LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-TR-407545

FY07 LDRD Final Report Heavy Quark Jet Tomography

R. Soltz, J. Newby, A. Glenn, J. Klay

October 7, 2008

Auspices Statement

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was funded by the Laboratory Directed Research and Development Program at LLNL under project tracking code 06-ERD-045.

FY07 LDRD Final Report
List Your LDRD Project Title Here
LDRD Project Tracking Code: 06-ERD-045
John Doe, Principal Investigator

Abstract

We propose and develop a new signature, the measurement of hadron-electon correlations to measure energy loss of heavy quarks in the quark-gluon plasma. This measurements will be used in future analyses to quantify the energy densities created in collisions of heavy ions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab and the Large Hadron Collider (LHC) at CERN. In addition we develop and implement a computing model that will leverage LLNL expertise in cost-effective high performance computing to perform data analyses and simulations for the ALICE experiment at CERN.

Introduction/Background

Relativistic heavy ion collisions are a unique tool for exploring the theory of strong interactions, Quantum Chromodynamics (QCD), in the laboratory. One of the phases of nuclear matter predicted by the theory is a quark-gluon plasma (QGP), made of interacting quarks and gluons, which is thought to have existed in the very early universe, less than a microsecond after the big bang. The search for a phase transition from hadronic degrees of freedom to this new state of highly compressed nuclear matter and the characterization of its properties are the goals of the heavy ion collider programs at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider (LHC) at CERN.

Normally, the QCD strong force keeps quarks bound in triplets (baryons), and quark-antiquark pairs (mesons), collectively known as hadrons. However, at asymptotically short distance scales, the force becomes weakened enough that the quarks and gluons (partons) are freed from their hadronic bound states. Wilczek, Gross and Politzer were awarded the 2004 Nobel Prize in physics for their discovery of this property of QCD, known as asymptotic freedom. In the most violent nuclear collisions at RHIC, the hadrons are compressed and heated so much that the partons are believed to roam more freely than in hadronic systems but yet are still very strongly interacting. This strong "sQGP" exhibits some extraordinary properties such as significant collective hydrodynamic behaviour and a high degree of opacity to energetic partons or jets.

In leading order perturbative QCD, a 2-body inelastic scattering between two partons produces back-to-back sprays of hadrons ("jets") which can be characterized experimentally through the spatial and momentum correlations of the measured hadrons. The reconstructed jet properties such as the energy, direction and particle content can be connected back to the properties of the originating parton.

The partons produced in hard scatterings which occur in nucleus-nucleus collisions are effected by the presence of the medium. As they travel through it they interact, exchanging energy with the medium through induced gluon bremsstrahlung radiation. The strength of the interaction depends on the color-charge density of the medium; a medium composed of free quarks and gluons has a significantly stronger effect on the parton than one made of hadrons.

At RHIC, we have observed a factor of 5 suppression in the yield of high transverse momentum (p_T) hadrons and a strong suppression of azimuthal back-to-back two-particle correlations in central Au+Au collisions compared to the expectation from scaled p+p and d+Au collisions. These measurements are an example of using "jet tomography" techniques to probe the produced medium and suggest that the initial energy density achieved at RHIC is a factor of 15-100 times the density of cold nuclear matter.

An entire toolbox of jet tomography techniques for probing a dense, strongly interacting nuclear medium are rapidly being developed and will become one of the most essential tools for investigating the medium produced in the 5.5 TeV Pb+Pb collisions delivered by the CERN LHC when it turns on in 2008-09. The factor of 30 increase in center-of-mass energy over RHIC translates to a substantially larger cross-section for jet and heavy quark production and is expected to result in a hotter, denser, longer-lived medium with different properties than at RHIC.

In QCD light vs. heavy quarks vs. gluons have different coupling strengths and interaction cross- sections, therefore differences in the number and characteristics of flavor-identified jets measured in heavy ion collisions are expected. Quantifying these differences in p+p, p+A and A+A collisions will provide further tomographic insight into the properties of the media created at RHIC and LHC.

Identifying jets and tagging the flavor of the parent parton in heavy ion collisions is extremely difficult because of the complicated background of uncorrelated particles produced from soft interactions of the target and pro jectile. However, azimuthal two-particle correlations have been used as an effective tool to identify jets statistically. Both charm and bottom quark jets, which fragment predominantly to energetic charm and bottom mesons that have a strong preference to decay to an energetic electron can be identified by looking at azimuthal electron-hadron correlations.

This LDRD will fund our efforts to develop the analysis techniques for measuring electron-hadron correlations using the current dataset and to apply the results for analysis of future p+p, d+Au and Au+Au collisions in PHENIX. Fig. 1 shows the schematic of the charmonium decay signature that can be detected via electron hadron (electron and Kaon or Pion) correlations.

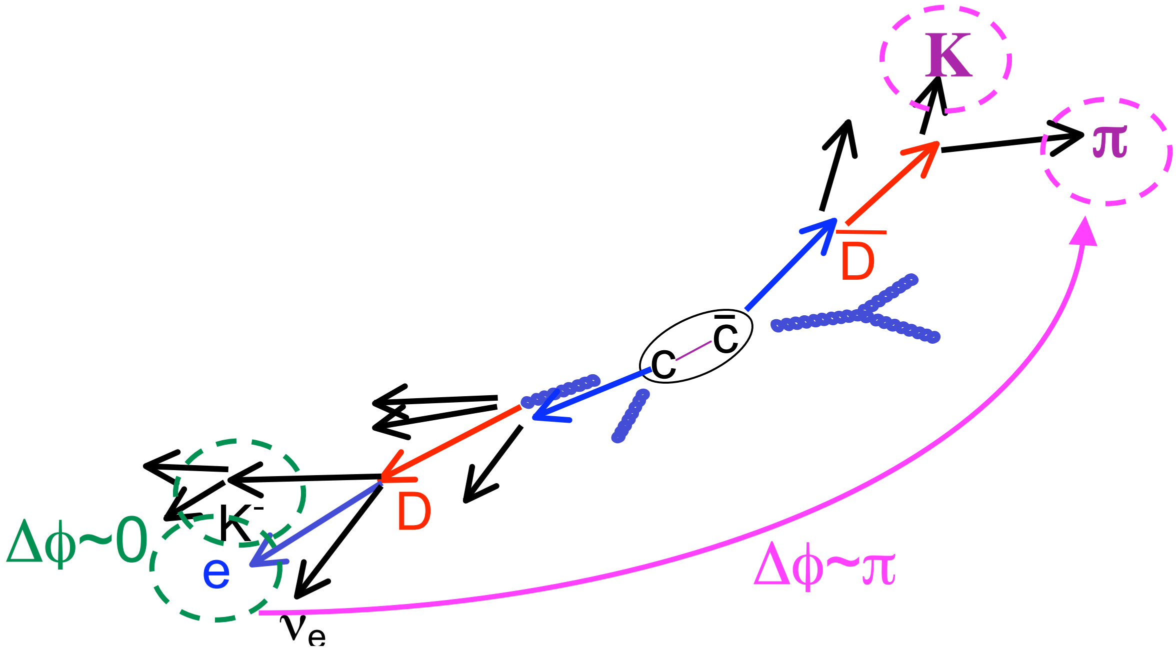

Figure 1. Charmonium semi-leptonic decay illustrates how electron-hadron correlations can be used to measure energy loss of the charm quark

Results/Technical Outcome

Fig. 2 shows a simulation of the signal in phenix. The non-photonic component includes the semi-leptonic decay of the charm quarks and represents the signal that can be used to measure the heavy quark energy loss in heavy ion collisions at RHIC and the LHC.

While performing the simulations and preliminary data analysis, the LLNL heavy ion group begin preparations to formally join the ALICE collaboration at CERN, and was officially admitted in 2007, and approval from DOE Office of Science Nuclear Physics Program was given shortly thereafter. LLNL participation in ALICE is predicated on two parts : contributions to the analysis of jets using the USA Electromagnetic Calorimeter (EmCal) detector, and contributions and leadership in computing. Contributions to the jet cone finding are described in UCRL-JRNL-228100 [1], co-authored by J.Klay.

The contributions to computing stem from the practice of purchasing Linux Scalable Units that has been developed by Livermore Computing to procure, install, and administer similar architectures and operating systems across several clusters. For this reason, LLNL is able to stage computing nodes at approximately half the cost compared to purchase of commodity computing. When coupled to the 700 TB Green data oasis that was purchased in 2006 for the benefit of the Program for Climate Modeling and Intercomparison (PCMDI).

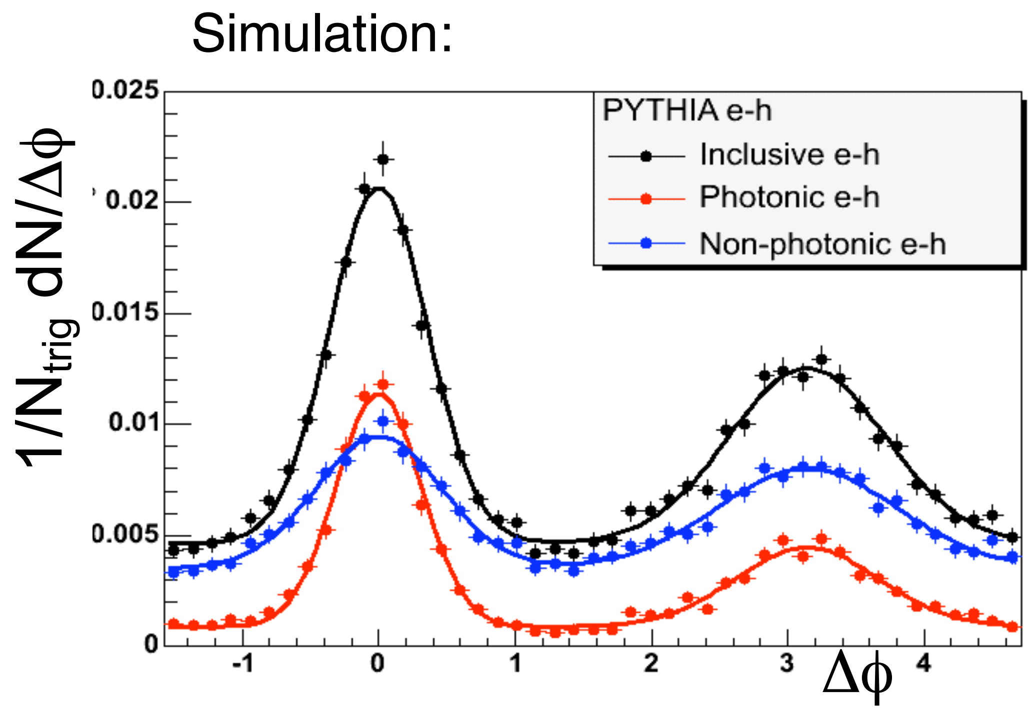

Figure 2. Simulation of electron-hadron correlation signal in PHENIX. The total inclusive electron hadron correlation is the sum of the photonic (background) signal and the non-photonic signal.

In 2007 we proposed to the DOE Office of Science Nuclear Physics Program to leverage the planned Tri-Lab Linux Capacity Cluster (TLCC) with an additional 20 nodes to be staged on the Green Network for Alice Grid Computing, UCRL-PROP-236007 [2]. This computing plan, shown schematically in Fig. 3, was adopted by the ALICE-USA collaboration as essential to meeting the US computing obligations for ALICE, and was formally included in the ALICE-USA Computing Plan, UCRL-PROP-401660. This figure shows the computing configuration as originally envisioned. A more functional implementation is now being used as a test case in which the glcc nodes directly mount the GDO disk via xrootd

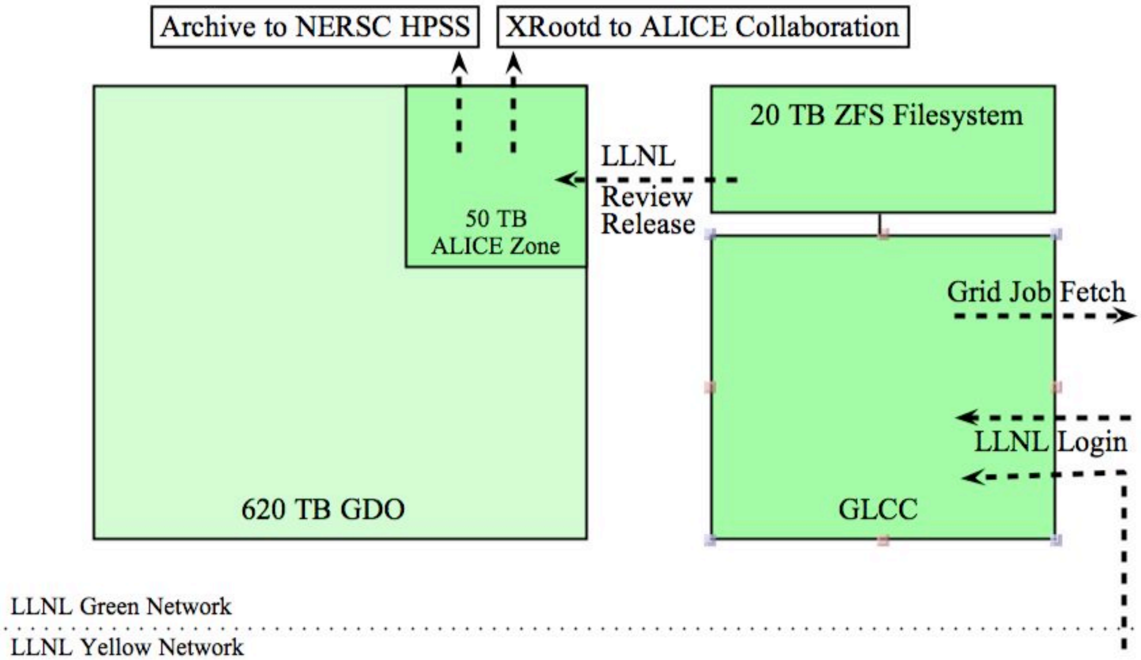

Figure 3. Schematic of the Green Linux Capacity Cluster (GLCC) for ALICE-USA grid computing.

Exit Plan

The long term goals of this LDRD were to increase funding from the DOE Office of Science to the LLNL Heavy Ion Group and to create the conditions for DOE Office of Science investment in computing at LLNL. During the period from 2005 thru 2008 DOE Office of Science funding grew by 75%, from $200k to $350k, and we have proposed a near doubling of 2008 funding levels by 2010. For computing, we have proposed a modest $120k investment in FY09 to purchase 20 TLCC nodes, with an upgrade scheduled for 2012 at triple that amount [2]. This investment is now an essential part of the overall ALICE computing plan [3], and we are currently in conversation with our DOE SC Program Manager regarding the timing of this investment.

Summary

We have established the analysis procedures to measure heavy quark energy loss in heavy ion collisions through electron-hadron correlations measured in PHENIX. We have officially joined the ALICE Collaboration and have established a jet-cone algorithm [1] that will be used to measure jet energy-loss using the US EmCal detector. We have established LLNL computing as an essential component of the overall US ALICE computing plan [2,3]. We have increased our DOE Office of Science funding by 75% during the course of this LDRD, proposed further increases for subsequent years.

References

[1] S-L Blyth, *et al.*, "A cone jet-finding algorithm for heavy-ion collisions at LHC energies", *J. Phys. G* 34:271, 2007, UCRL-JRNL-228100.

[2] R. Soltz, J. Newby, A. Glenn, Green Linux Capacity Cluster, UCRL-PROP-236007.

[3] R. Soltz, P. Jacobs, L. Pinsky, ALICE-USA Computing Plan, *Proposal submitted to DOE Office of Science, Feb 25, 2008*, LLNL-PROP-401660.