First measurement of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process and τ lepton electromagnetic moments at LHC

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Abstract

Inspired by recent theoretical calculations [1, 2], we propose to measure $\gamma\gamma \rightarrow \tau^+\tau^-$ using ultraperipheral heavy ion collisions at the LHC in order to probe the modified magnetic δa_τ and electric dipole moments δd_τ of the τ lepton. More specifically, the anomalous magnetic moment of the τ lepton, $a_\tau = (g_\tau - 2)/2$, lacks of a precise measurement since LEP even though it could be sensitive to physics beyond the standard model. The ATLAS and CMS experiments can rely on a suite of lepton (electron or muon) plus track(s) final states, taking full advantage of the clean photon fusion $\gamma\gamma \rightarrow \tau^+\tau^-$ events to reconstruct both leptonic and hadronic τ lepton decays. With 5–10% systematic uncertainty, the current lead-lead data set should already provide improved constraints, surpassing the 15 year old lepton collider precision by a significant factor while paving the way to improved determination at LHC Runs 3 and 4 [3].

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I. INTRODUCTION

Ultraperipheral (UPC) heavy ion collisions, where there is no hadronic interaction between the nuclei, provide a very clean environment to study various $\gamma\gamma$-induced processes. These reactions can also give rise to the production of τ lepton pairs. With this Letter we highlight the importance of measuring, for the first time at LHC, the $\gamma\gamma \to \tau^+\tau^-$ process using UPC and hence the anomalous magnetic (a_τ) and electric (d_τ) moments of the τ lepton, pursuing further past considerations [4] and recent advances in theory [1, 2]. The most stringent experimental constraints (95% CL) of $-0.052 < a_\tau < 0.013$ and $-0.22\,(-0.25) < Re\left[d_\tau\right]]\left(Im\left[d_\tau\right]\right) < 0.45\,(0.08) \times 10^{-16}$e cm come from DELPHI [5] and BELLE [6] collaborations, respectively. We believe that the proposed measurement can be already performed in the realm of the ATLAS [7] and CMS experiments [8], meaning feasibility studies should answer how competitive to these results the determinations with current or upcoming data sets at LHC are.

II. PROPOSED EVENT SELECTION

Selection of individual tracks from τ lepton decays with no other detector activity (e.g., low calorimetric energy deposit) is possible in the clean UPC events. To record $\gamma\gamma \to \tau^+\tau^-$ events, dedicated single- and double-lepton triggers, with exceptionally low calorimeter transverse energy deposit thresholds, are developed and already implemented [9–13]. With no other detector activity, the $\tau^+\tau^-$ system receives negligible transverse boost thus the transverse momentum (p_T) of the τ lepton reaches a few to tens of GeV at most. ATLAS and CMS experiments are already exploiting advances in low-p_T electron (e) [11, 13, 14], muon (μ) [9, 15], and τ [16] identification to efficiently reconstruct τ lepton decays, as shown in Ref. [17] or in Fig. 1, and to suppress leptonic ($\gamma\gamma \to \ell^+\ell^-, \ell \in [e, \mu]$) and hadronic ($\gamma\gamma \to q\bar{q}$) backgrounds.

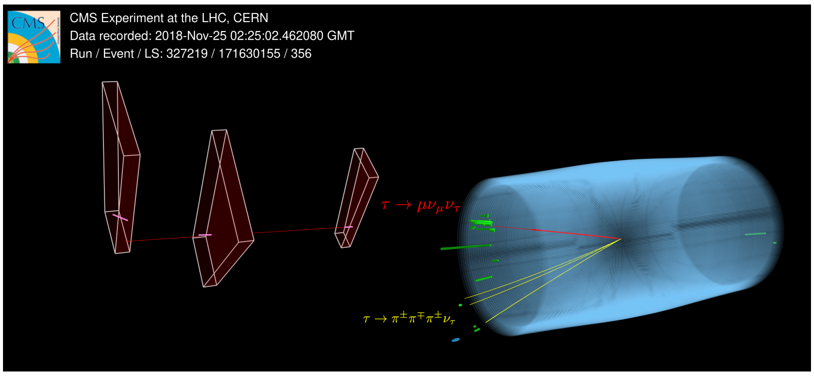

FIG. 1: Event display of a candidate $\gamma\gamma \to \tau^+\tau^-$ event measured in PbPb UPC collisions [8]. The event is interpreted as originating from the leptonic, $\tau \to \mu\nu_\mu\nu_\tau$, and hadronic, $\tau \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$, decay chains.

III. EXPERIMENTAL AND THEORETICAL UNCERTAINTY

The leptonic background is dominated by back-to-back leptons and hence is suppressed by a $|\Delta\phi_{\ell^+\ell^-}|$ requirement. Track impact parameters exploiting displaced τ lepton decays further suppress this background. The hadronic background is associated to parton showering and so produces more tracks than τ lepton decays. It can be reduced using lepton isolation and introducing a threshold on track multiplicity. Exchange of digluon (gg) color singlets also contributes to the hadronic background, but can be vetoed by the Zero Degree Calorimeters since more neutrons are emitted in gg events than pure QED processes.

Experimental systematic uncertainties from current UPC cross section measurements in PbPb, e.g., $gg \to \mu^+\mu^-$, amount to about 10%, dominated by luminosity (though recently updated [11]) and trigger efficiencies [9]. Lepton reconstruction can be controlled using clean $\gamma\gamma \to \ell^+\ell^-$ or $gg \to J/\psi$, Υ events. Theoretical systematic uncertainties are expected to be dominated by modeling of the photon flux, nuclear form factors and nucleon dissociation. Fortunately, these initial state effects are independent of the QED process and final state. So, we can use a control sample of $\gamma\gamma \to \ell^+\ell^-$ events to constrain these universal nuclear systematics or eliminate them in an analysis of the ratio $\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to\tau\tau}/\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to\ell^+\ell^-}$.

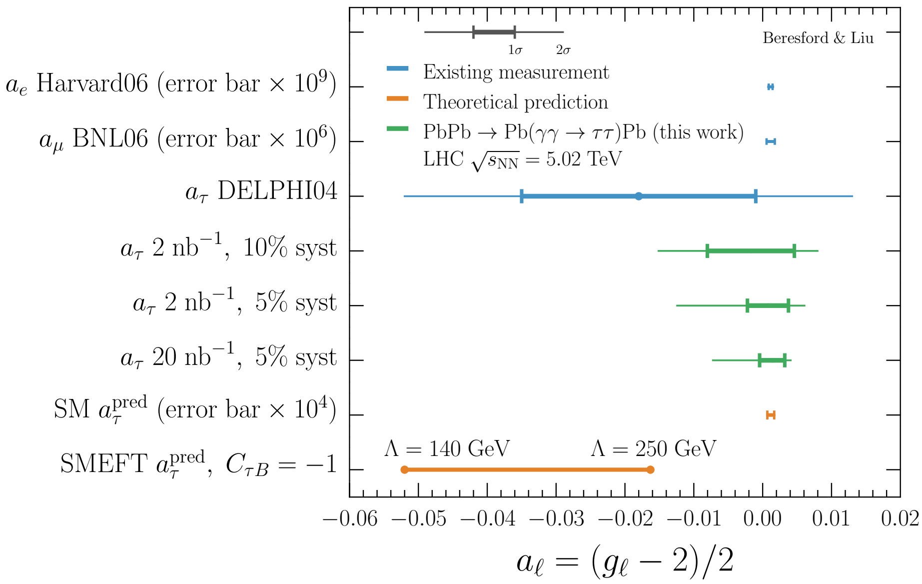

FIG. 2: Summary of lepton anomalous magnetic moments $a_\ell = (g_\ell - 2)/2$. Existing single-experiment measurements of a_e, a_μ, and a_τ are in blue. The benchmark projections of Ref. [1] is shown (green), assuming 2 (i.e., current data set at LHC) and 20 (i.e., close to the conjectured data set at LHC Runs 3 and 4) nb^{-1} for two benchmark (5 and 10%) levels of systematic uncertainty. For visual clarity, the 1σ error bars on a_e (a_μ) measurements by 10^9 (10^6), and 10^4 for the SM prediction $a_{\tau^{\mathrm{pred}}}$ (orange) are inflated. Collider constraints have thick (thin) lines denoting 68% CL, 1σ (95% CL, $\sim 2\sigma$). Some representative SMEFT prediction displays BSM at scales $140 < \Lambda < 250$ GeV (thick orange).

IV. PROPOSED ANALYSIS STRATEGY

We suggest following two methods: i) an absolute cross section measurement, and ii) a shape analysis that is sensitive to interfering SM and BSM amplitudes to enhance a_τ constraints. The strategy can also probe d_τ induced by CP violating BSM physics.

Method (i) can discriminate between the derived predictions of Refs. [1, 2], based on an effective field theory and first- principle approaches, respectively, that yielded significantly different inclusive cross sections. With method (ii) we can take advantage of the differential cross section, e.g., the τ lepton p_{T}, and its dependence on a_τ. In particular, the $\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to\tau\tau}/\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to\ell^+\ell^-}$ ratio could prove to be a more sensitive probe of a_τ since several systematic uncertainties, as previously described, cancel and the experimental knowledge of a_{e} and a_μ is several orders of magnitude more precise than a_τ itself.

We propose to build upon the existing knowledge, as summarized in Fig. 2, and carry out more detailed Monte Carlo studies and realistic physics-object reconstruction efficiency estimates.

V. SUMMARY

In this Letter, we suggest following the strategy recently suggested in Refs. [1, 2]. The LHC cross section receives a Z^4 enhancement ($Z = 82$ for Pb), with over one million $\gamma\gamma \to \tau^+\tau^-$ events produced to date. With the current proposal we invite ATLAS and CMS experiment to answer in more detail whether the currently available data sets of the LHC experiments are already sufficient to improve the sensitivity on a_τ by a multiple factor since LEP, hence, we consider this analysis as highly interesting and worthwhile to be performed taking into account further data sets in the future.

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