Light-by-light scattering, τ-lepton g-2, and axions searches in future ALICE

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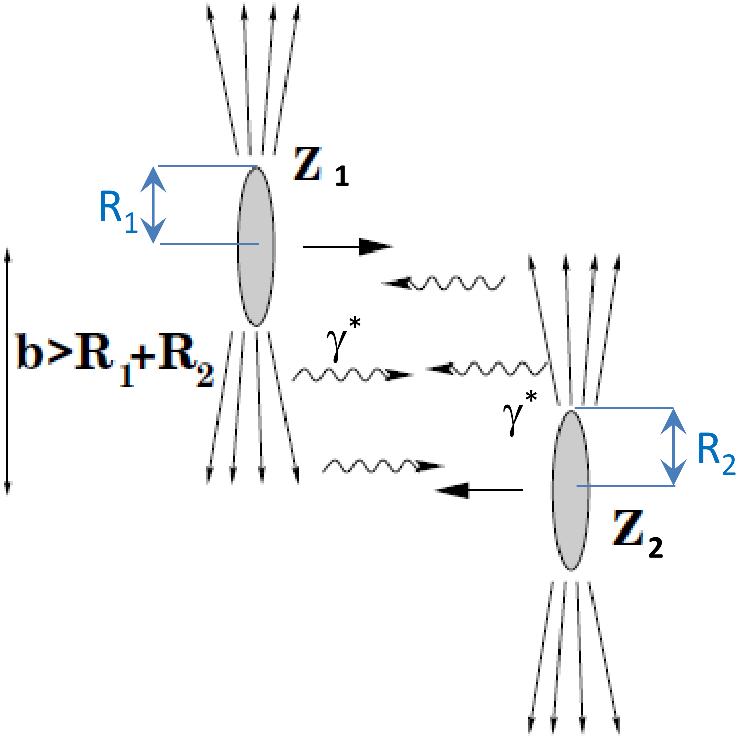
Real and virtual photon production at ultra-low transverse momentum and low mass at LHC

1 - 5 August 2022 – GSI, Darmstadt, Germany

Outline

- Ultra-peripheral collisions
- Light-by-light scattering
  - Theory considerations
  - Experimental measurements at LHC
  - Predictions for ALICE
  - ALPs upper limits
- τ pair production and the anomalous magnetic moment of τ lepton
  - Theory predictions
  - Measurements at LHC
  - Perspectives of measurements in ALICE
- Summary

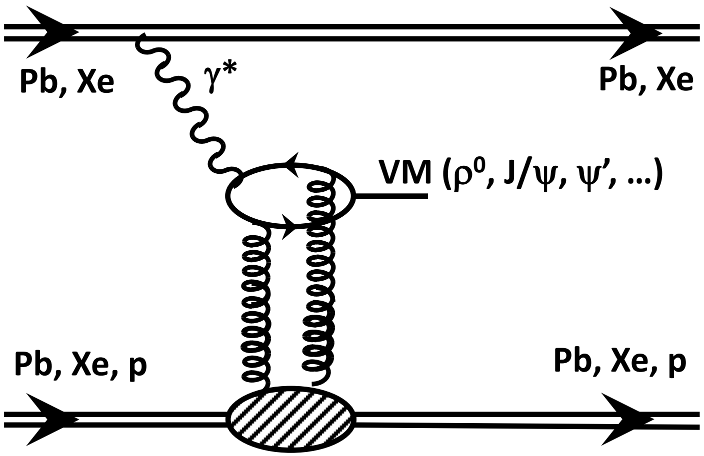
Ultra-peripheral collisions (UPC)

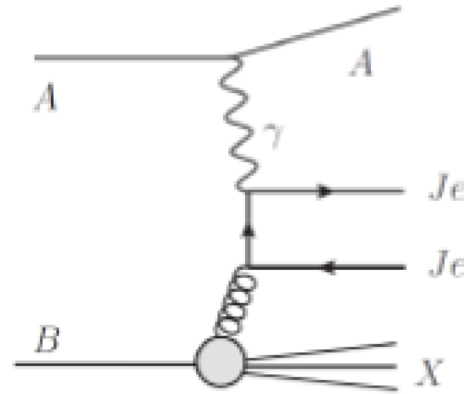


- Impact parameter $b > R_1 + R_2$
  - Hadronic interactions suppressed
- Photon induced reactions:
  - Well described in Weizsäcker-Williams approximation
  - Photon flux $\sim Z^2$ ($Z_{Pb} = 82$)
  - Large γ-induced interaction cross section
- Rapidity gap(s)

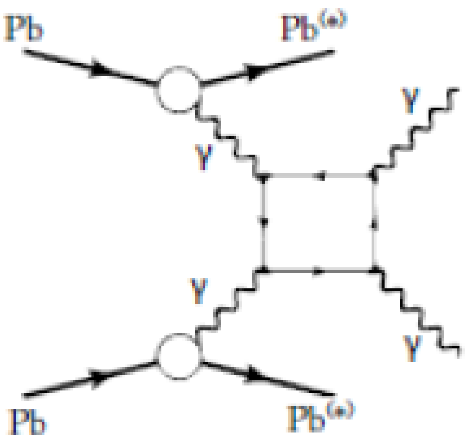
Photon induced processes

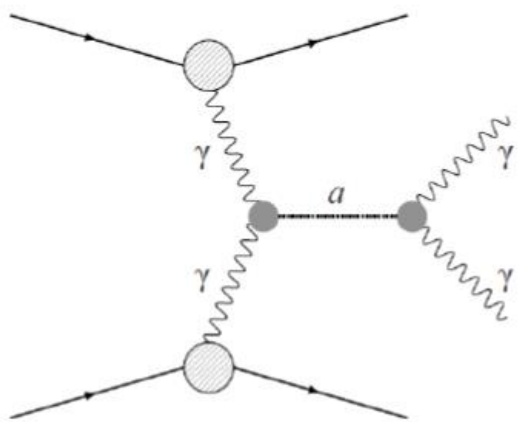
- Photon – hadron interactions

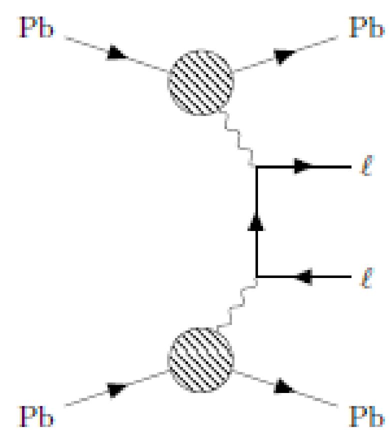




- Photon – photon interactions

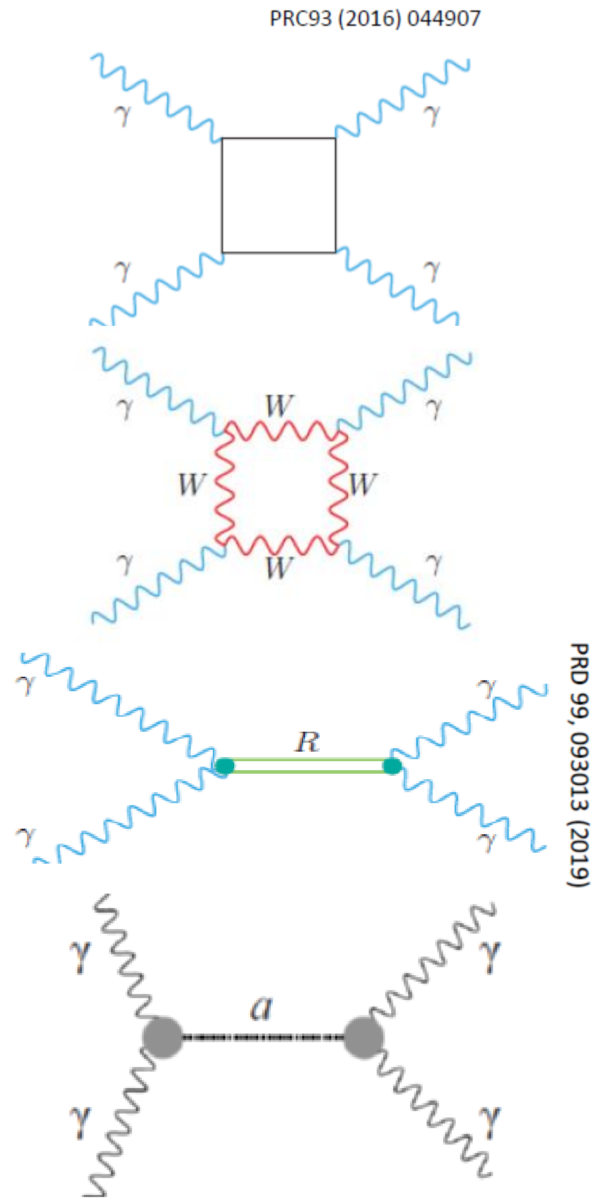






Light-by-light scattering

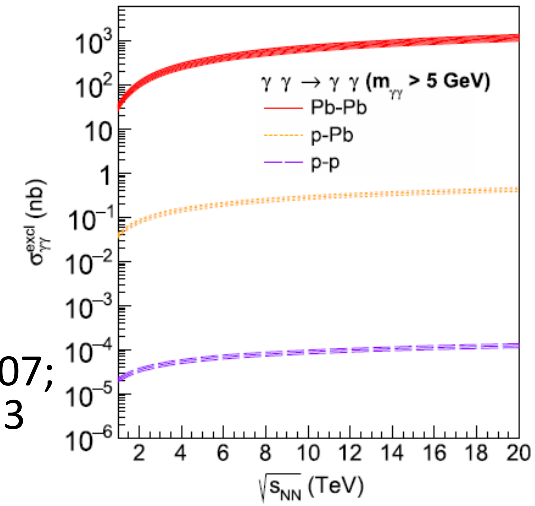
- Pure quantum effect
- Contributes to electron/muon anomalous magnetic moment (g-2)
- Challenging process: $O(\alpha_{em}{}^{4} \approx 3 \times 10^{-9})$
- Quarks, leptons or W bosons can be exchanged in the loop in the lowest order
- Higher order corrections allow also for mesons exchange: η, $\eta'(958)$, $\eta_c(1S)$, $\eta_c(2S)$, $\chi_{c0}(1P)$, …
- There is a place for Beyond Standard Model physics: SUSY particles, spin-even resonances (ALPs), magnetic monopoles, …



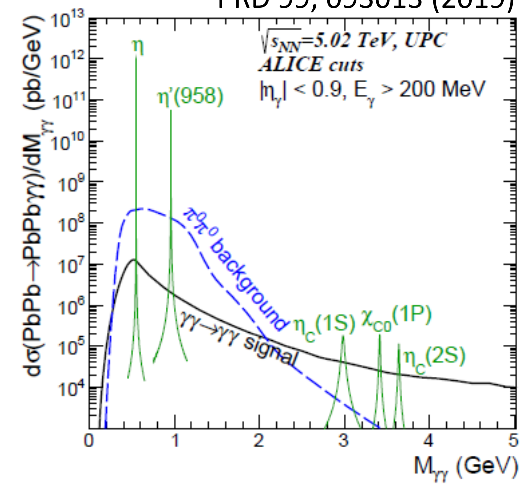
Cross-section predictions

- Calculations of cross-section at the LHC energies:
  - d'Enterria group:
    - d'Enterria, Silveira, PRL 111 (2013) 080405 + Erratum PRL 12 (2016) 129901.
    - High $W_{\gamma\gamma} > 5$ GeV/c^2
  - Kraków group:
    - Kłusek-Gawenda, Lebiedowicz, Szczurek, PRC 93 (2016) 044907; Kłusek-Gawenda, McNulty, Schicker, Szczurek, PRD 99, 093013 (2019)
    - Includes resonances contribution
    - Both high ($W_{\gamma\gamma} > 5$ GeV/c^2) and low ($W_{\gamma\gamma} < 5$ GeV/c^2) masses
    - ALICE and LHCb acceptance
- MC generators:
  - SuperChic 4 (Durham group):
    - Paper - EPJ C 79 (2019) 39
    - Code - https://superchic.hepforge.org/
  - gamma-UPC (d'Enterria et al.):
    - Paper - https://arxiv.org/abs/2207.03012
    - Code - http://cern.ch/hshao/gammaupc.html

PRL 12 (2016) 129901



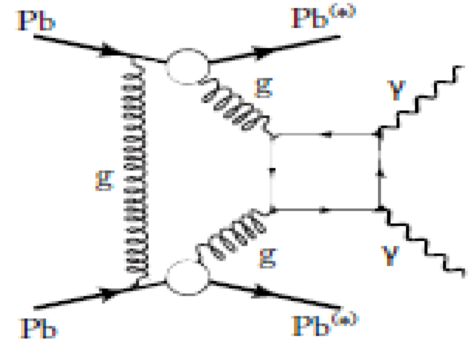
PRD 99, 093013 (2019)



Background sources

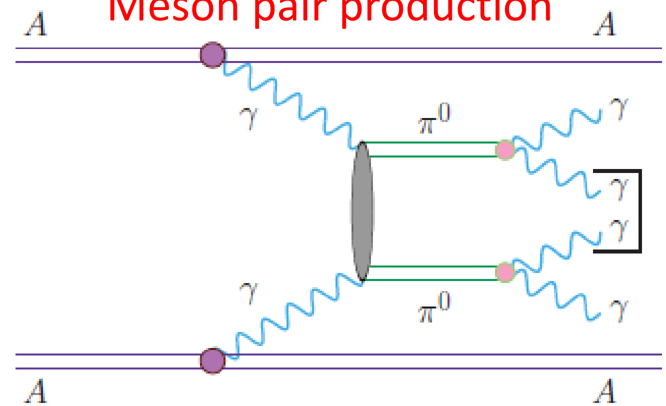
- 3 regimes:
  - $W_{\gamma\gamma} > 5$ GeV/c^2 – perturbative, well-known region
  - $2 < W_{\gamma\gamma} < 5$ GeV/c^2
  - $W_{\gamma\gamma} < 2$ GeV/c^2 – non-pertubative, not explored
- Background types
  - Central exclusive production (CEP)
  - (CE) Meson pair production ($\pi^0\pi^0$, $\eta\eta$, $\eta\eta'$, $\eta'\eta'$, …)
  - Combinatorial $\gamma\gamma$ from vector meson photoproduction ($\omega \to \pi^0\gamma \to \gamma\gamma\gamma$, $J/\psi \to \eta_c\gamma$, …)
  - Exclusive dielectron production $\gamma\gamma \to e^+e^-$
  - Hard bremsstrahlung photons emitted by electrons

CEP



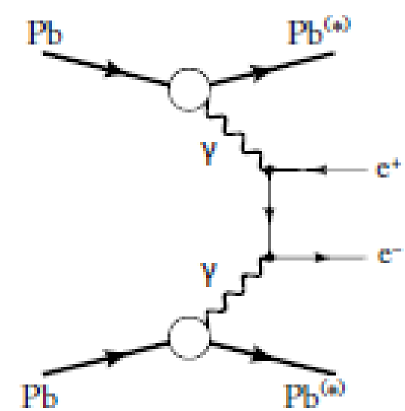
PLB 797 (2019) 134826

Meson pair production



PRD 99, 093013 (2019)

Dielectron production



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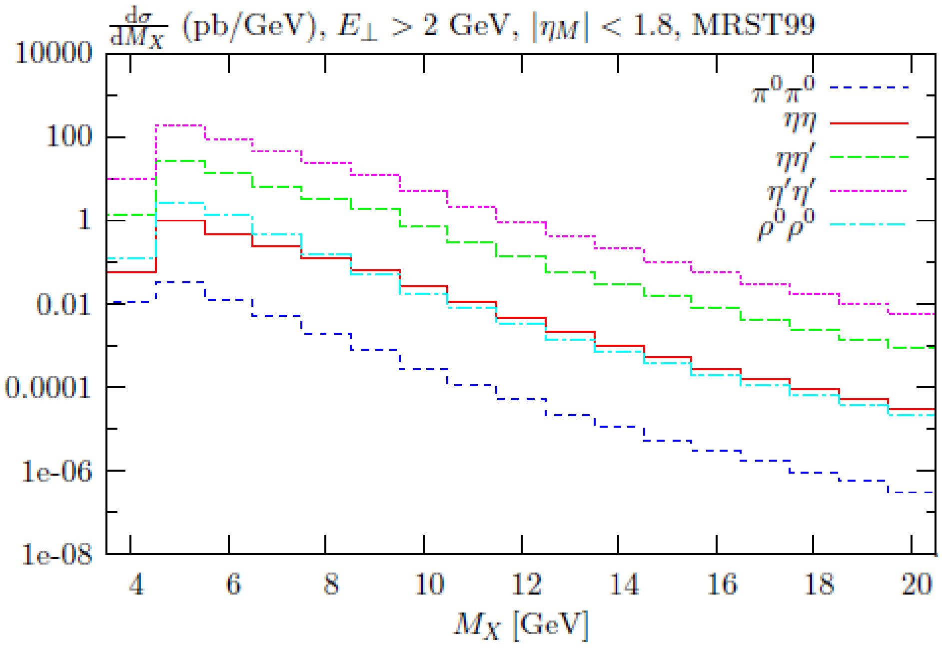
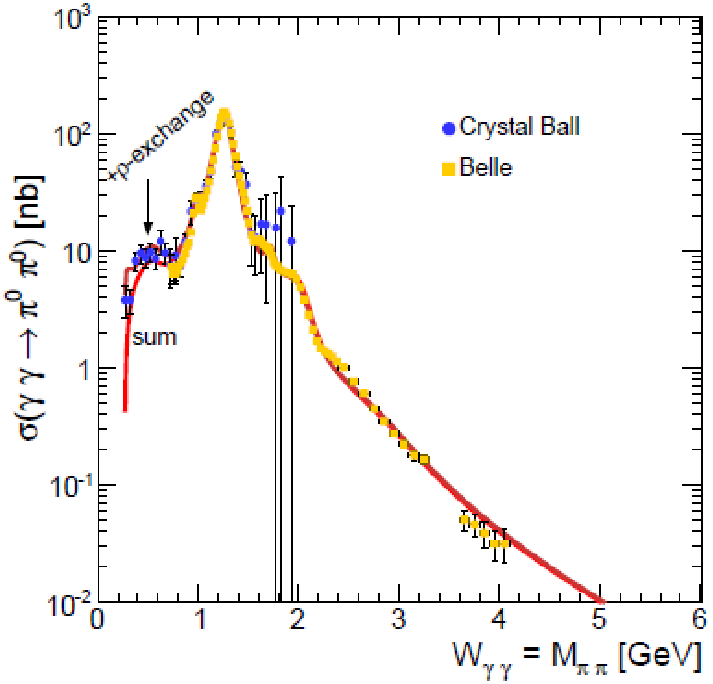
Known background sources





$\sigma(\eta'\eta') : \sigma(\eta\eta') : \sigma(\eta\eta) = 1 : 2\tan^2(\theta) : \tan^4(\theta)$
$\approx 1 : 1/19 : 1/1450$

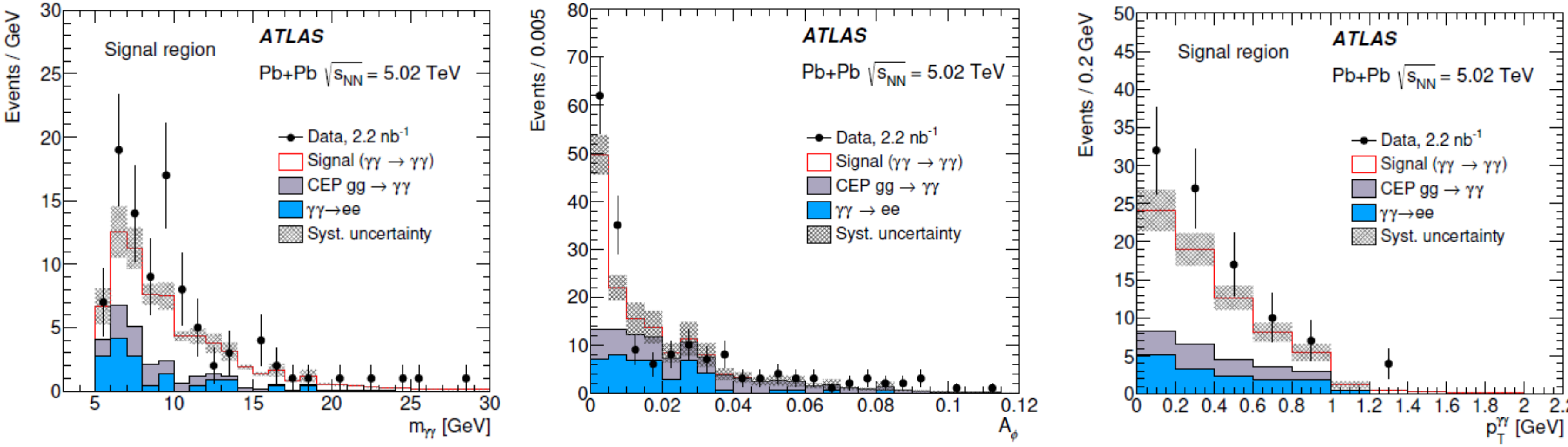
Description by different tensor f resonance contributions

CEP meson pairs production:
Harland-Lang, Khoze, Ryskin, Stirling,
1105.1626 (2011), 1302.2004 (2013),
1304.4262 (2013)
CEP $\gamma\gamma$: 1005.0695 (2010)

MKG+AS, PRC 87, (2013) 054908

Measurements

ATLAS: JHEP 03 (2021) 243



- $E_T^\gamma > 2.5$ GeV
- $|\eta_\gamma| < 2.4$
- $N_\gamma = 2$
- $W_{\gamma\gamma} > 5$ GeV/c^2
- Charged particle track veto to suppress $\gamma\gamma \to e^+e^-$
- $p_T^{\gamma\gamma} < 1$ GeV/c for $W_{\gamma\gamma} < 12$ GeV/c^2 or $p_T^{\gamma\gamma} < 2$ GeV/c for $W_{\gamma\gamma} > 12$ GeV/c^2 to reduce fake photons
- Acoplanarity $A_\phi = (1-|\Delta\phi_{\gamma\gamma}|/\pi) < 0.01$ to reduce CEP gg $\to \gamma\gamma$
- Efficiency factor $C^{ATLAS} = 0.35 \pm 0.024$

Data/Theory comparison

- Measurements at LHC:
  - ATLAS (Nature Phys. 13(2017) 852-858; PRL 123, 052001 (2019); JHEP 03 (2021) 243)
  - CMS (PLB 797 (2019) 134826)

Experiment	N_{events}	Cross-section [nb]	significance	$W_{\gamma\gamma}$ [GeV/c^2]
ATLAS (480 μb^{-1})	13	70 ± 24 (stat) ± 17 (syst)	4.4 σ	> 6
CMS (390 μb^{-1})	14	120 ± 46 (stat) ± 28 (syst) ± 12 (theo)	3.7 σ	> 5
ATLAS (1.73 nb^{-1})	59	78 ± 13 (stat) ± 7 (syst) ± 9 (lumi)	8.2 σ	> 6
ATLAS (2.2 nb^{-1})	97	120 ± 17 (stat) ± 13 (syst) ± 4 (lumi)		> 5

- Theory calculations at LHC:

Group	Cross-section [nb]	$W_{\gamma\gamma}$ [GeV/c^2]
d'Enterria et al.	45 ± 9	> 6
Kraków	51 ± 5	> 6
SuperChic	50 ± 5	> 6

Less than 2σ discrepancy

Data-to-theory ratio:

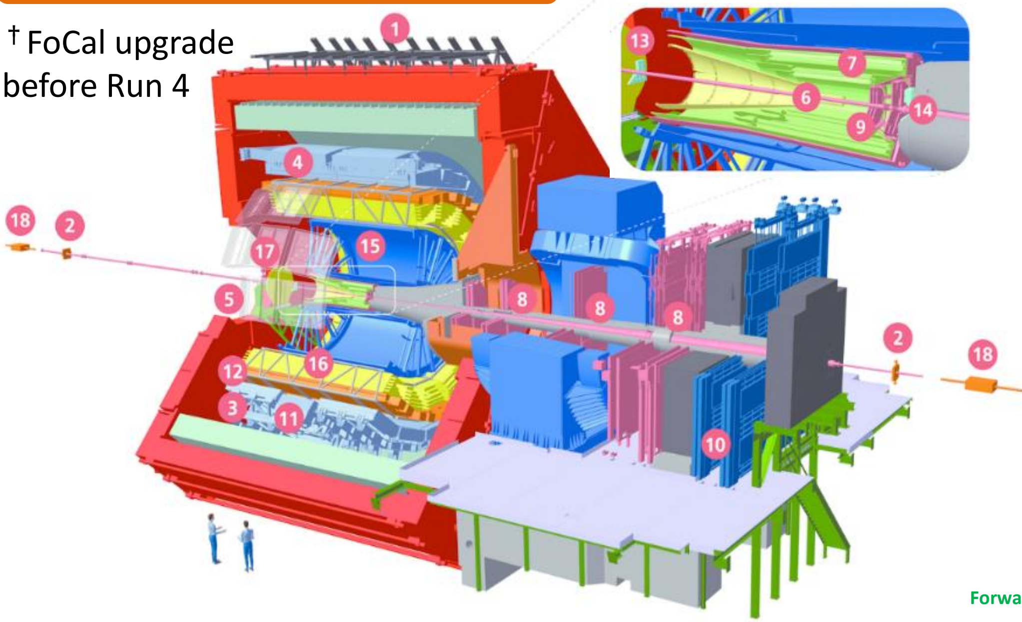
- 1.50 ± 0.32 (ATLAS – Kraków)
- 1.54 ± 0.32 (ATLAS – SuperChic)

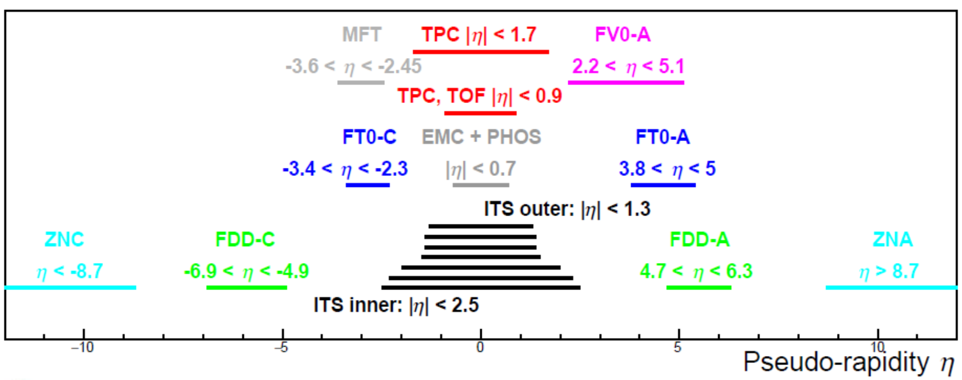
ALICE can provide complementary result in low $W_{\gamma\gamma} < 5$ GeV/c^2

ALICE 2 vs ALICE 3

ALICE in Run 3 + 4 (2022 - 2032 †)

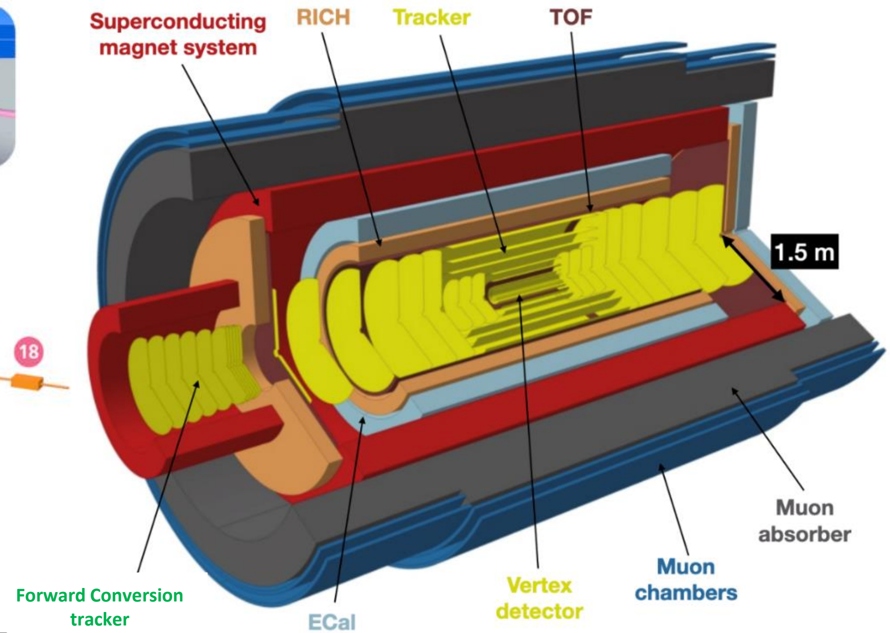
† FoCal upgrade before Run 4

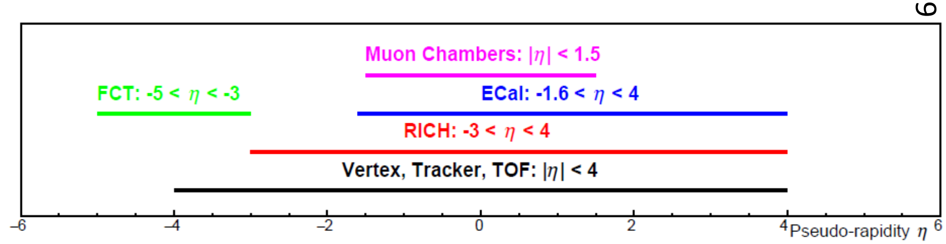




1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

ALICE 3 detector in Run 5 (2035 - 2038)

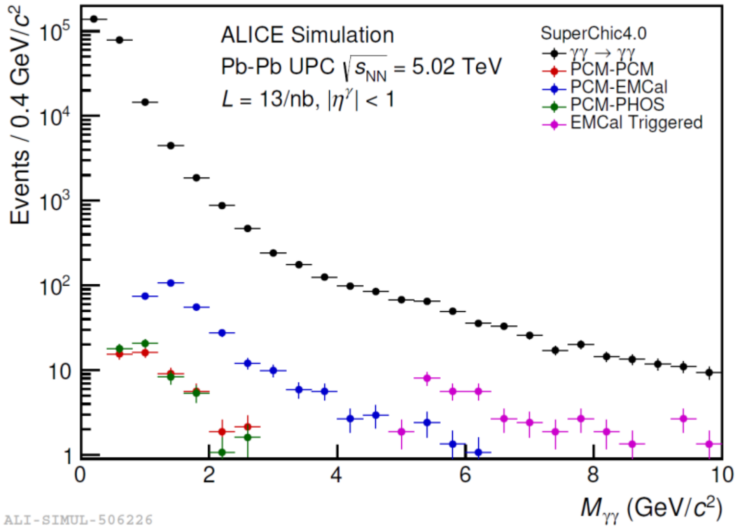




	Run 2	Run 3	Run 4	Run 5 per year
$L^{\text{Pb-Pb}}$	1/nb	6/nb	7/nb	5.6/nb

Adamova *et al.*, 1902.01211 (2019); CERN-LHCC-2022-009

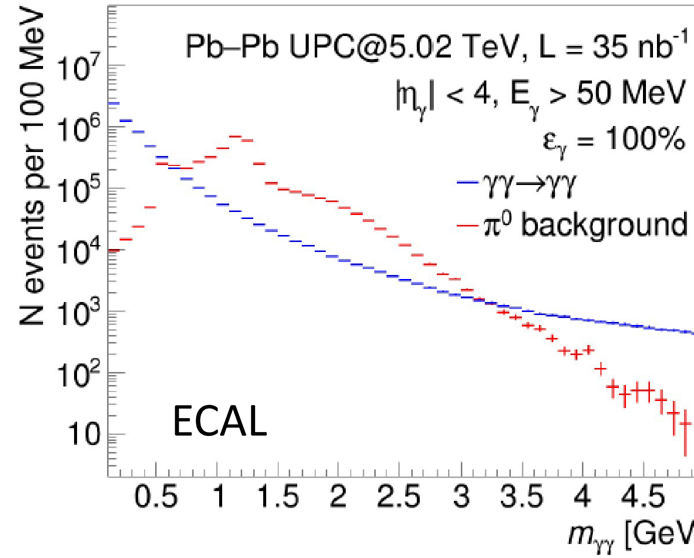
Feasibility studies for ALICE 2 and 3



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

Background reduction with A_S variable

ALICE3 LOI: CERN-LHCC-2022-009 / LHCC-I-038



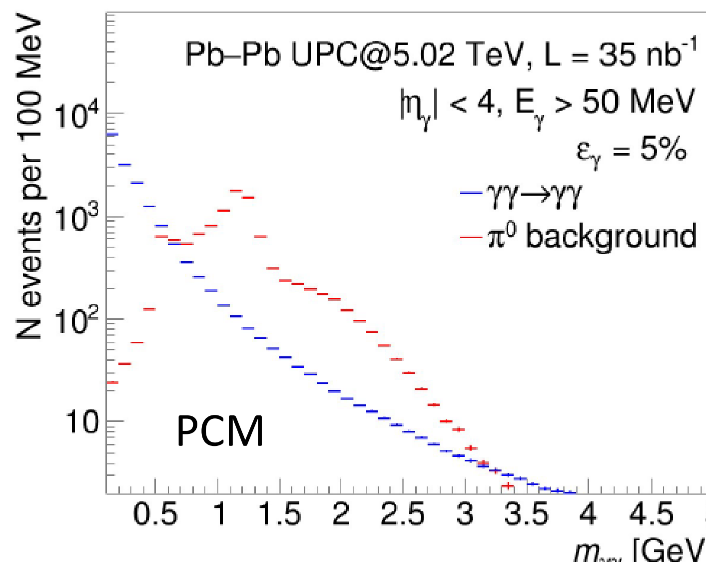
Considered topologies in Run 3 and 4

Both γ's reconstructed with Photon Conversion Method (PCM) from e^+e^- pairs
- $p_T^{\gamma,\ PCM} > 0.1$ GeV/c

One γ via PCM, other in EMCal acceptance
- $p_T^{\gamma,\ EMCal} > 0.5$ GeV/c
- $p_T^{\gamma,\ PCM} > 0.1$ GeV/c

One γ via PCM, other in PHOS acceptance
- $p_T^{\gamma,\ PHOS} > 0.3$ GeV/c
- $p_T^{\gamma,\ PCM} > 0.1$ GeV/c

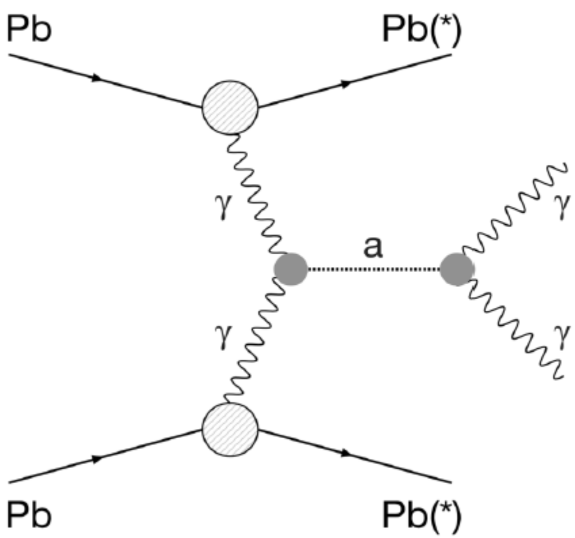
Both γ's in EMCal acceptance, one triggered
- $p_T^{\gamma,\ EMCal} > 0.5$ GeV/c
- $p_T^{\gamma,\ EMCal\ triggerd} > 2.5$ GeV/c

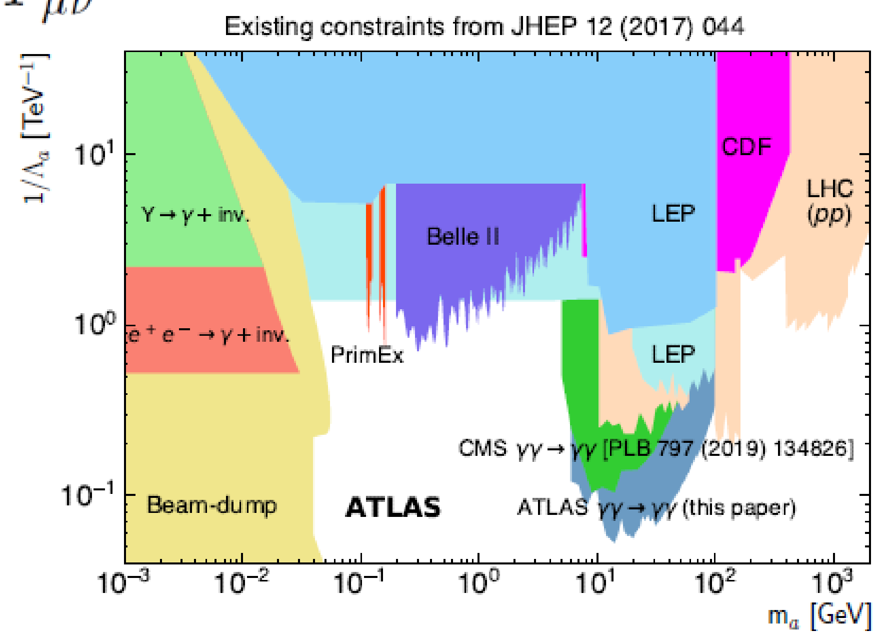


Search for axion-like particles (ALPs)

- Light-by-light scattering is sensitive for BSM physics
- ALPs are class of hypothetical pseudoscalar particles with unknown mass-coupling relation
- Dark matter candidates
- Axions initially proposed to solve CP problem

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





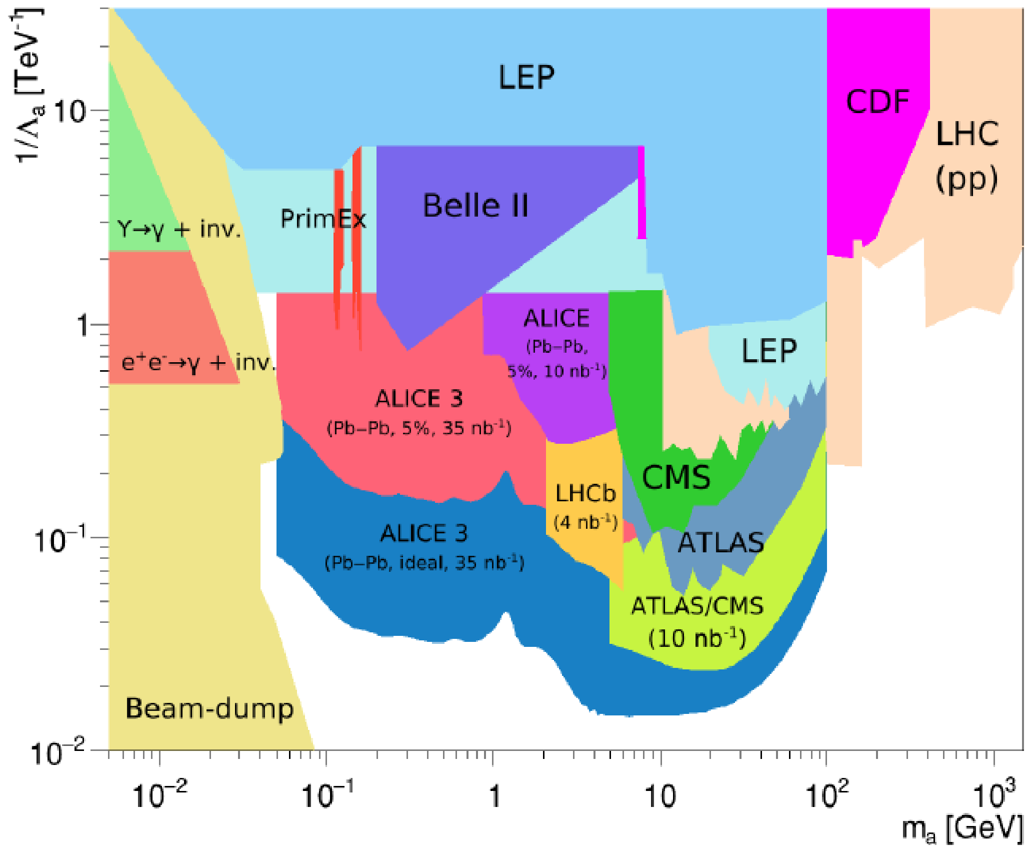
ATLAS: JHEP 03 (2021) 243

ATLAS and CMS set limits in a mass range $5 < m_a < 100$ GeV/c^2

Expected upper limits for ALP production

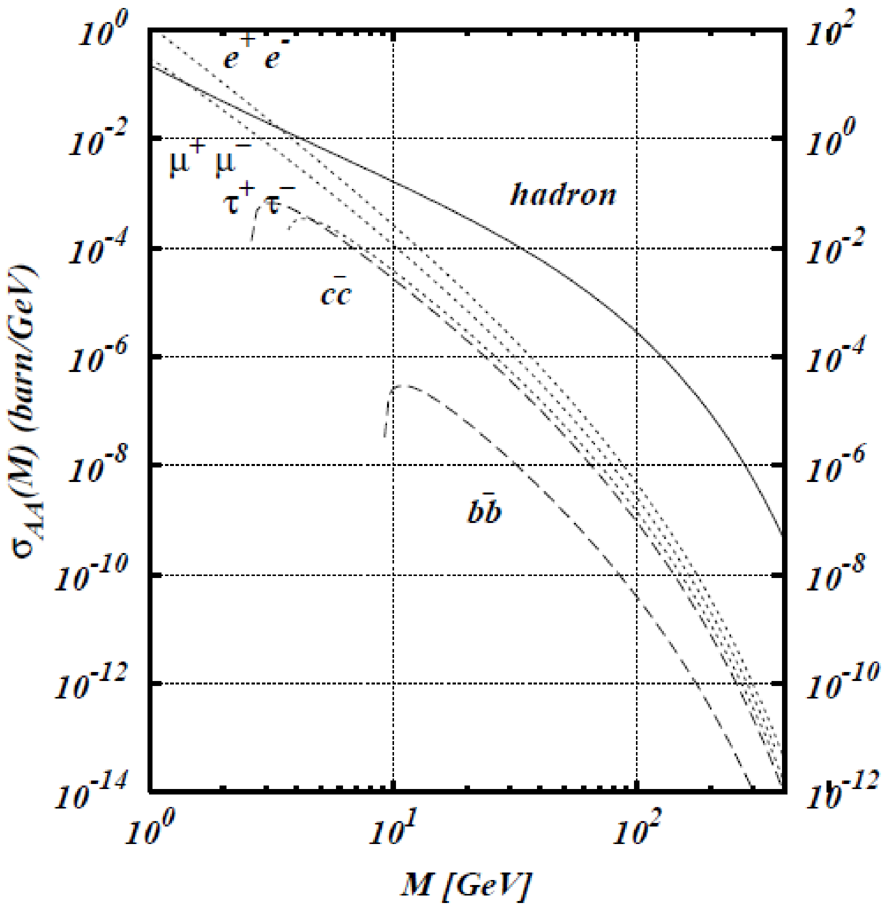
- Poissonian limits for ALPs in UPCs at $\sqrt{s_{NN}}$ = 5.5 TeV (Based on PRL 118, 171801 (2017))
- Signal: ALPs from STARlight; $\Gamma(a \to \gamma\gamma) = 1/64\pi\, m_a^3/\Lambda^2$
- Background: L-by-L, $\pi^0\pi^0$, fake electrons and bremsstrahlung
- Asymmetry requirement $A_S < 0.02$

- ALICE 3 is designed to measure very low particle p_T
- ALiCE 3 can provide complementary result in low mass region 50 MeV/c^2 < $M_{\gamma\gamma}$ < 5 GeV/c^2



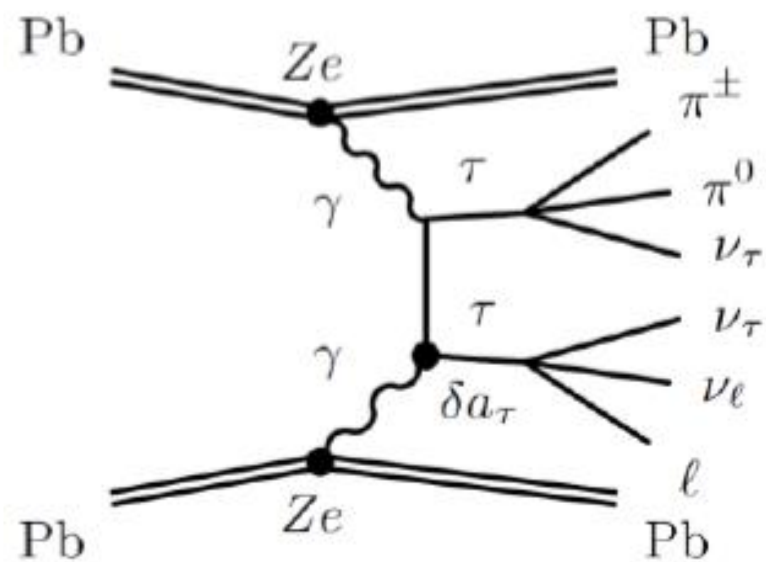
τ pair production

Pair production at LO at LHC for Pb-Pb collisions



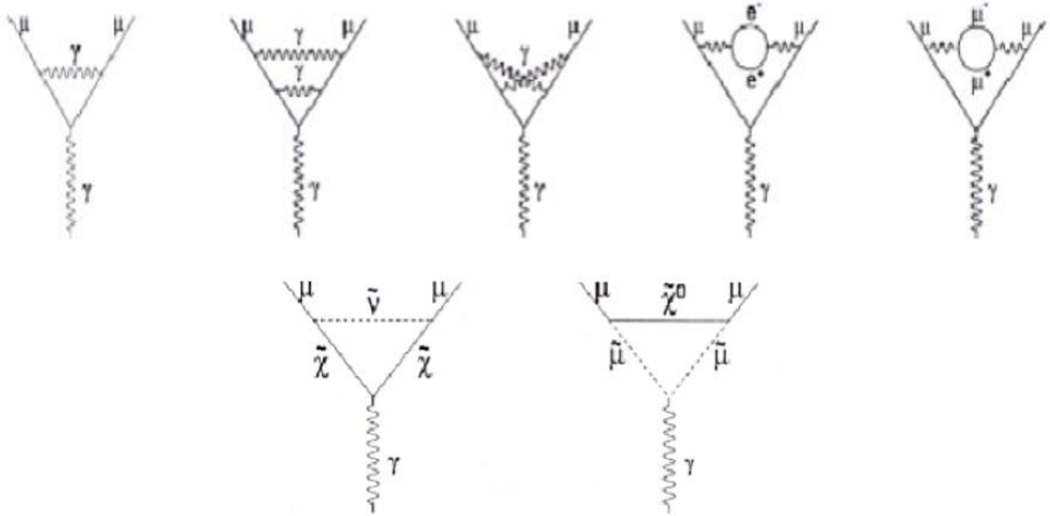
G. Baur at al., hep-ph/0112211 (2001)

- τ pair photoproduction in Pb-Pb UPC → Cross section scales with Z^4
- Suppression by factor $O(\alpha_{em}^2 \approx 5 \times 10^{-5})$
- τ leptons decay quickly and can not be observed directly
  - Lifetime 10^{-13} s
  - Difficult due to at least 1 ν in each τ decay
- Sensitive to anomalous magnetic moment: $a_\ell = (g-2)_\ell/2$



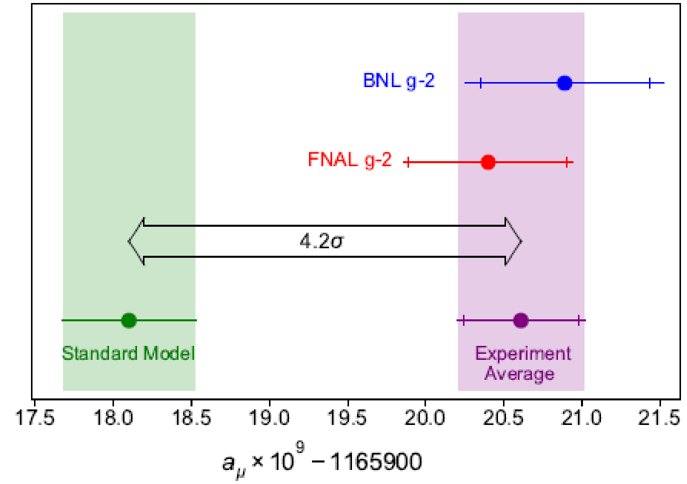
Anomalous magnetic moment

- $a_{\tau(\mu,e)} \neq 0$ because τ lepton (μ, e) is surrounded by virtual particles
- $a_{\tau(\mu,e)} \neq 0$ becomes evident in interaction of τ lepton (μ, e) with external B field
- $a_{\ell} = (g-2)_{\ell}/2$
  - g is gyromagnetic moment which relates particle's magnetic moment to its spin $\vec{\mu} = g\frac{q}{2m}\vec{s}$
  - Dirac's equation predicts g = 2
  - Higher order corrections (loops) make g $\neq$ 2
  - Sensitive to particles beyond SM



Anomalous magnetic moment – cont.

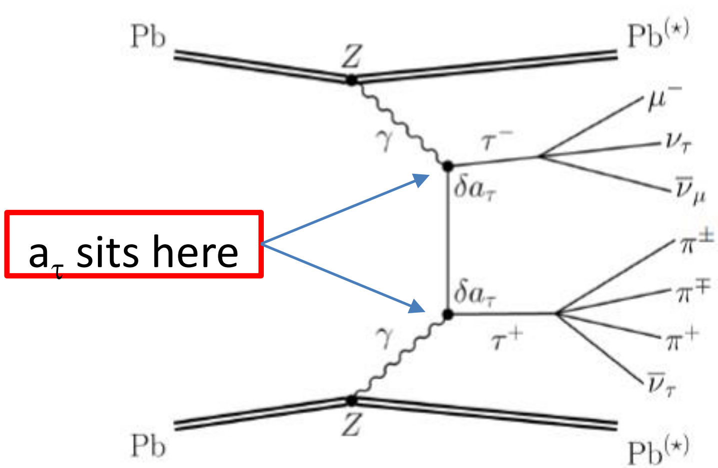
- For electrons:
  - $a_e^{exp} = 115\ 965\ 218\ 076\ (28) \times 10^{-14}$ (PDG22)
  - $a_e^{th} = 115\ 965\ 218\ 164.3\ (76.4) \times 10^{-14}$ (T. Aoyama et al., PRD. 91 (3): 033006)
    - $\Rightarrow$ 2.5 σ discrepancy
  - Contribution to a_e from particles heavier than electrons is $\sim 4 \times 10^{-12}$
    - $\Rightarrow$ Not so sensitive to BSM particles
  - $(m_\mu/m_e)^2 \approx 40000 \Rightarrow a_\mu$ is 40000 $\times$ more sensitive to new physics ($\delta a_l \sim m_l^2/M_S^2$) ; M_S – supersymmetry scale
- For muons:
  - $a_\mu^{exp} = 116\ 592\ 061 \pm 41 \times 10^{-11}$ (PDG22)
  - $a_\mu^{SM} = 116\ 591\ 810 \pm 43 \times 10^{-11}$ (0.37 ppm) (T. Aoyama et al., Phys. Rept. 887, 1(2020))
  - $\Rightarrow$ 4.2 σ discrepancy
  - $(m_\tau/m_\mu)^2 \approx 280 \Rightarrow a_\tau$ is 280 $\times$ more sensitive to new physics

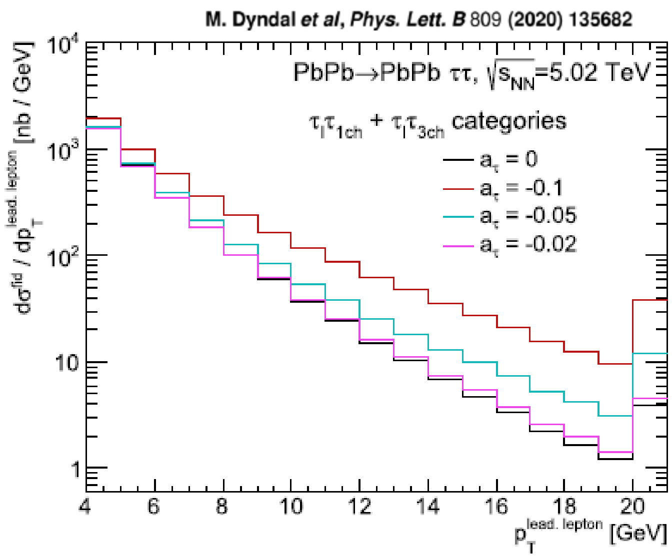


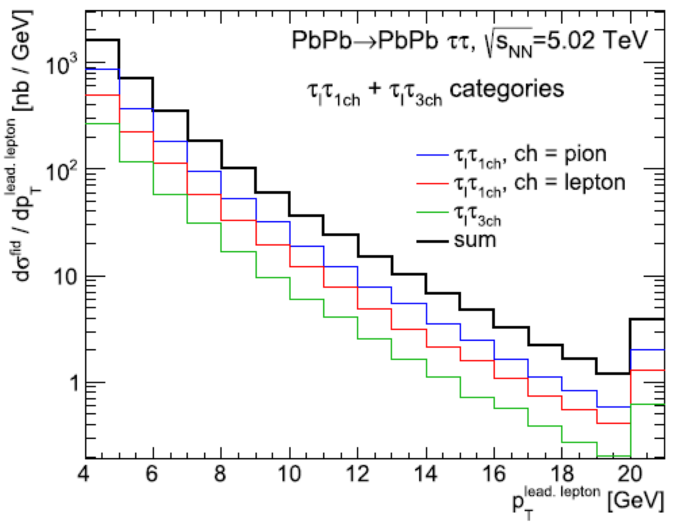
T. Aoyama et al., Phys. Rept. 887, 1(2020)

τ anomalous magnetic moment

- Anomalous magnetic moment:
  - $a_\tau^{exp} = -0.018(17)$ (DELPHI, EPJC 35 (2004) 159)
  - $a_\tau^{SM} = 0.00117721(5)$ (S. Eidelman and M. Passera, Mod. Phys. Lett. A 22, 159 (2007))
- Cross section and τ kinematics sensitive to a_τ
  - L. Beresford and J. Liu, PRD 102 (2020) 113008
  - M. Dyndał et al., PLB 809 (2020) 135682
  - Burmasov et al., arXiv:2203.00990 (2022)





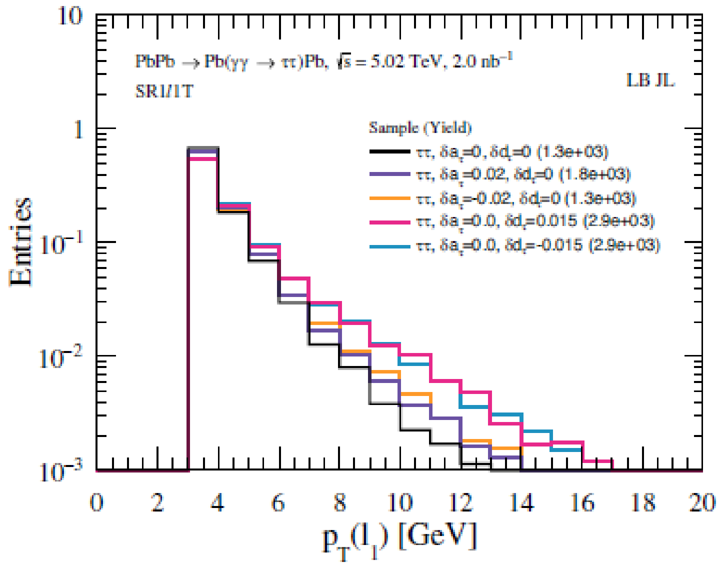


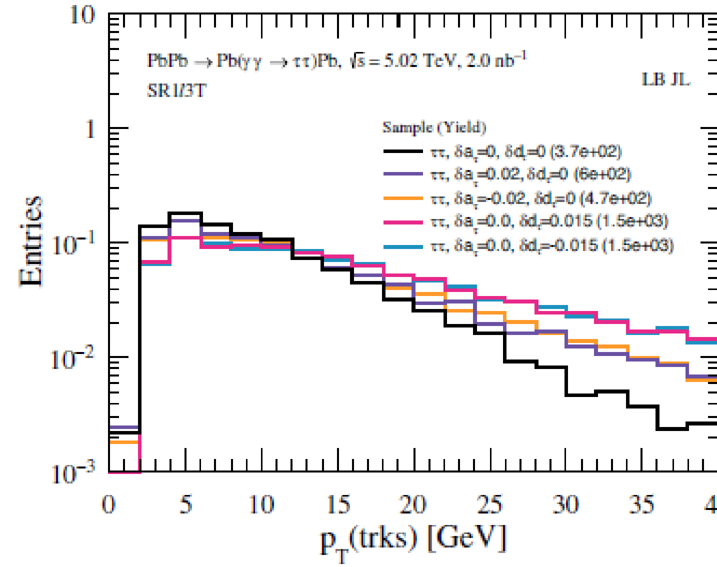
Analysis strategy

- τ decay channels:
  - 1 prong:
    - $BR(\tau^{\pm} \rightarrow \nu_{\tau}\, e^{\pm}\, \nu_{l}) = 17.8\ \%$
    - $BR(\tau^{\pm} \rightarrow \nu_{\tau}\, \mu^{\pm}\, \nu_{l}) = 17.4\ \%$
    - $BR(\tau^{\pm} \rightarrow \nu_{\tau}\, h^{\pm}\, n\pi^{0}) \approx 50\ \%$ ($h = \pi$, K)
  - 3 prongs:
    - $BR\ (\tau^{\pm} \rightarrow \nu_{\tau}\, 3\pi^{\pm}\, n\pi^{0}) \approx 15\ \%$
- Event topology:
  - 1+1 tracks ~ 70 %
    - e, μ, π, K tracks
  - 1+3 tracks ~ 25 %
    - e, μ, π, K tracks + 3 charged π
- Reject dilepton continuum production
- Use displaced vertex for 3 prong τ decay

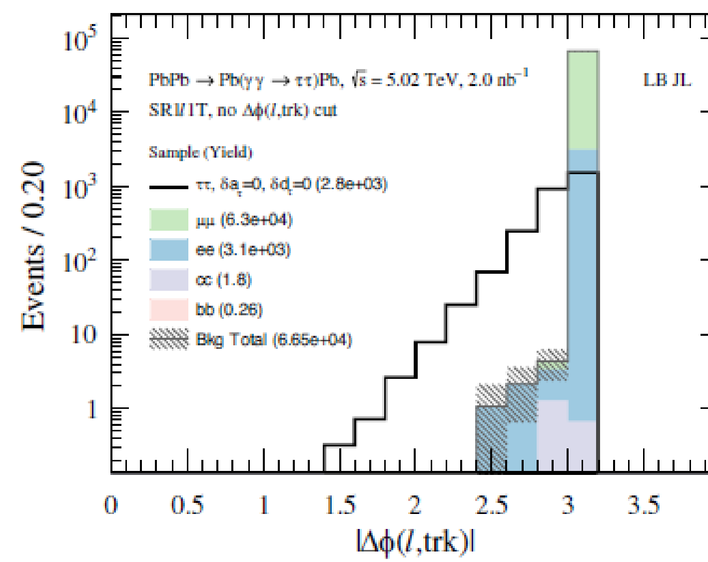
p_T and acoplanarity spectra

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

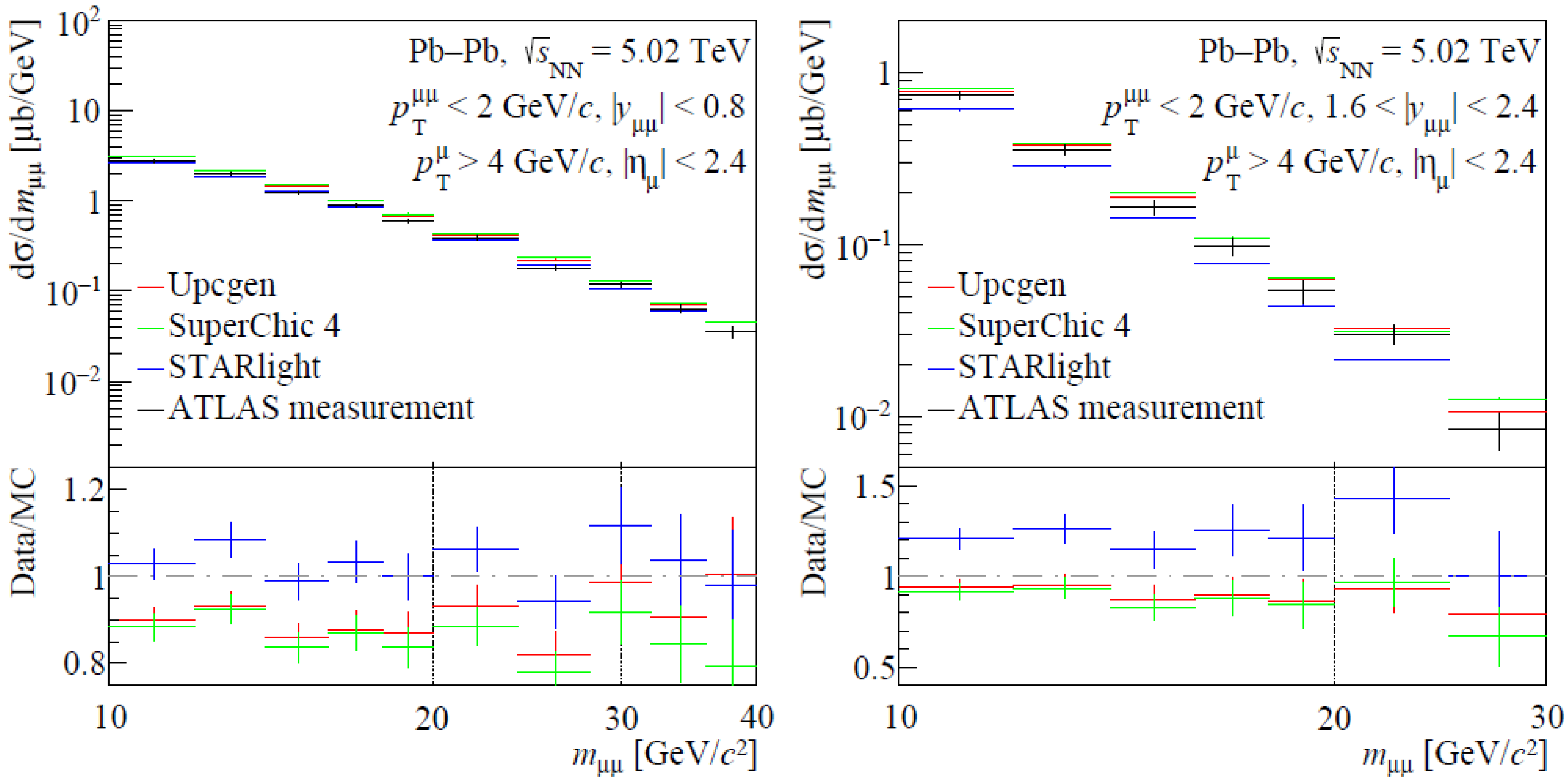




- p_T differential spectra give better a_τ sensitivity
- Expectations for different a_τ
- Acoplanarity shows large background reduction power



Background description



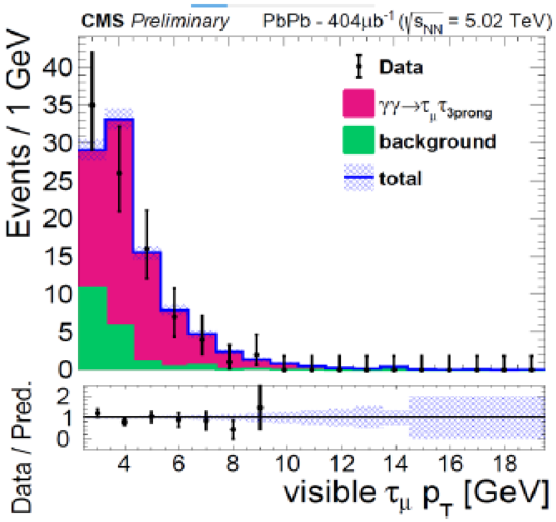
Burmasov et al., 2203.00990 (2022)

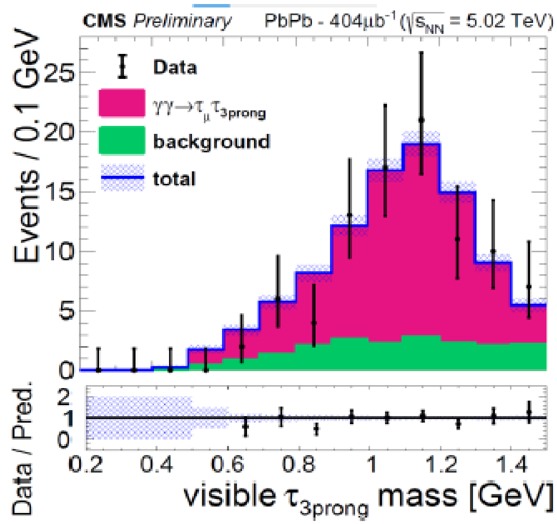
- Good description of background processes by MC generators:
  - UPCgen (Burmasov et al., arXiv:2111.11383 (2022))
  - STARlight (Klein et al., Comput. Phys. Commun. 212 (2017))
  - SuperChic (Harland-Lang et al., EPJ C80 (2020))

Measurement of τ pair production

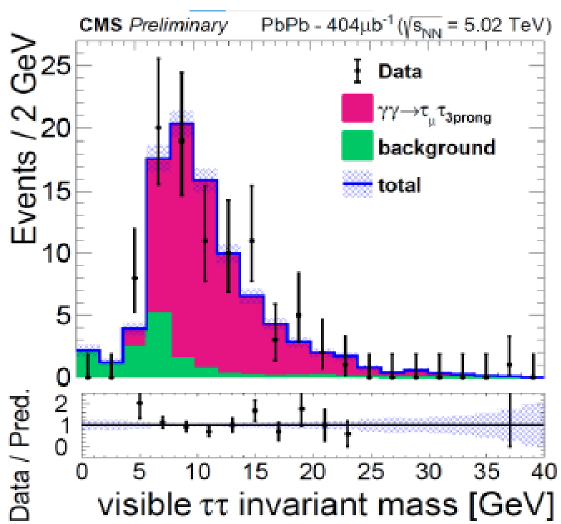
- CMS observation shown at QM2022

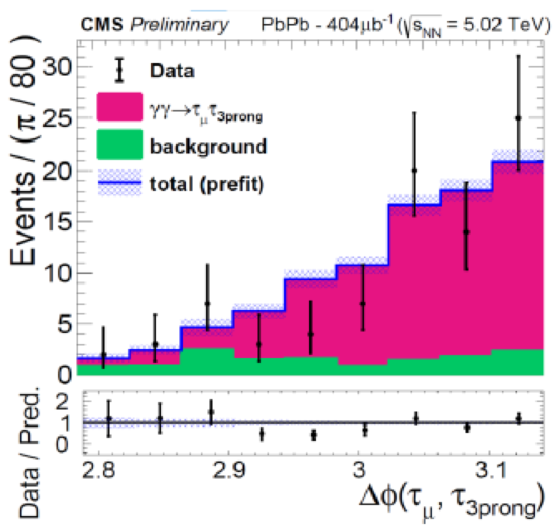
CMS-PAS-HIN-21-009





- μ + 3tracks topology
- N_{sig} = 77 ± 12
- L = 404 μb^{-1}

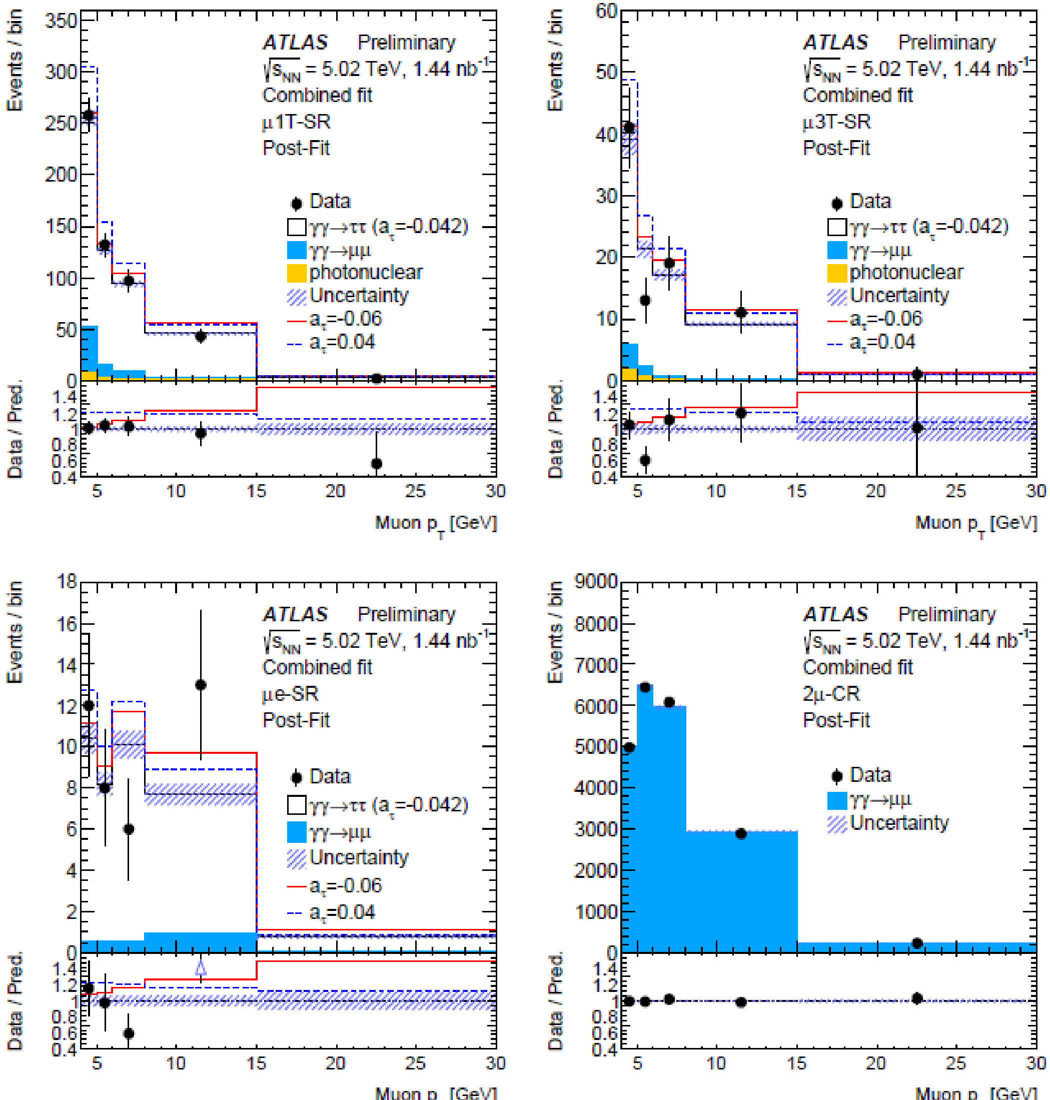




- Good agreement between MC and data
- Only 1+3 topology
- Only μ
- Not full statistics

Measurement of τ pair production

- ATLAS observations shown at QM2022



arXiv:2204.13478v1

- μ1T-SR: muon + 1 track (e/μ/hadron)
- μ3T-SR: muon + 3 tracks (3 hadrons)
- μe-SR: muon + electron

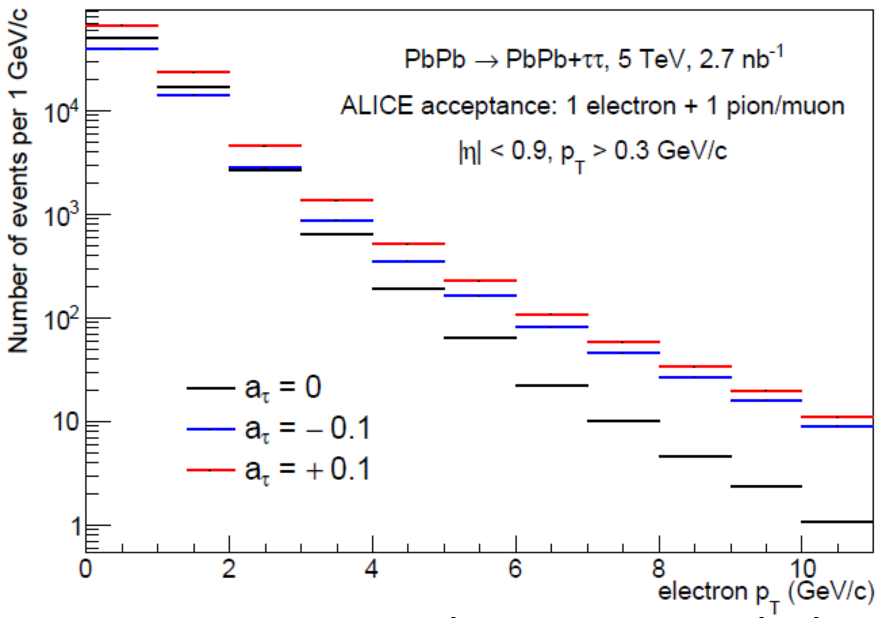
N_{sig} = 532, 85 and 39

L = 1.44 / nb

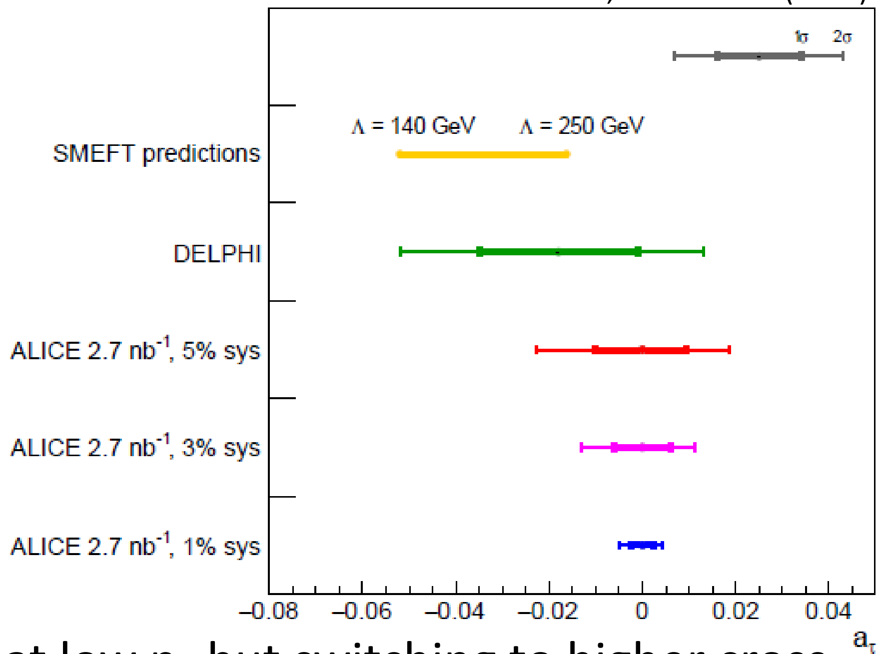
- Good agreement between MC and data
- Several topologies with μ
- Not full statistics

ALICE in Run 3 expectations

Burmasov et al., 2203.00990 (2022)



Burmasov et al., 2203.00990 (2022)



- Cross sections with a_τ = -0.1 are below SM at low p_T but switching to higher cross sections starting from p_T^e > 3 GeV/c → p_T differential measurements provide better sensitivity
- At least x2 improvements on a_τ limits with Pb-Pb data to be collected in 2022 with current ALICE (2)
- ALICE 3 will provide much more data
  - Finner binning
  - Lower p_T accesibility
  - Larger η range
  - Better PID (not only electrons will be used)

Summary

- Light-by-light measurement in ALICE 3 in low $M_{\gamma\gamma}$ < 5 GeV/c^2 range is complementary to other LHC measurements
  - Probe non-perturbative regime
- Potential to lower boundaries on ALP searches in a range 0.05 to 5 GeV/c^2
- Competitive result to ATLAS and CMS in τ pair production already in Run 3
- Better measurement of a_τ than currently existing from DELPHI

Backup

SuperChic 4.0 Settings

- Signal ($\gamma\gamma \rightarrow \gamma\gamma$)
  - $\sqrt{s_{NN}}$ = 5.02 TeV for Pb-Pb collisions
  - $p_{T,min}^{\gamma}$ = 0.1 GeV/c
  - $0.2 < M_{\gamma\gamma} < 200$ GeV/c^2
  - $|y| < 1$; $|\eta| < 1$
  - Output: $\sigma = 0.1854861 \times 10^8$ pb
    - σ = 195923 ± 1160 pb (for $2 < M_{\gamma\gamma} < 200$ GeV/c^2)
- CEP Background ($2 < M_{\gamma\gamma} < 200$ GeV/c^2):
  - $gg \rightarrow \gamma\gamma$ [σ = 120 ± 0.5 pb]
  - $gg \rightarrow \pi^0\pi^0$ (4 γ) [σ = 22.877 ± 0.007 pb]
  - $gg \rightarrow \eta\eta$ (4 γ) [σ = 1560 ± 2 pb]
  - $gg \rightarrow \eta\eta'$ (4 γ) [σ = 69175 ± 87 pb]

BR($\pi^0 \rightarrow \gamma\gamma$) = 98.8 %
BR($\eta \rightarrow \gamma\gamma$) = 39.4 %
BR($\eta' \rightarrow \gamma\gamma$) = 2.3 %