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Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

Exclusive dielectron production

Exclusive dielectron pairs from the reaction Pb+Pb $(\gamma\gamma) \to \mathrm{Pb}^{(*)}+\mathrm{Pb}^{(*)}\, e^+e^-$ are used for various aspects of the nominal analysis, in particular to validate the EM calorimeter energy scale and resolution.

To select these $\gamma\gamma \to e^+e^-$ candidates, events are required to pass the same trigger as in the diphoton selection. Each electron is reconstructed from EM energy cluster in the calorimeter matched to a track in the inner detector [1]. The electrons are required to have a transverse energy $E_{\mathrm{T}} > 2.5$ GeV and pseudorapidity $|\eta| < 2.47$ with the calorimeter transition region $1.37 < |\eta| < 1.52$ excluded. They are also required to meet "loose" identification criteria based on shower shape and track-quality variables [1]. Candidate events are selected by requiring two oppositely charged electrons and no further charged-particle tracks coming from an interaction region.

Selected events are compared with Monte Carlo (MC) simulation based on the Starlight 1.1 model [2], which combines the Pb+Pb equivalent photon approximation with the leading-order formula for $\gamma\gamma \to e^+e^-$. The detector response is modelled using GEANT4 [3, 4] and the simulated events are passed through the same reconstruction and analysis chain as the data.

Figure S1 presents kinematic distributions of the dielectron system after the event selection. They show good agreement between the data and the QED prediction. In total, 3216 dielectron events are selected in data and 3300 ± 600 events are expected from the simulation, where the uncertainty is due to limited knowledge of the initial photon fluxes. This modelling uncertainty is assigned as a global uncertainty and follows recommendations from Ref. [5].

Validation of CEP $gg \to \gamma\gamma$ background modelling

The central exclusive production (CEP) $gg \to \gamma\gamma$ is an important background process to consider in the nominal analysis, mainly due to similar two-photon final state and the "peripheral" nature of the interaction. The CEP $gg \to \gamma\gamma$ occurs via the strong interaction through a quark loop in the exchange of two gluons in a colour-singlet state, which is schematically presented in Fig. S2.

In Pb+Pb collisions this process can be modelled with SuperChic [6] MC generator, as suggested in Ref. [5]. Since the exchanged objects are short-ranged comparing to the size of the Pb nucleus, the CEP occurs at relatively small impact parameters (b): typically twice the radius of the nuclei ($2R$) [7]. Moreover, the exchanged objects would normally give a large momentum transfer to the nucleus [7], leading to moderate tails in the $\gamma\gamma$ acoplanarity (Aco). These two effects would also result in a large probability of the outgoing ions to break-up (incoherent production) and in a strong suppression of the coherent CEP. Due to small impact parameters in CEP, the coherent production is further altered by additional Coulomb excitations of the outgoing ions [8]. The probability for the additional Coulomb break-up of at least one nucleus is estimated to be 80% for $b = 2R$ [2].

When a nucleus breaks up, it produces neutrons at very small angles with respect to the Pb beams (forward neutrons). They are measured in ATLAS using zero-degree calorimeters (ZDC), which are sensitive to neutrons and photons with $|\eta| > 8.3$. Therefore, to check the modelling of the CEP $gg \to \gamma\gamma$ background, an analysis of energy deposits in ZDC is performed. The events are categorised for the signal

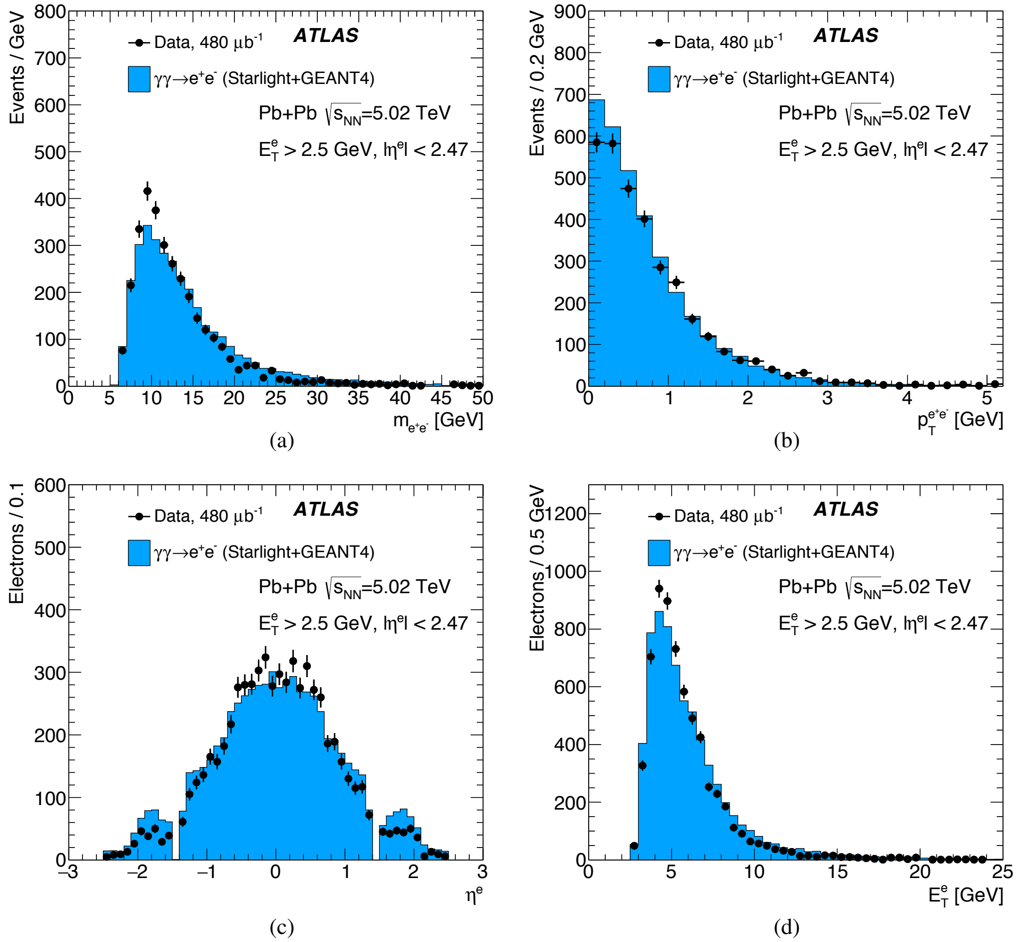

Figure S1: Kinematic distributions for Pb+Pb ($\gamma\gamma$) $\rightarrow$ Pb$^{(*)}$+Pb$^{(*)}$ e^+e^- event candidates: (a) dielectron mass, (b) dielectron p_T, (c) electron pseudorapidity and (d) electron transverse energy. Data (points) are compared to MC expectations (histograms). Electrons with $E_\mathrm{T} > 2.5$ GeV and $|\eta| < 2.47$ excluding the calorimeter transition region $1.37 < |\eta| < 1.52$ are considered. The statistical uncertainties on the data are shown as vertical bars. The uncertainty on the integrated luminosity, used to estimate the number of expected MC events, is 6%.

(Aco < 0.01) and the CEP-enhanced (Aco > 0.01) regions. To separate the ZDC signal from the noise of electronic modules, a calibrated ZDC energy greater than 40% of the single neutron peak is required.

In the CEP-enhanced region, 4 events with no ZDC signal and 4 events with ZDC signal corresponding to multiple neutron emission (8 events in total) are observed in data, where 3.5 CEP $gg \rightarrow \gamma\gamma$ events are expected from the simulation. A diphoton acoplanarity distribution for events with multiple forward neutron emission is presented in Fig. S3, which tends to agree with the CEP $gg \rightarrow \gamma\gamma$ MC expectation. This observation suggests that the transverse momentum transfer in incoherent heavy-ion CEP is comparable with the proton–proton case, which justifies the usage of SuperChic generator to model CEP $gg \rightarrow \gamma\gamma$ background contribution.

In the signal region, 11 events with no ZDC signal and 2 events with ZDC signal corresponding to

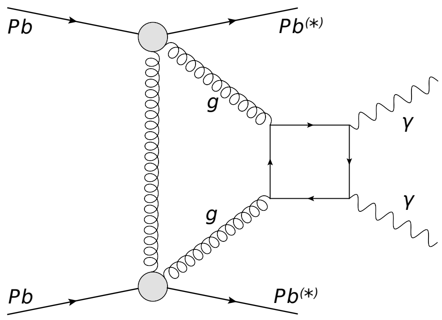

Figure S2: Schematic diagram for the CEP $gg \to \gamma\gamma$ process production mechanism.

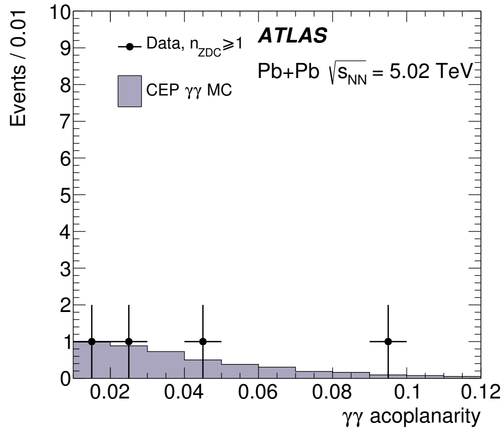

Figure S3: Diphoton acoplanarity distribution observed in data (points) for events in CEP-enhanced region (Aco > 0.01) with energy deposit in ZDC corresponding to multiple forward neutron emission. For comparison, CEP $gg \to \gamma\gamma$ MC predictions are also shown. The statistical uncertainties on the data are presented as vertical bars.

exactly one neutron emission (13 events in total) are observed in data. The expected event yield from CEP $gg \to \gamma\gamma$ MC is 0.9 events, however, events with one or more emitted neutrons are expected from the signal process, due to an excitation of the nuclear giant dipole resonance [2].

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