Observation of the $\gamma\gamma \rightarrow \tau\tau$ process in Pb+Pb collisions and constraints on the $\tau$-lepton anomalous magnetic moment with the ATLAS detector at LHC

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Abstract. This paper reports the observation of $\tau$-lepton pair production in ultraperipheral lead-lead collisions, $Pb(\gamma)Pb(\gamma) \rightarrow \tau\tau$ and constraints on the $\tau$-lepton anomalous magnetic moment, $a_\tau$, measured by the ATLAS experiment. The dataset corresponds to an integrated luminosity of 1.44 nb$^{-1}$ of LHC Pb+Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV. Selected events contain 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. The $\gamma\gamma \rightarrow \tau\tau$ process is observed in Pb+Pb collisions with a signal strength of $\mu_{\tau\tau}=1.03^{+0.06}_{-0.05}$. To measure $a_\tau$, a template fit to the muon transverse-momentum distribution from $\tau$-lepton candidates is performed, using a dimuon ($\gamma\gamma \rightarrow \mu\mu$) control sample to constrain systematic uncertainties. The observed 95% confidence-level interval for $a_\tau$ is $(-0.057, 0.024)$.

1 Introduction

The magnetic moment $\mu_B$ is proportional to the particle spin through the parameter $g$: $\mu_B = g\frac{e\hbar}{2m}$. In the Dirac theory $g = 2$ and the anomalous magnetic moment $a$ is defined as $a = \frac{\alpha}{2\pi}$. The first QED correction to Dirac theory for electrons was calculated by J. Schwinger in 1948: $a_e = \alpha/2\pi = 0.00116$ [1]. In the Standard Model (SM) higher order corrections predict $a$ to be of the order of $10^{-3}$ calculated with high precision that requires to be verified with corresponding accurate measurements. Discrepancies between the SM predictions and the measurements would suggest new physics beyond SM, eg: lepton-compositeness, supersymmetric particle, ...

For electrons and muons the measurements of $a$ have been performed with a precision of 0.28 ppb [2] and 0.46 ppm [3] with differences from SM predictions of 2.4 and 4.6 standard deviations, respectively. Therefore the precise measurements of the $\tau$-lepton anomalous magnetic moment represent one of the most powerful tools to check the validity of the SM in searching for new physics.

For $a_\tau$, at the present, the experimental measurement is much less precise than those possible for the other two charged leptons. On the other hand, theoretically, the larger $\tau$-mass enhances the contributions to $a$ from new particles of mass $M$; in fact the photon-lepton vertex coupling is expected to be of the order of $m_\tau^2/M^2$ for a lepton of mass $m_\tau$. Therefore new physics effects for $\tau$'s would be larger by a factor $m_\tau^2/m_\mu^2 = 286$ compared with the case of muons. The present experimental knowledge of $a_\tau$ is quite poor: the very short $\tau$-lifetime...
precludes the use of the precession frequency measurement method as done in the $\mu$-case. The method adopted was then to measure the $\tau$-pair production cross-section, total and differential, in photon-photon scattering, where these quantities are sensitive to $a_\tau$. The best $a_\tau$ measurement was obtained by the DELPHI experiment at LEP [4]: $-0.052 < a_\tau^{exp} < 0.013$ at 95% CL, or, expressed as a central value and an error, $a_\tau^{exp} = -0.018(17)$.

The theoretical SM expectation for $a_\tau$, which includes electroweak and hadronic contributions, is calculated in [5]: $a_\tau^{SM} = 117721(5) \times 10^{-8}$ with a precision by far better than that of the experiments. So any effort should be made experimentally to approach in precision at least the size of the prediction of the SM: $a_\tau = 10^{-3}$.

The ATLAS experiment [6] has measured $a_\tau$ using Pb-Pb ultra peripheral collisions (UPC) at LHC to single-out $\gamma - \gamma$ collisions yielding tau-pairs. This reaction has several advantages compared with other reactions at LHC. In fact in UPC Pb-Pb collisions, Figure 1, the $\tau$-pairs are generated by a $\gamma\gamma$ collision $^1$, Figure 2. The cross-section is strongly enhanced by a factor $Z^4$, largely compensating the lower luminosity compared with that available in proton-proton collisions. In addition, the request of the presence of only the tau-decay products in the detector, with essentially no pile-up background, makes the control of backgrounds (electron/muon/quark pairs) much easier than in case of p-p collisions.

2 The analysis strategy

This paper presents the observation of the $Pb(\gamma)Pb(\gamma) \rightarrow \tau\tau$ process and measurement of $a_\tau$ [6] using 1.44 nb$^{-1}$ integrated luminosity at $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb data recorded by ATLAS in 2018.

The $a_\tau$ measurement in ATLAS is performed by looking at the dependence of the $Pb(\gamma)Pb(\gamma) \rightarrow \tau\tau$ cross-section and $\tau$-$p_T$ distribution. Figure 3 [7] shows the $a_\tau$ dependence of cross-section, left plot, and of $\tau$-$p_T$ distribution, central and right plots, for negative and positive $a_\tau$, respectively.

$^1$The first idea of using photons accompanying fast moving charged particles for physics experiments is due to Enrico Fermi in 1924 [8].
The ATLAS detector [9] is a multipurpose particle detector with cylindrical geometry, comprising an inner detector (ID) tracker, electromagnetic (EM), hadronic calorimeters and a muon spectrometer (MS). The zero-degree calorimeters (ZDC) [10] are located at $z = 140$ m in both sides from the interaction point and detect neutral particles such as neutrons emitted from interacting nuclei.

![Figure 3. $\tau$-pair cross-section dependence on $a_\tau$ (normalised to $a_\tau = 0$) (left), and $\tau$-$p_T$ distribution as a function of positive (central) and negative (right) $a_\tau$[7].](image)

After the UPC Pb-Pb interaction, the ions can remain intact, enabling selection of low-multiplicity events with one muon originating from one of the $\tau$-leptons, while the other $\tau$-lepton decay is reconstructed as either an electron or one or three charged-particle tracks with low transverse momentum. The trigger required one muon with $p_T > 4$ GeV, low activity in the forward calorimeters and no neutron in the very forward calorimeter ZDC.

![Sample of simulated $\gamma\gamma \rightarrow \tau\tau$ signal events were produced at leading order in QED using the Starlight 2.0 [11] Monte Carlo (MC) generator for lepton-pair production in UPC events, interfaced with Tauola [12] for $\tau$-lepton decays. The dominant background sources is the $\gamma\gamma \rightarrow \mu\mu$ process, its contribution is estimated with the aid of MC samples generated using Starlight; Pythia 8 was used to model EM FSR from the muons.](image)

Selected events must contain one muon, which targets a muonic decay of one of the $\tau$ leptons. Three signal regions (SR) then categorise events by the decay signature of the other $\tau$-lepton. The $\mu\tau$-SR category additionally requires one electron, and no additional tracks which targets fully leptonic decays of both $\tau$-leptons. The $\mu1T$-SR ($\mu3T$-SR) category requires exactly one track (three tracks) separated from the muon by $\Delta R(\mu - trk) > 0.1$,

which targets $\tau$-lepton decays to one or three charged hadrons. The one-track requirement also captures leptonic $\tau$-lepton decays that fail electron or muon reconstruction. The electric charges of muon, electron, and tracks must sum to zero. Figure 4 shows the display of a candidate signal event in $\mu3T$-SR.

To constrain the $\gamma\gamma \rightarrow \mu\mu$, a control region (CR) of dimuon events called $2\mu$-CR is defined. It requires exactly two muons with invariant mass above 11 GeV to suppress quarkonia ($Y_{nS} \rightarrow \mu\mu$) backgrounds and no additional tracks separated from the muons by $\Delta R(\mu - trk) > 0.1$. The $2\mu$-CR sample was used also to constrain the systematic uncertainty arising from the knowledge of $\gamma\gamma$ flux.

\[ \Delta R(\mu - trk) = \sqrt{(\eta_\mu - \eta_{trk})^2 + (\Phi_\mu - \Phi_{trk})^2} \] where $\eta_\mu, \Phi_\mu$ and $\eta_{trk}, \Phi_{trk}$ are the pseudorapidity and the azimuthal angles of the muon and of the track, respectively.

\[ ^2 \]
The second most important background, significant only for $\mu 1T$-SR and $\mu 3T$-SR, comes from the diffractive photo-nuclear events where the Pb-ions may not dissociate failing the ZDC neutron veto. This background was estimated by a data-driven method using dedicated CRs called $\mu 2T$-CR and $\mu 4T$-CR, which apply the same selection as $\mu 1T$-SR and $\mu 3T$-SR, but require an additional low energy track satisfying $p_T < 0.5$ GeV, relaxing the veto on unmatched clusters and extrapolating the number of events to zero unmatched clusters (the signal region) (see ref. [6] for details).

Other sources of background are predicted to be negligible in the SRs. The uncertainty in the integrated luminosity is 1.9%, obtained using the LUCID-2 detector [13] for the primary luminosity measurements.

### 3 The prefit distributions

To verify the goodness of the Monte Carlo predictions compared to the data, the $2\mu$-CR events have been used. Figure 5 and Figure 6, show the leading muon $p_T$-distribution and the muon-pair invariant mass distributions in the $2\mu$-CR region. The data are compared to the predictions of STARLIGHT simulation improved at $p_T > 2$ GeV with events from the Madgraph Montecarlo which provides a better description of $\gamma\gamma \rightarrow \mu\mu(\gamma)$ processes. The agreement between prediction and data is fairly good, with a little contribution from non $\gamma\gamma \rightarrow \mu\mu$ events (including possible $\gamma\gamma \rightarrow \tau\tau$ events with both $\tau$’s decaying into muon + neutrinos).

Figure 7 shows for the 3 signal regions the prefit distributions of the muon-track $p_T$ ( $\mu 1T$-SR), left, 3track invariant mass distribution ( $\mu 3T$-SR), central, and $\mu\mu$ invariant mass distribution ( $\mu\mu$-SR), right; Figure 7 shows the data compared to the signal and background contributions estimated with STARLIGHT+Madgraph Montecarlo and with a data-driven method for the $\mu\mu$ and photonuclear events, respectively.
After applying the event selection, there are a total of 656 candidate events in the 3 signal regions with 80 and 16 estimated background events from $\mu\mu$ and photonuclear processes. The agreement between the predictions and the data is good for the three signal region plots.
4 Fitting the data

A profile likelihood fit to the muon-$p_T$ distribution in the three SRs and 2µ-CR regions was used to extract the $\gamma\gamma \rightarrow \tau\tau$ signal strength:

$$\mathcal{L}_{\text{data}} = \frac{\sigma_{\text{data}}}{\sigma_{\text{predicted}}} \text{ and } a_\tau.$$ 

To measure $a_\tau$, in particular, a fit is performed where $a_\tau$ is the only free parameter using the $p_T^\mu$ distribution in the three SRs and 2µ-CR; $p_T^\mu$ is chosen because of its high sensitivity to $a_\tau$ [7]. Simulated signal samples with various $a_\tau$ values are employed. In the nominal sample, $a_\tau$ is set to its SM value. Signal templates for alternative $a_\tau$ hypotheses, are obtained by modifying the $\gamma\tau$ coupling in the Montecarlo-Lagrangian describing the process. Then the nominal sample is reweighted in three dimensions: differentially in $\tau\tau$ invariant mass, $\tau\tau$ rapidity, and rapidity difference between the two $\tau$ - leptons, according to calculations from Ref. [7]. Note that the 3 kinematical parameters are sufficient to determine the $p_T$ of the two $\tau$’s and, as a consequence, the $p_T$ of the muon from the $\tau$ – decay.

![Figure 8. Prefit muon-$p_T$ distributions for data and predictions, in the 3 signal regions and in the control region \( \mu \)-CR. In the signal regions it is assumed the SM value of \( a_\tau \). Below each plot the ratio data/prediction is shown [6].](image)

The main systematic uncertainties (in addition to the uncertainty in the photon flux) are: the muon-trigger efficiency, the muon/electron reconstruction/identification efficiency and calibration and the track reconstruction efficiency.

Figure 8 shows, for data and predictions, the muon-$p_T$ distribution for the 3 signal regions and the control region 2µ-CR. The agreement between data and MC prediction is good; the largest systematic uncertainty in all distributions comes from the photon flux modelling which affects the signal yield by about 20%.

Figure 9 shows, for data and predictions, for the 3 signal regions and the control region 2µ-CR, the muon-$p_T$ distributions. The results are obtained by a simultaneous fit using all regions. The inclusion of the 2µ-CR sample in the combined fit, strongly reduces the uncertainty originated by the photon flux modelling. The fit describes the data well. The evidence
Figure 9. Muon $p_T$-distribution in $\mu 1T$-SR (top-left). Muon $p_T$-distribution in $\mu 3T$-SR (top-right). Muon $p_T$-distribution in $\mu e$-SR (bottom-left). Muon $p_T$-distribution in $2\mu$-CR (bottom-right). Black markers denote data and stacked histograms indicate the different components contributing to the regions. Post-fit distributions are shown with the signal contribution corresponding to the best-fit $\alpha_t$ value ($\alpha_t = 0.041$). For comparison, signal contributions with alternative $\alpha_t$ values are shown as solid red ($\alpha_t = 0.06$) or dashed blue ($\alpha_t = 0.04$) lines. The bottom panel shows the ratio of the data to post-fit predictions. Vertical bars denote uncertainties from the finite number of data events. Hatched bands represent $\pm 1\sigma$ systematic uncertainties of the prediction with the constraints from the fit applied [6].

of the measurement of the process $\gamma\gamma \rightarrow \tau\tau$ is beyond 5 standard deviations. After the fit, the photon-flux uncertainty becomes subdominant and the luminosity uncertainty becomes negligible relative to other sources. The leading contributions to the total systematic uncertainty are: the estimation of the muon trigger efficiency, the $\tau$-lepton decay modelling and the track reconstruction efficiency.

5 Signal strength and constraints on $\alpha_t$

The signal strength $\mu_{\tau\tau}$, defined as the ratio of the observed signal yield to the SM expectation assuming the SM value for $\alpha_t$, is measured to be: $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}\text{(tot)} = 1.03^{+0.05}_{-0.05}\text{(stat)} +^{0.03}_{-0.03}\text{(sys)}$, largely dominated by the limited statistics. A total of 14 templates for different $\tau$ values are created to model the dependence of the $\mu - p_T$ distribution on $\alpha_t$ in the three SRs. The combined-fit value of $\alpha_t$ is $\alpha_t = 0.041$, with the corresponding 68% CL and 95% CL intervals being $(-0.050, -0.029)$ and $(-0.057, 0.024)$, respectively. The higher-than-expected observed yields lead to the highly asymmetric 95% CL interval. This arises from the nearly quadratic signal cross-section dependence on $\alpha_t$, caused by the interference of the SM and BSM amplitudes. The expected 95% CL interval is $-0.039 < \alpha_t < 0.020$. The impact of systematic uncertainties on the final results is small relative to statistical uncertainties. Figure 10
Figure 10. Measurements of $a_\tau$ from fits to individual signal regions (including the dimuon control region), and from the combined fit. These are compared with existing measurements from the OPAL, L3 and DELPHI experiments at LEP. A point denotes the best-fit $a_\tau$ value for each measurement if available, while thick black (thin magenta) lines show 68% CL (95% CL) intervals. The expected interval from the ATLAS combined fit is also shown [6].

shows 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.

6 Conclusions

In summary, $\tau$-lepton pair production in ultraperipheral heavy-ion collisions, $Pb + Pb \to Pb(\gamma\gamma \to \tau\tau)Pb$, is observed by ATLAS with a significance exceeding 5 standard deviations in $1.44 \text{ nb}^{-1}$ of $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ data at the LHC. The observed event yield is compatible with that expected from the SM prediction within uncertainties. The events are used to set constraints on the $a_\tau$-lepton anomalous magnetic moment, corresponding to $-0.057 < a_\tau < 0.024$ at 95% CL. The precision of the present experiment is limited by the statistical error: there is a large room for significant improvements in run3 and HL-LHC data taking periods.
References

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