Probing anomalous electromagnetic moments of tau lepton with ultraperipheral heavy-ion collisions at the LHC

Mateusz Dyndał*

CERN, Geneva, Switzerland

Mariola Kłusek-Gawenda† and Antoni Szczurek[c§]

Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland

Matthias Schott¶

Johannes Gutenberg University, Mainz, Germany

(based on arXiv:2002.05503 [hep-ph])

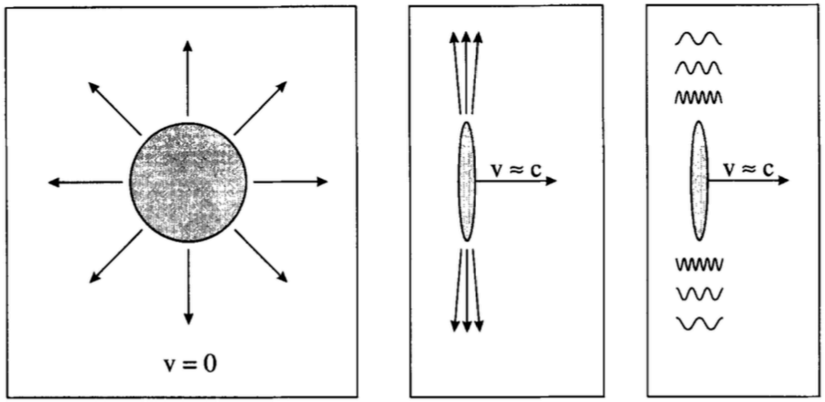
"Bialasowka" HEP Seminar, 5 Jun 2020

Outline

- Ultraperipheral collisions (UPC)
- Anomalous (electro-)magnetic moments of tau lepton
- Towards calculating Pb+Pb→Pb+Pb+τ τ reaction
- Tau decays and detector considerations
- Reaching ultimate precision: γγ→l+l- cross-section ratios
- Sensitivity of existing and future LHC data on a_τ

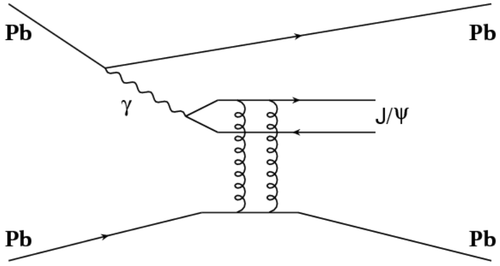
Ultraperipheral collisions

- Boosted nuclei are intense source of (quasi-real) photons
- **Equivalent photon flux**
  - **$Q \sim 1/R \sim 0.06$ GeV**
  - $\sqrt{s_{NN}} = 5.02$ TeV
    → Lorentz factor γ **~2700**
  - **$E_{max} \lesssim \gamma/R \sim 80$ GeV**
  - Each flux scales with **Z^2**



[Fermi, Nuovo Cim. 2 (1925) 143]

- Various types of interactions possible:



Photon-pomeron
(e.g. exclusive J/Psi)

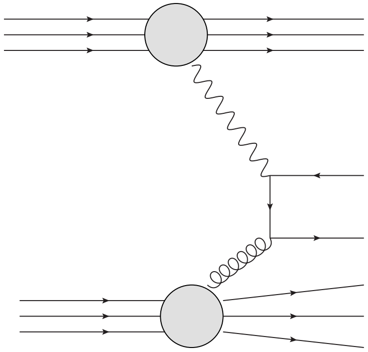
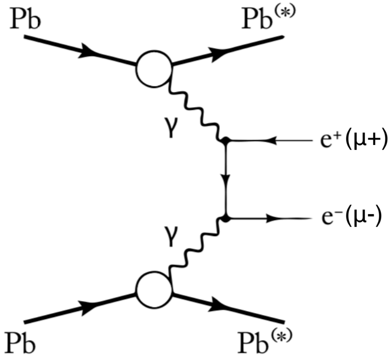


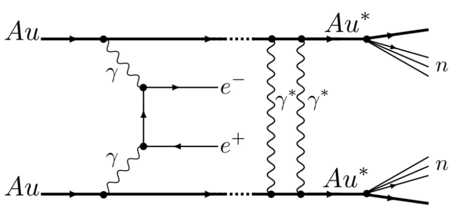
Photo-nuclear
(e.g. photoproduction of jets)

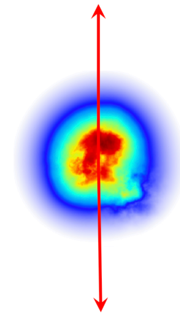


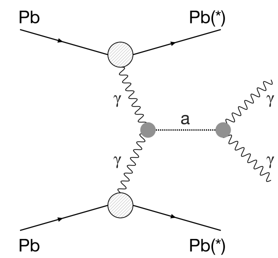
Photon-photon
(e.g. dilepton production)

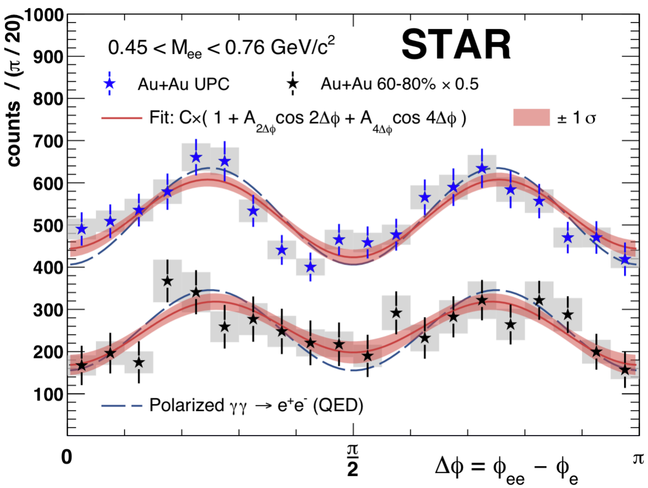
Photon-photon collisions in HI

- Photon-photon production mechanism has recently become intense field of research
  - Probing strong-field QED, QGP(?) and BSM effects!

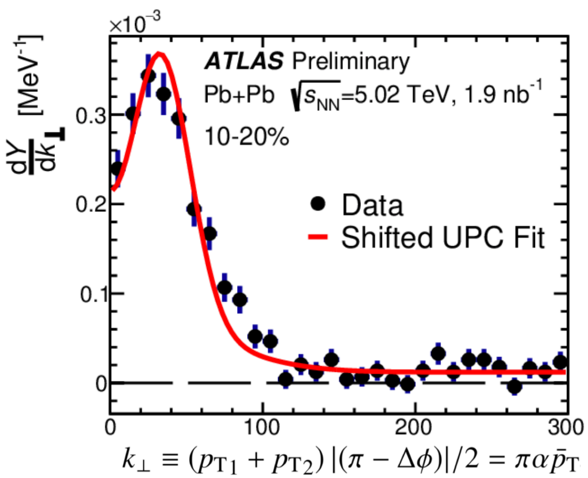




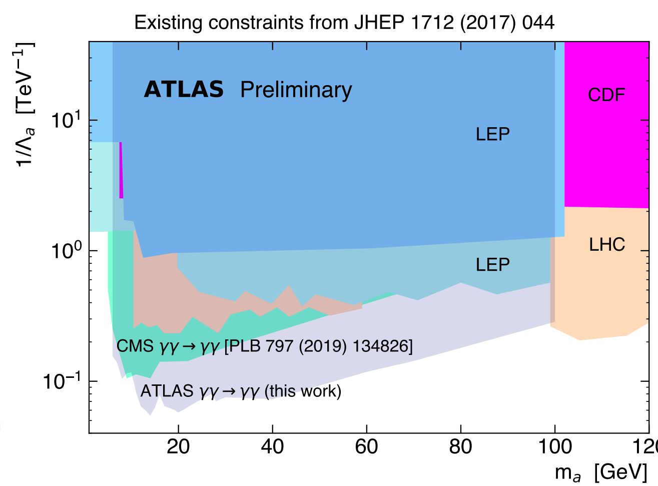




[1910.12400](https://arxiv.org/abs/1910.12400) [nucl-ex]



ATLAS-CONF-2019-051

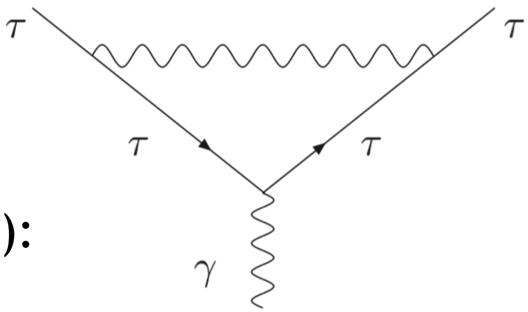


ATLAS-CONF-2020-010

Anomalous (electro-)magnetic moments of tau lepton

- τ anomalous electromagnetic moments
  - Poorly constrained experimentally so far (short tau lifetime of ~10^{-13} s)
  - Can be sensitive to BSM effects

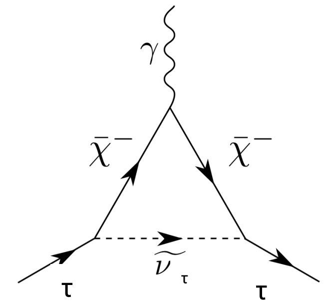
- Anomalous magnetic moment [$\mathbf{a_\tau = (g_\tau-2)/2}$]
  - Theory value: $a_\tau^{th} = 0.00117721 \pm 0.00000005$ (dominated by Schwinger term)
  - Strongest experimental constraints from DELPHI (LEP): **$-0.052 < a_\tau < 0.013$ (95% CL)**

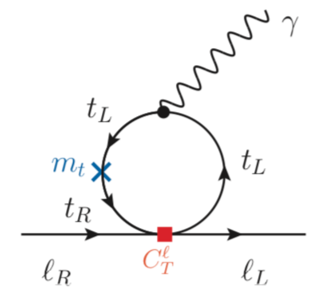


- Electric dipole moment [$\mathbf{d_\tau}$]
  - Highly suppressed in SM (arises at three-loop): $|d_\tau^{th}| < 10^{-34}$ e·cm
  - Most stringent constraints on d_τ set by Belle: $Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$ e·cm and $Im(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}$ e·cm

BSM effects

- Certain BSM effect can affect a_τ:
  - Supersymmetry predicts ~$(m_\tau/m_\mu)^2$ ~280x BSM enhancement of a_τ wrt a_μ (note tension in a_μ …)
    (but a_μ measurement precision is extremely good…)
  - Models with TeV-scale leptoquarks [see 1806.10155]
  - …

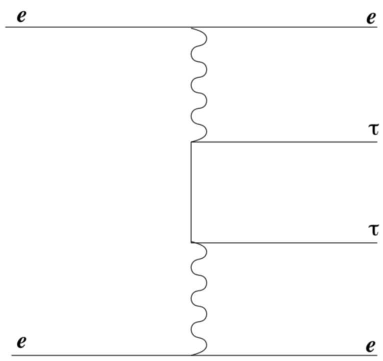




- CP-violating effects in the lepton sector can create anomalous τ EDM:
  - Extra dimensions
  - Seesaw model
  - 2HDM
  - Models with scalar leptoquarks
  - …

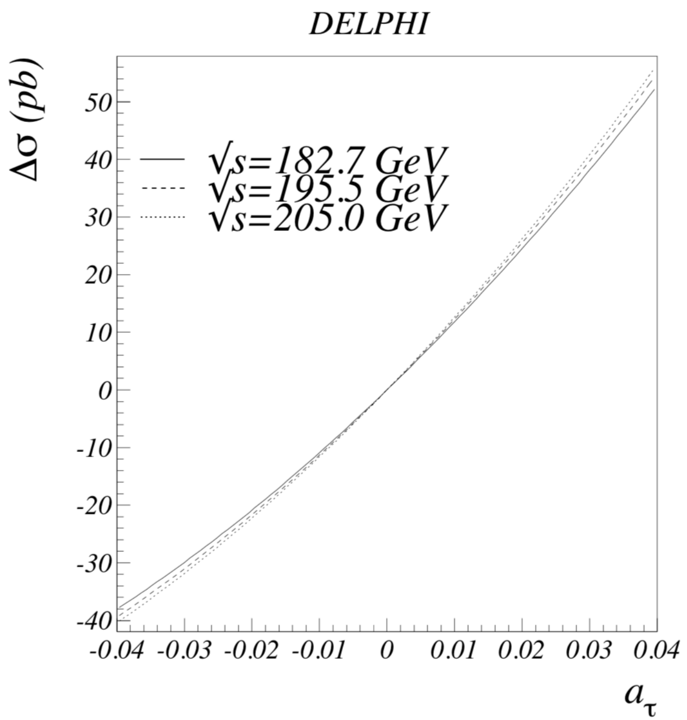
LEP (DELPHI) constraints on a_τ

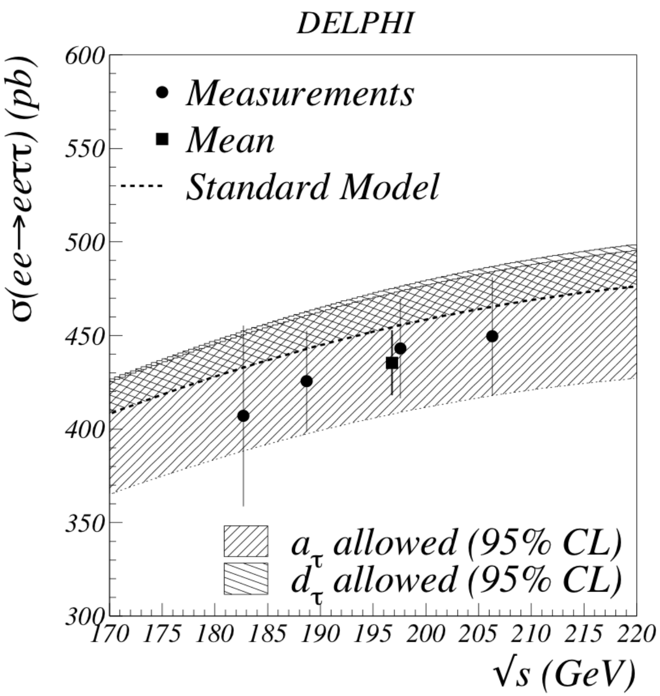
- Strongest experimental constraints on a_τ are set by DELPHI (LEP2)
  - Using ee → ee τ τ reaction
  - Measuring total cross section and check its dependence on a_τ



$-0.052 < a_\tau < 0.013$ (95% CL)

[arXiv:hep-ex/0406010]

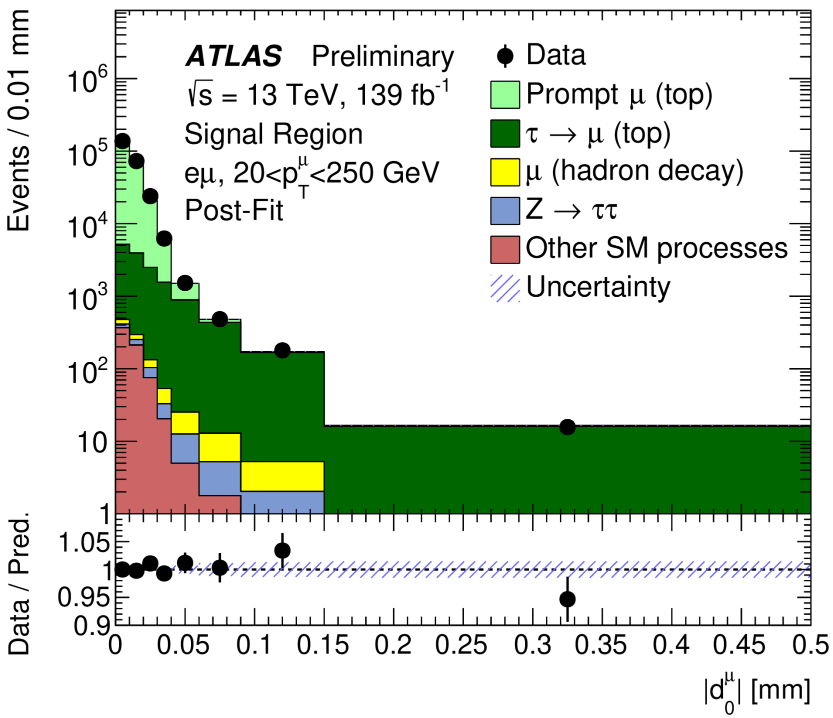


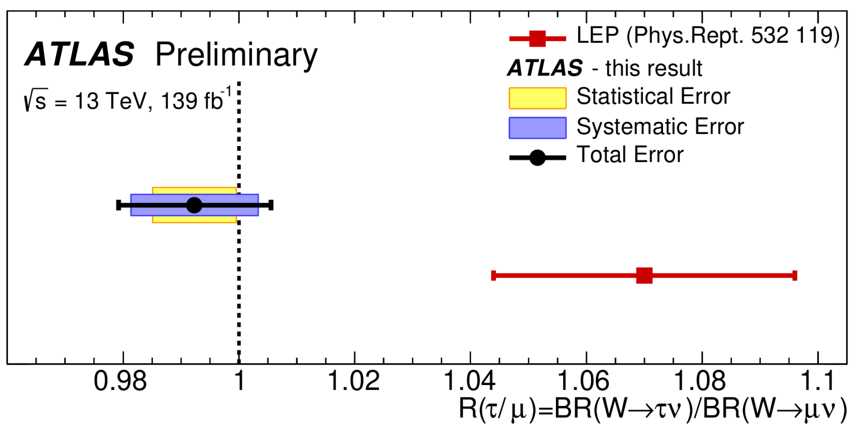


Precision tau physics at the LHC: example

- 2.7σ LEP puzzle of **R=B(W→τν)/B(W→μν)**=1.070±0.026

- Recent ATLAS studies: using top-pair events as clean probe for W's to measure the ratio of prompt to delayed muons from tau decays
  - Result **0.992 ± 0.013** is twice more precise than LEP and in agreement with lepton universality

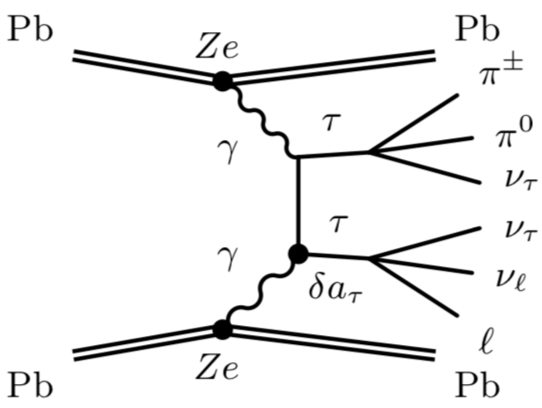




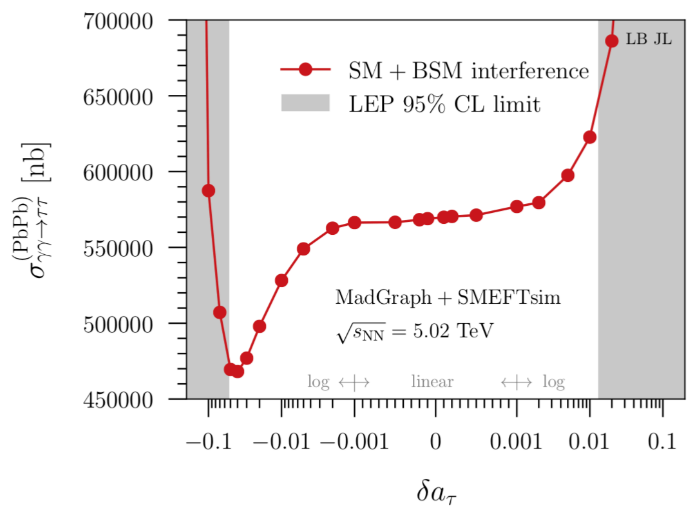
ATLAS-CONF-2020-014

Ideas behind this study

- Check the sensitivity of γγ→τ τ process in LHC Pb+Pb collisions on a_τ (and d_τ)



- Consider (semi-)leptonic ditau decays (for clean possible measurement)
- Explore differential distributions for better sensitivity
- Explore the ratio to γγ→ee (μμ) process for cancellation of uncertainties (both theoretical and experimental)
- Providing alternative study to recent work that uses Effective Field Theory [Beresford, Liu arXiv:1908.05180]→



Calculations

- We use standard approach to fold the elementary cross section with initial photon fluxes:

$$\sigma\left(AA \to AA\ell^+\ell^-;\sqrt{s_{AA}}\right) = \int \sigma\left(\gamma\gamma \to \ell^+\ell^-;W_{\gamma\gamma}\right) N(\omega_1,\boldsymbol{b_1})N(\omega_2,\boldsymbol{b_2})S^2_{abs}(\boldsymbol{b}) \times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{\ell\ell}\, d\bar{b}_x\, d\bar{b}_y\, d^2b\,. \quad (2.1)$$

- Elementary cross section has explicit dependence on photon-τ vertex function:

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

$=a_\tau\ (q^2=0)$ $\qquad$ $=d_\tau{*}2m_\tau/e\ (q^2=0)$

Elementary cross section

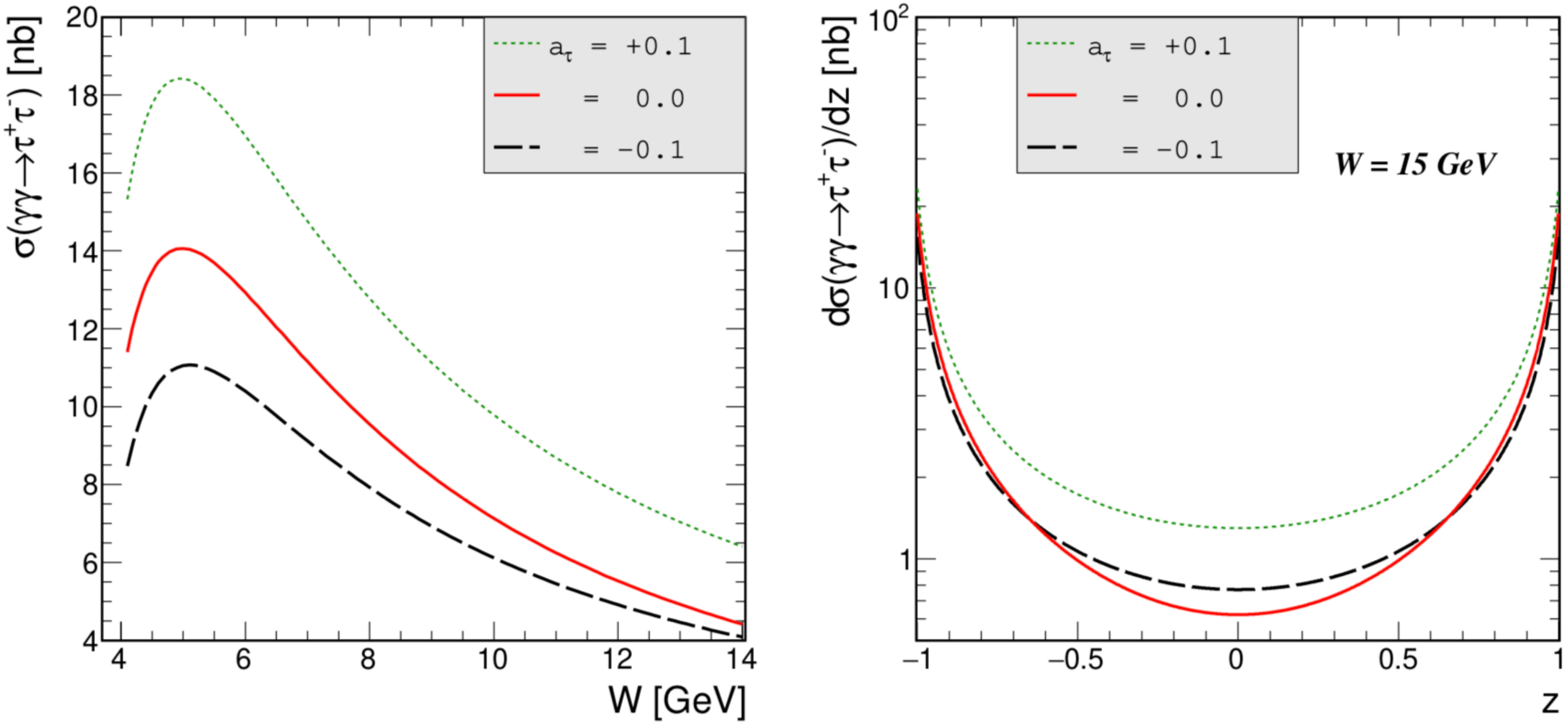
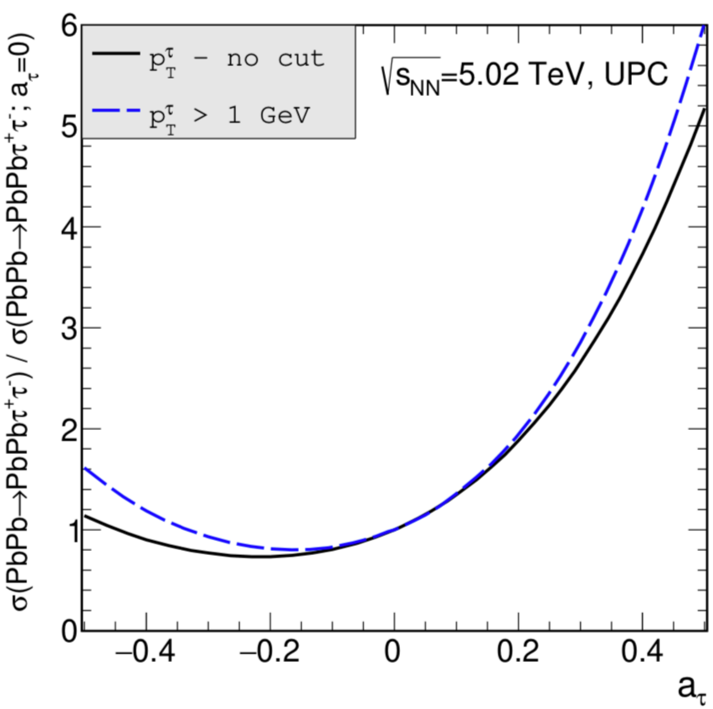


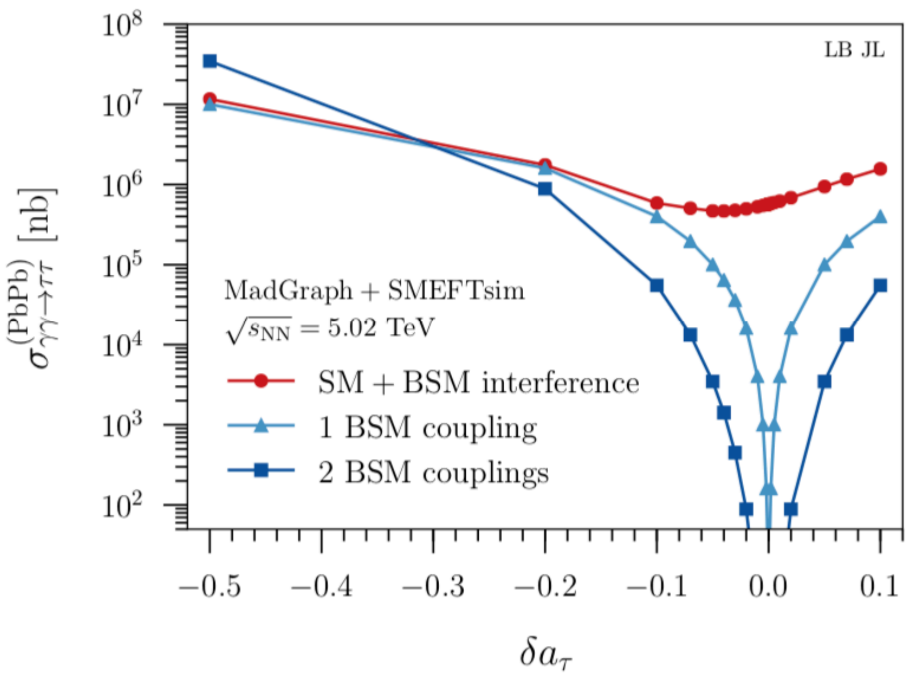
FIG. 1: Elementary cross section for $\gamma\gamma \to \tau^+\tau^-$ process as a function of $W_{\gamma\gamma} = m_{\tau\tau}$ (left) and as a function of $z = \cos\theta$ for $W_{\gamma\gamma} = 15$ GeV (right).

Nuclear cross sections

- Comparison of total nuclear cross section dependence on a_τ with Effective Field Theory (EFT) approach [arXiv:1908.05180]
  - Cross section minimum (at negative a_τ) happens at much higher values of a_τ in EFT
  - Significantly stronger cross section dependence on a_τ (at small a_τ values) is observed with EFT



arXiv:1908.05180

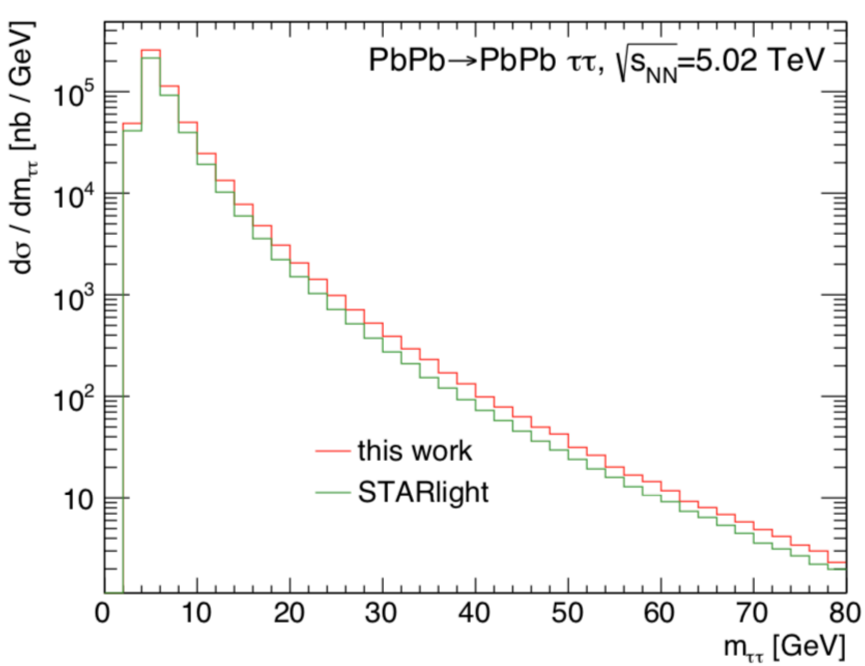


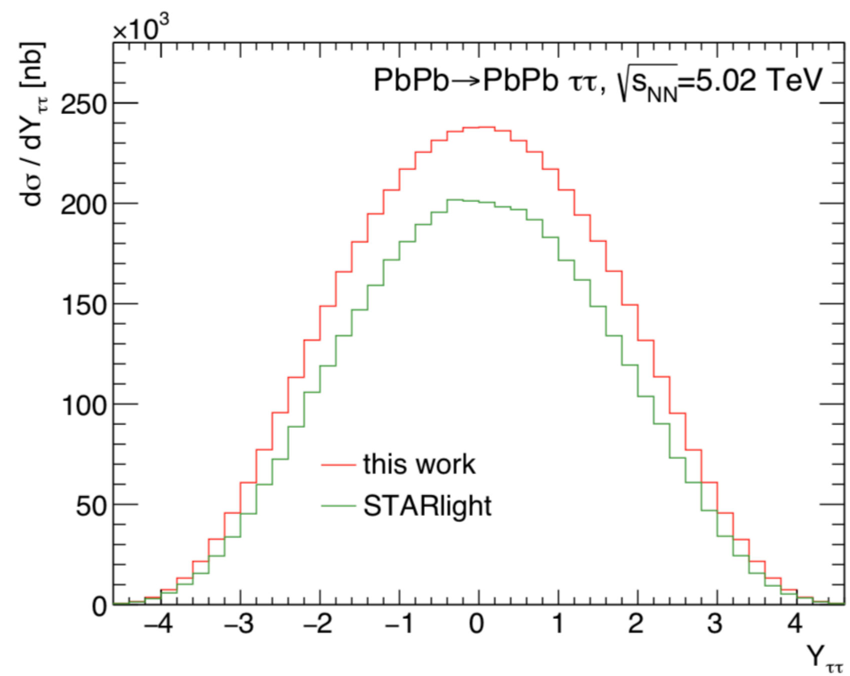
Nuclear cross sections

- We also compare SM results (a_τ=0) with STARlight
  - Got 20% higher xs than SL due to extra

    $$|\boldsymbol{b_1}| > R_{Pb} \text{ and } |\boldsymbol{b_2}| > R_{Pb}$$

    requirements applied in SL photon fluxes
  - Potentially large theory modeling uncertainties? → Build the ratios!

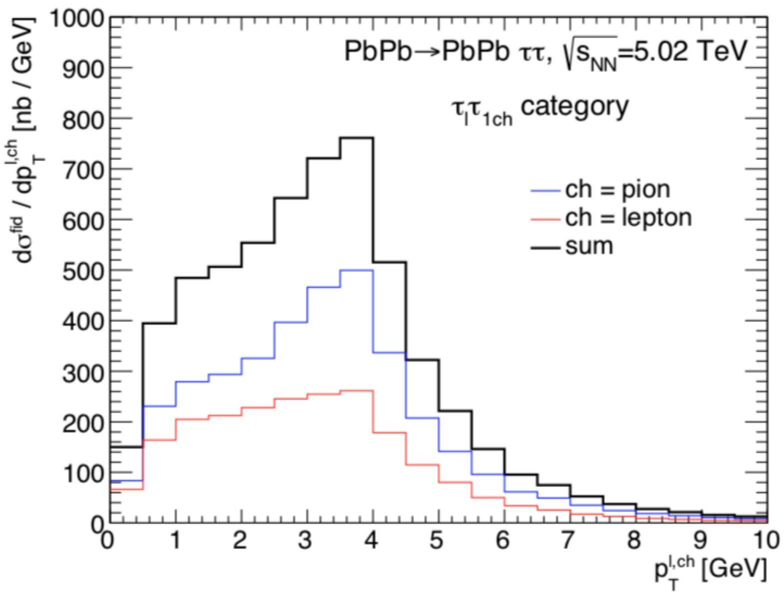


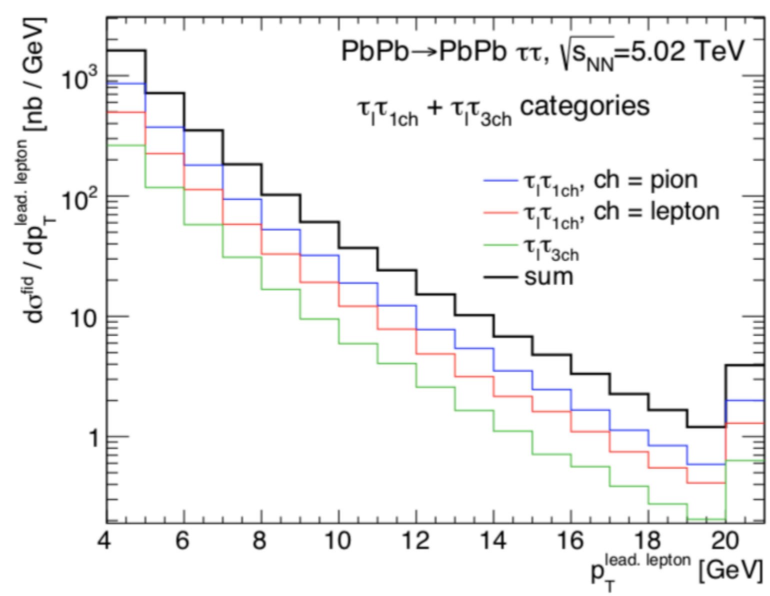


Tau decays

- Use Pythia8.243 for tau decays & FSR
  - No spin correlations since this feature is “buggy” in Pythia8 for $\gamma\gamma \to \tau\tau$ process
- Event selection:
  - Consider at least one leptonic tau decay ($p_T(l)>4$ GeV, $|\eta(l)|<2.5$)
  - No standard tau reconstruction algorithms are applicable at such low p_T -> categorize events wrt charged-particle multiplicity (p_T > 200 MeV and $|\eta|<2.5$) -> **lepton+1ch** or **lepton+3ch**
  - Apply extra cut pt(l,ch) > 1 GeV in lepton+1ch to suppress ee/μμ background

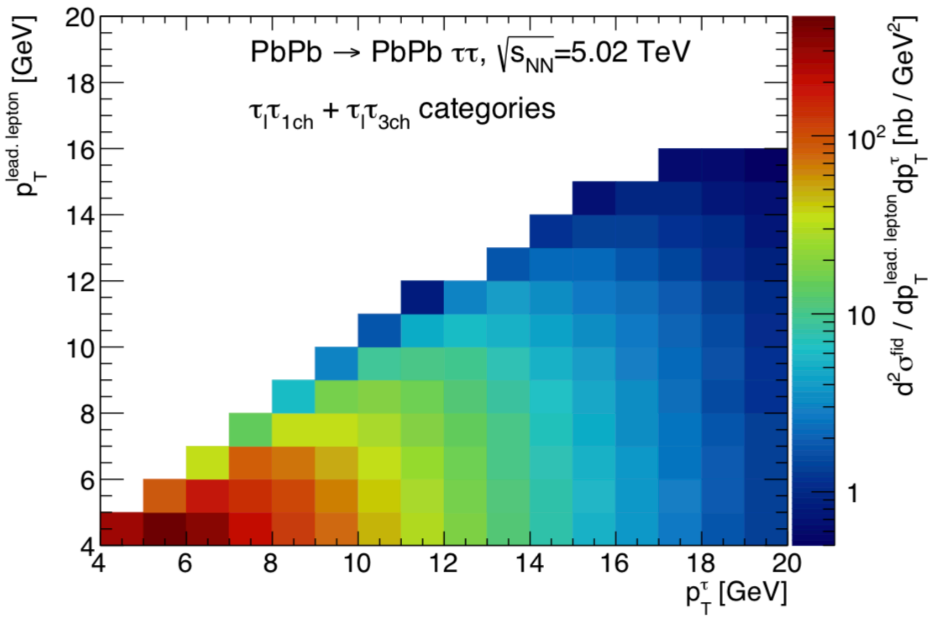
selection dedicated for ATLAS/CMS detectors

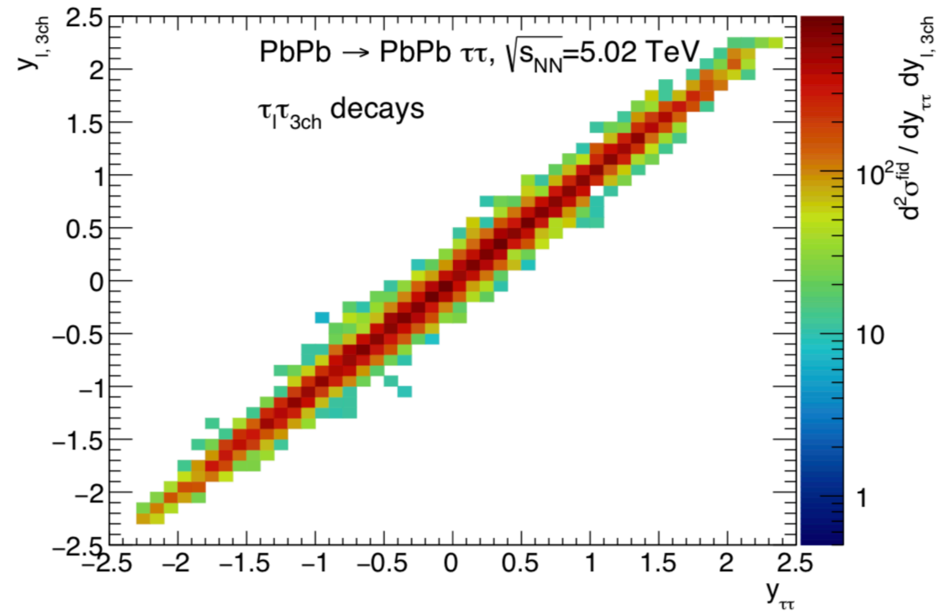




Tau decays

- Interesting correlations between tau kinematics and outgoing charged particle kinematics within the fiducial volume
  - p_T of the outgoing lepton is very smeared wrt initial tau p_T
  - Angular variables (eg system rapidity) in reasonable correlation with initial τ-τ kinematics





A note about possible background

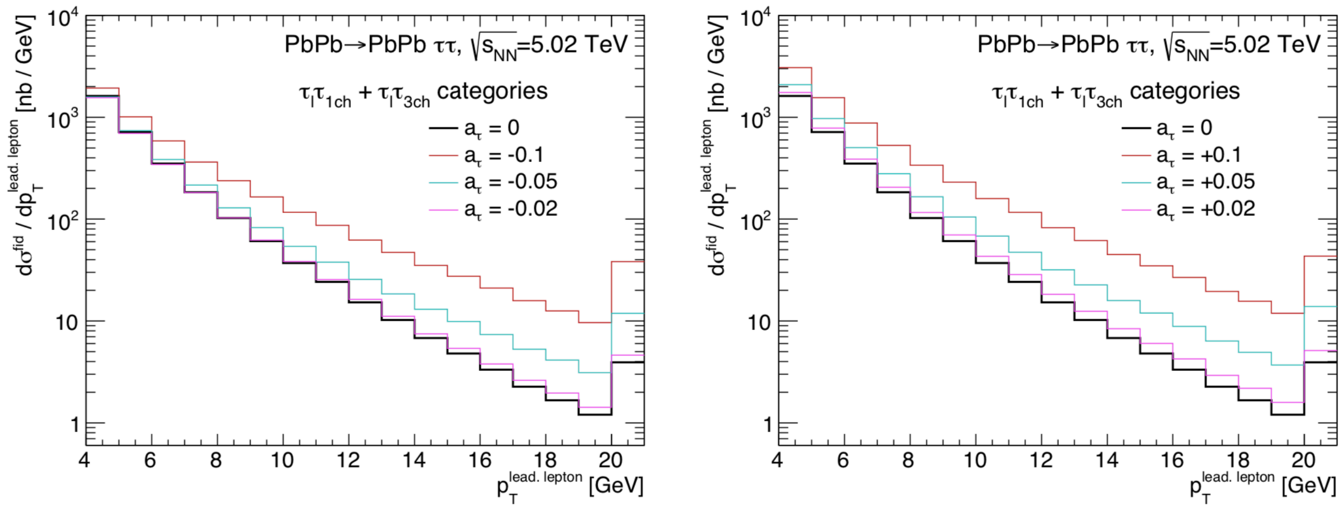
- yy → qq (esp. cc and bb)
  - Reducible with extra track veto, lepton isolation, ...)
- yy→ll+FSR
  - Can be fully suppressed with p_T(l,ch) > 1 GeV cut
- Photonuclear
  - Inclusive photonuclear: reducible with no neutron in Zero Degree Calorimeter cuts (not considered in this work)
  - Exclusive photonuclear, e.g. Upsilon → HF+X: should be reducible with lepton isolation
    + calorimeter cluster counting

a_τ dependence on fiducial cross section

- Provided for representative values of a_τ
  - 3D cross section weights [$m_{\tau\tau}$, $y_{\tau\tau}$, $\cos(\theta^*)$] are available

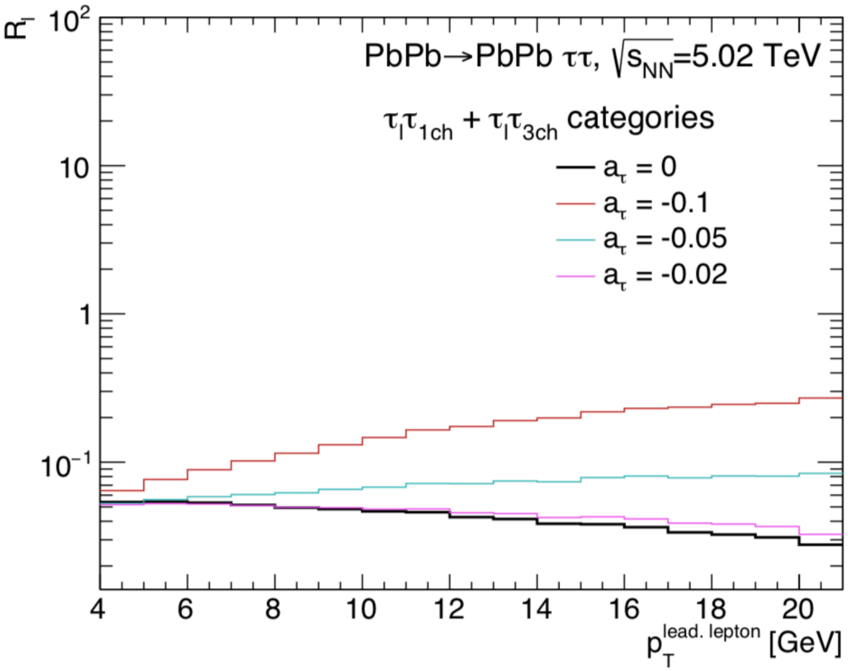
a_τ value	σ_{fid} [nb]	Expected events ($L_{int} = 2\ \text{nb}^{-1}$, $C = 0.8$)	Expected events ($L_{int} = 20\ \text{nb}^{-1}$, $C = 0.8$)
−0.1	4770	7650	76 500
−0.05	3330	5350	53 500
−0.02	3060	4900	49 000
0 (SM)	3145	5050	50 500
+0.02	3445	5500	55 000
+0.05	4350	6950	69 500
+0.1	7225	11550	115 500

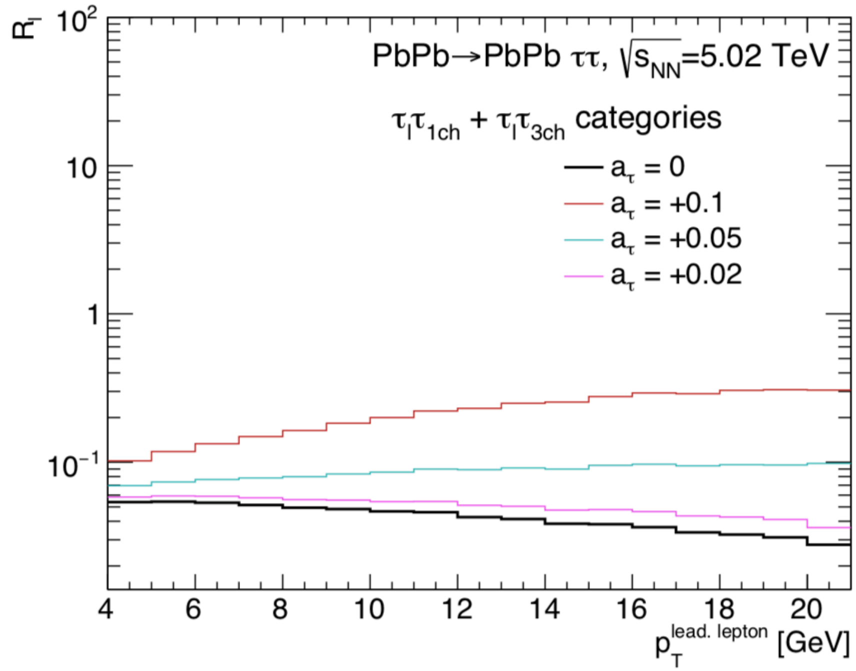
- Non-zero a_τ can also change **shape** of kinematic distributions
  - Checked many distributions, it seems pt(lead. lep) has the strongest dependence



Ratio to γγ→ee (γγ→μμ) process

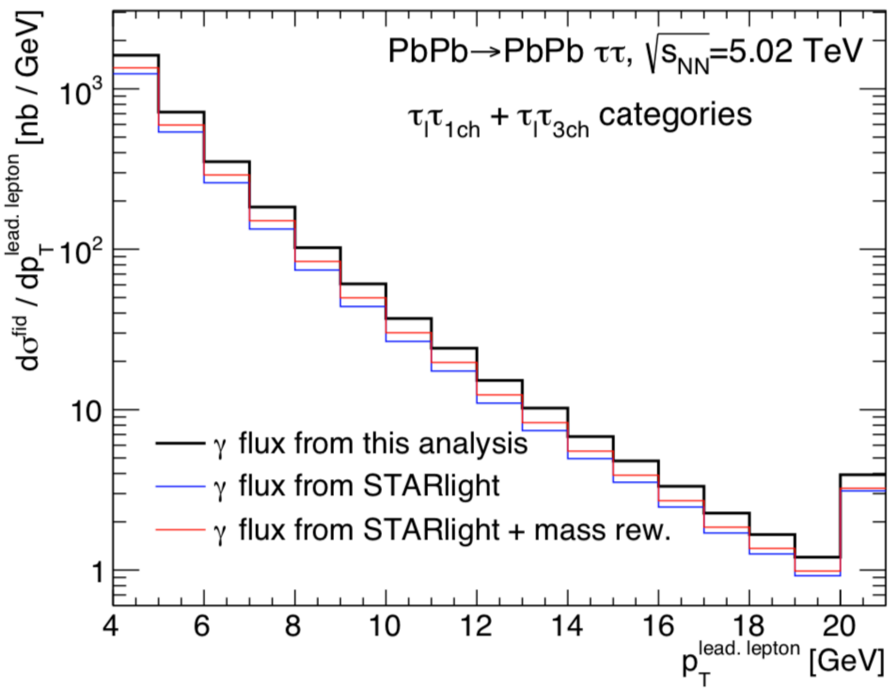
- γγ→ee/μμ events selected in similar fiducial region
  - $p_T(l) > 4$ GeV, $|\eta(l)| < 2.5$
- Ratio (SM) is below 5% and decreases with p_T(lead. lep)

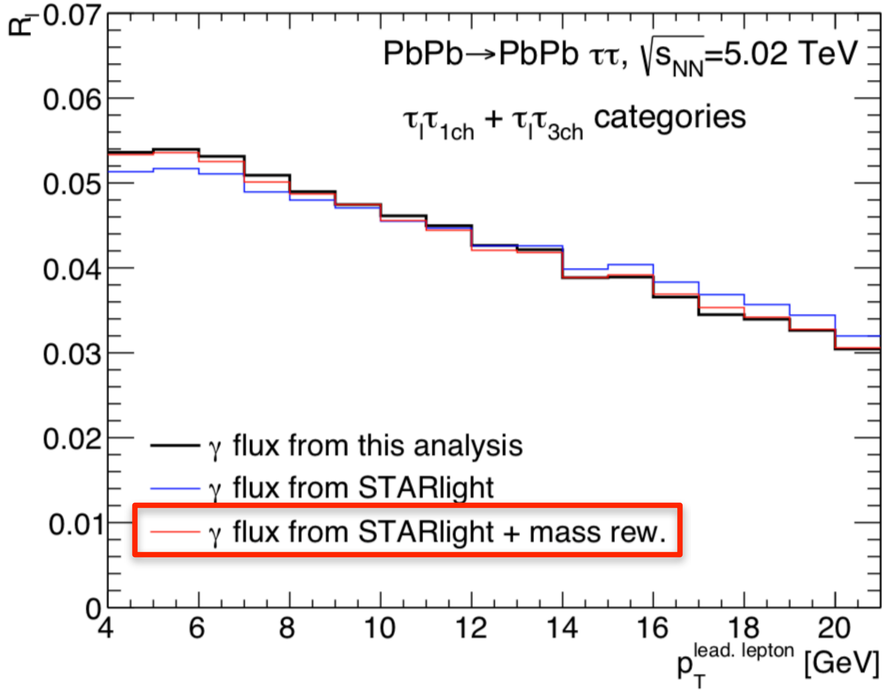




Ratio to γγ→ee (γγ→μμ) process

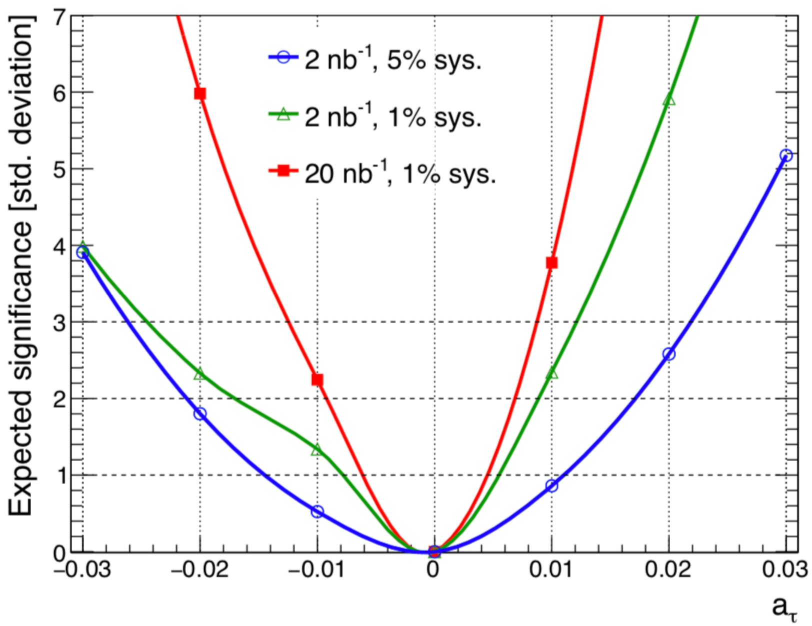
- 20% (STARlight vs this work) cross-section difference can be suppressed to ~5% when taking the ratio
- This can be further improved by reweighting m_{ll} shape in the fiducial region
  - Then the R_l values agree within 1%

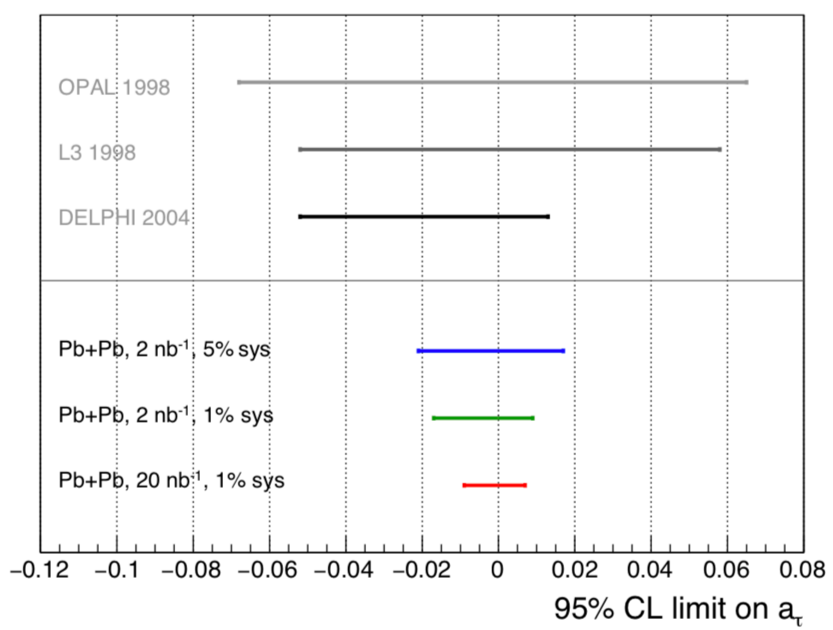




a_τ expected sensitivity @ LHC

- Using RooFit for statistical analysis
  - Assuming 80% reconstruction efficiency in the fiducial region
  - Assuming 5% or 1% systematic, and 2 nb^{-1} (current ATLAS/CMS dataset) or 20 nb^{-1} (dataset expected at High Luminosity LHC)
- Expected limits **~x2 better** than World's best results (with existing Run 2 data), **~x4 better** @HL-LHC
  - But: the limits are ~x2 worse than those from arXiv:1908.05180 (EFT approach)





Summary

- Calculations for Pb+Pb→Pb+Pb+τ τ cross section dependence on a_τ (and d_τ) at LHC energies are provided
- Exploration of the kinematic shape variations and the ratio to ee (μμ) process, as function of pt(lead. lep)
  - Allows to reach ultimate experimental precision (cancellation of uncertainties etc.)
- Expected limits on a_τ **~x2 better** with existing Run 2 ATLAS/CMS data (wrt current best experimental limits), **~x4 better** @HL-LHC
  - Expected limits on d_τ competitive with current best experimental limits → should be improved at Belle-II
- Significant difference observed wrt Effective Field Theory (EFT) calculations
  - Much stronger cross section dependence on a_τ is observed with EFT
  - This can point to **some issue with EFT approach** and clearly **needs further study by EFT experts**

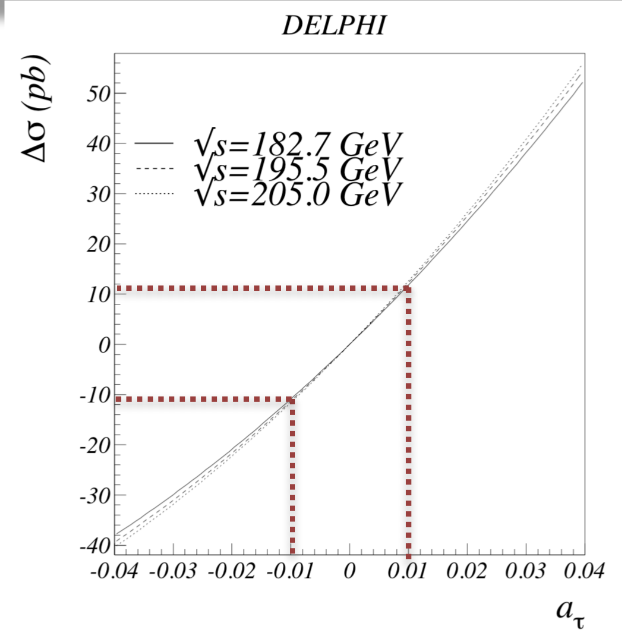
Backup

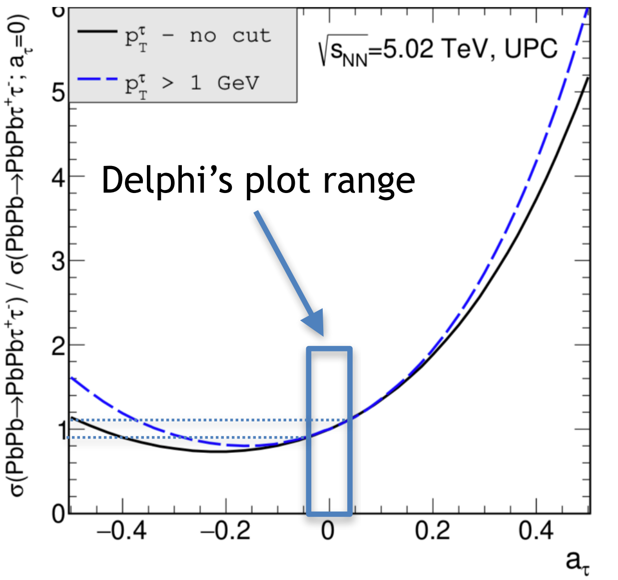
Compatibility with a_τ dependence used by DELPHI

- Relative total cross section variations (ee) from DELPHI (examples):
  - $d\sigma/\sigma = \pm 10\text{-}12\%$ for $a_\tau = \pm 0.04$
  - $d\sigma/\sigma = \pm 3\%$ for $a_\tau = \pm 0.01$

- Relative total cross section variations (Pb+Pb) from this study:
  - $d\sigma/\sigma = \pm 10\%$ for $a_\tau = \pm 0.04$
  - $d\sigma/\sigma = \pm 3\%$ for $a_\tau = \pm 0.01$

- Good agreement with DELPHI's calculations!





EFT approach

$$\tilde{a}_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\,\mathrm{Re}\left[\cos\theta_\mathrm{W} C_{lB}^{33} - \sin\theta_\mathrm{W} C_{lW}^{33}\right],$$

$$\tilde{d}_\tau = \frac{\sqrt{2}v}{\Lambda^2}\,\mathrm{Im}\left[\cos\theta_\mathrm{W} C_{lB}^{33} - \sin\theta_\mathrm{W} C_{lW}^{33}\right],$$

$v = 246$ GeV

$\sin\theta_\mathrm{W}$ is the weak mixing angle.