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PROBING THE NUCLEAR AND ELECTROMAGNETIC STRUCTURE OF HEAVY NUCLEI AT STAR

XIHE HAN[a] and NICHOLAS JINDAL
191 W Woodruff Ave, Columbus, [OH,] 43210, United States

Diffractive vector meson photoproduction has long been recognized as an unparalleled probe of the gluon distribution within nuclei, potentially key to elucidating non-linear QCD effects that lead to universal states of dense gluonic matter. ϕ meson photoproduction is particularly useful for studying small-x dynamics, especially gluon saturation, due to its sensitivity to larger dipole sizes compared to, for example, J/ψ and other heavy vector mesons. Compared to the ρ^0 meson, the ϕ meson has a larger mass, making it more amenable to theoretical investigation. For these reasons, the measurement of ϕ meson photonuclear production in A+A collisions has been long anticipated. In this talk, we present the measurement of exclusive diffractive photonuclear production of the ϕ meson via the K^+K^- decay channel from Au+Au collisions and utilize this newly obtained measurement to compare theoretical calculations incorporating gluon saturation effects across orders of magnitude in dipole size, thereby illuminating the small-x gluon distribution within nuclei. Furthermore, just as diffractive vector meson production has been employed in high-energy collisions to probe the spatial distribution of gluons within the nucleus, it has recently been demonstrated that photon photon interactions enable mapping of the photon Wigner distribution within heavy nuclei—a multidimensional image of the electromagnetic fields of high-energy nuclei. To this end, we present the measurement of $\gamma + \gamma \to e^+e^-$ from U+U collisions at $\sqrt{s_{NN}} = 193$ GeV and investigate various approaches for constraining the nuclear (electromagnetic) structure of uranium.

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1 Introduction

Ultra-peripheral collisions (UPCs) of heavy ions occur at impact parameters larger than twice the nuclear radius, where hadronic interactions are strongly suppressed and the Lorentz-contracted nuclei act as intense sources of quasi-real photons [1]. This enables photon-induced reactions at high energies and provides a clean environment to probe both the electromagnetic and nuclear structure of relativistic heavy ions.

Photonuclear interactions in UPCs, where a photon from one nucleus scatters off the gluon field of the other, are directly sensitive to the small-x gluon distribution. Diffractive vector meson photoproduction ($\gamma + A \to V + A$) proceeds via the fluctuation of the photon into a $q\bar{q}$ dipole. The cross section scales approximately with the square of the gluon density, making exclusive production of vector mesons such as ρ^0, ϕ, and J/ψ a powerful probe of small-x QCD dynamics and potential saturation effects [3].

In parallel, photon–photon processes in UPCs provide a complementary handle on the electromagnetic structure and nuclear geometry. The intense photon fluxes enable dielectron production via the Breit–Wheeler process, $\gamma\gamma \to e^+e^-$. The measured kinematic distributions in this channel are sensitive to the nuclear charge distribution through the photon Wigner function, which links photon momentum to spatial charge densities via its explicit impact-parameter dependence [2]. Consequently, dilepton production can be used to probe aspects of photon emission and to constrain features of the nuclear geometry.

The STAR experiment at RHIC has established a comprehensive UPC program covering both photonuclear and photon–photon processes. Building on earlier measurements, this work presents two complementary analyses: (i) diffractive $\phi \to K^+K^-$ photoproduction as a probe of the small-x nuclear gluon distribution, and (ii) $\gamma\gamma \to e^+e^-$ production as a tool to investigate the electromagnetic structure and geometry of heavy nuclei. Together, these measurements advance a unified picture of QCD and QED dynamics in nuclear UPCs.

[a]Xihe Han, email: han.1929@buckeyemail.osu.edu

2 Motivation

While UPCs enable a broad range of photon-induced phenomena, two channels are of particular interest at RHIC energies: diffractive vector meson photoproduction and photon–photon scattering. The former directly probes the small-x nuclear gluon distribution, while the latter provides sensitivity to the spatial distribution of electromagnetic fields.

The measurement of exclusive $\phi \to K^+K^-$ photoproduction extends STAR's earlier J/ψ studies [5] into a regime of larger dipole sizes, where saturation and nuclear shadowing effects are expected to become more pronounced. This analysis provides an essential test of models describing the transition between coherent and incoherent scattering and offers new constraints on the nuclear gluon density.

In parallel, the study of $\gamma\gamma \to e^+e^-$ production in U+U collisions explores photon–photon interactions in the strongest available electromagnetic fields. The resulting kinematic distributions are sensitive to the photon Wigner function, linking the transverse momentum of emitted photons to the underlying nuclear charge geometry [2,4]. Such measurements offer a complementary [6] probe of the electromagnetic structure of heavy nuclei. The uranium target, which is known to have a prolate deformation, provides an extension of using UPCs as an electromagnetic probe beyond the approximately spherical gold nucleus.

Together, these analyses form a coherent program to investigate both the gluonic and electromagnetic aspects of nuclear structure, advancing our understanding of QCD and QED dynamics in UPCs.

3 Analysis I: Diffractive $\phi \to K^+K^-$ Photoproduction

This section presents the measurement of exclusive ϕ meson photoproduction in Au+Au UPCs at $\sqrt{s_{NN}} =$ 200 GeV with the STAR detector. The analysis aims to study the small-x nuclear gluon distribution through the coherent components of the ϕ production cross section. The ϕ meson is reconstructed via its K^+K^- decay channel. The following subsections describe the experimental setup, event selection, signal extraction procedure, and physics interpretation.

3.1 Experimental Setup

The STAR experiment at RHIC collected data from Au+Au UPCs at $\sqrt{s_{NN}} = 200$ GeV in 2019. This dataset represents the first UPC run taken after the installation of the inner Time Projection Chamber (iTPC) upgrade, which significantly improved low-momentum tracking and particle identification. The upgraded iTPC extends the acceptance for charged particles down to $p_T \approx 60$ MeV/c, a critical enhancement for reconstructing coherently produced ϕ mesons via their charged-kaon decay channel. Simulations using the Starlight Monte Carlo generator indicate that most kaon daughters from coherent ϕ decays fall below the p_T threshold of the pre-upgrade TPC, which had a higher cutoff near 150 MeV/c.

3.2 Event and Track Selection

UPCs are selected by vetoing events with significant activity in the Beam Beam Counters (BBC), which are located at forward rapidities ($3.3 < |\eta| < 5.0$). Each BBC comprises of scintillator tiles designed to detect charged particles produced near the beam direction, typically originating from hadronic interactions. By requiring low BBC activity, events with hadronic overlap are efficiently suppressed, isolating the purely electromagnetic UPC sample. In this analysis, we follow the convention of the STAR UPC main trigger and apply a cut on the total BBC ADC sum of less than 50.

For triggering, the Zero Degree Calorimeters (ZDCs) are used to detect forward neutrons emitted from the excited nuclei. A coincidence requirement between the east and west ZDCs is imposed to ensure the triggering of genuine UPC events.

Coherent ϕ meson reconstruction requires identification of charged kaons. Particle identification is performed using the average ionization energy loss ($\langle dE/dx\rangle$) measured in the TPC. Both tracks originating from a common reconstructed vertex are required to satisfy $\chi^2_{KK} \leq 20$, where $\chi^2_{KK} \equiv N\sigma^2_{1,K} + N\sigma^2_{2,K}$ and $N\sigma_{i,K}$ denotes the number of standard deviations between the measured dE/dx of the i-th track and the expected kaon value.

To enhance the selection of coherent events, we impose kinematic requirements on the transverse momentum of both the individual kaon tracks and the reconstructed ϕ meson. Each kaon track must satisfy $p_T < 200$ MeV/c, and the ϕ meson candidate is required to have a pair transverse momentum $p_T^{\text{pair}} < 200$ MeV/c. These criteria exploit the characteristic low-p_T signature of coherently produced ϕ mesons.

3.3 Signal Extraction and Efficiency

The ϕ meson signal is extracted from the invariant mass distribution of K^+K^- pairs reconstructed in the TPC. Coherent candidates are selected within a narrow mass window around the nominal ϕ mass, after subtracting the combinatorial background estimated from same-event like-sign (K^+K^+ and K^-K^-) pairs. This approach provides a clean separation of the ϕ signal without the need for a functional fit to the mass distribution.

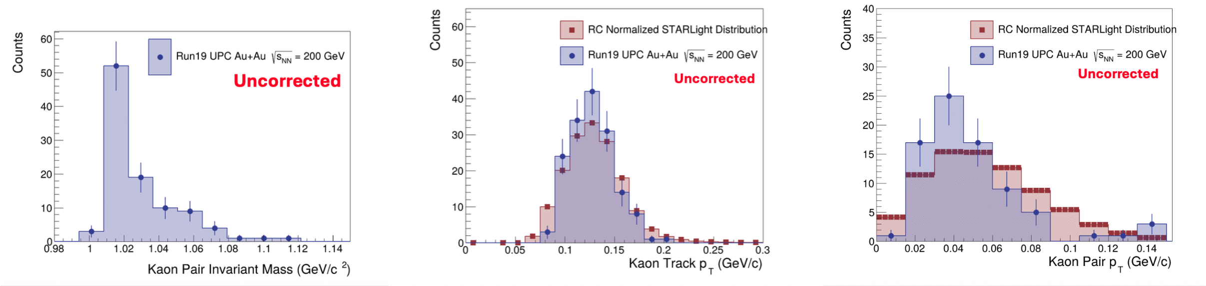

Figure 1 – Uncorrected distributions for coherent ϕ meson candidates in Run19 Au+Au UPC data at $\sqrt{s_{NN}}$ = 200 GeV: invariant mass of K^+K^- pairs, single-kaon transverse momentum (p_T^K), and pair transverse momentum (p_T^{pair}). Data points correspond to reconstructed tracks in the TPC, and shaded histograms indicate normalized STARLIGHT simulations. Error bars represent statistical uncertainties only.

Efficiency corrections are obtained from simulated events propagated through the full GEANT-based STAR detector simulation and reconstruction chain. Reconstructed tracks are matched to generated kaons to determine the detection and reconstruction efficiency. The raw ϕ yields are corrected as a function of pair transverse momentum (p_T^{pair}), rapidity (y^{pair}), and vertex z-position (v_z).

3.4 Results and Interpretation

The differential cross section in p_T^{pair}, y^{pair}, and $|y^{\text{pair}}|$ is shown. The major systematic error in the side rapidity bin is due to simulation uncertainty near STAR acceptance.

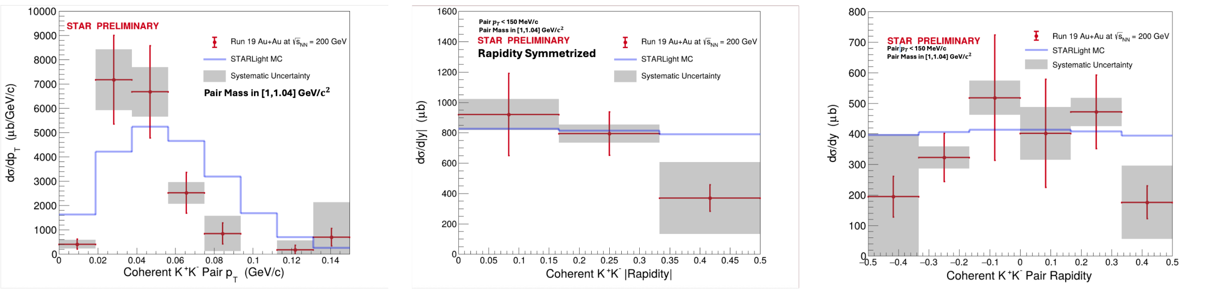

Figure 2 – Fully corrected differential cross section distributions for coherent ϕ meson candidates in Run19 Au+Au UPC data at $\sqrt{s_{NN}}$ = 200 GeV: p_T^{pair} K^+K^- pairs, $|y^{\text{pair}}|$ K^+K^- pairs, and y^{pair} K^+K^- pairs distributions. The error bar represents statistical uncertainty only, and the shaded box indicates the combined systematic uncertainty.

We highlight the mass dependence of vector meson photoproduction cross sections by comparing this result with previous STAR measurements [5], and emphasize the need for updated theoretical calculations. These results establish the first measurement of coherent ϕ meson photoproduction at RHIC energies, extending STAR's UPC program into the intermediate mass region and providing new constraints on the nuclear gluon density.

4 Analysis II: $\gamma\gamma \to e^+e^-$ in U+U Collisions

4.1 Experimental Setup

The STAR experiment at RHIC collected data from U+U UPCs at $\sqrt{s_{NN}}$ = 193 GeV and Au+Au UPCs at $\sqrt{s_{NN}}$ = 200 GeV during the 2010–2012 running period. Events were selected requiring dielectron

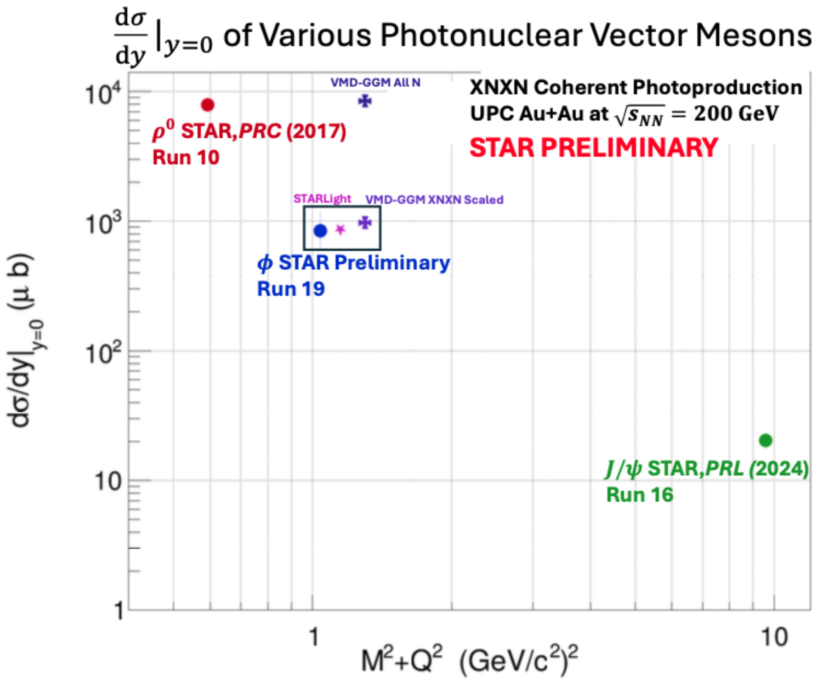

Figure 3 – Coherent photoproduction cross sections of various vector mesons measured by STAR as a function of meson mass. A clear mass dependence is observed, with the ϕ meson result from this analysis shown alongside previous ρ^0 and J/ψ measurements. The trend highlights the importance of theoretical calculations incorporating mass-dependent nuclear shadowing and saturation effects.

candidates within $|y_{ee}| < 1$ and an invariant mass range of $0.45 < M_{ee} < 0.76$ GeV/c^2. Differential cross sections and angular correlations were measured and compared to QED calculations.

4.2 Signal Extraction

Dielectron candidates are reconstructed from pairs of oppositely charged tracks measured in the STAR Time Projection Chamber (TPC). Electron identification is performed using the ionization energy loss (dE/dx) information in the TPC. Each track is required to satisfy $\chi^2_{ee} < 10$, where $\chi^2_{ee} \equiv N\sigma^2_{1,e} + N\sigma^2_{2,e}$ and $N\sigma_{i,e}$ represents the deviation of the measured dE/dx value from the expected electron response for the i-th track.

To suppress background from pion pairs—the dominant source of contamination in this channel—a pion rejection criterion is applied. The combined pion hypothesis is required to satisfy $\chi^2_{\pi\pi} > 3 \times \chi^2_{ee}$. This ensures that candidate pairs are much more consistent with the electron hypothesis than with the pion hypothesis, resulting in a clean selection of $\gamma\gamma \to e^+e^-$ events for subsequent analysis.

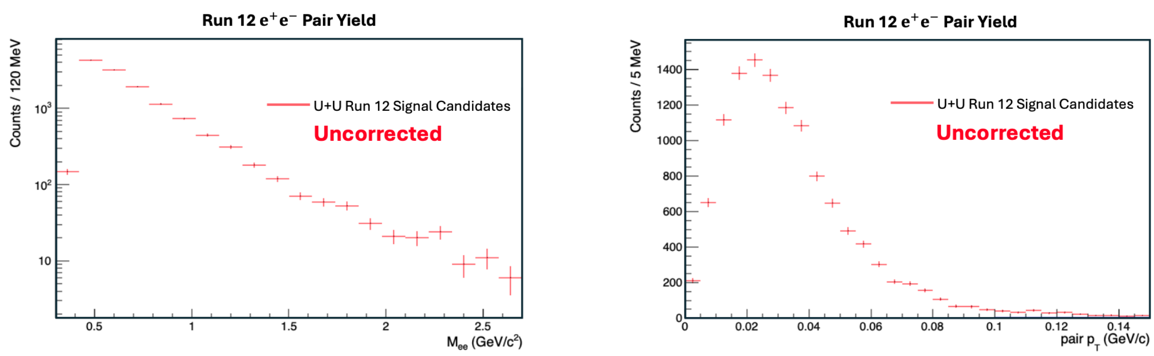

Figure 4 – Invariant mass distribution of dielectron candidates in U+U UPCs, and transverse momentum distribution of dielectron pairs.

4.3 Results and Interpretation

The differential cross section of di-electron distribution is shown in electron pair transverse momentum p_T^{pair}, electron pair mass m^{pair}, and electron pair rapidity y^{pair}.

The measured U+U Breit–Wheeler cross section within the STAR acceptance and primary signal region is:

$$\sigma_{\gamma\gamma\to e^+e^-} = 0.305 \pm 0.003 \text{ (stat.)} \pm 0.009 \text{ (syst.) mb.} \tag{1}$$

This result is consistent with leading-order Quantum Electrodynamics (QED) predictions, while models such as STARLIGHT underestimate the mean pair transverse momentum due to integrating over the impact parameter when calculating the photon flux.

Notably, the spherically averaged QED calculation for the uranium transverse-momentum-dependent cross section, assuming a 6.9 fm charge radius, fails to reproduce a small excess of production at high transverse momentum ($p_T \approx 0.1$ GeV/c). This is consistent with the expectation that the "end–end" initial configuration of uranium nuclei in some UPCs permits smaller impact parameters. Interpreted in terms of the photon Wigner distribution, this configuration should yield an enhanced production of higher-p_T pairs compared to a spherical nucleus of similar Z and A, such as gold. This behavior is indicative of nuclear shape effects, motivating further study through normalized cross-section ratios.

Comparisons of U+U and Au+Au data show that simple Z^4 scaling is insufficient to describe the observations. Instead, the data favor QED calculations incorporating realistic Woods–Saxon charge distributions and an impact-parameter-dependent photon flux for each collision event. Even so, the best QED ratio underestimates the observed excess at higher p_T, which may reflect contributions from the prolate deformation of uranium relative to gold in the initial state of UPCs.

These results establish UPC dielectron production as a sensitive probe of nuclear structure. The data show good consistency with QED calculations incorporating realistic charge densities and highlight the limitations of sim- plified photon flux models.

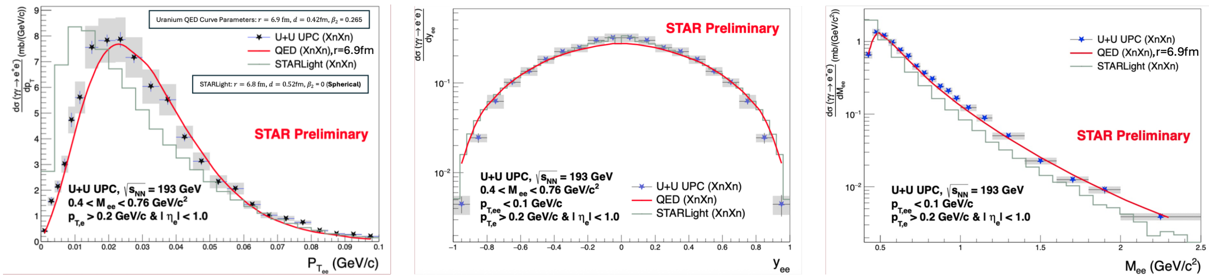

Figure 5 – Fully corrected differential cross section distributions for electron pair candidates in Run12 U+U UPC data at $\sqrt{s_{NN}} = 193$ GeV: p_T^{pair} electron pairs, $|y^{\text{pair}}|$ electron, and M^{pair} electron pairs distributions. The error bar represents statistical uncertainty only, and the shaded box indicates the combined systematic uncertainty.

5 Conclusions and Outlook

We have presented two complementary measurements probing the nuclear and electromagnetic structure of heavy nuclei in UPCs at RHIC. The first, the measurement of coherent $\phi \to K^+K^-$ photoproduction in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, represents the *first observation* of this process at RHIC. This result extends STAR's UPC program into the intermediate-mass vector meson region, providing new sensitivity to the nuclear gluon distribution at small x. The observed cross section demonstrates a clear mass dependence when compared with previous ρ^0 and J/ψ measurements, highlighting the importance of theoretical models that incorporate both nuclear shadowing and gluon saturation effects. With the forthcoming Run23 dataset, taken with the reduced magnetic field configuration, STAR expects to increase the available statistics by approximately three orders of magnitude. This will enable detailed studies of photon energy dependence and allow separation of photon direction using ZDC event classes.

The second analysis, the measurement of $\gamma\gamma \to e^+e^-$ production in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV, marks the *first application* of this technique to a deformed nucleus. The results provide evidence that the nuclear deformation of uranium influences the measured kinematic distributions, suggesting a connection between nuclear geometry and photon field configurations. Future work will employ high-dimensional QED calculations combined with systematic parameter scans to quantify the best-fit deformation parameters of the uranium charge distribution.

Together, these measurements establish a unified framework for exploring both the gluonic and electromagnetic structure of nuclei in UPCs. The upcoming high-statistics datasets and refined theoretical tools will enable unprecedented precision in constraining the spatial and momentum structure of nuclear matter at RHIC energies.

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