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Ultra-peripheral collisions and hadronic structure

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Abstract

Ultra-peripheral collisions are the energy frontier for photon-mediated interactions, reaching, at the Large Hadron Collider (LHC), $\gamma - p$ center of mass energies five to ten times higher than at HERA and reaching $\gamma\gamma$ energies higher than at LEP. Photoproduction of heavy quarkonium and dijets in pp and pA collisions probes the gluon distribution in protons at Bjorken-x values down to 3×10^{-6}, far smaller than can be otherwise studied. In AA collisions, these reactions probe the gluon distributions in heavy ions, down to x values of a few 10^{-5}. Although more theoretical work is needed to nail down all of the uncertainties, inclusion of these data in current parton distribution function fits would greatly improve the accuracy of the gluon distributions at low Bjorken-x and low/moderate Q^2. High-statistics ρ^0 data probe the spatial distribution of the interaction sites; the site distribution is given by the Fourier transform of $d\sigma/dt$. After introducing UPCs, this review presents recent measurements of dilepton production and light-by-light scattering and recent data on proton and heavy nuclei structure, emphasizing results presented at Quark Matter 2017 (QM2017).

Keywords: ultra-peripheral collisions, photoproduction, quarkonium, nuclear structure, RHIC, LHC

1. Introduction

Relativistic heavy ions are accompanied by strong electromagnetic fields. The electric and magnetic fields are perpendicular, so in the Weizsäcker-Williams approach, the combined fields may be treated as a flux of nearly-real virtual photons. The maximum photon energy depends on the width of the fields in the direction of motion: $k_{\max} = 2\gamma\hbar c/b$, where γ is the Lorentz boost of the ion, and b is the transverse distance from the ion (impact parameter).

UPCs are interactions between the electromagnetic fields of one ion and the other ion or its electromagnetic field [1, 2, 3]. Usually, UPCs are studied as exclusive reactions, unaccompanied by particles from hadronic interactions. However, ALICE and STAR have recently presented data on e^+e^- pairs in peripheral hadronic collisions, exhibiting the characteristic signature of coherent electromagnetic production: a large peak at low transverse momentum (p_T).

UPCs provide the highest energy electromagnetic probes available at particle accelerators. At the LHC, UPCs reach γp energies up to 2 TeV - ten times higher than were available at HERA, and sufficient to probe gluon distributions at Bjorken-x values down to 3×10^{-6}. For heavy-ion targets, the only previous data with electromagnetic probes is from fixed-target experiments;. The new UPC data is directly sensitive to nuclear shadowing of gluon distributions down to Bjorken$-x$ values down to about 10^{-5}.

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2. Dileptons

Purely electromagnetic dilepton production is important, both as a calibration tool and for physics studies. ALICE, ATLAS and STAR have all reported high-statistics samples. Figure 1 shows the rapidity distribution of the ATLAS dimuon sample [4] from proton-lead collisions along with the mass distribution for lead-lead collisions, compared to the predictions of the STARlight Monte Carlo [5]. The agreement is excellent, especially considering that STARlight uses the equivalent photon approximation with a lowest-order calculation [6]. Higher order corrections are not important for these dimuons.

At QM2017, ATLAS presented a particularly interesting process: light-by-light scattering, $\gamma\gamma \rightarrow \gamma\gamma$ [4, 7]. It occurs only via a higher-order quantum process, described by a box diagram (charge particle loop) connecting the incident and outgoing photons. Because all charged particles contribute to the loop, the process is sensitive to new, beyond-standard-model charged particles. ATLAS found 13 events within their kinematic selection and with pair mass above 6 GeV, compared to an estimated background of 2.6 ± 0.7 events. The resulting cross-section, 70 ± 24 (stat.) ± 17 (syst.) nb, is compatible with the standard model prediction [8]. The current statistical precision is not yet sensitive to beyond-standard-model physics.

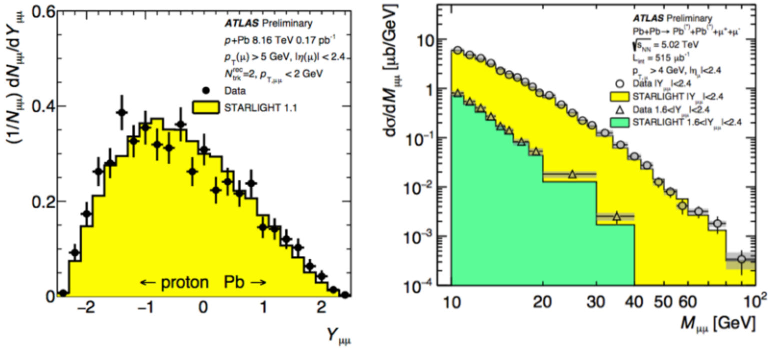

Fig. 1. (left) The rapidity distribution for exclusive $\mu^+\mu^-$ pairs observed in proton-lead collisions seen in ATLAS at $\sqrt{s_{NN}} = 8.16$ TeV. (right) The mass distribution for exclusive $\mu^+\mu^-$ pairs observed by the ATLAS collaboration in lead-lead collisions. Both distributions are in excellent agreement with STARlight [5] simulations. From Ref. [4].

UPCs also have implications for accelerator design. In Bound-Free Pair Production (BFPP), the electron is produced bound to one of the incident nuclei [1]. For lead ions at the LHC, the cross-section for BFPP is about 200 b [9], so it contributes significantly to the loss of ions from the beam. The ion momenta are nearly unchanged, but their charge is reduced by one, so the single-electron ions gradually separate from the main beam [10]. At the LHC, lead ions strike the beampipe about 135 m downstream from the interaction points, depositing their energy in a hadronic shower. In a recent test at a luminosity of $2.3 \times 10^{27}/\text{cm}^2/\text{s}$, the beam deposited about 53 Watts of power, enough energy to quench the dipole magnet that it struck [11]. The impact of these BFPP beams can be mitigated by using orbit bumps, but, even with this BFPP will nevertheless impact high luminosity operations and limit future, higher energy colliders.

3. Vector meson photoproduction

Vector meson photoproduction is the most intensively studied UPC reaction. The cross-sections are large, most of the final states are simple, and the process holds considerable theoretical interest. Cross-sections have been measured for ρ, ω, one or more ρ' states, J/ψ and ψ', and Υ states, along with directly produced $\pi^+\pi^-$. The photon energy k is related to the final state mass M_V and rapidity y:

$$k = \frac{M_V}{2} \exp{(\pm y)} \tag{1}$$