Feasibility studies of tau-lepton anomalous magnetic moment measurements with ultra-peripheral collisions at the LHC

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Anomalous magnetic moments

- Relation between magnetic moment and spin vectors:

$$\vec{\mu}_S = g \frac{q}{2m} \vec{S}$$

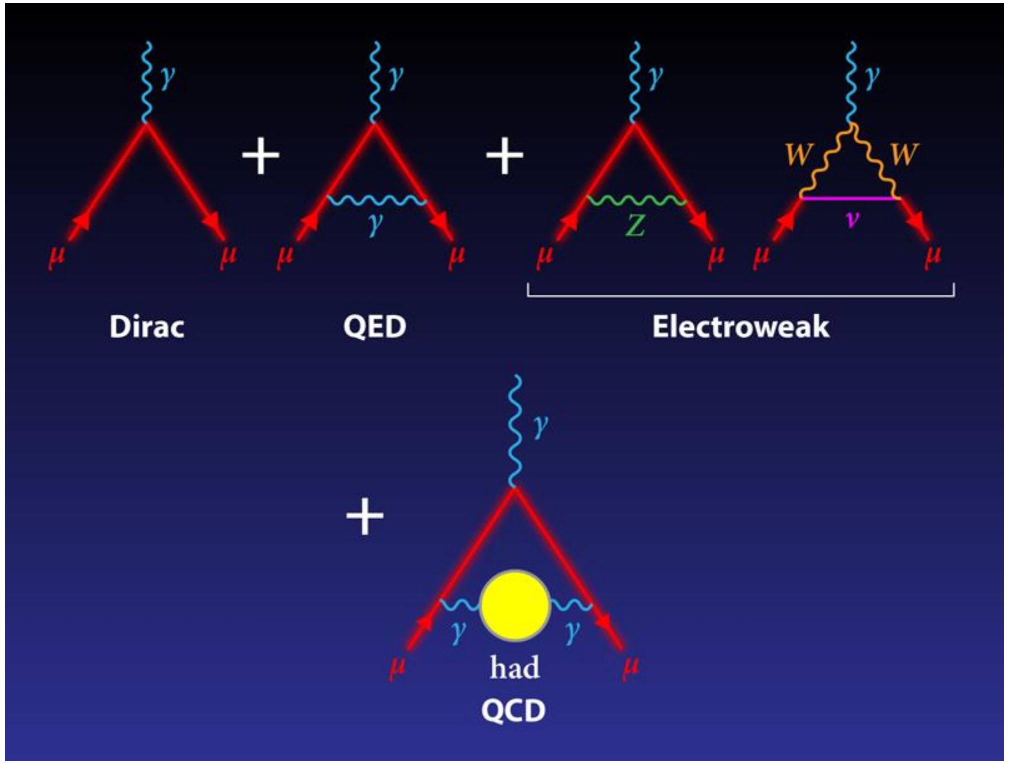
- Dirac magnetic moment corresponds to tree level:

$$g = 2$$

- Anomalous magnetic moments a_l appear due to loop corrections

$$a = \frac{g-2}{2}$$

- Electron anomalous magnetic moment is the most accurate verified QED prediction: 10^{-9} precision
- Muon anomalous magnetic moment represents one of the long-standing discrepancies in SM: 4.2σ tension
- Anomalous magnetic moments of leptons are sensitive to BSM physics, e.g. composite structure of leptons or SUSY particles



Theory: $a_e = 0.001\ 159\ 652\ 181\ 643(764)$

Experiment: $a_e = 0.001\ 159\ 652\ 180\ 73(28)$

Theory: $a_\mu^{\mathrm{SM}} = 0.001\ 165\ 918\ 04(51)$

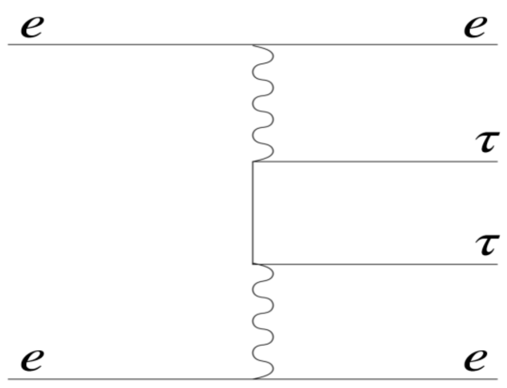
Experiment: $a_\mu = 0.001\ 165\ 920\ 61(41)$

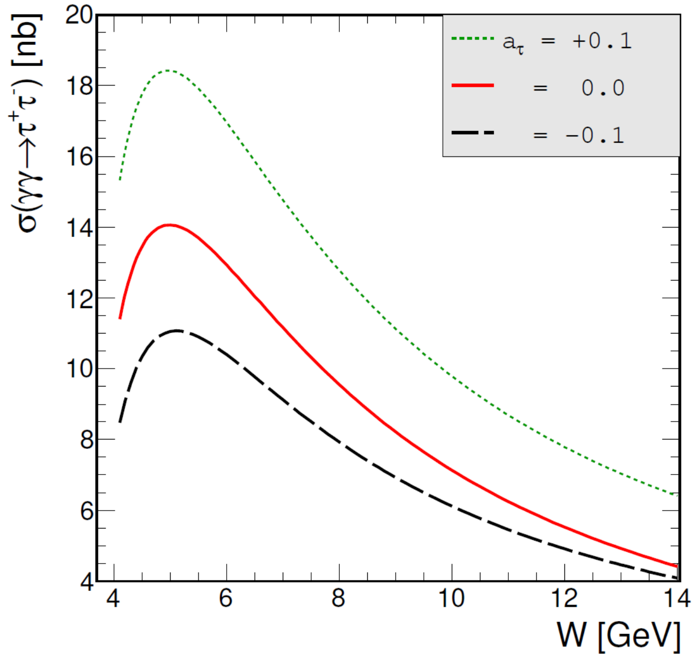
Tau anomalous magnetic moment

- Supersymmetry at a scale M_S leads to $\delta a_\ell \sim m_\ell^2/M_S^2$
  - τ is ~280 times more sensitive to BSM than μ
- Very short tau lifetime (10^{-13} s) → standard spin precession methods used in muon g-2 experiments are not applicable
- Workaround: τ production cross sections are sensitive to a_τ
  - Strongest constraints by DELPHI were set with $e^+e^- \to e^+e^-\tau\tau$

Theory: $a_\tau^{\mathrm{SM}} = 0.00117721(5)$

Experiment: **$-0.052 < a_\tau < 0.013$ (95% CL)** EPJC 35 (2004) 159





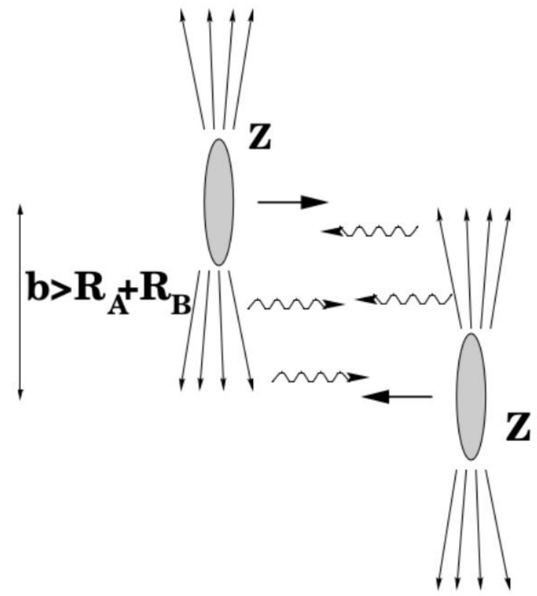
Dyndal et al., PLB 809 (2020) 135682

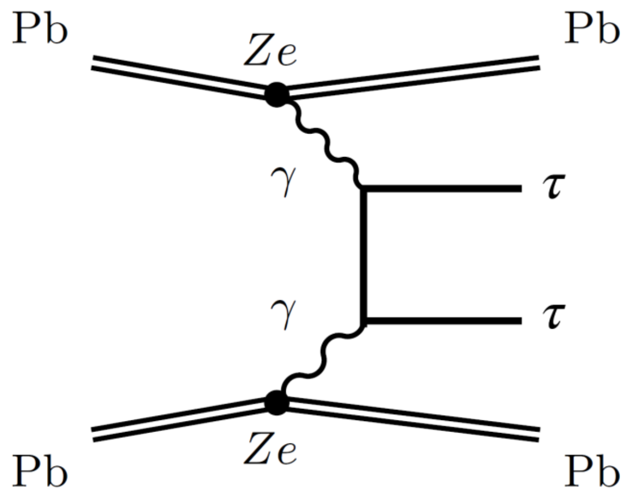
Ultra-peripheral collissions

- **b > R_a + R_b** :

  Hadronic interactions are strongly suppressed

- Heavy ions produce strong electromagnetic field
- Treated as a strong photon flux
  - Described in terms of Weizsäcker-Williams formalism
  - Proportional to Z^2
  - High cross section in γ-induced interactions

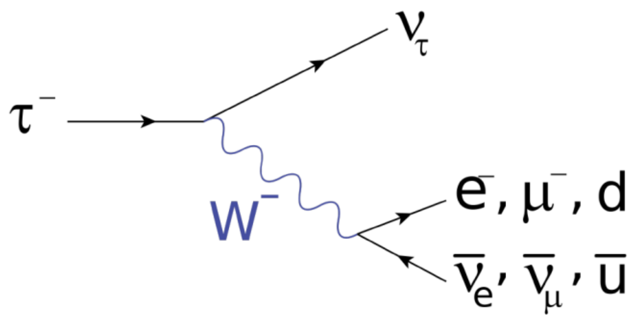




Tau decays

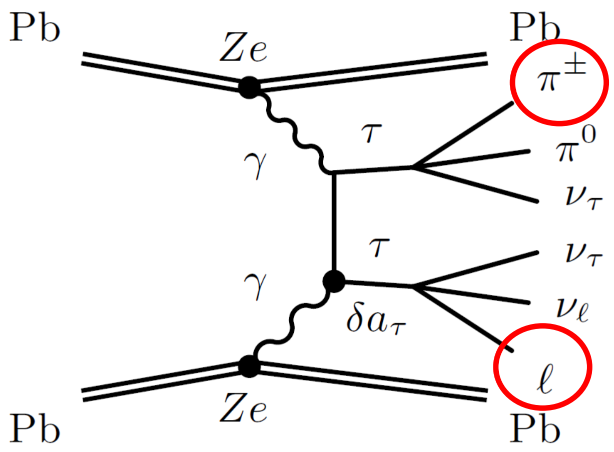
- 1-prong: tau decays into 1 charged particle with BR ~ 80%:

$$\mathrm{BR}(\tau^{\pm} \to \mathrm{e}^{\pm} + \nu_{\mathrm{e}} + \nu_{\tau}) = 17.8\%$$
$$\mathrm{BR}(\tau^{\pm} \to \mu^{\pm} + \nu_{\mu} + \nu_{\tau}) = 17.4\%$$
$$\mathrm{BR}(\tau^{\pm} \to \pi^{\pm} + \mathrm{n}\pi^{0} + \nu_{\tau}) = 45.6\%$$



- 3-prong: $\mathcal{B}(\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau} + \text{neutral pions}) = 19.4\%.$

- Selection in UPCs:
  - $\tau\tau \to$ 1 lepton + 1 charged particle
  - $\tau\tau \to$ 1 lepton + 3 charged particles



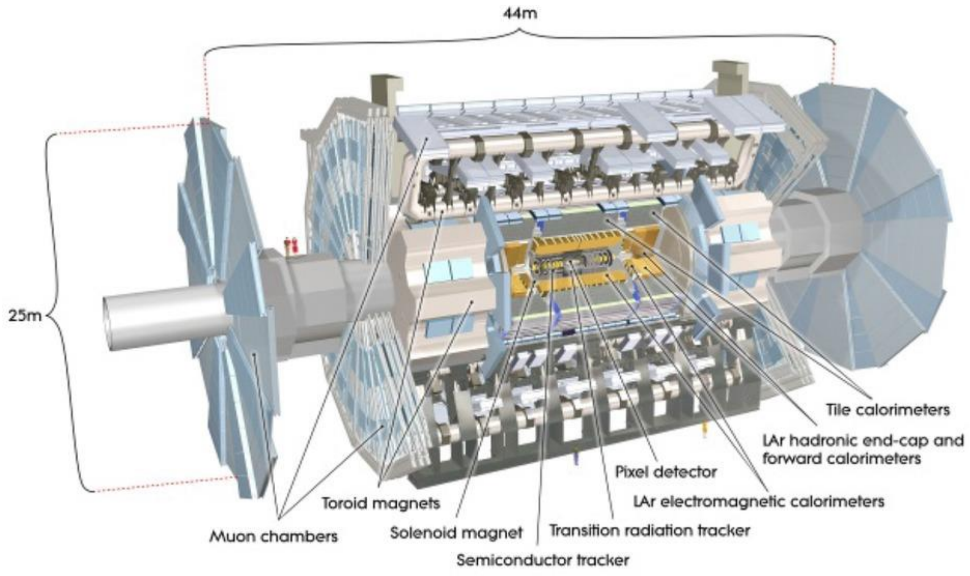
Tau decays in ATLAS/CMS

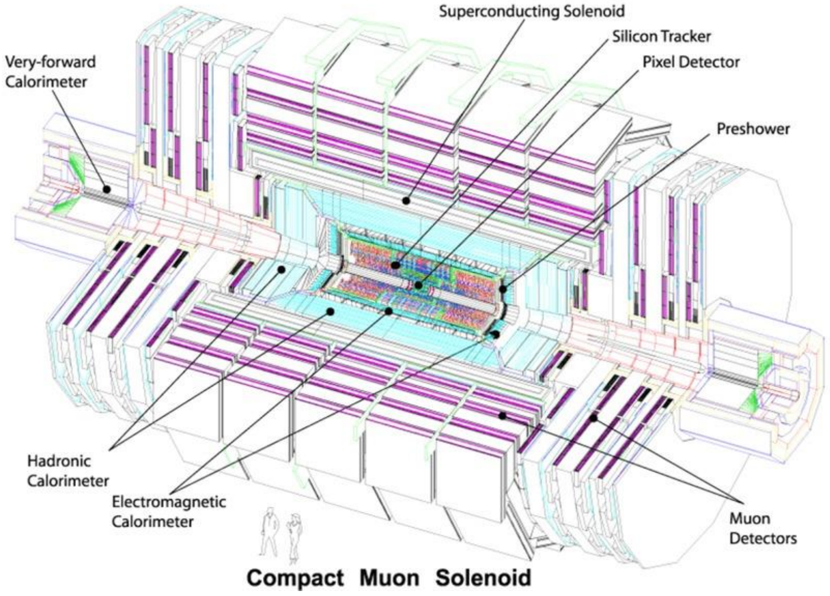
Studied by two groups:
- Beresford et al., PRD 102 (2020) 113008
- Dyndal et al., PLB 809 (2020) 135682

Trigger and reconstruction thresholds
- ATLAS:
  - Well-suited for electron+track channel
  - $|\eta| < 2.5$
  - $p_T > 4.5$ GeV

- CMS
  - Better for muon+track channel
  - $|\eta| < 2.4$
  - $p_T > 3$ GeV

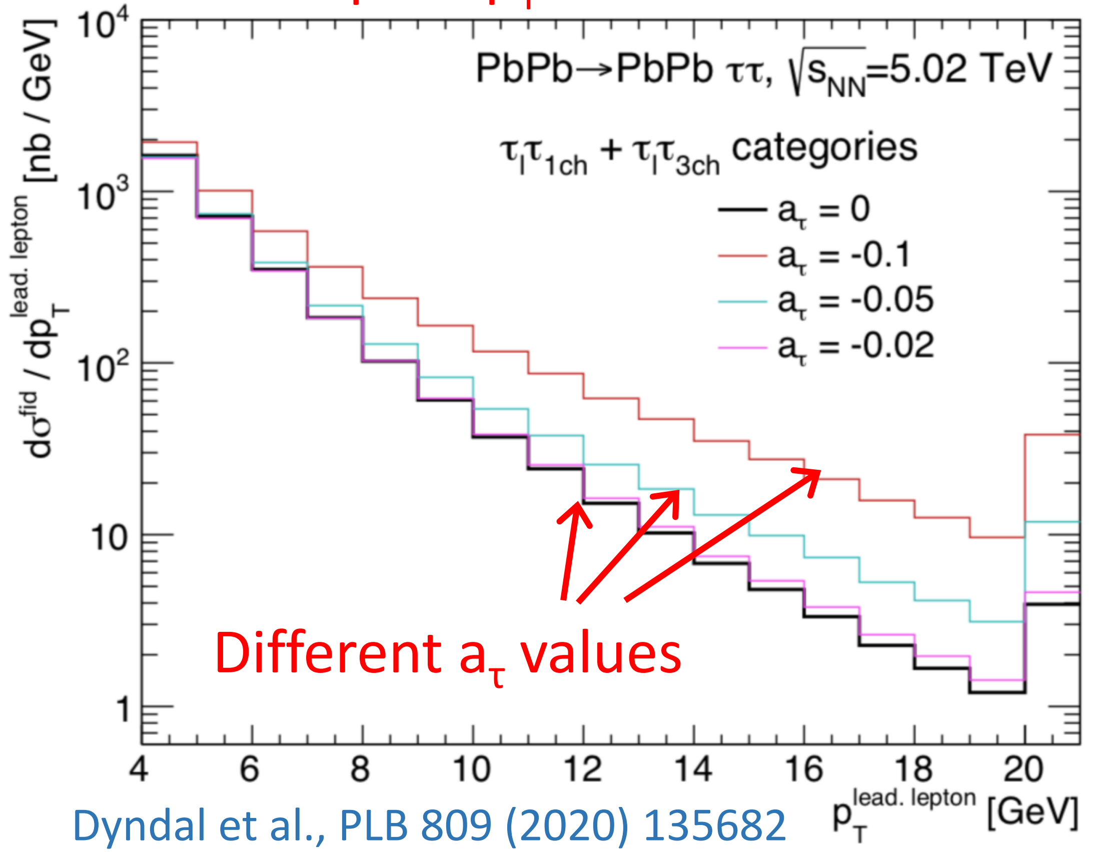
- All charged-particle tracks: $p_T > 0.5$ GeV





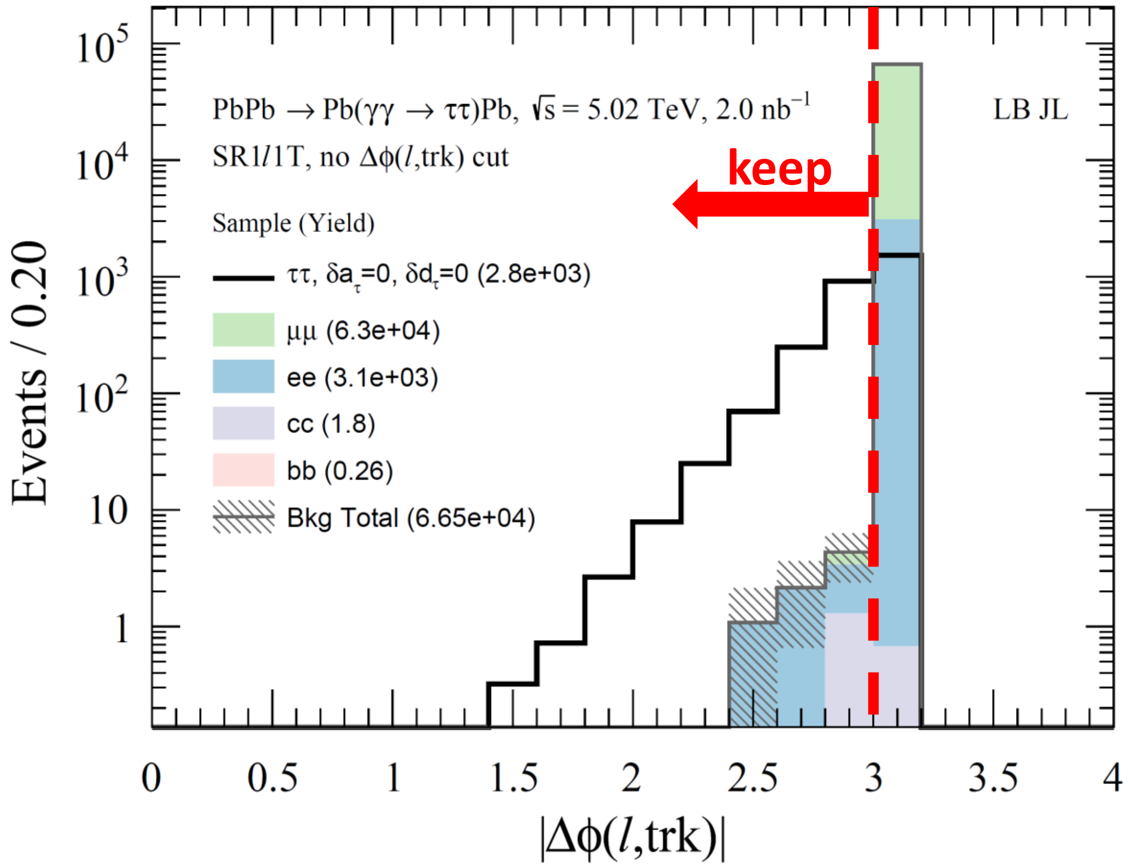
Lepton p_T spectra and background mitigation

lepton p_T distributions



Dyndal et al., PLB 809 (2020) 135682

Beresford et al., PRD 102 (2020) 113008

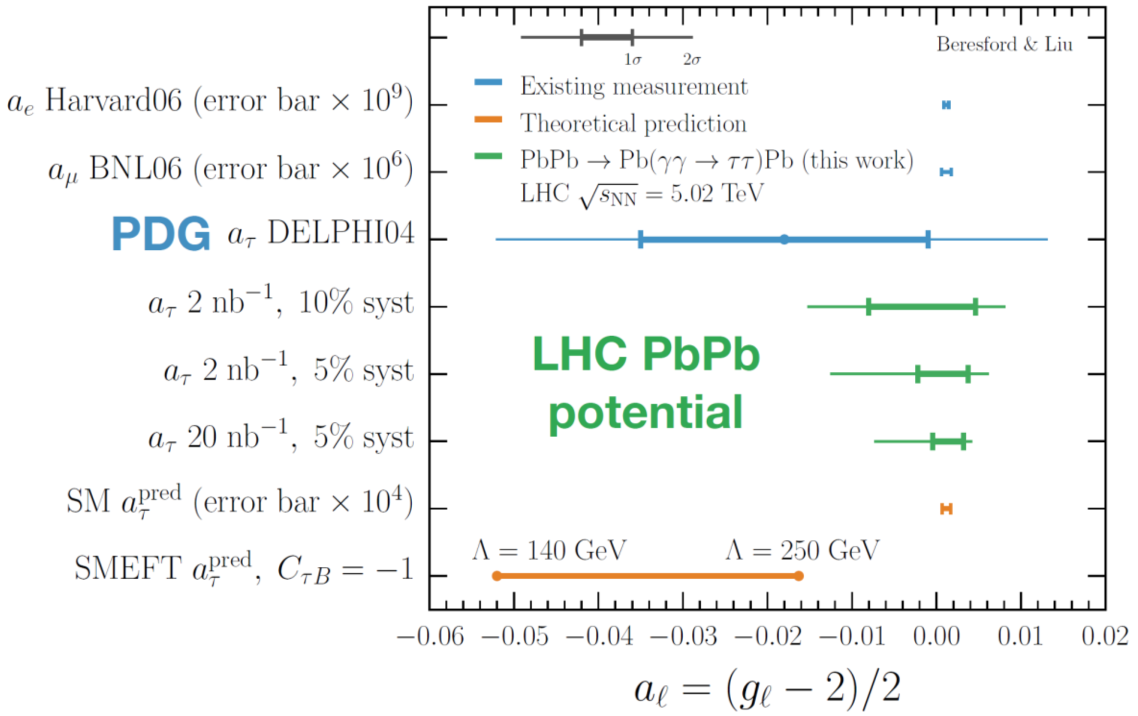


p_T differential measurements provide better sensitivity

Acoplanarity cuts can be used to suppress continuum dilepton background

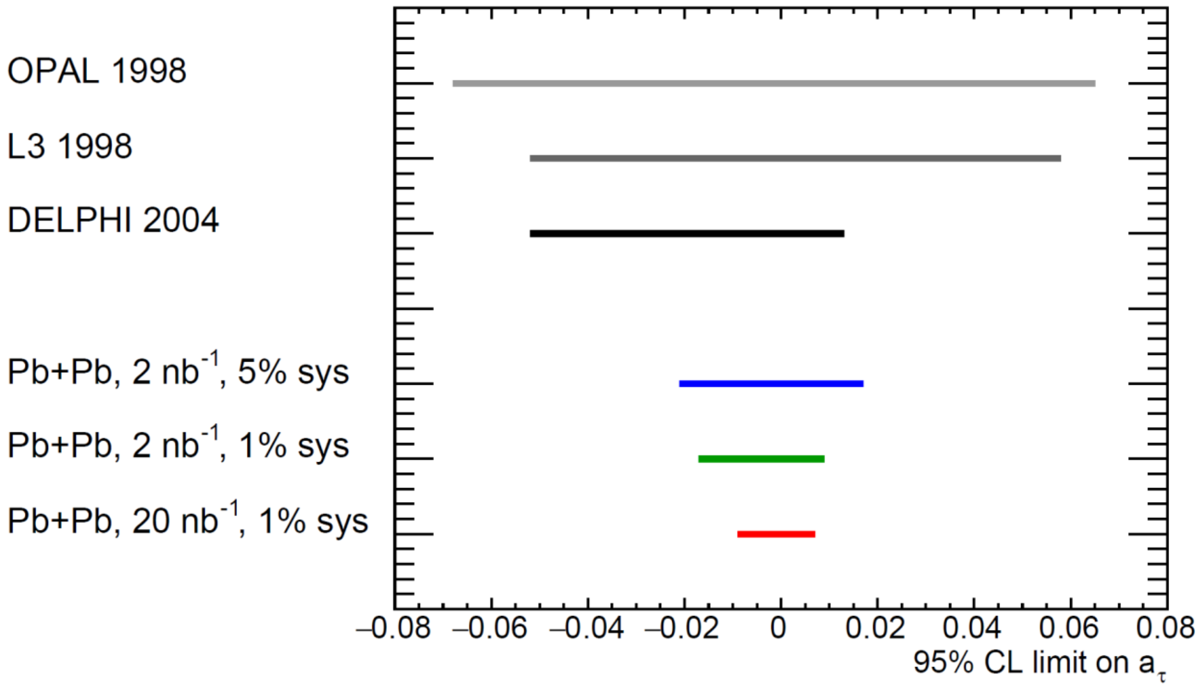
Possible constraints on a_τ with ATLAS/CMS

Beresford et al., PRD 102 (2020) 113008



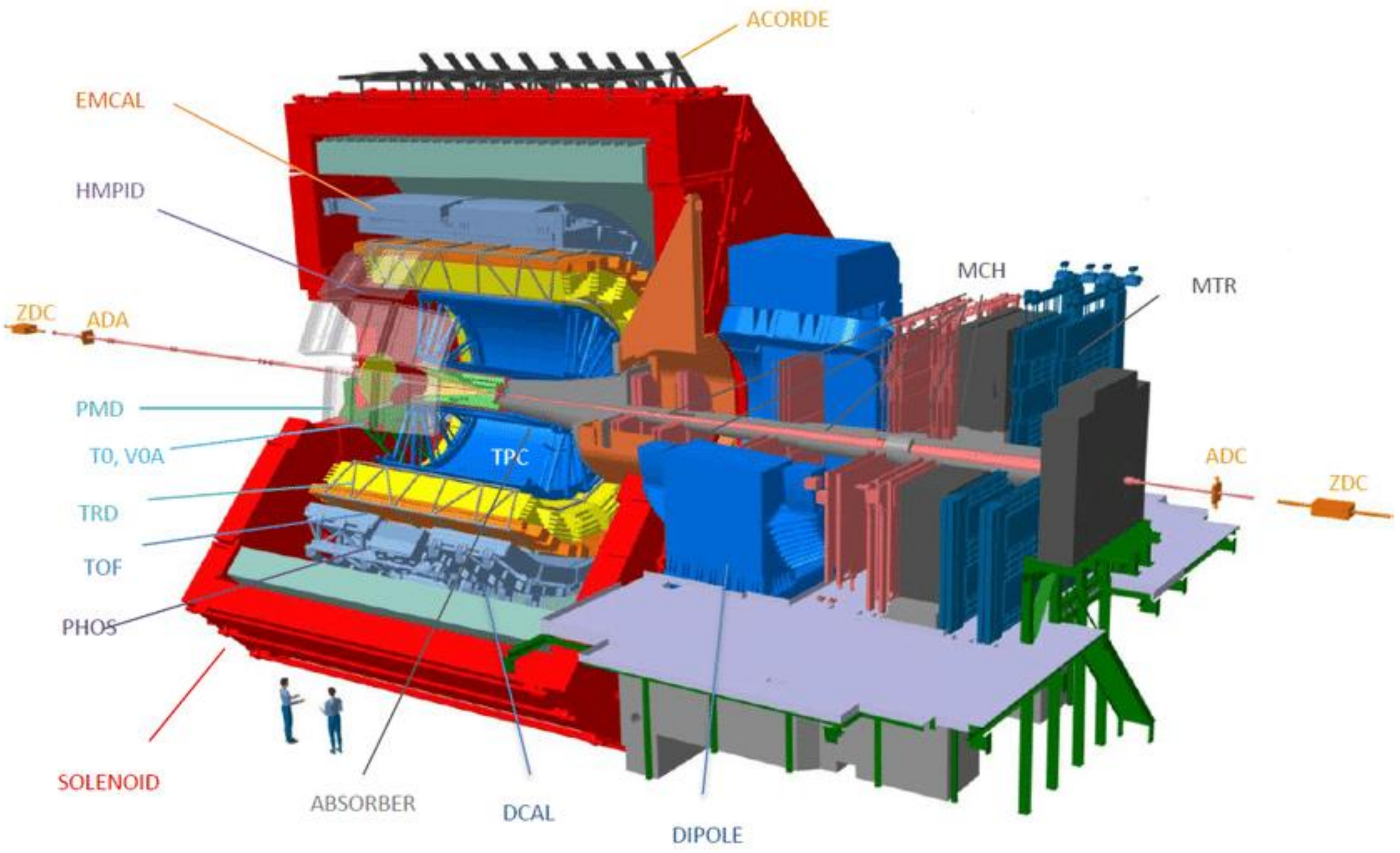
$$\chi^2 = \frac{(S_{\mathrm{SM+BSM}} - S_{\mathrm{SM}})^2}{B + S_{\mathrm{SM+BSM}} + (\zeta_s S_{\mathrm{SM+BSM}})^2 + (\zeta_b B)^2}$$

Dyndal et al., PLB 809 (2020) 135682



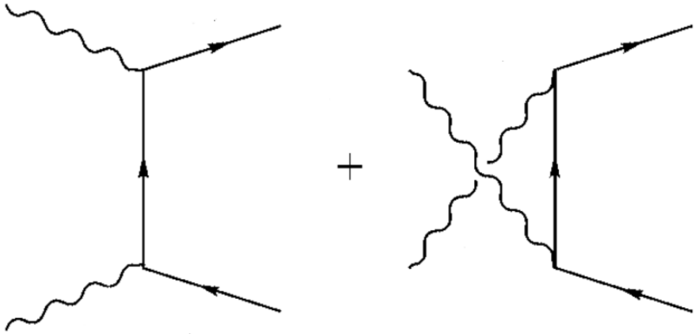
- Run 2 (2/nb) statistics estimates for ATLAS/CMS: 1280 events with 1-prong selection
- Looser limits predicted by Dyndal et al.
- Measurements may be limited by systematics

Possibilities with ALICE



- Relatively weak 0.5 T solenoid magnetic field → charged particles can be measured down to p_T ~ 0.15 GeV
- Charged-particle tracking within $|\eta| < 1$
- Event sample is dominated by low-p_T → leptons need to conduct a dedicated calculation to study sensitivity to a_τ at low transverse momenta

p_T-differential electron yields for arbitrary a_τ



- Following Dyndal et al., developed a dedicated UPC generator of tau pairs with arbitrary a_τ using generalized vertex:

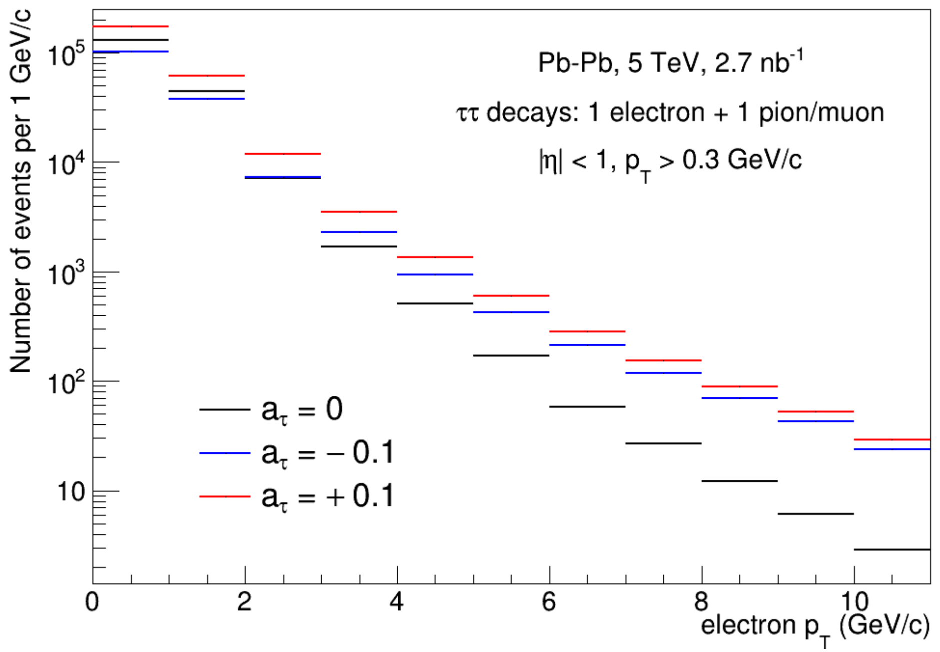
$$i\Gamma^\mu(q) = -ie\left(\gamma^\mu F_1(q^2) + \frac{i}{2m}\sigma_{\mu\nu}q^\nu F_2(q^2)\right) \rightarrow -ie\left(\gamma^\mu + \frac{i}{2m}\sigma_{\mu\nu}q^\nu a_\tau\right)$$

- UPC cross section:

$$\frac{\mathrm{d}\sigma(\mathrm{PbPb} \rightarrow \mathrm{PbPb} + \tau\tau)}{\mathrm{d}Y\mathrm{d}M} = \frac{\mathrm{d}N_{\gamma\gamma}}{\mathrm{d}Y\mathrm{d}M}\sigma\left(\gamma\gamma \rightarrow \tau\tau, \omega_{1,2} = \frac{M}{2}e^{\pm Y}\right)$$

$\frac{\mathrm{d}N_{\gamma\gamma}}{\mathrm{d}Y\mathrm{d}M}$ - two-photon luminosity in UPC

- Using Pythia8 for tau decays
- Looking into 1 electron + 1 pion/muon events
- Fiducial cuts:
  - $|\eta| < 1$
  - $p_T > 0.3$ GeV/c



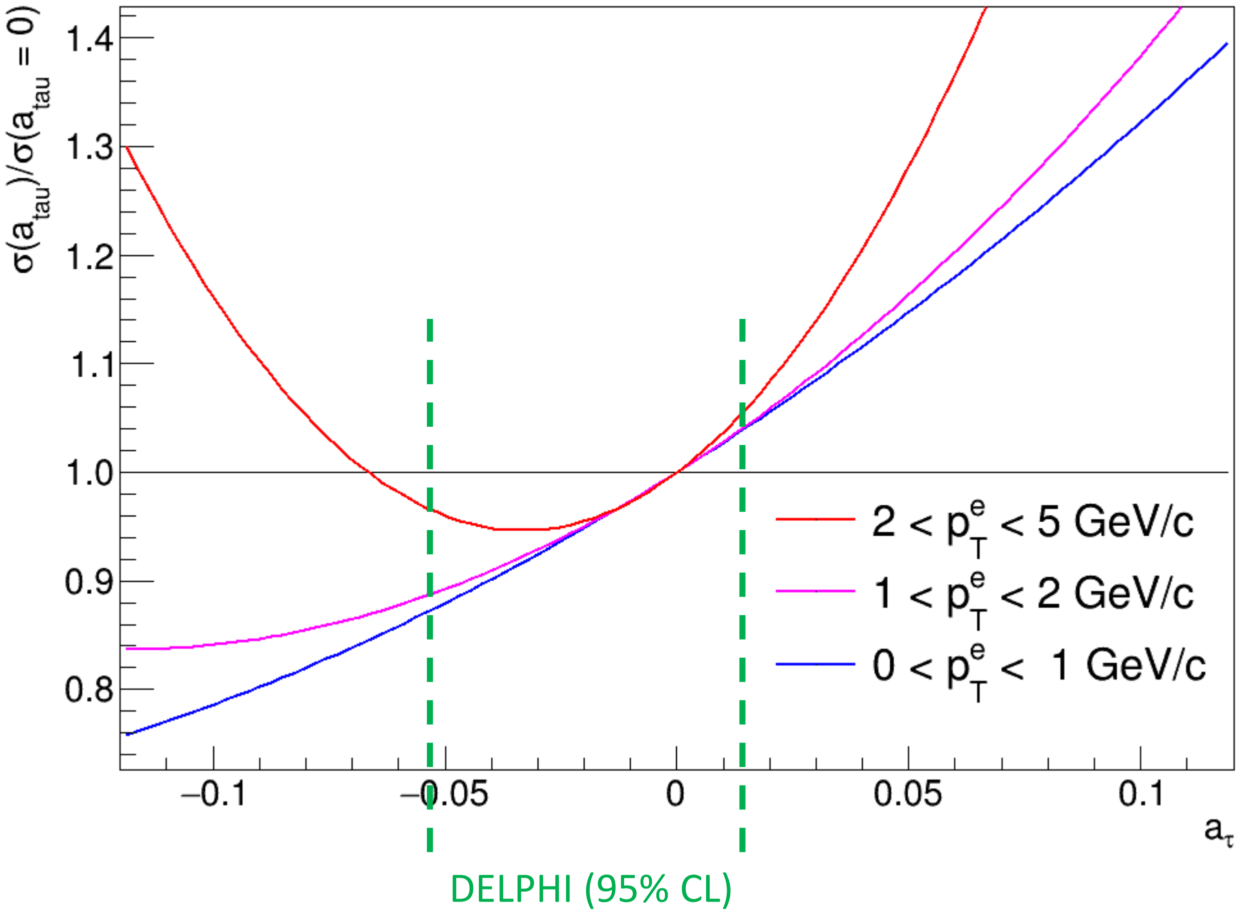
- Nontrivial dependence on a_τ:

  low p_T^e: yields for a_τ = -0.1 are below SM yields

  high p_T^e > 3 GeV: yields for a_τ = +0.1 are above SM yields

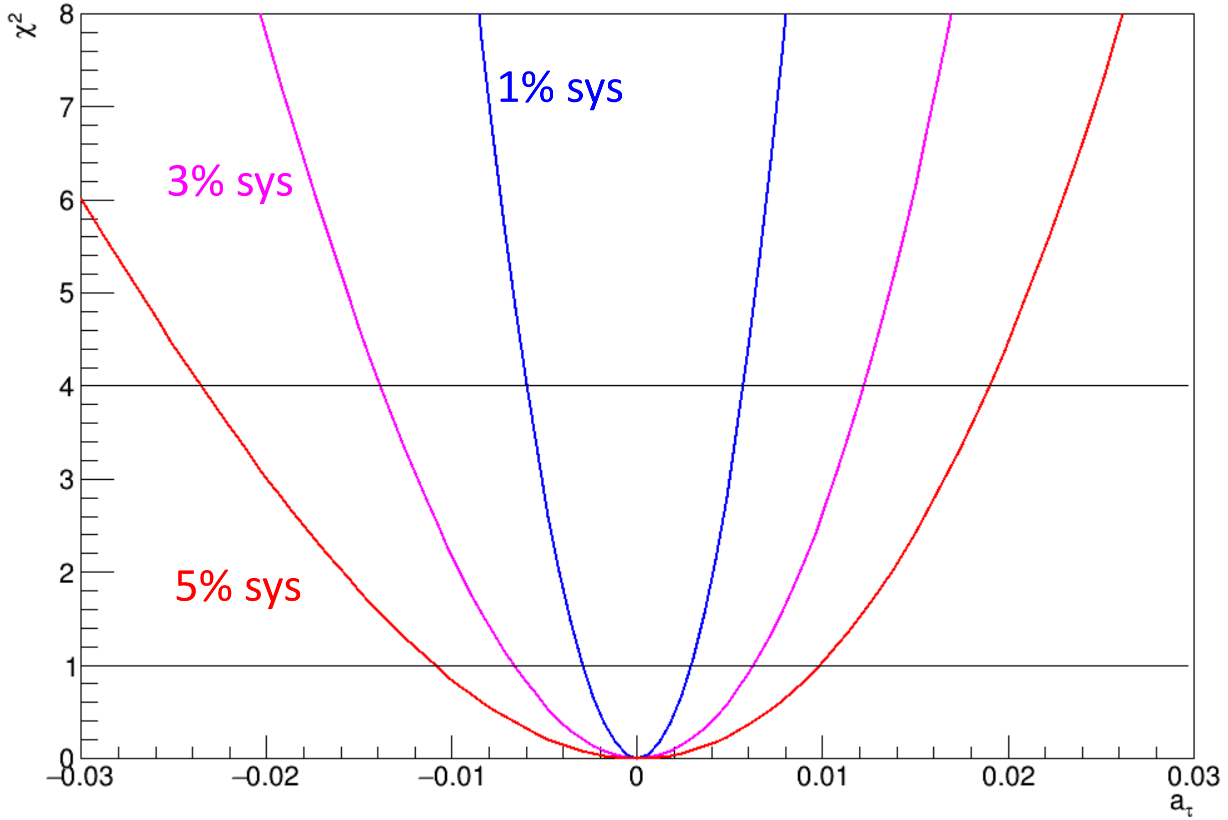
- p_T differential measurements provide better sensitivity

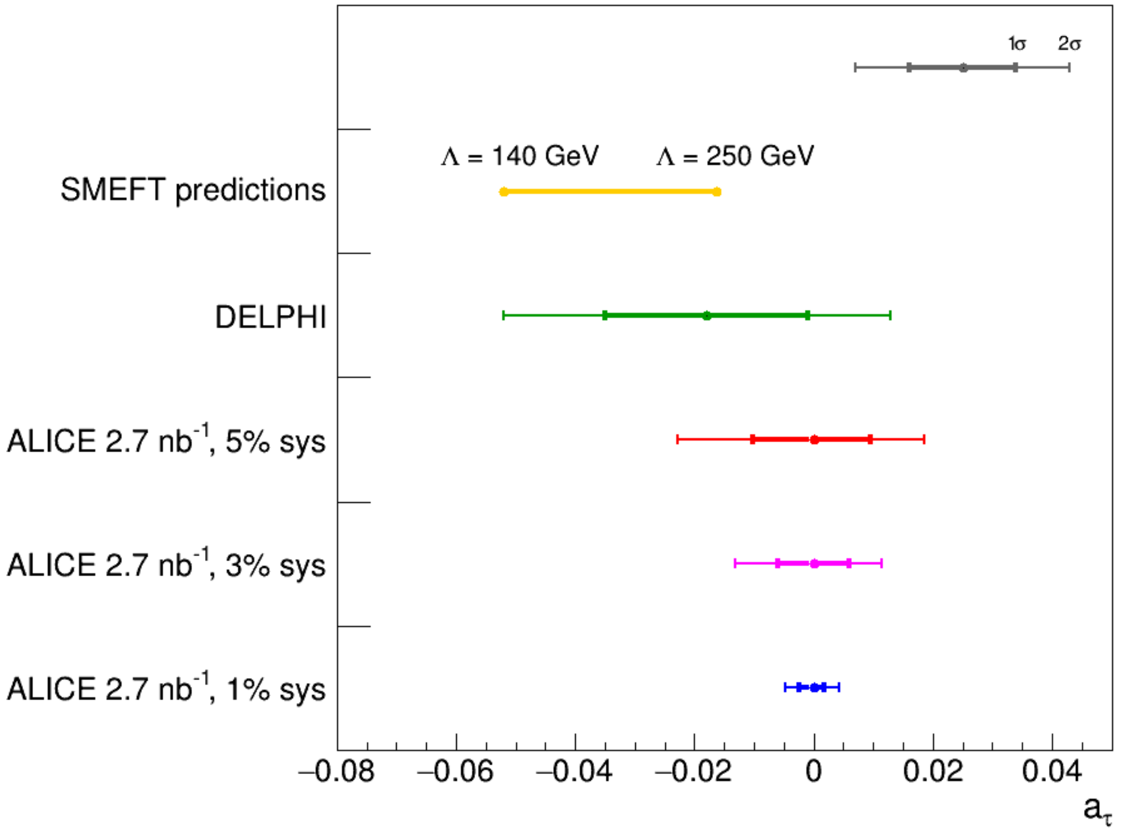
Closer look: sensitivity to a_τ in p_T bins



- Considering 3 p_T bins that provide 1% statistical uncertainty
- Ratio of electron p_T differential cross sections has a parabolic shape in the vicinity of $a_\tau = 0$
- Up to 15% variations of the yields within the range restricted by DELPHI limits

Possible a_τ limits with ALICE in Run 3





Deviation from SM

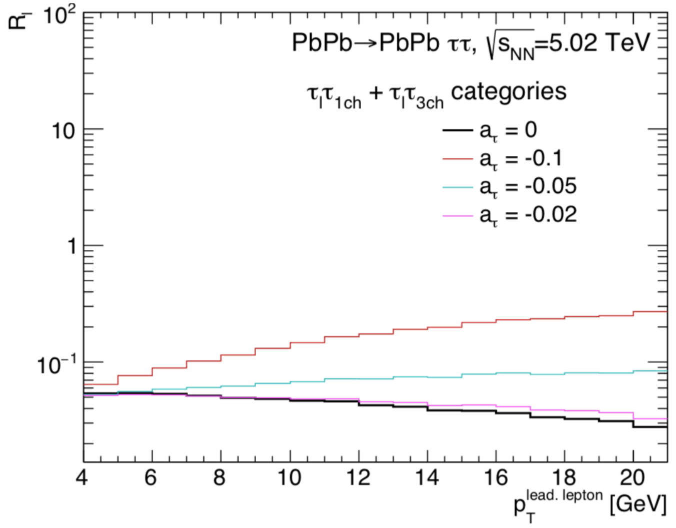
$$\chi^2 = \sum_{i=1}^{N_{\mathrm{bins}}} \frac{[S_i(0) - S_i(a_\tau)]^2}{\sigma^2_{\mathrm{stat}} + (\sigma^{\mathrm{uncorr}}_{\mathrm{syst}})^2}$$

S_i $(\zeta\, S_i)^2$

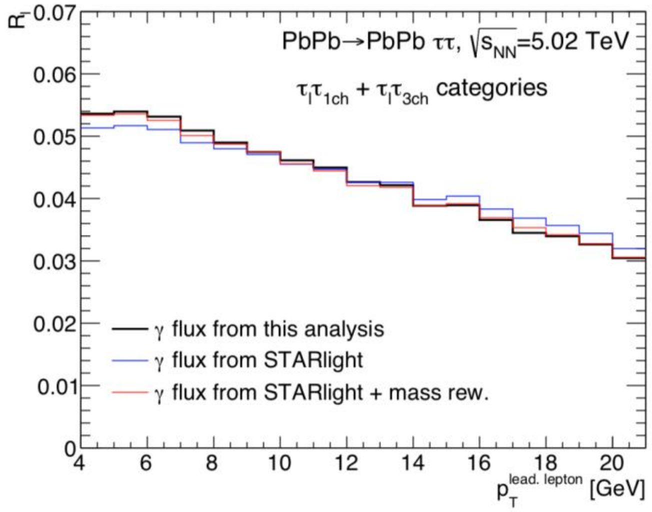
- Considering uncorrelated systematic uncertainties: ζ = 1%, 3%, 5%
- Precision limited by systematics

Caveats and future steps

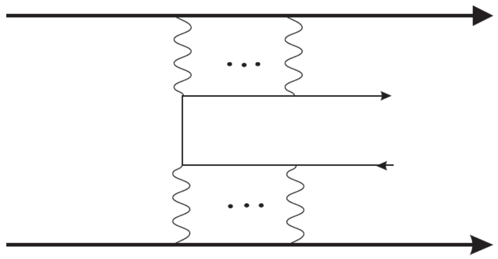
- Higher-order corrections
  - Multiple interactions due to high Zα, e.g. Hencken et al. PRC 75 (2007) 034903
  - Radiation from final state particles, e.g. S. Klein et al. PRD 102 (2020) 094013
- Precision of the equivalent photon approximation
  - Need to study flux uncertainties due to variation of Pb shape parameters
- Try ratios to electron/muon spectra to reduce systematics, proposed by Dyndal et al. PLB 809 (2020) 135682



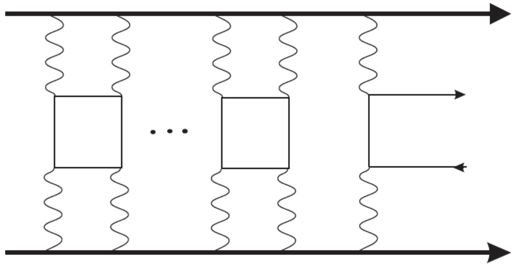
Ratio to electron/muon spectra



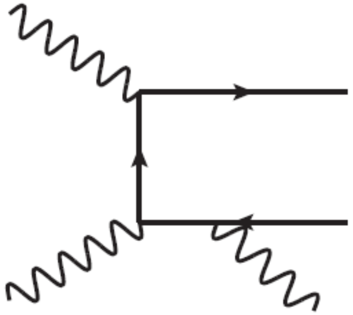
Flux differences in Starlight/Dyndal



Coulomb corrections



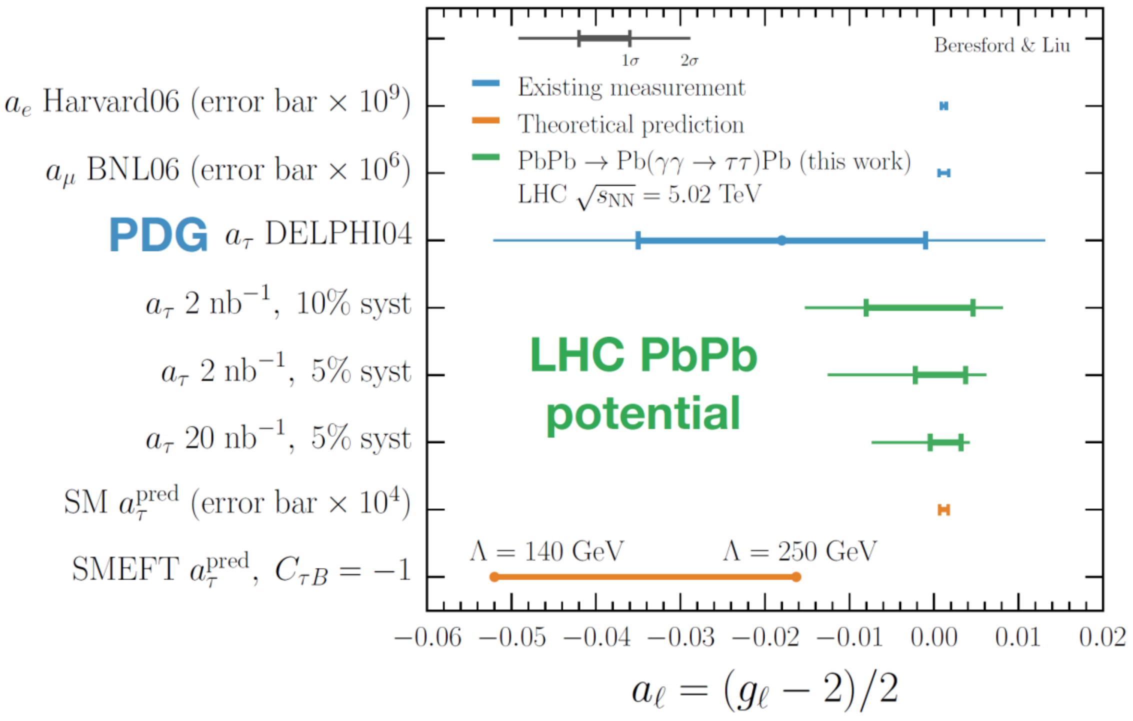
Unitarity corrections

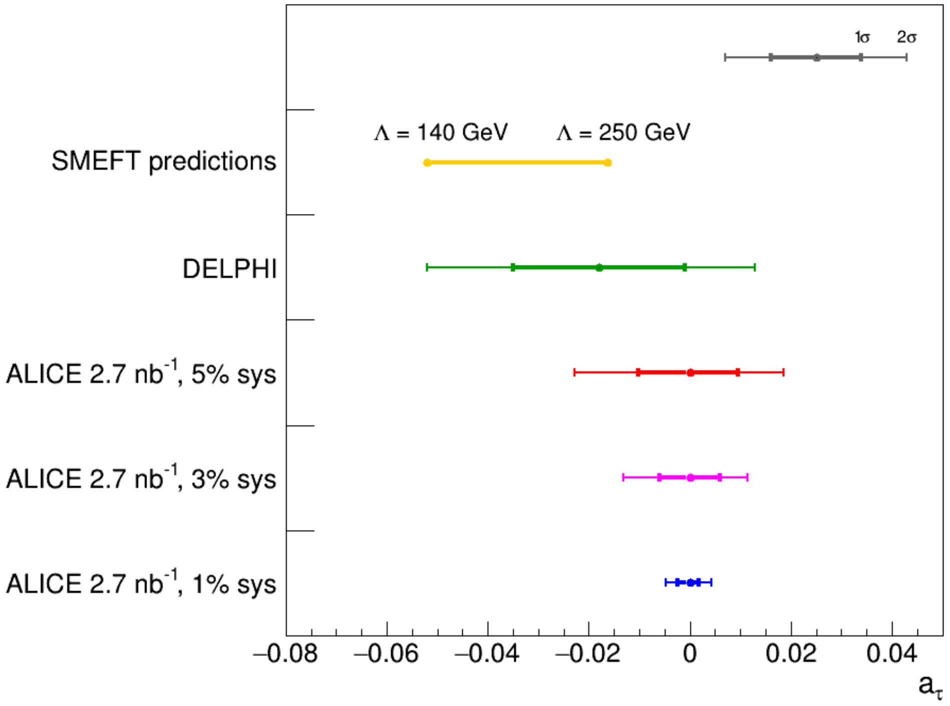


Final state radiation

Conclusions

- Possibilities for a_τ measurements with LHC experiments in Run 3 and 4 look promising
- Precision is limited by systematic uncertainties
- Expected limits on a_τ x2 better compared to DELPHI results



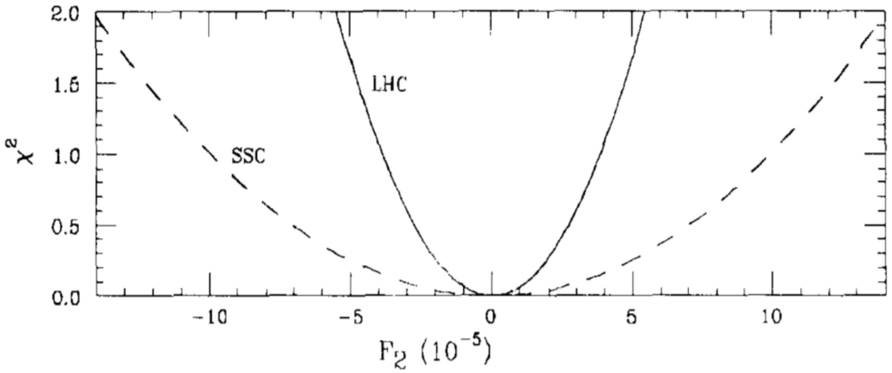


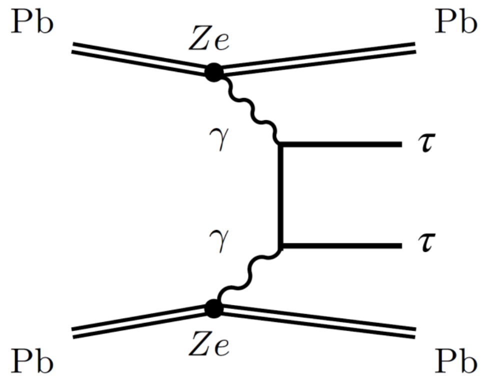
BACKUP

Idea to measure a_τ in UPC

- F. del Aguila, F. Cornet, J.I.Illana, PLB 271 (1991) 256

$$\chi^2 = \sum_i \frac{[N_i(F_{2(3)}) - N_i(0)]^2}{N_i(F_{2(3)})}$$





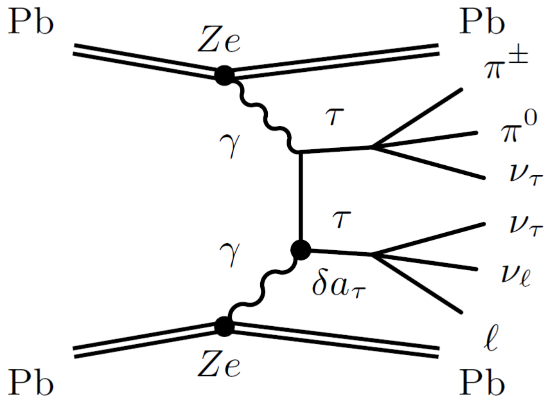
  - Considering taus in the final state
  - Systematic uncertainties ignored

- L. Beresford, J. Liu, PRD 102 (2020) 113008
  - Calculations withing SM effective field theory (SMEFT)
  - Tau decays into leptons
  - ATLAS/CMS kinematics: $p_T > 4$ GeV and $|\eta| < 2.5$.

$$\chi^2 = \frac{(S_{\mathrm{SM+BSM}} - S_{\mathrm{SM}})^2}{B + S_{\mathrm{SM+BSM}} + (\zeta_s S_{\mathrm{SM+BSM}})^2 + (\zeta_b B)^2}$$

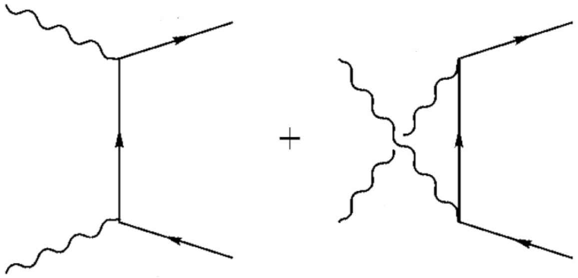
- M. Dyndal, M. Klusek-Gawenda, M. Schott , A. Szczurek, PLB 809 (2020) 135682
  - Direct calculations with generalized form of the γττ vertex:

$$i\Gamma_\mu^{\gamma\tau\tau}(q) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\tau}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\tau}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right] \qquad a_\tau = F_2(0)$$



  - Ideas to reduce systematics using ratios to dimuon/dielectron continuum production

Cross section calculation for arbitrary a_τ



- Following Dyndal et. al.:

$$\frac{d\sigma(\gamma\gamma \to \ell^+\ell^-)}{dz} = \frac{2\pi}{64\pi^2 s}\frac{|\boldsymbol{p}_{out}|}{|\boldsymbol{p}_{in}|}\frac{1}{4}\sum_{\text{spin}}|\mathcal{M}|^2 \qquad z = \cos\theta$$

- Amplitude:

$$\mathcal{M} = (-i)\epsilon_{1\mu}\epsilon_{2\nu}\bar{u}(p_3)\left(i\Gamma^\mu(p_1)\frac{i(\hat{p}_t+m)}{p_t^2-m^2+i\epsilon}i\Gamma^\nu(p_2) + i\Gamma^\nu(p_2)\frac{i(\hat{p}_u+m)}{p_u^2-m^2+i\epsilon}i\Gamma^\mu(p_1)\right)v(p_4)$$

- Generalized vertex:

$$i\Gamma^\mu(q) = -ie\left(\gamma^\mu F_1(q^2) + \frac{i}{2m}\sigma_{\mu\nu}q^\nu F_2(q^2)\right) \to -ie\left(\gamma^\mu + \frac{i}{2m}\sigma_{\mu\nu}q^\nu a_\tau\right) \qquad a_\tau = F_2(0)$$

- SM cross section at tree level:

$$\frac{d\sigma}{dz} = \frac{\pi\alpha^2}{s}\frac{\sqrt{k^2-m^2}}{k}\left(2+4x\frac{x(1-z^2)z^2+1-x}{(1-xz^2)^2}\right) \qquad x = \frac{k^2-m^2}{k^2} \qquad s = 4k^2$$

- In general: 4th order polynomial in a_τ (calculated with Mathematica package)
- UPC cross section:

$$\frac{d\sigma(\mathrm{PbPb}\to\mathrm{PbPb}+\tau\tau)}{dY\,dM} = \frac{dN_{\gamma\gamma}}{dY\,dM}\sigma\left(\gamma\gamma\to\tau\tau, \omega_{1,2} = \frac{M}{2}e^{\pm Y}\right) \qquad \frac{dN_{\gamma\gamma}}{dY\,dM}$$ - two-photon luminosity in UPC

- Using TPythia8Decayer for tau decays