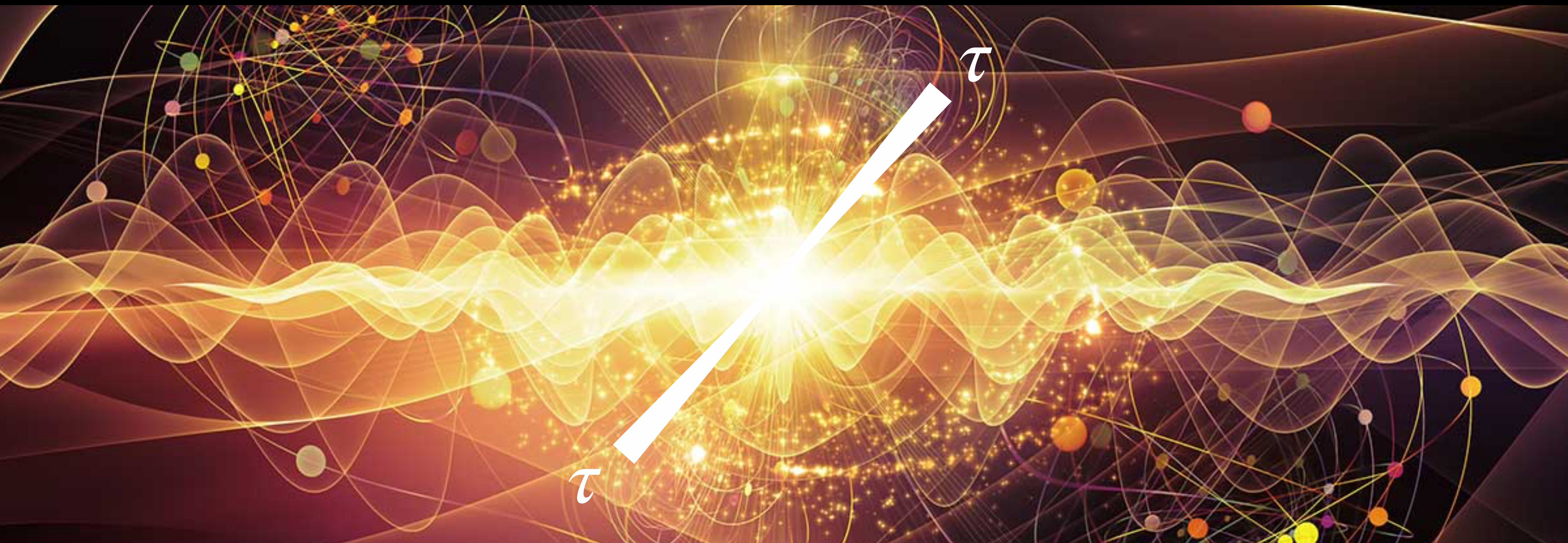
Measuring tau g-2 using ATLAS Pb+Pb collisions



Lydia Beresford on behalf of the ATLAS Collaboration

New Vistas in Photon Physics in Heavy-Ion Collisions
21st September 2022

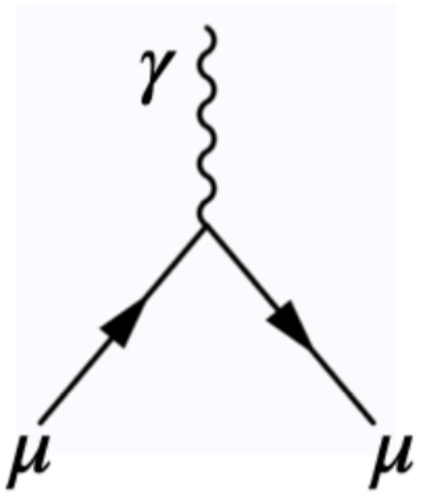
CERN

What is g-2?

Charged particles with spin have an intrinsic **magnetic moment:**

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

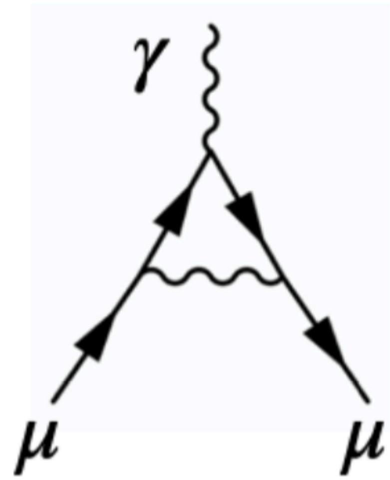
$g =$



2

Dirac 1928

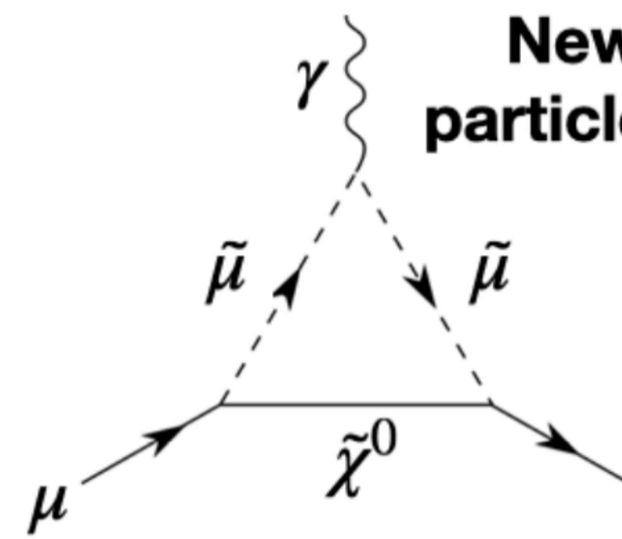
$+$



α/π

Schwinger 1948

$+ \cdots +$



New particles?

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

Lepton magnetic moments

Electron g-2: 10^{-8} precision, **-2.5σ, $+1.6\sigma$** discrepancy

Muon g-2: 10^{-7} precision, up to **$\sim 4.2\sigma$** discrepancy

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

What about the tau?

Do photons interact equally with all lepton generations?

→ Short tau lifetime 10^{-13}s

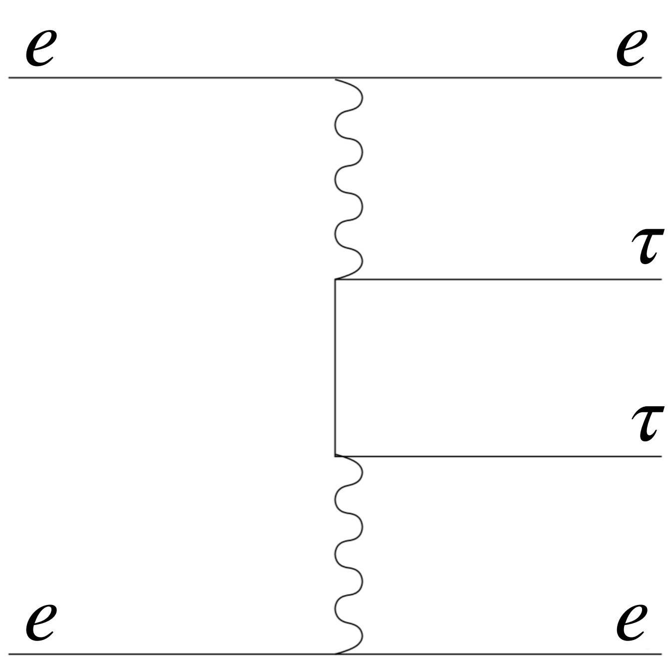
→ Extremely challenging experimentally!

Electron: Odom et at 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 collab Nature (2021)

Looking back …

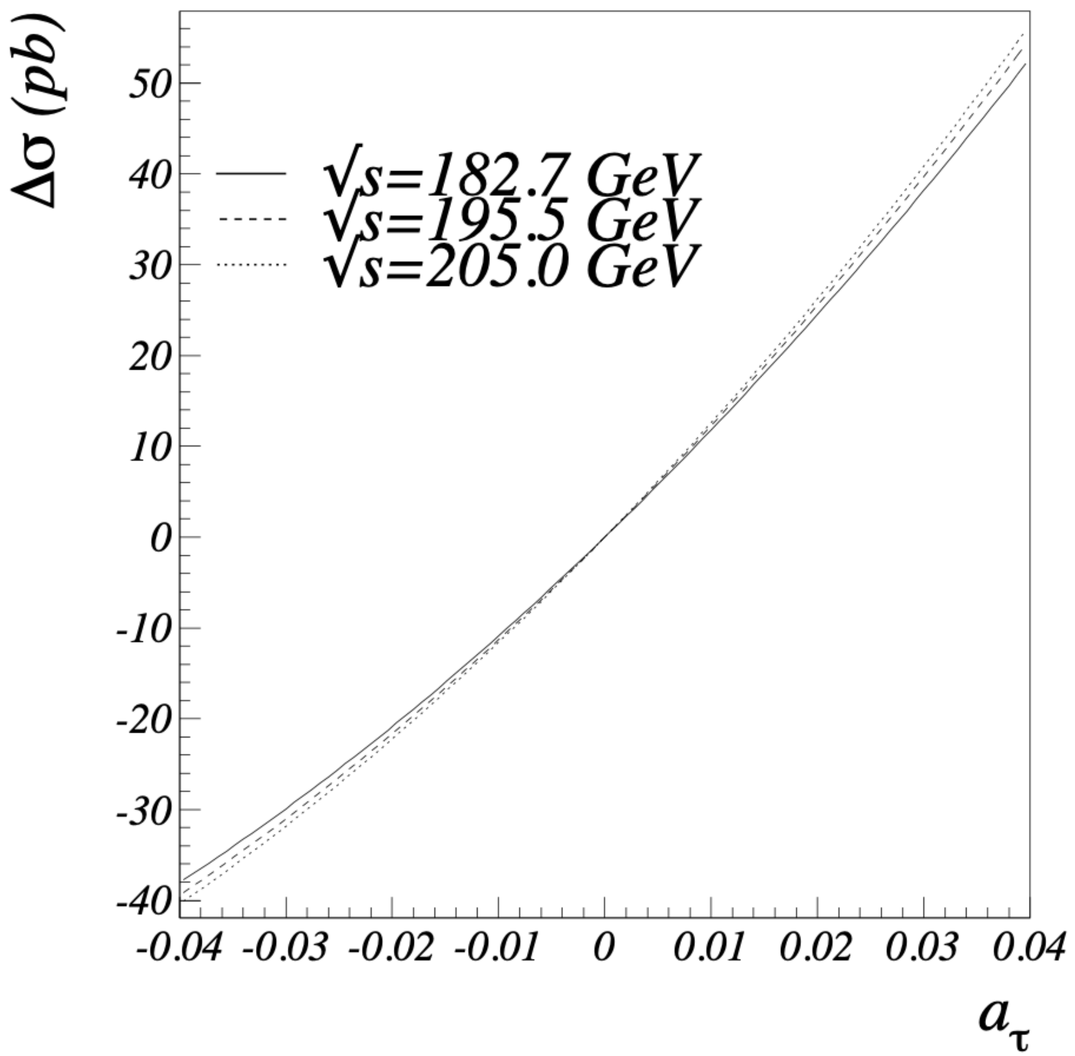
DELPHI Collaboration EPJC (2004)



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

Photo production of tau pairs

Idea: Measure cross-section, sensitive to a_τ



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

Limited by experimental uncertainty

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

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

Doesn't test 1-loop QED, Schwinger $a = \alpha/2\pi$ = 0.0012

Constraints also set by L3 & OPAL ($Z \to \tau\tau\gamma$)

Exp: DELPHI Collaboration EPJC (2004)

Theory: Eidelman & Passera MPLA (2007)

Can we beat it?

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

Potential to be most precise single-experiment measurement

Follow approach outlined in:

Beresford, Liu PRD (2020)

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

Highlights Recent Accepted Collections Authors Referees Search Press

Open Access

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

Dyndal, Kłusek-Gawenda, Szczurek & Schott PLB (2020)

ELSEVIER

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]

Aguila, Cornet & Illana PLB (1991)

ELSEVIER

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 realisation

ATLAS Collaboration [2204.13478](2204.13478) (accepted PRL)

arXiv > hep-ex > arXiv:2204.13478

Search...

Help | Advanced

High Energy Physics – Experiment

[Submitted on 28 Apr 2022]

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 $\mu_{\tau\tau} = 1.04^{+0.06}_{-0.05}$ 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 intervals for a_τ are $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$.

Physics briefing

See also CMS Collaboration [2205.05312](2205.05312)

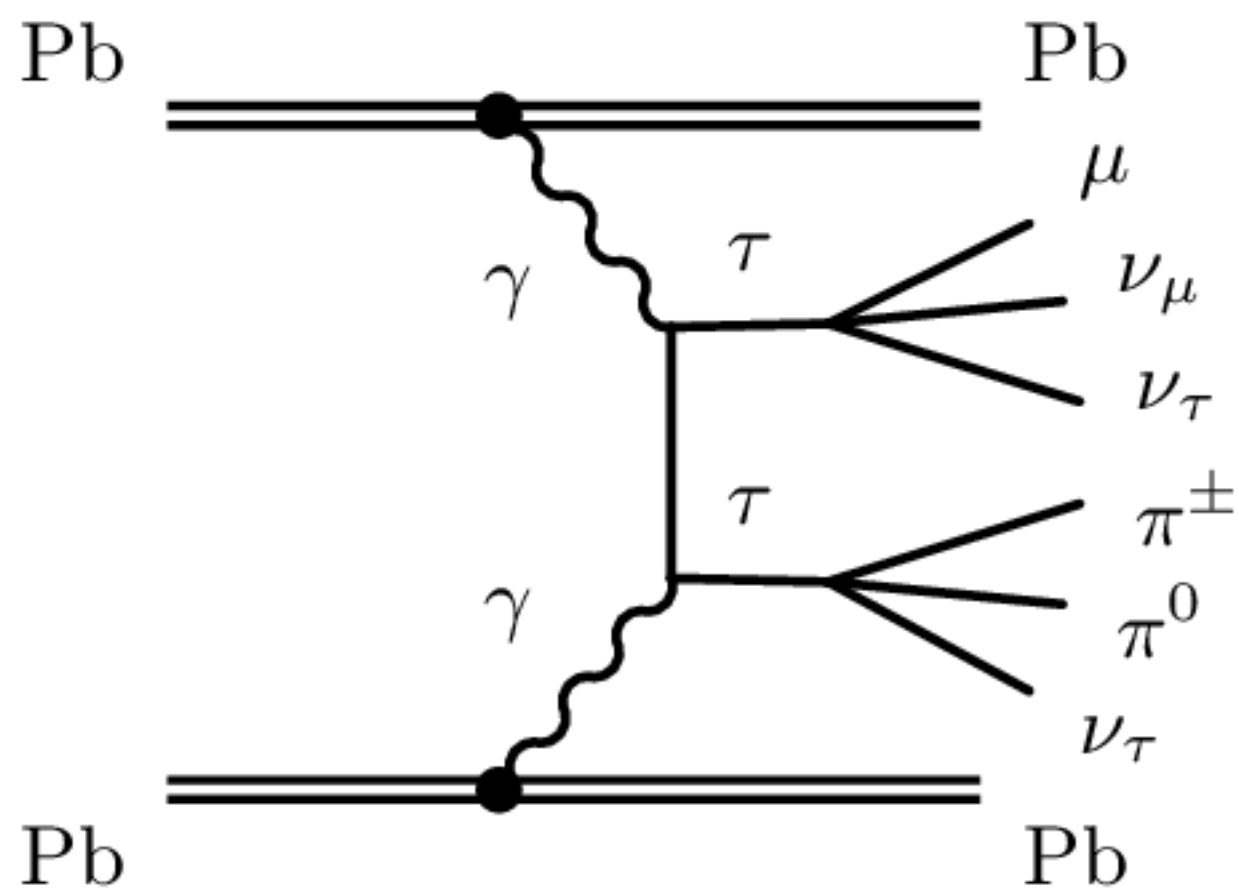
Our analysis strategy

See Jakub Kremer's talk for ATLAS UPC overview

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

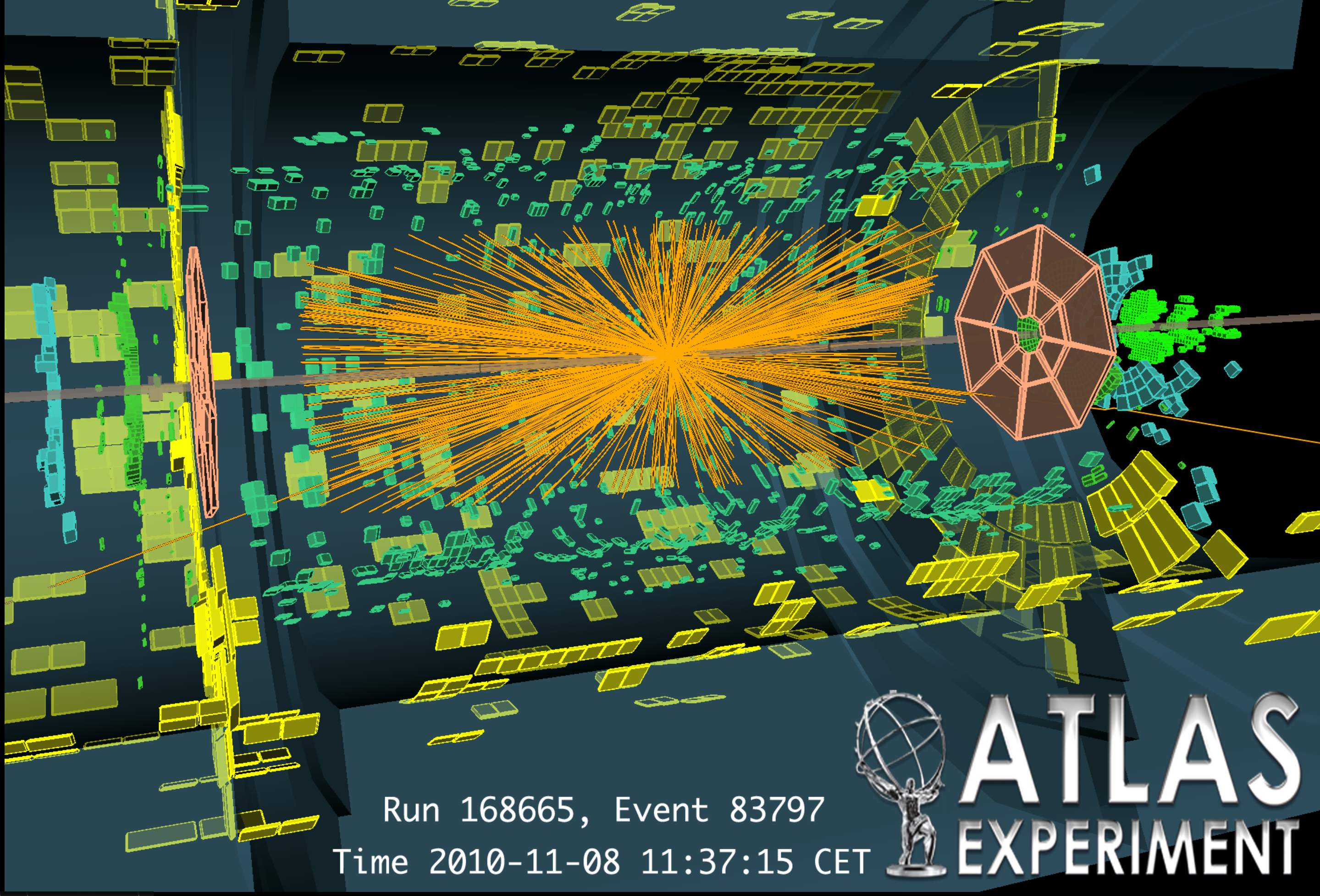
Photon collisions in Pb+Pb advantages:

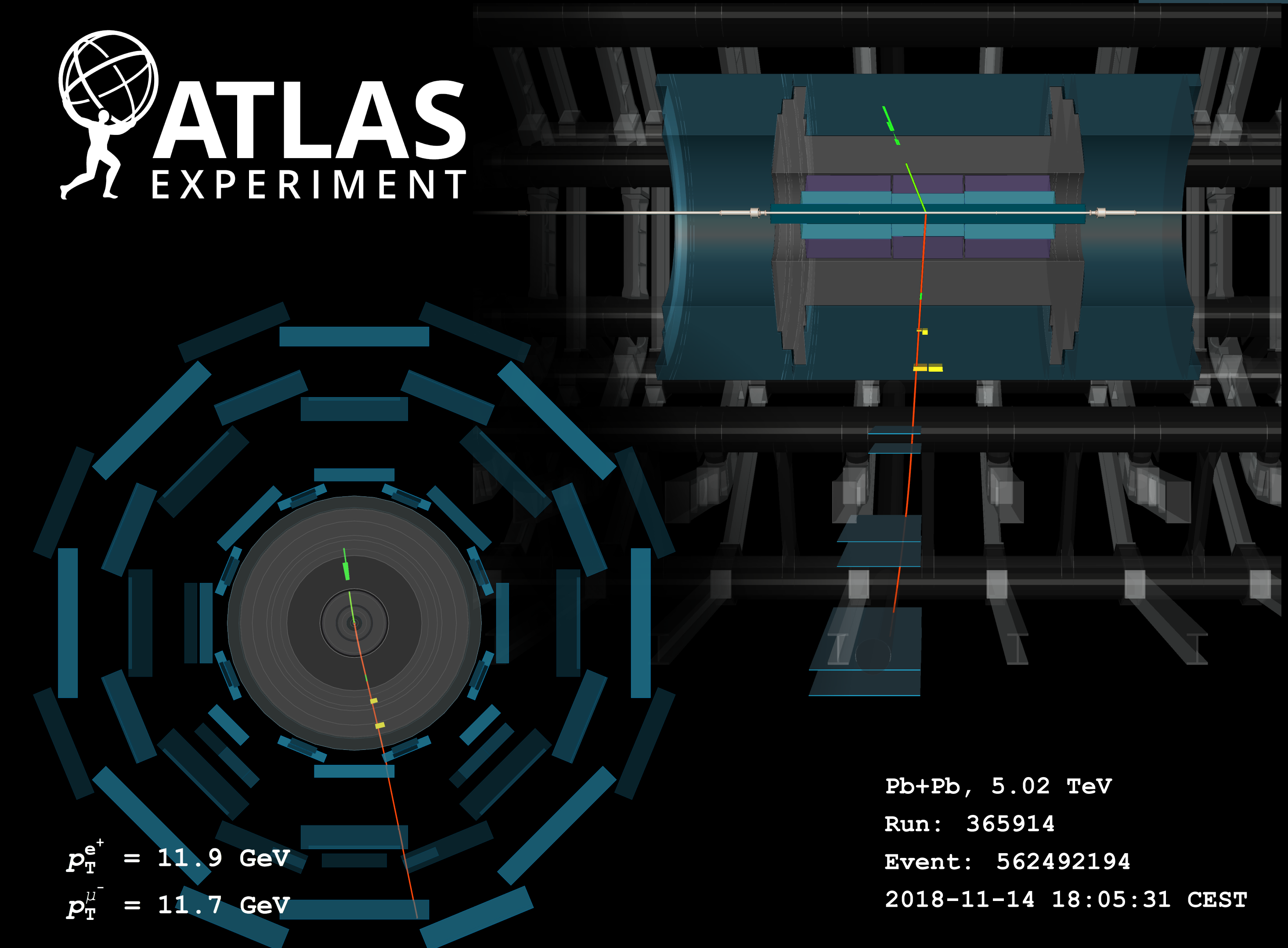
- Z^4 cross-section enhancement
- Super clean with ~0 pile-up
- Low trigger thresholds



$\sigma \sim$ 250 000 nb

Head-on Pb+Pb collision





Ultra-peripheral Pb+Pb collision

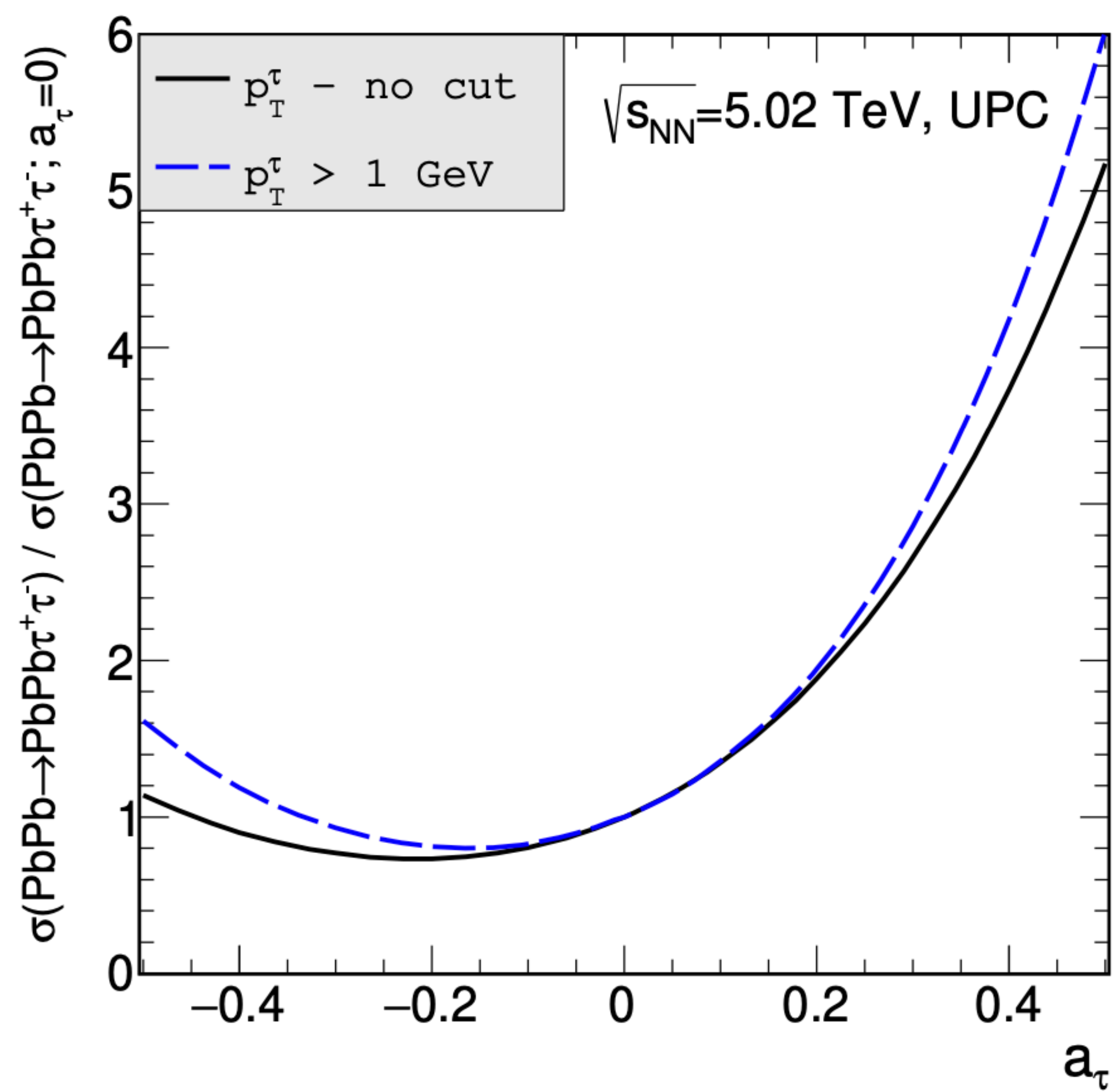
Our analysis strategy

Also sensitive to tau EDM

Cross-section sensitive to tau g-2

Additional sensitivity from measuring **differentially** in lepton p_T

Reduce uncertainties using $\gamma\gamma \rightarrow \mu\mu$ control region (2μ CR)
e.g. lumi, photon flux



Dyndal, Kłusek-Gawenda, Szczurek & Schutt PLB (2020)

Tau decays

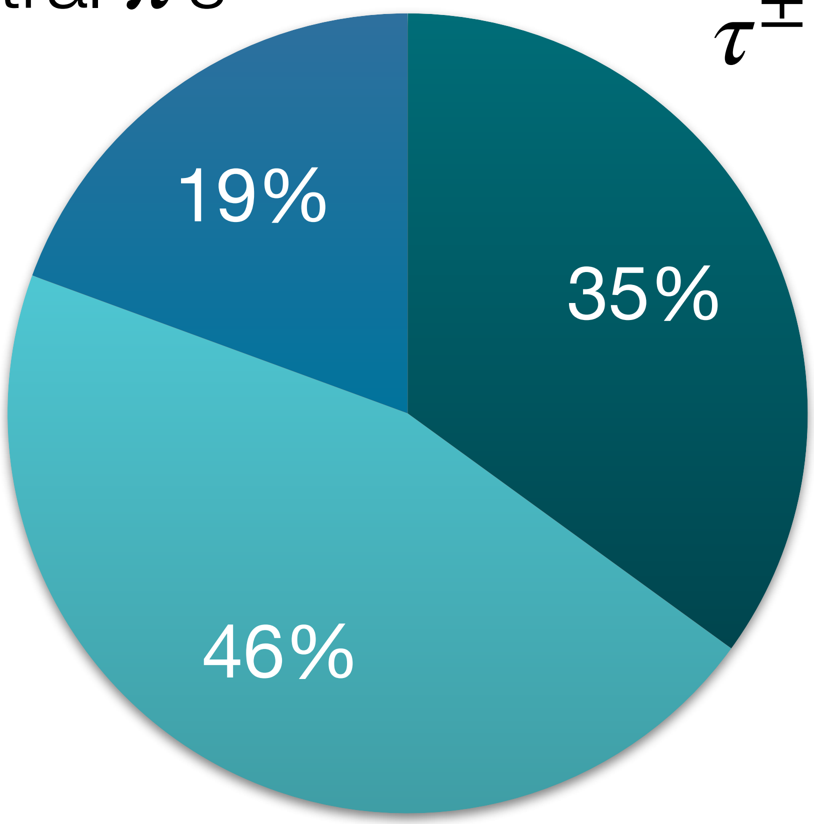
3 prong

$\tau^\pm \to \pi^\pm \pi^\mp \pi^\pm \nu_\tau$

$+ \geq 0$ neutral π's

Leptonic

$\tau^\pm \to l^\pm \nu_l \nu_\tau$



1 prong

$\tau^\pm \to \pi^\pm \nu_\tau$

$+ \geq 0$ neutral π's

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

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

Signature

Low momentum taus (up to a few 10s GeV)

Below ATLAS hadronic tau reconstruction threshold

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

Signal Regions (SRs)

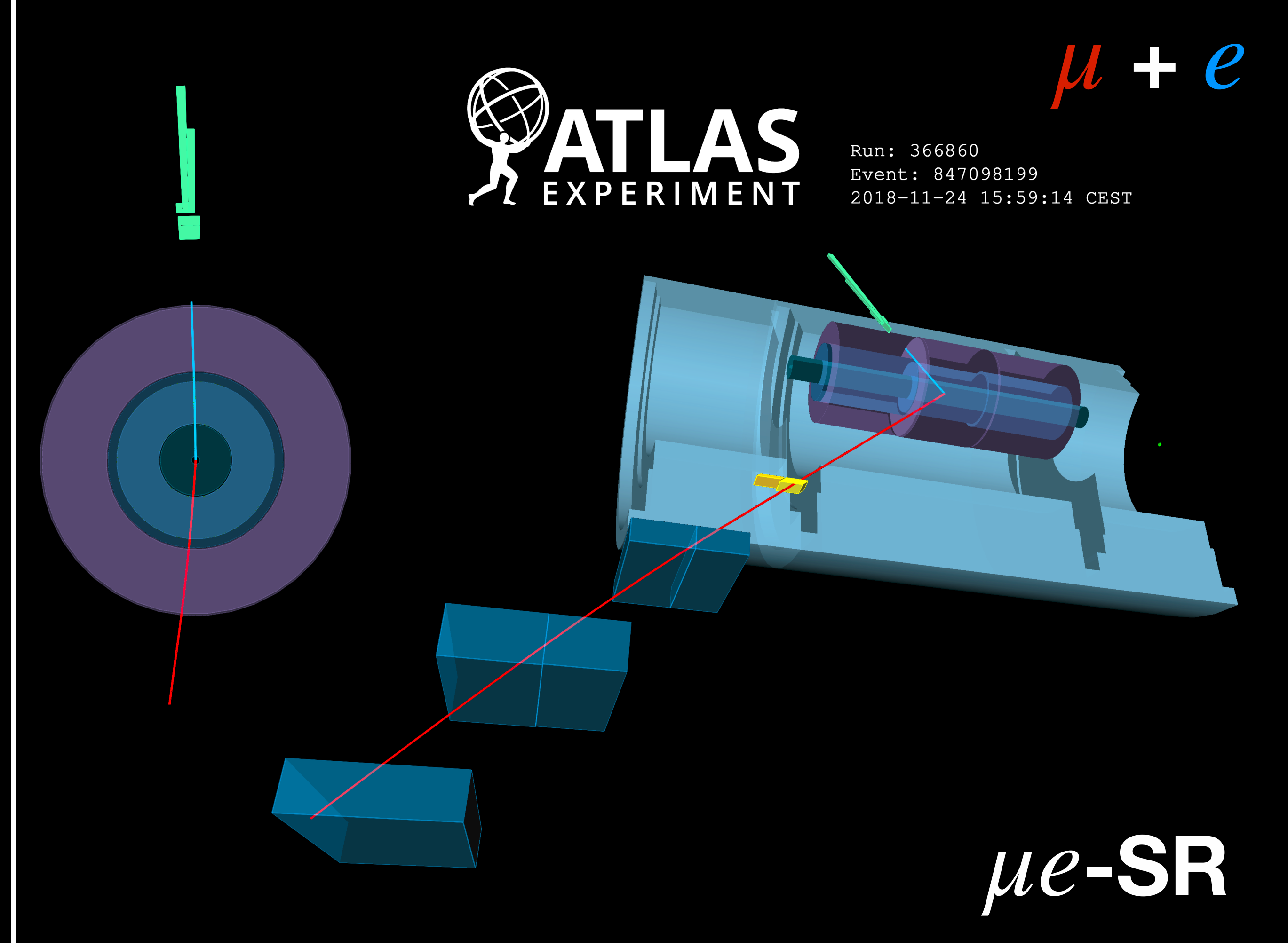
μ **+** e

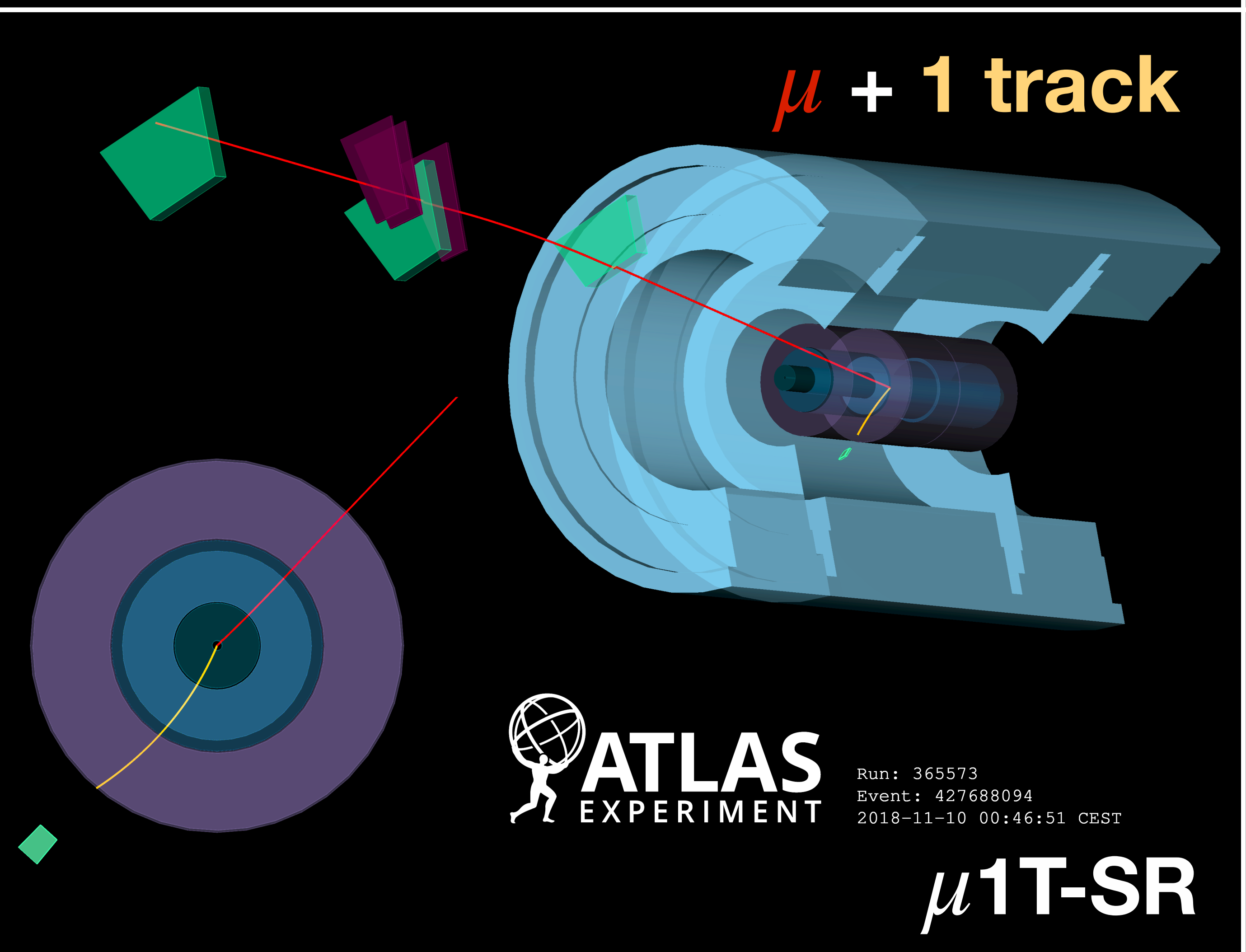
μ **+ 1 track** (from ℓ or hadron)

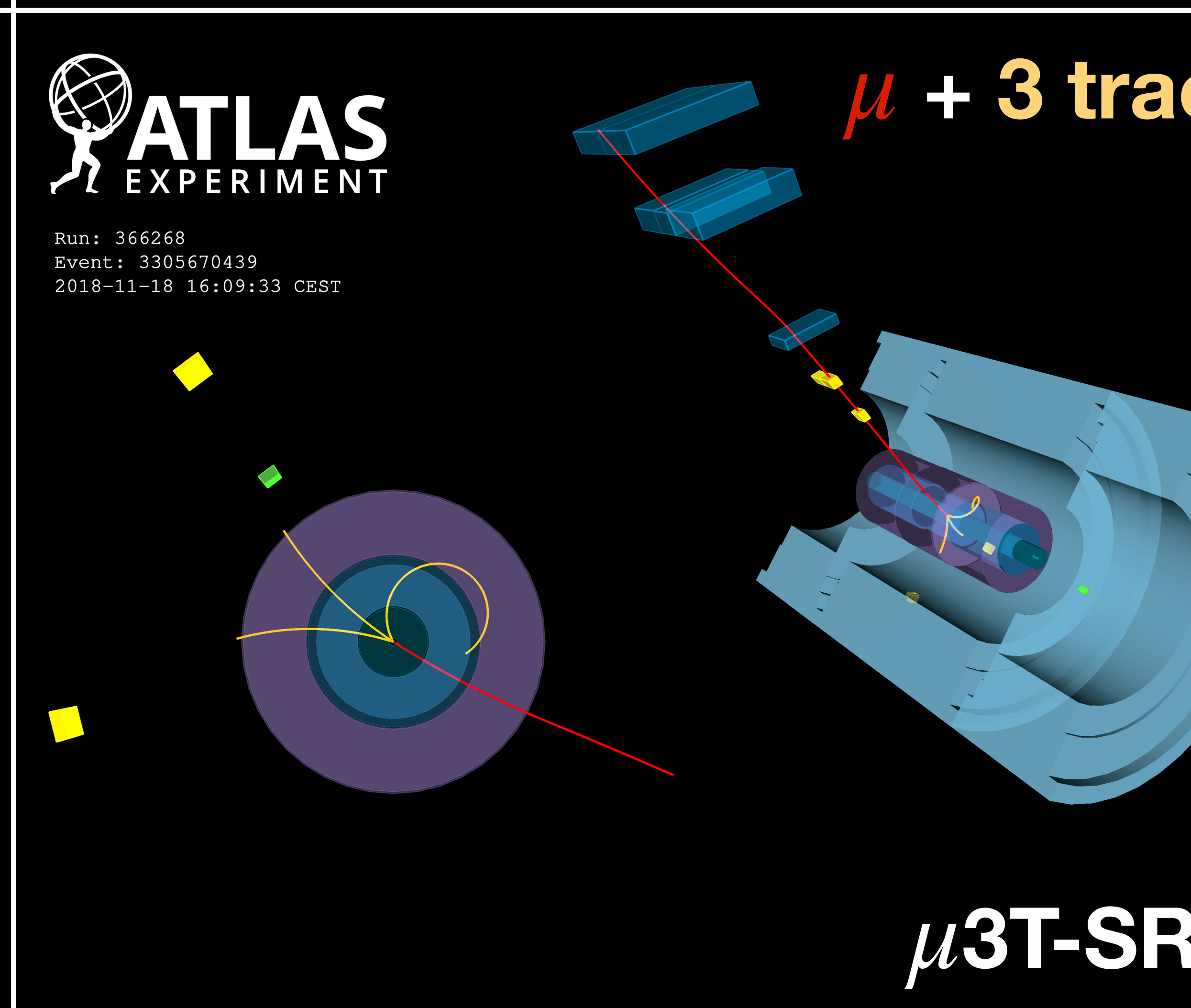
μ **+ 3 track** (from 3-prong τ decay)

← **Trigger on muon p_T > 4 GeV**

Signal Regions (SRs)



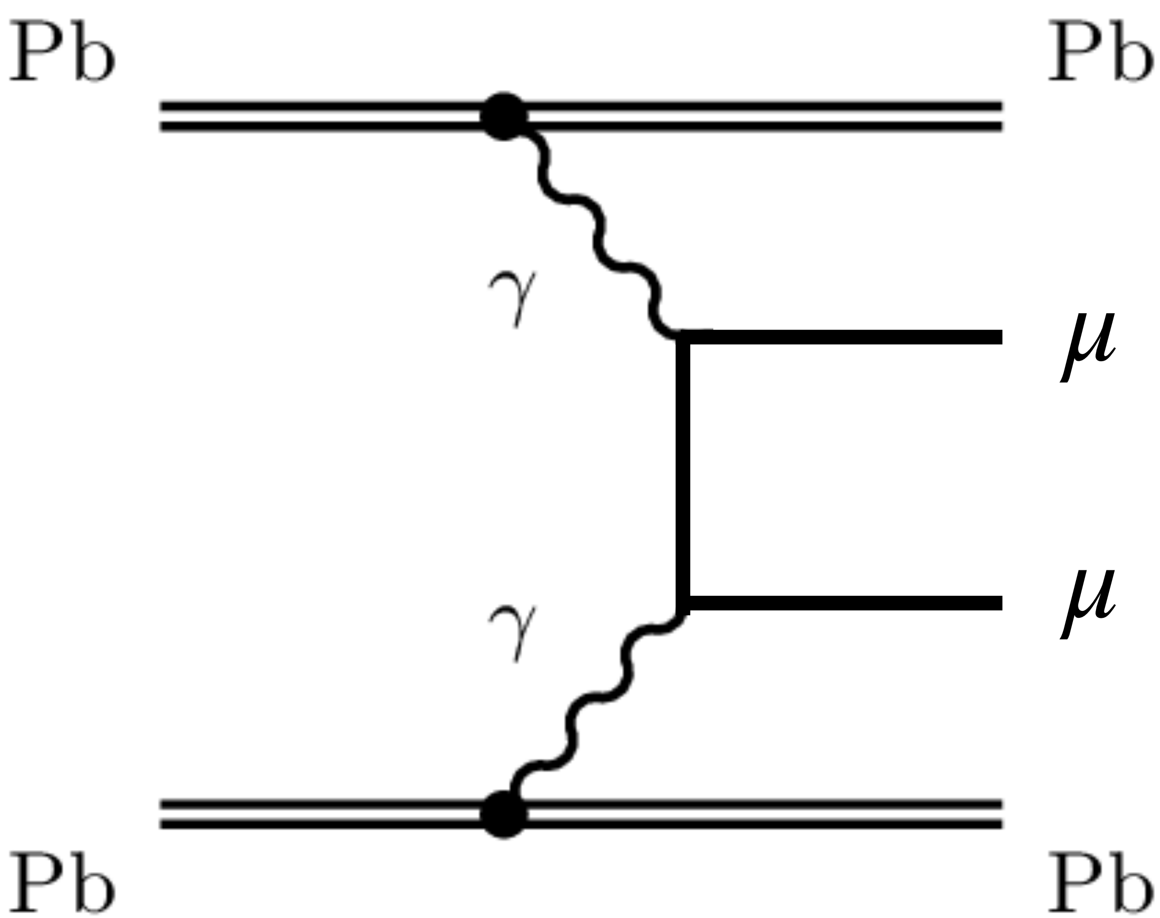




Main backgrounds

See Agnieszka Ogrodnik's talk for ATLAS UPC ee & $\mu\mu$ measurements

Di-muon



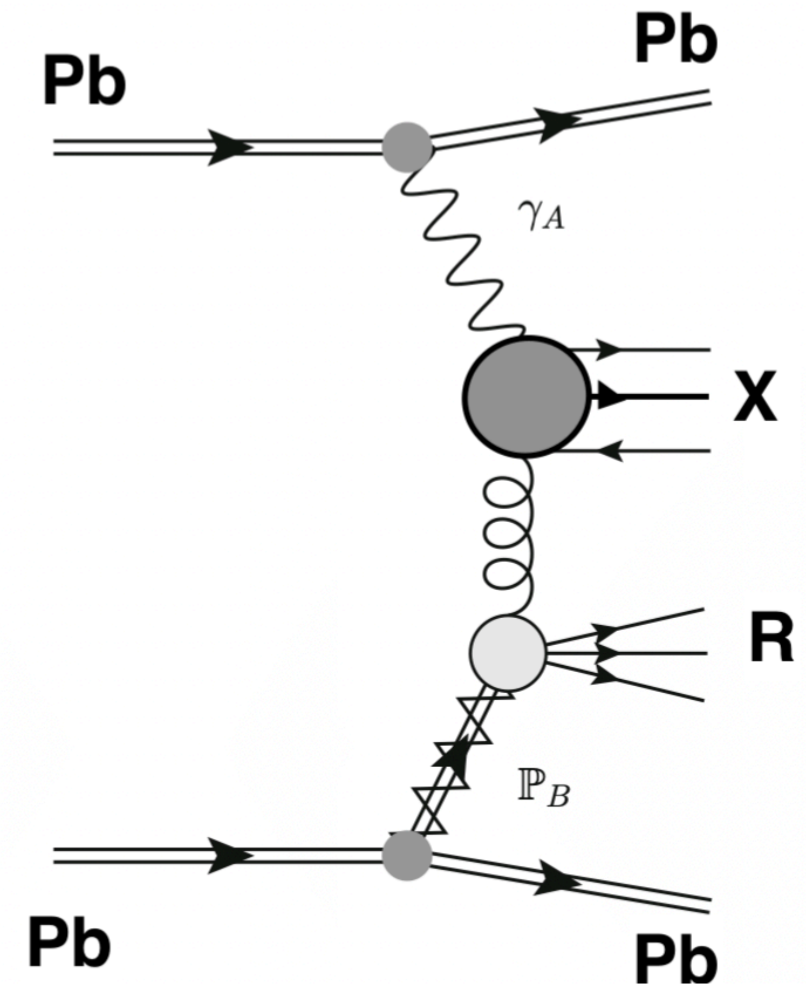
Estimate with MC

$\gamma\gamma \rightarrow \mu\mu$ Starlight + Pythia 8

$\gamma\gamma \rightarrow \mu\mu\gamma$ Madgraph 5

Photon flux re-weighted to SuperChic 3

Photonuclear e.g.



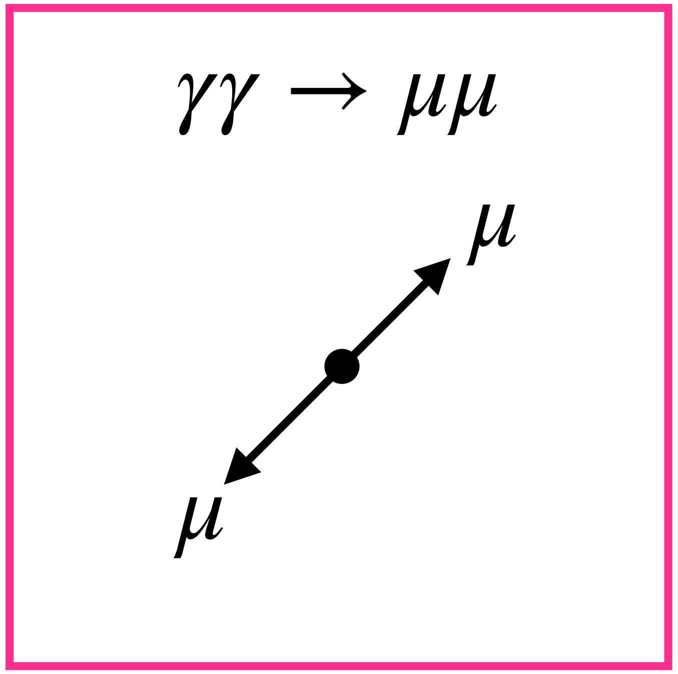
Data-driven estimate

Often leads to nucleus breakup

→ Forward neutrons

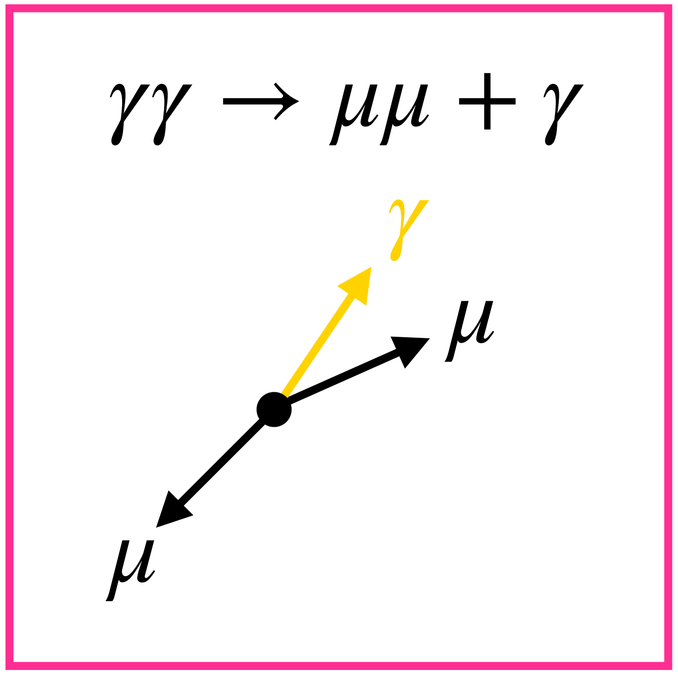
Rejecting background

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



Reject $\gamma\gamma \to \mu\mu$ (balanced 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

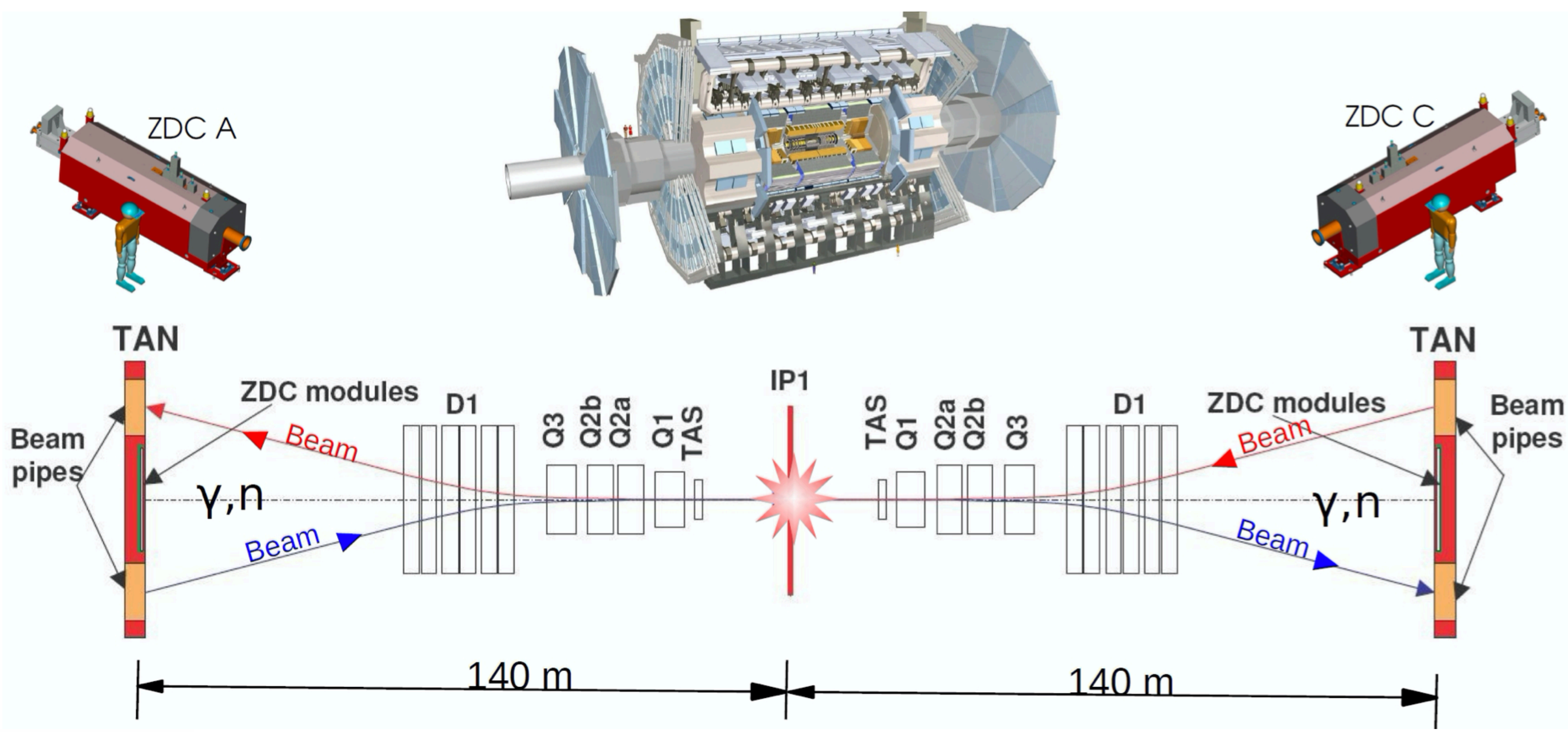
$E_T(\gamma) > 1.5$ GeV

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

Rejecting background

Rejecting photo-nuclear & other bkgs:

- Zero Degree Calorimeter Energy (E_{ZDC}) < 1 TeV on side A & C (0n0n)
- No unmatched clusters i.e. not near μ or track(s), for μ + track(s) SRs
- m(trks) < 1.7 GeV for μ3T-SR



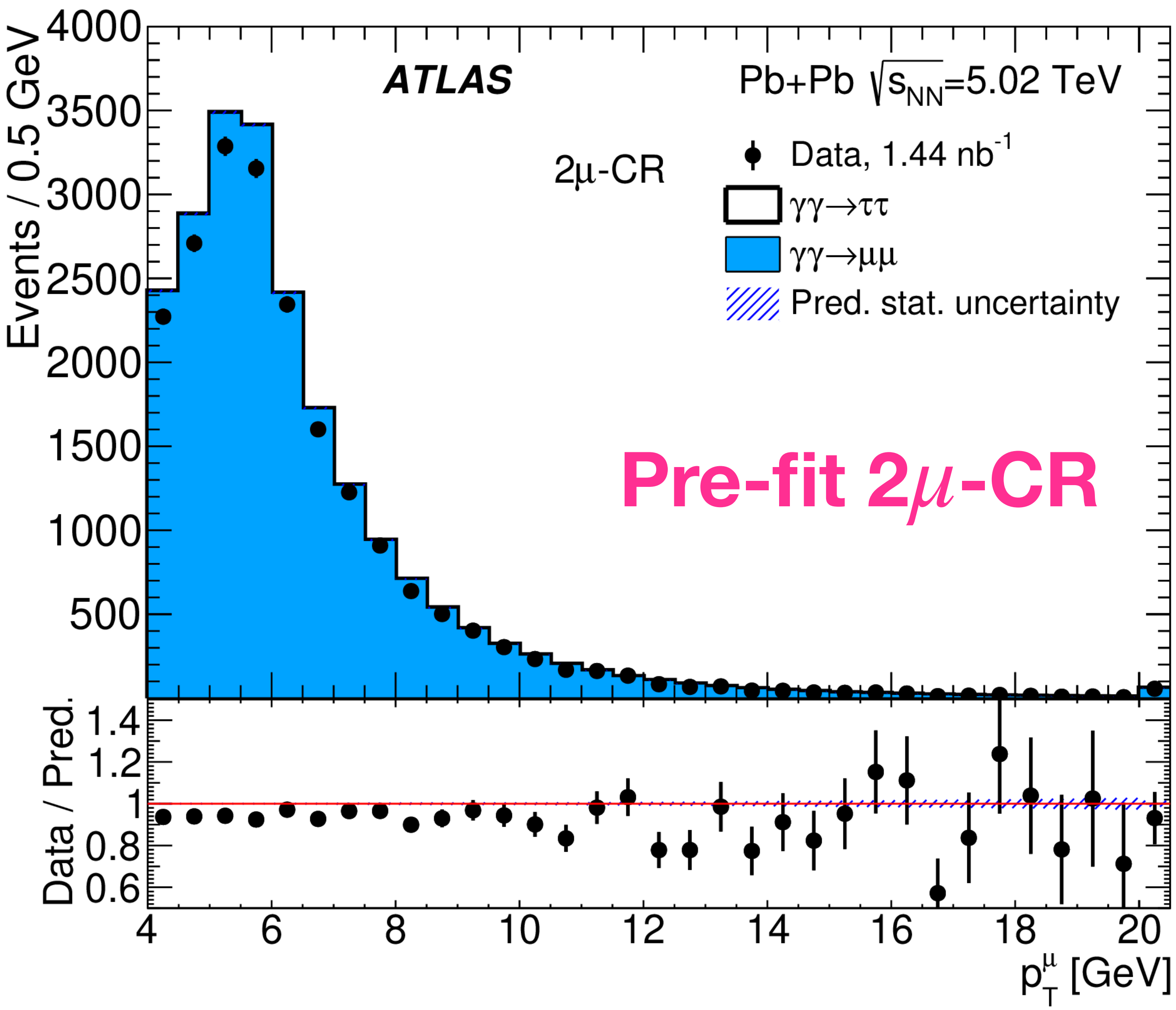
Background estimation: $\gamma\gamma \rightarrow \mu\mu(\gamma)$

Main background

MC with Superchic 3 photon flux (+6% overestimate)

c.f. -13% for Starlight photon flux

Difference = photon flux uncertainty

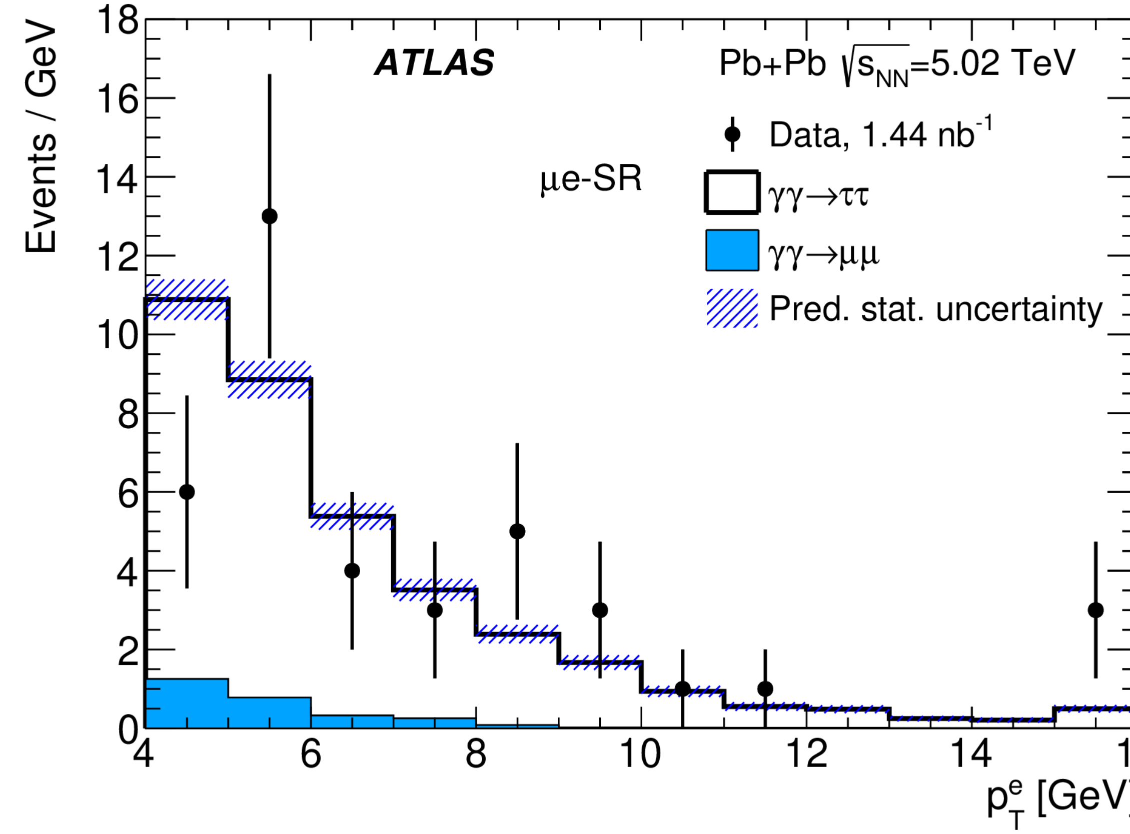


Signal region summary

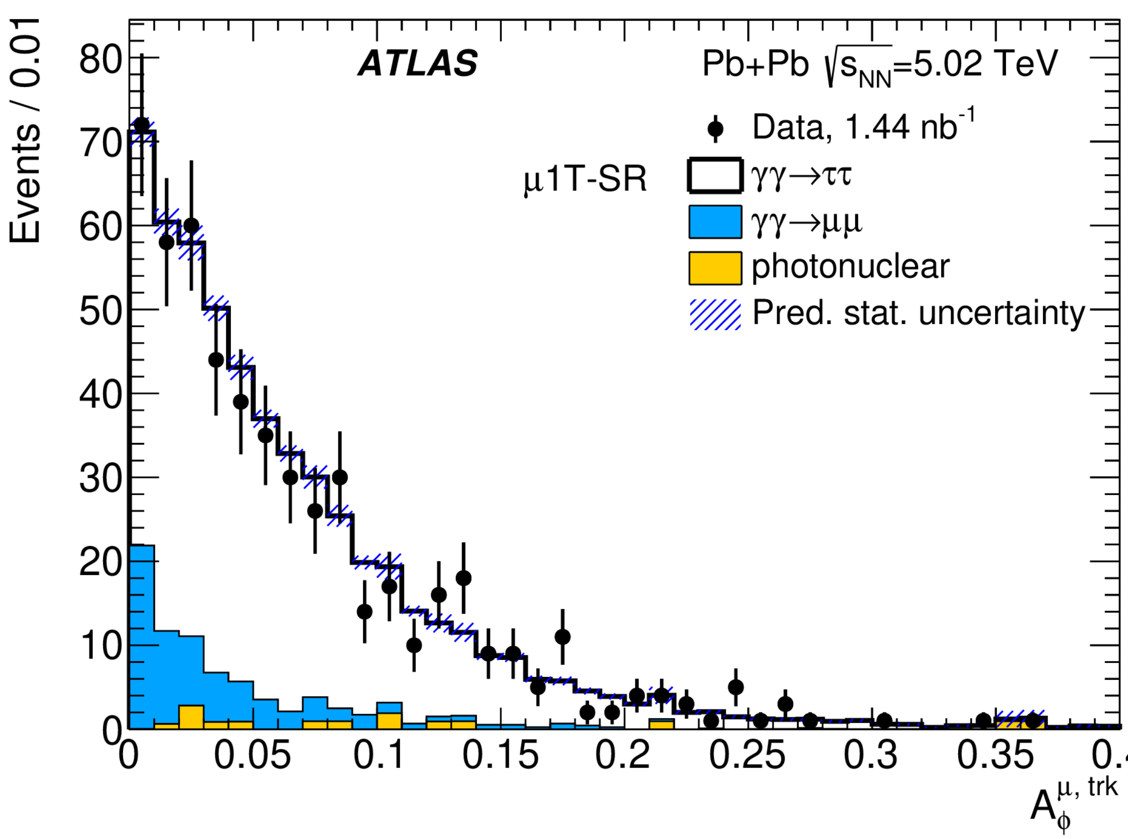
Pre-fit distributions

- Good modelling
- Minimal backgrounds

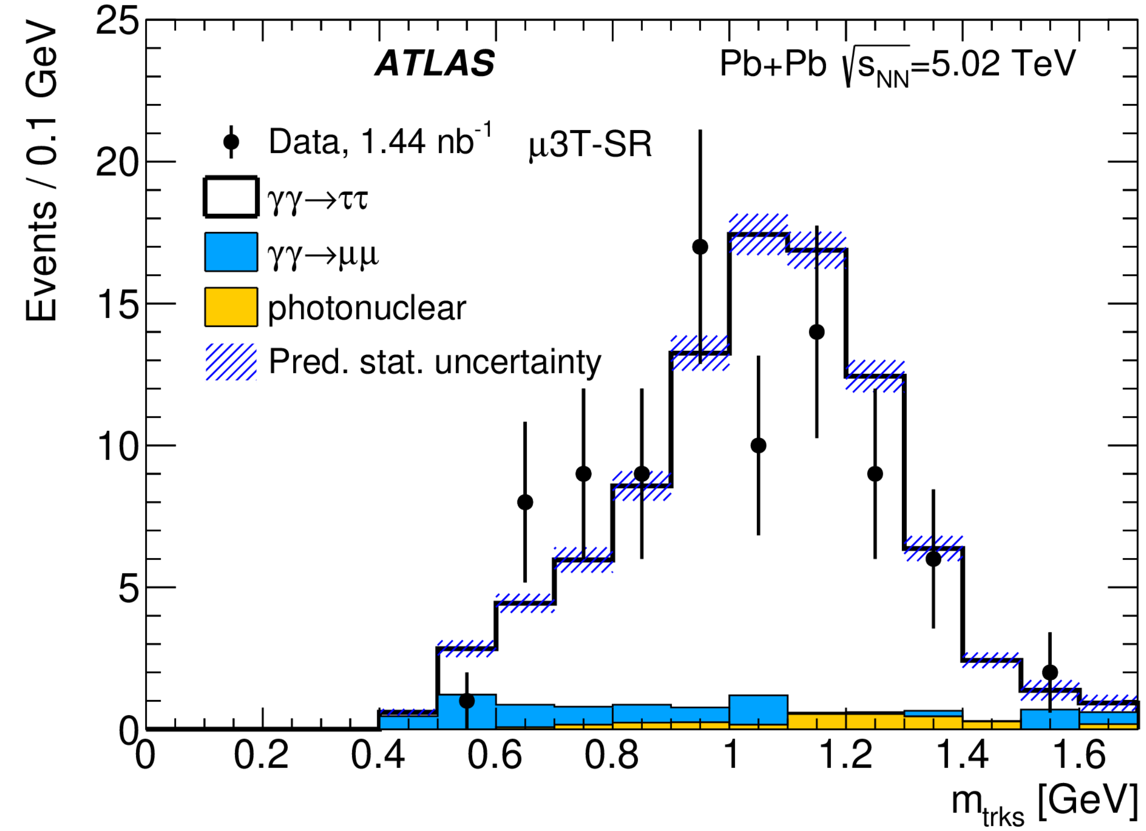
μe-SR: $N_{obs} = 39$, $N_{bkg} = 2.8 \pm 0.7$



μ1T-SR: $N_{obs} = 532$, $N_{bkg} = 84 \pm 19$



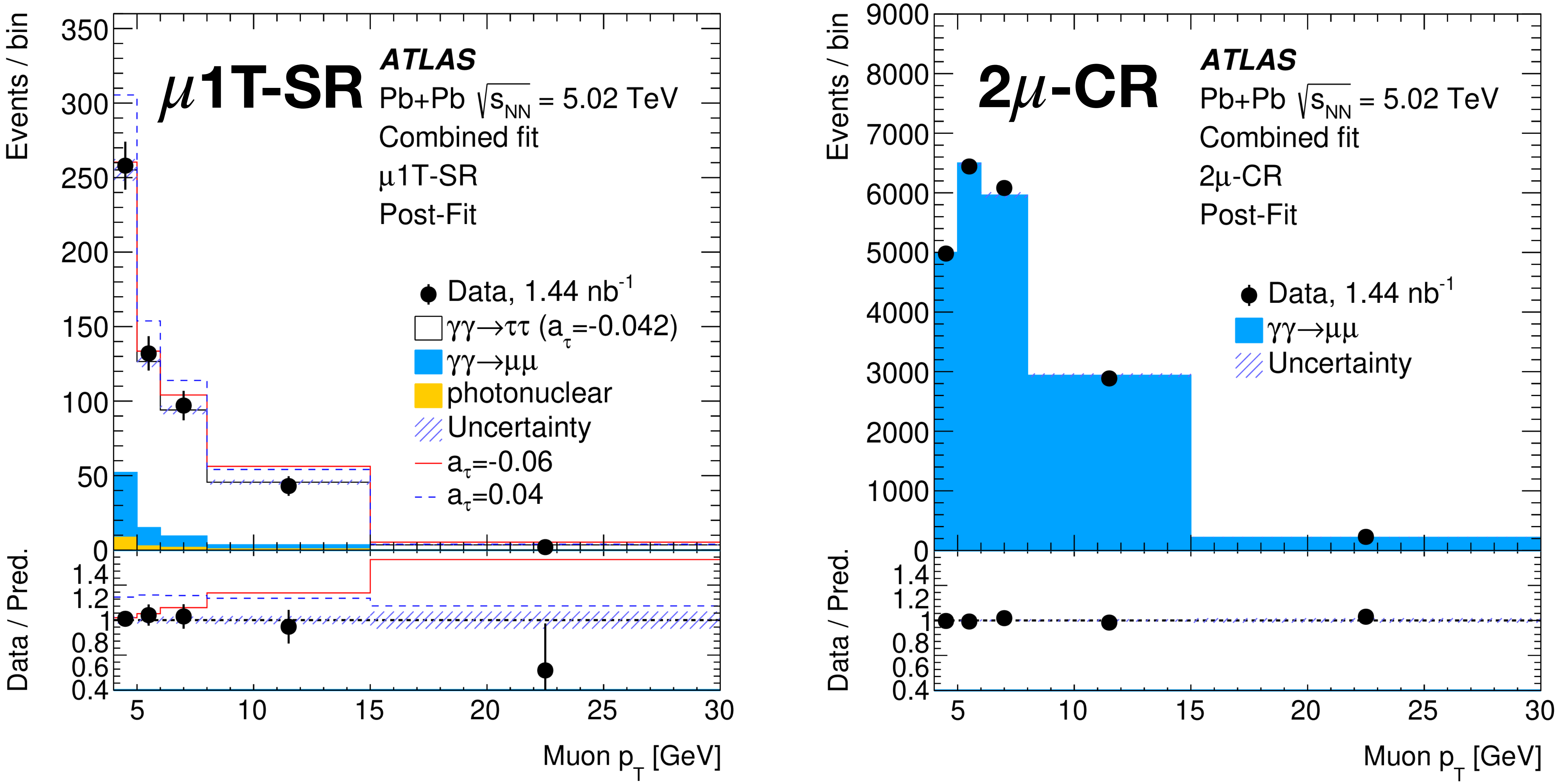
μ3T-SR: $N_{obs} = 85$, $N_{bkg} = 10 \pm 3$



Observing $\gamma\gamma \to \tau\tau$ in Pb+Pb

Extract signal strength and a_τ using profile likelihood fit

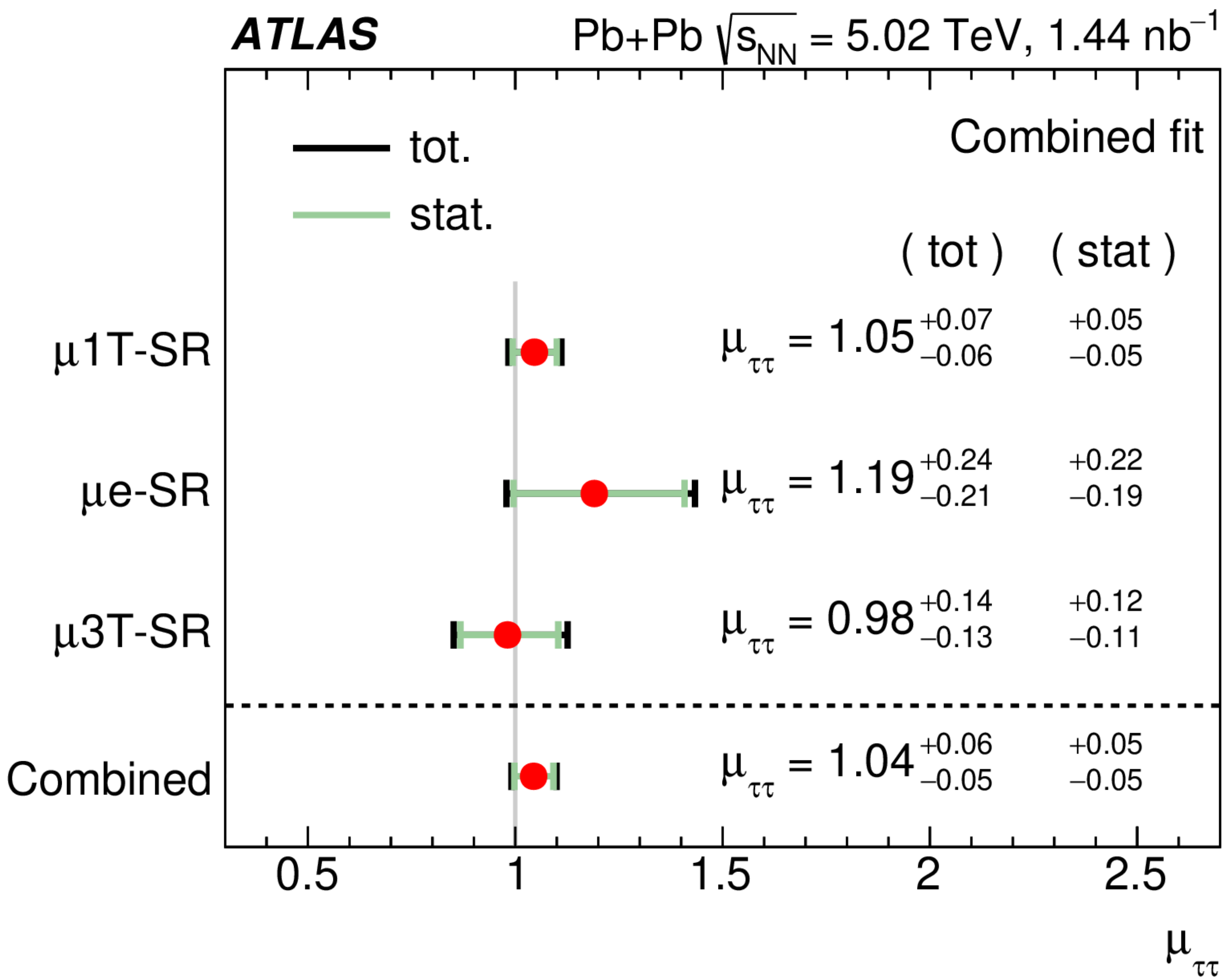
Fit muon p_T distribution in 3 SRs & 2μ-CR



Clear observation of $\gamma\gamma \to \tau\tau$ at the LHC

Signal strength

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

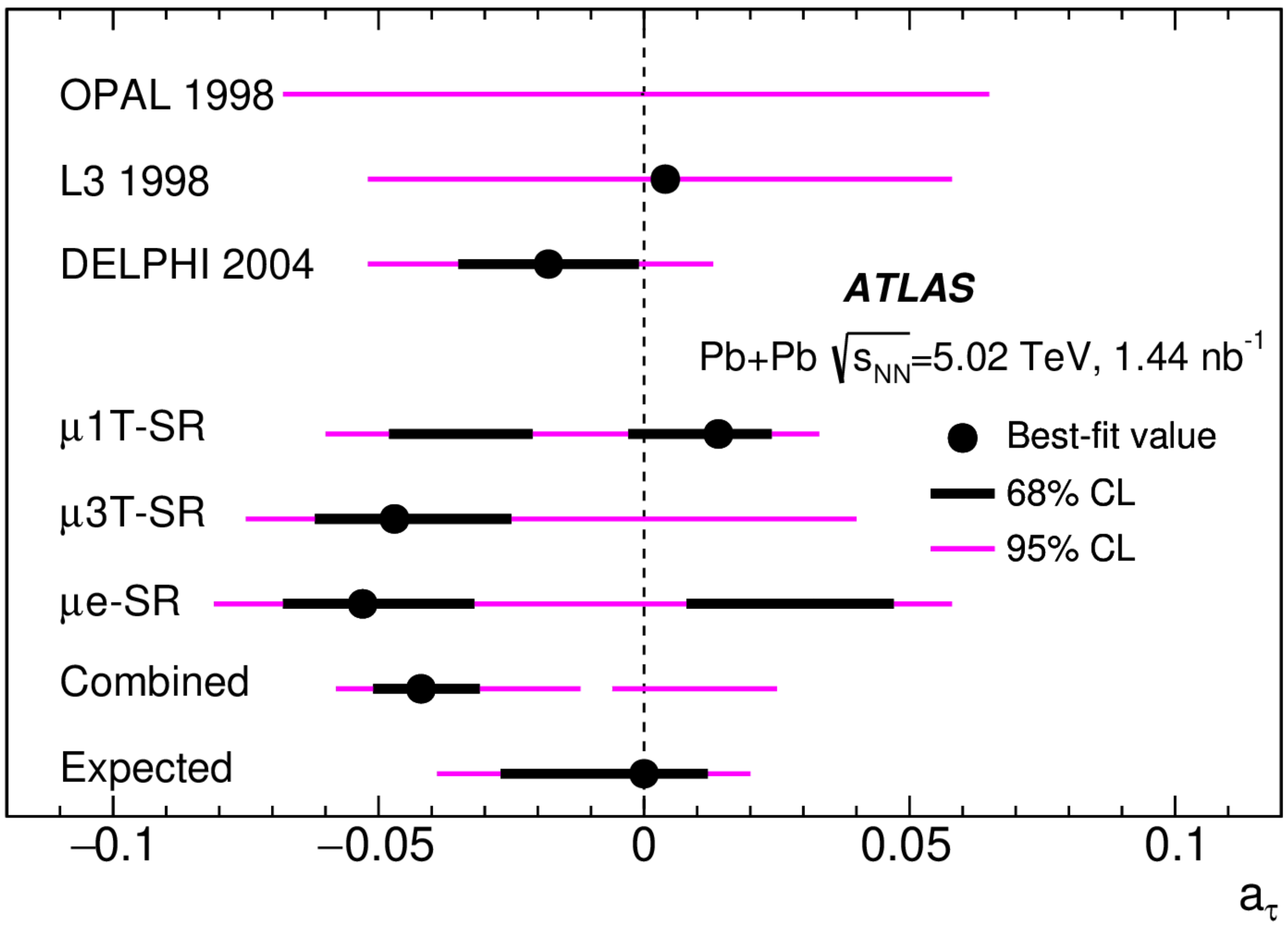


Each SR compatible with unity, 5% precision, **stats limited**

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



Competitive with DELPHI

5% precision on gτ

Statistical uncertainty dominates

Summary

Tau g-2 is interesting & important but poorly constrained

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

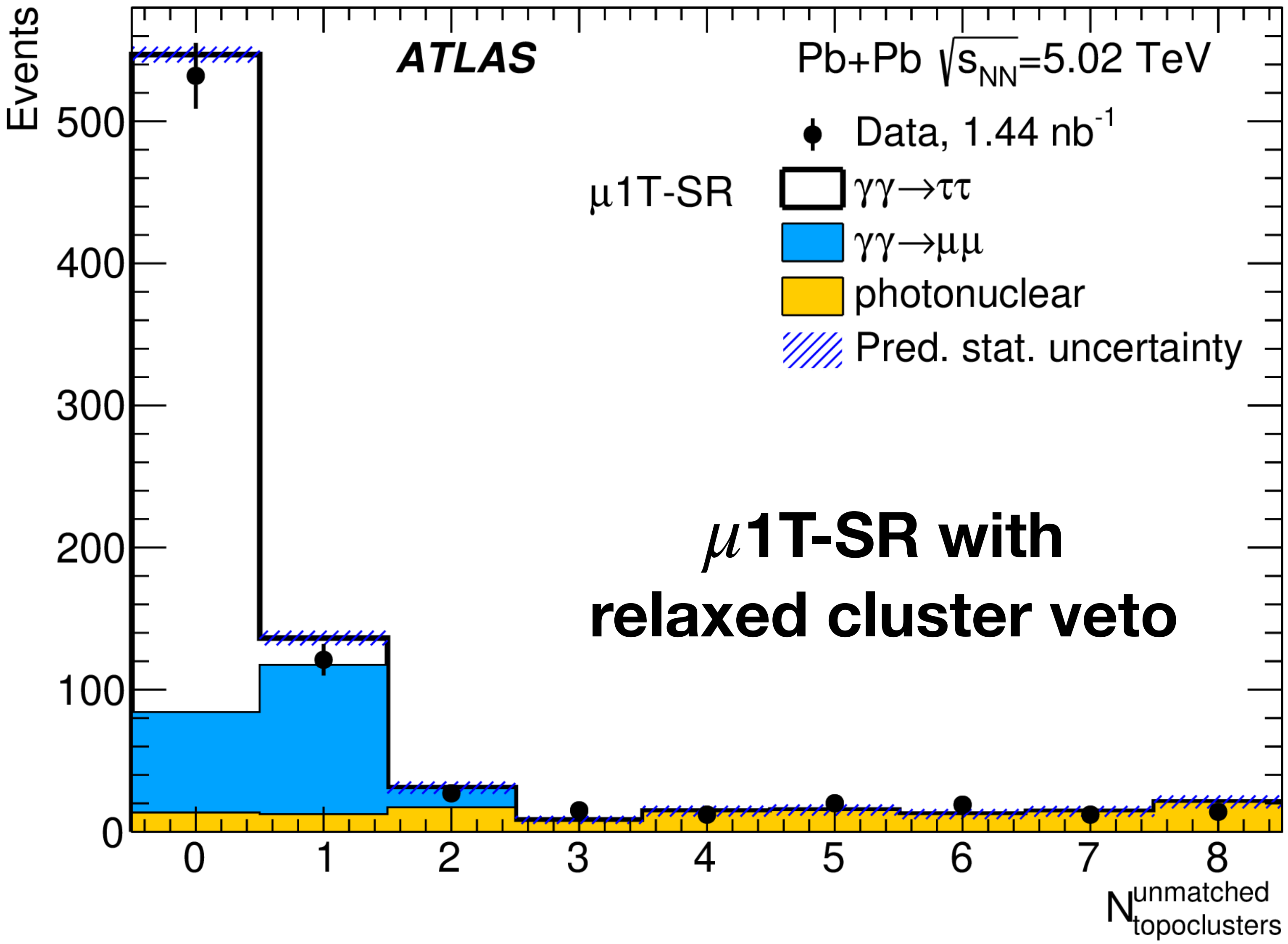
Hadron collider constraints competing with LEP

SR signal MC cutflow

Requirement	Number of $\gamma\gamma \rightarrow \tau\tau$ events
Common selection	
$\sigma \times \mathcal{L}$	352600
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	28399
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}} \times w_{\text{SF}}$	35400
Pass trigger	1852
$E_{\text{ZDC}}^{A,C} < 1$ TeV	1122
μ1T-SR	
$N_{\mu}^{\text{preselected}} = 1$	1029
$N_{\mu}^{\text{signal}} = 1$	906
$N_e = 0$	873
N_{trk} (with $\Delta R_{\mu,\text{trk}} > 0.1$) = 1	579
Zero unmatched clusters	556
$\sum$ charge = 0	550
$p_{\text{T}}^{\mu,\text{trk}} > 1$ GeV	506
$p_{\text{T}}^{\mu,\text{trk},\gamma} > 1$ GeV	485
$p_{\text{T}}^{\mu,\text{trk,clust}} > 1$ GeV	465
$A_{\phi}^{\mu,\text{trk}} < 0.4$	462
μ3T-SR	
$N_{\mu}^{\text{preselected}} = 1$	1029
$N_{\mu}^{\text{signal}} = 1$	906
$N_e = 0$	873
N_{trk} (with $\Delta R_{\mu,\text{trk}} > 0.1$) = 3	88.7
Zero unmatched clusters	85.8
$\sum$ charge = 0	84.7
$m_{\text{trks}} < 1.7$ GeV	84.0
$A_{\phi}^{\mu,\text{trks}} < 0.2$	83.9
μe-SR	
$N_{\mu}^{\text{signal}} = 1$	965
$N_e = 1$	34.1
N_{trk} (with $\Delta R_{\mu/e,\text{trk}} > 0.1$) = 0	32.8
$\sum$ charge = 0	32.7

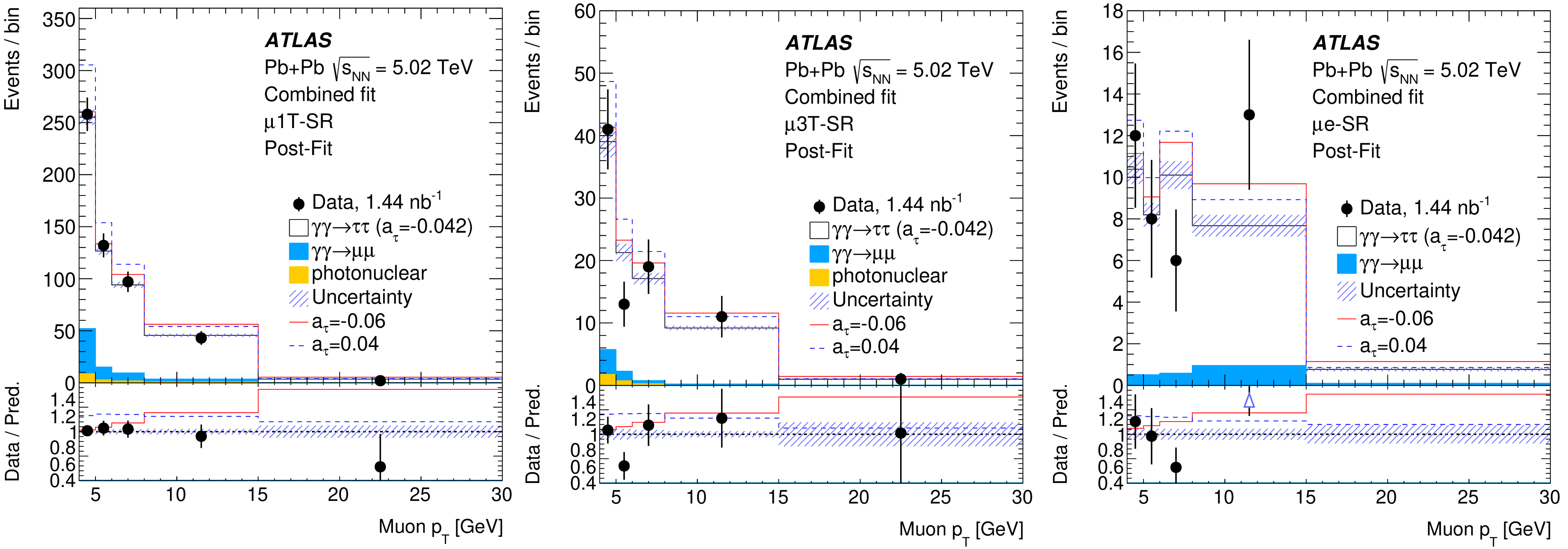
Estimating bkgs: Diffractive photo-nuclear

Data-driven estimate for μ + track(s) SRs



- Build μ2T & μ4T templates using events with extra low p_T track, allow 0n0n, 0nXn, Xn0n
- Reduce signal contamination in 1M2T: cuts on mass & acoplanarity
- Normalise in region with extra unmatched clusters (4-8 clusters)

Post-fit distributions

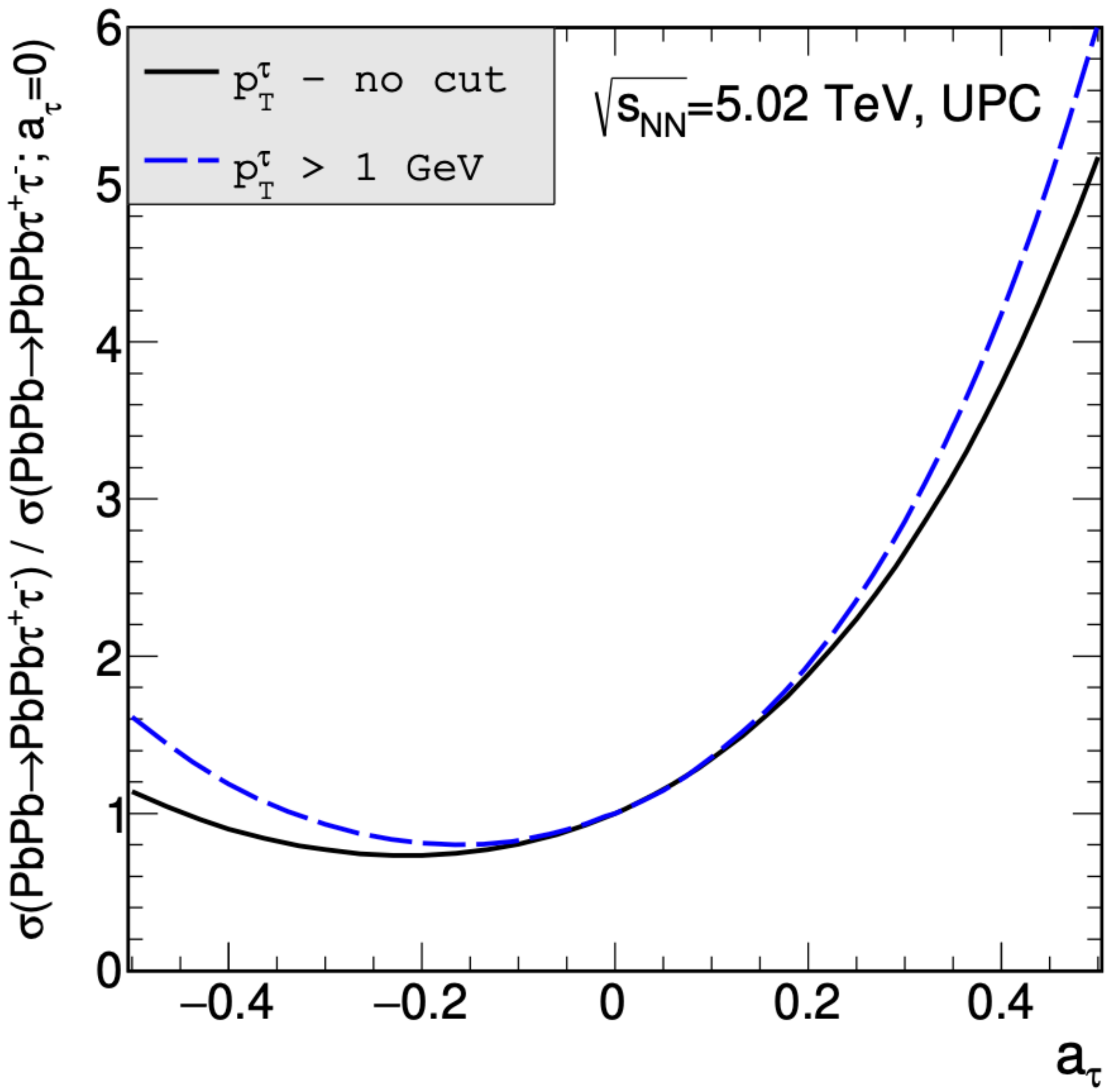


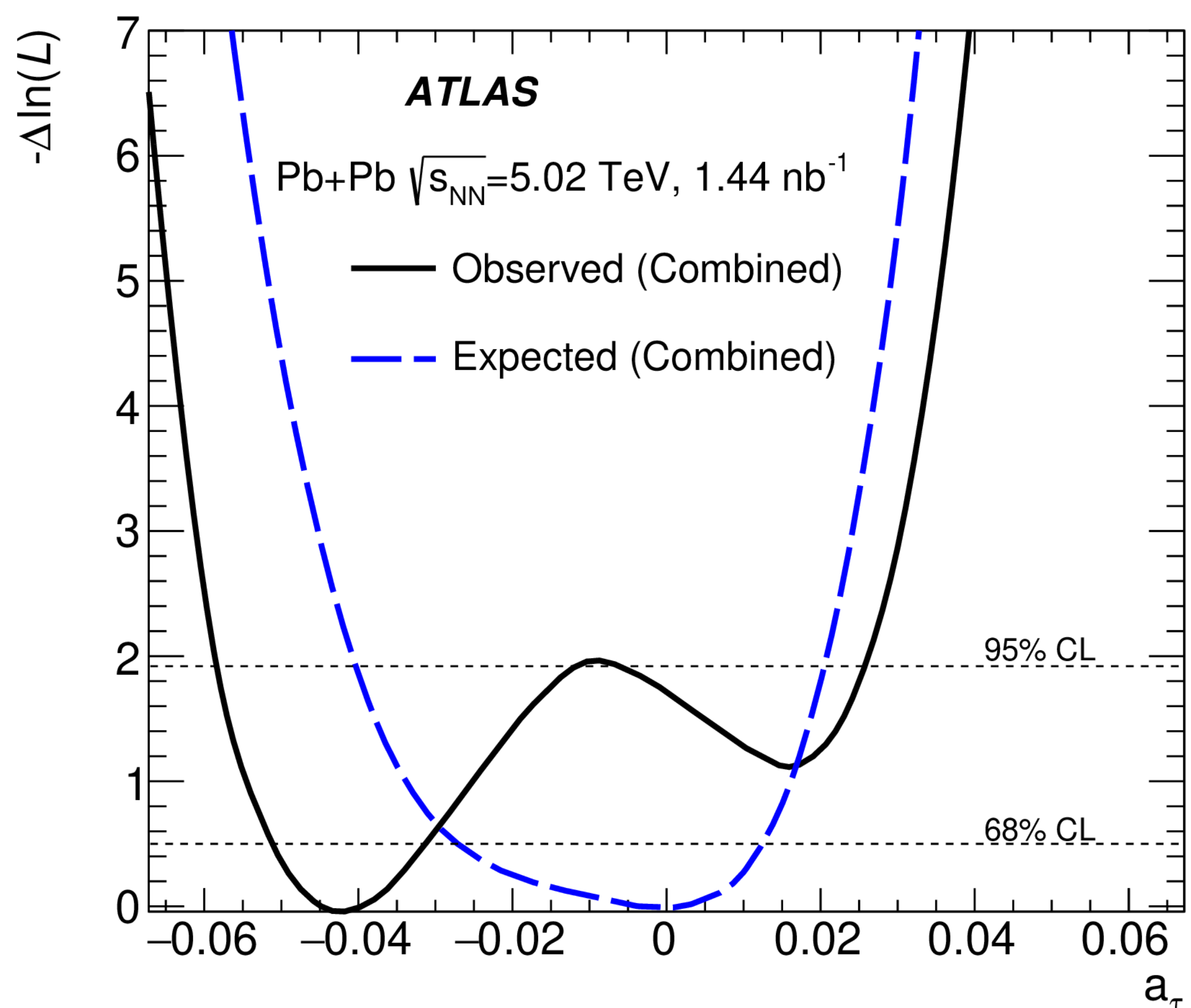
BSM Tau g-2

Re-weight SM signal MC to BSM a_τ values based on PLB (2020)

3D weighting in $m_{\tau\tau}$, $|y_{\tau\tau}|$, $|\Delta\eta_{\tau\tau}|$

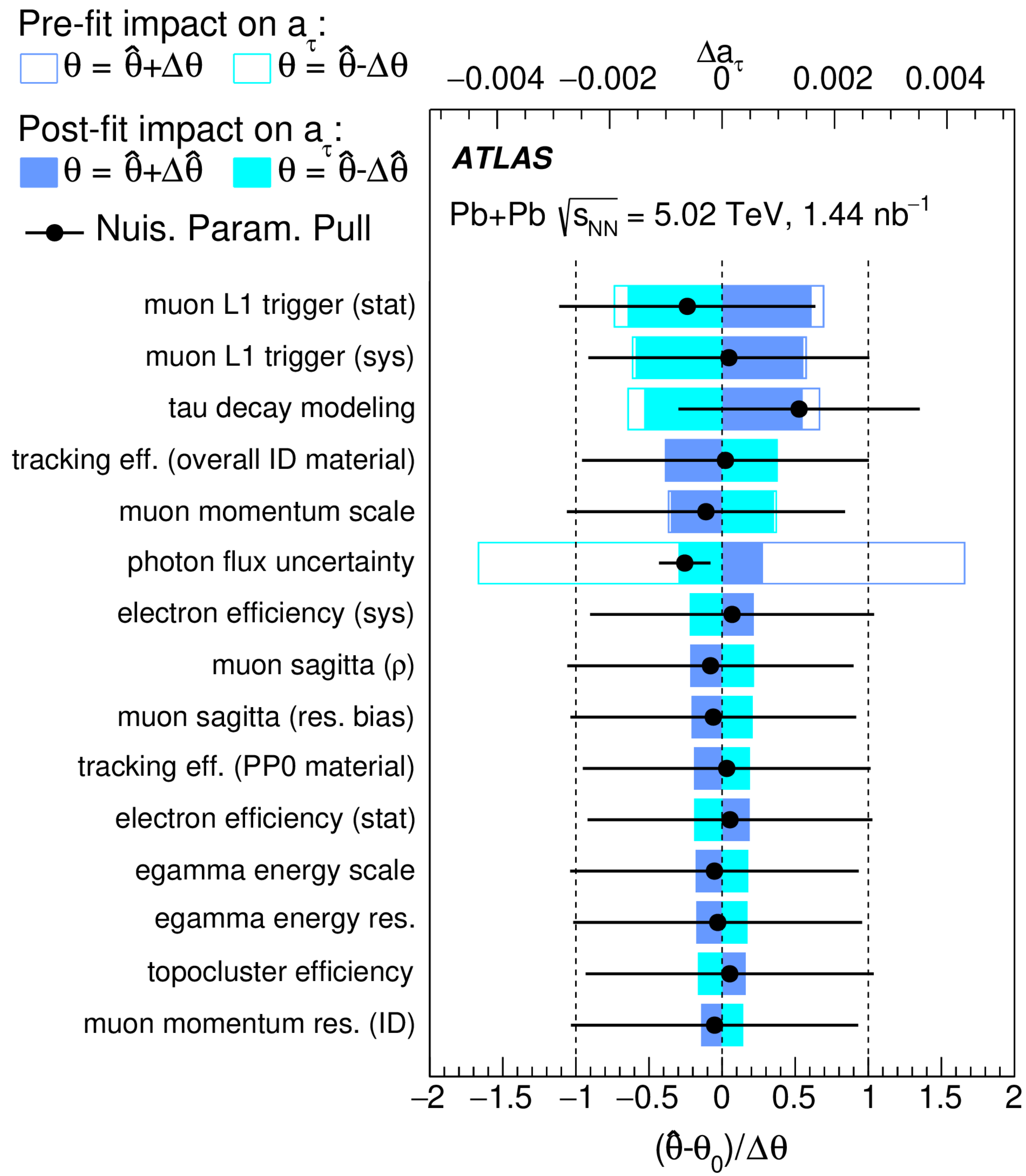
Calculations based on same parametrisation as LEP





Systematic uncertainties

Uncertainty	Impact on $\mu_{\tau\tau}$ [%]
τ decay modeling	1.0
muon Level-1 trigger (sys)	1.0
tracking eff. (overall ID material)	0.9
muon Level-1 trigger (stat)	0.7
topocluster reco. eff.	0.6
tracking eff. (PP0 material)	0.6
photonuclear template var. (μ1T-SR)	0.5
topocluster energy calib.	0.5
egamma scale	0.4
egamma res.	0.3
tracking eff. (IBL material)	0.3
Total systematic	2.5



Lydia Beresford