ANOMALOUS ELECTROMAGNETIC MOMENTS OF $\tau$ LEPTON
FROM $\gamma\gamma \rightarrow \tau^+\tau^-$ PROCESSES
IN ULTRAPHIPHERAL Pb+Pb COLLISIONS AT THE LHC

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Anomalous electromagnetic moments of $\tau$ lepton in $\gamma\gamma \rightarrow \tau^+\tau^-$ reaction in Pb+Pb collisions at the LHC,
UPC of heavy ions provide a very clean environment to study two-photon induced processes.

Study $Pb + Pb \rightarrow Pb + Pb + \tau^+\tau^-$ at the LHC.

The presence of $\gamma\tau\tau$ vertex (twice) gives sensitivity to anomalous ($a_\tau$) and electric ($d_\tau$) moments.

So far the strongest experimental constraints on $a_\tau$ comes from DELPHI (LEP2) measurement on $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$. 

- $-0.052 < a_\tau^{\text{exp}} < 0.013$

The theoretical Standard Model value is $a_\tau^{\text{th}} = 0.00117721 \pm 0.00000005$.

Physics beyond the Standard Model (BSM):

- lepton compositeness,
- TeV-scale leptoquarks,
- left-right symmetric models,
- unparticle physics,

$a_\tau$ can be $(m_\tau/m_\mu)^2$ times more sensitive than $a_\mu$.

Many interesting proposals how to improve experimental sensitivity on $a_\tau$ and $d_\tau$ using lepton beams.
THEORETICAL FRAMEWORK

Nuclear cross section in UPC:

\[
\sigma (PbPb \rightarrow PbPb\ell^+\ell^-; \sqrt{s_{AA}}) = \int \sigma (\gamma\gamma \rightarrow \ell^+\ell^-; W_{\gamma\gamma}) N(\omega_1, b_1)N(\omega_2, b_2) S_{abs}^2(b) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\ell^+\ell^-} d\bar{b}_x d\bar{b}_y d^2b \quad (1)
\]

Differential elementary cross section

\[
\frac{d\sigma(\gamma\gamma \rightarrow \ell^+\ell^-)}{d \cos \theta} = \frac{2\pi}{64\pi^2 s} \frac{p_{out}}{p_{in}} \frac{1}{4} \sum_{\text{spin}} |\mathcal{M}|^2 . \quad (2)
\]

The amplitude for the \( t \) - and \( u \)-channel

\[
\mathcal{M} = (-i) \epsilon_{1\mu} \epsilon_{2\nu} \bar{u}(p_3) \left( i\Gamma(\gamma\ell^+\ell^-) \mu(p_3, p_t) \frac{i(p_t + m_\ell)}{t - m_\ell^2 + i\epsilon} i\Gamma(\gamma\ell^+\ell^-) \nu(p_t' - p_4) 
\right.

\[
+ i\Gamma(\gamma\ell^+\ell^-) \nu(p_3, p_u) \frac{i(p_u + m_\ell)}{u - m_\ell^2 + i\epsilon} i\Gamma(\gamma\ell^+\ell^-) \mu(p_u' - p_4) \bigg) v(p_4). \quad (3)
\]

Photon-lepton vertex function as a function of momentum transfer \((q = p' - p)\)

\[
i\Gamma_\mu(\gamma\ell^+\ell^-)(p', p) = -i\epsilon \left[ \gamma_\mu F_1(q^2) + \frac{i}{2m_\ell} \sigma_{\mu\nu} q^\nu F_2(q^2) + \frac{i}{2m_\ell} \gamma^5 \sigma_{\mu\nu} q^\nu F_3(q^2) \right], \quad (4)
\]

\( \Rightarrow \) Dirac form factor  \( \Rightarrow \) Pauli form factor  \( \Rightarrow \) electric dipole form factor

\[
F_1(0) = 1 \quad F_2(0) = a_\ell \quad F_3(0) = d_\ell \frac{2m_\ell}{e}.
\]
**Elementary Cross Section, $a_\tau$ Dependence**

![Graphs showing $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$ and $d\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)/dz$ as functions of $W$ and $z$, respectively.]

- As a function of energy...
- As a function of $\cos \theta$ for $W = 15$ GeV...

$\gamma\gamma \rightarrow \tau^+\tau^-$ STRONGLY DEPENDS ON $a_\tau$
Nuclear cross section, $a_\tau$ dependence

Ratio of the total nuclear cross sections for Pb+Pb→Pb+Pb\(\tau\tau\) production @ LHC as a function of $a_\tau$, relative to SM ($a_\tau = 0$).

FOR $|a_\tau| < 0.1$

Relatively small dependence on $p_{t,\tau}$

Comparison of SM results with STARlight

D\(\text{DIFFERENCE} \approx 20\%\);

Modeling of photon fluxes and absorption factor
Fiducial selection and $\tau$ decays

- Tau is the heaviest lepton with a lifetime of $3 \times 10^{-13}$ s
- Tau can decay into lighter leptons (electron or muon) or hadrons (mainly pions and kaons)
- Tau decay channels produce:
  - one charged particle (denoted as $1\text{ch}$, or one-prong) $\approx 80\%$
    $$\tau \rightarrow \nu_{\tau} + \ell + \nu_{\ell} \ (\ell = e, \mu)$$
    $$\tau \rightarrow \nu_{\tau} + \pi^\pm + n\pi^0$$
  - three charged particles (denoted as $3\text{ch}$, or three-prong) $\approx 20\%$
    $$\tau \rightarrow \nu_{\tau} + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0$$

Selection requirements of the $\gamma\gamma \rightarrow \tau^+ \tau^-$ candidates events:

- at least one $\tau$ decays leptonically
- the leading lepton has $p_{t,e/\mu} > 4$ GeV & $|\eta| < 2.5$
- $\tau$ lepton pairs have low $p_{t} \rightarrow$ identification tools are not applicable $\rightarrow$ all charged-particle tracks from $\tau_{1\text{ch}}$ or $\tau_{3\text{ch}}$: $p_T > 0.2$ GeV & $|\eta| < 2.5$
- condition on lepton-track system: $p_{T,\ell,1\text{ch}} > 1$ GeV for $\tau_{\ell}\tau_{1\text{ch}}$ category to suppress $e^+e^-$ & $\mu^+\mu^-$ bkg

Selection for ATLAS & CMS detectors
Fiducial cross section for SM scenario

... as a function of $p_T$ of the lepton+track system ($p_T^{\ell\text{ch}}$) in the $\tau^\ell\tau_{1\text{ch}}$ category

$p_T^{\ell\text{ch}} > 1$ GeV ($\approx 90\%$ of signal events)

TO SUPPRESS $\gamma\gamma \rightarrow \mu^+\mu^- / e^+e^-$ BKG

... as a function of $p_T$ of the leading lepton for various event categories
Fiducial cross section for various $a_\tau$ values

.. as a function of $p_T$ of the leading lepton for all event categories summed together

Predictions for current LHC Pb+Pb dataset and expected HL-LHC dataset

<table>
<thead>
<tr>
<th>$a_\tau$ value</th>
<th>$\sigma_{fid}$ [nb]</th>
<th>Expected events ($L_{int} = 2$ nb$^{-1}$, $C = 0.8$)</th>
<th>Expected events ($L_{int} = 20$ nb$^{-1}$, $C = 0.8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.1</td>
<td>4770</td>
<td>7650</td>
<td>76 500</td>
</tr>
<tr>
<td>−0.05</td>
<td>3330</td>
<td>5350</td>
<td>53 500</td>
</tr>
<tr>
<td>−0.02</td>
<td>3060</td>
<td>4900</td>
<td>49 000</td>
</tr>
<tr>
<td>0 (SM)</td>
<td>3145</td>
<td>5050</td>
<td>50 500</td>
</tr>
<tr>
<td>+0.02</td>
<td>3445</td>
<td>5500</td>
<td>55 000</td>
</tr>
<tr>
<td>+0.05</td>
<td>4350</td>
<td>6950</td>
<td>69 500</td>
</tr>
<tr>
<td>+0.1</td>
<td>7225</td>
<td>11550</td>
<td>115 500</td>
</tr>
</tbody>
</table>
**Ratio between** \( \gamma \gamma \rightarrow \tau^+ \tau^- \) **and** \( \gamma \gamma \rightarrow \ell^+ \ell^- \)

... as a function of \( p_T \) of the leading lepton for all event categories summed together

**Fiducial cross section** &

**Results with extra** \( m_{\ell \ell} \) **shape reweighting**
Expected signal significance as a function of $a_\tau$

For various assumptions on Pb+Pb integrated luminosity and total systematic uncertainty.

Assuming 2 nb$^{-1}$ of integrated Pb+Pb luminosity and 5% systematic uncertainty:

$$-0.021 < a_\tau^{\text{expected}} < 0.017$$

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$^1$ DELPHI limits: $-0.052 < a_\tau^{\text{exp}} < 0.013$
**Electric Dipole Moment**

**EXPECTED**
Including 95% CL sensitivity on $|d_\tau|$ and assuming $a_\tau = 0$:
- at the LHC with 5% systematic uncertainty
  \[ |d_\tau| < 6.3 \cdot 10^{-17} \text{ e} \cdot \text{cm} \]
- at the LHC with 1% systematic uncertainty
  \[ |d_\tau| < 4.4 \cdot 10^{-17} \text{ e} \cdot \text{cm} \]
- at HL-LHC with 1% systematic uncertainty
  \[ |d_\tau| < 3.5 \cdot 10^{-17} \text{ e} \cdot \text{cm} \]

The **CURRENT** best limits are measured by Belle experiment:

\[ -2.2 < Re(d_\tau) < 4.5 \left(10^{-17} \text{ e} \cdot \text{cm}\right) \]
and
\[ -2.5 < Im(d_\tau) < 0.8 \left(10^{-17} \text{ e} \cdot \text{cm}\right) \]

**Our results on $d_\tau$ can be therefore competitive with Belle limits**
CONCLUSION

- We have used UPC calculation for $Pb + Pb \rightarrow Pb + Pb + \tau^+\tau^-$;
- We have studied the dependence of the $\gamma\gamma \rightarrow \tau^+\tau^-$ on $a_\tau$;
- All channels with at least one leading lepton have been accepted;
- We suggest to measure the ratio of 
  $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow (\ldots\ldots)$ to $\gamma\gamma \rightarrow e^+e^-(\mu^+\mu^-)$ 
  - This allows to significantly cancel many uncertainties 
  - The experimental knowledge of $a_e$ and $a_\mu$ is several orders of magnitude more precise than $a_\tau$ 
- The limitations from present analysis seems better than those from DELPHI;
- Spin-spin correlations probably small (see appendix of our paper);
- Our studies suggest that the currently available datasets of the LHC experiments are already sufficient to improve limits on $a_\tau$ by a factor of two, hence, we consider this analysis as highly interesting and worthwhile to be done in the future;
- ATLAS & CMS combination for better precision?
- High statistics studies may discover BSM effects.