BSM physics using photon-photon fusion processes in UPC in Pb+Pb collisions with the ATLAS detector

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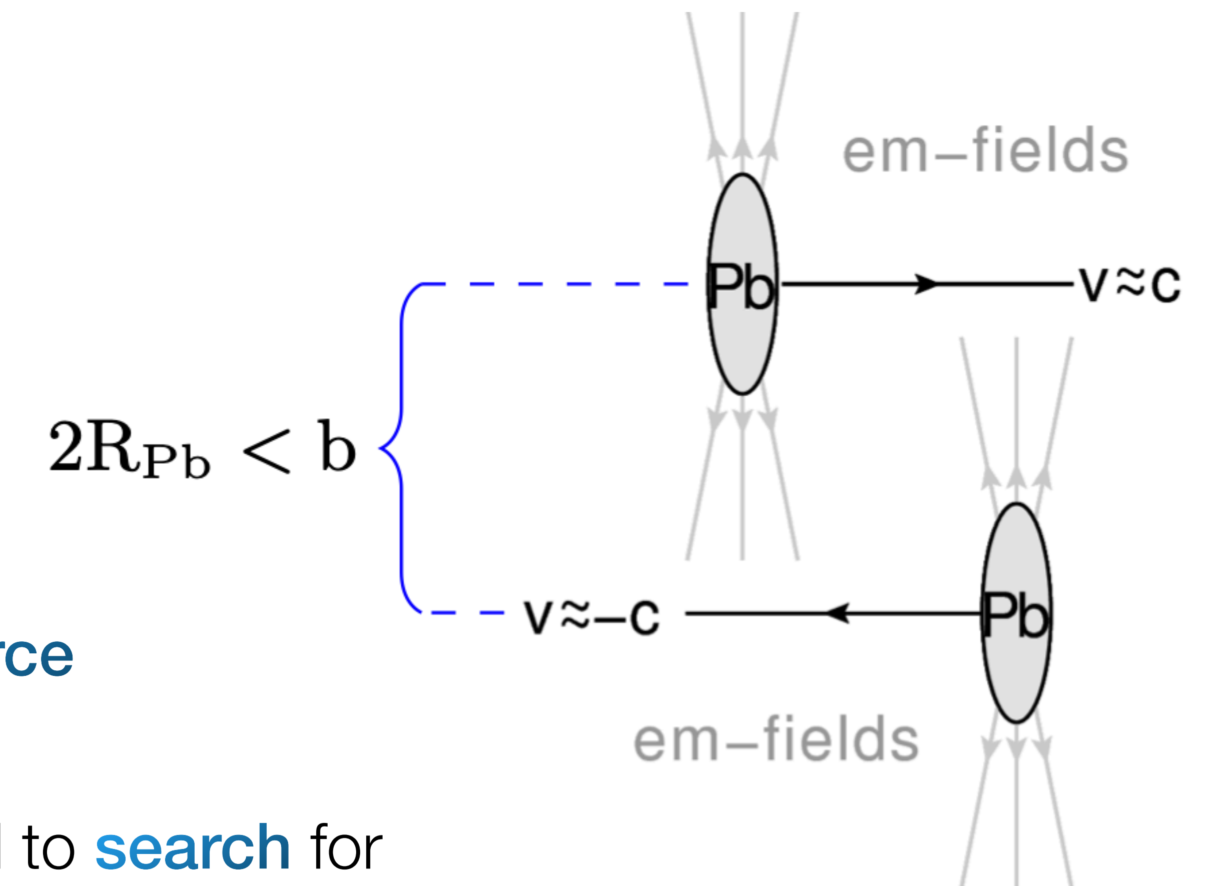
Ultraperipheral heavy-ion collisions

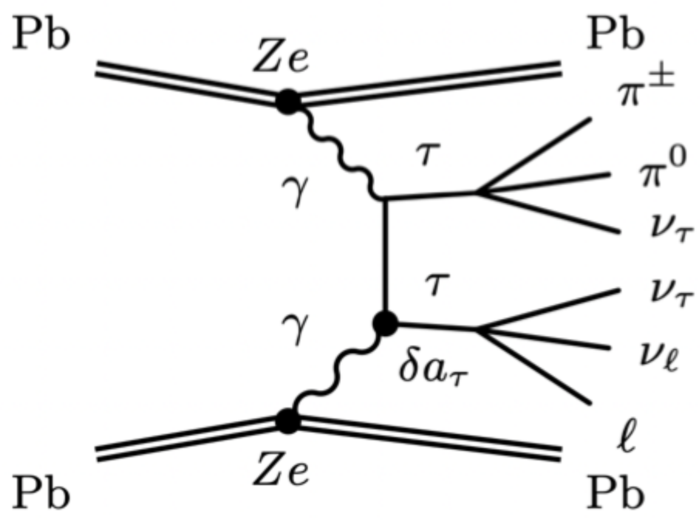
- **Ultraperipheral heavy-ion collisions** (UPC) provide very clean environment to study **photon-photon interactions**
    - Electromagnetic (EM) fields associated with relativistic ions treated as **photon fluxes**
    - Described in a **Equivalent Photon Aproximation** (EPA) framework
    - Equivalent photon flux scales with Z^2
    - 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



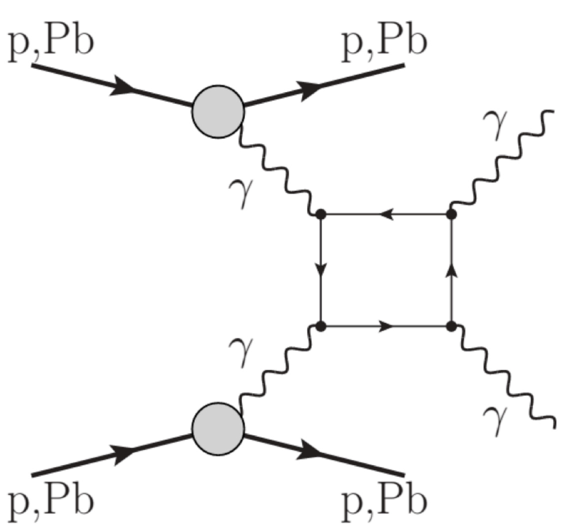
- **Advantages** of UPC over the proton-proton (pp) collisions:
    - Z^4 enhancement of cross sections in Pb+Pb wrt pp system
    - Very low hadronic pileup - exclusivity selections
    - Low p_T thresholds in trigger and offline reconstruction

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, …)



$$\gamma\gamma \to \tau^+\tau^-$$

Anomalous magnetic moment

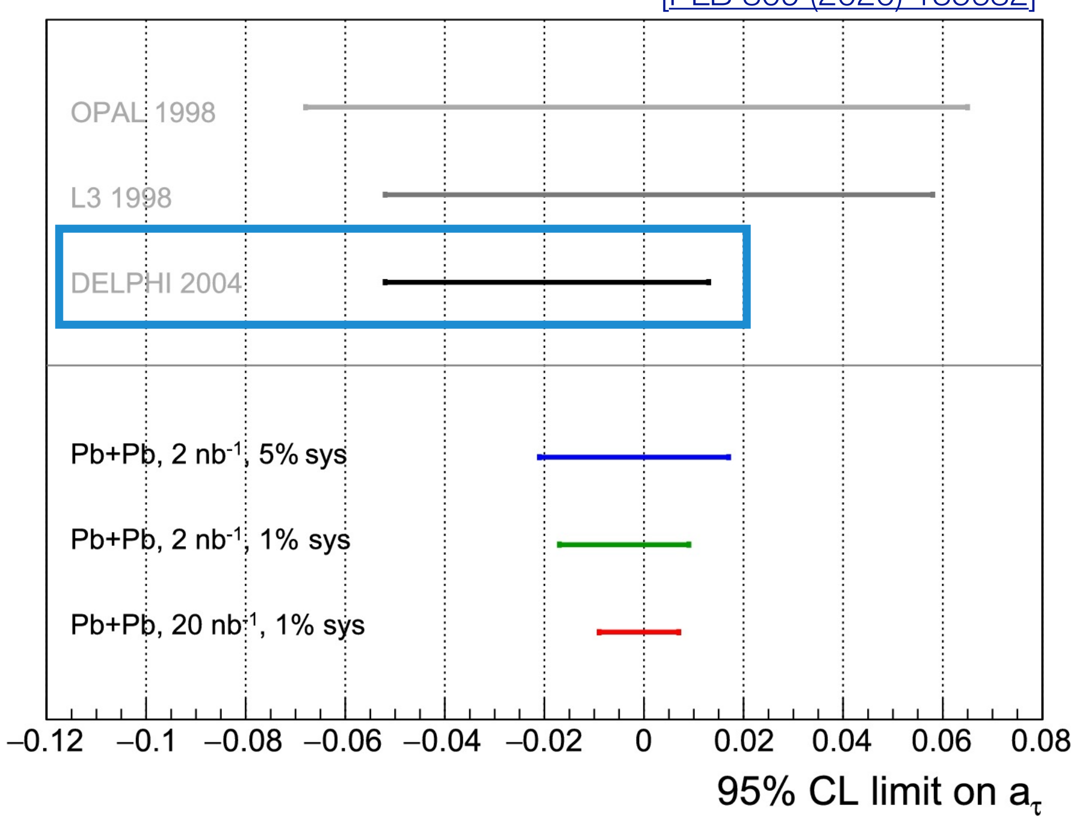
- Charged particles with spin have an intrinsic magnetic moment: $\vec{\mu} = g\frac{q}{2m}\vec{S}$

- For leptons Dirac equation predicts $g = 2$, but higher order corrections lead to $g \neq 2$

- Deviations of g-factor from 2 measured with lepton **anomalous magnetic moments**
$$a_l = \frac{(g-2)_l}{2}$$

- Best experimental limits on a_τ were set by DELPHI: -0.052 < a_τ <0.013 (95% CL) [EPJC 35 (2004) 159]

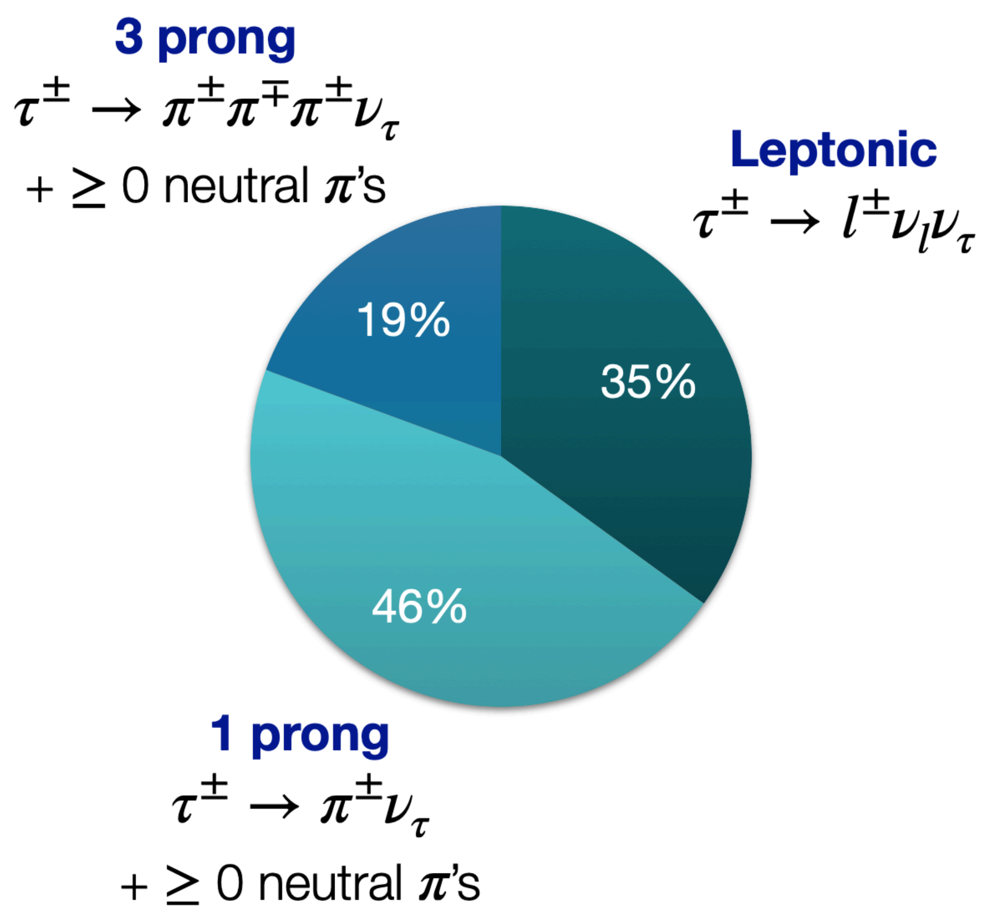
[PLB 809 (2020) 135682]



- Measurement of a_τ using HI UPC proposed by theory publications:
  - F. del Aguila, F. Cornet, J.I Illana [PLB 271 (1991) 256]
  - L. Beresford, J. Liu [PRD 102 (2020) 113008]
  - M. Dyndal, M. Schott, M. Klusek-Gawenda, A. Szczurek [PLB 809 (2020) 135682]

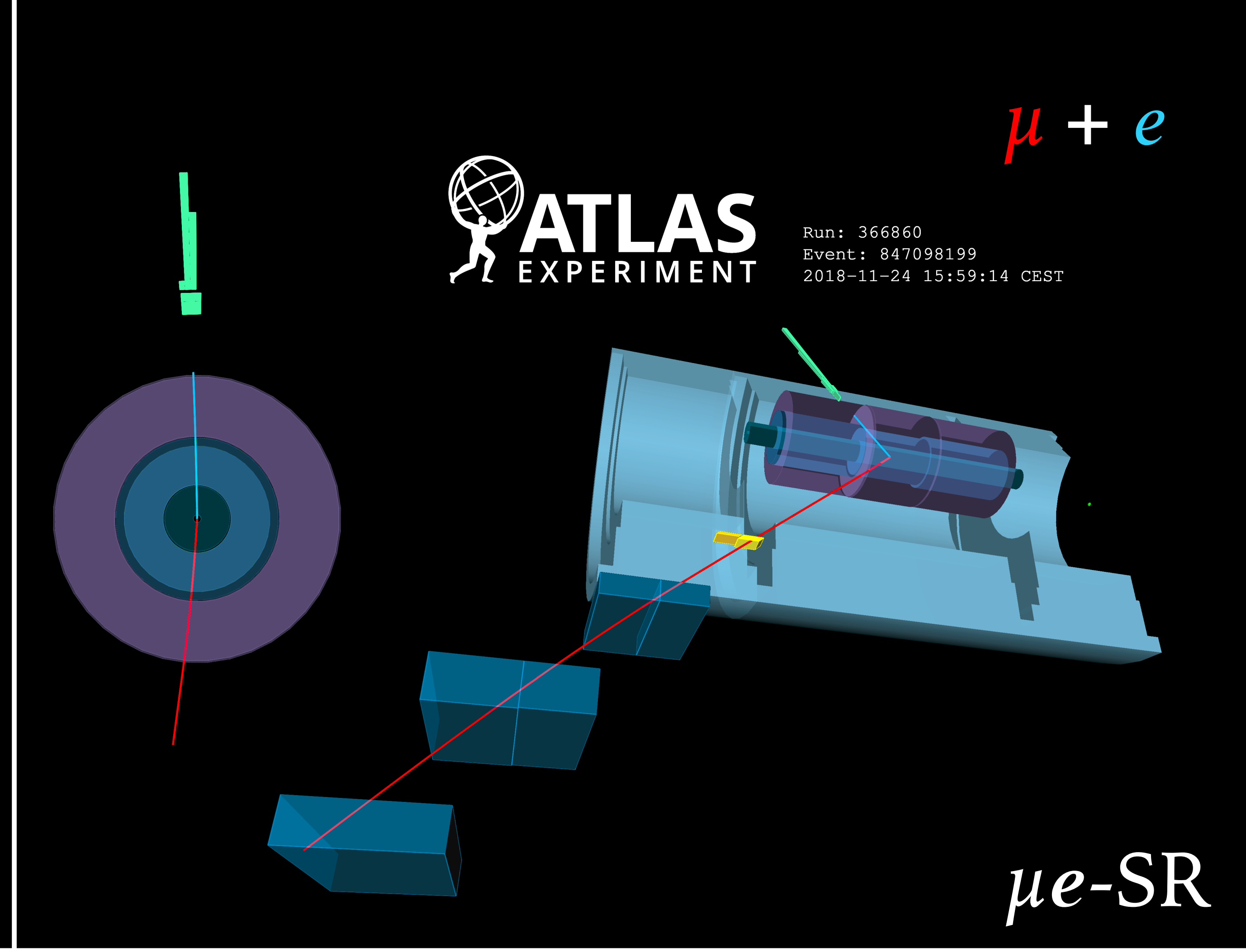
Measurement overview

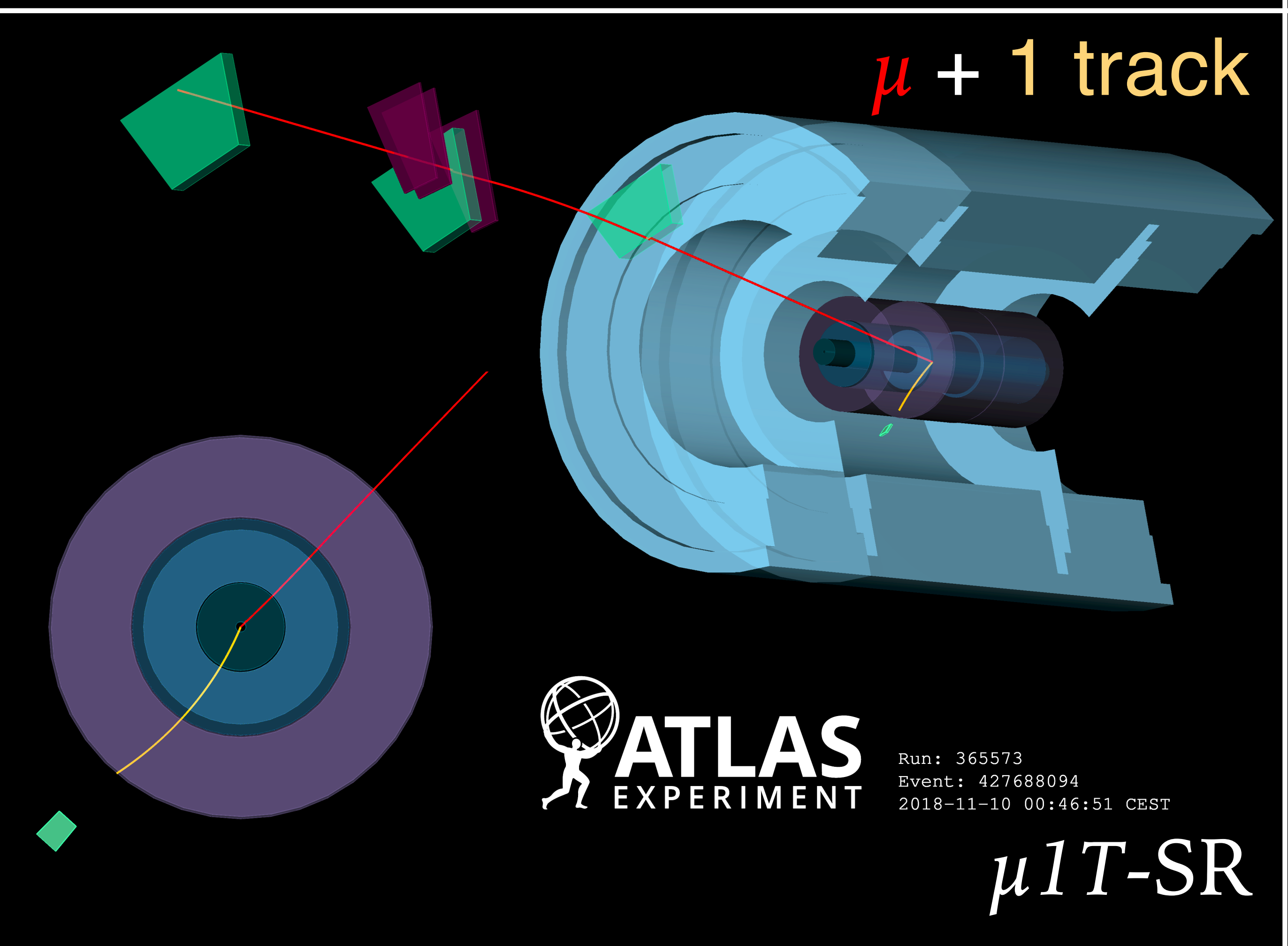
- **Signal** τ-leptons are **low-energetic**, typically with $p_T < 10$ GeV
- No standard ATLAS identification of τ-leptons is used
  - Instead events classified based on the charged τ-lepton decay products
- **Three signal categories:** $\mu + e$, μ + track, μ + 3 tracks
- Single muon trigger used to record signal events with muon $p_T > 4$ GeV

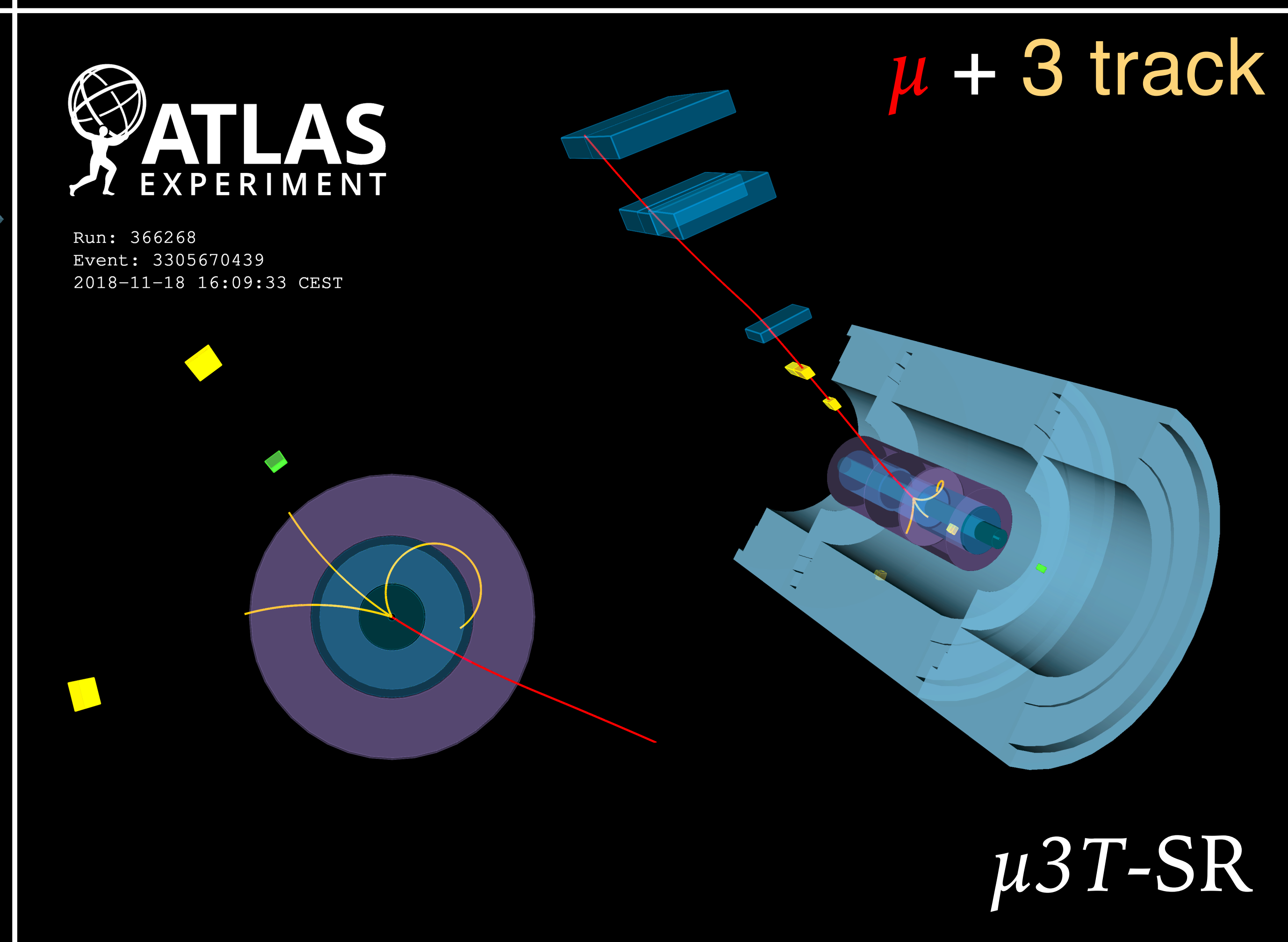


- **Exclusivity requirements:**
  - veto on forward neutron activity (using 0n0n configuration based on ZDC signal)
  - for μ + track and μ + 3 tracks: veto on additional tracks and low-p_T clusters
- **Main background contributions** are from dimuon production and diffractive photonuclear interactions

Signal Regions (SRs)



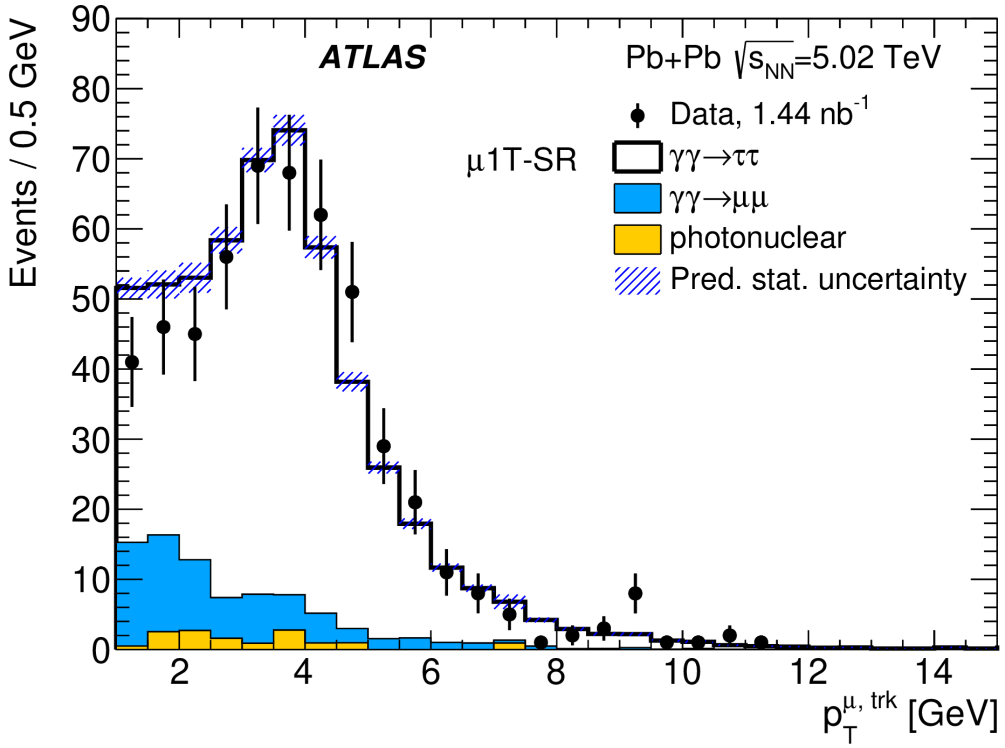




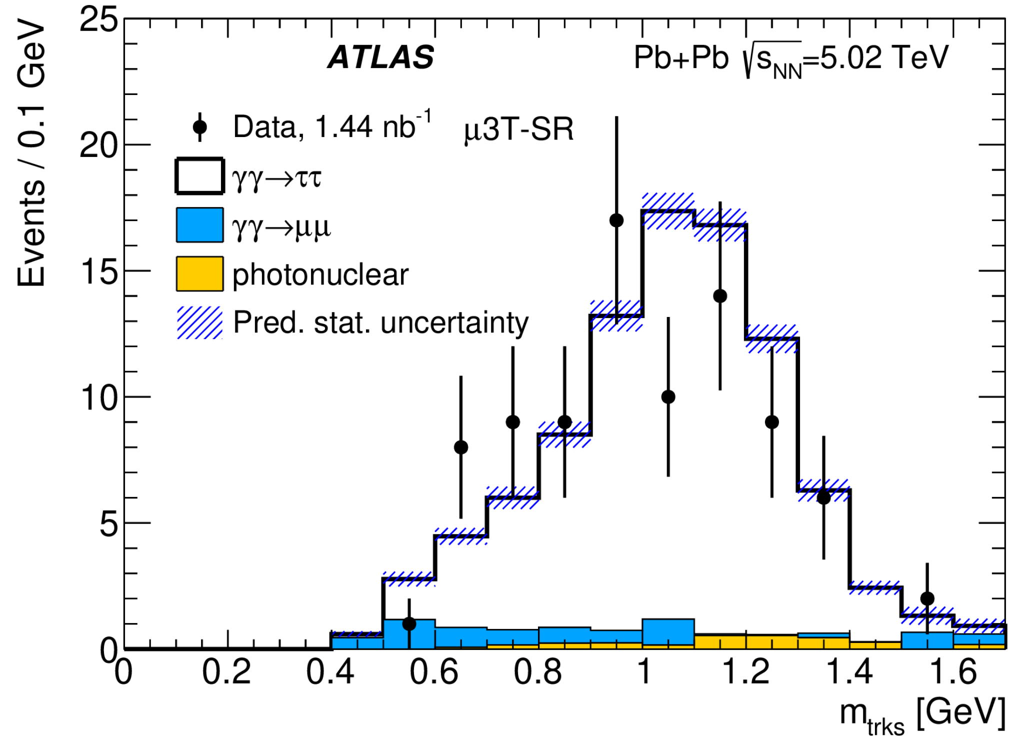
Signal region distributions

[arXiv:2204.13478]

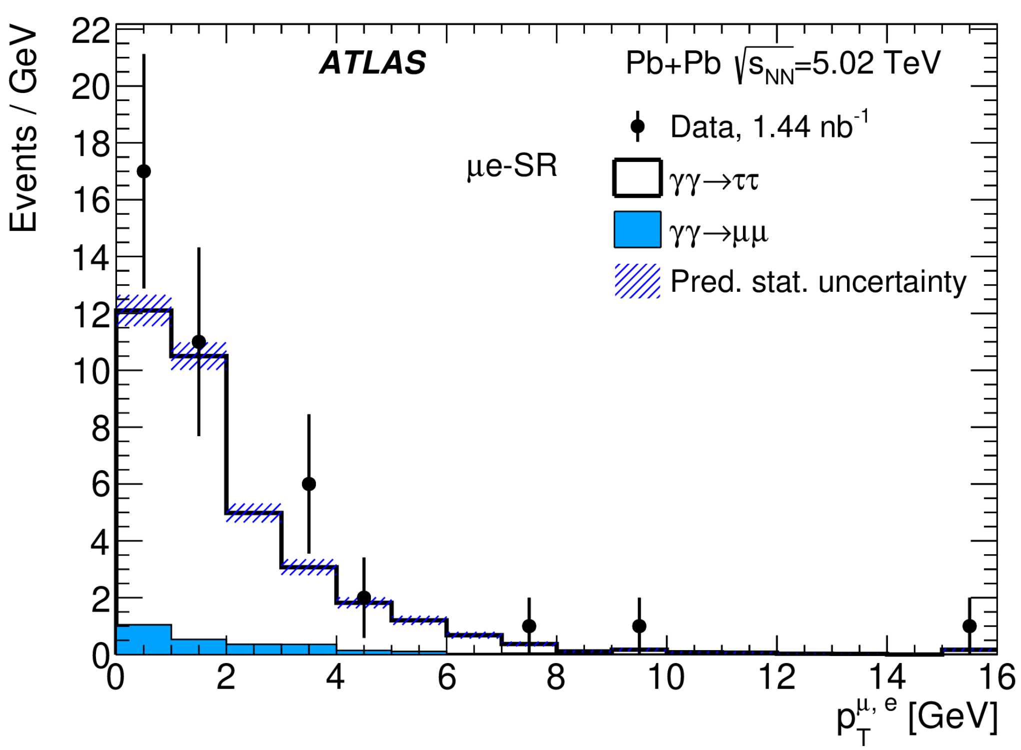
μ1T-SR: N_{obs}=532, N_{bkg}=84±19



μ3T-SR: N_{obs}=85, N_{bkg}=9±3



μe-SR: N_{obs}=39, N_{bkg}=2.8±0.7

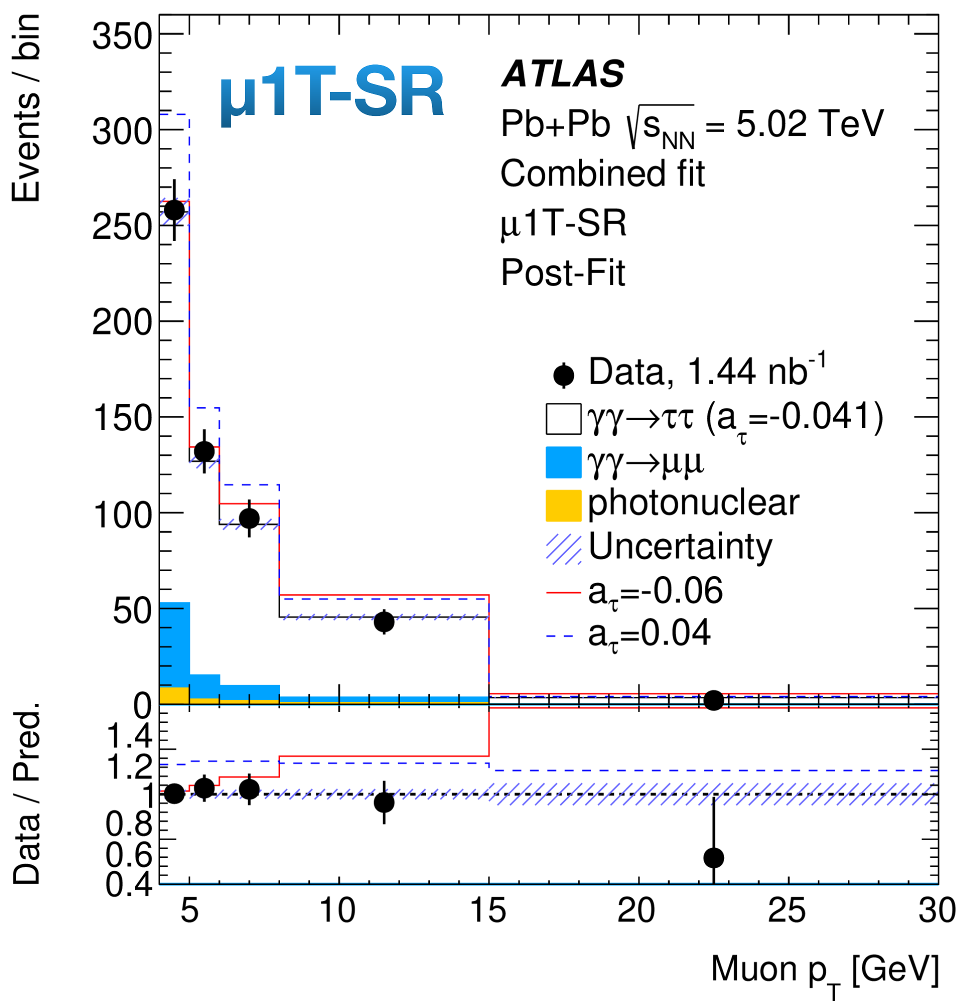


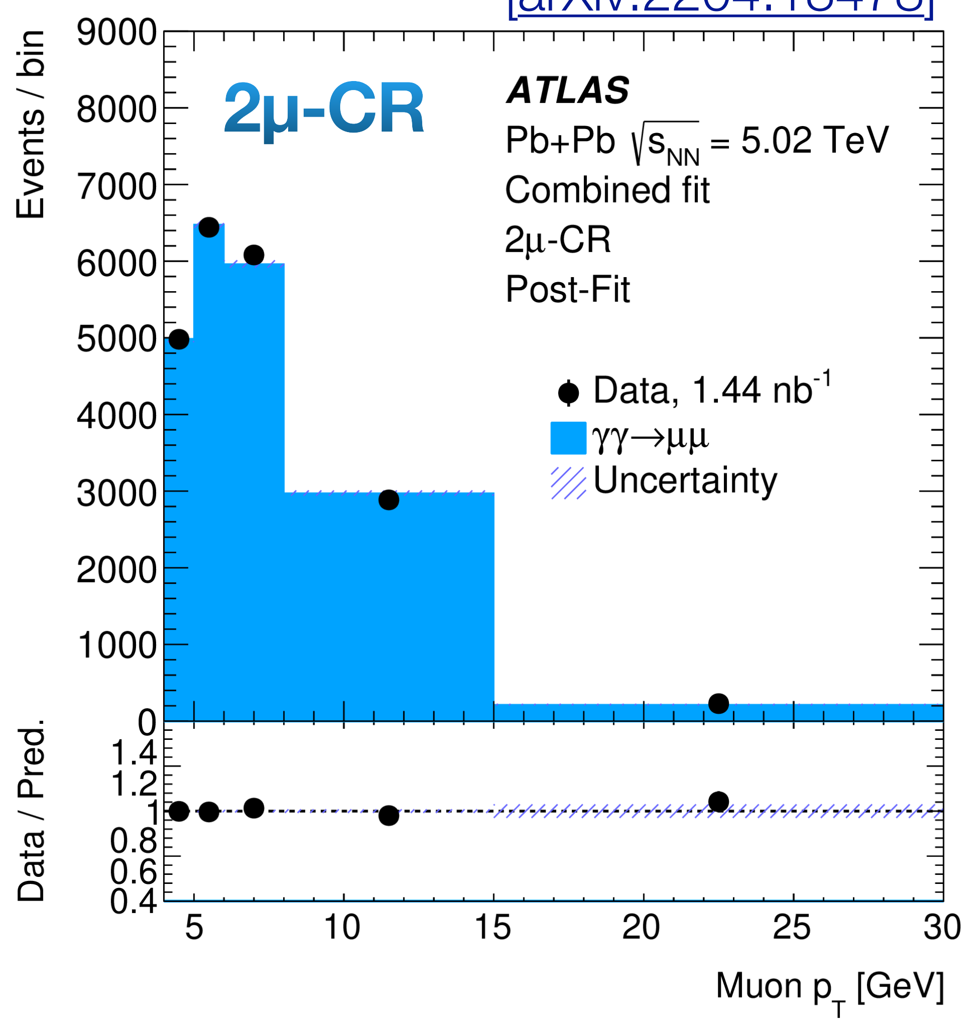
- Good agreement of pre-fit predictions with data
- Total of about 650 events across all SRs
- Small background contributions

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

- The $\gamma\gamma\to\tau\tau$ signal strenght and a_τ value is extracted using a **profile likelihood fit** using the muon p_T distribution in the three SRs and 2μ-CR
    - Dimuon **control region** ($\gamma\gamma\to\mu\mu$ events) used to reduce systematic uncertainty from the photon flux
- Build templates for different a_τ values by reweighting signal MC using weights from [PLB 809 (2020) 135682]
- **Clear observation (≫ 5σ) of $\gamma\gamma\to\tau\tau$ process at the LHC**

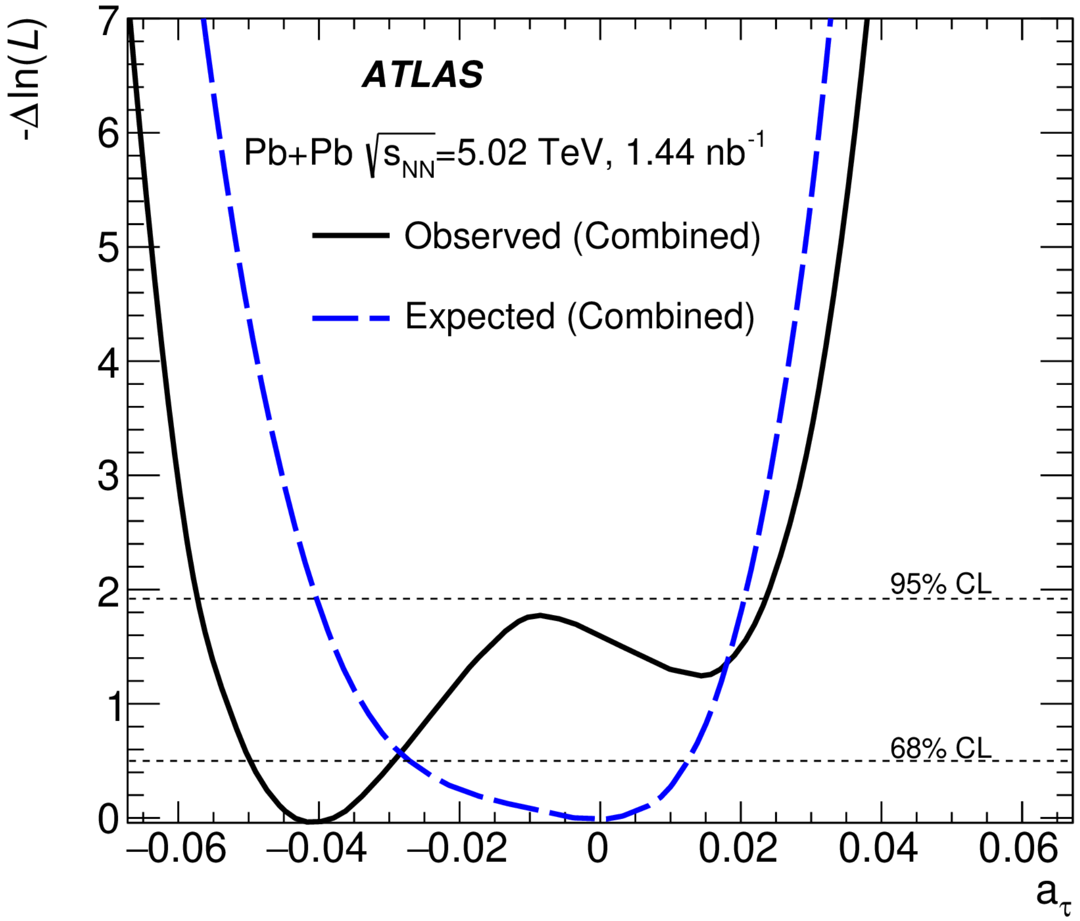
[arXiv:2204.13478]

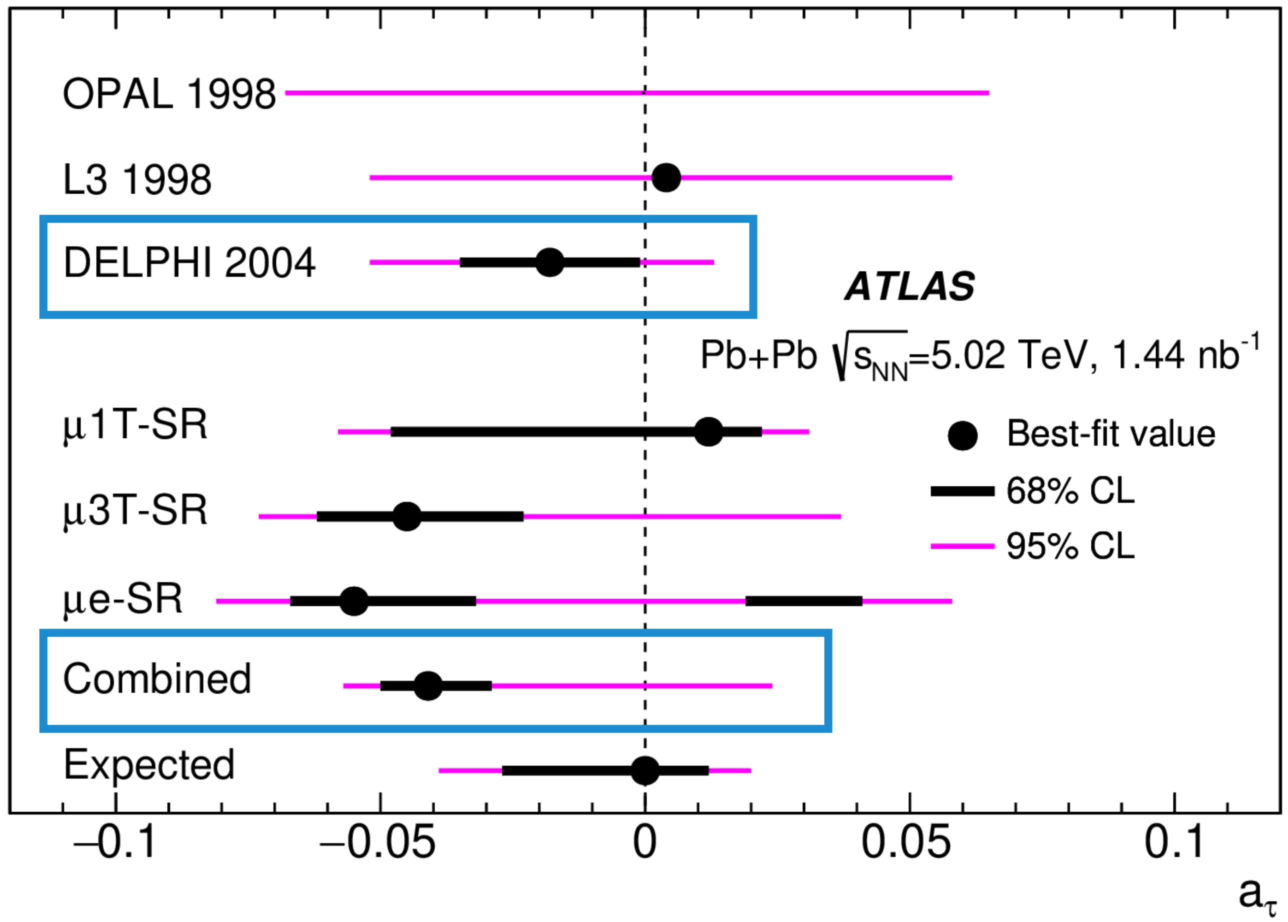




Results: a_τ

[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

$$\gamma\gamma \to \gamma\gamma$$

Light-by-light scattering

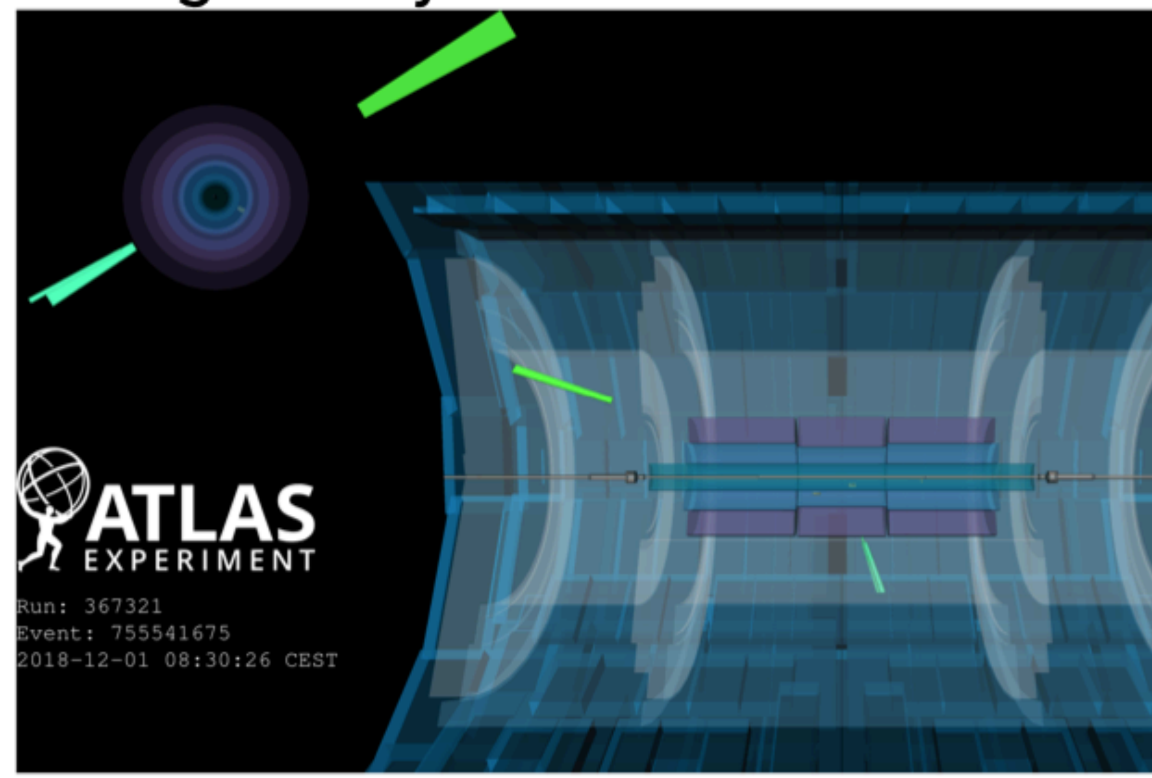
- Light-by-light (LbyL) scattering is a **very rare** QED process
- Several LbyL measurements performed with the LHC Pb+Pb UPC data:

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

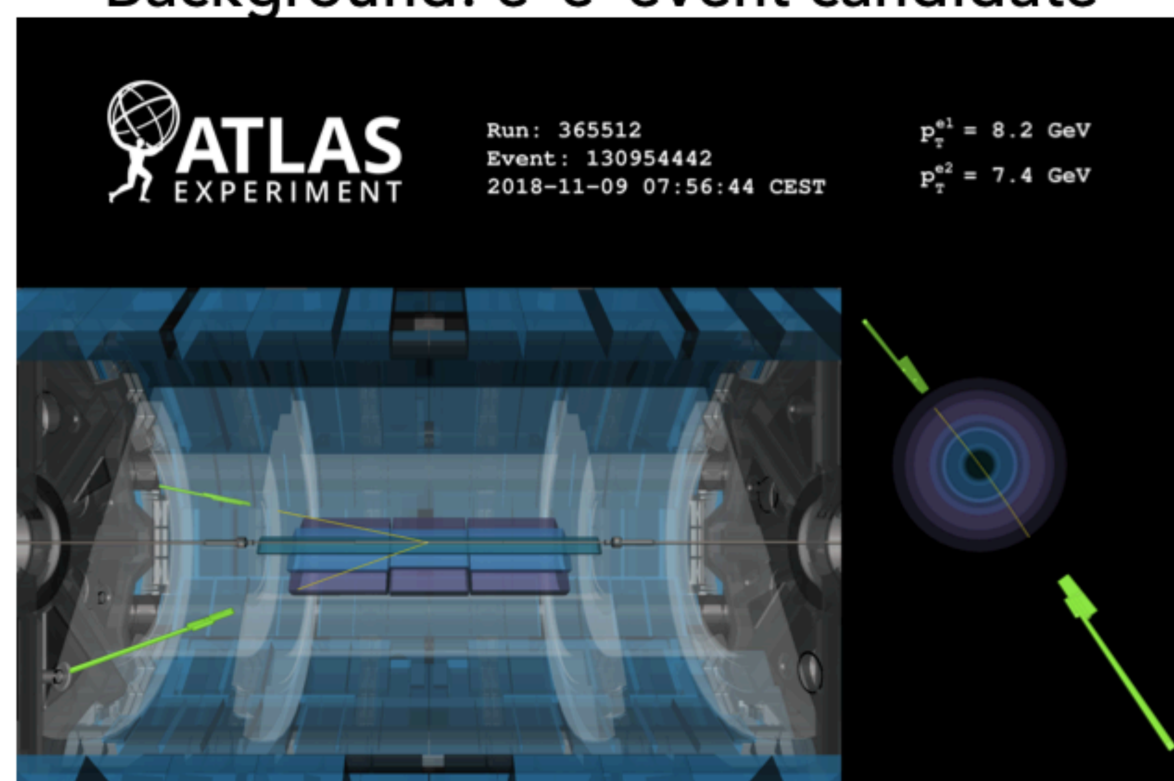
  CMS: 2015: [PLB 797 (2019) 134826]

- **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



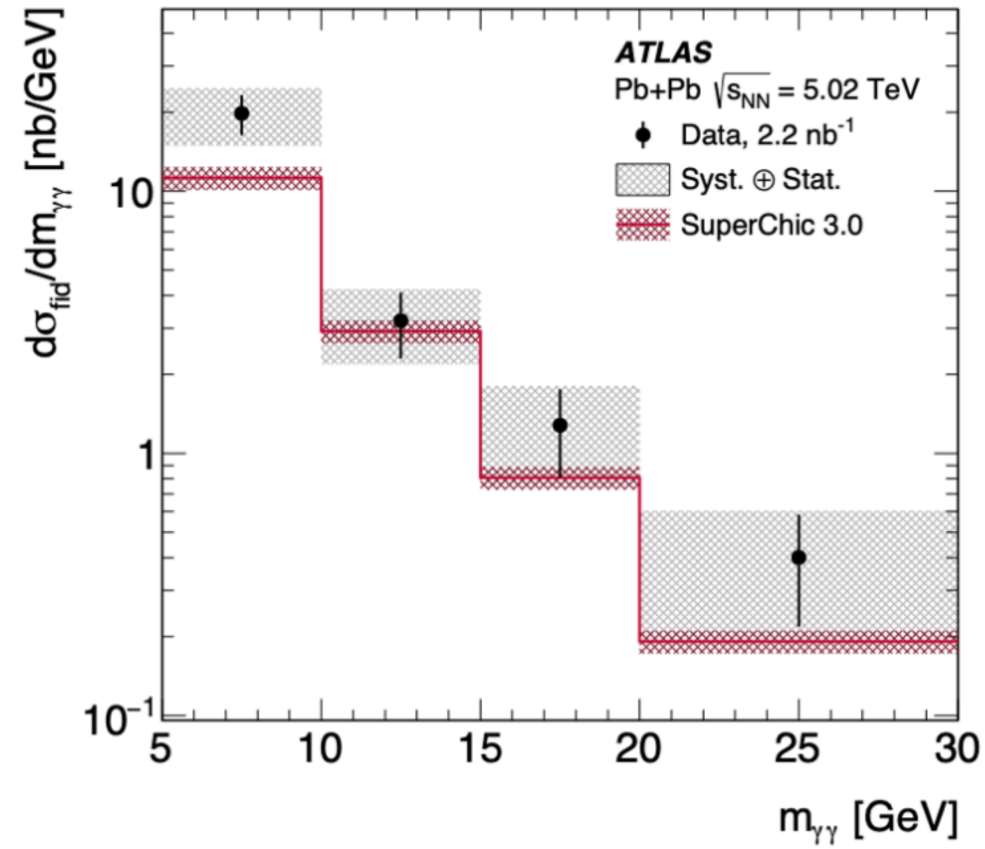
Light-by-light scattering: cross sections

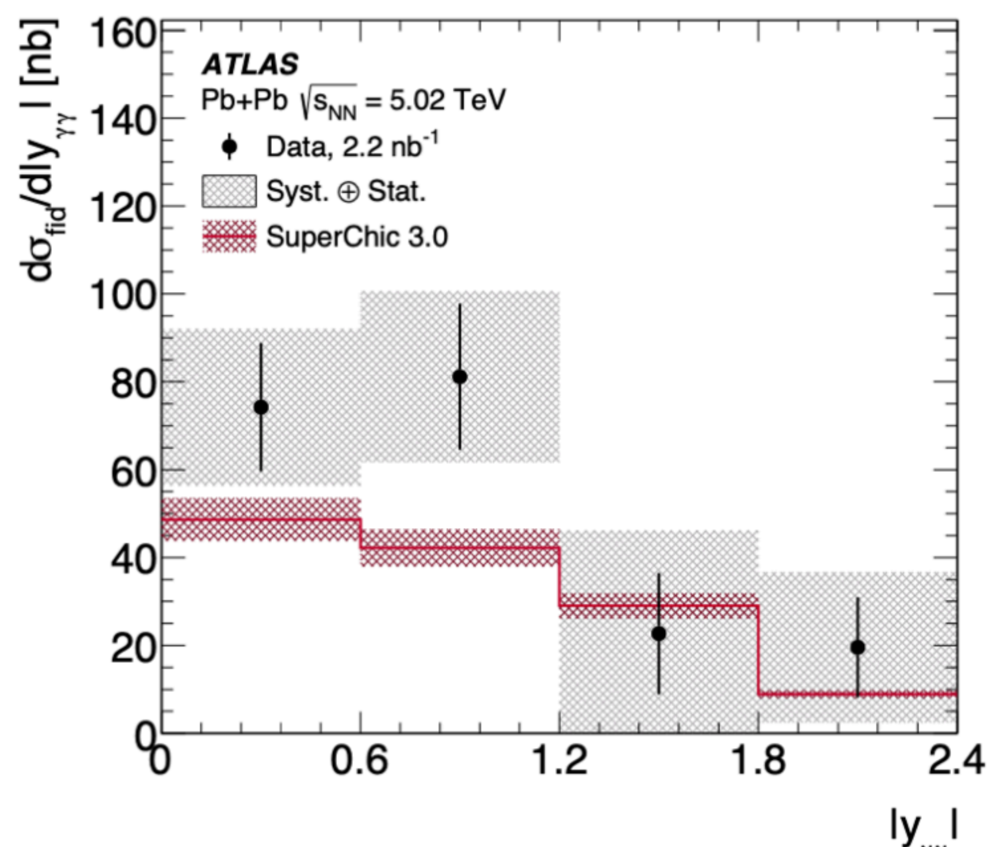
[JHEP 03 (2021) 243]

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

Measured fiducial cross section:
$\sigma_{\textbf{fid}} = \mathbf{120 \pm 17\,(stat.) \pm 13\,(syst.) \pm 4\,(lumi.)\,nb}$
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)

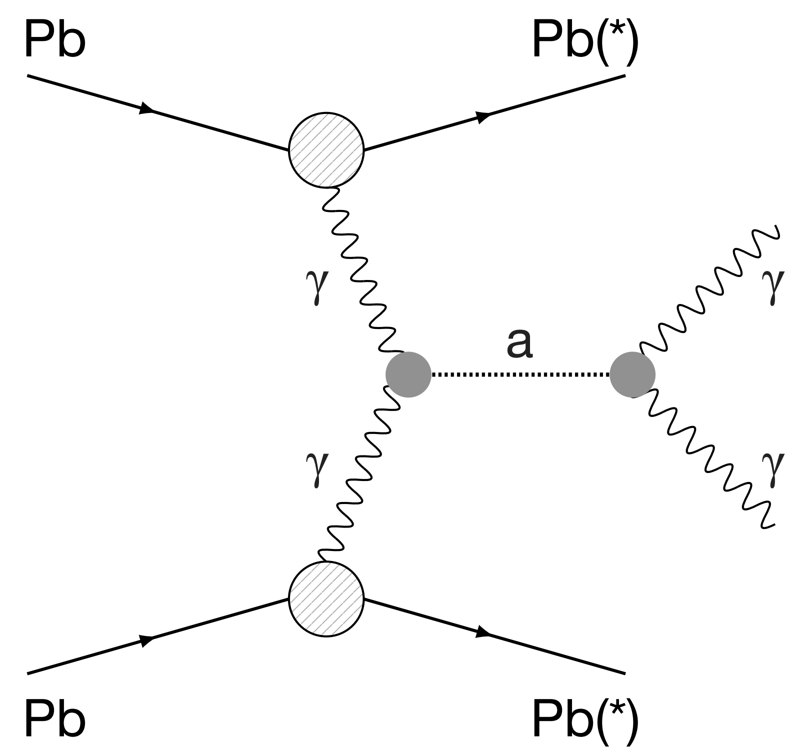
- Differential fiducial cross-sections measured in diphoton: $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, average p_T^{γ} and $|\cos\theta^*|$
- The unfolded differential fiducial cross-sections are compared with the predictions from SuperChic v3.0
  - **Good agreement in shape,** differences in the normalisation



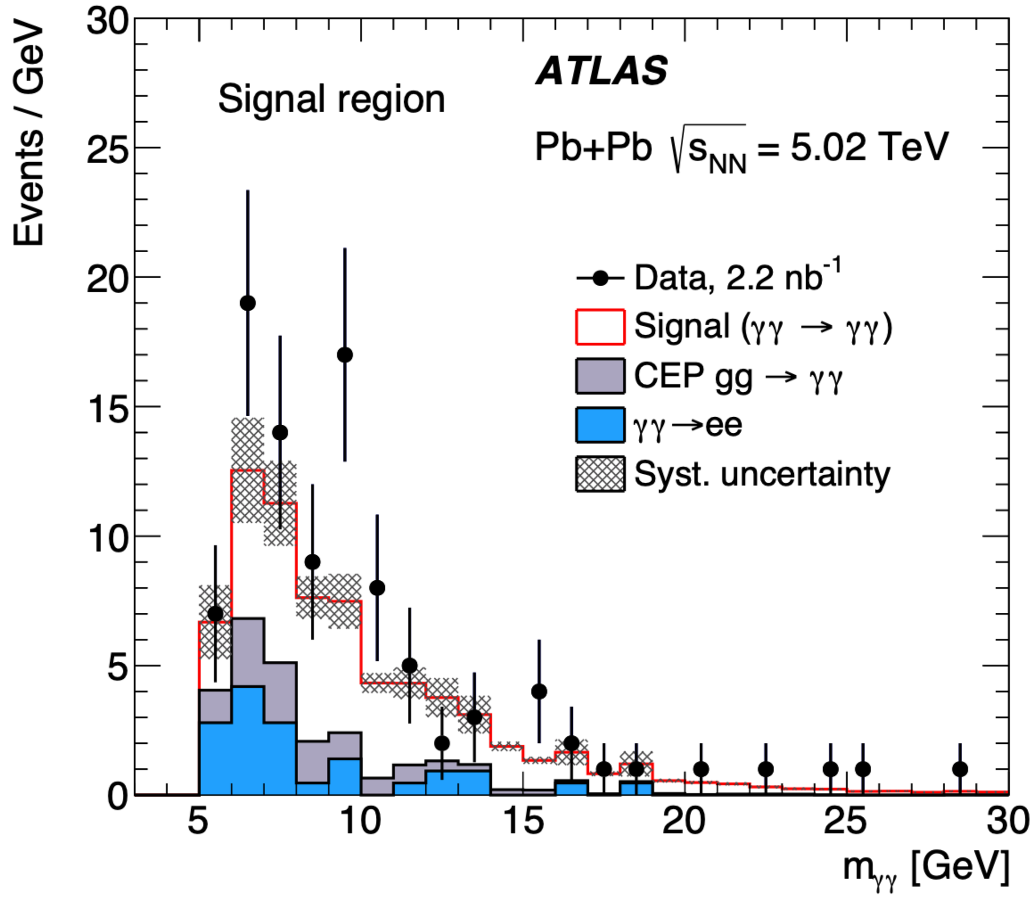


Search for ALP production

- 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

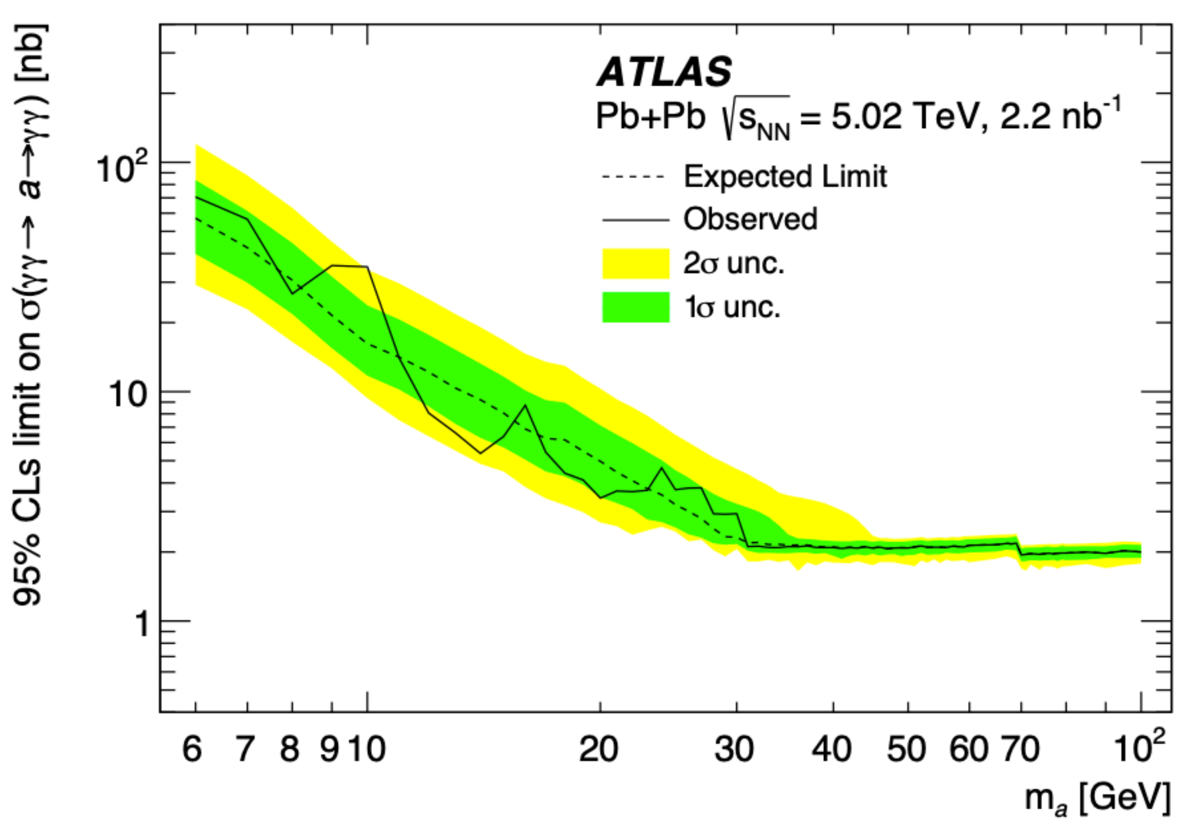


[JHEP 03 (2021) 243]



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



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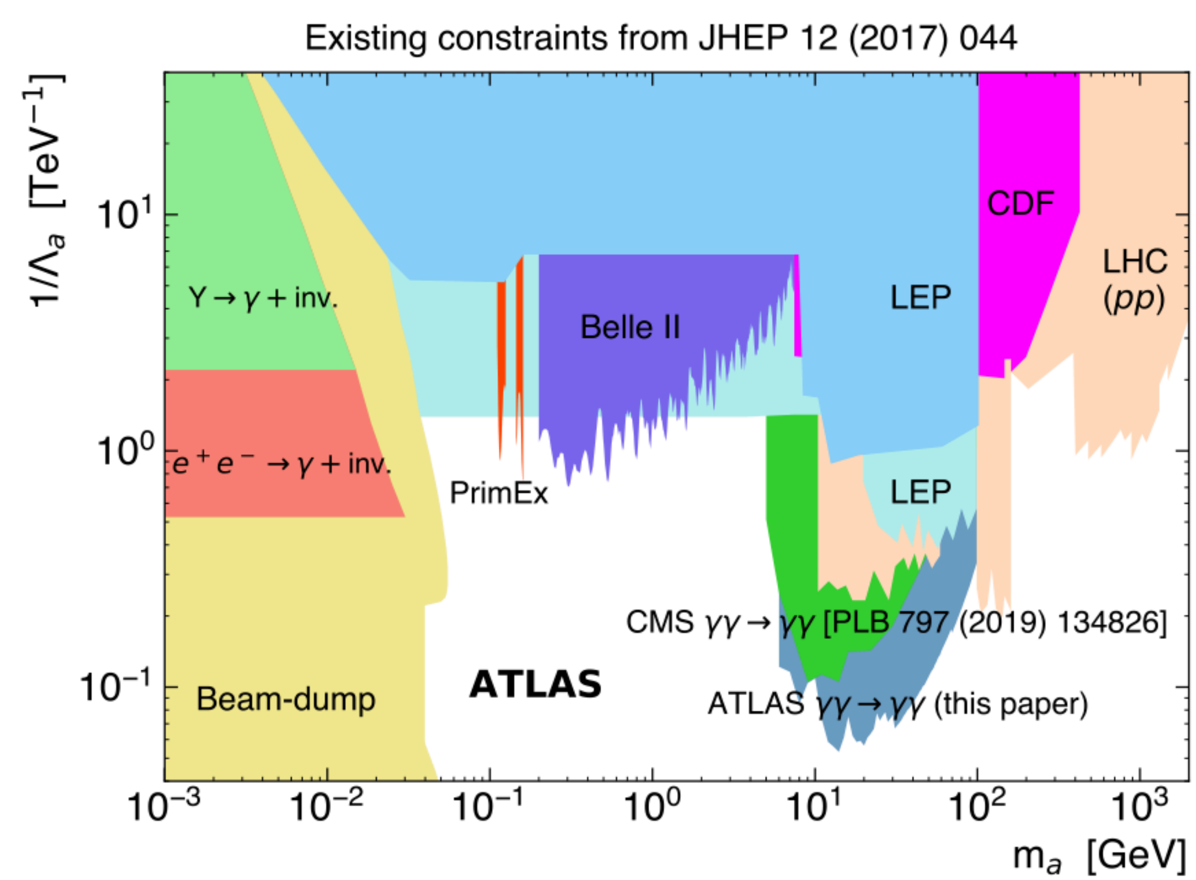
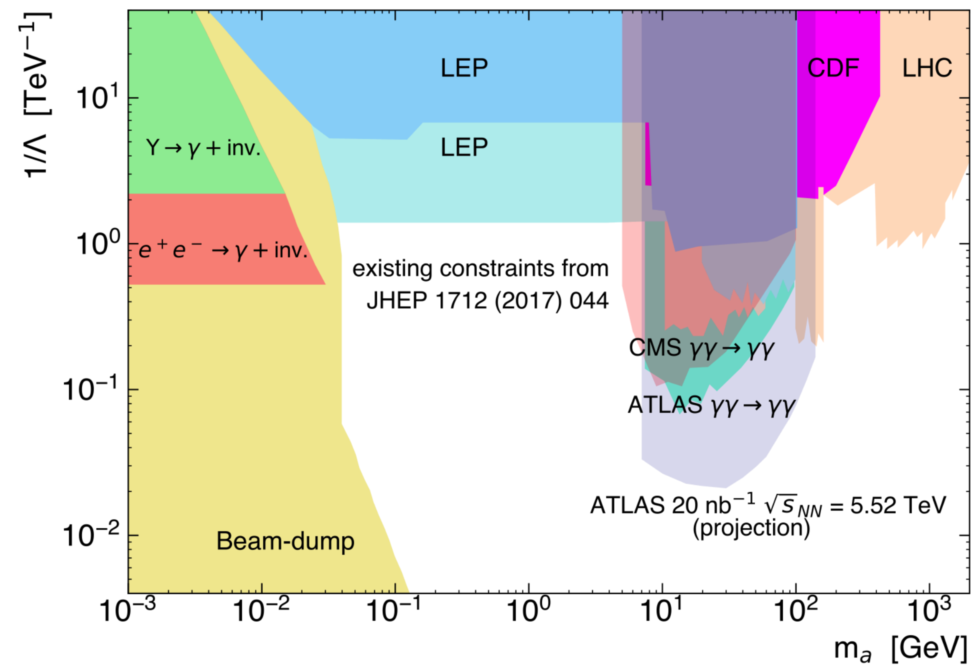


Summary

- UPCs can be used to probe rare SM processes and search for BSM phenomena
- ATLAS provides a **final measurement** of exclusive ditau production in Pb+Pb UPC at the LHC with **above 5σ significance**
- The measurement of the τ-lepton **anomalous magnetic moment is competitive** with previous best limit from the LEP era
  - **Improvement** in precision expected with **Run-3** data
- **Light-by-light scattering well established** by ATLAS experiment at the LHC
- The **LbyL ATLAS** result set **the most stringent limits** to date on ALP production for masses in the range 6-100 GeV
  - **Excellent prospects** for new searches with **Run-3** and **Run-4** data

[arXiv:1812.06772]



- All results from ATLAS Heavy Ion available at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Acknowledgements

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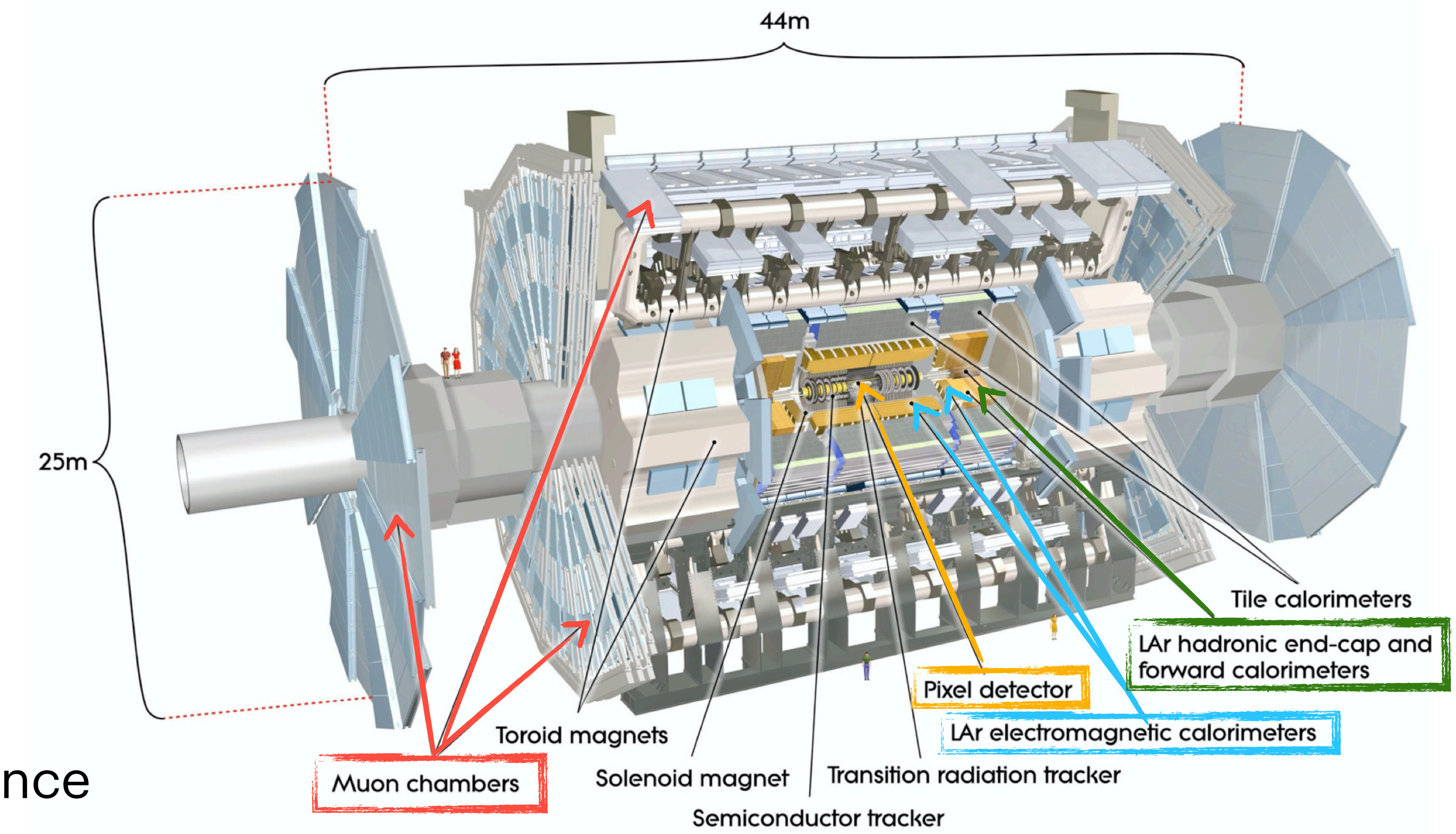
Additional slides

ATLAS detector

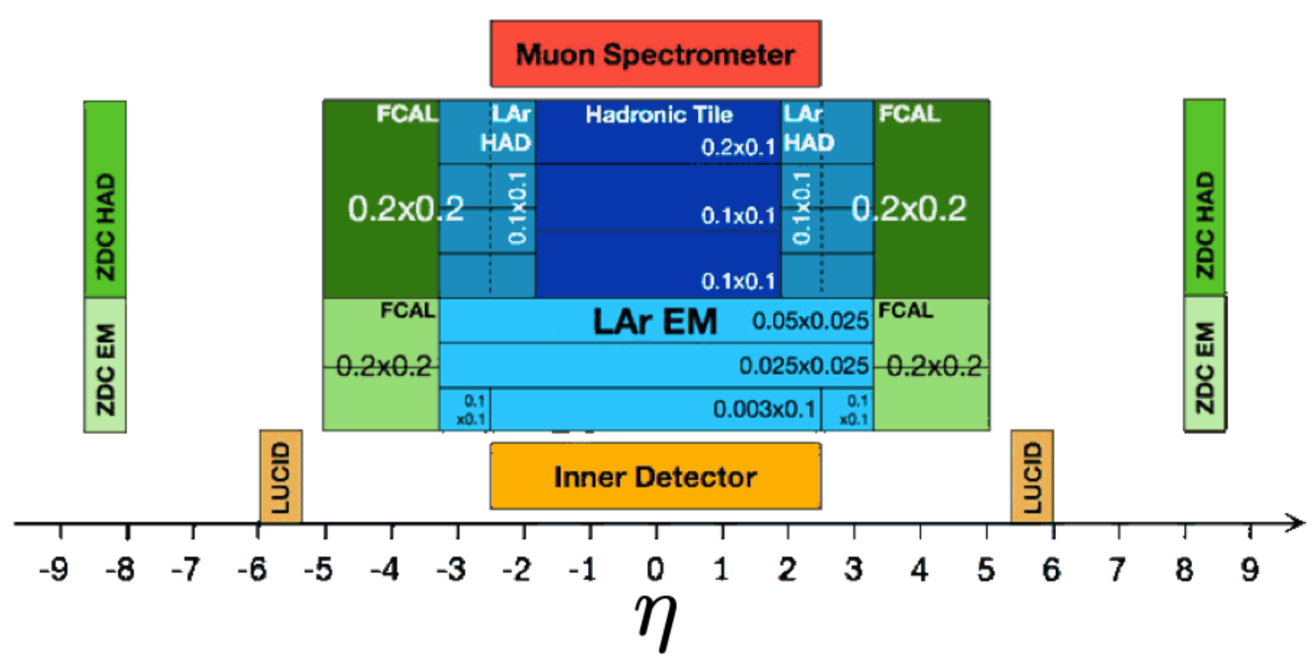
Main components:
inner tracker,
electromagnetic (EM),
and hadronic (HAD)
calorimeters,
and muon system



φ - full azimuth acceptance

η - broad pseudo rapidity coverage

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



p_T - transverse momentum

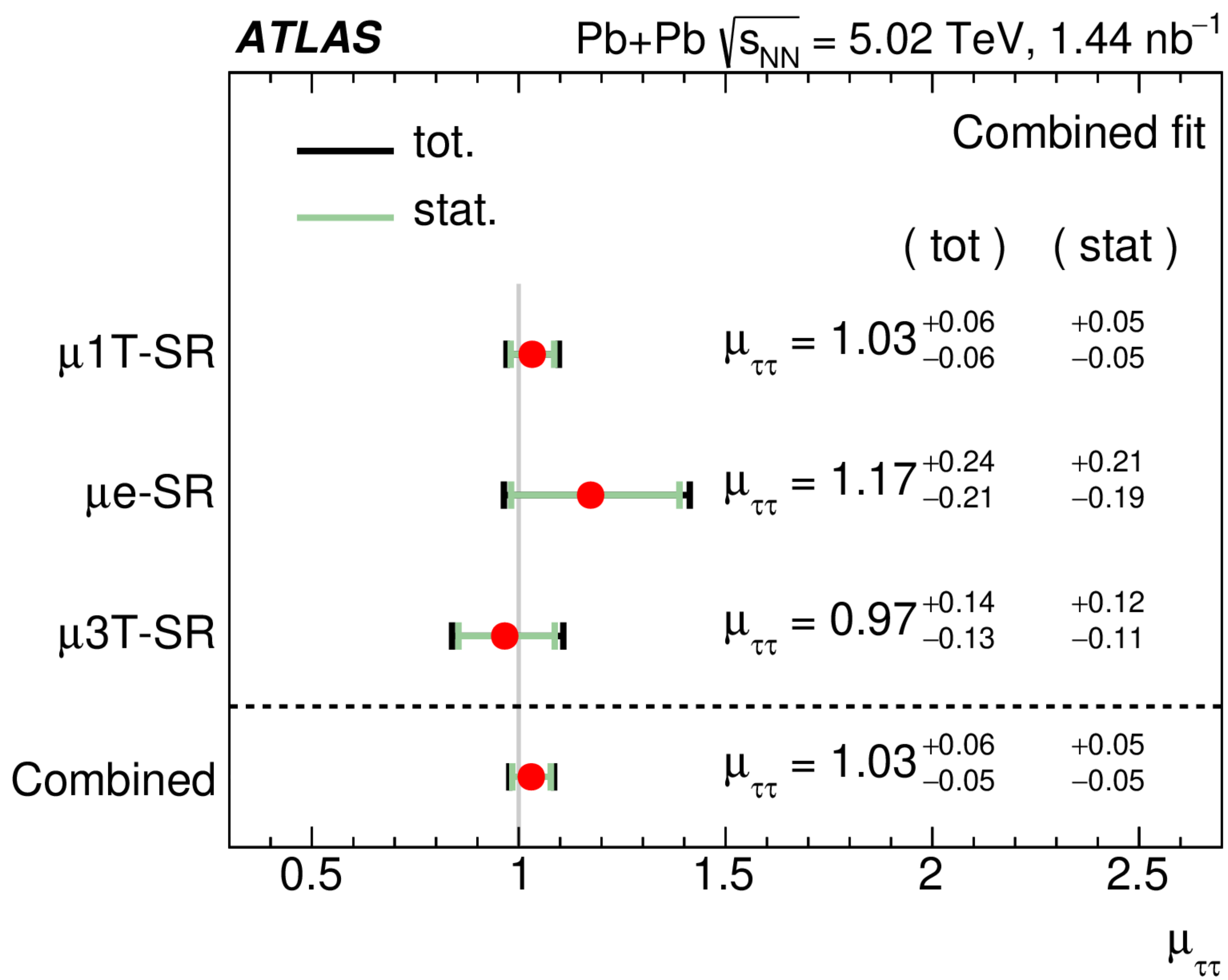
$$p_T = \sqrt{p_x^2 + p_y^2}$$

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

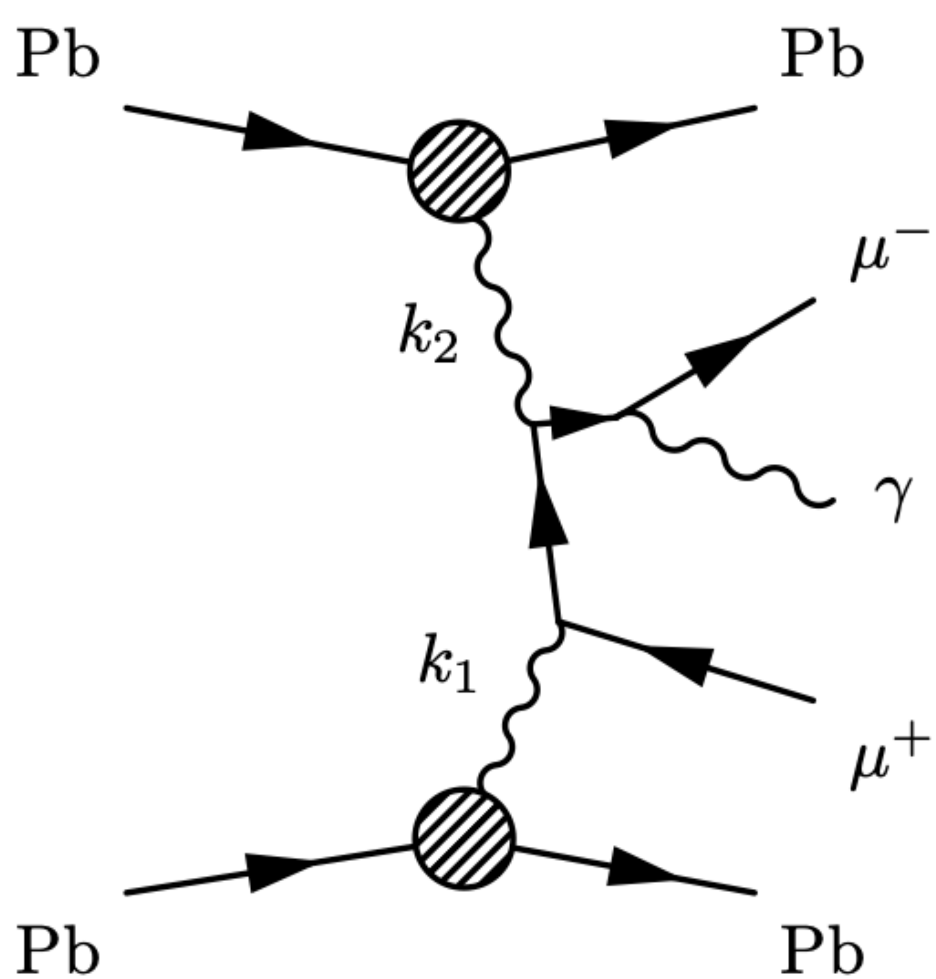
Results: Signal strength

- Fit of $\gamma\gamma \to \tau\tau$ 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

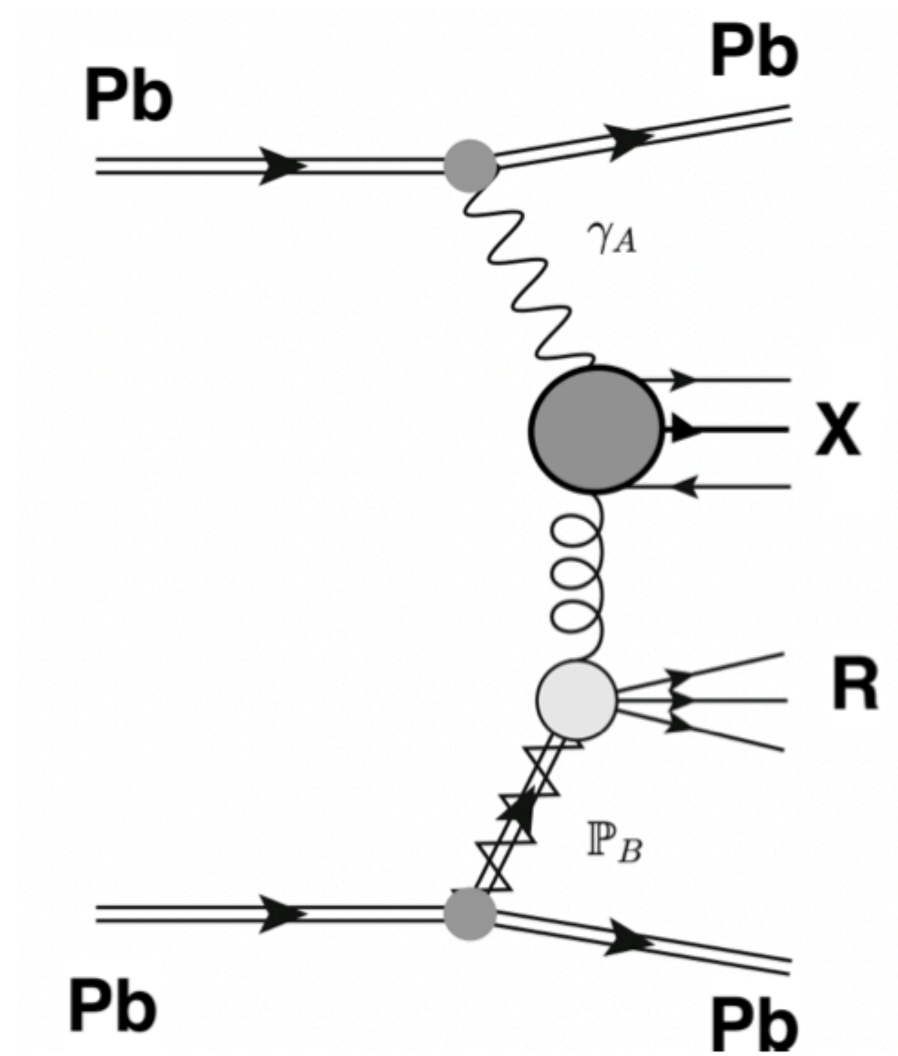


Background processes

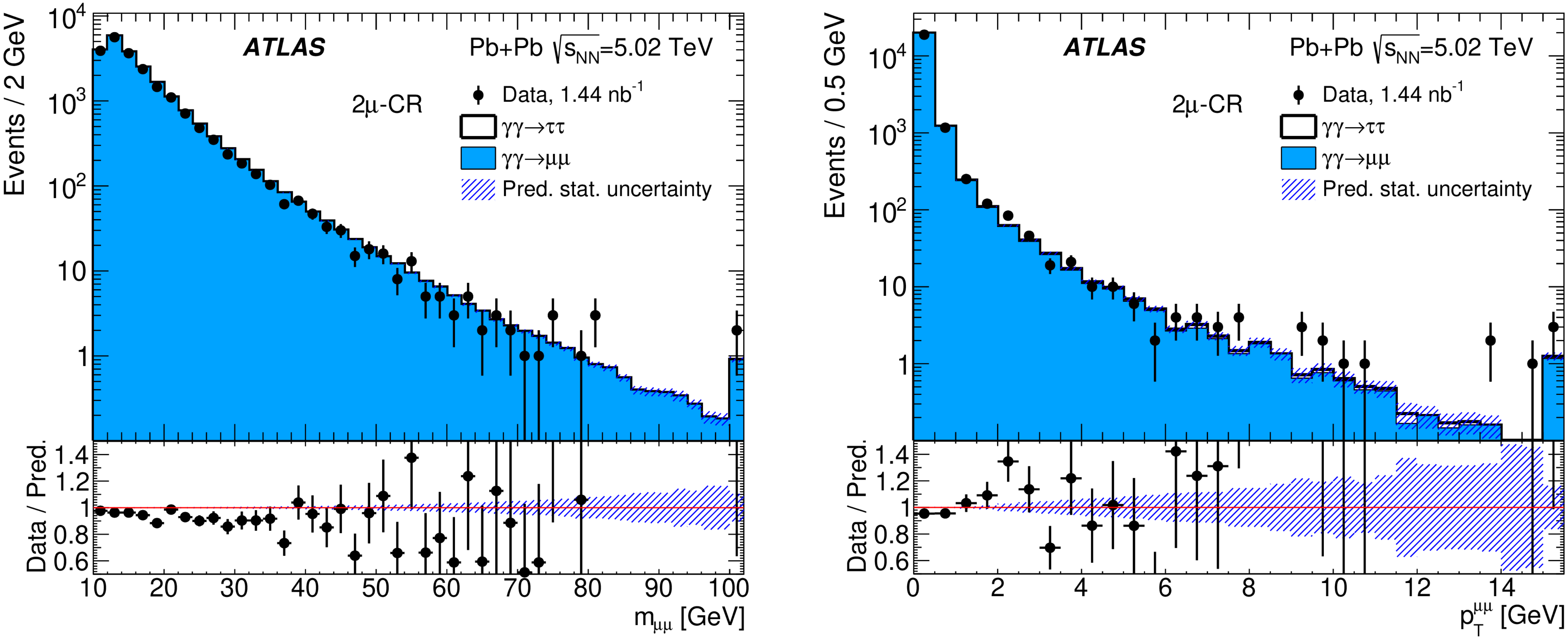
$\gamma\gamma \rightarrow \mu\mu(\gamma)$ production



diffractive photonuclear events

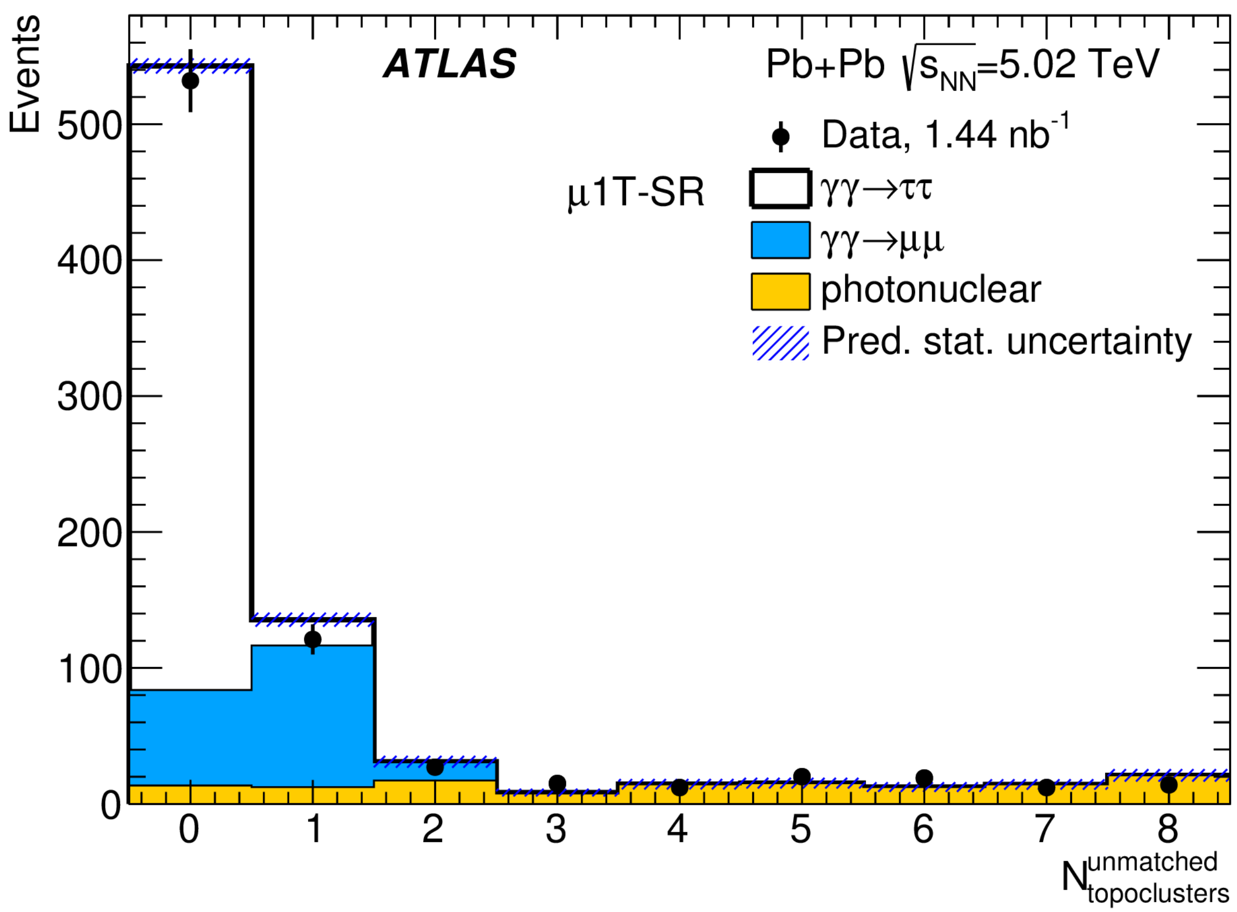


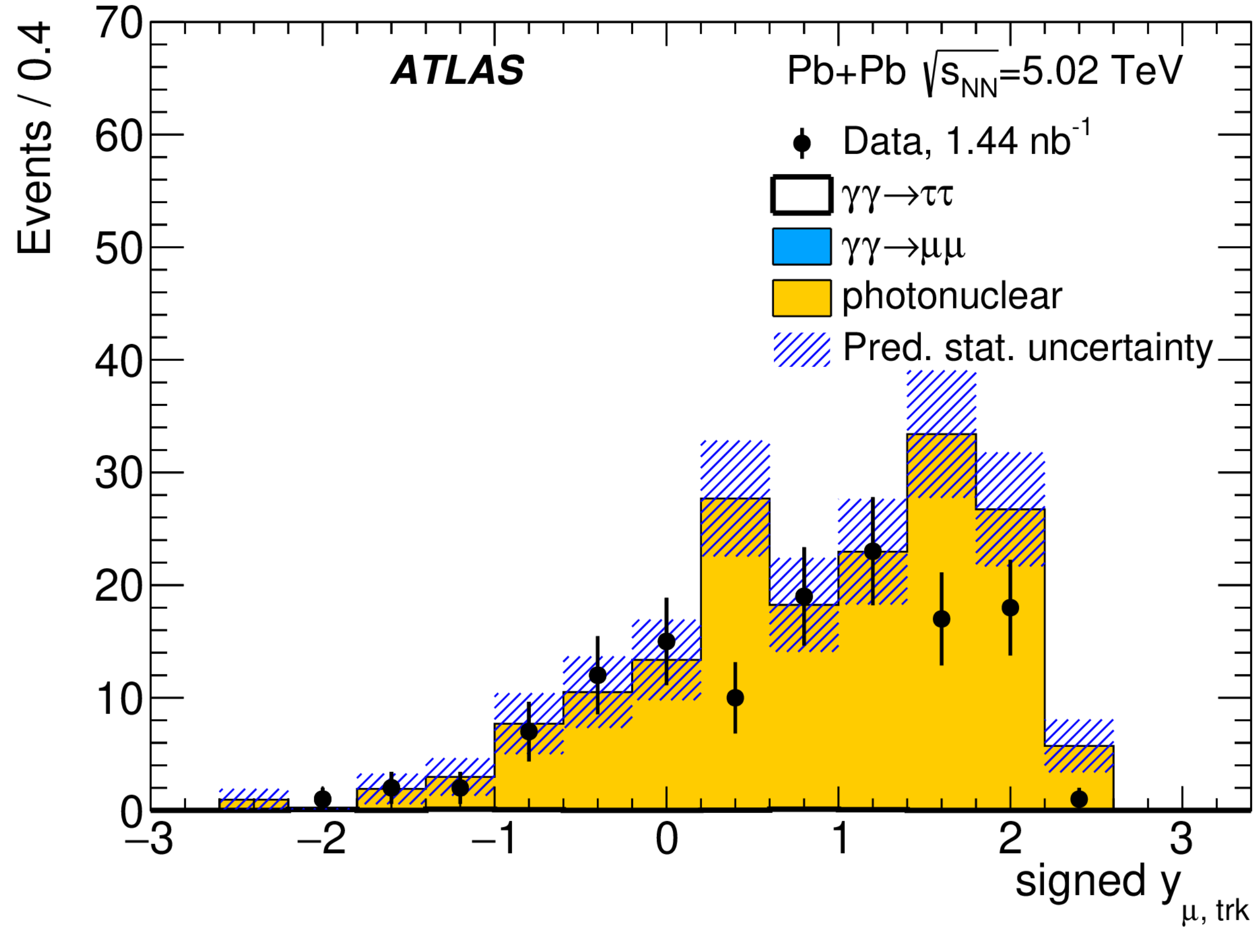
Background processes: $\gamma\gamma \rightarrow \mu\mu(\gamma)$ production



- 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

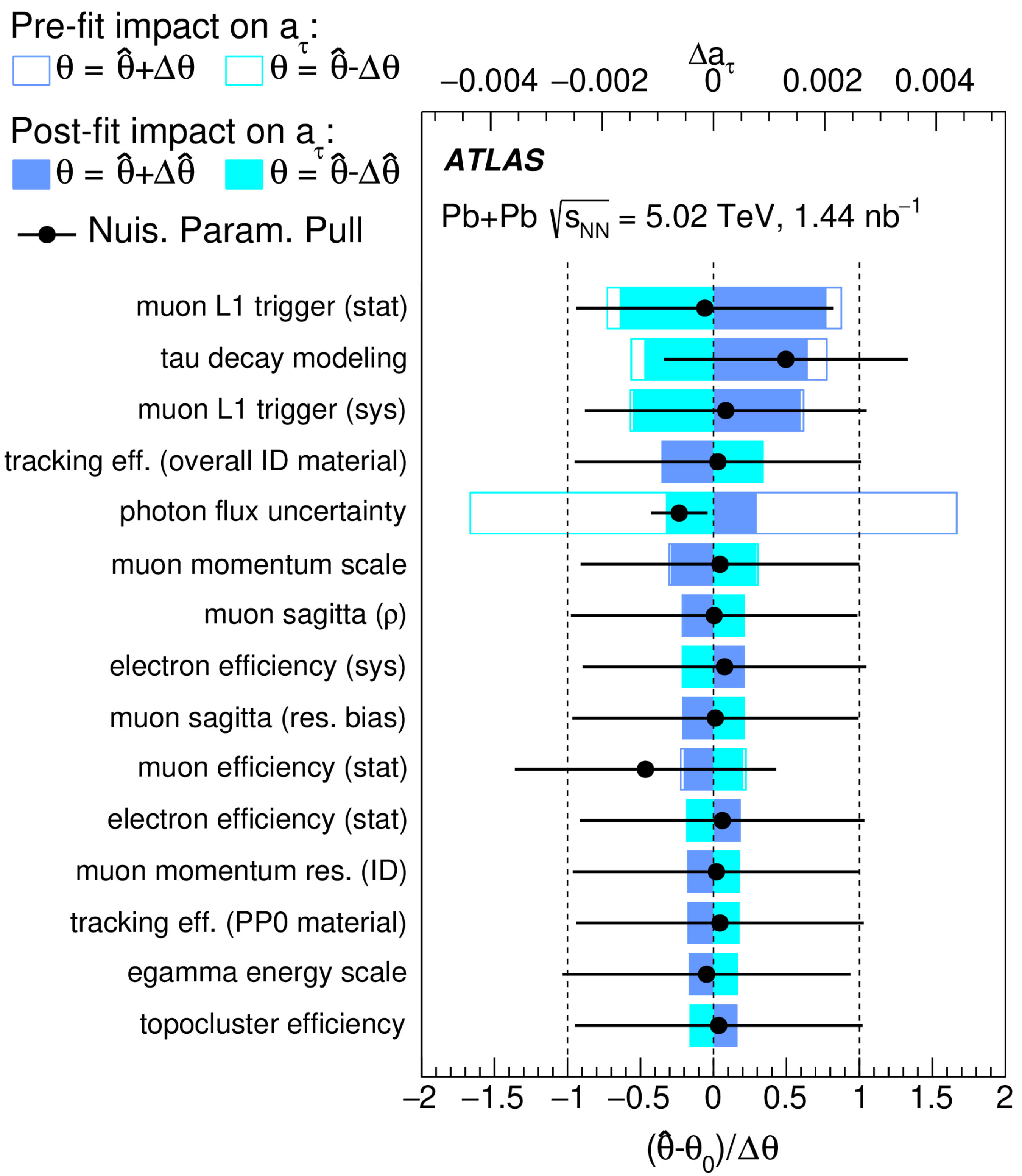




- Data-driven estimation of diffractive photonuclear events in μ1T-SR and μ3T-SR
- Templates built from control regions similar to SRs, but requiring an additional track with $p_T < 0.5$ GeV and allowing 0nXn ZDC events
- Normalization: relax cluster veto → use region with 4-8 unmatched clusters
- Kinematic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

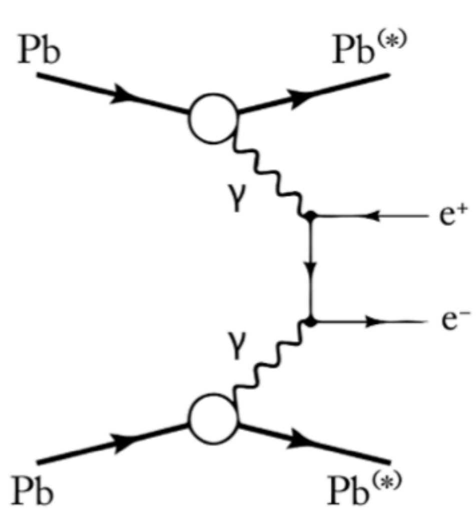
Systematic uncertainties in a_τ

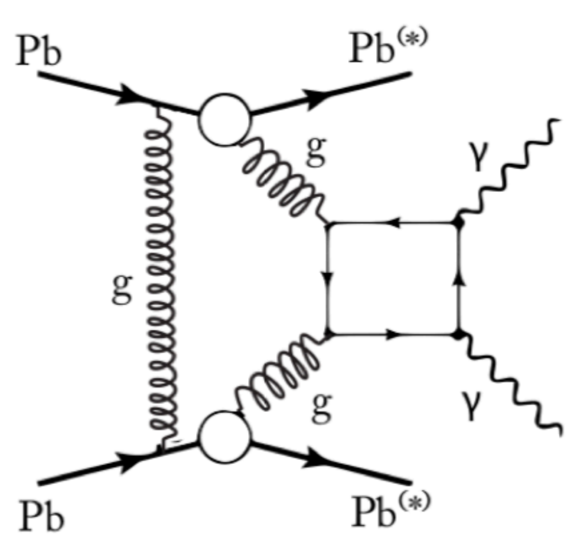
- Detector related
  - Muon trigger efficiency
  - Muon/electron reconstruction/ID efficiency and calibration
  - Track reconstruction efficiency
  - Cluster reconstruction efficiency and calibration
- Background
  - Photonuclear background template variation
- Theory
  - Photon flux modeling (SuperChic3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

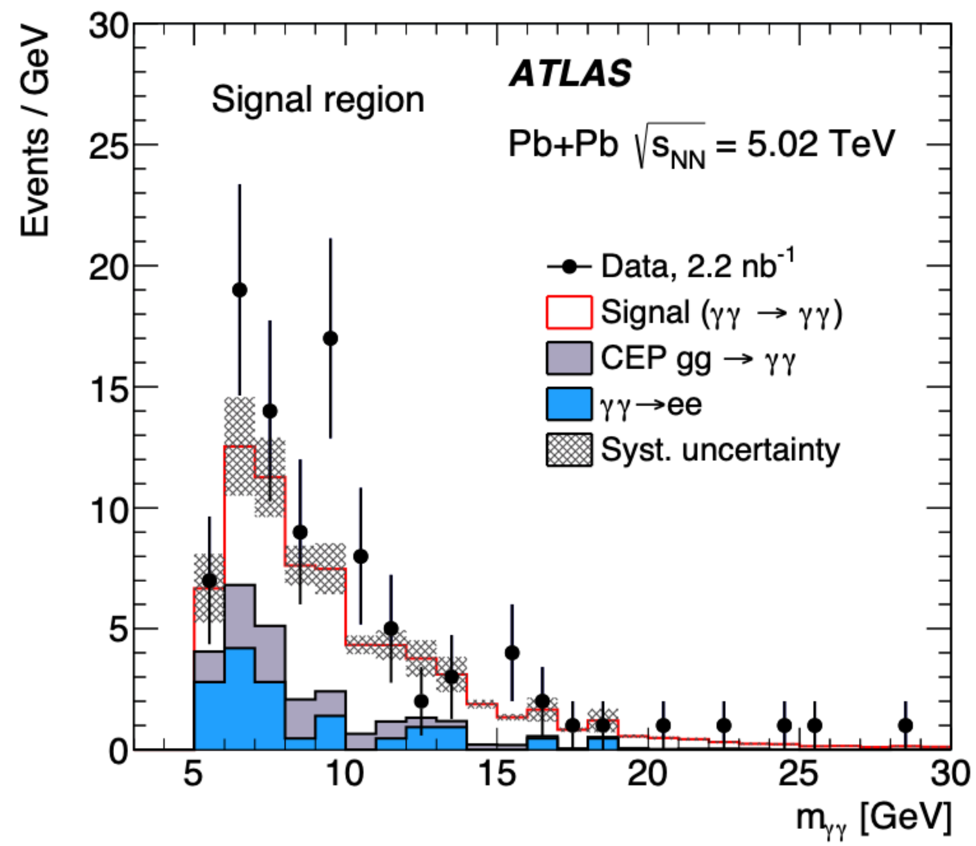


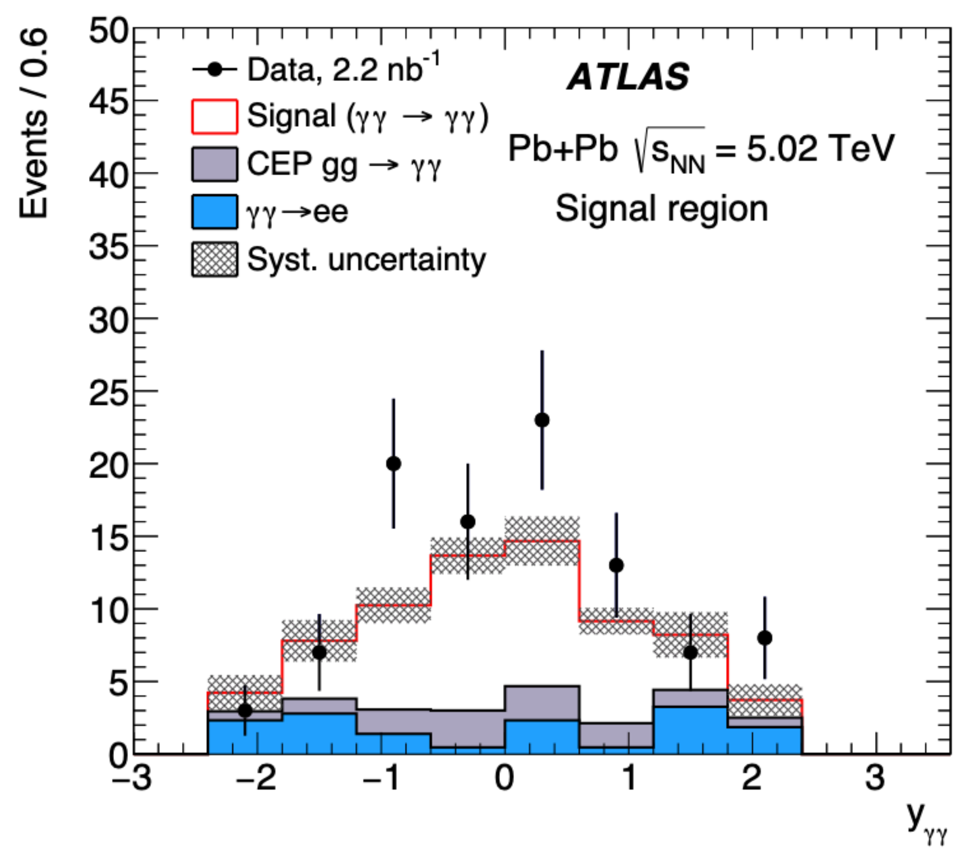
LbyL Background

- 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



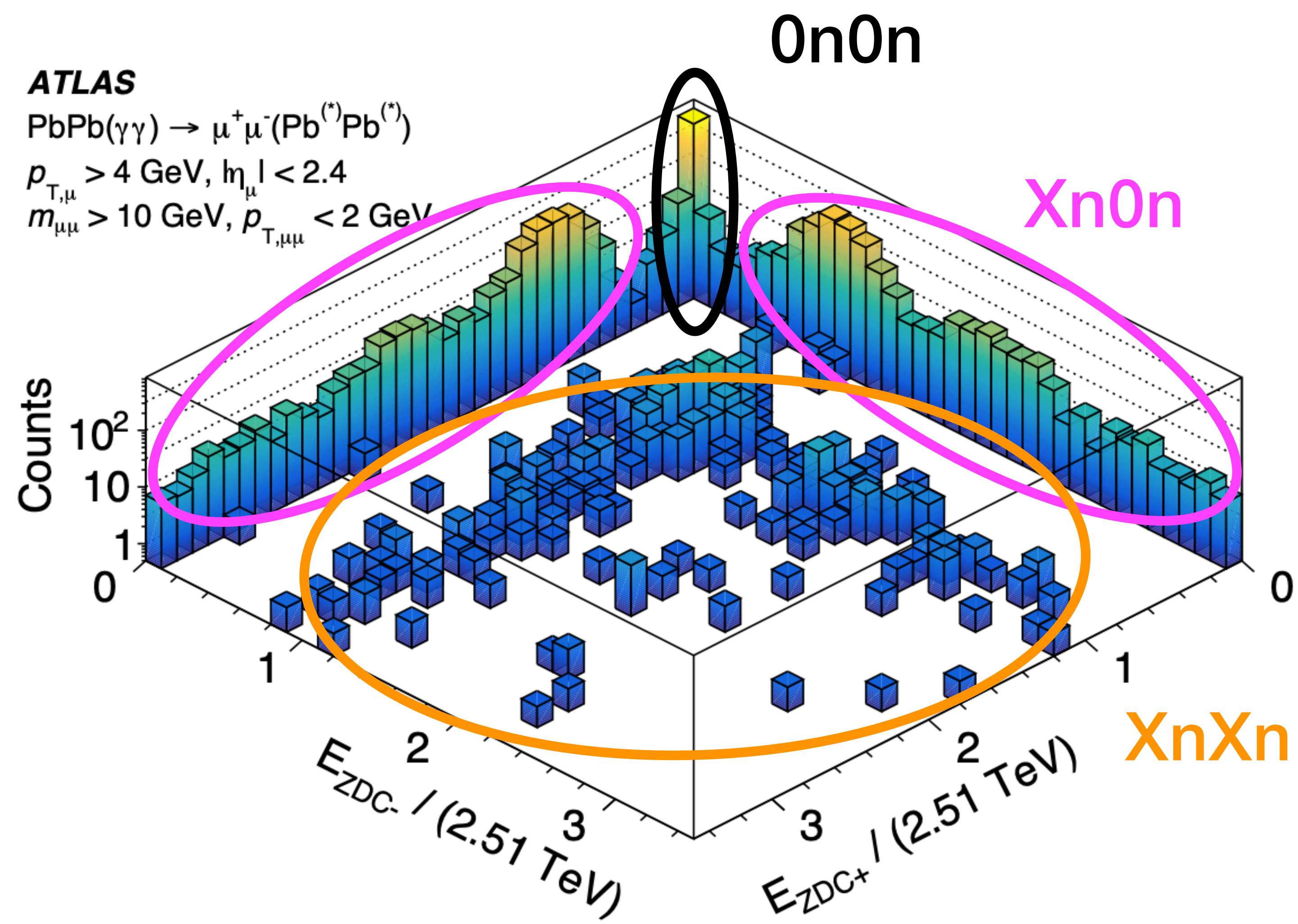






Signal categories - ZDC selection

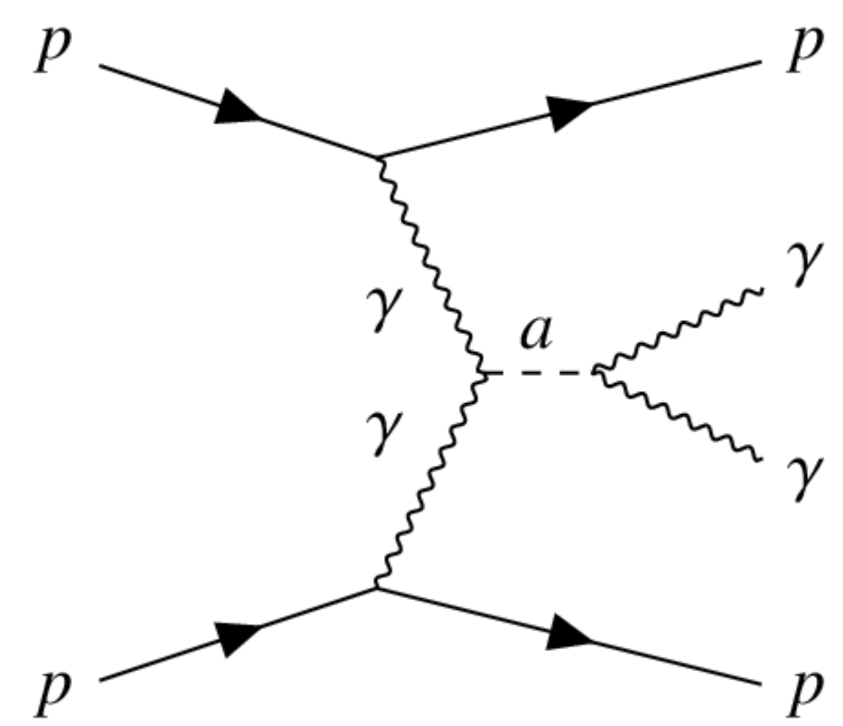
- Different processes present different activity in the forward region:
  - Exclusive dilepton production - ions stay intact
  - Background events with nuclear breakup
- Three classes defined, based on the signal in the ZDC

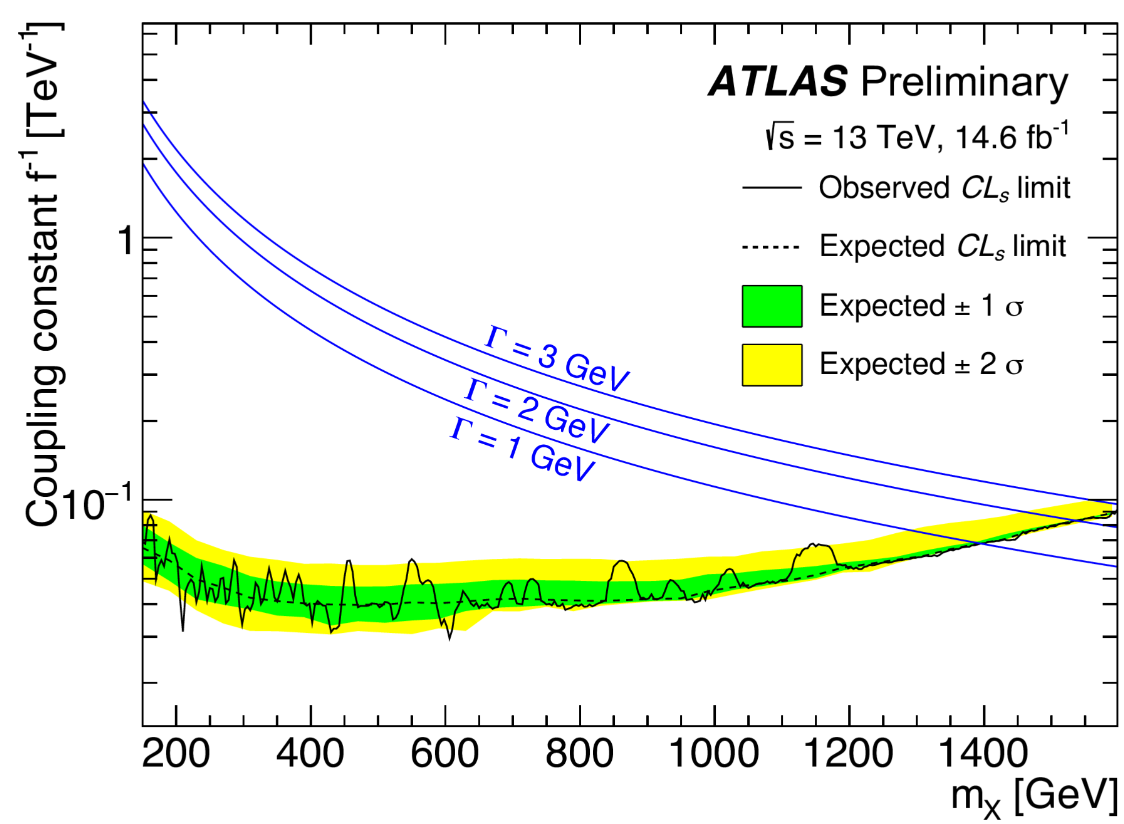


- The association between given ZDC signal and given process is nontrivial
  - Migrations due to ion excitation and presence of EM pile-up

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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