PROCEEDINGS OF SCIENCE

Measuring tau g-2 using ATLAS Pb+Pb collisions

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At the Large Hadron Collider (LHC), relativistic heavy-ion beams generate a large flux of equivalent photons, which can lead to photon-induced reactions. By measuring the production of tau lepton pairs through photon-induced processes, it becomes possible to set constraints on the anomalous magnetic dipole moment $(g-2)$ of the tau lepton. A recent study conducted by the ATLAS experiment involved observing the muonic decays of tau leptons in conjunction with electrons and particle tracks. This study has yielded one of the most stringent constraints on the $g-2$ of the tau lepton to date.

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1. Introduction

Precise measurements of anomalous magnetic moments of leptons $a_\ell = \frac{1}{2}(g_\ell - 2)$ (where g_ℓ is the g-factor) provide a powerful tool to test the validity of the Standard Model (SM) and investigate beyond the SM (BSM) scenarios, such as lepton compositeness [1] or supersymmetry [2].

In the case of electrons and muons, their anomalous magnetic moments are among the most precisely measured observables in nature [3–6] and are powerful probes for BSM phenomena. The τ-lepton can be even more sensitive to some BSM processes, however the measurement of τ-lepton renders experimental challenges, due to its short lifetime. The most stringent limits on a_τ ($-0.052 < a_\tau < 0.013$) were set by the DELPHI experiment [7] at LEP and the central value was reported to be compatible with the prediction, however with an error one order of magnitude larger than the predicted value ($a_\tau^{\text{exp}} = -0.018(17)$ compared to $a_{\tau,\text{SM}}^{\text{pred}} = 0.00117721(5)$) [8].

In this study, a_τ is probed using the Pb+Pb→Pb($\gamma\gamma \to \tau\tau$)Pb process, illustrated in Figure 1, in which the presence of $\gamma\tau\tau$ vertices gives sensitivity to electromagnetic couplings [9–11]. This reaction arises in so-called ultra-peripheral heavy-ion collisions (UPC) in the ATLAS detector [12], when the distance between two incoming nuclei is larger than twice the ion radius. The nuclei are surrounded by strong electromagnetic fields which can be viewed as a coherent flux of photons [13, 14]. Thus, UPC can lead to photon-photon interactions. Utilizing UPC has several advantages compared to photon-photon interactions in proton-proton collisions, such as a substantial cross-section enhancement, which scales as Z^4 (with Z representing the atomic number, which is 82 for Pb). Furthermore, the low level of pile-up provides a clean environment enabling low transverse momentum (p_T) thresholds in the trigger and offline reconstruction [15].

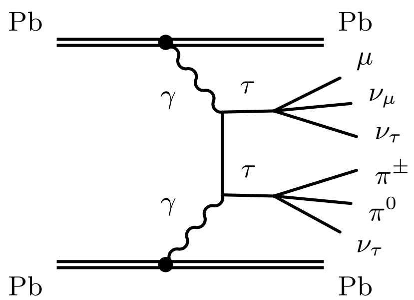

Figure 1: Schematic diagram showing photon-induced τ-lepton pair production in ultra-peripheral lead-lead interactions, Pb+Pb→Pb($\gamma\gamma \to \tau\tau$)Pb, with the τ-leptons decaying into an illustrative signature targeted by the event selection: one muon μ and one charged pion $\pi^\pm$.

2. Experimental method

The analysis utilizes 1.44 nb^{-1} of $\sqrt{s_\text{NN}} = 5.02$ TeV Pb+Pb data recorded by ATLAS. The signal samples were generated using the Starlight 2.0 Monte Carlo (MC) generator [16]. For the decay of τ-leptons, the simulation was interfaced with Tauola [17], and for modeling of the final-state radiation, Pythia 8.245 and Photos++ 3.61 [18, 19] were employed. The photon-flux distribution was re-weighted to Superchic 3.05 [20].

Signal candidates must contain exactly one muon, targeting a muonic decay of one of the τ−leptons. The decays of the other τ−lepton categorize events into three distinct signal regions

(SRs) depending on whether they include electrons or low-p_{T} tracks. The SRs are named μ1T-SR (muon + 1 track), μ3T-SR (muon + 3 tracks), and μe-SR (muon + electron). To enhance the precision of the analysis and minimize systematic uncertainties, a control region (CR), referred to as the di-muon control region (2μ-CR), was introduced [9, 10].

After applying the event selection criteria, the two primary sources of background are photon-induced di-muon events and photonuclear events. To estimate the former, Starlight 2.0 and Pythia 8.245 MC generators (or MadGraph5_aMC@NLO [21] in the case of radiative di-muon background) are employed, with the photon-flux distribution re-weighted to Superchic 3.05. For the estimation of the latter, a data-driven approach is adopted. This method involves constructing supplementary CRs, which are similar to the SRs but with modifications such as requiring an additional low-p_{T} track and the removal of the ZDC requirement. These CRs are used to estimate the contribution of photonuclear events to the background.

The analysis strategy hinges on two key dependencies: the cross-section dependence of $\gamma\gamma \to \tau\tau$ and the shape dependence of muon transverse momentum (p_{T}^{μ}) on the parameter a_τ. To extract the value of a_τ, a fit is carried out to the p_{T}^{μ} distribution in both the SRs and 2μ-CR.

3. Observation of the $\gamma\gamma \to \tau\tau$ in Pb+Pb

The $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions is observed with a significance much exceeding 5 standard deviations. Notably, the highest significance is achieved in the μ1T-SR, while the μe-SR exhibits the highest signal-to-background ratio among the signal regions.

The signal strength ($\mu_{\tau\tau}$) is defined as a ratio of the observed signal yield to the SM prediction, assuming the SM value of a_τ. It is determined with a profile-likelihood fit with $\mu_{\tau\tau}$ being the only parameter of interest. The measured value is $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}(\mathrm{tot}) = 1.03^{+0.05}_{-0.05}(\mathrm{stat.})^{+0.03}_{-0.03}(\mathrm{syst.})$, which is consistent with unity.

To measure a_τ, a profile-likelihood fit is conducted in three SRs and 2μ-CR in which a_τ is the only free parameter. The choice of using the p_{T}^{μ} distribution is motivated by its high sensitivity to a_τ. The analysis makes use of templates with various a_τ values and in the nominal signal sample, a_τ is set to the SM value. Samples representing different a_τ hypotheses are generated by reweighting the nominal sample in three dimensions: $\tau\tau$ invariant mass, rapidity, and the difference in pseudorapidity between the two τ-leptons [10]. This parametrization aligns with the one employed in prior LEP measurements [7, 22, 23]. In total, 14 samples encompassing a range of a_τ values are utilized in the analysis.

Pre-fit and post-fit distributions of p_{T}^{μ} in the μ1T-SR are shown in Figure 2. The fit to the data is seen to provide a good description, and it is evident that the uncertainties decrease noticeably in the post-fit distribution. It is worth noting that the difference between the SM and BSM values of a_τ depend on p_{T}^{μ}.

The best-fit a_τ value is determined to be $a_\tau = -0.041$, with corresponding 68% and 95% confidence levels (CL) of $(-0.050, -0.029)$ and $(-0.057, 0.024)$, respectively. The highly asymmetric 95% CL interval is a result of the observed yields being higher than expected, and the almost quadratic dependence of the cross-section on a_τ, which arises due to the interference between SM and BSM amplitudes [9, 10]. Figure 3 presents a comparison of the a_τ measurements with the previous results obtained by LEP [7, 22, 23]. The expected 95% CL limits from the combined fit are $-0.039 < a_\tau < 0.020$. The precision of the measurement is competitive with previous studies at electron colliders, however, the statistical uncertainties are significant in comparison to the systematic uncertainties.

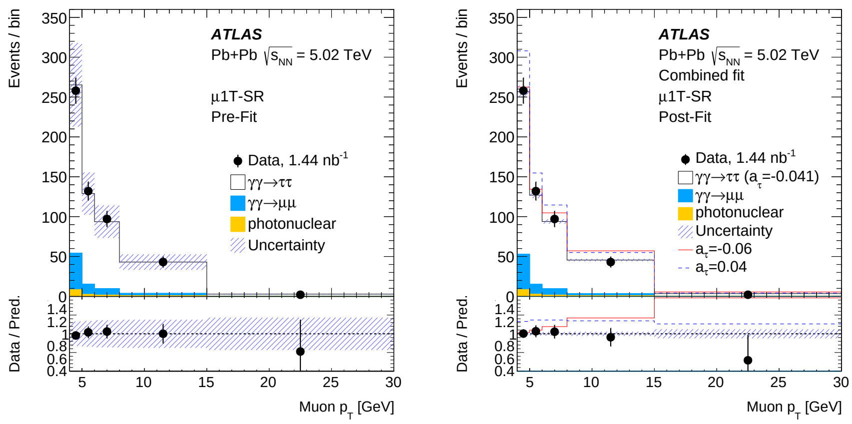

Figure 2: Pre-fit (left) and post-fit (right) muon transverse momentum distributions in the μ1T signal region. Black markers denote data and stacked histograms indicate different components contributing to the signal region. Hatched bands indicate $\pm 1\sigma$ systematic uncertainties of the prediction. Post-fit distributions are shown with the signal contribution corresponding to the best-fit a_τ value ($a_\tau = -0.041$). Figure from [15].

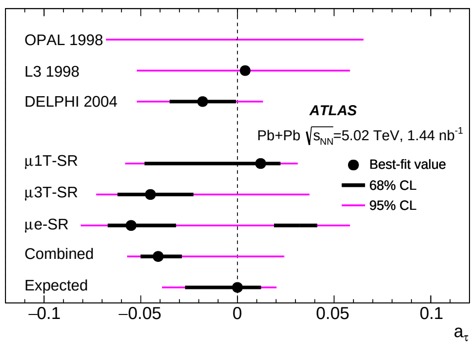

Figure 3: Results of a_τ measurement from fits to individual signal regions (and the di-muon control region), and from the combined fit, compared with existing measurements performed at LEP [7, 22, 23]. A point denotes the best-fit a_τ value for each measurement if available, while thick black (thin magenta) lines show 68% (95%) confidence level intervals. Figure from [15].

4. Conclusions

The process of τ-lepton production in ultra-peripheral Pb+Pb collisions in the ATLAS detector has been observed with a significance much exceeding 5 standard deviations, using 1.44 nb^{-1} of data at a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV. This result indicates the potential of UPCs as a tool for investigating rare SM processes and exploring BSM phenomena. It also introduces the possibility of conducting studies at hadron colliders to probe the electromagnetic properties of τ-leptons. The constraints obtained on a_τ are competitive with earlier results from electron colliders.

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