Anomalous electromagnetic moments of τ lepton from $\gamma\gamma \to \tau^+\tau^-$ processes in ultrapheripheral Pb+Pb collisions at the LHC

Mariola Kłusek-Gawenda

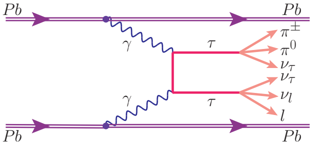
Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

✓ **M. Dyndał, M. K-G, M. Schott and A. Szczurek,**
Anomalous electromagnetic moments of τ lepton in $\gamma\gamma \to \tau^+\tau^-$ reaction in Pb+Pb collisions at the LHC,
Phys. Lett. **B809** (2020) 135682

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

INTRODUCTION

- UPC of heavy ions provide a very clean enviroment to study two-photon induced processes



- Study $Pb + Pb \to Pb + Pb + \tau^+\tau^-$ at the LHC
- The presence of $\gamma\tau\tau$ vertex (twice) gives sensitivity to **anomalous** (a_τ) and **electric** (d_τ) moments
- So far the strongest experimental constraints on a_τ comes from DELPHI (LEP2) measurement on $e^+e^- \to e^+e^-\tau^+\tau^-$

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

- The theoretical Standard Model value is

$$a_\tau^{th} = 0.00117721 \pm 0.00000005$$

- Physics beyond the Standard Model (BSM):
  - lepton compositeness,
  - TeV-scale leptoquarks,
  - left-right symmetric models,
  - unparticle physics,
  - a_τ can be $\left(\frac{m_\tau}{m_\mu}\right)^2$ times more sensitive than a_μ
- Many interesting proposals how to improve experimental sensitivity on a_τ and d_τ using lepton beams

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Theoretical framework

- Nuclear cross section in UPC: $\sigma\left(PbPb \to PbPb\ell^+\ell^-; \sqrt{s_{AA}}\right) =$

$$\int \sigma\left(\gamma\gamma \to \ell^+\ell^-; W_{\gamma\gamma}\right) N(\omega_1, b_1) N(\omega_2, b_2) S^2_{abs}(\boldsymbol{b}) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, d\mathrm{Y}_{\ell^+\ell^-}\, d\bar{b}_x\, d\bar{b}_y\, d^2b \quad (1)$$

- Differential elementary cross section

$$\frac{\mathrm{d}\sigma(\gamma\gamma \to \ell^+\ell^-)}{\mathrm{d}\cos\theta} = \frac{2\pi}{64\pi^2 s} \frac{\boldsymbol{p_{out}}}{\boldsymbol{p_{in}}} \frac{1}{4} \sum_{\mathrm{spin}} |\mathcal{M}|^2 \,. \quad (2)$$

- The amplitude for the t- and u-channel

$$\begin{aligned} \mathcal{M} \;=\; & (-i)\,\epsilon_{1\mu}\epsilon_{2\nu}\,\bar{u}(p_3)\Big(i\Gamma^{(\gamma\ell^+\ell^-)\,\mu}(p_3,p_t)\frac{i(\not{p}_t + m_\ell)}{t - m_\ell^2 + i\epsilon} i\Gamma^{(\gamma\ell^+\ell^-)\,\nu}(p_{t'} - p_4) \\ & + i\Gamma^{(\gamma\ell^+\ell^-)\,\nu}(p_3,p_u)\frac{i(\not{p}_u + m_l)}{u - m_\ell^2 + i\epsilon} i\Gamma^{(\gamma\ell^+\ell^-)\,\mu}(p_{u'} - p_4)\Big)v(p_4)\,. \end{aligned} \quad (3)$$

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

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

➢ Dirac form factor

$F_1(0) = 1$

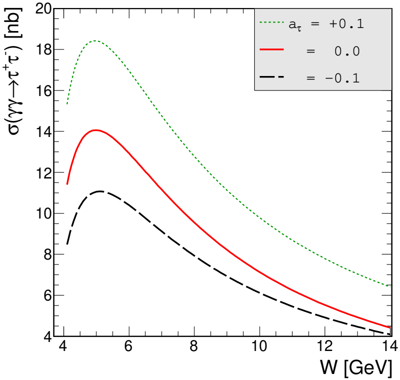
➢ Pauli form factor

$F_2(0) = a_\ell$

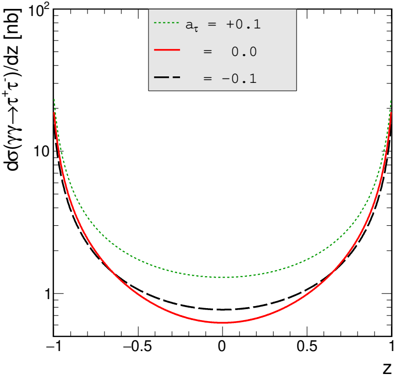
➢ electric dipole form factor

$F_3(0) = d_\ell \frac{2m_\ell}{e}$

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES



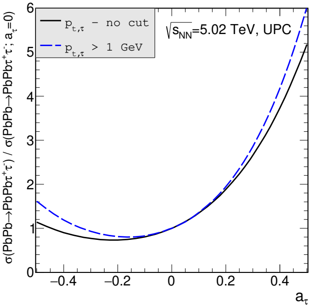
... as a function of energy



... as a function of $\cos\theta$ for $W = 15$ GeV

$\gamma\gamma \to \tau^+\tau^-$ **STRONGLY DEPENDS ON** a_τ

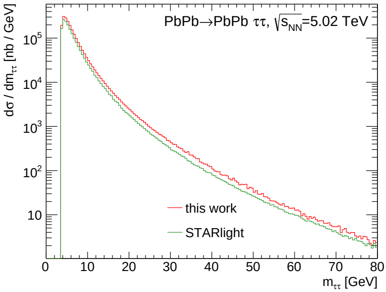
NUCLEAR CROSS SECTION, a_τ DEPENDENCE



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

FOR $|a_\tau| < 0.1$

RELATIVELY SMALL DEPENDENCE ON $p_{t,\tau}$



Comparison of SM results with STARLIGHT

DIFFERENCE ≈ 20%;

MODELING OF PHOTON FLUXES

AND ABSORPTION FACTOR

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Fiducial selection and τ decays

- Tau is the heaviest lepton with a lifetime of 3×10^{-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*ch*, or one-prong) $\approx$ 80%

    $$\tau \to \nu_\tau + \ell + \nu_\ell \; (\ell = e, \; \mu)$$

    $$\tau \to \nu_\tau + \pi^\pm + n\pi^0$$

  - ➡ three charged particles (denoted as 3*ch*, or three-prong) $\approx$ 20%

    $$\tau \to \nu_\tau + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0$$

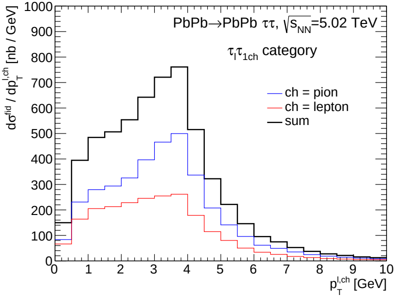
Selection requirements of the $\gamma\gamma \to \tau^+\tau^-$ candidates events:

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

Selection for ATLAS & CMS detectors

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

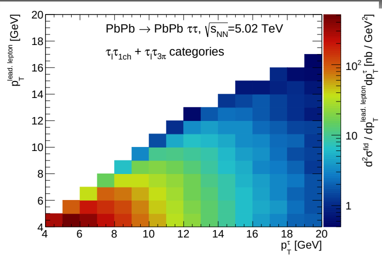
Fiducial cross section for SM scenario



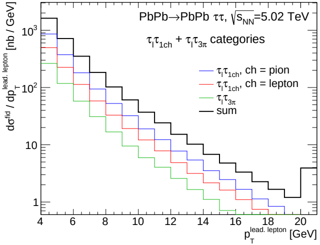
... as a function of p_T of the lepton+track system ($p_T^{\ell\ ch}$) in the $\tau_\ell \tau_{1ch}$ category

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

to suppress $\gamma\gamma \to \mu^+\mu^- / e^+e^-$ bkg



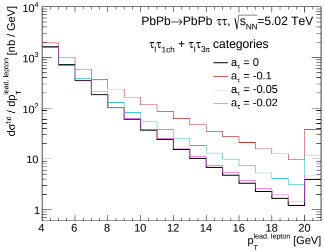
p_T^{τ} & $p_T^{lead.lepton}$ correlation

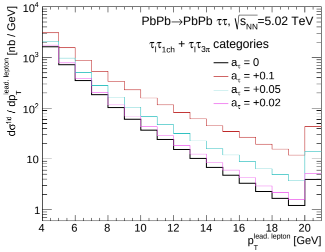


... as a function of p_T of the leading lepton for various event categories

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Fiducial cross section for various a_τ values



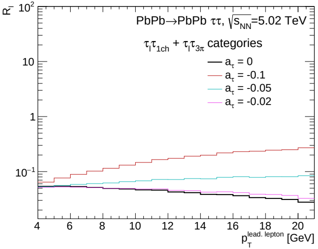


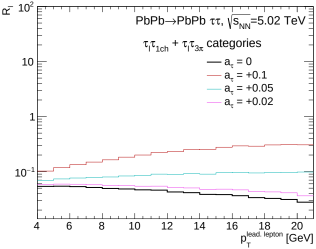
.. as a function of p_T of the leading lepton for all event categories summed together

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

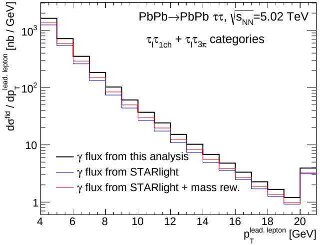
a_τ value	σ_{fid} [nb]	Expected events ($L_{int} = 2\ \mathrm{nb}^{-1}$, $C = 0.8$)	Expected events ($L_{int} = 20\ \mathrm{nb}^{-1}$, $C = 0.8$)
-0.1	4770	7650	76 500
-0.05	3330	5350	53 500
-0.02	3060	4900	49 000
0 (SM)	3145	5050	50 500
$+0.02$	3445	5500	55 000
$+0.05$	4350	6950	69 500
$+0.1$	7225	11550	115 500

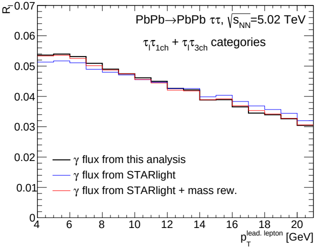
THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES





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





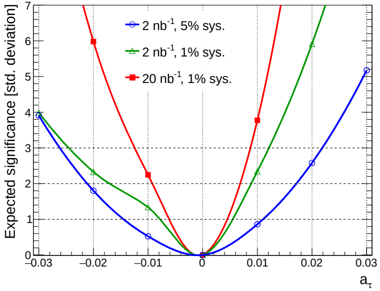
Fiducial cross section & Results with extra $m_{\ell\ell}$ shape reweighting

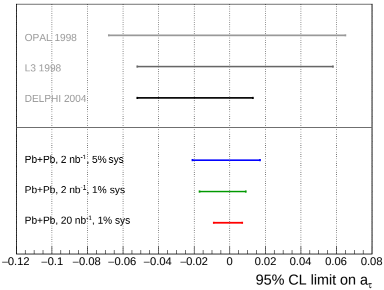
THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Expected signal significance as a function of a_τ

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:

$$-0.021 < a_\tau^{expected} < 0.017$$ [1]

[1] DELPHI limits: -0.052 $< a_\tau^{exp} <$ 0.013

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Electric dipole moment

EXPECTED

Including 95% CL sensitivity on $|d_\tau|$ and assuming $a_\tau = 0$:

- at the LHC with 5% systematic uncertainty

$$|d_\tau| < 6.3 \cdot 10^{-17}\ e \cdot \mathrm{cm}$$

- at the LHC with 1% systematic uncertainty

$$|d_\tau| < 4.4 \cdot 10^{-17}\ e \cdot \mathrm{cm}$$

- at HL-LHC with 1% systematic uncertainty

$$|d_\tau| < 3.5 \cdot 10^{-17}\ e \cdot \mathrm{cm}$$

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

$$-2.2 < Re(d_\tau) < 4.5\ (10^{-17}\ e \cdot \mathrm{cm})$$

and

$$-2.5 < Im(d_\tau) < 0.8\ (10^{-17}\ e \cdot \mathrm{cm})$$

OUR RESULTS ON d_τ CAN BE THEREFORE COMPETITIVE WITH BELLE LIMITS

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

CONCLUSION

- We have used UPC calculation for $Pb + Pb \to Pb + Pb + \tau^+\tau^-$;
- We have studied the dependence of the $\gamma\gamma \to \tau^+\tau^-$ on a_τ;
- All channels with at least one leading lepton have been accepted;
- We suggest to measure the ratio of

$$\gamma\gamma \to \tau^+\tau^- \to (........) \text{ to } \gamma\gamma \to e^+e^-(\mu^+\mu^-)$$

  - This allows to significantly cancel many uncertainties
  - The experimental knowledge of a_e and a_μ is several orders of magnitude more precise than a_τ
- 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_τ 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.

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES