# ATLAS measurements of photon-photon fusion processes in Pb+Pb collisions [a]

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Relativistic heavy-ion beams at the LHC are accompanied by a large flux of equivalent photons, leading to multiple photon-induced processes. This report presents a series of measurements of such processes performed by the ATLAS Collaboration. New measurements of exclusive dilepton production (electron, muon, and tau pairs) are discussed. These processes provide strong constraints on the nuclear photon flux and its dependence on the impact parameter and photon energy. In particular, measurements of the cross-sections in the presence of forward neutrons provide an additional experimental handle on the impact parameter range sampled in the observed events. Furthermore, the tau-pair production measurements can constrain the tau lepton's anomalous magnetic dipole moment. High statistics measurements of light-by-light scattering discussed in this report provide a precise and unique opportunity to investigate extensions of the Standard Model, such as the presence of axion-like particles.

## 1 Introduction

Collisions of nuclei at ultra-relativistic energies are typically studied for processes in which the nucleons interact hadronically at impact parameters less than twice the nuclear radius, producing a dense quark–gluon plasma in the overlap region, which can decay into thousands of outgoing hadrons. The strong electromagnetic (EM) fields of large nuclei can also induce interactions in ultra-peripheral collisions (UPC), events with impact parameters well beyond twice the nuclear radius, where any contributions from strong interactions are negligible.

At high energies of the Large Hadron Collider (LHC), UPC can induce a wide variety of exclusive final states – dileptons, dijets, and diphotons being the most commonly measured – for which no other activity in detectors is observed, except for nucleons emitted at very small angles relative to the beam direction. The photons are also characterised by small transverse momenta, such that high-energy decay products in these exclusive final states are almost perfectly balanced in the transverse direction. UPC processes have also been proposed to be utilised as a tool to search for beyond Standard Model (BSM) physics [1].

In this report the most recent results on photon-photon ($\gamma\gamma$) induced processes in UPC physics from the ATLAS experiment [2] are discussed.

## 2 Exclusive $\gamma\gamma \to \mu^+\mu^-$ production

ATLAS measured exclusive $\gamma\gamma \to \mu^+\mu^-$ production [3] in UPC Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} =$ 5.02 TeV collected in the 2015 run with an integrated luminosity of 0.49 nb$^{-1}$. The fiducial region of the measurement was defined by single muon $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.4$. Furthermore,

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requirements on invariant mass of the dimuon system, $m_{\mu\mu} > 10$ GeV, and its transverse momentum, $p_{\mathrm{T}}^{\mu\mu} < 2$ GeV, were imposed. The event selection allowed exactly two opposite-charge muons per event. It resulted in about 12k event candidates from the $\gamma\gamma \rightarrow \mu^+\mu^-$ process. After the evaluation and subtraction of dissociative background, which amounts to 3%, the integrated and differential cross sections were measured in $m_{\mu\mu}$, dimuon rapidity $y_{\mu\mu}$, scattering angle in the dimuon rest frame $\cos\theta^*$, initial-photon momenta $k_{\min}$, $k_{\max}$ and acoplanarity $\alpha = 1 - |\Delta\phi|/\pi$. The latter quantifies how two muons are aligned in the azimuthal angle.

Figure 1 presents differential cross-sections for exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production as a function of $m_{\mu\mu}$ and acoplanarity. The measurement is sensitive to masses up to 200 GeV. A good

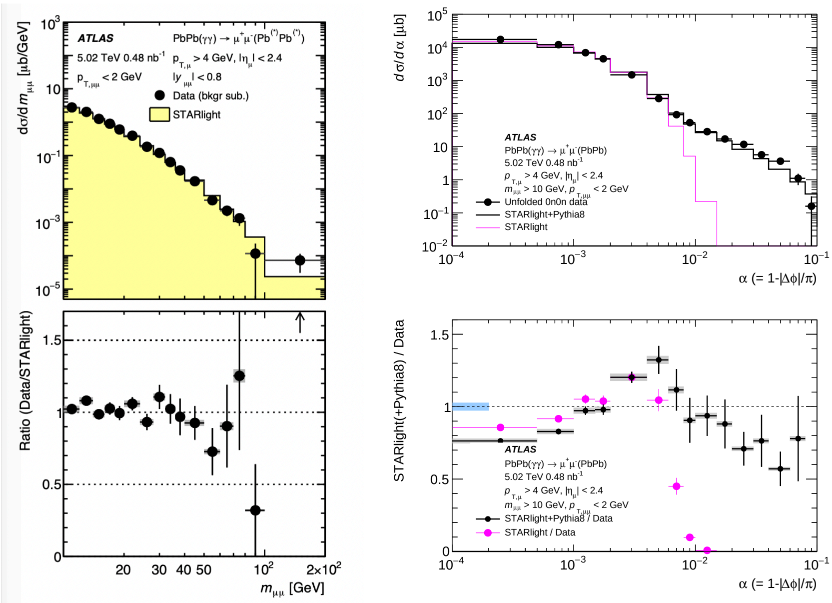


Figure 1 – Differential cross-sections as a function of dimuon mass (left) and acoplanarity (right) for exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production in UPC Pb+Pb collisions [3]. Data points are compared with predictions from STARLIGHT or STARLIGHT+PYTHIA to account for the FSR contribution.

agreement between data and MC predictions from STARLIGHT [4] is found in the entire $m_{\mu\mu}$ range for $|y_{\mu\mu}| < 0.8$. However, STARLIGHT fails in describing a tail of the differential cross-section as a function of acoplanarity which is shown in the right panel of Figure 1. For $\alpha > 5 \times 10^{-3}$ a contribution of signal events is suppressed and the excess of data is visible. It is caused by a contribution from the final state radiation (FSR) which is not accounted for in the STARLIGHT calculation. A better description of the full $\alpha$ distribution is obtained by interfacing STARLIGHT with PYTHIA which accounts for the FSR contribution.

## 3 Exclusive $\gamma\gamma \rightarrow e^+e^-$ production

A preliminary measurement of exclusive $\gamma\gamma \rightarrow e^+e^-$ production was performed [5] by ATLAS in the 2018 Pb+Pb data with an integrated luminosity of 1.72 nb$^{-1}$. The fiducial region of the measurement was defined by single electron $p_{\mathrm{T}} > 2.5$ GeV and $|\eta| < 2.5$. Furthermore, requirements on invariant mass of the dielectron system, $m_{ee} > 5$ GeV, and its transverse momentum, $p_{\mathrm{T}}^{ee} < 2$ GeV, were imposed. The event selection required exactly two opposite-charge electrons per event. In comparison to the $\gamma\gamma \rightarrow \mu^+\mu^-$ measurement discussed in Section 2, the dielectron analysis features a factor of three larger statistics, the extended fiducial coverage, and advancement in the analysis techniques.

Figure 2 shows differential cross-sections for exclusive $\gamma\gamma \rightarrow e^+e^-$ production as a function of absolute rapidity of the dielectron system, $|y_{ee}|$. The data was corrected to the Born level i.e. before the FSR. The cross-sections were measured in two event categories: inclusive for ZDC (left panel) and 0n0n (right panel). The measurements are compared with two MC predictions for the $\gamma\gamma \to e^+e^-$ process: STARLIGHT v3.13 and SUPERCHIC v3.05, which are systematically lower and higher than the data, respectively, by about 10%. SUPERCHIC tends to better describe the shapes of the distributions in both cases.

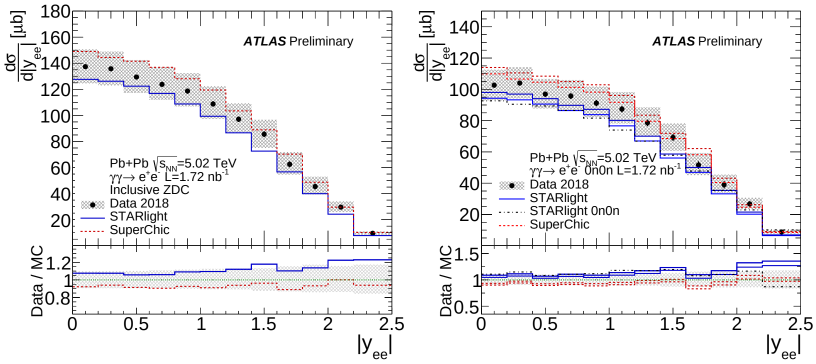


Figure 2 – Differential cross-sections as a function of dielectron rapidity for the ZDC inclusive (left) and 0n0n category (right) for exclusive $\gamma\gamma \to e^+e^-$ production in UPC Pb+Pb collisions [5]. In the bottom panel, data is compared with predictions from STARLIGHT and SUPERCHIC.

## 4 Forward neutron activity

An inclusive sample of $\gamma\gamma \to \ell^+\ell^-$ events with $\ell = \mu^\pm, e^\pm$ can be inspected using information from the Zero Degree Calorimeters (ZDC) which are located in the forward region $\pm 140$ m away from the interaction point (IP) of ATLAS. The ZDC detectors are designed to detect neutral particles originating from IP. In particular in hadronic Pb+Pb collisions they register spectator neutrons. On the other hand, for Pb nuclei the probability of exchanging more than one photon between the two ions in an individual collision is sizeable. The additional photons may dissociate one or both nuclei and cause emission of single neutrons in ZDC. Because of the radial dependence of the photon flux[6], the presence of these additional photons can preferentially select certain impact parameter ranges, and so can influence the photon spectrum of the other photons.

ATLAS measured forward neutron activity in exclusive $\gamma\gamma \to \mu^+\mu^-$ [3] and $\gamma\gamma \to e^+e^-$ [5] processes. In both cases, all $\gamma\gamma \to \ell^+\ell^-$ event candidates were divided into three categories: 0n0n - without activity on either side of ZDC, Xn0n - with activity on one side of ZDC, and XnXn - with activity on each side of ZDC. After subtracting the dissociative background contribution and accounting for simultaneous EM interactions in the same bunch crossing, fractions of events falling into each category were measured.

Figure 3 shows corrected fractions of events in the 0n0n category evaluated from $\gamma\gamma \to e^+e^-$ data as a function of $m_{ee}$ in three bins of $|y_{ee}|$. These fractions tend to drop with increasing $m_{ee}$, and are in general larger for higher $|y_{ee}|$ values. These observations are consistent with the conclusions for forward neutron activity measured in the $\gamma\gamma \to \mu^+\mu^-$ process[3].

## 5 Exclusive $\gamma\gamma \to \tau^+\tau^-$ production

ATLAS made the observation of exclusive $\gamma\gamma \to \tau^+\tau^-$ production[7] in 2018 Pb+Pb collisions with an intergated luminosity of 1.44 nb$^{-1}$. Selected events contained one muon from a $\tau$-lepton decay, an electron or charged-particle track(s) from the other $\tau$-lepton decay, little additional central-detector activity, and no forward neutrons. After applying the event selection, a total of 656 data events were observed in three signal regions (SR) in which the analysis was performed.

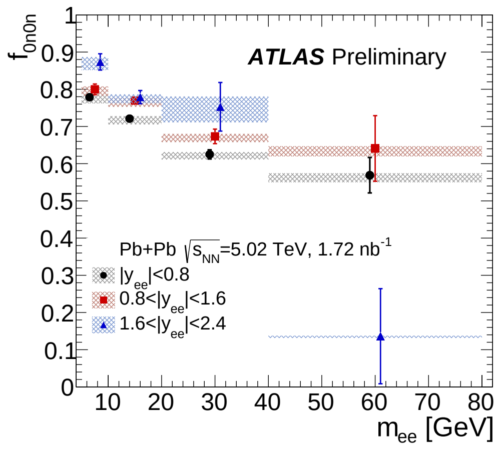


Figure 3 – Fractions of events in the 0n0n category evaluated from $\gamma\gamma \to e^+e^-$ data in three bins of $|y_{ee}|$, corrected for the presence of additional neutrons [5]. Error bars represent statistical uncertainties, while shaded boxes represent systematic uncertainties. Points for $|y_{ee}| < 0.8$ and $1.6 < |y_{ee}| < 2.4$ are displaced horizontally for better visibility.

The $\gamma\gamma \to \tau^+\tau^-$ process is observed with a significance exceeding 5 standard deviations, and a signal strength of $\mu_{\tau\tau} = 1.04^{+0.06}_{-0.05}$ assuming the Standard Model value for the anomalous magnetic moment of the $\tau$ lepton, $a_\tau$. Figure 4 shows $\mu_{\tau\tau}$ extracted from the fit, based on the individual SRs. The combined $\mu_{\tau\tau}$ is also shown which is in agreement with the prediction from the Standard Model.

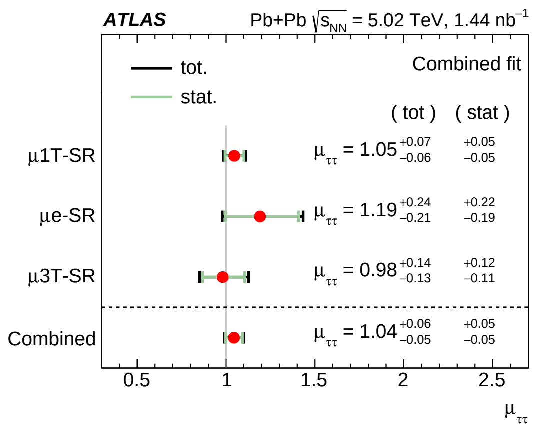


Figure 4 – Best-fit values of the signal strength parameter, $\mu_{\tau\tau}$, under the Standard Model $a_\tau$ value assumption, extracted from the fit based on the individual SRs [7].

## 6 Anomalous magnetic moment of $\tau$ lepton

The measurement of $\gamma\gamma \to \tau^+\tau^-$ production from ATLAS provided also constraints on $a_\tau$ [7]. To measure $a_\tau$, a fit to the muon $p_{\mathrm{T}}$ distribution was performed in the three SRs with $a_\tau$ being the only free parameter. Also a control region with events from the $\gamma\gamma \to \mu^+\mu^-$ process were used in the fit to constrain initial-photon fluxes. A left panel of Figure 5 shows a muon $p_{\mathrm{T}}$ distribution for the data and post-fit expectation in events falling into the SR with one muon and one track. The fit describes the data well. A right panel of Figure 5 depicts the $a_\tau$ measurement alongside previous results obtained at LEP. The precision of this measurement is similar to the most precise single-experiment measurement by the DELPHI Collaboration [8].

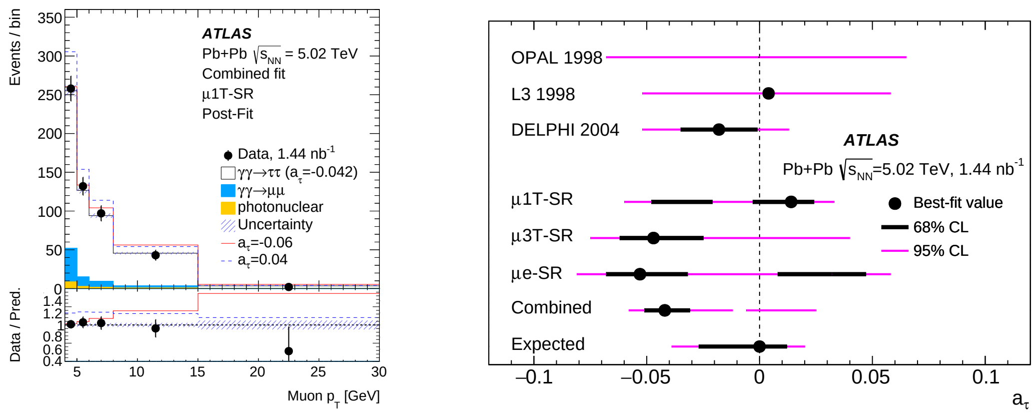


Figure 5 – (left) Muon $p_{\mathrm{T}}$ distribution in the SR with one muon and one track along with the MC expectations and (right) measurements of $a_\tau$ from fits to individual SRs, and from the combined fit [7]. These are compared with existing measurements from the OPAL, L3 and DELPHI experiments at LEP.

## 7 Summary

In this report, the latest results for $\gamma\gamma$ fusion processes from the ATLAS Collaboration were discussed. The UPC physics programme focused on precise measurements of exclusive $\gamma\gamma \to \mu^+\mu^-$ and $\gamma\gamma \to e^+e^-$ production including also forward neutron emission. Thanks to a large integrated luminosity of Pb+Pb collisions collected by ATLAS, rare processes such light-by-light scattering [9] (not discussed in the report due to the page limit) and $\gamma\gamma \to \tau^+\tau^-$ could be measured at the LHC for the first time. Also UPC collisions proved to be an excellent tool for BSM searches. In particular, they provided constraints on anomalous magnetic moment of $\tau$ lepton with the precision comparable to the LEP experiments.


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