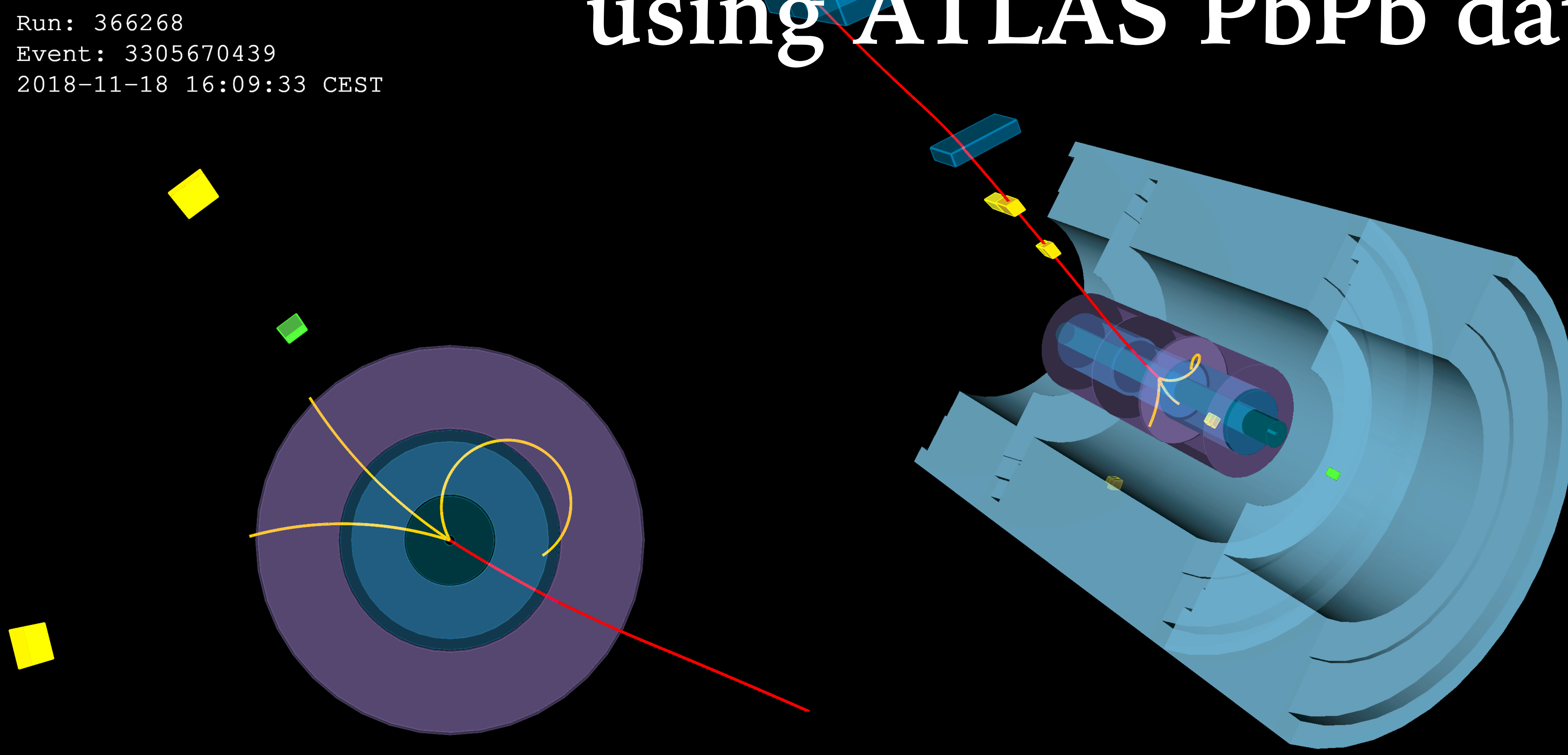
Measuring of tau g-2 using ATLAS PbPb data

ATLAS EXPERIMENT



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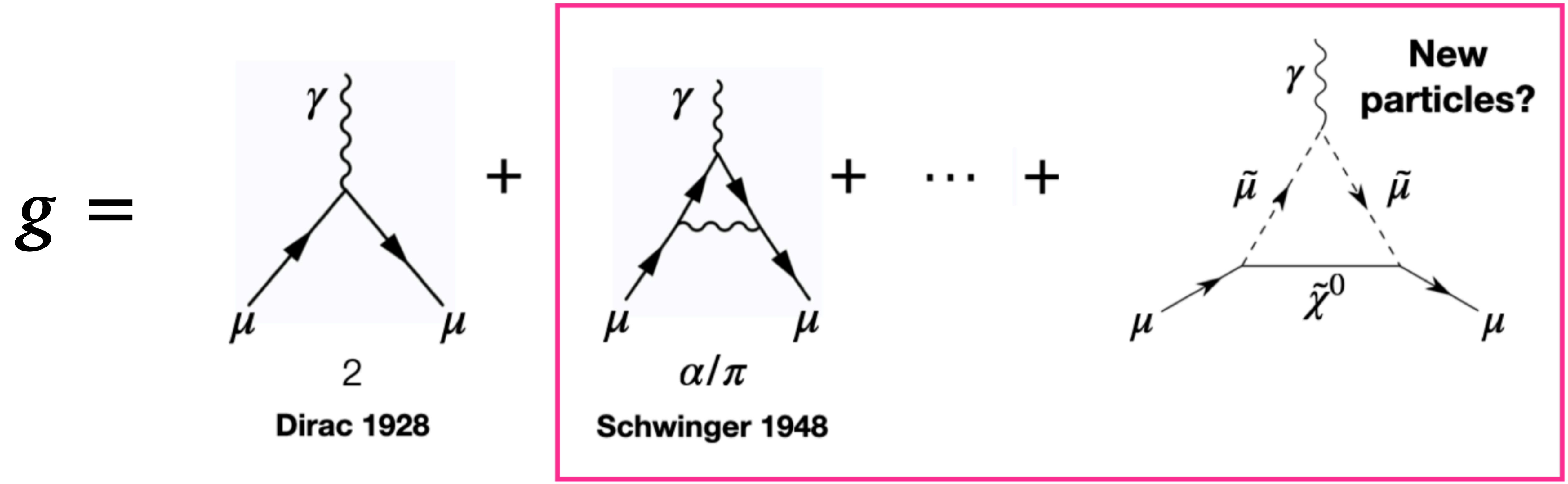
TES-HEP
Bezmiechowa Górna, 18 July 2023

Klaudia Maj
AGH University

What is g-2?

Charged particles with spin have an intrinsic magnetic moment

For spin 1/2 particles: $\overrightarrow{\mu} = g\frac{q}{2m}\overrightarrow{S}$



Anomalous magnetic moment: $a_l = \frac{(g-2)_l}{2}$

Lepton magnetic moments

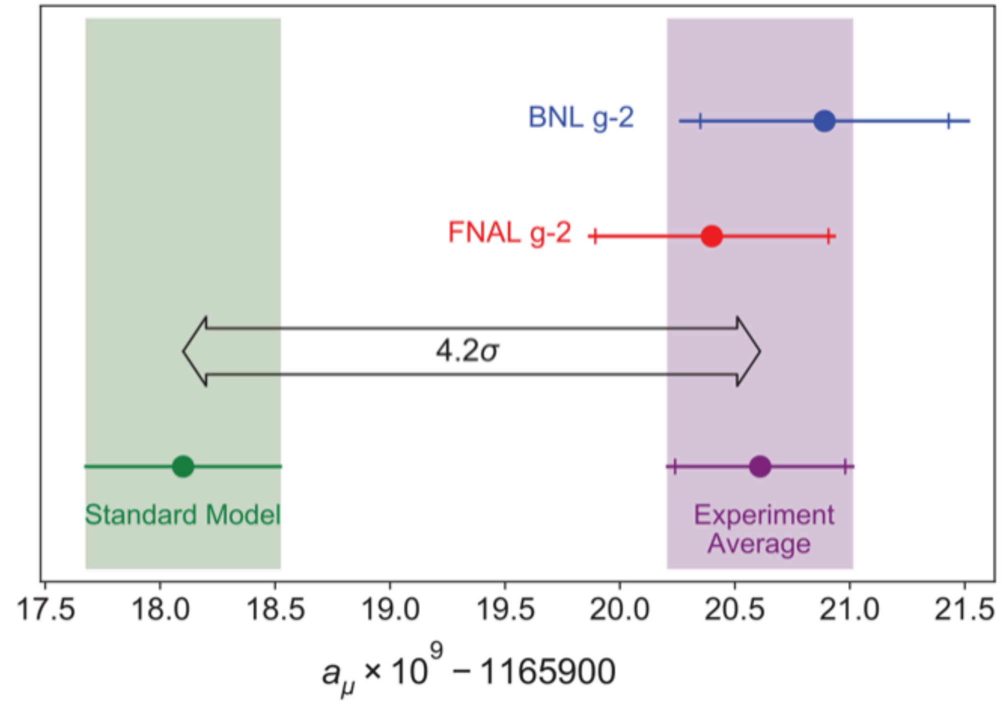
Electron g-2:

10^{-8} precision, **2.5σ** discrepancy

Muon g-2:

10^{-7} precision, **up to ~4.2σ** discrepancy

→ Tested extremely precisely for e and μ



Muon g-2 Collaboration
PRL 126 (2021) 141801

What about the tau?

Do photons interact equally with all lepton generations?

→ Short tau lifetime 10^{-13} s

→ Extremely challenging experimentally!

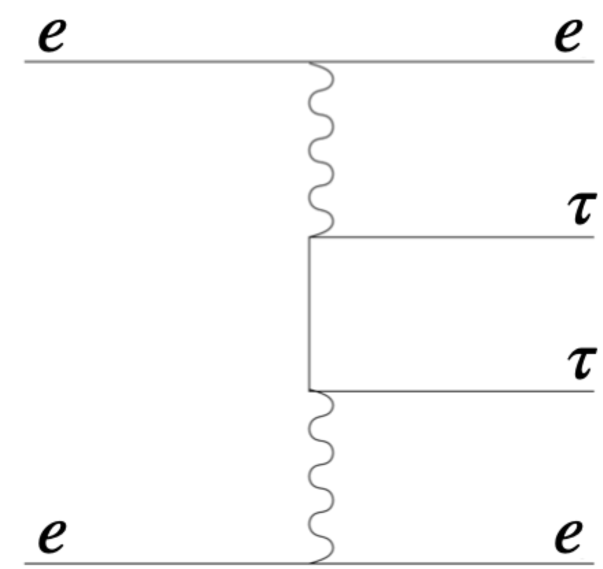
Electron: Odom et al PRL (2006) Bouchendira et al PRL (2011) Aoyama et al PRL (2012) Parker et al Science (2018) Morel et al Nature 2020

Muon: BNL PRD (2006) J-PARC PTEP (2019) Muon g-2 theory initiative JPhysRept (2020) BMW collar Nature (2021)

Looking back …

DELPHI 2004 $\sqrt{s} \approx$ 200 GeV, 650 pb^{-1}

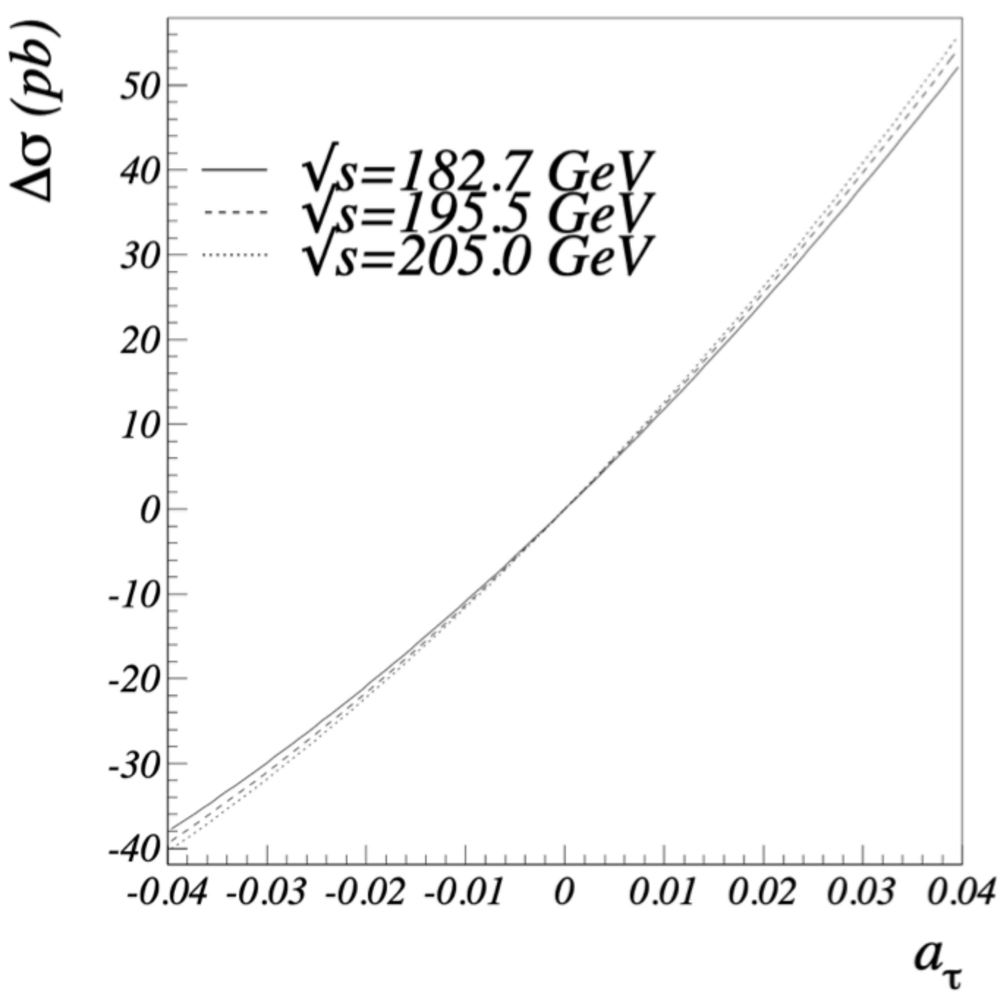
DELPHI Collaboration EPJC (2004)



$\sigma \sim$ **400 pb**

Photo production of tau pairs

Idea: Measure cross-section, sensitive to a_τ



Limited by experimental uncertainty

$$a_\tau^{exp} = -0.018(17)$$

$$a_\tau^{\text{theory}} = 0.00117721(5)$$

Exp: DELPHI Collaboration EPJC (2004)

Theory: Eidelman& Passera MPLA (2007)

Constraints also set by L3 and OPAL $Z \to \tau\tau\gamma$

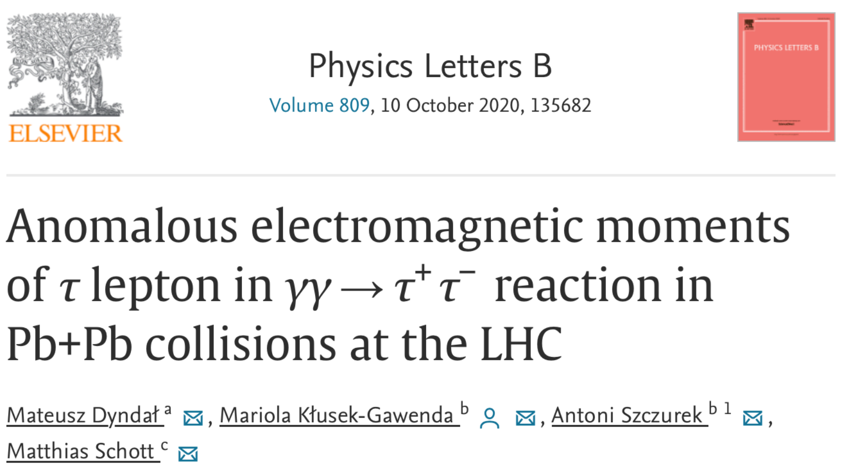
Can we beat it?

Proposal: Measure tau g-2 using LHC heavy ion data

Potential to be most precise single-experiment measurement

Follow approach outline in:

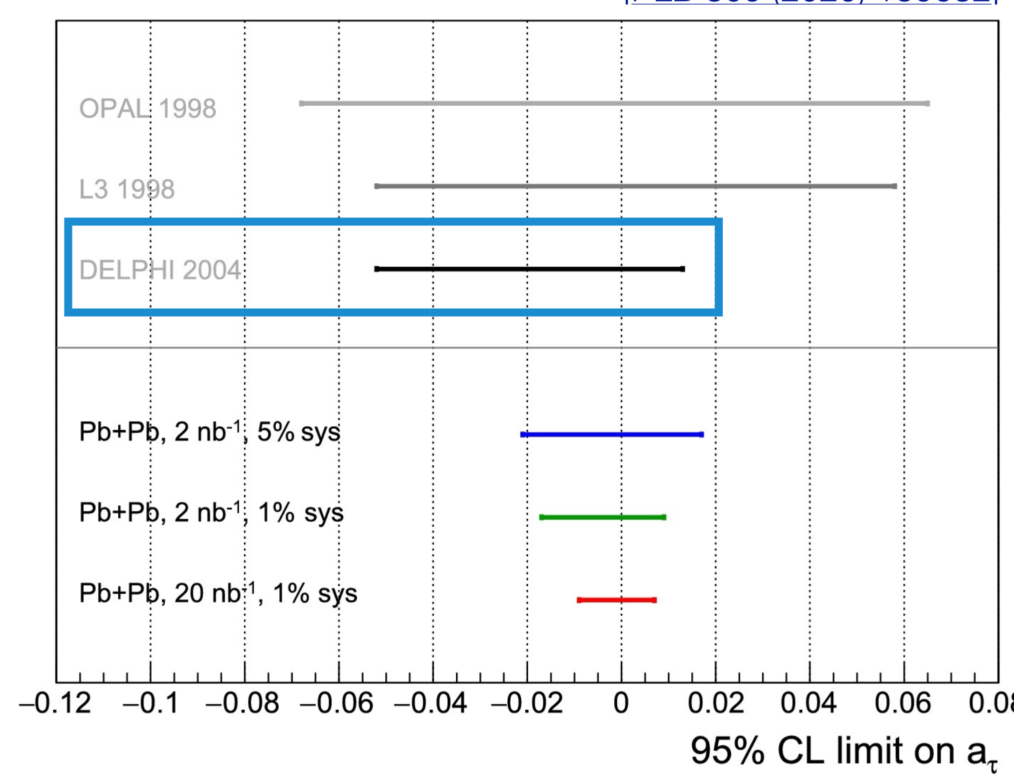
Dyndał, Kłusek-Gawęda, Szczurek, Schott PLB (2020)


Physics Letters B
Volume 809, 10 October 2020, 135682

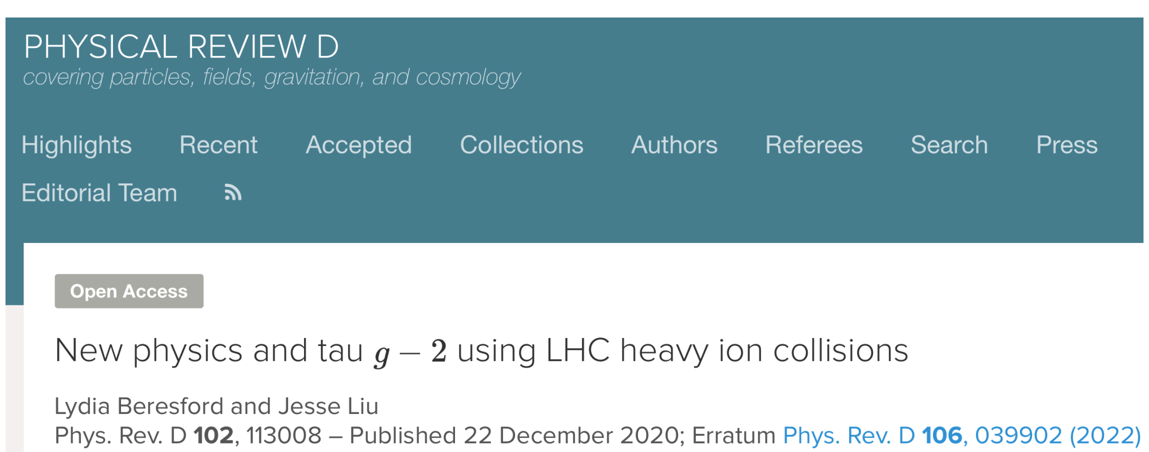
Anomalous electromagnetic moments of τ lepton in $\gamma\gamma \to \tau^+\tau^-$ reaction in Pb+Pb collisions at the LHC

Mateusz Dyndał [a], Mariola Kłusek-Gawenda [b], Antoni Szczurek [b 1], Matthias Schott [c]

[PLB 809 (2020) 135682]



Beresford, Liu PRD (2020)


PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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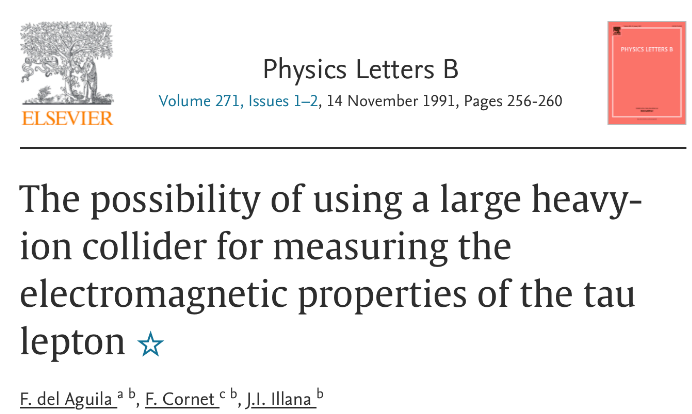
New physics and tau $g-2$ using LHC heavy ion collisions

Lydia Beresford and Jesse Liu
Phys. Rev. D **102**, 113008 – Published 22 December 2020; Erratum Phys. Rev. D **106**, 039902 (2022)

Aguila, Cornet, Illana PLB (1991)


Physics Letters B
Volume 271, Issues 1–2, 14 November 1991, Pages 256-260

The possibility of using a large heavy-ion collider for measuring the electromagnetic properties of the tau lepton ☆

F. del Aguila [a b], F. Cornet [c b], J.I. Illana [b]

Outline: Experimental realization

ATLAS Collaboration 2204.13478 (accepted PRL)

arXiv > hep-ex > arXiv:2204.13478

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High Energy Physics – Experiment

[Submitted on 28 Apr 2022 (v1), last revised 24 Nov 2022 (this version, v3)]

Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

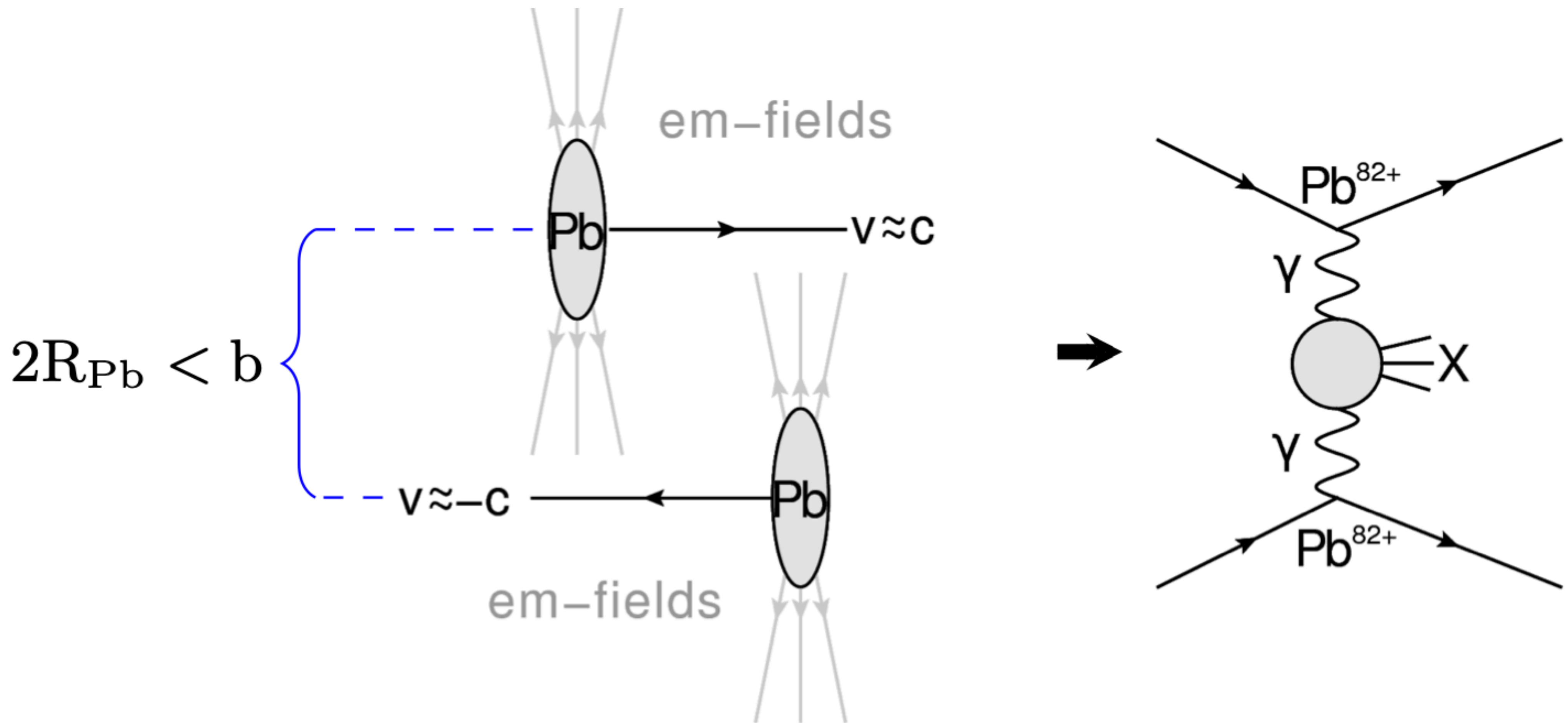
ATLAS Collaboration

This Letter reports the observation of τ-lepton pair production in ultraperipheral lead-lead collisions, $\mathrm{Pb+Pb} \to \mathrm{Pb}(\gamma\gamma \to \tau\tau)\mathrm{Pb}$, and constraints on the τ-lepton anomalous magnetic moment, a_τ. The dataset corresponds to an integrated luminosity of 1.44 nb^{-1} of LHC Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV recorded by the ATLAS experiment in 2018. Selected events contain one muon from a τ-lepton decay, an electron or charged-particle track(s) from the other τ-lepton decay, little additional central-detector activity, and no forward neutrons. The $\gamma\gamma \to \tau\tau$ process is observed in Pb+Pb collisions with a significance exceeding 5 standard deviations, and a signal strength of $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$ assuming the Standard Model value for a_τ. To measure a_τ, a template fit to the muon transverse-momentum distribution from τ-lepton candidates is performed, using a dimuon ($\gamma\gamma \to \mu\mu$) control sample to constrain systematic uncertainties. The observed 95% confidence-level interval for a_τ is $-0.057 < a_\tau < 0.024$.

Physics briefing

See also CMS Collaboration 2205.05312

Ultraperipheral heavy-ion collisions



Described in a **Equivalent Photon Aproximation (EPA)** framework

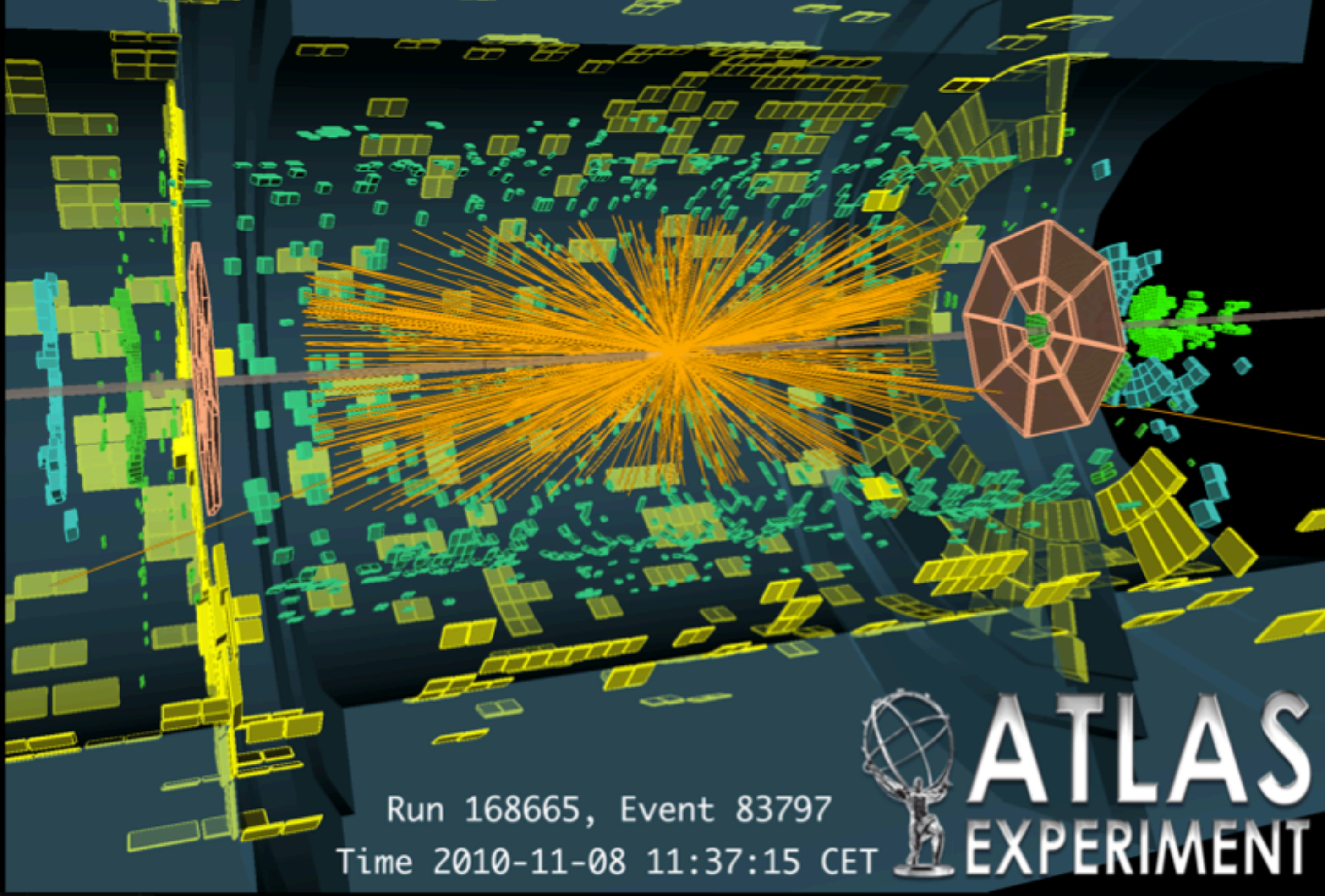
Equivalent photon flux scales with Z^2

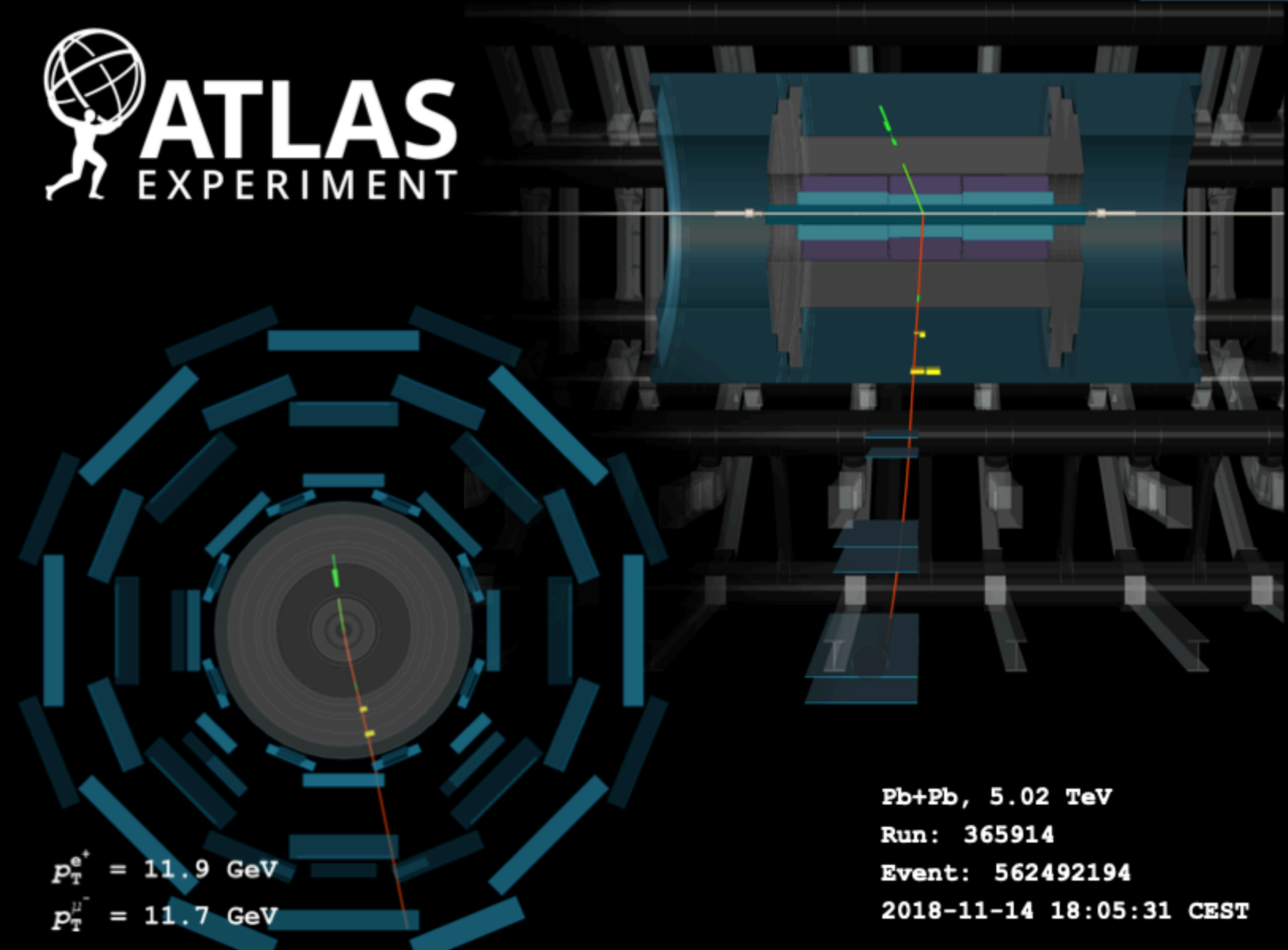
[Fermi, Nuovo Cim. 2 (1925) 143]
[Weizsacker, Z. Phys. 88 (1934) 612]
[Williams, Phys. Rev. 45 (10 1934) 729]

→ Pb+Pb collisions at LHC are a superb source of high energy photons!

Excellent tool to study rare processes and to search for beyond Standard Model (BSM) physics

Head-on
Pb+Pb collision



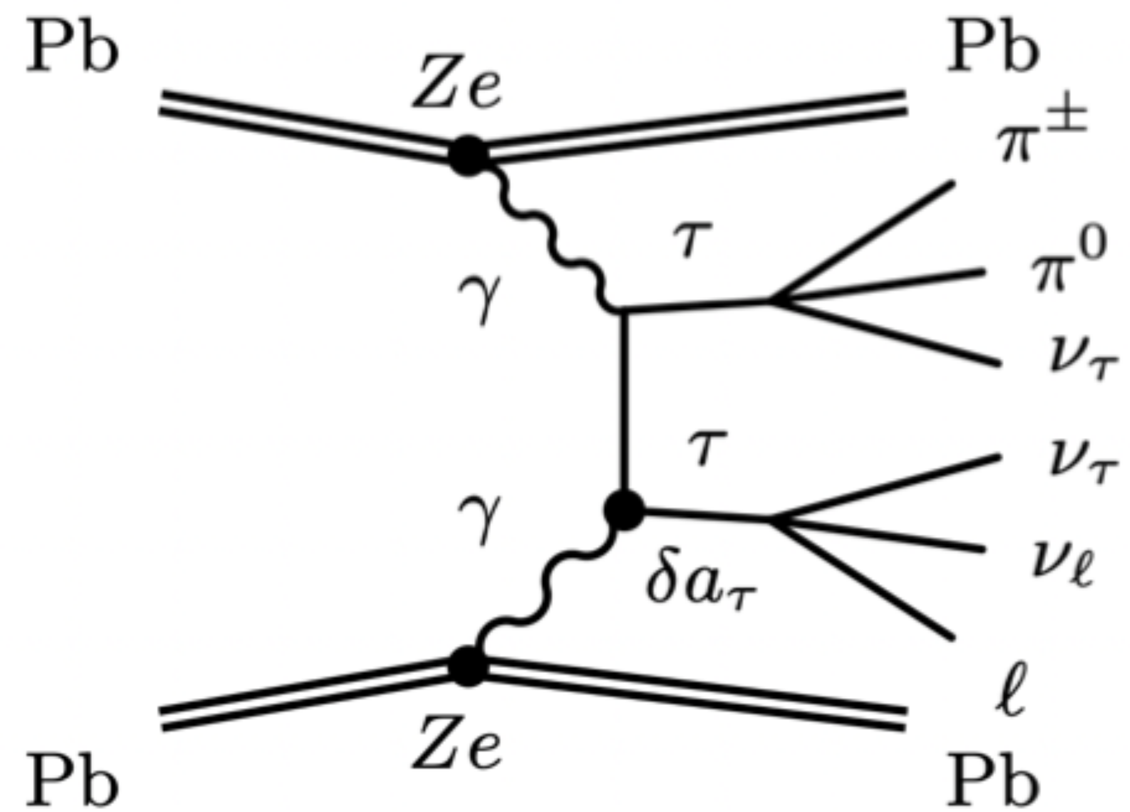


Ultra-peripheral
Pb+Pb collision

Our analysis strategy

Advantages of UPC over the proton-proton (pp) collisions:

- Z^4 enhancement of cross sections in Pb+Pb wrt pp system
- Very low hadronic pileup
  - exclusivity selections
- Low p_T thresholds in trigger and offline reconstruction



Use 1.44 nb^{-1} ATLAS Pb+Pb 2018 data, $\sqrt{s_{NN}} = 5.02$ TeV

Tau decays

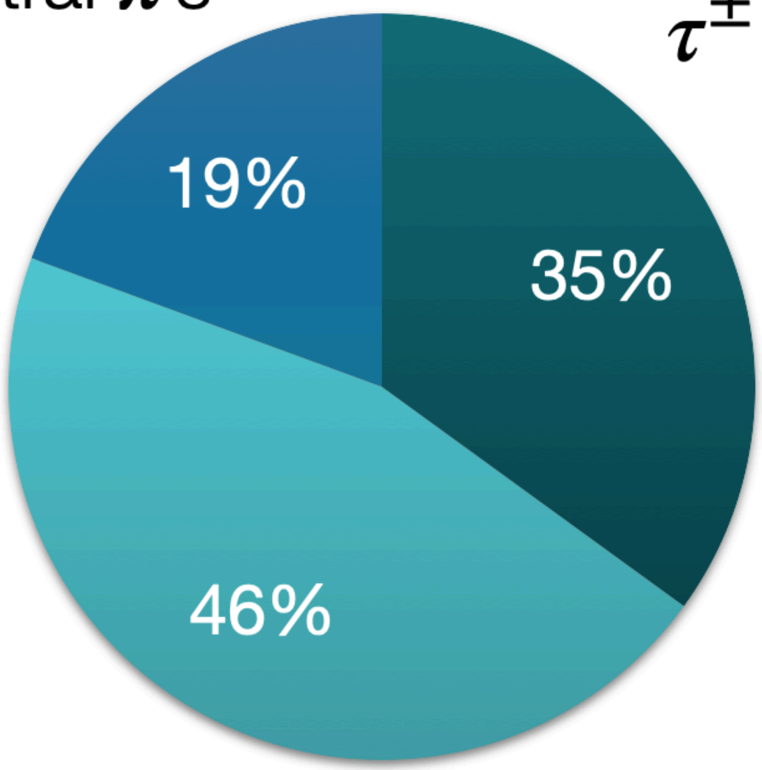
3 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$

$+ \geq 0$ neutral π's

Leptonic

$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$



1 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\nu_{\tau}$

$+ \geq 0$ neutral π's

$\gamma\gamma \rightarrow \tau\tau$ MC: Starlight + Tauola (Photos + Pythia 8 for QED FSR)

Photon flux re-weighted to SuperChic 3 (in $m_{\mu\mu}$, $|y_{\mu\mu}|$)

Signature

Signal τ-leptons are low-energetic, typically with $p_T < 10$ GeV

No standard ATLAS identification of τ-leptons can be used
→ Instead events classified based on the charged τ-lepton decay products

Use leptons: $p_T(\mu/e) > 4$ GeV and tracks: $p_T(trk) > 100$ MeV

Single muon trigger used to record signal events with muon $p_T > 4$ GeV

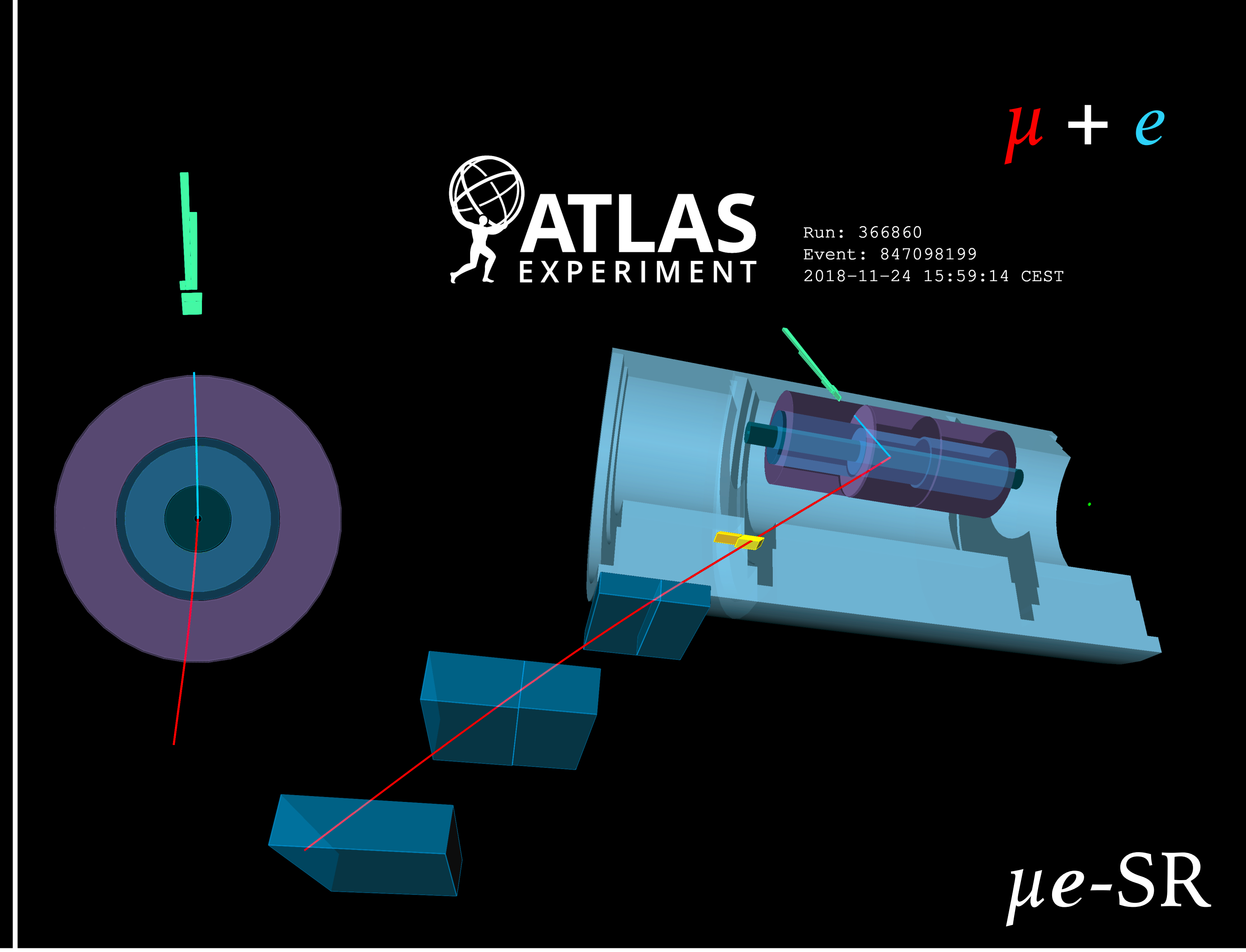
Three signal categories:

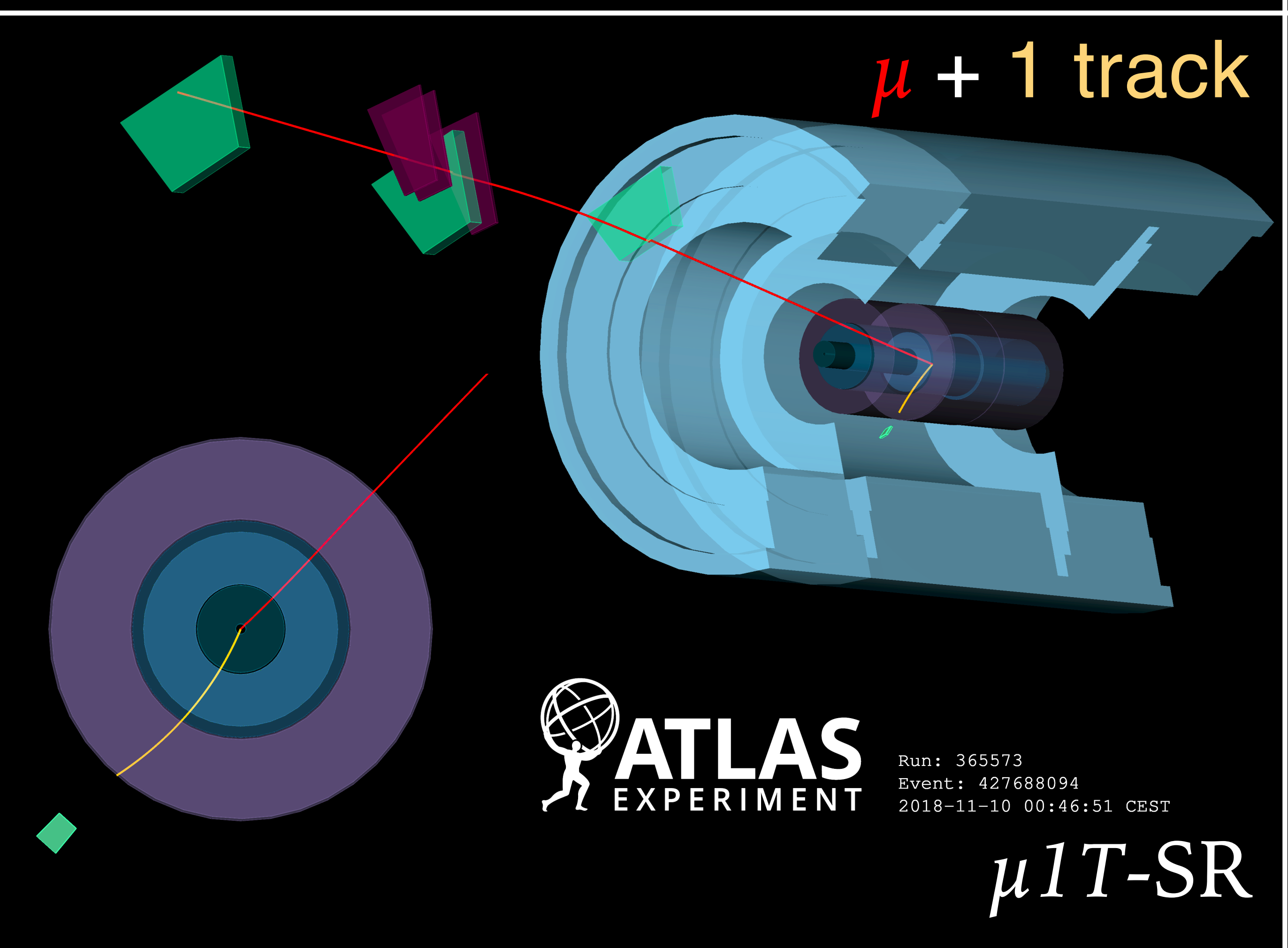
1μ1e-SR: $\mu + e$

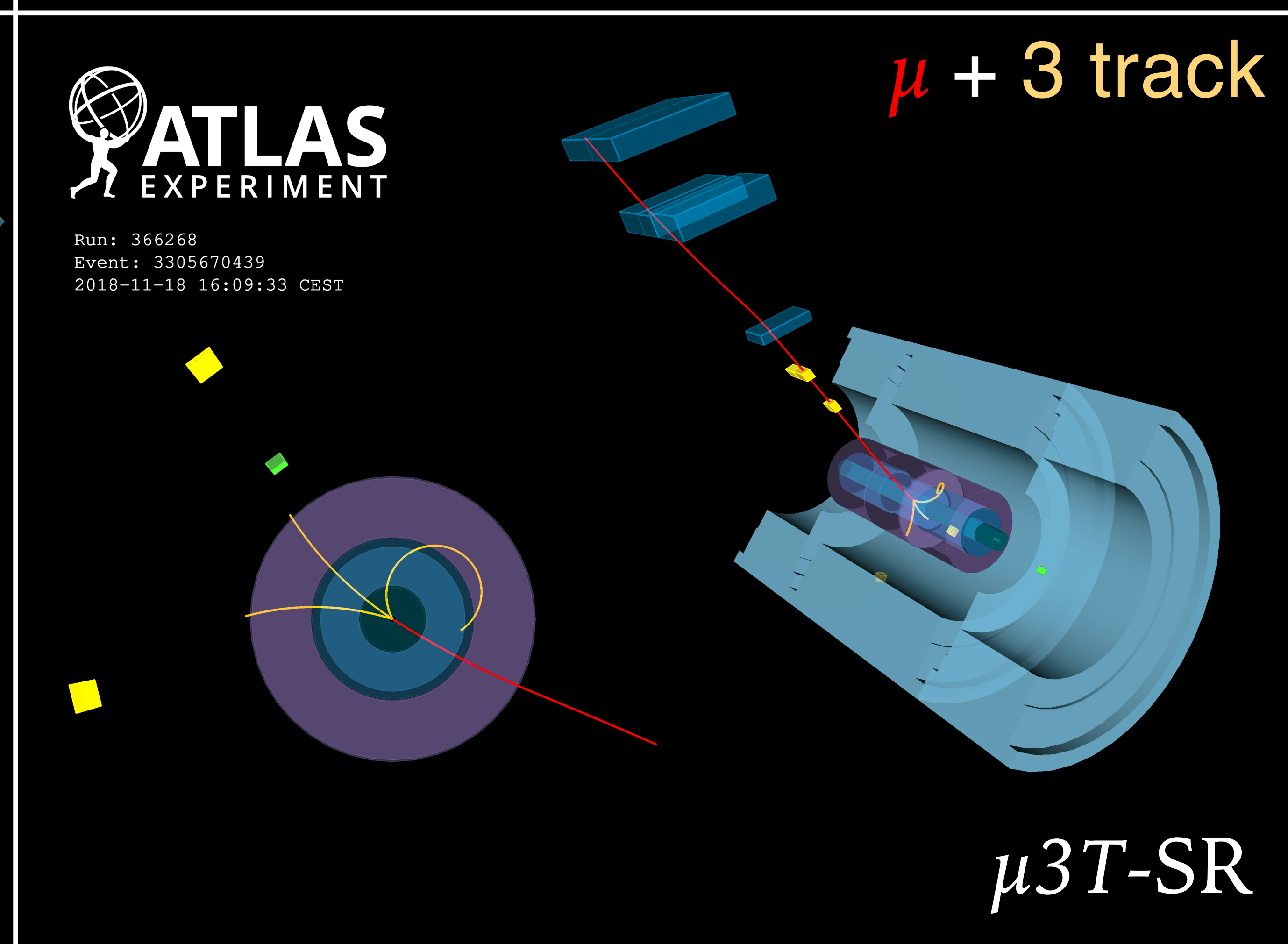
1μ1T-SR: μ + track (from ℓ or hadron)

1μ3T-SR: μ + 3 tracks (from 3-prong τ decay)

Signal Regions (SRs)

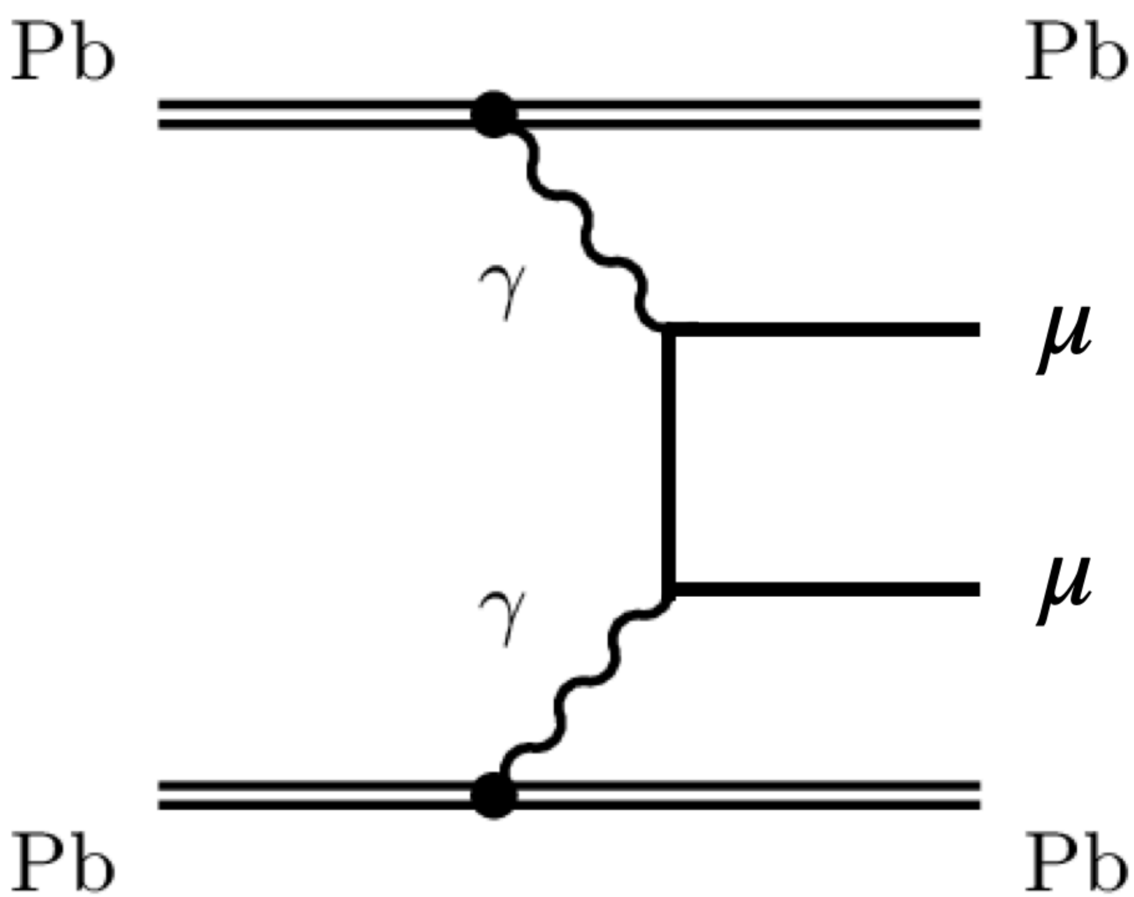






Main backgrounds

Di-muon



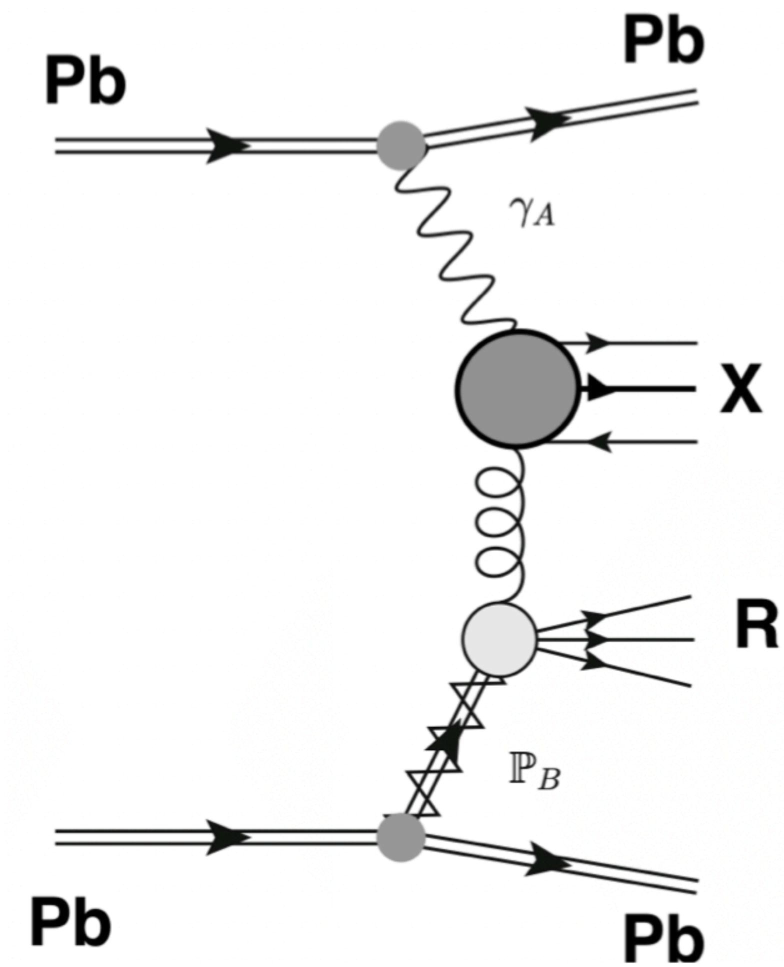
Estimate with MC

$\gamma\gamma \to \mu\mu$ Starlight+Pythia8

$\gamma\gamma \to \mu\mu\gamma$ Madgraph5

Photon flux re-weighted to SuperChic 3

Photonuclear



Data-driven estimate

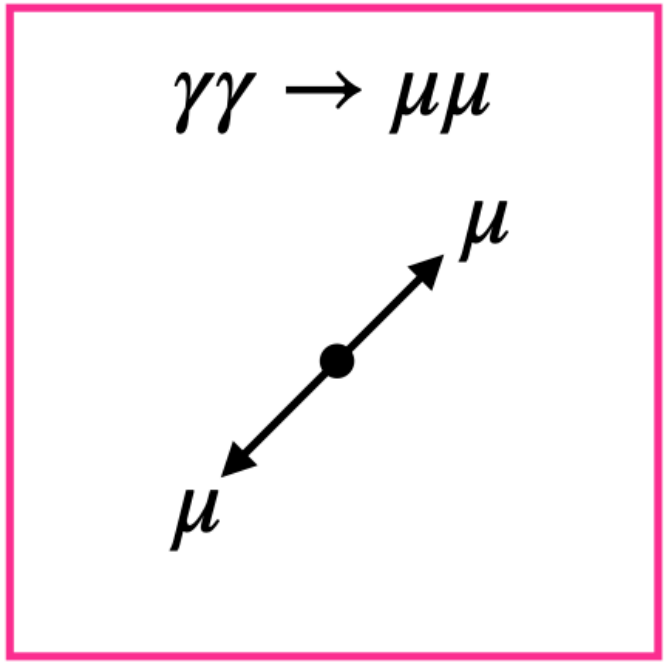
Often leads to nucleus breakup
→ Forward neutrons

Rejecting background

Exactly 1 μ + exactly 1 e or 1 or 3 tracks separated from μ

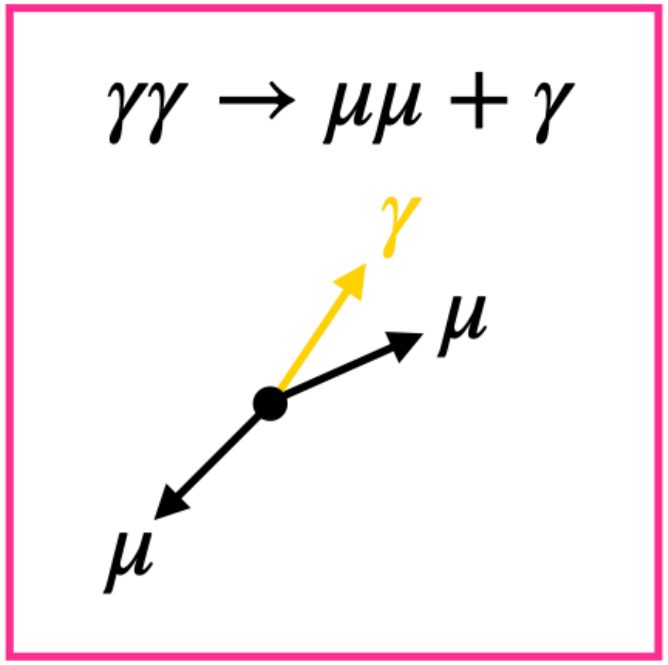
Reject $\gamma\gamma \to \mu\mu$ events:

- require $p_T(\mu, trk) > 1$ GeV for μ1T-SR



Additional rejection for $\gamma\gamma \to \mu\mu + \gamma$:

- require $p_T(\mu, trk, \gamma/cluster) > 1$ GeV for μ1T-SR



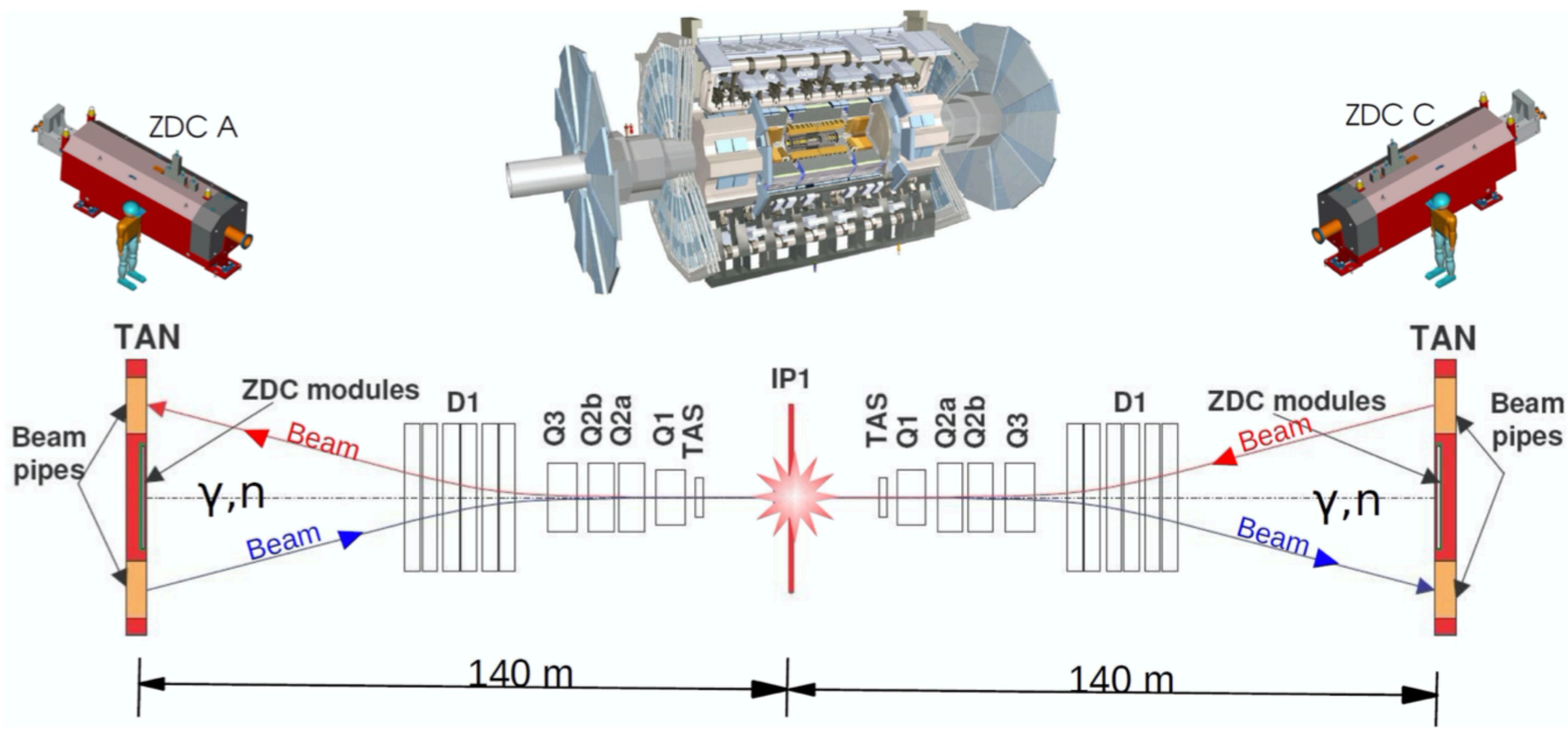
$E_T(\gamma) > 1.5$ GeV

$p_T(cluster) > 1$ GeV ($|\eta|<2.5$), 100 MeV ($2.5 < |\eta| < 4.5$)

Rejecting background

Rejecting photo-nuclear and other backgrounds:

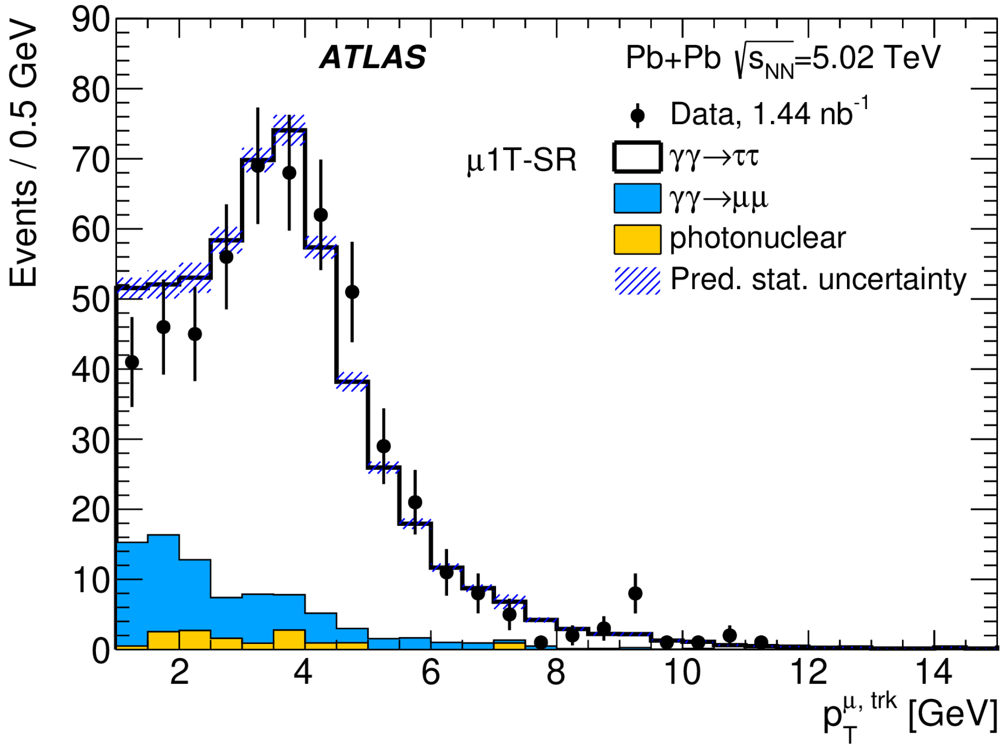
- Zero Degree Calorimeter Energy (E_{ZDC}) < 1 TeV on side A and C
- No unmatched clusters i.e. not near μ or track(s), for μ + track(s) SRs
- m(trks) < 1.7 GeV for μ3T-SR



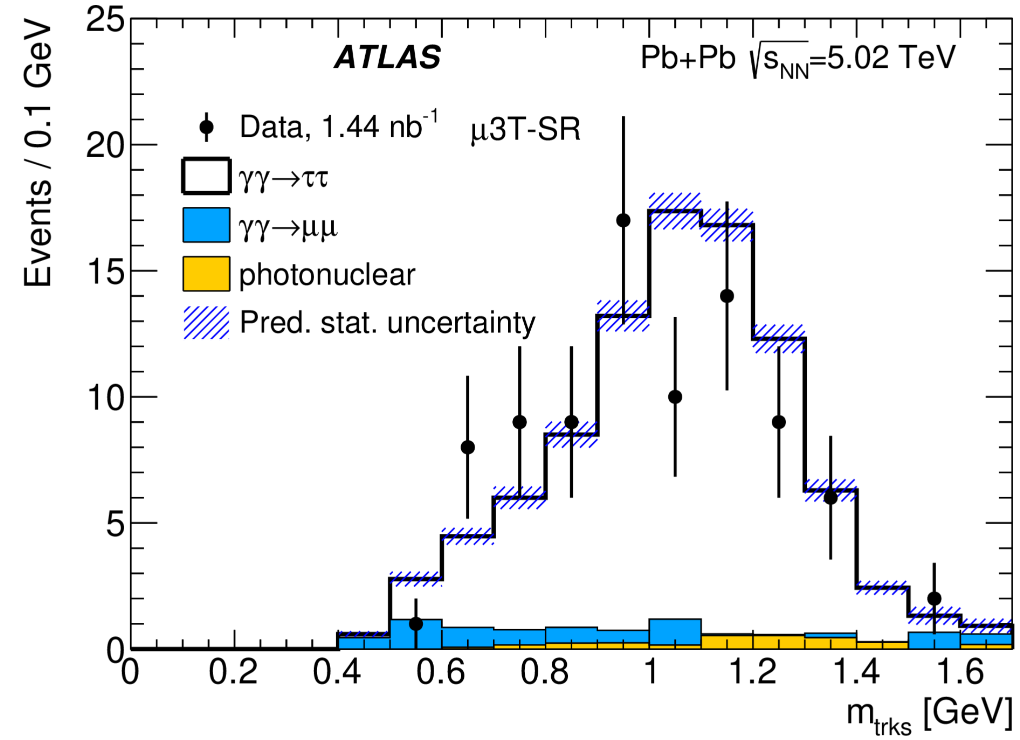
Signal region distributions

[arXiv:2204.13478]

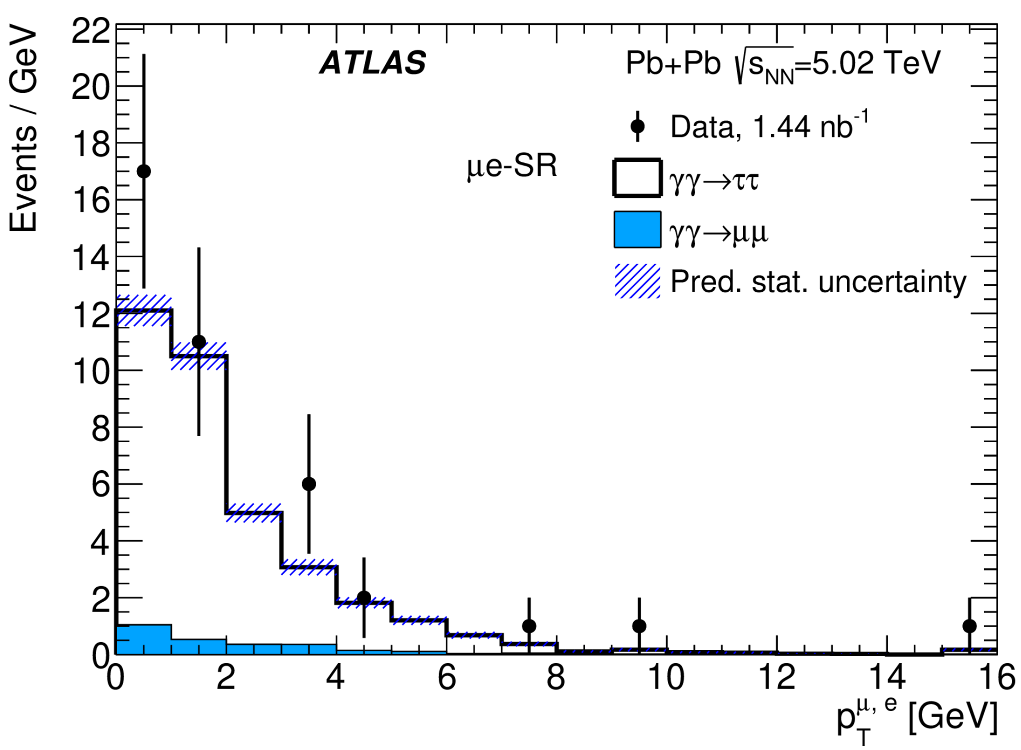
μ1T-SR: N_{obs}=532, N_{bkg}=84±19



μ3T-SR: N_{obs}=85, N_{bkg}=9±3



μe-SR: N_{obs}=39, N_{bkg}=2.8±0.7



Good agreement of pre-fit predictions with data

Total of about 650 events across all SRs

Small background contributions

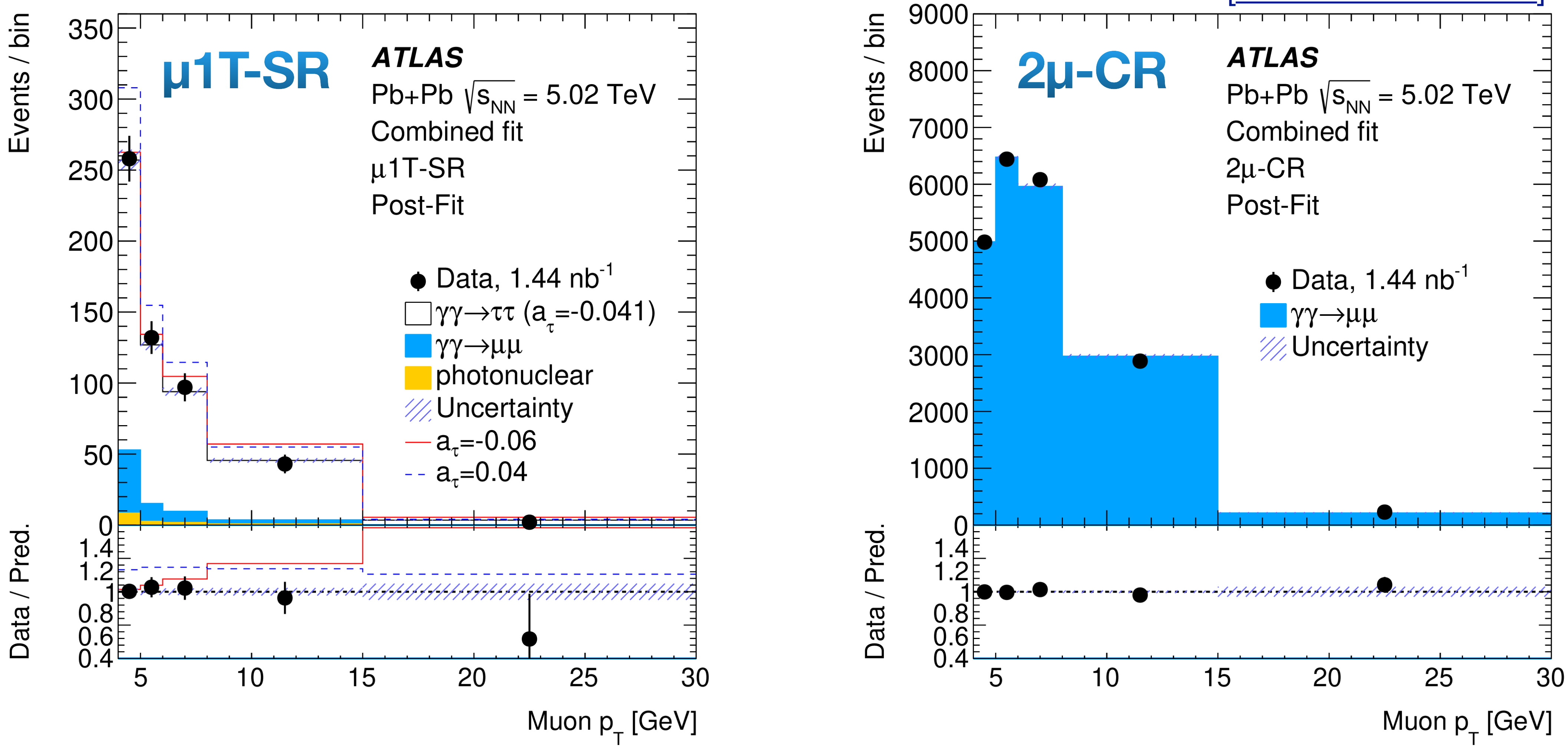
Observation of $\gamma\gamma \to \tau\tau$ in Pb+Pb

The $\gamma\gamma \to \tau\tau$ signal strength and a_τ value is extracted using a **profile likelihood fit**

Fit muon pT distribution in the three SRs and 2μ-CR

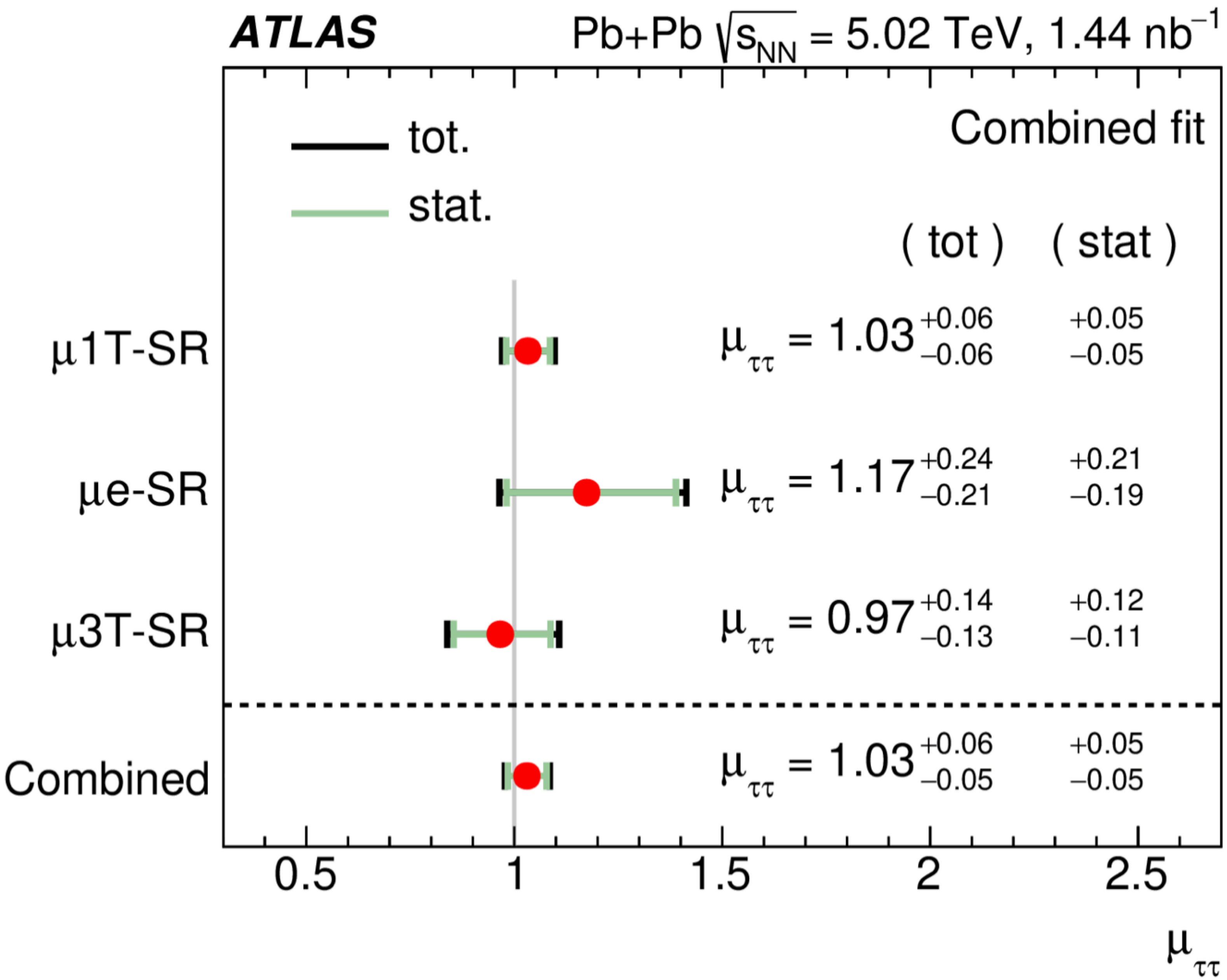
Clear observation ($\gg 5\sigma$) of $\gamma\gamma \to \tau\tau$ process at the LHC

[arXiv:2204.13478]



Signal strength

$\mu_{\tau\tau}$ = observed yield / SM expectation



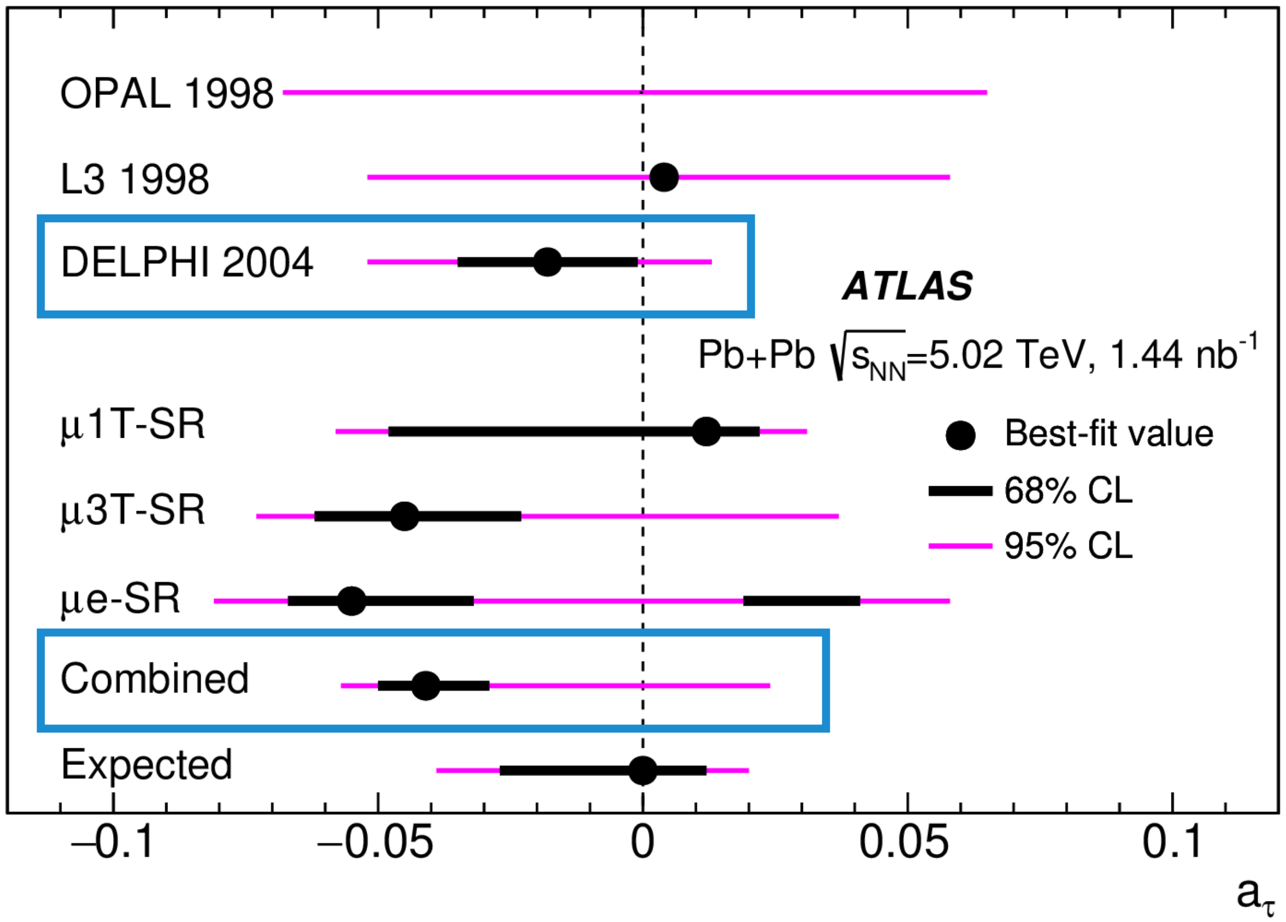
Each SR compatible with unity 5% precision, statistically limited

Tau g-2 competitive with LEP

ATLAS & CMS set first new constraints on a_τ since 2004

First measurements of τ leptons in heavy ion collisions

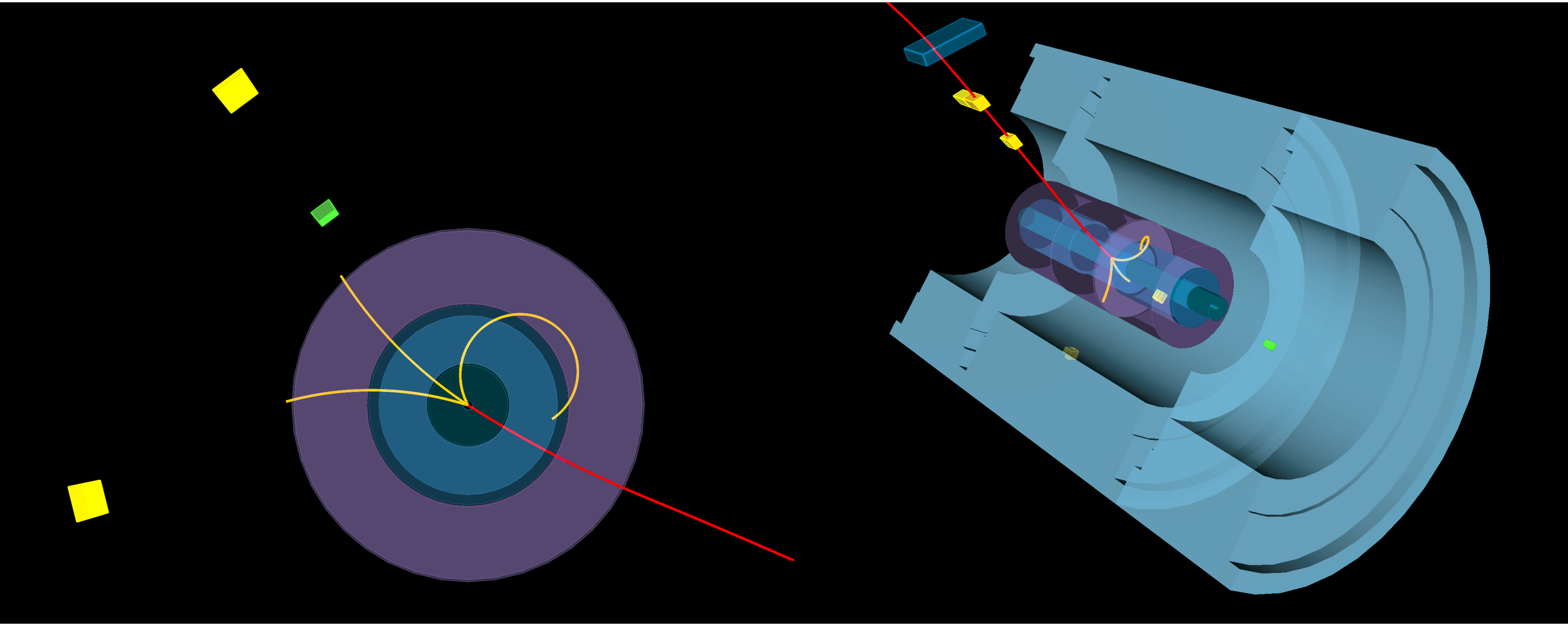
[arXiv:2204.13478]



Competitive with DELPHI

Statistical uncertainty dominates

Summary



Tau g-2 is interesting and important but poorly constrained

One of the first new constraints on tau g-2 in decades

Hadron collider constraints competing with LEP

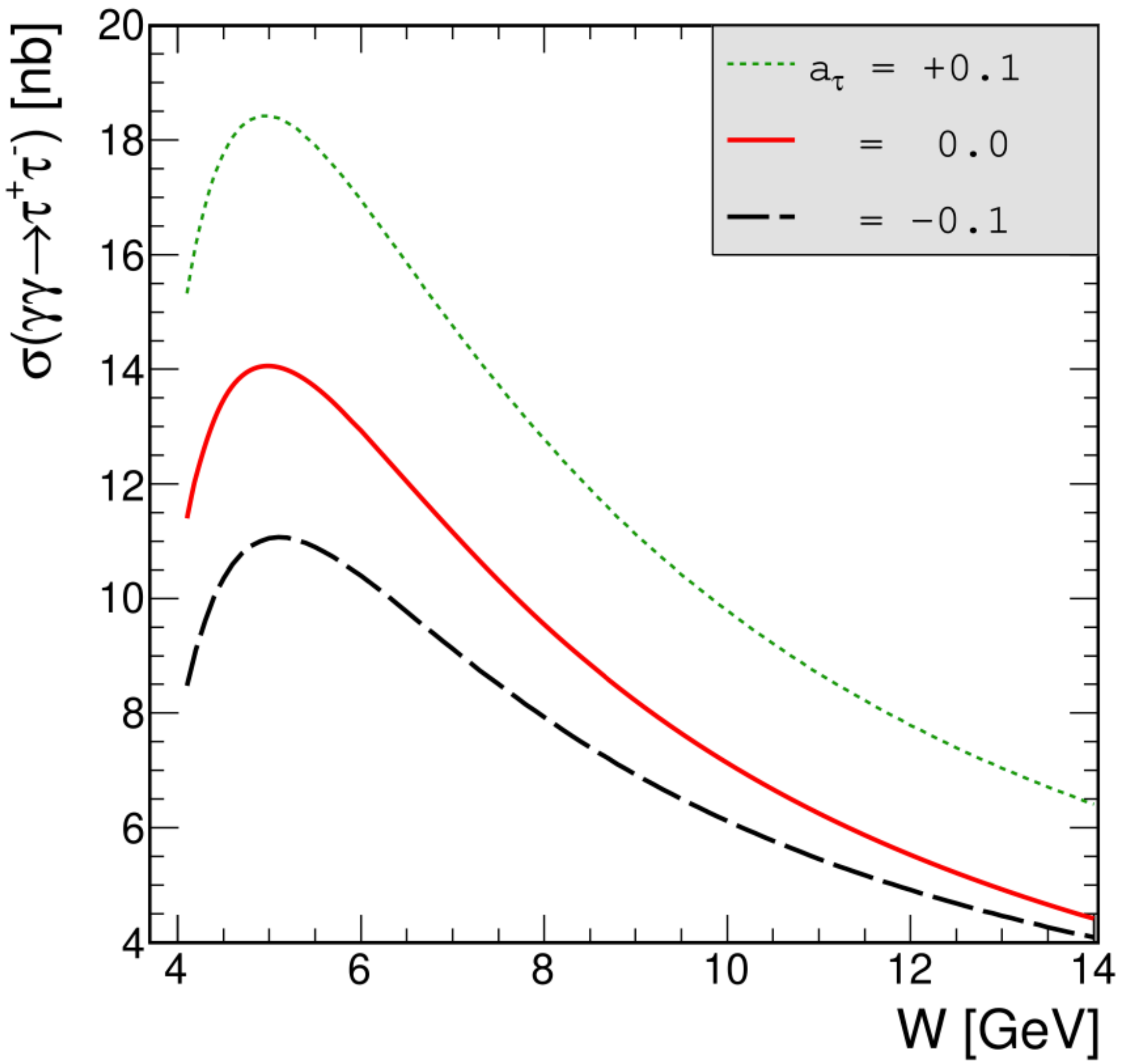
Research project partly supported by the National Science Centre of Poland under grant number UMO-2021/40/C/ST2/00187 and by PL-GRID infrastructure.”

Additional slides

Our analysis strategy

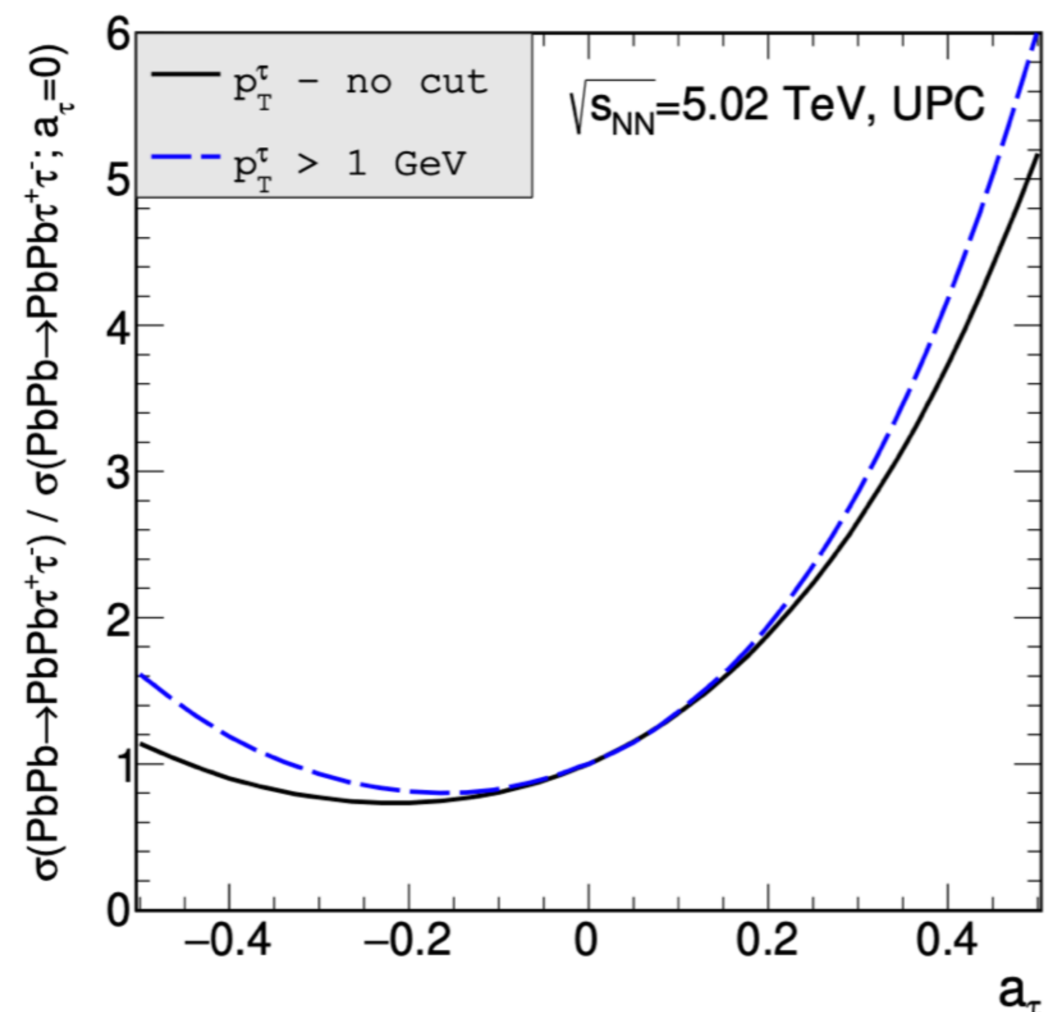
Cross-section sensitive to tau g-2

Also sensitive to tau EDM



Reduce uncertainties using $\gamma\gamma \to \mu\mu$ control region (2μCR), e.g. lumi, photon flux

Additional sensitivity from measuring differentially in lepton p_T



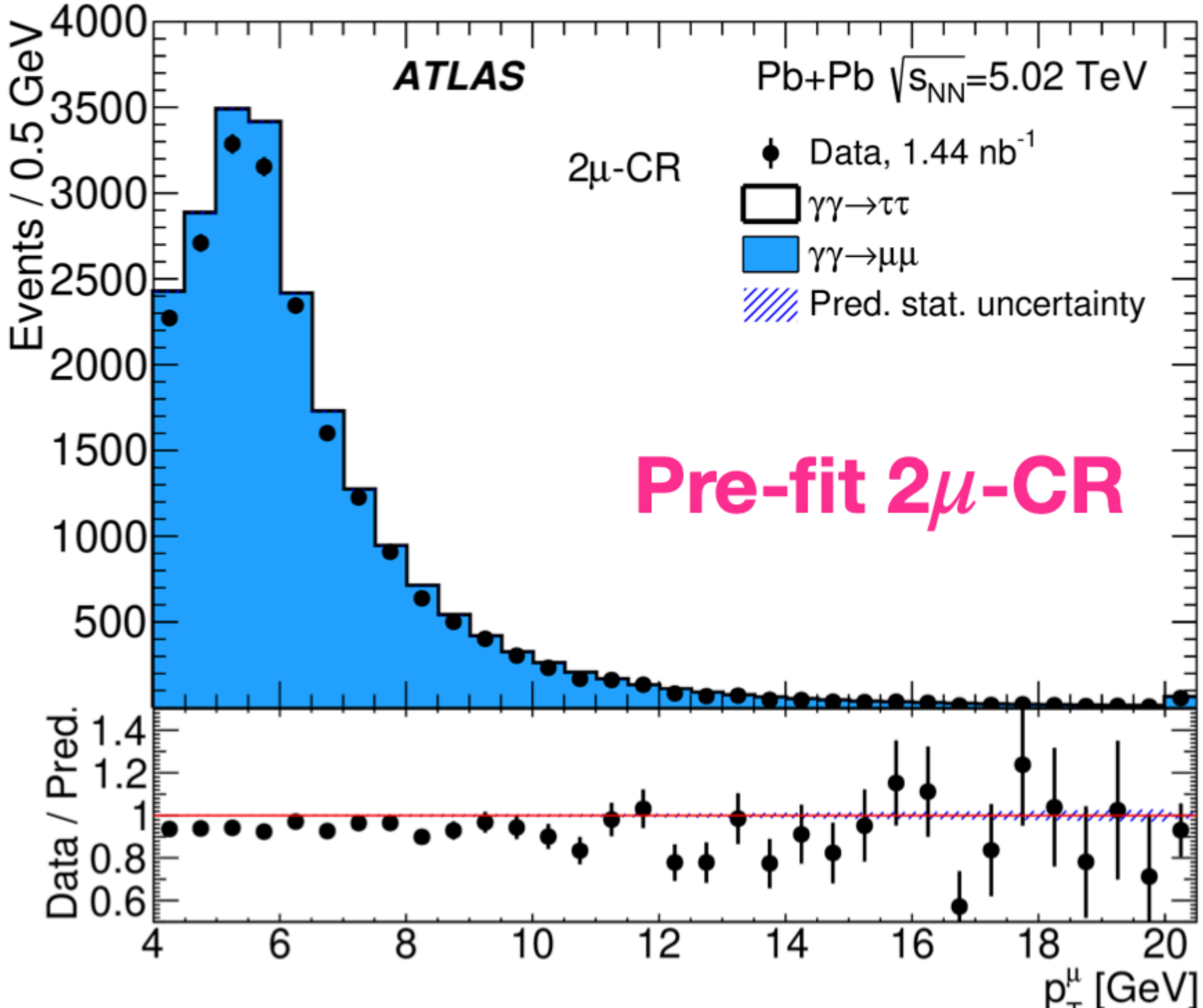
Dyndał, Kłusek-Gawęda, Szczurek, Schott PLB (2020)

Background estimation: $\gamma\gamma \rightarrow \mu\mu(\gamma)$

Main background

MC with Superchic3 photon flux (+6% overestimate)
c.f. -13% for Starlight photon flux

Difference = photon flux uncertainty

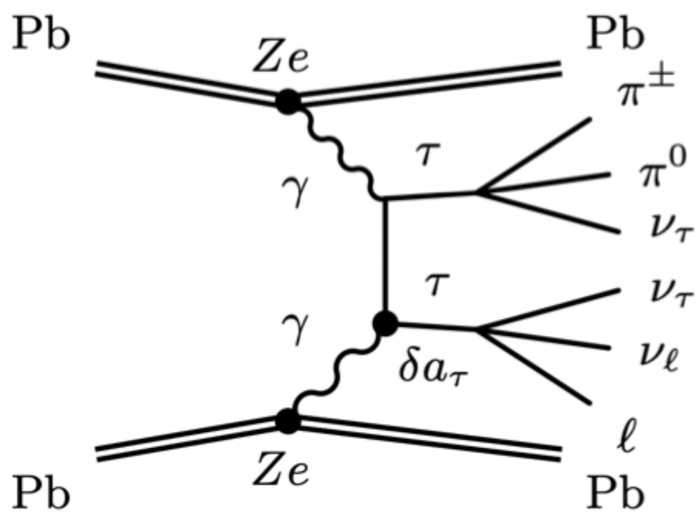


Motivation - BSM searches

- This talk covers following results from 5.02 TeV UPC Pb+Pb collisions from ATLAS:

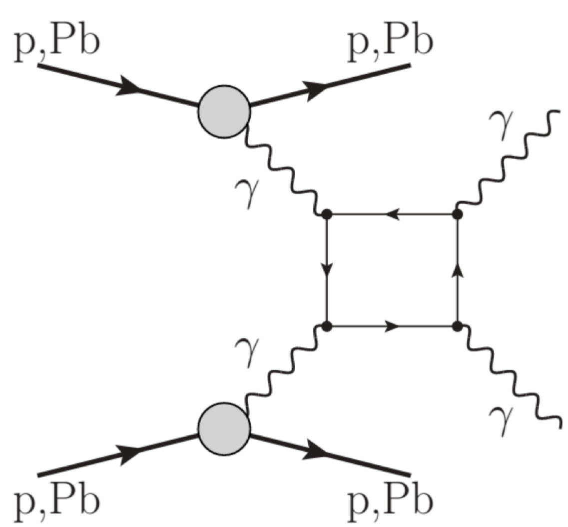
  - ***Observation of the $\gamma\gamma \to \tau^+\tau^-$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector*** [arXiv:2204.13478], accepted by PRL

    - **Constraints** on τ-lepton anomalous magnetic moment
    - Its value is sensitive to many BSM models (lepton compositeness, supersymmetry $\delta a_\tau \sim m_\tau^2 / M_S^2$, TeV-scale leptoquarks, …)



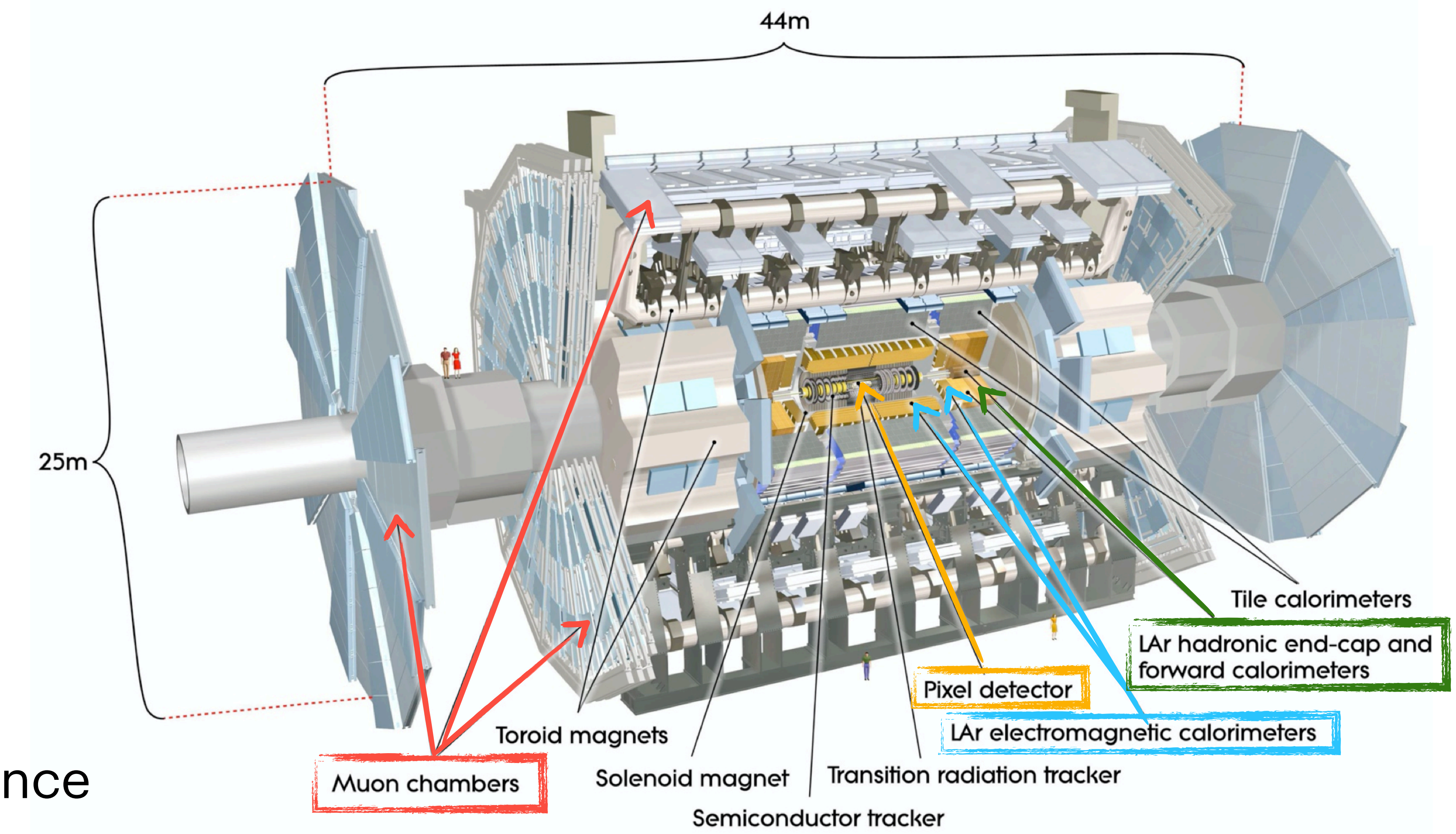
  - ***Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb⁻¹ of Pb+Pb data with the ATLAS detector*** [JHEP 03 (2021) 243]

    - **New particles** can enter the loop
    - Light-by-light (LbyL) cross-sections can be modified by various BSM phenomena (Born-Infeld extensions of QED, space-time non-commutativity in QED, extra spatial dimensions, …)



ATLAS detector

Main components:
inner tracker,
electromagnetic (EM),
and hadronic (HAD)
calorimeters,
and muon system



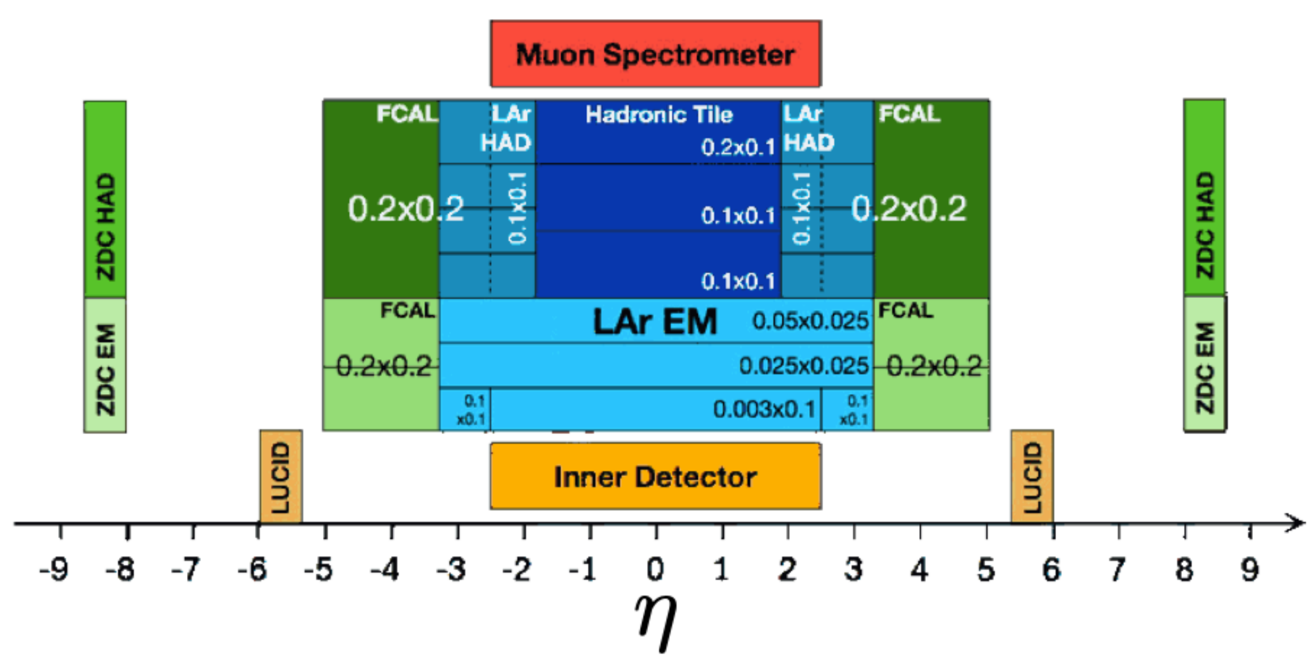
φ - full azimuth acceptance

η - broad pseudo rapidity coverage

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

p_T - transverse momentum

$$p_T = \sqrt{p_x^2 + p_y^2}$$

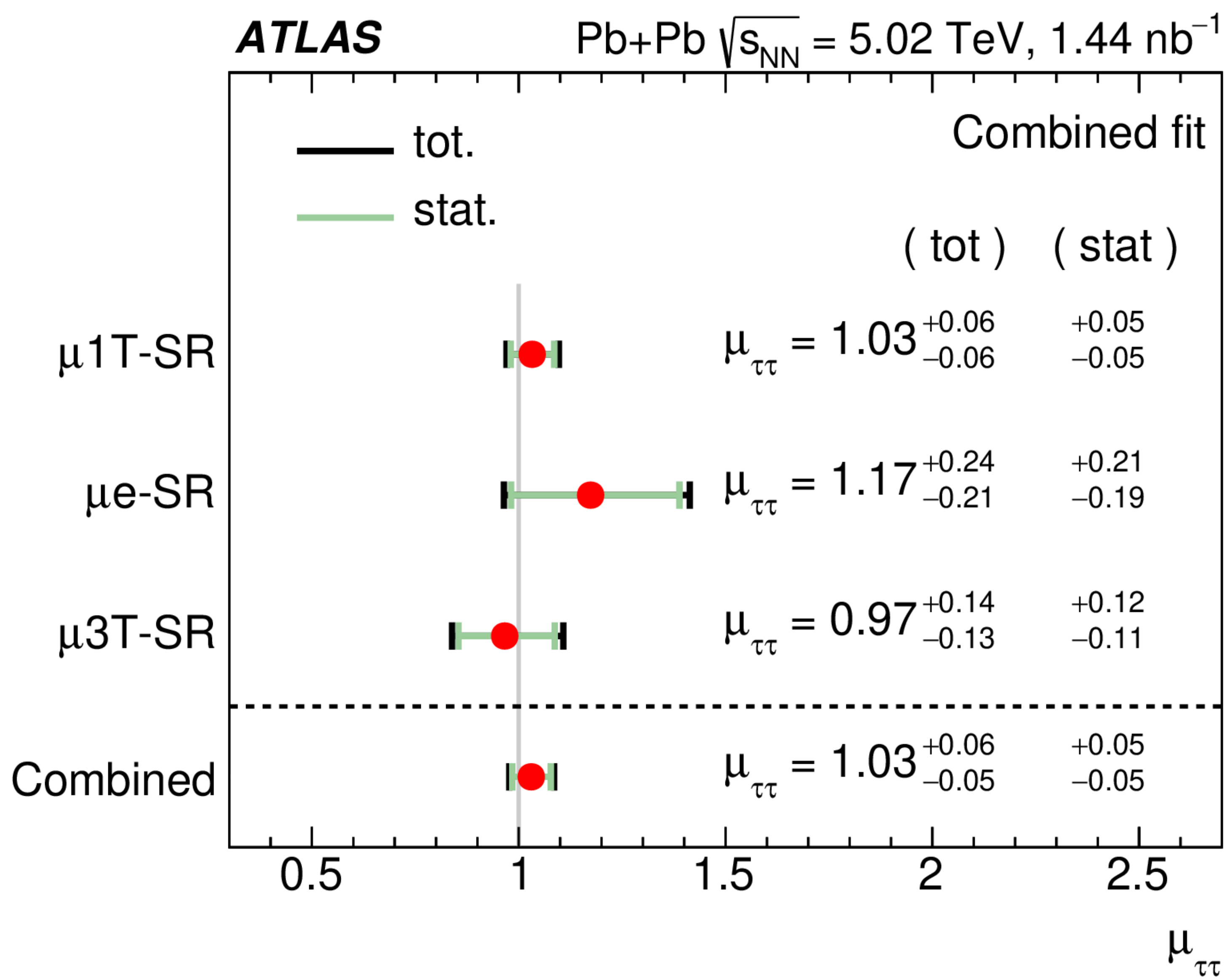


SR MC cutflow

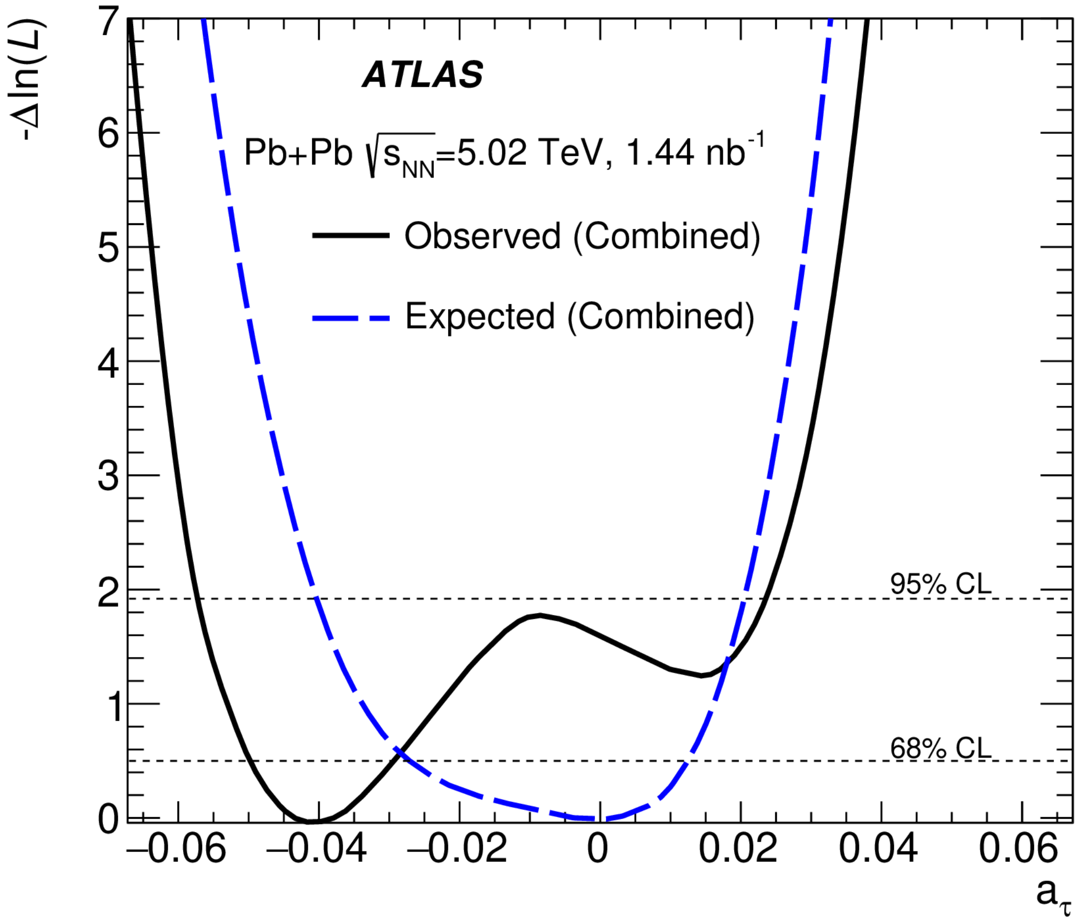
Requirement	Number of $\gamma\gamma \to \tau\tau$ events
Common selection	
$\sigma \times \mathcal{L}$	352611
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	28399
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}} \times w_{\text{SF}}$	35383
Pass trigger	1840
$E_{\text{ZDC}}^{A,C} < 1$ TeV	1114
μ1T-SR	
$N_{\mu}^{\text{preselected}} = 1$	1023
$N_{\mu}^{\text{signal}} = 1$	900
$N_e = 0$	867
N_{trk} (with $\Delta R_{\mu,\text{trk}} > 0.1) = 1$	575
Zero unmatched clusters	552
$\sum$ charge = 0	546
$p_{\text{T}}^{\mu,\text{trk}} > 1$ GeV	503
$p_{\text{T}}^{\mu,\text{trk},\gamma} > 1$ GeV	482
$p_{\text{T}}^{\mu,\text{trk,clust}} > 1$ GeV	462
$A_{\phi}^{\mu,\text{trk}} < 0.4$	459
μ3T-SR	
$N_{\mu}^{\text{preselected}} = 1$	1023
$N_{\mu}^{\text{signal}} = 1$	900
$N_e = 0$	867
N_{trk} (with $\Delta R_{\mu,\text{trk}} > 0.1) = 3$	88.1
Zero unmatched clusters	85.2
$\sum$ charge = 0	84.1
$m_{\text{trks}} < 1.7$ GeV	83.4
$A_{\phi}^{\mu,\text{trks}} < 0.2$	83.3
μe-SR	
$N_{\mu}^{\text{signal}} = 1$	958
$N_e = 1$	33.9
N_{trk} (with $\Delta R_{\mu/e,\text{trk}} > 0.1) = 0$	32.6
$\sum$ charge = 0	32.5

Results: Signal strength

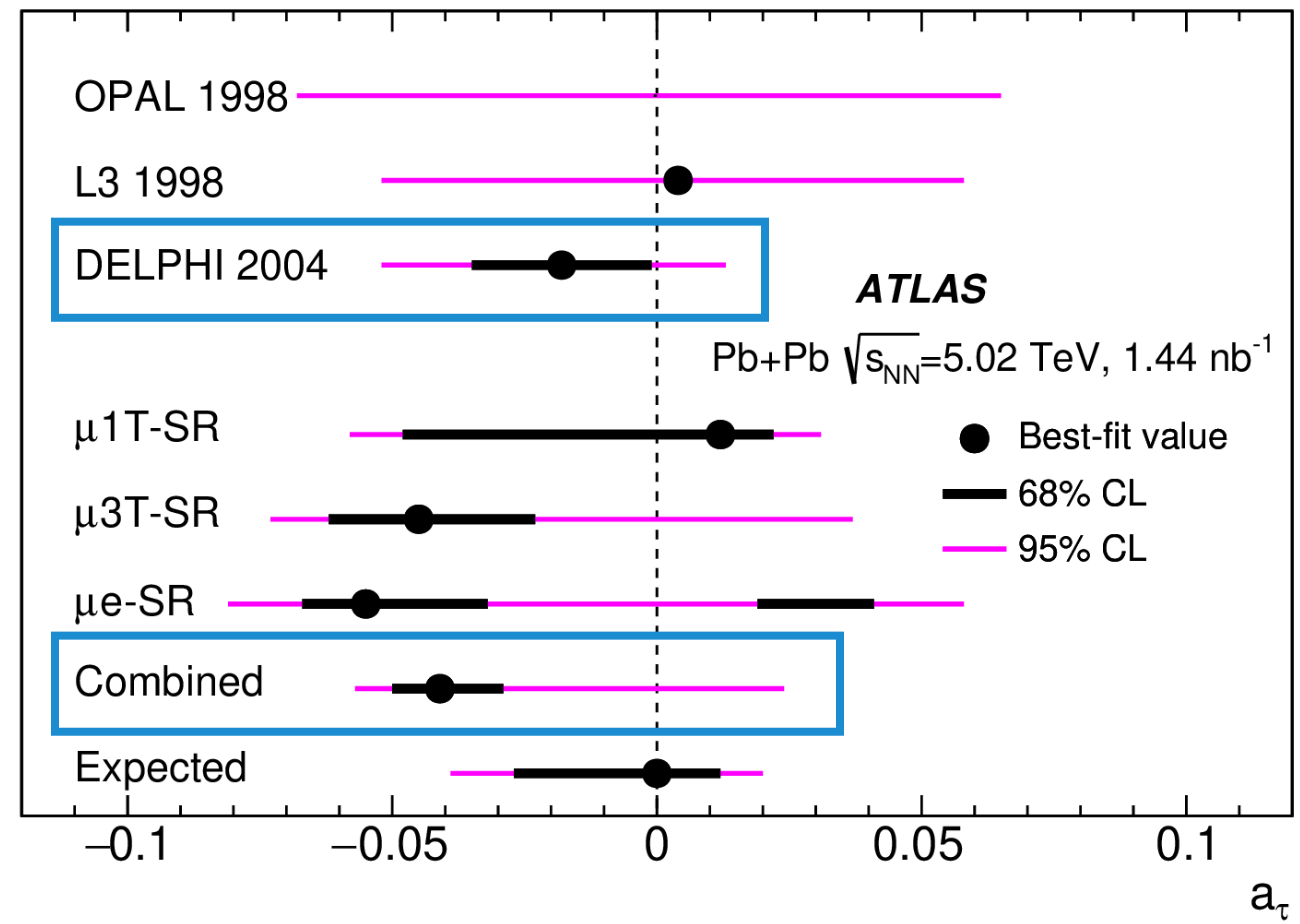
- Fit of $\gamma\gamma\rightarrow\tau\tau$ signal strength assuming SM value for a_τ :
  $\mu_{\tau\tau}$ = observed yield / SM expectation
- Result for each signal region compatible with unity
- Combined fit reaches 5% precision, limited by statistical uncertainties



Results: a_τ



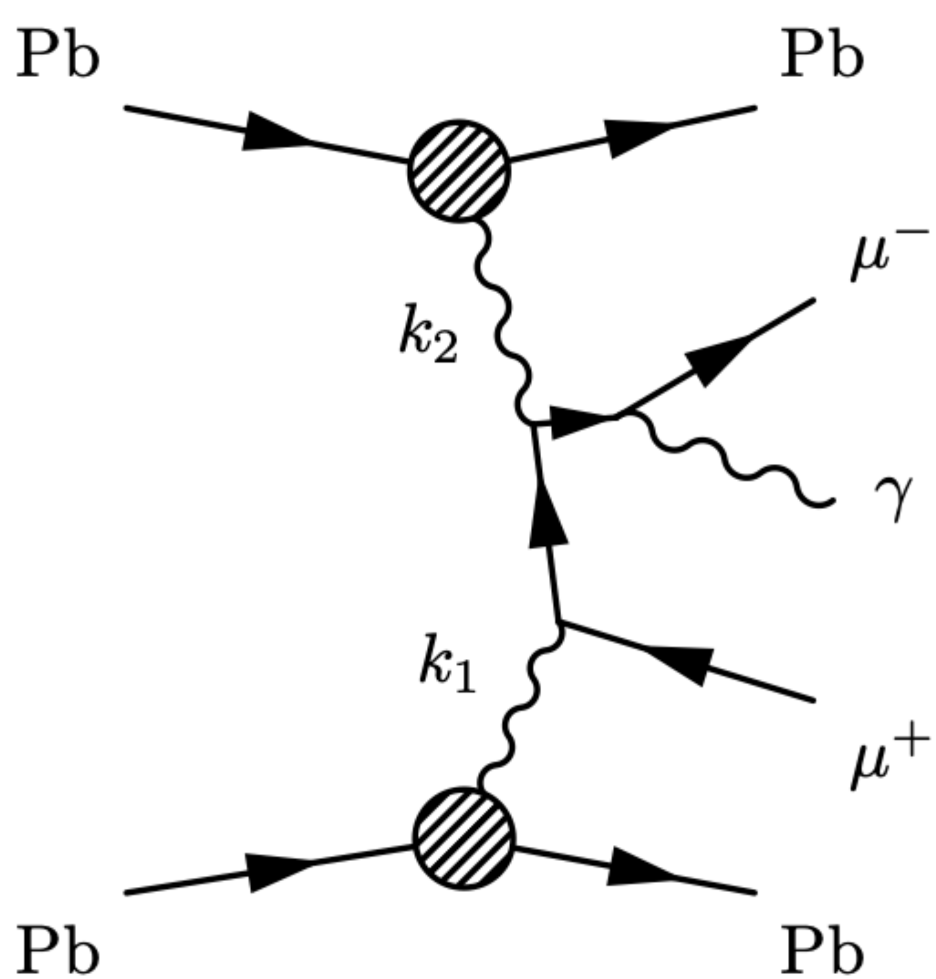
[arXiv:2204.13478]



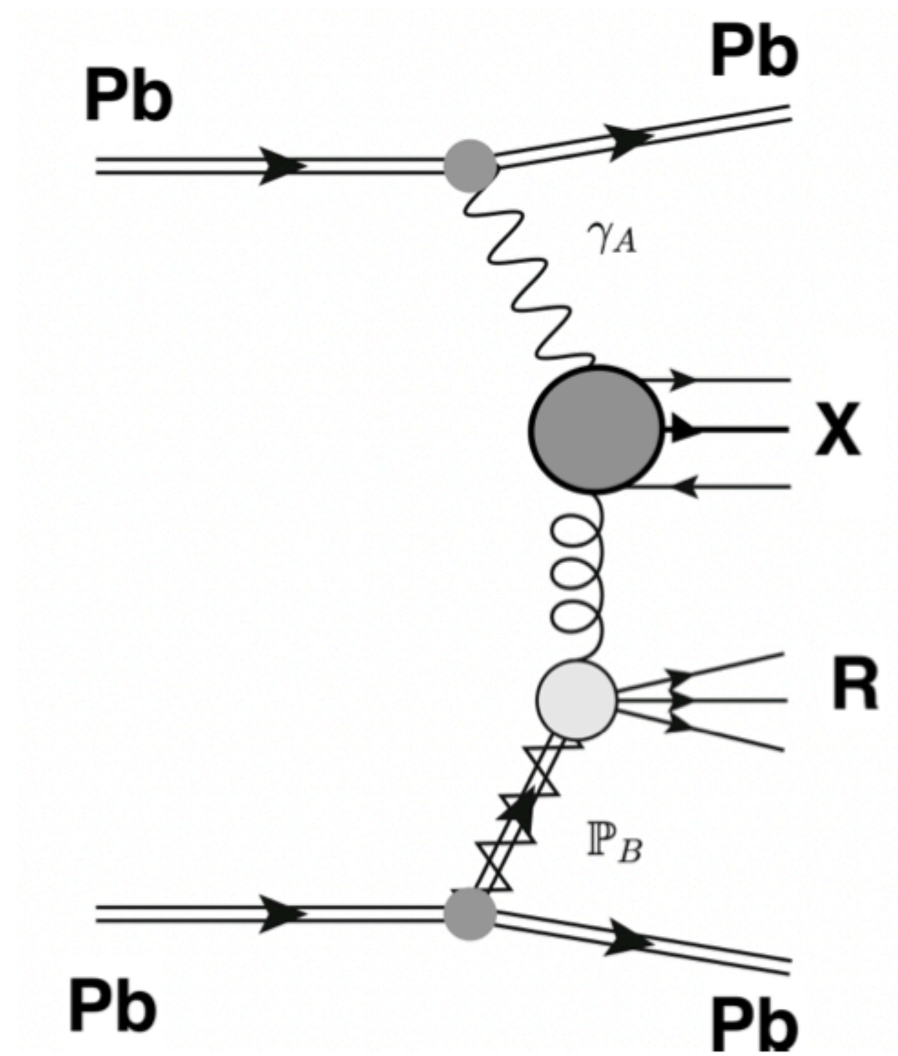
- The **best fit value** is a_τ = -0.041 with corresponding **95% CL interval** being **(-0.057, 0.024)**
- **Constraints on a_τ** have **similar precision** as those observed by **DELPHI** [EPJC 35 (2004) 159]
- Statistical uncertainties dominant → expected to **improve** with **Run-3** data
- Leading systematic uncertainties: trigger efficiency, τ decay modeling

Background processes

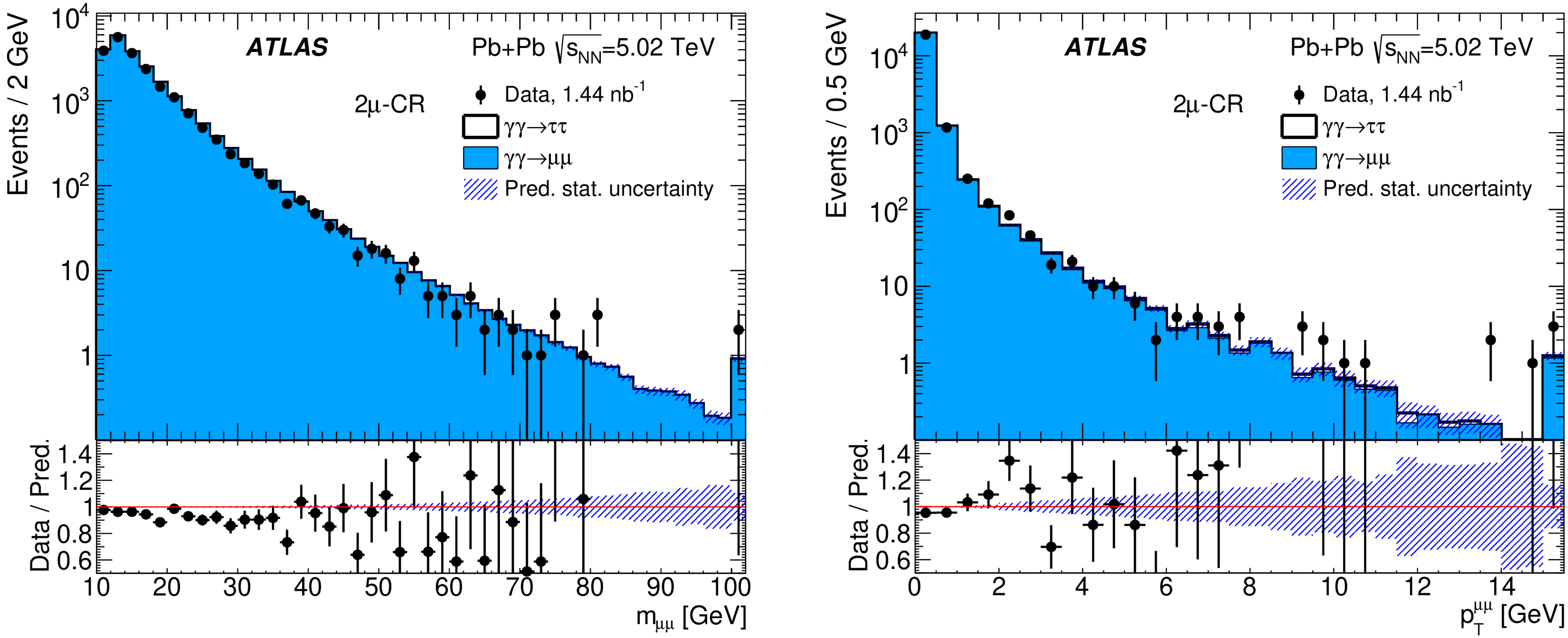
$\gamma\gamma \to \mu\mu(\gamma)$ production



diffractive photonuclear events

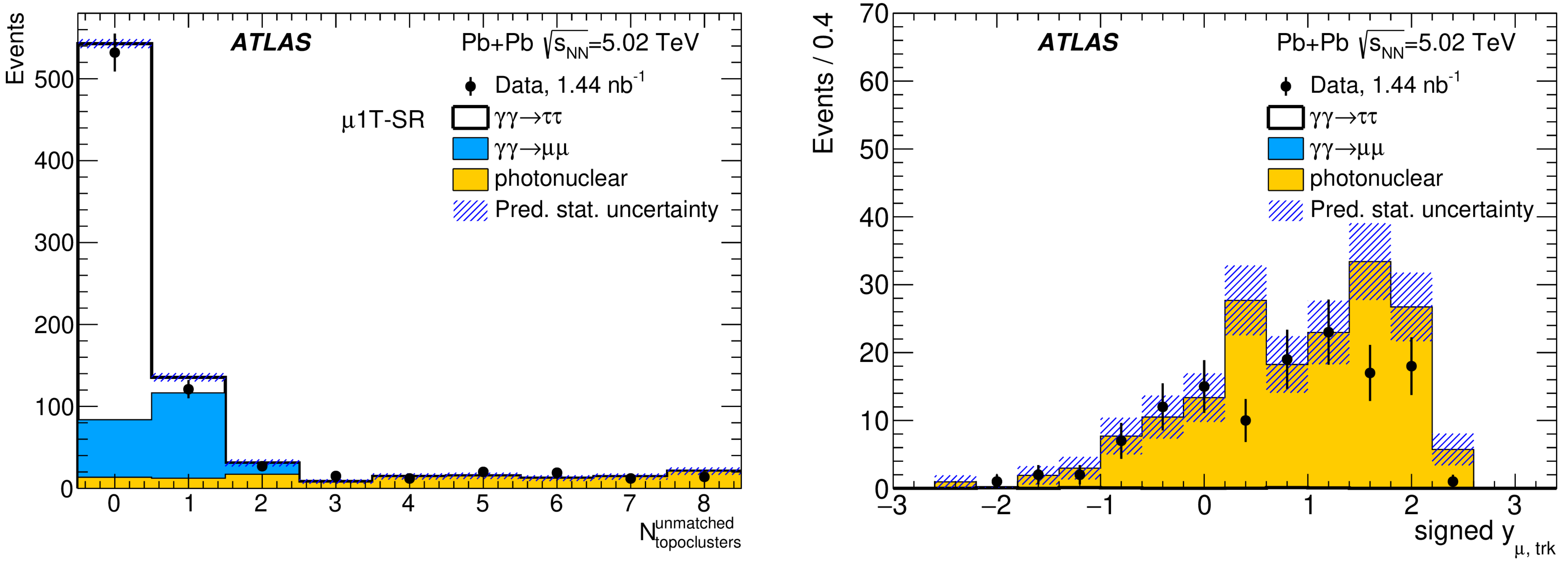


Background processes: $\gamma\gamma \rightarrow \mu\mu(\gamma)$ production



- Background from $\gamma\gamma \rightarrow \mu\mu(\gamma)$ production estimated using MC simulation
- Validation of modeling performed in dimuon control region (2μ-CR)
- Normalization off by +6% with SuperChic3 photon flux (Starlight: -13%)
- Good description of FSR emissions seen in $p_T^{\mu\mu}$ distribution tail

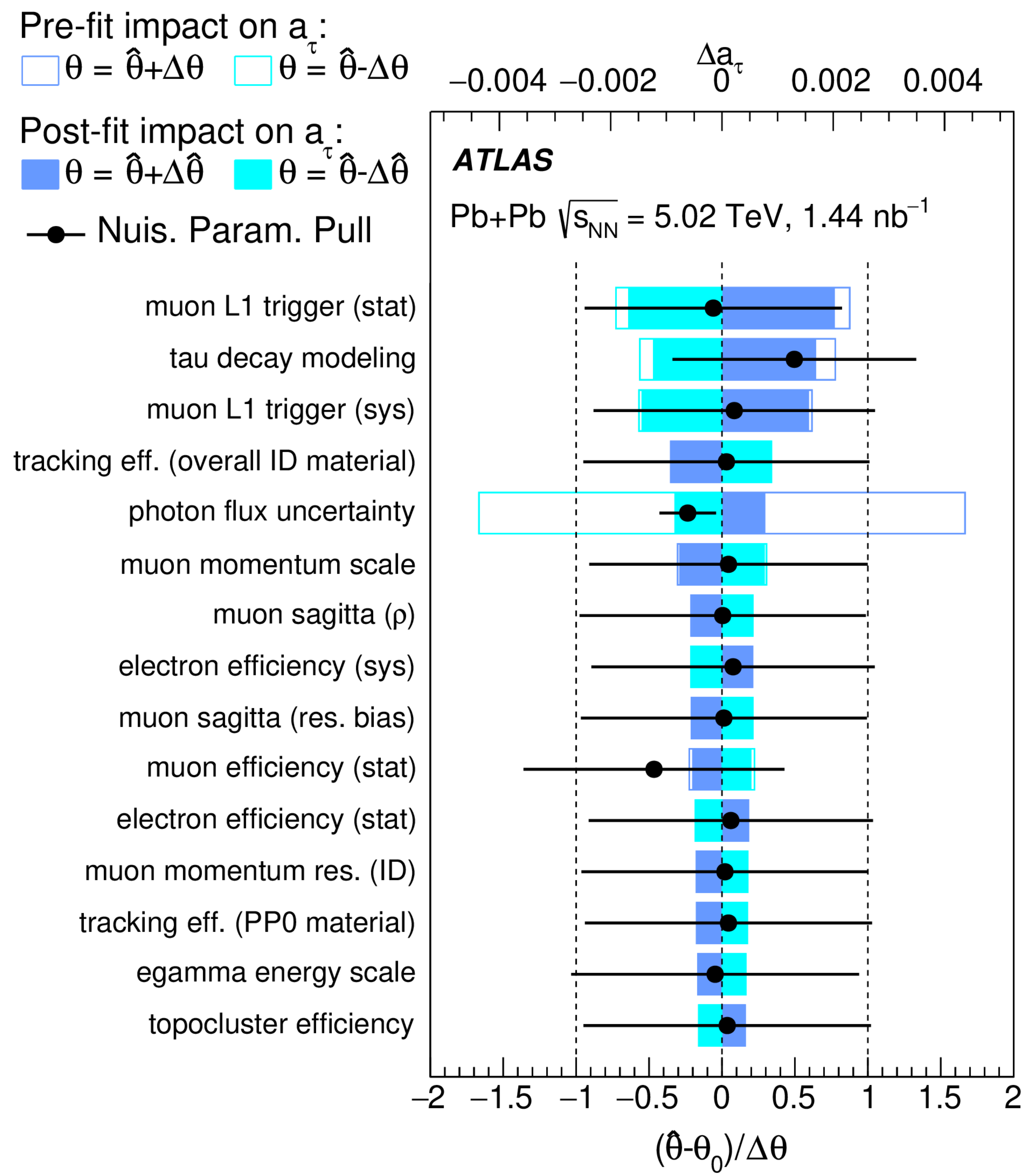
Background processes: diffractive photo nuclear events



- Data-driven estimation of diffractive photonuclear events in μ1T-SR and μ3T-SR
- Templates built from control regions similar to SRs, but requiring an additional track with p_T < 0.5 GeV and allowing 0nXn ZDC events
- Normalization: relax cluster veto → use region with 4-8 unmatched clusters
- Kinematic distributions in this region well described by the CR templates

Systematic uncertainties in a_τ

- Detector related
  - Muon trigger efficiency
  - Muon/electron reconstruction/ID efficiency and calibration
  - Track reconstruction efficiency
  - Cluster reconstruction efficiency and calibration
- Background
  - Photonuclear background template variation
- Theory
  - Photon flux modeling (SuperChic3 vs. Starlight)
  - τ decay modelling (Tauola vs. Pythia8)
  - 0n0n ZDC reweighing variation



Light-by-light scattering

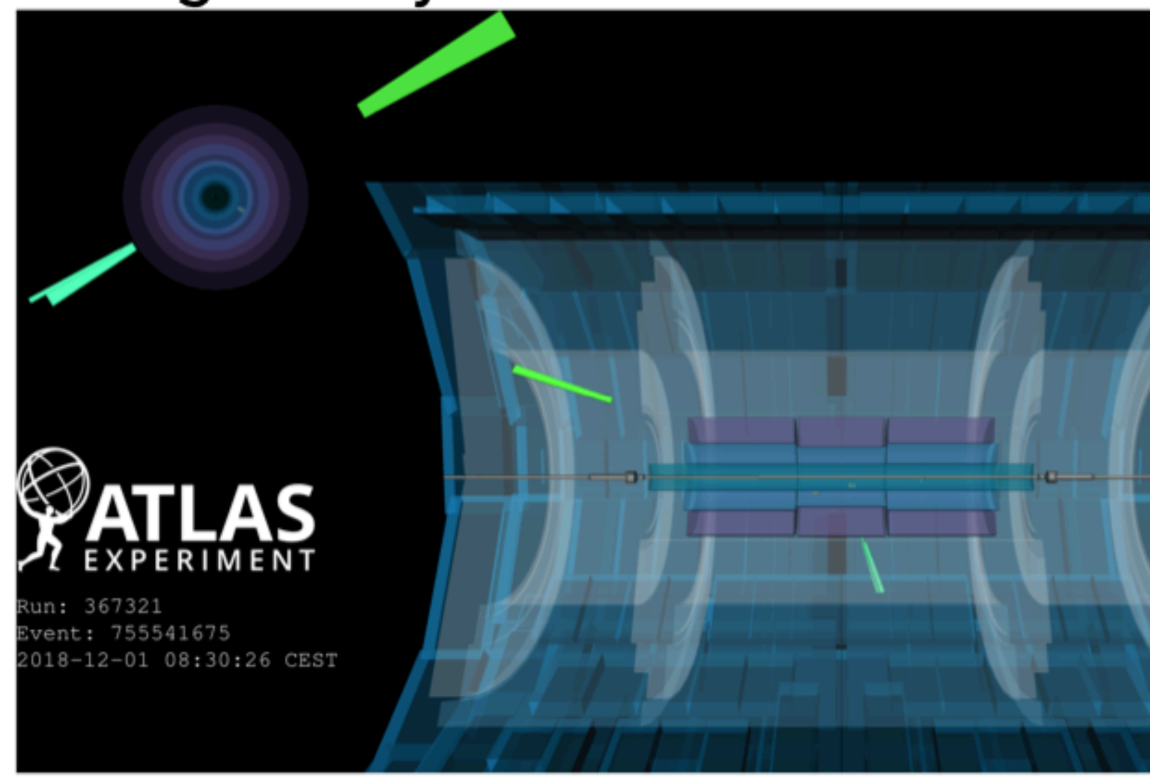
- Light-by-light (LbyL) scattering is a **very rare** QED process
- Several LbyL measurements performed with the LHC Pb+Pb UPC data:

  ATLAS: 2015: [Nature Physics 13 (2017) 852], 2018: [PRL 123 (2019) 052001]
  2015+2018: [JHEP 03 (2021) 243]

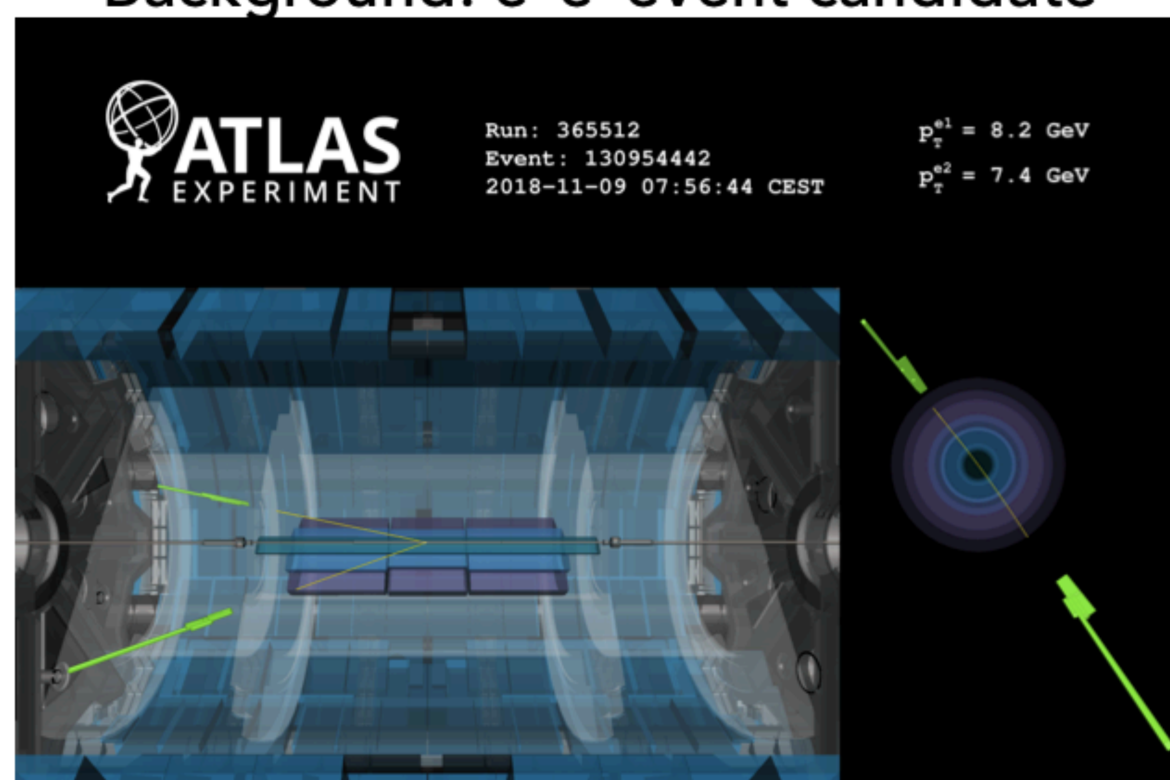
  CMS: 2015: [PLB 797 (2019) 134826]

- **Exclusive production of two photons (E_T > 2.5 GeV, $|\eta|$ < 2.37) with no activity observed in the detector**
  - Invariant diphoton mass $m_{\gamma\gamma}$ > 5 GeV, low diphoton $p_T^{\gamma\gamma} < 1$ GeV, low diphoton acoplanarity: $A_\phi = 1 - |\Delta\phi|/\pi < 0.01$
  - Veto on any extra low-p_T tracks
- Background: $\gamma\gamma \to e^+e^-$, central exclusive production of $gg \to \gamma\gamma$

Signal: LbyL event candidate



Background: e⁺e⁻ event candidate



Light-by-light scattering: cross sections

[JHEP 03 (2021) 243]

- Cross-section is measured in a fiducial phase space, defined by the requirements reflecting event selection

Measured fiducial cross section:

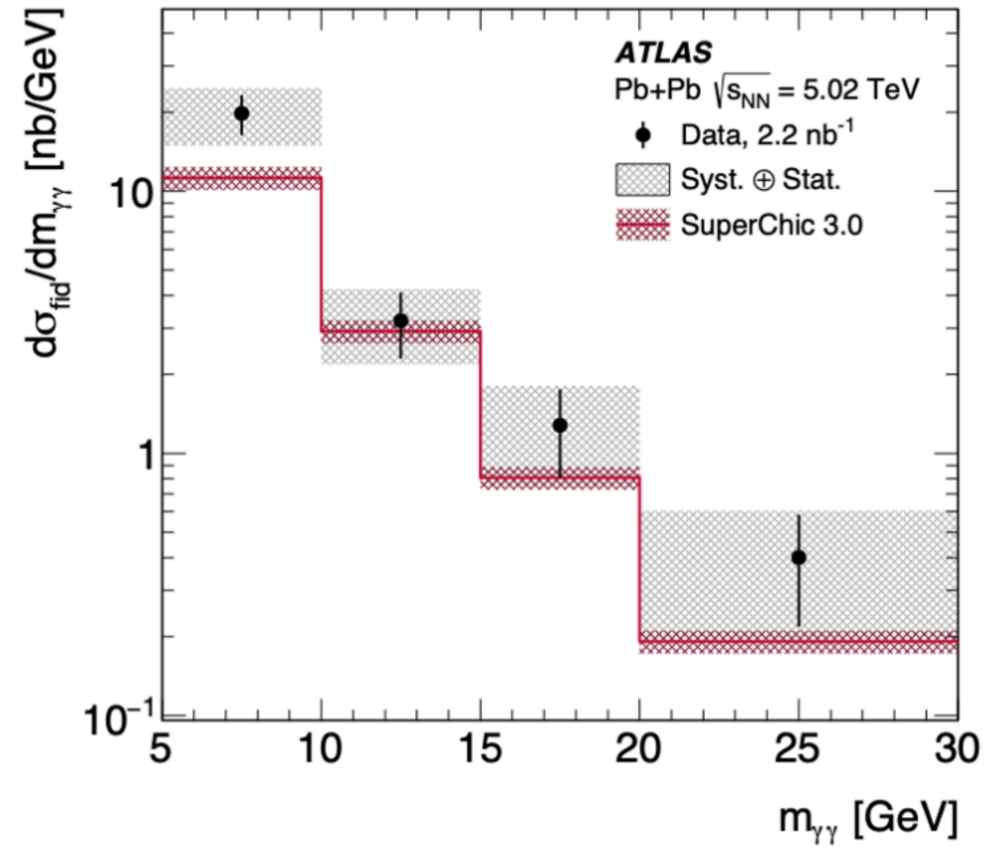
$\sigma_{\mathbf{fid}} = \mathbf{120 \pm 17\,(stat.) \pm 13\,(syst.) \pm 4\,(lumi.)\,nb}$

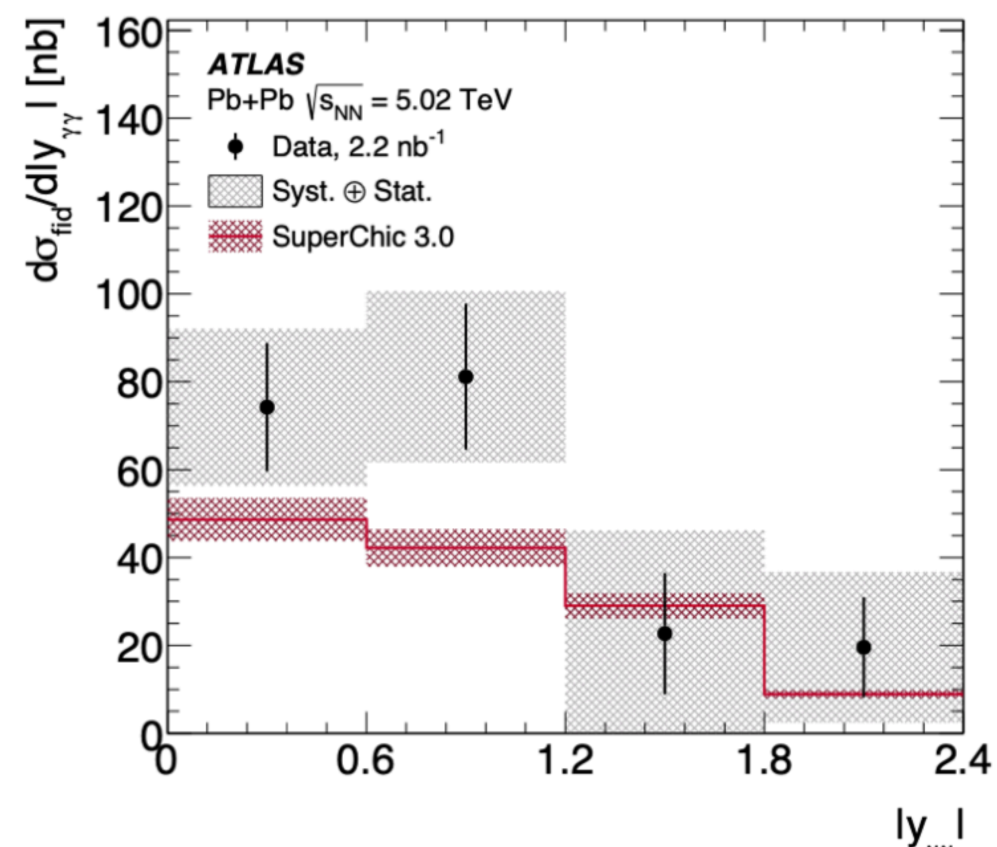
Theory predictions:

$\sigma_{\text{fid}}^{\text{theory1}} = 78 \pm 8$ nb (SuperChic 3 MC)

$\sigma_{\text{fid}}^{\text{theory2}} = 80 \pm 8$ nb (Phys. Rev. C 93 (2016) 044907)

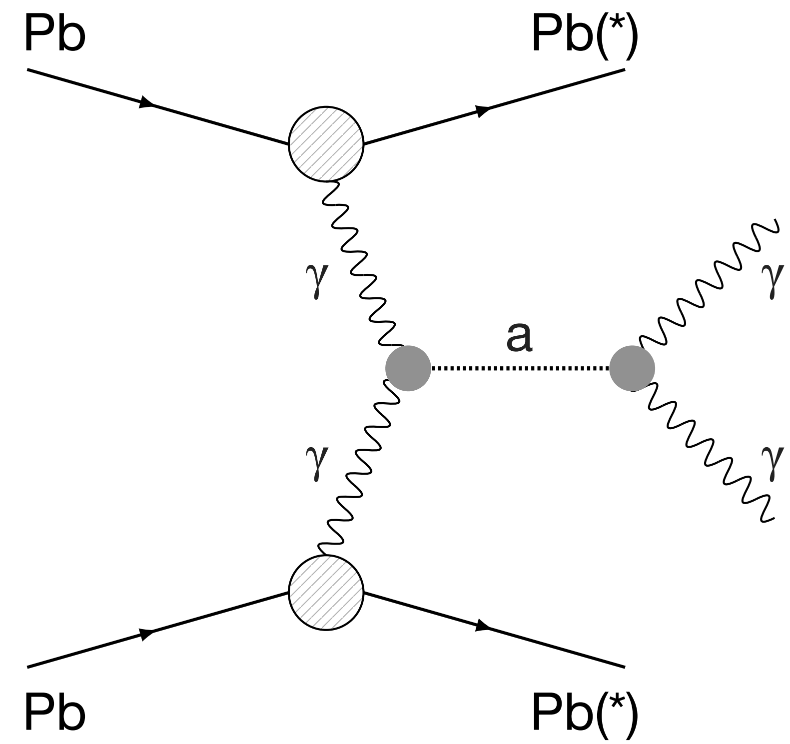
- Differential fiducial cross-sections measured in diphoton: $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, average p_T^{γ} and $|\cos\theta^*|$
- The unfolded differential fiducial cross-sections are compared with the predictions from SuperChic v3.0
  - **Good agreement in shape,** differences in the normalisation



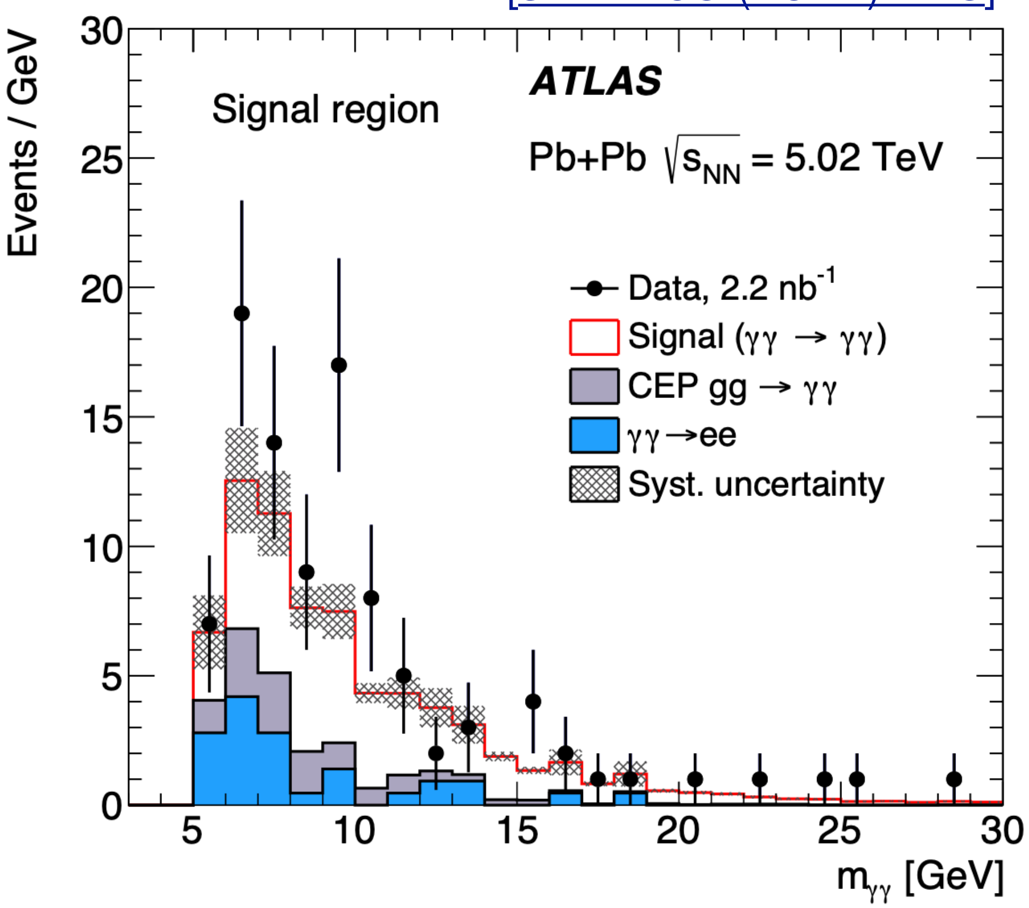


Search for ALP production

- LbyL scattering can be used to search for processes beyond the Standard Model, such as **axion-like particles** (ALP)
- ALP are **hypothetical**, (pseudo-)scalar particles that appear in many theories with a spontaneously broken global symmetry
- ALPs may have identical signature as SM LbyL scattering: $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$
- **ALP production** would lead to an **excess** of scattering events **with diphoton mass** equal to the mass of a
- The search performed using $m_{\gamma\gamma}$ distribution

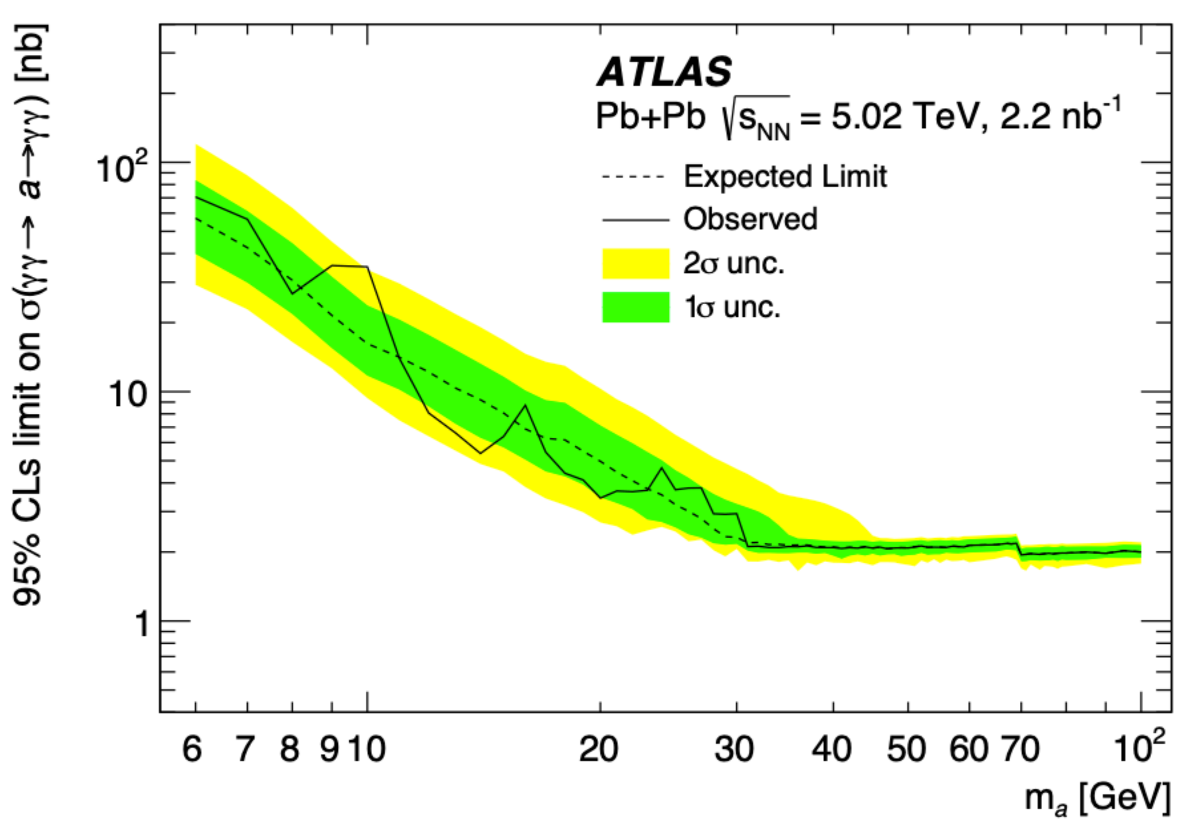


[JHEP 03 (2021) 243]

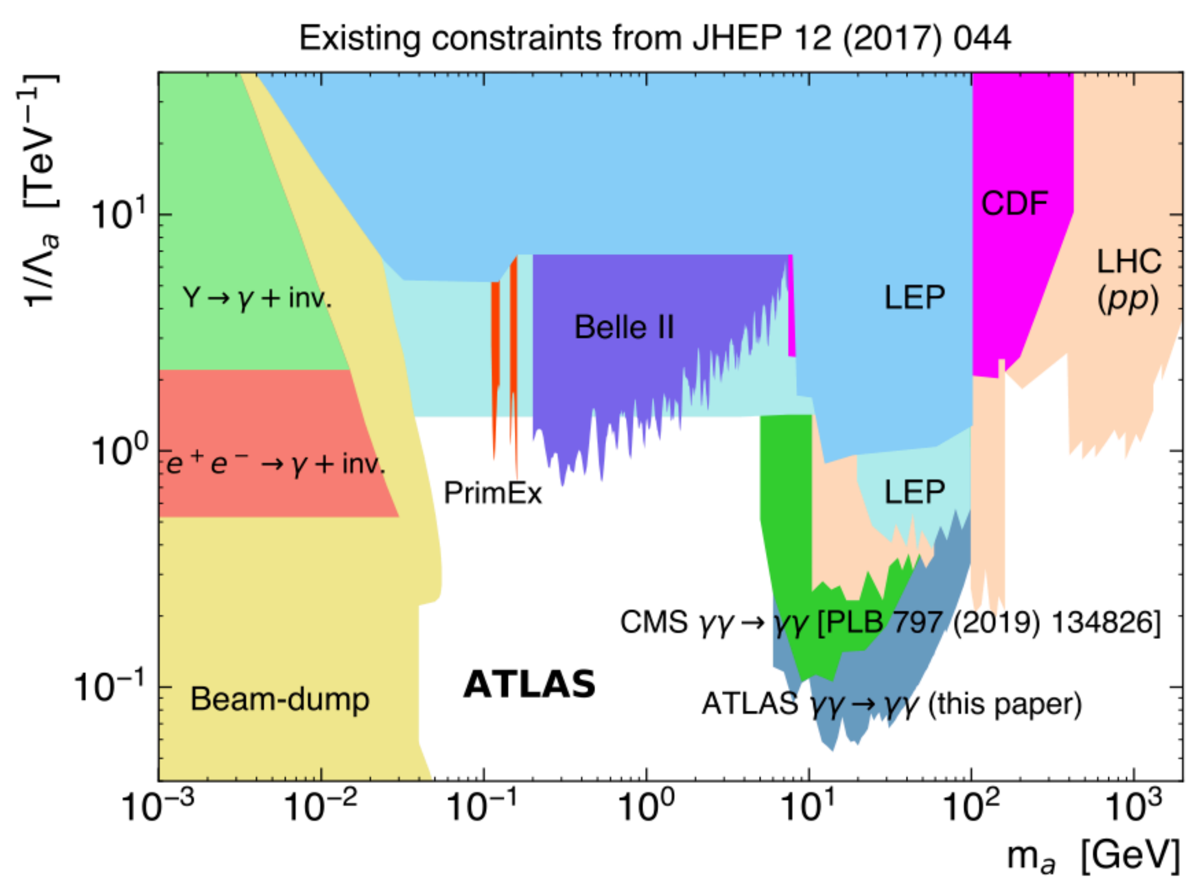


Search for ALP production

- ALP contribution fitted individually for every mass bin using a maximum-likelihood fit
- **No significant deviation** from the background-only hypothesis observed
- The upper limit on the ALP **cross-section** and ALP **coupling $1/\Lambda_a$** at 95% confidence level is **established**
- The obtained exclusion limits are **the strongest so far** in the mass range of $6 < m_a < 100$ GeV

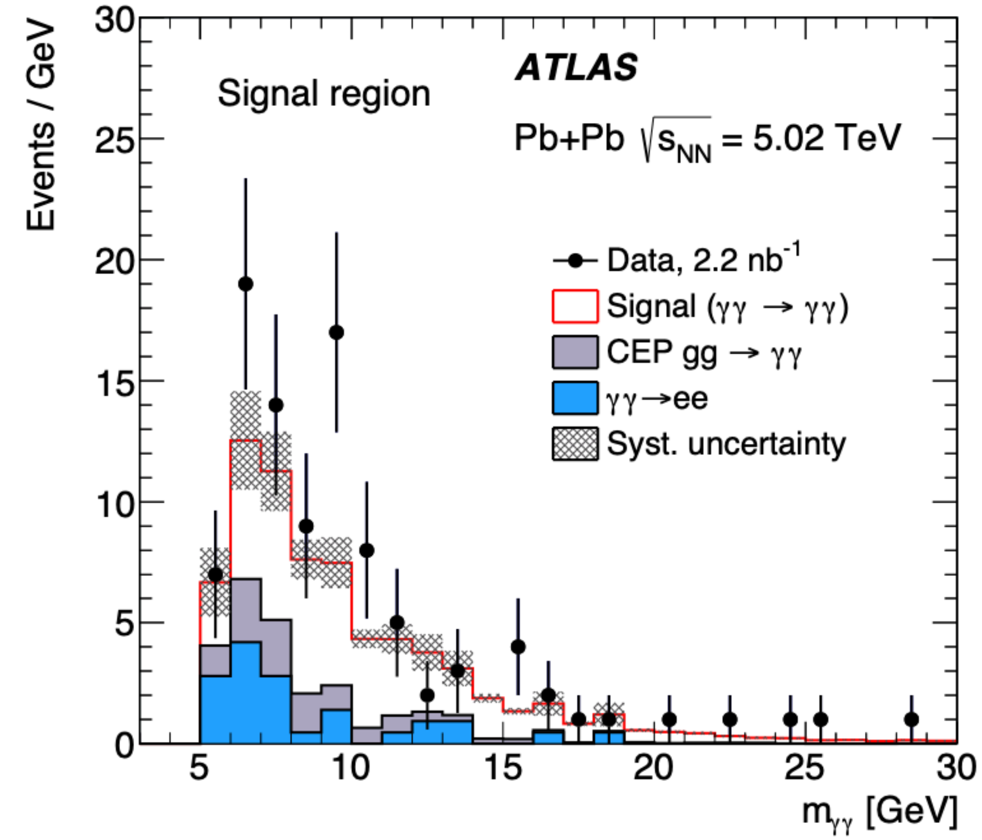


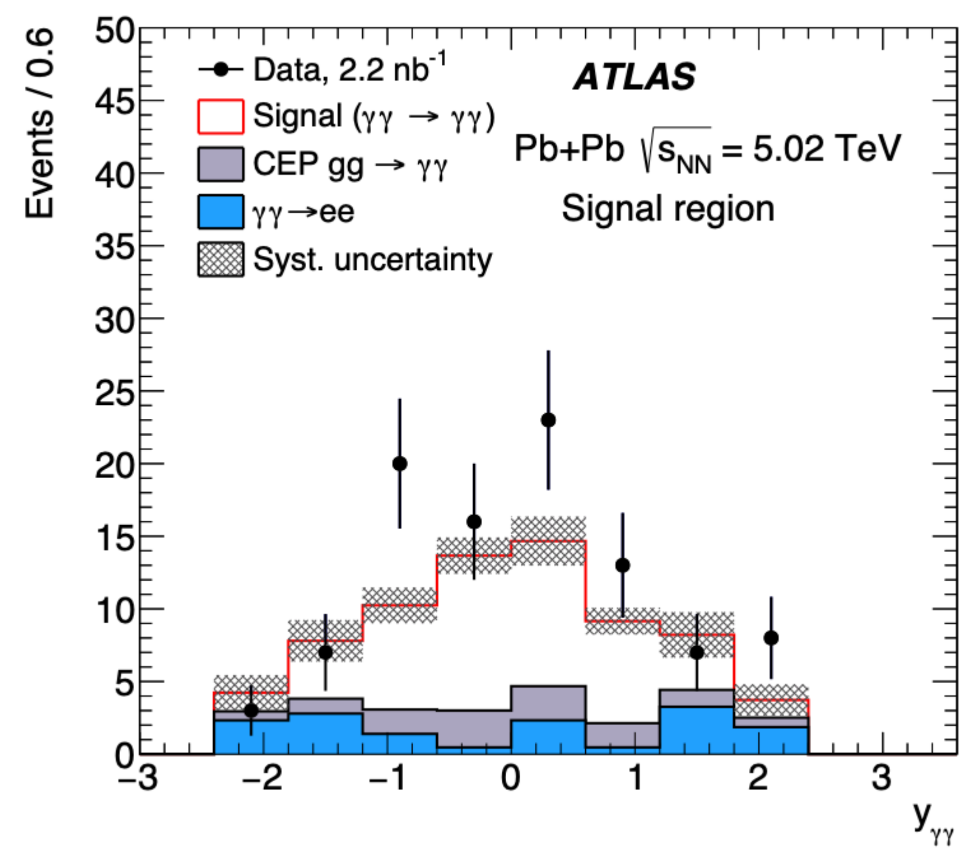
[JHEP 03 (2021) 243]

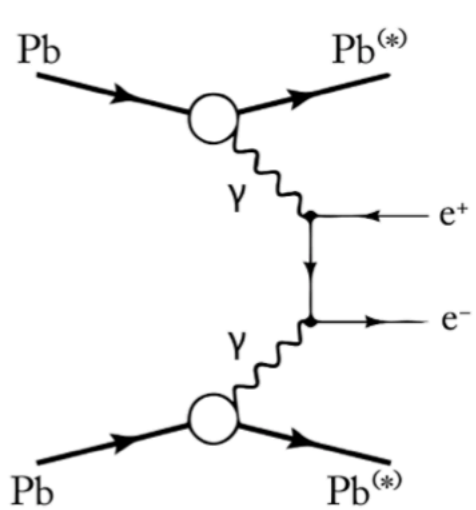


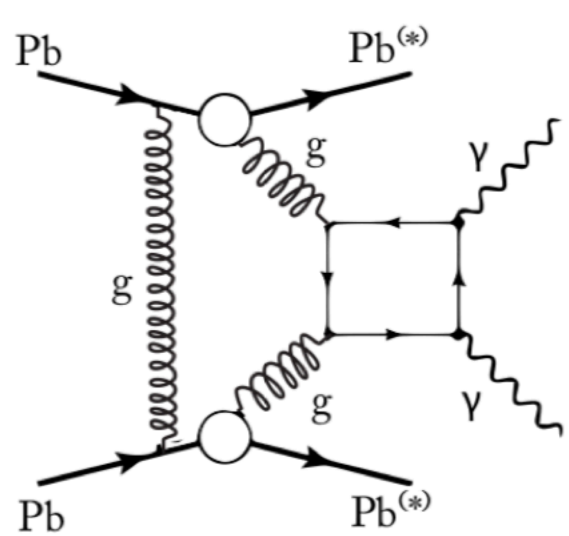
LbyL Background

- Various background sources considered, the largest contribution from:
    - Exclusive dielectron production $\gamma\gamma \rightarrow e^+e^-$
    - Central exclusive production (CEP) $gg \rightarrow \gamma\gamma$
- **Main background** sources are estimated using data-driven techniques
- Shapes of the distributions are in good agreement but data excess visible in both distributions



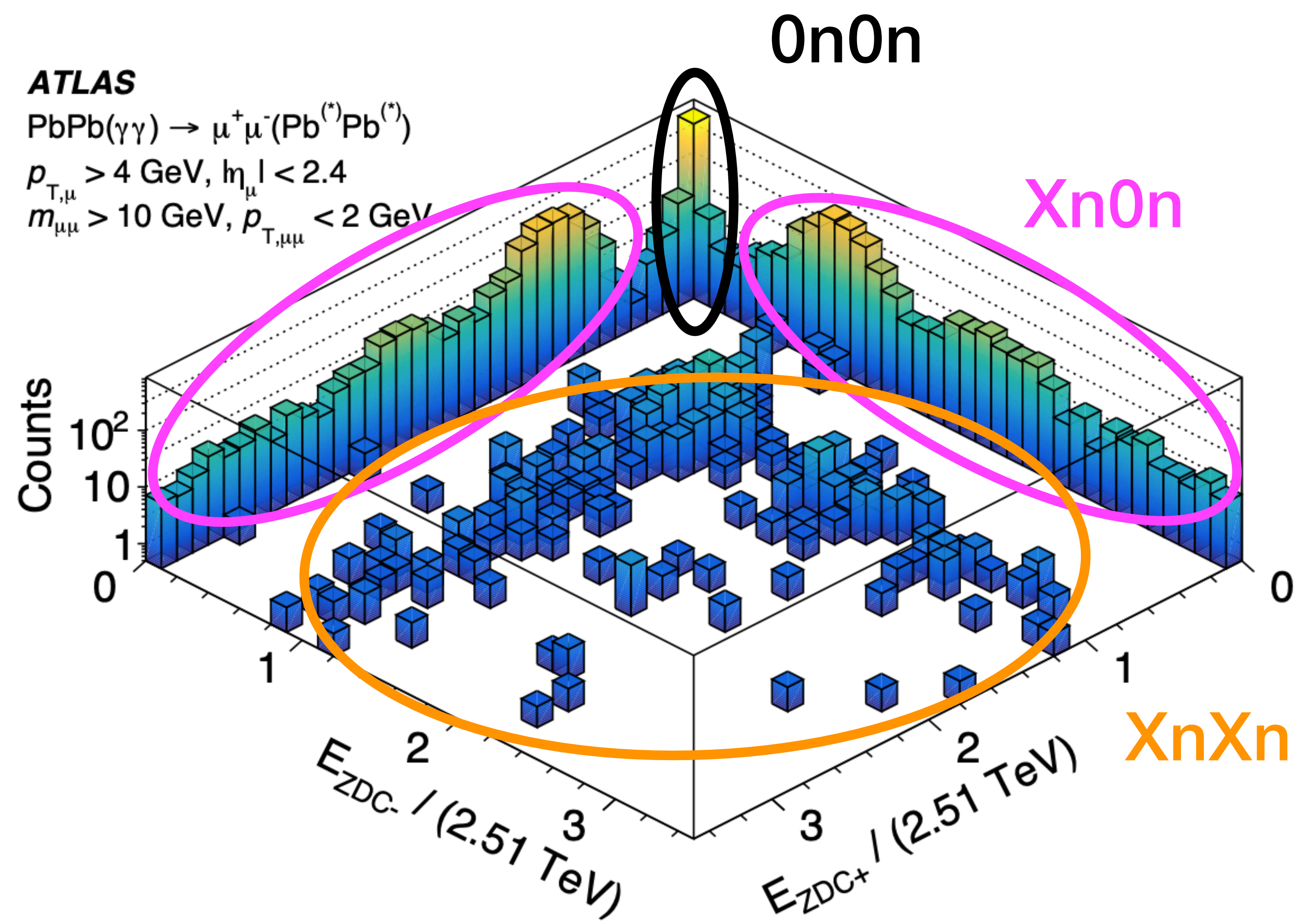






Signal categories - ZDC selection

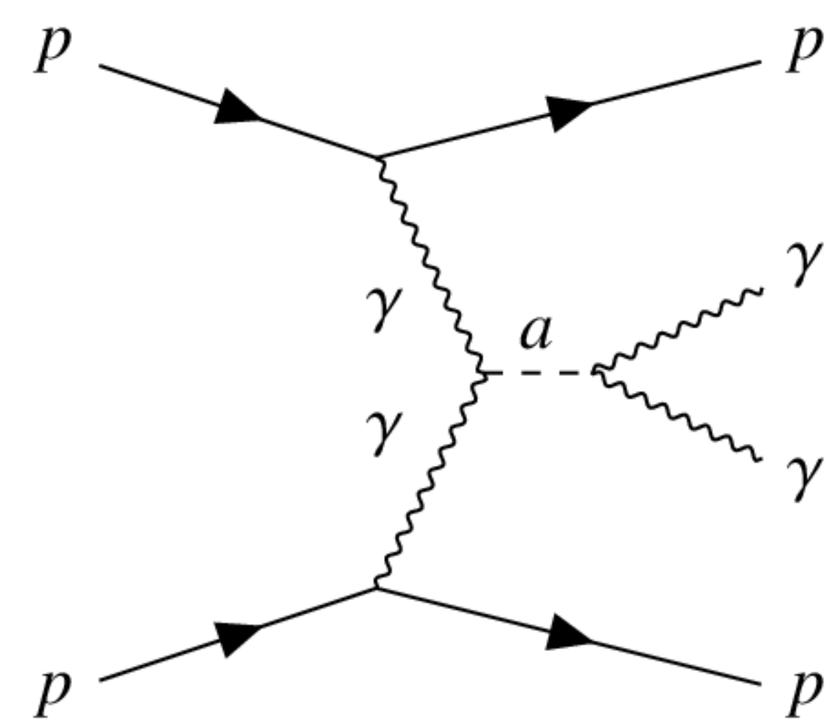
- Different processes present different activity in the forward region:
    - Exclusive dilepton production - ions stay intact
    - Background events with nuclear breakup
- Three classes defined, based on the signal in the ZDC

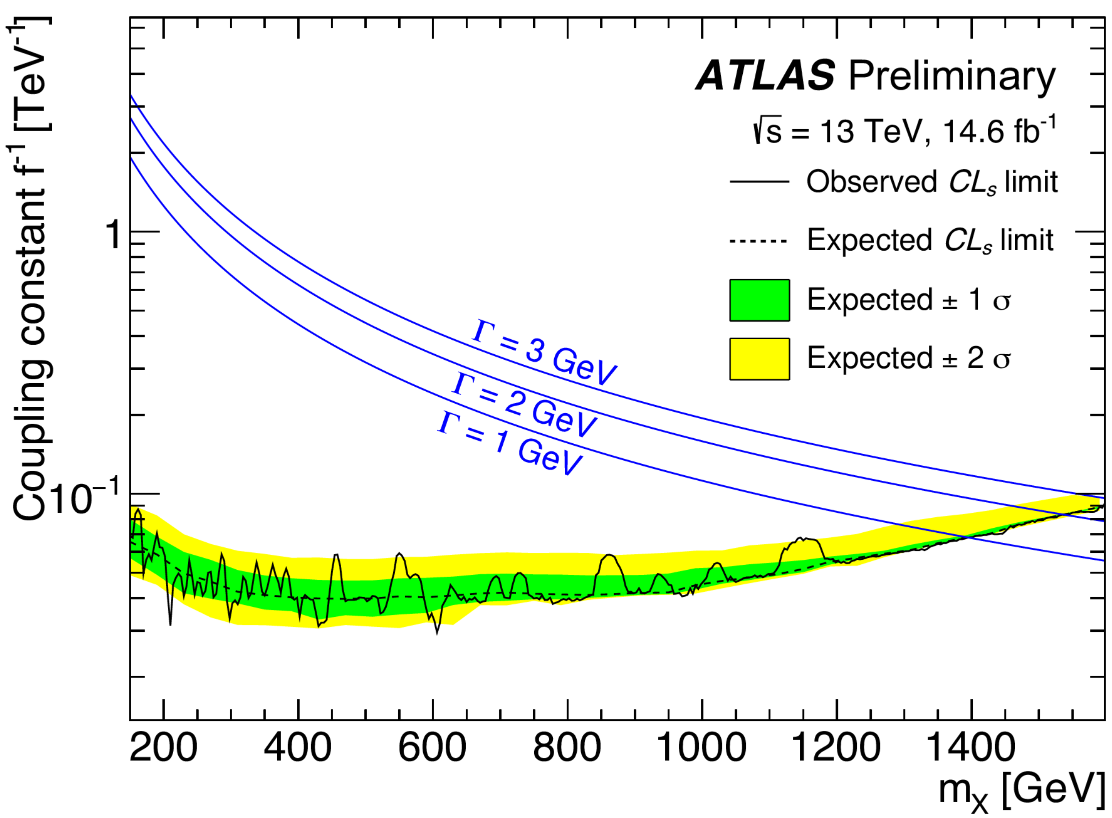


- The association between given ZDC signal and given process is nontrivial
    - Migrations due to ion excitation and presence of EM pile-up

Search for ALP production with ATLAS AFP

- A search for ALP carried out by ATLAS using pp collisions in the diphoton mass range $m_{\gamma\gamma}$ = [150,1600] GeV
- Exploit events with centrally produced photon pairs tagged by forward scattered protons
- Forward-scattered protons detected by the ATLAS Forward Proton (AFP) detector
- No signal is observed
    - Data consistent with a combinatorial SM background
- Upper limit on the ALP coupling constant to two photons set in the range 0.04-0.09 TeV^{-1} at 95% confidence level





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