Discoveries in Ultra-Peripheral Collisions: Past, Present, Future

James Daniel Brandenburg[1,*]

[1]Ohio State University, Columbus, Ohio 43210, USA

Abstract. Ultra-relativistic heavy-ion collisions produce extremely strong electromagnetic field which provide a uniquely intense and energetic source of photons. The photons manifest from such ultra-Lorentz contracted electromagnetic fields have, in recent years, enabled unique advances in Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD). This manuscript summarizes recent progress across the experimental and theoretical landscape as of 2023 and ends with a look to possible future advancements.

1 Introduction

Ultra-relativistic heavy-ion collisions provide a unique laboratory for harnessing the Universe's most intense electromagnetic fields. Heavy nuclei have a large charge, Z, which produce ultra-Lorentz contracted electromagnetic fields when accelerated to relativistic speeds. The fields of the colliding nuclei vary too quickly to be considered constant fields and must therefore be treated in terms of equivalent photon quanta. The photons manifest from these ultra-Lorentz contracted fields can reach energies, ω, of 3 GeV at the Relativistic Heavy Ion Collider (RHIC) and 80 GeV at the Large Hadron Collider (LHC), respectively.

The high energy photons manifest from the ultra-Lorentz contracted electromagnetic fields of fast-moving heavy ions can interact in two main categories of processes: photon-photon scattering or photonuclear interactions. In photon-photon scattering interactions, a photon manifest from the field of each nucleus scatter off one another elastically (leading to two outgoing photons) or fusing to produce a pair of leptons (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$). In the photonuclear process, the incoming photon fluctuates into a quark anti-quark pair which interacts directly with the target nucleus via a Pomeron (a two gluon state at leading order). Photonuclear processes often result in the exclusive production of a vector meson with a momentum distribution imprinted with the nuclear gluon density distribution. In both photon-photon and photonuclear interactions, the photons emitted coherently by the ultra-Lorentz contracted electromagnetic field have small transverse momentum ($k_\perp \approx 30$ MeV$/c \approx \omega/(\gamma c)$, where γ is the Lorentz boost factor). The small transverse momentum of the incident photon produces a characteristic feature of coherent photon-mediated processes, allowing them to be isolated not only in ultra-peripheral collisions free of hadronic overlap, but in recent years even in the violent head-on collisions of central heavy-ion collisions [1].

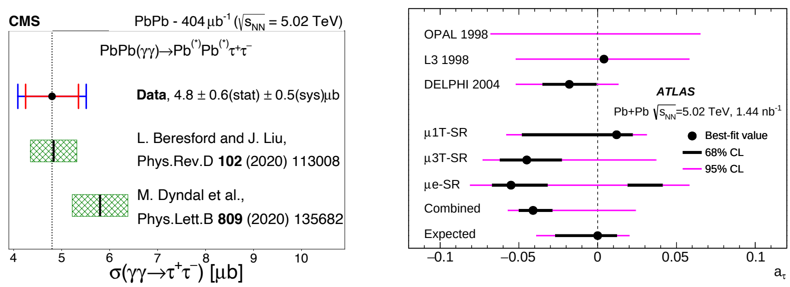

Figure 1. Measurement of the cross section for $\gamma\gamma \to \tau^+\tau^-$ from the CMS collaboration (left). Reproduced from [2]. Measurements from the ATLAS collaboration providing constraints on the anomalous magnetic moment (a_τ) from measurements of $\gamma\gamma \to \tau^+\tau^-$ events through various τ decay channels (right). Reproduced from [3]

2 Precision QED and Searches for BSM Physics

In the past decade, ultra-peripheral heavy-ion collisions have proven to be a unique laboratory for studying the frontiers of Quantum Electrodynamics (QED). In 2019, the ATLAS collaboration observed light-by-light (LbyL) scattering in ultra-peripheral heavy-ion collisions [4]. The observation of elastic LbyL scattering is a clear violation of the superposition principle, an essential feature of the linear theory of classical electromagnetism. Light-by-Light scattering has also been observed by the CMS collaboration [5]. In addition to being a long-awaited test of QED under extreme conditions, LbyL scattering also allows testing the limits of the Standard Model. At high energy LbyL scattering provides a clean channel to search for anomalous gauge couplings and for evidence of particles beyond the Standard Model. One specific application has been the search for axion-like particles (ALPs) which would lead to an anomalous increase in the observed LbyL cross-section (compared to SM sources alone) [6].

Another long-awaited test of QED was achieved in 2021 with the observation of the Breit-Wheeler process and vacuum birefringence[7, 8] - a non-linear effect of QED predicted in the early days of quantum mechanics by Euler, Heisenberg, Schwinger, and Toll [9, 10]. The fusion of two photons to produce an electron-positron pair is another herald of the *non-linear* regime of QED. The STAR collaboration has utilized the $\gamma\gamma \to e^+e^-$ process to constrain the electromagnetic field distribution of high-energy heavy ions [11, 12], and employed the newfound polarization sensitivity to search for Dark Photons [13].

The most precise measurement of the anomalous magnetic moment of the μ (a_μ) was recently announced by the Muon g-2 collaboration [14]. The measured value of a_μ is potentially in tension with the predicted value from Standard Model contributions alone, hinting at possible evidence of physics beyond the standard model. The CMS and ATLAS collaborations have recently pushed the limits of photon-photon fusion processes in heavy-ion collisions, pioneering measurements of $\gamma\gamma \to \tau^+\tau^-$. Photon-photon fusion into a pair of τ leptons ($m_\tau = 1.77\text{GeV}/c^2$) is only possible due to the extremely high energy photons manifest in ultra-relativistic heavy-ion collisions. Since the production cross section for $\gamma\gamma \to \tau^+\tau^-$ depends on the magnetic moment of the τ lepton (See figure 1 left), it provides a pristine channel for constraining the anomalous magnetic moment of the τ, a_τ. Existing measurements from the CMS and ATLAS collaborations have yielded measurements of a_τ competitive with the previous world's most precise measurements [15] The heavier mass compared to the muon

*e-mail: brandenburg.89@osu.edu

makes measurement of a_τ approximately 280× more sensitive to new physics compared to a_μ.

3 Photons as Probes of Dense Nuclear Matter

Besides exploring non-linear regimes of QED, the photons manifest from the ultra-Lorentz contracted electromagnetic fields of heavy-ions are also useful for studying dense nuclear matter [16]. High-energy photons have long been used to study nuclear targets through so-called photonuclear interactions, whereby the photon fluctuates into a quark anti-quark pair, allowing it to interact directly with the target via the exchange of a Pomeron (two gluons at leading order). Such interactions imprint the nuclear gluon distribution on the produced vector meson (ρ^0, J/ψ, etc.).

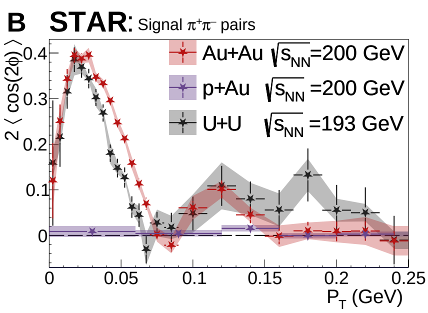

Figure 2. Measurement of the $\cos 2\phi$ modulation strength versus pair p_T in photonuclear production of $\rho^0 \to \pi^+\pi^-$ events. Reproduced from [17].

Depending on the momentum transfer ($-t \approx p_\perp^2$) of the process, photonuclear interactions probe various lengths scales. Coherent interactions, with $t \lesssim (50\ \mathrm{MeV}/c)^2$, probe the longest length scales and are sensitive to the overall size of the nuclear target. On the other hand, incoherent interactions, which dominate the cross section at higher momentum transfers (compared to coherent interactions), probe smaller length scales and are sensitive to nucleonic and sub-nucleonic structure within large nuclei [18]. In principle the gluon nuclear target's density distribution can be trivially recovered via a Fourier transform of the $d\sigma/dt$ distribution measured from coherent interactions. Nonetheless, for nearly two decades, such analysis has yielded unreasonably large nuclear radii [19], preventing detailed measurement of nuclear structure from ultra-peripheral heavy-ion collisions.

The STAR collaboration revisited this long-standing mystery in photonuclear production of $\rho^0 \to \pi^+\pi^-$ mesons with the spin-sensitive measurement technique developed in the $\gamma\gamma \to e^+e^-$ analysis [7]. Utilizing this technique revealed a sizable modulation in the angle ϕ (measured in the transverse plane) between the momentum vector sum ($p_{\pi^+} + p_{\pi^-}$) and difference ($p_{\pi^+} - p_{\pi^-}$) of the decay daughter π^+ and π^- [17]. The modulation, shown in Fig. 2, results from a previously unexpected interference effect [20–22] that takes place in symmetric A+A collisions, since the process can proceed through two possible amplitudes depending on which nucleus acts as the photon emitter and which acts as the target. The observation of such an interference effect is however unexpected, since the final state particles (π^+ and π^-) are distinguishable states. Correcting for this interference effect allowed the STAR collaboration to perform precise measurement of the nuclear gluon distribution in Au+Au and U+U collisions, extracting the neutron skin of ^{197}Au and ^{238}U [17].

Figure 3(left) shows the recent confirmation by the ALICE collaboration of the interference effect observed by STAR in ultra-peripheral $\rho^0 \to \pi^+\pi^-$ photoproduction [17], displayed in Fig. 3(left). The ALICE measurement further separates the photoproduction events according to the neutron emission categories, thereby providing access to the impact parameter dependence of the observed interference-induced modulation, showing both a consistency with the STAR result, and a strong impact parameter dependence on the average modulation strength. Figure 3(right) shows the STAR collaboration's search for a similar modulation effects in photonuclear J/ψ events. While no interference induced modulation (expected at

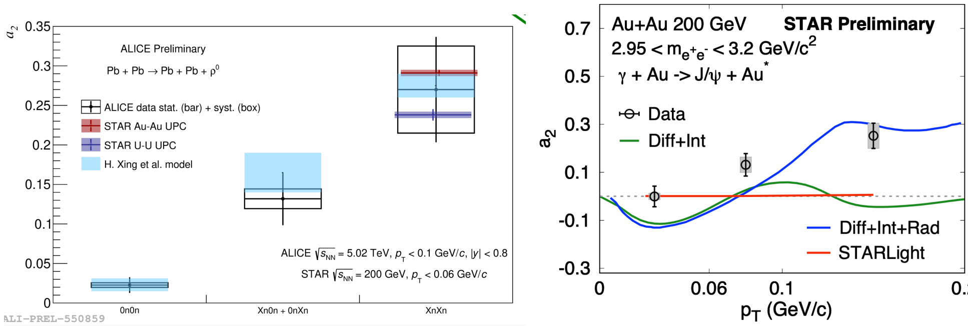

Figure 3. ALICE measurement of the $\cos 2\phi$ modulation strength (a_2) in photonuclear $\rho^0 \rightarrow \pi^+\pi^-$ events for various neutron emission scenarios (left). STAR measurement of the $\cos 2\phi$ modulation strength from photonuclear $J/\psi \rightarrow e^+e^-$ events (right).

low p_T) is currently observed (within experimental uncertainties), the higher p_T region shows evidence for modulation effects induced by soft-photon radiation (Sudakov radiation). The ALICE collaboration recently conducted a measurement of polarization in photoproduced J/ψ at very forward rapidity $2.5 < y < 4$. While a hint of non-zero transverse polarization is observed, it should be noted that polarization in the forward (backward) rapidity regions is expected even without any non-trivial interference effects.

Photonuclear production has also been proposed as a test of the gluon density scaling behavior at low x, and therefore a potential avenue for observing gluon saturation effects [25]. However, the ambiguity between which nucleus acts as the photon emitter and which as the nuclear target also obfuscates the detailed energy dependence of the process, mixing effects from large and small x. The ALICE [24], CMS [23], and STAR collaborations [26] recently employed an analysis method for disambiuating the photon energy between the two possible amplitudes, thus accessing the photon-nucleus center of mass energy $W_{\gamma A}$ and the Bjorken $x-$dependence of coherent J/ψ photoproduction. In each case, a strong suppression in the cross section is observed with respect to the impulse approximation, which treats scattering off large nuclei as the incoherent superposition of individual nucleons. Figure 4 shows the photon energy $W_{\gamma Pb}$ (lower x-axis) and the Bjorken$-x$ (upper x-axis) dependence of the coherent J/ψ cross section in terms of the suppresion factor $S_{Pb}(W_{\gamma Pb}) = \sqrt{\sigma_{\gamma Pb}/\sigma^{IA}_{\gamma Pb}}$, where $\sigma^{IA}_{\gamma Pb}$ is the expected cross section according to the impulse approximation.

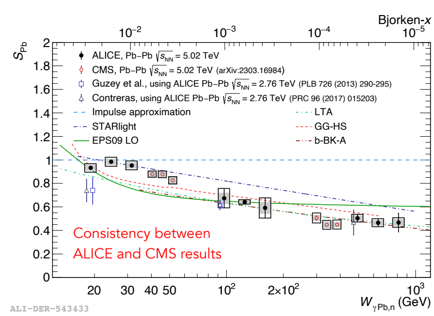

Figure 4. Measurement of the nuclear gluon suppression factor from coherently produced J/ψ as measured by the CMS [23] and ALICE [24] collaborations. The measurements are compared with various theoretical calculations over a broad range in Bjorken x, extending to $x \sim 10^{-5}$.

Figure 5(left) shows the recent LHCb collaboration measurement of coherent J/ψ photoproduction at forward rapidity [27]. The precise measurement is compared with a plethora of model calculations such as LO pQCD, NLO pQCD, and color dipole models. The broad range covered by models is starkly contrasted by the precision of the new measurement, indicating that the data are well suited to constrain existing models.

STAR and ALICE analyses have demonstrated that incoherent production, often treated as an inconvenient background to the coherent process, is itself an interesting process to study. The incoherent process dominates the cross section at larger momentum scales that probe the nucleonic and sub-nucleonic structure of large nuclear targets. Recent measurements have been used to investigate the amount of sub-nucleonic fluctuation of bound nucleons compared to the free proton and to observe strong suppression compared to the free proton (See Fig. 5(right)).

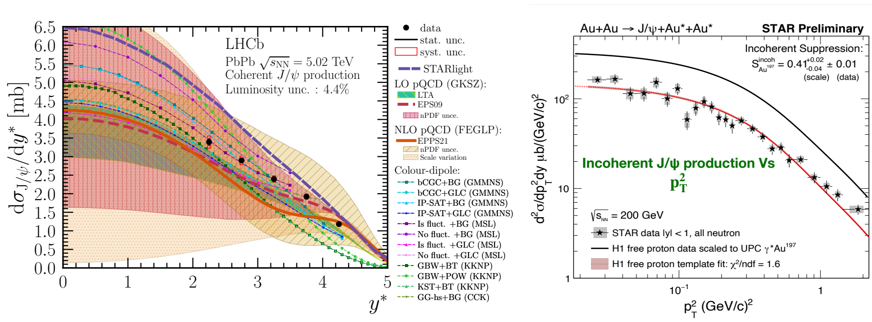

Figure 5. LHCb measurement of coherent J/ψ photoproduction events at forward rapidity(left). The measured cross section is compared with various theoretical models employing LO pQCD, NLO pQCD, and color dipole calculations. Reproduced from [27]. STAR measurement of the incoherent J/ψ cross section compared to appropriately scaled measurements from H1 (right).

The creation of a Quark-Gluon Plasma (QGP) droplet in central A+A collisions has been long ascertained by the presence of various signatures, like jet-quenching, flow, strangeness enhancement, etc. [28]. However, recent observations of several (but not all) “QGP signatures” in much smaller systems, (e.g p+p collisions), have challenged our understanding of the smallest system that might produce a QGP droplet. Ultra-peripheral heavy-ion collisions are also being employed to test the limits of QGP creation. Due to the hadronic structure of the photon, high energy photonuclear interactions can be thought of as hadron-nucleus collisions (e.g. ρ^0+A collisions). The ATLAS collaboration’s observation of non-zero elliptic flow in such events [29, 30] motivates the search for other QGP-like effects in photonuclear collisions. To this end the ATLAS collaboration has pioneered measurements of the mean p_T ($\langle p_T \rangle$) of high-multiplicity photonuclear events, to search for potential effects like radial flow in photonuclear events.

4 Outlook and Conclusions

The ultra-Lorentz contracted electromagnetic fields present in relativistic heavy-ion collisions have provided a unique source of high energy photons for studying the frontiers of QED and QCD. Recent discoveries have already become calibrated new instruments in the search for physics beyond the Standard Model. For instance, measurements of a_τ from $\gamma\gamma \rightarrow \tau^+\tau^-$ are already competitive with previous world’s best, and with future LHC runs, the CMS and ATLAS collaborations expect to significantly improve the precision of the measurements of a_τ, thereby reaching previously unachievable sensitivity to physics beyond the Standard Model. Future LHC data will also push the search for ALPs into unconstrained phase space while future RHIC data is expected to provide improved constraints on unexplored Dark Photon parameters through measurement of the angular modulation of the $\gamma\gamma \rightarrow e^+e^-$ process.

Photon-photon processes in ultra-peripheral heavy-ion collisions have pushed the experimental boundaries of non-linear QED, and photonuclear processes have provided new insight into the gluon distribution deep within large nuclei. Observation of a novel interference effect in coherent photonuclear interactions has allowed the most precise measurements of nuclear structure at high energy to date [17]. Theoretical advances and experimental achievements have provided a first look into the Bjorken-x dependence of coherent photonuclear J/ψ production [23, 24]. Similarly, measurements of incoherent production are starting to provide insight into the sub-nucleonic fluctuations within large nuclei, revealing new aspects of dense nuclear matter. Future datasets from RHIC, the LHC, and the future Electron Ion Collider will undoubtedly build upon these recent achievements to probe further unexplored regimes of QED and QCD.

References

[1] G. Aad et al. (ATLAS), Phys. Rev. C **107**, 054907 (2023), 2206.12594

[2] A. Tumasyan et al. (CMS), Phys. Rev. Lett. **131**, 151803 (2023), 2206.05192

[3] G. Aad et al. (ATLAS), Phys. Rev. Lett. **131**, 151802 (2023), 2204.13478

[4] G. Aad et al. (ATLAS), Phys. Rev. Lett. **123**, 052001 (2019), 1904.03536

[5] A.M. Sirunyan et al. (CMS), Phys. Lett. B **797**, 134826 (2019), 1810.04602

[6] G. Aad et al. (ATLAS), JHEP **03**, 243 (2021), [Erratum: JHEP 11, 050 (2021)], 2008.05355

[7] J. Adam et al. (STAR), Phys. Rev. Lett. **127**, 052302 (2021), 1910.12400

[8] J.D. Brandenburg, J. Seger, Z. Xu, W. Zha, Rept. Prog. Phys. **86**, 083901 (2023), 2208.14943

[9] W. Heisenberg, H. Euler, Z. Phys. **98**, 714 (1936), physics/0605038

[10] J.S. Schwinger, Phys. Rev. **82**, 664 (1951)

[11] J.D. Brandenburg, W. Zha, Z. Xu, Eur. Phys. J. A **57**, 299 (2021), 2103.16623

[12] X. Wang, J.D. Brandenburg, L. Ruan, F. Shao, Z. Xu, C. Yang, W. Zha, Phys. Rev. C **107**, 044906 (2023), 2207.05595

[13] I. Xu, N. Lewis, X. Wang, J.D. Brandenburg, L. Ruan (2022), 2211.02132

[14] D.P. Aguillard et al. (Muon g-2), Phys. Rev. Lett. **131**, 161802 (2023), 2308.06230

[15] J. Abdallah et al. (DELPHI), Eur. Phys. J. C **35**, 159 (2004), hep-ex/0406010

[16] S.R. Klein, H. Mäntysaari, Nature Rev. Phys. **1**, 662 (2019), 1910.10858

[17] M. Abdallah et al. (STAR), Sci. Adv. **9**, eabq3903 (2023), 2204.01625

[18] H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, W. Zhao, *Probing nuclear structure at the Electron-Ion Collider and in ultra-peripheral nuclear collisions*, in *30th International Conference on Ultrarelativstic Nucleus-Nucleus Collisions* (2023), 2312.07467

[19] J. Adam et al. (ALICE), JHEP **09**, 095 (2015), 1503.09177

[20] H. Xing, C. Zhang, J. Zhou, Y.J. Zhou, JHEP **10**, 064 (2020), 2006.06206

[21] J.D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou, Y. Zhou, Phys. Rev. D **106**, 074008 (2022), 2207.02478

[22] H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, W. Zhao, Phys. Rev. C **109**, 024908 (2024), 2310.15300

[23] A. Tumasyan et al. (CMS), Phys. Rev. Lett. **131**, 262301 (2023), 2303.16984

[24] S. Acharya et al. (ALICE), JHEP **10**, 119 (2023), 2305.19060

[25] H. Mäntysaari, F. Salazar, B. Schenke (2023), 2312.04194

[26] M. Abdallah et al. (STAR) (2023), 2311.13632

[27] R. Aaij et al. (LHCb), JHEP **06**, 146 (2023), 2206.08221

[28] J.W. Harris, B. Müller (2023), 2308.05743

[29] G. Aad et al. (ATLAS), Phys. Rev. C **104**, 014903 (2021), 2101.10771

[30] W. Zhao, C. Shen, B. Schenke, Phys. Rev. Lett. **129**, 252302 (2022), 2203.06094