Short thesis for the degree of doctor of philosophy (PhD)

High Energy Particles in Heavy Ion Collision & Solar Observation

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A Summary of the Dissertation

Theoretical Background

As the universe expanded and cooled, quarks and gluons, the components of subatomic particles referred to as partons, were more scattered. A phase transition transpires. Particles combine and become confined inside colorless hadrons due to an increased binding force between them [1].

The Standard Model provides detailed descriptions of three out of all four basic interactions; namely the electromagnetic, strong, and weak forces. These interactions govern the behavior of fundamental particles that constitute everything that exists. A profound comprehension of the gluons and quarks, the most fundamental particles explained within the Standard Model, make up nuclei, which are formed of protons and neutrons [2].

QCD is a non-Abelian theory of quantum fields that describes the strong interactions between particles. Investigating non-perturbative phenomena in QCD represents a primary objective in the field of URHI physics. During URHI collisions, a state of matter known as QGP forms [3], which allows for the investigation of the QCD phase transition. QGP describes an environment characterized by the absence of binding between quarks and gluons. At the very beginning of the universe, an extremely quick period after the Big Bang, such a situation was present.

Ultra-relativistic heavy-ion collisions at RHIC create conditions similar to those in the early universe, forming a quark–gluon plasma (QGP). High-energy photons and neutral pions (π^0) serve as essential probes for studying the properties of this hot, dense medium.

This study offers a larger conceptual connection between photon generation in high-energy nuclear collisions and in astronomical contexts, including solar flares and coronal mass ejections (CMEs). Despite the substantial differences in conditions—one taking place in ultra-relativistic collisions inside a laboratory, the other in the magnetized plasma of the Sun—both systems use high-energy photons as crucial probes of extreme physical states. In heavy-ion collisions, direct photons reflect the initial circumstances and early dynamics of the quark-gluon plasma (QGP). In solar flares and coronal mass ejections, high-energy photons, such as X-rays and gamma rays, indicate particle acceleration mechanisms, magnetic reconnection, and extensive energy release in the solar corona.

The Goal of the Study

This research focuses on the study of high-energy gold-gold (Au+Au) collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV, conducted at the RHIC at Brookhaven National Laboratory (BNL). These collisions create an environment of extremely high energy density and low net baryon number at mid-rapidity, resembling the early universe microseconds after the Big Bang. Under such extreme conditions, it is possible to form a QGP—a state of deconfined quarks and gluons—which allows for detailed exploration of QCD in the non-perturbative regime.

This thesis also draws a broader conceptual connection between photon production in high-energy nuclear collisions and in astrophysical phenomena such as solar flares and coronal mass ejections (CMEs). While these two research areas differ fundamentally in scale and environment—one taking place in controlled laboratory settings on Earth, the other occurring naturally in space—they both rely on high-energy photons as critical messengers of extreme physical conditions. In heavy-ion collisions, direct photons emerge during the earliest moments of the reaction, providing insight into the formation and properties of the quark-gluon plasma (QGP). Similarly, solar flares and CMEs accelerate particles to high energies and generate electromagnetic radiation across a broad spectrum, including X-rays and gamma rays. These photons offer vital clues about particle acceleration mechanisms, magnetic field dynamics, and energy release processes in the solar corona.

The study of such solar events has gained significant attention due to their profound impact on space weather and modern technology. Solar energetic particle (SEP) events, driven by CMEs and flares, can disrupt satellite operations, communication systems, and power grids. Therefore, understanding the physical conditions under which photons are produced in these cosmic environments is essential for improving predictive models and developing mitigation strategies for technological vulnerabilities [4].

By exploring the mechanisms that govern photon production in both nuclear and astrophysical contexts, this work emphasizes the universal role of high-energy photons as probes of early-time dynamics in extreme environments. This cross-disciplinary perspective highlights how insights from nuclear experiments can inform space science, and vice versa, reinforcing the central importance of photons in advancing our broader understanding of energetic matter throughout the universe.

Objective

Using high-statistics Au+Au $\sqrt{s_{NN}} = 200$ GeV data from Run 14, the study measures corrected yields of π^0 and direct photons with the PHENIX EMCal [5].

The PHENIX (Pioneering High Energy Nuclear Interaction eXperiment) detector is located at one of the six intersection points of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) [6]. PHENIX was designed to investigate the properties of the quark gluon plasma (QGP), a state of matter believed to have existed in the early universe, by studying high-energy heavy-ion collisions. Its subsystems are optimized to measure a wide variety of final-state particles and electromagnetic probes produced in these collisions. EMCal Designed to measure energies from a few hundred MeV up to 80 GeV, the EMCal achieves an energy resolution of approximately 2% for single photons and around 10% for π^0 cross sections. Its fine segmentation ($\Delta\eta \times \Delta\phi \approx 0.01 \times 0.01$) ensures low occupancy, even in the most central Au+Au collisions. The combination of PbSc and PbGl technology allows for robust cross-checks and systematic control between the two subsystems.

The PbSc calorimeter [7] is a shashlik-type detector consisting of 15,552 towers covering approximately 48 m^2. PHENIX contains two PbSc sectors in the east arm and four in the west central arm. The detector records scintillation light produced at multiple depths, enabling precise reconstruction of the energy deposited by incident particles.

The PbGl calorimeter, first deployed in the WA98 experiment at CERN [8] for direct photon measurements, was later installed in PHENIX's east central arm as two sectors. Each sector houses 192 supermodules (SMs), each comprising 24 PbGl modules in a 6×4 array. The modules are wrapped in carbon fiber and epoxy, equipped with photomultiplier tubes, and feature an integrated LED system for gain monitoring.

MB Trigger event selection in PHENIX is based on the Beam Beam Counters (BBC) [9], positioned symmetrically at 144 cm from the interaction point within the pseudorapidity range $3.0 < |\eta| < 3.9$. The BBC provides vertex determination and centrality information. For the BBC Level-1 (BBCLL1) trigger to be satisfied, a coincidence between the north and south BBC detectors is required, along with a reconstructed collision vertex within $|z| < 30$ cm.

The EMCal RICH Trigger (ERT) further enhances photon and electron detection capabilities by combining information from the Ring Imaging Cherenkov Detector (RICH) and the EMCal. An ERT trigger is satisfied when a ring is identified in the RICH and a matching cluster is registered in the EMCal. **Solar photons** Solar energetic par- ticle (SEP) events, driven by CMEs and flares, can disrupt satellite operations (SOHO LASCO), communication systems, and power grids.

Points of the thesis

This thesis contains three points as the following:

1. DHM & Timing Calibration

The Dead Hot Map (DHM) creation and precise timing calibration methods, which foundation this thesis, have been fully examined and confirmed in my recent publication [10].These methods provide a solid framework for accurate physics measurements and were used in this study.

DHM Analysis

In order to reduce false hits, I create the Dead/Hot map by removing the malfunctioning (dead) towers or towers with too many false hits (hot) by identify the "malfunction" towers and just use the "efficient" towers for my research. The towers considered "malfunction" are identified as the Dead Hot Map (DHM) in this statement. This DHM principally includes two groups of malfunctions as suggested by its name. When the tower fails to responds or just partially responses, it becomes known as the Dead Tower. In calorimeter-based investigations, a “Hot” tower describes a detector channel that displays an unusually elevated signal rate. This may result from electronic noise, hardware failures, or radiation damage; in summary, they produce signals without an energy deposit. Such towers can affect energy measurements and negatively impact the precision of direct photon studies. Consequently, recognizing and rectifying hot towers is crucial for preserving data integrity. Therefor, I studied the multiplicity of the cluster in every run (order of 1000 runs are available for Run14), in 39 energy bins in order to calculate unique cuts. I extended the dead and hot towers per run and per energy bin by statistical methods to a global dead-hot map I used for the Run14 data set. I studied different dead-hot maps to achieve the best possible data quality for my direct photon analysis.This work titled "Run14 Au+Au Dead Hot Map" and published it in completely with the TN number "486.0" [11].

Timing Calibration

A precise time calibration is necessary to differentiate between a hadron traveling the calorimeter and generating a signal, and a photon, since hadrons show slower velocities. With an accurate timing calibration, I can effectively discriminate between a photon cluster and a hadron cluster. In my work with π^0, I consistently utilize two clusters; however, when dealing with a direct photon, there were only one cluster used. Therefore, it is necessary to confirm that the detected signal is indeed a photon and not a hadron that gives a photon-like cluster. Within a quark-gluon plasma, the prevalence of hadrons results in numerous false clusters in the calorimeter, similar to those produced by π^0. Consequently, it is essential to eliminate these false signals, and one effective method for limiting the hadronic background is through timing calibration (time-of-flight cut), in my Au+Au 200 GeV data set. I developed a new fit (5 parameters fit) for each tower to ensure precise timing for clusters. With this new ToF information the gamma and the hadron clusters can be distinguished, the hadron backgrounds from direct photon analysis can be subtracted. I successfully implemented the PID cuts (abs(corrected ToF$<$ 5 ns) to remove effectively the contamination from hadrons.

I uploaded all the above work inside PHENIX system and published it in full with the TN number "TN489.0" and the title "Calibration of EMCal ToF in Run-14 Au+Au collisions" [12].

2. Analysis of π^0s & Direct γ

I analyzed the neutral pions (π^0) as the main origin of decay photons. The method of invariant mass reconstruction is used to identify and isolate π^0 particles. I obtained the raw output of $pi0$ particles and then applied corrections to the raw output. To modify the raw output, I use a two-dimensional response matrix that I create using $pi0$ simulations. I confirmed the $pi0$ yield based on the results of the research and recorded it in the internal review conducted by the PHENIX collaboration. The systematic uncertainty were calculated for the raw $pi0$ and the raw direct photon were calculated.

I performed a simulation of π^0 in order to account for detector effects such as acceptance, efficiency, and smearing. Then I used PISA to simulate the decay and interactions by generating and processing input events. I incorporated simulated energy deposits into actual events to compensate for deformities. I build a two-dimensional response matrix to provide a mapping between the produced P_t and the measured P_t. I used iterative adjustments to modify the raw yield spectrum by unfolding techniques to obtain corrected direct photon spectra. After this, I investigated the systematic uncertainties by varying PID parameters and energy asymmetry cuts for the corrected yield of π^0 and PID parameters and Time-of-Flight (TOF) for the corrected yield of direct γ and several comparisons conducted to prove the consistency between my findings and another PHENIX result.

I have published this study as an Analysis Note under reference number "1505," titled "Run 14 pi0 and direct photon analysis in 200 GeV Au+Au collisions" [13]. Furthermore, I analyzed and published this article [14] about the small system collisions to provide a reference for my calculation of the ratio of direct photons to π^0s as a validation of centrality, using the methodology tested in the small system.

3. High Energy Solar Particle Events and Photon Studies

High-energy solar particle events (SPEs) involve charged particles accelerated and expelled from the Sun, often associated with solar flares and shocks from coronal mass ejections (CMEs). Alongside these particles, intense photon emissions occur across the electromagnetic spectrum, providing critical insights into the underlying acceleration mechanisms [15].

I do an analysis of the high-energy solar particle events (SEPs), flares, and coronal mass ejections (CMEs) showing the relationship between photon energy flux and the velocity of a Coronal Mass Ejection (CME) at different photon energy densities during Solar Cycle 25, focused on photon emission related to solar events across different energy ranges. My research analyzed correlations between CME velocity, angular width, and photon energy flux by investigating the origins, processes, and effects of these events on space weather highlighted the importance of photon monitoring in forecasting. Emphasized the need for improved predictive models for solar-terrestrial interactions.

I have documented this research under the title "High Energy Solar Particle Events and Their Correlation with Associated Flare and CME during the Early Solar Cycle 25", the paper is submitted [16].

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List of publications related to the dissertation

Foreign language scientific articles in international journals (3)

1. **Abdulameer, N. J.**, Oniga, I. L., Ujvári, B.: Advanced Big Data Solutions for Detector Calibrations for High-Energy Physics.
   Electronics (Switzerland). 14 (10), 1-28, 2025. EISSN: 2079-9292.
   IF: 2.6 (2024)
2. **Abdulameer, N. J.**, PHENIX Collaboration: Centrality Dependence of [gamma]dir and [pi]0 Production in d + Au Collisions.
   Mosc. Univ. Phys. Bull. 79 (Suppl.1), 396-402, 2025. ISSN: 0027-1349.
   DOI: https://doi.org/10.3103/S0027134924701133
   IF: 0.4 (2024)
3. **Abdulameer, N. J.**, Allawi, H., Ujvári, B.: Study of the relationships between flares and coronal mass ejections in high-energy solar particle events during the early stages of Solar Cycle 25.
   Int. J. Mod. Phys. A. 40 (21), 1-24, 2025. ISSN: 0217-751X.
   DOI: https://doi.org/10.1142/S0217751X25420072
   IF: 1.2 (2024)

List of other publications

Foreign language scientific articles in international journals (8)

4. **PHENIX Collaboration**: Nonprompt direct-photon production in Au+Au collisions at root{s_NN} = 200 GeV.
   Phys. Rev. C. 109 (4), 1-26, 2024. ISSN: 2469-9985.
   DOI: http://dx.doi.org/10.1103/PhysRevC.109.044912

5. **PHENIX Collaboration**: Improving constraints on gluon spin-momentum correlations in transversely polarized protons via midrapidity open-heavy-flavor electrons in p^[uparrow] plus p collisions at root{s}=200 GeV.
   Phys. Rev. D. 107 (5), 1-8, 2023. ISSN: 2470-0010.
   DOI: http://dx.doi.org/10.1103/PhysRevD.107.052012

6. **PHENIX Collaboration**: Low-pT direct-photon production in Au+Au collisions at root{s_NN} = 39 and 62.4 GeV.
   Phys. Rev. C. 107 (2), 1-8, 2023. ISSN: 2469-9985.
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7. **PHENIX Collaboration**: Measurement of [phi]-meson production in Cu plus Au collisions at root{s_NN}=200 GeV and U plus U collisions at root{s_NN}=193 GeV.
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   DOI: http://dx.doi.org/10.1103/PhysRevC.107.014907

8. **PHENIX Collaboration**: Measurement of Direct-Photon Cross Section and Double-Helicity Asymmetry at root{s}=510 GeV in [vector]p+[vector]p Collisions.
   Phys. Rev. Lett. 130 (25), 1-8, 2023. ISSN: 0031-9007.
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9. **PHENIX Collaboration**: Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in p+p, p+Au, d+Au, and 3He+Au collisions at root{s_NN}=200 GeV.
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   DOI: http://dx.doi.org/10.1103/PhysRevC.107.024907

10. **PHENIX Collaboration**: Transverse single-spin asymmetry of charged hadrons at forward and backward rapidity in polarized p plus p, p plus Al, and p plus Au collisions at root{S_NN}=200 GeV.
    Phys. Rev. D. 108 (7), 1-13, 2023. ISSN: 2470-0010.
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11. **PHENIX Collaboration**: Transverse single-spin asymmetry of midrapidity [tau]^0 and [eta] mesons in p+Au and p+Al collisions at root{s_NN}=200 GeV.
    Phys. Rev. D. 107 (11), 1-9, 2023. ISSN: 2470-0010.
    DOI: http://dx.doi.org/10.1103/PhysRevD.107.112004

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