Results on photon-induced processes in ultraperipheral Pb+Pb collisions with ATLAS

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on behalf of the ATLAS Collaboration

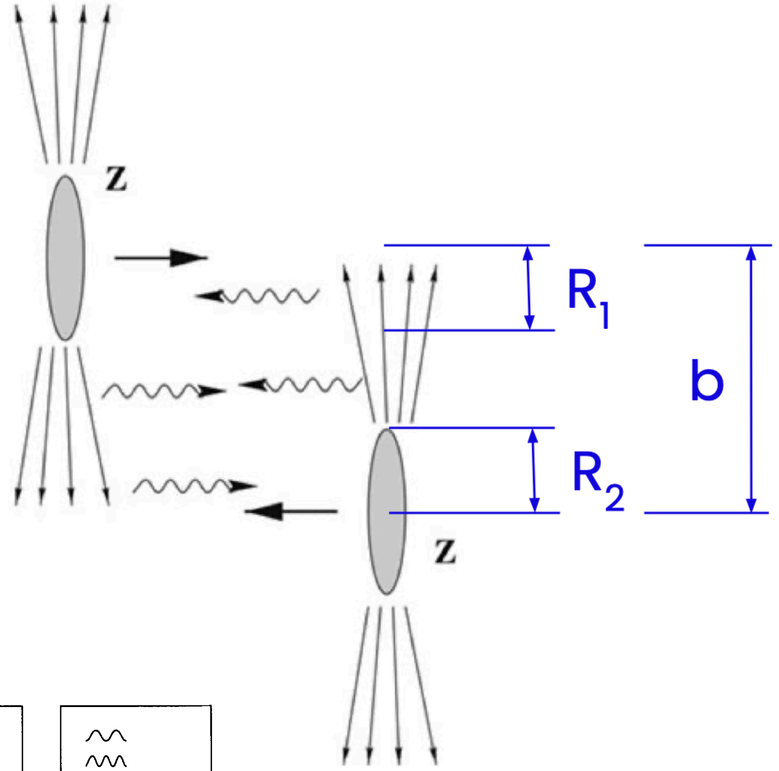
Hard Probes 2024

LHC as a photon collider

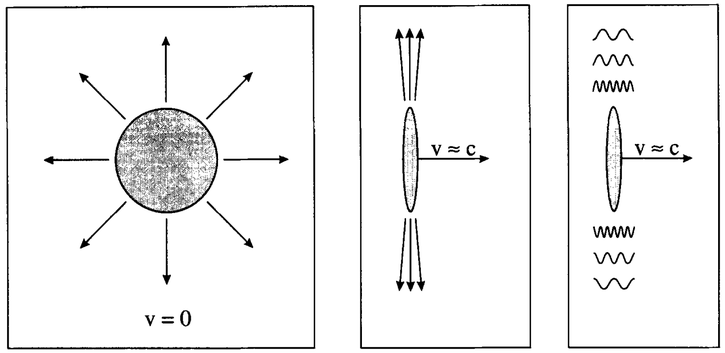
- Boosted nuclei are intense source of EM fields

- Ultraperipheral collisions (UPC)
  - **b > 2R**
  - Hadronic interactions strongly suppressed

- EM fields
  - Treated as **quasi-real photon** fluxes
  - Small virtuality Q < 1/R ~ 30 MeV
  - Proportional to $\mathbf{Z^2}$

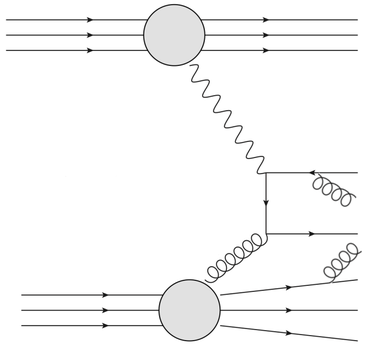


Fermi, Nuovo Cim. 2 (1925) 143

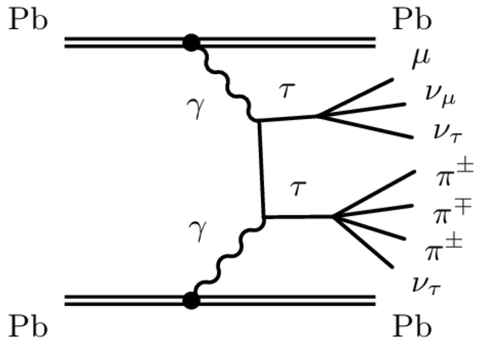


UPC reviews:
Baltz et al., Phys. Rept. 458 (2008) 1-171; Klein & Steinberg, Ann. Rev. Nuclear Part. Sci. 70 (2020) 323

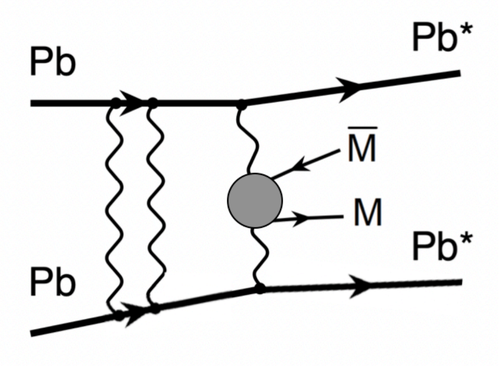
Outline



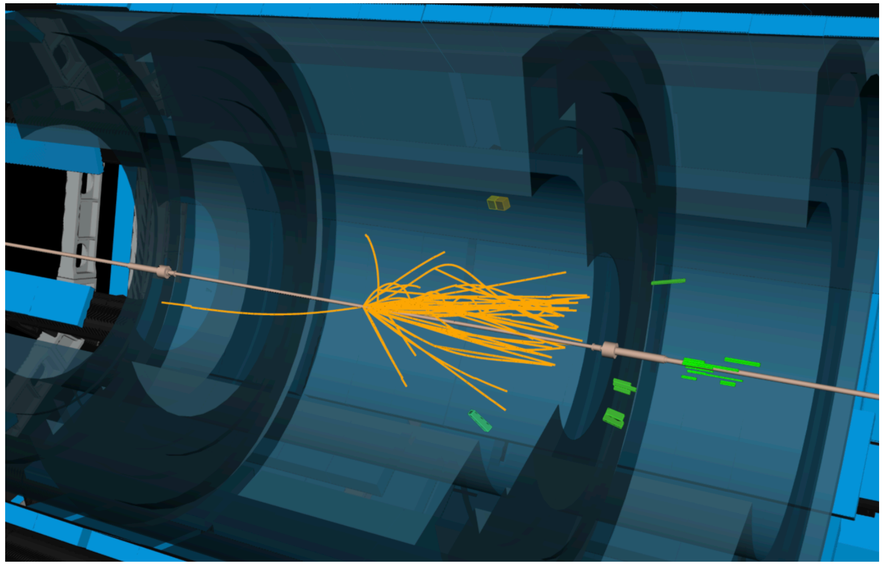
ATLAS Collaboration,
ATLAS-CONF-2023-059

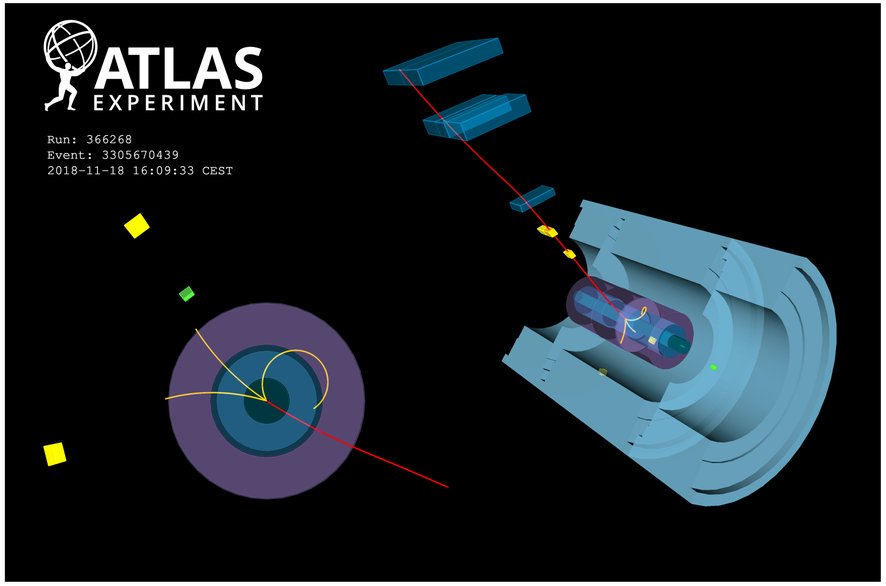


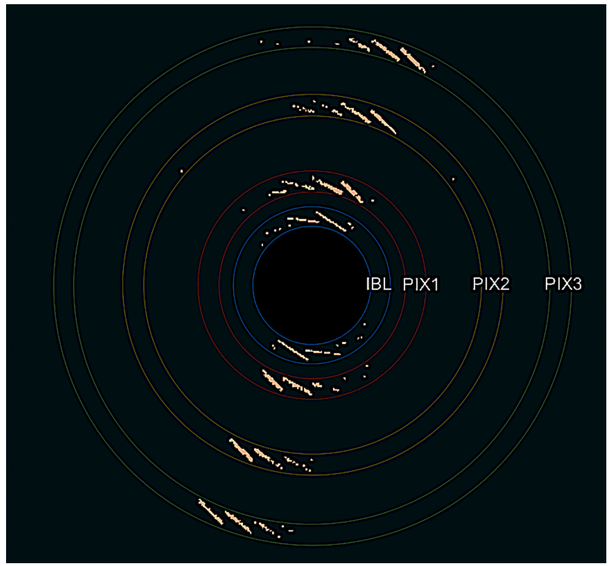
ATLAS Collaboration,
Phys. Rev. Lett. 131 (2023) 151802



ATLAS Collaboration,
arXiv:2408.11035 (NEW, Run-3 data)



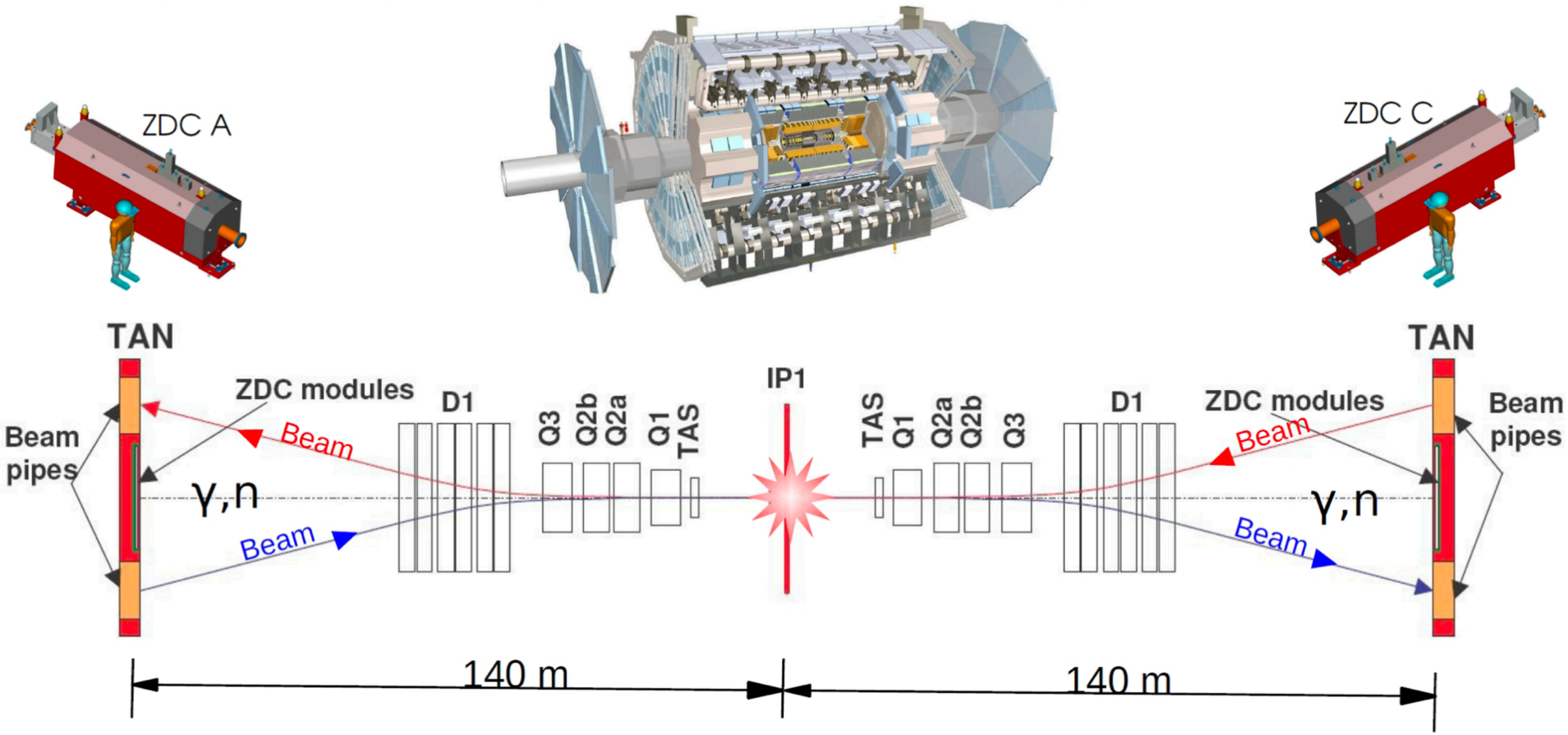




[see also ATLAS photonuclear jets measurement by Ben Gilbert in the same session]

Experimental considerations

- **Rapidity gaps** & **Exclusive final states** → Veto requirements are essential
  - Many sub-detectors available in ATLAS (|eta|<4.9)
- (Absence of) ion dissociation tagged with **Zero Degree Calorimeters (ZDC)**



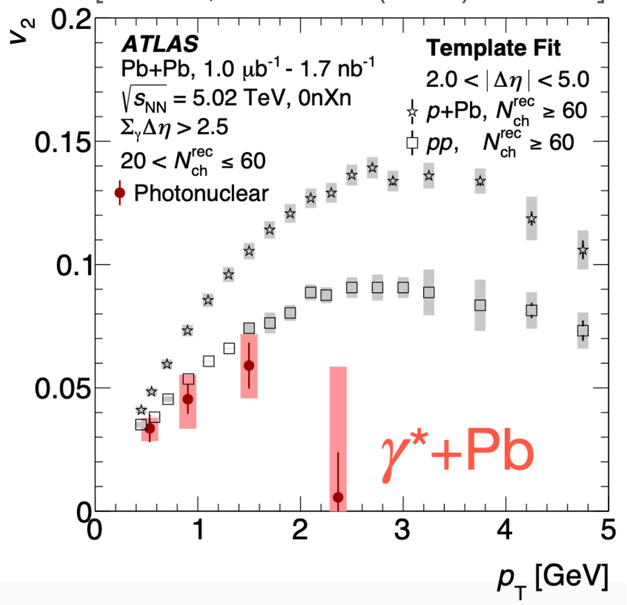
Characterising photonuclear γ+Pb collisions

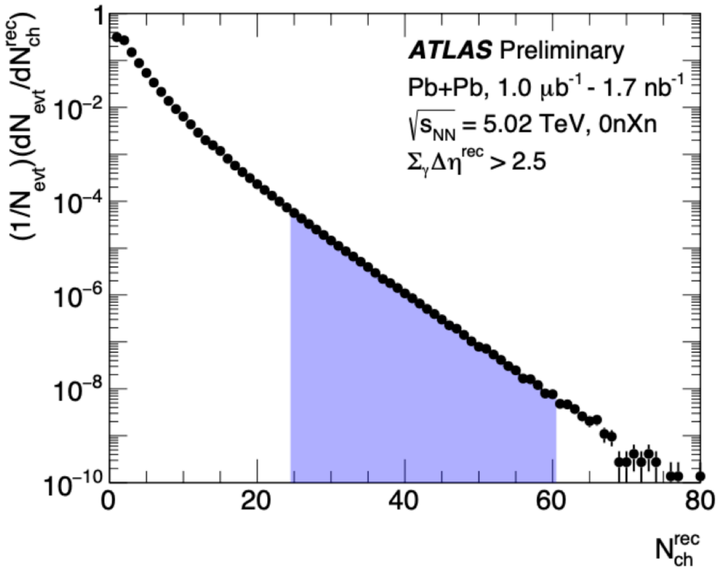
- Collective flow (v2) found by ATLAS in γ+Pb collisions
  - Motivation to look for more QGP-like signals!
  - Comparison between γ**+Pb** and **p+Pb** collisions

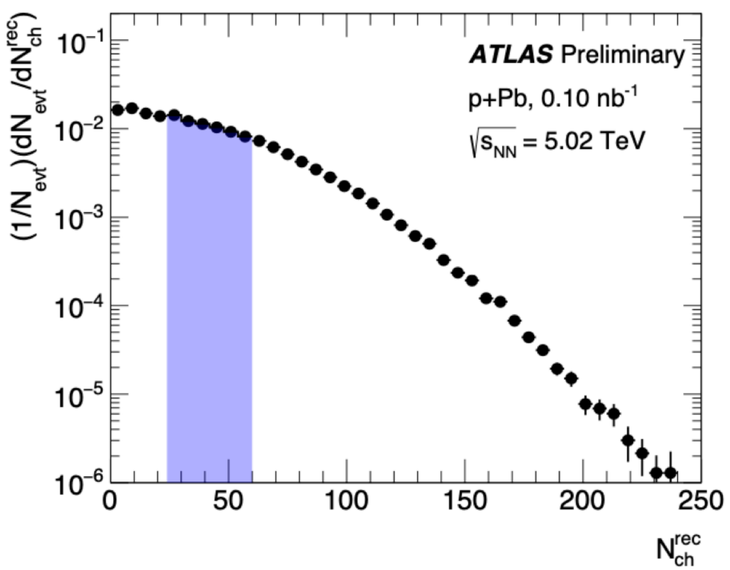
- Relevant observables
  - **dN/dEta, <pT>** at similar N_{ch}

- Event selection
  - 0nXn ZDC requirement
  - rapidity gap on photon-going side
  - N_{ch} [25, 60]

[ATLAS, PRC 104 (2021) 014903]

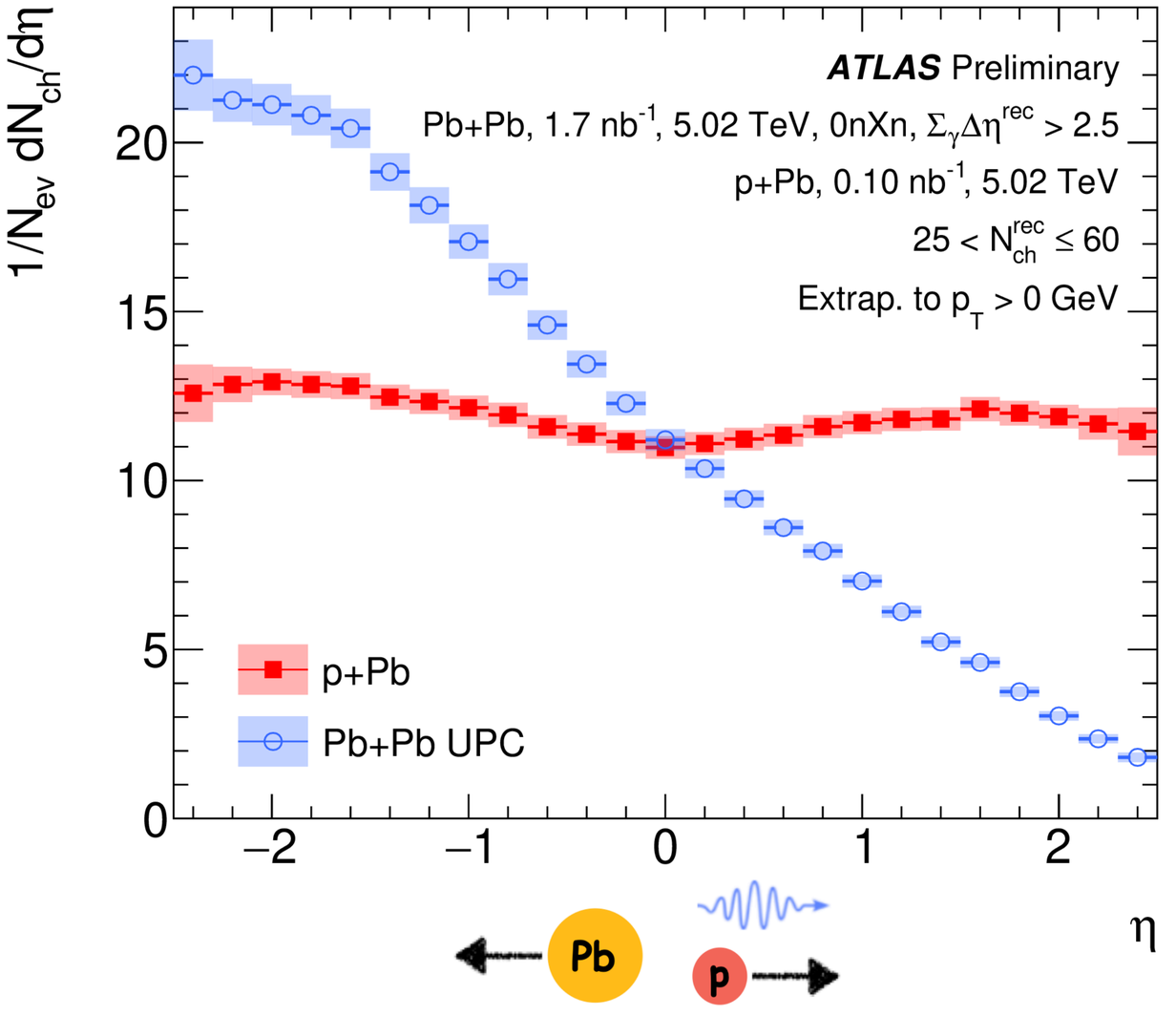






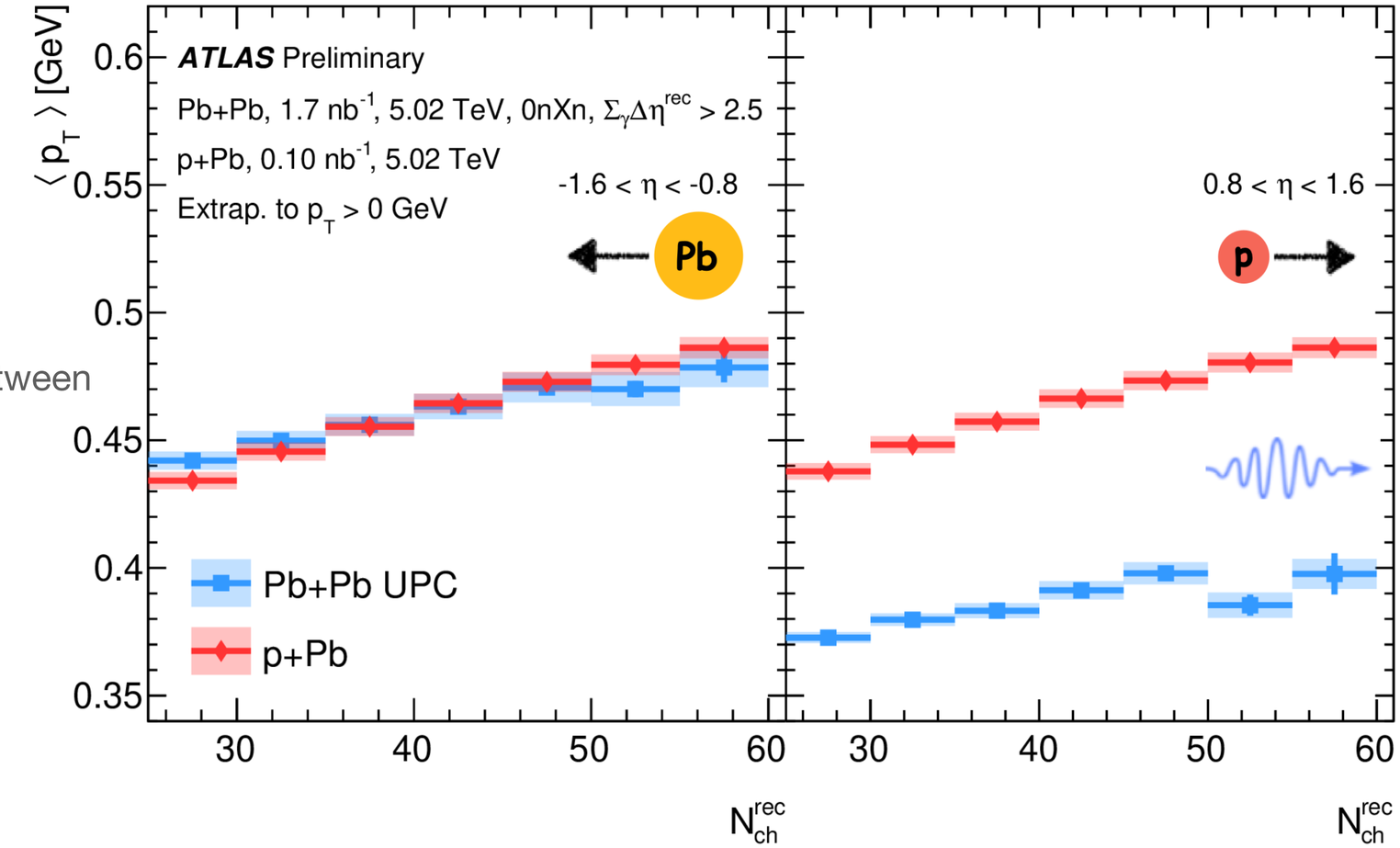
Characterising photonuclear γ+Pb collisions

- γ+Pb distribution is highly asymmetric
  - photon energy lower compared to energy per nucleon in Pb
- p+Pb distribution is nearly symmetric for selected low multiplicity events
- Important to study γ+Pb properties in different η regions separately



Characterising photonuclear γ+Pb collisions

<pT> matches well between γ+Pb and p+Pb



<pT> lower in γ+Pb than p+Pb

- Theory (3+1D hydrodynamics) predicts both γ+Pb and p+Pb should have same radial flow, therefore same <pT> (in backward rapidity) [Zhao, Shen, Schenke, Phys. Rev. Lett. 129, 252302]

Phys. Rev. Lett. 131 (2023) 151802

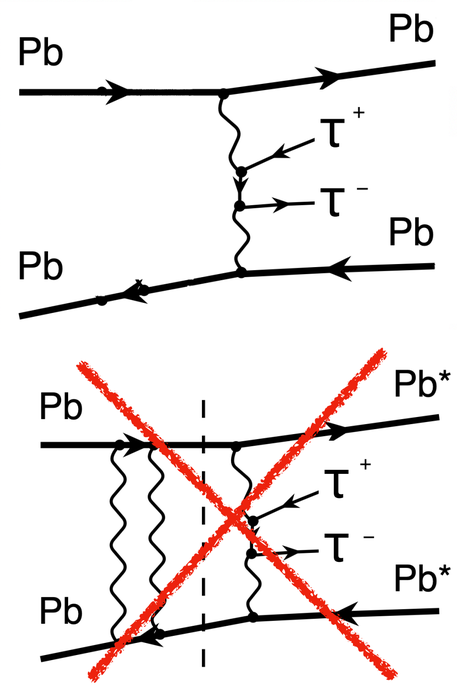
Exclusive tau-pair production in Pb+Pb UPC

- Study (low-energy) **taus for the first time in nuclear collisions**
- Strategy: exploit semi-leptonic decays with pT>4 GeV muon
  - **μe-SR**: muon + electron
  - **μ1T-SR**: muon + 1 track (soft e/μ/pion)
  - **μ3T-SR**: muon + 3 tracks (3 pions)

see also related ATLAS **ee** [JHEP 06 (2023) 182] and **μμ** [PRC 104 (2021) 024906] measurements

- **Exclusivity**:
  - Veto extra tracks
  - Veto additional calorimeter clusters (μ1T-SR and μ3T-SR only)

- **0n0n** ZDC selection to further suppress hadronic backgrounds (mainly photonuclear production)



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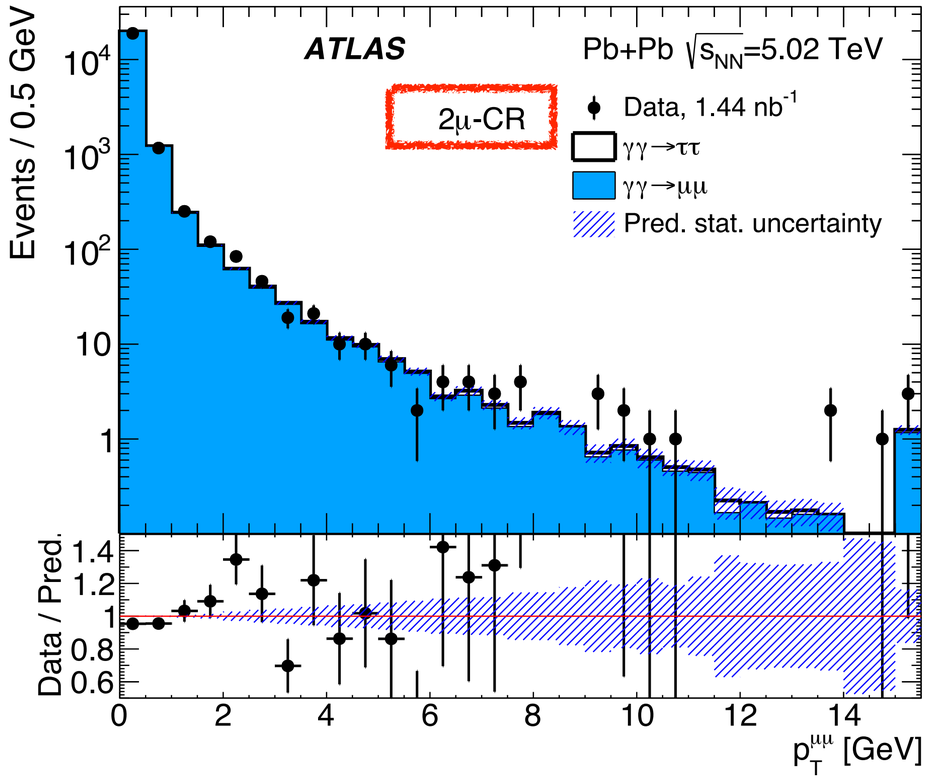
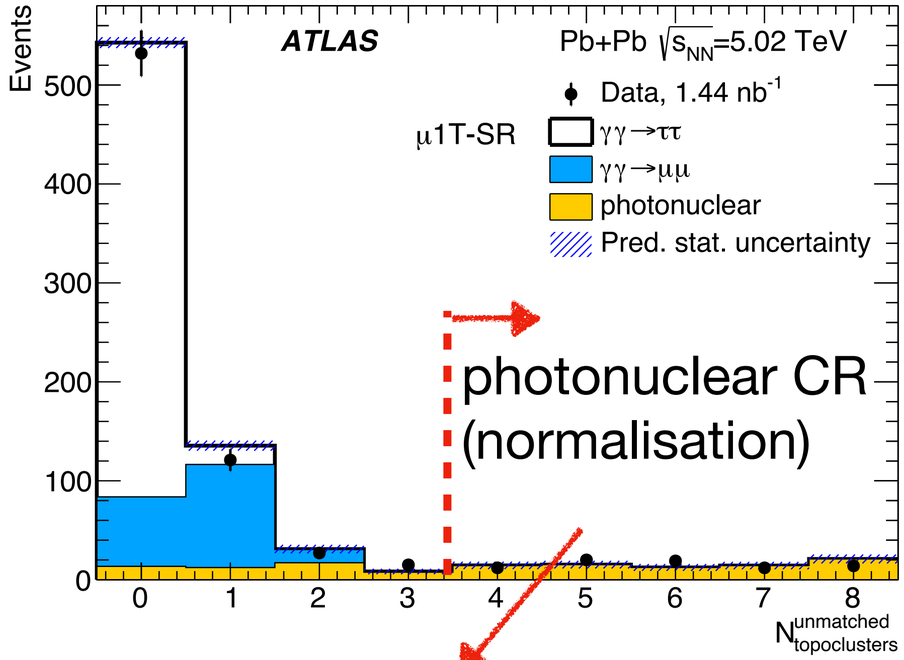
Exclusive tau-pair production in Pb+Pb UPC

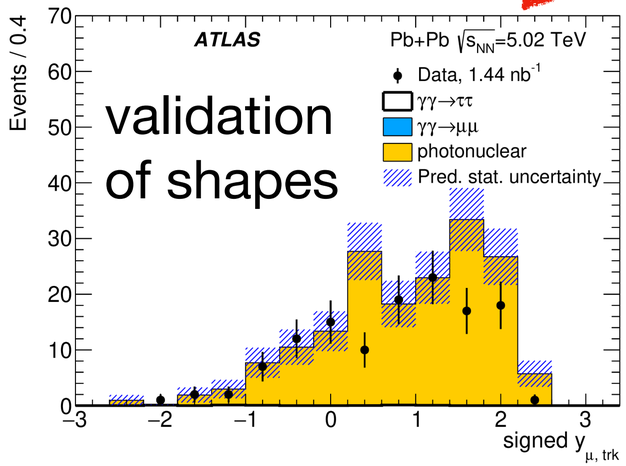
- **Main backgrounds**

γγ → μμγ (MC-based)



Diffractive photonuclear (data-driven)

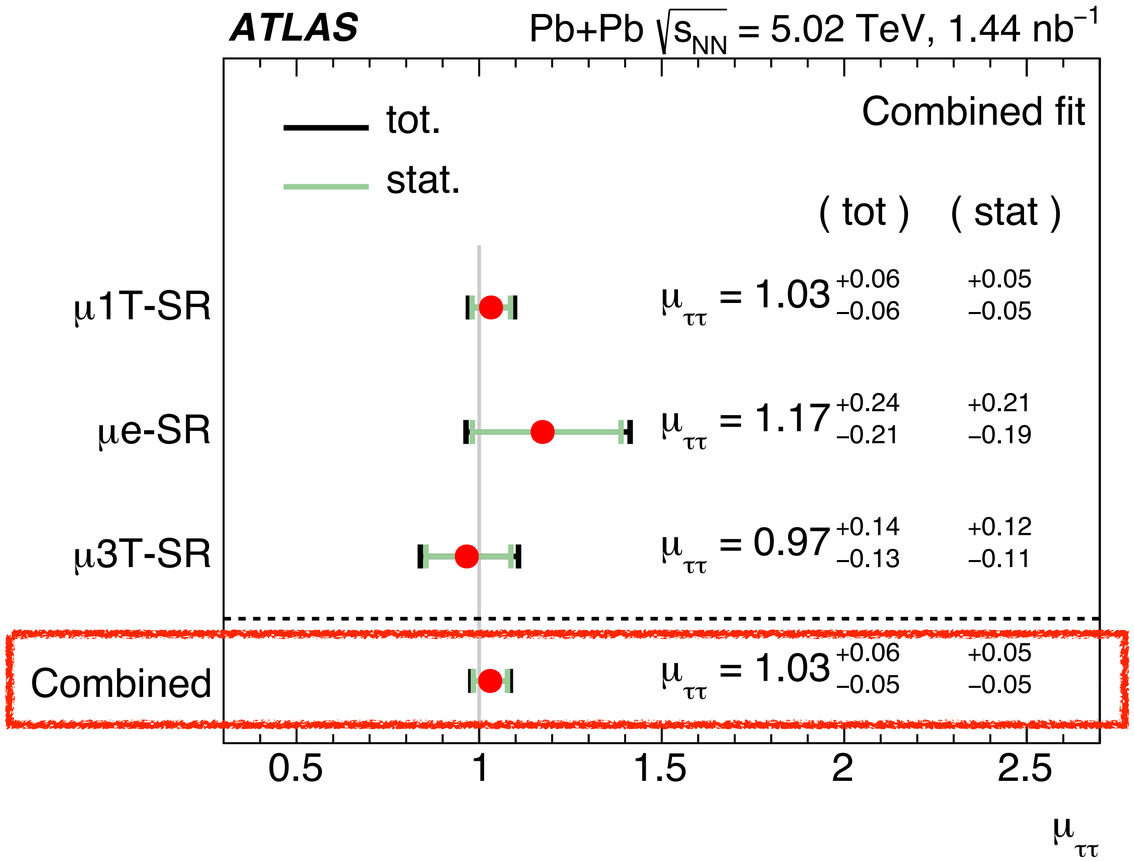


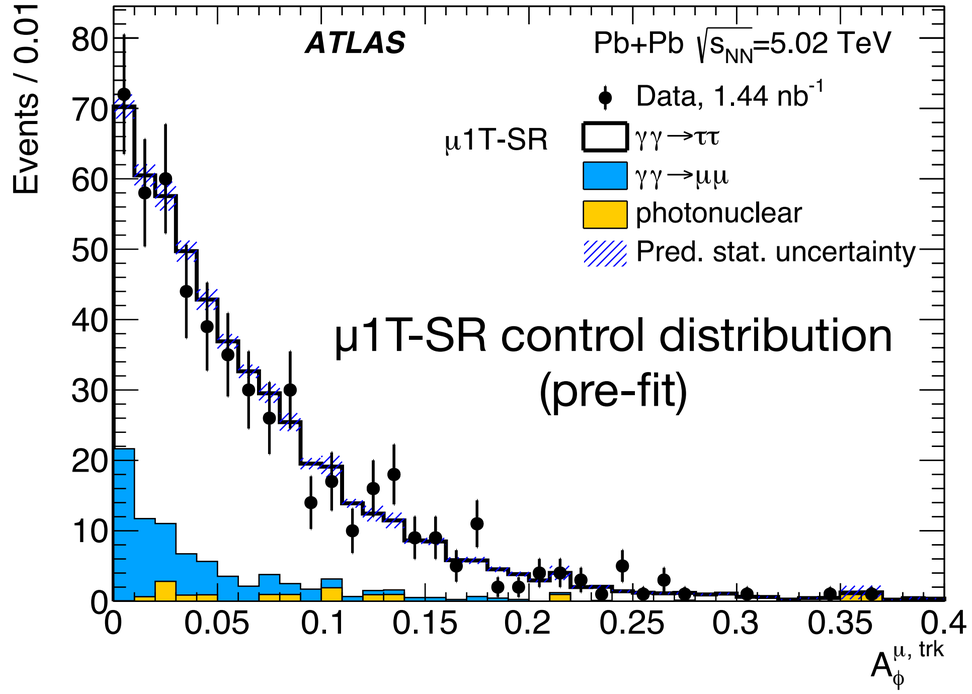


Phys. Rev. Lett. 131 (2023) 151802

Exclusive tau-pair production in Pb+Pb UPC

- Signal strength extraction
  - Simultaneous fit to μ1T-SR, μ3T-SR, μe-SR and 2μ-CR
  - Many systematics **correlated** between SRs and 2μ-CR → get reduced!





Exclusive tau-pair production in Pb+Pb UPC

- **$a_{tau} = (g_{tau}-2)/2$** poorly constrained experimentally; can be sensitive to BSM

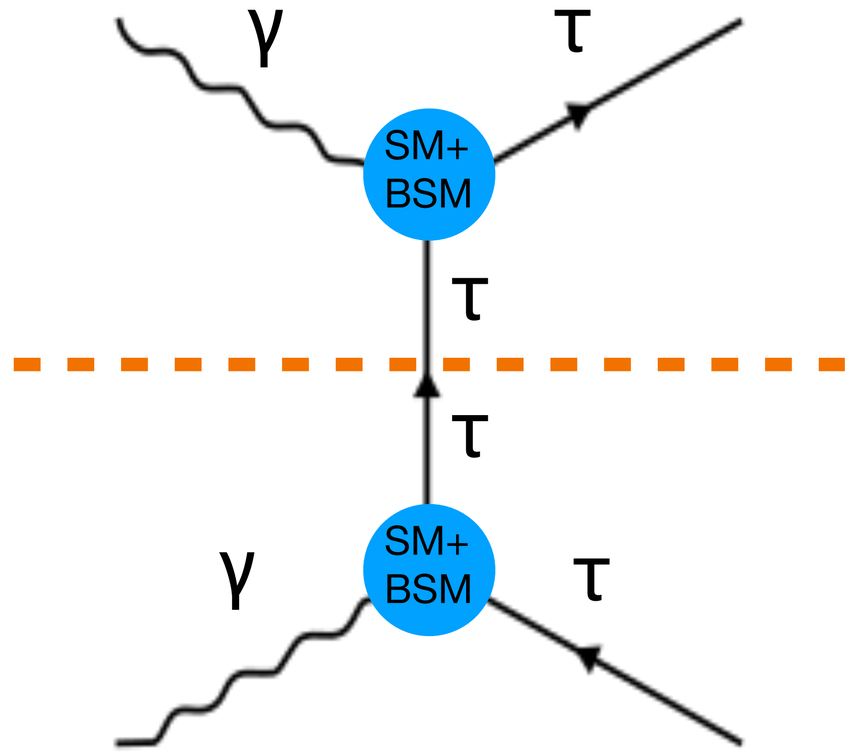
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

τ

$J = \frac{1}{2}$

Mass $m = 1776.86 \pm 0.12$ MeV
$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8 \times 10^{-4}$, CL = 90%
Mean life $\tau = (290.3 \pm 0.5) \times 10^{-15}$ s
$c\tau = 87.03\ \mu$m
Magnetic moment anomaly > -0.052 and < 0.013, CL = 95%
$\text{Re}(d_\tau) = -0.220$ to $0.45 \times 10^{-16}\ e$ cm, CL = 95%
$\text{Im}(d_\tau) = -0.250$ to $0.0080 \times 10^{-16}\ e$ cm, CL = 95%

$$a_\tau^{\text{SM}} = 0.001\,177\,21\ (5)$$



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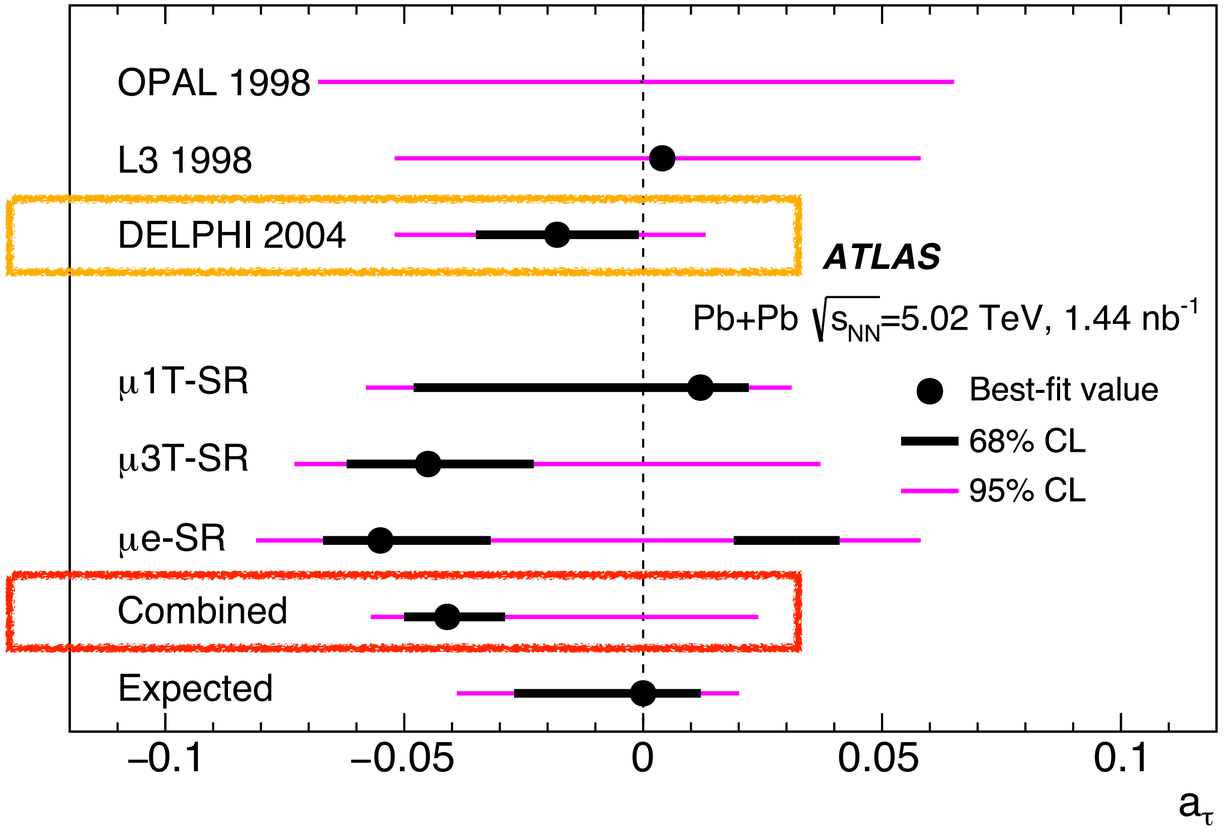
Exclusive tau-pair production in Pb+Pb UPC

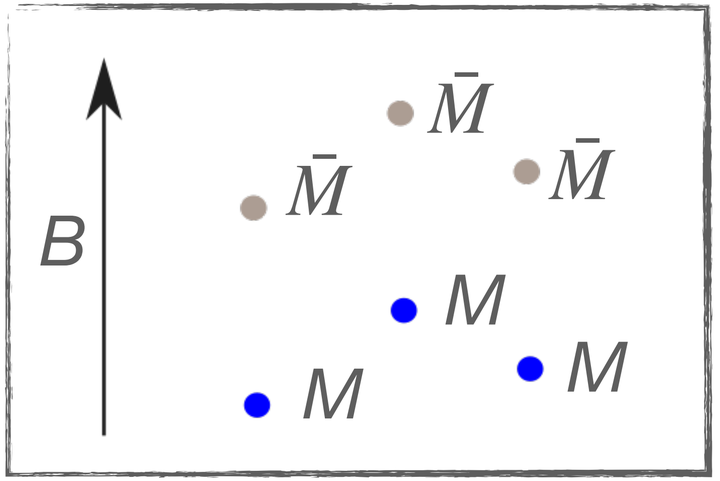
- Measure $\mathbf{a_\tau = (g_\tau - 2)/2}$ with template fit
  - Using muon pT distribution in the three SRs and 2μ-CR
- Constraints on a_τ similar to those observed at LEP



see also follow-up measurements from CMS (Mon session)

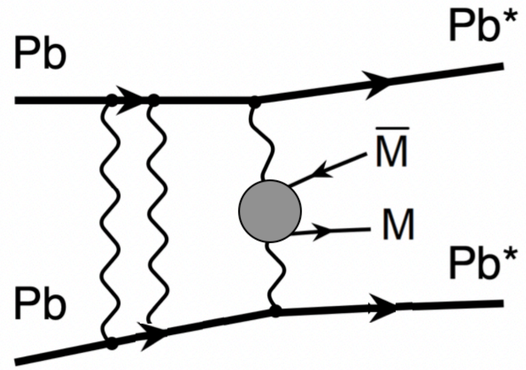
Magnetic monopole search in Pb+Pb UPC

- Production via the **Schwinger mechanism** in strong magnetic fields [Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021)]
  - peak **B ~ 10^{16} T** at LHC Pb+Pb collisions

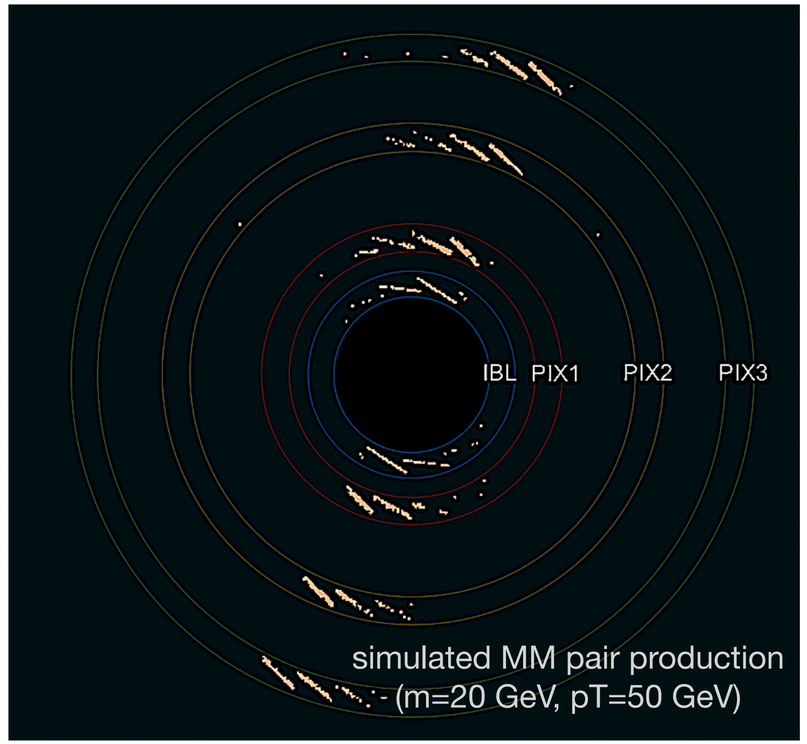


- Advantages over *pp* searches:
  - Cross-sections calculated using semiclassical techniques → do not suffer from **non-perturbative nature of coupling**
  - **Composite** monopoles **enhance** the cross section
  - No exponential suppression ($e^{-4/\alpha} \sim 10^{-236}$) for composite monopole models
    [Drukier & Nussinov, Phys. Rev. Lett. 49 (1982) 102]

Magnetic monopole search in Pb+Pb UPC



- Use 0.262/nb of 2023 Pb+Pb data at 5.36 TeV
- **Trigger strategy**
  - **low-energy MM would loose energy primarily in the innermost Si layers**
  - **L1**: coincidence of **ZDC A+C** signals
    + veto on total transverse energy in calo (E_T<10 GeV)
  - **HLT**: **> 100 Pixel clusters** w/o any specific tracking selection



- **Event selection**
  - **$N_{tracks} \leq 1$, $N_{topoclusters} \leq 1$** → removes collision background
  - $N_{PixelClusters}$ >150, including $N_{IBLclusters}$ > 50
    → suppress beam-induced background (BIB)
  - Fraction of Pixel clusters from a single module,
    $f_{leading\text{-}module}$<0.9 → to suppress events from noisy modules

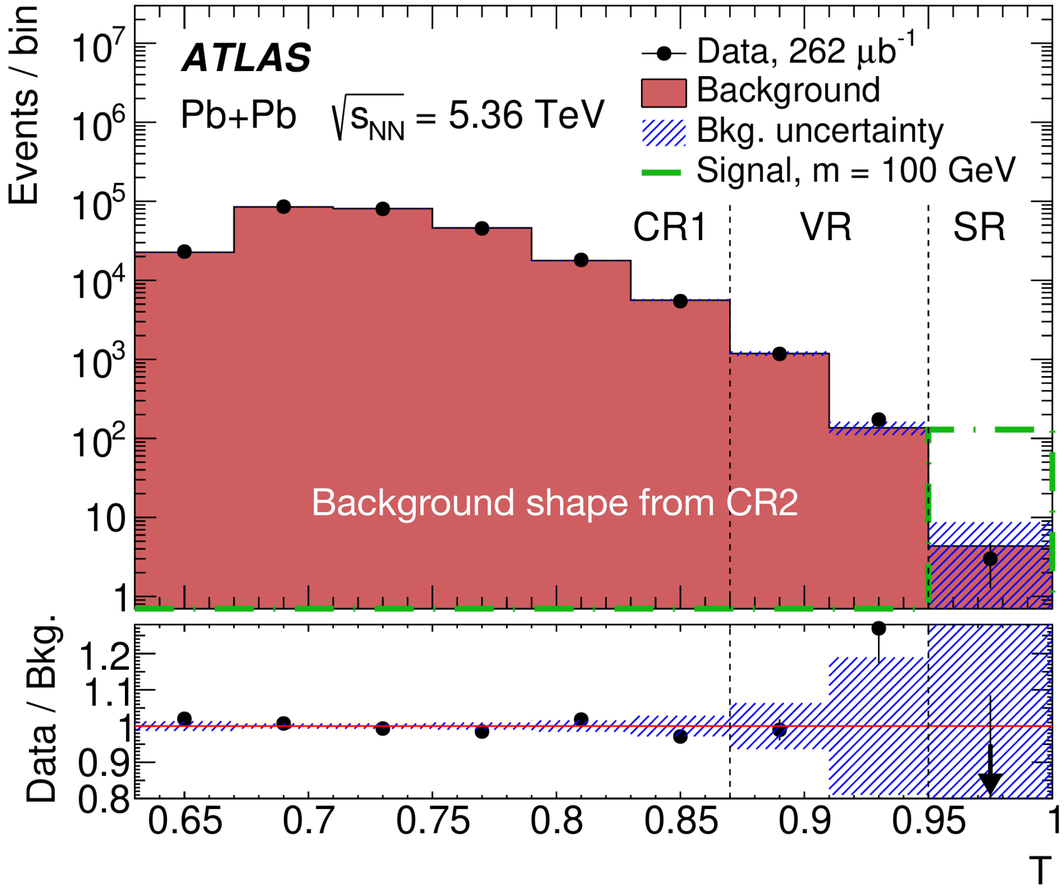
Magnetic monopole search in Pb+Pb UPC

- Final signal region (**SR**) selection: T>0.95

$$T = 1/n_{\mathrm{PixCl}} \sum_{i=1}^{n_{\mathrm{PixCl}}} |\hat{r}_i \cdot \hat{n}|$$

- Background estimate fully data-driven:
  - **CR1** for events having T<0.87
  - **CR2** from ZDC_XOR-triggered events with 1-3 (soft) calorimeter clusters, incl. at least one out-of time (t<-10 ns)
  - CR1 and CR2 sample is enriched with BIB and so:

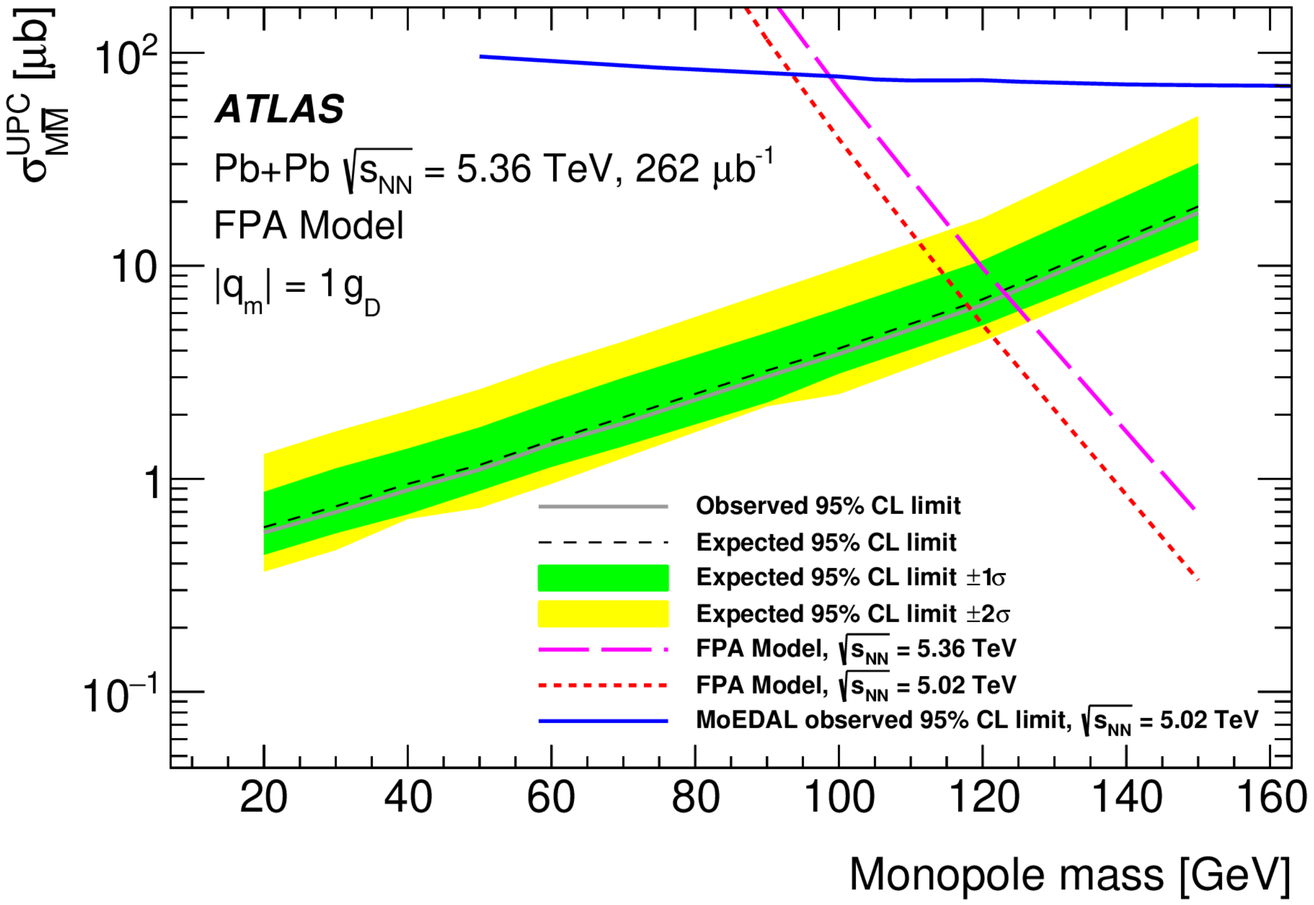
$$N_{\mathrm{bkg}}^{\mathrm{SR}} = \frac{N^{\mathrm{CR1}}}{N_{T<0.87}^{\mathrm{CR2}}} N_{T>0.95}^{\mathrm{CR2}}$$



- SR bkg estimate: **4 ± 4** events expected

Magnetic monopole search in Pb+Pb UPC

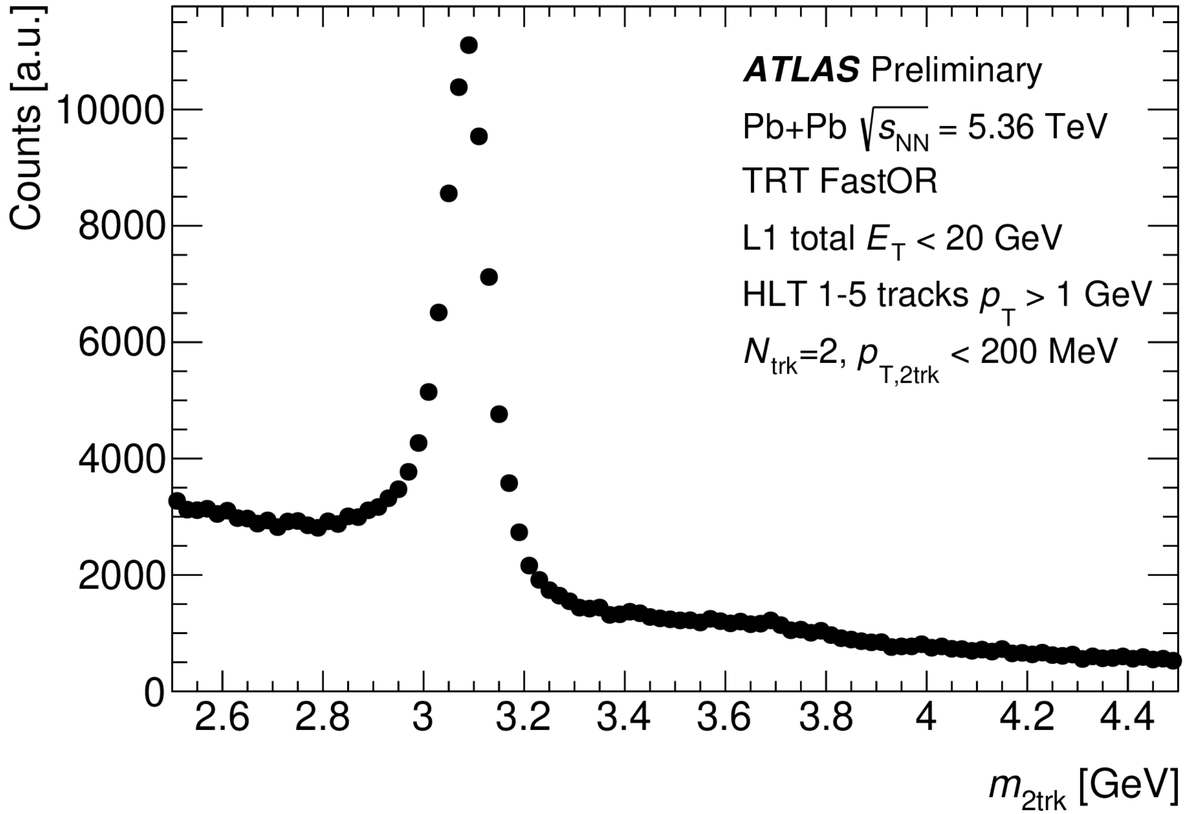
- **3** events in SR, consistent with background estimate (4 ± 4)
- Cross-section upper limits assuming non-perturbative $g=1g_D$ FPA model
  [Gould et al., PRD 104 (2021) 015033]
- Significantly better sensitivity compared to MoEDAL
  [Nature 602 (2022) 63]
- Introducing new approach in detecting highly-ionising particles at the LHC



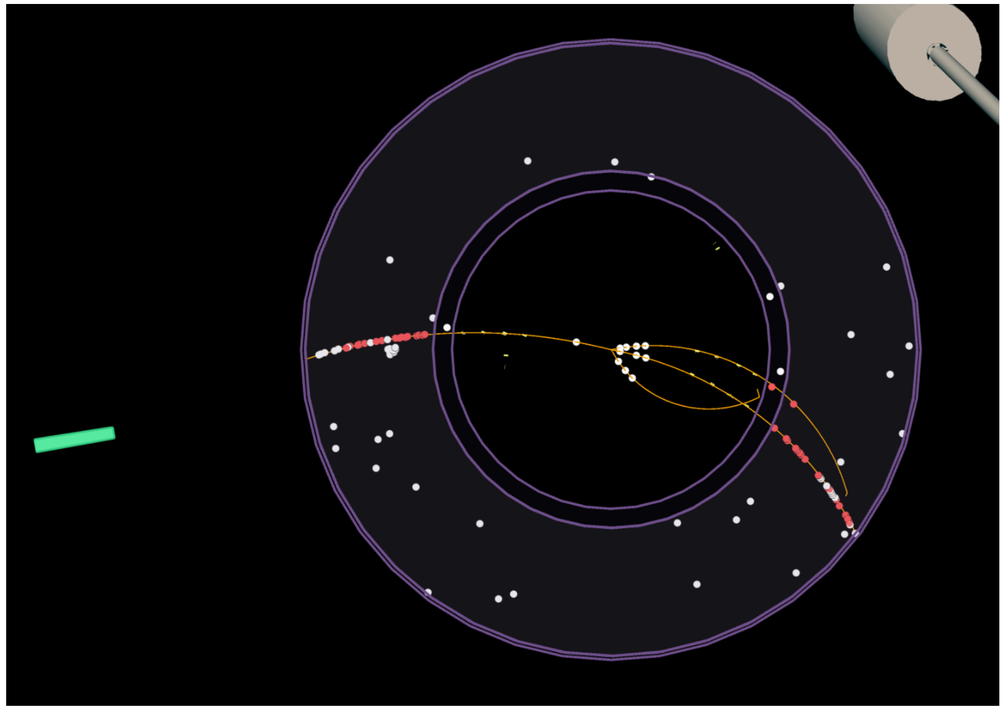
Future ATLAS UPC measurements

- ~1.7/nb of 5.36 TeV data recorded in 2023 by ATLAS
- Thanks to the offline and **ATLAS TRT "Fast-OR" L1 trigger** improvements, we can reach much lower transverse momenta in Run3!

2-track selection



γγ→ τ τ → e πππ candidate



Summary

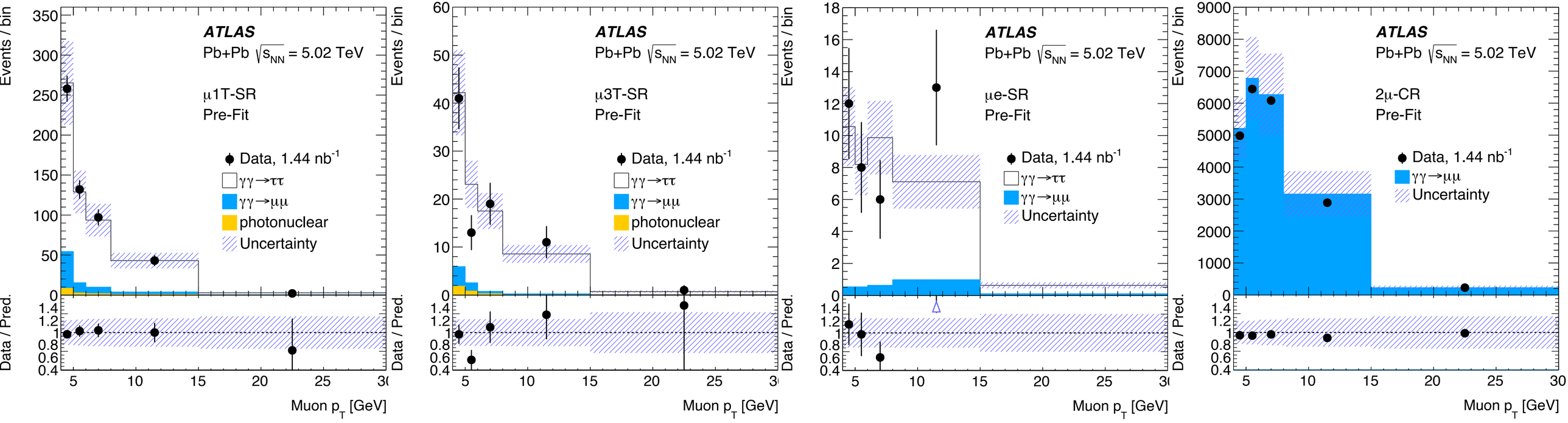
- Rich physics programme of HI UPC at the LHC with ATLAS
  - Crucial role of ZDC detectors in disentangling various ion-breakup classes (0nXn, 0n0n, XnXn)
- Photonuclear events provide unique insight into small collision systems phenomena
- UPC γγ collisions are excellent QED (and BSM) laboratories
- LHC Run 3 data provides new opportunities (with L1 track-sensitive trigger, offline improvements etc.)

* Research project partly supported by program „Excellence initiative – research university” for the AGH University of Krakow

Backup

Exclusive tau-pair production in Pb+Pb UPC

- Measure $a_\tau = (g_\tau - 2)/2$ with template fit
  - Using pT(μ) distribution in the three SRs and 2μ-CR
  - a_τ templates: reweighting signal MC [weights from PLB 809 (2020) 135682] + morphing



Pre-fit

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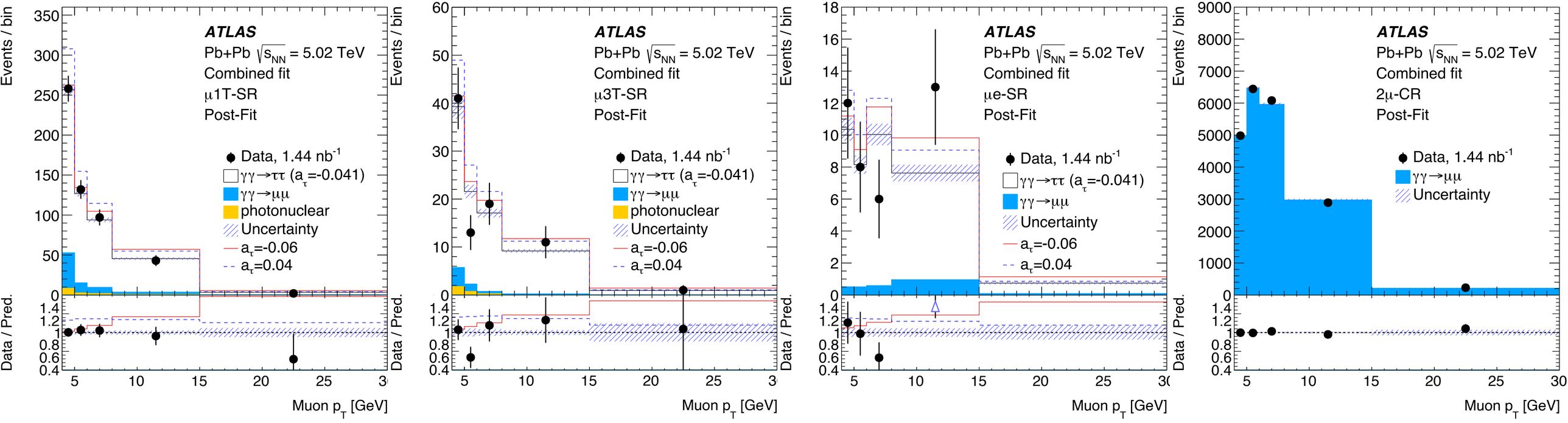
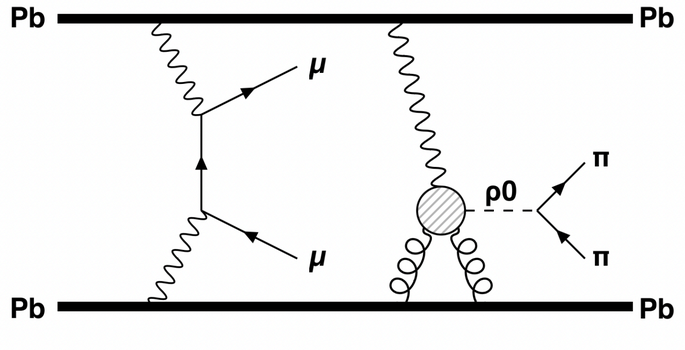
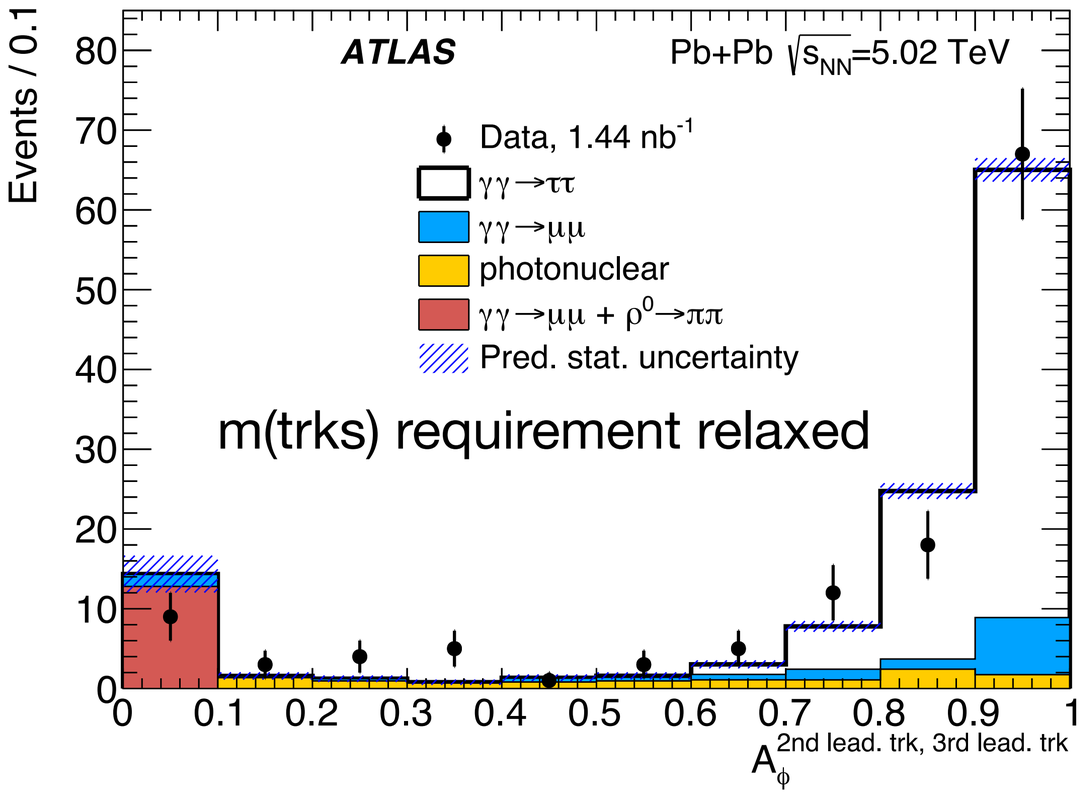


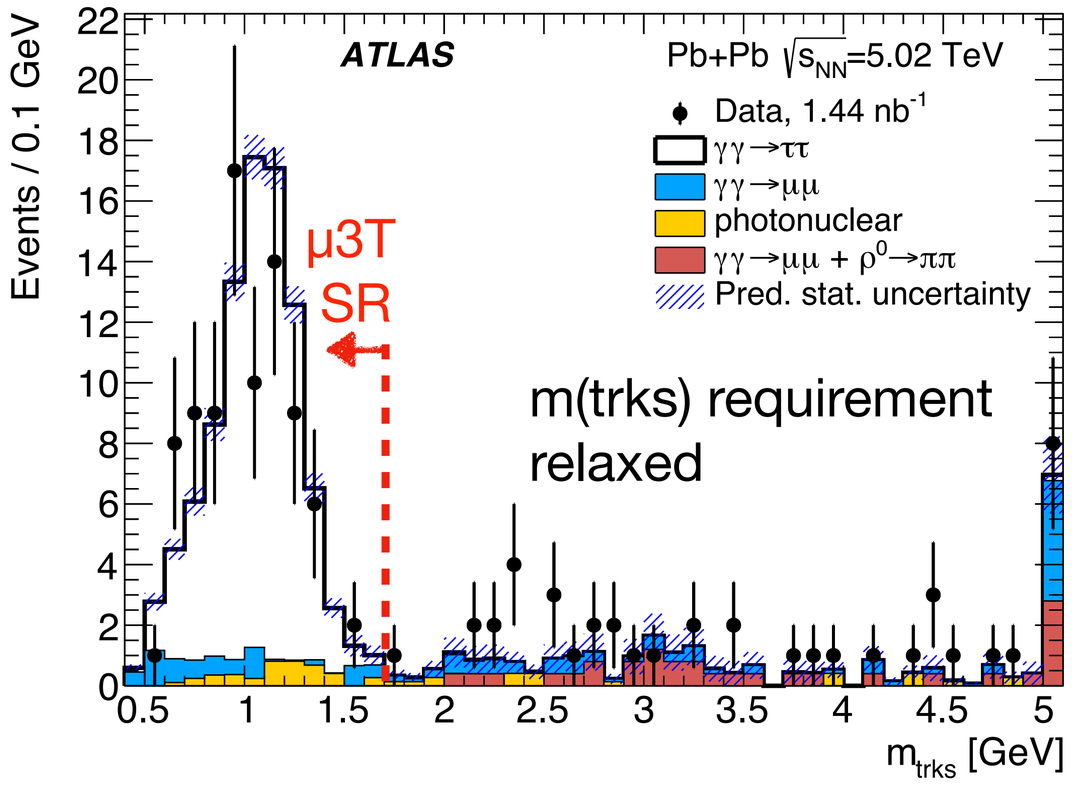
Post-fit

Exclusive tau-pair production in Pb+Pb UPC

- Other backgrounds
  - Simultaneous **γγ→μμ and γPb→ρ0→π+π-** production ('DPS') observed
  - μ3T-SR: Cut on m(trks)<1.7 GeV removes it fully







Exclusive tau-pair production in Pb+Pb UPC

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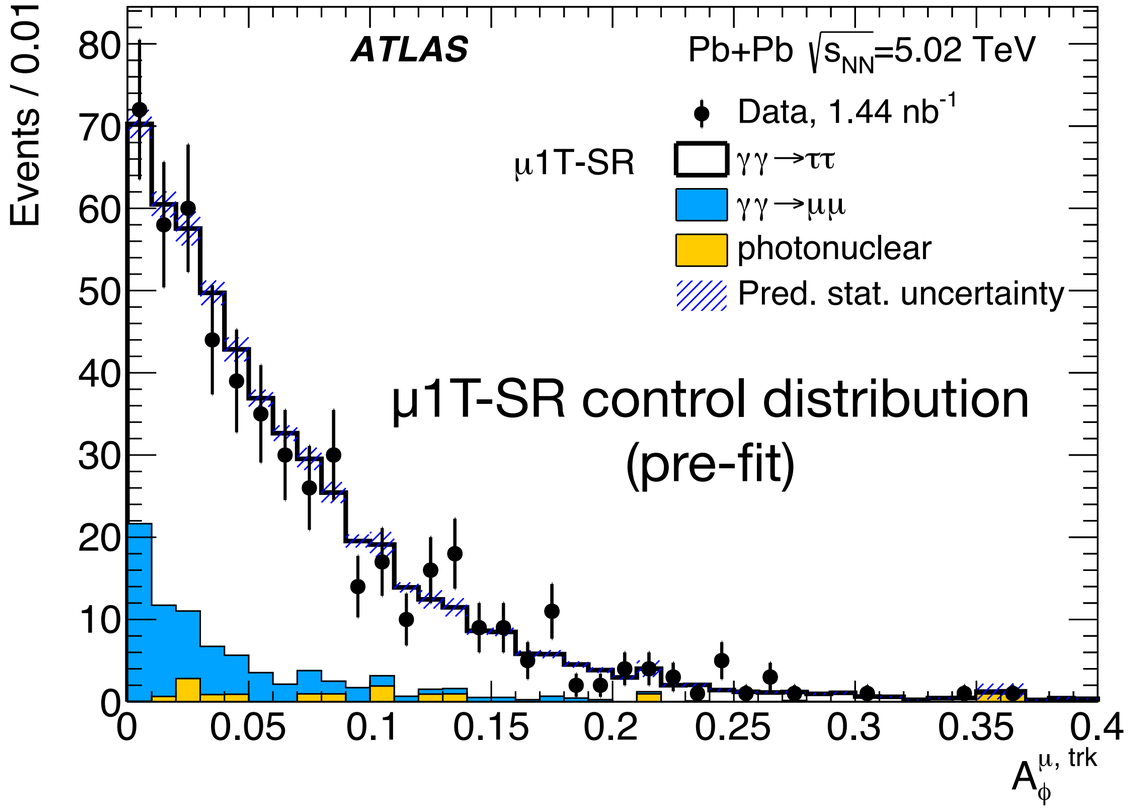


Post-fit impact

Uncertainty	Impact on $\mu_{\tau\tau}$ [%]
muon Level-1 trigger (sys)	1.0
τ decay modeling	1.0
tracking eff. (overall ID material)	0.9
muon Level-1 trigger (stat)	0.7
topocluster reco. eff.	0.6
muon reco. eff. (stat)	0.6
tracking eff. (PP0 material)	0.6
topocluster energy calib.	0.5
muon reco. eff. (sys)	0.5
photonuclear template var. (μ1T-SR)	0.5
Total systematic	2.6

a_τ parameterisation

- Elementary γγ→τ τ cross section has explicit dependence on photon-τ vertex function:

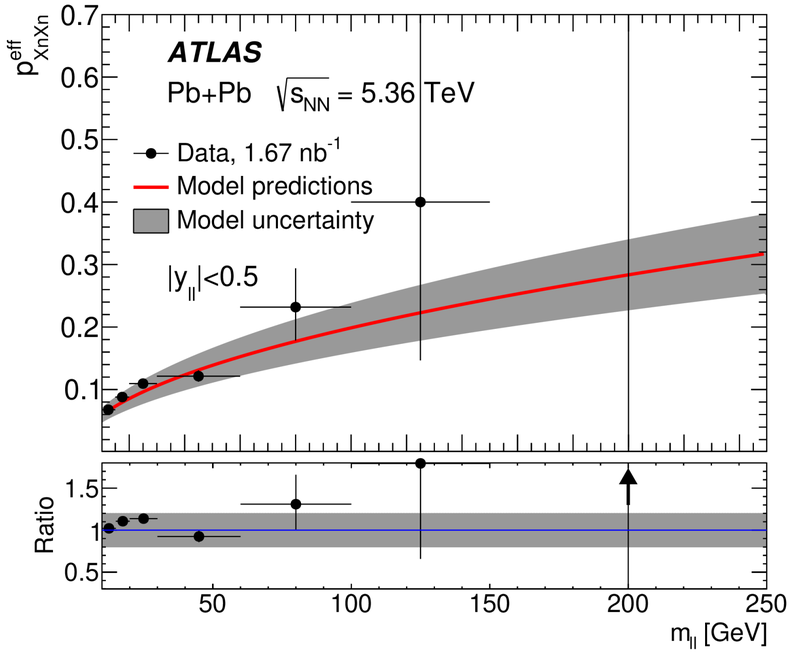
$$i\Gamma_\mu^{(\gamma\ell\ell)}(p',p) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\ell}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right]$$

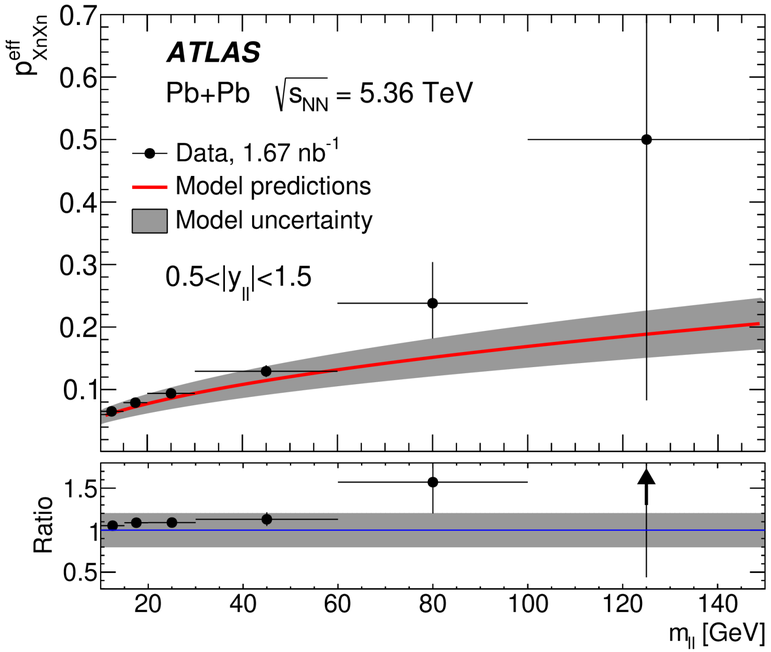
$=a_\tau$ $(q^2=0)$ $=d_\tau * 2m_\tau/e$ $(q^2=0)$

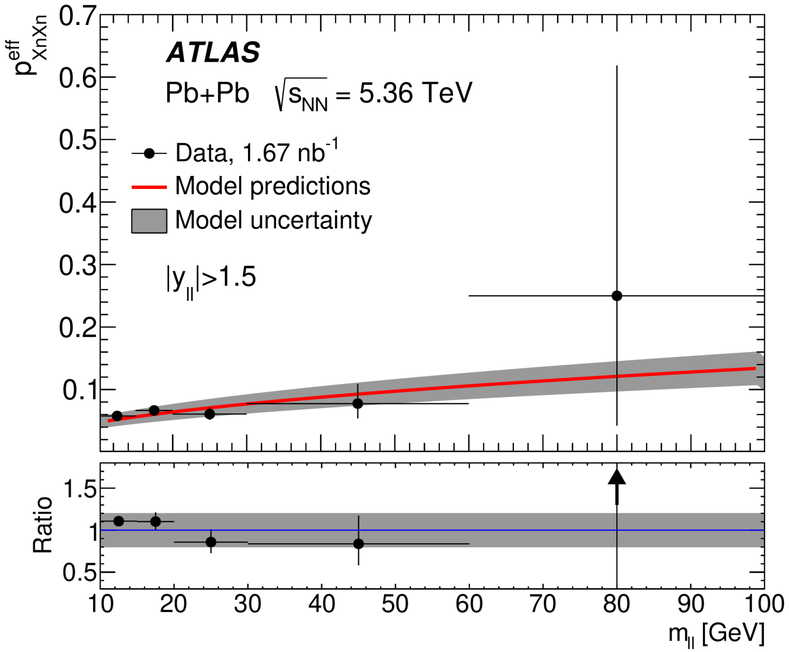
Magnetic monopole search in Pb+Pb UPC

- Signal model has no EM breakup embedded → **correcting signal MC for XnXn** requirement applied in data
- **Breakup model** based on SuperChic 4.2 MC for γγ → l+l- process is used
- Full model also takes into account:
  - EM pileup (outflow of events primarily from 0nXn class to XnXn)
  - Run-2 UPC γγ → l+l- data/MC comparison
  - possible incoherent contribution to the signal

Model validated against γγ → ee (μμ) Run-3 data

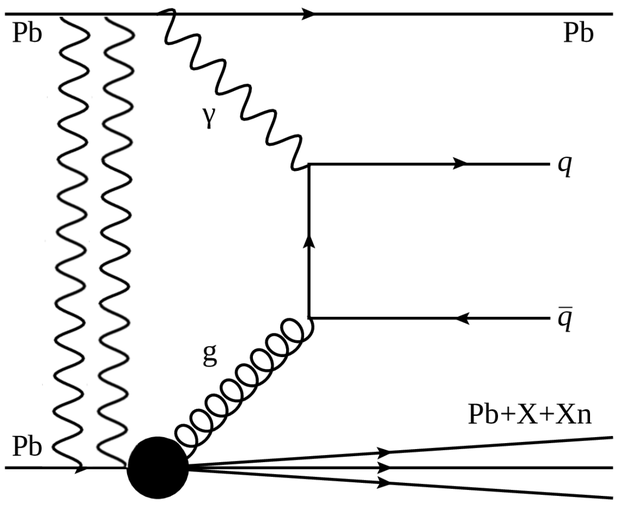


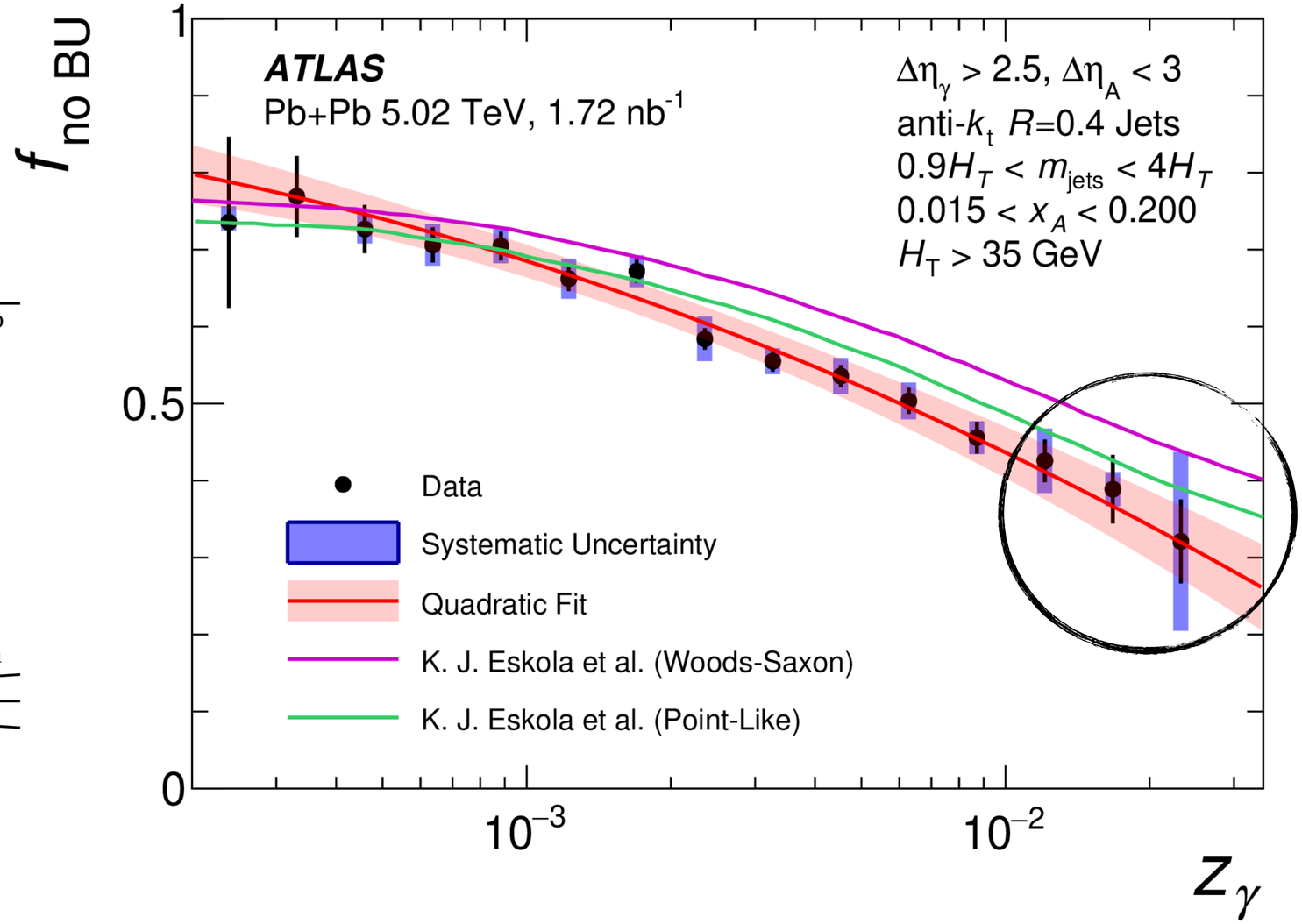




Breakup fraction at b~2R

ATLAS, arXiv:2409.11060





b→2R region