply inelastic scattering (SIDIS) and verified the factorization at twist-four. We also calculated the radiative energy loss induced by longitudinal diffusion for both light and heavy quarks. These improvements can be incorporated into the final jet transport MC simulation package.

- **Event-by-event hydrodynamics**: We have developed and refined the 2+1D VISHNU and 3+1 D MUSIC viscous hydrodynamics simulation suites with the UrQMD hadronic after-burner for modeling the event-by-event dynamical evolution of the bulk medium in relativistic heavy-ion collisions. We also developed and tested alternative numerical algorithms for solving hydrodynamic equations and studied anisotropic hydrodynamics for early time non-equilibrium evolution. We developed the code package iEBE-VISHNU and an interface with the Monte Carlo jet shower evolution and hadronization codes for performing jet quenching and jet shape modification studies.

- **Parton recombination model for jet hadronization**: We have developed a hybrid model of parton recombination and remnant string fragmentation including recombination with thermal partons for MC simulations of hadronization of jet showers in heavy-ion collisions. Such a code is an integral part of the MC package for jet transport and hadronization in heavy-ion collisions. A description of heavy flavor hadronization based on recombination and consistent with in-medium scattering rates of heavy

quarks has also been developed and applied for the study of open and hidden heavy flavor hadrons in heavy-ion collisions.

- **Monte Carlo model of jet propagation and evolution**: We made significant progress in developing components of a full Monte Carlo simulation program for jet quenching in an event-by-event hydrodynamic medium including CUJET, High-twist (HT), Linear Boltzmann Transport (LBT), and MARTINI models that couple to the iEBE-VISHNU hydrodynamic code package for bulk evolution. These models plus iEBE-VISHNU are being combined with the parton recombination module for jet hadronization in heavy-ion collisions to produce the final complete Monte Carlo simulation package.

- **Electromagnetic probes of QGP**: An electromagnetic radiation module was developed for the calculation of thermal photon emission from the QGP and hadron resonance gas stages of heavy-ion collisions, with emission rates corrected for viscous effects in the expanding medium consistent with the bulk evolution. This electromagnetic radiation module has been integrated with the iEBE-VISHNU code package and used to calculate photon and dilepton spectra and elliptic flow.

- **Phenomenology and extraction of the jet transport parameter**: As an intermediate step to a full Monte Carlo package for jet quenching, we have assembled an integration of programs that incorporated five different approaches to parton energy loss and suppression of single hadron spectra. With this package, we carried out a first comprehensive study of single hadron suppression in heavy-ion collisions at both RHIC and LHC. We extracted values of the jet transport parameter at RHIC and LHC with significantly smaller theoretical uncertainties than previous studies. Other phenomenological studies of jet quenching, modification of constructed jets, heavy quark transport, collective bulk expansion and novel models of jet-medium interaction such as the sQGMP model were also carried out within each parton energy loss module and hydrodynamic models, respectively.

During the 5-year funding period, the JET Collaboration provided a unique environment conducive for collaborative work among participating scientists and for close interaction between theorists and experimentalists through regular video group meetings, symposia and topical workshops. We closely worked with experimentalists on topics related to both current data analyses and R&D for future experiments and organized 9 workshops and symposia focusing on topics of current interest to the community. We organized 5 annual JET summer schools together with JET Collaboration meetings at member institutions that attracted a large number of graduate students and postdoctoral fellows. We have successfully created 2 JET-bridged faculty positions and funded another junior university faculty position all of whom become active members of the JET Collaboration and young leaders in the field.

Combining different expertise with coordinated efforts, research activities organized by the JET Collaboration and achievements made through both individual PI's and collaborative work within and outside the JET Collaboration have had a great impact on hard probes physics and overall heavy-ion physics worldwide, as evidenced in the large number of publications, conference talks by JET members and citations to the JET collective work.

# 1 Introduction

Jets and electromagnetic probes have been a successful tool to establish the formation of a strongly coupled quark-gluon plasma in high-energy heavy-ion collisions at RHIC and LHC. However, more quantitative study of the properties of the dense matter through these jet and EM probes requires the understanding and reduction of theoretical uncertainties in the description of phenomena such as parton recombination, heavy quark energy loss, path length dependence of the jet quenching and collective medium excitation induced by a propagating jet. The Topical Collaboration on Quantitative Jet and Electromagnetic Tomography (JET) of Extreme Phases of Matter in Heavy-ion Collisions, referred to as the JET Collaboration, was funded by the US Department of Energy during 2010-2015 to address the outstanding challenges in the study of hard probes in high-energy heavy-ion collisions. The goal of the JET Collaboration is to address theoretical and phenomenological challenges for quantitative study of the properties of the dense matter through hard and electromagnetic probes. Specifically, the JET Collaboration was proposed to

(a) Extend the theoretical framework for jet-medium interaction beyond soft and collinear approximations and thereby reduce uncertainties intrinsic to the current theoretical studies;
(b) Develop new and powerful Monte Carlo algorithms for jet propagation and evolution inside a dynamic medium;
(c) Implement in the jet-medium interaction a realistic space-time evolution of the bulk medium as described by a combination of viscous hydrodynamics with parton and hadron cascades;
(d) Carry out systematic phenomenological studies of experimental data on single hadron (including heavy flavors) and photon spectra, multi-hadron and $\gamma$-hadron correlation and jet shape.

According to the proposal submitted to and approved by DOE, the JET Collaboration planned to carry out 5-year collaborative research activities with well defined milestones. The final goals of the JET Collaboration during the proposed 5-year funding period are:

- Extend the calculation of medium induced gluon bremsstrahlung beyond collinear and soft approximation and explore matching schemes connecting collinear and hard gluon radiation, thereby reducing a major theoretical uncertainty in jet tomographic studies.

- Consider hadronization via quark recombination and possible effects of rescattering between hadrons from jet fragmentation and the bulk medium, including the heavy flavor mesons.

- Develop and utilize viscous hydrodynamics and parton and hadron cascade models for a complete description of all stages of the expanding medium; explore applying jet tomography to constrain initial conditions for accurate extraction of shear viscosity within viscous hydrodynamics; study collective excitations induced by jet-medium interaction.

- Develop a general framework and numerical implementations of different approaches to jet modification in a medium, incorporating elastic and radiative energy loss, flavor conversion, quark mass dependence (heavy quarks) and exact four-momentum conservation. Develop Monte Carlo simulation codes in the form of Open Source Codes and Algorithmic Routines (OSCAR) and make them available to the entire heavy-ion community

- Calculate direct $\gamma$ production within NLO pQCD, including effects of parton energy loss, induced gluon bremsstrahlung and gluon conversion. thermal emission from QGP and hadronic phases.
- Calculate jet and high-$p_T$ hadron spectra, multi-hadron and $\gamma$-hadron correlations, and jet shape within NLO pQCD and their medium modification in high-energy heavy-ion collisions. Carry out systematic and quantitative phenomenological studies of experimental data on jet and electromagnetic tomography to extract properties of the sQGP, such as jet transport parameter, shear viscosity, initial temperature and screening mass of the medium.

In addition, the JET Collaboration proposed to organize annual summer schools with pedological lectures that emphasize on basic knowledge and skills in pQCD, multiple scattering in medium, thermal field theory at finite temperature, jet and electromagnetic tomography, experimental heavy-ion physics. The JET Collaboration planned to engage participating students and postdoctoral fellows through coordinated activities and provide joint mentoring of students and postdoctoral fellows. The JET Collaboration also planned to provide a platform for close interaction and collaboration between theorists and experimentalists working on the same problems and provide community-wide service. The JET Collaboration proposed to advance the nuclear theory workforce in the US by leveraging the limited incremental funding from DOE to support graduate students and postdoctoral fellows, and support one or two bridged junior faculty positions at universities that presently have strong experimental programs at RHIC and LHC, but no theorists working in this area.

Over all, we have fully completed the planned research activities according to the timelines outlined in the proposal and achieved all of the scientific goals and beyond. The final product of a comprehensive MC package is being assembled and will soon be publicly available for phenomenological studies. In this report, we describe the research activities and accomplishments by the JET Collaboration during the 5-year funding period, June 1, 2010 - May 31, 2015.

# 2 Manpower and activities supported by the JET Collaboration

The JET Collaboration provided partial funding for two bridged positions, Paul Romatschke at University of Colorado at Boulder and Michael Strickland at Kent State University. It also provided research funding for Abhijit Majumder after he transitioned from a postdoctoral position at the Ohio State University to a junior position at the Wayne State University. JET provided partial support for the following postdoctoral fellows and students during June 1, 2010 - May 31, 2015 (for detailed information on students see reports from university groups):

- Postdoctoral fellows: R. Abir (WSU), A. Buzzatti (LBNL), S. Cao (LBNL), M. Hahrgang (Duke), Z. Kang (LANL), R. D. Neufeld (LANL), A. Majumder (OSU), M. Martinez

(OSU), G. Ovanesyan (LANL), R. Ryblewski (Kent), H. Xing (LANL), J. J. Zhang (LBNL), G. Y. Qin (OSU, Duke, WSU).

- Graduate students (year of Ph. D. awarded or expected):
  Columbia: A. Buzzatti (2013), J. Xu (2015);
  UC Boulder: T. Gorda (2016), M. Habich (2017), R. E. Young (2018);
  Duke: C. Coleman-Smith (2014), D. Yang (2014) , S. Cao (2014), J. Bernhard (2015), J. S. Moreland (2016), Y. Xu (2018), X. Yao (2018), W. Ke (2019);
  KSU: M. Nopoush (201x);
  OSU: Dennis Bazow (2017), J. Liu (2015) , C. Shen (2014) , C. Plumberg (2016), Z. Qiu (2013), D. White (left group in 2012);
  Purdue: D. Sun (2015), D. Hemphill (2015), M. Damodaran (2016), Z. Wolf (2014);
  TAMU: K. Han (2015), F. Li (2015), Y. Sun (2017), Z. Yang (2017), S. Rose (2016), S. Somanathan (2016), G. Chen (2013);
  WSU: G. Kaur ( M.S. 2013), K. Burke (M.S. 2014) , M. Kordell (2016);

The JET Collaboration organized 5 annual JET summers schools and provided local support for student participants, as well as travel and local support for lecturers. The JET Collaboration also provided travel support to all members and some associated collaboration members during Summer Schools and collaboration meetings, and travel support for exchange visits by members and students within the JET Collaboration. The JET Collaboration also organized two symposia on JET physics and 7 workshops. The JET working groups used EVO video conference service for regular meetings; the cost of the service has been provided by JET since 2013 when the service started to charge a fee.

Grants for Duke, OSU, Purdue and TAMU were sent directly from DOE. Support for the bridged position at UC Boulder was sent via a subcontract from LBNL for the first two years (with some forward funding) and converted into a direct grant from DOE for the remainder of the JET funding. Support for the bridged position at KSU and funding for Columbia University and WSU were provided via subcontracts from LBNL. Funding to LBNL supported 50% two postdoctoral positions over two years each, some of the JET Summer Schools, JET Collaboration meetings, workshops, symposia and visits between collaboration members and external associated members.

# 3 Research Activities and Accomplishments

To accomplish the planned goals in the JET proposal and coordinate research activities within the JET Collaboration, we formed 4 Working Groups in 2010-2012:

1. Parton energy loss Working Group: Convener - Abhijit Majumder, Members: N. Armesto, C. Coleman-Smith, M. Djordjevic, R. J. Fries, C. Gale, M. Gyulassy, U. Heinz, W. Horowitz, P. M. Jacobs, S. Jeon, D. Molnar, B. Mueller, J. Owens, G-Y. Qin, R. Rodriguez, C. A. Salgado, B. Schenke, H. Song, C. Shen, X.-N. Wang.

2. Monte-Carlo Working Group: Convener - Björn Schenke, Members: Huichao Song, Xin-Nian Wang, Christopher Coleman-Smith, Steffen Bass, Berndt Mueller, Korinna Zapp, Urs Wiedemann, Abhijit Majumder, Sangyong Jeon, Charles Gale, Carlos Salgado, Nestor Armesto.

3. Bulk Evolution Working Group: Convener - Denes Molnar, members: Steffen Bass, Berndt Mueller, Guangyou Qin, Hanna Petersen, Ivan Vitev, Xin-Nian Wang; Huichao Song, Long-Gang Pang, Deke Sun, Cristina Moody, Ulrich Heinz, Abhijit Majumder, Chun Shen, Zhi Qiu, Daniel White, Che-Ming Ko, Rainer Fries.

4. Parton Recombination Working Group: Convener - Rainer Fries, Members: Guangyao Chen, Kyongchol Han, Ulrich Heinz, Zi-Wei Lin, Che-Ming Ko, Berndt Mueller, Björn Schenke, Xin-Nian Wang

As we made progress in planned research activities, we merged the parton energy loss and Monte Carlo Working Groups in 2013. So from 2013 to 2015 there were three working groups within the JET Collaboration:

1. Monte Carlo Working Group: Convener - Abhijit Majumder, Members: N. Armesto, C. Coleman-Smith, M. Djordjevic, R. J. Fries, C. Gale, M. Gyulassy, U. Heinz, W. Horowitz, P. M. Jacobs, S. Jeon, D. Molnar, B. Mueller, J. Owens, G-Y. Qin, R. Rodriguez, C. A. Salgado, B. Schenke, H. Song, C. Shen, X.-N. Wang, Björn Schenke, Christopher Coleman-Smith, Steffen Bass,Korinna Zapp, Urs Wiedemann, Sangyong Jeon, Charles Gale, Carlos Salgado.

2. Bulk Evolution Working Group: Convener - Michael Strickland, Members: Steffen Bass, Berndt Mueller, Guangyou Qin, Hanna Petersen, Ivan Vitev, Xin-Nian Wang; Huichao Song, Long-Gang Pang, Deke Sun, Cristina Moody, Ulrich Heinz, Abhijit Majumder, Chun Shen, Zhi Qiu, Christopher Plumberg, Che-Ming Ko, Rainer Fries, Paul Romatschke (Convener during 2013-2014).

3. Parton Recombination Working Group: Convener - Rainer Fries, Members: Guangyao Chen, Kyongchol Han, Ulrich Heinz, Zi-Wei Lin, Che-Ming Ko, Berndt Mueller, Björn Schenke, Xin-Nian Wang

Members of each Working Group carried out coordinated research in their respective area and met regularly through internet teleconferences. Associated members of the JET Collaboration and occasionally outside physicists were also invited to the video meetings. Annual collaboration meetings and some ad hoc working group meetings were organized to discuss progress, research results and coordinate community-wide efforts. Results of the research were published in papers that were coauthored by members of the collaboration and external associated members that were involved in the project. In total, members of the JET Collaboration have published 409 papers (34 to be published, including refereed conference proceedings) and gave 551 conference/workshop presentations (these numbers include published 57 papers, 13 submitted papers and 109 talks by members of McGill group who contributed very actively but did not receive direct funding from DOE through JET).

The following are highlights of the accomplishments of the JET Collaboration in the past 5 years.

## 3.1 Parton Energy Loss and Jet Quenching

Eight institutions (Columbia University, Duke University, LANL, LBNL, LLNL, McGill University, OSU, TAMU and WSU) were involved in the study of parton propagation, parton energy loss, jet tomographic and related study of heavy-ion collisions.

**Comparative study of parton energy loss**: We have worked together with the TECHQM group members to continue the work on a comparative study of different parton energy loss models in a simple brick problem. Such a comparative study was necessary to understand the basic differences between different models and their effect in the final tomographic study and it required the collaboration among different groups both within and outside the JET Collaboration. We reviewed the currently available formalisms for radiative energy loss of a high-momentum parton in a dense strongly interacting medium. The underlying theoretical framework of the four commonly used formalisms was discussed and the differences and commonalities between the formalisms were highlighted. A quantitative comparison of the single gluon emission spectra as well as the energy loss distributions were given for a model system consisting of a uniform medium (the Brick) with a fixed length ($L = 2$ fm and $L = 5$ fm). Sizable quantitative differences were found. The largest differences can be attributed to specific kinematic approximations made in the calculation of the radiation spectrum.

**QCD factorization for single inclusive deeply inelastic scattering (SIDIS) at twist-4 in NLO**: Within the framework of the high-twist approach, we calculated the next-to-leading order (NLO) perturbative QCD corrections to the transverse momentum broadening in semi-inclusive hadron production in deeply inelastic $e + A$ collisions, as well as lepton pair production in $p + A$ collisions. With explicit calculations of both real and virtual contributions, we verified for the first time the factorization theorem at twist-4 in NLO for the transverse momentum weighted differential cross section and demonstrated the universality of the associated twist-4 quark-gluon correlation function. Our results provide a first identification of the QCD evolution equation for the twist-4 quark-gluon correlation function, which can be solved to determine the scale dependence of the jet transport parameter in the study of jet quenching.

**Medium-induced splitting kernels from soft collinear effective theory (SCET)**: We derived the splitting kernels for partons produced in large $Q^2$ scattering processes that subsequently traverse a region of strongly-interacting matter, using the recently-developed soft collinear effective theory SCET. We included all corrections beyond the small-$x$ approximation, consistent with the power counting of SCET. We demonstrated how medium recoil, geometry and expansion scenarios, and phase space cuts can be implemented numerically for phenomenological applications. For the simplified case of infinite transverse momentum kinematics and a uniform medium, we derived closed-form analytic results that can be used to validate the numerical simulations. Fig. 1 shows the parton splitting intensity $x(dN/dx)$ for the $q$ to $q + g$ process. The solid black line in Fig. 1 is the result with exact kinematics and recoil of the particles in the medium.

**Angular distributions of higher order splitting functions**: We studied the angular distributions of the final-state partons of higher order, 1 to 3, collinear splitting functions in vacuum and in dense QCD matter. We concentrated our investigation on the illustrative example of the $q$ to $qgg$ splitting. In dense QCD matter we used SCET to derived the medium-induced $q$ to $ggq$ splitting, to first order in opacity, beyond the soft gluon approximation. We found that in all cases the amount of radiation that leaks out of angular

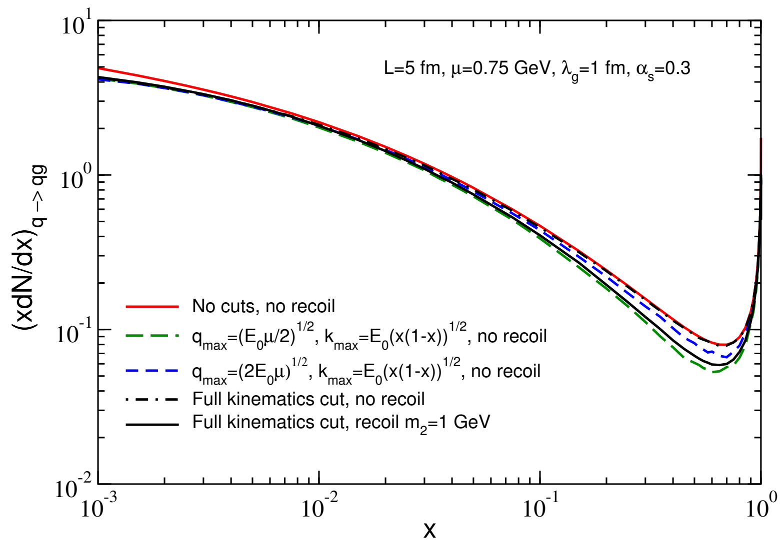


Figure 1: Parton splitting intensity for the $q$ to $q+g$ process in the medium, including finite $x$ corrections, nuclear recoil, finite kinematic cuts. The energy of the quark jet was chosen to be 100 GeV.

ordered cones corresponds to no angular ordering. In fact, standard parton cascade based on binary branchings reproduces very well the distribution of the final-state partons. Our results indicate that the proper angular distributions inside the parton shower are different from the angular ordering ansatz. Still the traditional approach to include angular ordering into collinear splitting functions is claimed to resum infrared large Sudakov logarithms and is phenomenologically successful. One thing to verify is whether or not the amount of collinear radiation that leaks outside of the angular ordered cones leads to a significant correction for parton shower phenomenology. This has to be checked for intra-jet observables, such as jet shapes, of well-isolated jets. The same conclusion holds for the medium induced parton shower. Our detailed analysis found no evidence of angular ordering or angular anti-ordering. An important feature is that the broad angular distribution, noticeably broader than in the vacuum case, found in the lowest order, 1 to 2, branchings persists to higher order.

One example is shown in Fig. 2. We choose the following numerical values: $z_1 = 0.01$, $z_2 = 2/3$ for the light-cone momentum fractions of 2 out of the 3 final-state partons. For the angles of the 2 hard partons we chose 10 and 20 degrees. $\theta_{01}$ is the running angle between the soft gluon and the initial parton is on the horizontal axis. For the in-medium calculation we choose a Debye screening length $\mu = 0.75$ GeV, a size of the medium $L = 5$ fm and a gluon scattering length $\lambda_g = 1$ fm. We see that the medium-induces splitting (black curve) and the medium cascade (green curve) do not show angular ordering or angular anti-ordering. The same is true for the vacuum splitting (red curve). The most characteristic feature is the broad angular distribution that is also found in the lowest order in-medium splitting kernels.

**Energy loss of heavy quarks**: We have made a first attempt to calculate radiative loss induced by longitudinal diffusion within the HT formalism for both light and heavy quarks. We found that, for heavy quarks, both $\hat{q}$ and $\hat{e}$ can stimulate radiation. Also, stimulated emission for heavy quarks is found to be more sensitive to a larger $x$ part of the in-medium

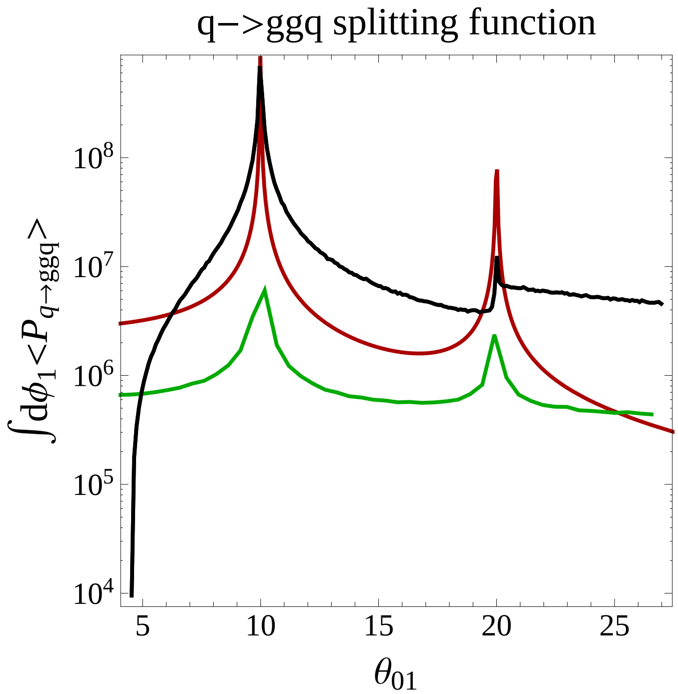


Figure 2: The $q$ to $ggq$ splitting function for 10 and 20 degree opening angles for 2 of the final-state partons relative the original direction. The black line is the result in the medium. The red line is the result in the vacuum and the green line is an unnormalized binary cascade.

transport coefficients $\hat{q}$ and $\hat{e}$. We can further calculate induced transverse diffusion and longitudinal drag induced by multiple scattering .

Within the framework of the Langevin equation, we also studied the evolution and energy loss of heavy quarks in a quark gluon plasma due to quasi-elastic multiple scatterings. The effect of QGP geometry and flow profiles was investigated in details and we found they play important role in heavy quark energy loss and the development of elliptic flow, thus affect the spectra and elliptic flow of final state $D$-mesons and non-photonic electrons. The relative contributions of charm and bottom quarks are found to affect the quenching and elliptic flow patterns of heavy flavor decay electrons. We have further studied heavy quark evolution at LHC energies with the inclusion of elastic collisions as well as medium-induced gluon radiation. Radiative energy loss was found to be very important to heavy quark energy loss, especially at high transverse momentum regime reached by the LHC. Combining with a (2+1)-dimensional viscous hydrodynamic model, we have provided a good description of the measured $D$ meson suppression, and made a prediction for $B$ meson suppression and elliptic flow.

**Radiative energy loss in an evolving bulk medium**: We studied two aspects of the coupling between radiative energy loss and bulk medium evolution. First, continuing past work that combined first-order Gyulassy-Levai-Vitev (GLV) energy loss with realistic expanding bulk medium evolution from the parton transport MPC, we investigated the distribution of harmonic flow coefficients for fluctuating initial conditions in Au+Au at RHIC. For a Monte-Carlo Glauber initial condition ensemble, fluctuations of normalized flow coefficients

$v_n/\langle v_n\rangle$ for $n = 2, 3$ and 4 were *both* for the bulk medium (transport) and pions from the jets (energy loss) largely *independent* of transverse momentum, and followed the distributions of the corresponding normalized initial spatial anisotropy moments. We found best agreement if spatial coefficients were weighted with radius squared in the transverse plane. In addition, the orientation of 2nd and 3rd harmonic planes was also highly correlated with the plane of the corresponding spatial anisotropy coefficient. These features are quite remarkable because initial density fluctuations are by no means small, individual events exhibit spikes that often exceed 3 times the average density at the very center of the collision zone. We also extended the calculation to charm quarks in the DGLV framework and found very similar results. Our findings also agree qualitatively with the behavior of bulk medium flow coefficients seen in ideal and viscous hydrodynamics, so they see that those observations carry over to transport and (D)GLV energy loss as well.

We used our new MPC/Grid radiative transport code to cross-check some of the earlier thermalization results by BAMPS and the $gg \to ggg$ cross section (the infamous factor of 6). We first calculated rates in thermal equilibrium, with Debye-screened LO pQCD matrix elements. For $gg \leftrightarrow ggg$ we compared the Bertsch-Gunion form in BAMPS to the full leading order result. The 2$\to$ 3 rates we find are much lower than those in the BAMPS paper, unless they are multiplied by a factor 5-6. This does seem to support the argument by Chen *et al* that a factor 1/3! has been missed by the BAMPS authors.

## 3.2 Monte Carlo simulation

The Jet propagation and Monte Carlo working group was charged with the development of a comprehensive jet in medium Monte-Carlo event generator, which will include an event by event hydrodynamic simulation coupled with a shower Monte-Carlo routine and jet hadronization. Individual groups have made progress in developing and improving different jet quenching modules with different implementation of parton energy loss and jet-medium interaction models. These different modules will be coupled to a choice of hydrodynamic evolution of the bulk medium and a parton recombination module for hadronization. The last stage of coupling to parton recombination module recently developed is being carried out and the final product will become available soon.

**HT-M Monte-Carlo module**: We have developed an in-medium shower Monte-Carlo event generator based on the higher-twist formalism of jet modification. By undoing one of the light-cone integrals which sets the corresponding light-cone momentum to be equal in the amplitude and the complex conjugate, an uncertainty in the smaller light-cone momentum component was introduced. This allows for the generalization of the standard analytic formalism to a Wigner transform like formalism, where the non-conjugate large light-cone momentum and position are retained for each parton. Jets were generated event-by-event by simulating this Wigner transform kernel.

This model has been applied to study jets in d+Au collisions. The basic Monte Carlo picture of the initial state, which so far has included sampling the Woods-Saxon distribution is extended to the MC sampling of shell model distributions. These are combined with simulations of the deuteron using the Hulthen potential. The nucleon-nucleon collisions are simulated with PYTHIA, and the final hard outgoing partons are modified using the in-medium HT Monte-Carlo. This work will offer the most detailed look at the hard sector in d-Au ever carried out.

Using this in-medium MC event generator, we have also calculated the mean rate of jet mass depletion as a jet propagates through dense matter. Along with energy loss, jet mass depletion allows another means to compare with jets produced in p-p collisions. It has been demonstrated that escaping partons with reduced energies tend to have a much smaller mass than a corresponding parton produced in a hard interaction in p-p collisions.

**MARTINI Monte Carlo module**: For the study of hard parton propagation at finite temperature, MARTINI (Modular Algorithm for Relativistic Treatment of IoN Interactions) event generator was developed, which is a Monte-Carlo simulation based on PYTHIA 8.1 and the AMY (Arnold, Moore, and Yaffe) energy loss formalism. Our work focuses on how finite-temperature effects modify jet observables and the hadronic spectrum in heavy-ion collisions. Bulk dynamics of QGP is implemented using 3+1-dimensional viscous hydrodynamics simulation with event-by-event initial conditions, within MUSIC developed at McGill. Coupling MUSIC with the UrQMD hadronic afterburner and MARTINI is also implemented. The modification of heavy quark properties in QGP, and the modeling of their propagation is also studied. We also investigated finite size effect on the radiative energy loss. This model has been used to explain the di-jet asymmetry.

**Linear Boltzmann Transport (LBT) module** : We have developed a Linear Boltzmann Transport (LBT) model for jet propagation, within which the propagation of jet shower partons and medium excitation are simulated according to a linearized Boltzmann equation with elastic and inelastic parton collisions. The elastic scattering amplitude in pQCD is used with Debye screened propagators. The induced radiation during each elastic scattering is carried out according to the high-twist approach with a Poisson-like multiple emissions. In this approach, both shower and recoiled medium partons are followed after each scattering and go through further scatterings in the medium. To account for the back-reaction in the Boltzmann transport, initial thermal partons that participate in each scattering , or negative partons, are transported according to the Boltzmann equation. Their energies and momenta will be subtracted from all final observables. These negative partons are considered as part of the recoiled partons that are responsible for jet-induced medium excitations. Thermal recoil and "negative" partons are collectively referred to as jet-induced medium partons and will have significant effect on distributions and structures of reconstructed jets. The parton recombination module developed by JET is also incorporated into LBT and is ready for simulations of final hadron spectra from jets propagating and hadronizing in medium.

**CUJET Monte Carlo module**: During the early stage of JET funding period, we constructed a new open source CUJET1.0=DGLV+HTL+Bjorken 1+1D Monte Carlo code to evaluate the jet opacity series in Bjorken 1+1 evolving plasma including dynamical magnetic scattering enhancement effects. We showed that this generalization of the static DGLV opacity series kernel explained quantitatively the heavy quark non-photonic electron data. CUJET1.0 code was further generalized to include multi-scale running QCD jet medium coupling effects in the DGLV scattering kernel and used to show that the surprising similarity of nuclear modification of jets discovered at LHC to that observed at RHIC and which could be quantitatively explained with CUJET1.0 as due to perturbative QCD running couplings at high $Q$ and high $T$.

Based on CUJET1.0, we constructed a much more powerful CUJET2.0 numerical code that coupled for the first time our pQCD based CUJET1.0 model of high $p_T$ jet-medium dynamics to the bulk matter via 2+1D viscous hydrodynamic temperature profiles. The current CUJET3.0 code was further developed to include two novel competing nonperturbative and nonconformal effects near the QCD cross-over transition temperature $T_c \sim 160$ MeV: (1) the suppression of quark and gluon chromo charge degrees of freedom near $T_c \sim 160$ MeV, aka the semi-QGP model and (2) emergent chromo magnetic monopoles near $T_c$, aka the magnetic scenario. This model of jet-medium interaction generalizes the pQCD quasiparticle picture assumed in earlier models to be transformed into an emergent semi-Quark-Gluon-Monopole-Plasma (sQGMP) near $T_c$ that smoothly interpolates and reduces to the perturbative QCD/HTL picture at high $Q \gg T_c$ or $T \gg T_c$ scales. We showed that the enhanced jet-monopole component coupling greatly enhanced the effective $\hat{q}(E,T)$ jet transport coefficient near $T_c$ and solves quantitatively the $v_2$ puzzle while preserving the agreement with the world data on azimuthal averaged $R_{AA}$. We demonstrated furthermore that the generalized DGLV theory of jet energy loss coupled to the emergent sQGMP medium provides a first quantitative, robust, and consistent link between hard jet quenching phenomenon and soft bulk peffect fluidity.

**Semi-analytic jet quenching package**: The study of jet modification in relativistic heavy-ion collisions has entered the quantitative era, aiming for a precise determination of jet transport coefficients via detailed comparison between sophisticated phenomenological calculations and available various experimental measurements. As an intermediate step, we have constructed an integrated computing package for studying jet energy loss in high energy nuclear collisions. Several jet quenching model calculations, which are currently available, have been incorporated in this package including the Higher-Twist-Majumder (HT-M), the Higher-Twist-Berkeley-Wuhan (HT-BW), and the AMY formalism. These are combined with realistic hydrodynamic models for simulating the space-time evolution of a quark gluon plasma created at RHIC and the LHC heavy-ion experiments. Utilizing this package, one may perform calculations for various jet quenching observables, such as the modification of single inclusive hadron production, the correlations between back-to-back hadron pairs, and the energy loss and elliptic flow of heavy flavors, with the flexibility to utilize different jet quenching models and hydrodynamics models, for a large class of centralities for both Au+Au collisions at RHIC and Pb+Pb collisions at the LHC. The package will serve as the first powerful theoretical tool for performing systematic phenomenological study of jet quenching and allow users to compare their own calculations to experimental measurements of various observables. This package was made available to the JET community. It allows the user to pick from a variety of centralities, collision energies and system sizes to run a hydro simulation. Following this, the user, may pick either the AMY or the HT energy loss kernel to calculate the modification of hard jets in this medium. The current version of the code includes single and double inclusive calculations. The user also has the ability to incorporate his or her own fluid dynamical simulation and/or jet quenching model to calculate these observables. First study of jet quenching data and extraction $\hat{q}$ was completed and published. Shown in Fig. 3 is one example of the comparison of HT-M model calculations with experimental data on single hadron suppression at LHC energies.

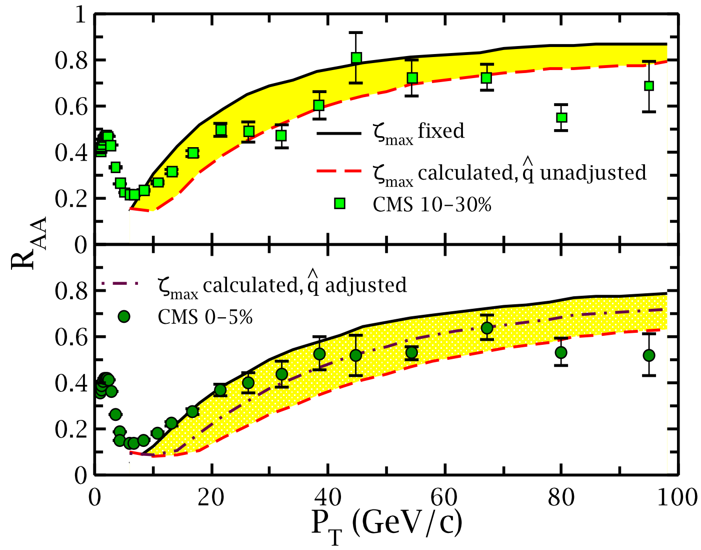


Figure 3: A calculation of the $R_{AA}$ with the HT-M model in the 0-5% most central and 20-30% central Pb+Pb collisions at the LHC compared with CMS data.

## 3.3 Bulk Evolution

The Bulk Evolution Working Group mainly provides quantitative modeling of the bulk medium evolution to enable accurate calculation of hard probe observables. Major theory frameworks pursued are: Viscous Hydrodynamics, Anisotropic Viscous Hydrodynamics and Covariant Transport for Final Hadronic Evolution. The Bulk Evolution Working Group (Bulk WG) consists of twelve PIs and twenty ancillary personnel from nine U.S. and international institutions.

**iEBE-VISHNU hydrodynamic code package:** We developed a Python-based interactive program package that allows users to do their own event-by-event hydrodynamic simulations for heavy-ion collisions, with or without UrQMD cascade afterburner. At the moment the package includes modules for computing the fluctuating initial density profile, for (2+1)-dimensional hydrodynamic evolution with the code VISH2+1 (a module for (3+1)-dimensional evolution with MUSIC is currently under construction), for the computation of spectra and anisotropic flow coefficients from the Cooper-Frye spectra (including all resonance decays if desired), for Monte-Carlo sampling the Cooper-Frye spectra to obtain input for the UrQMD cascade (spectra sampler), and a Python-based analysis module that uses an SQLite data base, in which the results from all event-by-event runs are stored, to compute any soft hadron observable desired. A version that includes a module for computing electromagnetic radiation has also been developed, as is a module for computing HBT correlations. The hydro code was successfully tested against a semi-analytic solution of azimuthally symmetric and longitudinally boost-invariant (1+1)-dimensional viscous expansion, found by Gubser in the Navier-Stokes limit and recently generalized by Marrochio et al. for the second-order Israel-Stewart approach. The spectra sampler was tested against the exact Cooper-Frye spectra, and the sampling routine was optimized for speed and accuracy.

A recent improvement includes multiplicity fluctuations in the initialization module so that experimental multiplicity distributions in pp collisions are correctly described. The package is open to the public at https://u.osu.edu/vishnu.

**MUSIC hydrodynamic simulation**: We have developed a 3+1 dimensional viscous hydrodynamics simulation of relativistic heavy-ion collisions, named MUSIC (MUScl for Ion Collisions). It has been used to describe bulk dynamics of systems created at both RHIC and the LHC, including event-by-event fluctuations and finite shear viscosity. We have also shown that inclusion of the sub-nucleonic fluctuations to be crucial in understanding the details of the anisotropic flow in heavy ion collisions at RHIC and the LHC.

**SuperSONIC**: We have studied alternative approaches towards a realistic viscous hydrodynamics algorithm. We found that the main stumbling block to performing realistic event-by-event heavy-ion medium simulations through 'traditional' hydrodynamics algorithms such as VH2+1 could be removed by performing local smearing of low energy-density regions. This opened up the possibility of performing fully dynamic 2+1d viscous hydrodynamics simulations of heavy-ion and even light-on-heavy ion collisions on an event-by-event basis.

Coupled with first-principles simulations of dynamical equilibration from AdS/CFT and coupled to a late-stage hadronic cascade simulation, this approach has led to the creation of a 'super-hybrid' algorithm of hydrodynamic medium simulations in relativistic ion collisions, dubbed 'superSONIC'. The superSONIC package has been used to simulate $^3\mathrm{He}+Au$ collisions and was an important ingredient in motivating the experimental $^3\mathrm{He}+Au$ program at RHIC. Furthermore, superSONIC (and its predecessor SONIC) have been used to perform super-hybrid simulations of nuclear collisions of C + C, Al + Al, Cu + Cu, Au + Au, and Pb + Pb from $\sqrt{s} = 62.4$ - 2760 GeV, storing the simulated space-time medium information in publicaly available format for use in JET modification simulations of these collision systems. Moreover, superSONIC has been used to simulate collisions of p+Au d+Au, $^3$He+Au and p+Pb for various collision energies ranging from $\sqrt{s} = 7$ GeV to $\sqrt{s} = 5.02$ TeV, making predictions for experimental flow signatures, the limits of hydrodynamic applicability in small systems as well as identifying possible experimental signatures of pre-equilibrium QCD dynamics (see Fig. 4).

**Anisotropic hydrodynamics**: The non-equilibrium evolution of the QGP is complicated because the quark gluon plasma (QGP) is not isotropic in the local rest frame (LRF) at early times and near the edges of the system. To account for these large early-time deviations from local momentum isotropy non-perturbatively, a framework called anisotropic hydrodynamics (aHydro) was developed. Anisotropic hydrodynamics extends traditional viscous hydrodynamical treatments to cases in which the local transverse-longitudinal momentum-space anisotropy of the plasma can be large. The dynamical equations of aHydro were derived from kinetic theory using the zeroth and first moments of the Boltzmann equation in the relaxation time approximation.

At next-to-leading order, one can include deviations from the spheroidal leader-order form. The resulting framework provides non-perturbative dynamical equations for the momentum-space anisotropy ($\xi$), the transverse temperature ($\Lambda$), the LRF velocity ($\mathbf{u}$), and the longitudinal boost-angle associated with the LRF ($\vartheta$). These equations are coupled to an evolution equation for the dissipative corrections generated by $\tilde{\delta f}$. As a way to test to

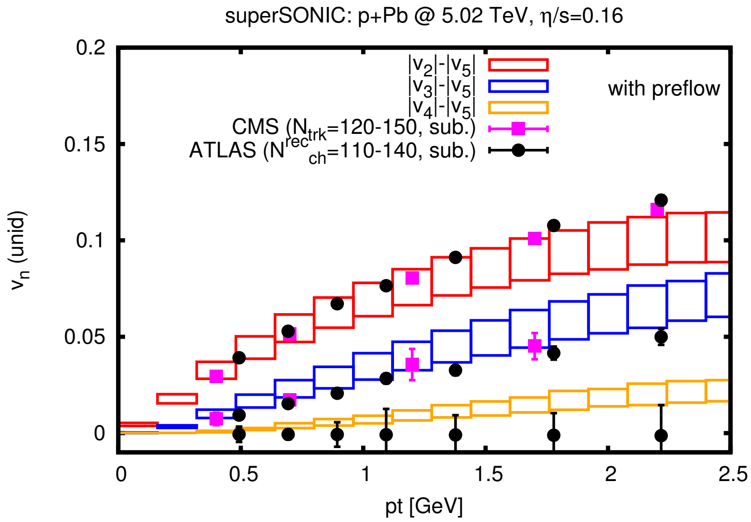


Figure 4: Flow anisotropy coefficients $v_n$ from superSONIC simulations of p+Pb collisions at $\sqrt{s} = 5020$ GeV compared to experimental data from the CMS and ATLAS experiments.

the efficacy of this approach, one can check how well the equations above reproduce exact numerical solution of the Boltzmann equation in the case of transversely homogeneous boost invariant (0+1)d system (see Fig. 5).

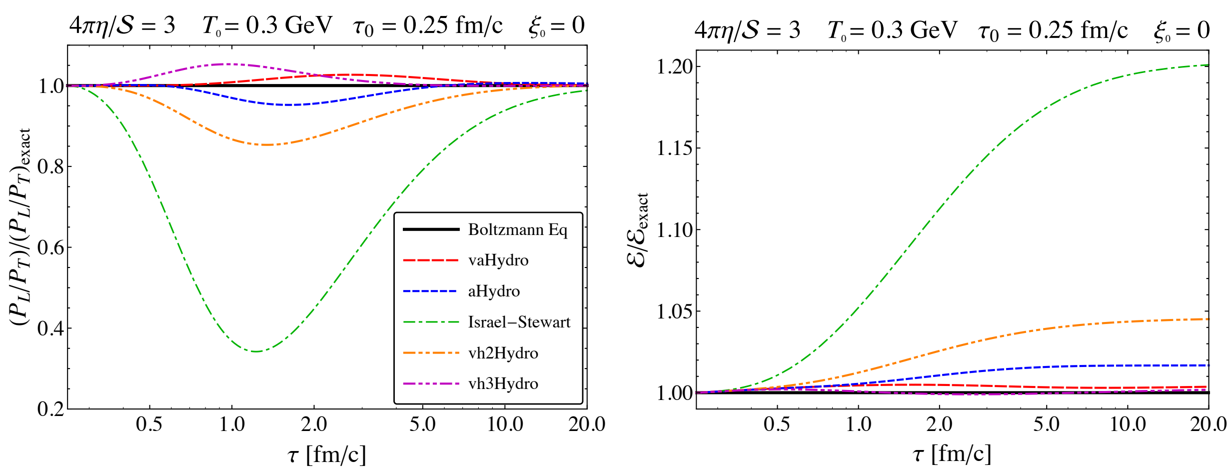


Figure 5: (Color online) Relative error of various dissipative hydrodynamics approaches compared to the exact solution of the (0+1)d Boltzmann equation in relaxation time approximation. The left panel shows the relative error in the pressure ratio and the right panel shows the relative error in the energy density. The legend applies to both panels.

**The Little Bang fluctuation spectrum**: The influence of event-by-event fluctuations in the initial density profile of the fireballs created heavy-ion collisions on the finally observed flow patterns, and the extraction of QGP transport coefficients from flow data, was a focus of attention of the Bulk WG of the JET Collaboration. We found that the flow angles associated with the anisotropic flow coefficients depend on transverse momentum and particle species, and that their fluctuations have a significant and measurable influence on experimentally used anisotropic flow measures. We predicted specific features of the so-called breaking of flow-factorization in two-particle correlations due to these flow angle fluctuations, in conjunction with simultaneous fluctuations of the magnitudes of the anisotropic flow coefficients. Our predictions were successfully verified by the CMS Collaboration in Pb+Pb collisions at the LHC.

**Event plane correlations in high-energy heavy-ion collisions**: Event plane correlations as a function of pseudo-rapidity gap and event-by-event $v_n$ fluctuations in heavy-ion collisions at the LHC are investigated within both the AMPT model and a 3+1D ideal hydrodynamic model. The initial conditions for both models are given by the HIJING model that incorporates a Monte Carlo Glauber model for multiple nucleon interactions and two component model for particle production. Particle production from soft coherent interaction of overlapping nucleons and incoherent semi-hard parton scatterings leads to fluctuations of local energy density in the transverse as well as longitudinal direction. Event plane correlations as a function of rapidity gap are calculated. They are shown to become decorrelated at large rapidity gap due to longitudinal fluctuations in initial energy density and their sensitivity to transport properties of the medium are studied.

**Conversion of viscous fluid to particles**: We studied question of how to properly convert the output of viscous hydrodynamics simulations to hadronic particles. The main challenge in generating particle spectra from viscous hydrodynamics calculations is to determine $\chi_j(p/T)$ in the general form of viscous corrections $\delta f_j \sim \chi_j(p/T)p^\mu p^\nu \pi_{\mu\nu}/[2(e+p)T^2]f_{eq,j}$ for *all* particle species $j$. It is customary to assume quadratic momentum dependence, with a universal coefficient for all hardon species (democratic Grad ansatz). This ignores microscopic hadron gas dynamics, and so introduces uncontrolled errors into comparison of hydrodynamic and hydrodynamics+transport calculations to data and the extraction of medium parameters. We have been addressing this problem in a self-consistent approach based on linearized transport theory, which provides viscous corrections that depend on microscopic interactions in the hadron gas. We calculated the momentum dependence of viscous corrections for different hadron gases, and implemented feeddown from resonance decays so that they can better address observables.

**Initial conditions from classical gluon fields**: We also worked on the question of how to precisely fix the initial conditions necessary for the bulk evolution from classical gluon fields. Previously, we have developed a framework together with J. Kapusta and Y. Li to solve the classical Yang-Mills equations for colliding nuclei analytically for small times. We used this approach to calculate the event-averaged energy momentum tensor of the initial gluon field in nuclear collisions. The two most interesting results of this study are (a) analytic expressions for the time evolution of transverse and longitudinal pressure; (b) analytic expressions for the space-time structure of the transverse flow field. It turns out that Gauss Law mandates the existence of a rapidity-odd flow field that can lead to directed flow in finite impact parameter collisions and to interesting asymmetries in asymmetric collisions systems like Cu+Au and p+Pb. Our results are valid only at the earliest times, up to $\sim 1/Q_s$. However they could be useful, either directly as initial conditions for hydrodynamics with large dissipative stress, or as input for a simulations of thermalizing color fields. While the current analytic results are event-averaged, it is straight forward to construct an event-generator based on this method.

**Mean-field effects in baryon-rich matter**: Within the framework of a multiphase transport (AMPT) model that includes both initial partonic and final hadronic interactions, we have shown that including mean-field potentials in the baryon-rich hadronic matter leads to a splitting of the elliptic flows of particles and their antiparticles, thus providing a partial explanation for the larger $p$ than $\bar{p}$, $K^+$ than $K^-$, and $\pi^-$ than $\pi^+$ elliptic flows observed in the beam energy scan (BES) program at the Relativistic Heavy-Ion Collider (RHIC). Using a partonic transport model based on the Nambu-Jona-Lasinio (NJL) model, we have further found a similar effect on the quark and antiquark elliptic flows from the vector mean field in the baryon-rich quark matter. Results from including both the partonic and the hadronic mean-field potentials in the AMPT model further indicate that an appreciable vector mean field in the partonic matter is needed to describe the observed elliptic flow differences between particles and their antiparticles. To further understand the properties of baryon-rich quark-gluon plasma, we have used both the quantum linear response theory and the semi-classical Vlasov equation to study the growth rate of its unstable modes due to the spinodal instability.

## 3.4 Electromagnetic Probes of QGP

Photons and dileptons rarely interact with the medium in which they are produced, owing to the smallness of the fine structure constant. Hence, they constitute clean probes of QGP properties and the details of its evolution in heavy ion collisions. With the realistic hydrodynamics background provided by VISH2+1 MUSIC, we have been investigating the effect of initial states as well as the effect of non-zero viscosities in photon and dilepton productions.

**Photon and dilepton emission**: One of the major goals of our efforts has been understanding the direct photon puzzle. RHIC and the LHC data have shown that the direct photons flow as strongly as the hadrons. This is puzzling in the sense that one would expect that photons would be produced mainly in the early times when anisotropy of the system is not so pronounced. Therefore getting both the spectrum of the direct photons and the elliptic flow of the photons is a very stringent test of our understanding of the photon production.

We have completed and published the derivation of viscous corrections to the thermal photon emission rates from all 2-to-2 scattering processes in both the QGP and the chemically non-equilibrated late hadronic phase. The new rates, together with our viscous hydrodynamic evolution code, have enabled the first theoretical prediction of higher-order anisotropic flow coefficients for thermal photons, and shed new light on the physical interpretation of the experimentally measured large inverse slope parameters for thermal photons at RHIC and LHC. We find that state-of-the-art calculations of thermal photon emission under-predict the soft photon yield in the transverse momentum distribution, the thermal photon elliptic and triangular flow, and they over-predict the slope of the centrality dependence of the total thermal photon yield. All these observations point to missing brightness of our thermal medium during its late hadronic stage and/or the phase transition region. With our latest efforts, we are very close to resolving this puzzle.

Dileptons have an important additional feature – the invariant mass – which can be tuned to the energy and/or the time scale of interest. Anticipating more detailed data soon to be released by the LHC experiments, we have made predictions showing the importance of the viscosities as well as the initial state flow and also the effect of the color suppression near $T_c$.

**Jet-triggered photons**: We have previously reported on our project to devise ways to identify photons from interactions of jets with quark gluon plasma. Those photons are an important but elusive probe of jet-medium interactions. It is difficult to extract them from either the single inclusive direct photon spectrum or the elliptic photon flow. We have suggested to use jets as triggers and to look for photons emitted from Compton back scattering of the away-side jet off QGP. Over the past year we have worked out corrections to this process due to energy loss of the trigger jets. With the currently available data the residual signal from Compton back-scattering is small, but improvements in jet reconstruction techniques in heavy ion collisions could increase the signal to background ration in the future.

## 3.5 Parton Recombination

A dedicated Parton Recombination (PR) working group, convened by R. J. Fries, has existed since the beginning of the JET collaboration. Its charge was to work out a general formalism for quark recombination of jet showers in vacuum and in a medium, and to implement it in an event-by-event Monte Carlo code. The working group has met regularly online. Over the past year the meetings were usually shared between the QR and the shower Monte Carlo working group. A first version of the JET hadronization MC code via parton recombination is now implemented in JET shower MC codes.

**Jet fragmentation via shower parton recombination**: We have studied hadron production in jets by applying quark recombination to jet shower partons on an event-by even basis. We augment perturbative vacuum jet showers, for example those obtained from PYTHIA, by additional non-perturbative effects like gluons splitting into quark-antiquark pairs. We then apply an instantaneous recombination model in phase space, using Wigner functions for mesons and baryons, to calculate the recombination probability for pairs or triplets of quarks and antiquarks. The hadron Wigner functions are based on harmonic oscillator potentials, with quarks modeled as Gaussian wave packets which leads to overlap integrals which are positive definite and amenable to Monte Carlo techniques. We throw dice to determine recombined hadrons from those probabilities. Subsequently we connect leftover partons with strings which are treated according to the Lund fragmentation model (as incorporated in PYTHIA). We have computed hadron spectra in $e^+ + e^-$ collisions at $\sqrt{s} = 200$ GeV. Including contributions from resonance decays, we have found that the resulting longitudinal and transverse (with respect to the jet axis) momentum spectra for pions, kaons, and protons reproduce reasonably those from the string fragmentation as implemented in PYTHIA.

**Jet fragmentation in the presence of a hot medium**: We have extended our jet shower hadronization model to include hadron production from quenched jets in the quark-gluon plasma produced in heavy ion collisions. In this case shower partons have to be propagated to the $T = T_c$ hyper-surface. The thermal quark distribution on the critical surface is sampled and recombination probabilities of all possible quark/antiquarks pairs and triplets are considered as long as they contain at least one shower parton. An enhanced production of intermediate-momentum hadrons is obtained as a result of the recombination of shower partons from quenched jets with thermal partons in the quark-gluon plasma.

## 3.6 Jet Quenching Phenomenology

During the funding period, we carried out a wide range of phenomenological studies of jet quenching in heavy-ion collisions using models and Monte Carlo codes developed within each group individually and collaboratively within JET. The following are some highlights.

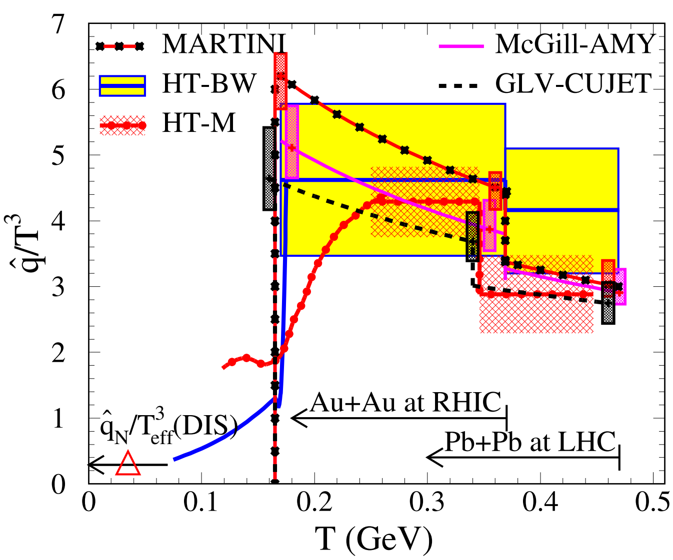


Figure 6: Scaled jet transport parameter $\hat{q}/T^3$ in different jet quenching models for an initial quark jet with energy $E = 10$ GeV at the center of the most central A+A collisions at an initial time $\tau_0 = 0.6$ fm/$c$ . Errors from the fits are indicated by filled boxes at three separate temperatures at RHIC and LHC, respectively. The triangle indicates the value of $\hat{q}_N/T^3_{\rm eff}$ in cold nuclei from DIS experiments.

**Extraction of jet transport parameter at RHIC and LHC**: With a package that combined different parton energy loss models as implemented in pQCD parton model and realistic 2+1D or 3+1D hydrodynamic model for bulk evolution, we carried out a first comprehensive study of suppression of single hadron spectra. Within five different approaches to parton propagation and energy loss in dense matter, a phenomenological study of experimental data on suppression of large $p_T$ single inclusive hadrons in heavy-ion collisions at both RHIC and LHC was carried out, see Fig. 6. The evolution of bulk medium used in the study for parton propagation was given by 2+1D or 3+1D hydrodynamic models which are also constrained by experimental data on bulk hadron spectra. Values for the jet transport parameter $\hat{q}$ at the center of the most central heavy-ion collisions are extracted or calculated within each model, with parameters for the medium properties that are constrained by experimental data on the hadron suppression factor $R_{AA}$. For a quark with initial energy of 10 GeV we find that $\hat{q} \approx 1.2 \pm 0.3$ GeV$^2$/fm at an initial time $\tau_0 = 0.6$ fm/$c$ in Au+Au collisions at $\sqrt{s} = 200$ GeV/n and $\hat{q} \approx 1.9 \pm 0.7$ GeV$^2$/fm in Pb+Pb collisions at $\sqrt{s} = 2.76$

TeV/n. Compared to earlier studies, these represent significant convergence on values of the extracted jet transport parameter, reflecting recent advances in theory and the availability of new experiment data from the LHC.

**$\gamma$-triggered jet suppression**: We have studied the medium modification of $\gamma$-tagged jets in high-energy heavy-ion collisions within a Linearized Boltzmann Transport model for jet propagation that includes both elastic parton scattering and induced gluon emission. Inclusion of recoiled medium partons in the reconstruction of partonic jets is found to significantly reduce the net jet energy loss. Experimental data on $\gamma$-jet asymmetry and survival rate in Pb + Pb collisions at LHC can be reproduced. Medium modifications of reconstructed jet fragmentation function, transverse profile and energy flow outside the jet-cone are found to be sizable especially for $\gamma$-tagged jets with small values of $x = p_T^{jet}/p_T^{\gamma}$. $\gamma$-jet events with different values of $x = p_T^J/p_T^{\gamma}$ can be used as jet quenching tomography tools. It is found that larger $x$ jets are mainly produced from the surface of the medium, while smaller $x$ jets are from those jets which have traversed longer distance of medium. Combined with the momentum spectrum of the $\gamma$-tagged jets, this leads to stronger suppression and centrality dependence for larger $x$ jets, and weaker suppression (or enhancement) for smaller $x$ jets.

Two puzzling features in the experimental study of jet quenching in central Pb+Pb collisions at the LHC are explained within a linearized Boltzmann transport model for jet propagation. A $\gamma$-tagged jet is found to lose about 15% of its initial energy while its azimuthal angle remains almost unchanged due to rapid cooling of the medium. The reconstructed jet fragmentation function is found to have some modest enhancement at both small and large fractional momenta as compared to that in the vacuum because of the increased contribution of leading particles to the reconstructed jet energy and induced gluon radiation and recoiled partons. A $\gamma$-tagged jet fragmentation function is proposed that is more sensitive to jet-medium interaction and the jet transport parameter in the medium (see Fig. 7).

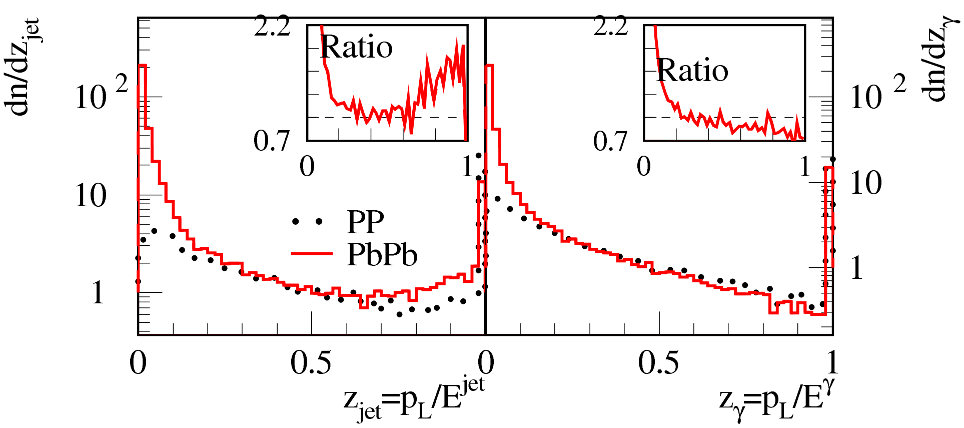


Figure 7: The reconstructed (left) and $\gamma$-tagged jet fragmentation functions (right) within a jet cone $R = 0.3$ of $\gamma$-tagged jets in central (0%–10%) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV.

**Jet mass evolution in a dense medium**: Using the in-medium MC event generator, which was developed within JET based on the higher-twist formalism of jet modification, including a space-time dependent information along with momentum information for all the partons in the shower, we have calculated the mean rate of jet mass depletion as a jet propagates through dense matter. Along with energy loss, jet mass depletion allows another means to compare with jets produced in p-p collisions. It has been demonstrated that escaping partons with reduced energies tend to have a much smaller mass than a corresponding parton produced in a hard interaction in p-p collisions.

**Single hadron suppression at LHC within the HT-M model**: We have improved the standard calculation of single inclusive calculation in the HT formalism. Two different extreme calculations of the mean length traversed by surviving jets has been carried out. This length controls the virtuality of the jet on exit from the medium. Using this range of exit virtualities, one calculates the the multiple emission evolved medium modified fragmentation function in a 2+1 D viscous hydro.

$Z_0$**-tagged jets**: Electroweak bosons produced in conjunction with jets in high energy collider experiments is one of the principle final-state channels that can be used to test the accuracy of perturbative Quantum Chromodynamics calculations and to assess the potential to uncover new physics through comparison between data and theory. In proton-proton reactions at LHC (see Fig. 8) we elucidated up to $\mathcal{O}(G_F\alpha_s^2)$ the constraints that jet tagging via the $Z_0/\gamma^*$ decay dileptons provide on the momentum distribution of jets. In nucleus-nucleus reactions (see Fig. 9) we demonstrated that tagged jets can probe important aspects of the dynamics of quark and gluon propagation in hot and dense nuclear matter and characterized the properties of the medium-induced parton showers in ways not possible with more inclusive measurements. We gave specific predictions for the anticipated suppression of the $Z_0/\gamma^*$+jet production cross section in the quark-gluon plasma that is expected to be created in central lead-lead collisions at the LHC relative to the naive superposition of independent nucleon-nucleon scatterings.

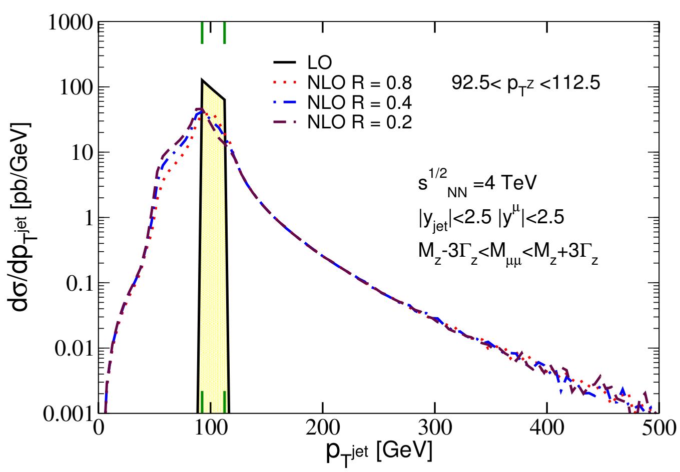


Figure 8: The distribution of jets associated with a $Z_0$ tag (via its dilepton decay channel) at lowest and next-to-leading orders for $\sqrt{s} = 4$ TeV in p+p collisions at the LHC. At LO the pT of the jet is well-determined. At NLO, large uncertainty $\pm$ 25% arises from radiative processes.

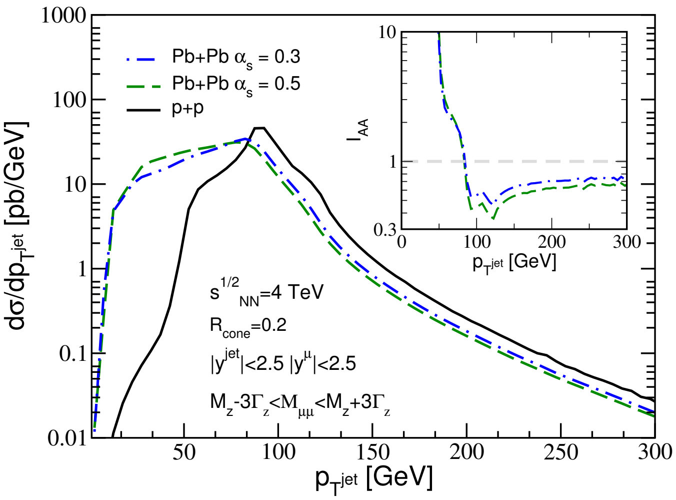


Figure 9: The modification of jets associated with a $Z_0$ tag in central Pb+Pb collisions at the LHC. We find suppression for momenta larger than the momentum of the $Z_0$ and string enhancement for lower momenta. The insert shows the final-state QGP induced modification that depends on the jet cone radius.

**Photon-tagged light and heavy meson production at RHIC and LHC**: We also studied the photon-triggered light and heavy meson production in both p+p and A+A collisions. We found that a parton energy loss approach that successfully describes inclusive hadron attenuation in nucleus-nucleus reactions at RHIC can simultaneously describe well the experimentally determined photon-triggered light hadron fragmentation functions. Using the same framework, we generalized our formalism to study photon-triggered heavy meson production. We found that the nuclear modification of photon-tagged heavy meson fragmentation functions in A+A collision is very different from that of the photon-tagged light hadron case. While photon-triggered light hadron fragmentation functions in A+A collisions are suppressed relative to p+p, photon-triggered heavy meson fragmentation functions can be either enhanced or suppressed, depending on the specific kinematic region. The anticipated smaller energy loss for $b$-quarks manifests itself as a flatter photon-triggered $B$-meson fragmentation function compared to that for the $D$-meson case. We made detailed predictions for both RHIC and LHC energies. The LHC example is shown in Fig. 10. We concluded that a comprehensive comparative study of both photon-tagged light and heavy meson production can provide new insights in the details of the jet quenching mechanism.

$b - \bar{b}$ **jets and photon-tagged** $b$**-jets**: We have now had the opportunity to extend the results for inclusive b-jets to photon-tagged b-jets. Jets tagged by photons or electroweak boson $(W, Z)$ are particularly well suited to studying heavy-ion collisions since the tagging particle escapes the region of strongly-interacting matter unscathed. For example, the CMS collaboration measurements in lead-lead (Pb+Pb) collisions show absence of significant modification of high transverse momentum photon production relative to the binary collision-scaled proton-proton (p+p) result within the current statistical and systematic uncertainties. Thus, in the collinear factorization approach gammas can provide, on average, constraints on the energy of the away-side parton shower. Furthermore, jets tagged by photons or elec-

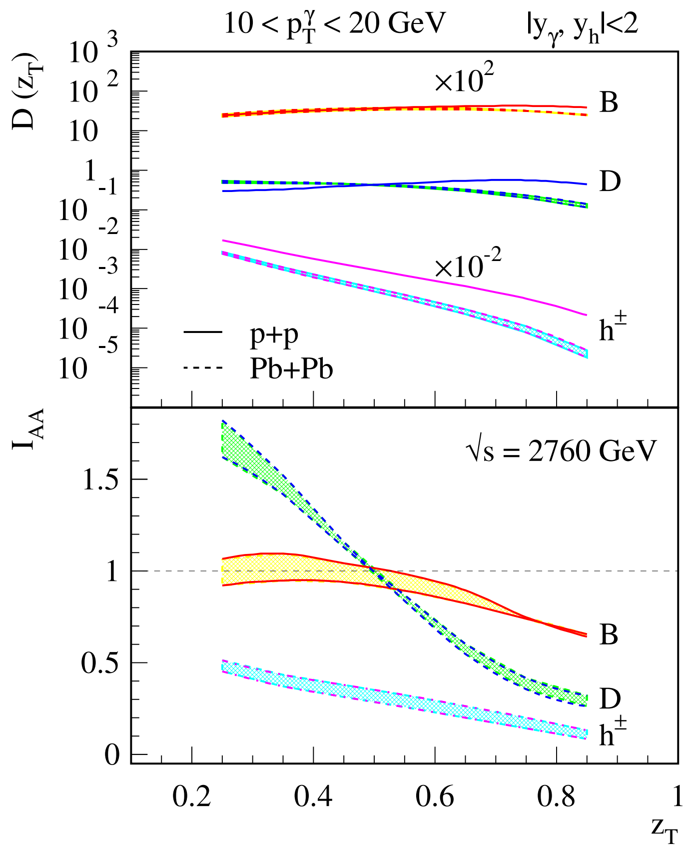


Figure 10: Top panel: predictions for the photon-triggered fragmentation functions, where the solid lines are for proton-proton collisions at center of mass energy 2.76 TeV. Bottom panel: predictions for the nuclear modification factor, where the solid lines are for $B$-mesons, the dashed lines are for $D$-mesons, and the dash-dotted lines are for charged hadrons.

troweak bosons are largely unaffected by the fluctuations of the soft hadronic background that may complicate the interpretation of di-jet modification in heavy-ion collisions. We also extended the calculation to $B$-meson tagged $b$-jets.

We predicted the 2-D nuclear modification $R_{AA}$ and the related momentum imbalance shift of isolated-photon-tagged and $B$-meson-tagged $b$-jets in Pb+Pb collisions at $\sqrt{s} = 5.1$ TeV at the LHC, see Figure 10 for example. We validated the Pythia 8 simulations of tagged b-jet cross sections in nucleon-nucleon collisions through comparison of photon-tagged b-jet results at $\sqrt{s} = 1.96$ TeV from the Tevatron. We also found that particle tagging can significantly increase the fraction of recoiling $b$-jets that originate from prompt $b$-quark relative to the inclusive b-jet case. While in the latter case this fraction can be as low as 20%, $B$-meson tagging in particular can increase the contribution of prompt $b$-quarks to 70-80%. In Pb+Pb collisions in the LHC we further considered the medium-induced parton shower in the soft gluon energy loss limit and any additional dissipation of its energy in the QGP due to collisional interactions. We found significant nuclear suppression when the trigger particle momentum is similar to the $b$-jet momentum $p_T^B$ $p_T^j$ . A modest 5-10% increase in the transverse momentum imbalance for $\gamma + b$-jet production in Pb+Pb collisions is predicted from our calculations, depending on the specific kinematic cuts, which is slightly smaller than that observed for gamma+light jet production. For $B$-tagged $b$-jets we found an even larger suppression of the double differential cross section since both the jet and the tagging b-quark lose energy. On the other hand, the asymmetry variable $z_{jB}$ in $B + b$-jet production shows a slight increase from p+p to A+A collisions, a behavior quite different from the one observed in dijet asymmetry distributions. By using the flexibility of b-jet tagging, comparison of upcoming experimental measurements to theoretical calculations, such as the ones presented here, can provide us with unique new insights into heavy flavor dynamics in the strongly-interacting plasma. In the future, we expect that the theoretical uncertainty of b-jet production in nuclear matter can be further reduced by going beyond the current radiative energy loss approximations and by including higher order computations for multiple scattering with full account of heavy quark mass effects.

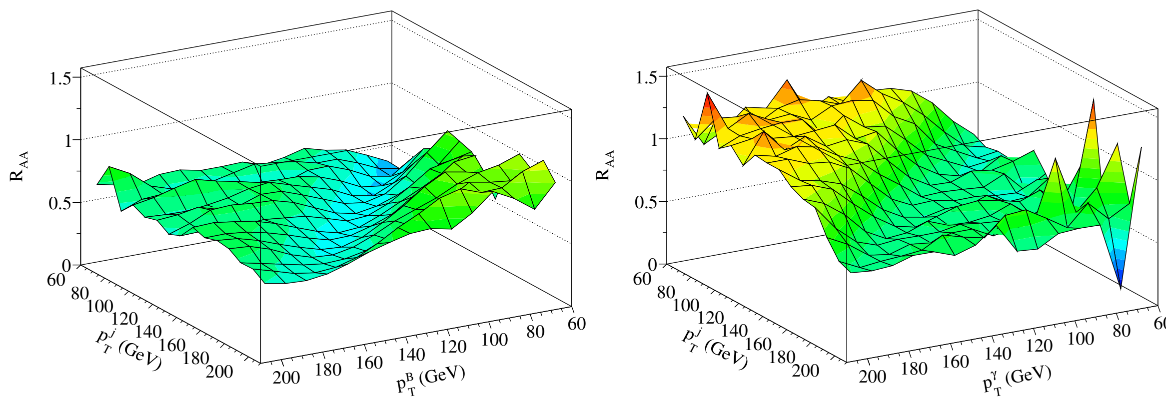


Figure 11: Left: The nuclear modification factor $R_{AA}$ for $\gamma$+$b$-jet production in Pb+Pb collisions at LHC at $\sqrt{s} = 5.1$ TeV is plotted as a function of the $b$-jet transverse momentum $p_T^j$ and the photon $p_T^\gamma$. Right: $R_{AA}$ for $B$-meson-tagged $b$-jet production as functions of $b$-jet $p_T^j$ and $B$-meson $p_T^B$.

**Di-jet asymmetry in Pb+Pb collisions at the LHC**: We developed a model for jet quenching and in-medium energy transport with the goal of understanding the physics mechanisms for the modified di-jet asymmetry $A_J$ in Pb+Pb collisions at the LHC observed by ATLAS and CMS. The model treats radiative energy loss in the perturbative higher-twist formalism and collisional energy loss as a deterministic process involving longitudinal energy degradation and transverse momentum diffusion. The radiated gluons are allowed to interact with the medium via elastic collisions resulting in energy degradation and transverse momentum diffusion. Gluons that fall below a certain energy threshold are considered as thermalized. The model contains three parameters: the transverse momentum diffusion coefficient $\hat{q}$, the longitudinal energy loss parameter $dE/dx$, and the thermalization threshold $E_{\text{cut}}$. The medium geometry is treated schematically using a Glauber model profile of the hot medium.

We found that the model can nicely explain the shift of the $A_J$-distribution from a shape sharply peaked at $A_J = 0$ to one that shows a broad shoulder at $A_J \approx 0.6$ as observed by CMS. We could not reproduce the peak at $A_J = 0.6$ seen in the most central ATLAS data (but neither could anyone else's model!). The required energy loss parameters are in quite good agreement with those needed to explain the RHIC jet quenching data (mainly $R_{AA}$), with linear entropy density (multiplicity) extrapolation to Pb+Pb collisions at the LHC.

**CUJET3.0 and jet transport coefficient**: Using the most recent version of jet quenching model CUJET3.0 that incorporated a novel model of semi-Quark-Gluon-Monopole Plasma (sQGMP) with non-conformal and non-perturbative dynamical effects near $T_c$, we have carried out a systematic study of single hadron spectra suppression and azimuthal anisotropy simultaneously. The results of the study lead to to several highly nontrivial findings: a consistent and robust description of both bulk perfect fluidity and high $p_T$ jet quenching phenomena; a strong increase of $\hat{q}/T^3$ (see Fig. 12) accompanied by a strong decrease of $\eta/s$ toward $T_c$; that provides a simultaneous description consistent with *all* current high $p_T > 10$ GeV $R_{AA}$ and $v_2$ data at RHIC and the LHC for both light and heavy flavor jets. Future tests on small $p+p$ and $p+A$ systems will be important to test and constrain the dynamical details of sQGMP state of matter produced in high energy $B+A$ nuclear collisions at RHIC and LHC. The CUJET3.0 link between high $p_T$ jet quenching and low $p_T$ perfect fluidity is particularly exciting because it shows that demanding robustness and consistency between these two classes of observables at RHIC and LHC may eventually provide the strongest experimental evidence for the existence of the cross over deconfinement transition from hadronic degrees of freedom toward partially deconfined but still strongly coupled and screened sQGMP chromodynamic degrees of freedom as $T$ crosses $T_c$, as predicted by lattice QCD.

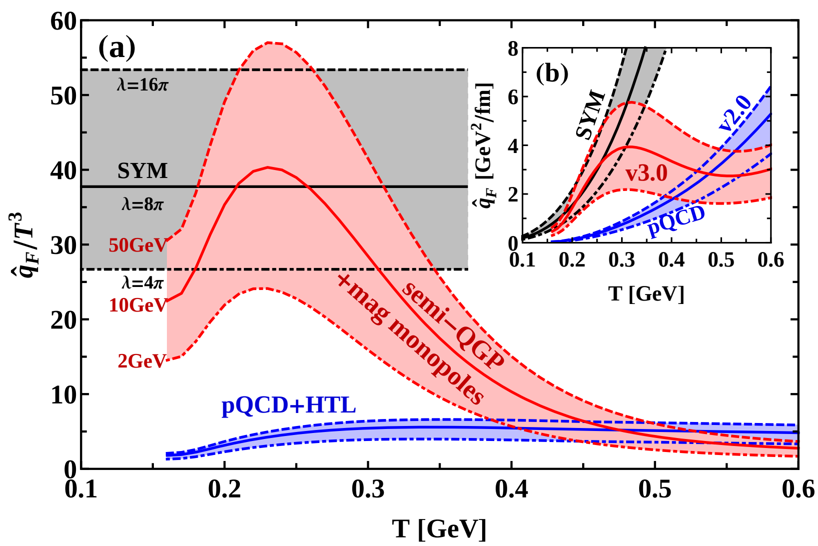


Figure 12: Temperature dependence of (a) the dimensionless jet transport coefficient $\hat{q}/T^3$ and (b) $\hat{q}$ for a quark jet with energy $E = 2, 10, 50$ GeV, from CUJET3.0 (red) assuming an sQGMP medium compared to CUJET2.0 (blue) pQCD+ HTL medium, and to a $\mathcal{N} = 4$ Super Yang-Mills (SYM) 5D Black Hole.

**Predictions for p+Pb at 5 TeV** We coordinated a community-wide effort to compile predictions by JET Collaboration members and external associated members for the $p$+Pb run at the LHC in the winter of 2013. Predictions include charged hadrons; identified particles such as $\pi^0$, $K^{\pm}$, and $p/\overline{p}$; photons; jets; $J/\psi$; and gauge bosons. The observables included individual distributions, ratios such as $R_{p\mathrm{Pb}}$, and correlation functions. The paper in which these predictions were compiled was submitted and published in International Journal of Modern Physics E before the $p$+Pb run began.

# 4 Collaboration Events

The JET Collaboration organized annual JET Summer Schools and JET Collaboration meetings during each year of the funding period. We also organized two symposia, several topical workshops and topic group meetings. The following is the list of collaboration events in chronological order. Details of these schools and meetings can be found at the JET website: http://jet.lbl.gov.

- **JET Summer School 2010**
  Date: June 14-17, 2010
  Place: Lawrence Berkeley National Laboratory, Berkeley, California
  Local Organizer: X.-N. Wang
  Number of students: 63
  Description: The first JET Summer School was held with 6 series of lectures in both theory and experiment. Since this is the first JET Summer School, the lectures focused on pedagogical lectures in pQCD and over view of experimental status. Each day was supplemented with few short student seminars on their current research. We had total 63 registered participants in the JET Summer School, 41 of the participants received full local support from the JET Collaboration. The overall rating for the Summer School Program by the participating students are very positive. According to the exit survey, students rated the overall Summer School program 4.16 (out of 5) and many thought the Summer School learned something new about JET physics (4.39 out of 5) and increased their interest in JET physics (4.26 out of 5).

- **JET Inaugural Symposium 2010**
  Date: June 18, 2010 Place: Lawrence Berkeley National Laboratory, Berkeley, California
  Organizers: P. Jacobs, V. Koch, B. Müller, X.-N. Wang (Chair) and Y. Feng
  Number of Participants: 71
  Description: We also held a one-day inaugural Symposium on Jet and Electromagnetic Tomography of Dense Matter on June 18, 2010, immediately following the JET Summer School, with 15 invited speakers and 71 registered participants. The symposium provided an overview of the past achievements and future challenges in the JET physics. Discussions focused on strategies and collaborative effects that are needed to use JET for future quantitative studies of the properties of the sQGP in heavy-ion collisions at RHIC and LHC.

- **Collaboration Meeting 2010**
  Date: June 14-17, 2010
  Place: Lawrence Berkeley National Laboratory, Berkeley, California
  Local Organizer: X.-N. Wang
  Description: All PI members of the JET Collaboration attended the JET Symposium

and the JET Collaboration meeting. During the collaboration meeting we have discussed the physics problems that we plan to study within the framework of the JET Collaboration. We decided to form 4 working groups each focusing one set of problems as outlined in the JET Proposal. These working groups and the respective conveners played a crucial role in coordinating research activities across the JET Collaboration. We agreed to form the Collaboration Council. One representative PI from each institution. We have agreed to add two more associated members to the JET Collaboration: William Horowitz and Ralf Rapp. Both have agreed to become JET associate members after having been approved by the JET Collaboration Council. In the meantime, Björn Schenke has left McGill university and started a postdoctoral position at BNL. The Collaboration also voted to make him an associated member of the JET Collaboration.

- **JET Summer School 2011**
  Date: June 15-17, 2011
  Place: Duke University, Durham, NC
  Organizers: S. Bass and B. Müller
  Number of students: 23
  Description: The JET Summer School 2011 at Duke University had 7 series of lectures in both theory and experiment. The lectures focused on jet physics within pQCD and experimental techniques of jet studies. The school was supplemented with two short sessions with student seminars on their current research.

- **JET Collaboration Meeting 2011**
  Date: June 18-19, 2011
  Place: Duke University
  Local Organizers: S. Bass and B. Müller
  Description: Following the JET Summer School, DOE carried out a mini-review of the JET Collaboration which was followed by the second JET Collaboration meeting during June 18-19, 2011. During the collaboration meeting we reviewed the progress and discussed the physics problems and adjustment to the program and organization of the JET Collaboration. We agreed to form a NLO working group.

- **Jets @ RHIC Mini-workshop 2012**
  Date: March 3-4, 2012
  Place: Duke University, Durham, NC.
  Organizers: S. Bass and B. Müller
  Number of participants: 18
  Description: The Jets@RHIC Mini-workshop was organized at the Duke University to investigate the future opportunities of jet physics at RHIC. The workshop is motivated by discussion with experimentalists about future potential and opportunities at RHIC. We discussed various aspects of jet physics that are unique in the RHIC energy regime and specific theoretical calculations that can be made within the JET Collaboration to illustrate the physics opportunities at RHIC.

- **JET Collaboration Meeting 2012**
  Date: June 14-15, 2012
  Place: McGill University, Montreal, Canada
  Local Organizer: C. Gale and S. Jeon

Description: The third annual JET Collaboration meeting was held at McGill University prior to the 2012 JET Summer School. Conveners of the working groups gave progress reports and several young people gave talks on their latest work. With the progress made in each working group, we felt it was time to integrate all different studies into a single MC simulation package. This requires the merging of all different efforts. We spent most of the time discussing how to integrate the different efforts over the next 2 years. We identified Abhijit Majumder to be the convener of this coordinated effort and decided on the strategy for the end-game and the funding scheme.

- **JET Summer School 2012**
  Date: June 16-18, 2012
  Place: McGill University, Montreal, Canada
  Organizers: C. Gale and S. Jeon
  Number of students: 30
  Description: The third JET Summer School was held at McGill University during June 16-18, 2012. There were 19 hours of lectures given by 7 lecturers in 3 days, on topics ranging from jet physics in QCD, hydrodynamics and heavy quarks to experimental study of jet physics. The summer school was attended by 30 students from around the world.

  **Workshop on Jet Modification in the RHIC and LHC era 2012**
  Date: August 20-23, 2012
  Place: Wayne State University, Detroit, MI
  Organizers: T. Cormier, A. Majumder (Chair), C. Pruneau, J. Putschke, S. Gavin and S. Voloshin
  Number of Participants: 40
  Description: The JET Collaboration co-organized the Quark Matter 2012 Satellite Workshop on Modification in the RHIC and LHC era during August 20-23, 2012 at Wayne State University. The goal of this 3.5-day satellite meeting was to review the most important new experimental measurements and theoretical breakthroughs presented at Quark Matter 2012, and to critically address the question whether a consistent picture of jet quenching has emerged.

- **JET Collaboration Meeting 2013**
  Date: June 10-11, 2013
  Place: The Ohio State University, Columbus, OH
  Local Organizer: U. Heinz
  Description: The JET Collaboration meeting was held before the JET Summer School 2013. Conveners from working groups and delegates from individual member institutions gave progress reports, the iEBE interactive software package for event-by-event hydrodynamic + cascade evolution on demand was presented to the Collaboration and demonstrated in a tutorial, and the status of the jet quenching software package and jet-hydro interface was reported with a demonstration. In the morning of the second day we heard 5 talks by experimentalists on the latest progress on jet reconstruction with the PHENIX and STAR detectors at RHIC and the ALICE, ATLAS and CMS detectors at the LHC. In the afternoon, short presentations from each group of their plans for the coming year were followed by specific work assignments and a discussion of how to best integrate the various efforts in preparation of the end game of the

Collaboration during Year 5.

- **JET Summer School 2013**
  Date: June 12-14, 2013
  Place: The Ohio State University, Columbus, OH
  Organizer: U. Heinz
  Number of students: 43
  Description: The fourth JET Summer School was held at The Ohio State University. Over a period of 3 days, 7 lecturers from the US and Europe (4 theorists and three 3 experimentalists) delivered 19 hours of lectures on electromagnetic signatures, jet medium modification and jet quenching, initial fluctuations and hydrodynamic evolution, and the ridge in pp, pA, and AA collisions at RHIC and LHC. The summer school was attended by 43 students and young postdocs from around the world.

- **The 2nd Workshop on Jet Modification at RHIC and LHC era 2013:**
  Date: August 22 -23, 2013
  Place: Wayne State University, Detroit, MI
  Organizers: A. Majumder, J. Putschke and C. Pruneau
  Number of Participants: 25
  The JET Collaboration sponsored the Second Workshop on Jet Modification at RHIC and LHC era at WSU during Aug. 20-22, 2013. The goal of this meeting was to review the most important new experimental measurements and theoretical breakthroughs that have occurred in the past year and to throughly explore the limits of perturbative QCD based approaches to the description of hard processes in heavy-ion collisions. Over the period of three days, topics covered will include new experimental observables that may discern between different perturbative approaches, the inevitable transformation of analytic schemes to Monte-Carlo event generators, and the progress made towards Next to Leading Order calculations of energy loss. We also had a work-fest meeting focusing on future perspective of jet physics at RHIC.

- **JET Collaboration Meeting on NLO Calculation and MC Simulations 2013**
  Date: August 22-23, 2013
  Place: Wayne State University, Detroit, MI
  Local Organizer: A. Majumder
  Description: An additional JET Collaboration meeting was held at WSU during Aug. 22-23, 2013 where we developed the main idea behind the first comprehensive study of jet quenching using the integrated package of jet quenching programs and extracting values of $\hat{q}$. We also had a working group meeting on NLO parton energy loss.

- **JET at RHIC Strategy Meeting 2013**
  Date: August 24-25, 2013
  Place: Wayne State University, Detroit, MI
  Organizer: A. Majumder
  Number of Participants: 20
  Description: The JET Collaboration organized a strategy meeting on jet-modification at RHIC at Wayne State University. The goal of the meeting was to chart out a road map of what needs to be done theoretically and experimentally to carry out an un-

ambiguous extraction of jet transport coefficients $\hat{q}$, $\hat{e}$, their temperature dependences and any other transport coefficients that may be discerned by jet modification.

- **Workshop on NLO Energy Loss 2014**
  Date: March 3-14, 2014
  Place: Lawrence Berkeley National Laboratory, Berkeley, CA
  Organizers: X.-N. Wang and B. Xiao
  Number of participants: 14
  Description: The JET Collaboration held a small working group meeting on NLO jet energy loss at Lawrence Berkeley National Laboratory from March 3 to 14., 2014. This was a small informal meeting with active experts in this subfield to discuss recent progresses and near term challenges on calculation of parton energy loss and momentum broadening at the next-to-leading order (NLO). Only 1-2 talks were scheduled each day and the rest was devoted to informal and in-depth discussions.

- **JET Collaboration Meeting 2014**
  Date: June 17-18, 2014
  Place: UC Davis, Davis, CA
  Local Organizer: R. Vogt
  Description: The JET Collaboration Meeting was held at UC Davis during the summer of 2014. Working Group conveners and some individual PI gave reports on the progress of JET projects. We discussed in particular the final version of the report on the extraction of $\hat{q}$ from RHIC and LHC experimental data with the semi-analytical JET package and possible plans to continue the JET Collaboration after the funding period.

- **JET Summer School 2014**
  Date: June 19-21, 2014
  Place:UC Davis, Davis, CA
  Organizers: D. Cebra, M. Calderon, X.-N. Wang and R. Vogt (Chair)
  Number of students: 26
  Description: The fifth JETSummer School was held at UC Davis. There were 26 registered students at the summer school from 14 institutions, both domestic and international. Most of the lecturers gave 3 hour-long lectures each but two of the experimental talks, on bulk properties, were one hour each. The interactions between students and lecturers was very good. There were also four student seminars on the last afternoon.

- **The 3rd Workshop on Jet Modification at RHIC and LHC era 2013:**
  Date: August 18 - 20, 2014
  Place: Wayne State University, Detroit, MI
  Organizers: A. Majumder, J. Putschke, C. Pruneau and Rosi Reed
  Number of Participants: 30
  The JET Collaboration sponsored the Third Workshop on Jet Modification at RHIC and LHC era at WSU during Aug. 19 -20, 2014. This 3 day international workshop was held to review the most important new experimental measurements and theoretical breakthroughs in the study of quark-gluon plasma using the modification of jets. The workshop was slow paced with a mixture of longer invited talks and shorter contributed

talks, allowing sufficient time for discussion, as well as time to follow up on more technical aspects of the data analysis and theoretical calculations.

- **JET Closing Symposium 2015**
  Date: June 26-27, 2015
  Place: McGill University, Montreal, Canada
  Organizers: C. Gale, U. Heinz, S. Jeon, C. Shen, G. Denicol, A. Majumder and X.-N. Wang
  Number of Participants: 30 Descriptions: This second symposium on Jet and Electromagnetic Tomography of Dense Matter, hosted by McGill University (one of the member institutions of the JET Collaboration) just before the start of the Hard Probes 2015 Conference, reviewed the accomplishments of the JET Collaboration at this transition point, assessed the progress made so far, and outline future challenges for the field and how collaborative activities would continue to maintain a strong research program, but without dedicated DOE funding.

- **EVO Video Conferences**
  Each of the Working Groups within the JET Collaboration meet regularly online to discuss progress and technical details of the project. Slides and notes of these meetings can be found at the JET web site: http:
  jet.lbl.gov.

# 5 List of Publications and Conference Talks (2010-2015)

## 5.1 Published papers

1. N. Armesto, *et al.*
   Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma 'Brick',
   Phys. Rev. C **86**, 064904 (2012).

2. J. L. Albacete *et al*,
   Predictions for $p$+Pb collisions at $\sqrt{s_{NN}} = 5$ TeV,
   Int. J. Mod. Phys. E **22** (2013) 1330007.

3. K. M. Burke, A. Buzzatti, N. Chang, C. Gale, M. Gyulassy, U. Heinz, S. Jeon, A. Majumder, B. Müller, G.-Y. Qin, B. Schenke, C. Shen, X.-N. Wang, J. Xu, C. Young, and H. Zhang (The JET Collaboration),
   Extracting jet transport coefficient from jet quenching at RHIC and LHC,
   Phys. Rev. C 90 (2014) 014909.

4. B. Wu and P. Romatschke,
   Shock wave collisions in AdS5: approximate numerical solutions,
   Int. J. Mod. Phys. C **22** (2011) 1317.

5. P. Romatschke,
   Relativistic (Lattice) Boltzmann Equation with Non-Ideal Equation of State,
   Phys. Rev. D **85** (2012) 065012.

6. P. Romatschke and R. E. Young,
   Implications of hydrodynamic fluctuations on the minimum shear viscosity of the dilute Fermi gas at unitarity,
   Phys. Rev. A **87** (2013) 053606.

7. P. Romatschke and J. D. Hogg,
   Pre-Equilibrium Radial Flow from Central Shock-Wave Collisions in AdS5,
   JHEP **1304** (2013) 048.

8. W. van der Schee, P. Romatschke and S. Pratt,
   A fully dynamical simulation of central nuclear collisions,
   Phys. Rev. Lett. **111** (2013) 222302.

9. A. M. Adare, M. P. McCumber, J. L. Nagle and P. Romatschke,
   Tests of the Quark-Gluon Plasma Coupling Strength at Early Times with Heavy Quarks,
   Phys.Rev. **C90** (2014) 2, 024911.

10. J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. O. Koop, D. McGlinchey, P. Romatschke and J. Carlson *et al.*,
    Exploiting Intrinsic Triangular Geometry in Relativistic He3+Au Collisions to Disentangle Medium Properties,
    Phys. Rev. Lett. **113** (2014) 11, 112301.

11. M. Habich and P. Romatschke,
Onset of cavitation in the quark-gluon plasma,
JHEP **1412** (2014) 054.

12. P. Kovtun, G. D. Moore and P. Romatschke,
Towards an effective action for relativistic dissipative hydrodynamics,
JHEP **1407** (2014) 123.

13. T. Gorda and P. Romatschke,
Precision studies of $v_n$ fluctuations,
Phys. Rev. C **90** (2014) 5, 054908.

14. P. Arnold, P. Romatschke and W. van der Schee,
Absence of a local rest frame in far from equilibrium quantum matter,
JHEP **1410** (2014) 110.

15. M. Habich, J. L. Nagle and P. Romatschke,
Particle spectra and HBT radii for simulated central nuclear collisions of C + C, Al + Al, Cu + Cu, Au + Au, and Pb + Pb from $\sqrt{s} = 62.4$ - 2760 GeV,
Eur. Phys. J. C **75** (2015) 1, 15.

16. H. Bantilan and P. Romatschke,
Simulation of Black Hole Collisions in Asymptotically Antide Sitter Spacetimes, Phys. Rev. Lett. **114** (2015) 8, 081601.

17. T. Gorda and P. Romatschke,
Equation of state in two-, three-, and four-color QCD at nonzero temperature and density,
Phys. Rev. D **92** (2015) 1, 014019.

18. P. Romatschke,
Light-Heavy Ion Collisions: A window into pre-equilibrium QCD dynamics?
Eur. Phys. J. C **75** (2015) 7, 305.

19. A. Buzzatti and M. Gyulassy,
Dynamical magnetic enhancement of light and heavy quark jet quenching at RHIC,
Nucl. Phys. A **855**, 307 (2011) [arXiv:1012.0614 [hep-ph]].

20. M. Gyulassy, A. Buzzatti, A. Ficnar, J. Noronha and G. Torrieri,
Jet tomography versus holography at RHIC and LHC,
EPJ Web Conf. **13**, 01001 (2011).

21. A. Buzzatti and M. Gyulassy,
Jet Flavor Tomography of Quark Gluon Plasmas at RHIC and LHC,
Phys. Rev. Lett. **108**, 022301 (2012) [arXiv:1106.3061 [hep-ph]].

22. A. Buzzatti and M. Gyulassy,
An overview of the CUJET model: Jet Flavor Tomography applied at RHIC and LHC,
Nucl. Phys. A **910-911**, 490 (2013) [arXiv:1207.6020 [hep-ph]].

23. A. Buzzatti and M. Gyulassy,
A running coupling explanation of the surprising transparency of the QGP at LHC,
Nucl. Phys. A **904-905**, 779c (2013) [arXiv:1210.6417 [hep-ph]].

24. J. Xu, A. Buzzatti and M. Gyulassy,
Azimuthal jet flavor tomography with CUJET2.0 of nuclear collisions at RHIC and LHC,
JHEP **1408**, 063 (2014) [arXiv:1402.2956 [hep-ph]].

25. J. Xu, J. Liao and M. Gyulassy,
Consistency of Perfect Fluidity and Jet Quenching in semi-Quark-Gluon Monopole Plasmas,
Chin. Phys. Lett. **32**, 9 (2015) [arXiv:1411.3673 [hep-ph]].

26. B. Muller,
Parton Energy Loss in Strongly Coupled AdS/CFT,
Nucl. Phys. A **855**, 74 (2011) [arXiv:1010.4258 [hep-ph]].

27. G. Y. Qin, H. Petersen, S. A. Bass and B. Muller,
Translation of collision geometry fluctuations into momentum anisotropies in relativistic heavy-ion collisions,
Phys. Rev. C **82**, 064903 (2010) [arXiv:1009.1847 [nucl-th]].

28. H. Petersen, G. Y. Qin, S. A. Bass and B. Muller,
Triangular flow in event-by-event ideal hydrodynamics in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200A$ GeV,
Phys. Rev. C **82**, 041901 (2010) [arXiv:1008.0625 [nucl-th]].

29. H. Song, S. A. Bass, U. W. Heinz, T. Hirano, C. Shen,
Hadron spectra and elliptic flow for 200 A GeV Au+Au collisions from viscous hydrodynamics coupled to a Boltzmann cascade,
Phys. Rev. C **83**, 054910 (2011) [arXiv:1101.4638 [nucl-th]].

30. C. E. Coleman-Smith, S. A. Bass, D. K. Srivastava,
Implementing the LPM effect in a parton cascade model,
Nucl. Phys. A **862-863**, 275 (2011) [arXiv:1101.4895 [hep-ph]].

31. H. Song, S. A. Bass, U. W. Heinz,
Viscous QCD matter in a hybrid hydrodynamic+Boltzmann approach,
Phys. Rev. C **83**, 024912 (2011) [arXiv:1012.0555 [nucl-th]].

32. H. Song, S. A. Bass, U. W. Heinz, T. Hirano, C. Shen,
200 A GeV Au+Au collisions serve a nearly perfect quark-gluon liquid,
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33. H. Petersen, T. Renk, S. A. Bass,
Medium-modified Jets and Initial State Fluctuations as Sources of Charge Correlations Measured at RHIC,
Phys. Rev. **C83**, 014916 (2011). [arXiv:1008.3846 [nucl-th]].

34. J. Fuini, III, N. S. Demir, D. K. Srivastava, S. A. Bass,
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J. Phys. G **G38**, 015004 (2011). [arXiv:1008.2306 [nucl-th]].

35. G. R. Shin, S. A. Bass, B. Muller,
Transport Theoretical Description of Collisional Energy Loss in Infinite Quark-Gluon Matter,
J. Phys. G **G37**, 105112 (2010). [arXiv:1006.1668 [nucl-th]].

36. G. Y. Qin and A. Majumder,
A pQCD-based description of heavy and light flavor jet quenching
Phys. Rev. Lett. **105**, 262301 (2010) [arXiv:0910.3016 [hep-ph]].

37. G. -Y. Qin and B. Müller,
Explanation of Di-jet asymmetry in Pb+Pb collisions at the Large Hadron Collider,
Phys. Rev. Lett. **106**, 162302 (2011) [arXiv:1012.5280 [hep-ph]].

38. C. E. Coleman-Smith, S. A. Bass and D. K. Srivastava,
Implementing the LPM effect in a parton cascade model,
Nucl. Phys. A **862-863**, 275 (2011) [arXiv:1101.4895 [hep-ph]].

39. H. Song, S. A. Bass and U. Heinz,
Elliptic flow in 200 A GeV Au+Au collisions and 2.76 A TeV Pb+Pb collisions: insights from viscous hydrodynamics + hadron cascade hybrid model,
Phys. Rev. C **83**, 054912 (2011) [arXiv:1103.2380 [nucl-th]].

40. C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. -C. Song and U. Heinz,
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41. S. Cao and S. A. Bass,
Thermalization of charm quarks in infinite and finite QGP matter,
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AIP Conf. Proc. **1441**, 892 (2012) [arXiv:1108.5662 [hep-ph]].

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Heavy quark energy loss and thermalization in hot and dense nuclear matter.
J. Phys. Conf. Ser. **420**, 012022 (2013) [arXiv:1209.5405 [nucl-th]].

45. S. Cao, G. -Y. Qin, S. A. Bass, B. Müller
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Nucl. Phys. A **904-905** (2013) 653c [arXiv:1209.5410 [nucl-th]].

46. C.E.Coleman-Smith, B. Müller,
What can we learn from dijets? A systematic study with VNI/BMS.
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47. C.E.Coleman-Smith, B.Müller,
What can we learn from Dijet suppression at RHIC?.
Phys. Rev.C, **86**, 5, (2012)

48. E. Caceres, A. Arnab, D.-L. Yang,
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49. B. Müller, D.-L. Yang
Light Probes in a Strongly Coupled Anisotropic Plasma ,
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50. B.V Jacak, B. Müller,
The exploration of hot nuclear matter ,
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51. G. -Y. Qin.
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52. G. -Y. Qin.
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54. M. Younus, C.E. Coleman-Smith, S.A. Bass and D.K. Srivastava
Charm Quark Energy Loss In Infinite QCD Matter Using A Parton Cascade Model,
Phys. Rev. C **91**, no. 2, 024912 (2015) [arXiv:1309.1276 [nucl-th]].

55. H. Song, S.A. Bass and U.W. Heinz
Spectra and elliptic flow for identified hadrons in 2.76A TeV Pb + Pb collisions,
Phys. Rev. C **89**, no. 3, 034919 (2014) [arXiv:1311.0157 [nucl-th]].

56. B. Müller
Investigation of hot QCD matter: theoretical aspects,
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57. M. Nahrgang, J. Aichelin, P. B. Gossiaux and K. Werner,
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Dynamical Evolution, Hadronization and Angular De-correlation of Heavy Flavor in a Hot and Dense QCD Medium,
Nucl. Phys. A **932**, 38-44 (2014) [arXiv:1404.1081 [nucl-th]].

62. M. Nahrgang, J. Aichelin, S. Bass, P. B. Gossiaux and K. Werner,
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Heavy-flavor observables at RHIC and LHC,
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Heavy Flavor Dynamics in QGP and Hadron Gas,
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65. P. B. Gossiaux, J. Aichelin, T. Gousset, M. Nahrgang, V. Ozvenchuk and K. Werner,
Gluon radiation by heavy quarks at intermediate energies and consequences for the mass hierarchy of energy loss,
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68. M. Nopoush, R. Ryblewski and M. Strickland,
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Indian J. Phys. **85**, 873 (2011)

## 5.2 Preprints and submitted papers


1. P. Romatschke and S. Pratt,
   Extracting the shear viscosity of a high temperature hadron gas,
   arXiv:1409.0010 [nucl-th].

2. P. Romatschke,
   Collective flow without hydrodynamics: simulation results for relativistic ion collisions,
   arXiv:1504.02529 [nucl-th].

3. J. Xu, A. Buzzatti and M. Gyulassy,
   The Tricky Azimuthal Dependence of Jet Quenching at RHIC and LHC via CUJET2.0,
   arXiv:1404.0384 [hep-ph].

4. C.E.Coleman-Smith, B. Müller,
   Constituent mass dependence of transport coefficients in a quark-gluon plasma.
   arXiv:1209.3328 [hep-ph],

5. E. Caceres, A. Arnab, B. Müller, D. Vaman, D.-L. Yang,
   Jet Quenching and Holographic Thermalization ,
   arXiv:1208.6368 [hep-th]

6. A. Monnai and B. Mueller,
   Collinear parton splitting in early thermalization and chemical equilibration,
   arXiv:1403.7310 [hep-ph].

7. M. Nahrgang, J. Aichelin, P. B. Gossiaux and K. Werner,
   D mesons in non-central heavy-ion collisions: fluctuating vs. averaged initial conditions,
   arXiv:1405.0938 [hep-ph].

8. S. Cao, G. Y. Qin and S. A. Bass,
   Energy loss, hadronization and hadronic interactions of heavy flavors in relativistic heavy-ion collisions,
   arXiv:1505.01413 [nucl-th].

9. S. Cao, G. Y. Qin and S. A. Bass,
   Correlations of heavy flavor pairs in Au-Au collisions at 200 AGeV at RHIC,
   arXiv:1505.01869 [nucl-th].

10. Z.B. Kang, E. Wang, X.N. Wang and H. Xing,
    Transverse momentum broadening in semi-inclusive deep inelastic scattering at next-to-leading order,
    arXiv: 1409.1315 [hep-ph], submitted to Phys. Rev. D.

11. C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz,
    The iEBE-VISHNU code package for relativistic heavy-ion collisions,
    Comp. Phys. Comm., in press [arXiv:1409.8164 [nucl-th] (47 pages).

12. A. Majumder and J. Putschke,
Mass depletion: a new parameter for quantitative jet modification,
arXiv:1408.3403 [nucl-th].

13. Y. Akiba *et al.*,
The Hot QCD White Paper: Exploring the Phases of QCD at RHIC and the LHC,
arXiv:1502.02730 [nucl-ex].

14. A. Majumder and J. Putschke,
Mass depletion: a new parameter for quantitative jet modification,
arXiv:1408.3403 [nucl-th].

15. A. Majumder,
Possibility of a superfluid in high multiplicity p-p and p-Pb collisions,
arXiv:1402.1912 [nucl-th].

16. R. Vogt,
Gluon shadowing effects on $J/\psi$ and $\Upsilon$ production in $p$+Pb collisions at $\sqrt{s}_{NN} = 115$ GeV and Pb+$p$ collisions at $\sqrt{s}_{NN} = 72$ GeV,
*AFTER@LHC*, Adv. High Energy Phys., in press.

17. S. J. Brodsky, R. Vogt *et al.*,
A review of the intrinsic heavy quark content of the nucleon,
arXiv:1504.06287 [hep-ph], Adv. High Energy Phys., in press.

18. V. Kumar, P. Shukla and R. Vogt,
Quarkonia suppression in Pb+Pb collisions at $\sqrt{s}_{NN} = 2.76$ TeV,
accepted for publication in Phys. Rev. C.

19. N. N. Chang, W. T. Deng and X. N. Wang,
Medium-induced flavor conversion and kaon spectra in electron-ion collisions,
arXiv:1411.7007 [hep-ph].

20. D. Boer *et al.*,
Gluons and the quark sea at high energies: Distributions, polarization, tomography,
arXiv:1108.1713 [nucl-th].

21. D. Molnar and D. Sun,
High-pT suppression and elliptic flow from radiative energy loss with realistic bulk medium expansion,
arXiv:1305.1046 [nucl-th], to appear in Phys. Rev. C

## Additional Submitted Papers by the McGill Group

22. T. Epelbaum, F. Gelis, S. Jeon, G. Moore and B. Wu,
Kinetic theory of a longitudinally expanding system of scalar particles,
arXiv:1506.05580 [hep-ph].

23. C. Shen, J.-F. Paquet, G. S. Denicol, S. Jeon and C. Gale,
Thermal photon radiation in high multiplicity p+Pb collisions at the Large Hadron Collider,
arXiv:1504.07989 [nucl-th].

24. J. Noronha and G. S. Denicol,
Perfect fluidity of a dissipative system: Analytical solution for the Boltzmann equation in $AdS_2 \otimes S_2$,
arXiv:1502.05892 [hep-ph].

25. G. S. Denicol, C. Gale and S. Jeon,
The domain of validity of fluid dynamics and the onset of cavitation in ultrarelativistic heavy ion collisions,
arXiv:1503.00531 [nucl-th].

26. S. Ryu, J.-F. Paquet, C. Shen, G. S. Denicol, B. Schenke, S. Jeon and C. Gale,
The importance of the bulk viscosity of QCD in ultrarelativistic heavy-ion collisions,
arXiv:1502.01675 [nucl-th].

27. K. Dasgupta, C. Gale, M. Mia, M. Richard and O. Trottier,
Vector Meson Spectrum from top-down Holographic QCD,
arXiv:1408.1660 [hep-th].

28. R. P. G. Andrade, J. Noronha and G. S. Denicol,
Jet quenching effects on the anisotropic flow at RHIC,
arXiv:1405.0178 [nucl-th].

29. H. Niemi and G. S. Denicol,
How large is the Knudsen number reached in fluid dynamical simulations of ultrarelativistic heavy ion collisions?,
arXiv:1404.7327 [nucl-th].

30. G. S. Denicol, C. Gale, S. Jeon, J.-F. Paquet and B. Schenke,
Effect of initial-state nucleon-nucleon correlations on collective flow in ultra-central heavy-ion collisions,
arXiv:1406.7792 [nucl-th].

31. I. Kozlov, M. Luzum, G. Denicol, S. Jeon and C. Gale,
Transverse momentum structure of pair correlations as a signature of collective behavior in small collision systems,
arXiv:1405.3976 [nucl-th].

32. G. Vujanovic, J. F. Paquet, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon and C. Gale,
Probing the early-time dynamics of relativistic heavy-ion collisions with electromagnetic radiation,
arXiv:1404.3714 [hep-ph].

33. C. Young, S. Jeon, C. Gale and B. Schenke,
Monte-Carlo simulation of jets in heavy-ion collisions,
arXiv:1109.5992 [hep-ph].

34. S. Jeon and T. Epelbaum,
Perturbative Vacuum Wavefunctional for Gauge Theories in the Milne Space
arXiv:1506.00672 [hep-ph].

## 5.3 Conference Talks

1. Miklos Gyulassy,
   *Jet Studies in the next decade*,
   JET Symposium, Berkeley, June 18, 2010

2. A. Buzzatti,
   *Can dynamical expanding inhomogeneous QCD medium explain heavy jet quenching?*
   JET Summer School, Berkeley, June 14-17, 2010

3. Miklos Gyulassy,
   *Jet Tomography at RHIC vs LHC*,
   INT-10-2A Workshop, Seattle, June 28, 2010.

4. Miklos Gyulassy,
   *Holographic vs. Tomography of Hot sQGP at RHIC ad LHC*,
   Hot and Cold Baryonic Matter 2010, Budapest, Aug. 16, 2010.

5. Miklos Gyulassy,
   *Heavy quark energy loss*,
   Hard Probes 2010, Eilat, Israel, Oct. 10-15, 2010.

6. Z. Buzzatti,
   High order Monet Carlo DGLV heavy quarkl energy loss with dynamic interaction in expanding diffuse A+A system,
   Int. workshop on Heavy Quark Production in Heavy-ion Collisions, Purdue University, Jan. 4-6, 2011.

7. A. Buzzatti,
   *Heavy Quark Jet Puzzle*,
   APS Spring Meeting 4/30/11, Annaheim CA.

8. M. Gyulassy,
   $R_{AA}$ *and high* $p_T$ *azimuthal anisotropy,*
   RBRC workshop on Jet Quenching at RHIC vs LHC in Light of Recent dAu vs pPb Controls, 4/17/2013, BNL, New York.

9. M. Gyulassy,
   *Does E and A make a difference?*
   Frontier of nuclear physics 2013, Guadaloupe.

10. M. Gyulassy,
    *Heavy flavor probes of QGP*,
    RHIC and LHC jet quenching, EMMI2013, 11/2-/2-13, LBNL, California.

11. J. Xu,
    *Azimuthal jet flavor topography via CUJET with running coupling in 2+1D viscous QGP fluids,*
    Hard Probes 2013, 11/4/2013, Cape Town, South Africa.

12. M. Gyulassy,
*Jet flavor and azimuthal tomography in 2+1D perfect fluid QGP at RHIC and LHC,*
Yukawa Institute Theoretical Physics Workshop, 12/5/2013, Kyoto, Japan.

13. J. Xu,
*Azimuthal jet flavor topography via CUJET with running coupling in 2+1D viscous QGP fluids,*
New Frontier in QCD 2013, YITP, Kyoto, Japan.

14. M. Gyulassy,
*Will perfect fluidity of the sQGP survive in light of the BES & D+Au & p+Au data?*
contributed talk at QM2014, Darmstadt, May 19-24, 2014.

15. J. Xu,
*Azimuthal Jet Flavor Tomography with CUJET2.0 of Nuclear Collisions at RHIC and LHC*,
student talk at Huada School on QCD 2014, Central China Normal University, Wuhan, China, June 6, 2014.

16. M. Gyulassy,
*The Open Jet v2 Problem @ RHIC and LHC*,
JET Collaboration Meeting, Davis, CA, June 16, 2014.

17. J. Xu,
*Azimuthal Jet Flavor Tomography with CUJET2.0 of Nuclear Collisions at RHIC and LHC*,
Student talk at JET Summer School 2014, University of California, Davis, CA, June 21, 2014.

18. M. Gyulassy,
*In Celebration of 7 Decades of Rings of Fire (A+A) by Nagamiya-sensei*,
2nd Int. Symp. on Science at J-PARC, July 17, 2014.

19. M. Gyulassy,
*Initial-State Bremsstrahlung versus Final-State Hydrodynamic Sources of Azimuthal Harmonics at RHIC and LHC*,
APS/JPS Joint Meeting, Waikoloa Village, HI, Oct 11, 2014

20. J. Xu,
*Azimuthal Jet Flavor Tomography at RHIC and LHC via CUJET*,
Joint APS/JPS Meeting, Waikoloa Village, HI, Oct 11, 2014.

21. J. Xu,
*pQCD energy loss and flavor dependence in CUJET v2.0 & v3.0*,
SGW2014 - The Second Sapore Gravis Workshop on Heavy Flavor and Quarkonium Production in High-Energy Heavy-Ion Collisions, Padova, Italy, Dec 12, 2014.

22. J. Xu,
*Open heavy flavor at high $p_T$ in A+A collisions (within CUJET)*,
Heavy Flavor Workshop, LBNL, Berkeley, CA, Jan 8, 2015.

23. M. Gyulassy,
*The Strongly Coupled Quark-Gluon-Monopole Plasma (sQGMP) as viewed through jet v2 at RHIC and LHC*,
The 31st Winter Workshop on Nuclear Dynamics, 25-31 January 2015, Keystone Lodge and Spa, Keystone Resort, Colorado, USA

24. M. Gyulassy,
*Perspective on Large versus Small and the pA+DA+BES challenge since 2012*,
RBRC Workshop Collectivity in Small Colliding Systems with High Multiplicity, BNL, March 5, 2015.

25. J. Xu,
*Anisotropic Jet Quenching in semi-Quark-Gluon Plasmas with Magnetic Monopoles*,
APS April Meeting 2015, Baltimore, MD, April 11, 2015.

26. J. Xu,
*Anisotropic jet quenching in semi-quark-gluon plasmas with magnetic monopoles*,
6th Workshop of the APS Topical Group on Hadronic Physics, Baltimore, MD, April 10, 2015.

27. M. Gyulassy,
*Jet Tomography of Quark Gluon Plasmas in High Energy Nuclear Collisions,*
2015 Bonner Prize session, APS April Meeting, Baltimore, MA, April 13, 2015.

28. J. Xu,
*Anisotropic Jet Quenching in semi-Quark-Gluon Monopole Plasmas*,
ALICE Jet Workshop 2015, Yale University, New Haven, CT, May 14, 2015.

29. Paul Romatschke,
*A non-AdS/CFT bound on* $\eta/s$,
talk at Xth Quark Confinement, Munich October, 2012

30. Paul Romatschke,
*The Good, the Bad and the Perfect Fluid*,
Talk at Garcia Collin Meeting, Mexico City, Septem- ber 2013

31. Paul Romatschke,
*Modelling Heavy-Ion LHC Experiments as black hole collisions in AdS5*,
Talk at New Frontiers in Dynamical Gravity, Cambridge, UK, 24-28 March 2014

32. Paul Romatschke,
*Strong coupling far-from-equilibrium thermalization for 'nuclei'* ,
Talk at the Approach to Equilibrium in Strongly Interacting Matter, BNL 2 -4 April 2014

33. Paul Romatschke,
*Exploiting intrinsic triangular geometry in relativistic He3+Au collisions to disentangle medium properties*,
Talk at Quark Matter 2014, Darmstadt, 19-24 May 2014

34. Paul Romatschke,
*Colorado Group Activities*,
Talk at Jet Collaboration Meeting, UC Davies, 17 - 18 June 2014

35. Paul Romatschke,
*Phenomenology from AdS/CFT pre-equilibrium flow in pA and AA*,
Talk at Initial Stages in Heavy-Ion Collisions, Napa Valley, 3 - 7 Dec 2014

36. Paul Romatschke,
*Simulation of Black Hole Collisions in Asymptotically AdS Spacetimes*,
Talk at Numerical Holography, CERN, 8 - 18 Dec 2014

37. Paul Romatschke,
*Simulation of Black Hole Collisions in AdS spacetimes*,
Talk at Holographic Methods for Strongly Coupled Systems, Florence, 9-30 April 2015

38. Paul Romatschke,
*Extracting the shear viscosity of a high temperature hadron gas*,
Talk at the 31st Winter Workshop Nuclear Dynamics, Keystone, 25 - 31 Jan 2015

39. G.Y. Qin,
*Gamma-jet correlations*,
invited talk at RHIC/AGS Annual Users' Meeting, June 7-11, 2010, Brookhaven National Laboratory, NY, USA.

40. G.Y. Qin,
*Fluctuating initial conditions from Glauber and CGC*,
talk at 2010 JET collaboration meeting, June 19-20, 2010, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

41. Chris Coleman-Smith,
*Implementing the LPM effect in a Parton Cascade*,
talk at 2010 JET collaboration meeting, June 19-20, 2010, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

42. G.Y. Qin,
*Perturbative description of jet-medium interaction*,
invited talk at 2010 INT workshop on "Quantifying properties of Hot QCD Matter", June 21-25, 2010, University of Washington, Seattle, WA, USA.

43. G.Y. Qin,
*Interactions between jets and the hot, dense medium*,
talk for hadronic physics seminar in Physics Department at McGill University, July 27, 2010, Montreal, Canada.

44. B. Müller,
*Exploration of Hot QCD Matter: The Next Decade*
CERN Theory Institute: The first heavy ion collisions at the LHC (HIC10), CERN, Geneva (Switzerland).

45. S.A. Bass,
*The Quest for the Quark-Gluon-Plasma - from Discovery to Quantitative Exploration*,
Keynote talk at the HIM conference, Daegu, South Korea.

46. B. Müller,
*Parton Energy Loss in Strongly Coupled AdS/CFT*,
Hard Probes 2010, Eilat (Israel).

47. G.Y. Qin,
*High transverse momentum jets*,
plenary talk at the 3rd Asian Triangle Heavy-Ion Conference, October 18-20, 2010, Huazhong Normal University, Wuhan, China.

48. G.Y. Qin,
*QGP with hot spots*,
talk at STAR Regional Meeting, Shandong University, October 22-24, Jinan, China.

49. S.A. Bass,
*What do we know about the viscosity of QCD matter?*
Invited plenary talk at the $6^{th}$ *International Conference on Physics and Astrophysics of the Quark Gluon Plasma* (ICPAQGP-2010), December 6-10 2010, Goa, India.

50. Chris Coleman-Smith,
*Implementing the LPM effect in a Parton Cascade*,
$6^{th}$ *International Conference on Physics and Astrophysics of the Quark Gluon Plasma* (ICPAQGP-2010), December 6-10 2010, Goa, India.

51. G.Y. Qin,
*From geometry fluctuations to harmonic flows*,
invited talk at the RIKEN BNL Research Center Workshop on Initial State Fluctuations and Final-State Particle Correlations, Brookhaven National Laboratory, Upton, NY, USA, February 2-4, 2011.

52. G. Qin,
*Jet shower evolution in medium and dijet asymmetry at the LHC*
Quark Matter 2011, May 23-28, 2011, Annecy, France.

53. G. Qin, *Jet evolution in matter*
Lectures at the 2nd JET School & Collaboration Meeting, June 15–19, 2011, Durham, NC USA.

54. S. Cao,
*Thermalization of charm quarks in infinite and finite QGP matter*,
Annual JET Collaboration Meeting, June 19–20, 2011, Duke University, Durham, NC.

55. B. Müller,
*Compelling open and quantitatively addressable questions requiring a next generation of RHIC*,
BNL Users Meeting, June 21, 2011, Brookhaven National Laboratory, Upton, NY.

56. G. Qin,
*Exploring quark-gluon plasma in relativistic heavy-ion collisions*,
Invited talk, Workshop in Preparation for the Institute for Advance Studies, Huazhong USTC, Wuhan, China.

57. G. Qin,
*The nuclear modification of di-jet asymmetry at the LHC*,
Invited talk at Symposium on Jet Physics at RHIC and LHC, Hangzhou, China.

58. G.Qin,
*The nuclear modification of dijet asymmetry at the LHC*,
Selected talk at 19th Particles & Nuclei International Conference (PANIC 2011), July 24–29, 2011, MIT, Boston, USA.

59. C. Coleman-Smith,
*Jet Modification in a Brick of QGP Matter*,
talk at 19th Particles & Nuclei International Conference (PANIC 2011), July 24–29, 2011, MIT, Boston, USA.

60. B. Müller,
*Jets in the QGP: What do we want to know? What should be measured?*
PHENIX Decadal Planning Workshop, September 9, 2011, BNL, Upton, NY.

61. S.A. Bass,
*High Energy-Density QCD Matter*,
Invited talk at the XLI International Symposium on Multiparticle Dynamics (ISMD 2011), September 26–30, 2011, Miyajima Island, Hiroshima, Japan.

62. B. Mueller,
*Future challenges of heavy ion physics*,
Workshop on Future Directions of High Energy QCD, October 20-22, 2011, RIKEN Nishina Research Center, Wako-shi, Japan.

63. D.-L.Yang,
*Jet Quenching and Holographic Thermalization*,
INT Program 11-3: Frontiers in QCD, September 19 – November 18, 2011, Institute of Nuclear Theory, Seattle, WA.

64. S.A. Bass,
*What do we know about the viscosity of QCD matter?*,
Invited talk at the 7th International Workshop on the Critical Point and Onset of Deconfinement (CPOD 2011), November 7-11, 2011, CCNU, Wuhan, China.

65. C. Coleman-Smith,
*Dijets at RHIC with VNI/BMS*,
RHIC Jets Workshop, 2 March 2012, Duke, NC, USA

66. G.-Y. Qin,
*Jet modification at RHIC* ,

Talk at the Workshop on JET@RHIC, Duke University, Durham, NC, USA, March 3-4, 2012.

67. S. Cao,
*Thermalization of Charm Quarks in Infinite and Finite QGP Matter*,
11th International Conference on Nucleus-Nucleus Collisions, San Antonio, USA.

68. B. Müller,
*No Pain, No Gain: Hard Probes of the QGP Coming of Age (Opening Lecture)*,
International Conference on Hard Probes 2012, Cagliari, Italy.

69. C. Coleman-Smith,
*What can we learn from the Dijets? A systematic study at RHIC and the LHC with VNI/BMS*,
Hard Probes 2012, 27-01 May/June 2012, Caligari, Sardina, Italy

70. S.A. Bass,
*What do we know about the viscosity of QCD matter?*,
Invited talk at the Symposium on Contemporary Subatomic Physics, June 12-14, 2012, Montreal, Canada.

71. D.-L. Yang,
*Jet Quenching and Holographic Thermalization* ,
Parallel talk at the 11th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2012), St. Petersburg, FL, USA, May 29 - June 3, 2012.

72. G.-Y. Qin,
*Jet modification in dense nuclear matter*
Invited talk at the 11th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2012), St. Petersburg, FL, USA, May 29 - June 3, 2012.

73. B. Müller,
*Jets as QCD Matter Probes (Summary Lecture)*
Workshop on Jet Modification in the RHIC and LHC Era, Wayne State University, Detroit, MI.

74. S. Cao,
*Heavy Quark Evolution and Flow in Hot and Dense Medium*
Quark Matter 2012, 12-18 August 2012, Washington D.C, USA

75. C. Coleman-Smith,
*Systematic Monte-Carlo studies of dijets at the LHC and RHIC*
Quark Matter 2012, 12-18 August 2012, Washington D.C, USA

76. D.-L. Yang,
*Jet Quenching and Holographic Thermalization (Poster)*
Quark Matter 2012, 12-18 August 2012, Washington D.C, USA

77. B. Müller,
*Exploring the sQGP with Relativistic Heavy Ions at LHC and RHIC*
XXXV Reunião de Trabalho sobre Fisica Nuclear, Maresias, SP, Brasil.

78. S.A. Bass,
*A Decade of Quark-Gluon-Plasma Physics: what have we learned and what does the future hold?*
Invited lecture at the Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya, Japan.

79. S.A. Bass,
*What do we know about the viscosity of QCD matter?*
Invited talk at the Nagoya Mini-Workshop 2012 on the Phenomenology and Experiments at RHIC and LHC, September 25-26 2012, Nagoya, Japan.

80. B. Müller,
*The Exploration of Hot QCD Matter: Insights and Open Questions*
Symposium on Hot Topics in Hot Matter, Weizmann Institute, Rehovot, Israel.

81. S. Cao,
*Heavy Quark Energy Loss in Hot and Dense Nuclear Matter*
Hot Quarks 2012, 14-20 October, Copamarina, Puerto Rico, USA

82. C. Coleman-Smith,
*Systematic Studies of Dijet Modification At RHIC and the LHC with VNI/BMS*
Hot Quarks 2012, 14-20 October, Copamarina, Puerto Rico, USA

83. S.A. Bass *Hot and Dense QCD Matter – Unraveling the Mysteries of the Strongly Interacting Quark Gluon Plasma*
Relativistic Heavy-Ion Town Hall Meeting at the Division of Nuclear Physics fall meeting, October 24-28 2012, Newport Beach, CA, USA

84. G.-Y. Qin,
*Parton transport in matter*
Invited talk at the 8th International Workshop on High pT Physics at LHC (HPT2012), 21-24 October 2012, Central China Normal University, Wuhan, China.

85. D.-L. Yang,
*Jet Quenching of Light Probes in Non-Equilibrium Strongly Coupled Plasmas*
Talk at Non-Equilibrium and String Theory Workshop, University of Michigan, Ann Arbor, MI, USA, October 19-21, 2012.

86. G.-Y. Qin,
*Correlations between jets and neutral bosons*
Invited talk at the 4th Asian Triangle Heavy-Ion Conference (ATHIC 2012), Pusan, South Korea, on November 14-17, 2012.

87. S.A. Bass,
*Heavy-Quark Dynamics in the QGP*

Invited talk at the 5th International Workshop on Heavy Quark Production in Heavy-Ion Collisions, 14-17 November 2012, Utrecht, Netherlands.

88. B. Müller,
*Quark-Gluon Plasma: From RHIC to LHC*
Strong Coupling Gauge Theories in the LHC Perspective (SCGT 12), Kobayashi-Maskawa Institute, Nagoya, Japan.

89. S.A. Bass,
*Computational Modeling of Relativistic Heavy-Ion Collisions*
Lecture at the SERC 2013 School at the Variable Energy Cyclotron Centre, Kolkata, India.

90. S.A. Bass,
*What do we know about the viscosity of QCD matter*
Lecture at the SERC 2013 School at the Variable Energy Cyclotron Centre, Kolkata, India.

91. S.A. Bass,
*Phenomenology of Jet Energy-Loss*
Lecture at the SERC 2013 School at the Variable Energy Cyclotron Centre, Kolkata, India.

92. S.A. Bass,
*A Decade of QGP Physics: What have we learned and what does the future hold?*
Lecture at the SERC 2013 School at the Variable Energy Cyclotron Centre, Kolkata, India.

93. S.A. Bass,
*Heavy Quark Dynamics in the QGP*
Invited talk at the International Workshop on Frontiers in Nuclear Physics, Guadaloupe, France.

94. B. Müller,
*Investigation of hot QCD matter with relativistic heavy ions*
Nobel Symposium on LHC Results, Uppsala, Sweden,

95. S. Cao,
*Heavy Quark Energy Loss and Hadronization in a QGP Medium*
invited talk at 2013 RHIC & AGS Annual Users' Meeting, Brookhaven National Lab, USA.

96. S.A. Bass,
*A brief History of Hybrid Hydro+Micro Transport Models*
Invited talk at the Workshop on Particle Sampling on the Cooper-Frye transition surface, Schmitten, Germany.

97. B. Müller,
*The exploration of hot and cold nuclear matter*
Nuclear Physics Summer School, Central China Normal University, Wuhan, China.

98. B. Müller,
*High energy nuclear collisions: The future*
Future Trends in High Energy Nuclear Collisions, Beijing, China.

99. C.E. Coleman-Smith,
*The Parton Cascade Model and Jet Quenching in Heavy Ion Physics*
2nd Workshop on Jet Modification in the RHIC and LHC Era, Wayne State University Detroit.

100. C.E. Coleman-Smith,
*What can we learn from modified jets in Heavy Ion collisions?*
9th International Workshop on High-pT physics at the LHC, Grenoble, France.

101. S. Cao,
*Heavy Flavor Dynamics and Angular De-correlation in a QGP Medium*
invited talk at the Workshop on Heavy Flavor Correlations in Nuclear Collisions, Bergen, Norway.

102. J. Scott Moreland,
*Heavy Quark Propagation in a Linearized Boltzmann Description*
2013 DNP fall meeting of the APS, Newport News, VA, USA.

103. S. Cao,
*Dynamical Evolution, Hadronization and Angular De-correlation of Heavy Flavor in Hot and Dense QCD Matter at RHIC and LHC*
Hard Probes 2013, Cape Town, South Africa.

104. B. Müller,
*The physics of QCD matter: Challenges and opportunities*
YITP Workshop on New Frontiers in QCD, Yukawa Institute, Kyoto University, Kyoto, Japan.

105. S.A. Bass,
*Heavy Quark Dynamics in the QGP*
YITP Workshop on New Frontiers in QCD, Yukawa Institute, Kyoto University, Kyoto, Japan.

106. M. Nahrgang,
*Theory: Heavy quark production*
invited overview talk, STAR Collaboration meeting, FIAS, Frankfurt, Germany.

107. S. Cao,
*Heavy-flavor Evolution in QGP and Hadron Gas: Suppression, Flow and Angular De-correlation*
Quark Matter 2014, Darmstadt, Germany.

108. M. Nahrgang,
*Correlations and higher-order flow: new heavy-quark observables in relation to the bulk dynamics*
Quark Matter 2014, Darmstadt, Germany.

109. S. Cao,
*Heavy Flavor Dynamics in QGP and Hadron Gas*
INT Workshop on Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions, Seattle, USA.

110. S.A. Bass,
*Heavy Quark Dynamics in the QGP*
Workshop on Heavy Quark Physics in Heavy-Ion collisions: experiments, phenomenology and theory, March 16th - March 20th, ECT*, Trento, Italy.

111. S.A. Bass,
*Heavy Quark Dynamics in a Hot and Dense QCD Medium*
2015 JET Symposium, June 26th - 27th, Montreal, Canada.

112. M. Strickland,
*Testing dissipative hydrodynamics using exact solutions of the Boltzmann equation*,
sQGP and extreme QCD workshop, Kavli Institute for Theoretical Physics, Beijing, China, June 2015.

113. M. Strickland,
*Non-perturbative reorganization of viscous hydrodynamics,*
Fourth Joint Meeting of the Nuclear Physics Divisions of the American Physical Society and The Physical Society of Japan, Kona, Hawaii, October 2014.

114. M. Strickland,
*Anisotropic Hydrodynamics* (Three Lectures),
Cracow School of Theoretical Physics, Zakopane, Poland, June 2014.

115. M. Strickland,
*Second-Order Anisotropic Hydrodynamics*,
New Frontiers in QCD 2013, Yukawa Institute for Theoretical Physics, Kyoto, Japan, November 2013.

116. M. Strickland,
*Anisotropic Hydrodynamics*,
International Conference on the Initial Stages in High-Energy Nuclear Collisions, Illa da Toxa, Spain, September 2013.

117. M. Strickland,
*Anisotropic Hydrodynamics* (Three Lectures),
JET Summer School, Ohio State University, June 2013.

118. I. Vitev,
*The GLV approach and next-to-leading order calculations*, JET collaboration meeting, June 2010, LBNL, Berkeley, CA

119. I. Vitev,
*Lecture 1: Introduction, color algebra, cross sections and decay rates*,
JET summer school, June 2010, LBNL, Berkeley, CA

120. I. Vitev,
*Lecture 2: Collisional Interactions of Partons and Particles in Nuclear Matter*,
JET summer school, June 2010, LBNL, Berkeley, CA

121. I. Vitev,
*Lecture 3: Medium-induced bremsstrahlung, LPM effects, applications to jet quenching*,
JET summer school, June 2010, LBNL, Berkeley, CA

122. I. Vitev,
*Lecture 4: Inclusive & tagged jets, jet shapes and cross sections in nuclear collisions*,
JET summer school, June 2010, LBNL, Berkeley, CA

123. R. B. Neufeld,
*Tagged jets and jet reconstruction as a probe of QGP induced partonic energy loss*,
JET Workshop in Prague, The Emauzy Abbey, Prague, Czech Republic, August 12-14, 2010.

124. R. B. Neufeld,
*Tagged jets and reconstructed jets as a probe of hot and dense QCD matter*,
Hard Probes, Eilat, Israel, October, 10-15, 2010.

125. R. B. Neufeld,
*Theoretical advances in understanding jet and open heavy flavor production*,
Fall meeting of the APS Division of Nuclear Physics, Santa Fe, New Mexico, November, 2-6, 2010

126. R. B. Neufeld,
*NLO calculations of the dijet asymmetry for sPHENIX*,
Mini SPHENIX workshop, Duke University, Duke, NC

127. G. Ovanesyan,
*Effective Theory for jets in medium*,
Meeting of division of particles and fields of the American Physical Society, Providence, August 2011.

128. I. Vitev,
*The Energy Frontier, Heavy Ions at the LHC*,
Invited overview talk atthe QCD workshop, APS Division of Nuclear Physics Meeting, October 2011, East Lansing, MI.

129. I. Vitev,
*Next-to-leading order analysis of inclusive jet, tagged jet and di-jet production in Pb+Pb collisions at the LHC*,
Invited talk at the international conference Quark Matter 2011, May 2011, Annacy, France.

130. G. Ovanesyan,
*Angular distributions of partons inside the parton shower: from vacuum to dense QCD matter*,
Winter Workshop on Nuclear Dynamics 2013, Squaw Valley, CA, February, 2013.

131. G. Ovanesyan,
*Medium-induced splitting kernels from SCETG*,
Quark Matter 2012, Washington D.C., August 2012

132. G. Ovanesyan,
*Electroweak radiative corrections and unitarity of Standard Model*,
SCET Workshop 2012, Madrid, Spain, March 2012

133. H. Xing,
*Cold nuclear matter effects in p+A collisions*,
Invited talk, PHENIX collaboration, Los Alamos National Laboratory, NM, October 2012.

134. I. Vitev,
*The Z-tagged jet event asymmetry at LHC*,
Winter workshop on nuclear dynamics, Puerto Rico, April 2012

135. I. Vitev,
*Jet probes of QCD matter*,
Quark Matter 2012 , Washington, DC, August 2013

136. I. Vitev,
*Electroweak boson-tagged jet event asymmetries at the Large Hadron Collider*,
Quark Matter 2012 , Washington, DC, August 2013

137. I. Vitev,
*Hadron, photon and jet production at the LHC*,
High pT at the LHC workshop, CCNU, Wuhan, China, October 2102

138. I. Vitev,
*Jet Quenching*,
QCD Structure I, CCNU, Wuhan, China, October 2102

139. H. Xing,
*Transverse momentum broadening at next-to-leading order*,
?Invited talk, JET collaboration meeting on NLO & MC, Wayne State University, MI, USA, August 22 - 23, 2013 (T2), Los Alamos National Laboratory, NM, October 2012.

140. I. Vitev,
*Heavy ion physics with the sPHENIX upgrades*,
sPHENIX workshop, Santa Fe, NM, February 2014

141. I. Vitev,
*Selected topics in Jet Quenching*,
International workshop on high $p_T$ physics at the LHC, Grenoble, France, September 2013

142. Z. B. Kang,
*Forward physics from a theoretical perspective*,
Invited theory overview, STAR Meeting on eSTAR Letter of Intent, Forward-Upgrades

and Results from U+U Collisions, University of California Los Angeles, Los Angeles, CA, August 28-30, 2013.

143. Z. B. Kang,
*Parton multiple scattering and small-x physics*,
Invited talk, Berkeley Summer Program 2013, QCD Landscape of the Nucleon and Atomic Nuclei, Lawrence Berkeley National Laboratory, Berkeley, CA, August 12-16, 2013.

144. Z. B. Kang,
*Unique opportunities in p+A collisions at RHIC and LHC*,
Invited talk for Phases of QCD Matter, APS Division of Nuclear Physics 2014 Long-range plan: Joint Town Meetings on QCD, Temple University, Philadelphia, PA, September 13-15, 2014.

145. Z. B. Kang,
*Energy loss and heavy flavor jet production*,
The 3rd Workshop on Jet Modification in the RHIC and LHC Era, Wayne State University, Detroit, MI, August 18-20, 2014.

146. H. Xing,
*Transverse momentum broadening in nuclear medium*,
The 31st Winter Workshop on Nuclear Dynamics, Keystone Resort, CO, USA, January 25-31, 2015.

147. H. Xing,
*NLO computations of pt-broadening and proof of twist-4 factorization*,
Invited talk, Physics Opportunities at an ElecTron-Ion Collider, Yale University, CT, USA, September 22-26, 2014.

148. H. Xing,
*Probing QCD dynamics of multiple parton interaction*,
Invited talk, POSTDOC SUMMER SEMINAR SERIES, Los Alamos National Laboratory, NM, USA, August 13, 2014.

149. H. Xing,
*Multiple scattering in cold nuclear matter*,
Invited talk, Jet Collaboration Meeting 2014, UC Davis, CA, USA, June 17-18, 2014.

150. I. Vitev,
*Inclusive and tagged b-jet production as a probe of heavy flavor dynamics in the QGP*,
Invited talk CIPANP, Aspen, CO, May 2015

151. I. Vitev,
*Jet quenching phenomenology from Soft Collinear Effective Theory with Glauber Gluons*,
Winter Workshop on Nuclear Dynamics, Keystone, CO, January 2015

152. I. Vitev,
*Theoretical interpretation of pA results*,
ICPAQGP 2015, Kolkata, India February 2015.

153. I. Vitev,
*Jet quenching phenomenology from Soft Collinear Effective Theory with Glauber Gluons*,
PIETOC V Conference, Yale U, New Haven, CT September 2014

154. I. Vitev,
*Jet quenching phenomenology from Soft Collinear Effective Theory with Glauber Gluons*,
Joint APS-JPS Meeting, Waikoloa, HI October 2014

155. Z. Kang,
*Jet quenching phenomenology form soft collinear effective theory with Glauber gluons*,
JET symposium, McGill University, Montreal, Canada June 2015.

156. H. Xing,
*Photon-tagged and B-meson-tagged b-jet production at the LHC*,
Hard probes 2015 McGill University, Montreal, Canada June 2015.

157. U. Heinz,
*Hydrodynamics at RHIC (ideal and viscous): Where it works, where and how it breaks down, and why,*
invited lecture at the *Berkeley School on Collective Dynamics in High-Energy Collisions*, LBNL, June 7-11, 2010.

158. A. Majumder,
*Alternate mechanisms of charge separation in heavy-ion collisions,*
invited talk, Workshop on *Local Strong Parity Violation*, 2010 RHIC & AGS Annual Users' Meeting, BNL, 6/7/2010.

159. W. A. Horowitz,
*Theory update on energy loss,*
invited talk, 2010 RHIC & AGS Users' Meeting, BNL, 6/8/2010.

160. Guang-You Qin,
*Gamma-jet correlations*,
invited talk, 2010 RHIC & AGS Annual Users' Meeting, BNL, June 7-11, 2010.

161. H. Song,
*Results from viscous hydrodynamics coupled to UrQMD*,
invited talk, INT Workshop on *Quantifying the Properties of Hot QCD Matter*, Institute for Nuclear Theory, University of Washington, 6/14/2010.

162. A. Majumder,
*The factorized approach to jet modification*,
invited talk, Symposium on *Jet and Electromagnetic Tomography of Dense Matter*, LBNL, 6/18/2010.

163. H. Song,
*Viscous hydrodynamics + UrQMD – medium for JET*,
report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

164. W. A. Horowitz,
*Theory comparisons*,
report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

165. Guang-You Qin,
*Fluctuating initial conditions from Glauber and CGC models*,
report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

166. A. Majumder,
*The Higher Twist approach*,
report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

167. A. Majumder,
*Heavy-flavor suppression in Higher Twist*,
report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

168. H. Song,
*Parton shower simulation in the Higher Twist formalism*,
report, 1st JET Collaboration Meeting, LBNL, 6/20/2010.

169. W. A. Horowitz,
*RHIC challenges and LHC Outlook*,
invited talk, INT Workshop on Quantifying the Properties of Hot QCD Matter, Institute for Nuclear Theory, University of Washington, 6/21/2010.

170. A. Majumder,
*The Higher twist approach to jet modification*,
invited talk, INT Workshop on *Quantifying the properties of Hot QCD Matter*, Institute for Nuclear Theory, University of Washington, 6/21/2010.

171. Guang-You Qin,
*Perturbative description of jet-medium interaction*,
invited talk, INT Workshop on Quantifying the properties of Hot QCD Matter, Institute for Nuclear Theory, University of Washington, 6/24/2010.

172. W. A. Horowitz,
*Energy loss mechanisms and jet physics*,
invited talk, PHENIX Collaboration Meeting, Iowa State University, 7/12/2010.

173. W. A. Horowitz,
*Heavy ion physics and Electron Ion Colliders*,
Electron-Ion Collider Collaboration Meeting, Catholic University of America, 7/29/2010.

174. A. Majumder,
*A factorized approach to hard jet modification in dense matter*,
invited talk at the International Workshop on *High Energy Strong Interactions (HESI 2010)*, Yukawa Institute, Kyoto University, Kyoto, Japan, 8/2/2010.

175. U. Heinz,
*The QCD brick problem*,
invited talk, International Workshop on *Jets in Proton-Proton and Heavy-Ion Collisions*, Prague, Aug. 12-14, 2010.

176. U. Heinz,
*Status of viscous hydrodynamics and the extraction of* $(\eta/s)_{\rm QGP}$ *from experimental data*,
opening talk, CERN Theory Institute on *The first heavy ion collisions at the LHC (HIC10)*, CERN, 8/16/2010.

177. A. Majumder,
*A factorized approach to hard jet modification in dense matter*,
talk at the CERN Theory Institute on *The first heavy ion collisions at the LHC (HIC10)*, CERN, 9/2/2010.

178. Zhi Qiu,
*Scaling in viscous hydrodynamics*,
talk at the 2010 Midwest Theory Get-Together, Argonne National Laboratory, 9/10/2010.

179. W. A. Horowitz,
*The EIC, heavy quarks, and QGP phenomenology*,
invited talk, INT Workshop on *Gluons and the quark sea at high energies: distributions, polarization, tomography*, Institute for Nuclear Theory, University of Washington, 10/4/2010.

180. A. Majumder,
*Using hard jets to study soft matter at the EIC*,
invited talk, INT Workshop on *Gluons and the quark sea at high energies: distributions, polarization, tomography*, Institute for Nuclear Theory, University of Washington, 10/12/2010.

181. U. Heinz,
*Quark Soup – The Perfect Liquid?* invite overview talk in the KITPC Program on *AdS/CFT and Novel Approaches to Hadron and Heavy Ion Physics*, KITPC, Beijing, 10/14/2010.

182. U. Heinz,
*Viscous hydrodynamics and the extraction of* $(\eta/s)_{\rm QGP}$ *from heavy-ion collision data*,
invited talk, *3rd Asian Heavy-Ion Triangle Conference (ATHIC2010)*, Institute of Particle Physics, Huazhong Normal University, Wuhan, China, 10/19/2010.

183. Zhi Qiu,
*Scaling in viscous hydrodynamics, and robust viscous hydro*,
talk at the *2010 Midwest Critical Mass* conference, University of Toledo, Toledo, OH, 10/23/2010.

184. U. Heinz,
*From the sparking vacuum to the perfect QGP liquid – aspects of strongly coupled quantum field systems*,
invited talk, Symposium *From Strong Fields to Colorful Matter*, Asheville, NC, 10/26/2010.

185. A. Majumder,
*The study of soft color fields with hard jets in DIS and heavy-ion collisions*,
contributed talk, Symposium *From Strong Fields to Colorful Matter*, Asheville, NC, 10/26/2010.

186. J. S. Moreland,
*Fluctuating initial conditions in viscous hydrodynamics*,
poster, CEU Conference at the 2010 Fall Meeting of the APS Division of Nuclear Physics, Santa Fe, NM, Nov. 2-6, 2010.

187. A. Majumder,
*Jet modification in dense matter via leading hadrons*,
invited opening talk for the Mini-Symposium on *Lessons from Leading Particle Jet Energy Loss* at the 2010 Fall Meeting of the APS Division of Nuclear Physics, Santa Fe, NM, Nov. 2-6, 2010.

188. U. Heinz,
*Event-by-event shape and flow fluctuations in RHIC fireballs*,
invited talk, RIKEN/RBRC Workshop on *Initial-State Fluctuations and Final-State Particle Correlations*, BNL, 2/04/2011.

189. U. Heinz,
*Elliptic flow from RHIC to LHC*,
Workshop on *Heavy Ions at the LHC: a first assessment*, CERN, 3/4/2012.

190. Chun Shen,
*Viscous hydrodynamic radial and elliptic flow from RHIC to LHC*,
APS April Meeting, Mini-symposium on *Early-Time and Long-Range Correlations in Relativistic Heavy Ion Collisions*, Anaheim, CA, 4/30/2011.

191. Huichao Song,
*Viscous QCD matter at RHIC and LHC energies: Results from viscous hydrodynamics + hadron cascade*,
poster (presented by U. Heinz), *Quark Matter 2011*, Annecy, France, May 23-28, 2011.

192. A. Majumder,
*Twist expansion of QCD processes and jet propagation in dense matter*,
3 lectures presented at the *2011 JET Summer School*, Duke University, June 15-17, 2011.

193. U. Heinz,
*Bulk evolution and JET interface*,
*2nd JET Collaboration Meeting*, Duke University, June 17-19, 2011.

194. A. Majumder,
*Developments in the theory of parton energy loss*,
*2nd JET Collaboration Meeting*, Duke University, June 17-19, 2011.

195. U. Heinz,
*VISHNU  a dynamical evolution model for heavy-ion collisions*,
invited talk, 2011 RHIC&AGS Annual Users' Meeting, BNL, June 20-24, 2011.

196. U. Heinz,
*Thoughts on a RHIC research program for the next decade*,
contribution to the panel discussion *The Future of RHIC* at the 2011 RHIC&AGS Annual Users' Meeting, BNL, June 20-24, 2011.

197. U. Heinz,
*The quark-gluon plasma shear viscosity from RHIC to LHC*,
International Workshop on *Non-equilibrium Dynamics*, Heraklion, Crete, Aug. 31  Sep. 3, 2011.

198. Zhi Qiu,
*Event-by-event hydrodynamic calculations for heavy-ion collisions*,
*Mid-Western Theory Get-Together*, Argonne National Laboratory, 9/21/2011.

199. D. White,
*Early flow from matching pre-equilibrium dynamics to viscous hydrodynamics*,
*Mid-Western Theory Get-Together*, Argonne National Laboratory, 9/21/2011.

200. Chun Shen,
*Viscous elliptic and triangular flows at the LHC*,
*Mid-Western Theory Get-Together*, Argonne National Laboratory, 9/22/2011.

201. U. Heinz,
*The shear viscosity of quark-gluon plasma at RHIC & LHC*,
invited keynote talk, *DNP11 Mini-Symposium: From RHIC to LHC – Lessons Learned about the QGP*, Michigan State University, East Lansing, 26-29 Sep. 2011.

202. Zhi Qiu,
*Event-by-event viscous hydrodynamics for RHIC and LHC*,
contributed talk, *DNP11 Mini-Symposium: From RHIC to LHC – Lessons Learned about the QGP*, Michigan State University, East Lansing, 26-29 Sep. 2011.

203. Daniel White,
*Early flow from matching pre-equilibrium dynamics to viscous hydrodynamics*,
contributed talk , *DNP11 Mini-Symposium: From RHIC to LHC – Lessons Learned about the QGP*, Michigan State University, East Lansing, 26-29 Sep. 2011.

204. Huichao Song,
*Hydrodynamics in heavy ion collisions*,
invited lecture, *International School for High-Energy Nuclear Collisions*, Wuhan, China, Oct. 31 - Nov. 6, 2011.

205. Huichao Song,
*QGP viscosity at RHIC and LHC energies*,
*7th International Workshop on Critical Point and Onset of Deconfinement*, Wuhan, China, Nov. 7-11, 2011.

206. U. Heinz,
*Initial shape and final flow fluctuations in event-by-event hydrodynamics for RHIC and LHC*,
invited talk, International Workshop *Exploring QCD Frontiers: From RHIC and LHC to EIC*, Stellenbosch, South Africa, Jan. 30 - Feb. 3, 2012.

207. Chun Shen,
*Hydrodynamic flows from RHIC to LHC*,
contributed talk, *2012 Edward F. Hayes Graduate Research Forum*, Ohio State University, 2/24/2012.

208. Zhi Qiu,
*The shear viscosity of quark-gluon plasma extracted from heavy-ion collisions*,
contributed talk, *2012 Edward F. Hayes Graduate Research Forum*, Ohio State University, 2/24/2012.

209. U. Heinz,
*Phenomenological limits on QGP shear viscosity and what they imply for QGP thermalization*,
Workshop Program on *Gauge Field Dynamics In and Out of Equilibrium (INT-12-1)*, Institute for Nuclear Theory, 3/19/2012.

210. U. Heinz,
*How perfect is 'perfect'? The Quark-Gluon Plasma at RHIC & LHC*,
invited plenary talk, *11th International Conference on Nucleus-Nucleus Collisions (NN2012)*, San Antonio, TX, May 27 - June 1, 2012.

211. Huichao Song,
*QGP viscosity at RHIC and LHC*,
invited talk, *Eleventh Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2012)*, St. Petersburg, FL, May 29-June 3, 2012.

212. U. Heinz,
*Quark-gluon plasma – the perfect liquid*,
invited talk, Symposium on *Contemporary Subatomic Physics*, McGill University, June 12-14, 2012.

213. U. Heinz,
*Perfect fluidity in relativistic heavy-ion collisions*,
invited talk, EMMI Workshop on *Relaxation, Turbulence and Non-Equilibrium Dynamics of Matter Fields (RETUNE 2012)*, Heidelberg, Germany, June 21-24, 2012.

214. Zhi Qiu,
*Reducing initial condition ambiguities using multiple measured anisotropic flows*,

invited talk, workshop on *Initial State Fluctuations and Final State Correlations in Heavy-Ion Collisions*, ECT*, Trento, July 1-6, 2012.

215. U. Heinz,
*Initial state fluctuations and final state flows in heavy-ion collisions*,
invited talk, workshop on *Initial State Fluctuations and Final State Correlations in Heavy-Ion Collisions*, ECT*, Trento, July 1-6, 2012.

216. J. S. Moreland,
*Imprinting quantum fluctuations on hydrodynamic initial conditions*,
poster presentation, DOE Stewardship Science Graduate Fellowship Conference, Washington, DC, July 26-27, 2012.

217. U. Heinz,
*Theory flow overview: Describing the evolving medium in heavy-ion collisions*,
invited talk, QM12 Satellite Workshop *Jet Modification in the RHIC and LHC Era*, Wayne State University, August 20-23, 2012.

218. U. Heinz,
*Quark-gluon-plasma: the perfect liquid phase of QCD*,
invited overview talk, International Workshop on *Quantum Chromodynamics: History and Prospects*, Oberwölz, Austria, Sep. 3-8, 2012.

219. Zhi Qiu,
*Flows from event-by-event hydrodynamical simulations for relativistic heavy-ion collisions*,
contributed talk, 25th Annual Midwest Theory Get-Together, Argonne National Laboratory, 9/7/2012.

220. Jia Liu,
*Matching pre-equilibrium dynamics to viscous hydrodynamics*,
contributed talk, 25th Annual Midwest Theory Get-Together, Argonne National Laboratory, 9/8/2012.

221. Chun Shen,
*Thermal photon emission with partial chemical equilibrium equation of state*,
contributed talk, 25th Annual Midwest Theory Get-Together, Argonne National Laboratory, 9/8/2012.

222. U. Heinz,
*Towards the Little Bang Standard Model*,
invited talk, International Workshop on *Discovery Physics at the LHC (Kruger2012)*, Krueger Park, South Africa, Dec. 3-7, 2012.

223. Christopher Plumberg,
*HBT inteferometry with respect to the 3rd-order event plane*,
contributed talk, *Ohio Section of the APS Spring Meeting*, Ohio University, Athens, OH, March 30, 2013.

224. Ulrich Heinz,
*Flow angle fluctuations and anisotropic flow measures*,
contributed talk, *Ohio Section of the APS Spring Meeting*, Ohio University, Athens, OH, March 30, 2013.

225. Zhi Qiu,
*Hydrodynamic event-plane correlations in Pb+Pb collisions at the LHC*,
contributed talk, *Ohio Section of the APS Spring Meeting*, Ohio University, Athens, OH, March 30, 2013.

226. Ulrich Heinz,
*Fluctuations, flow and viscosity in the Little Bang*,
invited talk, RBRC Workshop *Jet quenching at RHIC vs. LHC in Light of Recent dAu vs. pPb Controls*, Brookhaven National Laboratory, April 15-17, 2013.

227. Ulrich Heinz,
*Hydrodynamics for Relativistic Heavy-Ion Collisions*,
invited lecture series (three 90-minute lectures) at the *11th Korean Nuclear Physics School*, Jeju Island, South Korea, June 24-28, 2013.

228. Zhi Qiu,
*Knee structure in the elliptic flow from hydrodynamic simulations for U+U collisions*,
invited talk, Workshop on *U+U and Cu+Au shape studies at RHIC*, *2013 RHIC & AGS Users Meeting*, Brookhaven National Laboratory, June 26, 2013.

229. Ulrich Heinz,
*Towards the Little Bang Standard Model*,
invited talk,*2013 Heavy Ion Meeting*, Jeju National University, Korea, June 28, 2013.

230. Ulrich Heinz,
*Hydrodynamics for Relativistic Heavy-Ion Collisions*,
invited lecture series (three 90-minute lectures) at the *Peking Summer School for Phenomena & Theories in Heavy Ion Physics*, Peking University, Beijing, July 1-5, 2013.

231. Chun Shen,
*Improved sampling procedure in iEBE+VISHNU*,
invited talk, *Workshop on Sampling Particles on the Cooper-Frye Transition Surface (Sampling 2013)*, Frankfurt, Germany, July 18, 2013.

232. Ulrich Heinz,
*Uncertainties in the underlying e-by-e viscous fluid simulation*,
invited talk, *Jet Workfest*, Wayne State University, Aug. 24-25, 2013.

233. Ulrich Heinz,
*U+U Collisions from Hydrodynamics*,
invited talk, *STAR Collaboration Meeting*, UCLA, Aug. 30, 2013.

234. Dennis Bazow,
*Ellipsoidal anisotropic hydrodynamics*,

contributed talk, *Midwestern Theory Get-Together 2013*, Argonne National Laboratory, September 6, 2013.

235. Chun Shen,
*Thermal photons as a quark-gluon plasma thermometer?*
contributed talk, *Midwestern Theory Get-Together 2013*, Argonne National Laboratory, September 6, 2013.

236. Christopher Plumberg,
*HBT inteferometry with respect to the 3rd-order event plane*,
contributed talk, *Midwestern Theory Get-Together 2013*, Argonne National Laboratory, September 7, 2013.

237. Andy Goldschmidt,
*Knee structure in elliptic flow from hydrodynamic U+U collisions*,
contributed talk, *Midwestern Theory Get-Together 2013*, Argonne National Laboratory, September 7, 2013.

238. Amy Weisman,
*Initial conditions for asymmetric Cu+Au collisions*,
contributed talk, *Midwestern Theory Get-Together 2013*, Argonne National Laboratory, September 7, 2013.

239. Jia Liu,
*Importance of pre-equilibrium dynamics in heavy-ion collisions*,
contributed talk, *Midwestern Theory Get-Together 2013*, Argonne National Laboratory, September 7, 2013.

240. Ulrich Heinz,
*The Little Bang fluctuation spectrum*,
invited opening talk, *9th International Workshop on Relativistic Aspects of Nuclear Physics (RANP 2013)*, Rio de Janeiro, Sep. 23-27, 2013.

241. Ulrich Heinz,
*Electromagnetic fingerprints of the Little Bang*,
invited plenary talk, *Hard Probes 2013*, Stellenbosch, South Africa, Nov. 3-8, 2013.

242. Chun Shen,
*Anisotropic flow of thermal photons as a quark-gluon plasma viscometer*,
selected parallel talk, *Hard Probes 2013*, Stellenbosch, South Africa, Nov. 3-8, 2013.

243. Christopher Plumberg,
*HBT inteferometry with respect to the 3rd-order event plane*,
invited talk, *IX Workshop on Particle Correlations and Femtoscopy (WPCF 2013)*, Catania, Sicily, November 8, 2013.

244. Ulrich Heinz,
*The Little Bang Standard Model*,
invited talk, *New Frontiers in QCD 2013 (NFQCD 2013)*, Kyoto, Dec. 2-6, 2013.

245. Chun Shen,
*Photon emission from viscous hydrodynamics in relativistic heavy-ion collisions*, invited talk, *EMMI Rapid Reaction Task Force on the Direct Photon Flow Puzzle*, GSI, Darmstadt, Germany, Feb. 24, 2014.

246. D. Bazow,
*Viscous hydrodynamics for systems undergoing strongly anisotropic expansion*, contributed talk, *Midwest Critical Mass 2014*, University of Toledo, Ohio, March 8, 2014.

247. J. Liu,
*Free-streaming limit of pre-equilibrium evolution in heavy-ion collisions*, contributed talk, *Midwest Critical Mass 2014*, University of Toledo, Ohio, March 8, 2014.

248. M. Martinez,
*Next-to-eikonal corrections to the shock wave in QCD*, contributed talk, *Midwest Critical Mass 2014*, University of Toledo, Ohio, March 8, 2014.

249. C. Plumberg,
*3rd order HBT interferometry and event-by-event fluctuations*, contributed talk, *Midwest Critical Mass 2014*, University of Toledo, Ohio, March 8, 2014.

250. C. Shen,
*Thermal photons as a quark-gluon plasma thermometer revisited*, contributed talk, *Midwest Critical Mass 2014*, University of Toledo, Ohio, March 8, 2014.

251. U. Heinz,
*Viscous fluid dynamics for anisotropically expanding fireballs*, invited talk, RBRC Workshop *The Approach to Equilibrium in Strongly Interacting Matter*, Brookhaven National Laboratory, April 2-4, 2014.

252. U. Heinz,
*A Standard Model for the Little Bang – how far are we from the goal?*, invited talk, International Workshop on *Hydrodynamics of Strongly Coupled Fluids*, ECT*, Trento, May 12-16, 2014.

253. U. Heinz,
*Thoughts on opportunities from high-energy nuclear collisions*, invited talk, *Think Tank on the Future of Relativistic Heavy-Ion Physics*, Mont Sainte Odile, France, May 24-26, 2014.

254. U. Heinz,
*Viscous relativistic hydrodynamics for heavy-ion collisions*, ten 90-minute lectures at the *2014 Huada School on QCD*, IOPP, Wuhan, China, June 10-14, 2014.

255. U. Heinz,
*The Little Bang Standard Model*,
invited talk, International Symposium on *The Frontier of Hadron Physics – Celebrating Al Mueller's 75th Birthday*, Center for Nuclear Matter Science, Wuhan, China, June 14-15, 2014.

256. C. Shen,
*The iEBE program package*,
invited talk, *2014 JET Collaboration Meeting*, UC Davis, June 17-18, 2014.

257. U. Heinz,
*Hydrodynamics*,
three 1-hour lectures at the *2014 JET Summer School*, UC Davis, June 19-21, 2014.

258. C. Plumberg,
*HBT interferometry with respect to the triangular flow-plane*,
student talk, *2014 JET Summer School*, UC Davis, June 21, 2014.

259. C. Shen,
*Thermal photon emission in relativistic heavy-ion collisions*,
student talk, *2014 JET Summer School*, UC Davis, June 21, 2014.

260. C. Plumberg,
*How to measure a distribution of HBT radii*,
contributed talk, MADAI Workhop *Toward quantitative conclusions for heavy-ion collisions*, NCSL, Michigan State University, July 8, 2014.

261. C. Shen,
*The iEBE program package*,
invited talk, MADAI Workhop *Toward quantitative conclusions for heavy-ion collisions*, NCSL, Michigan State University, July 8, 2014.

262. M. Martinez,
*Decoherence between the initial and final state radiation in a dense QCD medium*,
contributed talk, *3rd Workshop on Jet Modification in the RHIC and LHC Era*, Wayne State University, Detroit, Michigan, August 19, 2014.

263. C. Shen,
*Photon tomography of relativistic heavy-ion collisions*,
invited talk, RBRC Workshop on *Thermal Photons and Dileptons in Heavy-Ion Collisions*, Brookhaven National Laboratory, Aug. 20-22, 2014.

264. A. Goldschmidt,
*Orientation resolution in U+U collisions*,
invited talk, *International Workshop on Particle Correlations and Femtoscopy (WPCF 2014)*, Károly Róbert College, Gyöngyös, Hungary, August 26, 2014.

265. C. Plumberg,
*How to measure a distribution of HBT radii (and why you might want to)*,

contributed talk, *27th Annual Midwest Theory Get Together*, Argonne National Laboratory, Sep. 5, 2014.

266. J. Liu,
*Towards phenomenological limits on the thermalization time in relativistic heavy-ion collisions*,
contributed talk, *27th Annual Midwest Theory Get Together*, Argonne National Laboratory, Sep. 5, 2014.

267. M. Martinez,
*A new exact solution to the relativistic Boltzmann equation and its hydrodynamical limit*,
contributed talk, *27th Annual Midwest Theory Get Together*, Argonne National Laboratory, Sep. 6, 2014.

268. U. Heinz,
*Why I still don't know what we have learnt from BES I*,
invited presentation, International Workshop on *Beam Energy Scan II at RHIC*, Lawrence Berkeley National Laboratory, Sep. 27-29, 2014.

269. U. Heinz,
*Report from the Joint QCD Town Meeting, Philadelphia, Sep. 13-15, 2014*,
invited presentation, Long Range Plan session at the 2014 Joint Fall Meeting of the APS DNP and JPS, Waikoloa, Hawaii, Oct. 7-11, 2014.

270. U. Heinz,
*A standard model for the Little Bang – how far are we from the goal?*
invited overview talk, Workshop on *The Future of Hydrodynamic Modeling of Relativistic Heavy Ion Collisions* at the 2014 Joint Fall Meeting of the APS DNP and JPS, Waikoloa, Hawaii, Oct. 7-11, 2014.

271. U. Heinz,
*The physics of heavy-ion collisions – recent insights and open questions*,
invited talk, 3rd International Workshop on *Discovery Physics at the LHC (Kruger 2014)*, Kruger Gate, South Africa, Dec. 1-6, 2014.

272. U. Heinz,
*Bulk dynamics and soft observables in relativistic heavy ion collisions*,
eight 1-hour lectures at the School *Frontiers in Nuclear and Hadronic Physics*, Galileo Galilei Institute for Theoretical Physics, Florence, Italy, Feb. 23-27, 2015.

273. U. Heinz,
*The physics of the Little Bang*,
invited overview talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 27, 2015.

274. U. Heinz,
*Constraining the quark-gluon plasma viscosity with thermal photons*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 27, 2015.

275. K. Welsh,
*Initial conditions for relativistic light-ion collisions*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 27, 2015.

276. A. Goldschmidt,
*Collision geometry and flow in U+U collisions*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 27, 2015.

277. C. Plumberg,
*Event-by-event fluctuations of HBT radii and the QGP shear viscosity*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 27, 2015.

278. D. Bazow,
*Nonconformal viscous anisotropic hydrodynamics*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 28, 2015.

279. J. Liu,
*Pre-equilibrium evolution effects on heavy-ion collision observables*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 28, 2015.

280. M. Martinez,
*Investigating the domain of validity of the recently found new solution to the relativistic Boltzmann equation*,
contributed talk, *Ohio-Region Section of the APS (OSAPS) Spring Meeting 2015*, Kent State University, Kent, Ohio, March 28, 2015.

281. A. Majumder,
*The temperature dependence of jet transport coefficients*,
International Conference on the Physics and Astrophysics of the Quark Gluon Plasma (ICPAQGP 2015), Invited plenary talk, Saha Institute, Kolkata India, Feb. 1-6, 2015.

282. A. Majumder,
*The temperature dependence of jet transport coefficients*,
Division of Nuclear Physics of the APS, annual fall meeting 2014, Invited talk, Kona, HI, Oct. 6-10, 2014.

283. A. Majumder,
*Calculating Jet Transport Coefficients in Lattice QCD*,
APS Division of Nuclear Physics, Long range plan joint town meetings on QCD,brief contribution, Temple University, Philadelphia PA, Sept. 13-15, 2014.

284. A. Majumder,
*Topical Collaborations and Graduate Education*,
APS Division of Nuclear Physics, Long range plan meeting on education and innovation, Invited talk, Michigan State University, Lansing, MI, Aug 6-8, 2014.

285. A. Majumder,
*Progress in the Monte-Carlo simulation of jets and jet quenching*,
JET collaboration meeting, University of California Davis, CA, June 17-18, 2014.

286. A. Majumder,
*Jet Modification as a function of energy lost and jet mass depletion*,
Quark Matter 2014: The Twenty-fourth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, parallel talk, Darmstadt, Germany, May 19-24, 2014.

287. A. Majumder,
*What remains to be done at Leading Order*,
invited talk, Workshop on energy loss at NLO, Lawrence Berkeley National Laboratory, Berkeley, CA, Mar 3-14, 2014.

288. A. Majumder,
*Full jet modification and transport coefficients of the Quark Gluon Plasma*,
Parallel talk, Workshop on High Energy Physics and Phenomenology, 2013, Puri, India, Dec 12-21, 2013.

289. A. Majumder,
*Hard Probes from RHIC to LHC and onwards to the EIC* ,
Plenary talk, Workshop on High Energy Physics and Phenomenology, 2013, Puri, India, Dec 12-21, 2013.

290. A. Majumder,
*Color Propagation in Nuclei JLAB12, EIC, RHIC, LHC* ,
Invited talk, QCD Frontier workshop, JLAB Oct. 21-22, 2013.

291. A. Majumder,
*Jet Modification in heavy-ion collisions: Theory Overview*,
Invited talk, ISMD 2013, Illinois Institute of Technology, Chicago, Sept 16-20, 2013.

292. A. Majumder,
*The HT-MC event generator* ,
JET NLO-MC group meeting, Wayne State University, Aug 22-23, 2013.

293. A. Majumder,
*The JET(HT)MC event generator and coordination* ,
4th annual JET collaboration meeting, Columbus, OH, June 10-11, 2013.

294. A. Majumder,
*JET Progress at Wayne State University*,
4th annual JET collaboration meeting, Columbus, OH, June 10-11, 2013.

295. A. Majumder,
*Jet modification in A-A, p-A and D-A at RHIC and LHC*,
Invited talk, RIKEN BNL workshop on Jet Quenching at RHIC and LHC, BNL, April 15-17, 2013.

296. A. Majumder,
*Calculating the jet quenching parameter* $\hat{q}$ *in lattice gauge theory* ,
Parallel talk at Hard Porbes 2012, Cagliari, Sardinia, Italy, May 27 - June 1, 2012

297. A. Majumder,
*First principles modification of full jets at the LHC: the brick road to Geneva from Monte-Carlo*,
Invited talk at Heating nuclei, boiling black holes and burning rubber: a symposium on contemporary subatomic physics, McGill University, Montreal, QC Canada, Jun 11-14, 2012.

298. A. Majumder,
*Developments in the theory of parton energy loss (Year 2)*,
3rd annual JET collaboration meeting, McGill University, Montreal, QC Canada, Jun 14-15, 2012

299. A. Majumder,
*Calculating the jet quenching parameter* $\hat{q}$ *in lattice gauge theory* ,
Parallel talk at Quark Matter 2012, Washington, D.C. Aug 11-18, 2012.

300. A. Majumder,
*Jet Tomography at Lower Energies and the temperature dependence of Jet transport coefficients* ,
Invited talk, annual DNP meeting of the APS, New Port Beach, CA, Oct 24-27, 2012.

301. A. Majumder,
*Correlations between jets and neutral bosons* ,
Invited talk at the 4th Asian Triangle Heavy-Ion Conference (ATHIC 2012), Pusan, South Korea, on November 14-17, 2012.

302. A. Majumder,
*Parton transport in matter* ,
Invited talk at the 8th International Workshop on High pT Physics at LHC (HPT2012), 21-24 October 2012, Central China Normal University, Wuhan, China.

303. A. Majumder,
*Jet modification in dense nuclear matter* ,
Invited talk at the 11th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2012), St. Petersburg, FL, USA, May 29 - June 3, 2012.

304. A. Majumder,
*Jet modification at RHIC* ,
Talk at the Workshop on JET@RHIC, Duke University, Durham, NC, USA, March 3-4, 2012.

305. G.-Y. Qin,
*Calculating NLO medium-modified fragmentation function*,
JET Collaboration Meeting on NLO & MC, Detroit, MI, USA, August 22-24.

306. G.-Y. Qin,
*Jet Medium Interaction*,
2nd workshop on jet modification in the LHC & RHIC era, Detroit, MI, USA, August 20-22.

307. G.-Y. Qin,
*Progress report on JET midterm Package*,
JET Collaboration Meeting, Columbus, OH, June 10, 2013.

308. G.-Y. Qin,
*Jet modification at RHIC*,
Mini Workshop on JET@RHIC, Duke University, Durham, NC, USA, March 3-4, 2012.

309. R. Abir,
*Drag induced radiative loss and the excess suppression of heavy-flavors*,
Hard Probes 2015, McGill University, June 29, 2015 - July 3, 2015.

310. R. Abir,
*Heavy quark energy loss*,
Workshop on energy loss at NLO, Lawrence Berkeley National Laboratory, Berkeley, California, March 3-14, 2014.

311. M. Kordell,
*A structure based study of initial state fluctuations in D-Au collision*,
the APS April Meeting 2013, Denver, CO.

312. R. Vogt,
*Quarkonium as a Tool: What Kind of Tool Would It Be?; Open Heavy Flavor Production at RHIC*,
Quarkonium 2010: Three Days of Quarkonium Production in $pp$ and $pA$ collisions, Ecole Polytechnique, Palaiseau, France, 7/10.

313. R. Vogt,
*$J/\psi$ Production and Absorption in $pA$ and $d$+$Au$ Collisions*,
talk at the 4$^{\text{th}}$ International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions, Eilat, Israel, 10/10.

314. R. Vogt,
*Fraction of $J/\psi$ production from $B$ decays at RHIC and LHC*,
APS Division of Nuclear Physics Fall Workshop, Santa Fe, NM, 11/10.

315. R. Vogt,
*$J/\psi$ production and absorption in $pA$ and $d$+$Au$ collisions*,
International Workshop on Heavy Quark Production in Heavy-Ion Collisions, Purdue University, West Lafayette, IN, 1/11.

316. R. Vogt,
*Estimating Uncertainties on Quarkonium production in the Color Evaporation Model*,
Invited talk at Quarkonium Production: Probing QCD at the LHC, Institute of High Energy Physics, Vienna, Austria, 4/11.

317. R. Vogt,
*Estimating the Uncertainty on $J/\psi$ Production*,
Invited talk at Quarkonium Production in Elementary and Heavy Ion Collisions, Brookhaven National Laboratory, Upton, NY, USA, 6/11.

318. R. Vogt,
*Heavy Quark Discussion*,
JET Collaboration meeting, Duke University, Durham, NC, USA, 6/11.

319. R. Vogt,
*Uncertainty Quantification of Quarkonium and Heavy Flavor Production*,
Invited talk at EMMI Workshop on Deconfined Matter, Acitrezza, Italy, 9/11.

320. Randy Nelson,
*Determining the uncertainty on the charm cross section and the effect on the $J/\psi$ cross section*,
APS April Meeting, Atlanta, GA, USA, 3-4/12. Talk presented by UC

321. R. Vogt,
*Charmonium Production*,
Invited talk at 4$^{\rm th}$ Berkeley School of Collective Dynamics in High-Energy Collisions, LBNL, Berkeley, CA, USA, 5/12.

322. R. Vogt,
*Improving the $J/\psi$ Production Baseline at RHIC and the LHC*,
5$^{\rm th}$ International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Cagliari, Sardinia, Italy, 5-6/12.

323. R. Vogt,
*Heavy Flavor and Quarkonium Production at RHIC and the LHC*,
Invited talk: Confinement X, 10$^{\rm th}$ Quark Confinement and the Hadron Spectrum, Munich, Germany, 10/12.

324. R. Vogt,
*Heavy Flavor and Quarkonium Production at RHIC and the LHC*,
Invited talk: Hot Topics in Hot Matter, 70$^{\rm th}$ Birthday Symposium for Itzhak Tserruya, Weizmann Institute, Rehovot, Israel, 10/12.

325. R. Vogt,
*Predictions for $\sqrt{s_{NN}} = 5$ TeV p+Pb Collisions*,
Invited talk: 8$^{\rm th}$ International Workshop on High $p_T$ Physics at the LHC, Central China Normal University, Wuhan, China, 10/12.

326. R. Vogt,
*Heavy Quarks and Quarkonia in pA Collisions*,
Invited talk: Physics at A Fixed Target Experiment using the LHC beam, Trento, Italy, 2/13.

327. R. Vogt,
*$J/\psi$ Production in Cold Nuclear Matter*,
Talk: GHP 2013, Denver, CO, USA, 4/13.

328. R. Vogt,
*Predictions for p+Pb Collisions at the LHC*,
Invited talk: Workshop on proton-nucleus collisions at the LHC, Trento, Italy, 5/13.

329. R. Vogt,
*Open and Hidden Heavy Flavor Production in pp, pA and AA Collisions*,
Invited plenary talk: Strangeness in Quark Matter, University of Birmingham, Birmingham, UK, 7/13.

330. R. Vogt,
*Predictions for p+Pb Collisions at $\sqrt{s_{NN}} = 5$ TeV: Expectations vs. Data*,
Talk: 6th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Stellenbosch, South Africa 11/13.

331. R. Vogt,
*$J/\psi$'s Are Jazzy*,
Talk: 45 Years of Nuclear Theory at Stony Brook: A Tribute to Gerald E. Brown State University of New York at Stony Brook, Stony Brook, NY, USA, 11/13.

332. R. Vogt,
*Predictions for p+Pb collisions at $\sqrt{s_{NN}} = 5$ TeV: Expectations vs. data*,
Talk: Quark Matter 2014, 24th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions.

333. R. Vogt,
*Update on p+Pb Collisions: Expectations vs. Data*,
Talk: JET Collaboration Meeting and Summer School, UC Davis, Davis, CA, 6/14.

334. R. Vogt,
*Quarkoniun and jet production in studies of nucleon/nuclear parton densities*,
Invited talk: Future directions in forward heavy-ion physics & *The LHC Forward Physics and Diffraction WG meeting*, University of Kansas, Lawrence, KS, 9/14.

335. R. Vogt,
*Quarkonium in cold nuclear matter and nuclear parton densities*,
Talk: 10th International Workshop on Heavy Quarkonium, CERN, Geneva, Switzerland, 11/14.

336. R. Vogt,
*Cold Nuclear Matter Effects on Open and Hidden Heavy Flavor Production in p+Pb Collisions*,
Invited talk: Heavy Quark Physics in Heavy-Ion Collisions: Experiments, phenomenology and theory, Trento, Italy, 3/15.

337. R. Vogt,
*Nuclear Modification of Quarkonium Production in p+Pb Collisions at the LHC*,
Talk: GHP 15, Baltimore, MD, 4/15.

338. X.-N. Wang,
*Jet transport parameters from jet quenching at RHIC and LHC*,
The 31st Winter Workshop on Nuclear Dynamics, 25-31 January 2015, Keystone Lodge and Spa, Keystone Resort, Colorado, USA

339. X.-N. Wang,
*Probing properties of QGP with jets at RHIC and LHC: a theoretical perspective*,
Town meeting on phases of QCD Matter, Temple University, Sept. 13-15, 2014.

340. X.-N. Wang,
*Qualitative extraction of $\hat{q}$ from combined jet quenching at RHCI and LHC,*
contributed talk at QM2014, Darmstadt, May 19-24, 2014

341. X.-N. Wang,
*Properties of the hottest matter at a future high-energy collider,*
Center for future high-energy physics Symposium, IHEP, Beijing Feb. 24-25, 2014.

342. X.-N. Wang,
*Jet transport coefficients in heavy-ion collisions, Symposium on New Frontiers in QCD 2013*,
December 2 - 6, 2013, Yukawa Institute for Theoretical Physics, Kyoto, Japan

343. X.-N. Wang,
*Theory: what hard probes tell us about quark-gluon plasma,*
plenary talk at HP2013, Cape Town, Nov. 3-7, 2013

344. X.-N. Wang,
*Charting the phase diagram of strong-interaction matter*,
opening workshop of the DAAD network on "From extreme matter to financial markets", Bielefeld, October 8-10, 2013

345. X.-N. Wang,
*Towards the extraction of $\hat{q}$ and $\hat{e}$ from factorized high-twist approach*,
RHIC physics strategy meeting, Wayne State University, Detroit, August 24-25, 2013

346. X.-N. Wang,
*High-twist approach to jet quenching,*
2nd workshop on "jet modification in RHIC and LHC era", Wayne State University, Detroit, August 20-22, 2013

347. X.-N. Wang,
*Jet tomography of high-energy nuclear collisions,*
workshop on "Future trends in High-energy nuclear collisions", Beijing, August 19-22, 2013

348. X.-N. Wang,
*Hard and Soft Probes of Dense Matter,*
Hadron and Nuclear Physics Conference 2013, Zhang Jia Jie, China, July 18-22, 2013

349. X.-N. Wang,
*QCD and Heavy-ion Collisions: a Theoretical Overview,*
Summer School on Phenomenology and theory in heavy-ion physics, Peking University, Beijing, China, July 1-5, 2013

350. X.-N. Wang,
*Ultrarelativistic heavy-ion collisions: a theoretical overview,*
Plenary talk at International Nuclear Physics Conference 2013, Firence, Italy, 2-7 July 2013.

351. X.-N. Wang,
*Strong interacting matter at high temperature and high density,*
"Shuang Qing Forum" National Natural Science Foundation of China, Beijing, Nov. 3-4, 2012

352. X.-N. Wang,
*Jet Modification in Medium,*
Post QM2012 Workshop on "Jet Modification in the RHIC and LHC Era", Wayne State University, Detroit, August 20-23, 2012.

353. X.-N. Wang,
*Jet Induced Excitation in Anisotropic Medium,*
STAR Regional Meeting, Weihai, China, July 22-15, 2012

354. X.-N. Wang,
*Jet-induced hadron correlation*,
Symposium on contemporary subatomic physics, Joe-fest, McGill, June 12-14, 2012

355. X.-N. Wang,
*Parton energy loss in cold nuclei and implications on jet quenching in AA collisions,*
Hard Probes, Cagliari, Italy, May 27- June 1, 2012

356. X.-N. Wang,
*Hot spots and dihadron correlations*,
INT workshop on "Ridge Correlations, May 7-11, 2012

357. X.-N. Wang,
*Jet Quenching and Dihadron Correlations*,
Berkeley School of Collectivity, Berkeley, May 14-18, 2012

358. X.-N. Wang,
*Properties of dense matter in high-energy heavy-ion collisions,*
YIPQS Symposium: Perspective in Theoretical Physics - From quark-hadron science to unification of theoretical physics, Feb. 6-8, 2012 Yukawa Institute for Theoretical Physics, Kyoto, Japan

359. X.-N. Wang,
*Jet propagation in medium,*
Hirschegg 2012: Facets of strong interaction physics- International Workshop XL on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Kleinwalsertal, Austria, January 15 - 21, 2012

360. X.-N. Wang,
*Parton propagation in nuclear medium,*
plenary talk at the 3rd Workshop on Hadron Physics in China and Opportunities in the US, Weihai, August 9-11, 2011

361. X.-N. Wang,
*Jet and Electromagnetic Tomography of High-energy Heavy-ion Collisions,*
RHIC and AGS Annual Users Meeting, June 20-24, 2011.

362. X.-N. Wang,
*Introduction to pQCD and jets,*
3 lectures given at the 2011 JET Summer School, Duke University, June 15-19, 2011

363. X.-N. Wang,
*Summary,*
RIKEN BNL Research Center Workshop on "Initial State Fluctuations and Final-State Particle Correlations", February 2-4, 2011

364. X.-N. Wang,
*Hot spots, Ridges, Jets and Dihadron Correlation,*
From Strong Fields to Colorful Matter: A symposium in honor of B. Mueller's 60th Birthday, October 24-27, 2010, Asheville, NC.

365. X.-N. Wang,
*Mach cones induced by ?-triggered jets in high-energy heavy-ion collisions,*
Hard Probes 2010, Eilat, Israel, Oct. 10-15, 2010

366. X.-N. Wang,
*Jet Quenching and Medium Excitation in Heavy-ion Collisions,*
CERN TH Institute, First Heavy-ion Collisions at LHC, CERN, August 23-27, 2010

367. X.-N. Wang,
*Jet and Electromagnetic Tomography of Dense Matter in High-energy Heavy-ion Collisions,*
Symposium on High-energy Strong Interaction 2010, Yukawa Institute for Theoretical Physics, Kyoto, August 9-13, 2010

368. X.-N. Wang,
*Jet and Electromagnetic Tomography of Dense Matter in High-energy Heavy-ion Collisions,*
invited talk at CAP Congress 2010, University of Toronto, June 7-11, 2010

369. S. Cao,
*Theoretical Progress on Open Heavy Flavors in Heavy-Ion Collisions,*
at Hard Probes 2015, Montreal, Canada, 07/02/15

370. S. Cao,
*Heavy Flavor Production in Heavy-Ion Collisions,*
at 2015 RHIC & AGS Annual Users' Meeting, Brookhaven National Lab, USA, 06/10/15

371. S. Cao,
*Suppression, Flow and Two-Particle Correlations of Open Heavy Flavor in Relativistic Nuclear Collisions,*
at CIPANP 2015, Vail, USA, 05/22/15

372. S. Cao,
*Transport of Open Heavy Flavor in Relativistic Heavy-Ion Collisions,*
at Workshop on Heavy Flavor Production in High-Energy Collisions, Berkeley, USA, 01/08/15

373. S. Cao,
*Heavy Flavor Dynamics in QGP and Hadron Gas*,
talk at INT Workshop on Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions, Seattle, USA, 09/30/14

374. Denes Molnar & Deke Sun,
*Realistic medium averaging in GLV energy loss*, Hard Probes, May 27 - Jun 1, 2012, Cagliari, Italy

375. Denes Molnar & Deke Sun,
*GLV energy loss in realistic expanding medium*,
8th International Workshop on High pT Physics at the LHC, Oct 21-24, 2012 Central China Normal University, Wuhan, China

376. Denes Molnar & Deke Sun,
*Hard and soft responses from parton transport*,
Workshop on Jet Quenching at RHIC vs LHC in Light of Recent dAu vs pPb controls, Apr 15-17, Brookhaven National Laboratory, Upton, NY

377. Denes Molnar & Deke Sun,
*Event-by-event correlation between medium and jet flow*,
Strange Quark Matter, Jul 21-27, 2013, Birmingham, UK

378. Denes Molnar & Deke Sun,
*Interplay between bulk medium evolution and (D)GLV energy loss*,
Hard Probes, Nov 4-8, 2013, Stellenbosch, South Africa

379. Denes Molnar,
*Jet energy loss and fluid dynamics*,
Workshop on Jet Modification in the RHIC and LHC Era, Aug 18-20, 2014, Wayne State University, Detroit, Michigan

380. Deke Sun & Denes Molnar,
*Interplay between bulk medium evolution and covariant (D)GLV energy loss*,
31st Winter Workshop on Nuclear Dynamics (WWND2015), Jan 26-31, 2015, Keystone, Colorado

381. Denes Molnar,
*Jet quenching and fluid dynamics*,
12th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2015), May 19-24, Vail, Colorado

382. C. M. Ko,
Strings, Jets and Quark Coalescence in Transport Models,
International Workshop on Critical Examination of RHIC Paradigms, Austin, Texas, April 14-17, 2010.

383. C. M. Ko,
Overview of Relativistic Heavy Ion Collisions,
International Workshop on Exotics in Heavy Ion Collisions, Kyoto, Japan, May 17-29, 2010.

384. C. M. Ko,
Exotic Hadrons from Heavy Ion Collisions,
International Mini-Symposium on Exotics in Heavy Ion Collisions, Kyoto, Japan, May 19, 2010.

385. C. M. Ko,
Charmonium Production and Elliptic Flow in Relativistic Heavy Ion Collisions,
International Workshop on Hot and Cold Baryonic Matter, Budapest, Hungary, August 15-20, 2010.

386. C. M. Ko,
Identified Hadrons of Intermediate and High Transverse Momenta in Relativistic Heavy Ion Collisions,
International Workshop on Interplay between Soft and Hard Interaction in Particle Production at Ultra-Relativistic Energies, Catania, Italy, September 8-10, 2010.

387. C. M. Ko,
Particle Production in Heavy Ion Collisions,
Colloquium, Institute for Theoretical Physics, University of Frankfurt, Frankfurt, Germany, October 21, 2010.

388. T. Song,
J/$\psi$ Production and Elliptic Flow in Relativistic Heavy-Ion Collisions,
Seminar, McGill University, Montreal, Quebec, Canada, November 25, 2011.

389. T. Song,
J/$\psi$ Production and Elliptic Flow in Relativistic Heavy-Ion Collisions,
International Workshop on Heavy Quark Production in Heavy-Ion Collisions, West Lafayette, Indiana, January 4-7, 2011.

390. J. Xu,
The Effect of Triangular Flow on Di-hadron Azimuthal Correlations,
RIKEN BNL Workshop on Initial State Fluctuations and Final-State Particle Correlations, Upton, New York, February 2-4, 2011.

391. C. M. Ko,
Triangular Flow in Relativistic Heavy Ion Collisions,
International Workshop on In-Medium Effects in Hadronic and Partonic Systems, Obergurgl, Austria, February 21-25, 2011.

392. C. M. Ko,
Hadronziation by Quark Coalescence,
Jet and Electromagnetic Tomography Summer School, Duke University, Durham, North Carolina, June 15-17, 2011.

393. C. M. Ko,
Triangular flow in Relativistic Heavy Ion Collisions,
Workshop on QCD Phase Transitions and Relativistic Heavy Ion Collisions, Hangzhou, China, July 18-20, 2011.

394. C. M. Ko,
Quarkonia Production in HIC,
International Symposium on Non-equilibrium Dynamics, Heraklion, Crete, Greece, August 31 - September 3, 2011.

395. C. M. Ko, Anisotropic Flows and Dihadron Correlations in Heavy Ion Collisions,
International Workshop on Particle Correlations and Femtoscopy, Tokyo, Japan, September 20-24, 2011.

396. C. M. Ko, Quarkonia Production in Heavy Ion Collisions,
International Conference on Primordial QCD Matter in LHC Era, Cairo, Egypt, December 4-8, 2011.

397. C. M. Ko,
Exotic Hadrons Production in HIC,
Workshop on Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions, Brookhaven National Laboratory, Upton, New York, February 29 -March 2, 2012.

398. C. M. Ko,
Resonances In AMPT,
Workshop on Hadronic Resonance Production in Heavy Ion and Elementary Collisions, Austin, Texas, March 5-7, 2012.

399. C. M. Ko,
Anisotropic Flows in HIC,
Symposium on Cosmo, Cancer, Criticality and Chromoplasmology, Seattle, Washington, May 6, 2012.

400. C. M. Ko,
Dihadron Correlations in AMPT,
Workshop on the Ridge Correlation in High-Energy Collisions at RHIC and LHC, Seattle, Washington, May 7-11, 2012.

401. C. M. Ko,
Why Particles and Antiparticles Flow Differently?,
Symposium on Contemporary Subatomic Physics, Montreal, Canada, June 12-14, 2012.

402. C. M. Ko,
Effects of Hadronic Mean-Field Potentials on Elliptic Flows in HIC,
Second International Symposium on Non-Equilibrium Dynamics, Heraklion, Greece, June 25-30, 2012.

403. C. M. Ko,
Anisotropic Flows and Dihadron Correlations in AMPT,
Workshop on Initial State Fluctuations and Final State Correlations in Heavy-Ion Collisions, Trento, Italy, July 2-6, 2012.

404. C. M. Ko,
Quarkonia Production in Relativistic Heavy Ion Collisions,
Conference on Heavy Ion Collisions in the LHC Era, Qui Nhon, Vietnam, July 15-21, 2012.

405. C. M. Ko,
Mean-Field Effects on Elliptic Flow in Relativistic Heavy Ion Collisions,
Bertsch Symposium on Nuclear Physics, Seattle, Washington, September 6-9, 2012.

406. C. M. Ko,
On Physics and Status of AMPT,
International Workshop on Particle Production in Proton-Proton Interactions and Beyond, Bad Liebenzell, Germany, April 19 - May 3, 2013.

407. C. M. Ko,
Elliptic Flow Difference between Particles and Antiparticles and The EOS of Baryon-Rich Matter,
XXXI Max Born Symposium and HIC for FAIR Workshop on Critical Behavior in Hot Dense QCD, Wroclawski, Poland, June 14 16, 2013.

408. C. M. Ko,
Hadronization via Coalescence in the AMPT Approach,
International Workshop on Transport Theory in Heavy Ion Collisions, Frankfurt, Germany, July 15 - 17, 2013.

409. C. M. Ko,
Elliptic Flow as a Probe of the QCD Phase Diagram at Finite Chemical Potential,
10th International Workshop on QCD Phase Transition and Relativistic Heavy Ion Physics, Chengdu, Sichuan, China, August 8 - 10, 2013.

410. C. M. Ko,
Fluctuations and Correlations in AMPT,
2nd Workshop on Initial Fluctuations and Final Correlations, Chengdu, China, August 11 - 14, 2013.

411. C. M. Ko,
Elliptic Flow of Baryon-Rich Matter,
The 9th International Workshop on Relativistic Aspects of Nuclear Physics, Rio de Janeiro, Brazil, September 23 - 27, 2013.

412. C. M. Ko,
Mean-Field Effects in Hot Dense Matter,
Tribute to Gerald E. Brown Conference, Stony Brook, New York, November 24 - 26, 2013.

413. C. M. Ko,
Elliptic flow as a probe of the properties of baryon-rich QGP,
International Workshop on New Frontiers in QCD, Kyoto, Japan, December 2 - 6, 2013.

414. C. M. Ko,
Particle Production in Heavy Ion Collisions,
International Workshop on Simulations of Low and Intermediate Energy Heavy Ion Collisions, Shanghai, China, January 8-12, 2014.

415. C. M. Ko,
Jet Fragmentation via Shower Parton Recombination,
Third International Symposium on Non-Equilibrium Dynamics, Hersonissos, Crete, Greece, June 9-14, 2014.

416. C. M. Ko,
Baryon-Rich Matter in Heavy-Ion Collisions,
Workshop on High Temperature and High Density Nuclear Matter Study, Weihai, Shandong, China, August 19-22, 2014.

417. R. J. Fries,
Quark Recombination in Heavy Ion Collisions,
JET Collaboration Meeting, Berkeley CA, June 19, 2010.

418. R. J. Fries,
Jet Chemistry and Contributions to EM Probes,
INT Workshop Quantifying Properties of Hot QCD Matter,
Institute for Nuclear Theory, University of Washington, Seattle WA, July 14, 2010.

419. R. J. Fries,
Event-by-Event Jet Quenching and Fourier Moments,
4th International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions (Hard Probes 2010), Eilat, Israel, October 14, 2010.

420. R. J. Fries,
Quark Recombination and Quark Scaling  Still Puzzling?,
Workshop From Strong Fields to Colorful Matter,
Asheville NC, October 26, 2010.

421. R. J. Fries,
Event-by-Event Jet Quenching and Fourier Moments,
APS Division of Nuclear Physics Meeting (DNP 2010), Santa Fe NM, October 21, 2010.

G. Chen*,
Behavior of Early Time Gluon Fields in High Energy Nuclear Collisions,
APS Division of Nuclear Physics Meeting (DNP 2010), Santa Fe NM, November 6, 2010.

422. R. J. Fries,
Quark Recombination and Heavy Quarks,
Invited Talk, 6th Workshop on High-PT Physics at the LHC, Utrecht NL, April 6, 2011

423. R. J. Fries,
Quark Recombination and Heavy Quarks,
Nuclear Physics Seminar, University of Minnesota, Minneapolis MN, April 20, 2011

424. R. J. Fries,
Quark Recombination and Heavy Quark Diffusion,
Quark Matter 2011, Annecy, France, May 23, 2011

425. R. J. Fries,
Jet-Triggers for Photons,
Workshop on Jet Measurements at RHIC, Duke University, Durham NC, March 3, 2012.

426. R. J. Fries,
Quark Recombination,
Workshop Cosmos, Cancer, Criticality and Chromoplasmology, Seattle WA, May 6, 2012.

427. R. J. Fries,
Jet-Triggered Back-Scattering Photons for QGP Tomography,
5th Hard Probes 2012, Cagliari (Italy), May 31, 2012.

428. R. J. Fries,
Flowing Gluon Fields,
Symposium on Contemporary Subatomic Physics (SCSP 2012), McGill University, Montreal QC, June 13, 2012.

429. R. J. Fries,
Jet-Triggered Back-Scattering Photons for QGP Tomography,
Quark Matter 2012, Washington DC, August 15, 2012.

430. R. J. Fries,
Toward a Comprehensive Description of Heavy Flavor Dynamics,
KMI Workshop QGP 2012, Kobayashi-Maskawa Institute, Nagoya (Japan), September 26, 2012.

431. R. J. Fries,
Open Heavy Flavor Probes in Strongly Interacting Nuclear Matter,
Invited Talk, 8th Workshop on High-PT Physics at LHC, Wuhan (China), October 24, 2012.

432. R. J. Fries,
Recombination for JET Shower MC: Status and Discussion,
JET NLO and Monte Carlo Meeting, Detroit, August 22-23, 2013.

433. R. J. Fries,
Uncertainties In Jet Event Generators due to Hadronization Scheme, Other Issues with Energy Loss on E-by-E hydro, and the Extraction of Transport Coefficients, RHIC Strategy Meeting, Detroit MI, August 24-25, 2013.

434. R. J. Fries,
Flowing Gluon Fields: Collective Phenomena in Classical QCD,
15th Conference on Elastic and Diffractive Scattering (EDS Blois 2013), Saariselka (Finland), September 9-13, 2013.

435. R. J. Fries, Flowing Gluon Fields: Collective Phenomena in Classical QCD, 9th Workshop on High PT @ LHC, Grenoble (France), September 25-28, 2013.

436. R. J. Fries,
Initial Flow of Gluon Fields in Heavy Ion Collisions,
Hard Probes 2013, Cape Town (South Africa), November 4-8, 2013.

437. R. J. Fries,
Flow and Energy Momentum Tensor From Classical Gluon Fields,
New Frontiers in QCD (NFQCD 2013), Kyoto (Japan), December 2-6, 2013.

438. R. J. Fries,
Energy Density, Pressure and Flow At Early Times,
XXX. Winter Workshop on Nuclear Dynamics, Galveston TX, April 6-12 2014.

439. R. J. Fries,
Hadronization for Jet Shower Monte Carlos,
Workshop on Jet Modifications in the RHIC and LHC Era", Wayne State University, Detroit MI, August 18-20 2014.

440. R. J. Fries,
In Medium Hadronization: Hadrons and Jets,
Workshop on Jet Modifications in the RHIC and LHC Era", Wayne State University, Detroit MI, August 18-20 2014.

441. R. J. Fries,
The (3+1)-D Structure of Nuclear Collisions,
II. International Conference on the Initial Stages in High-Energy Nuclear Collisions (IS 2014), Napa CA, December 3-7 2014.

442. R. J. Fries,
Quark Recombination,
ICPAQGP 2015, VECC Kolkata, India, February 2, 2015.

## Conference talks by the McGill Group

443. C. Gale,
*QCD under extreme conditions: Hot, shiny fluids and sticky business*,
Invited plenary talk, Annual Congress of the Canadian Association of Physicists, University of Alberta, June 15 2015.

444. C. Gale,
*Extreme QCD: characterizing the quark-gluon plasma*,
Talk at Town Hall Meeting of the Canadian Institute of Nuclear Physics, University of Alberta, June 13 - 14, 2015.

445. C. Gale,
*Electromagnetic radiation and hydrodynamics*,
Invited opening plenary talk, RIKEN-BNL Research Center Workshop on Thermal Photons and Dileptons, Brookhaven National Laboratory, August 20 - 22, 2014.

446. C. Gale,
*Heavy-ion collisions: Theory update*,
Invited plenary talk, 37th International Conference on High-Energy Physics (ICHEP 2014), Valencia, Spain, July 2 - 9, 2014.

447. C. Gale,
*Photons and dileptons in relativistic heavy-ion collisions: Light from the hydro*,
Invited talk at International Workshop on the Hydrodynamics of Strongly Coupled Fluids, European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT$^*$), Trento, Italy, May 12 - 16, 2014.

448. C. Gale,
*The photon flow puzzle : A theoretical overview*,
Invited talk at EMMI Rapid Reaction Task Force on "Photon flow puzzle", GSI, Darmstadt, Germany, February 24 - 28, 2014:

449. C. Gale,
*Electromagnetic radiation from high-energy heavy-ion collisions: from microscopic aspects to bulk dynamics*,
Invited talk at EMMI Rapid Reaction Task Force on "Emissivity of matter under extreme conditions, dileptons and chiral symmetry: established connections and missing links", GSI, Darmstadt, Germany, October 5 - 15, 2013.

450. C. Gale,
*Photons and dileptons from relativistic nuclear collisions*,
Invited talk, International Workshop on Nuclear Dynamics and Thermodynamics, Texas A&M University, August 19 - 22, 2013.

451. C. Gale,
*Relativistic nuclear collisions: Hot fluids and sticky business*,
Invited talk, Annual Congress of the Canadian Association of Physicists, Université de Montréal, May 27 - 31, 2013.

452. C. Gale,
*High pT photons from the quark-gluon plasma*,
Invited talk, Workshop on Electromagnetic Probes of Strongly Interacting Matter: Status and Future of Low-Mass Lepton-Pair Spectroscopy, European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Trento, Italy, May 20 - 24, 2013:.

453. C. Gale,
*Finite-Temperature field theory: Theory and Applications*,
Invited lecturer, Summer School on QCD, Central China Normal University, Wuhan, China.

454. C. Gale,
*Electromagnetic radiation in relativistic heavy-ion collisions: Progress and puzzles*,
Invited talk, International Workshop on Hot Topics in Hot Matter, Weizmann Institute, Rehovot, Israel, October 17-18, 2012.

455. C. Gale,
*Electromagnetic radiation in relativistic heavy-ion collisions: Progress and puzzles*,
Invited talk, International Workshop on Nuclear Physics, Institute for Nuclear Theory, Seattle, WA, September 7-9, 2012.

456. C. Gale,
*Rapporteur Summary Talk on Heavy Flavors and Electro-Weak Probes*,
Invited plenary summary talk, The XXXIII International Conference on Ultrarelativistic Nucleus-Nucleus Collisions ¡D0¿ Quark Matter 2012, Washington, DC, August 13-18, 2012.

457. C. Gale,
*Initial state fluctuations, shear viscosity, and electromagnetic observables*,
Invited talk, International Workshop on Initial State Fluctuations and Final State Correlations in Heavy-Ion Collisions, European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Trento, Italy, July 2-6, 2012.

458. C. Gale,
*Electromagnetic radiation in relativistic heavy-ion collisions: Progress and puzzles*,
Invited plenary talk, 5th International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions (Hard Probes 2012), Cagliari, Italy, May 27-June 1, 2012.

459. C. Gale,
*Viscous photons in relativistic heavy ion collisions*,
Invited talk, Workshop on thermal photons and dileptons, Brookhaven National Laboratory, December 5 -7, 2011.

460. C. Gale,
August *Real photons from hot and dense ideal and viscous media*,
Invited talk, International workshop on Non-equilibrium dynamics, Heraklion, Greece, August 31st - September 3rd.

461. C. Gale,
*Photons at RHIC and the LHC: the role of viscosity and of event-by-event fluctuations*,
Selected talk, Quark Matter 2011, Annecy, France, May 22 - 28, 2011

462. C. Gale,
*Dileptons and direct photons in heavy ion collisions*,
Invited talk, STAR Collaboration Analysis Meeting, UCLA, June 17, 2010

463. C. Gale,
*High pT photons from the quark-gluon plasma*,
Invited talk, International Workshop on Electromagnetic Probes of Strongly Interacting Matter: Status and Future of Low-Mass Lepton-Pair Spectroscopy, ETC*, Trento, Italy, Sept. 13 17, 2010.

464. C. Gale,
*QCD Basics*,
Invited lecture, 4th International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions (Hard Probes 2010), Eilat, Israel, October 10 -15, 2010.

465. C. Gale,
*High pT photons from heavy ion collisions*,
Invited talk, From Strong Fields to Colorful Matter an International Symposium on Modern Nuclear Physics, Asheville, NC, October 24 - 27, 2010.

466. C. Gale,
*High pT photons from relativistic nuclear collisions*,
Invited talk, EMMI Workshop on Strongly Coupled Systems, GSI Helmholtzzentrum Schwerionenforschung, Darmstadt, Germany, November 15 -17, 2010.

467. S. Jeon,
em Dissipation in Quanturm Field Theory,
Invited lecture, CNT LECTURES ON HOT/DENSE MATTER-2015, 24th February - 28th February, 2015, VECC, Kolkata, India

468. S. Jeon,
em News and highlights in the Quark Gluon Plasma characterization,
Plenary talk, 11th Conference on Quark Confinement and the Hadron Spectrum, St. Petersburg, Russia, September 2014.

469. S. Jeon,
em Lectures on Hydrodynamics,
Invited Lectures, the Central China Normal University, Wuhan, China, June 2014.

470. S. Jeon,
em Recent developements in Relativistic Heavy Ion Physics,
Invited Seminar in Rare Isotope Science Project, Institute for Basic Science, Daejeon, Korea, June 2014.

471. S. Jeon,
em Theoretical Overview of Initial State and Flow Physics,
Plenary talk, 6th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Capetown, South Africa, November 2013.

472. S. Jeon,
em Jets in MARTINI,
Second Workshop on Jet Modification, Wayne State University, Detroit, USA, August 2013.

473. S. Jeon,
em Introduction to Hard Probes in Heavy Ion Collisions & Hydrodynamics in Heavy Ion Collisions,
Invited Lectures, National Nuclear Physics Summer School, Stonybrook University, Stonybrook, USA, July 2013.

474. S. Jeon,
em Introduction to Hard Probes in Heavy Ion Collisions,
Invited Lectures, Summer School for Phenomena & Theories in Heavy Ion Collisions, Peking University, Beijing, China, July 2013.

475. S. Jeon,
em Introduction to Hard Probes in Heavy Ion Collisions,
Invited Lectures, 11th Nuclear Physics Summer School, Jeju Island, Korea, June 2013.

476. S. Jeon,
*Jet asymmetry at LHC*,
, Symposium on jet physics at RHIC and LHC, Hangzhou, China, Jul. 21, 2011.

477. S. Jeon,
em Initial state fluctuations in hydrodynamic simulations,
Plenary talk, Asian Triangle Heavy Ion Conference 2012, Pusan, Korea, November 2012.

478. S. Jeon,
em sQGP – A theorist's point of view,
Invited talk, APS DNP meeting, Newport Beach, CA, USA, October 2012.

479. S. Jeon,
*MUSIC with the UrQMD Afterburner*,
Contributed talk, Quark Matter 2012, Washington D.C., USA, August 2012.

480. S. Jeon,
*The First 30 Yocto Seconds of Little Big Bang*,
Invited Seminar, Nagoya University, Nagoya, Japan, July 2012.

481. S. Jeon,
*Higher Harmonics in Heavy Ion Collisions*,
Conference on Heavy Ion Collisions in the LHC Era, Quy Nhon, Vietnam, Jul. 16 – Jul. 20, 2012

482. S. Jeon,
*Elliptic and Triangular Flows in 3+1D Viscous Hydrodynamics with Fluctuating Initial Conditions*,
Quark Matter 2011, Annecy, France, May.27, 2011.

483. S. Jeon,
*Anisotropic flow from viscous hydrodynamics*,
The 9th workshop on QCD phase transitions and relativistic heavy ion collisions, Hangzhou, China, Jul. 19, 2011.

484. S. Jeon,
*MARTINI and MUSIC*,
Brookhaven National Laboratory, Upton, NY. Nov. 16, 2010.

485. S. Jeon,
*MARTINI and MUSIC*,
The 3rd Asian Triangle Heavy-Ion Conference, Wuhan, China, Oct. 18-20, 2010.

486. B. Schenke,
*Event-by-event Hydrodynamic Description of Anisotropic Flow and Correlations*,
at RHIC and LHC RIKEN workshop on Initial State Fluctuations and Final-State Particle Correlations, Brookhaven National Laboratory, Upton, NY, 02/02/2011.

487. B. Schenke,
*Monte-Carlo Simulation of Heavy-Ion Collisions*,
Hard Probes 2010 Eilat, Israel,10/11/2010

488. B. Schenke,
*Monte-Carlo Simulations for Heavy-Ion Collisions*,
Nuclear Theory and RIKEN Seminar Brookhaven National Laboratory, Upton, NY, 08/27/2010.

489. B. Schenke,
*MARTINI: Monte-Carlo for Heavy-Ion Collisions*,
Workshop on Jets in p+p and Heavy-Ion Collisions Prague, Czech Republic,08/13/2010.

490. B. Schenke,
*Monte-Carlo Simulations for the Hard Probes in Heavy-Ion Collisions*,
International Nuclear Physics Conference 2010 University of British Columbia, Vancouver, BC, Canada,07/08/2010.

491. B. Schenke,
*Jet evolution in a weakly coupled QGP*,
JET Collaboration Symposium Lawrence Berkeley National Laboratory, Berkeley, CA, 06/18/2010.

492. B. Schenke,
*Monte-Carlo simulation of high-energy nucleus-nucleus collisions*,
2010 Canadian Association of Physicists (CAP) Congress University of Toronto, Toronto, Canada, 06/09/2010.

493. B. Schenke,
*Hadron-hadron correlations. A theory overview*,
RHIC/AGS users' meeting Brookhaven National Laboratory, Upton, NY, 06/08/2010.

494. C. Young,
*Heavy quark diffusion and quarkonium transport*,
Heavy Quark Production in Heavy-Ion Collisions, Purdue University, 5 January 2011.

495. C. Young,
*Quarkonium production in sQGP*,
Quarkonium Production in Elementary and Heavy-Ion Collisions, Brookhaven National Laboratory, 10 June 2011.

496. C. Young,
*Hard-scale probes of heavy-ion collisions*,
University of Minnesota, 15 February 2012.

497. G. Denicol,
*Extracting the bulk viscosity of the quark-gluon plasma*, New Frontiers in QCD (NFQCD) 2013, Kyoto, Japan, 2013.

498. G. Denicol,
*Extracting the bulk viscosity of the quark-gluon plasma*,
URHIC group seminar, Jyväskylä University, Finland, 21.2.2014.

499. G. Denicol,
*Derivation of fluid dynamics from kinetic theory*,
International Conference on the Initial Stages in High-Energy Nuclear Collisions 2013 (IS2013), Illa de A Toxa, Galicia, Spain, Sep. 2013.

500. G. Denicol,
*Extracting the bulk viscosity of the quark-gluon plasma*,
Relativistic Aspects of Nuclear Physics 2013 (RANP2013), Rio de Janeiro, RJ, Brazil, Sep. 2013.

501. G. Denicol,
*Hydrodynamics in heavy ion collisions and its derivation from kinetic theory*,
Topical Group on Hadronic Physics (GHP) Workshop 2013, Denver, Colorado, USA, Apr. 2013.

502. M. Luzum,
*$p_T$ structure of two-particle correlations: flow, non-flow and fluctuations*,
JET Collaboration Bulk working group remote seminar, February 2013.

503. M. Luzum,
*Hot Quark Soup: VIscosity, Flow, and Flow Fluctuations in Relativistic Heavy-Ion Collisions*,
CNRS job interview, Paris VI, 28 March 2013.

504. M. Luzum,
*Mapping the hydrodynamic response to initial conditions in heavy-ion collisions*,
LBNL, Heavy-Ion Tea Seminar, 7 May 2013.

505. M. Luzum,
*$p_T$ structure of two-particle correlations: flow, non-flow and fluctuations*,
LBNL, informal seminar with STAR group, 9 May 2013.

506. M. Luzum,
*$p_T$ structure of two-particle correlations: flow, non-flow and fluctuations*,
2nd International Workshop on Initial State Fluctuations and Final State Correlations Chengdu, China, 11 August 2013.

507. M. Luzum,
*Constraining properties of the initial state from flow data*,
Invited plenary, IS2013, Spain, 12 September 2013.

508. M. Luzum,
*Hot Quark Soup: Viscosity, Flow and Flow Fluctuations in Relativistic Heavy-Ion Collisions*,
Invited colloquium, University of Houston, 29 October 2013.

509. M. Luzum,
*Hot Quark Soup: Viscosity, Flow and Flow Fluctuations in Relativistic Heavy-Ion Collisions*,
Invited seminar, Rice University, 30 October 2013.

510. C. Shen,
*MUSIC with diffusion – theory and modeling for the bean energy scan*, BNL RBRC workshop, Feb. 26-27, 2015

511. C. Shen,
*MUSIC with diffusion – recent theory developments for beam energy scan*, Seminar in nuclear physics, the Ohio State University, Mar. 6, 2015.