Snowmass2021 - Letter of Interest

Photon physics at the energy frontier

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Abstract: (maximum 200 words)

Ultra-peripheral collisions (UPCs) involving heavy ions and protons are the energy frontier for photon-mediated collisions. UPC photons can be used for many purposes, including probing low$-x$ gluons via photoproduction of dijets and vector mesons, probes of beyond-standard-model processes, such as those enabled by light-by-light scattering, and studies of two-photon production of the Higgs.

UPCs as the energy frontier Since the closure of the HERA ep collider, there have been no dedicated high-energy photon facilities. Instead, the photon energy frontier has been studied in ultra-peripheral collisions at CERN's Large Hadron Collider[1–7]. The protons and heavy ions accelerated there carry electromagnetic fields which may be treated as a flux of nearly-real (virtuality $Q^2 < (\hbar/R_A)^2$, where R_A is the hadron radius) photons. The photon spectra extend up to energies of $\gamma\hbar c/R_A$, where γ is the Lorentz boost of the ion. At the LHC, these photons lead to γp collisions at center of mass energies up to 5 TeV, γA collisions at center of mass energies up to 700 GeV/nucleon, and two-photon collisions up to $\sqrt{s_{\gamma\gamma}} = 30$ TeV. The γp energies are higher than were accessible at HERA, and the γA energies are many orders of magnitude higher than are accessible at fixed-target experiments.

These photons have been used to study a wide variety of physics processes: measurements of low$-x$ gluon densities in protons and studies of shadowing in heavier nuclei, studies of higher order terms in dilepton production, and light-by-light scattering. $\gamma\gamma \rightarrow \tau^+\tau^-$ has also been observed.

Photoproduction and parton distributions Parton distributions have been probed in γp and γA collisions Photoproduction of dijets (and, still to come, open charm) is, from the theoretical point of view, a fairly direct probe of the single gluon distribution. So far, ATLAS has preliminary results on dijet production[8], while CMS has released preliminary results on coherent dijet photoproduction, where both nuclei remain intact[9]. This can be used to measure the diffractive structure functions and study "elliptic gluons" dynamics[10–16]. UPCs at the LHC can probe to Bjorken$-x$ values of at least a few 10^{-6}; this could reach even lower x with far-forward detectors like the proposed ALICE FOCAL[17].

Exclusive vector mesons are produced when an incident photon fluctuates to a virtual quark-antiquark pair, which then scatters elastically (or quasi-elastically) from a proton or nuclear target. Since elastic scattering requires two-gluon exchange for color neutrality, the cross-section scales as the square of the gluon density. One limitation is that the color neutrality requirement introduces some systematic uncertainty[18;19]. ALICE[20] and LHCb have studied J/ψ production on proton targets, finding, for the most part, that the power-law behavior seen at HERA extends to higher energies. ALICE, LHCb and CMS have also studied ψ'[21;22]and Υ production[23–25], finding good agreement with NLO-inspired cross-section calculations. Some calculations indicate that the saturation scale has been reached[26].

The cross-sections on nuclear targets are sensitive to gluon shadowing, and probe phenomena like gluon saturation of the colored glass condensate. The ALICE[27;28] and CMS[29] experiments have studied J/ψ production on lead, and found moderate suppression, consistent with leading-twist calculations[30;31]. There have also been studies on ρ photoproduction[32–34]. The ρ cross-section is larger than predicted by the Glauber model, pointing to the importance of high-mass internal states, as expected in the Glauber-Gribov model[35].

Looking ahead, the LHC and HL-LHC should collect much larger data sets, which will allow multi-dimensional analyses, and lead to the anticipated error bars shown in Fig. 1. Further,in the Good-Walker paradigm[36], coherent and incoherent photoproduction allow access to information that goes beyond one-dimensional average shadowing measurements[31]. The coherent cross-section $d\sigma/dt$ provides information on the spatial distribution of the target scatterers - the nuclear equivalent of a Generalized Parton Distribution - while the incoherent $d\sigma/dt$ provides information on event-by-event fluctuations in the nuclear configuration, including both nucleon positions and gluonic hot spots[37–40]. STAR has used $d\sigma/dt$ to measure the spatial distribution of target scatters in ρ and direct $\pi^+\pi^-$ photoproduction[41]. HL-LHC can do this measurement with heavier quarkonia, where pQCD is clearly applicable. CMS data on ρ[32] shows sensitivity for finding the onset of gluon saturation using differential studies in both momentum transfer (t) and γp center-of-mass energy[42]. The HL-LHC can provide the needed precision provided there are available triggers in pPb running.

Light-by-light scattering, W pair and dilepton production. Two-photon interactions at the LHC also

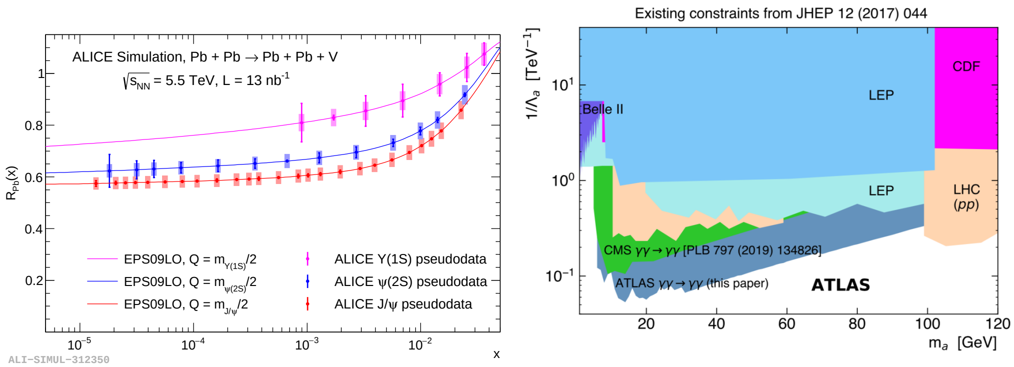

Figure 1: (left) Pseudodata projections for the nuclear suppression factors for photoproduction of three vector mesons in PbPb UPCs. The central points are for the EPS09 nuclear PDFs; the suppression scales with the square of the gluon density. three vector mesons. From Ref.[43]. (right) Exclusion limits on ALP-photon coupling $(1/\Lambda_a)$ vs. ALP mass, from light-by-light scattering and other processes. From[44]

probe the energy frontier. Photons couple to all electrically charged particles and some neutrals (like axions), so two-photon reactions are sensitive to many beyond-standard-model processes.

One process that has already been exploited to probe BSM physics is light-by-light scattering, $AA \rightarrow AA\gamma\gamma$[45]. The subprocess $\gamma\gamma \rightarrow \gamma\gamma$ proceeds only via a charged-particle box diagram. The cross-section is sensitive to all charged particles, including BSM particles[46;47] such as vector fermions, axion-like particles (ALPs)[48] and magnetic monopoles. It is also sensitive to non-linear (BSM) corrections to electromagnetism[49;50]. The ATLAS[44;51] and CMS[52] collaborations have both observed this process with a cross-section consistent with the standard model. They then set limits on ALP production, as shown in Fig. 1.

The ATLAS collaboration has recently studied $\gamma\gamma \rightarrow W^+W^-$; this is a sensitive probe for BSM physics. Production of dileptons, $\gamma\gamma \rightarrow l^+l^-$ has been studied by many collaborations. Electrons, muons and tau pairs have been observed. Tau pairs are of particular interest because the τ-γ coupling may be sensitive to BSM physics, including the τ dipole moment, lepton compositeness or supersymmetry. They have recently been observed by ATLAS[53].

Looking ahead, light-by-light scattering is luminosity hungry, and future HL-LHC running should lead to much larger data samples for these final states[43]. The ALICE detector may also be able to probe this reaction at lower diphoton masses than is currently possible[54]. High statistics studies of dilepton production may also be sensitive to BSM processes, particularly at high masses. This is especially true for the τ, where the decay angular correlations can also be used to search for new physics. And, it may be possible to study two-photon production of heavy quark states and study pentaquarks[55], tetraquarks[56] and other exotica.

Strong fields, Quantum correlations and quantum tomography UPCs also offer opportunities to use the very strong fields to explore reactions involving multiple photon exchange, such as production of $\rho^0\rho^0$ pairs, where each ρ is produced by a single, independent photon[57;58]. These pairs should exhibit quantum correlations which will allow for a more detailed study of decay dynamics, including with polarized photons. EPR-type experiments can also be carried out to test quantum mechanics, and use quantum tomography for probing quantum correlations and entanglement[59;60].

Ultra-peripheral physics program at LHC and synergies with future colliders Further ahead, photon exchange at the FCC will allow probes at even higher energies, allowing for more extensive BSM physics and also the study of top photoproduction[61;62]. A future electron-ion collider (EIC)[63] will allow for precision measurements of many photon-mediated reactions, over a large Q^2 range, but at lower energies.

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