

Snowmass2021 - Letter of Interest

New opportunities at the photon energy frontier

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Abstract: Ultra-peripheral collisions (UPCs) involving heavy ions and protons are the energy frontier for photon-mediated interactions. 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 UPCs 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 $Q^2 < (\hbar c/R_A)^2$, 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 $\sqrt{s_{\gamma\gamma}} = 4.2$ 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 of parton densities in heavier nuclei, studies of higher order terms in dilepton production, and light-by-light scattering.

Photoproduction and parton distributions Parton distributions have been probed in γp and γA collisions. Photoproduction of dijets (and, still to come, open charm⁸) is, from the theoretical point of view, a fairly direct probe of the gluon distribution. So far, preliminary results from ATLAS on dijet production⁹ and from CMS on exclusive dijet photoproduction¹⁰ have been released. This can be used to measure the diffractive structure functions and study “elliptic gluon” dynamics^{11–17}. 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 FoCal¹⁸.

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^{19;20}. ALICE²¹ 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 $\psi(2S)$ ^{22;23} and Υ production^{24–26}, finding good agreement with NLO-inspired cross section calculations. Some calculations indicate that the saturation scale has been reached²⁷.

The nuclear-target cross sections are sensitive to gluon shadowing, and probe phenomena like gluon saturation of the color-glass condensate. ALICE^{28;29} and CMS³⁰ have studied J/ψ production on lead, and found moderate suppression, consistent with leading-twist calculations^{31–33}. There have also been studies on ρ photoproduction^{34–36}. The ρ cross section is about 40% smaller than predicted by the Glauber model, pointing to the importance of high-mass internal states, as expected in the Glauber-Gribov model³⁷.

Looking ahead, the LHC and HL-LHC will collect much more data, which should lead to precise measurements of shadowing (the anticipated error bars are shown in Fig. 1) and enable new types of measurements. In the Good-Walker paradigm³⁸, coherent and incoherent photoproduction allow access to qualitatively new studies^{32;39}. The coherent cross section $d\sigma/dt$ encodes the transverse spatial distribution of the targets - 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, due to varying nucleon positions and gluonic hot spots^{39–42}. STAR has used $d\sigma/dt$ for ρ and direct $\pi^+\pi^-$ photoproduction to measure the spatial distribution of target scatters in gold⁴³. HL-LHC can do this measurement with heavier quarkonia, where pQCD is clearly applicable. CMS data on ρ ³⁴ shows sensitivity to the onset of gluon saturation in lead using differential studies in both momentum transfer (t) and γp center-of-mass energy⁴⁴. Other opportunities include study of perturbative Pomeron dynamics⁴⁵, color fluctuations in the photon^{46;47}, the gluonic Sivers function⁴⁸, search for the Odderon⁴⁹, among other studies. Finally, next-to-leading (NLO) order calculations for these processes are one of the future directions of the theoretical program^{50–52}.

Light-by-light scattering, W pair and dilepton production. Two-photon interactions at the LHCb probe the energy frontier. Photons couple to all electrically charged particles and some neutrals scalars (like

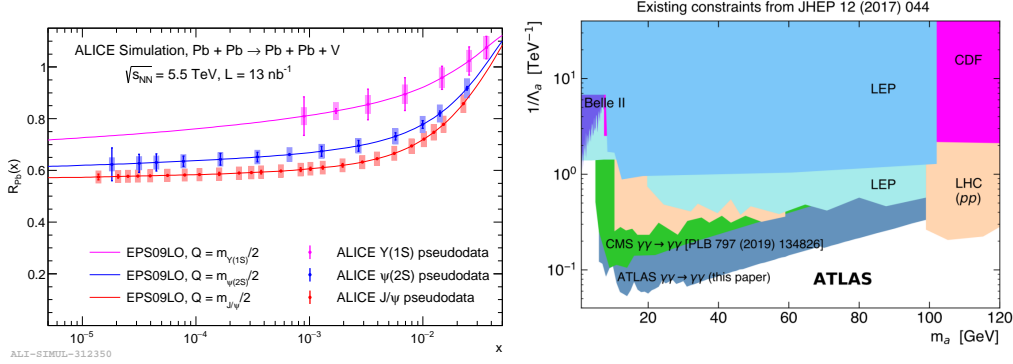


Figure 1: (left) Pseudodata projections for the nuclear suppression factors of the nuclear gluon density as a function of Bjorken- x for photoproduction of three vector mesons in PbPb UPCs. The points are EPS09-projections using the method described in³¹. From Ref.⁵³. (right) Exclusion limits on ALP-photon coupling ($1/\Lambda_a$) vs. ALP mass, from light-by-light scattering and other processes. From Ref.⁵⁴.

axions and the Higgs), so two-photon reactions are sensitive to many beyond-standard-model processes.

One process that has already been used to probe BSM physics is light-by-light scattering, $AA \rightarrow AA\gamma\gamma$ ^{55;56}. 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^{57;58} such as vector fermions, GeV- mass axion-like particles (ALPs)^{59;60} and magnetic monopoles. The reaction also probes non-linear (BSM) corrections to electromagnetism^{61;62}. ATLAS^{54;63;64} and CMS⁶⁵ have both observed this process at a cross section consistent with the standard model. They then set limits on ALP production, as shown in Fig. 1.

In pp collisions, ATLAS⁶⁶ and CMS⁶⁷ have also studied $\gamma\gamma \rightarrow W^+W^-$ and CMS/TOTEM $\gamma\gamma \rightarrow \gamma\gamma$ ⁶⁸, thereby placing stringent limits on anomalous quartic gauge couplings. Production of electron and muon pairs via $\gamma\gamma \rightarrow l^+l^-$, has been studied by many collaborations. Exclusive $e - \mu$ events, as expected from tau pairs⁶⁹ have been seen. Tau pairs are of particular interest because the τ - γ coupling is sensitive to BSM physics, including the τ dipole moment, lepton compositeness or supersymmetry.

Looking ahead, $\gamma\gamma \rightarrow \gamma\gamma$ is a rare process and future HL-LHC running should lead to much larger data samples for this final states⁵³. ALICE and LHCb may be able to probe this reaction at lower diphoton masses than is currently possible⁷⁰. 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 cross section⁷¹ and kinematic distributions⁷² are sensitive to new physics. It may also be possible to study two-photon production of heavy quark states, $\gamma\gamma \rightarrow p\bar{p}$ ⁷³, and search for pentaquarks⁷⁴, tetraquarks⁷⁵ 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 $\rho^0\rho^0$, where each ρ^0 is produced by a single, independent photon⁷⁶⁻⁷⁸. These pairs should exhibit quantum correlations which will allow for a more detailed study of decay dynamics, including with polarized photons. EPR (Einstein-Podolsky-Rosen)-type experiments can also be carried out to test quantum mechanics, and quantum tomography techniques can probe quantum correlations and entanglement^{79;80}.

UPCs at the FCC and synergies with future colliders Photon exchange at the future FCC, or at the proposed LHeC⁸¹, will allow probes at even higher energies, allowing for more extensive BSM physics and also the study of top photoproduction^{82;83} and $\gamma\gamma$ production of the Higgs⁸⁴. The future electron-ion collider⁸⁵, planned to be built at BNL around 2030, will make precise measurements of photon-mediated reactions over a wide Q^2 range, but at lower energies.

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