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ATLAS

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Electromagnetic processes with quasireal photons in Pb+Pb collisions: QED, QCD, and the QGP

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Abstract

Electromagnetic processes, both photon-photon and photon-nucleus, are shown to be useful in studying aspects of QED, QCD, and potentially the QGP. Using lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, the ATLAS detector has performed measurements of exclusive dimuon production, light-by-light scattering (via exclusive diphoton production), and photo-nuclear dijet production. These are all important examples of ultraperipheral collisions, where the nuclei do not interact hadronically. A recent study of the opening angles of dimuons produced in hadronic heavy-ion collisions, after subtracting heavy-flavor backgrounds, demonstrates that the dimuons carry information correlated with the overlap geometry, potentially about the density of charges in the QGP itself.

1. Ultraperipheral collisions with ATLAS

Collisions of heavy ions at high energy are generally understood to be an ideal system to study hot, dense quark-gluon plasma (QGP). However, the large nuclear charge in lead-lead collisions, coupled with a large relativistic boost, also provides intense electromagnetic fields which can interact at much larger distances, both with the oncoming nucleus or its electric field. These are "ultraperipheral" collisions and have been seen as a promising topic since well before the LHC started up [1]. The photon luminosity of each beam is typically treated using the equivalent photon approximation (EPA), also known as the Weizsäcker-Williams approximation. In this approximation the classical field is effectively quantized and the nucleus coherently produces nearly-real photons with a rate scaling as Z^2, a maximum virtuality of $Q \sim \hbar/R \sim 30$ MeV and a maximum energy of approximately $E = \gamma\hbar c/R \sim 80$ GeV for lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [2, 3]. Protons provide a maximum of 1.4 TeV, due to the smaller source, but with a much lower luminosity. With the increased luminosities available in the LHC Run 2, all of the LHC experiments are carrying out a systematic investigation of ultraperipheral processes including photon-pomeron (diffractive vector meson production), photo-nuclear (typically via photon-gluon fusion), and photon-photon production of dileptons (ee and $\mu\mu$) and diphotons. The latter is known as "light-by-light" scattering, and had never been observed directly before the recent LHC data.

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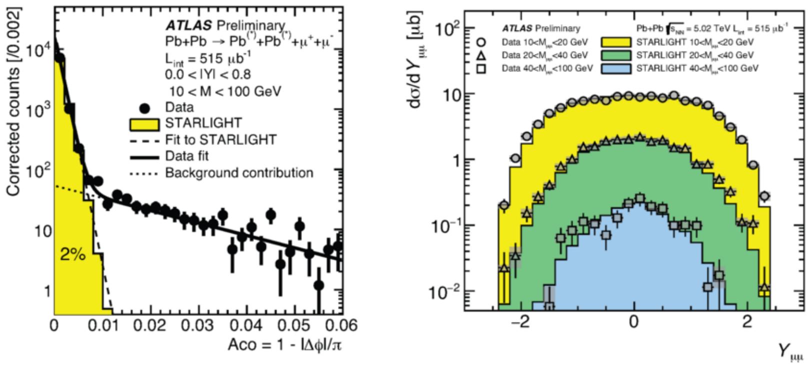

Fig. 1. (left) Acoplanarity distribution from exclusive dimuon production from photon-photon interactions. (right) Measured dimuon pair rapidity-dependent cross sections for three mass selections, compared to STARLIGHT 1.1 calculations. Results from Ref. [6].

The ATLAS detector at the LHC [4] is an ideal detector for ultraperipheral measurements, since it combines precise charged particle tracking in $|\eta| < 2.5$ and precision muon measurements in $|\eta| < 2.7$ with hermetic calorimetry out to $|\eta| < 4.9$. The latter is particularly important for photon-induced final states, since it is essential for identifying events with "gaps", regions of the detector with no significant activity. The ATLAS zero-degree calorimeters (ZDCs) are also important for tagging photon-induced events since photon-photon events typically have no forward neutrons in either beam direction, while photo-nuclear events typically have forward neutrons in only one direction. However, these topological characteristics are not guaranteed, since the soft photon flux is sufficiently high that a separate single or mutual excitation of the nuclei, which leads to forward neutron emission, can accompany the primary process of interest.

2. Photon-photon processes

Exclusive dileptons at the LHC were first measured by ALICE out to a dielectron invariant mass of 10 GeV [5]. ATLAS extended this measurement using dimuons out to much larger phase space region, with pair mass $M_{\mu\mu} < 100$ GeV and pair rapidity $|Y_{\mu\mu}| < 2.4$ [6]. The distributions are all corrected for trigger efficiency, reconstruction efficiency, and vertex reconstruction efficiency. The left panel of Fig. 1 shows the distribution of "acoplanarity" defined as $Aco = 1 - |\Delta\phi|/\pi$, where $\Delta\phi$ is the difference between the azimuthal angles of the two muons. It compares the experimental data from lead-lead collisions with calculations from the STARLIGHT event generator [7]. STARLIGHT implements the Breit-Wheeler formula (containing the two leading-order diagrams leading to strict back-to-back emission), but lacks both higher order QED processes and dissociative processes involving photons emitted by quarks in the nucleons. The ATLAS result does not yet account for these contributions but the systematic uncertainties cover whether the acoplanarity tails are all signal or all background. The dimuon yields, shown in the right panel of Fig. 1 are found to be in reasonable agreement with the STARLIGHT predictions.

Light-by-light scattering was expected since the advent of QED, as indicated in the diagram in the left panel of Fig. 2. However, its cross section was known to be minuscule due to it scaling with $\alpha^4 \sim 10^{-9}$. Ultimately, it was measured by ALTAS in the same data set [8] as the dimuons using an experimental trigger based on observing at least 5 GeV of transverse energy in the full ATLAS calorimeter, but with a requirement of a maximum number of hits in the ATLAS pixel detector to suppress hadronic interactions. After accounting for backgrounds from both exclusive dielectron production masquerading as diphotons and exclusive diphotons from the exchange of gluon ladders – both of which lead to much wider acoplanarity distributions for the diphoton candidate events, as shown in Fig. 2 – a significance of 4.4σ was observed, with 3.8σ expected.

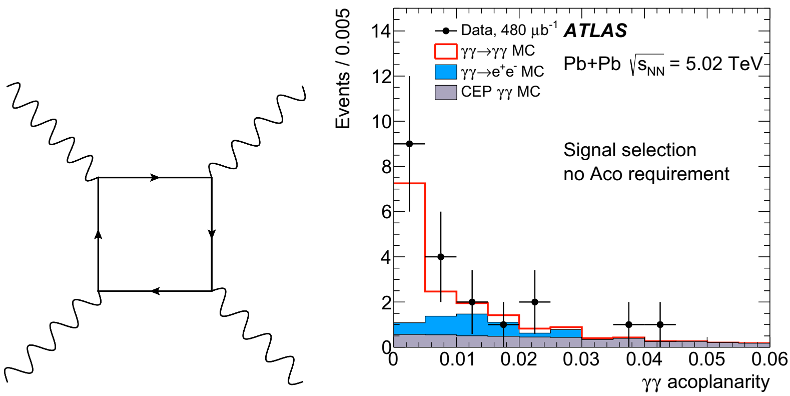

Fig. 2. (left) Feynman diagram for direct light-by-light scattering. (right) Acoplanarity dependent cross sections for light-by-light scattering, compared to a SM calculation and known background contributions from misidentified electrons, and central exclusive production. Results from Ref. [8].

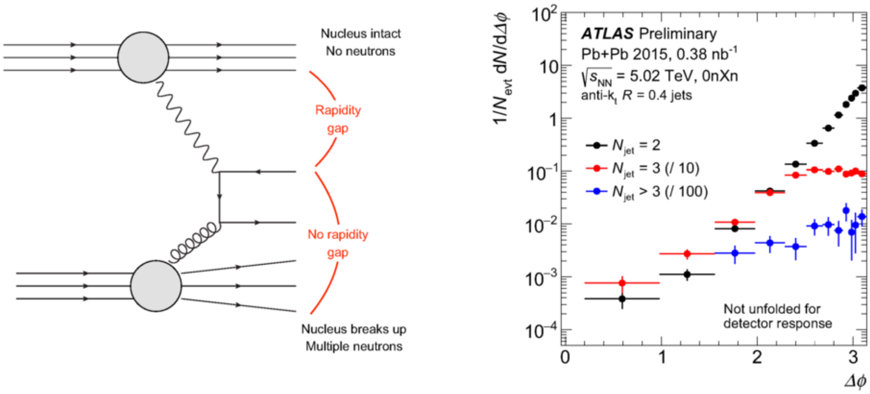

Fig. 3. (left) Schematic diagrams for direct dijet production from photonuclear interactions. (right) $\Delta\phi$ distributions for 2 or more jets in photo-nuclear interactions. Results from Ref. [10].

3. Studying QCD and the QGP with EM processes

Interactions of the nearly-real photons of one nucleus with the partonic structure of the other nucleus are able to produce dijet pairs, with an extended gap in the photon direction. This makes them useful tool to probe the gluonic structure of the nucleus at low-x and high-Q^2. Ranges of $x = 10^{-3} - 1$ and $Q^2 = 200 - 10000$ GeV^2, where nuclear PDF effects are expected at the 10-20% level [9], should be accessible. The diagram in the left panel of Fig. 3 shows a schematic view of the event topology, with one nucleus emitting a photon that interacts with a gluon from the other nucleus, which leads to breakup and neutrons emitted into the ZDC in the direction opposite to the photon. The triple differential cross sections (before unfolding) have been measured in Ref. [10], and compare well with PYTHIA6 photoproduction calculations with no nuclear shadowing after reweighing the photon spectrum to agree with STARLIGHT. The analysis also measures the $\Delta\phi$ distribution, which is dominated by the back-to-back dijet topology, shown in the right panel of Fig. 3.

While photonuclear dijets are a promising new technique to study the initial state of heavy-ion collisions in full detail, the first electromagnetic process described here may be providing a way to study the

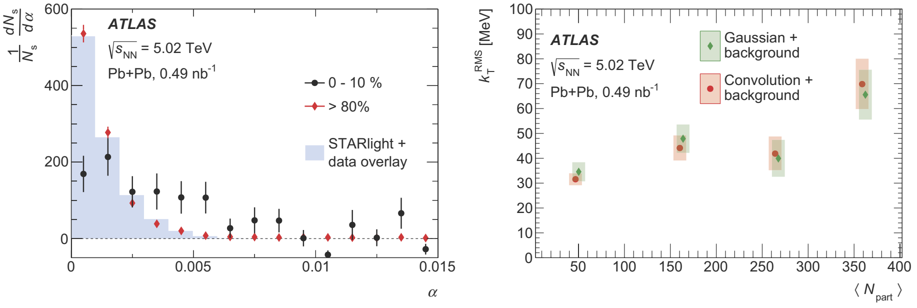

Fig. 4. (left) comparison of acoplanarity (here called α) distributions for dimuons produced in hadronic heavy-ion collisions, after subtracting heavy-flavor background, in $> 80\%$ central events (dominated by UPC) and the 0-10% centrality interval. (right) The per-muon RMS k_T extracted from the wider dimuon α distributions. Results from Ref. [11].

final state. It had long been assumed that measuring UPC-like processes, such as dilepton production, in hadronic interaction would be too complicated by the presence of the underlying event. However, no source of dileptons in hadronic interactions, e.g. the decay of heavy-flavor particles, is able to emit dileptons so close on average to being back-to-back, i.e. with zero acoplanarity. Using a dimuon trigger, the heavy-flavor background has been estimated primarily using data driven techniques. After subtracting the background, the dimuon acoplanarity distribution (shown in the left panel of Fig. 4 from Ref. [11]) is found to systematically broaden in more central collisions, relative to the 80-100% centrality interval which is dominated by the UPC dimuons described in Sec. 2. The right panel of Fig. 4 shows the results of a simple calculation based on fits to the acoplanarity distributions, modeling the increasing broadening as a per-muon RMS(k_T), possibly imparted by scattering off of charged constituents in the hot, dense medium. The scales involved are small, from 30-70 MeV, but easily accessible based on the known precision of muon measurements in ATLAS. Some indications of a similar effect have been noticed at RHIC using dielectrons [12].

4. Conclusion and outlook

Measurements from the ATLAS detector at the LHC have demonstrated that electromagnetic processes in heavy-ion collisions offer opportunities for new measurements in QED (the dilepton acoplanarity tails, and light-by-light scattering), QCD (nuclear partonic structure using photonuclear processes), and possibly even the QGP (from a centrality dependent broadening of dimuon opening angles). The upcoming 2018 Pb+Pb run offers a jump in event statistics by a factor of approximately four, which should allow consolidating progress on all of these fronts in the next years.

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