THE SENSITIVITY TO BSM IN DI-TAON PRODUCTION 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

INTRODUCTION

- UPC of heavy ions provide a very clean enviroment 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_τ) and **electric** (d_τ) moments
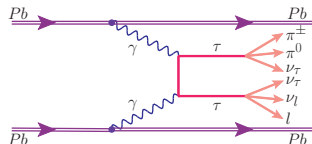
- So far the strongest experimental constraints on a_τ comes from DELPHI (LEP2) measurement on $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$

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

- The theoretical Standard Model value is

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

- Physics beyond the Standard Model (BSM):
  - ✳ lepton compositness,
  - ✳ 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

Theoretical framework

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

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

- Differential elementary cross section

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

- The amplitude for the t- and u-channel

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

- 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 $\qquad$ ➢ Pauli form factor $\qquad$ ➢ electric dipole form factor

$F_1(0) = 1 \qquad\qquad F_2(0) = a_\ell \qquad\qquad F_3(0) = d_\ell\frac{2m_\ell}{e}$

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

ELEMENTARY CROSS SECTION, a_τ DEPENDENCE
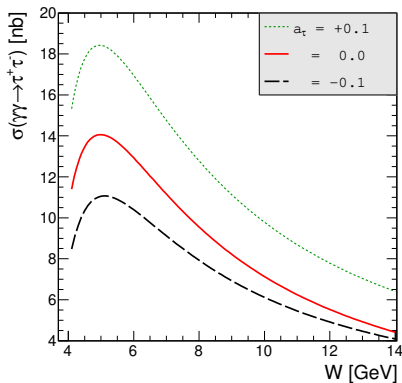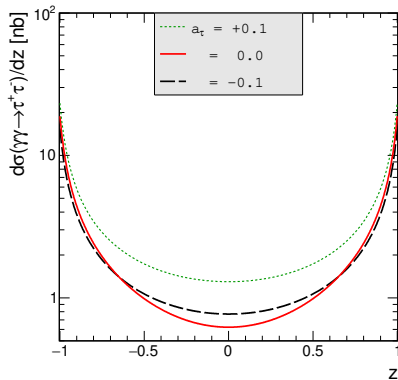

FIG.: ... as a function of energy   ... as a function of $\cos\theta$ for $W = 15$ GeV

$\gamma\gamma \to \tau^+\tau^-$ **STRONGLY DEPENDS ON a_τ**
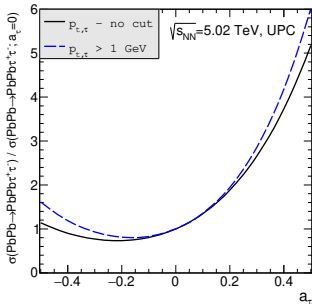
FIG.: Ratio of the total nuclear cross sections for Pb+Pb→Pb+Pb$\tau\tau$ production @ LHC as a function of a_τ, relative to SM ($a_\tau = 0$).

FIG.: Comparison of SM results with STARLIGHT

FOR $|a_\tau| < 0.1$

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

DIFFERENCE $\approx$ 20%;

MODELING OF PHOTON FLUXES

AND ABSORPTION FACTOR

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
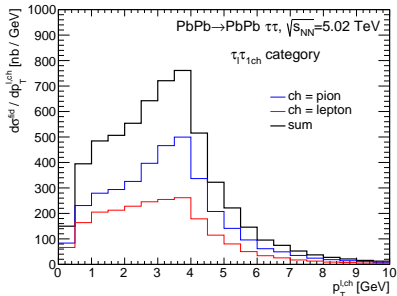POLISH ACADEMY OF SCIENCES

FIDUCIAL CROSS SECTION FOR SM SCENARIO

FIG.: ... 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 ($\approx 90\%$ OF SIGNAL EVENTS)
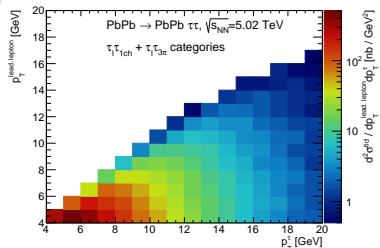
TO SUPPRESS $\gamma\gamma \to \mu^+\mu^-/e^+e^-$ BKG
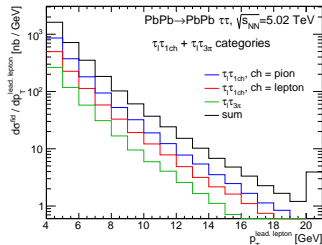

FIG.: p_T^τ & $p_T^{lead.\,lepton}$ correlation

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

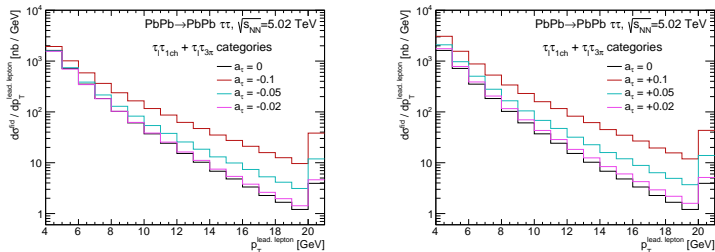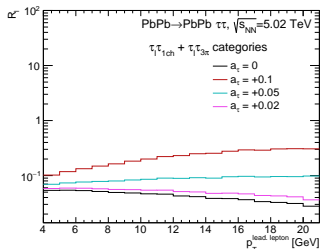# FIDUCIAL CROSS SECTION FOR VARIOUS a_τ VALUES

FIG.: .. 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 ($L_{int} = 2$ nb^{-1}, $C = 0.8$)	Expected events ($L_{int} = 20$ 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

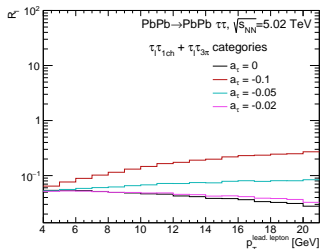# RATIO BETWEEN $\gamma\gamma \to \tau^+\tau^-$ AND $\gamma\gamma \to \ell^+\ell^-$

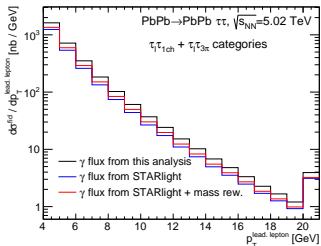FIG.: ... as a function of p_T of the leading lepton for all event categories summed together
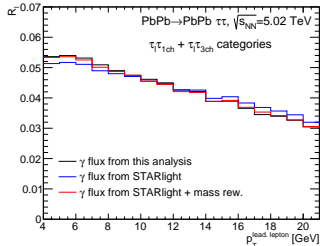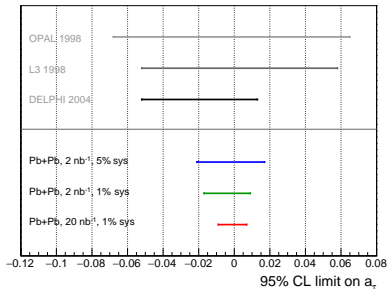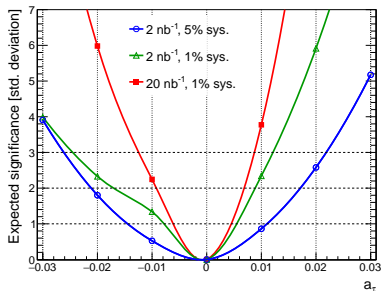

FIG.: Fiducial cross section   &   Results with extra $m_{\ell\ell}$ shape reweighting

EXPECTED SIGNAL SIGNIFICANCE AS A FUNCTION OF a_τ

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

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

---

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

ELECTRIC DIPOLE MOMENT

EXPECTED

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

- at the LHC with 5% systematic uncertainty

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

- at the LHC with 1% systematic uncertainty

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

- at HL-LHC with 1% systematic uncertainty

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

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

$$-2.2 < Re(d_\tau) < 4.5 \, (10^{-17} \, e \cdot \text{cm})$$
$$\text{and}$$
$$-2.5 < Im(d_\tau) < 0.8 \, (10^{-17} \, e \cdot \text{cm})$$

OUR RESULTS ON d_τ 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_τ;
- All channels with at least one leading lepton have been accepted;
- We suggest to measure the ratio of
  $$\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow (........) \text{ to } \gamma\gamma \rightarrow e^+e^-(\mu^+\mu^-)$$
  - ○ 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.