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Sponsoring Office: Department of Energy
Name of recipient: University of Colorado
Institution/address: 3100 Marine Street, 572 UCB, Boulder, CO 80309-0572
Name of PI: Dennis Perepelitsa
Email: Dennis.Perepelitsa@colorado.edu
Phone: (303) 735-5493

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Abstract. This technical report summarizes the main accomplishments of the research performed under the U.S. Department of Energy (DOE) Office of Science, Early Career Award (ECA), grant number DE-SC0018117, from 9/1/2017 to 8/31/2022, with Prof. Dennis Perepelitsa as the single PI. The grant proposal was to investigate the quark-gluon plasma (QGP) created in ultra-relativistic collisions of large nuclei with the ATLAS experiment at the Large Hadron Collider (LHC) and to prepare for this physics with the sPHENIX experiment at the Relativistic Heavy Ion Collider (RHIC). In particular, the focus was on QGP regions of different sizes and shapes, including the tradtional "large" collision systems such as Pb+Pb as well as small collision systems such as p+Pb, where there has been evidence of QGP "flow" but not yet the accompanying energy loss from hard-scattered partons traversing the QGP medium. Additionally, a particular tool was the use of photon+jet events, where the photon is unaffected by the QGP and thus serves as the "control" while the jet (the result of parton fragmentation) is the "probe" of the QGP. The research was successfully carried out, resulting in over ten publications of experimental measurements in peer-reviewed journals, and the significant training of junior scientists.

Summary. The research program successfully carried out the proposed research, and was even able to expand into new directions not originaly foreseen at the time of the grant proposal.

The first major component of the research was to perform measurements of electroweak boson-tagged energy loss in the QGP. This included a measurement of the photon+jet p_{T} balance, where one can determine the absolute energy loss of the jet in a calibrated way, using the photon p_{T} as reference, published in PLB [1]. This measurement was performed with the first 5.02 TeV Pb+Pb data, and included a number of technical advances for the photon reconstruction and in the analysis technique, opening the door for several followup measurements. Next, we performed a measurement of how the jet fragmentation function is modified for photon+jet events in, in Pb+Pb events compared to that in pp, published in PRL [2]. By comparing this measurement to the fragmentation function for inclusive jets, we learned something interesting about how the QGP acts on quark-jets (which make up most of the photon+jet sample) vs. gluon jets (which is what most of the inclusive jets are). We continued this series of measurements with a measurement of Z-boson tagged charged particle production, where rather than attempt a full jet reconstruction at these low-p_{T} values, we instead look at the jet fragments. This measurements was also published in PRL [3], again enabled for the first time by high-luminosity LHC data and some new techniques. This measurement brought new information about the modification of very low-p_{T} jets and the resulting redistribution of the lost energy by the medium. Finally, we completed a measurement comparing the nuclear modification factor in Pb+Pb collisions of inclusive jets to that for photon-tagged jets - a novel way to determine how jet energy loss depends on the QCD color factor of the initiating parton. At the closing of the award, this measurement was in Preliminary form but has since now been submitted as a paper for publication [4].

The second major component of the research was to understand the nature of the system produced in small collision systems such as p+Pb or pp. This included a measurement of isolated photon production in p+Pb collisions, published in PLB [5], which introduced for the first time a qualitatively new channel into global fits of nuclear parton densities (which until then had otherwise relied on di-jets and heavy bosons). Then, we performed a series of measurements aimed at trying to understand the limiting conditions for the collective behavior seen in small systems. We performed a measurement which observed for the first time that heavy flavor hadrons “flow” (participate in collective behavior, as evidenced by an azimuthal anisotropy) in high-multiplicity pp collisions, published in PRL [6]. Interestingly, while charm hadrons were observed to flow, the azimuthal anisotropy for bottom hadrons was compatible with zero - potentiallyv offering a key tool to distinguish the underlying mechanism for this physics. Next, we performed a measurement, published in EPCJ [7], which revealed that the azimuthal anisotropy remained non-zero out to very high p_{T} in p+Pb collisions, which is a region where this signal would be interpreted as jet quenching in the larger systems. Thus, this measurement heightened the challenge in understanding the behavior of small systems in a comprehensive way. In fact, we then performed a follow-up measurement of the jet-tagged hadron yields in p+Pb collisions, using the Zero Degree Calorimeter (ZDC) to select the most central events without bias. This measurement, in press at PRL [8], set some of the strongest limits on parton modification in the QGP to date. Finally, we performed a novel measurement of two-particle correlations in high-multiplicity photo-nuclear events, published in PRC [9]. Even in these exotic collisions, we observed an azimuthal anisotropy signal, providing a new system with a very different configuration which would thus be used to understand their origin, and which may have interesting implications for the physics of the EIC.

Furthermore, this award helped support additional, bonus research efforts which were not envisioned in the original proposal. For example, after the successful demonstration of charm to bottom separation with heavy-flavor decay muons in ATLAS, our group extended these techniques to measurements of heavy-flavor-separated flow [10] and nuclear modification [11], both published in PLB.

This award was instrumental in the training of several junior personnel, who were either directly supported by the ECA grant or were supervised by the PI. The graduate students include Dr. Kurt Hill, defended his Ph.D. in 2019, received the ATLAS Thesis Award, working on the measurements in Refs. [5, 7], and now working in industry; Dr. Blair Seidlitz, defended his Ph.D. in 2021, working on the measurement in Ref. [9], and now a post-doc at Columbia University; and Dr. Jeff Ouellette, defended his Ph.D. in 2022, working on the measurements in Refs. [3, 8], and now working in industry. The post-docs include Dr. Qipeng Hu, who particularly led the measurements in Refs. [6, 10, 11], who then went on to a post-doc at LLNL and is now a tenure-track faculty member at USTC and will be the incoming ATLAS Heavy Ion co-Convener.

The junior people involved were also able to participate directly in data-taking (with ATLAS at CERN for the 2016, 2017, and 2018 heavy-ion data-taking) or in detector construction and R&D (sPHENIX electronics development, test beam data and analysis leading to a publication in the IEEE TNS [12], and physical detector construction around the country).

References

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