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Can we contrain anomalous magnetic and/or electric dipole moments of τ lepton from $PbPb \rightarrow PbPb\tau^+\tau^-$ reaction at the LHC?

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We discuss a possibility of extracting anomalous electromagnetic couplings of the tau lepton in ultraperipheral ultrarelativistic heavy ion collisions. Nuclear cross section for exclusive $\tau^+\tau^-$ production shows sizeable dependence on anomalous magnetic moment. We also investigated the expected sensitivity on a_τ and d_τ, assuming standard LHC detectors using the currently available as well as future datasets. The expected limits on a_τ with existing Pb+Pb dataset are found to be better by a factor of two comparing to the current best experimental limits and can be further improved by another factor of two at High Luminosity LHC.

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1. Introduction and theoretical framework

Physics of the ultraperipheral collisions (UPC) of heavy ions gives a good opportunity to study several QED processes [1]. Feynman diagram for the Pb+Pb→Pb+Pb+$\tau^+\tau^-$ process includes two $\gamma\tau\tau$ vertices providing an enhanced sensitivity to the anomalous magnetic (a_τ) and electric (d_τ) moments of the τ lepton.

Cross section for the two-lepton production in heavy-ion UPC is the convolution of the two-photon fusion cross section and photon fluxes. Details of the framework are explained in [2]. The amplitude for the elementary cross section, $\gamma\gamma \to \ell^+\ell^-$ was derived in [3]. Denoting p' and p as momenta of incoming and outgoing lepton and $q = p' - p$, respectively, a photon-lepton vertex function can be written as:

$$i\Gamma_\mu^{(\gamma\ell\ell)}(p',p) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\ell}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right], \tag{1}$$

where $\sigma_{\mu\nu} = \dfrac{i}{2}[\gamma_\mu, \gamma_\nu]$ is the spin tensor, $F_1(q^2)$ and $F_2(q^2)$ are the Dirac and Pauli form factors, $F_3(q^2)$ is the electric dipole form factor. The asymptotic values of the form factors, in the $q^2 \to 0$ limit, are the moments describing the electromagnetic properties of the lepton: $F_1(0) = 1$, $F_2(0) = a_\ell$ and $F_3(0) = d_\ell \frac{2m_\ell}{e}$.

In order to study the experimental sensitivity on a_τ in the $\gamma\gamma \to \tau^+\tau^-$ processes at the LHC, one has to record UPC events, which contain two reconstructed tau candidates and no further activity in the detector. Since the tau is the heaviest lepton with a lifetime of 3×10^{-13} s, it decays into lighter leptons ($\tau^\pm \to \nu_\tau + \ell^\pm + \nu_\ell$, $\ell = e, \mu$) or hadrons ($\tau^\pm \to \nu_\tau + \pi^\pm + n\pi^0$, $\tau^\pm \to \nu_\tau + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0$) before any direct interaction with the detector material. The reconstruction of tau candidates depends therefore on the identification of its unique decay signatures. Approximately 80% of all τ decays are one charged particle type and 20% of them are the three-prong decays.

2. Results and conclusion

The DELPHI collaboration at the LEP2 [4, 5] has obtained the limit: $-0.052 < a_\tau < 0.013$ (95% CL). The experimental limits on a_τ were also derived by the L3 and OPAL collaborations in radiative $Z \to \tau^+\tau^-\gamma$ events at LEP [6, 7], but they are typically weaker by a factor of two comparing to the DELPHI limits. For comparison, the theoretical Standard Model (SM) value of a_τ [8] is: $a_\tau^{\text{th}} = 0.00117721 \pm 0.00000005$.

Taking into account the requirement that $\gamma\gamma \to \tau^+\tau^-$ candidates events are selected when at least one τ decays leptonically and the leading electron or muon is detected in the kinematic limits: $p_\text{T} > 4$ GeV and $|\eta| < 2.5$, one can observe a good correlation between the rapidity of $\tau^+\tau^-$ system and the rapidity of the final-state charged-particle system. The fiducial cross sections for $\gamma\gamma \to e^+e^-$ and $\gamma\gamma \to \mu^+\mu^-$ processes are found to be nearly identical, hence one can equally use either of the processes. Experimentally, one can match $\tau_e\tau_{1(3)ch}$ channels with e^+e^- events and $\tau_\mu\tau_{1(3)ch}$ channels with $\mu^+\mu^-$ events to maximize cancellation of systematic uncertainties.

The expected number of events for Pb+Pb→Pb+Pb+$\tau^+\tau^-$ process [9] for different a_τ values can be translated into expected sensitivity for probing a_τ. We treat SM results ($a_\tau = 0$) as background and the difference between $a_\tau = 0$ and $a_\tau = X$ distributions as signal. We use two values of expected systematic uncertainty (5% and 1%) and two assumptions on Pb+Pb integrated luminosity (2 nb^{-1} to reflect existing ATLAS/CMS dataset, or 20 nb^{-1} for HL-LHC expectations). The expected significance can be directly transformed into expected 95% CL limits on a_τ. Assuming 2 nb^{-1} of integrated Pb+Pb luminosity and 5% systematic uncertainty, the expected limits are $-0.021 < a_\tau < 0.017$. Smaller systematic uncertainty or larger value of luminosity allow to predict a narrower limit on a_τ [9]. The expected results at the LHC have therefore the potential to significantly improve the current limits on a_τ.

Using the same methods we studied the sensitivity on tau lepton electric dipole moment, d_τ. Our expected 95% CL sensitivity on $|d_\tau|$ assuming $a_\tau = 0$ is: $|d_\tau| < 6.3\ (4.4) \cdot 10^{-17}\ e \cdot$cm at the LHC with 5% (1%) systematic uncertainty and $|d_\tau| < 3.5 \cdot 10^{-17}\ e \cdot$cm at HL-LHC (1% systematic uncertainty). For comparison, the current best limits are measured by Belle experiment [10]: $-2.2 < Re(d_\tau) < 4.5\ (10^{-17}\ e \cdot \text{cm})$ and $-2.5 < Im(d_\tau) < 0.8\ (10^{-17}\ e \cdot \text{cm})$. Our projected results on d_τ can be therefore competitive with the Belle limits.

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