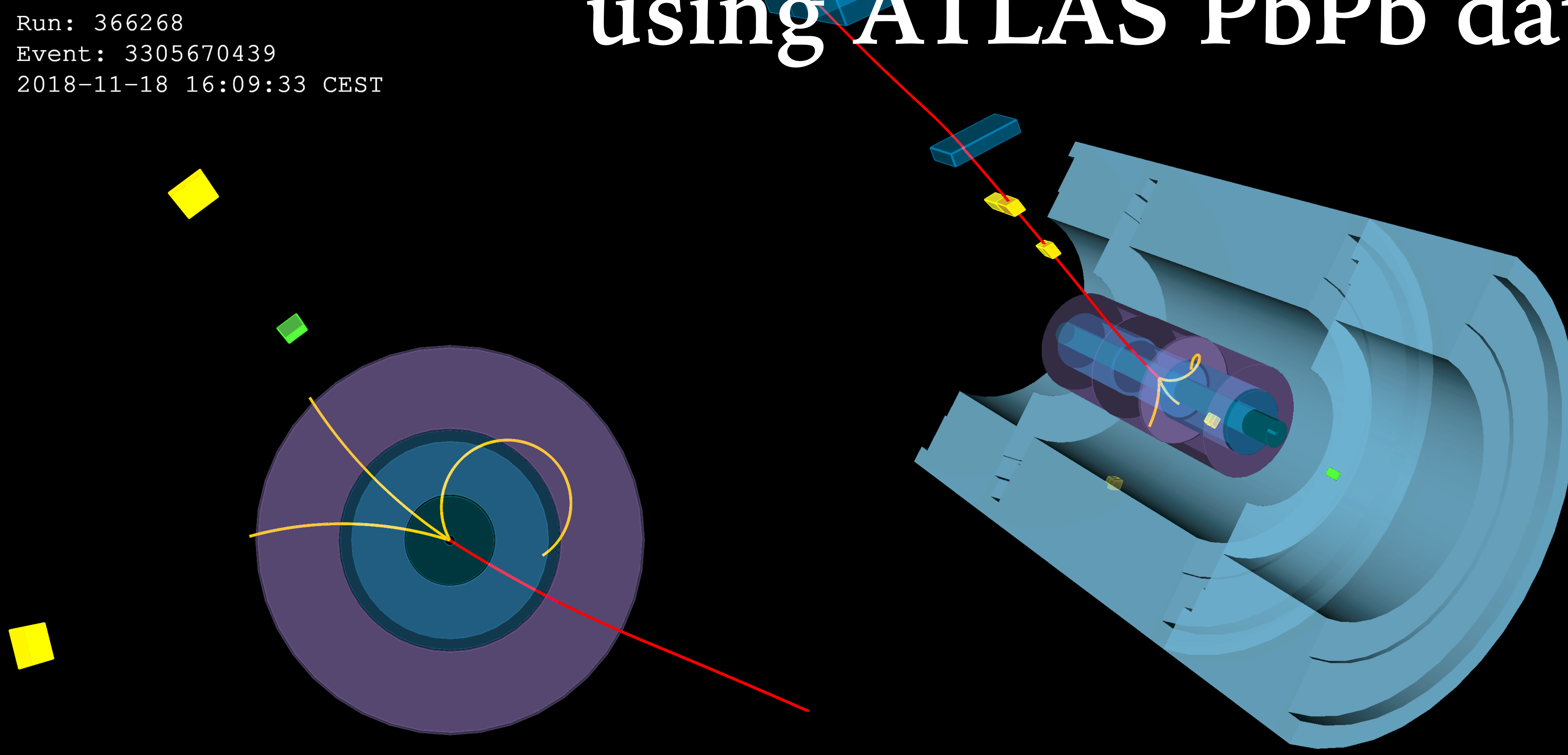
ATLAS EXPERIMENT

Measuring of tau g-2 using ATLAS PbPb data



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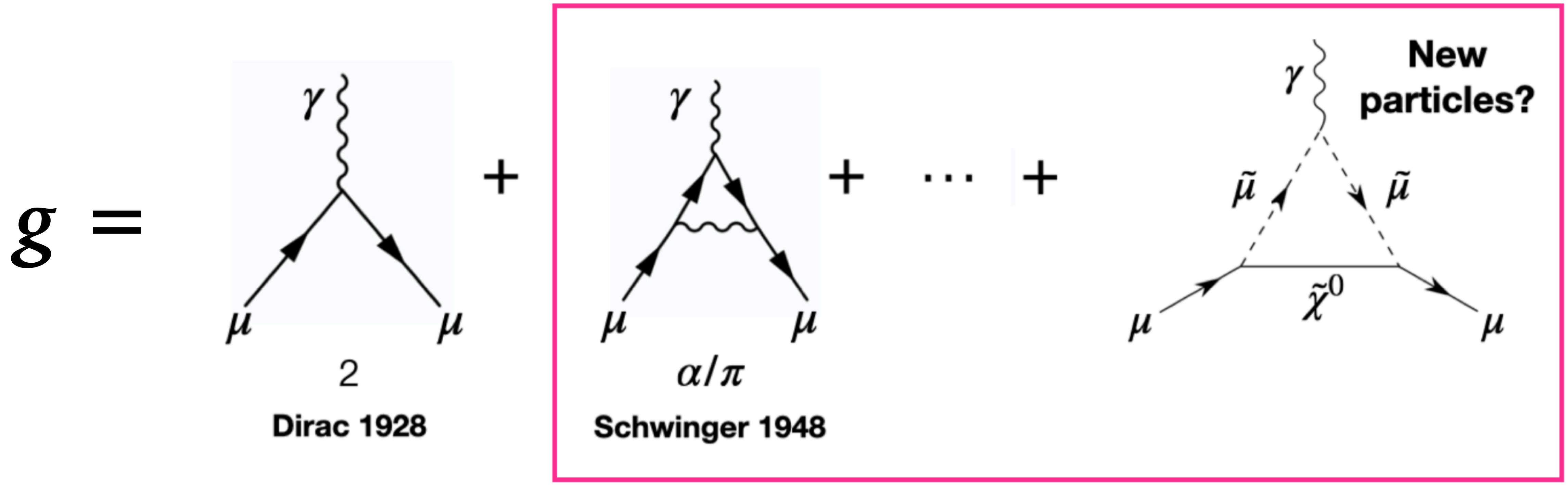
EMMI Forward Physics in ALICE 3
Heidelberg, 20 Oct. 2023

Klaudia Maj
AGH University

Introduction to tau g-2

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 correction lead to g≠2



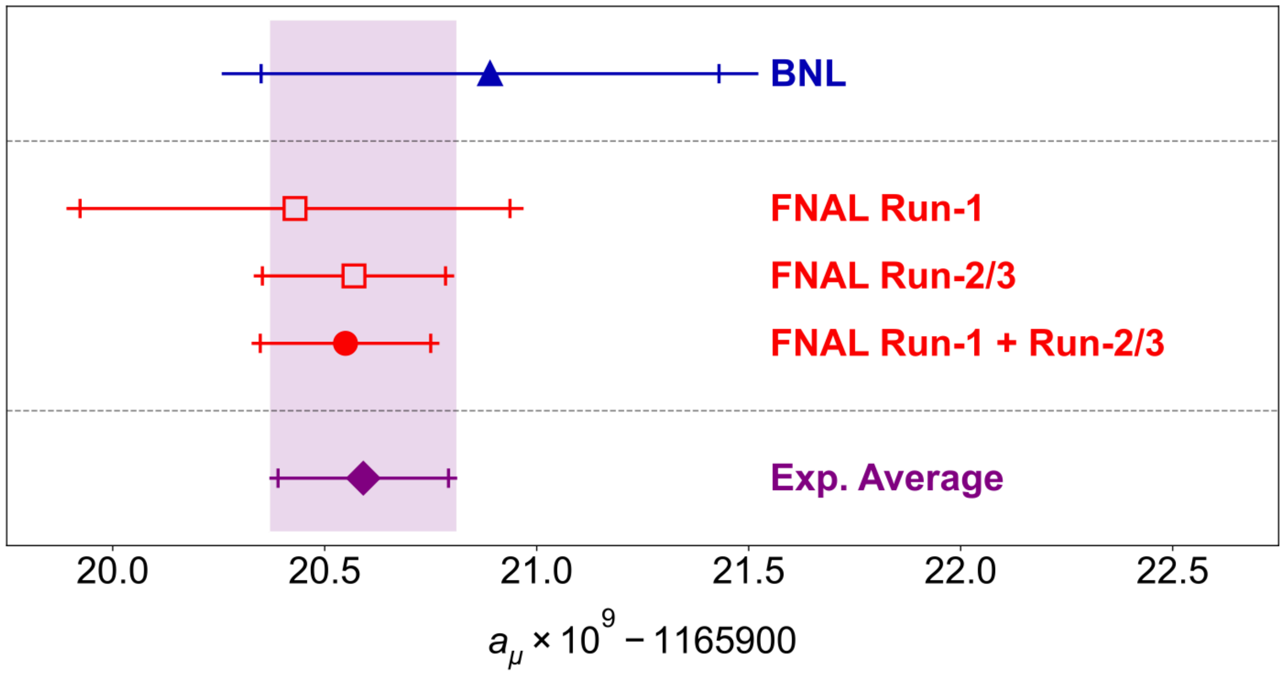
Deviations of g-factor from 2 measured with lepton anomalous magnetic moment:

$$a_l = \frac{(g-2)_l}{2}$$

Lepton magnetic moments

Electron g-2:
10^{-8} precision, **2.5*σ*** discrepancy

Muon g-2:
10^{-7} precision, **~5*σ*** discrepancy
(not yet conclusive)



→ Tested extremely precisely for *e* and *μ*

Muon g-2 Collaboration, 2023
arxiv: 2308.06230

What about the tau?

Do photons interact equally with all lepton generations?

→ Short tau lifetime 10^{-13} s

→ Extremely challenging experimentally!

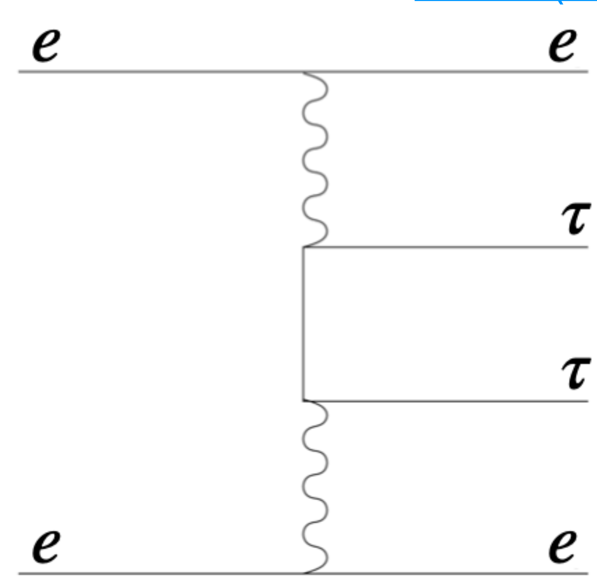
Electron: Odom et al PRL (2006) Bouchendira et al PRL (2011) Aoyama et al PRL (2012) Parker et al Science (2018) Morel et al Nature 2020

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

DELPHI results on a_τ

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

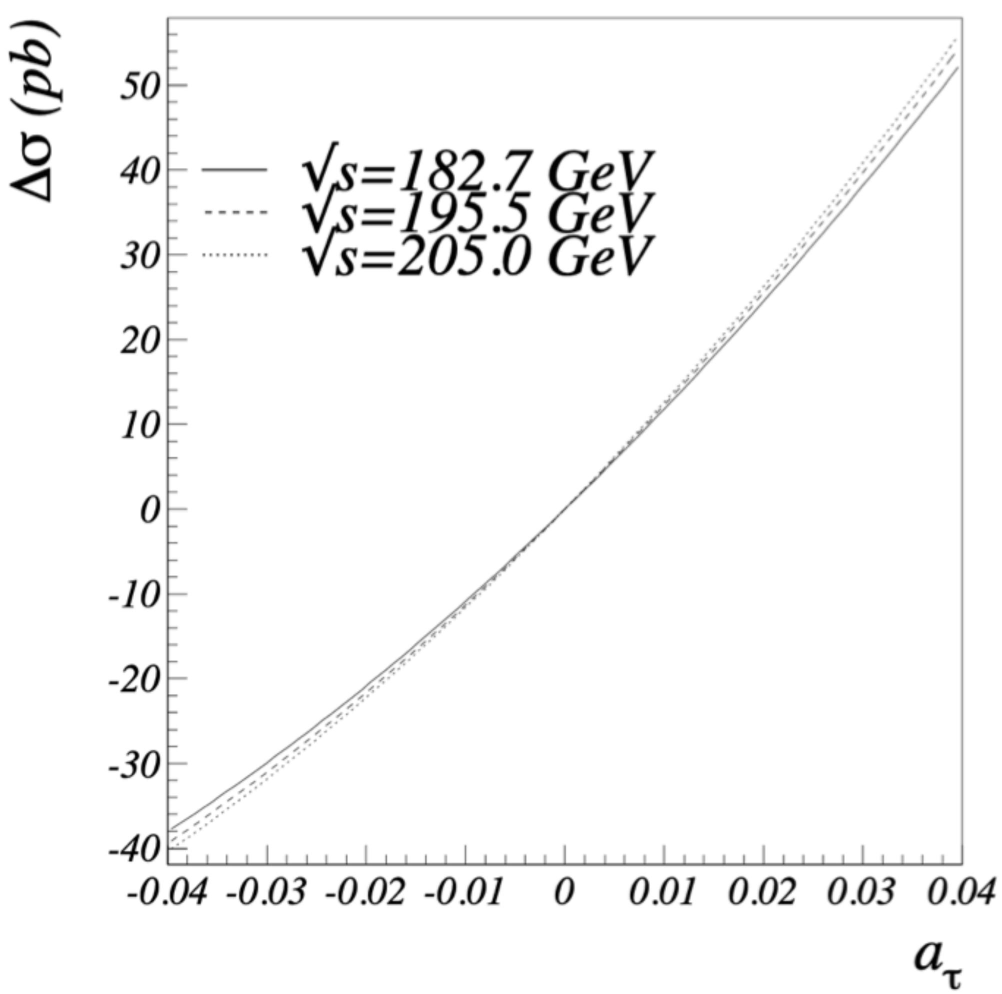
DELPHI Collaboration EPJC (2004)



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

Photo production of tau pairs

Idea: Measure cross-section, sensitive to a_τ



Limited by experimental uncertainty

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

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

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

Exp: DELPHI Collaboration EPJC (2004)

Theory: Eidelman& Passera MPLA (2007)

Tau magnetic moments

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

Potential to be most precise single-experiment measurement

Follow approach outline in:

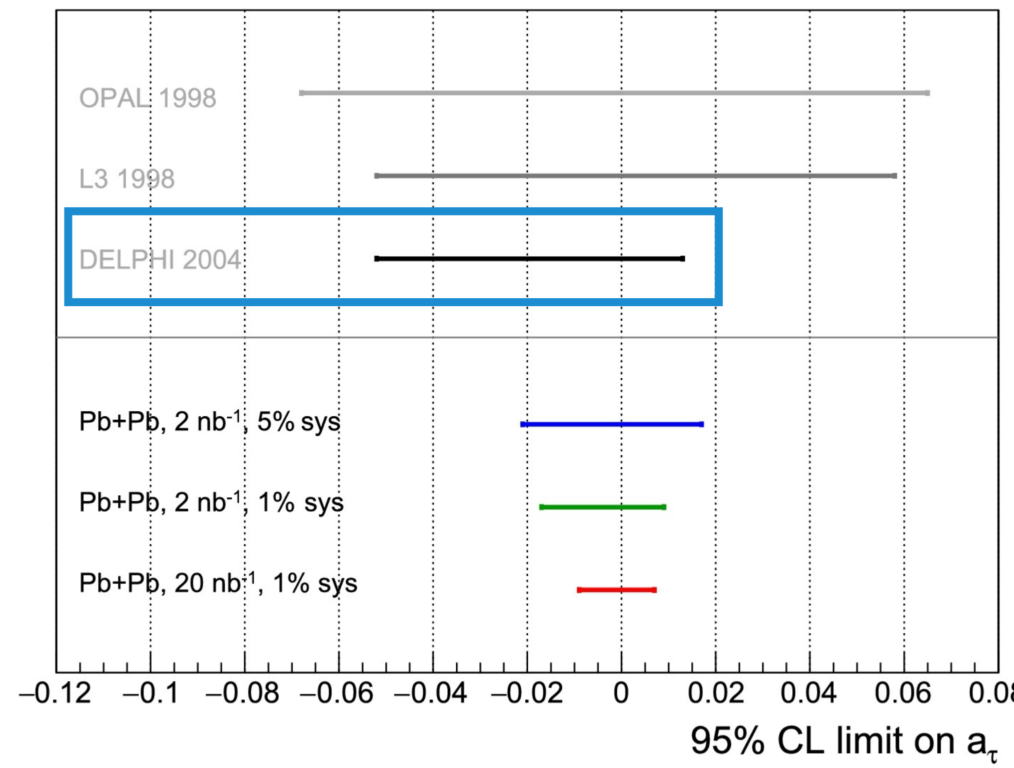
Dyndał, Kłusek-Gawęda, Szczurek, Schott PLB (2020)

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)

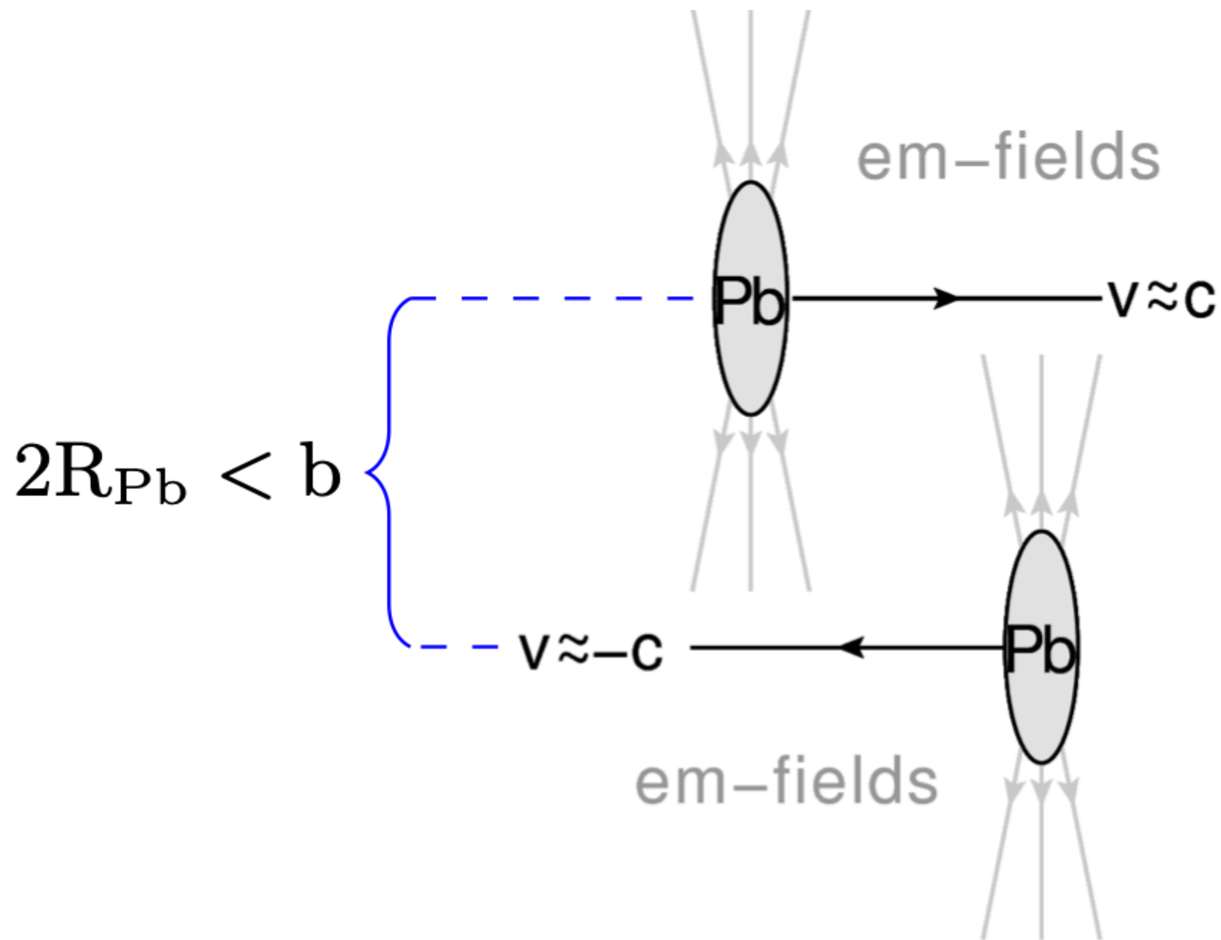
Aguila, Cornet, Illana PLB (1991)

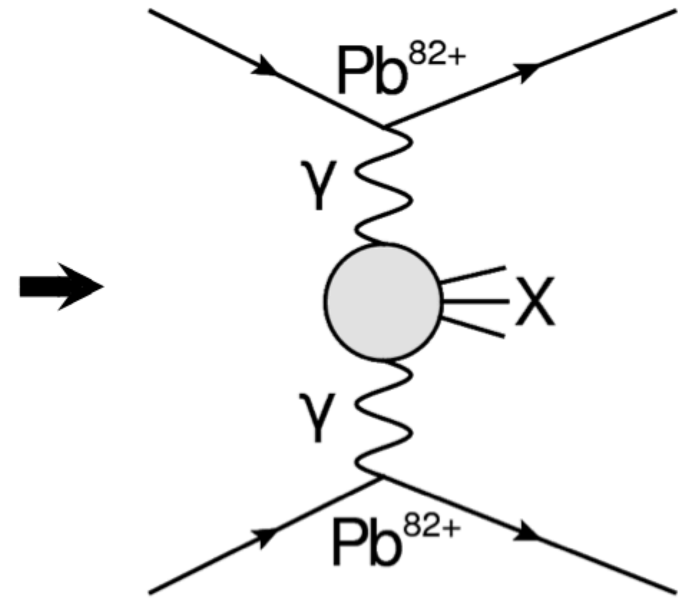
Physics Letters B
Volume 271, Issues 1–2, 14 November 1991, Pages 256-260

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]

Ultraperipheral heavy-ion collisions





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

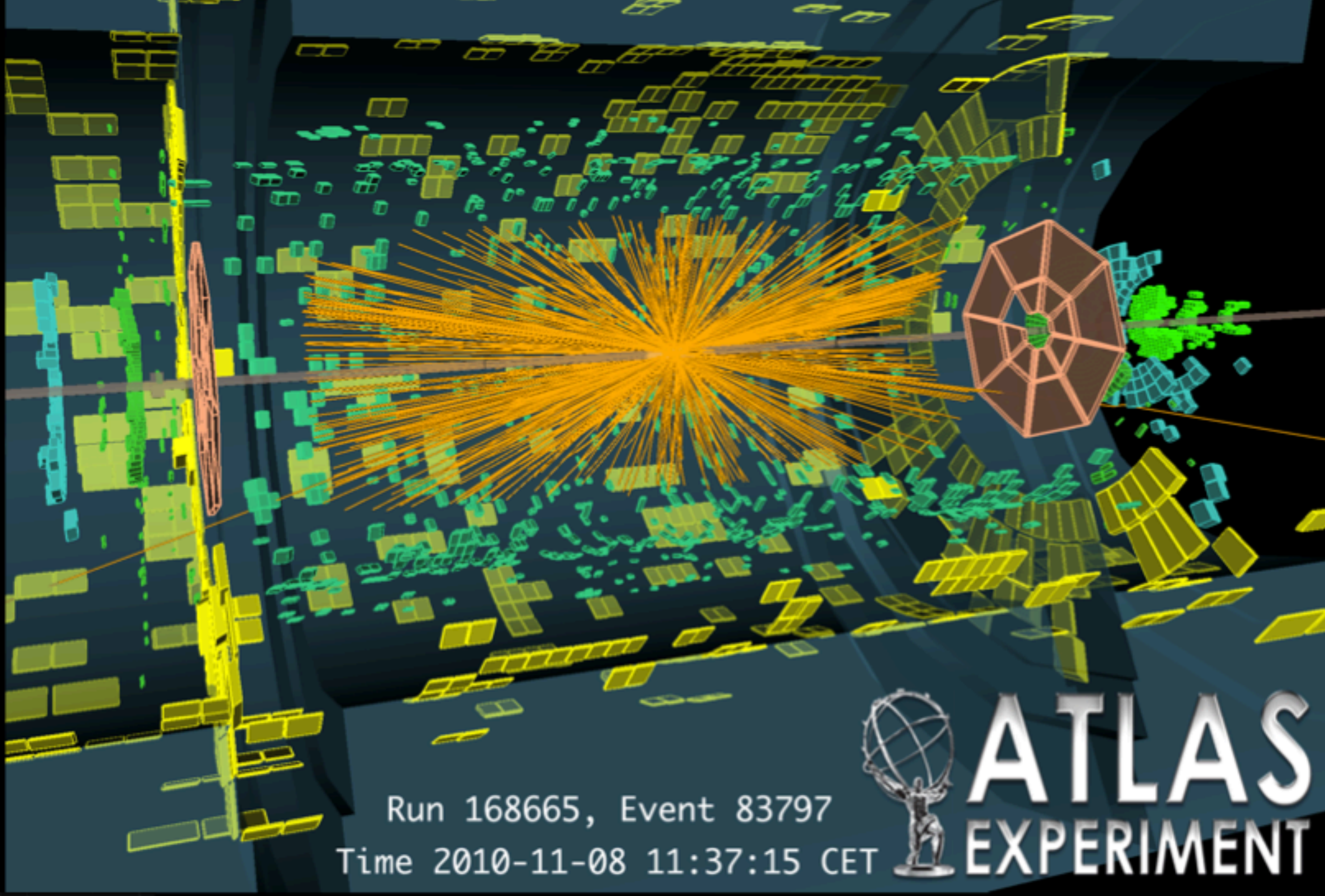
Equivalent photon flux scales with Z^2

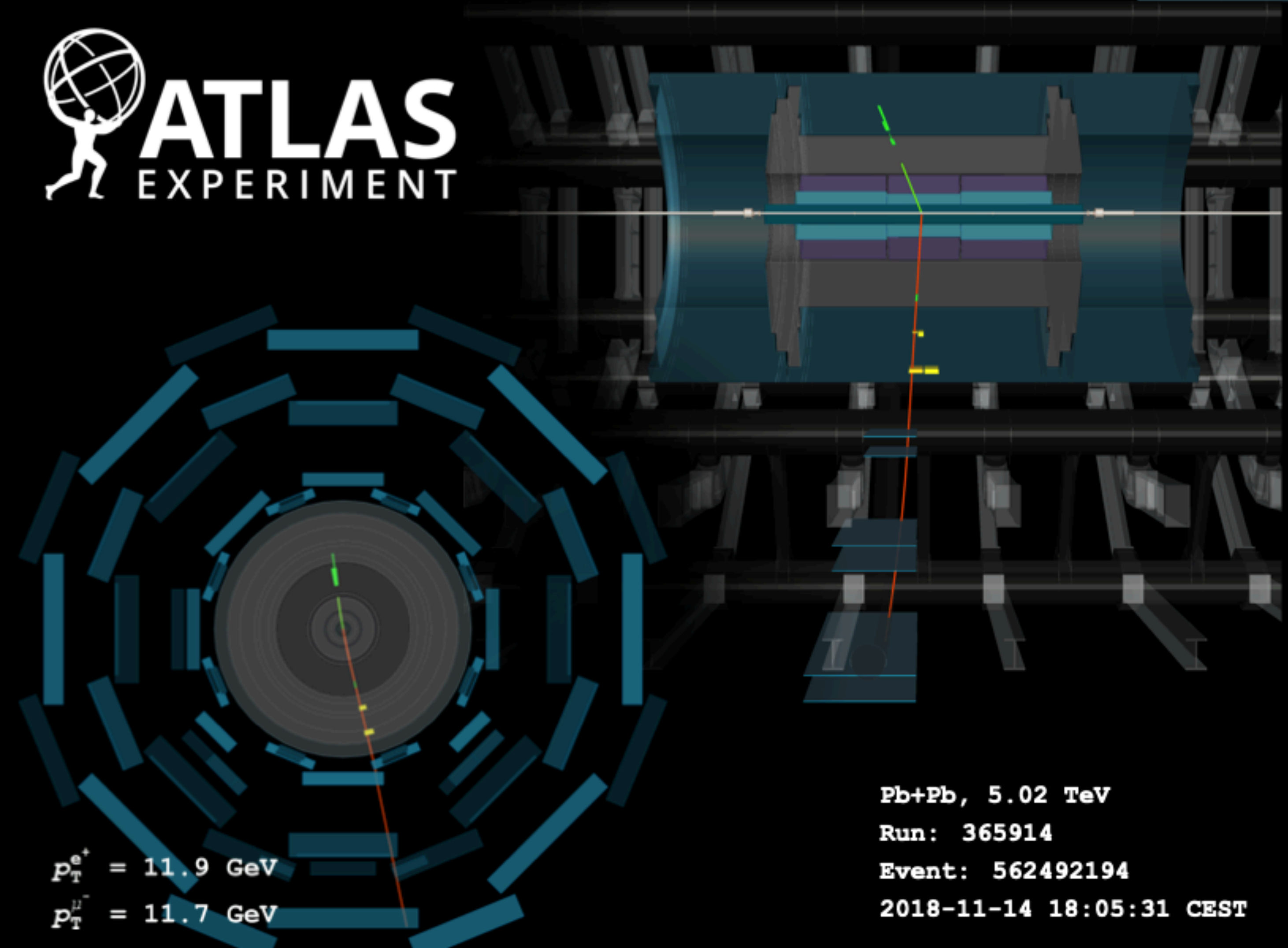
[Fermi, Nuovo Cim. 2 (1925) 143]
[Weizsacker, Z. Phys. 88 (1934) 612]
[Williams, Phys. Rev. 45 (10 1934) 729]

→ 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



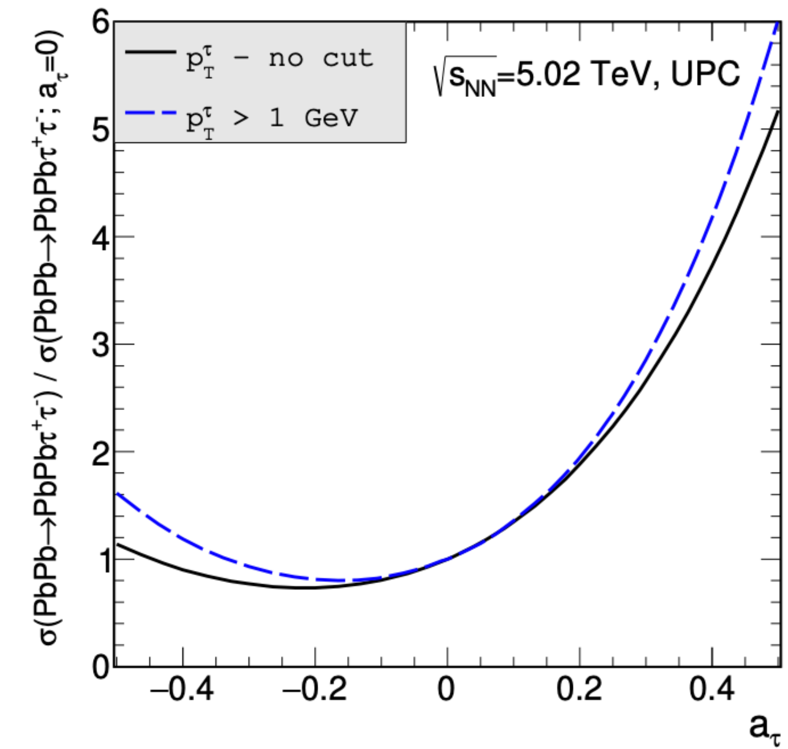


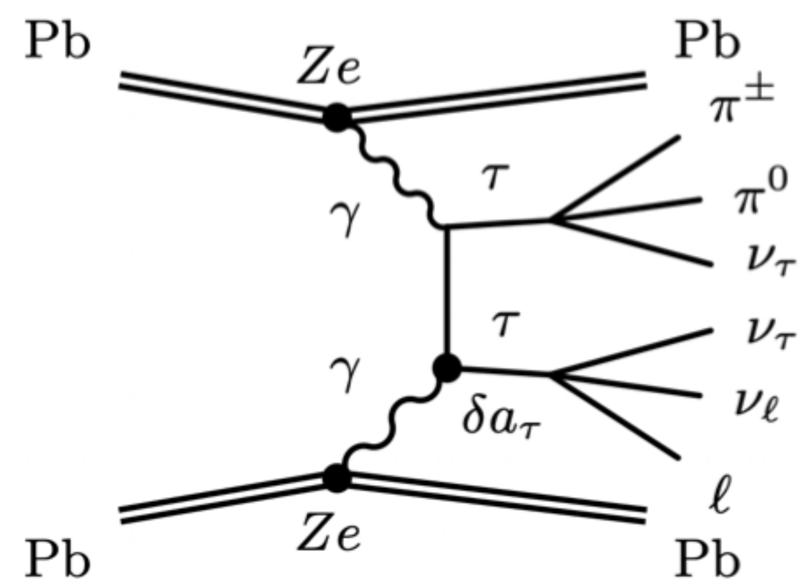
Ultra-peripheral
Pb+Pb collision

Measuring a_τ in UPC

- Exploit $\gamma\gamma \to \tau\tau$ cross-section to set limits on a_τ
- Experimental challenges:
  - Hadronic backgrounds
  - Neutrinos in the final state
- Advantages of UPC over the 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
- τ-leptons never directly targeted in measurements using nucleus-nucleus data
- **Use 1.44 nb^{-1} ATLAS Pb+Pb 2018 data, $\sqrt{s_{NN}} = 5.02$ TeV**

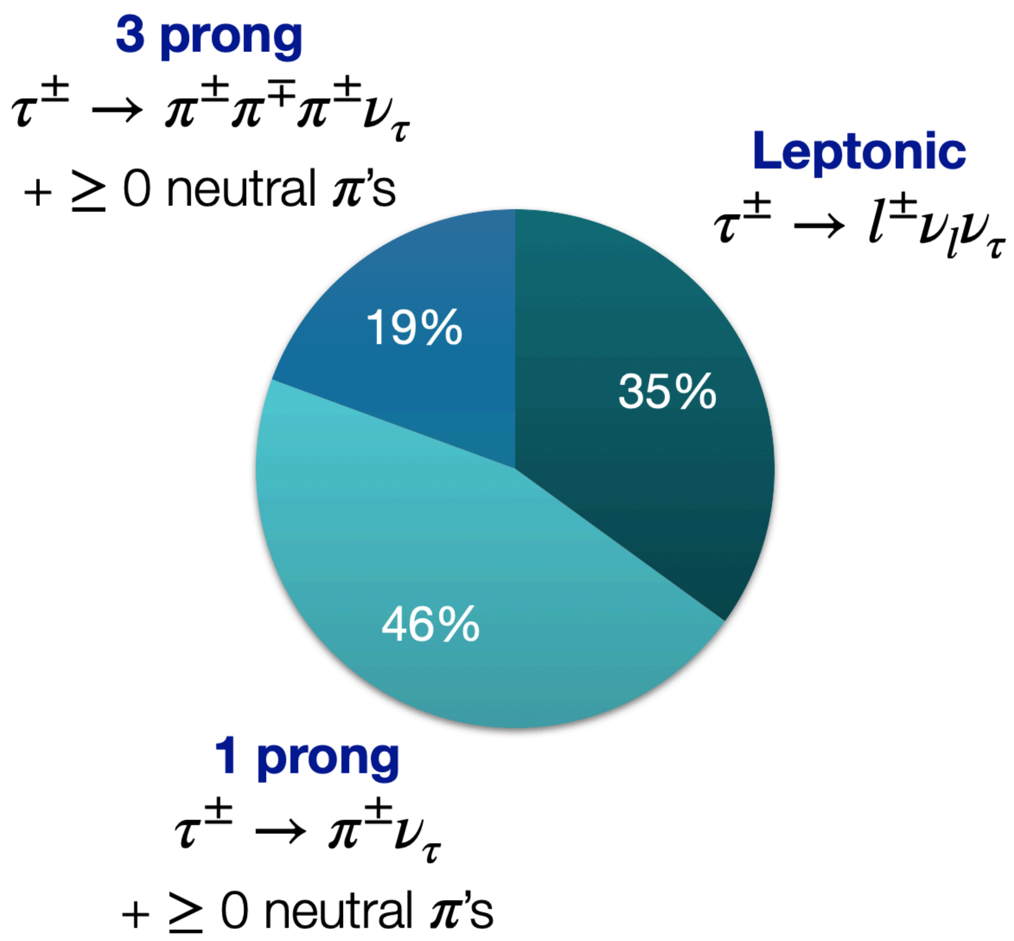
PLB 809 (2020) 135682





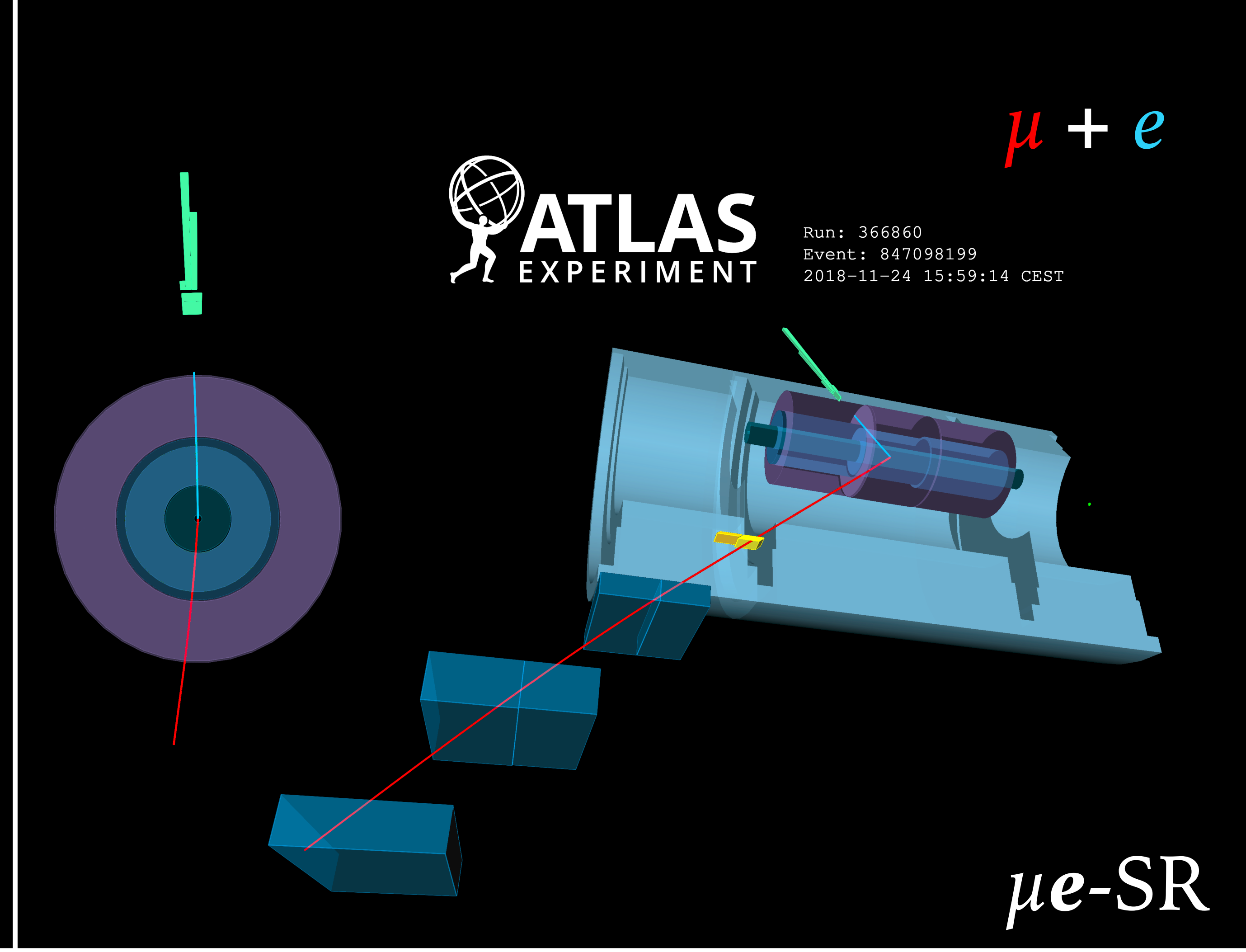
Measurement overview

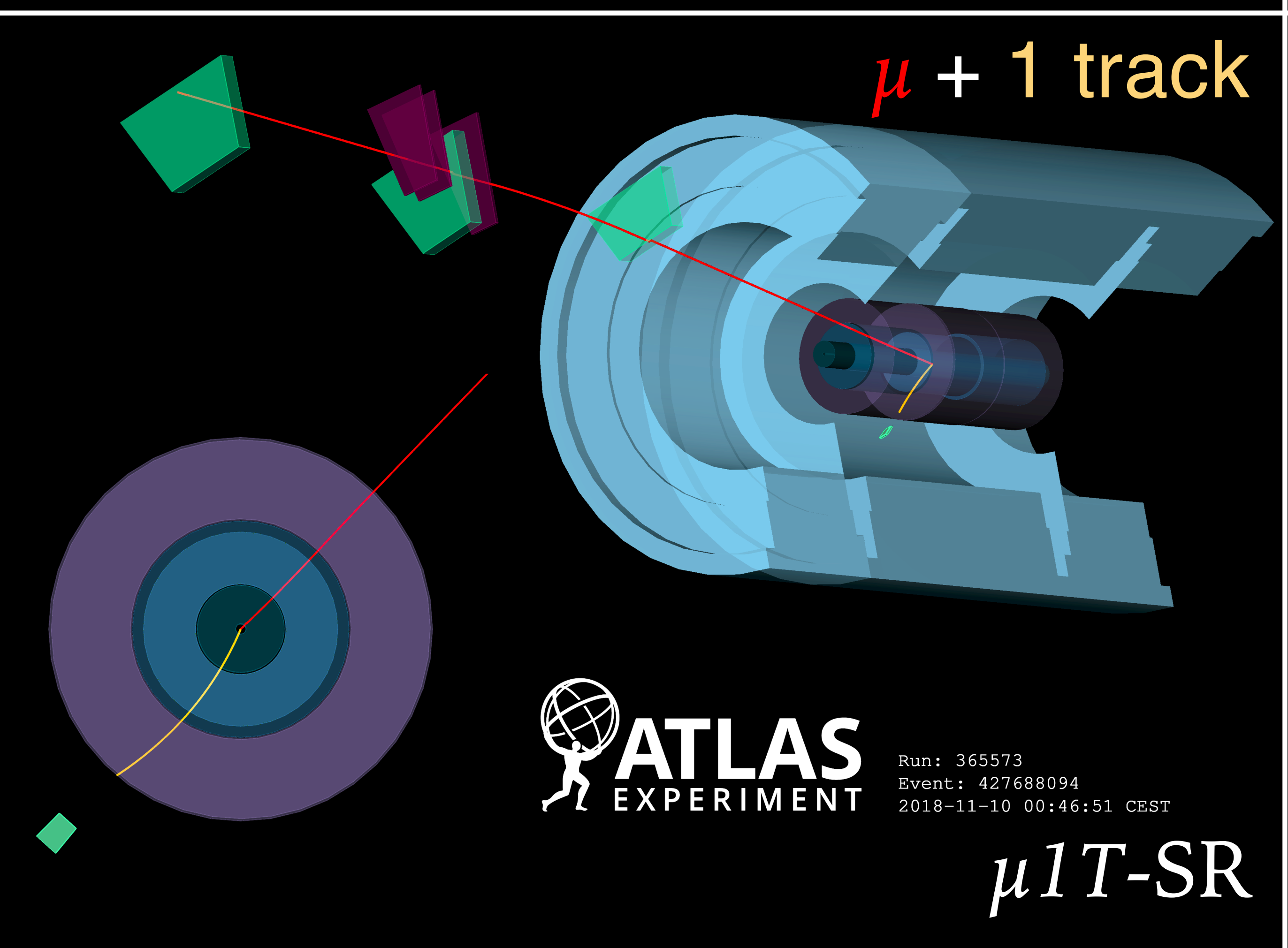
- Signal τ-leptons are low-energetic, typically with $p_T < 10$ GeV
- No standard ATLAS identification of τ-leptons is used
    - Instead events classified based on the charged τ-lepton decay products
- Three signal categories: $\mu + e$, μ + track, μ + 3 tracks
- Use leptons: $p_T(\mu/e) > 4$ GeV and tracks: $p_T(trk) > 100$ MeV
- Single muon trigger used to record signal events with muon $p_T > 4$ GeV

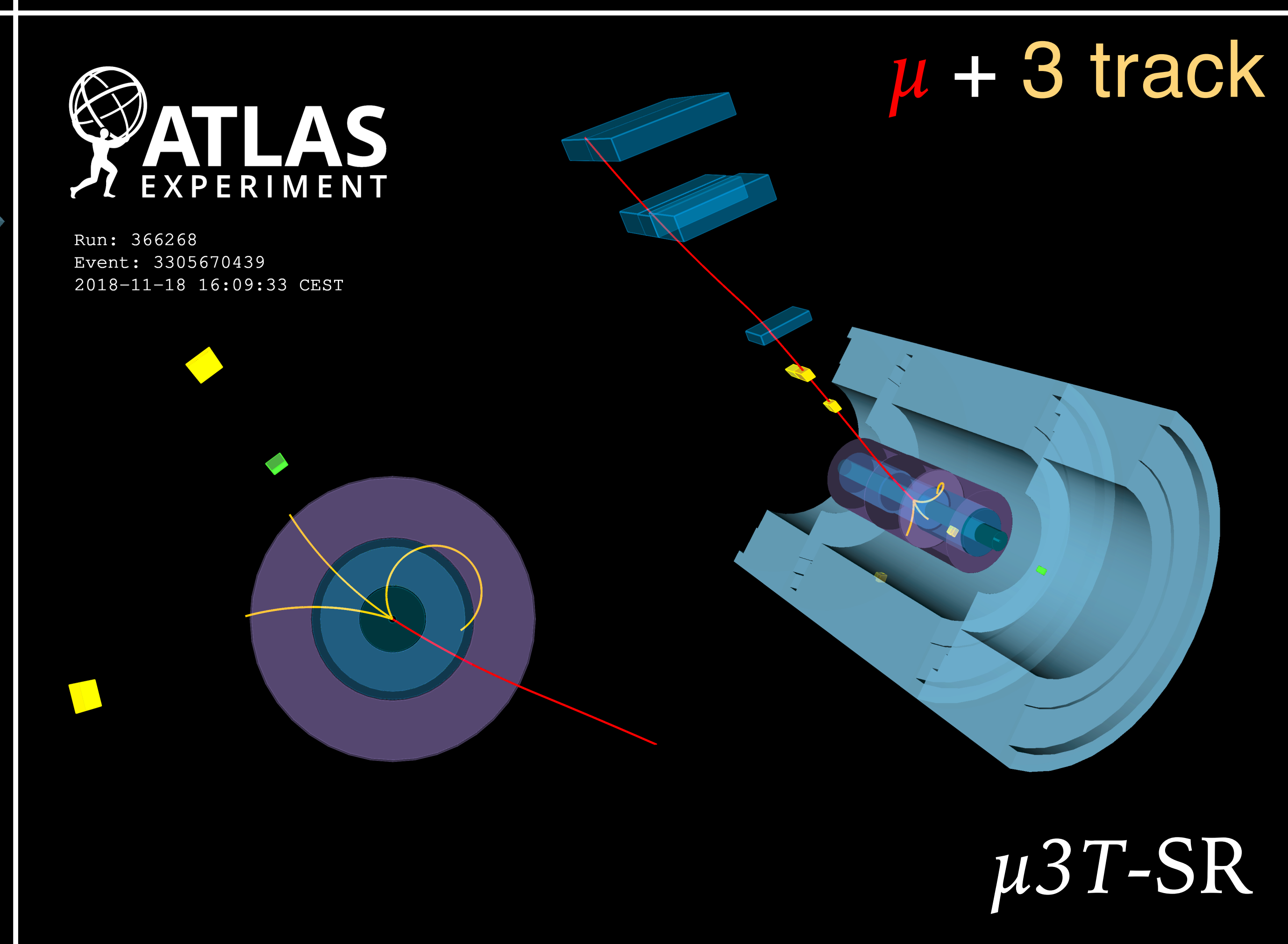


- Exclusivity requirements:
    - veto on forward neutron activity (using 0n0n configuration based on ZDC signal)
    - for μ + track and μ + 3 tracks: veto on additional tracks and low-p_T clusters
- Main background contributions are from dimuon production and diffractive photonuclear interactions

Signal Regions (SRs)

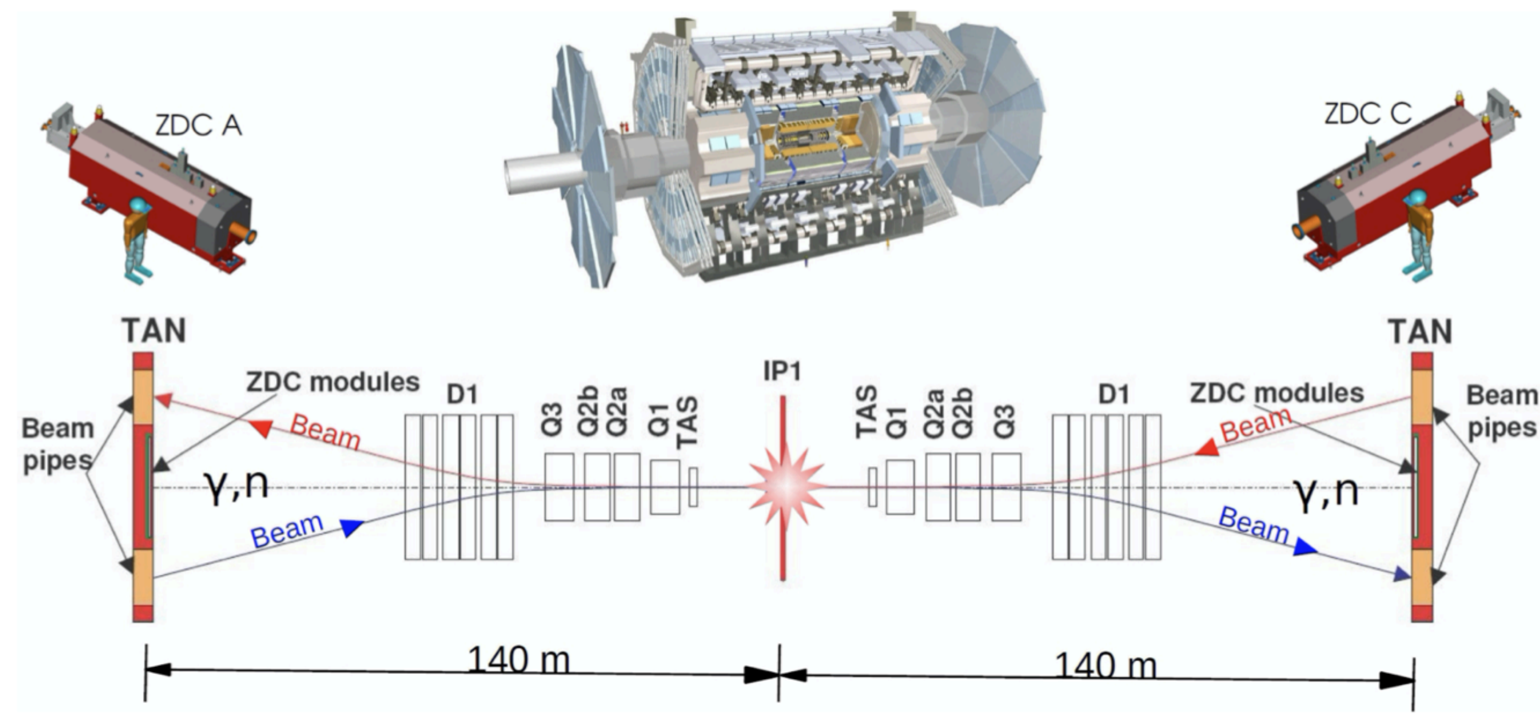




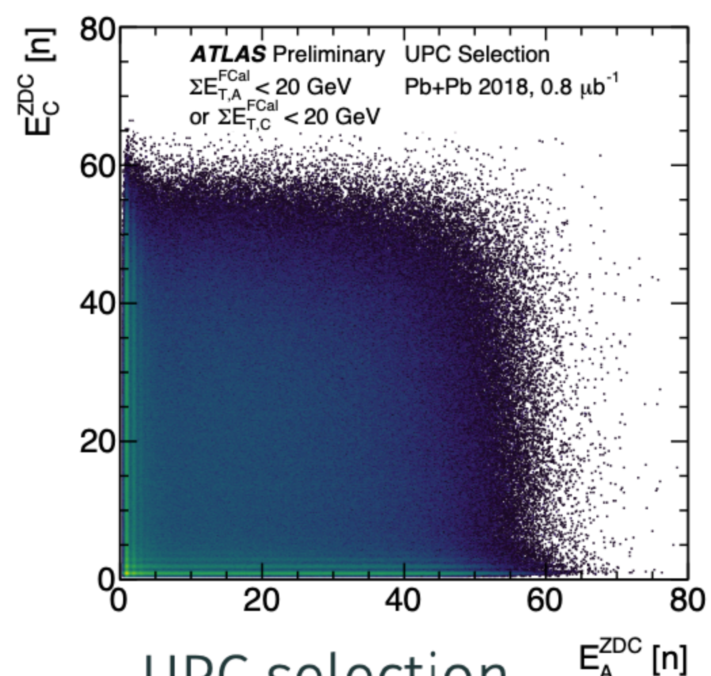


Zero Degree Calorimeters (ZDC)

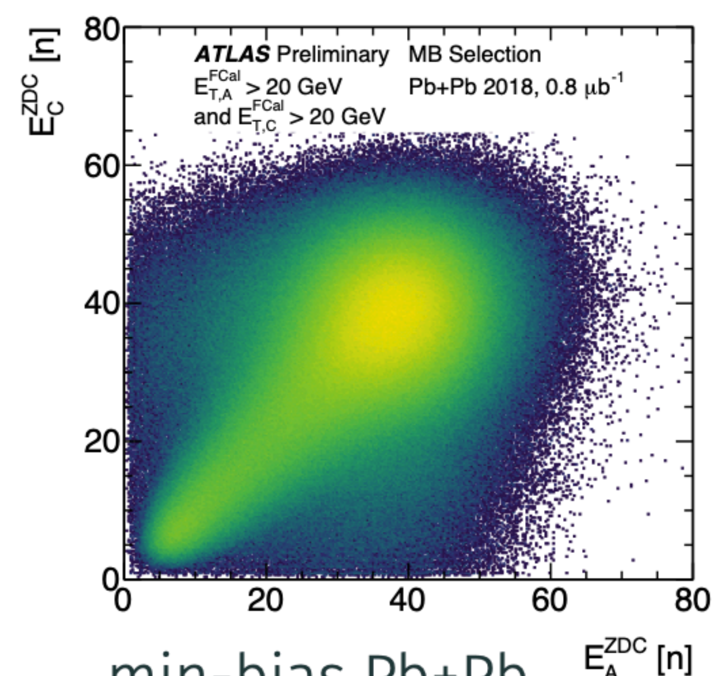
- Two ZDC arms: measure energies of forward neutrons
- Separate UPCs from inelastic Pb+Pb collisions
- Categorise events into 0n0n / 0nXn / XnXn



- Neutron emissions if nuclei excited through secondary photon exchanges
- Exclusive $\gamma\gamma$ processes: mostly 0n0n
- Photonuclear processes: typically 0nXn



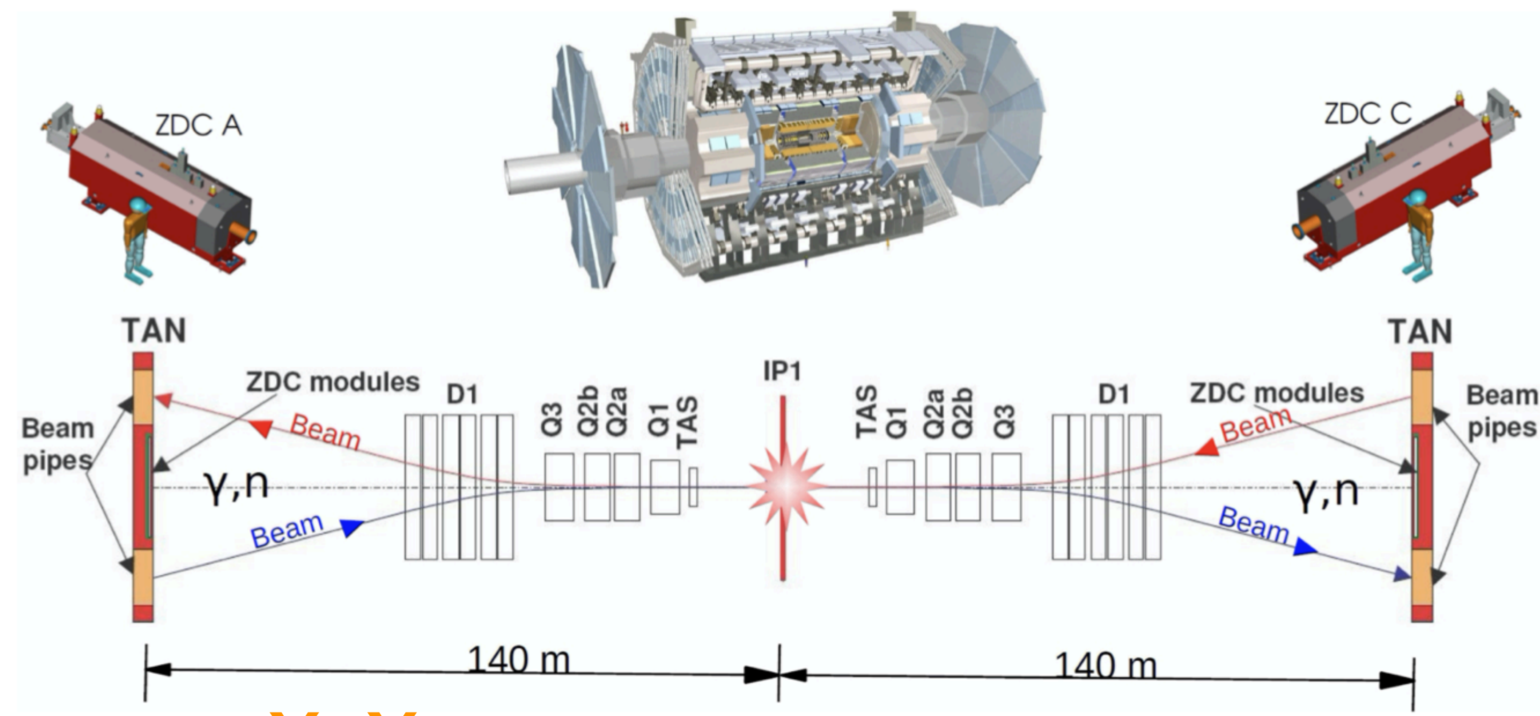
UPC selection



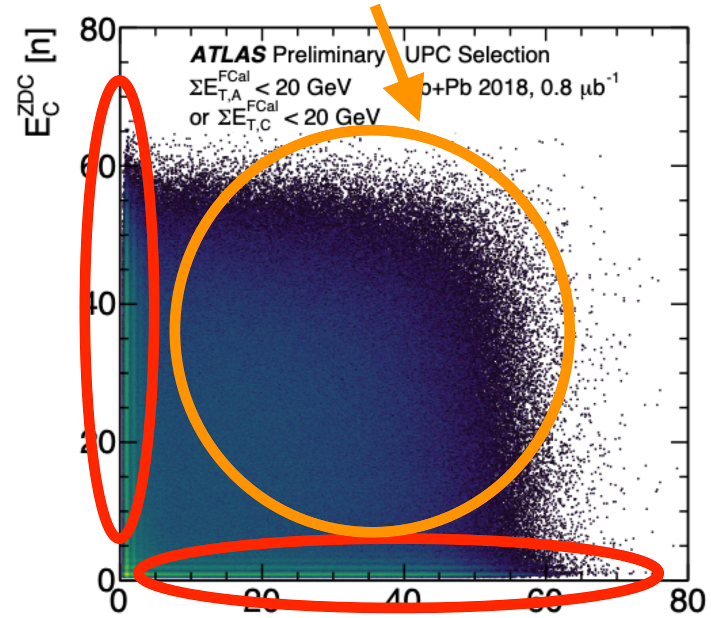
min-bias Pb+Pb selection

Zero Degree Calorimeters (ZDC)

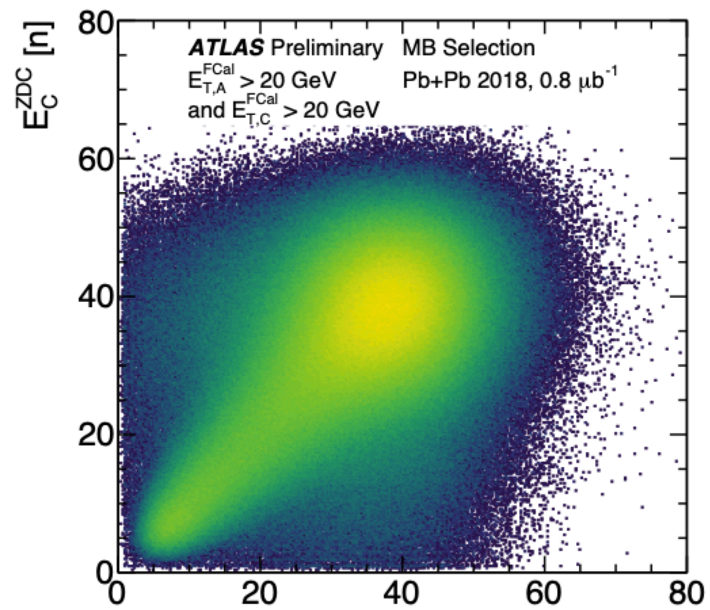
- **Two ZDC arms: measure energies of forward neutrons**
- Separate UPCs from inelastic Pb+Pb collisions
- **Categorise events into 0n0n / 0nXn / XnXn**



XnXn



UPC selection



min-bias Pb+Pb selection

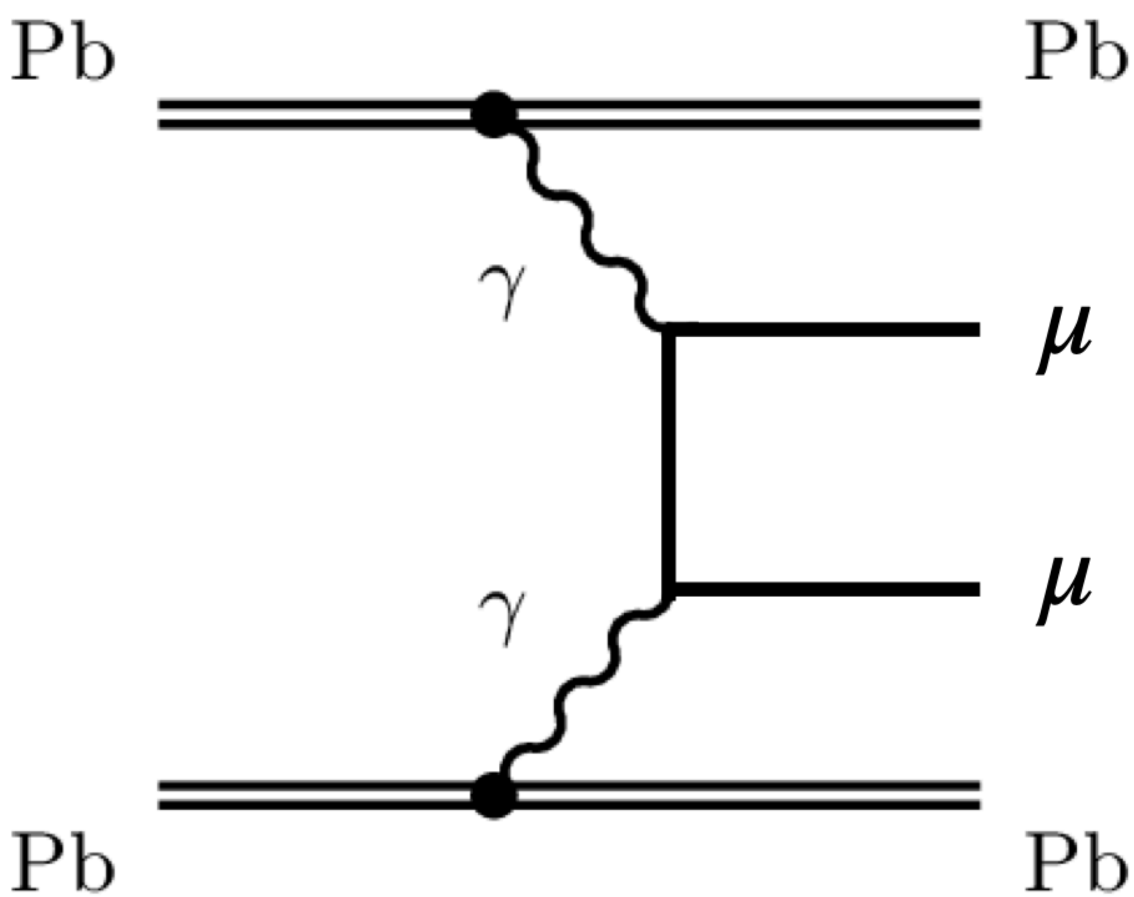
0n0n

0nXn

- Neutron emissions if nuclei excited through secondary photon exchanges
- Exclusive $\gamma\gamma$ processes: mostly 0n0n
- Photonuclear processes: typically 0nXn

Main backgrounds

Di-muon



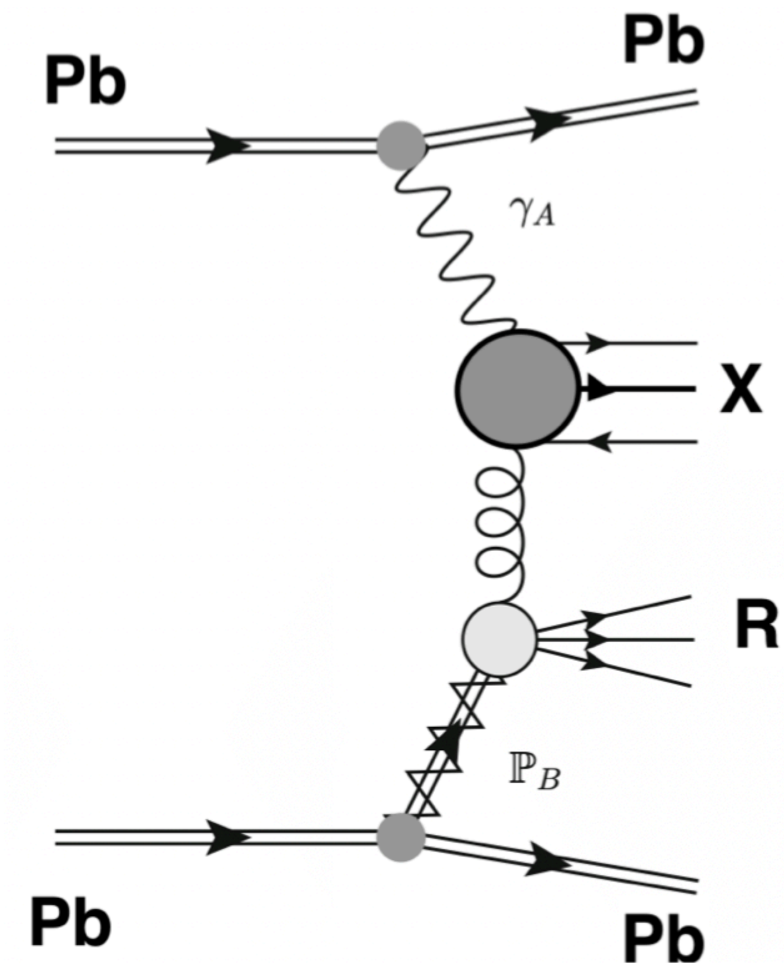
Estimate with MC

$\gamma\gamma \rightarrow \mu\mu$ Starlight+Pythia8

$\gamma\gamma \rightarrow \mu\mu\gamma$ Madgraph5

Photon flux re-weighted to SuperChic 3

Photonuclear

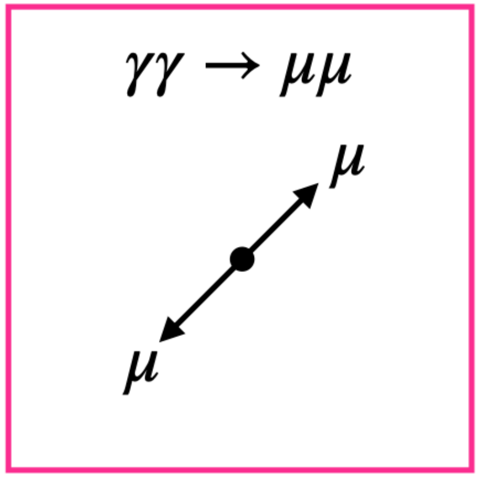


Data-driven estimate

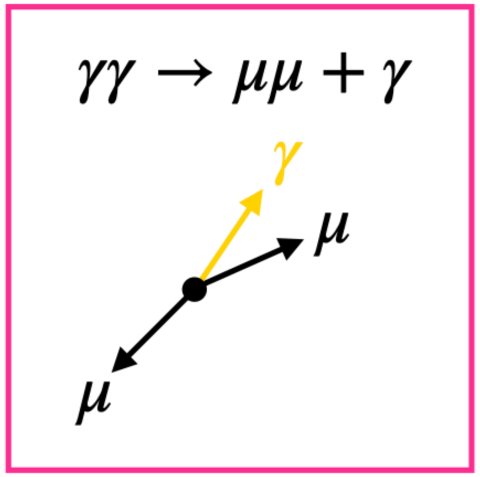
Often leads to nucleus breakup
→ Forward neutrons

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

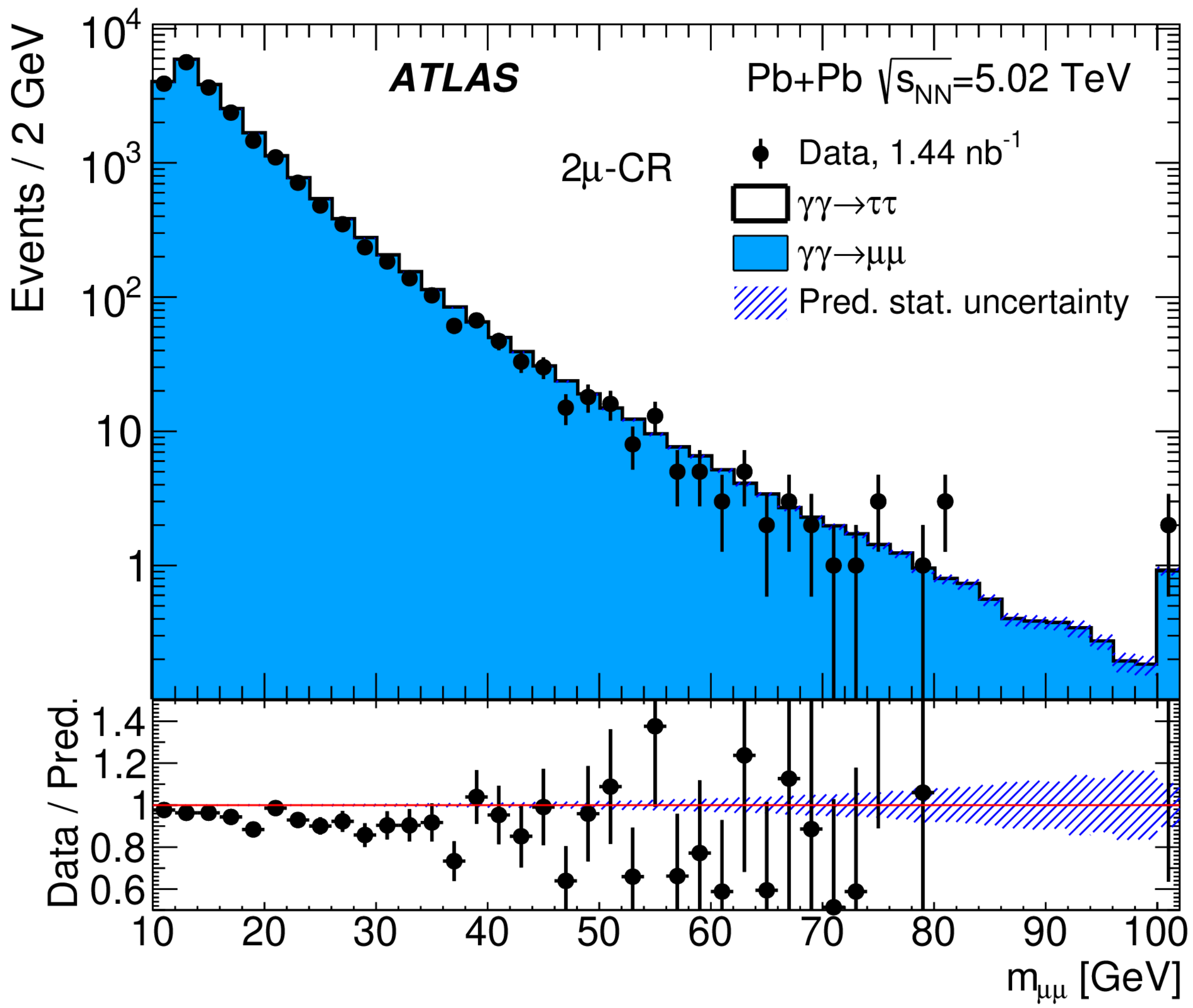


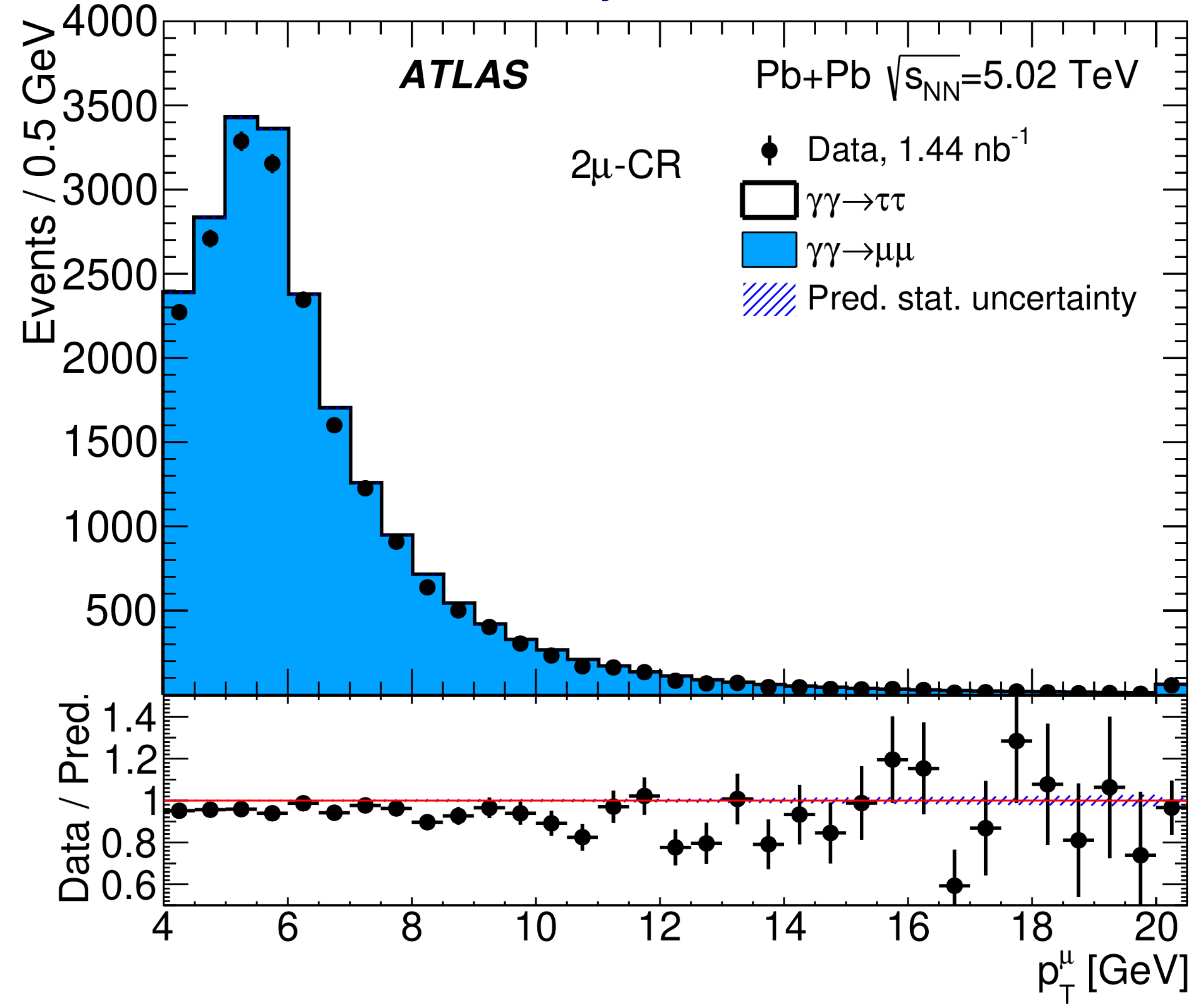
- Additional rejection for $\gamma\gamma \to \mu\mu + \gamma$:
  - require $p_T(\mu$,trk,γ/cluster) > 1 GeV for μ1T-SR

- **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

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

Phys. Rev. Lett. 131, 151802



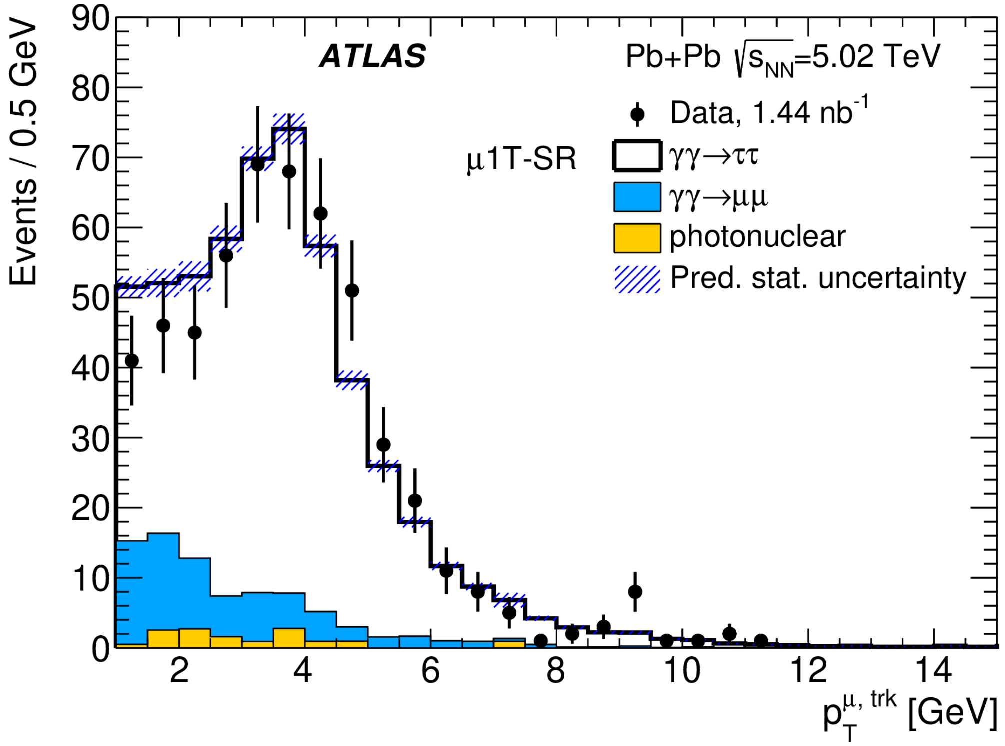


- Background from $\gamma\gamma \rightarrow \mu\mu(\gamma)$ production estimated using MC simulation
- Validation of modeling performed in dimuon control region (2μ-CR)
- Normalization off by +6% with SuperChic3 photon flux (Starlight: -13%)
- The difference is photon flux uncertainty

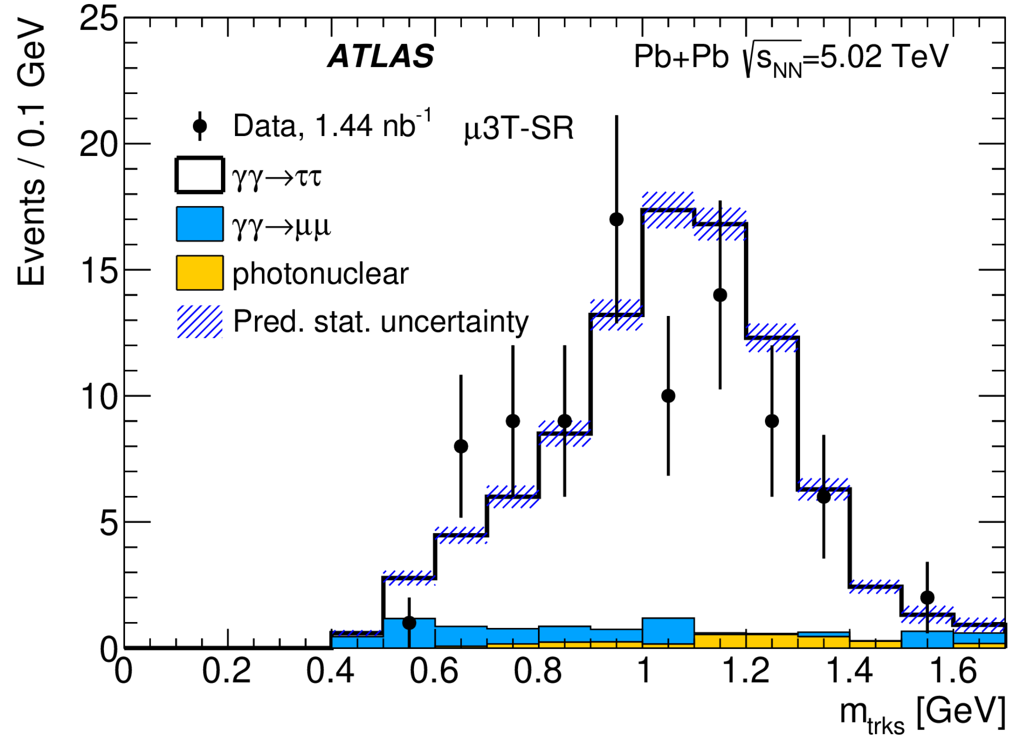
Signal region distributions

Phys. Rev. Lett. 131, 151802

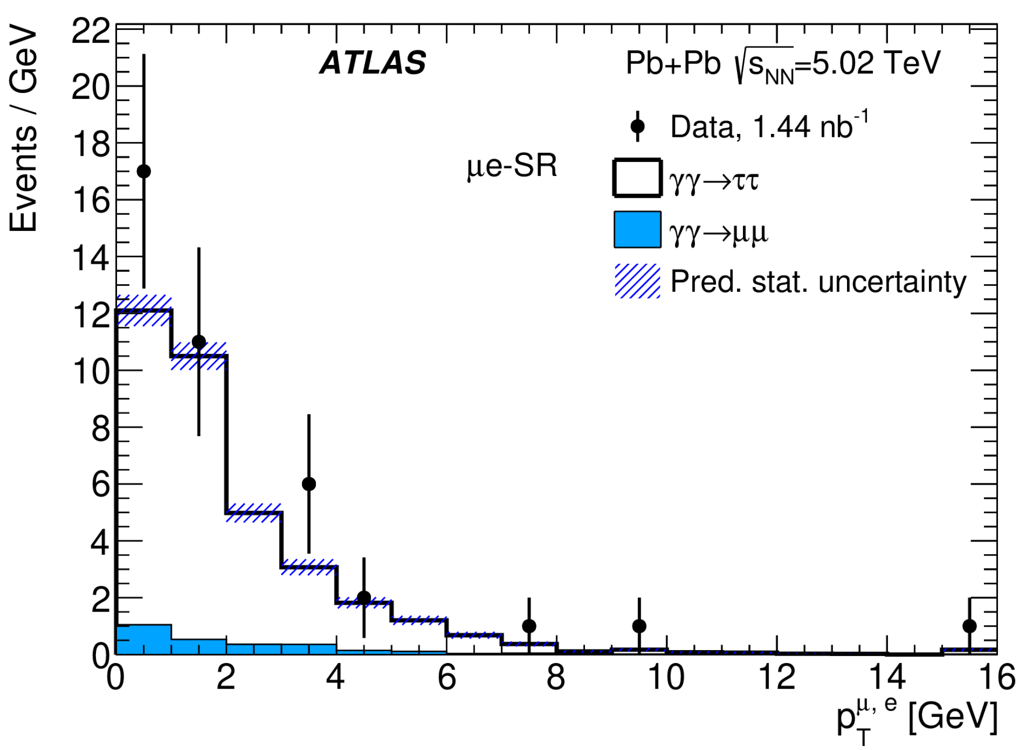
μ1T-SR: N_{obs}=532, N_{bkg}=84±19



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**

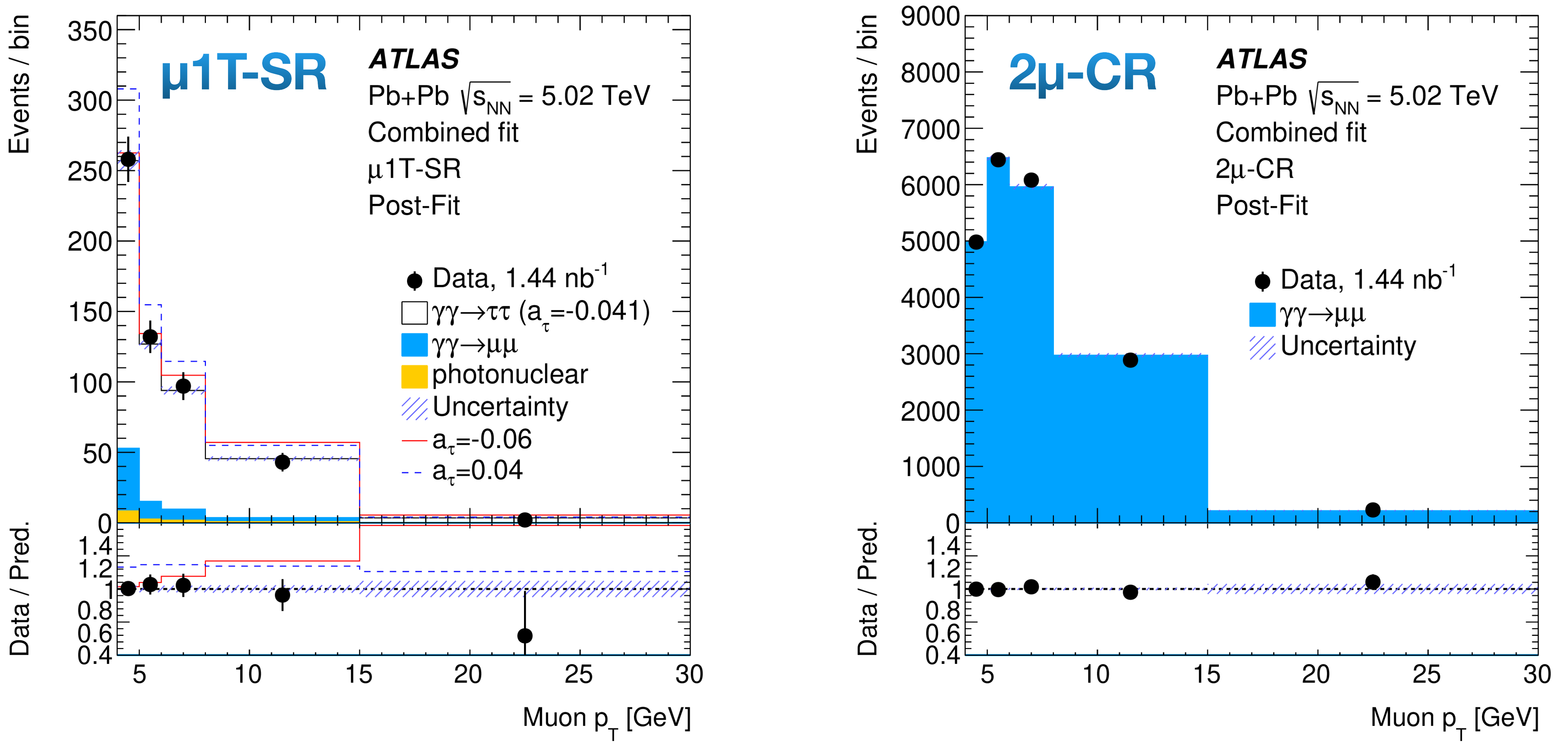
Observation of $\gamma\gamma\to\tau\tau$ in Pb+Pb

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

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

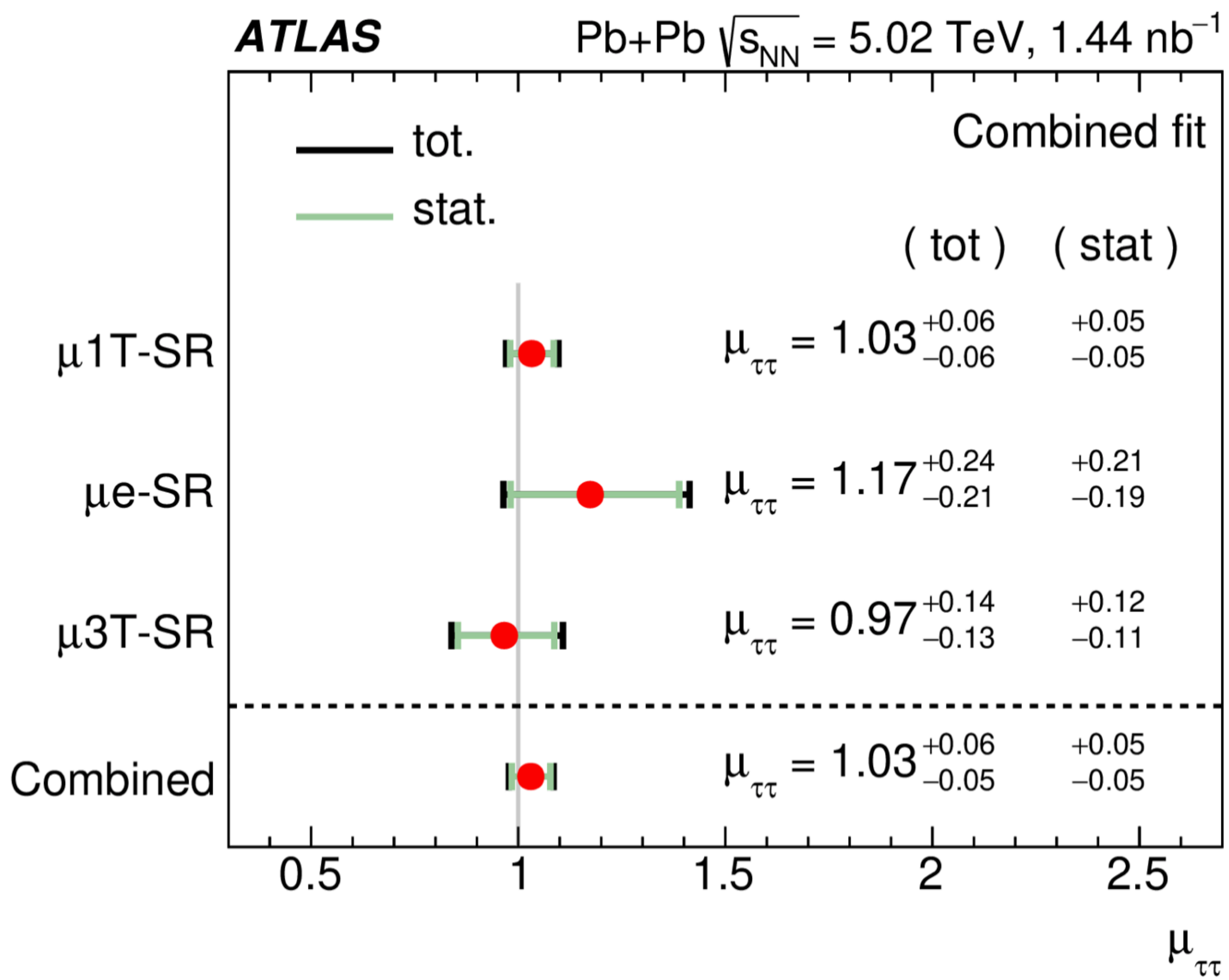
Clear observation (≫ 5σ) of $\gamma\gamma\to\tau\tau$ process at the LHC

Phys. Rev. Lett. 131, 151802



Signal strength

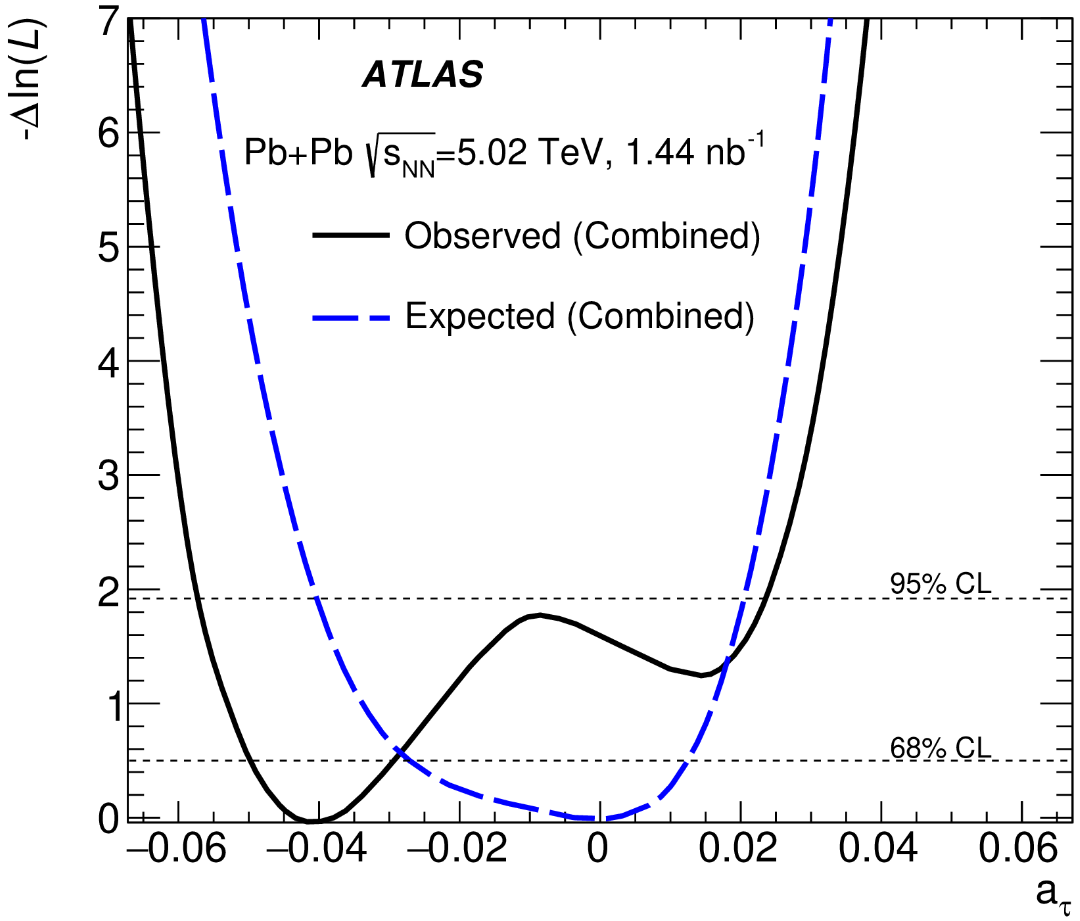
$\mu_{\tau\tau}$ = observed yield / SM expectation

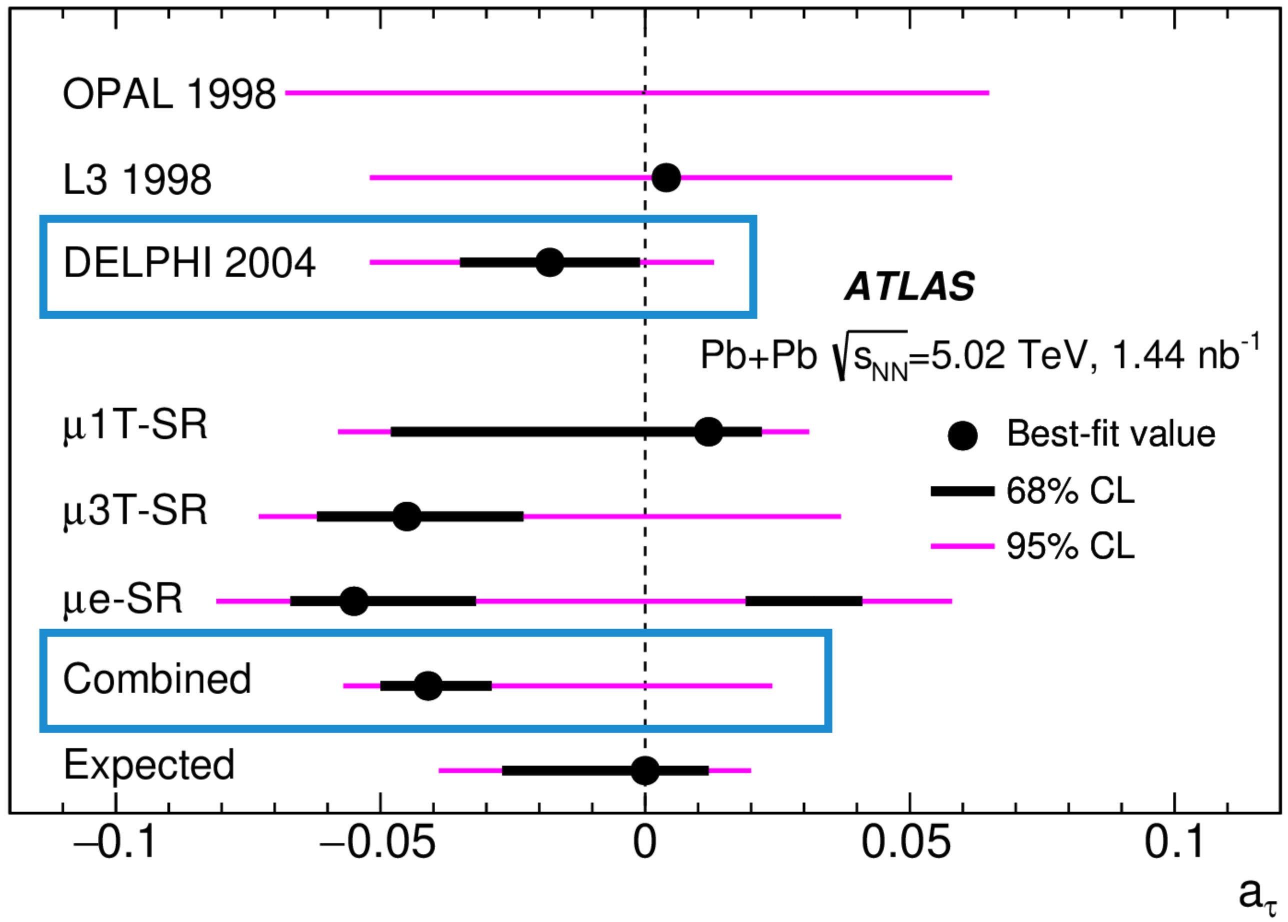


- Fit of $\gamma\gamma \rightarrow \tau\tau$ signal strength assuming SM value for a_τ
- Results for each signal region compatible with unity
- Combined fit reaches 5% precision, limited by statistical uncertainties

Tau g-2 competitive with LEP

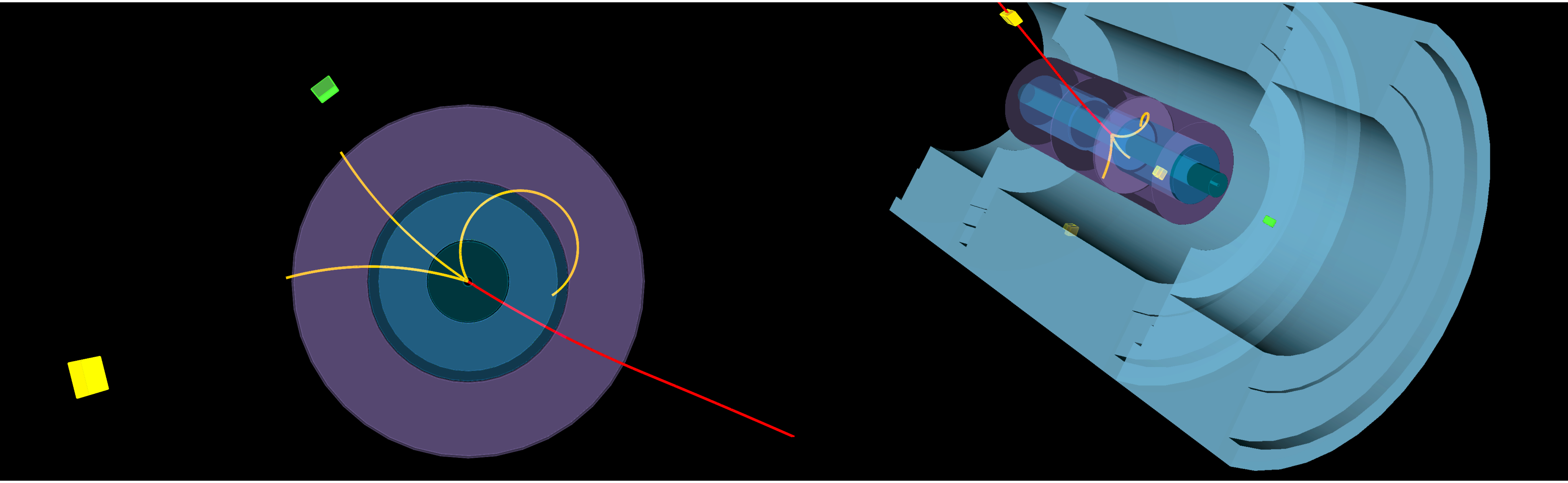
[Phys. Rev. Lett. 131, 151802]





- 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

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

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.”

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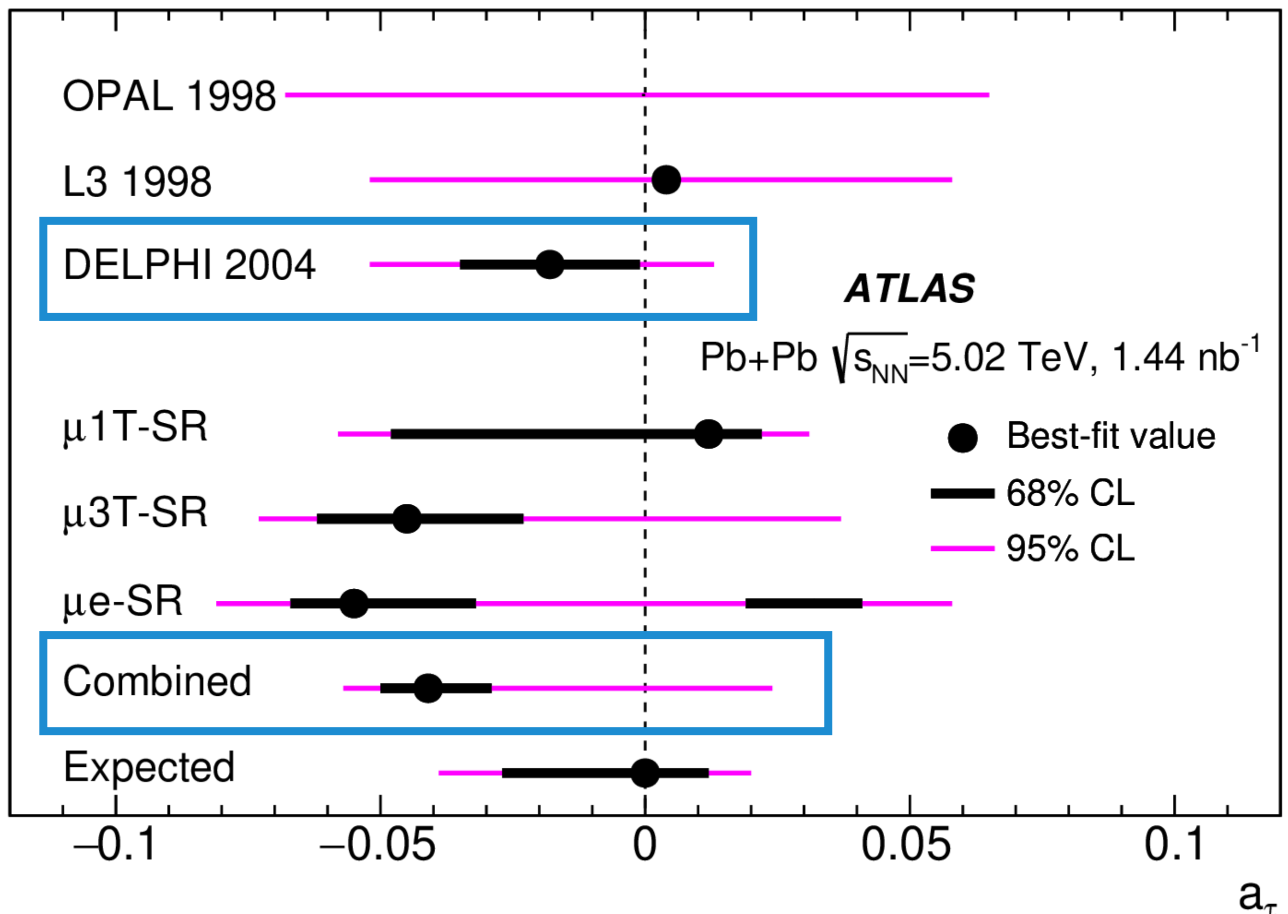
Additional slides

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]

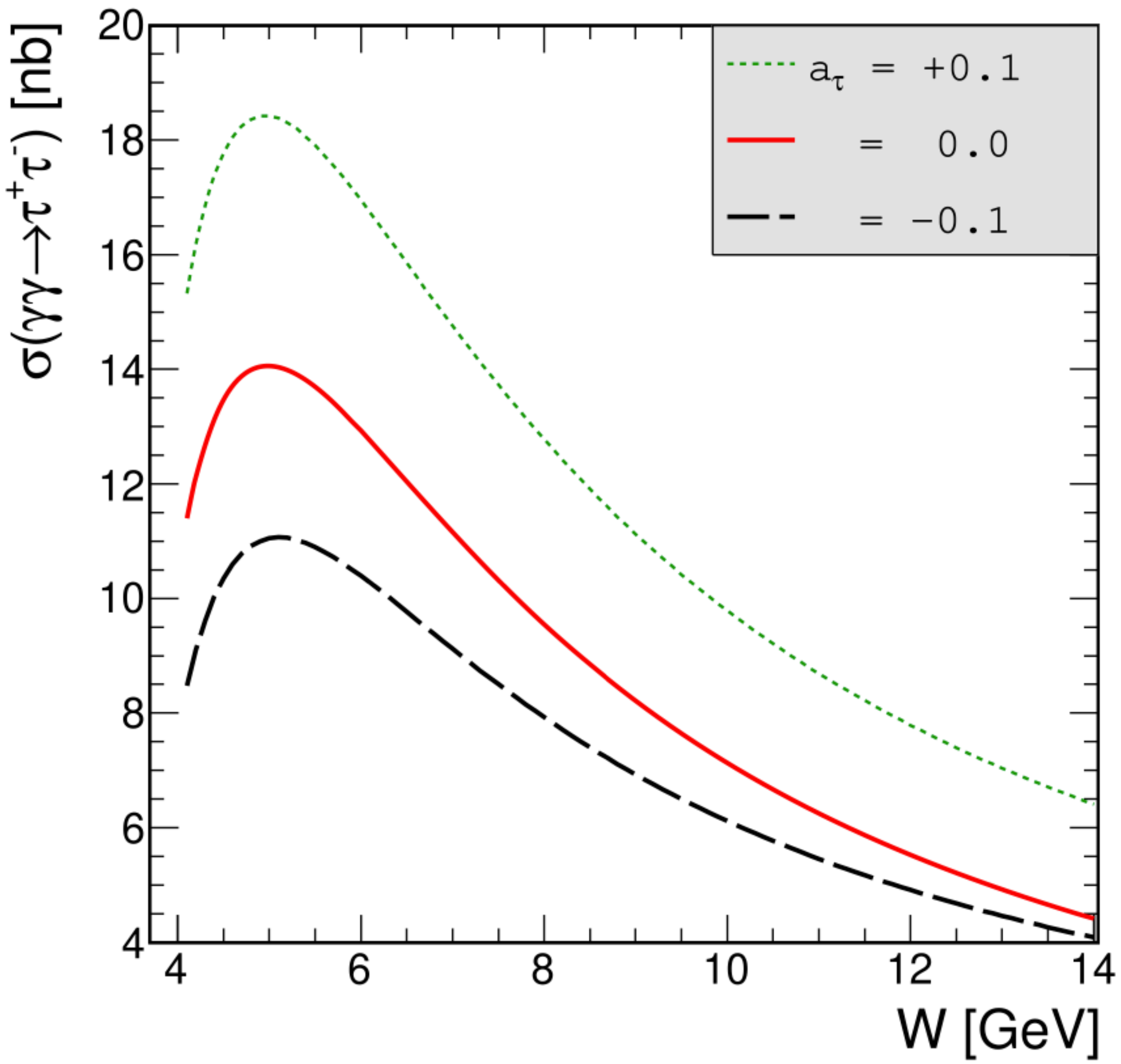


Competitive with DELPHI

Statistical uncertainty dominates

Our analysis strategy

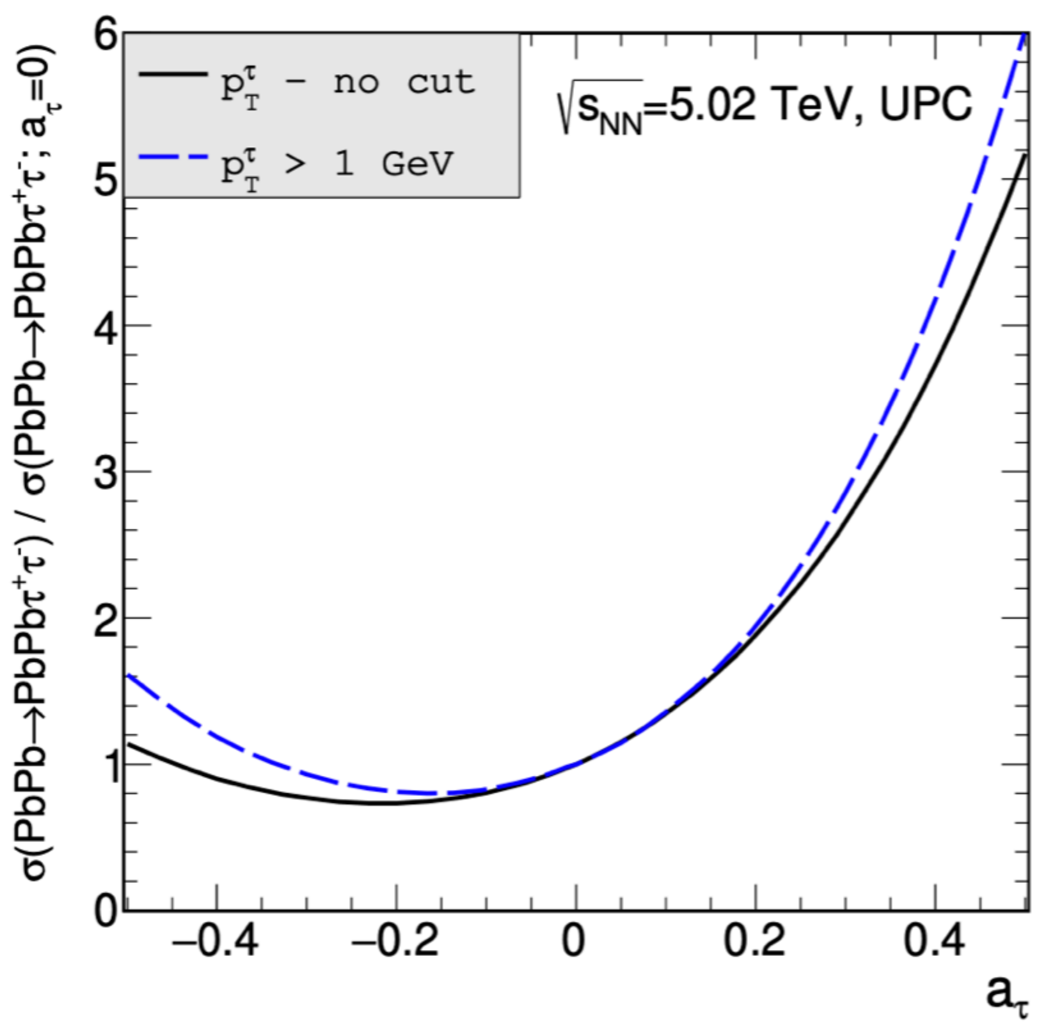
Cross-section sensitive to tau g-2



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

Also sensitive to tau EDM

Additional sensitivity from measuring differentially in lepton p_T



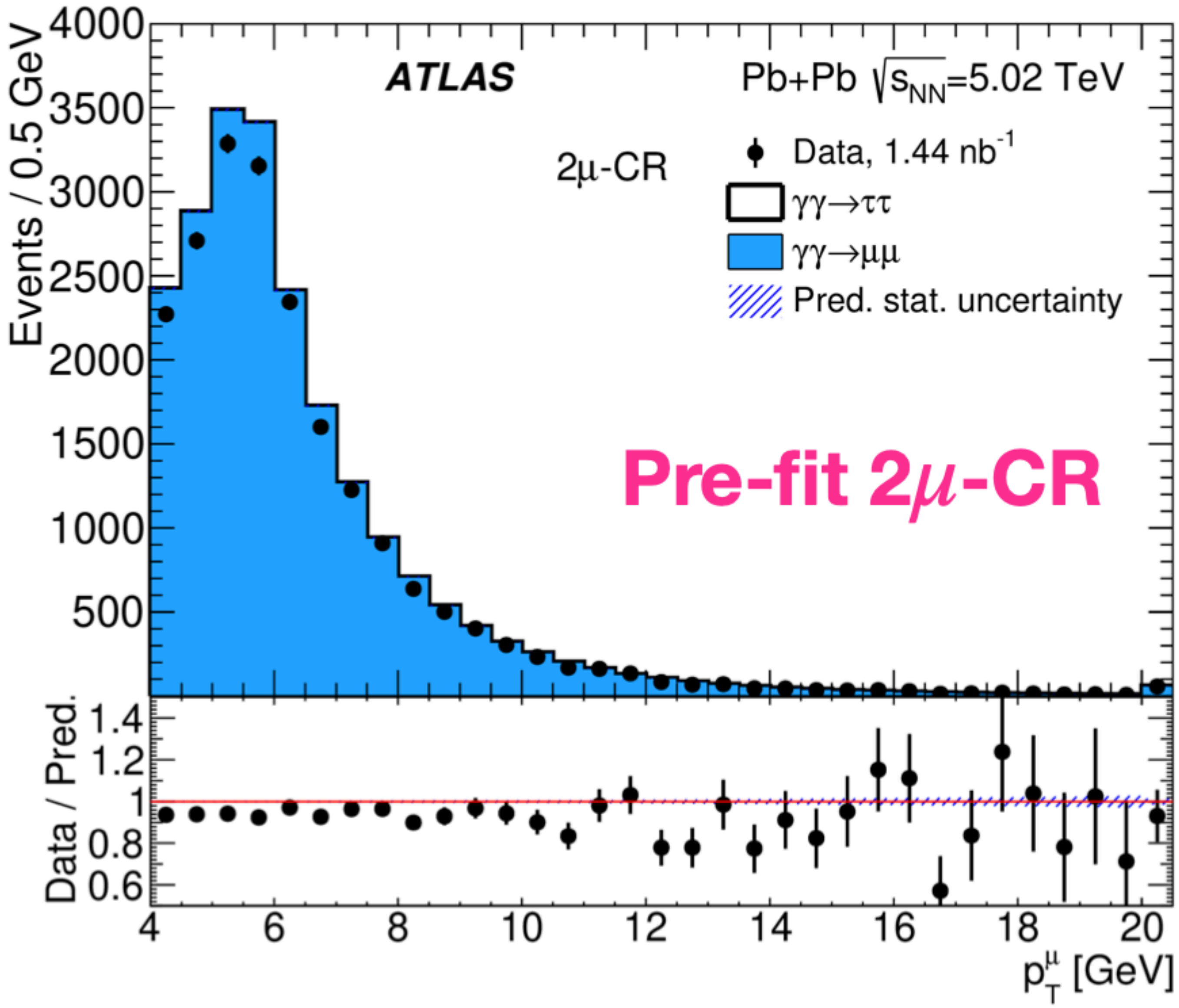
Dyndał, Kłusek-Gawęda, Szczurek, Schott PLB (2020)

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

Main background

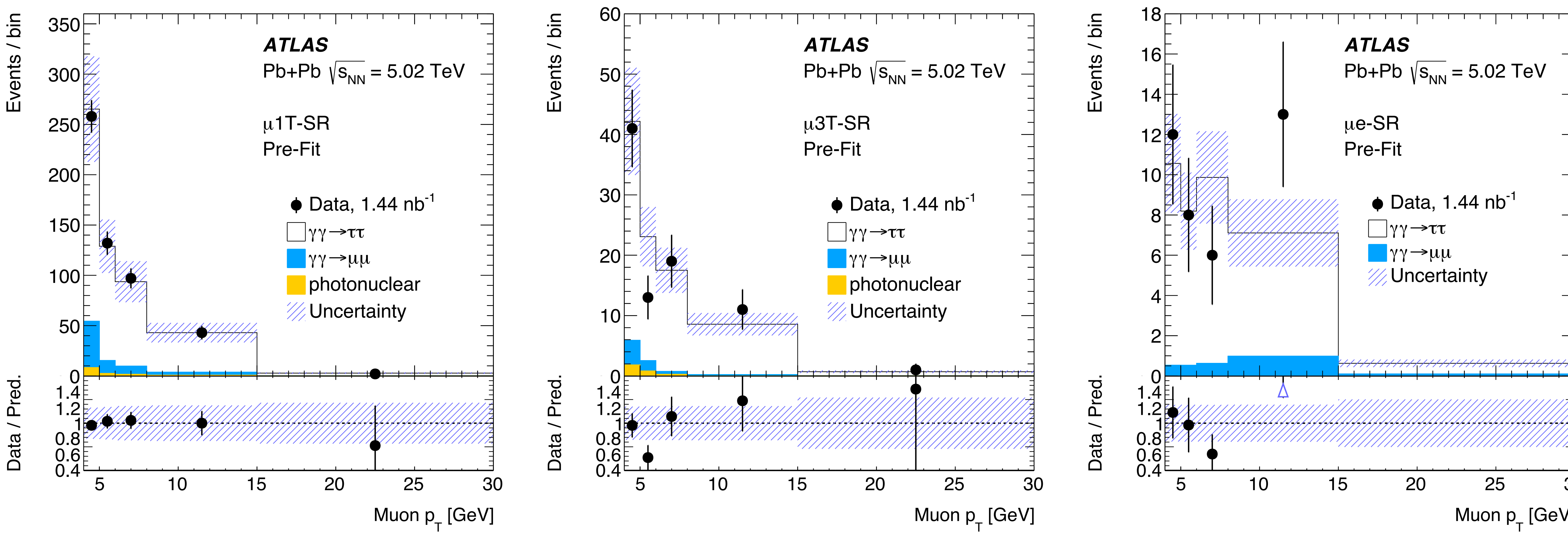
MC with Superchic3 photon flux (+6% overestimate)
c.f. -13% for Starlight photon flux

Difference = photon flux uncertainty



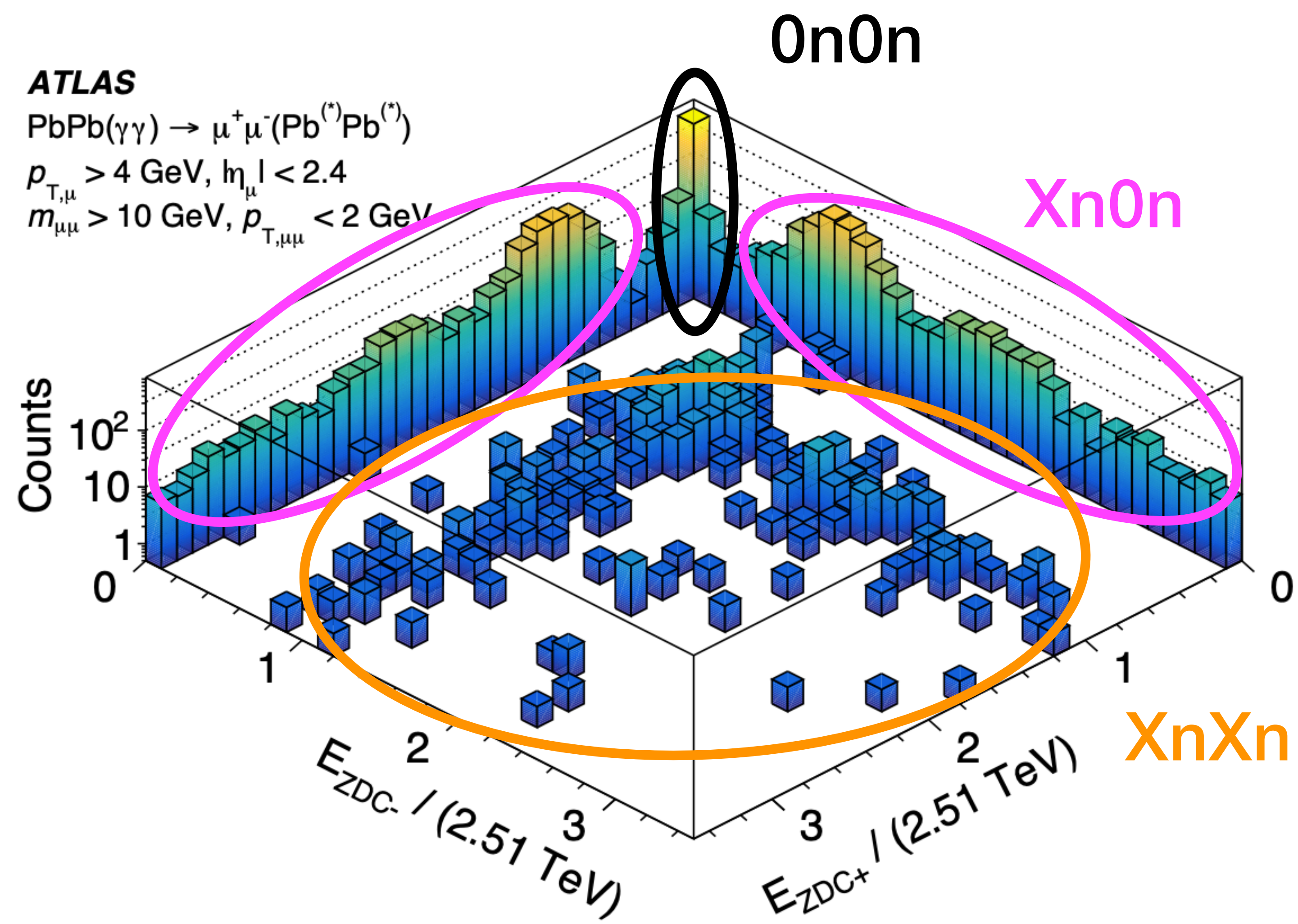
Fit setup

- Measure $\gamma\gamma\rightarrow\tau\tau$ signal strength and a_τ using profile likelihood fit to the muon pT distribution in the three SRs and 2μ-CR
- Build templates for different a_τ values by reweighing signal MC using weights from PLB 809 (2020) 135682:
  - a_τ values: 0, ±0.01, ±0.02, ±0.03, ±0.04, ±0.05, ±0.06, ±0.1
  - 3D weights in $m_{\tau\tau}$, $|y_{\tau\tau}|$, $|\Delta\eta_{\tau\tau}|$
- **Pre-fit distributions of p_T^μ in the SRs assuming SM value of a_τ:**



Signal categories - ZDC selection

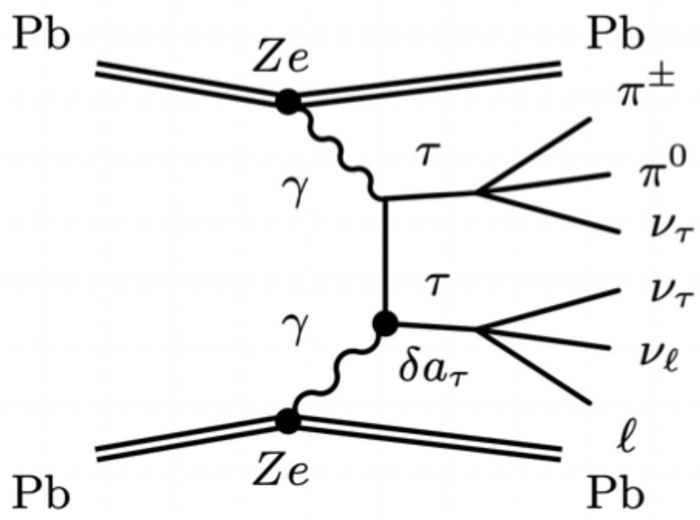
- Different processes present different activity in the forward region:
  - Exclusive dilepton production - ions stay intact
  - Background events with nuclear breakup
- Three classes defined, based on the signal in the ZDC



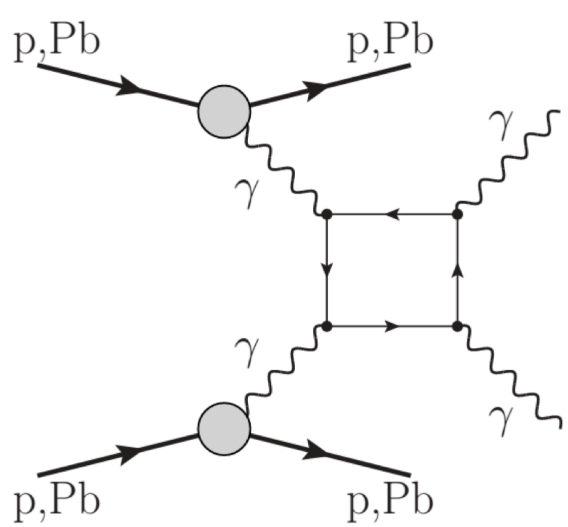
- The association between given ZDC signal and given process is nontrivial
  - Migrations due to ion excitation and presence of EM pile-up

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, …)

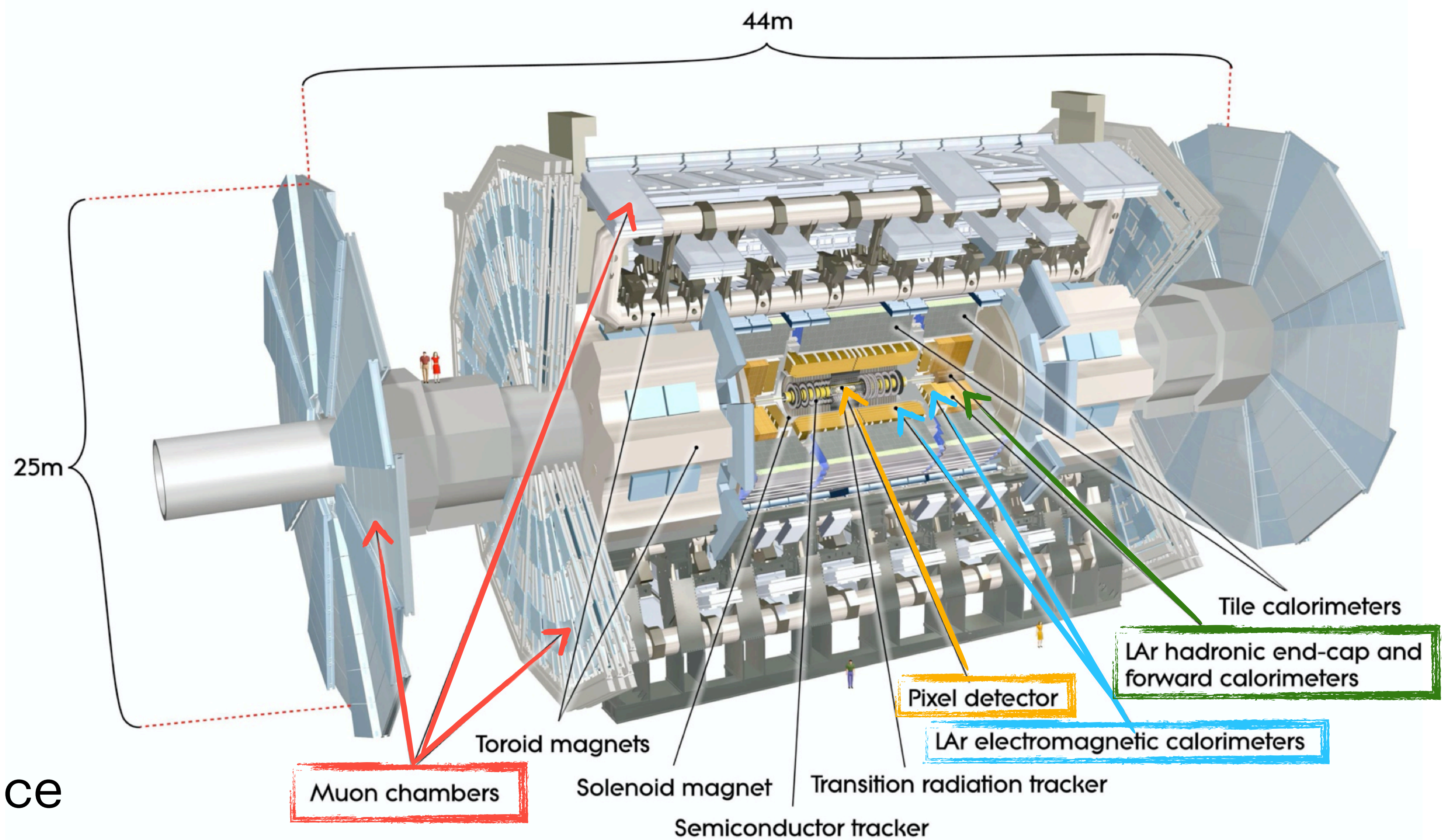


  - ***Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector*** [JHEP 03 (2021) 243]
    - **New particles** can enter the loop
    - Light-by-light (LbyL) cross-sections can be modified by various BSM phenomena (Born-Infeld 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



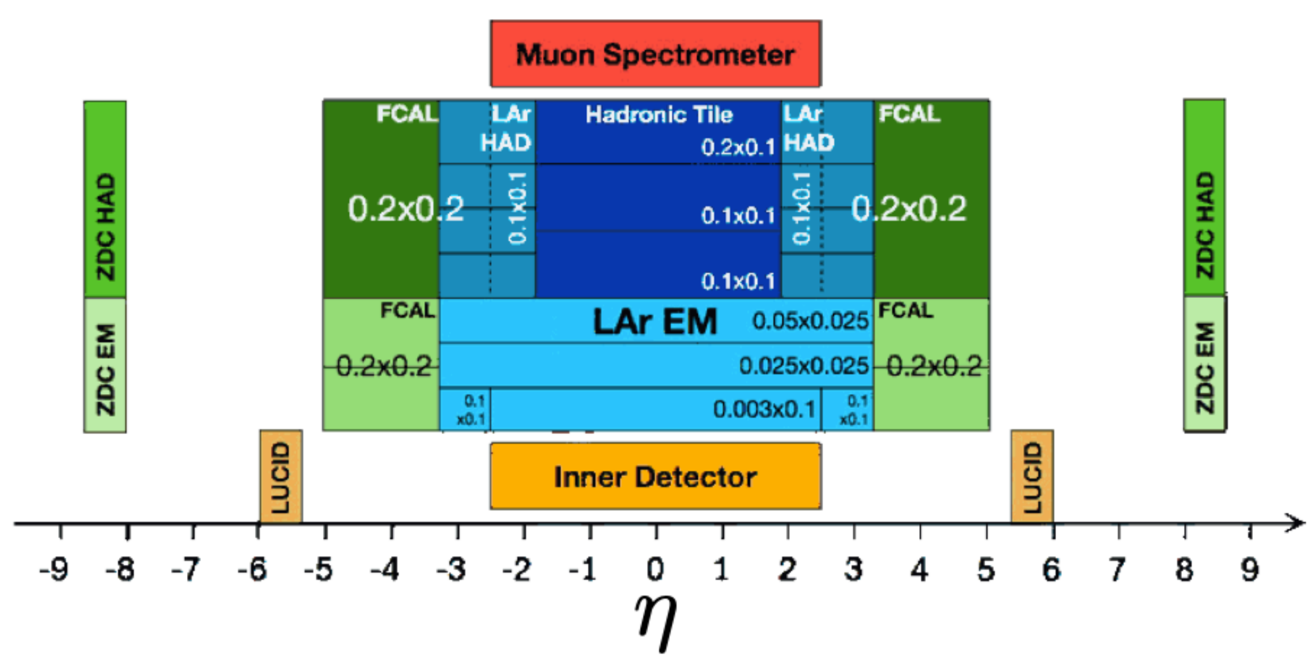
φ - full azimuth acceptance

η - broad pseudo rapidity coverage

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

p_T - transverse momentum

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

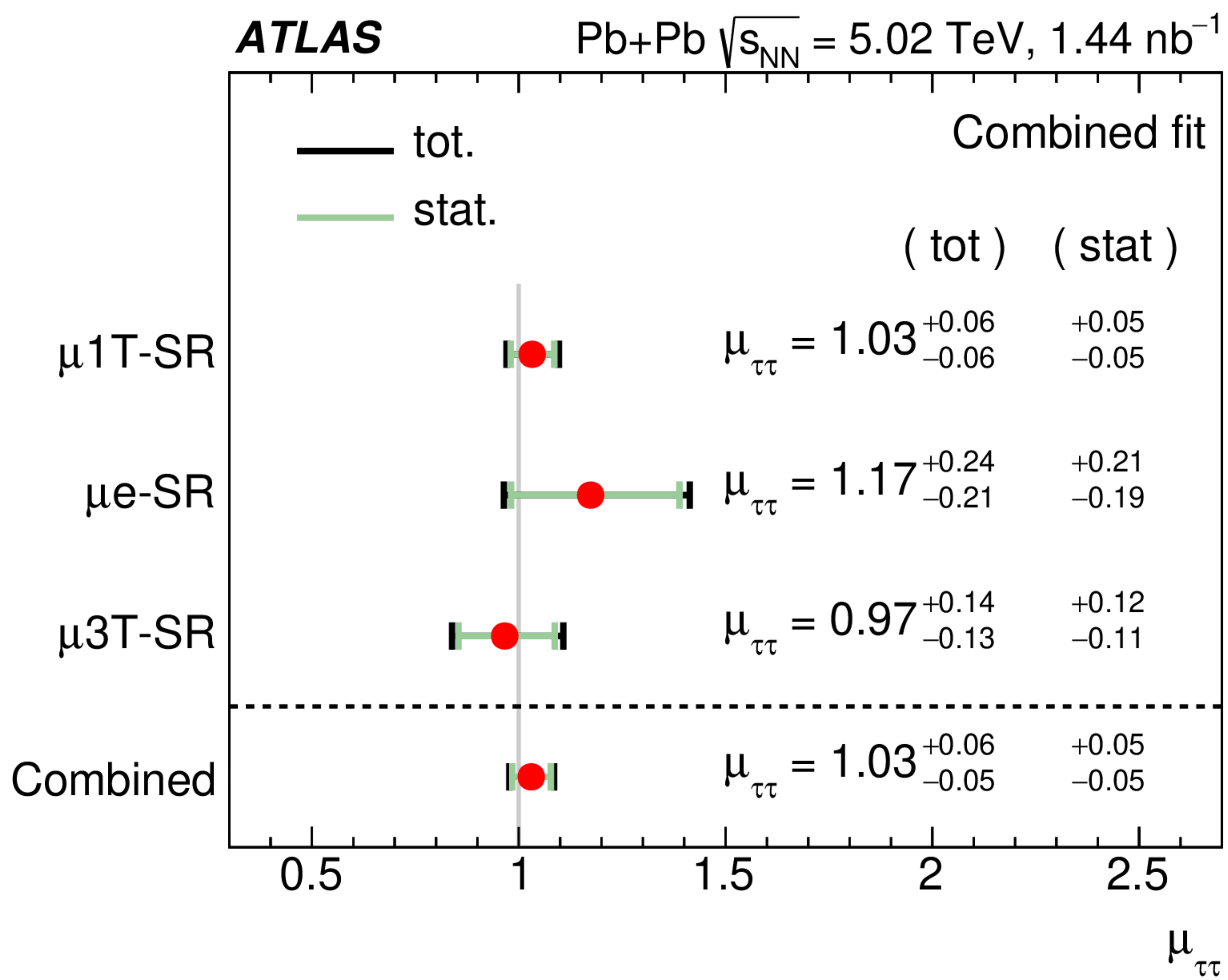


SR MC cutflow

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

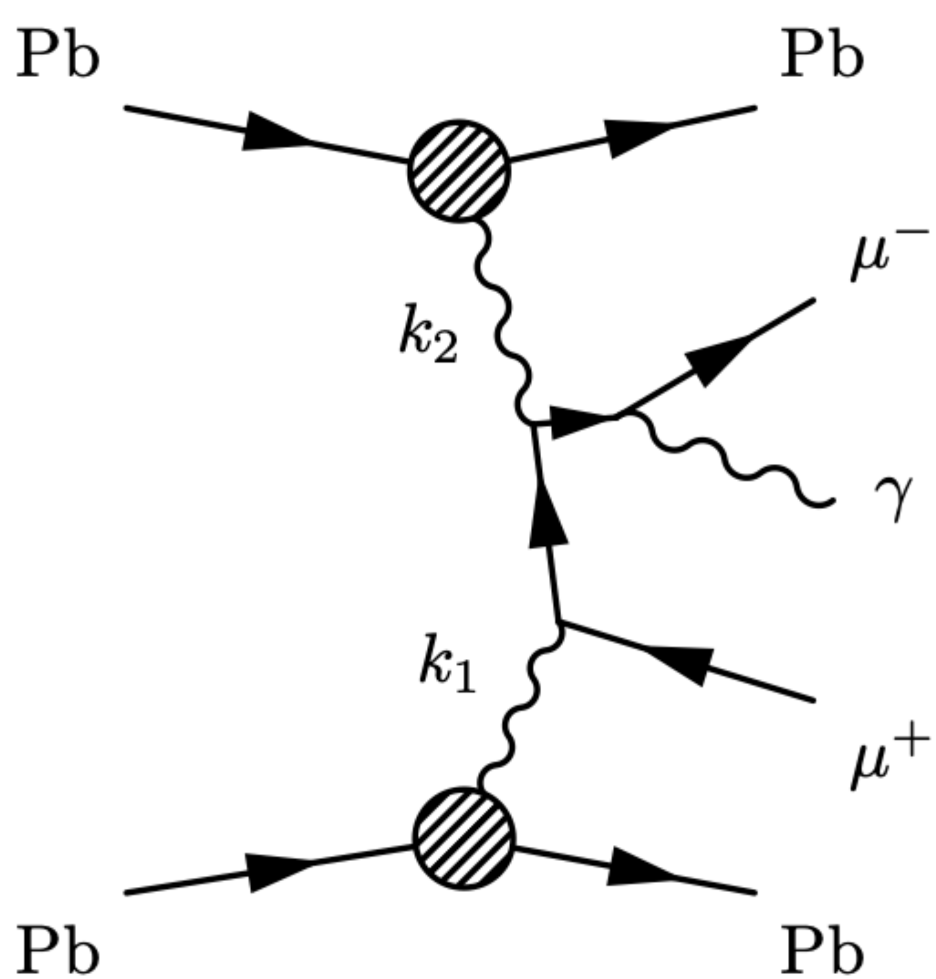
Results: Signal strength

- 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

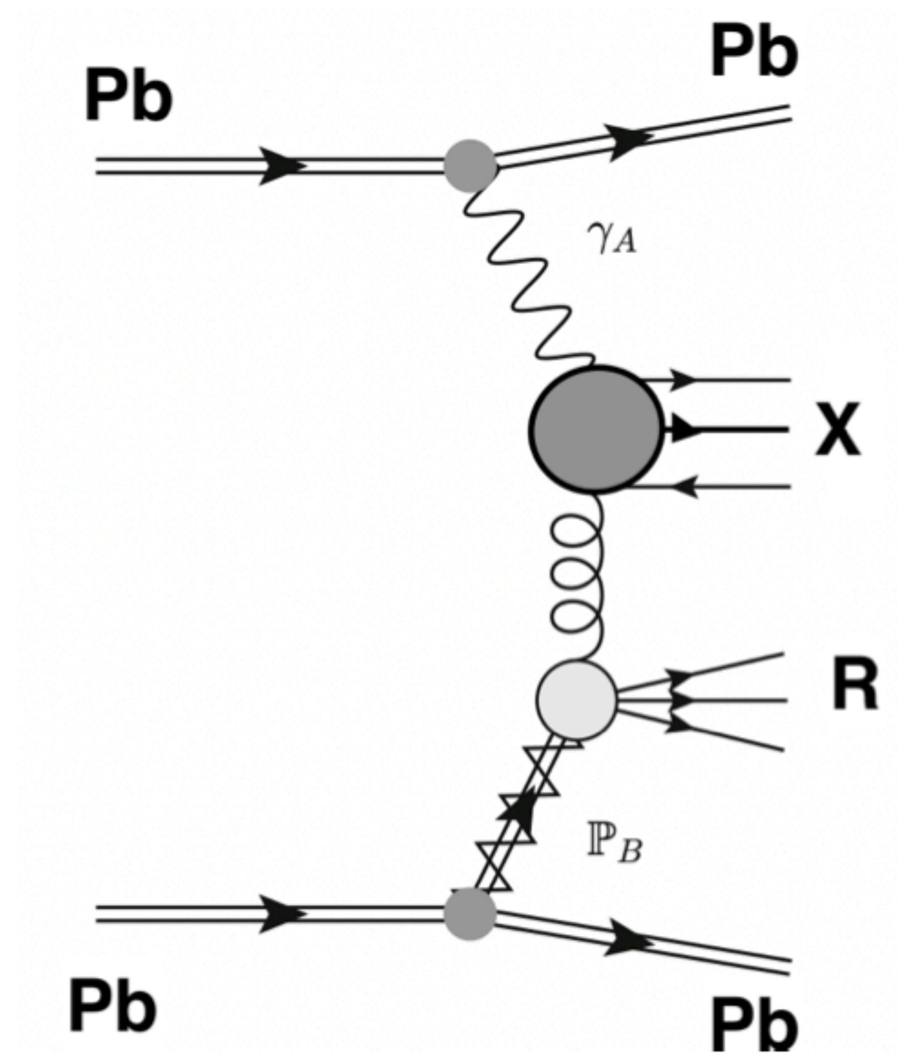


Background processes

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

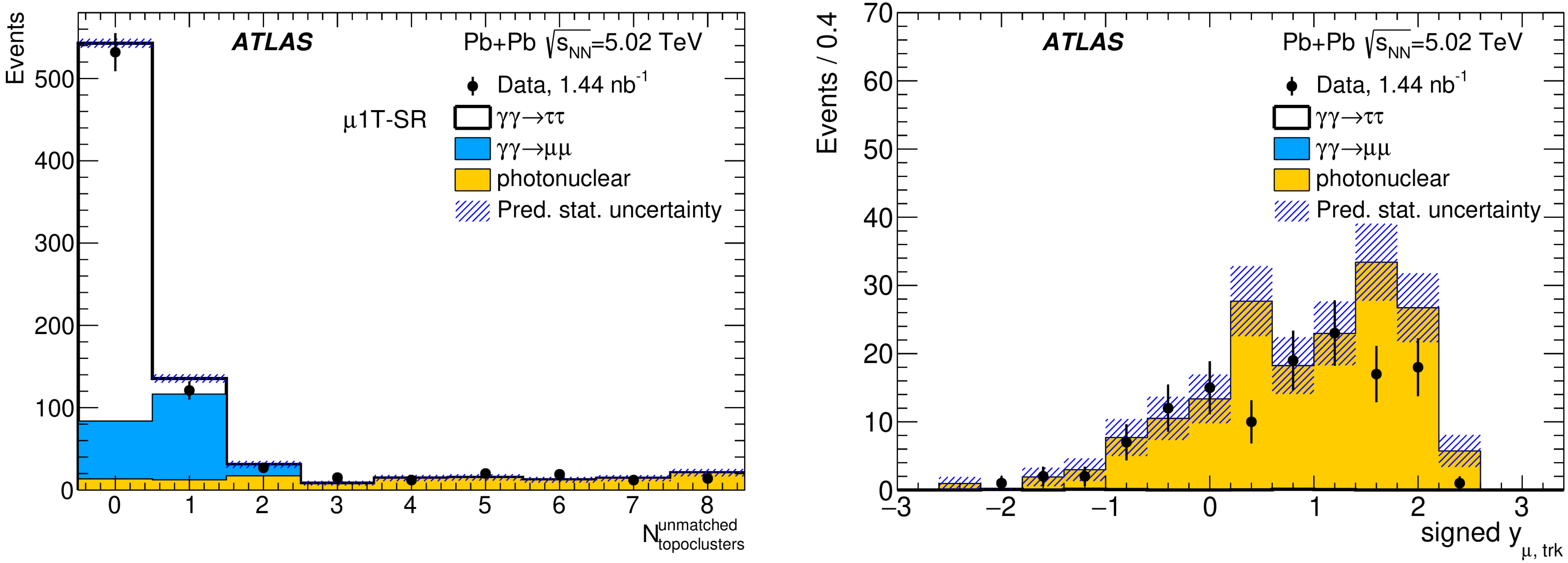


diffractive photonuclear events



Background estimation: diffractive photonuclear events

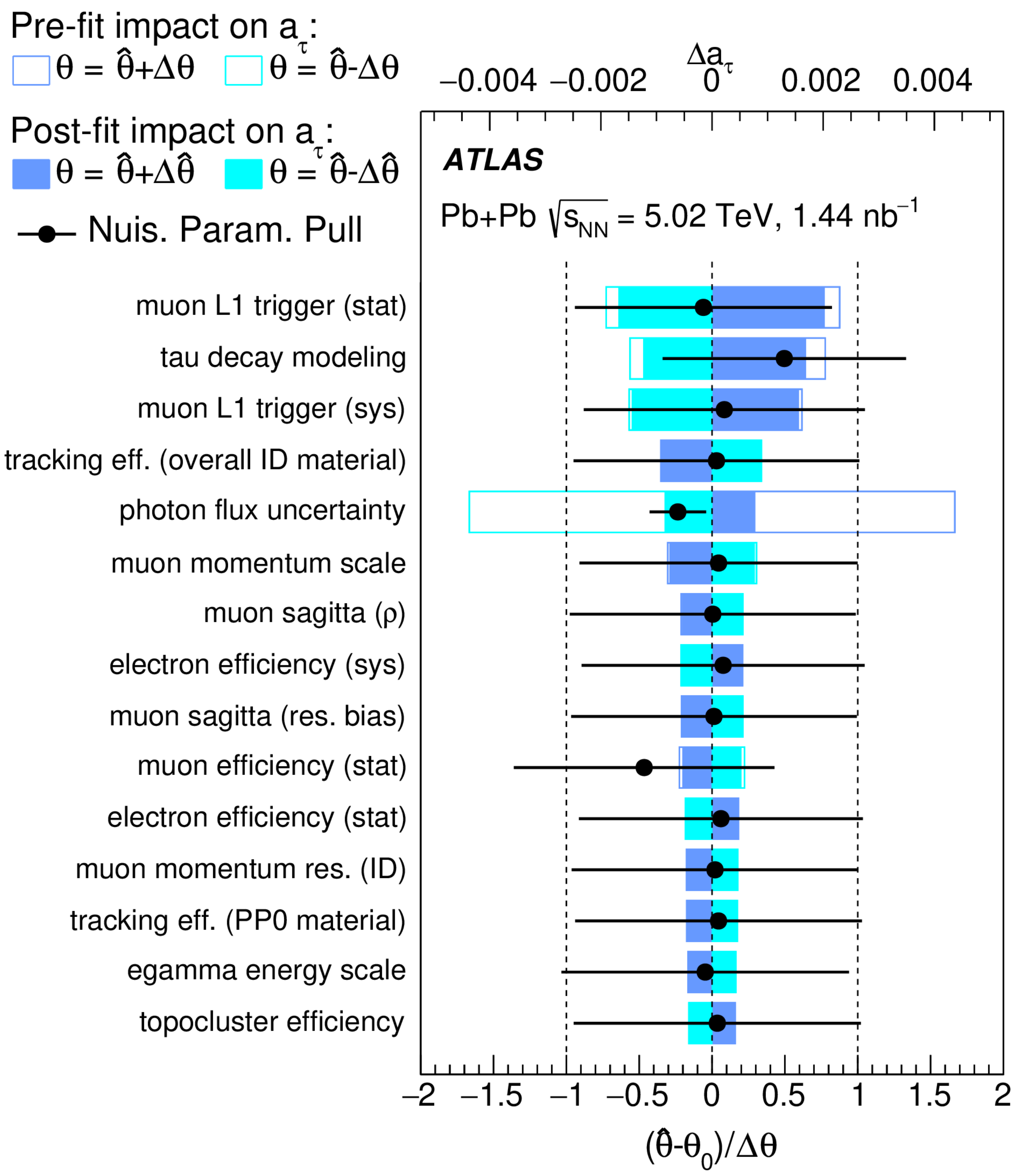
Phys. Rev. Lett. 131, 151802



- 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



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 $\gamma\gamma \rightarrow \tau\tau$ 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, $\mathrm{Pb+Pb} \rightarrow \mathrm{Pb}(\gamma\gamma \rightarrow \tau\tau)\mathrm{Pb}$, 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 $\gamma\gamma \rightarrow \tau\tau$ 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 ($\gamma\gamma \rightarrow \mu\mu$) 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