Light-by-light measurements, axion-like particle searches and tau g-2 constraints with ultra-peripheral collisions

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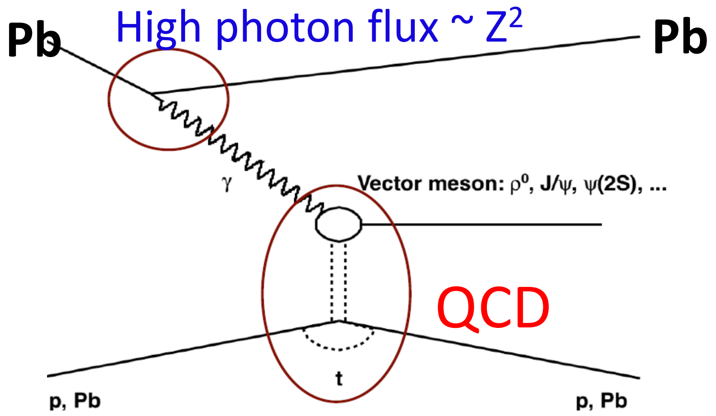
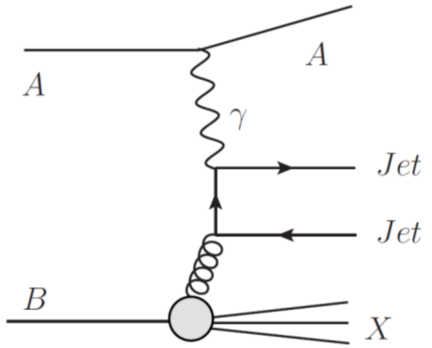
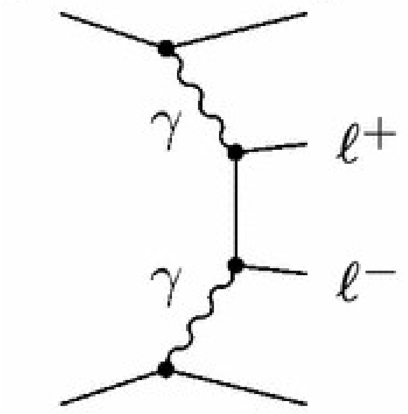
Photon-induced processes in UPC

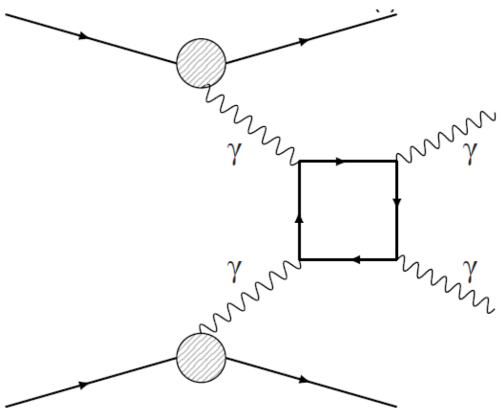
- Ultra-peripheral collisions (UPC): $b > R_1+R_2$
- Flux of quasi-real photons proportional to Z^2
- Photon-hadron interactions

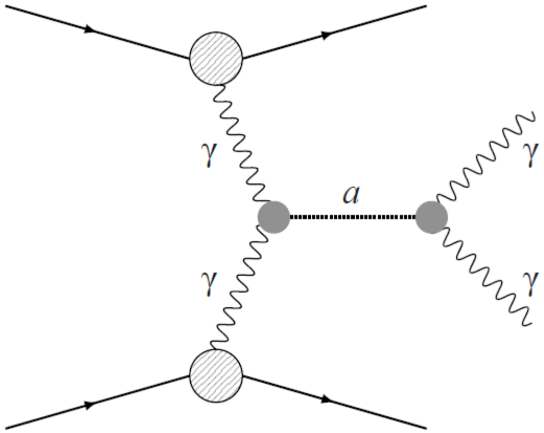


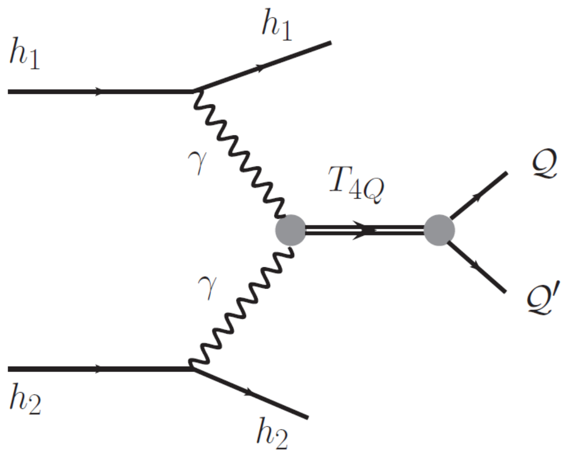


- Photon-photon reactions

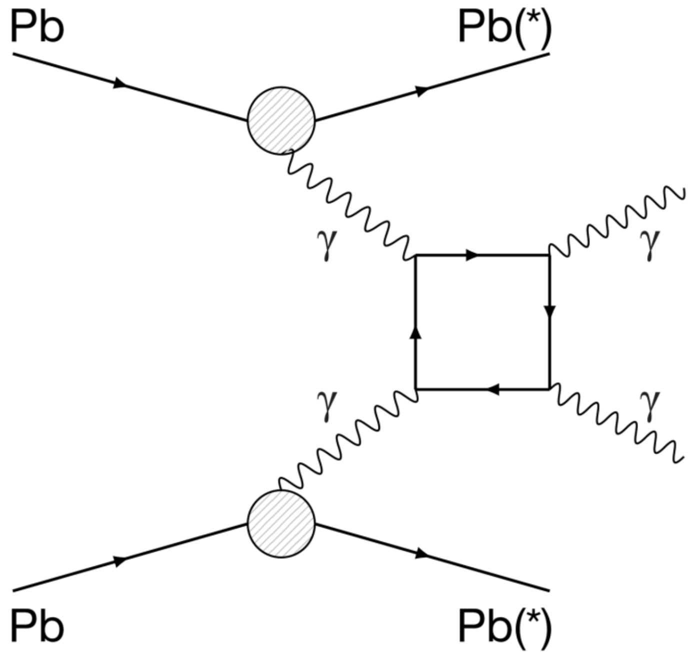






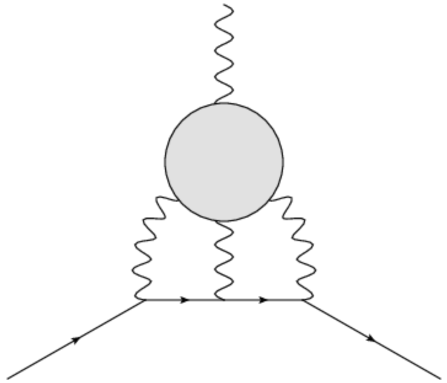


Light-by-light scattering



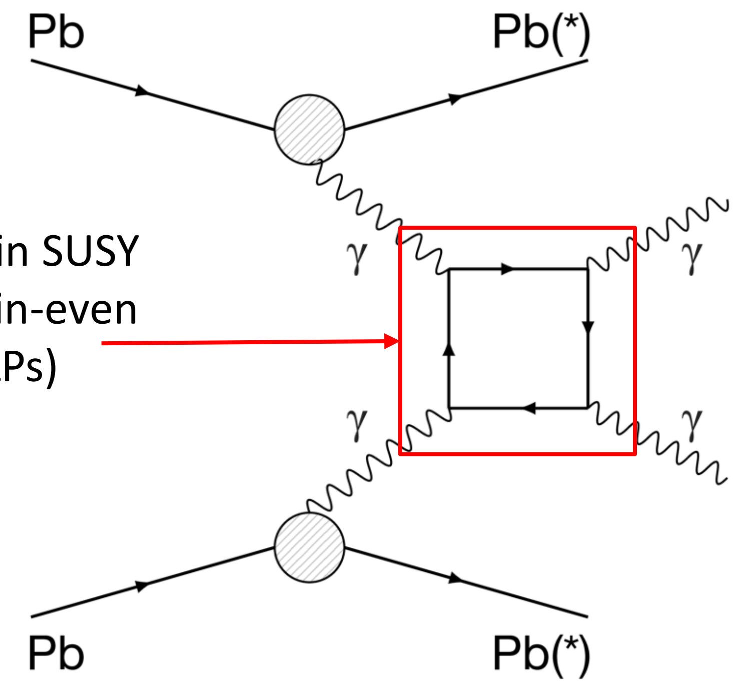
Light-by-light scattering

- Forbidden in classical ED
- Sensitive to BSM physics
- Contributes to electron/muon g-2

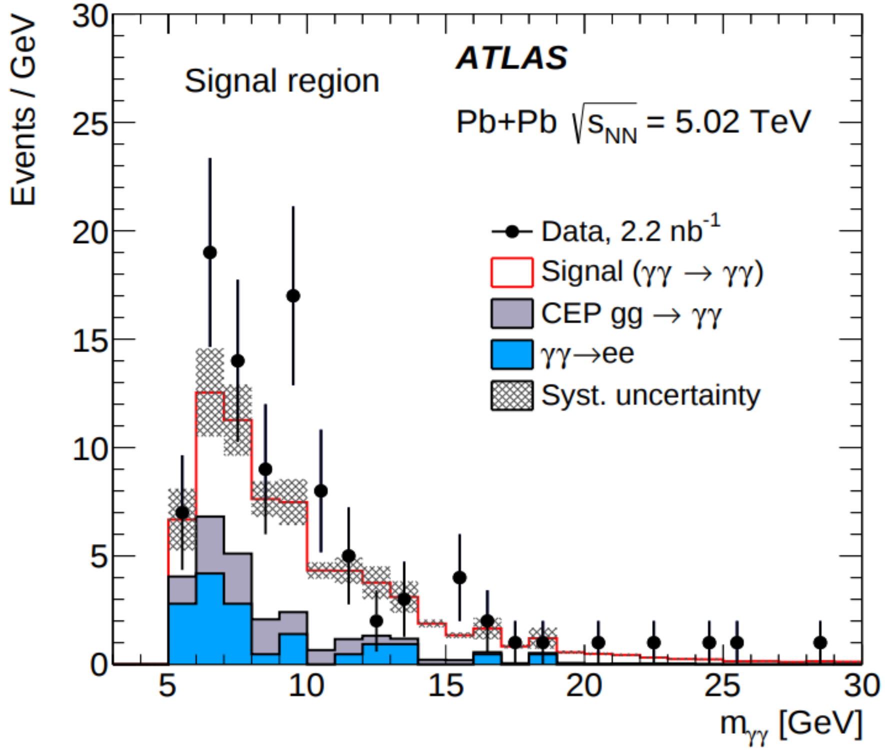


- First direct evidence found by ATLAS and CMS in Pb-Pb UPC
- Not yet probed in low diphoton mass region $M_{\gamma\gamma} < 5$ GeV

The loop can contain SUSY particles or new spin-even resonances (e.g. ALPs)

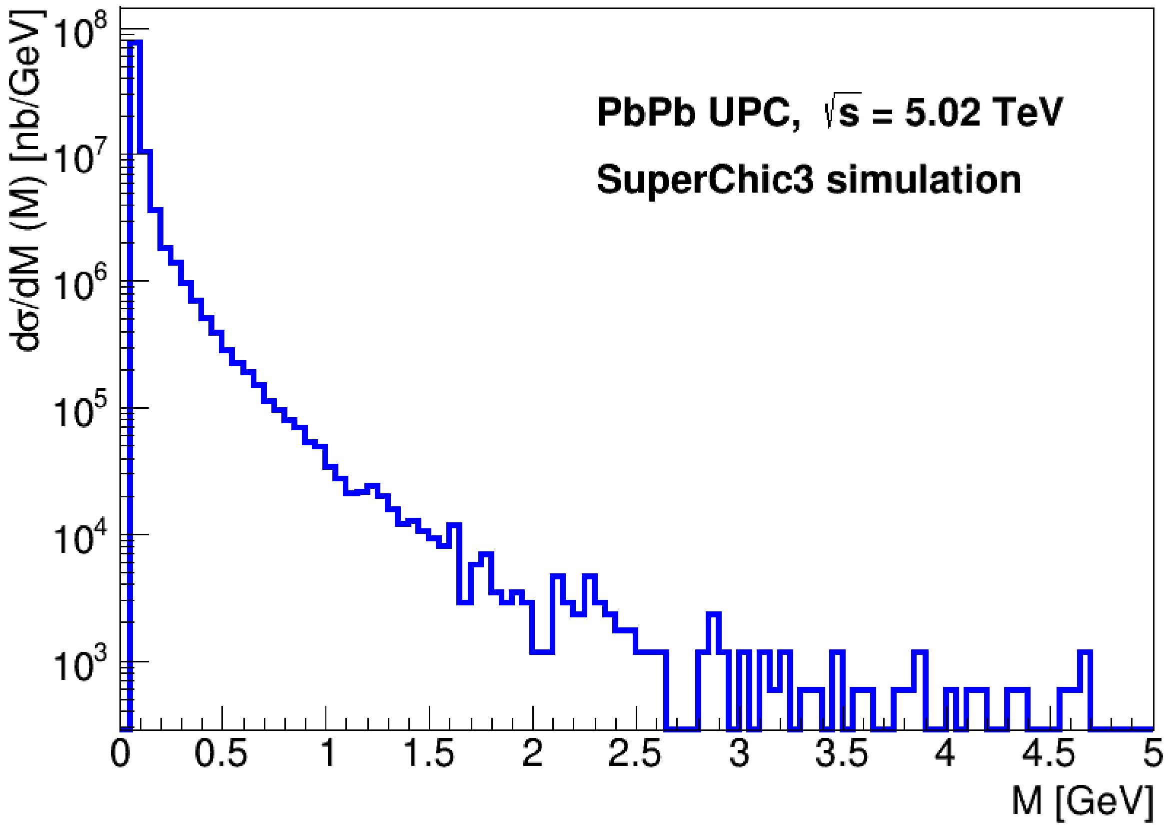


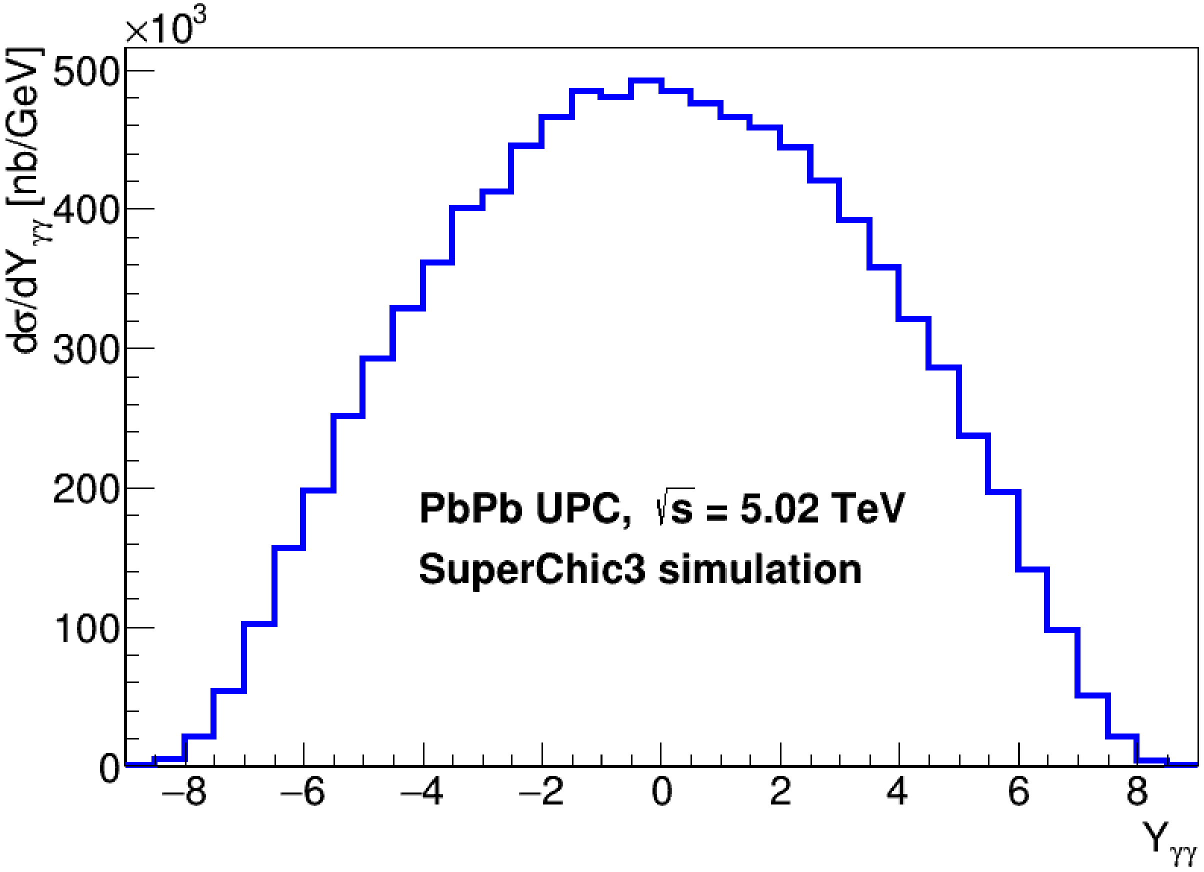
The ATLAS collaboration, JHEP 03, 243 (2021)



Light-by-light at low masses

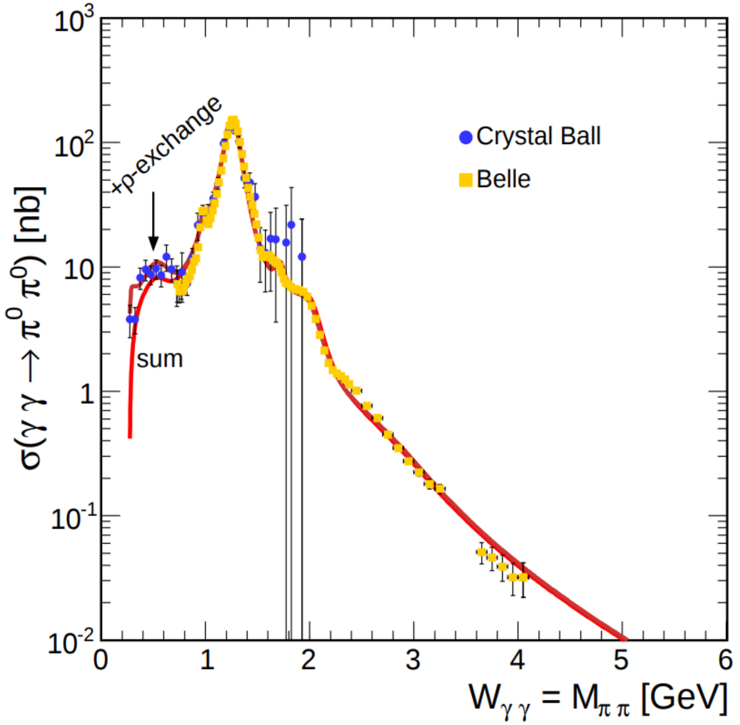
- Using SuperChic 3
- σ_{total} ($M_{\gamma\gamma}$ > 50 MeV) $\simeq$ 5 mb
  $\longrightarrow$ significant cross section compared to $\sigma_{hadronic}$ ~ 8 b



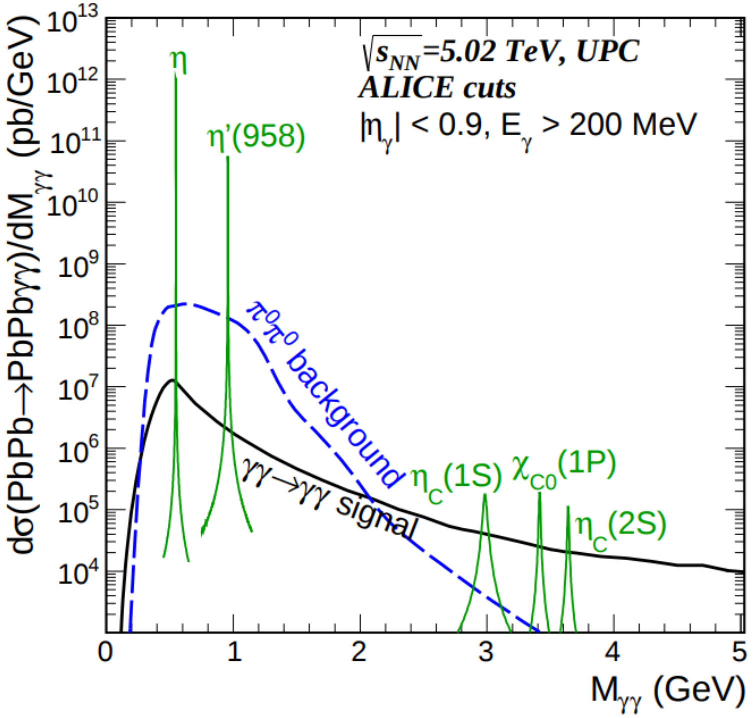


Background sources at low masses

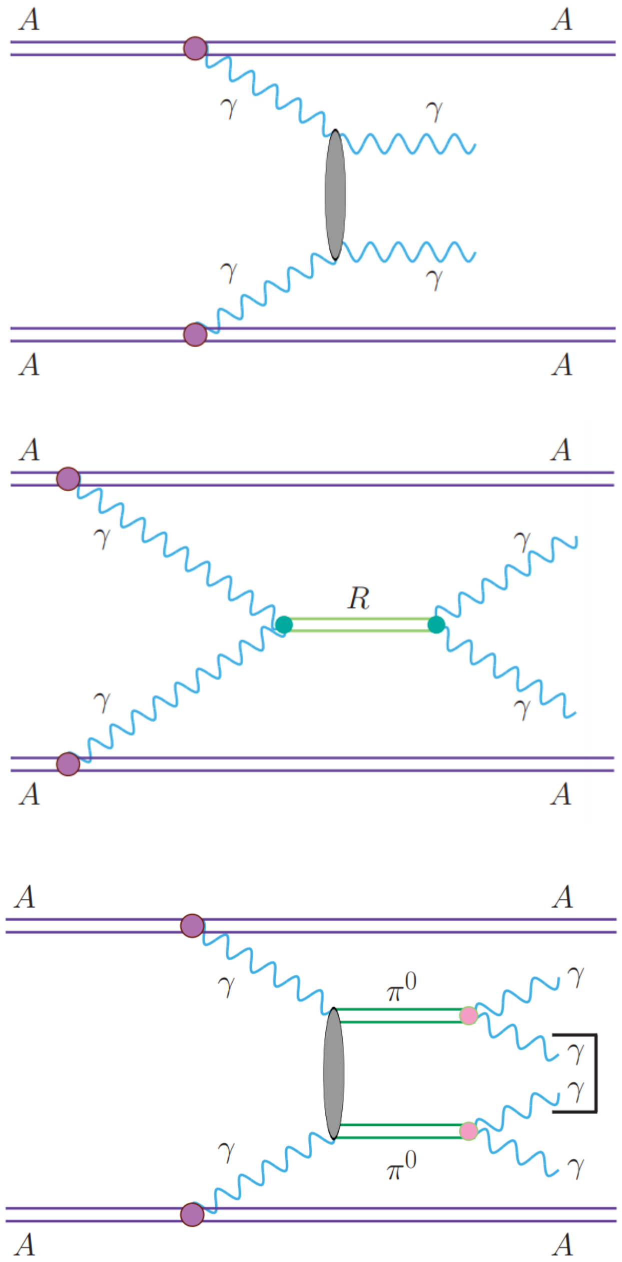
- $M_{\gamma\gamma}$ < 2 GeV: γγ spectrum is dominated by combinatorial background from $\pi^0\pi^0$ pair production
  - → Developed a dedicated $\pi^0\pi^0$ generator based on phenomenological model by M. Kłusek-Gawenda and A. Szczurek



M. Kłusek-Gawenda and A. Szczurek, PRC **87** (2013) 054908

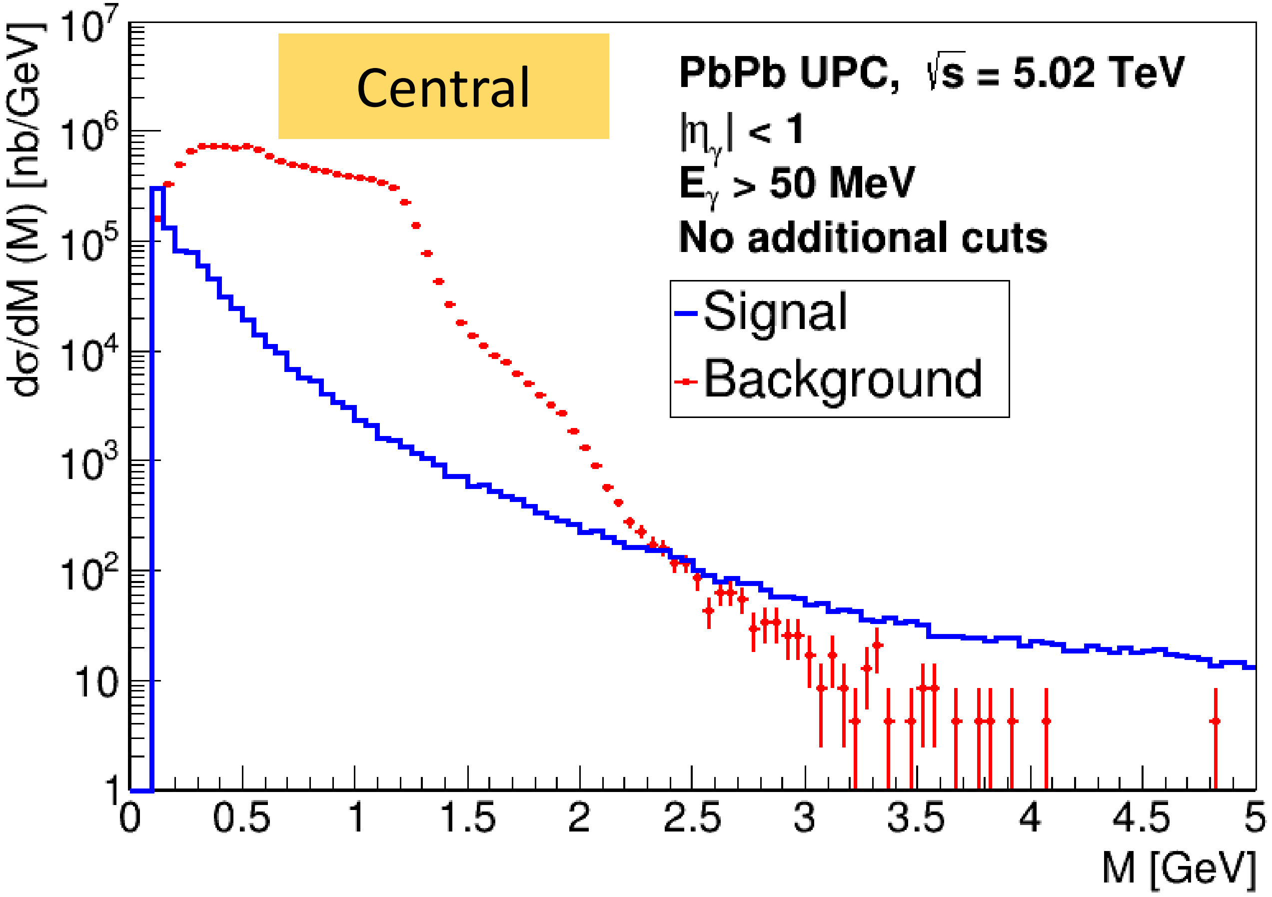


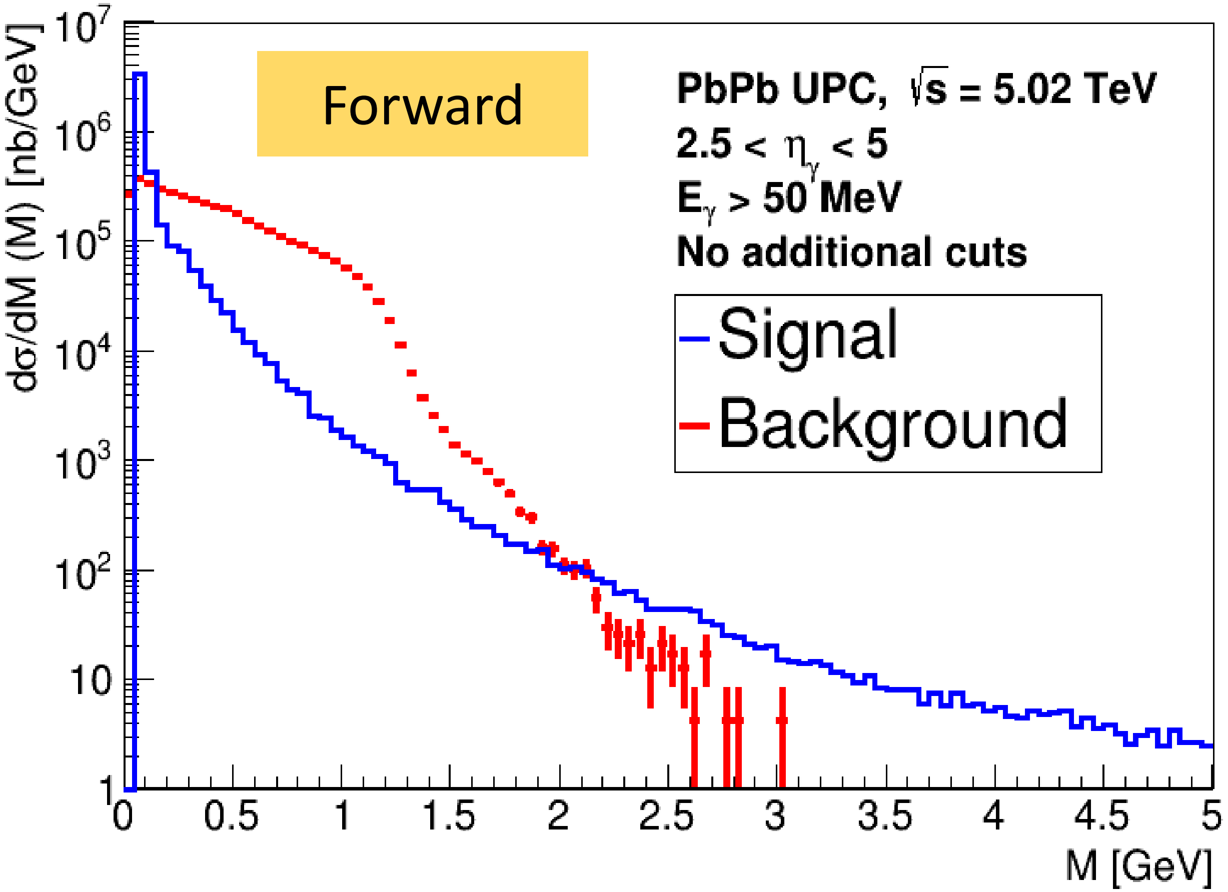
M. Kłusek-Gawenda, R. McNulty, R. Schicker, A. Szczurek, PRD **99** (2019) 093013



Signal vs background in ALICE 3

- Assuming low photon energy cut-off: $E_\gamma > 50$ MeV
- Comparing central ($|\eta|<1$) and forward FCT-like ($2.5<\eta<5$) regions



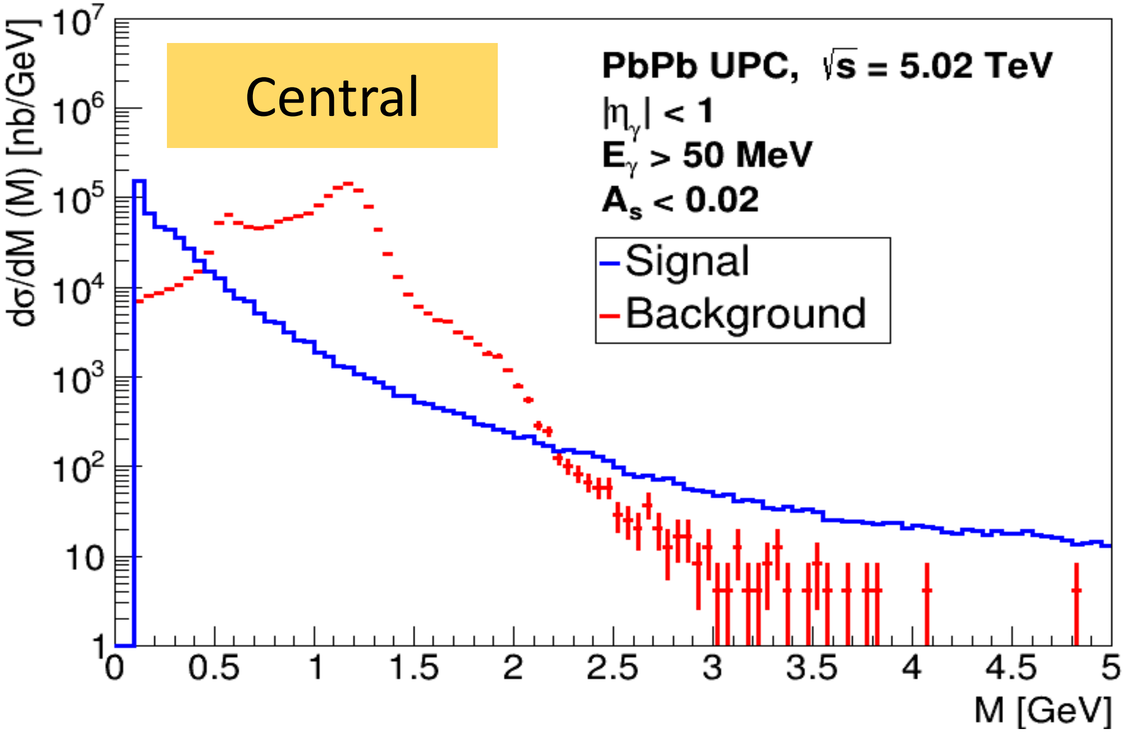


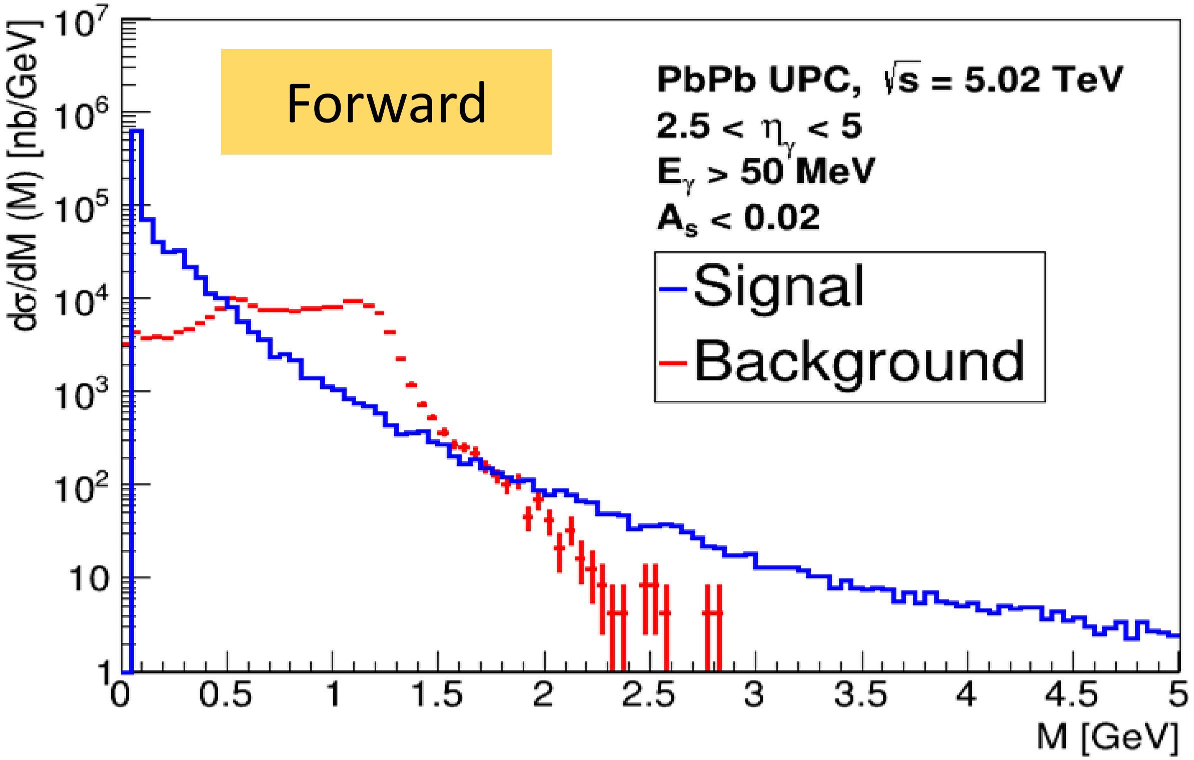
Huge background below 2 GeV

Signal vs background with asymmetry cuts

- Signal events have back-to-back topology
- Asymmetry cuts can be used to suppress background events

$$A_S = \left| \frac{|\vec{p}_T(1)| - |\vec{p}_T(2)|}{|\vec{p}_T(1)| + |\vec{p}_T(2)|} \right|$$





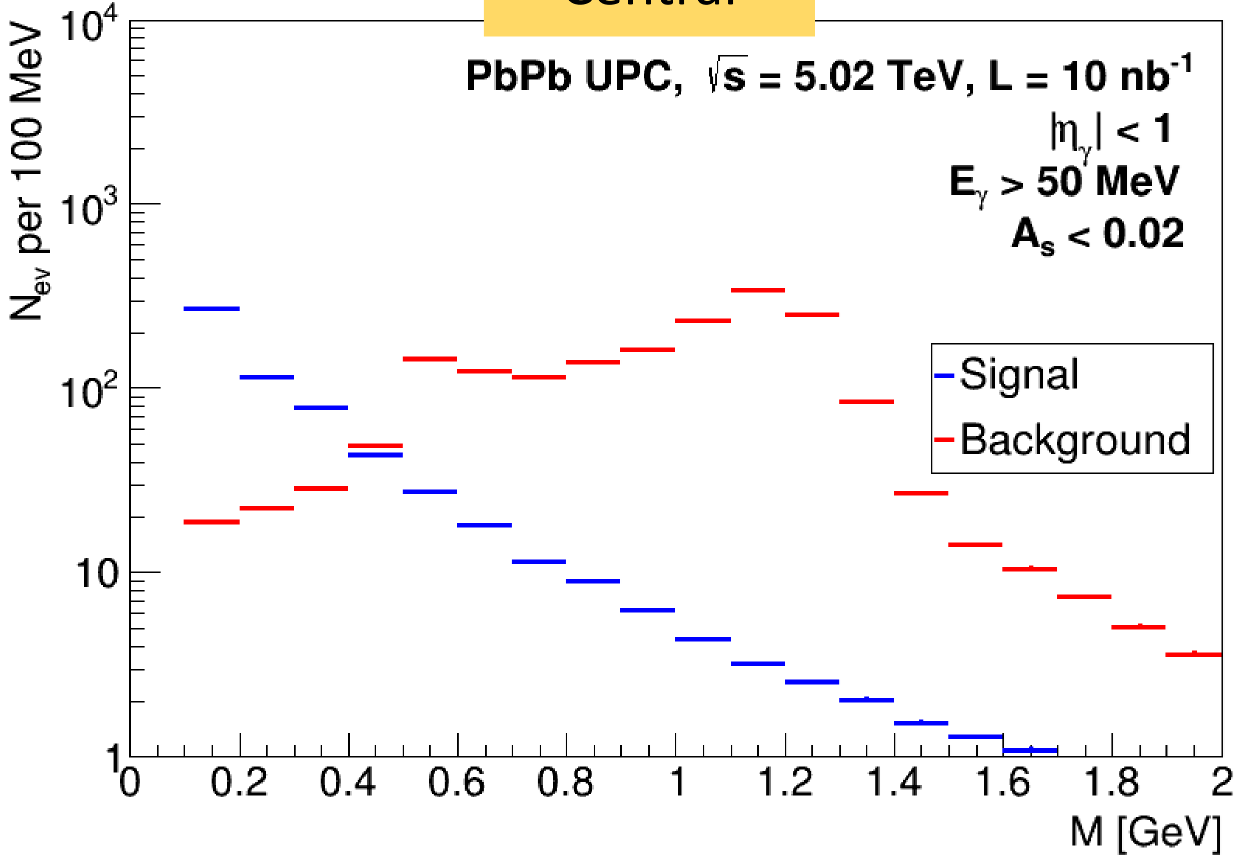
- LbyL measurements below 0.5 GeV might be promising
- Background contribution can be extracted in 0.5 < M < 2 GeV using A_S sideband analysis*

*proposed by M. Kłusek-Gawenda et al, PRD **99** (2019) 093013 (see backup)

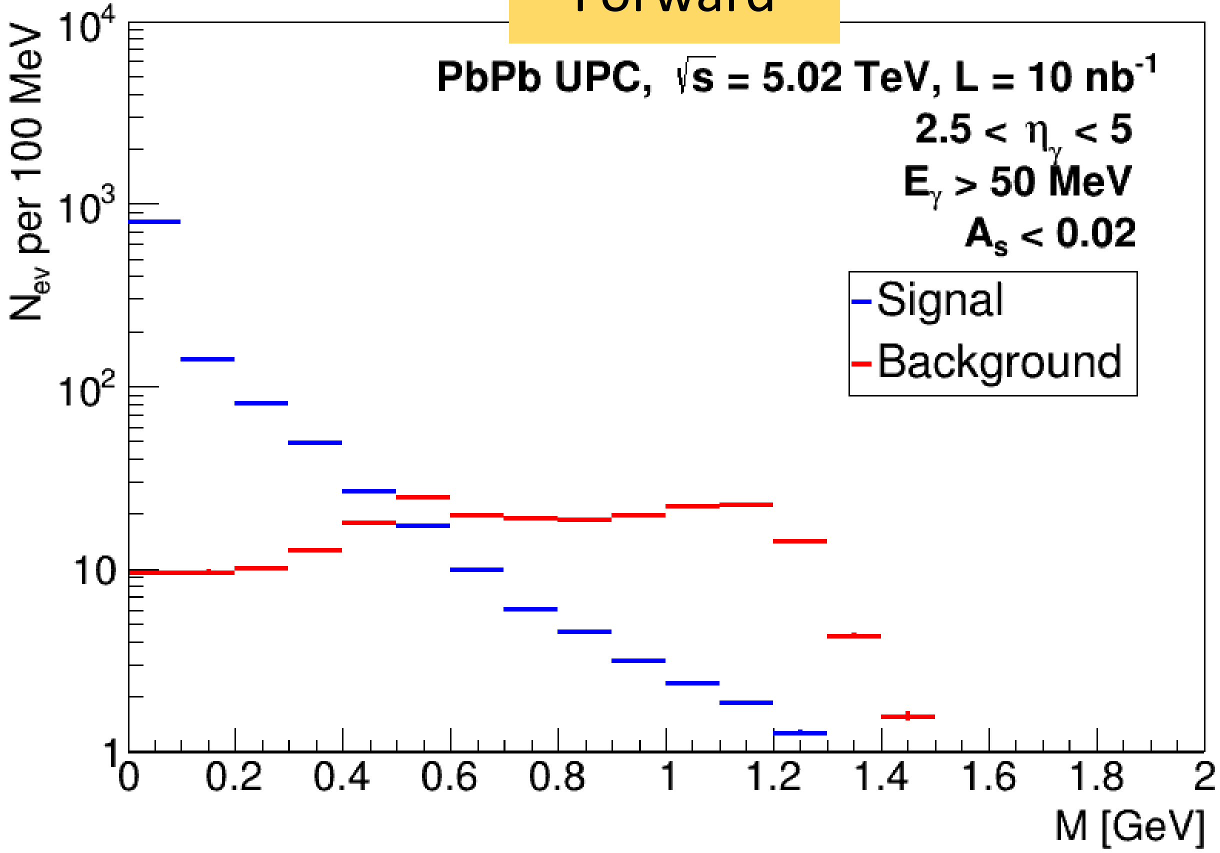
Signal and background spectra with conversions

- Considering PbPb UPC, L = 10 /nb
- Assuming photon reconstruction efficiency of 5% (either insertable barrel converter or FCT)

Central



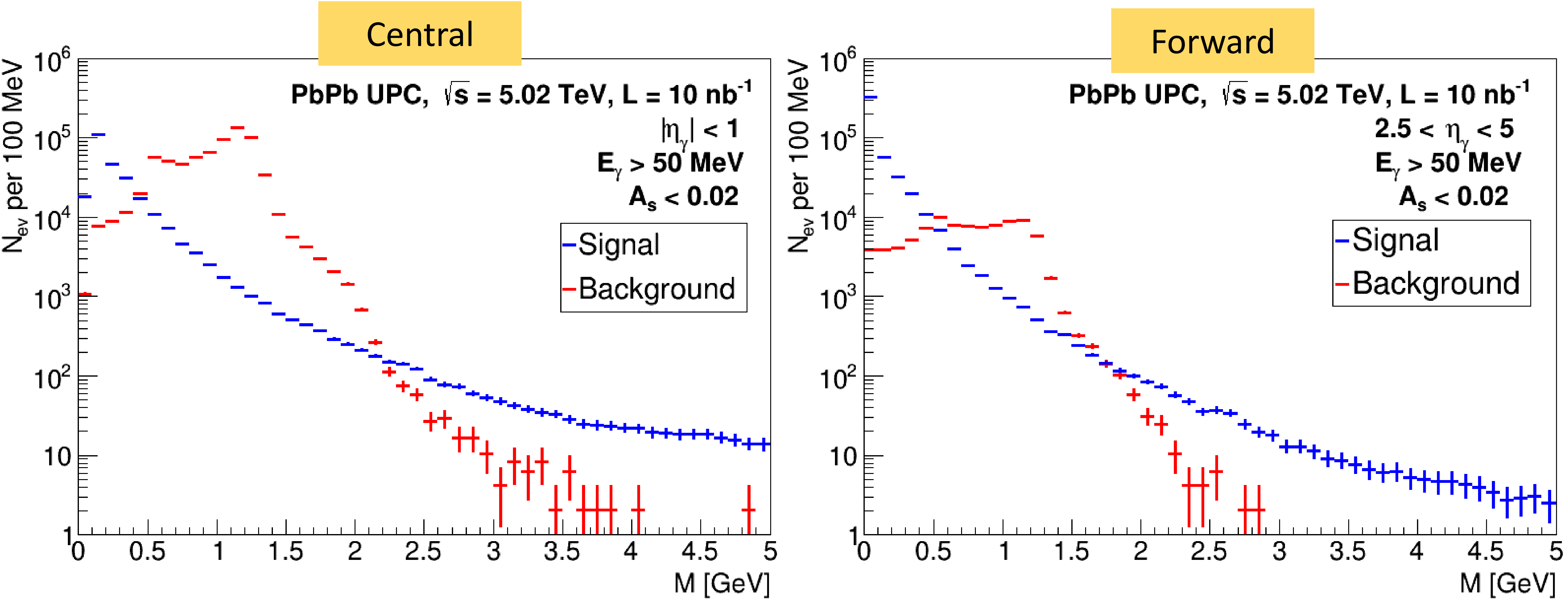
Forward



- Possibility for measurements at low masses (<0.5 GeV)
- But statistics is limited

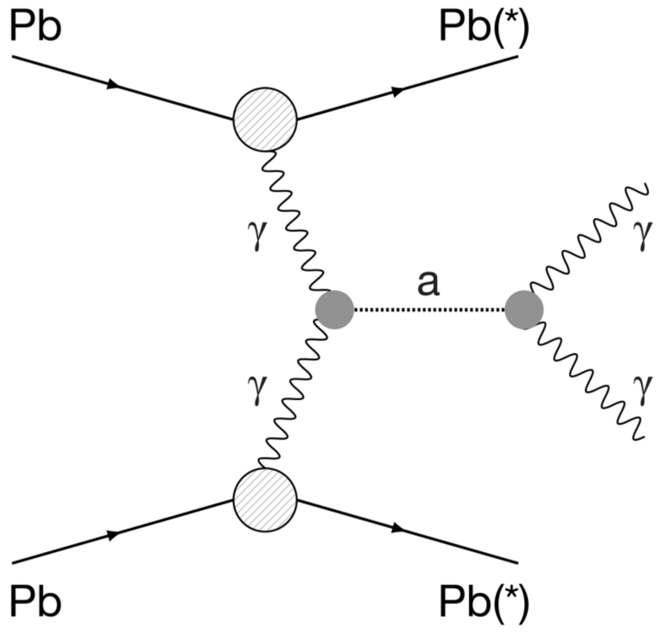
Signal and background spectra: ideal case

- Assuming 100% photon reconstruction efficiency → ideal case



- Possibility for measurements in a wide $M_{\gamma\gamma}$ range
- Caveat: photon/electron misidentification and other backgrounds not taken into account yet

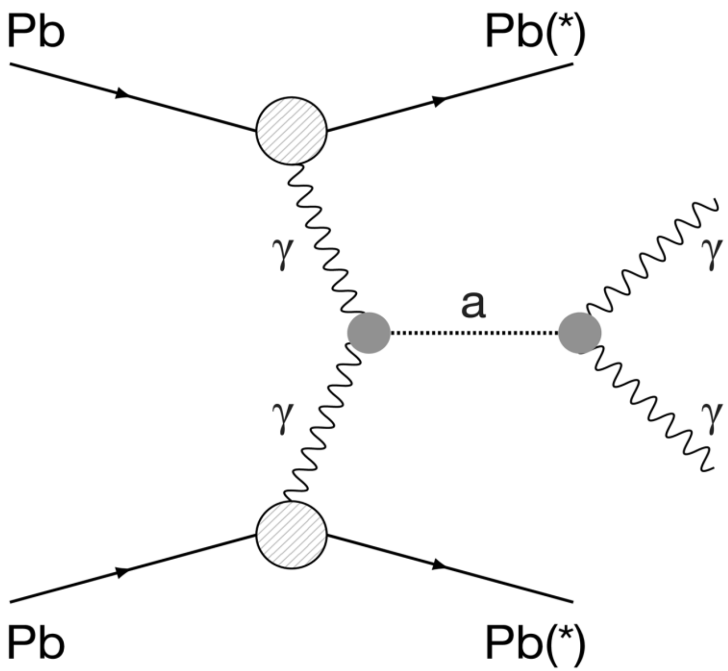
Search for axion-like particles

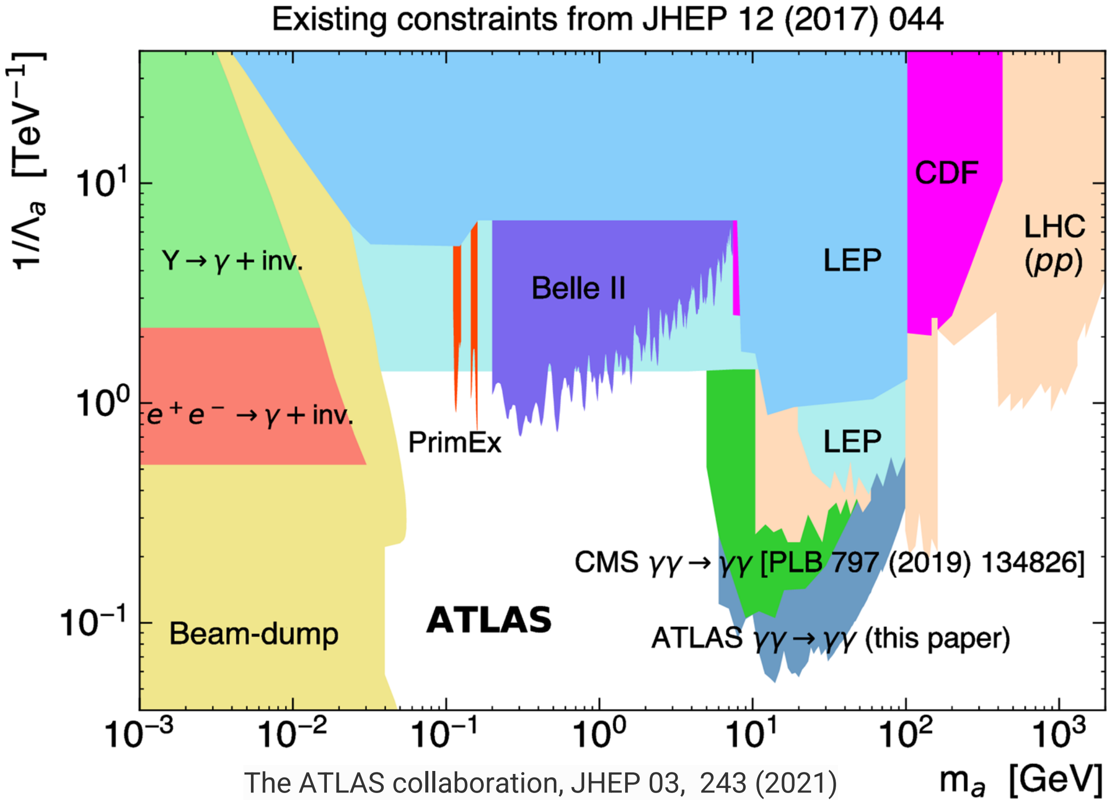


Axion-like particles (ALPs)

$$\mathcal{L} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- $\gamma\gamma \to \gamma\gamma$ is sensitive to BSM signals such as ALPs
- Axion-like particles (ALPs) - elementary pseudoscalar particles, appear in many BSM extensions as Goldstone bosons
- Dark matter candidates/mediators



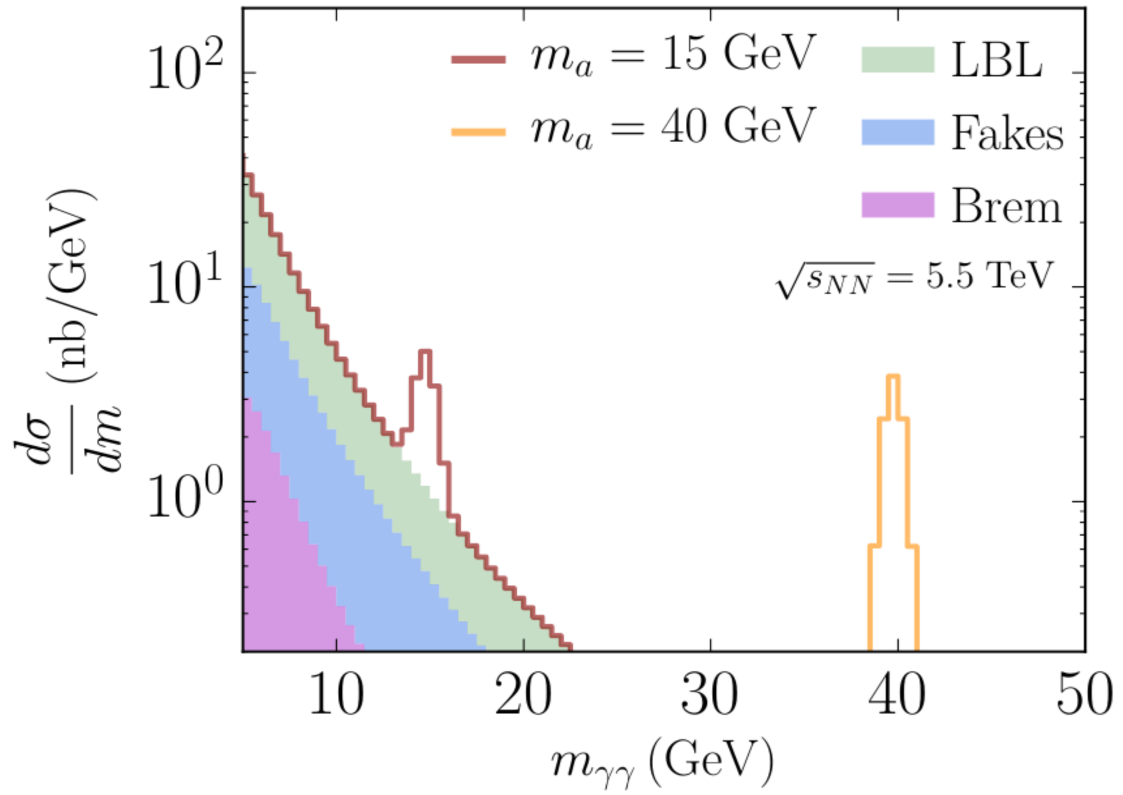


The ATLAS collaboration, JHEP 03, 243 (2021)

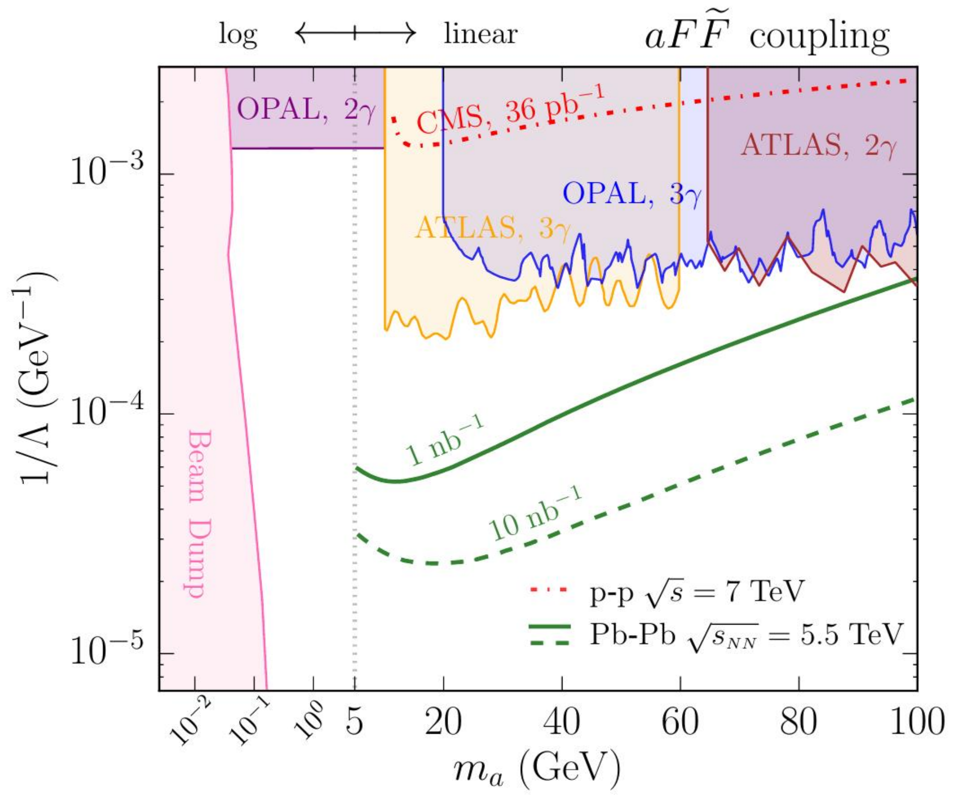
Setting upper limits for ALP production

- Following PRL 118, 171801 (2017): poisson limits for ALPs in UPCs at the LHC at 5.5 TeV
- ALPs from STARlight (ALP peaks are assumed to be entirely inside 0.5 GeV mass bins)
- Background: LbyL + fake photons from electrons + bremsstrahlung

$$\Gamma(a \to \gamma\gamma) = \frac{1}{64\pi}\frac{m_a^3}{\Lambda^2}$$

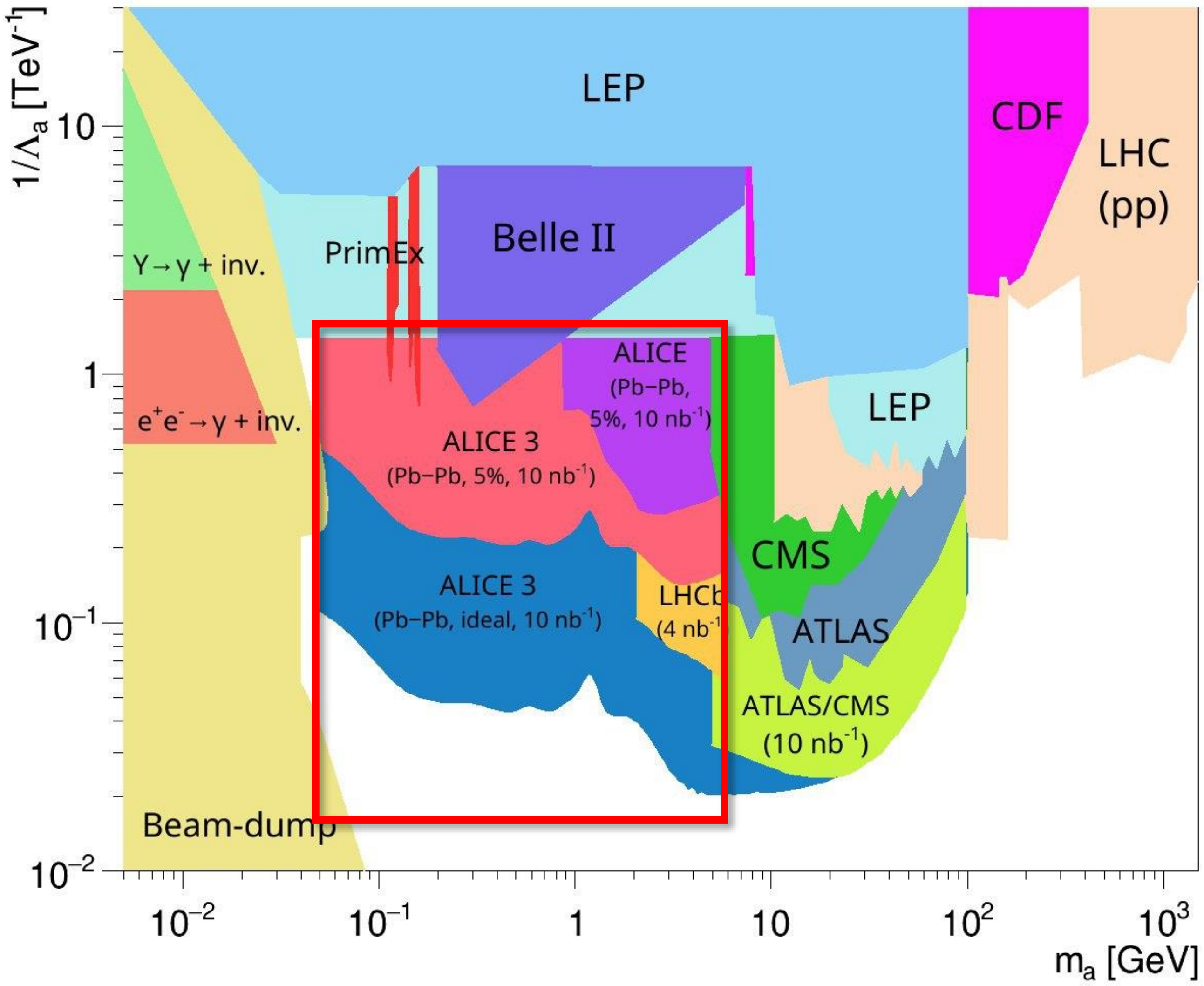


Differential cross section for signal and background



Calculated projections for UPCs (**green**) in comparison to the existing constraints

ALICE 3 projections for ALP exclusion limits



Existing limits from ATLAS, JHEP 03, 243 (2021)

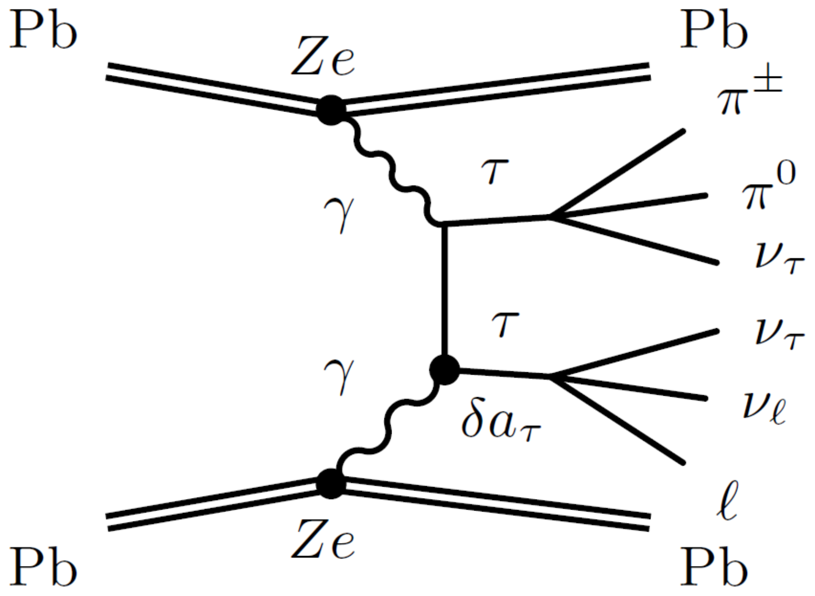
Projections for ATLAS/CMS from PRL 118 (2017), 171801

Projections for LHCb from Goncalves et al. EPJC 81 (2021), 522

- Assuming PbPb, L = 10 nb^{-1}
- Signal: ALPs from STARlight
- Background: LbyL + $\pi^0\pi^0$
- Applying asymmetry cut: $A_s < 0.02$
- Caveat: ALP searches are hardly possible in the vicinity of π^0, η, η', χ_c peak regions

- Potential to fill the gap from 0.05 to 5 GeV
- Ideal case can be approached with ECAL

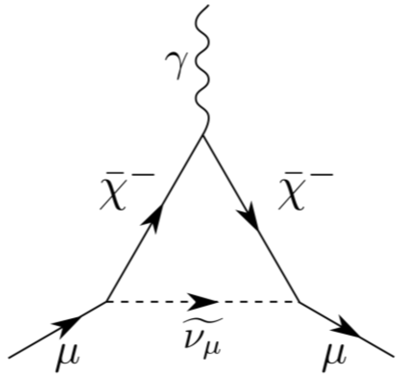
Tau anomalous magnetic moment measurements in UPC



This work is supported by the Austrian Science Fund (FWF, I 5277-N) and the Russian Foundation for Basic Research (RFBR, project No. 21-52-14006)

Tau g-2

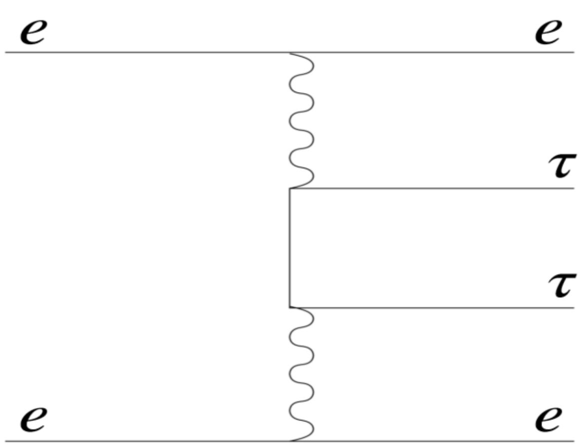
$a_\tau = (g_\tau - 2)/2$



- Sensitive to BSM physics, e.g. composite leptons or SUSY
- Supersymmetry at a scale M_S leads to $\delta a_\ell \sim m_\ell^2/M_S^2$

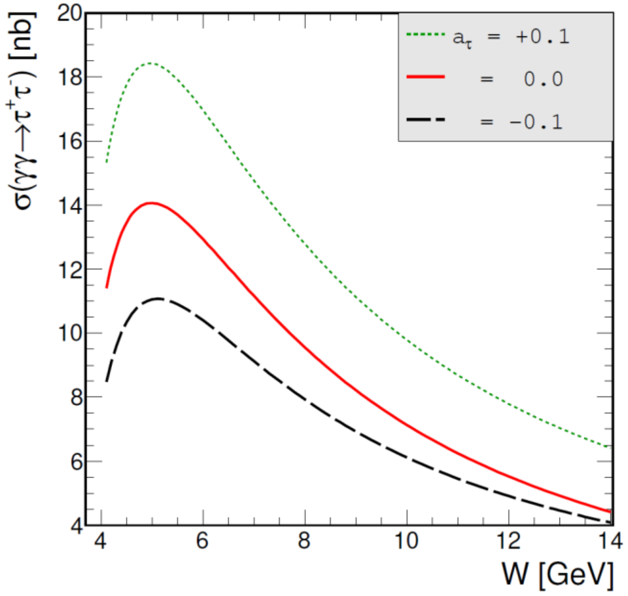
  → tau is ~280 times more sensitive to BSM than muon

- 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 in : $e^+e^- \rightarrow e^+e^-\tau\tau$



−0.052 < a_τ < 0.013 (95% CL)

EPJC 35 (2004) 159



Dyndal et al.,
PLB 809 (2020) 135682

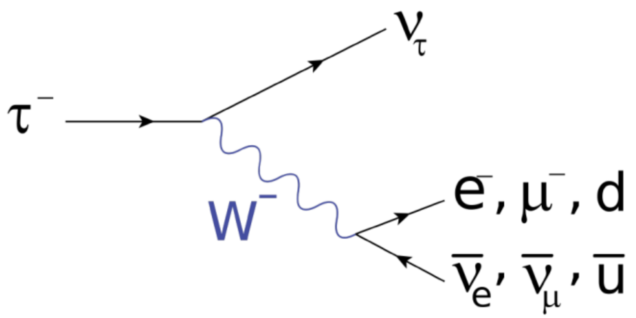
Tau decays

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

$$\mathrm{BR}(\tau^{\pm} \to \mathrm{e}^{\pm} + \nu_{\mathrm{e}} + \nu_{\tau}) = 17.8\%$$

$$\mathrm{BR}(\tau^{\pm} \to \mu^{\pm} + \nu_{\mu} + \nu_{\tau}) = 17.4\%$$

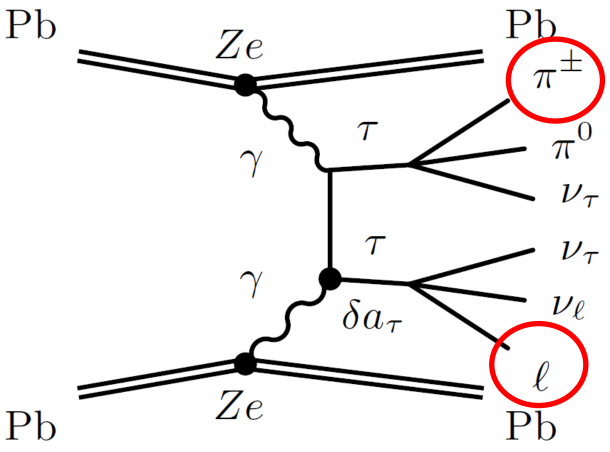
$$\mathrm{BR}(\tau^{\pm} \to \pi^{\pm} + \mathrm{n}\pi^{0} + \nu_{\tau}) = 45.6\%$$



- 3-prong:

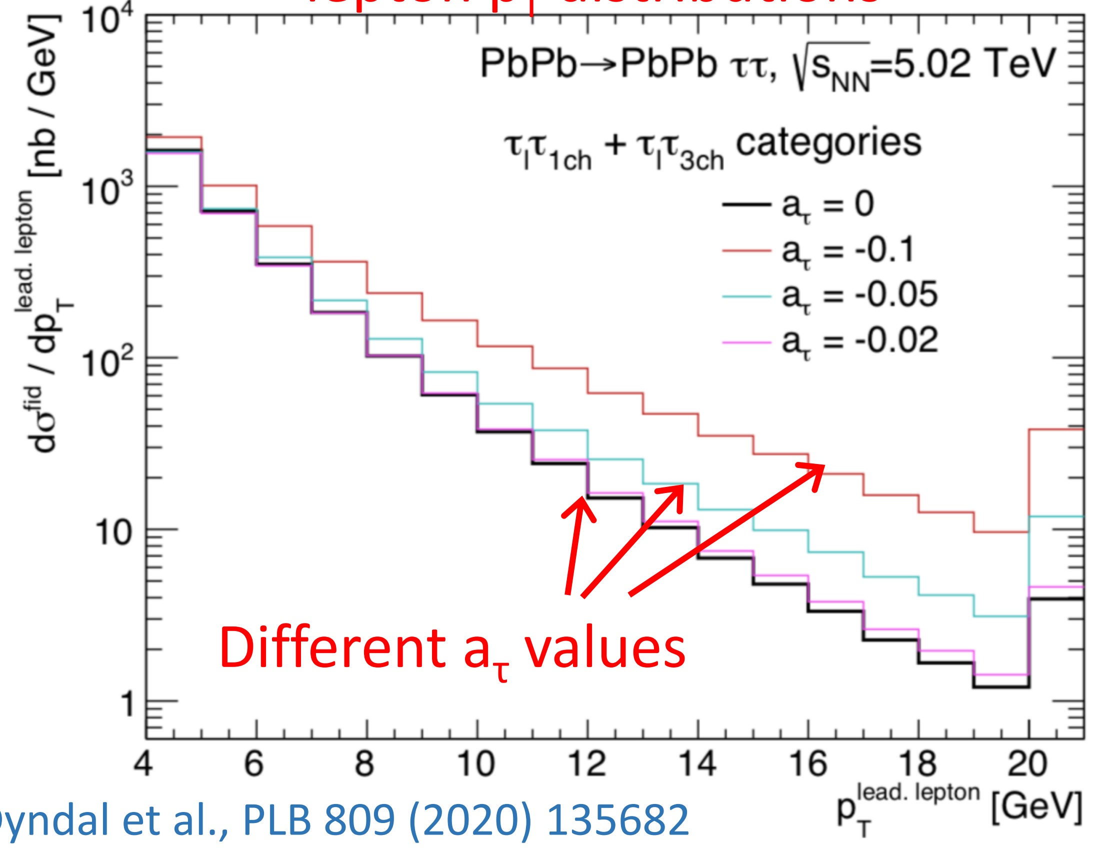
$$\mathcal{B}(\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau} + \text{neutral pions}) = 19.4\%.$$

- Selection in UPCs:
  1 lepton + 1 charged particle
  1 lepton + 3 charged particles



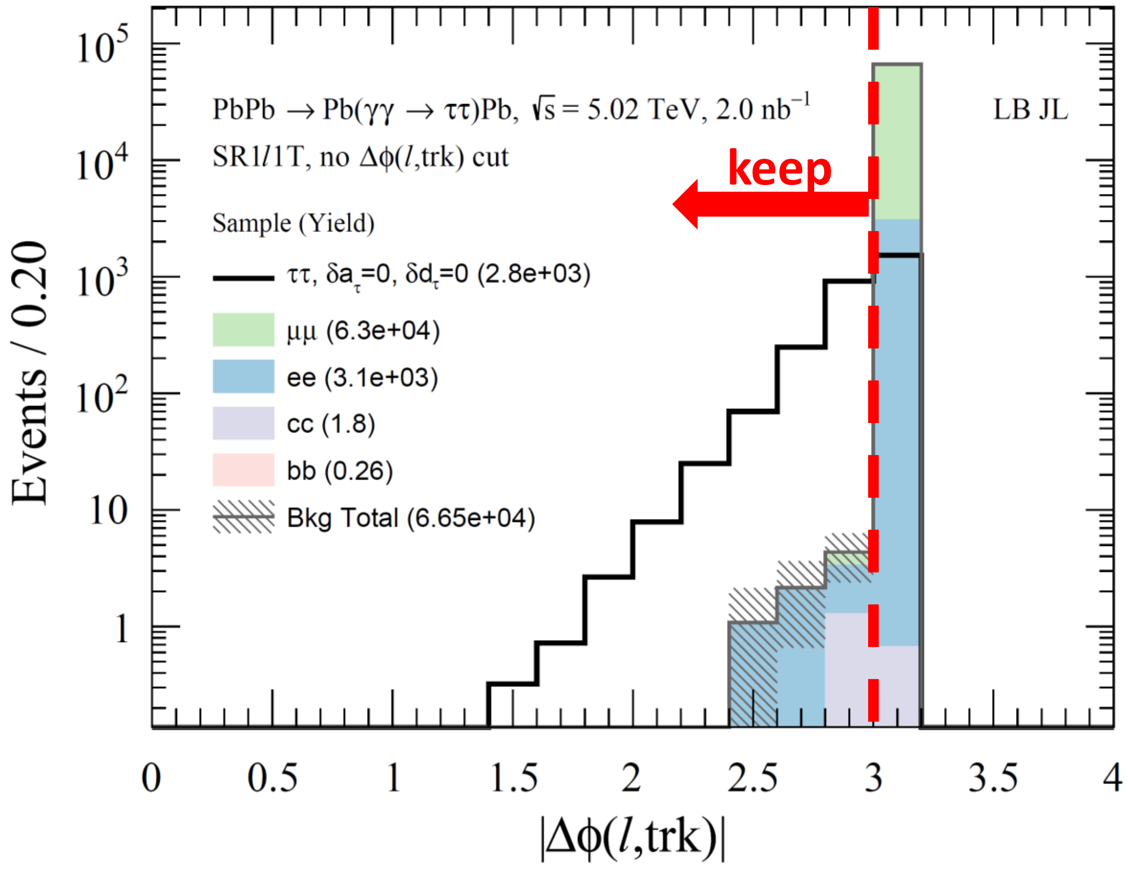
Lepton p_T spectra and background mitigation

lepton p_T distributions



Dyndal et al., PLB 809 (2020) 135682

L. Beresford, J. Liu, PRD 102 (2020) 113008

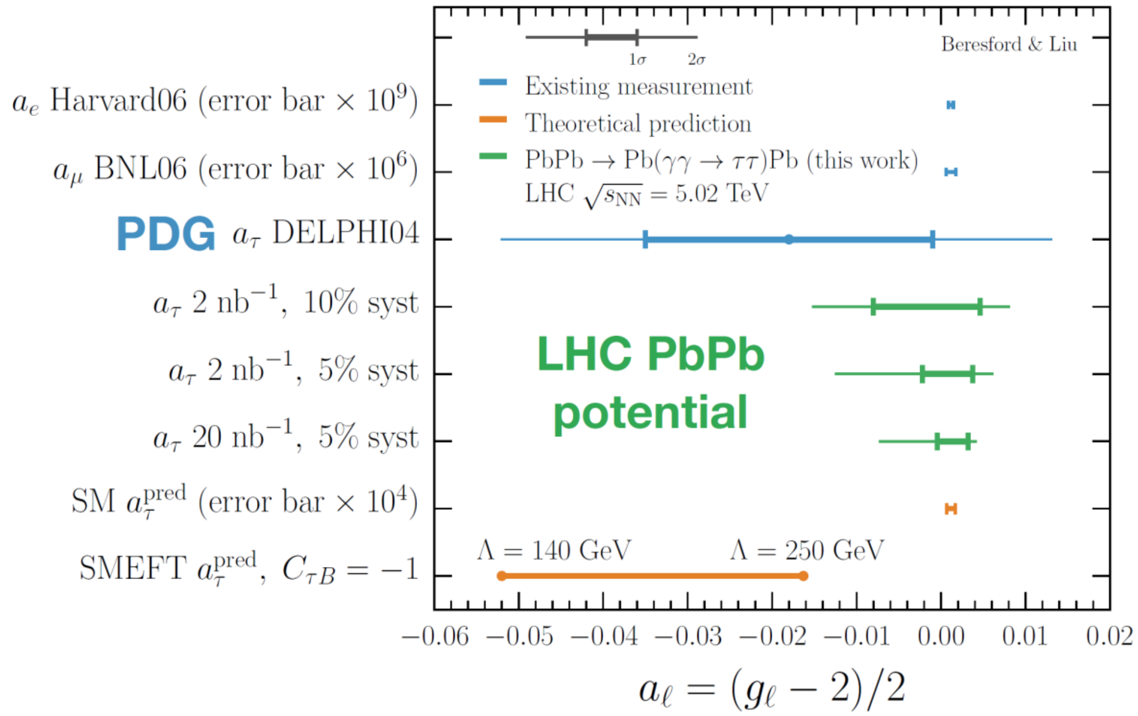


p_T differential measurements provide better sensitivity

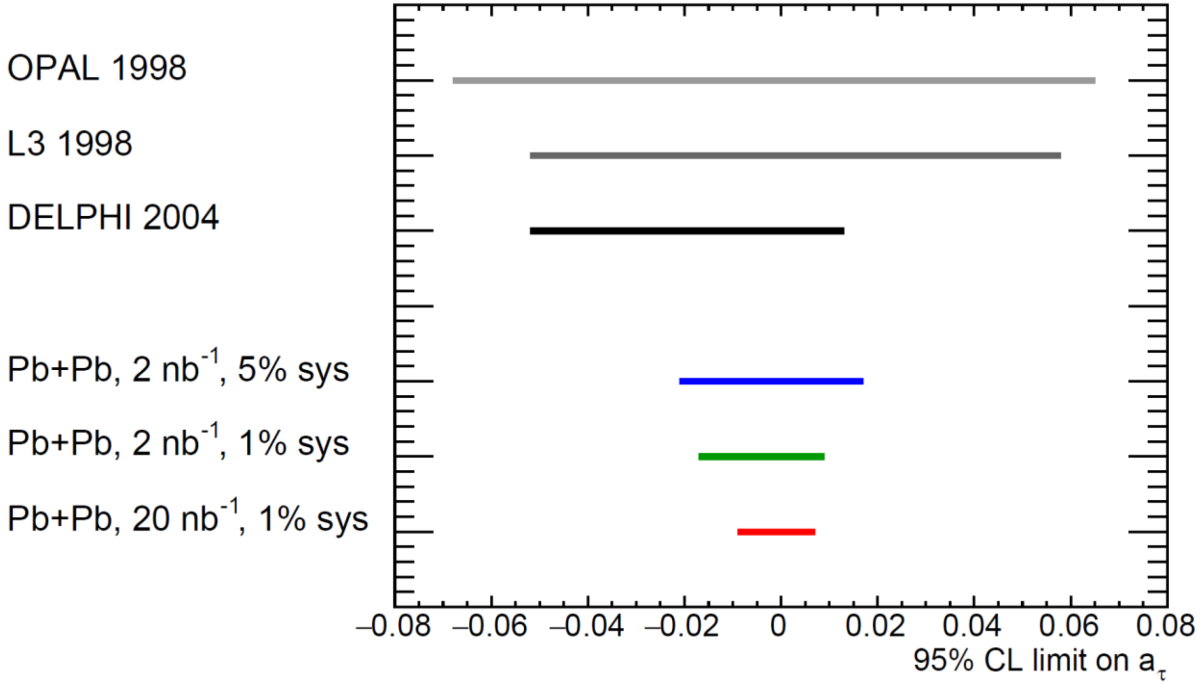
Acoplanarity cuts can be used to suppress continuum dilepton background

Possible constraints on a_τ with ATLAS/CMS

Beresford et al.



Dyndal et al. PLB 809 (2020) 135682



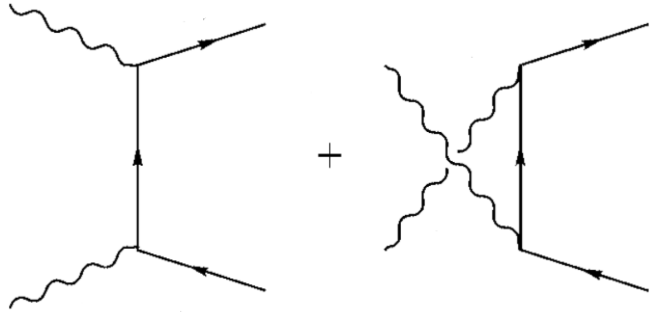
$$\chi^2 = \frac{(S_{\mathrm{SM+BSM}} - S_{\mathrm{SM}})^2}{B + S_{\mathrm{SM+BSM}} + (\zeta_s S_{\mathrm{SM+BSM}})^2 + (\zeta_b B)^2}$$

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

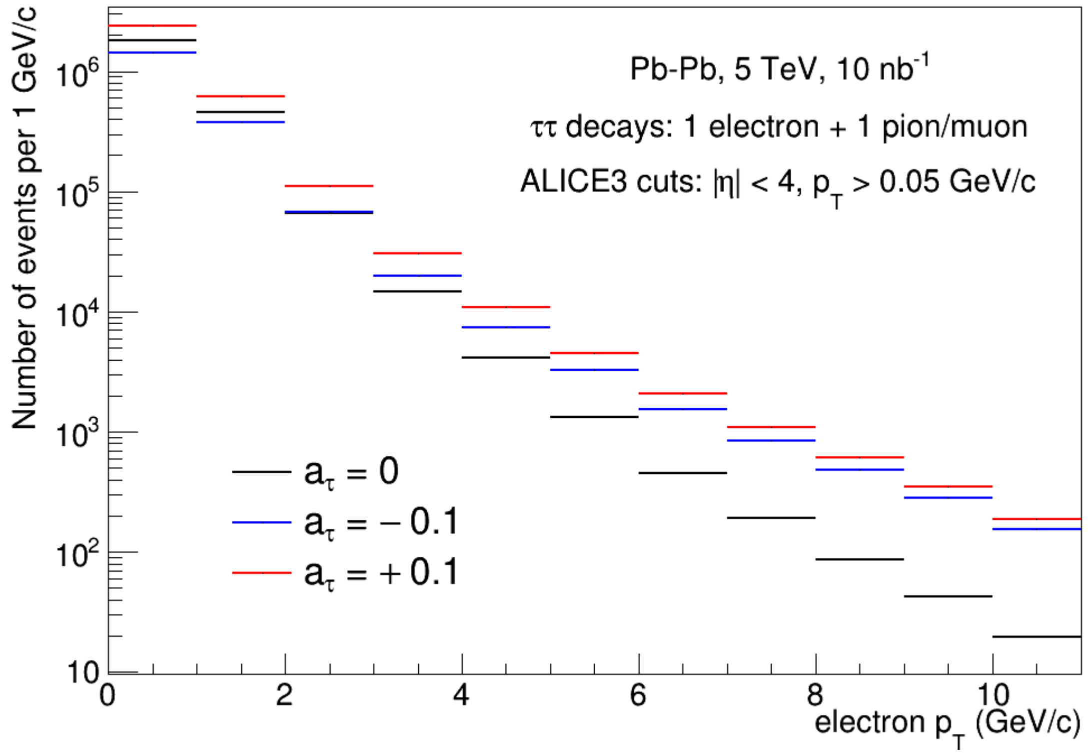
p_T-differential yields for ALICE 3

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

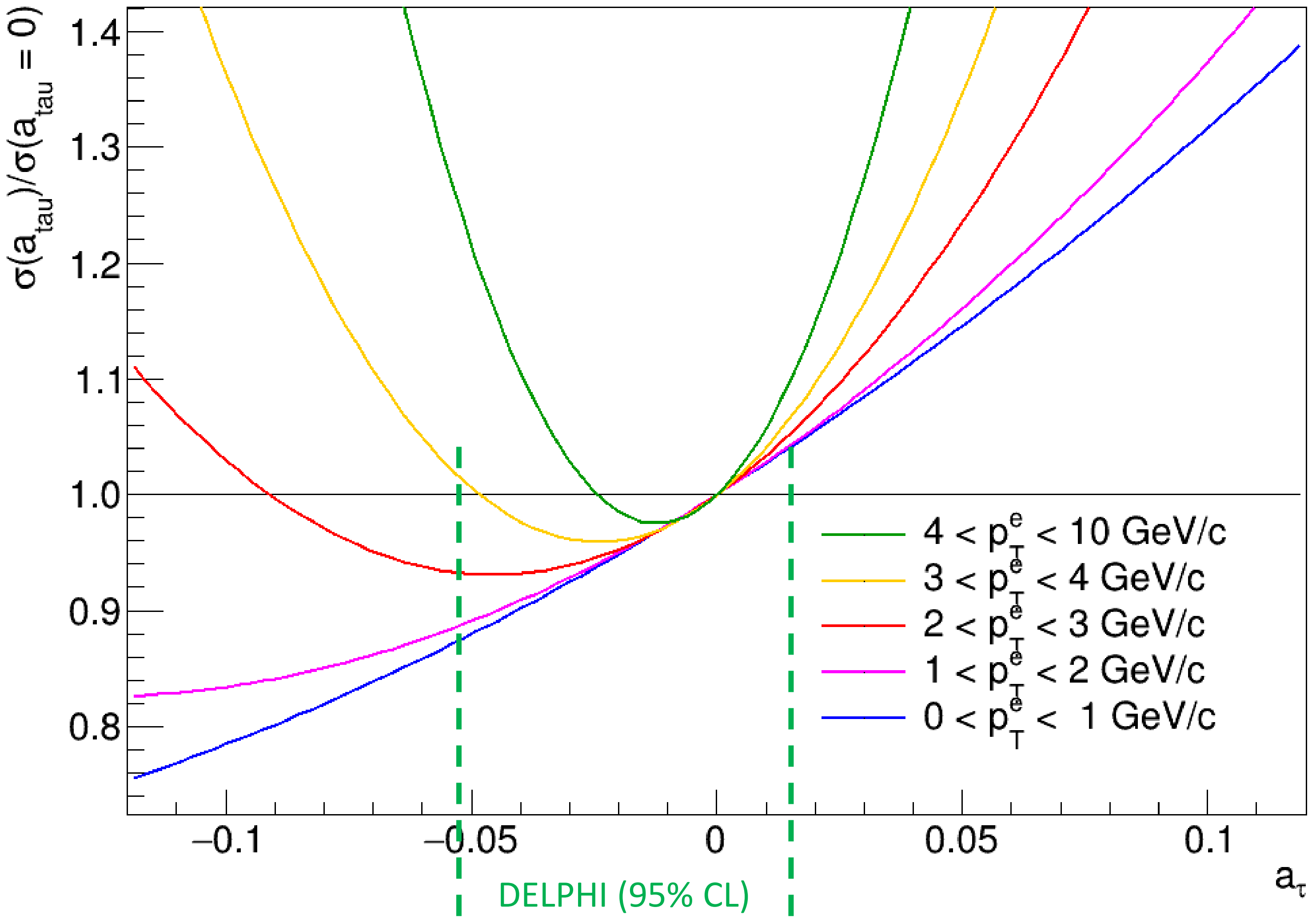
$$i\Gamma^\mu(q) = -ie\left(\gamma^\mu F_1(q^2) + \frac{i}{2m}\sigma_{\mu\nu}q^\nu F_2(q^2)\right) \rightarrow -ie\left(\gamma^\mu + \frac{i}{2m}\sigma_{\mu\nu}q^\nu a_\tau\right)$$



- Using Pythia8 for tau decays
- Looking into 1 electron + 1 pion/muon events
- Assuming Pb-Pb, L = 10 nb^{-1}
- Fiducial cuts:
  - $|\eta|<4$
  - $p_T > 0.05$ GeV/c
- ~ 2.3 mln events with 1 electron + 1 pion/muon

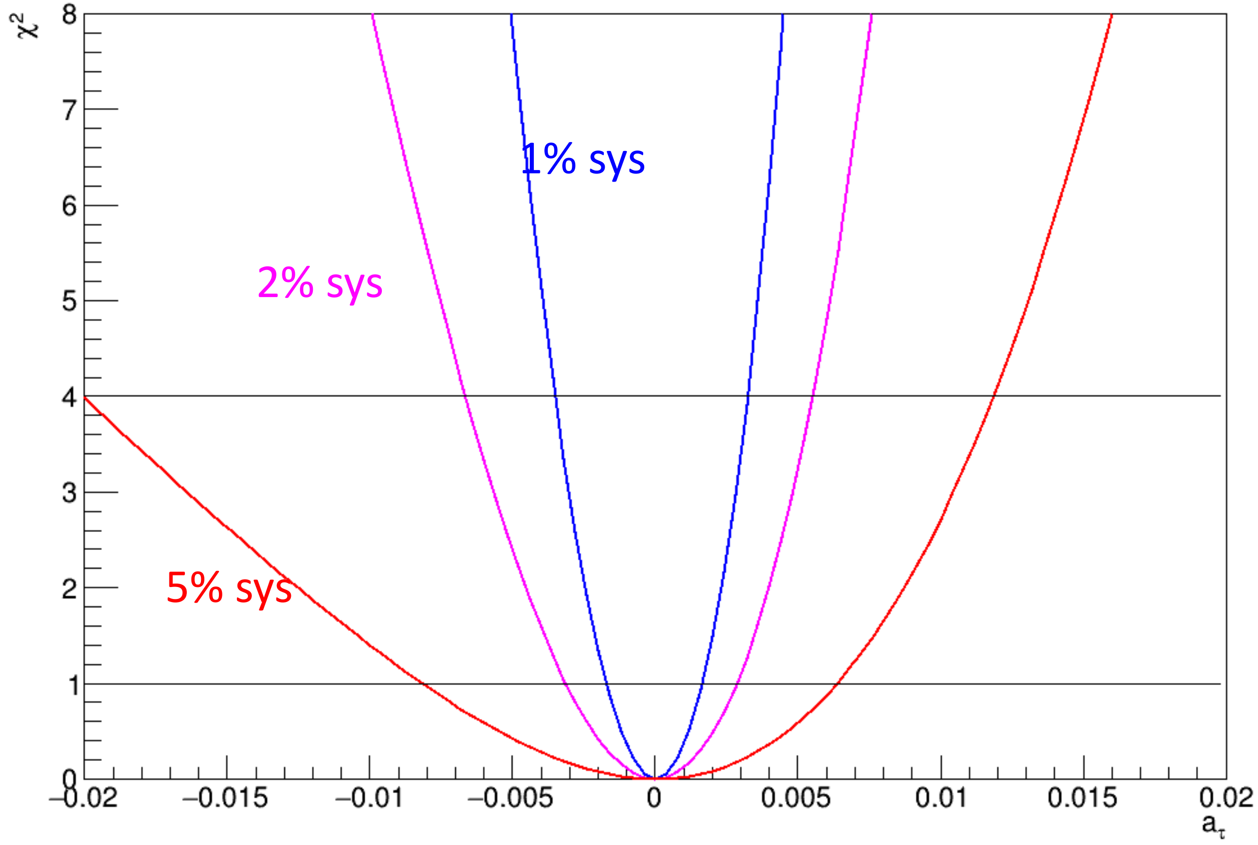


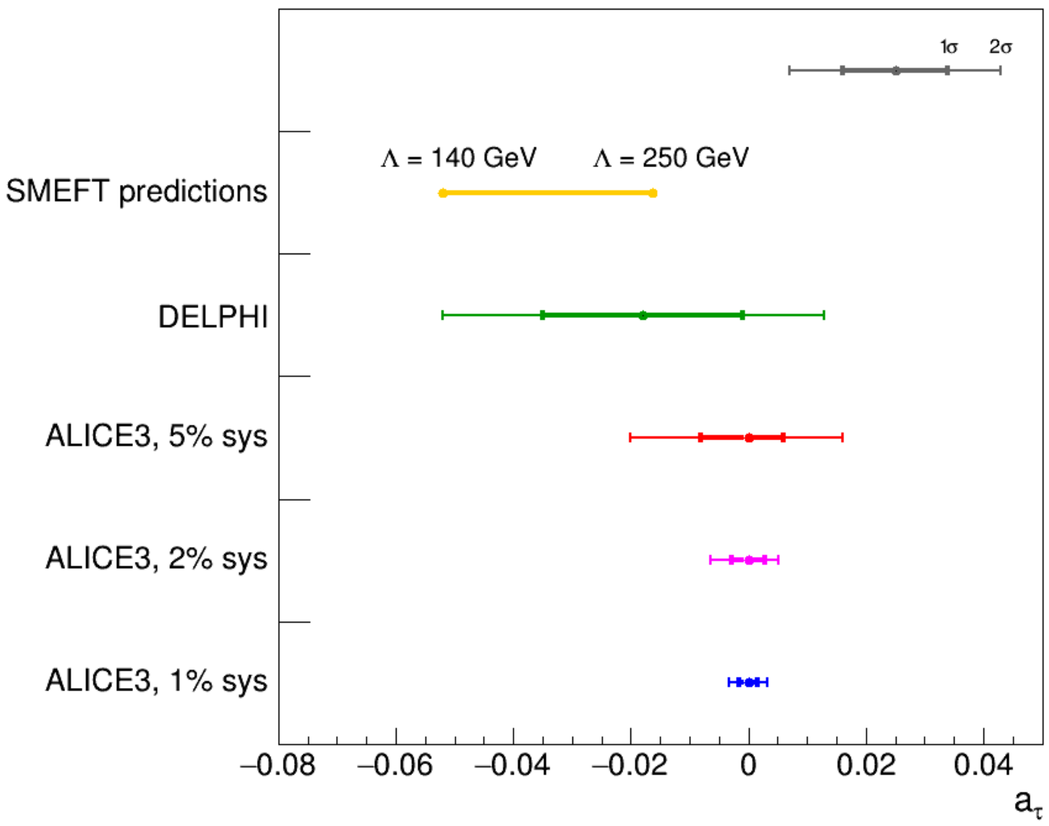
Closer look: sensitivity to a_τ in p_T bins



- Ratio of electron p_T differential cross sections has a parabolic shape in the vicinity of $a_\tau = 0$
- The minimum is moving closer to 0 for high p_T

χ^2 distributions and a_τ limits for ALICE 3





Deviation from SM

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

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

- Assuming uncorrelated systematic uncertainties (ζ = 1%, 2%, 5%)
- Precision limited by systematics

Possibility to tighten a_τ limits by factor 10

Conclusions

- Light-by-light: high potential to extend the measurements down to low masses
- ALP searches: potential to fill the gap from 0.05 to 5 GeV
- High precision and wide-acceptance ECAL would be desirable
- a_τ measurements with ALICE 3 look promising and competitive
  - precision is limited by systematic uncertainties