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

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ATLAS EXPERIMENT

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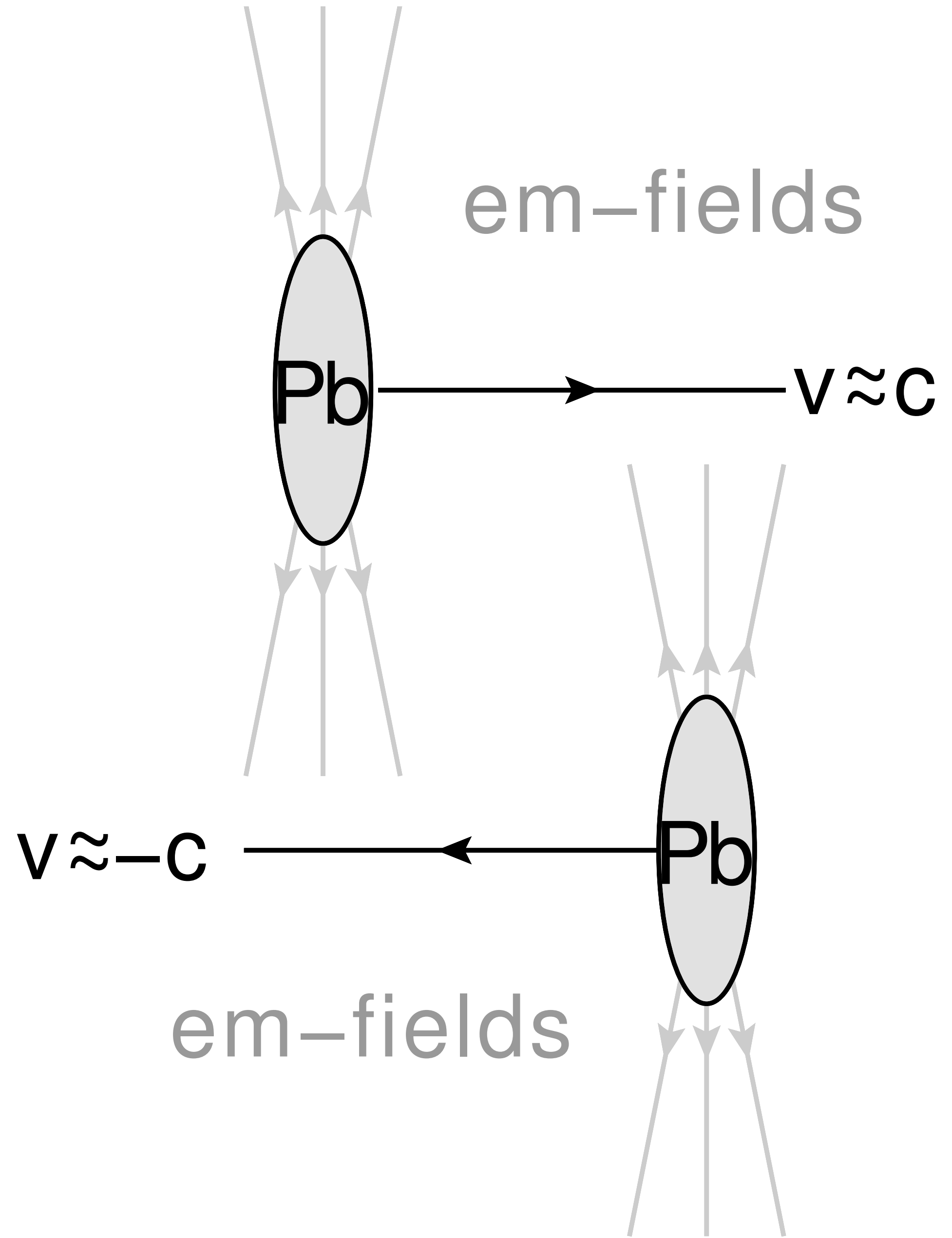
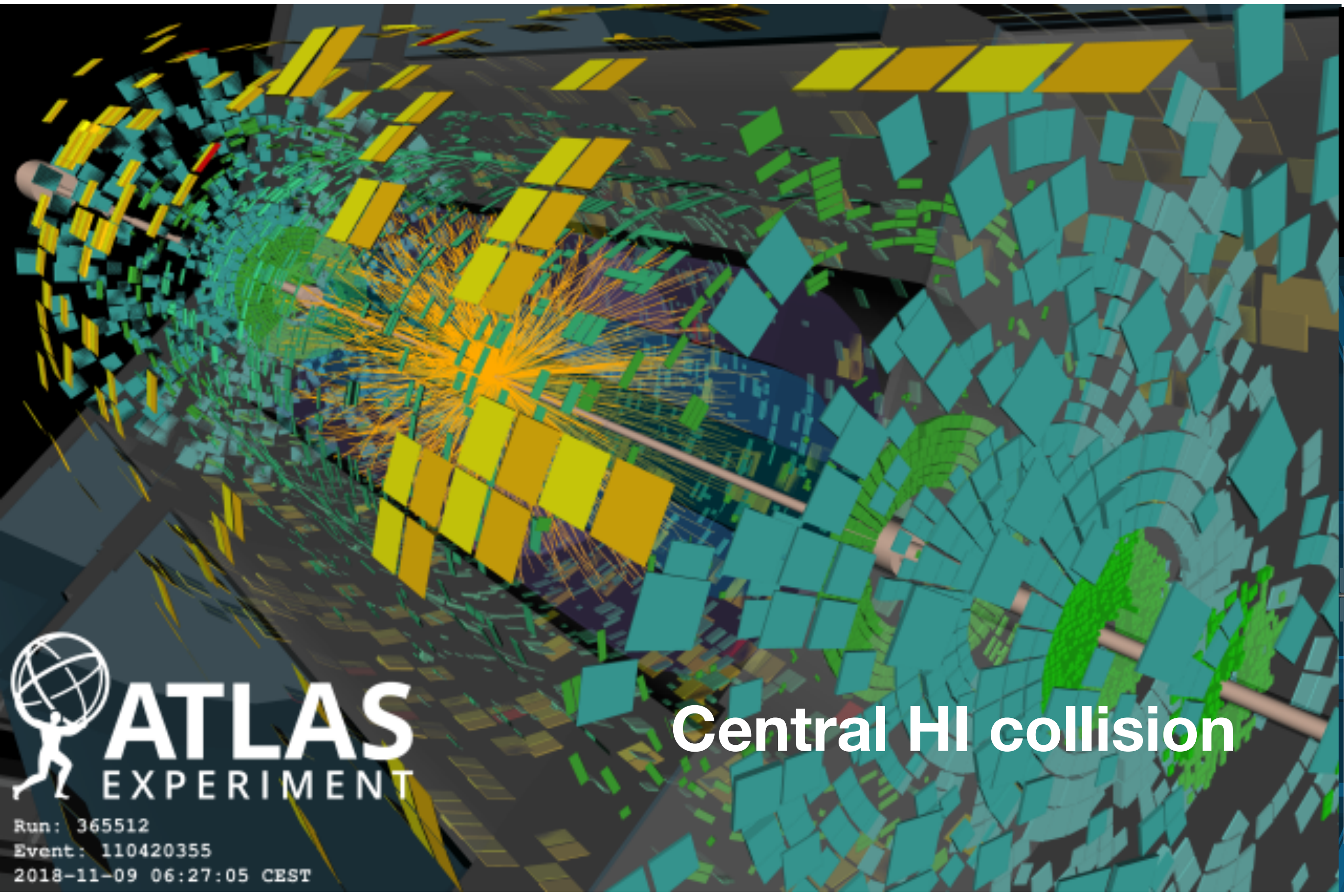
Ultra-peripheral collisions

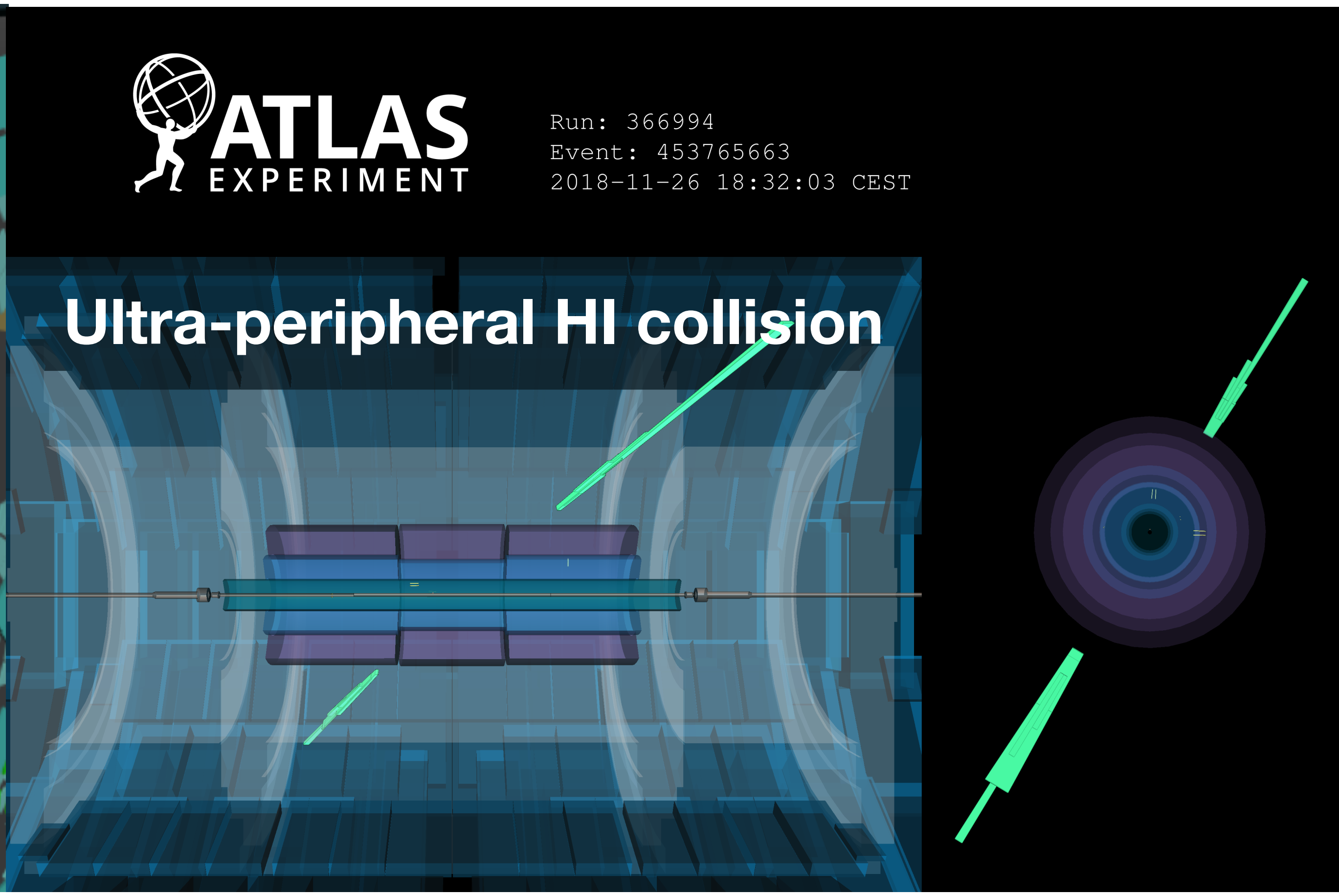
- In **ultra-peripheral heavy-ion collisions (UPC)** we observe photon-photon interactions
  - **New research opportunities**
- Electromagnetic (EM) fields of relativistic ions considered as **fluxes of photons** (they scale with ~ Z^2)
- Described in a **Equivalent Photon Approximation** (EPA) formalism
- Reaction cross-section calculated by **convolving** the respective **photon flux** with the **elementary cross-section** for the process



Ultra-peripheral collisions

- Advantages of UPC heavy-ion collisions:
  - Increased cross-sections wrt to pp collisions (cross-sections scale by Z^4 what is ~4.5×10^7)
  - Very low hadronic pileup - exclusive selections possible
  - Low p_T particles can be triggered and reconstructed



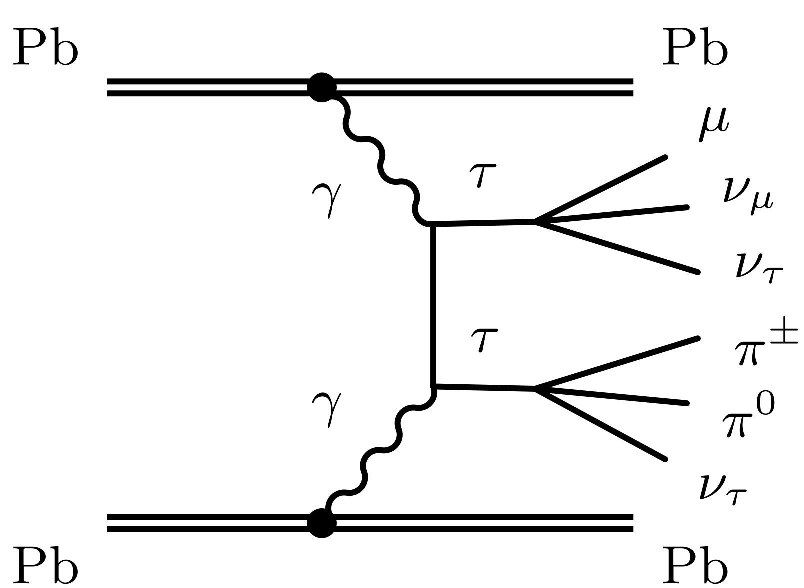


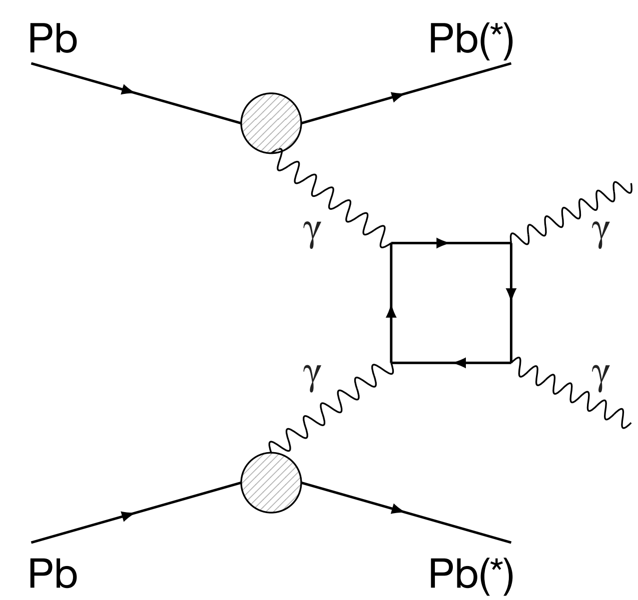
Motivation

- This talk discusses new measurements performed by the ATLAS Collaboration in UPC PbPb at 5.02 TeV:

  - **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

  - **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



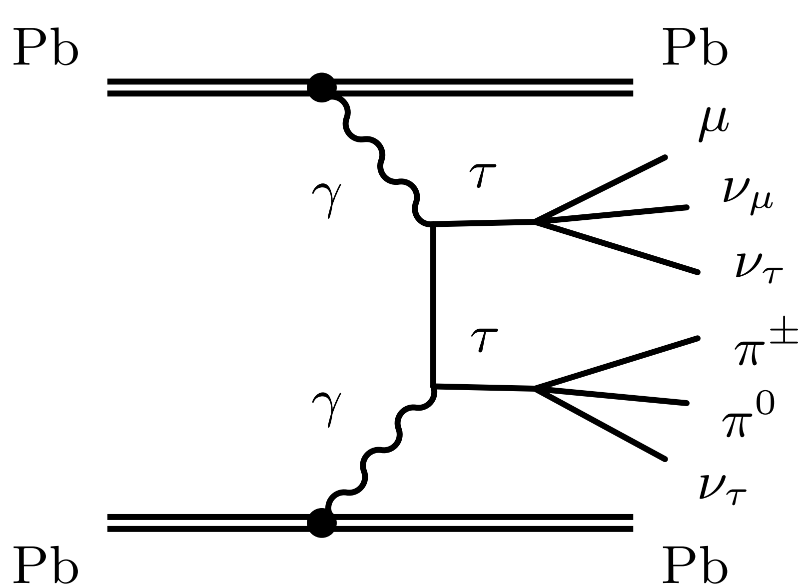


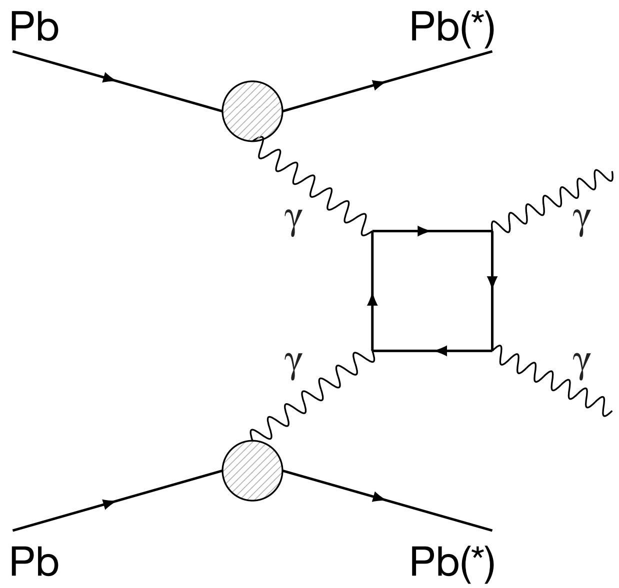
- Other ATLAS measurements in UPC discussed by Iwona

Motivation

- **Constraints** on τ-lepton anomalous magnetic moment
- Its value can be modified by various BSM phenomena (leptoquarks, lepton compositeness, SUSY, …)

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



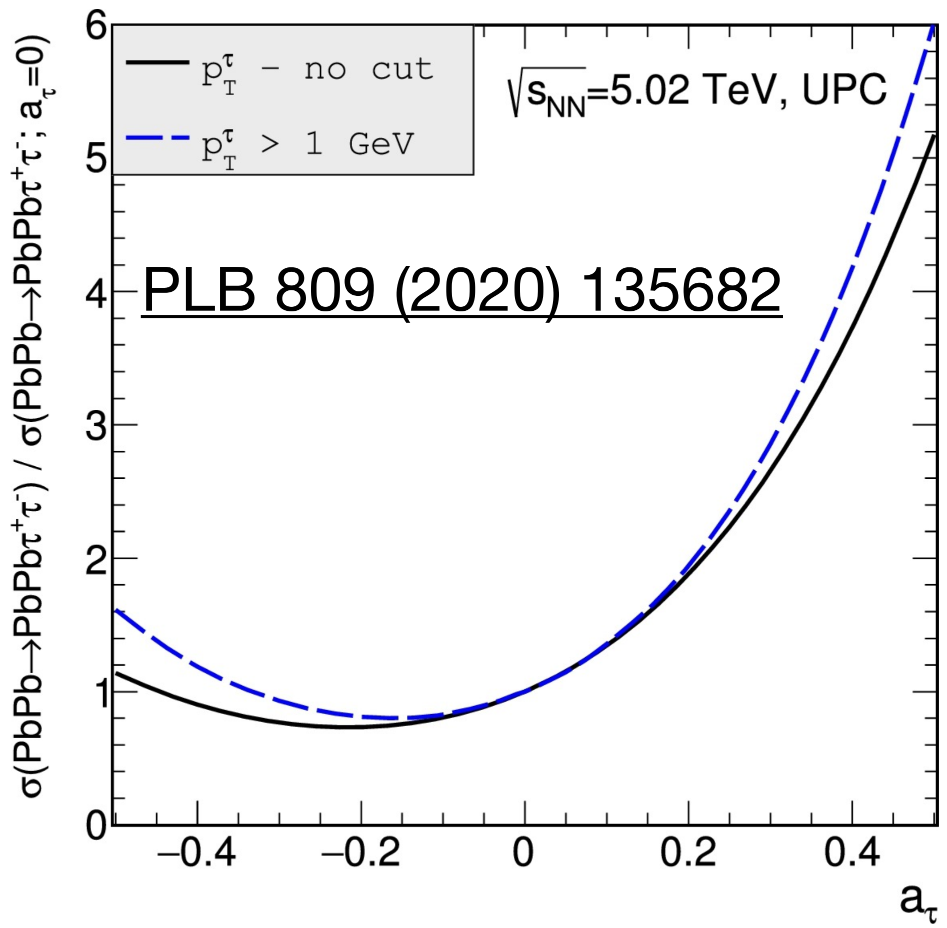


$\gamma\gamma \to \tau\tau$

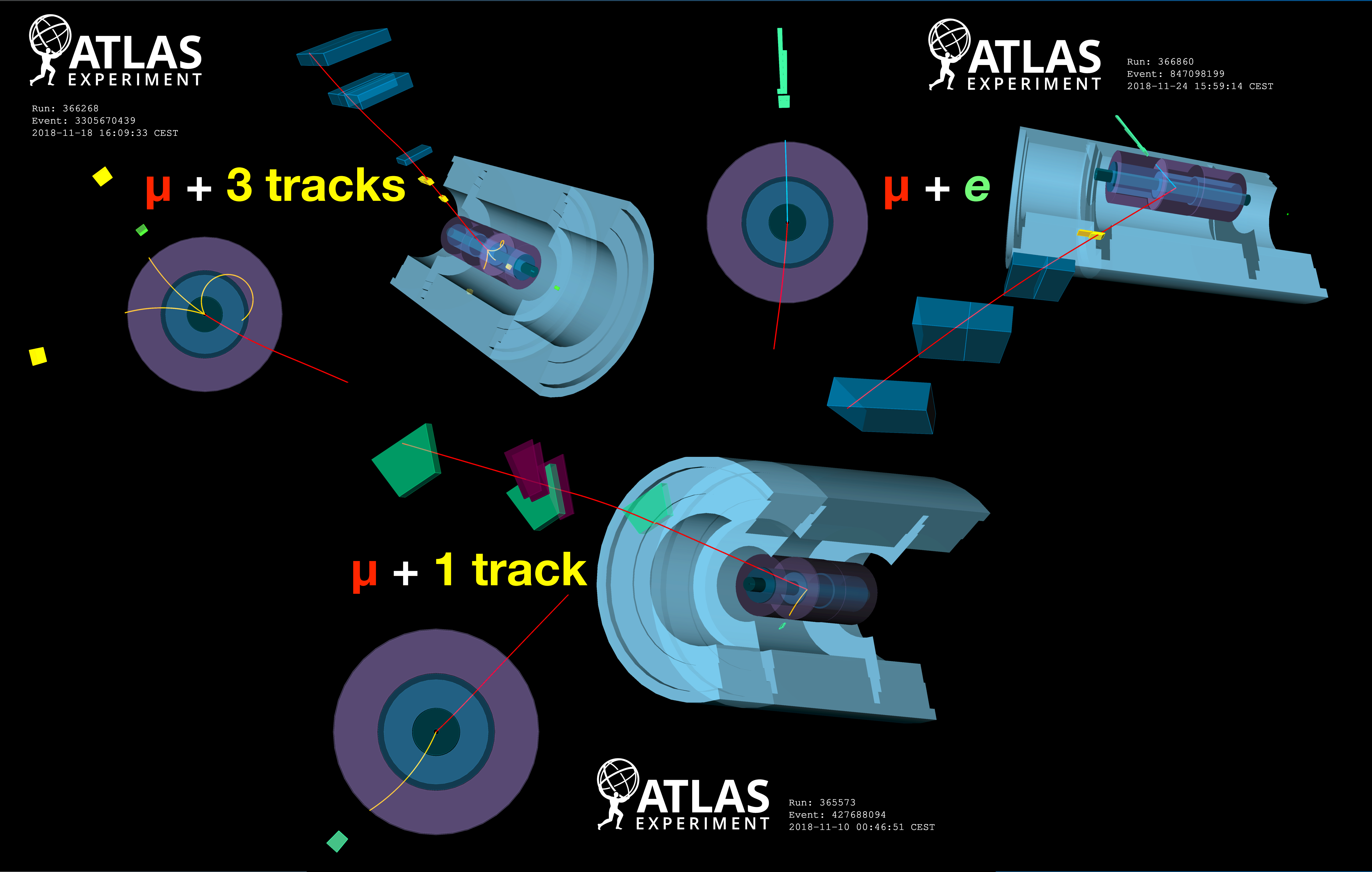
arXiv:2204.13478

a_τ - measurement strategy

- Magnetic moment of the particle and its spin are related by *g*-factor: $\boldsymbol{\mu} = g\, q/2m\, \mathbf{S}$
- Dirac's equation predicts $g=2$ for charged leptons, higher-order corrections result in $g \neq 2$,
- These discrepancies are quantified by the lepton **anomalous magnetic moments** $a_\ell = (g-2)_\ell/2$
- Currently the **best constraints** for a_τ are from **DELPHI** experiment: $-0.052 < a_\tau < 0.013$ (95% CL) EPJC 35 (2004) 159
- Measurement of **a_τ in HI UPC collisions** using $\gamma\gamma \to \tau\tau$ events proposed in several publications:
  - F. del Águila, 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



Ditau events

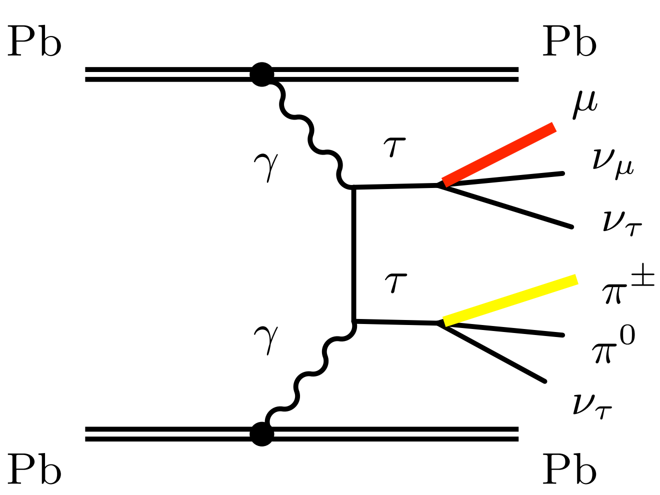


Signal categories

- **First observation** of $\gamma\gamma\rightarrow\tau\tau$ process in HI UPC using 1.44 nb^{-1} of Pb+Pb data recorded by ATLAS in 2018
- **Signal** τ-leptons are **low-energetic**, typically with $p_T < 10$ GeV
    - No standard ATLAS identification of τ-leptons is used
- Events classified based on the charged τ-lepton decay products
- **Three signal categories:**

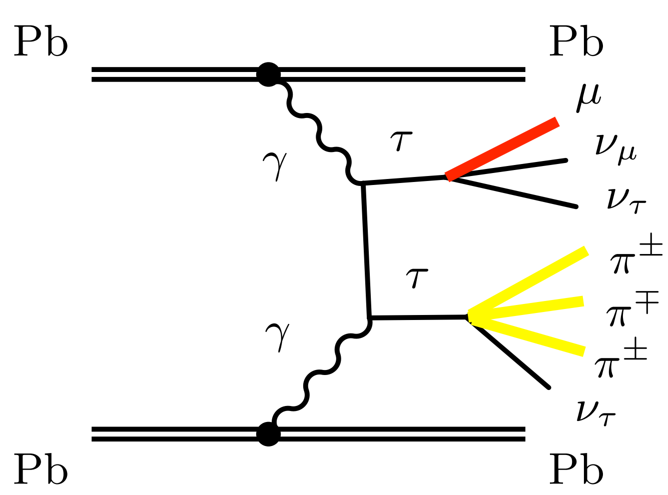
μ1T-SR:

muon + 1 track



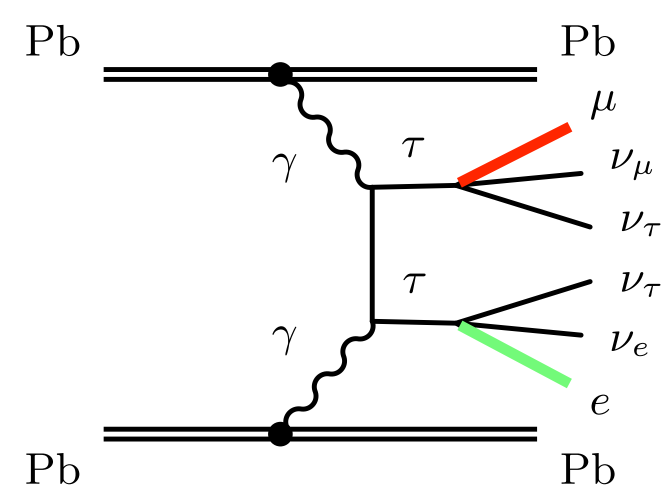
μ3T-SR:

muon + 3 tracks



μe-SR:

muon + electron

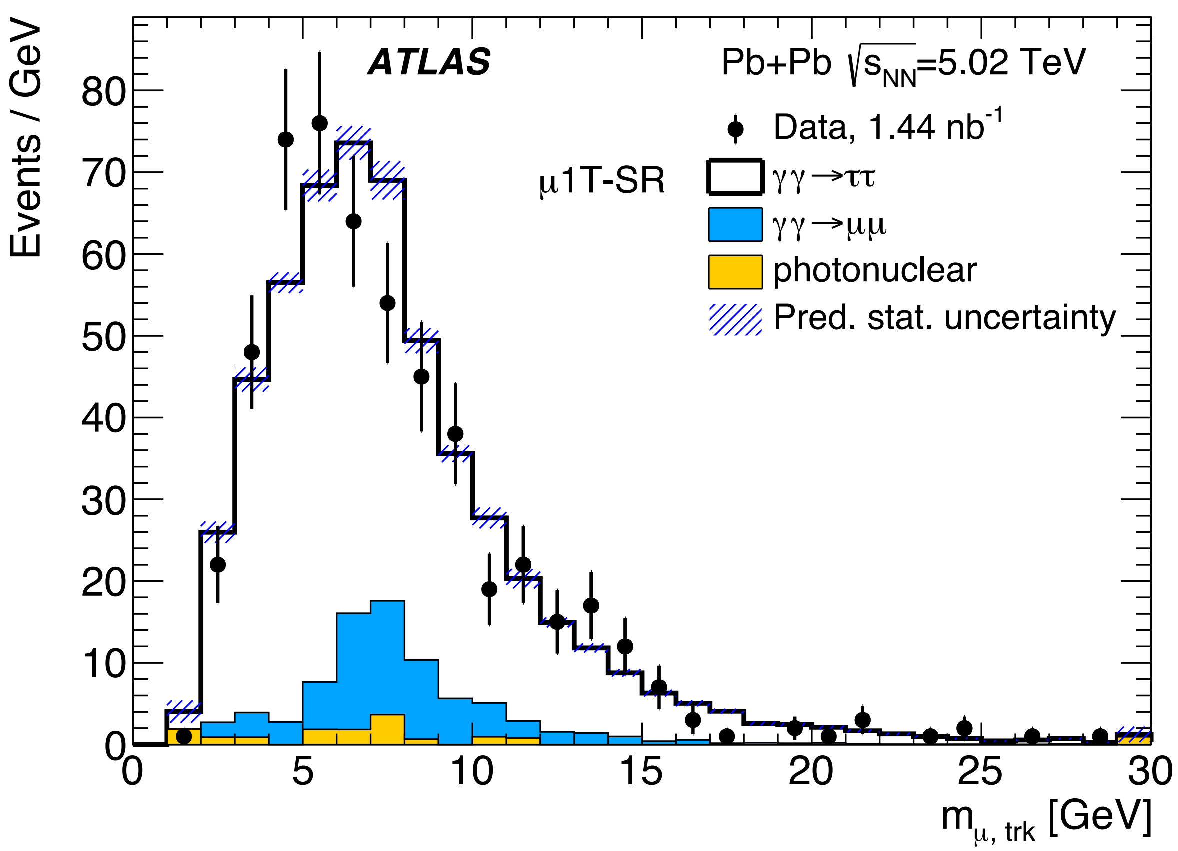


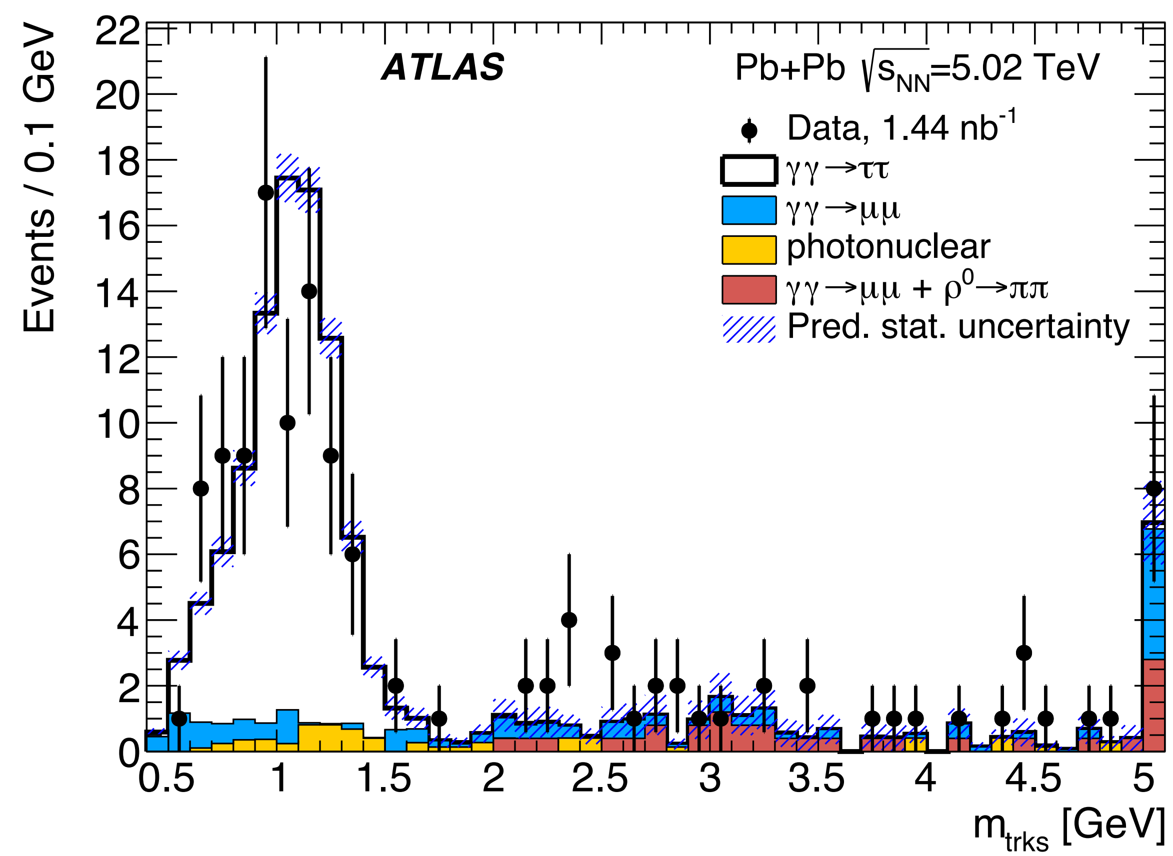
Ditau event selection

- Single muon trigger recording events having muon with $p_T > 4$ GeV
- Veto on forward neutron activity (based on ZDC signal) -> MC samples reweighed

- **Kinematic selection:**
  - muons: $p_T > 4$ GeV, $|\eta| < 2.4$
  - electrons: $p_T > 4$ GeV, $|\eta| < 2.47$
  - tracks: $p_T > 100$ MeV, $|\eta| < 2.5$

- **Other requirements:**
  - veto on additional low-p_T clusters (for μ1T-SR and μ3T-SR) and low-p_T tracks
  - For μ1T-SR: $p_T^{\mu,trk} > 1$ GeV
  - For μ3T-SR: $m_{3trks} < 1.7$ GeV

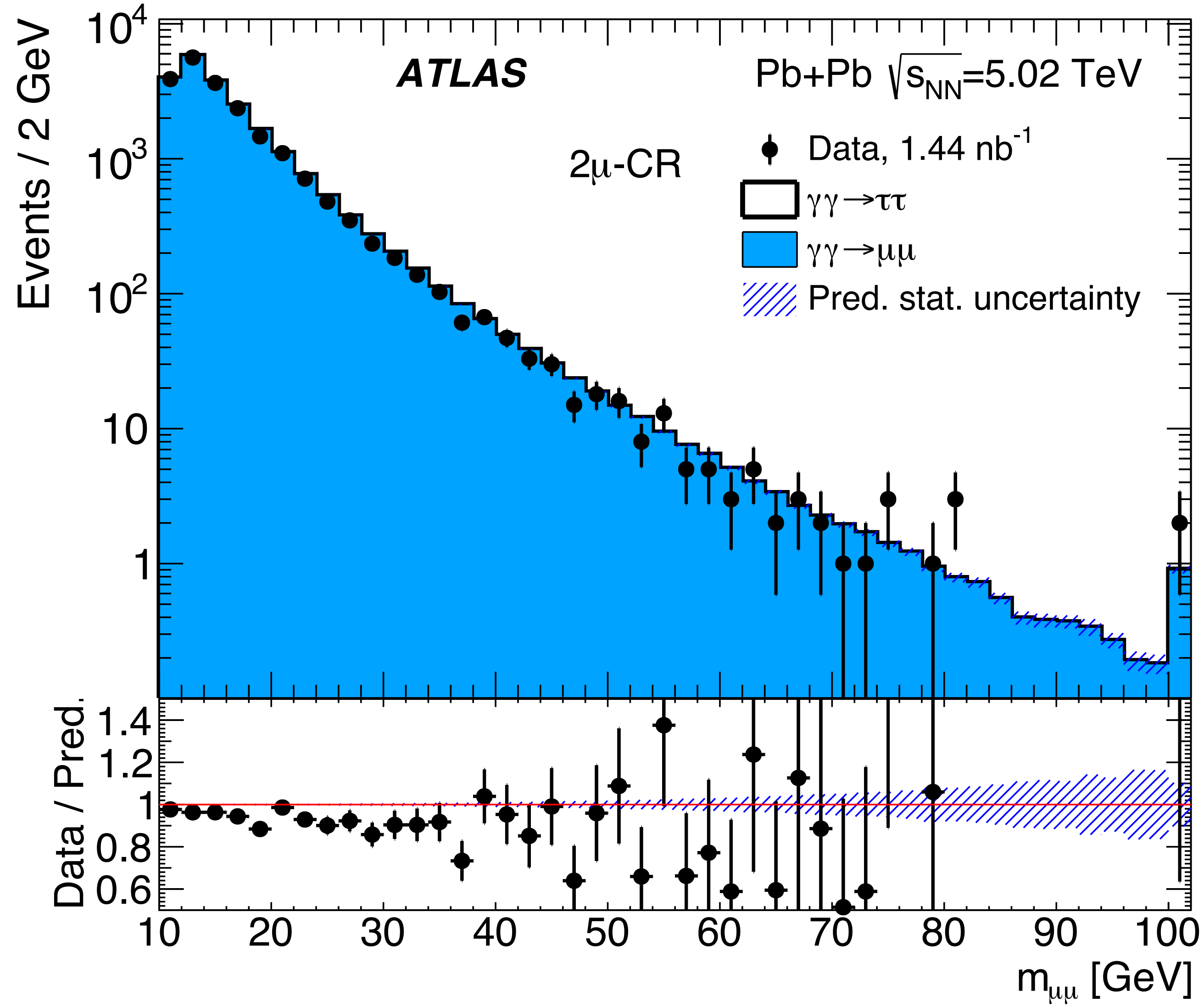




arXiv:2204.13478

Backgrounds

- Main **background contributions** from dimuon production and diffractive photonuclear interactions
- Background from **$\gamma\gamma \rightarrow \mu\mu(\gamma)$ production** estimated using **MC simulation (STARLight+Pythia8, Madgraph5),** constrained by a data CR
- Already pre-fit distributions in the 2μ-CR show good agreement of data and MC



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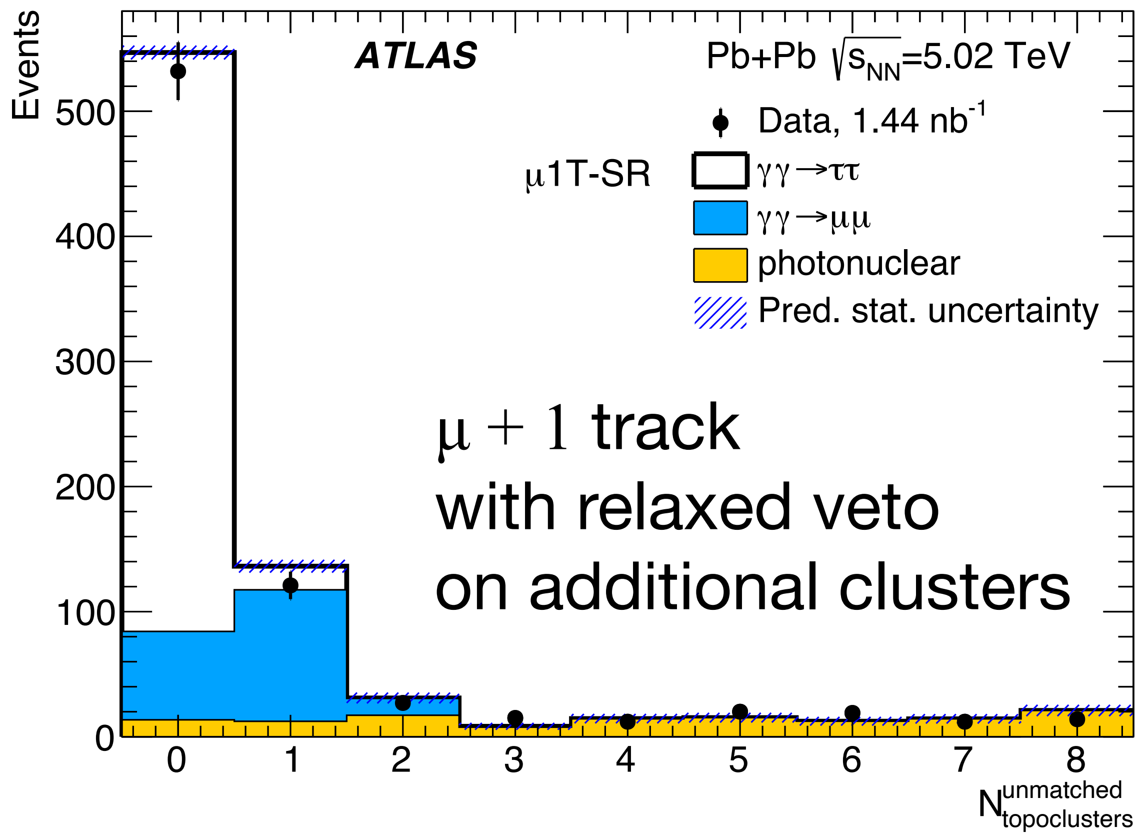
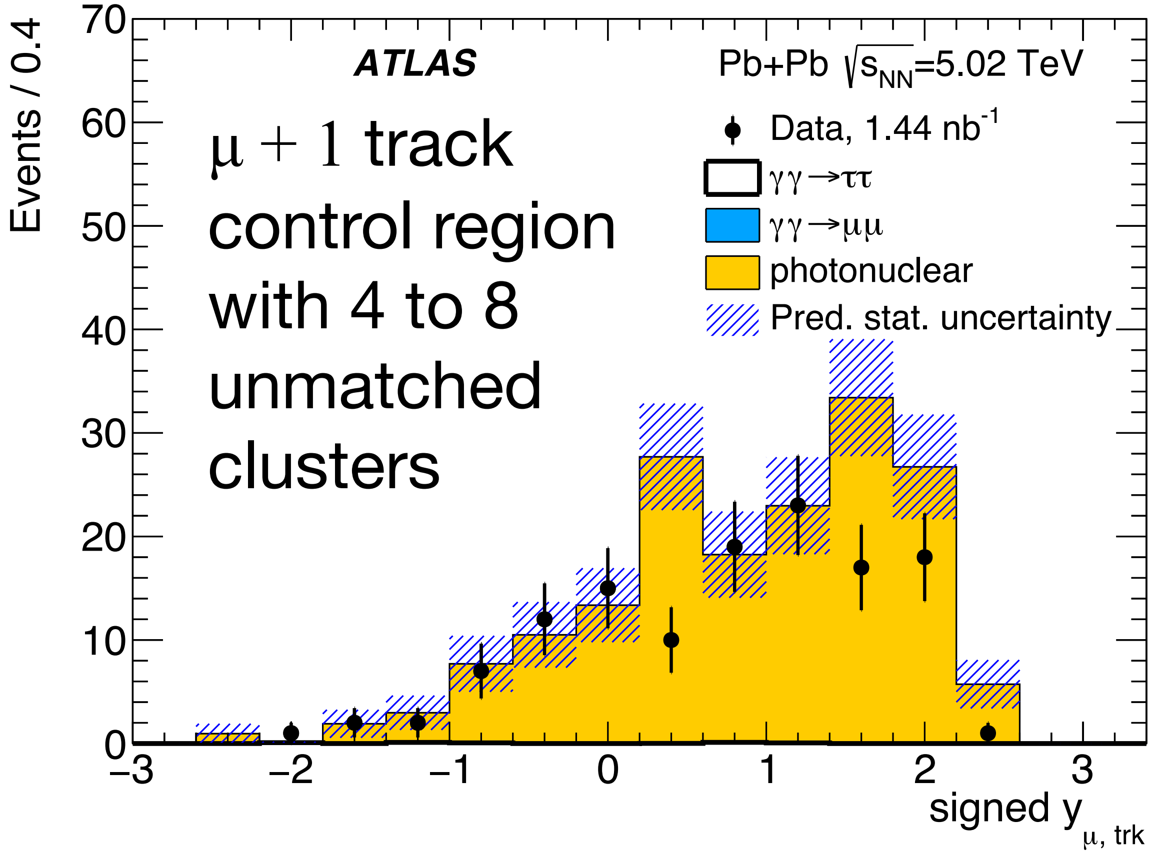
Backgrounds

- **Diffractive photonuclear** present in μ1T-SR and μ3T-SR signal regions, estimated with **data-driven** technique
  - Control regions defined with additional track with p_T < 500 MeV and allowing events from Xn0n category
  - Event yields extrapolated from control to signal region by relaxing the veto on additional (unmatched) clusters from 0 to 8
  - Normalisation done to the event yield in the region with 4 to 8 unmatched clusters



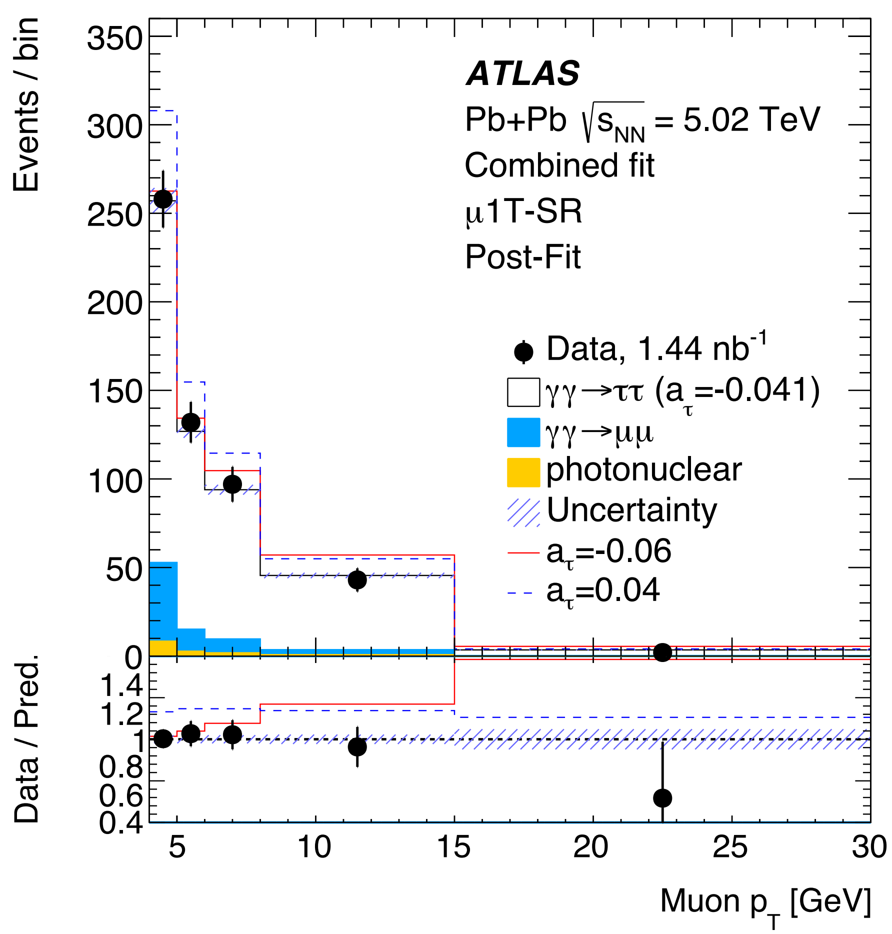


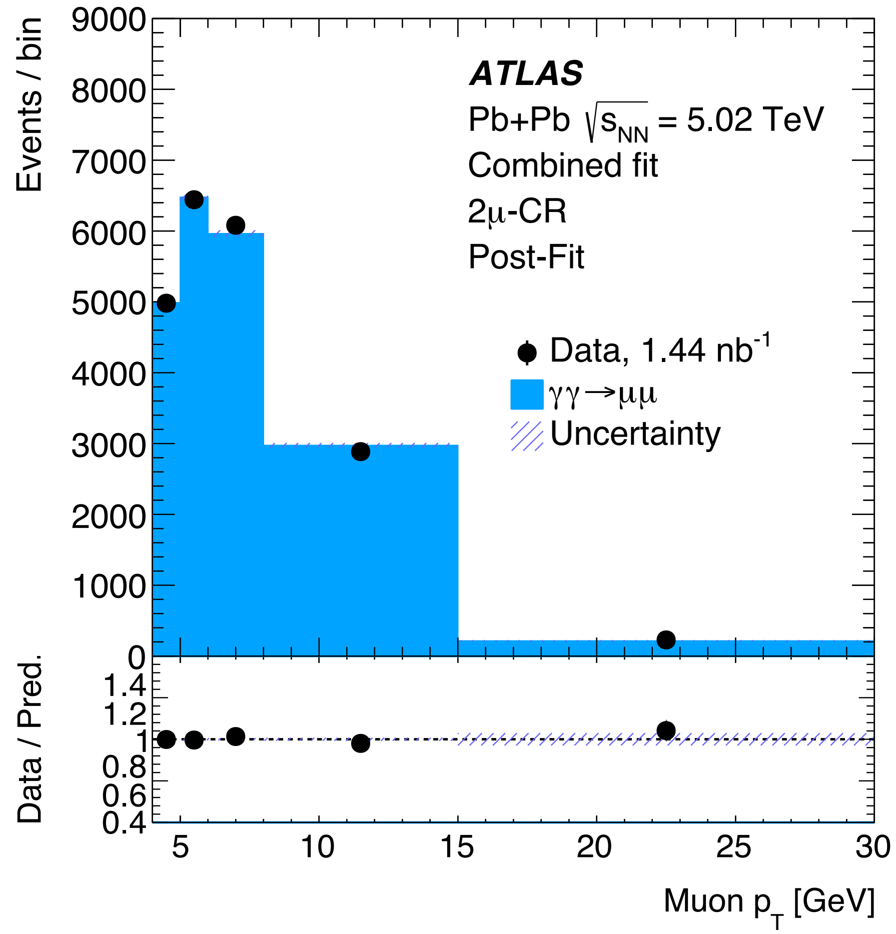
Observation of exclusive ditau production

- The $\gamma\gamma \to \tau\tau$ signal strength and a_τ value is extracted using a **profile likelihood fit** using the muon p_T distribution
- **Simultaneous fit** combining all signal regions and dimuon control region
  - Dimuon **control region** ($\gamma\gamma \to \mu\mu$ events) used to **reduce systematic uncertainty** from the photon flux

arXiv:2204.13478

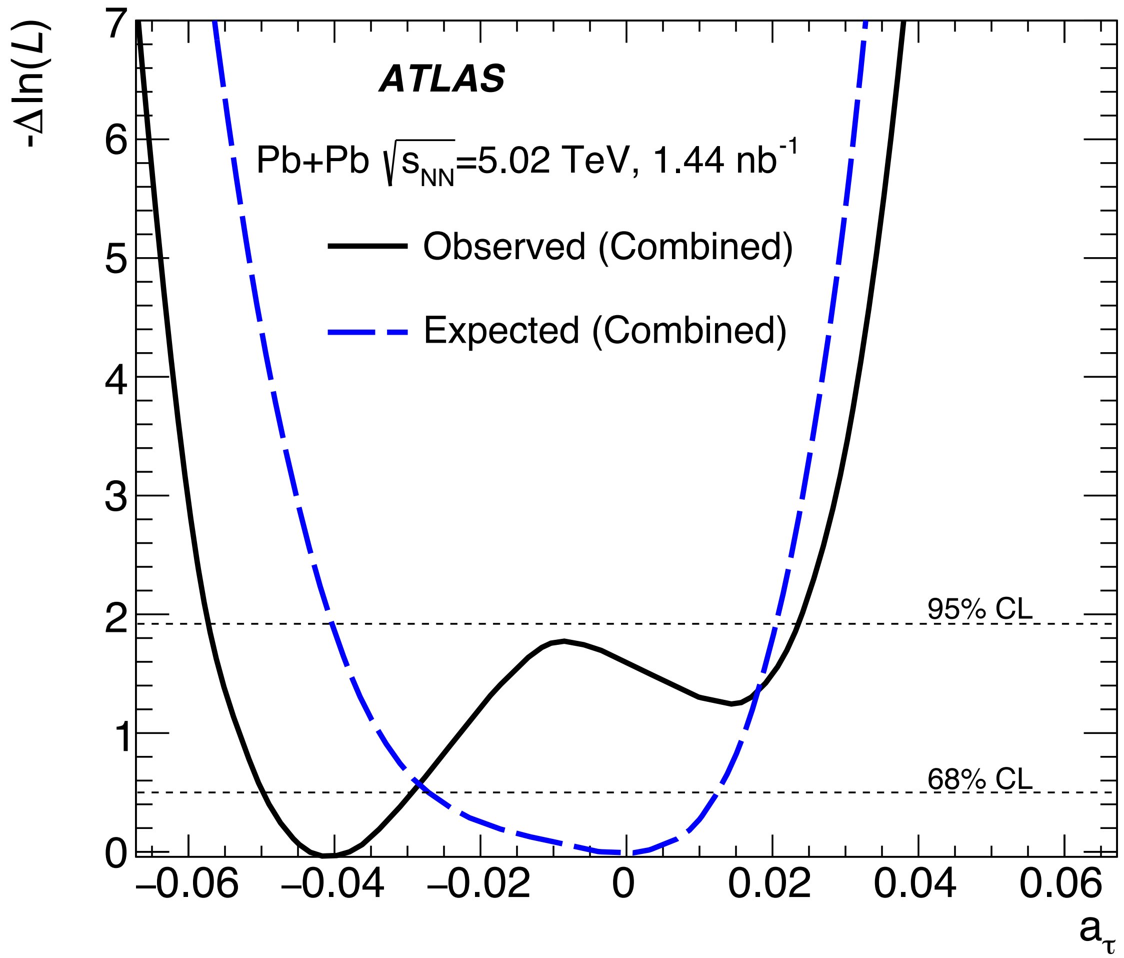
- Calculations are based on the same parameterization as was used in previous LEP measurements
- Clear observation ($\gg 5\sigma$) of $\gamma\gamma \to \tau\tau$ process

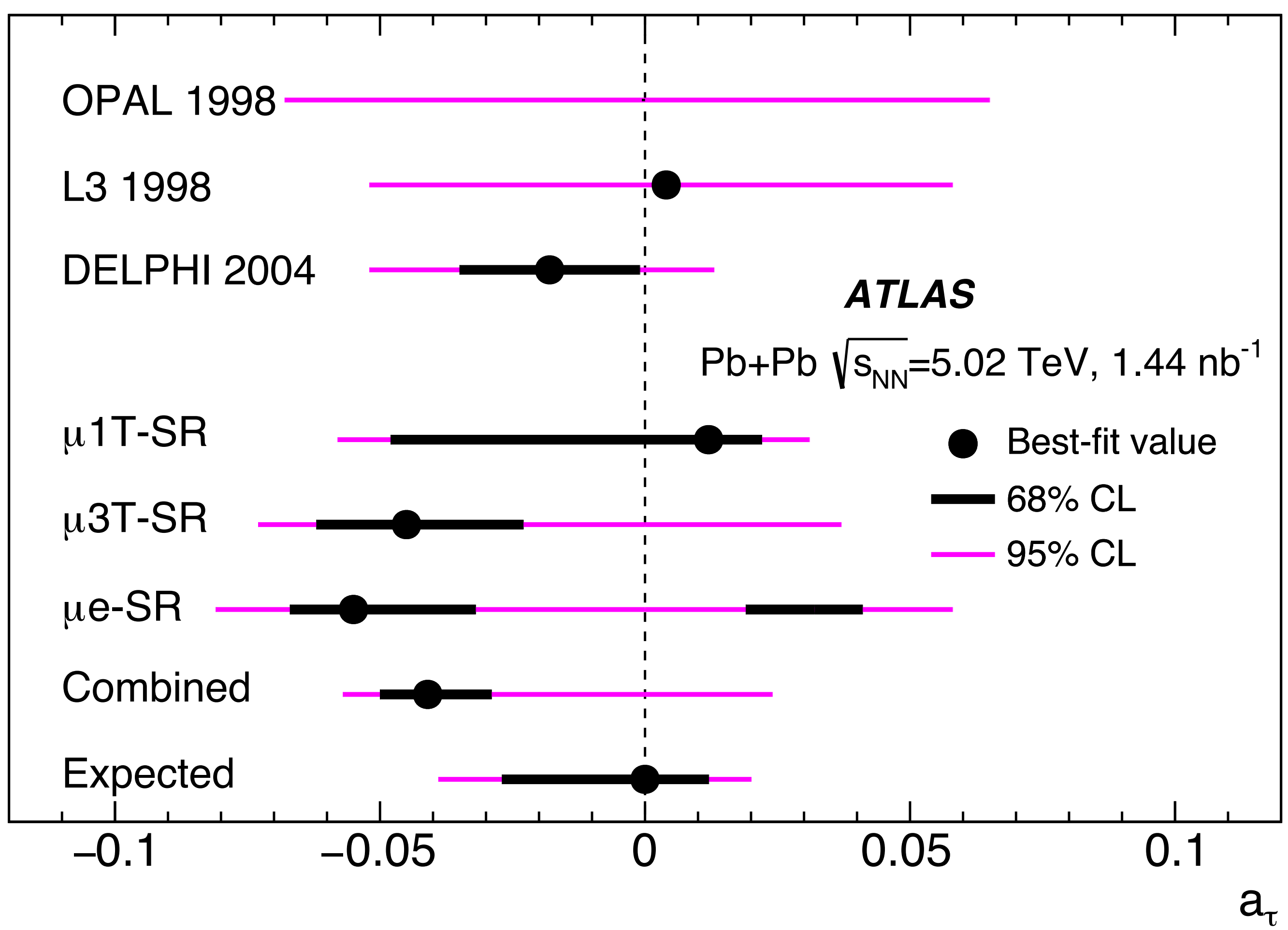




τ-lepton g–2

- Expected 95% CL limits from combined fit: $-0.039 < a_\tau < 0.020$
- The **best fit value** is $a_\tau = -0.041$, with the corresponding **95% CL interval** being **(–0.057, 0.024)**
- The result is largely limited by statistics, what will improve with Run-3 data
- Constraints similar to DELPHI (EPJ C 35 (2004) 159)





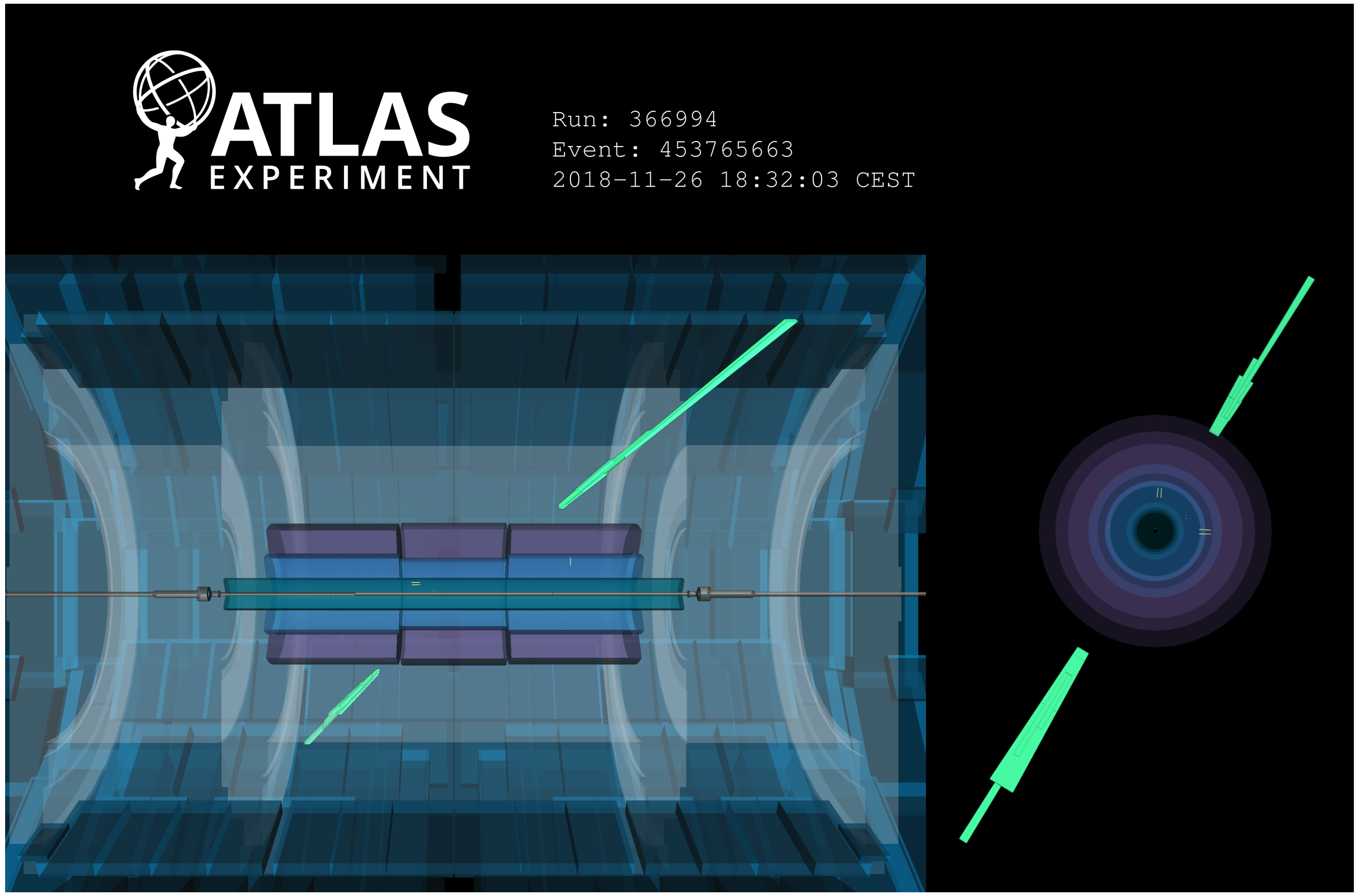
arXiv:2204.13478

$\gamma\gamma \rightarrow \gamma\gamma$

JHEP 03 (2021) 243

Light-by-light scattering

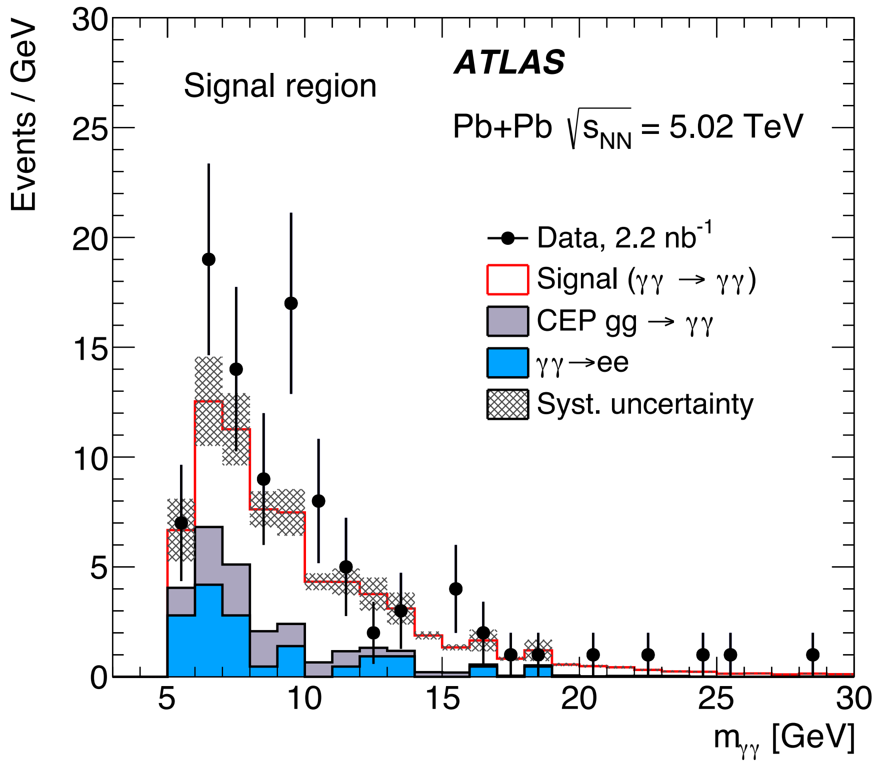
- **Light-by-light (LbyL) scattering** is a rare Quantum Electrodynamics (QED) process
- Several LbyL measurements done using Pb+Pb collision data at 5.02 TeV, collected by LHC experiments
- ATLAS: 2015: Nature Physics 13 (2017) 852, 2018: Phys. Rev. Lett. 123 (2019) 052001 **2015+2018: JHEP 03 (2021) 243**
- CMS: 2015: Phys. Lett. B 797 (2019) 134826
- Signal selection:
  - Two photons with $E_T > 2.5$ GeV, identified with dedicated NN ID algorithm)
  - Diphoton mass above 5 GeV, low diphoton p_T, low diphoton acoplanarity: $1 - |\Delta\phi|/\pi < 0.01$
  - Veto on any extra low-p_T tracks

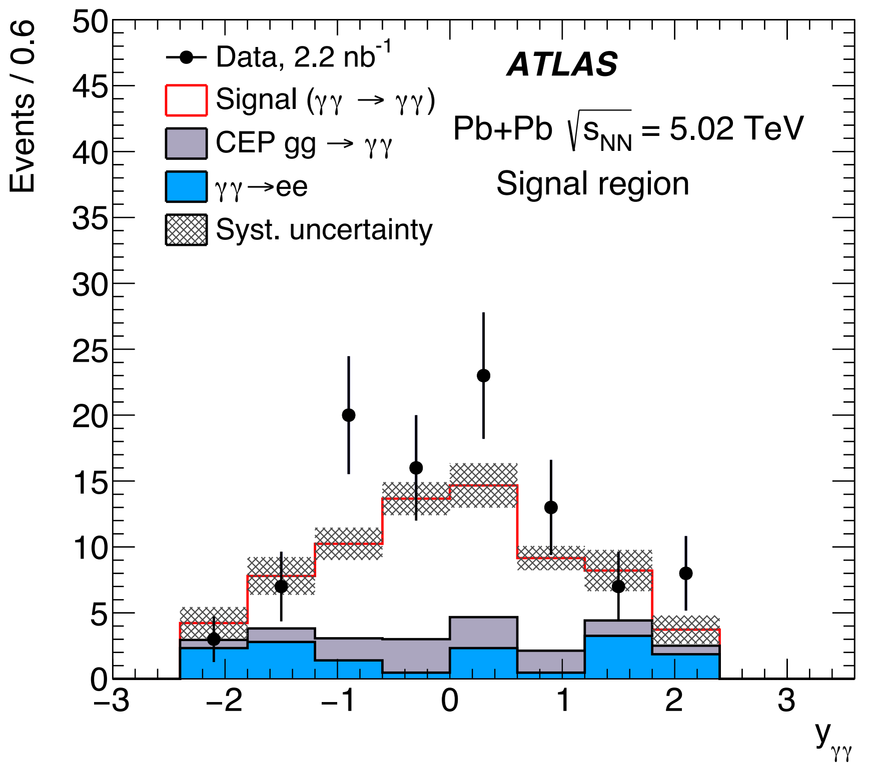


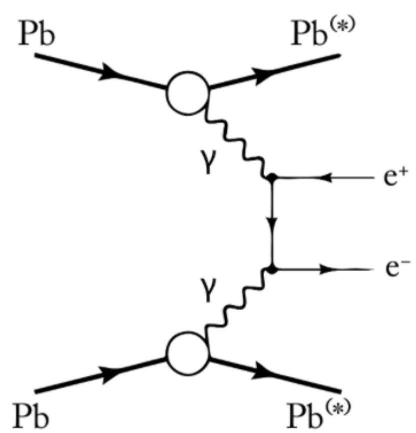
JHEP 03 (2021) 243

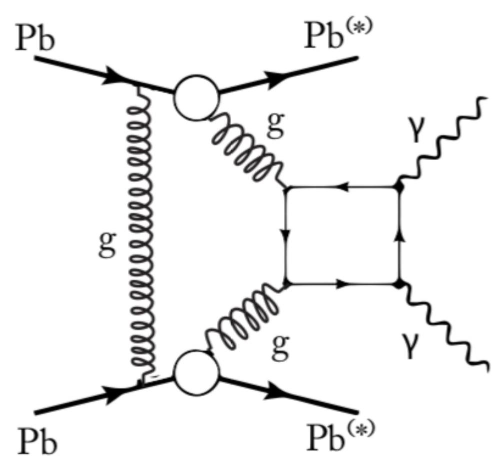
Backgrounds

- Various background sources considered, the largest contributions 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





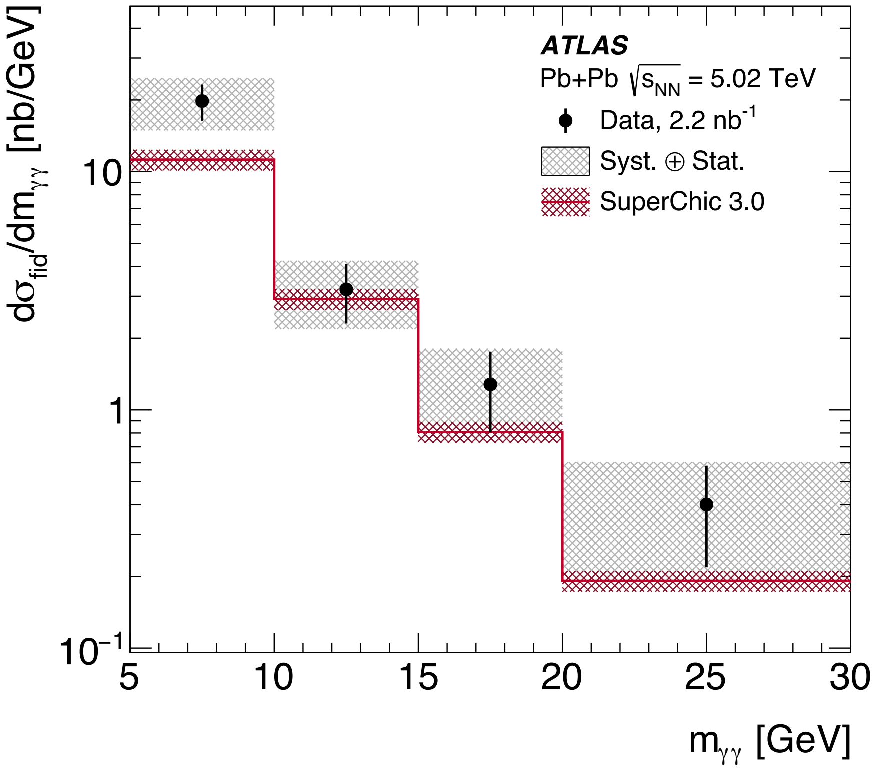


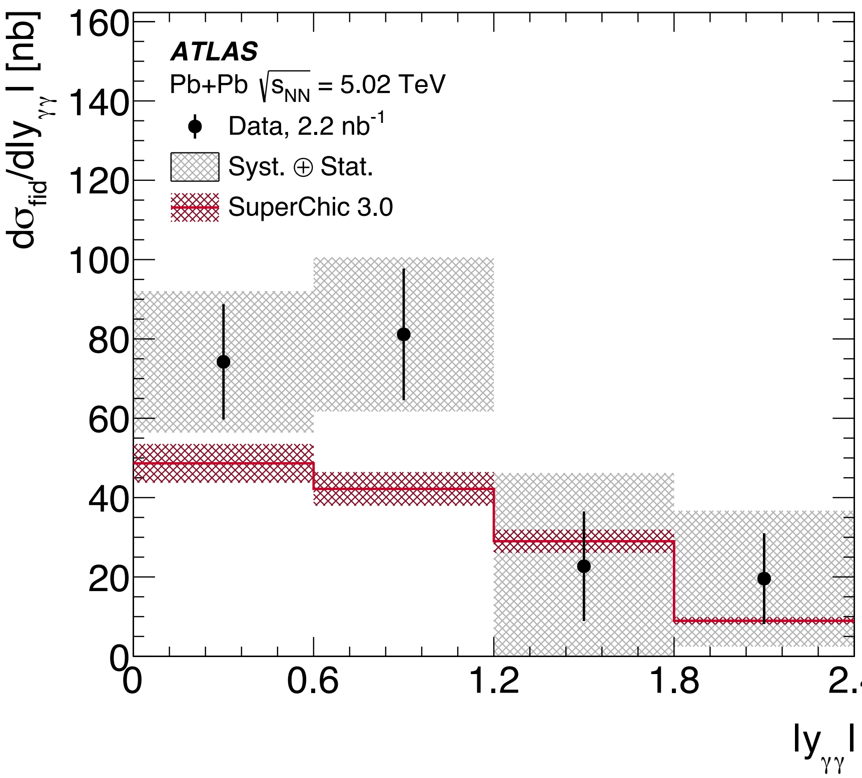


JHEP 03 (2021) 243

Differential cross sections

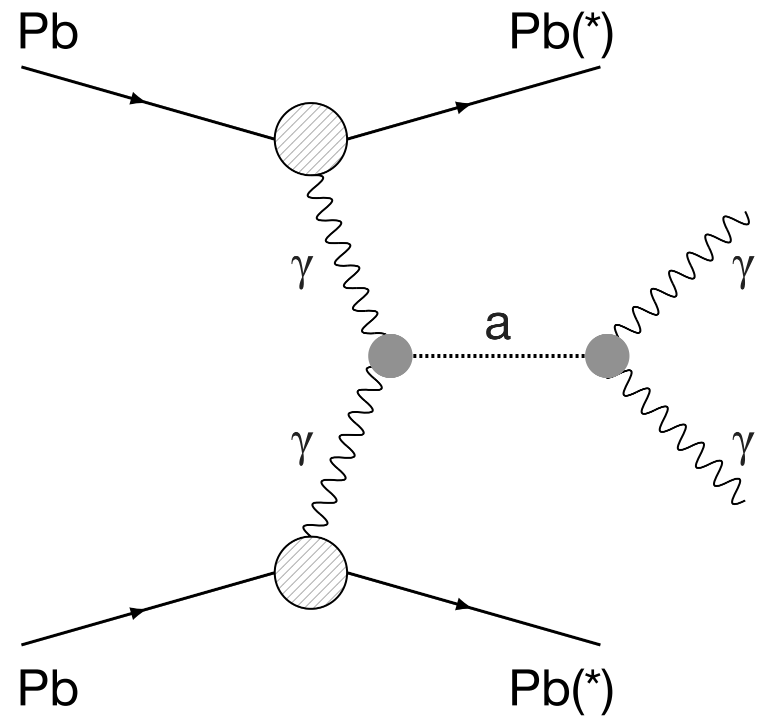
- Cross-section is measured in a fiducial phase space, defined by the requirements reflecting event selection
- The measured **integrated fiducial cross-section** is **σ_{fid} = 120 ± 17(stat.) ± 13(syst.) ±4 (lumi.) nb**, while the predicted values are 80 ± 8 nb (Szczurek et al.) and 78 ± 8 nb (SuperChic3)
- Differential fiducial cross-sections are **unfolded to particle level** in the fiducial phase space to correct for bin migrations due to detector resolution effects
- The unfolded differential fiducial cross-sections are compared with the predictions from SuperChic v3.0
- **No significant differences** between predictions and data are seen





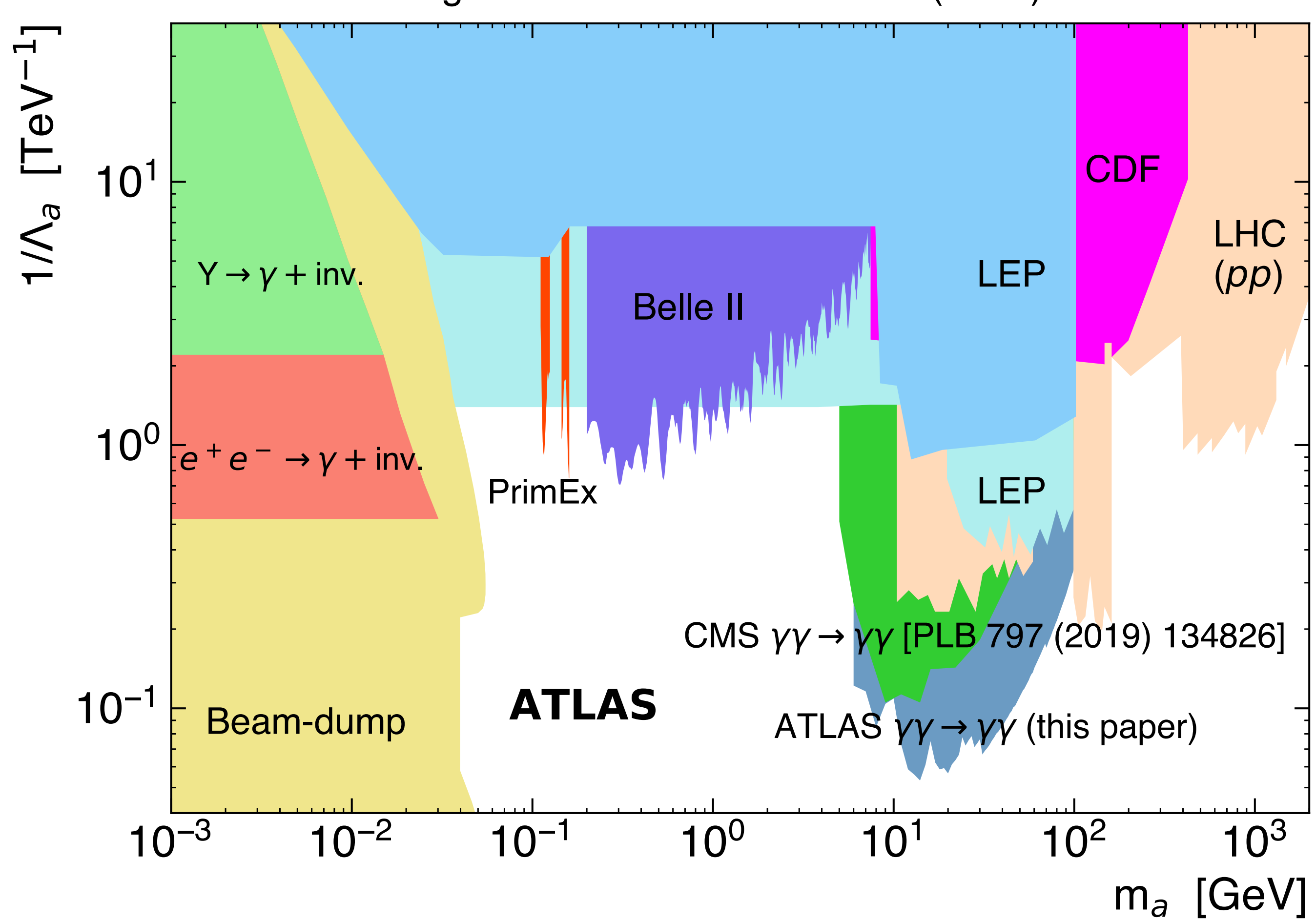
JHEP 03 (2021) 243

ALP limits



- Axion-like particles (ALP) are **hypothetical particles** that appear in many theories with a spontaneously broken global symmetry
- ALPs may **decay to two photons,** what might be visible as an excess in $m_{\gamma\gamma}$ distribution
- Simulated LbyL events are normalized to the data yield, after subtracting $\gamma\gamma \rightarrow e^+e^-$ and CEP $gg \rightarrow \gamma\gamma$ contributions and excluding the mass search region
- ALP contribution is fitted individually for every mass bin
- **No significant deviation** from the **background-only hypothesis** is observed
- The result is used to estimate the upper limit on the **ALP cross-section** and **ALP coupling** $1/\Lambda_a$ at 95% confidence level

Existing constraints from JHEP 12 (2017) 044



JHEP 03 (2021) 243

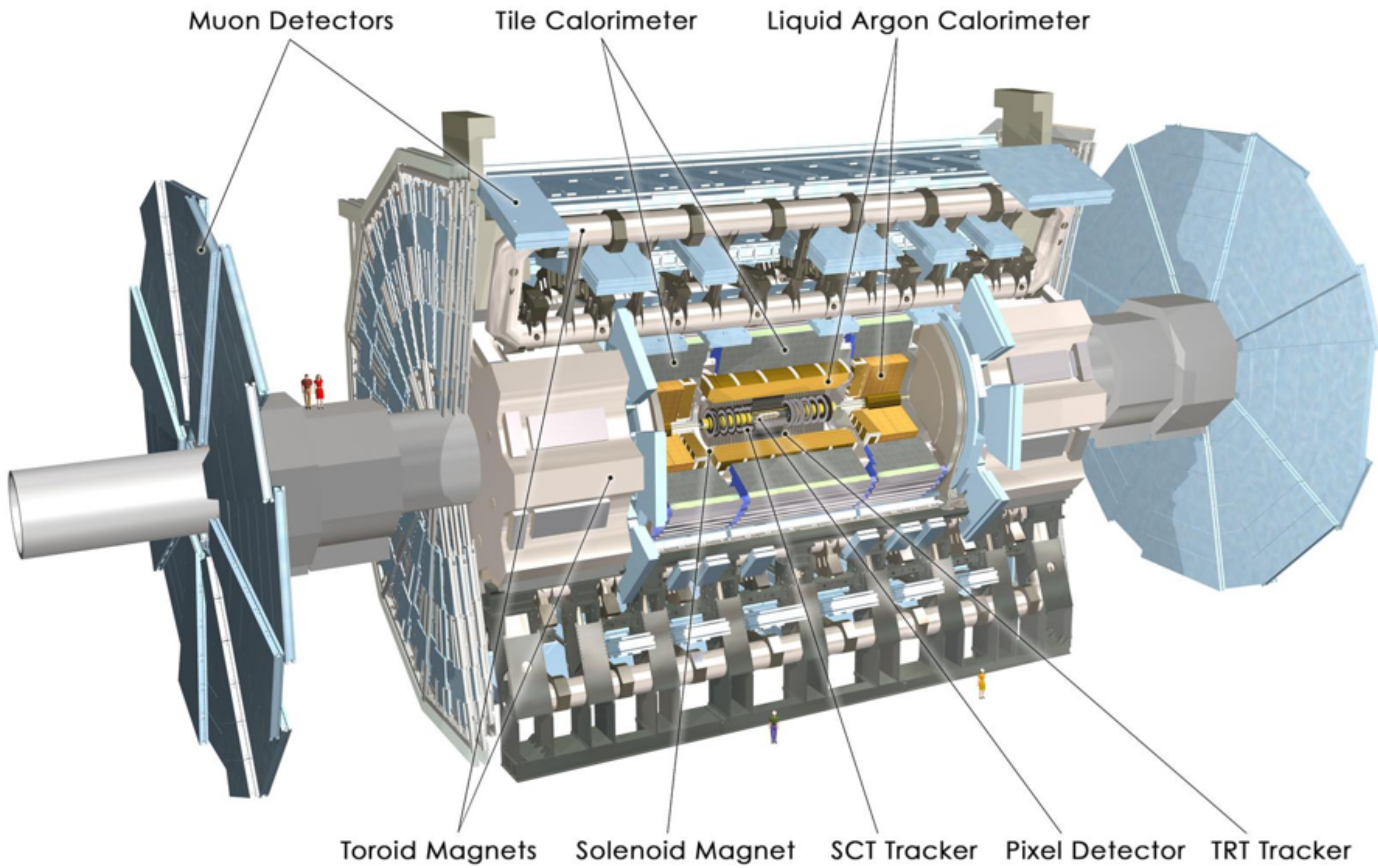
Summary

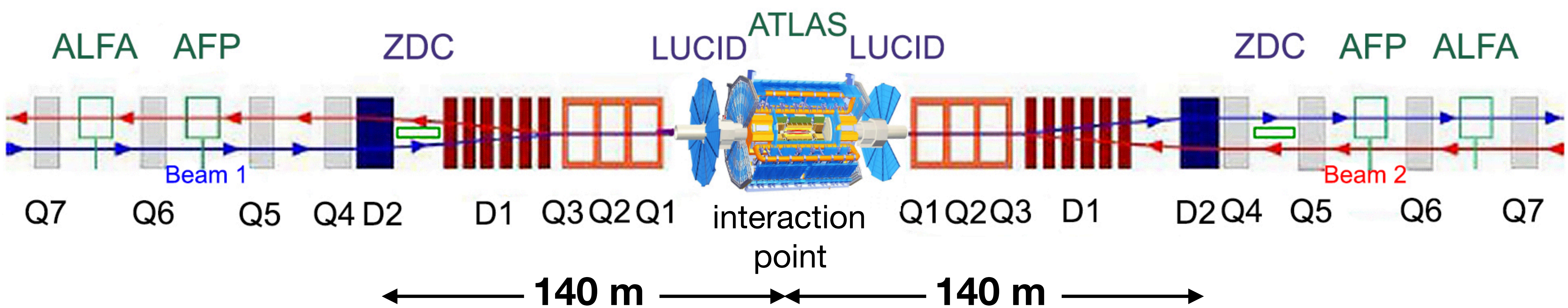
- The $\gamma\gamma \rightarrow \tau\tau$ production was clearly observed by ATLAS in UPC Pb+Pb collisions
- The measurement of the **τ-lepton anomalous magnetic moment is competitive** with previous measurements
  - Improvement in precision expected with more data
- **Light-by-light scattering** was measured using data from **Pb+Pb collisions** at 5.02 TeV from 2015 and 2018 collected with the ATLAS detector
- **Ratio** of the measured cross-section **to the SM predictions** is 1.50 ± 0.32 (Szczurek et al.) and 1.54 ± 0.32 (SuperChic3)
- The **exclusion limits** for ALP cross-section and coupling were obtained for the mass range of $6 < m_a < 100$ GeV

Backup

ATLAS detector

- Large general-purpose detector with almost 4π coverage
- $\eta = -\ln(\tan(\theta/2))$
- Inner detector $|\eta|<2.5$
- Muon system $|\eta|<2.7$ (trig. 2.4)
- Calorimetry out to $|\eta|<4.9$
- Zero-Degree-Calorimeters capture neutral particles with $|\eta|>8.3$





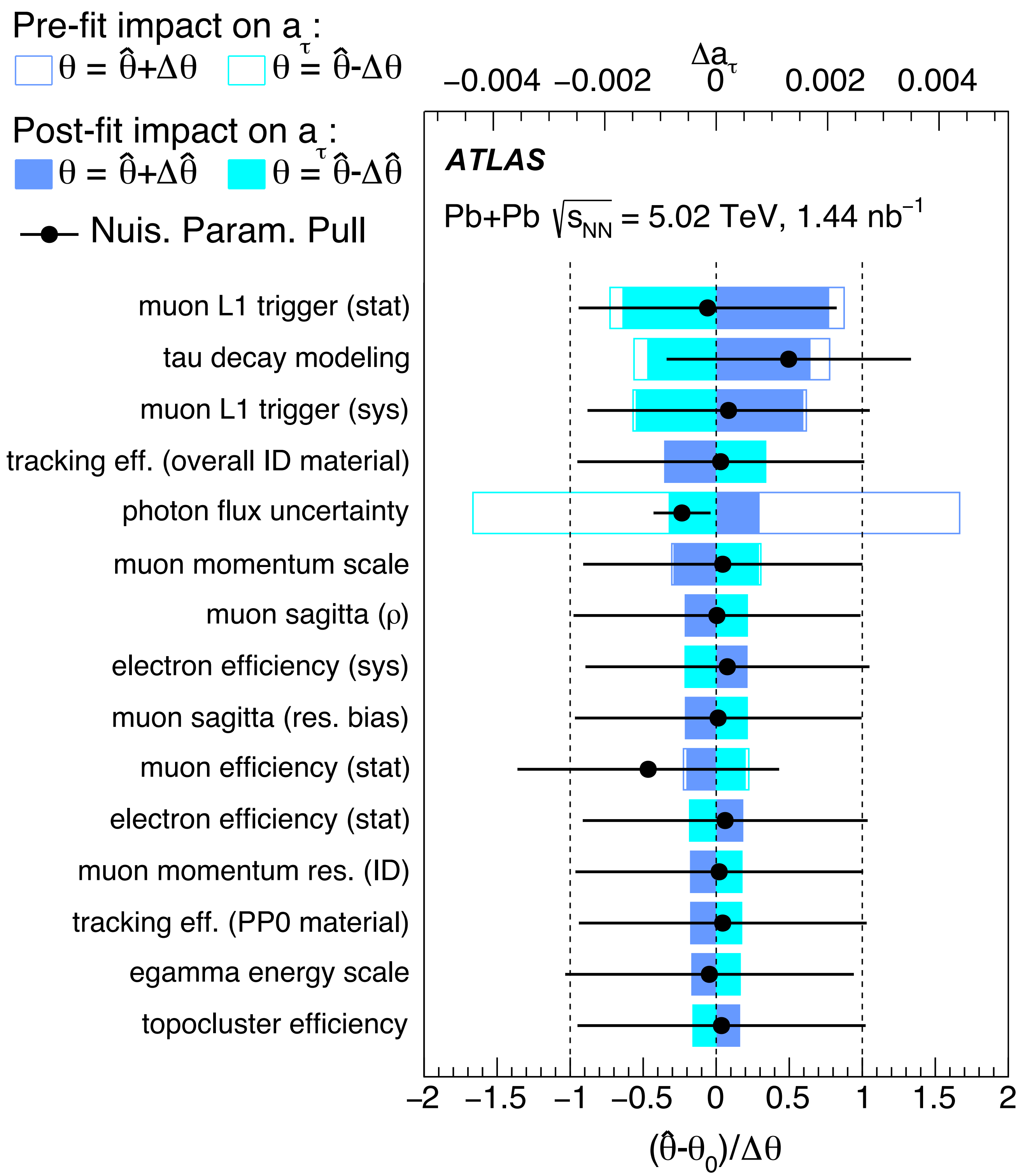
γγ→ττ cutflow in MC

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
$p_{\text{T}}^{\mu,\text{trk},\text{clust}} > 1$ GeV	462
$A_{\phi}^{\mu,\text{trk}} < 0.4$	459

Requirement	Number of $\gamma\gamma \to \tau\tau$ events
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

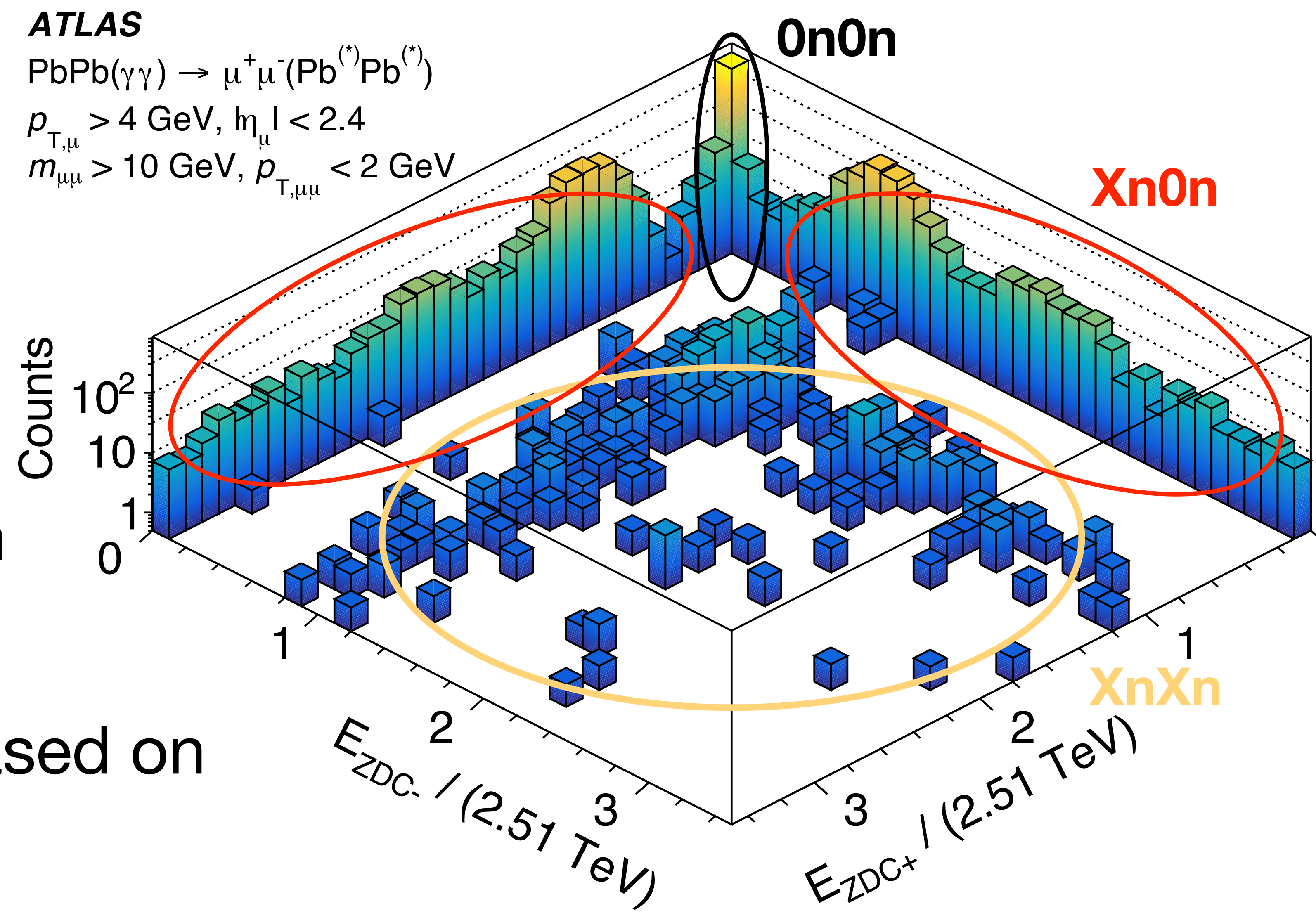
τ-lepton g–2 , systematic uncertainties

- Approximately 80 **nuisance parameters** (statistical and systematic uncertainties) are included in the fit
- Many of them correlated between signal and control region
  - Using dimuon **control region** ($\gamma\gamma \rightarrow \mu\mu$ events) significantly **reduced systematic uncertainty** from the photon flux



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