

Final Close-Out Report for DE-FG02-93ER40764

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Project Narrative

Abstract This is a final close-out report for DOE contract DE-FG02-93ER40764 at Columbia University in New York that funded nuclear theory research at Columbia from 12/15/1992 to 12/14/2015. Highlight of research results from the last FY 2015 period, a list of all 12 PhD students trained through the whole grant, and a list of 201 original papers published from 1993-2015 with impact factor metrics are presented.

1. Introduction and Highlights of FY15 Research:

During the period 12/15/1992-12/14/2015 the PI was a tenured professor of physics in the Physics Department at Columbia University in New York and performed high energy nuclear theory research on the topic of the THEORY OF ULTRA DENSE MATTER AND THE DYNAMICS OF HIGH ENERGY INTERACTIONS. The DOE grant DE-FG02-93ER40764 supported the summer salary of the PI, 1 Post-Doctoral Fellow, and the salary and tuition of 1-2 PhD students per year along with occasional short term visitors. It also supported the travel expenses, supplies, office expenses, and indirect costs of the group. A total of 12 graduate students listed in section 2.0 received their PhD in nuclear theory at Columbia under the training and supervision of the PI.

The PI retired from Columbia University on 12/31/16 after the DOE grant terminated on 12/15/15. He was honored upon retirement by being appointed as a Professor Emeritus of Physics of the department. During his 23 year tenure, the PI published 201 papers listed in section 3. The work covered a wide array of nuclear theory topics related to the field of high energy nuclear collisions explored at the AGS, SPS, RHIC and LHC facilities spanning a center of mass energy 2-5500 AGeV and nuclear beams ranging from $A=1$ -208. The PI's goal was to develop ever more sophisticated theoretical tools to predict signatures of novel states and phases of nuclear matter at very high energy densities and to utilize those tools to help interpret phenomenologically the new physics implications from the tsunami of data streaming from those facilities. The theoretical tools utilized perturbative and non-perturbative QCD, relativistic viscous hydrodynamics, parton transport theory, Monte Carlo A+B event generators, and gravity dual holographic models inspired from string theory.

A major milestone of our work was the case made with Larry McLerran[94] that two new forms of nuclear matter are routinely made in nuclear collisions at RHIC energies- the strongly coupled Quark Gluon Plasma near thermal final state and the classical Yang-Mills Color Glass Condensate initial state. This has been confirmed by extensive further experiments at LHC covering an order of magnitude broader kinematic windows. The combined RHIC plus LHC data confirm that the quark gluon plasma produced in high energy nuclear reactions behaves as nearly perfect fluidity limited only by the uncertainty principle and that the medium produced at about 100 times the density of ground state nuclei is highly opaque to jets of all flavors.

The PI has worked closely with experimentalists and the nuclear theory community (esp. the Riken BNL Research Center, the DOE Topical JET Collaboration, and the Wigner Research Center) during this time period.

In recognition for the success of that work, the PI was honored in 2015 by sharing the

Tom W. Bonner Prize in Nuclear Physics prize with LBNL experimentalist Howard Wieman

“For developing foundational experimental and theoretical tools to enable and guide generations of experiments in relativistic heavy ion physics. The combination of experiment and theory led to the initial discoveries at RHIC, ongoing precision studies of the properties of hot nuclear matter, and to exploration of the nuclear matter phase diagram.”

“Miklos Gyulassy received his B.A. (1970) and Ph.D. (1974) from the University of California Berkeley. Between 1974-76 as a postdoctoral fellow with W. Greiner in Frankfurt, his interests turned to the theory of high density nuclear matter and the phenomenology of relativistic heavy ion reactions. Between 1976-92 he worked at LBNL on pion interferometry, charmonium dissociation, baryon stopping, QCD transport theory, and bulk collective flow hydrodynamics. In 1991 he developed with X.N. Wang the widely used HIJING model to predict exclusive event observables in high-energy pp, pA, and AA collisions and predicted strong nuclear modification of high transverse momentum jets confirmed experimentally at RHIC/BNL in 2001. He moved to Columbia University in 1992 as a Professor of Physics. His group continues to develop the DGLV theory of QCD jet quenching and tomography of quark gluon plasmas at RHIC/BNL and LHC/CERN. In 2004, he proposed with L. McLerran an interpretation of the first three years of RHIC data that pointed to the discovery at RHIC of two new forms of ultra-dense QCD matter: the strongly-interacting quark-gluon plasma (sQGP) and its color glass condensate nuclear initial state (CGC). Since 2007 his group also works on testing strong coupling AdS/CFT holography modeling of heavy ion reactions. His current focus is on understanding the implications of recent data on p+A reactions from LHC and RHIC. (URL: <https://www.aps.org/programs/honors/prizes/bonner.cfm>)

During his tenure at Columbia, the PI extensive collaborated with Hungarian theorists that led to some of his highest cited works on jet quenching and jet tomography listed in section 4. In recognition for that work the PI also received in 2015 the Hungarian Government Order of Merit Officer's Cross. The PI is an external member of the Hungarian Academy of Sciences and professor of the Hungarian Academy of Sciences at Wigner Research Centre of Research. He was recognized *“for his world-renowned achievements in high-energy nuclear physics research and reinforcement of the Hungarian-American nuclear cooperation and action in favor of Hungarian researchers to promote international recognition.* Hungarian President Jnos der in the company of Prime Minister Viktor Orbn and Speaker of the House Laszlo Kover presented the award. 'http://www.kormany.hu/hu/miniszterelnokseg/hirek/peldaerteku-a-48-as-honvedek-batorsaga'

The PI has also maintained extensive collaborations with Chinese physicists during this period (esp. the group of Xin-Nian Wang (LBNL & Wuhan)). In recognition of the successes of those long term collaborations, the PI was also honored in 2015 with the appointment as the Bian Peng Visiting Professor at the Central China Normal University (CCNU) in Wuhan, China for a term of 5 years.

Yearly continuation progress reports on the physics highlights of the research from 1993 to 2014 have been submitted to DOE previously and therefore will not be repeated here. In this final close-out report only the research work performed during 2015 will be highlighted.

On January 1, 2016 upon retirement from Columbia University, the PI moved to California and will continue research part-time at the Lawrence Berkeley National Lab, Nuclear Science Division as a visiting affiliate, part-time at the CCNU Wuhan IOPP, and part-time

at the Wigner research center in Budapest, Hungary.

The nuclear theory group at Columbia was an active member of the DOE Topical Jet Collaboration during 2010-2015 (see <http://jet.lbl.gov/>) and developed several increasingly sophisticated versions of Monte Carlo code CUJET to enable numerical computation of our group's DGLV perturbative QCD opacity series [95, 105, 110, 114, 116, 121, 122, 129, 133, 143, 145] theory of jet quenching and jet tomography up to high orders in opacity even when coupled to state of the art realistic viscous hydrodynamic fields. In 2014 our CUJET2.0 code [16, 19] Jiechen Xu was able to evaluate our running coupling DGLV jet quenching theory in realistic bulk constrained 2+1D viscous hydrodynamic temperature and flow fields. (Results were compared to other JET Collaboration model results and to data in ref.[19])

The main problem in 2014 with CUJET2.0 was a theoretical discrepancy with respect to data was that in the range $2 < p_T < 20$ GeV the predicted jet elliptic asymmetry, $v_2(p_T, \sqrt{s}, M_Q)$, was found [16, 18] to be underestimate data by a factor ~ 2 . In fact all perturbative QCD based jet quenching models in the JET Collaboration were found to under predict fit the observed v_2 asymmetry data. We found also that even our strongly coupled “Shooting String” proposal [20, 15] generalization of AdS/CFT string drag holography was incapable of solving the high p_T jet v_2 problem.

We therefore proposed in the FY14 continuation report to try to solve the jet v_2 puzzle [16] in FY15 by including specific non-perturbative physics near the critical QCD temperature range (as suggested in 2006 by Shuryak and Liao). We therefore formed a collaboration in 2015 with Jinfeng Liao to implement their qualitative “magnetic scenario” model into our quantitative Monte Carlo framework coupled to state of the art viscous hydrodynamics in order to test if the emergent color magnetic monopole degrees of freedom near T_c *constrained by lattice QCD* could help resolve the v_2 puzzle without destroying agreement with the RHIC and LHC R_{AA} systematics.

This work in 2015 led to the development of a new version CUJET3.0 [3, 7, 10] in which the previously assumed weakly coupled HTL model of the quasiparticle constituents of quark gluon plasmas was replaced by a non-perturbative strongly coupled quasiparticle model that we called a sQGMP (standing for “semi-Quark-Gluon-Monopole-Plasma”) In sQGMP non-perturbative parameters were fixed from available lattice QCD data. We showed in detail in [7] “Bridging Soft-Hard Transport Properties of Quark-Gluon Plasmas with CUJET3.0,” (to appear in JHEP soon) that CUJET3.0 could account quantitatively for all RHIC and LHC data on light and heavy quark quenching and elliptic asymmetries simultaneously! Perhaps an even more significant bonus of the sQGMP model encoded in CUJET3.0 is that it predicted quantitatively a jet transport parameter $\hat{q}(E, T)/T^3$ that had a strong enough peak near T_c that when the jet energy is extrapolated down toward thermal energy scale $E \sim 3T$, the inferred η/s of the sQGMP naturally approached the AdS lower bound near T_c as needed to explain how could the QGP be a really a perfect fluid. This is a very exciting new connection between long and short wavelength properties of quark gluon plasmas produced in nuclear collisions that the PI plans to follow up even into retirement.

This successful result was made possible by the relentless hard work of my last PhD graduate student at Columbia, Dr. Jiechen Xu. He is now a postdoc fellow at Indiana University working with Prof. Jinfeng Liao.

In FY14 and FY15 the PI continued work also with Barbara Betz (ITP, Frankfurt) to explore a wide range of BBMG jet energy loss models, $dE/dx = \kappa(T)E^a x^b T^c \zeta_q$, that can

interpolate and extrapolate between pQCD and AdS/CFT model limits. The goal is to try to constrain the domain of “model parametric space” ($a, b, c, q, \kappa(T/T_c)$) that specify the energy, path, and temperature dependence and energy loss fluctuation distributions when coupled to bulk constrained realistic 2+1 D viscous hydro flow fields. We found that a surprisingly large domain of this parameter space could fit R_{AA} equally well in the χ^2 sense. The v_2 data on the other hand are equally poorly fit using parameters constrained by R_{AA} data except for the Shuryak Liao type “volcano” magnetic scenario. In FY15 we generalized our past studies limited to smooth 2+1D expanding geometries to explore what happens when BBMG is coupled to much more realistic bulk flow observables constrained *event-by-event* v-SPhydro inhomogeneous viscous fields. In 2015 Dr. Jaquelyn Noronha-Hostler from Sao Paulo University worked as a postdoc at Columbia to utilize her code to advance our objectives. As a major bonus, with hiring Dr. Jaquelyn Noronha in FY15, Professor Jorge Noronha (Sao Paulo University) chose to spend his sabbatical leave at Columbia at at no cost burden to the limited PI’s DOE grant. This collaborative work bore fruit in FY15 that was recently posted [1] on the topic “Soft-Hard Event Engineering in Ultrarelativistic Heavy Ion Collisions”. SHEE is a new technique proposed to study the variation of high $p_T > 10$ GeV azimuthal harmonics, $^{hard}v_n(p_T)$, on sub-classes of event selected not only by centrality but also bulk low $p_T < 2$ GeV event asymmetries. We found that SHEE could help to deconvolute effects due to fluctuations of initial state bulk geometries and the sough after constraints on the coupling between jets and the perfect fluids produced in A+A.

Another major open problem in the field is the surprising similarity of azimuthal asymmetry moments $v_n(p_T < 2 \text{ GeV})$ in central $p + A$ and peripheral $A + A$ systems at the same rapidity multiplicity. In 2014 the PI and collaborators tried to addressed this unexpected pA puzzle in GLVB[12, 13] using a purely Yang-Mills field theoretic non-hydrodynamic Color Scintillation Array model. A possibly related other open experimental puzzle posed by the RHIC beam energy scan (BES) is the near independence of the bulk low p_T harmonic moments to the cm energy over a three decades range!

One solution to the transverse size and beam energy independence of harmonic moments is simply to assume that perfect fluidity of the QGP produced in A+B is in fact scale invariance! Perfect fluid hydrodynamics is sufficient to fit all data by suitably varying the assumed initial conditions. However, conformal scale invariance is contradicted by the manifestly nonconformal variation of the lattice QCD equation of state in the critical temperature range. There exists a fundamental scale, T_c of nonperturbative QCD physics.

PI proposed in several conferences and workshops in FY14 that an alternate *nonequilibrium* field interference mechanism could be responsible for the harmonics in $p + A$ motivated in large part by work on glasma diagrams by R. Venugopalan and collaborators. The PI also proposed that while perfect fluidity is sufficient to describe all flow data, it may not be necessary even in A+A! In reference GLVB[13], the PI and collaborators generalized the GLV radiative formalism to compute analytically the azimuthal asymmetry harmonics and scaling properties predicted by multiple interfering beam jet bremsstrahlung radiation sources operating in $p + A$ collisions. We discovered the remarkable result that the azimuthal asymmetries due to interference from multiple recoiling color antenna along the beam direction lead to multi gluon azimuthal correlations with magnitude and p_T dependence very similar to that observed in p+A (and A+A) at LHC. In addition the scaling properties of those moments with the harmonic number n and the number of gluons, 2ℓ , used to define

those moments also obeyed the same power law scaling as observed.

In 2015 the PI and a summer student extended the above studies to test the sensitivity of the azimuthal interference patterns from multiple beam jet bremsstrahlung to uncertainties of hadronization schemes. In ref.[8] ‘Hadronization scheme dependence of long-range azimuthal harmonics in high energy $p + A$ reactions,’ we found that only the simplest local parton models of hadronizations are consistent with the low $p_T < 2$ GeV pA data. However, more realistic LUND hadronization models including resonances and basic kinematic recoil constraints were found to significantly distort and smear out the azimuthal field interference patterns. This indicates that models such as GLVB, CGC and IP-glasma are very sensitive to the current uncertainties about the physics of hadronization. This remains therefore an urgent open problem for the Yang-Mills field modeling of the dynamics.

2. Graduate Students Tracking

Table 1: Ph.D Nuclear Theory Graduate Students Trained by PI

	Name	Start	PhD	Thesis	Current Position
1	Ziwei Lin	6/1993	9/1996	Open Charm Production and Lepton Pairs at RHIC	Assistant Prof. East Carolina University
2	Bin Zhang	6/1994	6/1998	Covariant Parton Transport in AA	Tenured Professor of Physics Arkansa State University
3	Steve Vance	6/1996	9/1999	Baryon Junctions in AA	Finance
4	Denes Molnar	9/1997	8/2002	Gluon Transport Theory Elliptic Flow	Professor Purdue University
5	Ivan Vitev	6/1998	8/2002	Radiative Energy Loss	tenured Los Alamos National Lab
6	Magda. Djordjevic	9/2001	8/2005	Heavy Quark Energy Loss	Prof. U. Belgrad
7	Azfar Adil	6/2003	8/2007	Hard Probes of sQGP	Finance
8	William Horowitz	9/2004	9/2008	QCD vs AdS/CFT Heavy Quarks	Lecturer University Cape Tow
9	Simon Wicks	9/2005	7/2008	QCD Jet Tomography	Finance
10	Alessandro Buzzatti	6/2009	9/2013	QCD Jet Tomography	Finance
11	Andre Ficnar	6/2009	9/2014	AdS/CFT Holographic	PD Oxford
12	Jiechen Xu	6/2013	12/2015	QCD Jet Tomography	PD Indiana Univ

Columbia Nuclear Theory Group Publications since 12/15/1992
201 sorted by date decending

(for all 310 PI publications, see inspirehep.net)

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4.0 Research Impact Citation Metrics

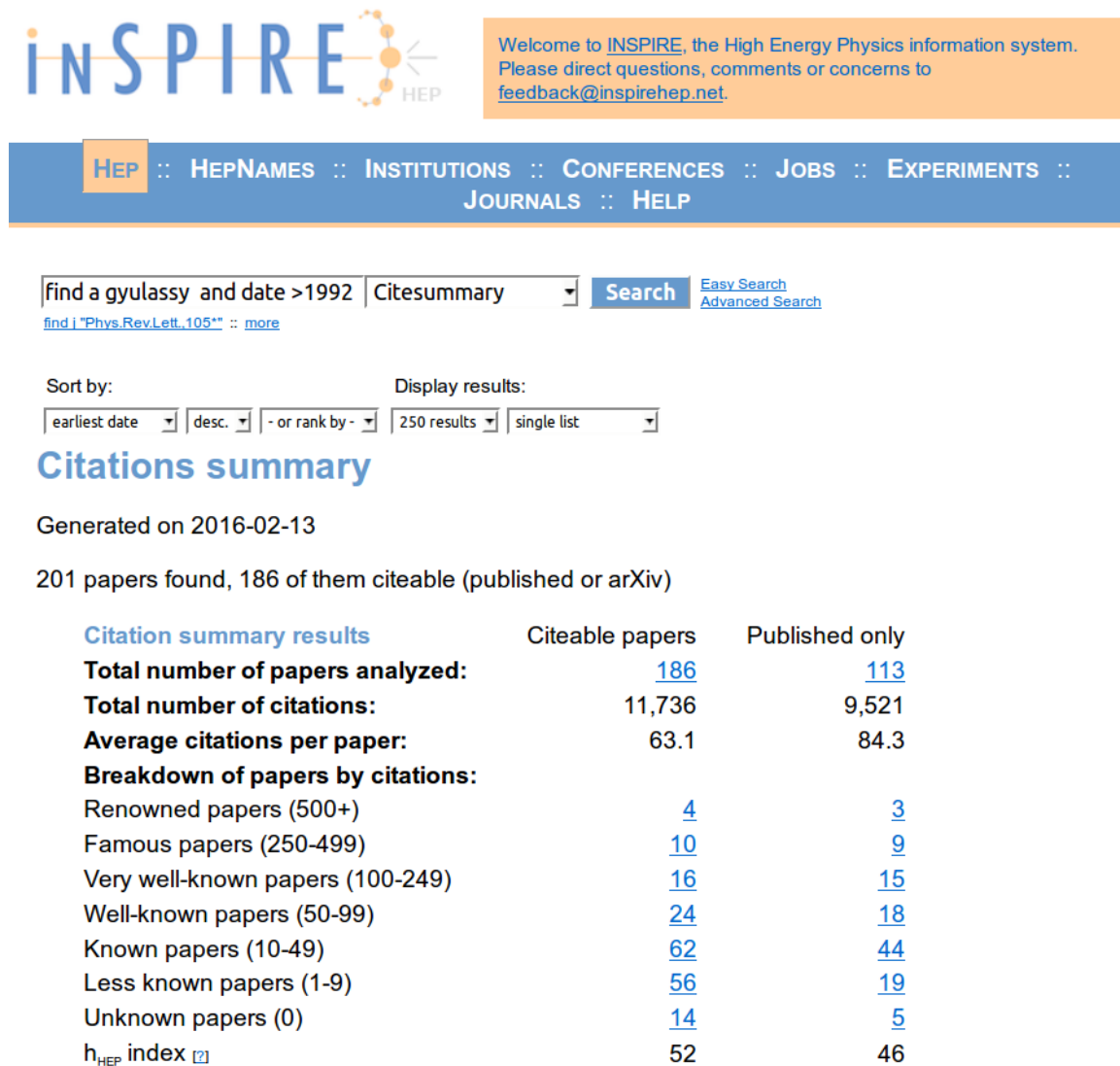


Figure 1: Citation summary as of 2/12/16 for papers between 1993 and 2016. For a complete list of citable publications since 1974 see inspirehep.net.

**5.0 Top 30 cited papers written between 1993 and 2016 (with citations exceeding 99)
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