Results and prospects of two-photon interaction studies with the ALICE experiment at the LHC

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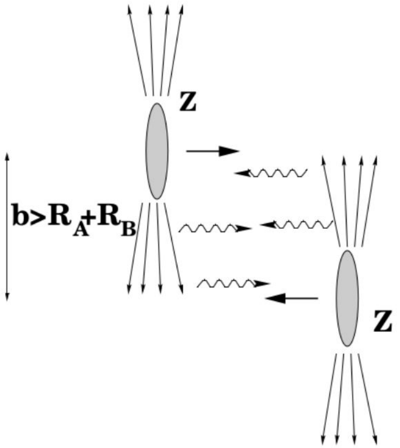
on behalf of the ALICE collaboration

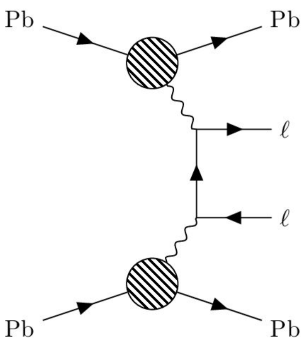
Twenty-first Lomonosov conference, Moscow
25.08.2023

Ultraperipheral collisions

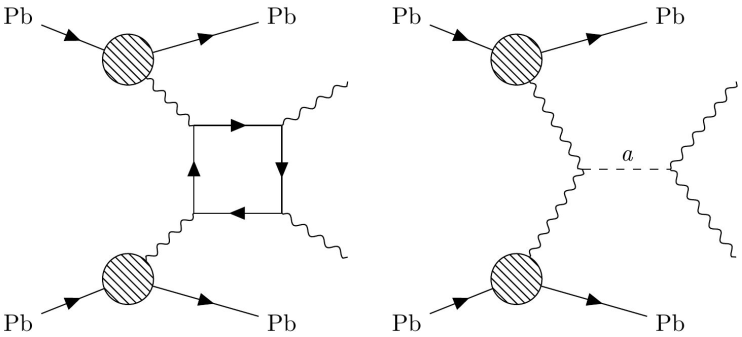


- $b > R_A + R_B$

  Hadronic interactions strongly suppressed
- Nuclei create strong electromagnetic fields
  - Can be described in terms of equivalent photon fluxes
  - Quasi-real photons with $q < \hbar c/\mathrm{R} \sim$ 30 MeV
  - Photon fluxes ∝ Z^2 →cross sections of $\gamma\gamma$ interactions ∝ Z^4
- Unique opportunity to test the Standard model in a very clean environment



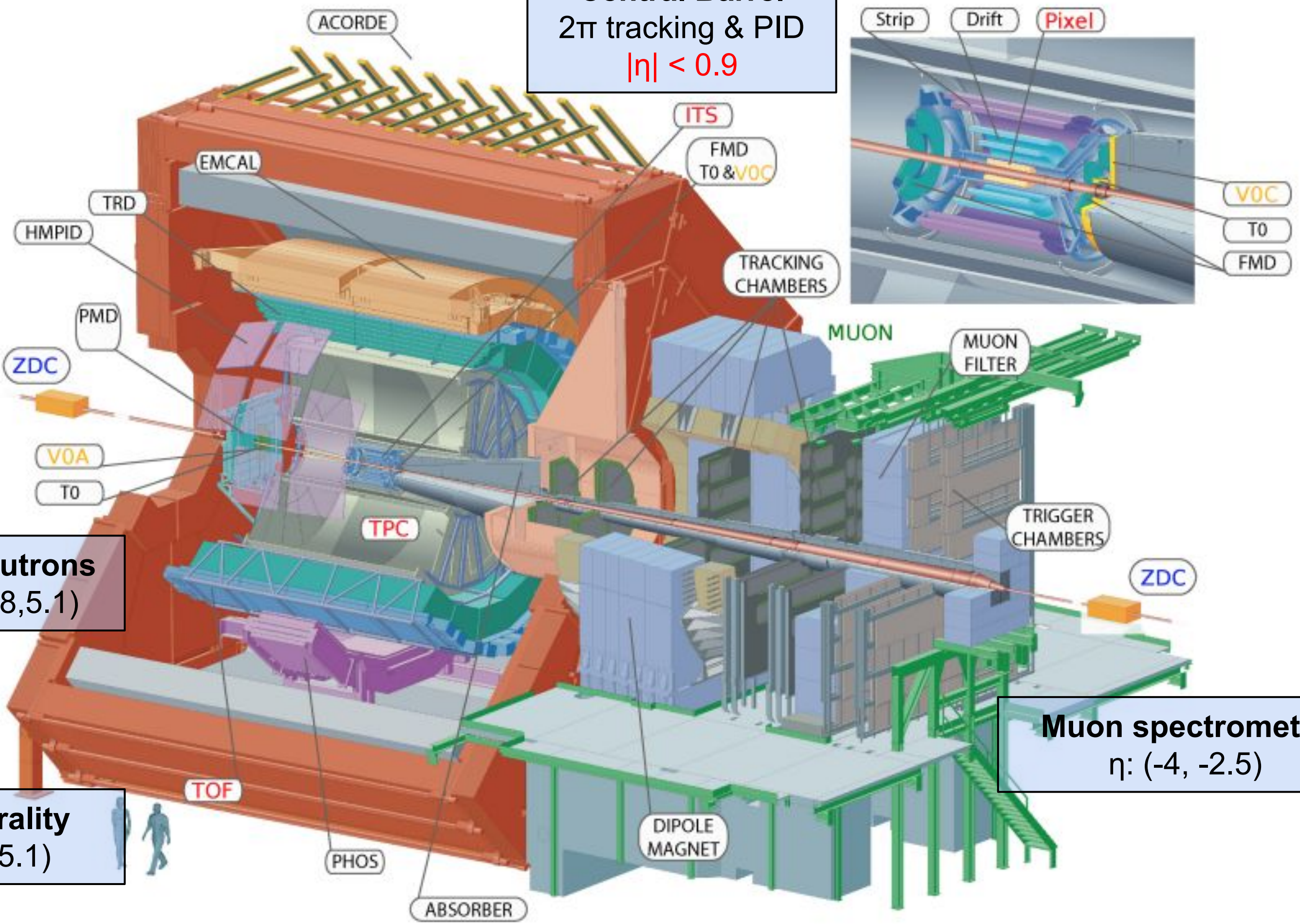
Lepton pair production



Light-by-light scattering and ALP production

ALICE during Runs 1-2

Central Barrel
2π tracking & PID
|η| < 0.9

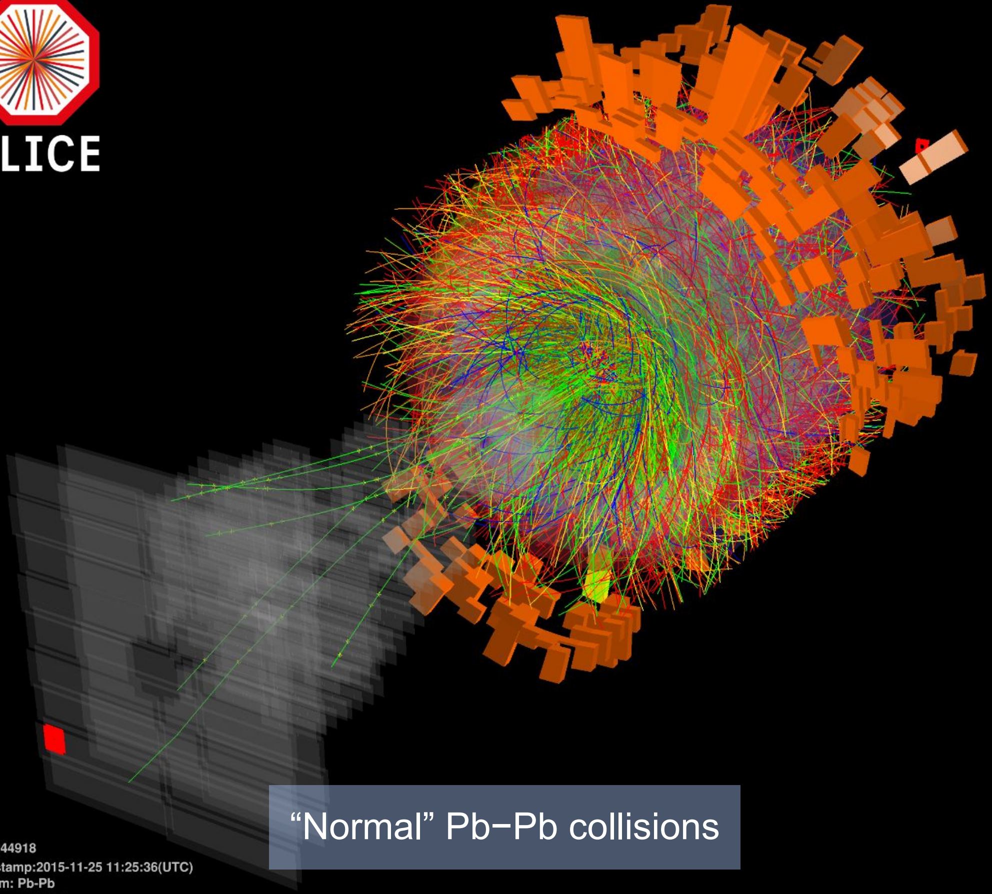


ZDC - forward neutrons
η: (-1.7, -3.7), (2.8,5.1)

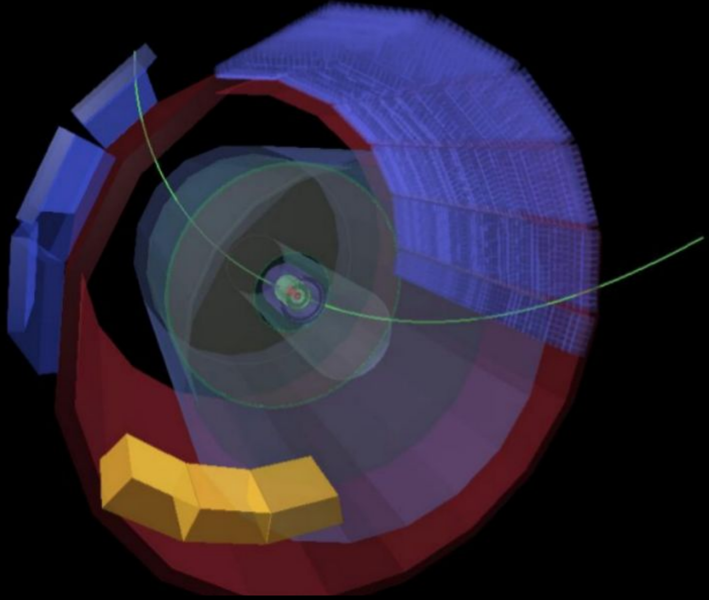
Muon spectrometer
η: (-4, -2.5)

V0A/V0C - centrality
η: (-1.7, -3.7), (2.8,5.1)

ALICE

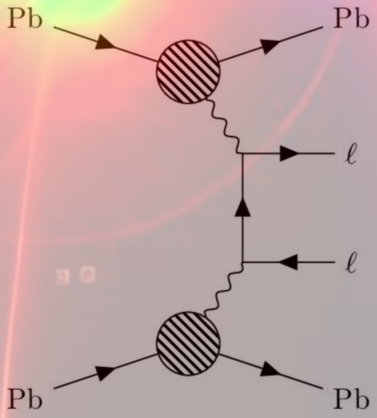


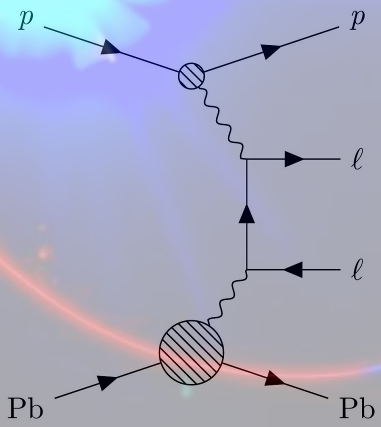
“Normal” Pb−Pb collisions



Ultraperipheral collisions

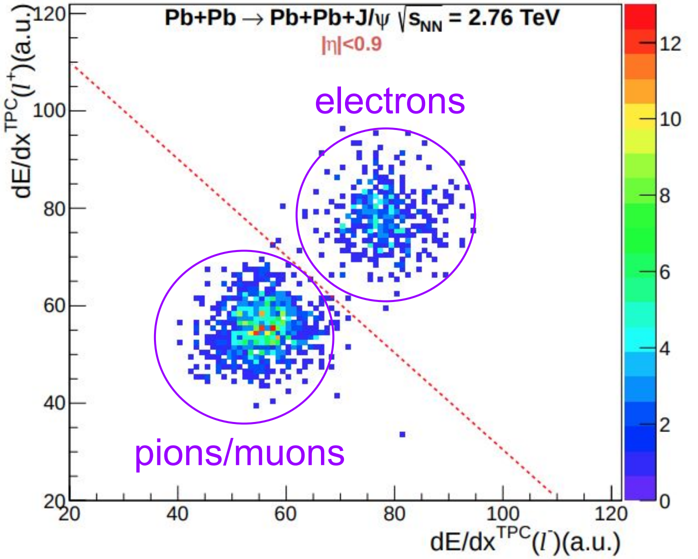
- ★ Minimum bias collision → thousands of tracks!
- ★ UPC→several tracks

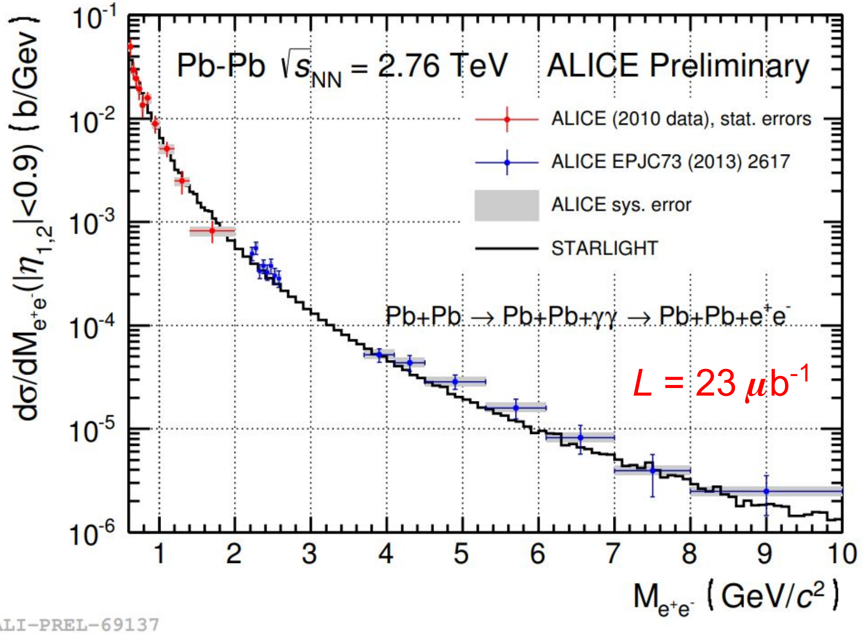




Dilepton continuum

Dielectrons in Pb−Pb collisions

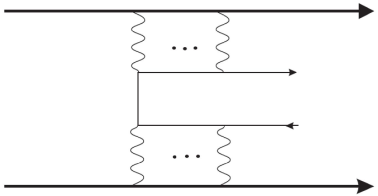




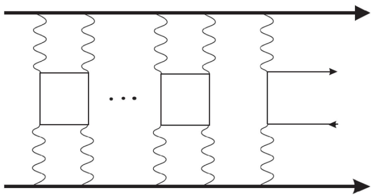
- ALICE covered mass range $0.6 < m_{ee} < 10$ GeV/c^2
- More data expected in Run 3→~13 nb^{-1}
- Data 20% above the STARlight predictions (compatible within ~1.5σ)

Dimuons in Pb−Pb collisions

- ATLAS data on dimuon continuum also above STARlight predictions
- Equivalent photon approximation
  - STARlight: hard cut-off on nuclear radius
  - Superchic, Upcgen: realistic form-factor
- Higher-order corrections to the LO QED?
  - Multiple interactions due to high Zα, e.g. Hencken et al. PRC 75 (2007) 034903

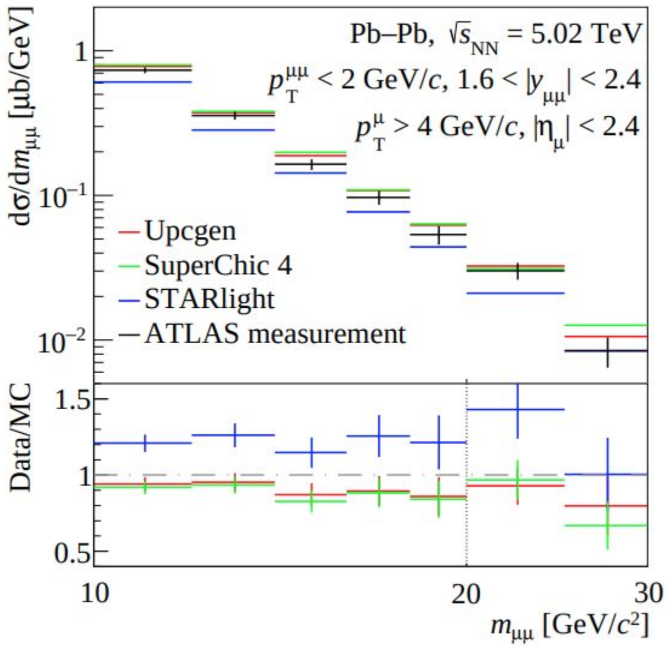


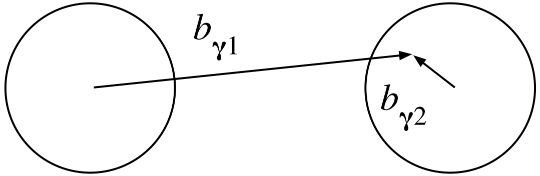
Coulomb corrections



Unitarity corrections

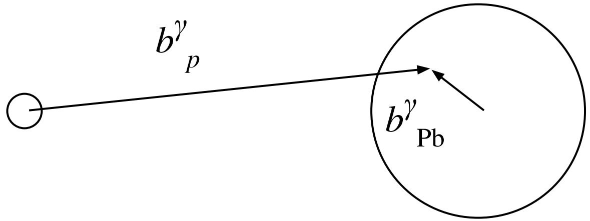
Burmasov et al., CPC 277 (2022) 108388

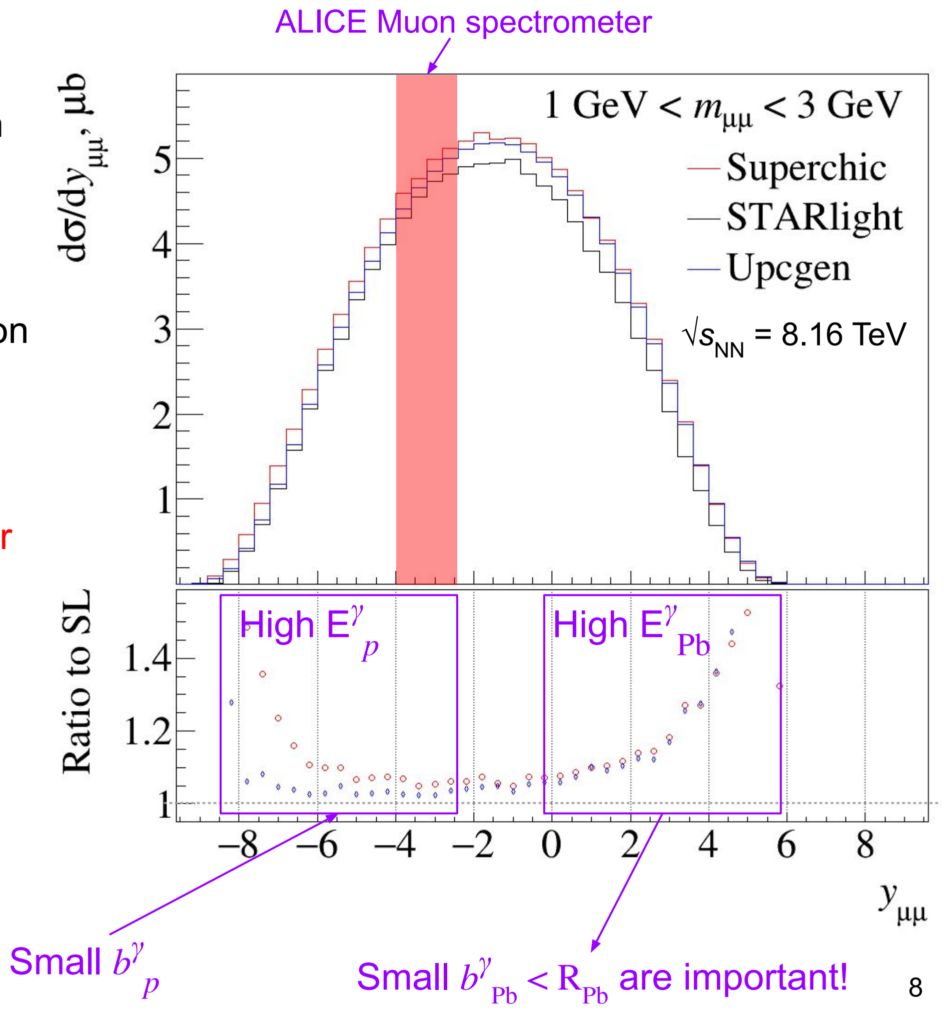




Dimuons in p−Pb collisions

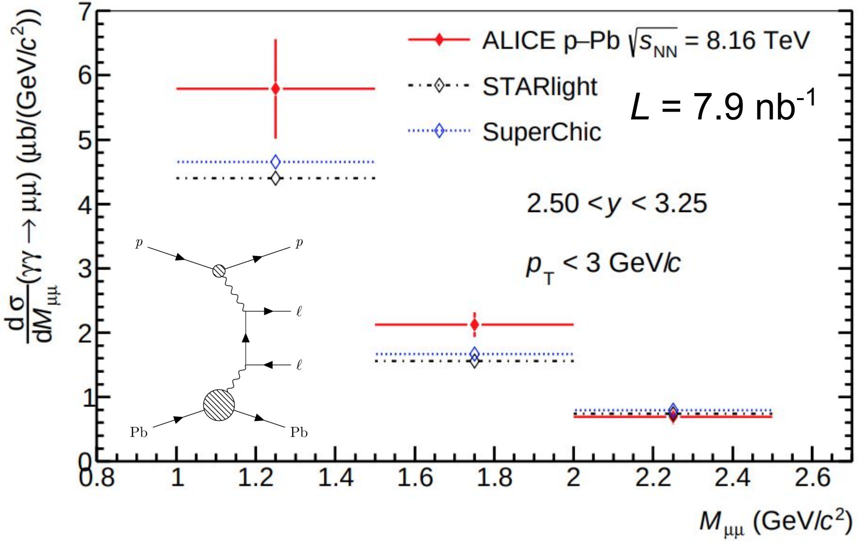
- Simulations with STARlight, Superchic and Upcgen
- In p-Pb:
  - STARlight, Upcgen→equivalent photon approximation
  - Superchic→amplitude-level calculations, photon flux from protons based on photon PDFs
- Negative rapidities correspond to high-energy photons emitted from protons
- p-Pb collisions allow to study effects of higher-order corrections and small b^{γ} independently

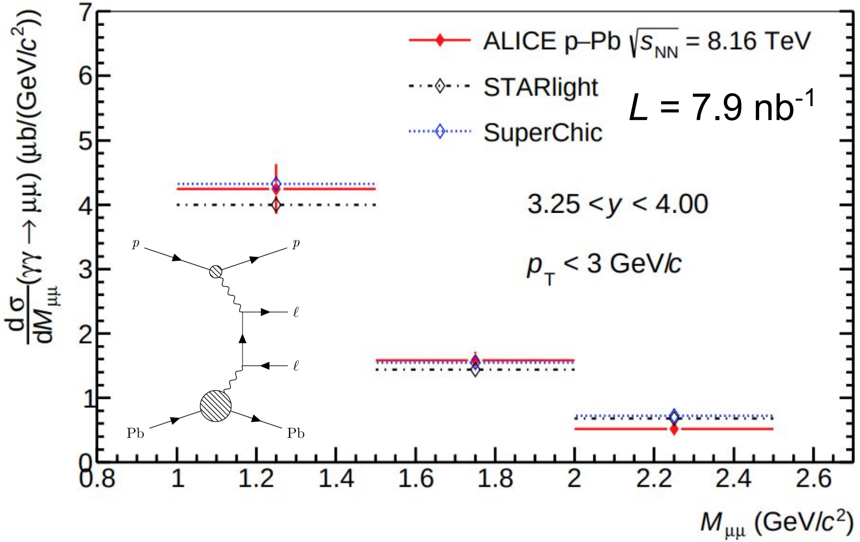




Dimuons in p−Pb collisions

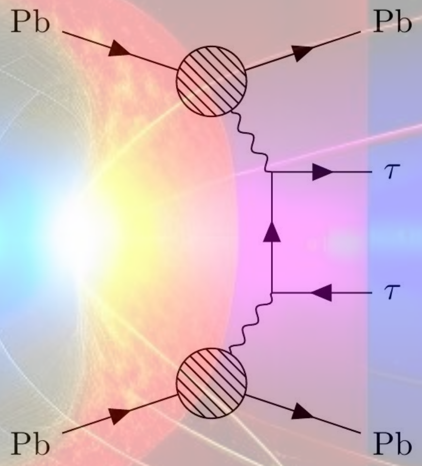
ALICE Collab., 2304.12403





- Analysis of dimuons in the Muon spectrometer
- Superchic is in general closer to data than STARlight, but…
- …Deviation of up to 20% between data and predictions

- Analysis of dilepton continuum is interesting! And also useful for other analyses…



Tau anomalous magnetic moment

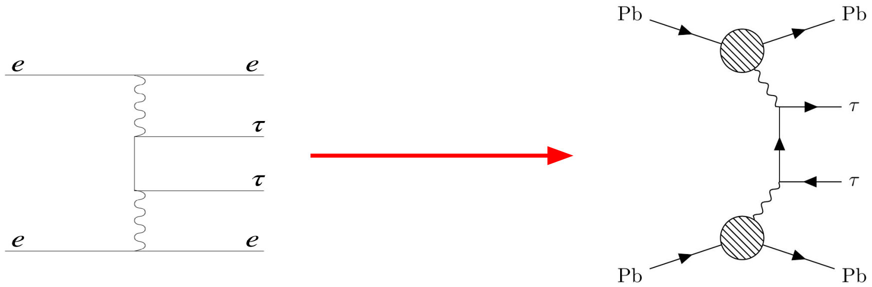
Anomalous magnetic moment of τ lepton

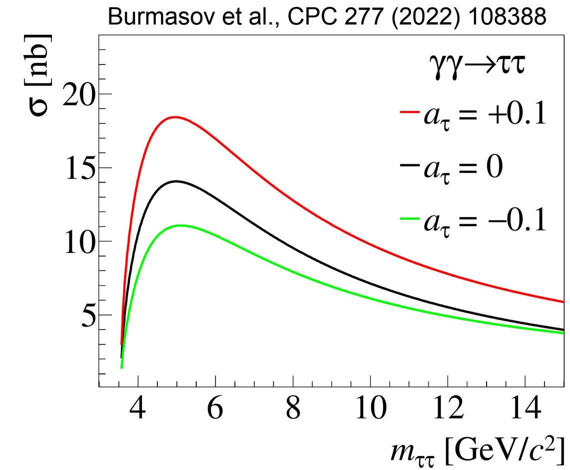
- Muon anomalous magnetic moment →4.2σ deviation from SM
- Tau is short-lived → unable to use standard methods
- Alternative: cross section of tau pairs production in **γγ**
- Constraints by DELPHI with $e^+e^- \to e^+e^- \tau\tau$

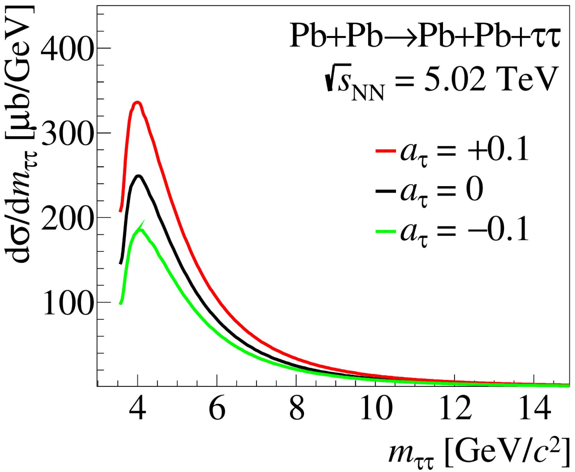
Theory: $a_\tau^{\mathrm{SM}} = 0.00117721(5)$

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

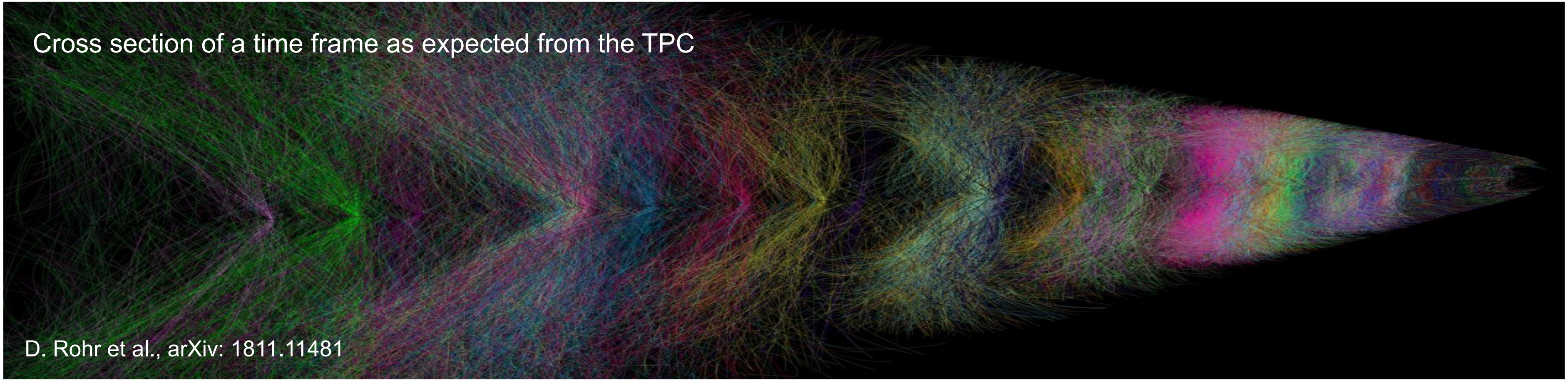
- F.del Aguila et al., PLB, 271, 256-260, 1991:
  Pb-Pb UPCs can be used for the measurement





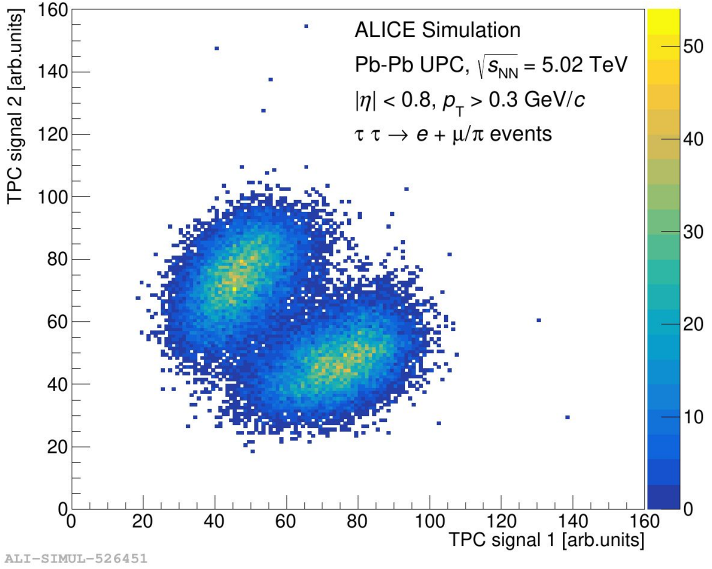


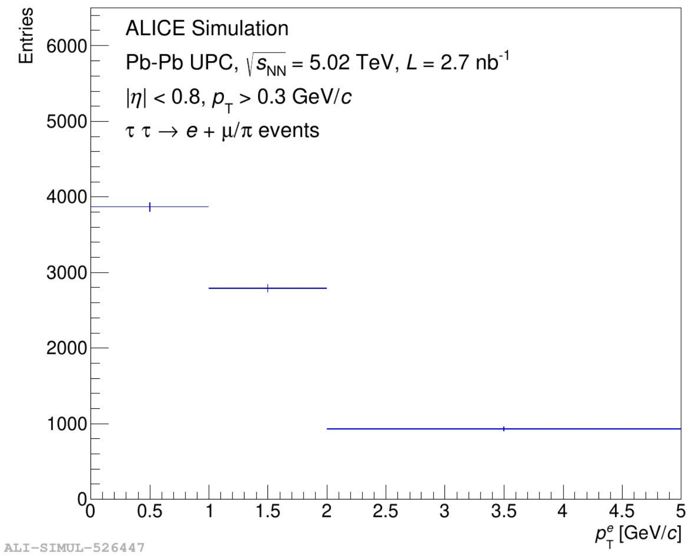
Realistic simulations for Run 3



- Simulations in continuous readout mode using the Alice O2 framework
  - Recording data timeframe-by-timeframe
  - Relying on TOF matching for accurate timing
- Minimum-bias Pb−Pb from Pythia 8
- Signal events:
  - Signal from dedicated generator — Upcgen (Burmasov et al. CPC 277 (2022) 108388)
  - Events of interest: electron + muon or pion from tau decays: $\tau\,\tau \rightarrow e + \mu/\pi$
  - Track cuts on generator level: p_{T} > 0.3 GeV, $|\eta|$ < 1

Expected electron p_T spectra

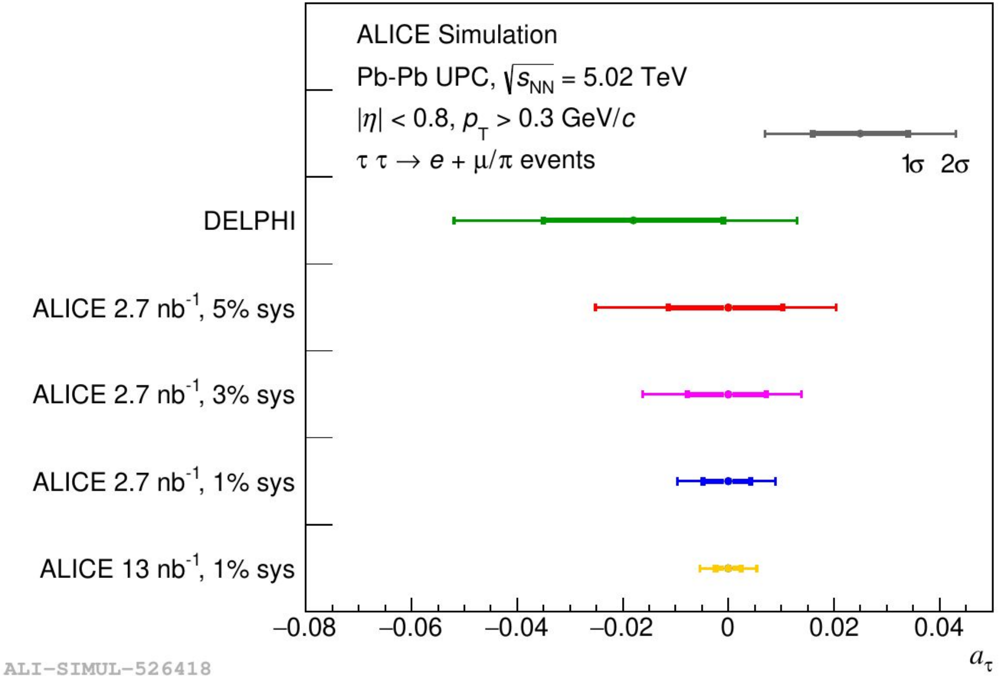




- Matching pairs of tracks using timing
- Using only tracks with TOF
- Veto on signals in the forward detectors
- TPC PID: electron + pion/muon

- Expected yields:
  ~7600 events at 2.7 nb^{-1}→first year of Run 3
  ~36000 events at 13 nb^{-1}→Run 3+4 statistics
- Purity of selection: higher than 96%
- Possible sources of background: e^+e^- , $\mu^+\mu^-$, $\pi^+\pi^-$, vector meson decays, etc.

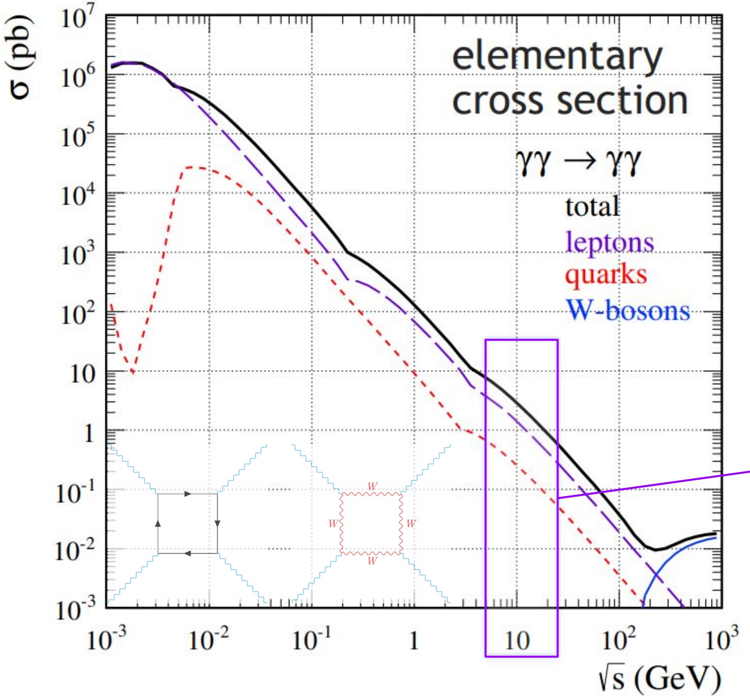
Expected a_τ limits with ALICE

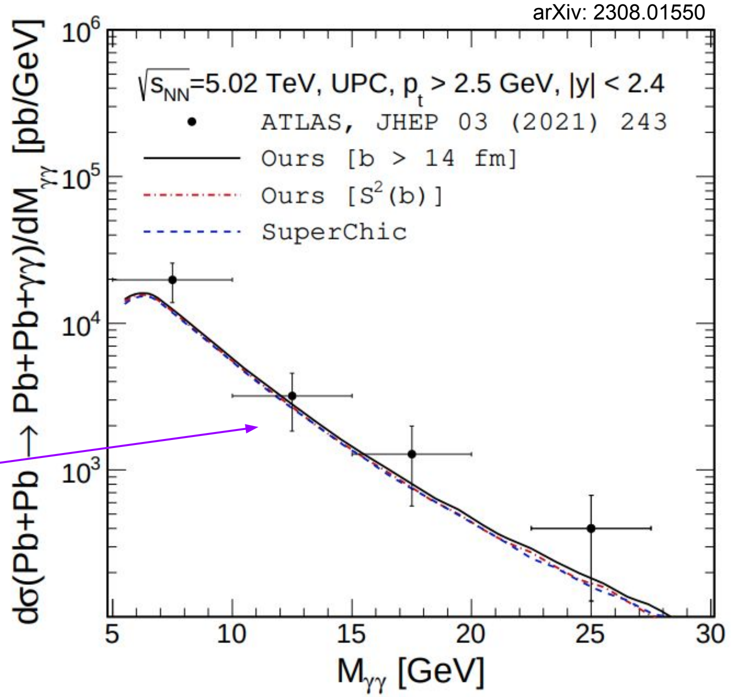


- Limits using χ^2 calculated with expected yields
- Uncorrelated systematic uncertainties: ζ = 1%, 3%, 5%
- Systematic uncertainties are crucial precision — try to reduce using ratios to $\gamma\gamma \to e^+e^-$ ($\mu^+\mu^-$) process
- Best case scenario — limits on level of ±0.005 at L = 13 nb^{-1} and ~1% sys.

Light-by-light scattering

Light-by-light scattering



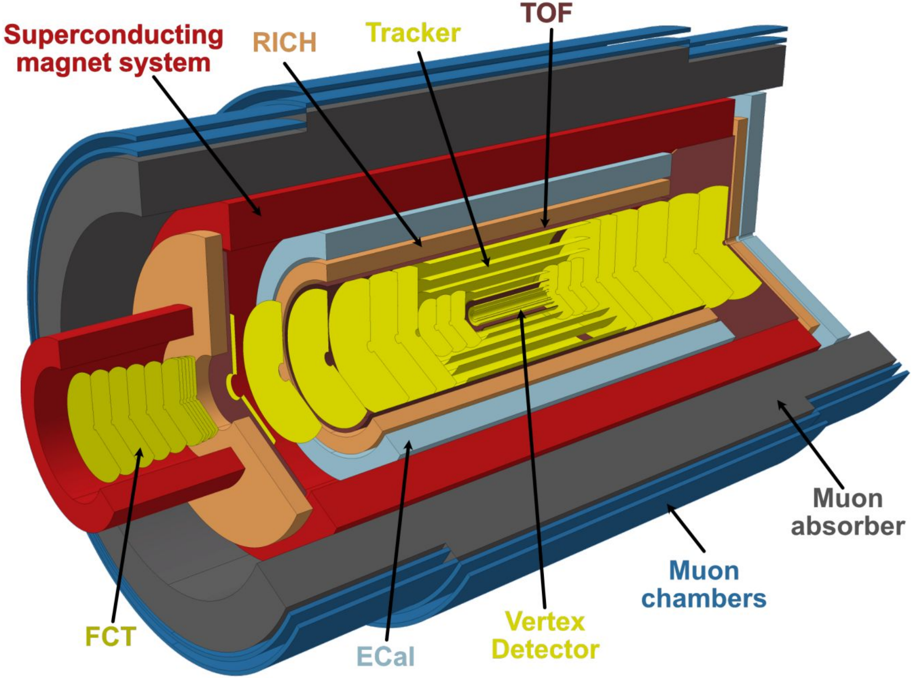


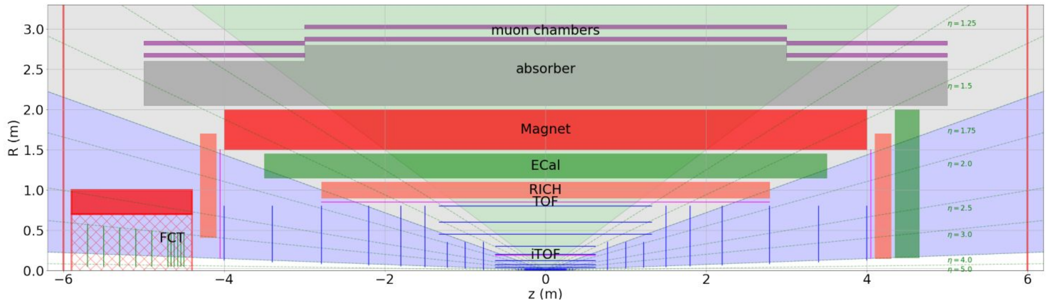
- In the Standard Model: leptons, quarks, W
- Sensitive to new physics: SUSY, axion-like particles
- First evidence: ATLAS (*Nature Phys. 3, 852, 2017*) and CMS (*Phys.Lett.B, 797, 134826, 2019*) with Pb-Pb UPCs
- Measurement is limited by trigger: $m_{\gamma\gamma}$ > 5 GeV → precision is limited by statistics

ALICE 3

Run 5: 2032+
CERN CDS: LHCC-I-038

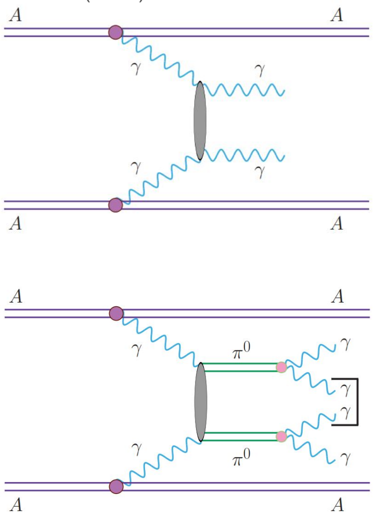
- Magnetic field up to ~2 T
- Large pseudorapidity range $|\eta| < 4$
- Charged particle tracking down to $p_T \sim 10$ MeV → soft photons measurements with photon conversion method

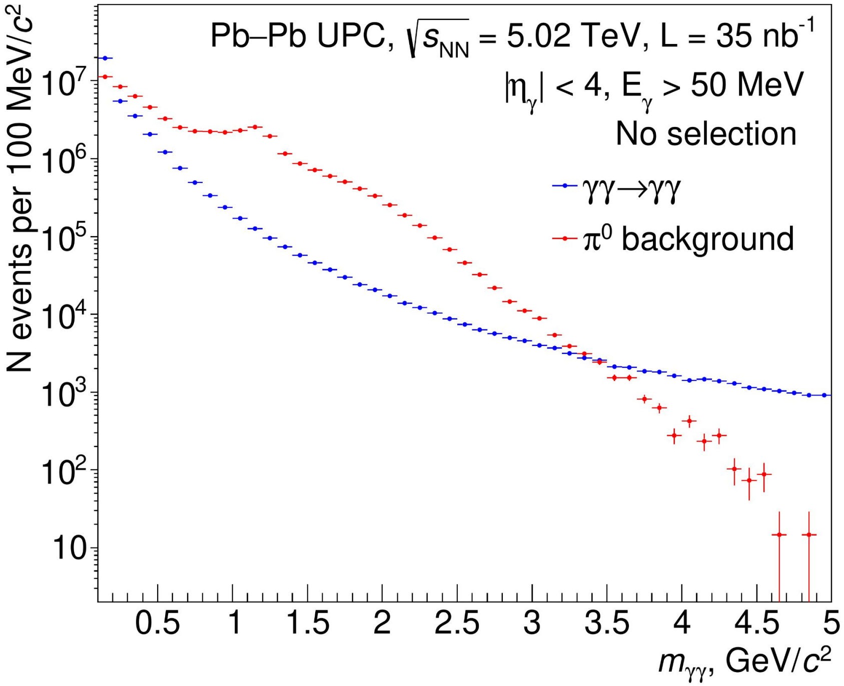




Difficulties at low invariant masses

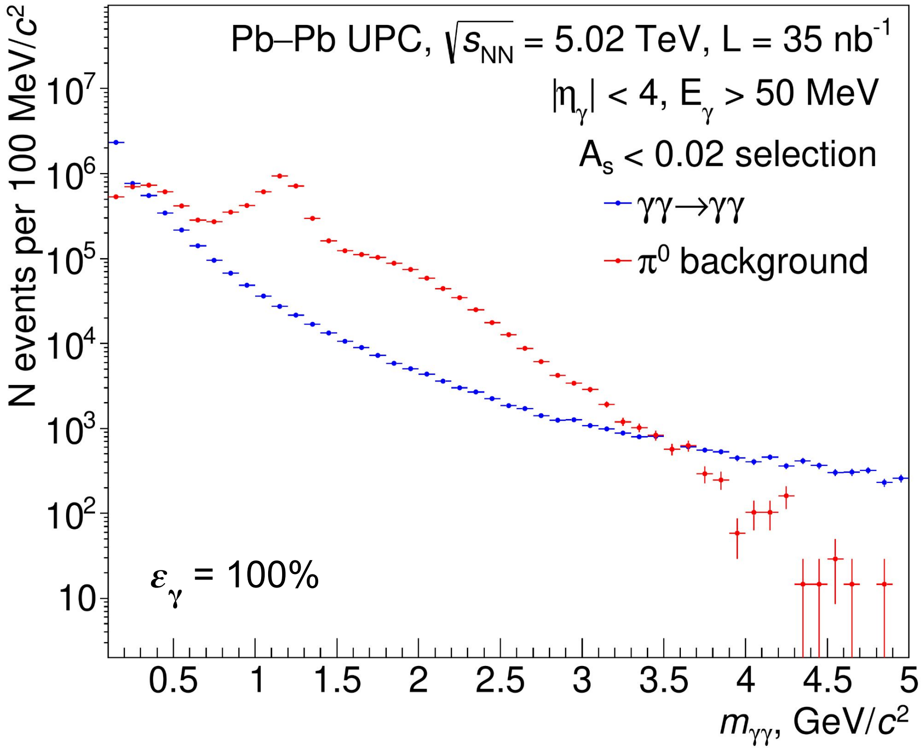
PRD **99** (2019) 093013

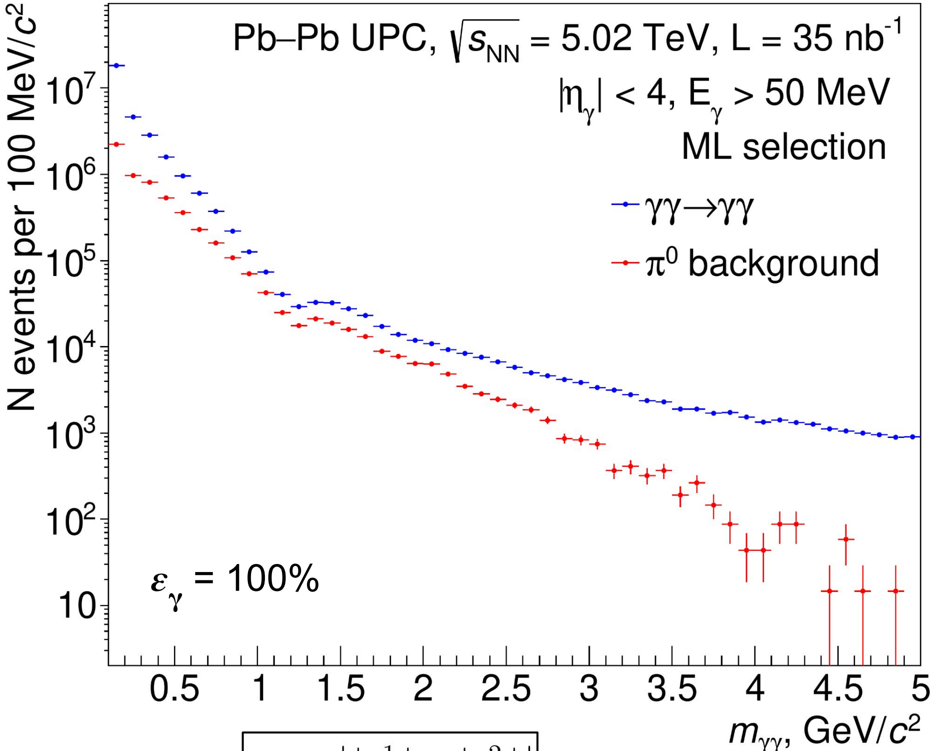




- Simulations of signal and background with a dedicated event generator — Upcgen [CPC 277 (2022) 108388]
- Significant $\gamma\gamma$ background from $\pi^0\pi^0$ decays at $m_{\gamma\gamma}$ < 3 GeV

Event selection



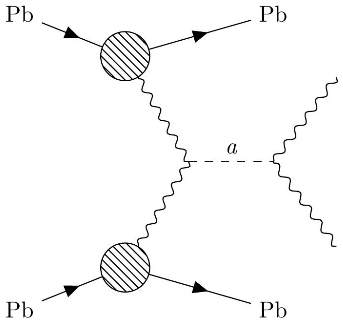


$$A_s = \left| \frac{|p_T^1| - |p_T^2|}{|p_T^1| + |p_T^2|} \right|$$

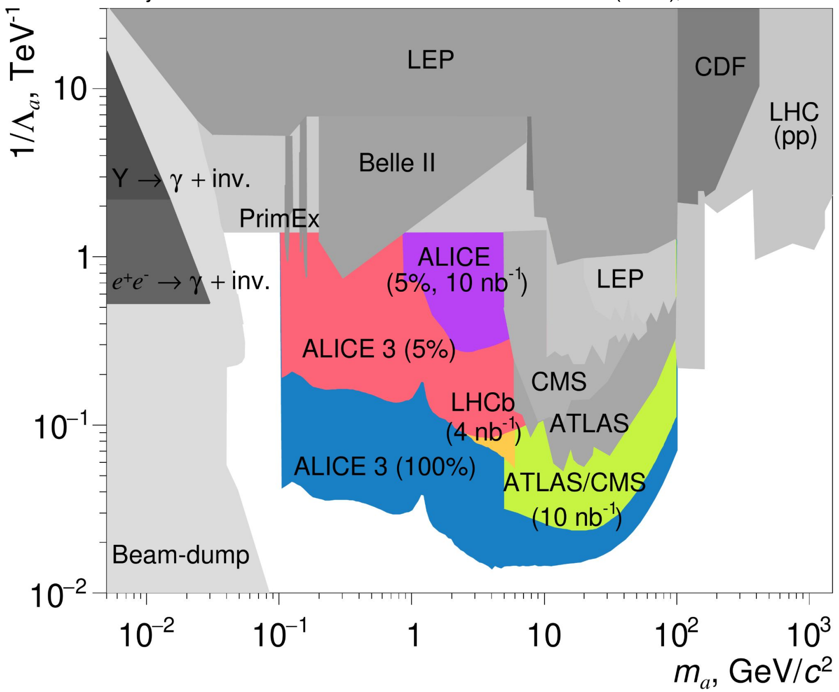
- Asymmetry cut slightly improves the situation at low masses
- Selection with gradient boosted decision tree suppresses the background in a wide mass interval

Axion-like particles

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}$$



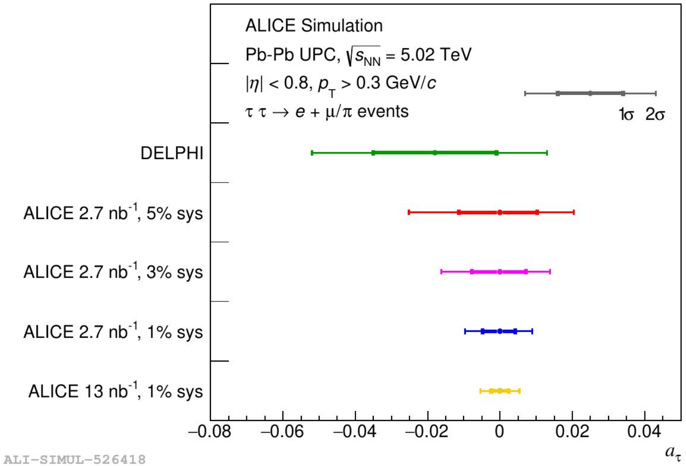
Limits from ATLAS, JHEP 03, 243 (2021)
Projections for ATLAS/CMS from PRL 118 (2017), 171801
Projections for LHCb from Goncalves et al. EPJC 81 (2021), 522

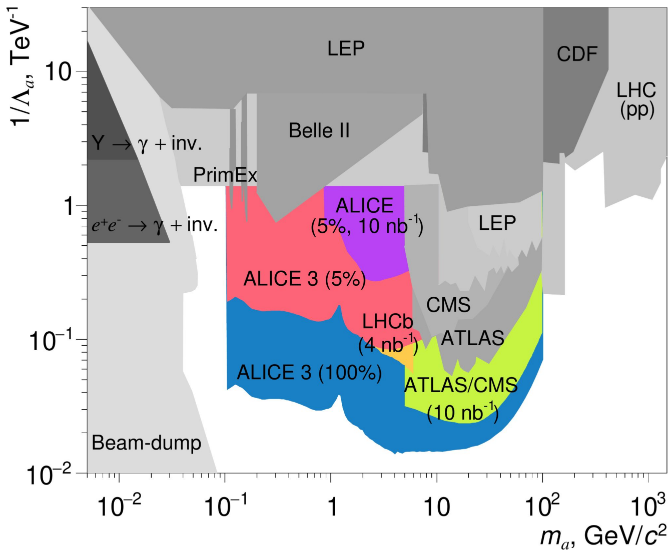


- Axions: in Peccei-Quinn theory to approach strong CP symmetry
- Axion-like particles — a class of pseudoscalar particles
  - Possible dark matter candidates
- Estimates for Λ limits: signal, light-by-light scattering, $\pi^0\pi^0$ decays from Upcgen
- Photon reconstruction efficiency: 5% — photon conversions, 100% — ideal
- Searches are hardly possible near π^0, η, η', χ_c

Summary and outlook

- Detailed analysis of dilepton continuum can reveal subtle effects in two-photon interactions
- Possibility to obtain competitive results for tau anomalous magnetic moment
- Future ALICE 3 experiment can give a unique opportunity for light-by-light scattering studies
- Possibility to perform a search for axion-like particles in untouched region





This work was supported by the Russian Foundation for Basic Research (21-52-14006), the Austrian Science Fund (FWF, I 5277-N) and the Russian Science Foundation (22-42-04405)

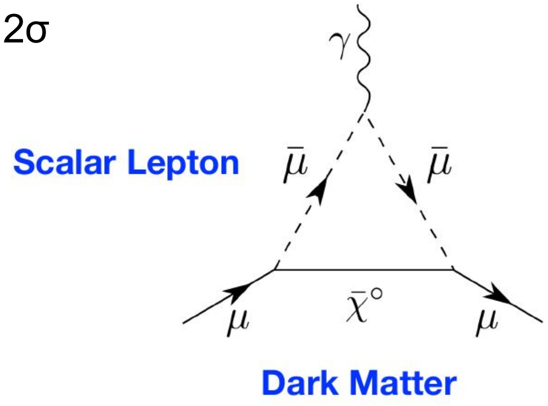
BACKUP

Anomalous magnetic moment of τ lepton

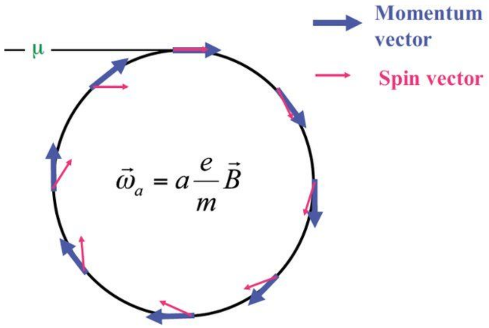
- Muon anomalous magnetic moment deviates from SM predictions by 4.2σ
- Sensitivity to supersymmetry effects depends on lepton mass

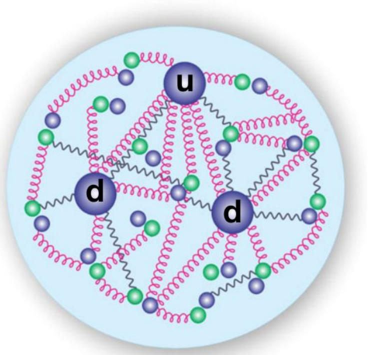
$$\delta a_\ell \sim m_\ell^2 / M_S^2$$

  - ➢ τ is up to ~280 more sensitive to new physics than μ
- Possible deviations may indicate composite nature of leptons
  - ➢ Example — neutron and proton *g-2*
- Short lifetime (10^{-13} sec) makes direct measurements with spin precession methods very difficult



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

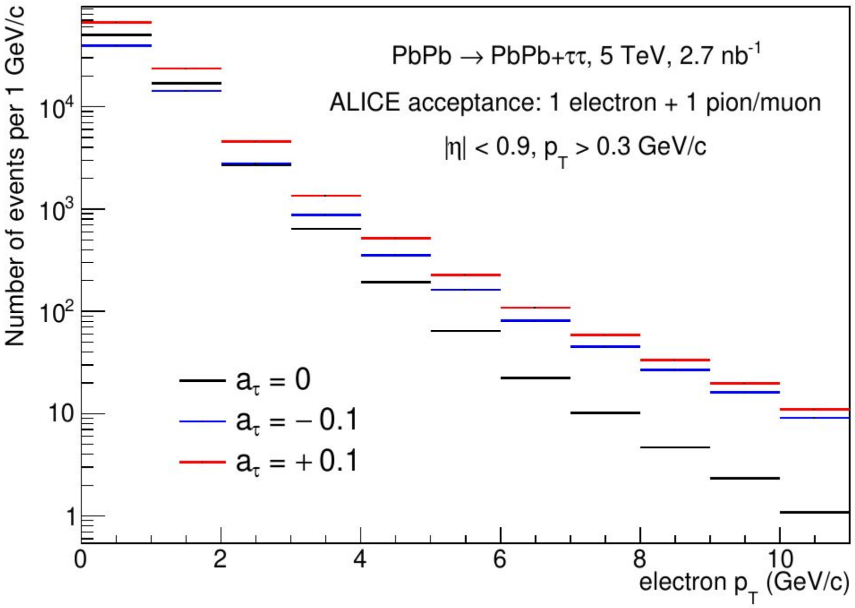




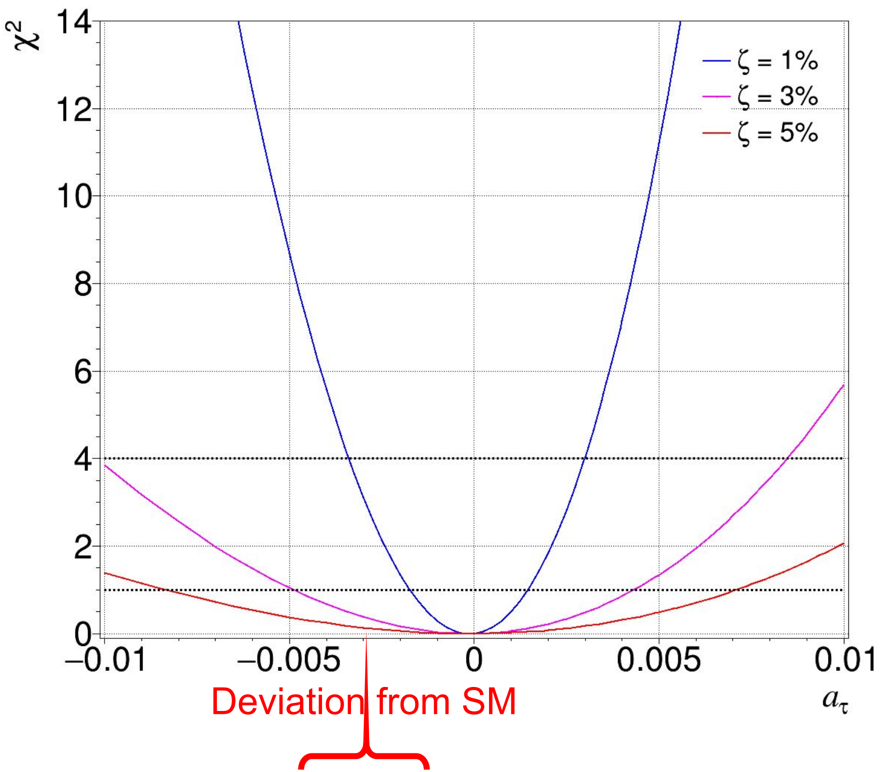
Generator-level studies in ALICE acceptance

- Upcgen for ditau production
  CPC 277 (2022) 108388
- Pythia 8 for tau decay simulations
- 1 electron + 1 π/μ
- Central barrel: $|\eta| < 0.9$
- p_T > 300 MeV→for good TOF matching

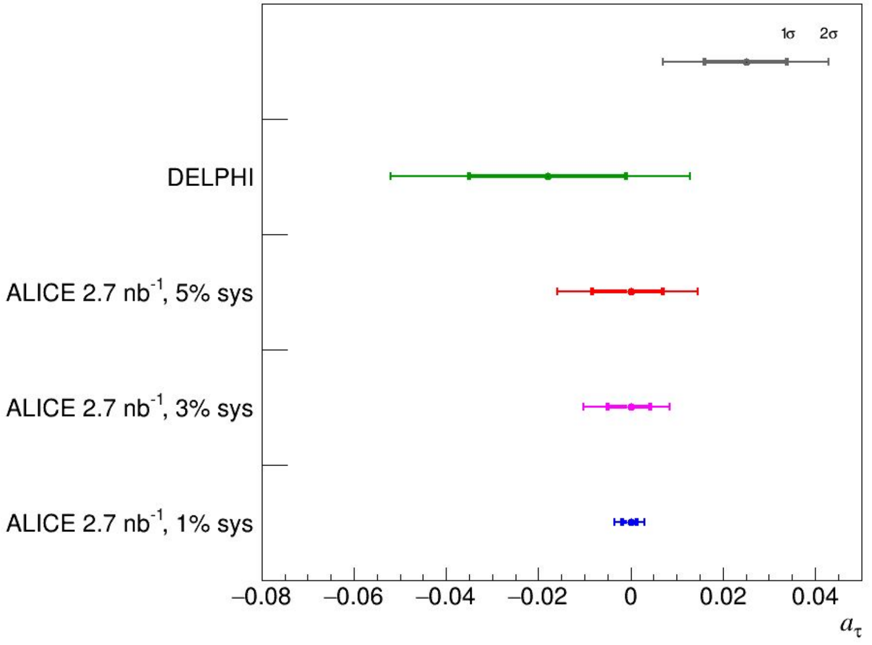
Burmasov et al., arXiv: 2203.00990



Expected a_τ limits with ALICE



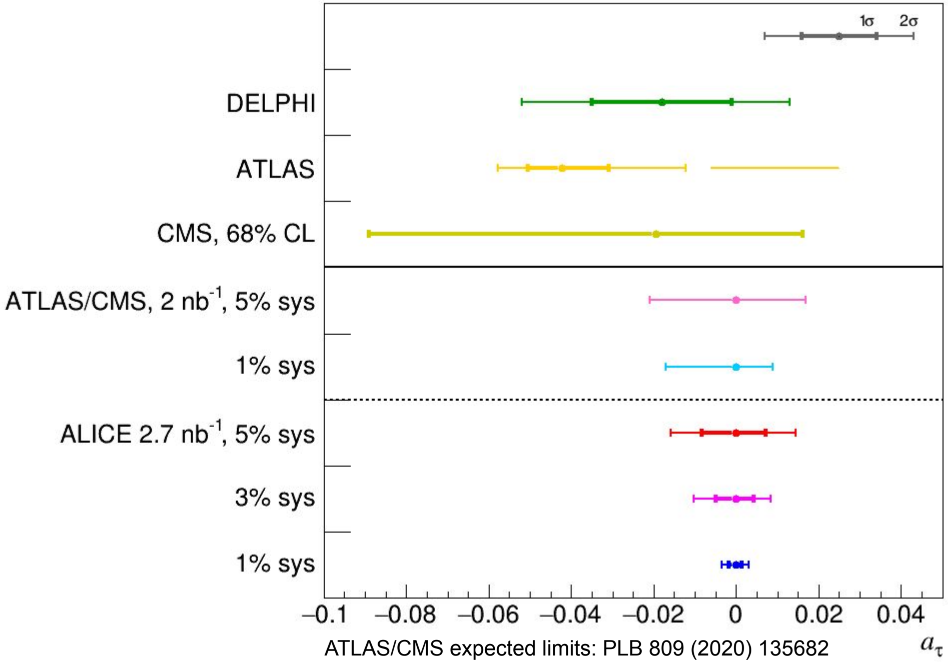
Burmasov et al., arXiv: 2203.00990



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

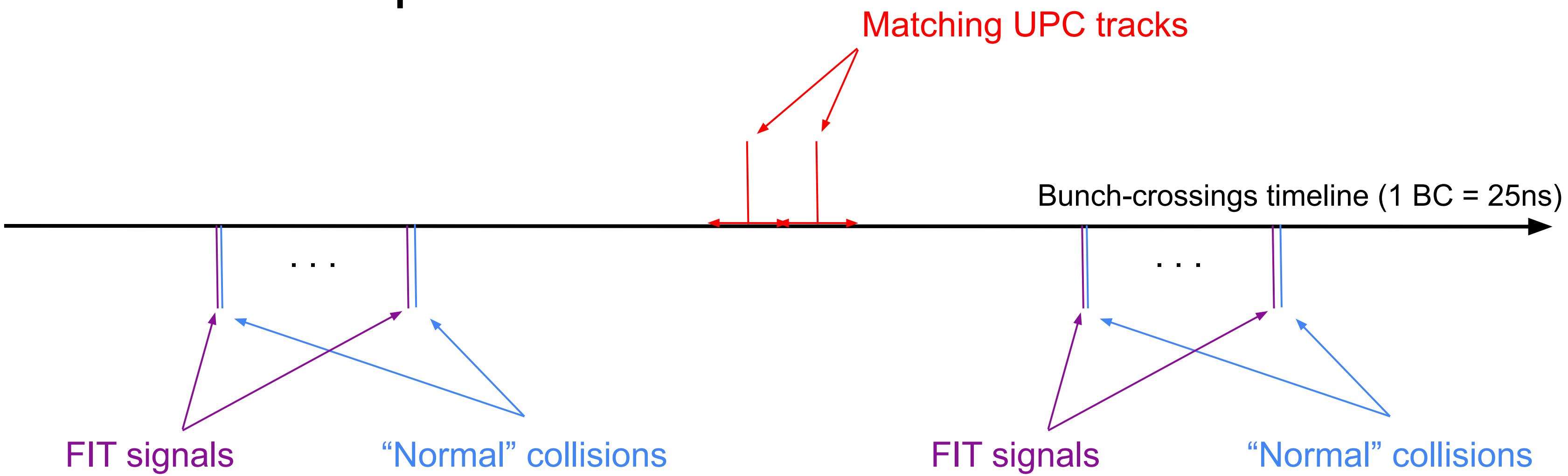
- Uncorrelated systematic uncertainties: ζ = 1%, 3%, 5%
- Precision is limited by systematics
- Need to perform realistic simulations to account for detector response

Expected a_τ limits with ALICE



ATLAS/CMS expected limits: PLB 809 (2020) 135682
ATLAS results: arXiv:2204.13478
CMS results: DIS 22' talk and CDS: CMS-PAS-HIN-21-009

Event selection procedure



- Using only tracks with TOF matches →very precise timing
- Matching pair of tracks in the same bunch-crossings
- No simultaneous activity in forward detectors
  →no FIT signals in the bunch-crossing
  →excluding minimum-bias events
- Unlike-sign tracks