Recent measurements in ultraperipheral collisions with the ATLAS detector

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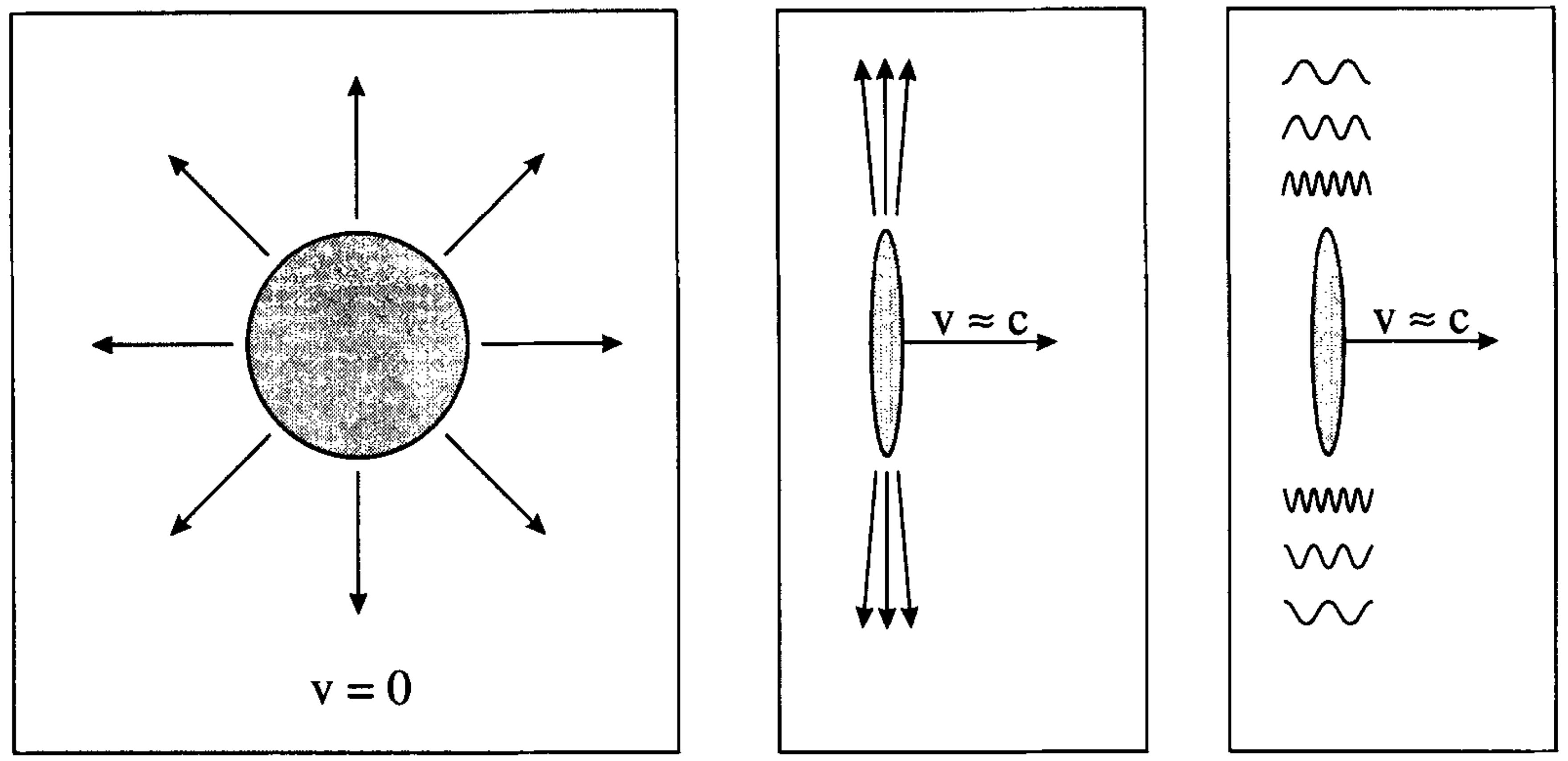
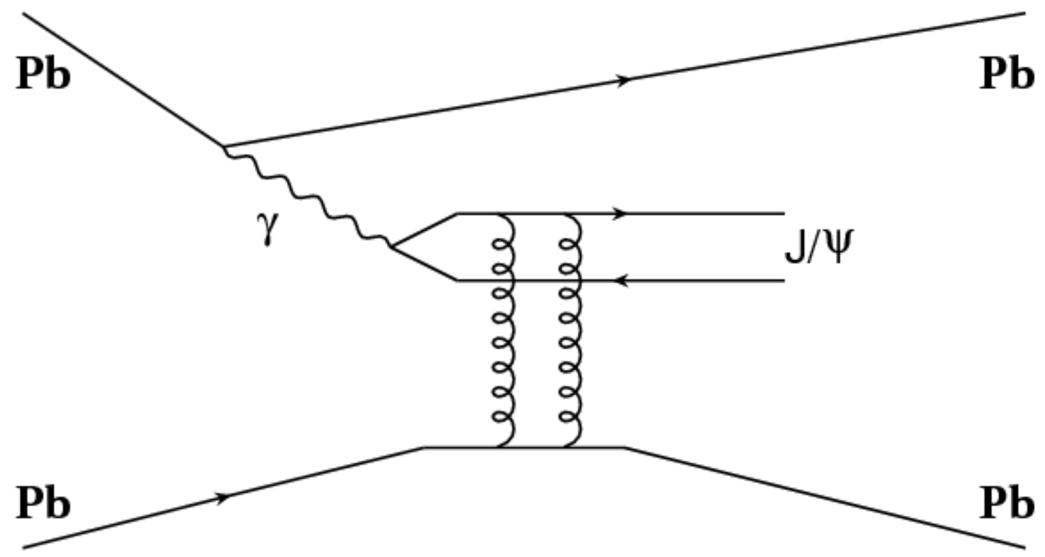
IFJ seminar

Quasi-real photons from heavy ions

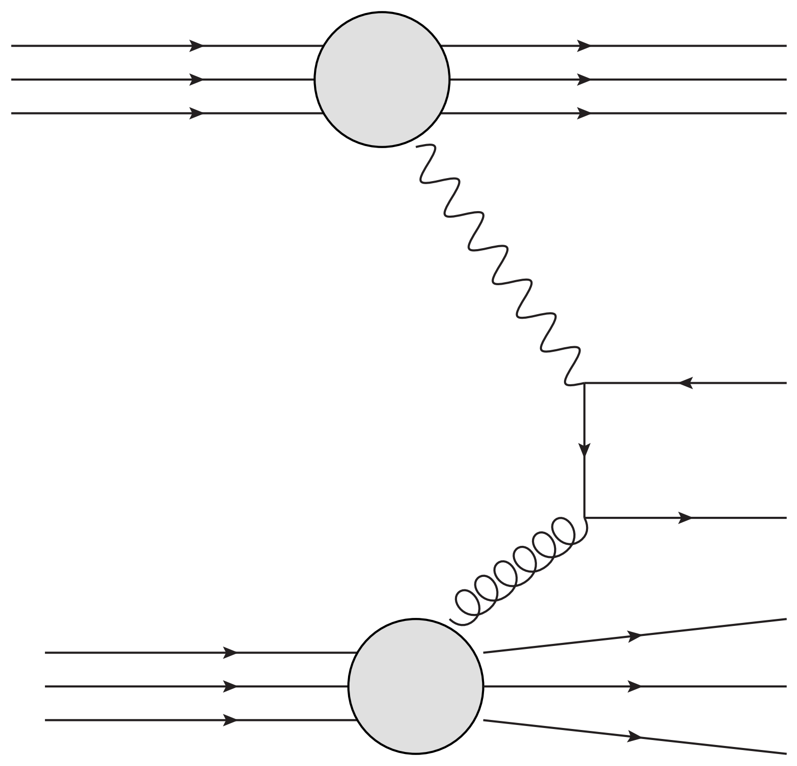
- Boosted nuclei are intense source of quasi-real photons
- **Coherent** photon flux
  - $\mathbf{E_{max} \lesssim \gamma/R \sim 80\ GeV}$ @LHC (**~3 GeV** @RHIC)
  - **Q ~ 1/R ~ 30 MeV** @ LHC/RHIC
  - Each photon flux scales with ~$\mathbf{Z^2}$



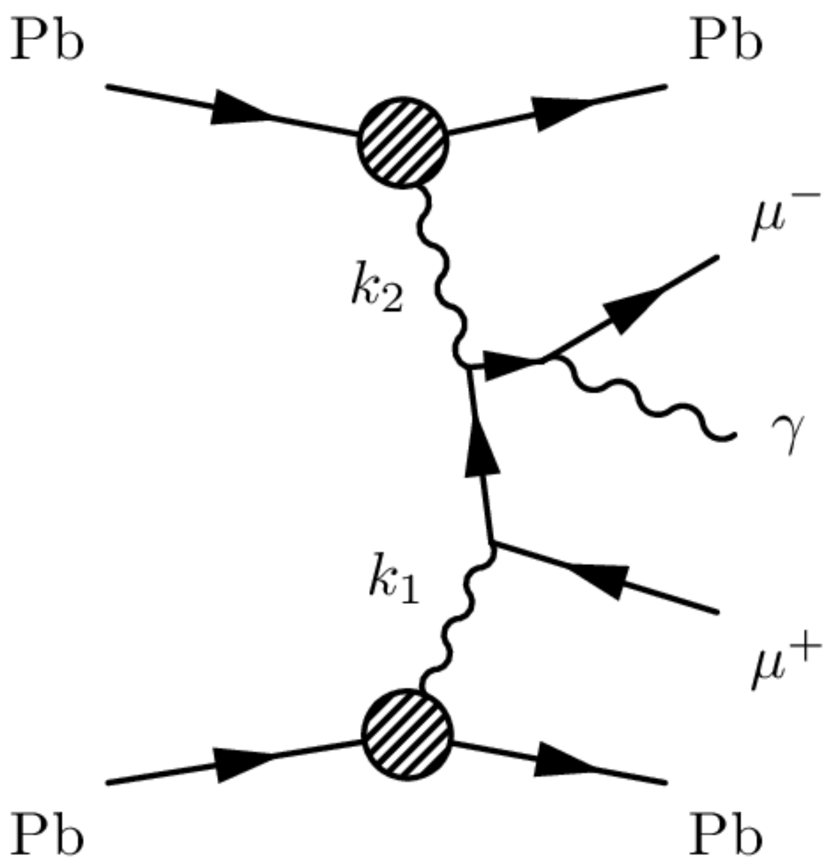
- Various types of interactions possible:



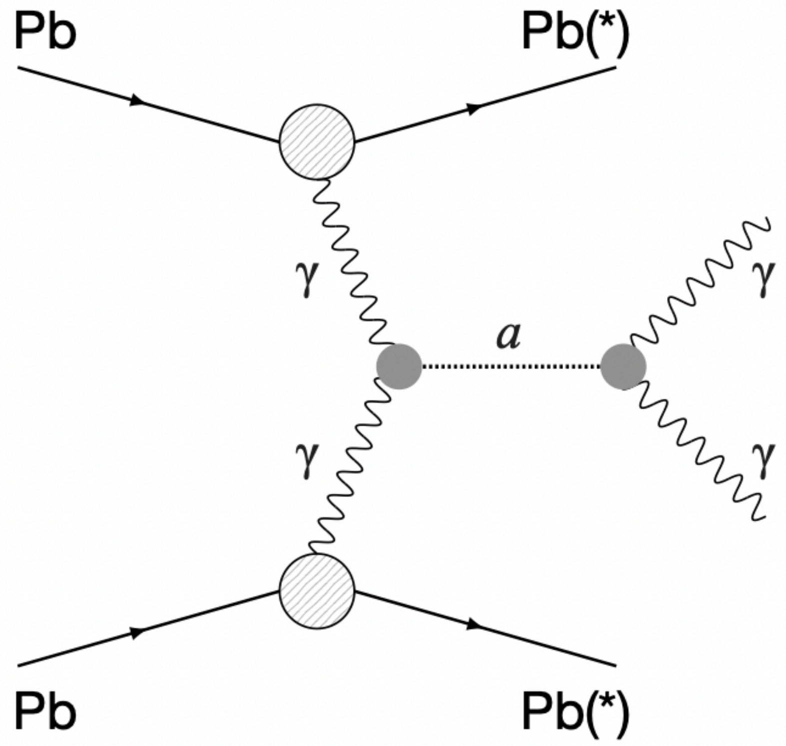
(coherent) **Photo-nuclear**



(Inelastic) **Photo-nuclear**



(SM) **Photon-photon**

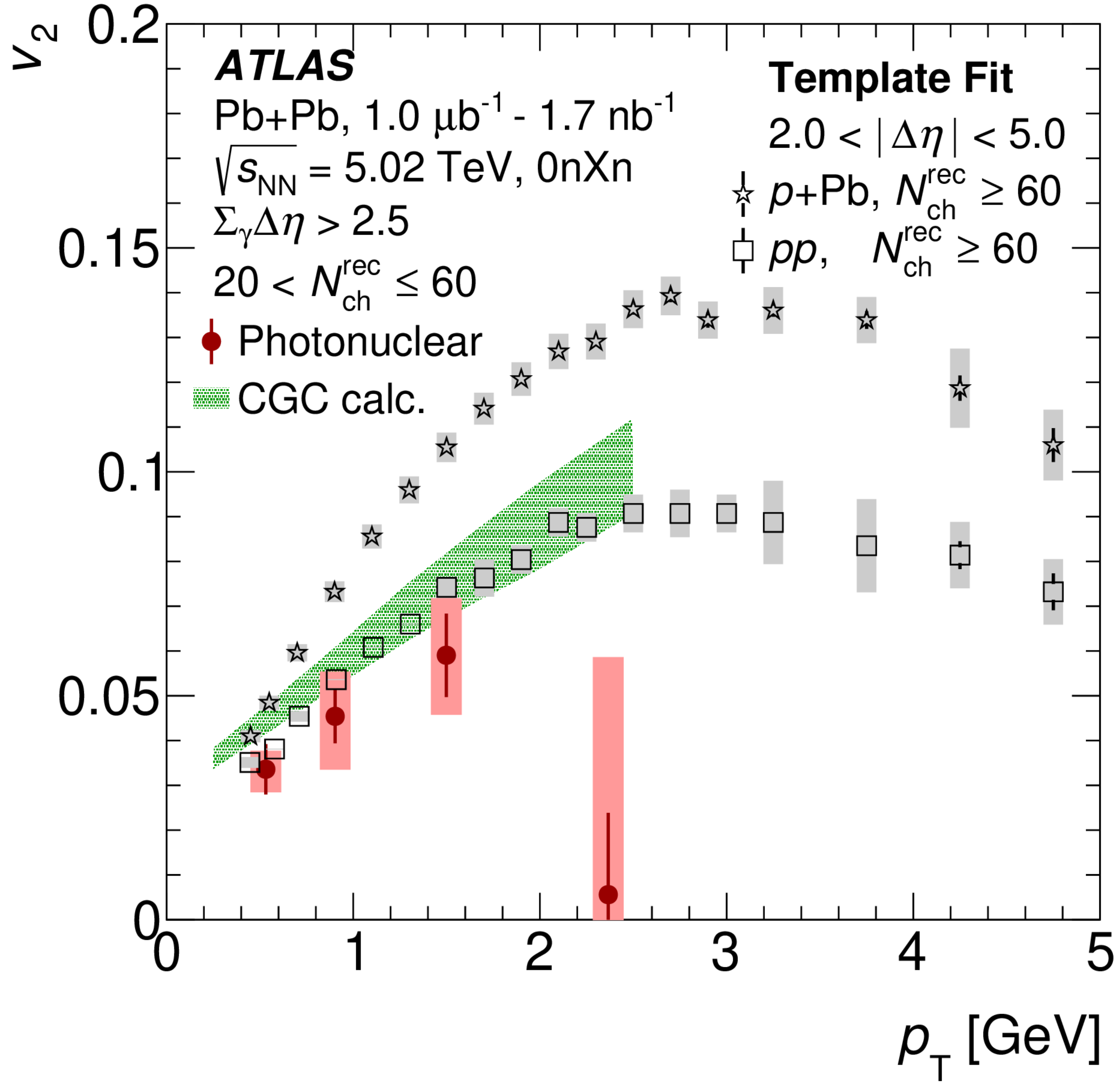


(BSM) **Photon-photon**

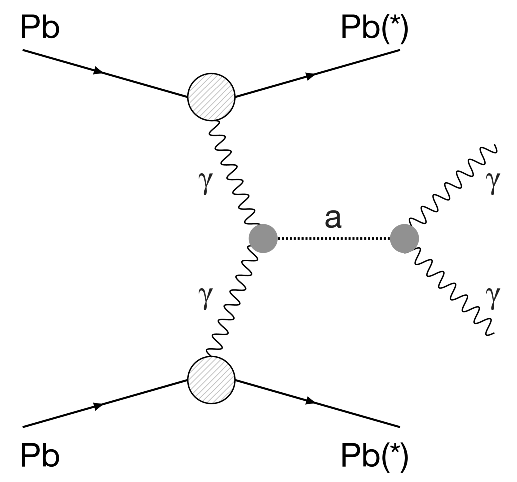
Ultraperipheral collisions at the LHC

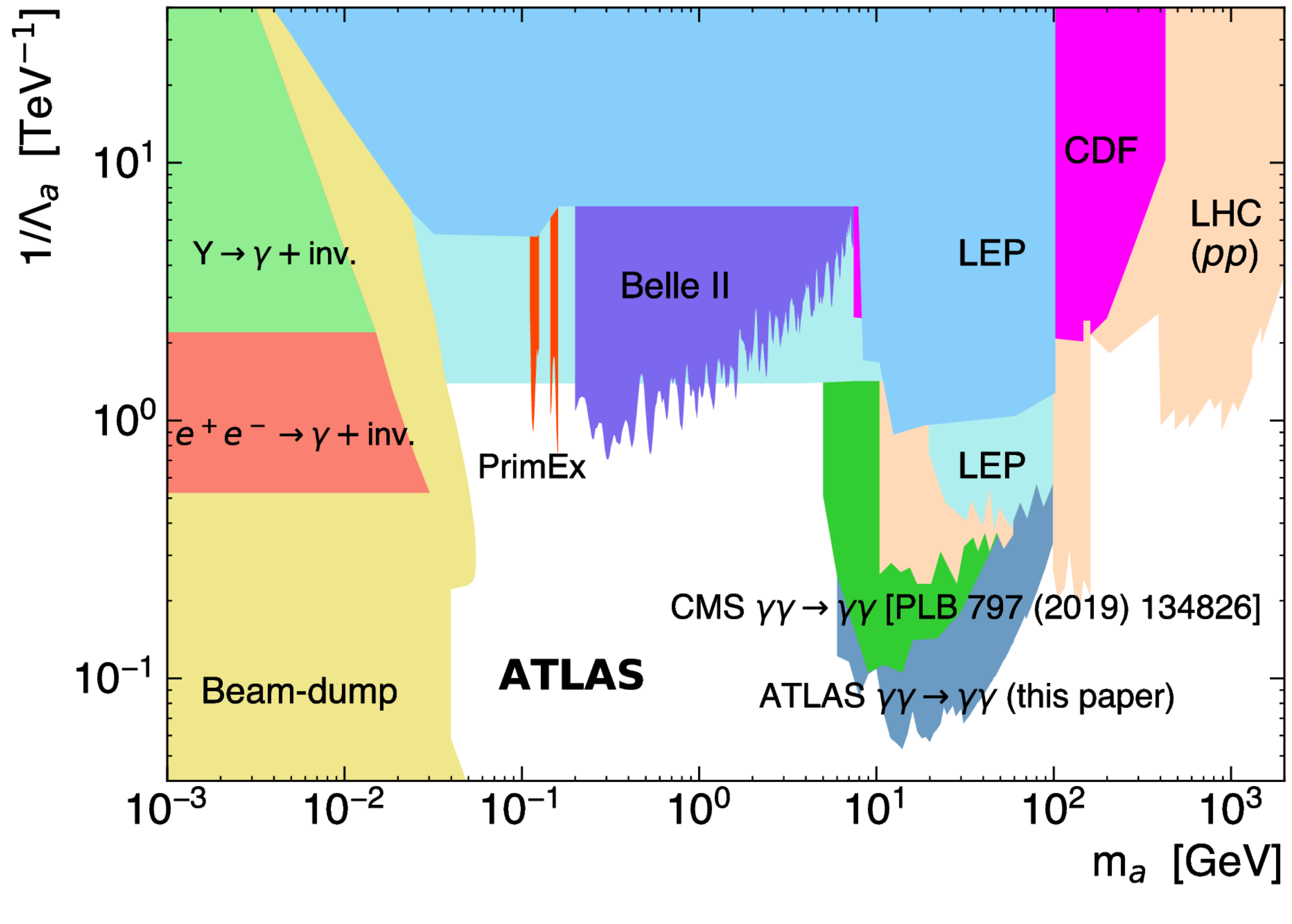
- UPC became very active research field

ATLAS, Phys. Rev. C. 104 (2021) 014903



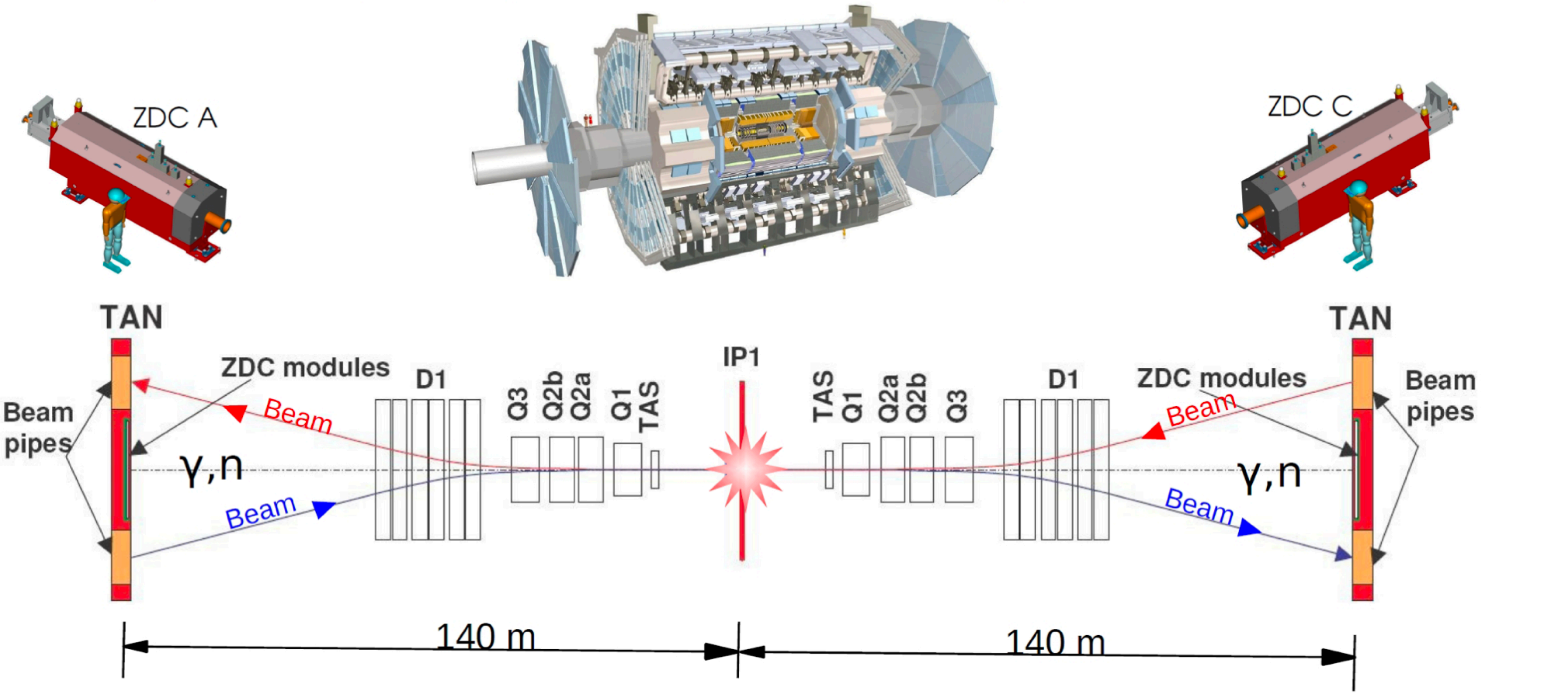
ATLAS, JHEP 03 (2021) 243



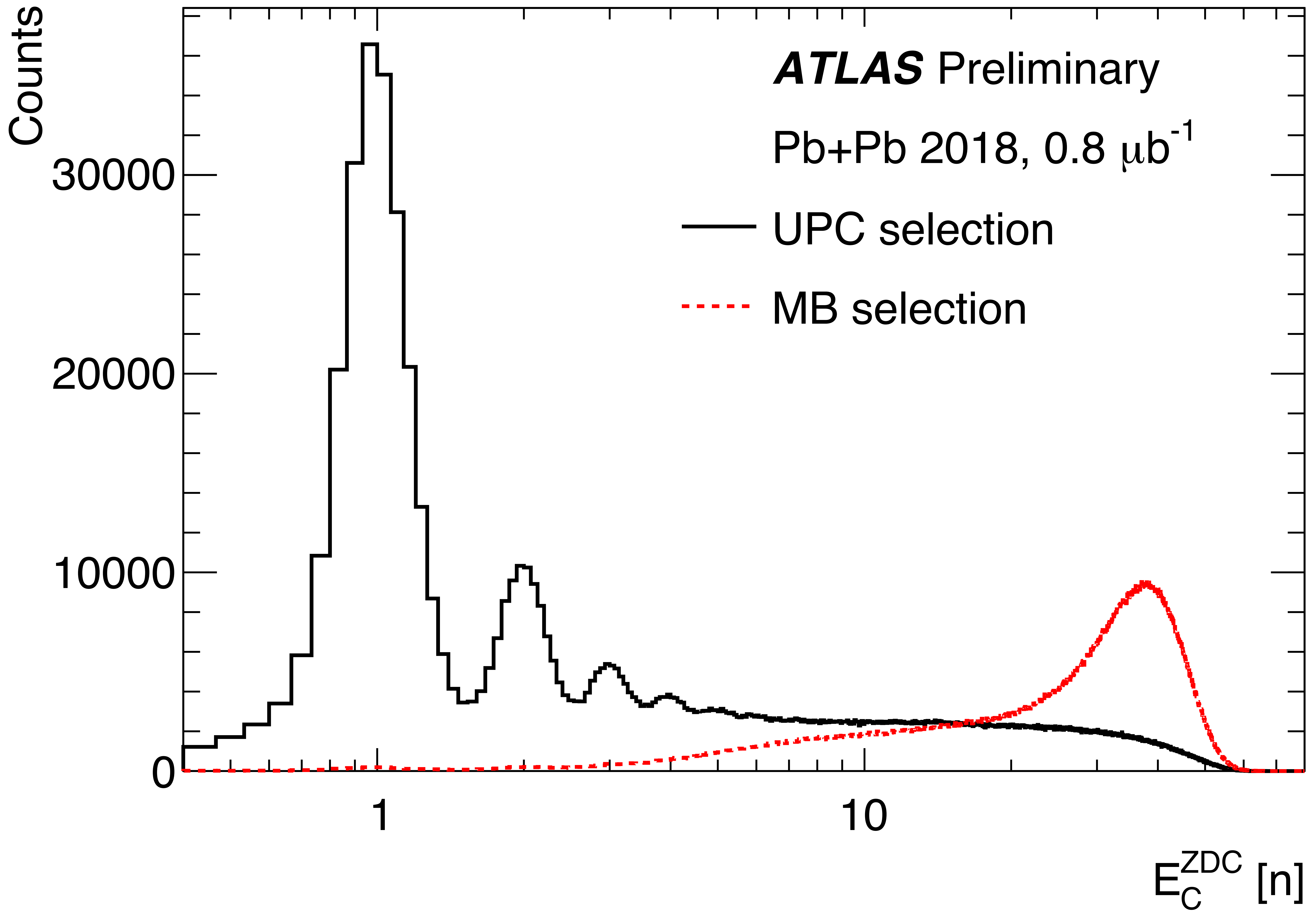


Experimental considerations

- **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)**



ATLAS ZDC performance



(1n = 2.51 TeV!)

Outline

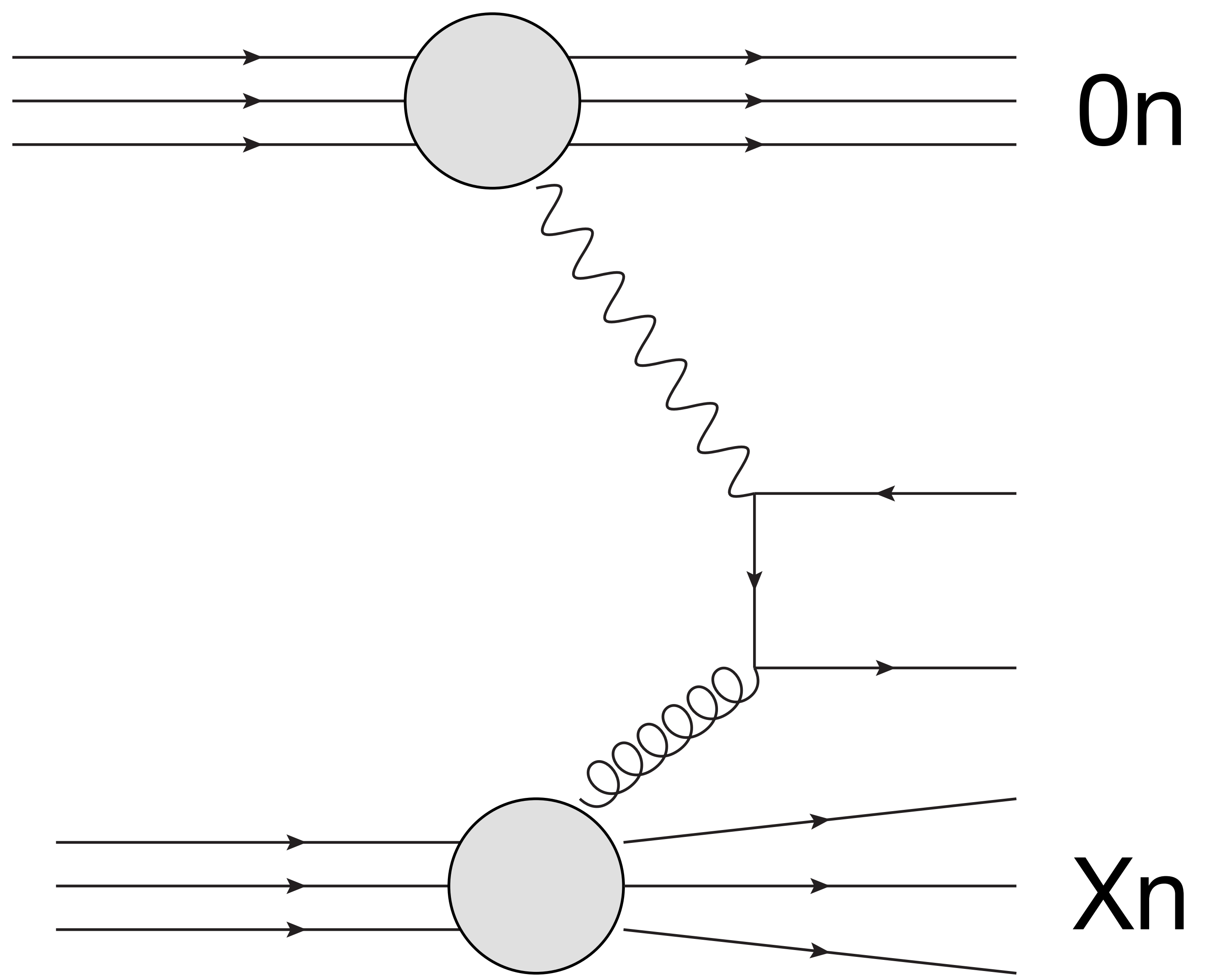
- A set of **new** ATLAS measurements will be covered in this talk:

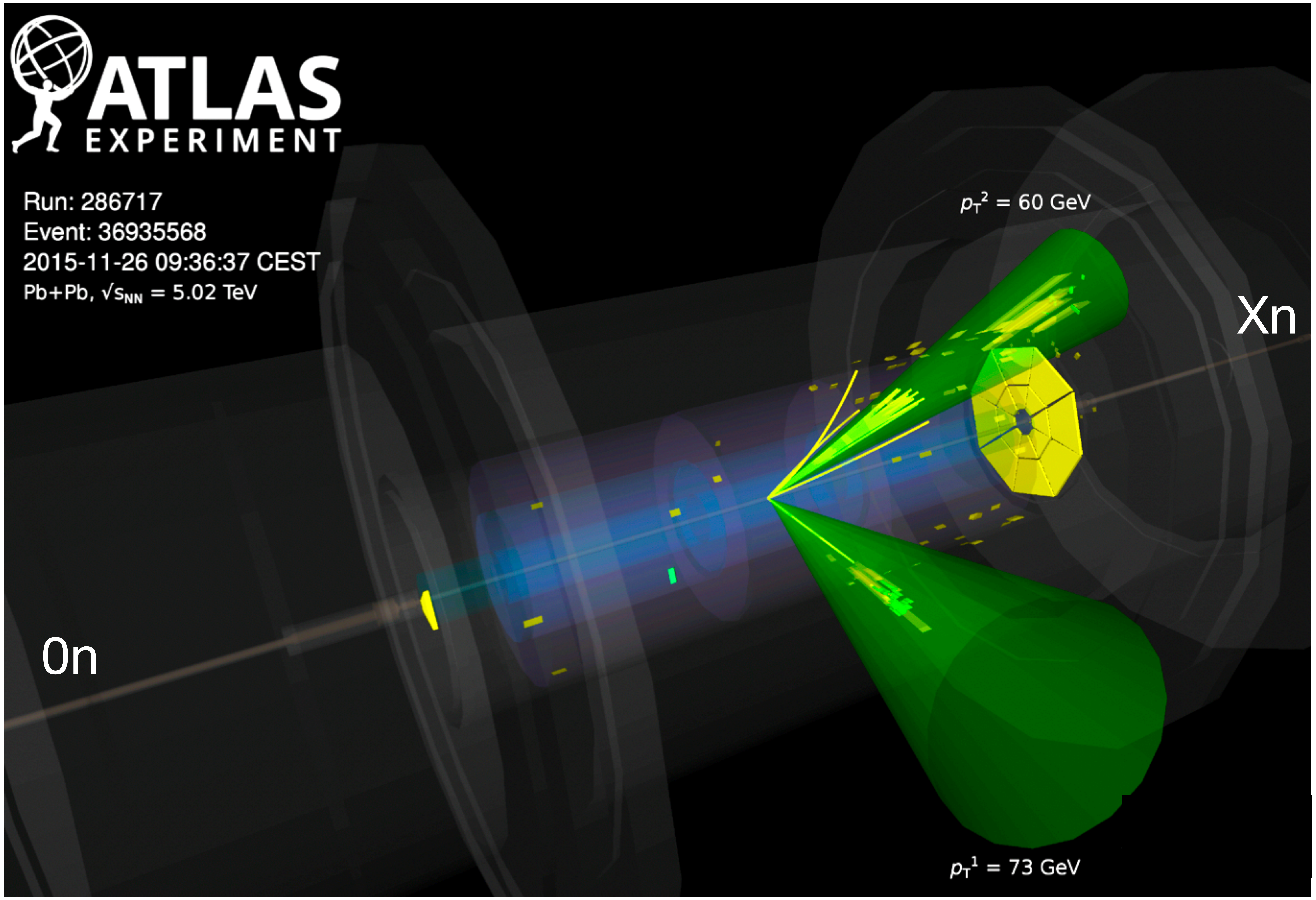
  - Photo-nuclear jet production in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ATLAS detector, **ATLAS-CONF-2022-021**

  - Exclusive dielectron production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ATLAS, **ATLAS-CONF-2022-025**

  - 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, **arXiv:2204.13478 [hep-ex]**

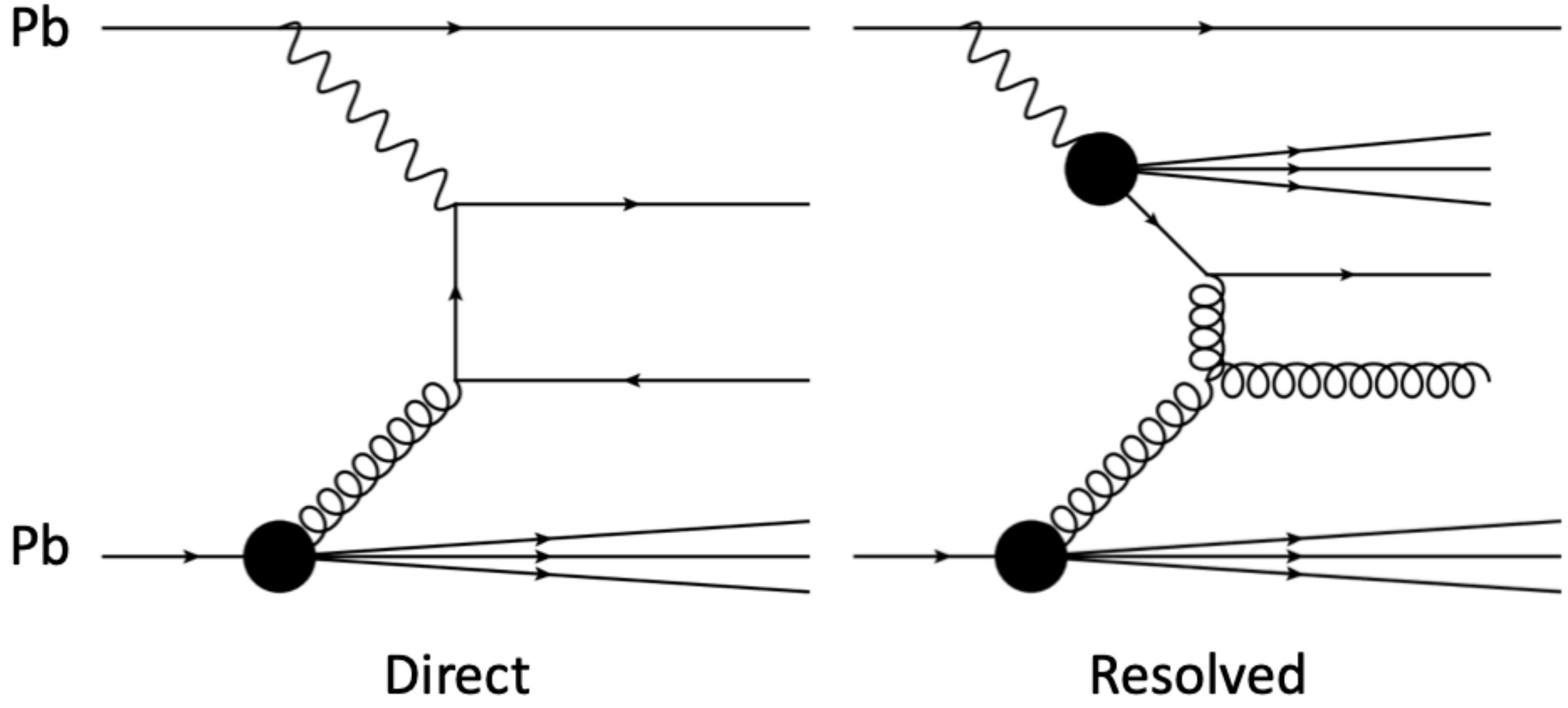
(I) Photo-nuclear dijets

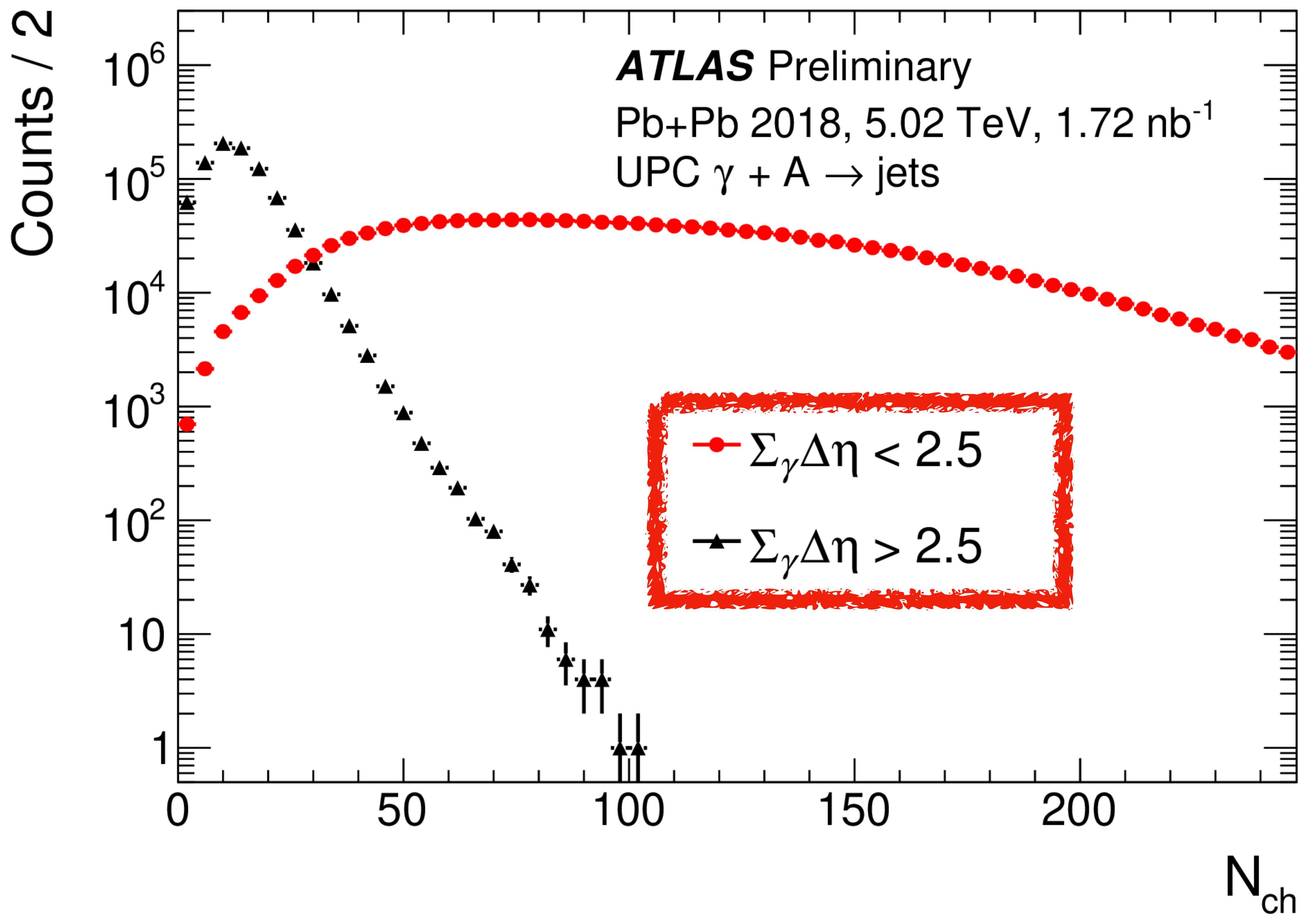




Measurement of photo-nuclear dijet production in Pb+Pb

- Both direct and resolved photon interactions are possible
- Large rapidity gaps are required on one side of the detector
  - This side is dictated by the “**0nXn**” ZDC requirement





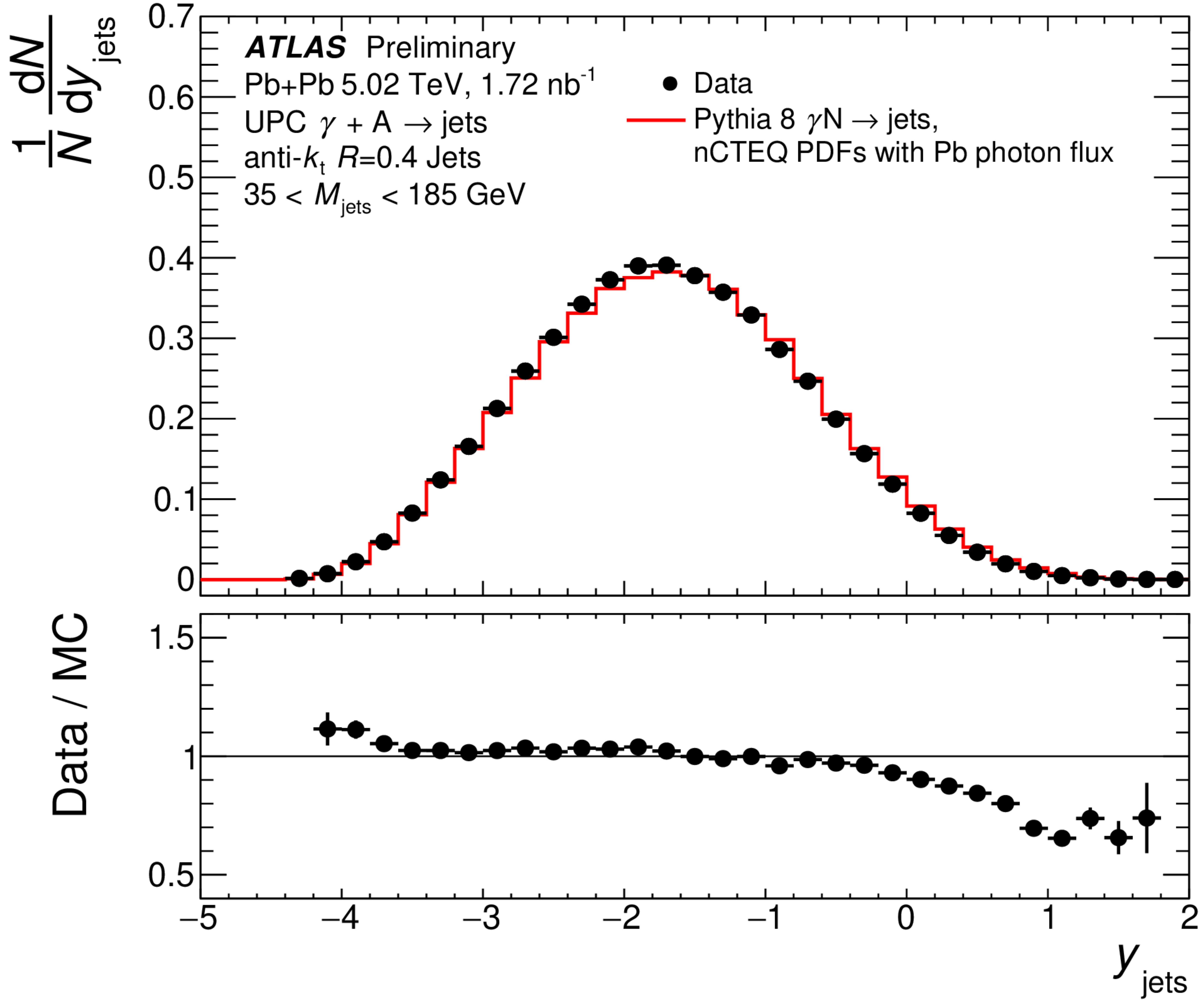
Measurement of photo-nuclear dijet production in Pb+Pb

- Jet selection: 2 jets with pT>15 GeV
- Jet kinematics provide access to the hard-scattering kinematics, directly probing nuclear PDF effects:

$$H_T \equiv \sum_i p_T^i$$

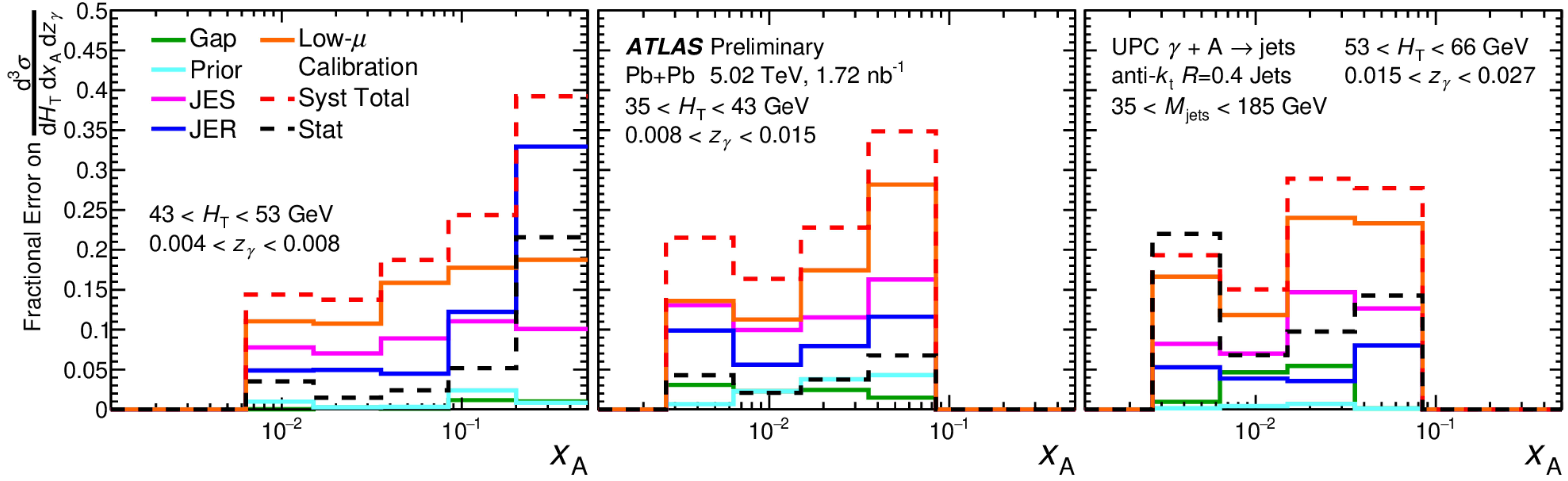
$$x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}$$

$$z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$



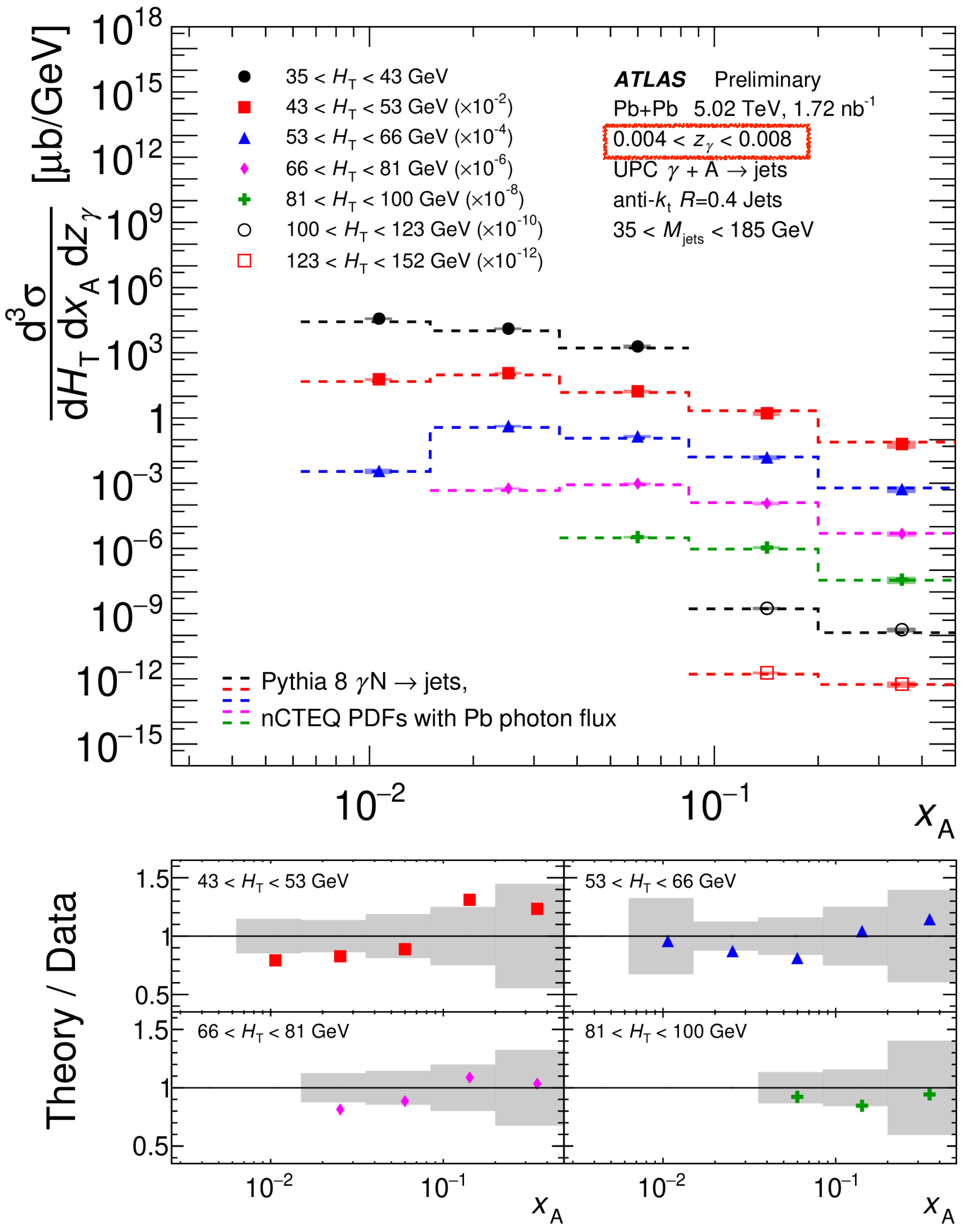
Measurement of photo-nuclear dijet production in Pb+Pb

- Systematic uncertainties (aka: the key limiting factor in our sensitivity to nuclear PDFs)
  - Jet calibration dominates



Measurement of photo-nuclear dijet production in Pb+Pb

- Measurement fully unfolded for detector effects
- Triple-differential cross-sections extracted (x_A, z_γ, H_T)
- Comparison to Pythia 8 + nPDFs
- Potential to constrain nPDFs



intermediate photon energies
→ can access higher-x partons

Measurement of photo-nuclear dijet production in Pb+Pb

- Measurement fully unfolded for detector effects
- Triple-differential cross-sections extracted (x_A, z_γ, H_T)
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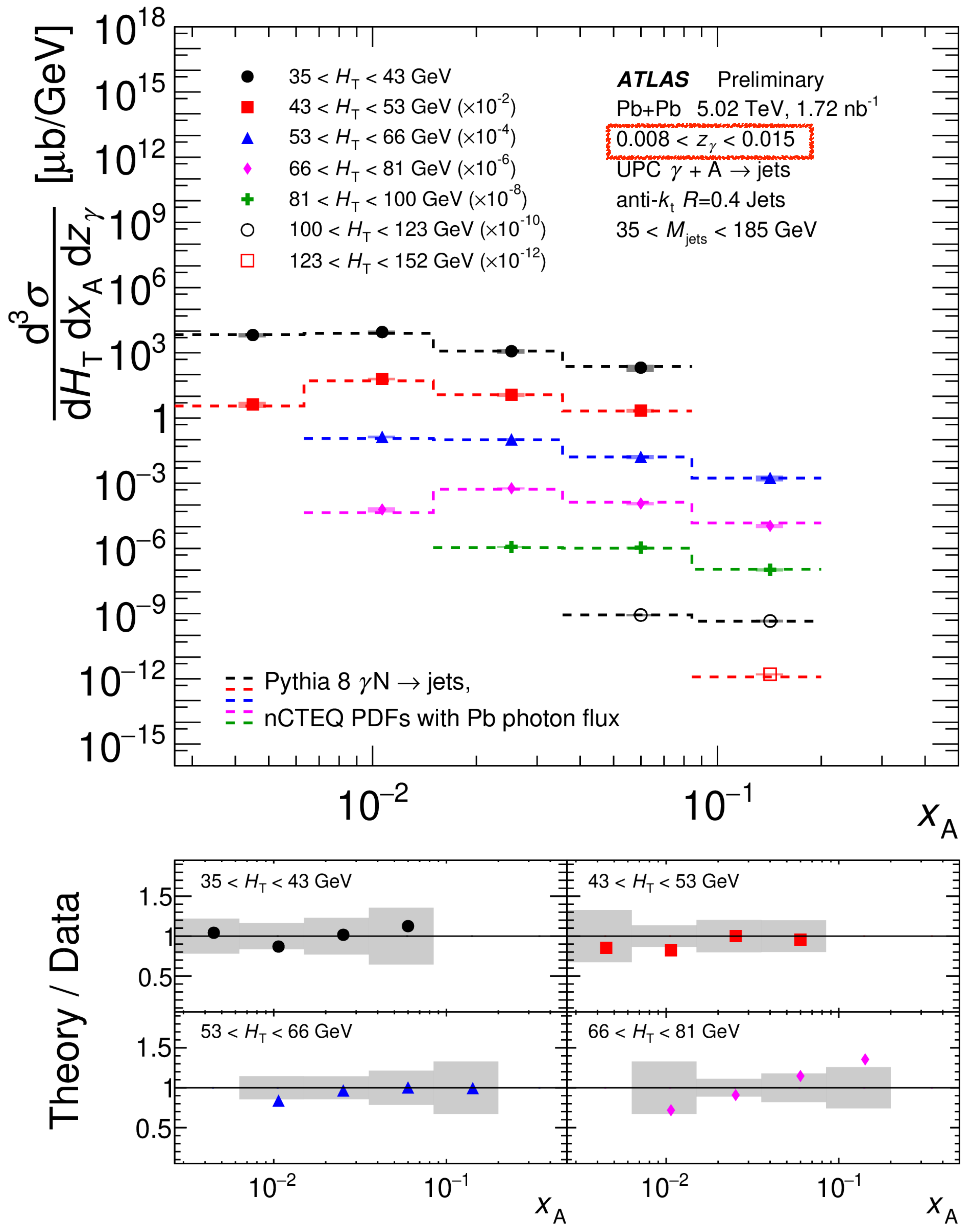
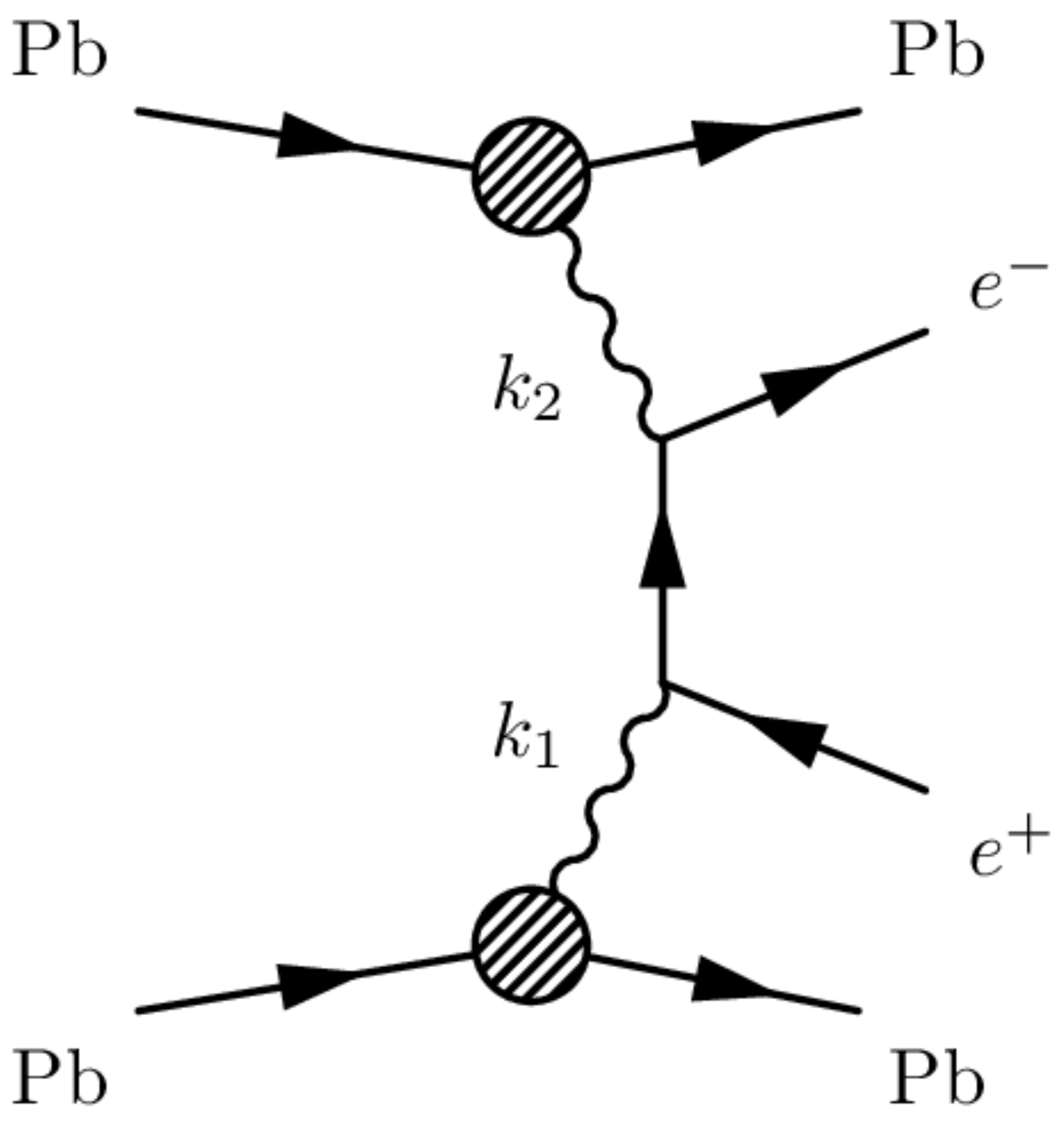
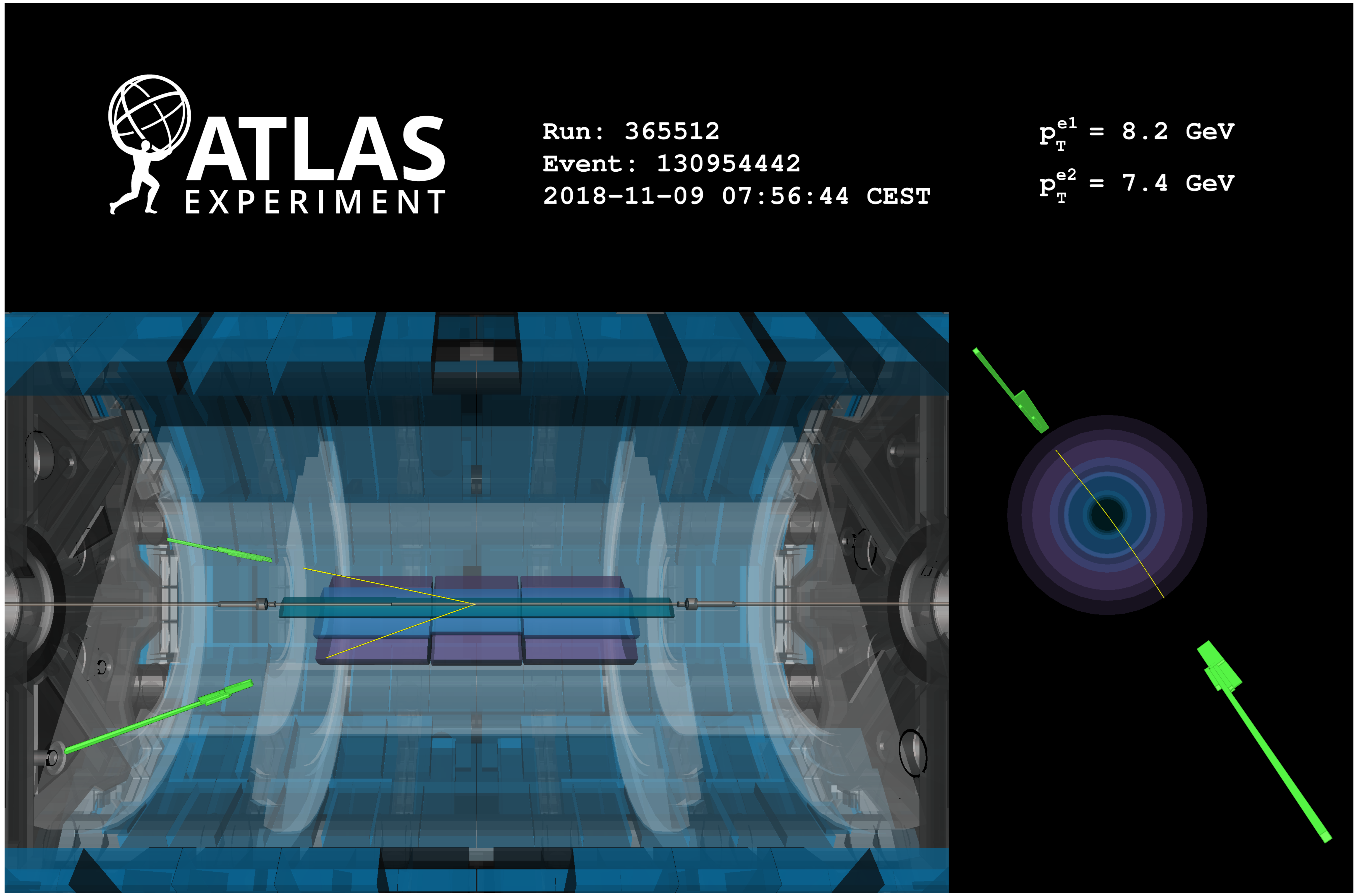


Going higher in photon energy → low-x

(II) Exclusive dielectron production



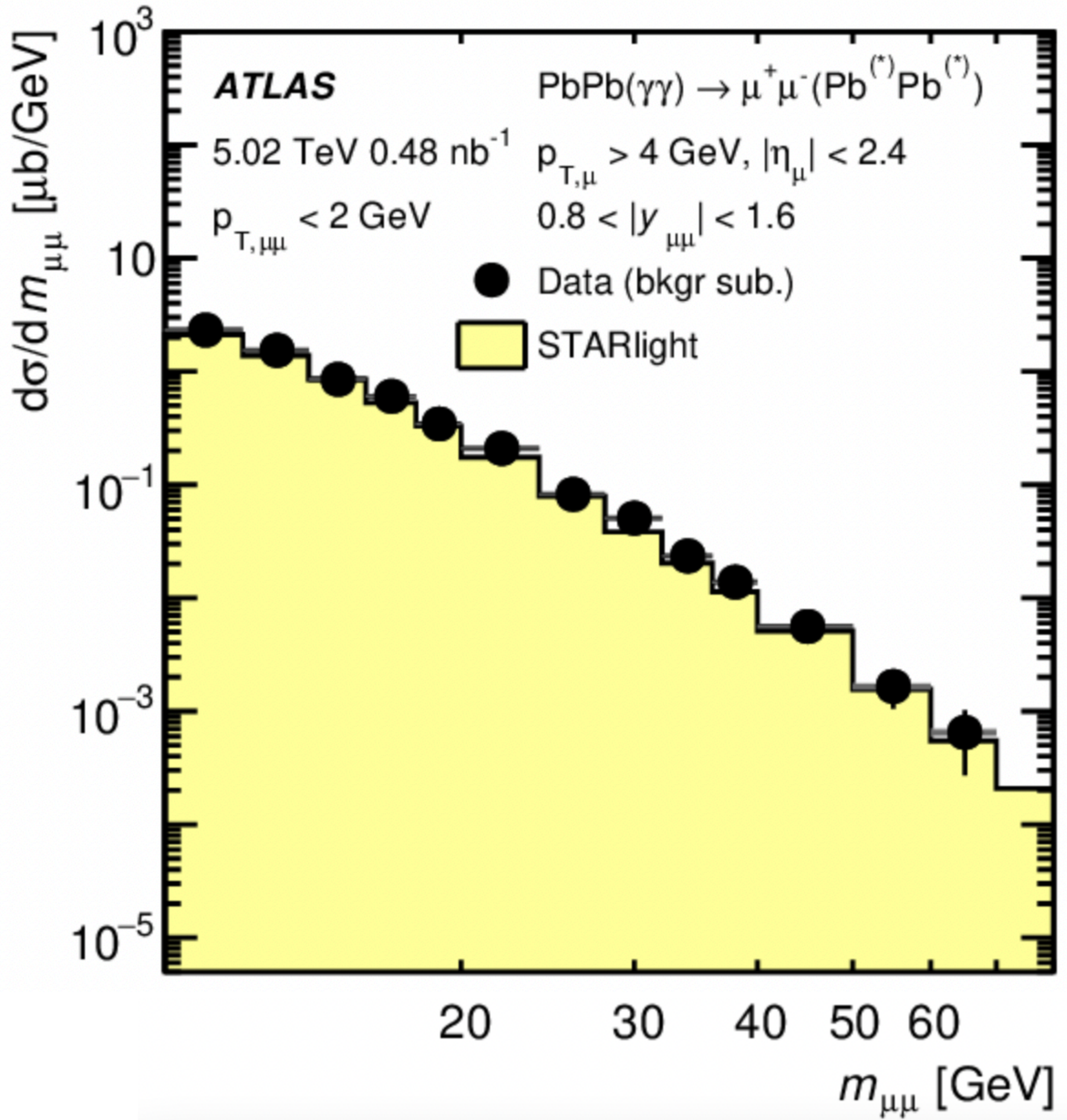


Exclusive dielectron production in Pb+Pb UPC

- 'Standard candle' process
  - Good sensitivity for Pb EM formfactors → photon flux modeling
  - Sensitivity to probe higher-order corrections
- New ATLAS measurement (ee) extends the previous dimuon study

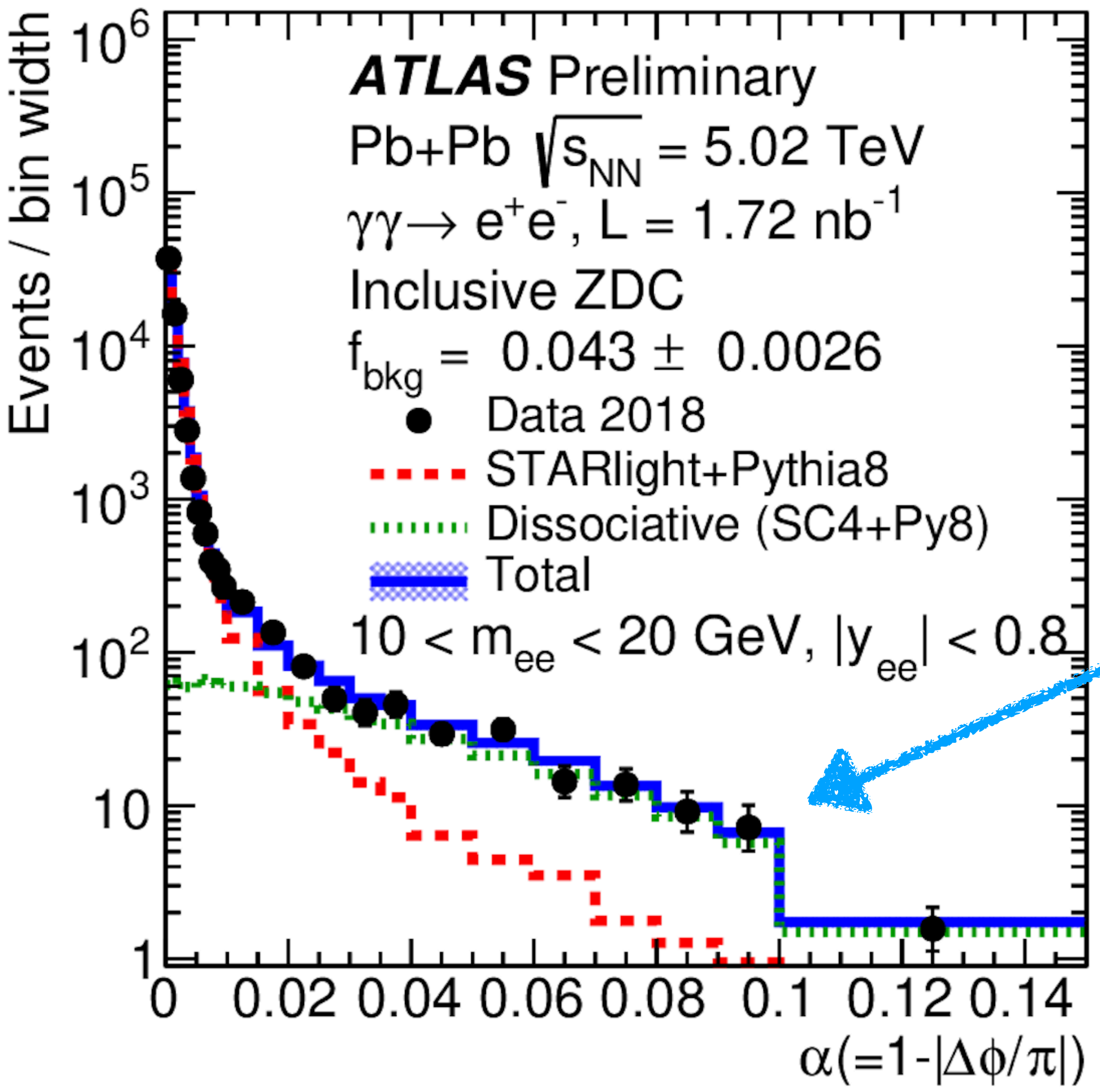
	$\gamma\gamma \to \mu^+\mu^-$	$\gamma\gamma \to e^+e^-$
Data	2015	2018
Int lumi	0.48 nb^{-1}	1.72 nb^{-1}
Fiducial	$p_T^\mu > 4$ GeV $\lvert\eta^\mu\rvert < 2.4$ $m_{\mu\mu} > 10$ GeV	$p_T^e > 2.5$ GeV $\lvert\eta^e\rvert < 2.5$ $m_{ee} > 5$ GeV
	$p_T^{\ell\ell} < 2$ GeV	

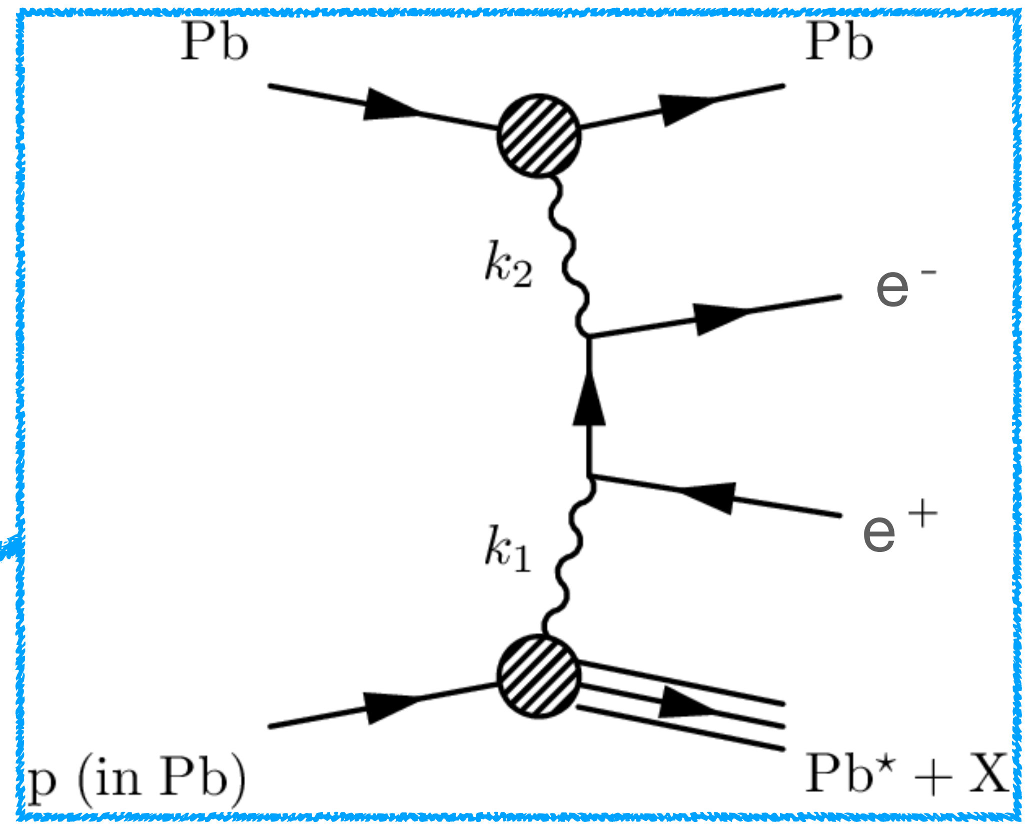
Phys. Rev. C 104 (2021) 024906

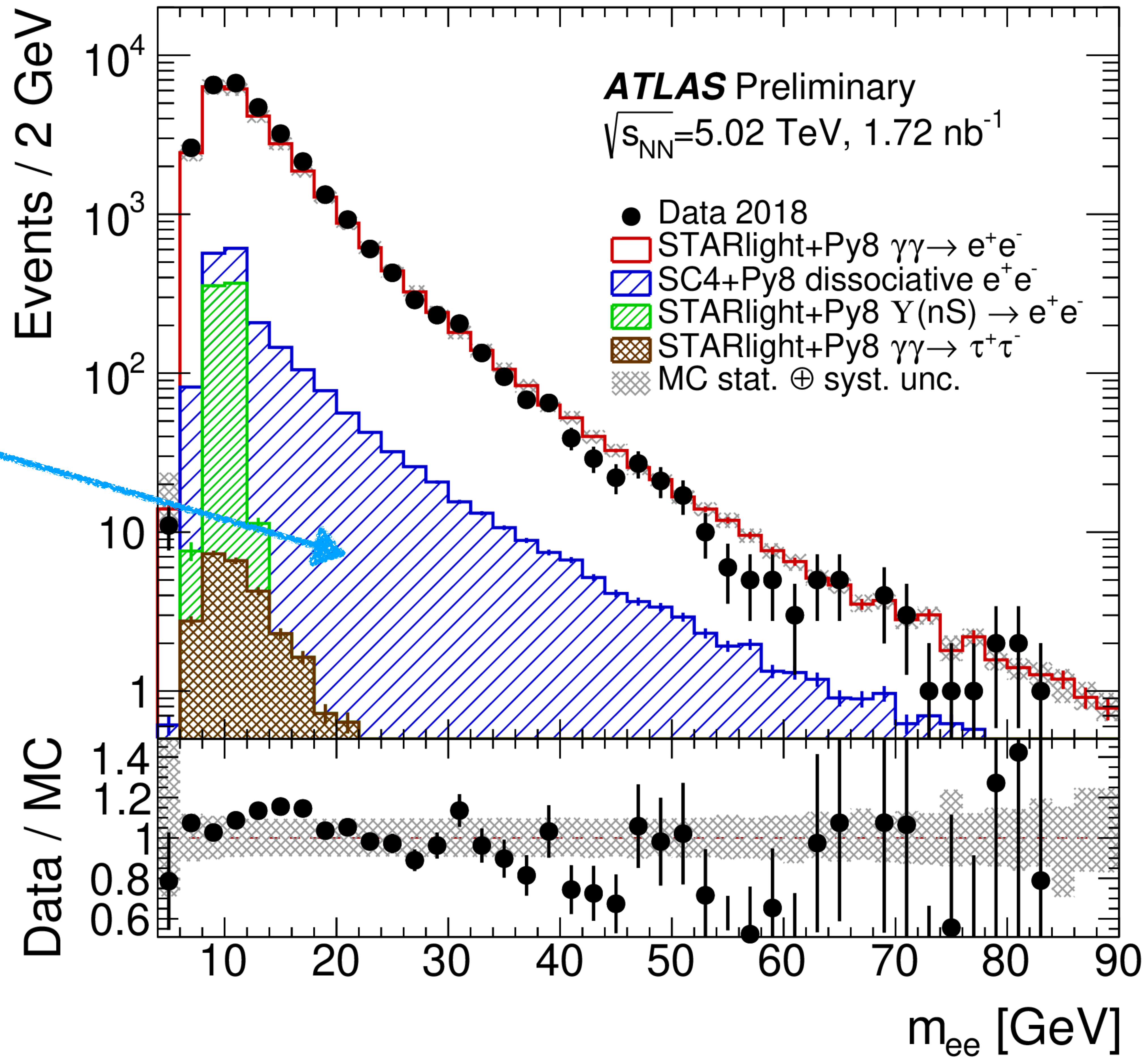


Exclusive dielectron production in Pb+Pb UPC

- Background dominated by dissociative production with off-shell photon
  - Extracted using template fit to dielectron acoplanarity

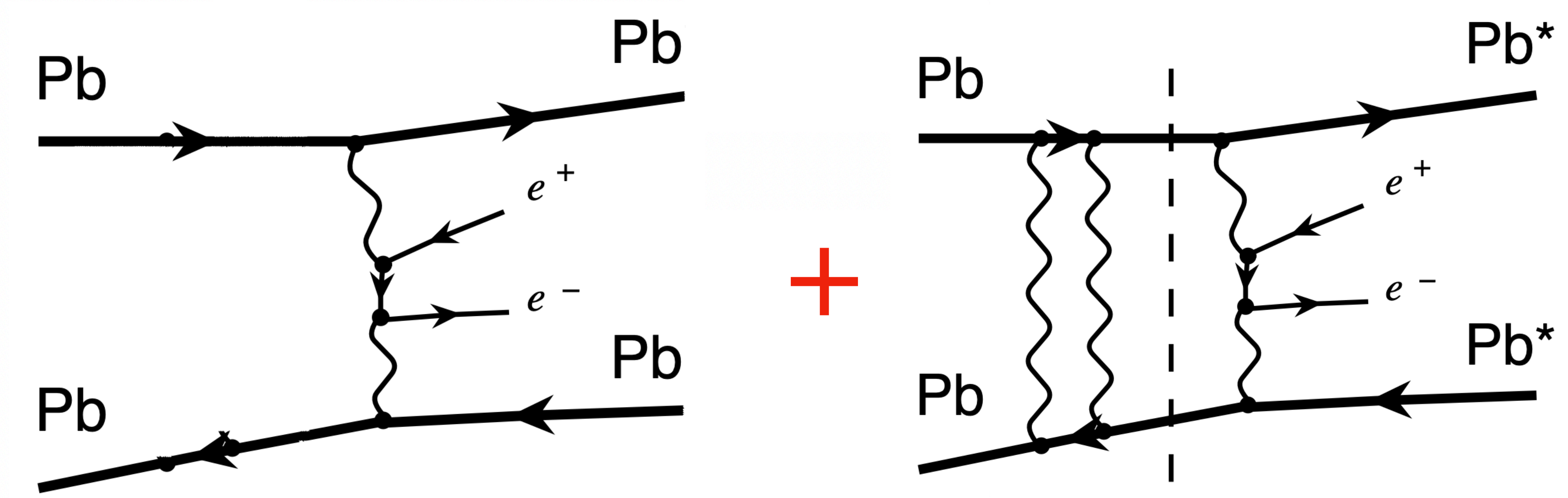






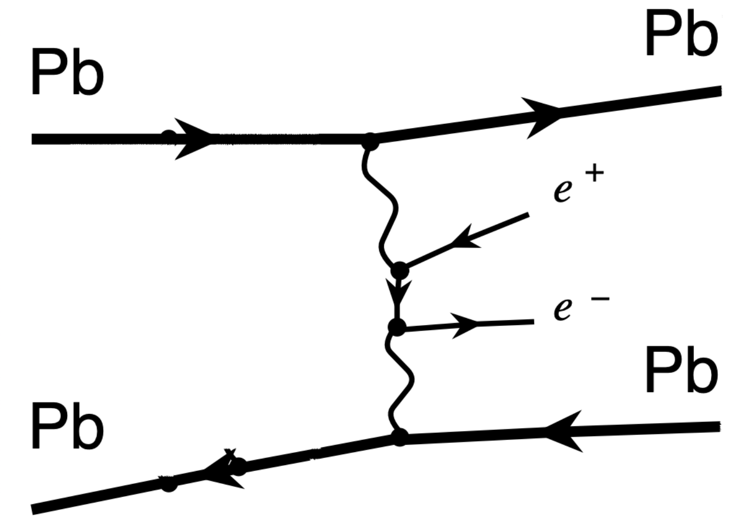
Exclusive dielectron production in Pb+Pb UPC

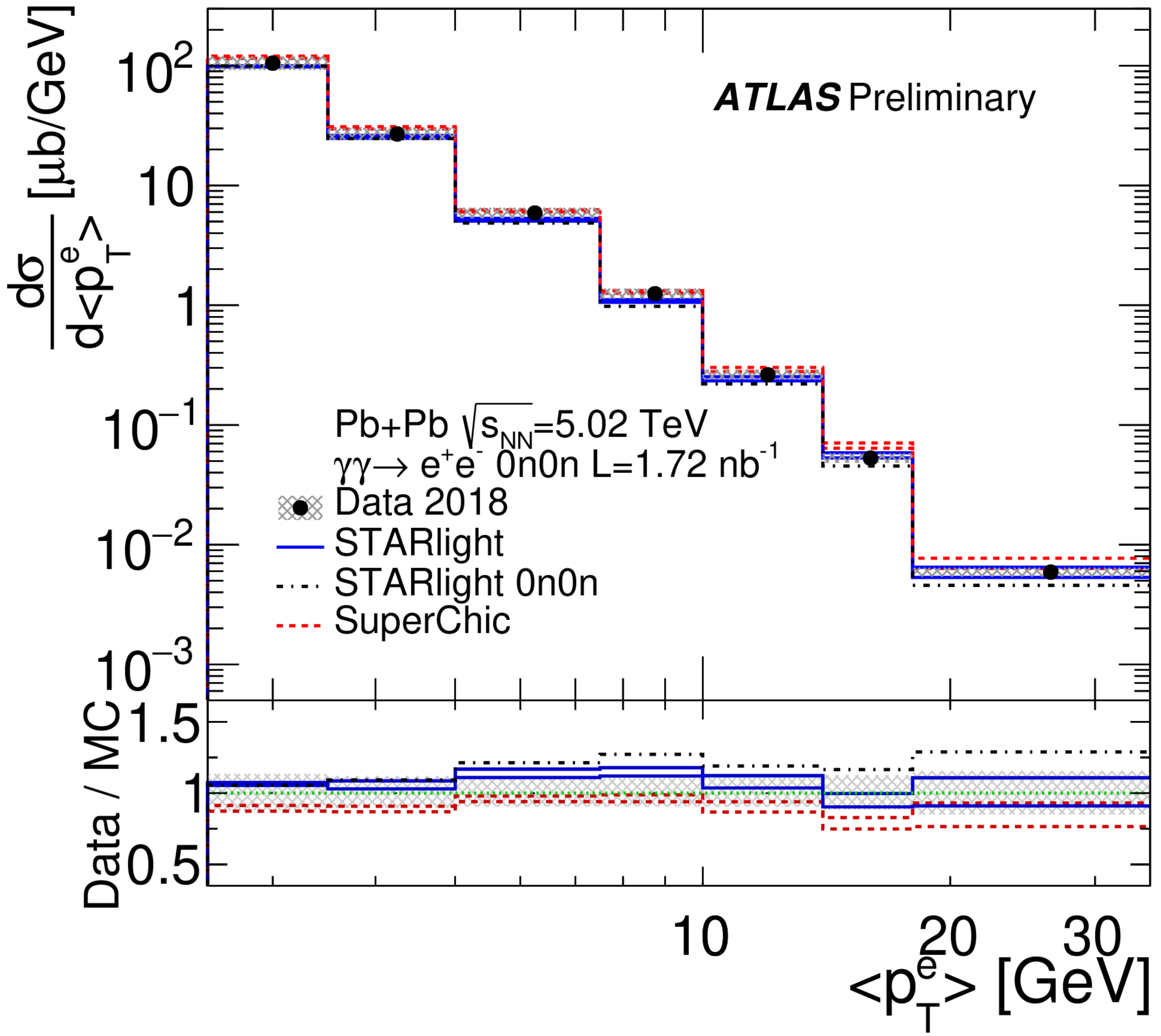
- Results for “inclusive ZDC” selection

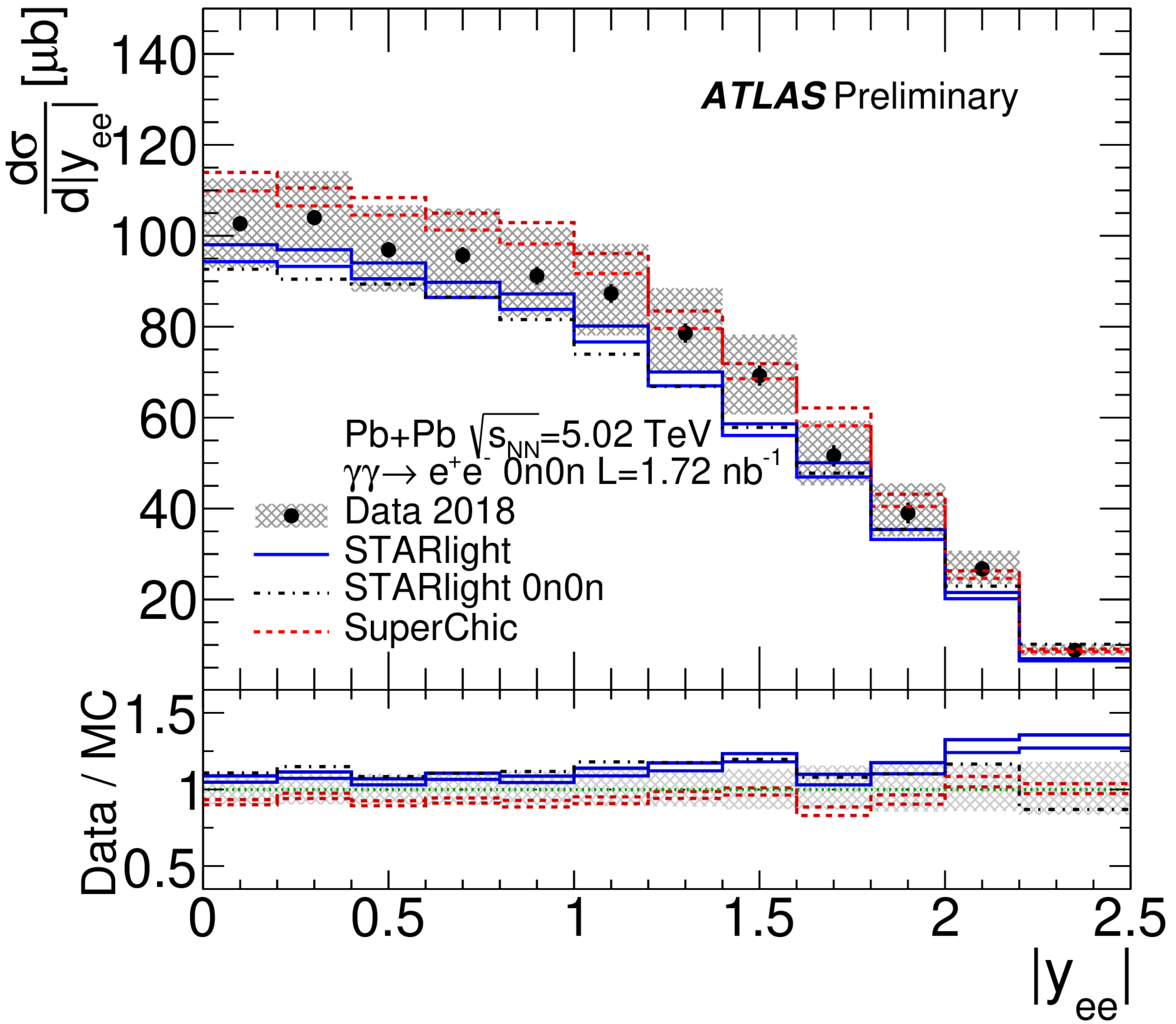


Exclusive dielectron production in Pb+Pb UPC

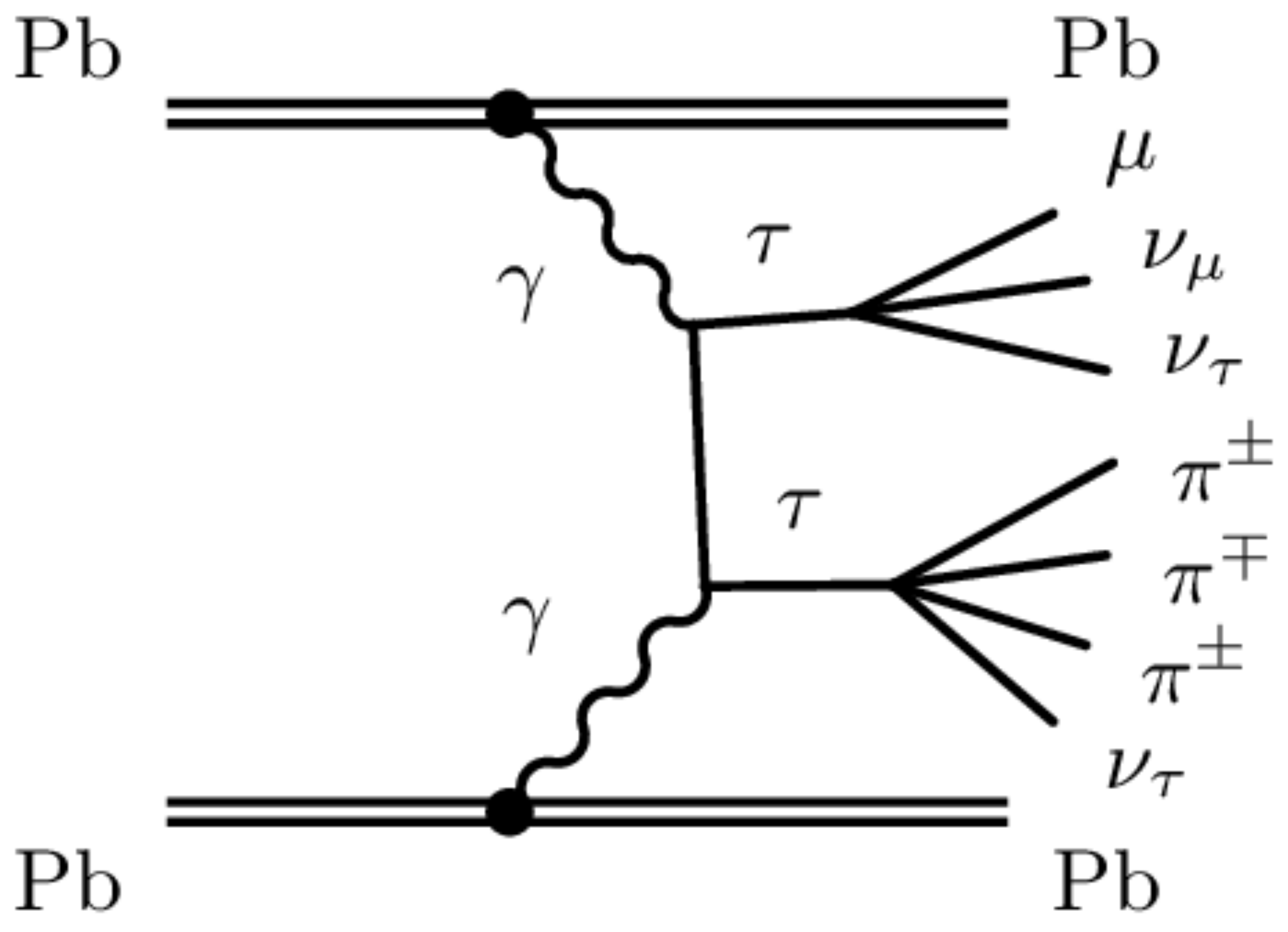
- Results for “0n0n” ZDC selection

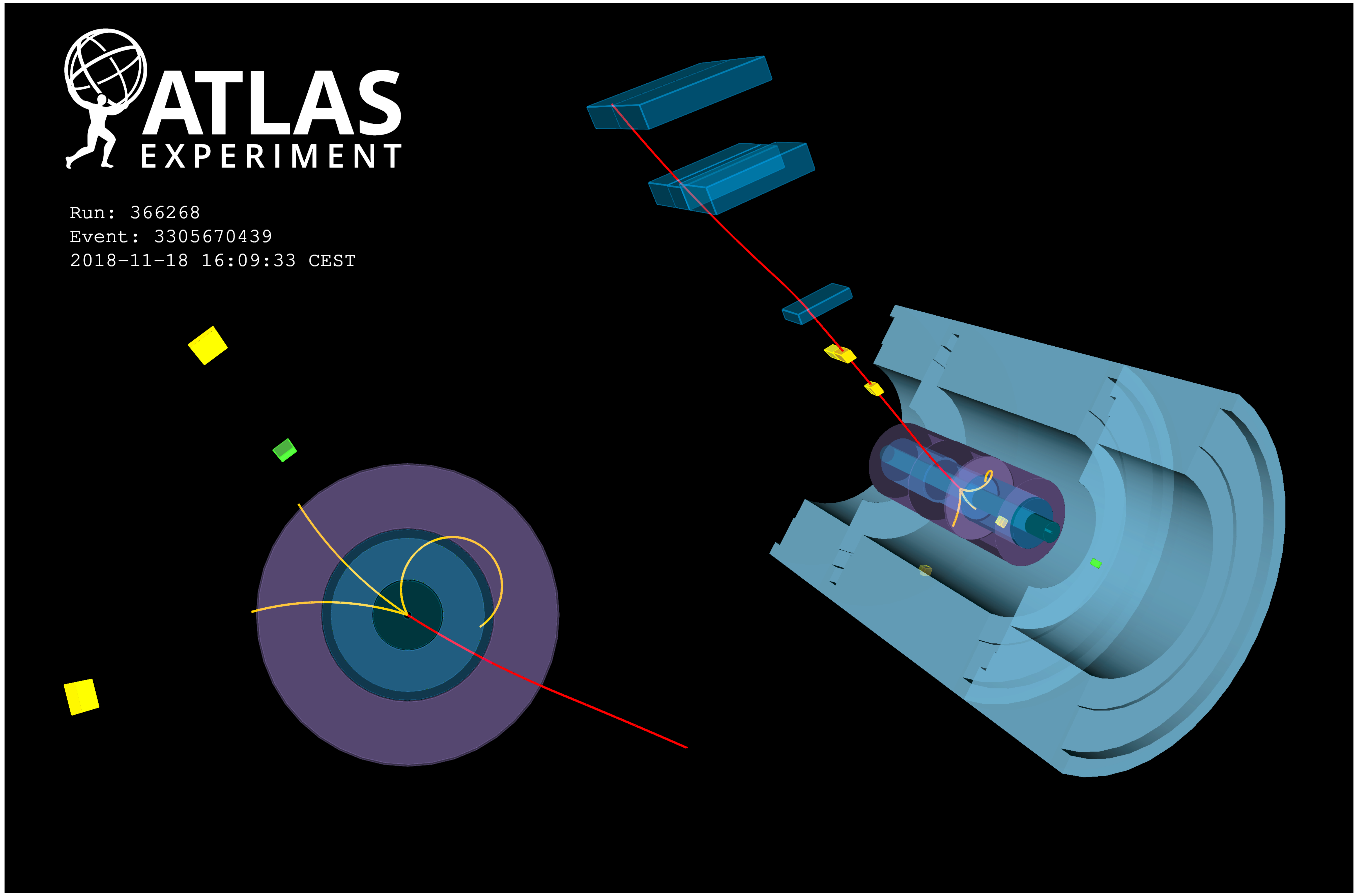






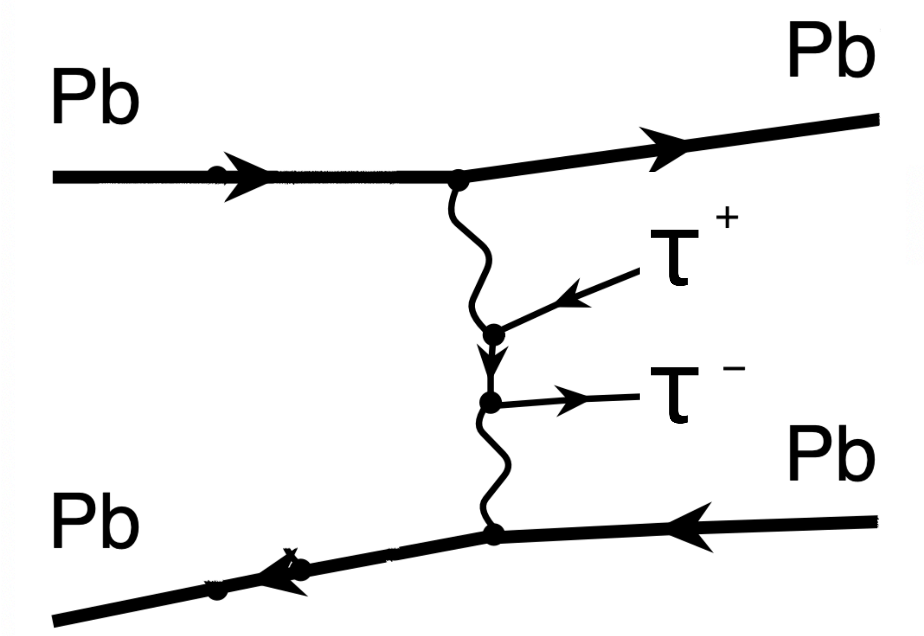
(III) Exclusive tau-pair production

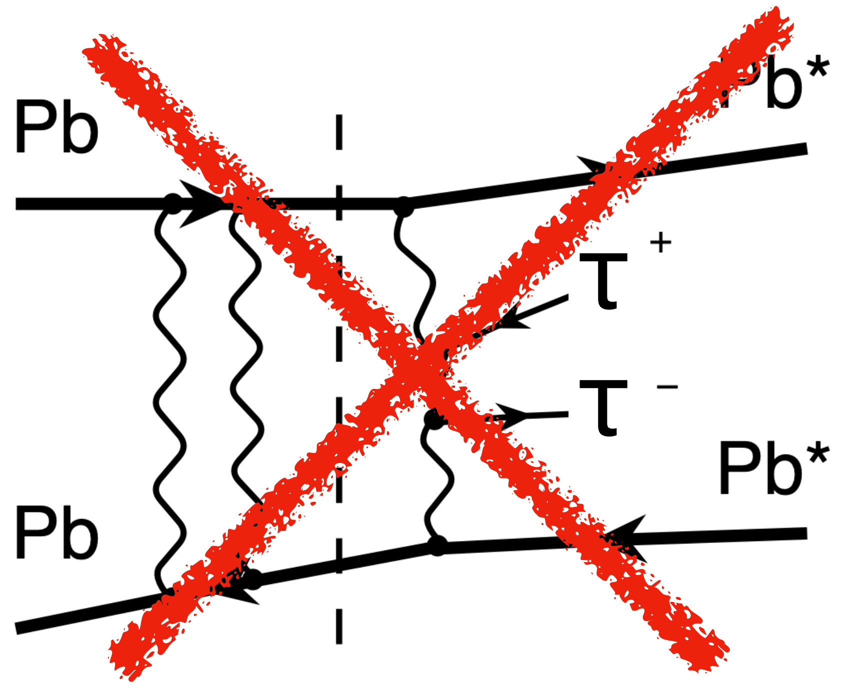




Exclusive tau-pair production in Pb+Pb UPC

- More challenging experimentally due to **low-energy tau decays**
- Strategy: exploit semi-leptonic decays with muon
    - **μ1T-SR**: muon + 1 track (e/μ/pion)
    - **μ3T-SR**: muon + 3 tracks (3 pions)
    - **μe-SR**: muon + electron
- **"0n0n"** ZDC selection to suppress hadronic backgrounds (mainly photonuclear production)
- **Exclusivity**:
    - Veto extra tracks
    - Veto additional calo clusters (μ1T-SR and μ3T-SR only)

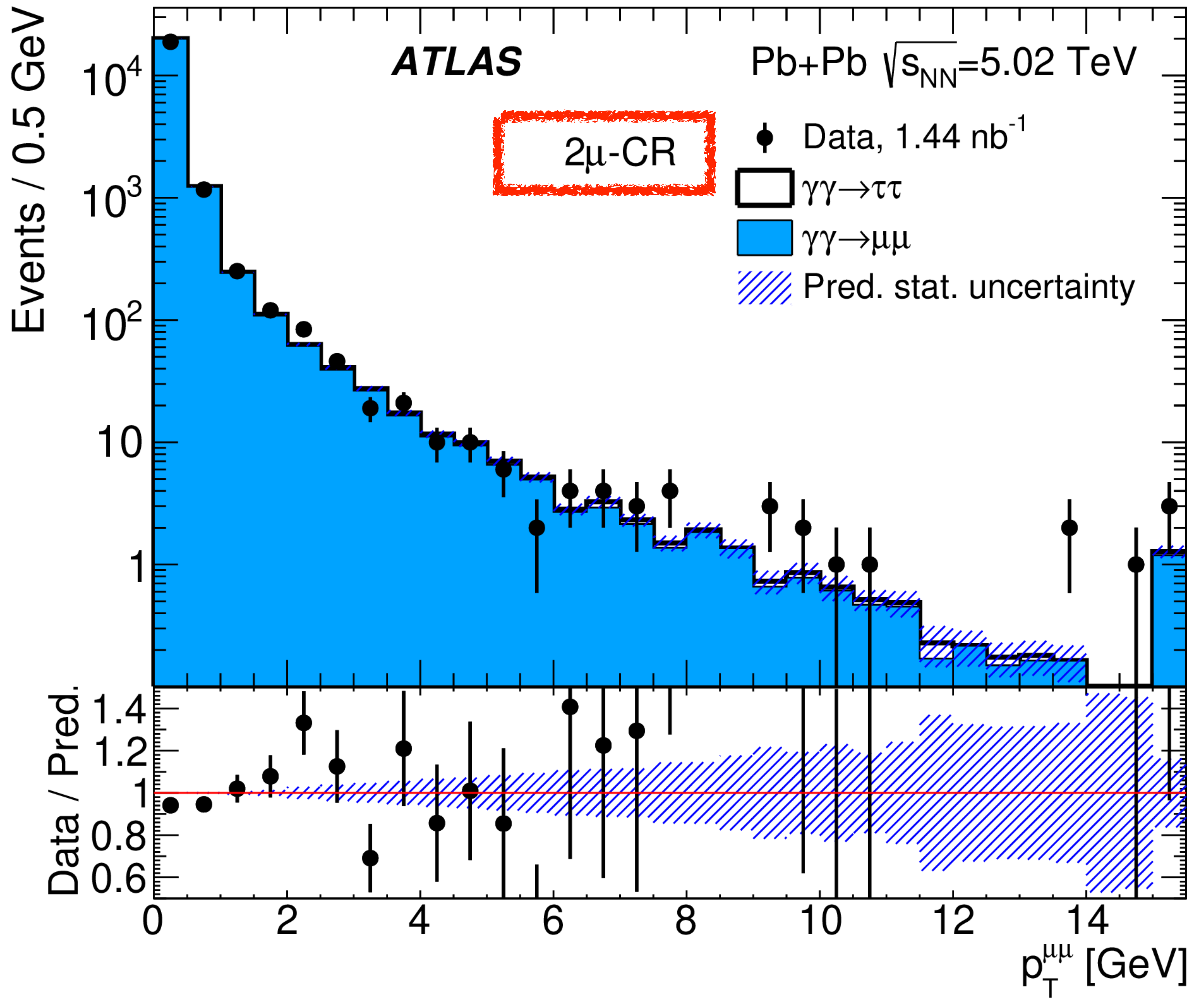




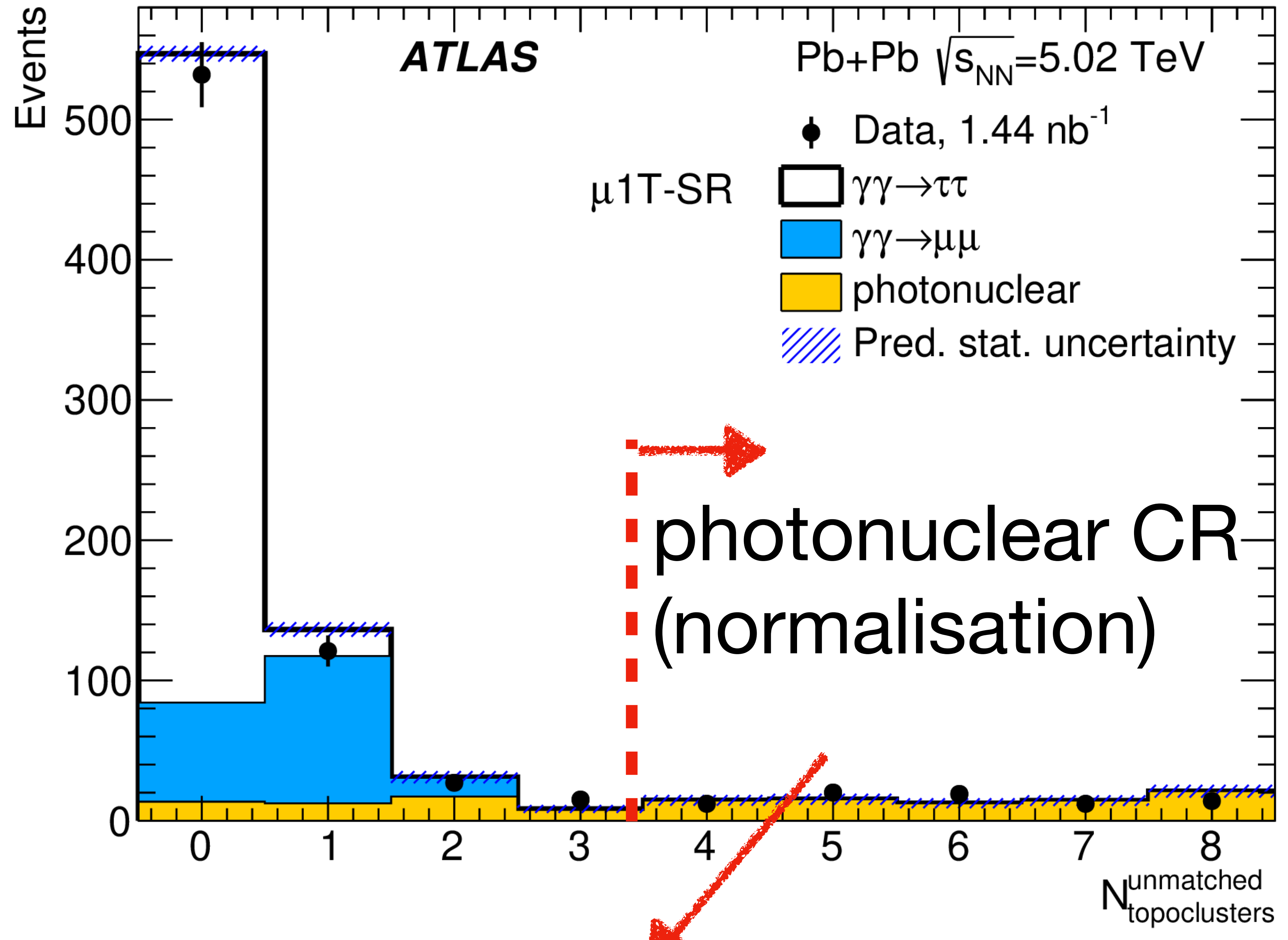
Exclusive tau-pair production in Pb+Pb UPC

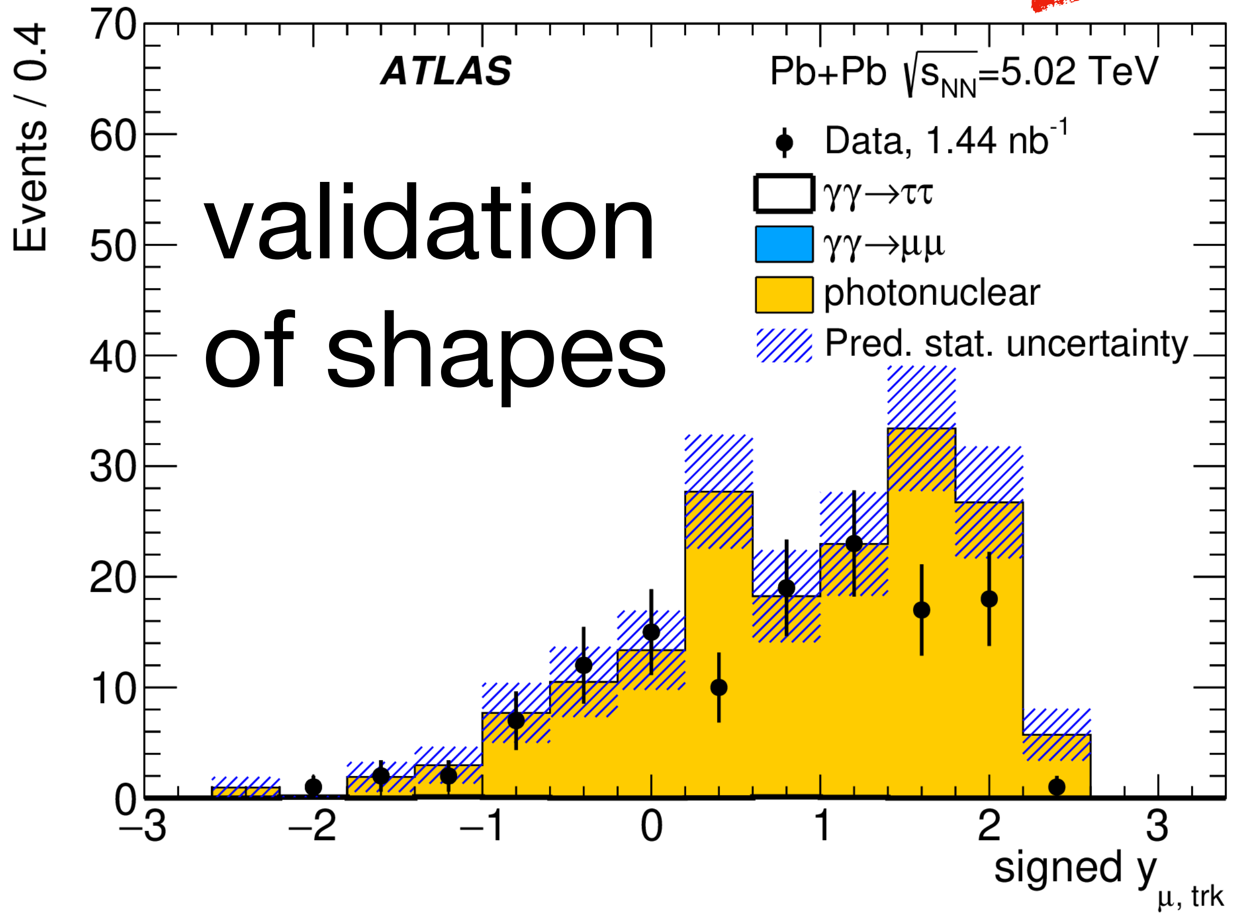
- **Main backgrounds**

γγ → μμγ (MC-based)



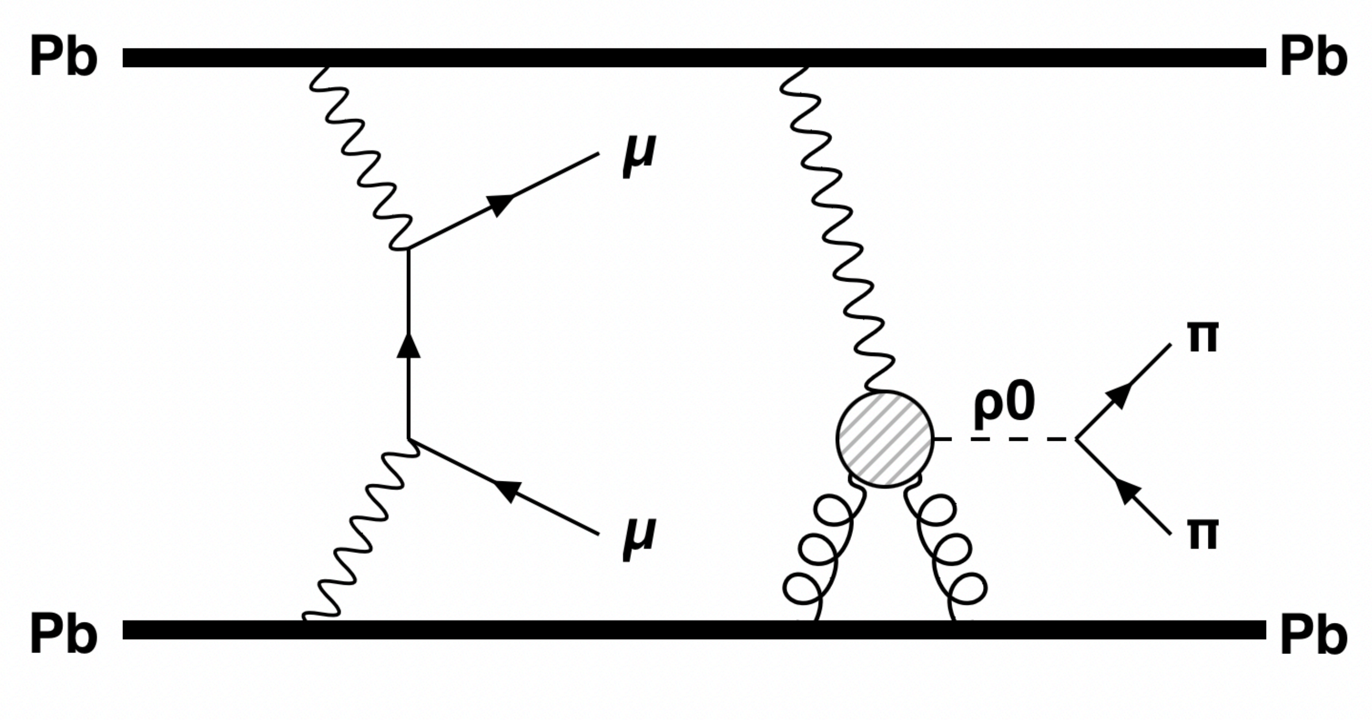
Diffractive photonuclear (data-driven)

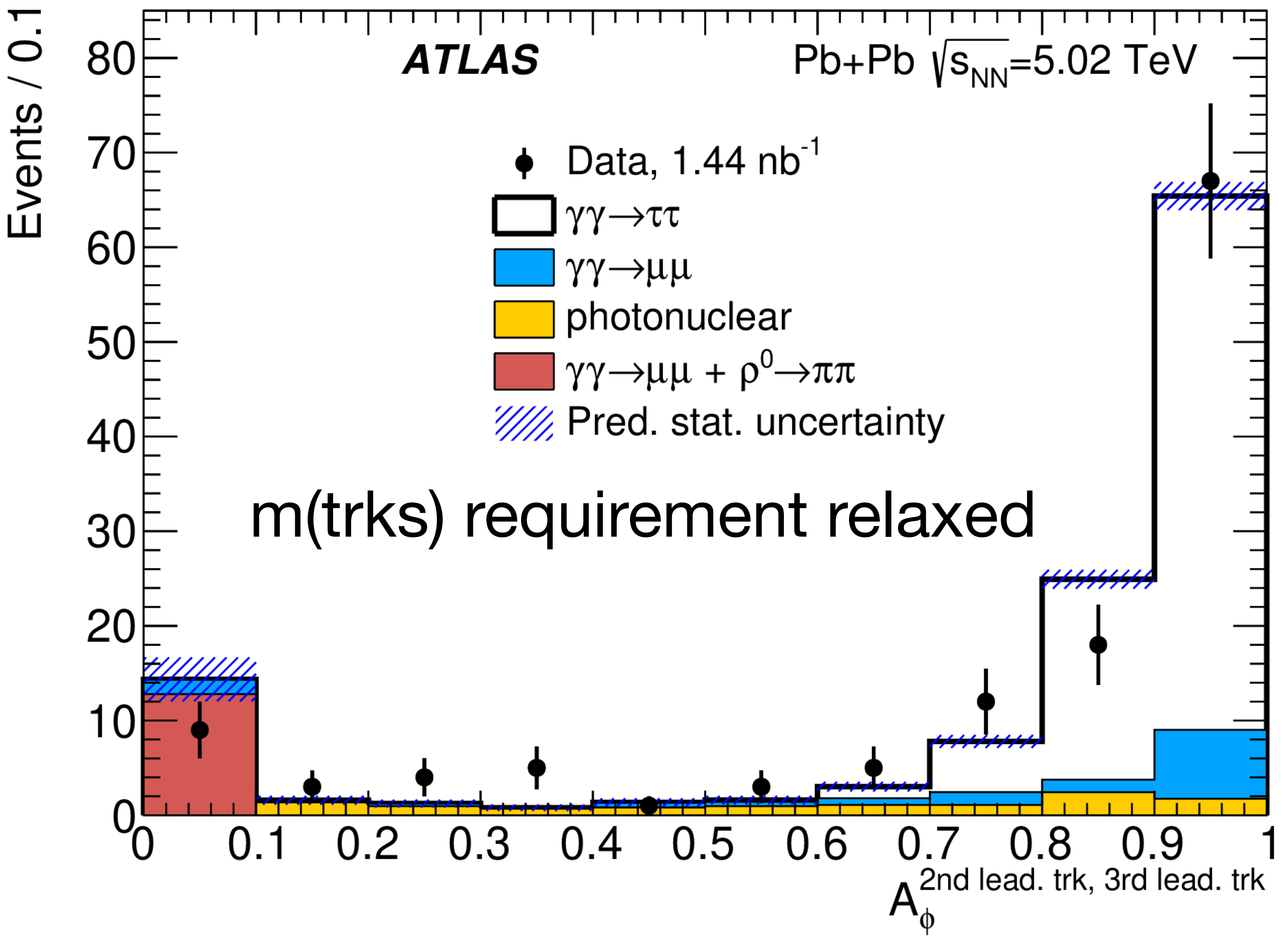


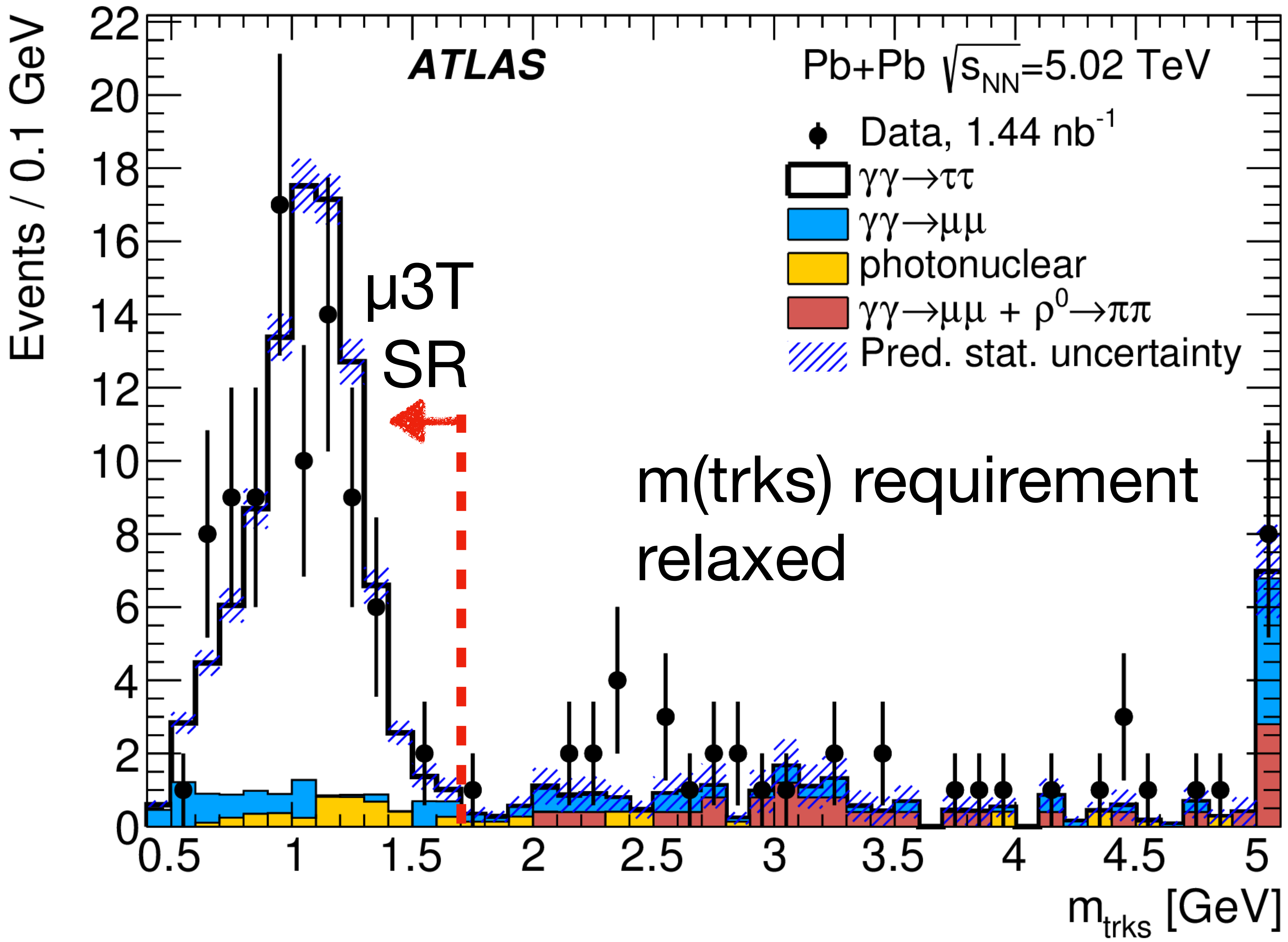


Exclusive tau-pair production in Pb+Pb UPC

- 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

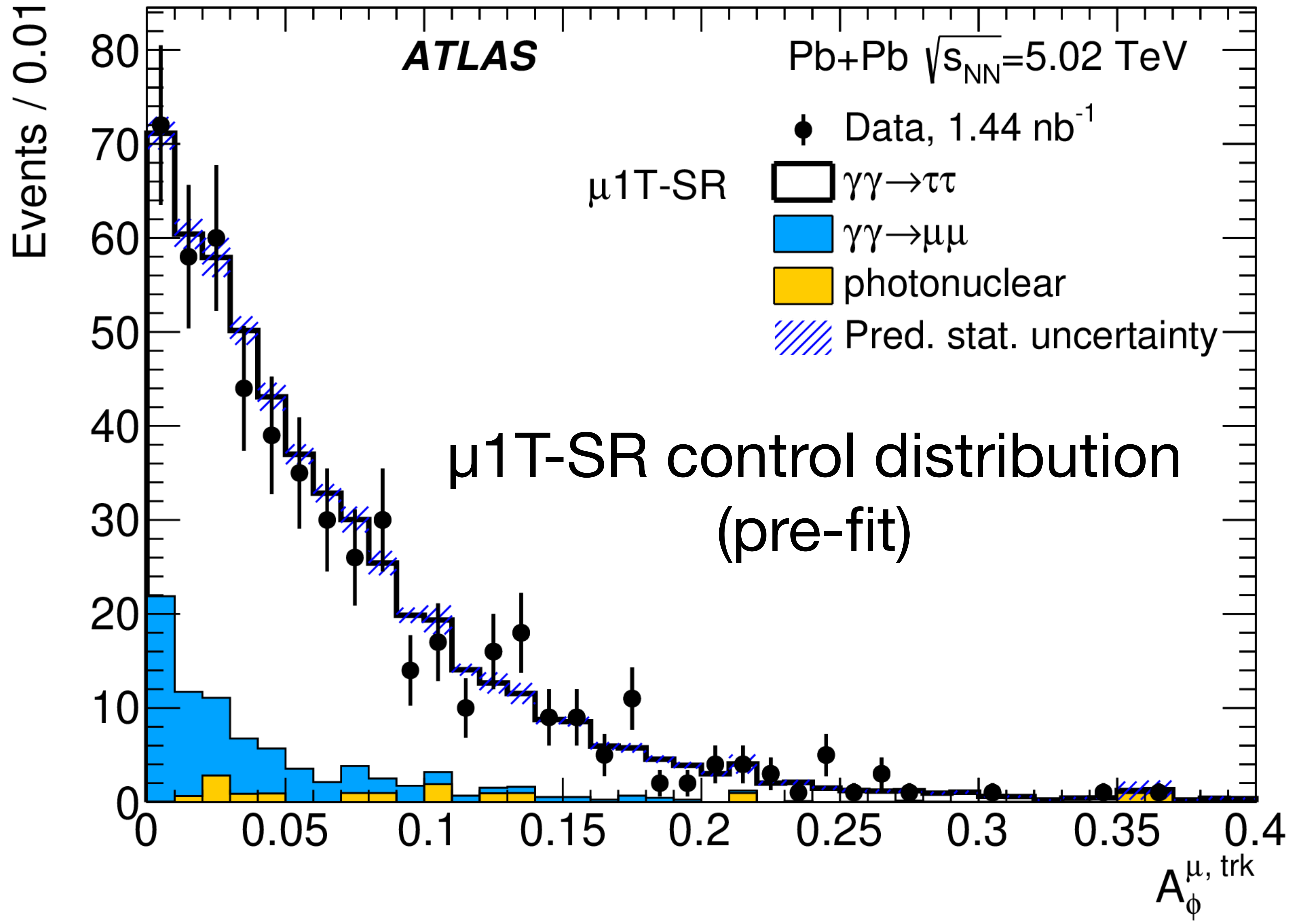






Exclusive tau-pair production in Pb+Pb UPC

- 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!

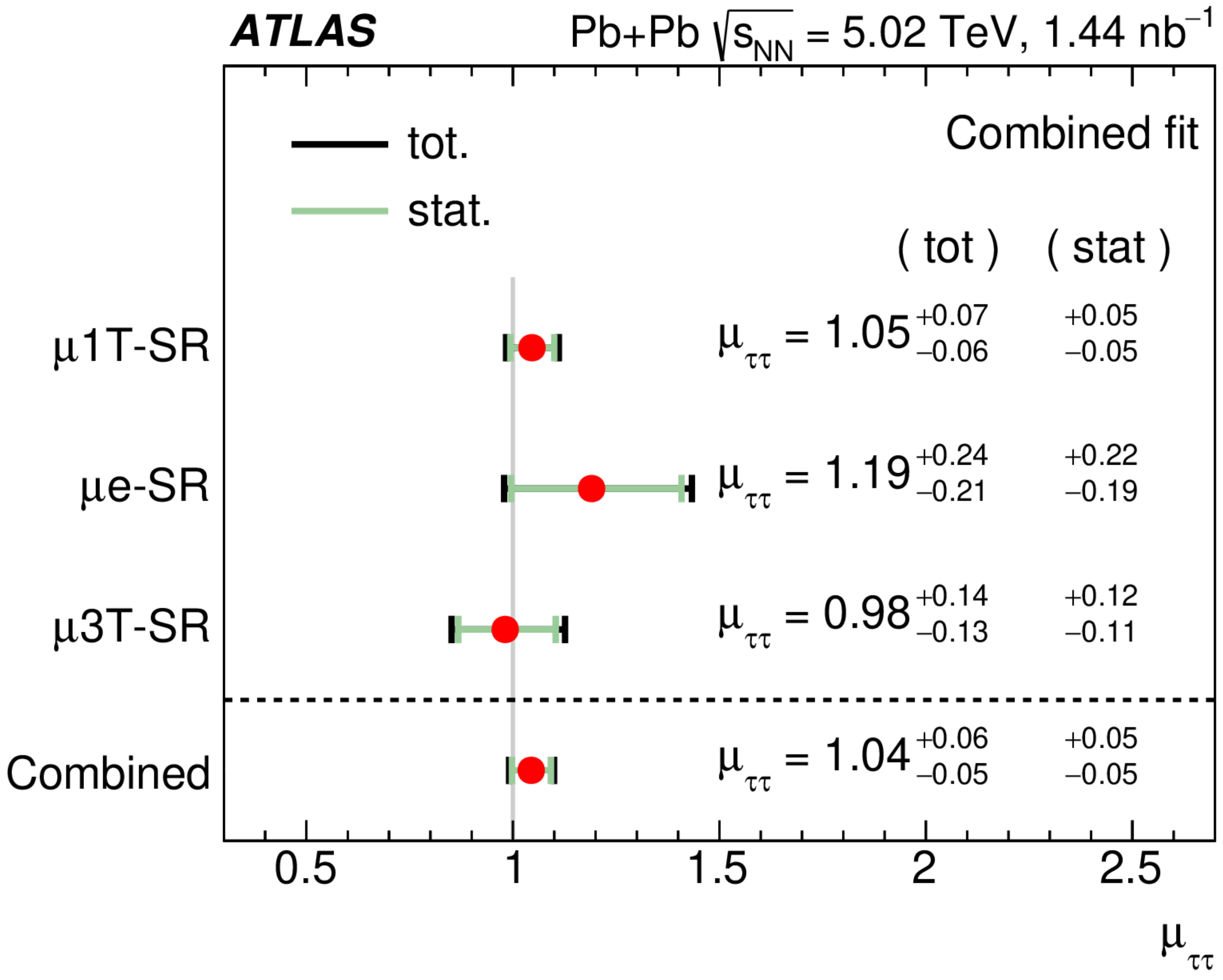


Post-fit impact

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

Exclusive tau-pair production in Pb+Pb UPC

- Signal strength extraction
  - Total measurement precision: **5%**
  - Total uncertainty dominated by statistical errors



Constraints on tau anomalous magnetic moment

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

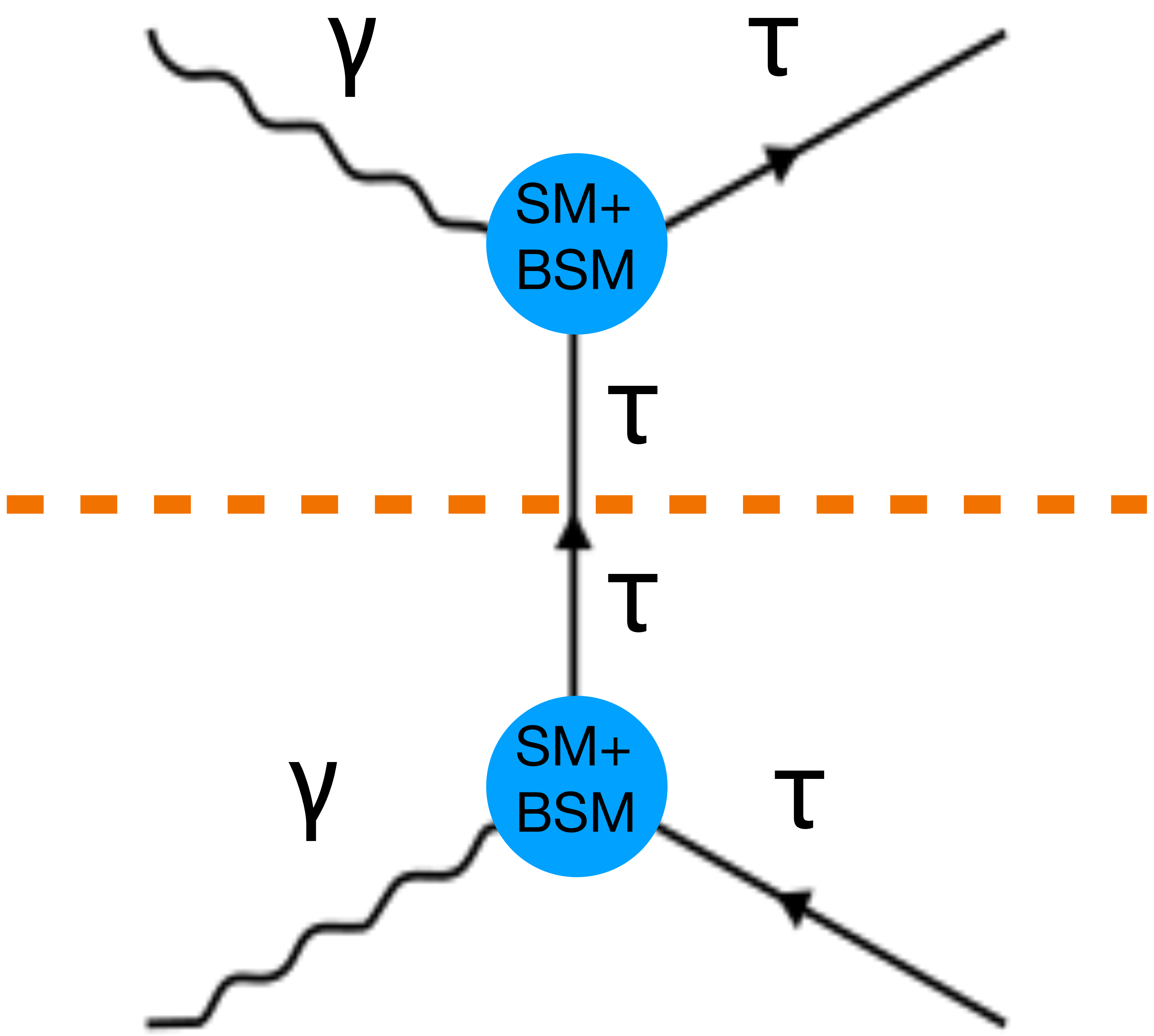
R.L. Workman et al. (Particle Data Group), to be published (2022)

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
$c\tau = 87.03$ μm
Magnetic moment anomaly > -0.052 and < 0.013, CL = 95%
$\text{Re}(d_\tau) = -0.220$ to 0.45×10^{-16} e cm, CL = 95%
$\text{Im}(d_\tau) = -0.250$ to 0.0080×10^{-16} e cm, CL = 95%

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



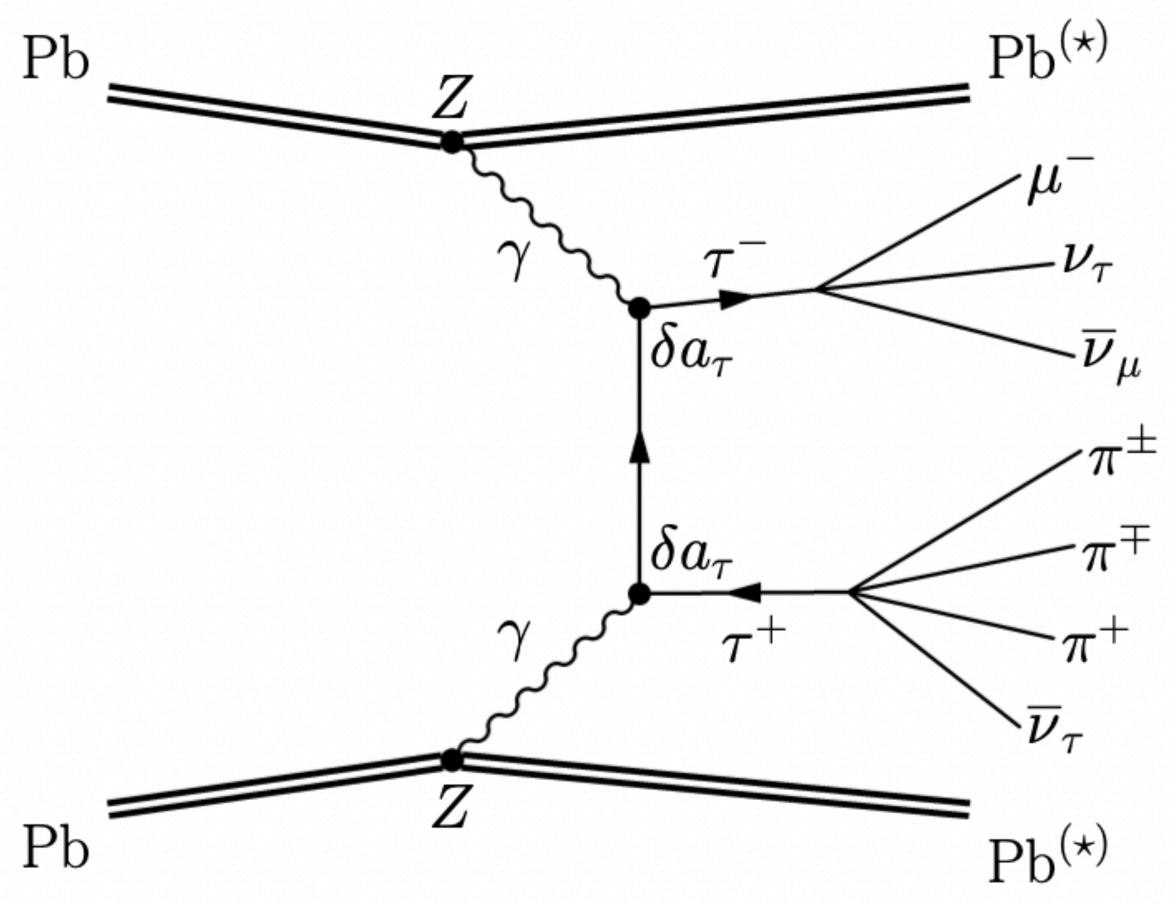
Constraints on tau anomalous magnetic moment

- Interest in measuring a_{tau} at the LHC revisited recently

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]



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]

PHYSICAL REVIEW D **102,** 113008 (2020)

New physics and tau $g-2$ using LHC heavy ion collisions

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(Received 1 November 2019; revised 5 April 2020; accepted 16 November 2020; published 22 December 2020)

The anomalous magnetic moment of the tau lepton $a_\tau = (g_\tau - 2)/2$ strikingly evades measurement but is highly sensitive to new physics such as compositeness or supersymmetry. We propose using ultraperipheral heavy ion collisions at the LHC to probe modified magnetic δa_τ and electric dipole moments δd_τ. We design a suite of analyses with signatures comprising one electron/muon plus track(s), leveraging the exceptionally clean photon fusion $\gamma\gamma \to \tau\tau$ events to reconstruct both leptonic and hadronic tau decays sensitive to $\delta a_\tau, \delta d_\tau$. Assuming 10% systematic uncertainties, the current 2 nb^{-1} lead-lead dataset could already provide constraints of $-0.0080 < a_\tau < 0.0046$ at 68% C.L. This surpasses 15-year-old lepton collider precision by a factor of 3 while opening novel avenues to new physics.

DOI: 10.1103/PhysRevD.102.113008

Constraints on tau anomalous magnetic moment

- Measure $\mathbf{a_\tau = (g_\tau - 2)/2}$ 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

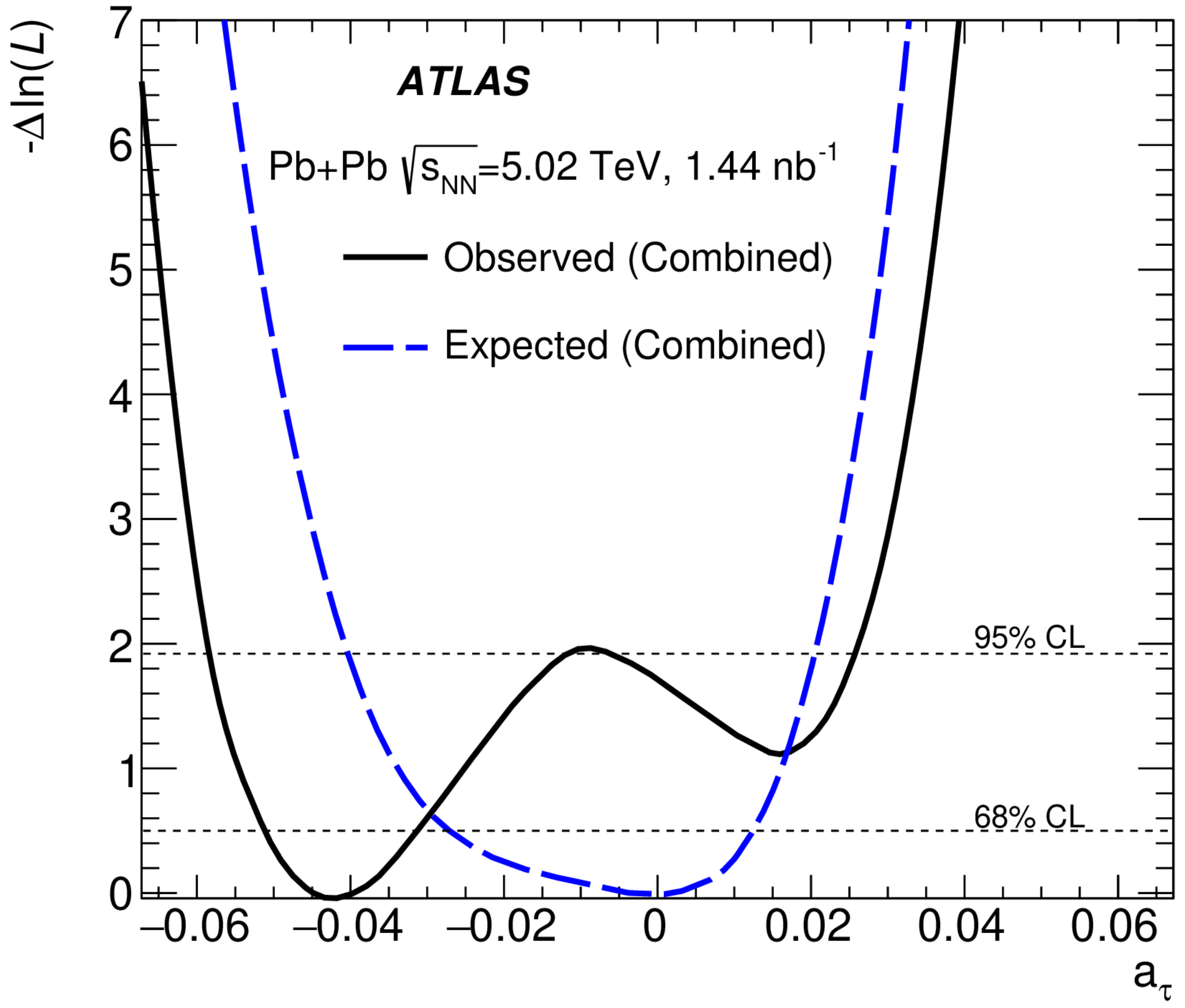
Constraints on tau anomalous magnetic moment

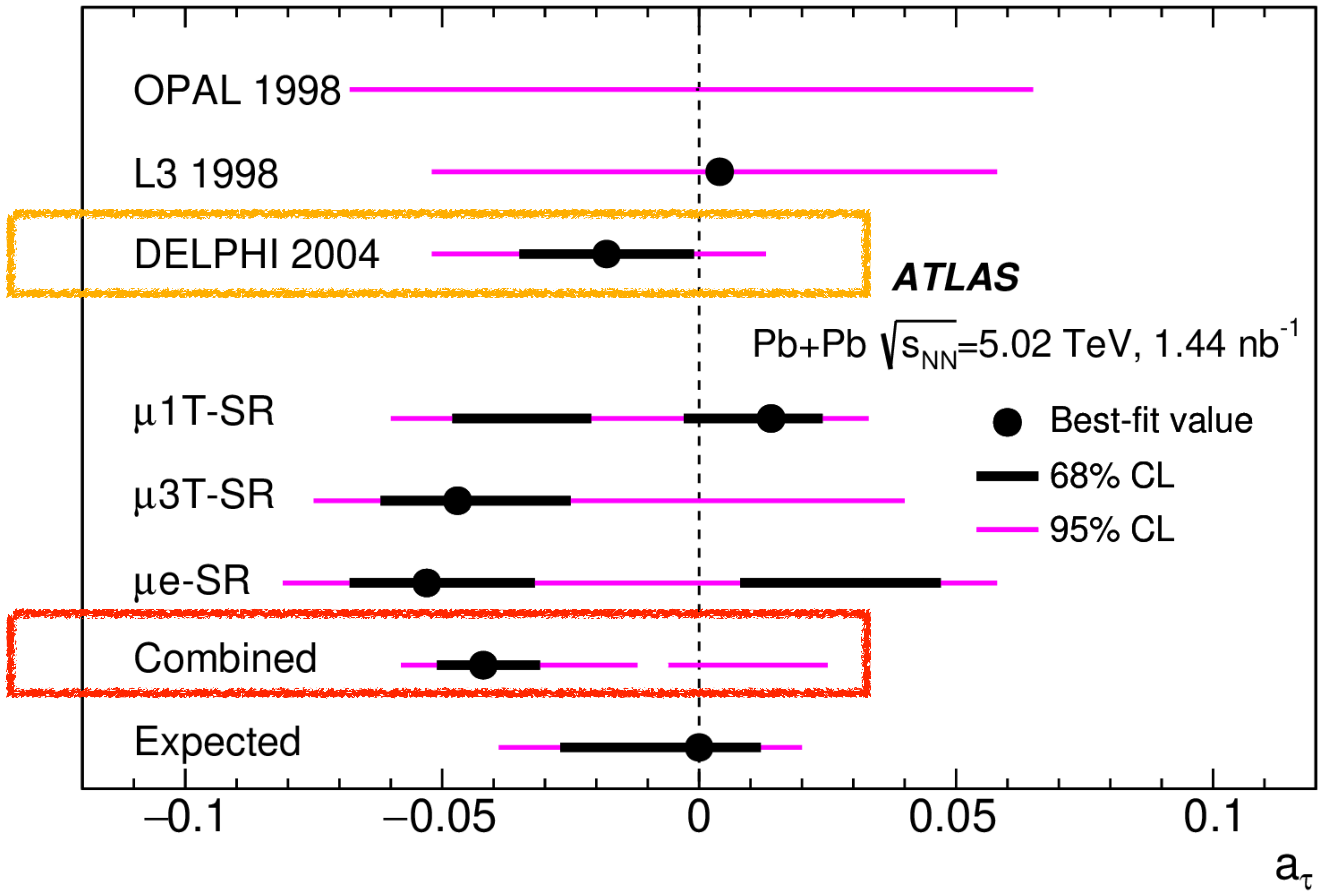
- Measure **a_τ = (g_τ – 2)/2** with template fit
  - Using pT(μ) distribution in the three SRs and 2μ-CR
  - a_τ templates: reweighting signal MC [weights from PLB 809 (2020) 135682] + morphing

Post-fit

Constraints on tau anomalous magnetic moment

- Constraints on a_τ similar to those observed by DELPHI (current PDG value)
  - Stat.-dominated measurement → Excellent prospects for LHC Run 3 & beyond





Summary

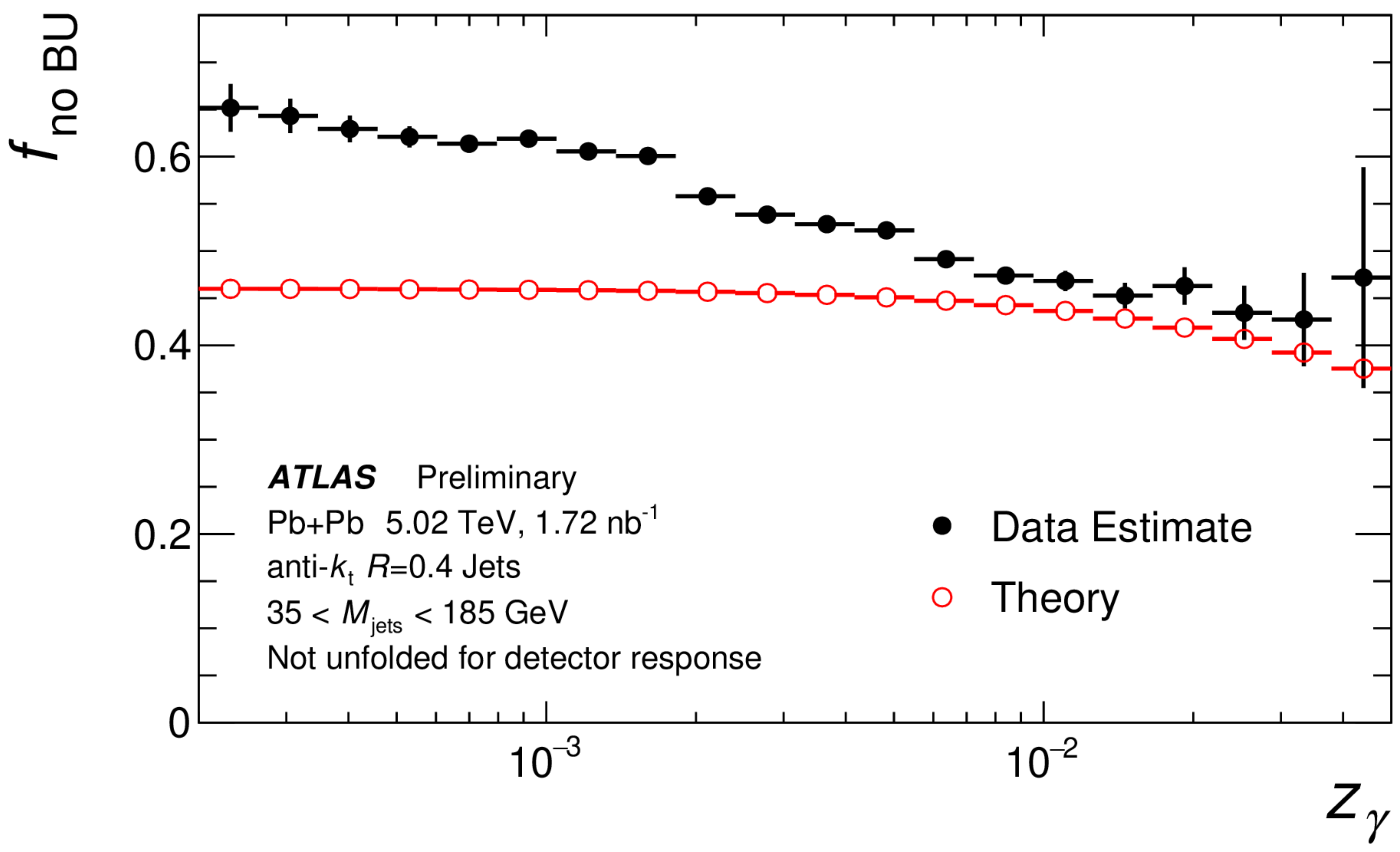
- Rich physics programme with UPC at the LHC
- Interesting opportunities to explore photo-nuclear interactions
    - Dijet production → potential to constrain nPDFs, small-x gluon tomography
- HI UPC collisions are excellent QED and BSM laboratories
    - Tau g-2 constrained using LHC UPC data with precision compatible with LEP (PDG)
    - Clean way to search for BSM particles that couple to photons

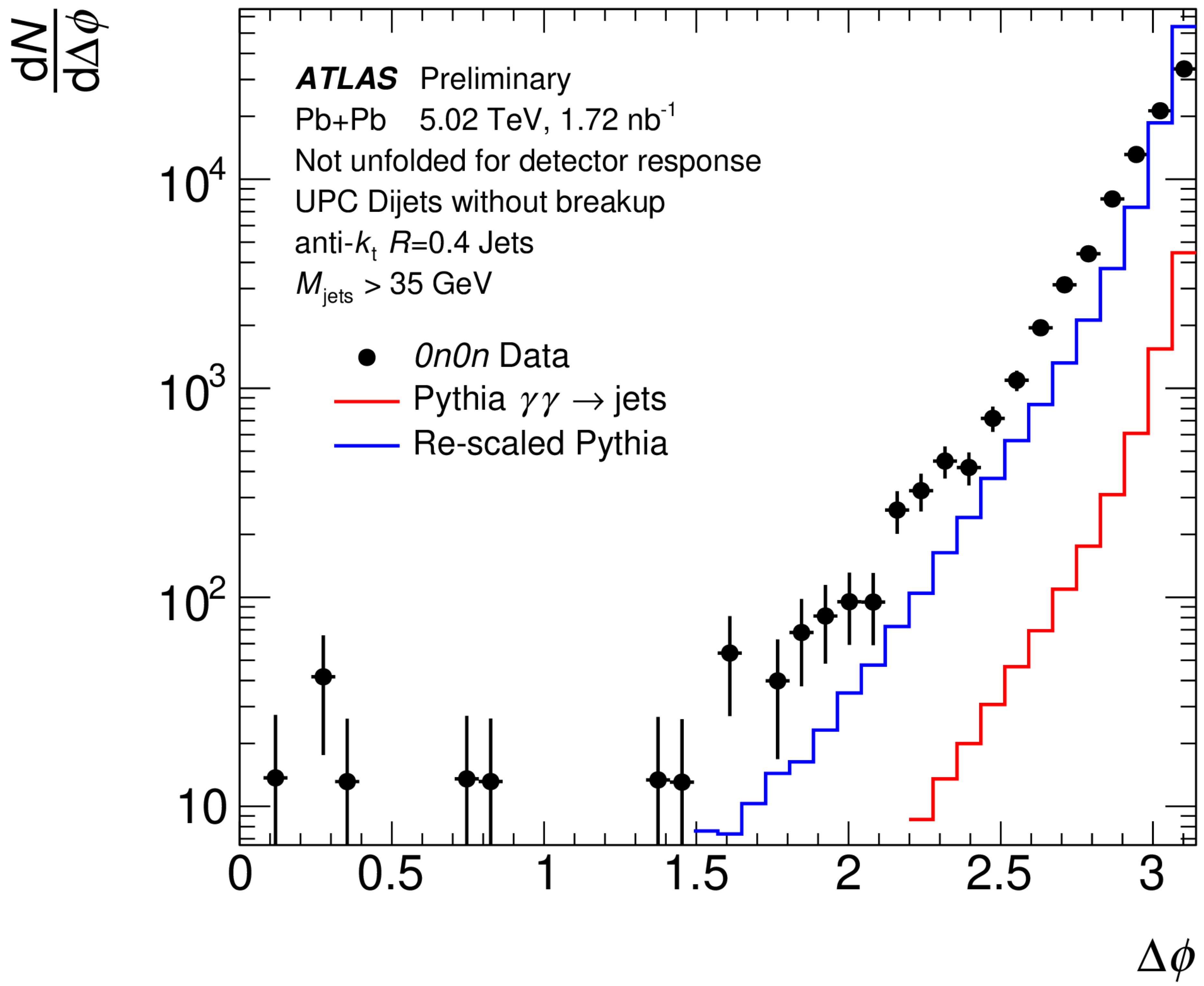
Backup

Measurement of photo-nuclear dijet production in Pb+Pb

ATLAS-CONF-2022-021

- “No-breakup” fraction is measured by comparing 0nXn and XnXn topologies
  - Provides valuable input for theory calculations
- Observation of exclusive dijet events (0n0n “no-breakup” topology)
  - Likely a mixture of diffractive + photon-photon production mechanisms

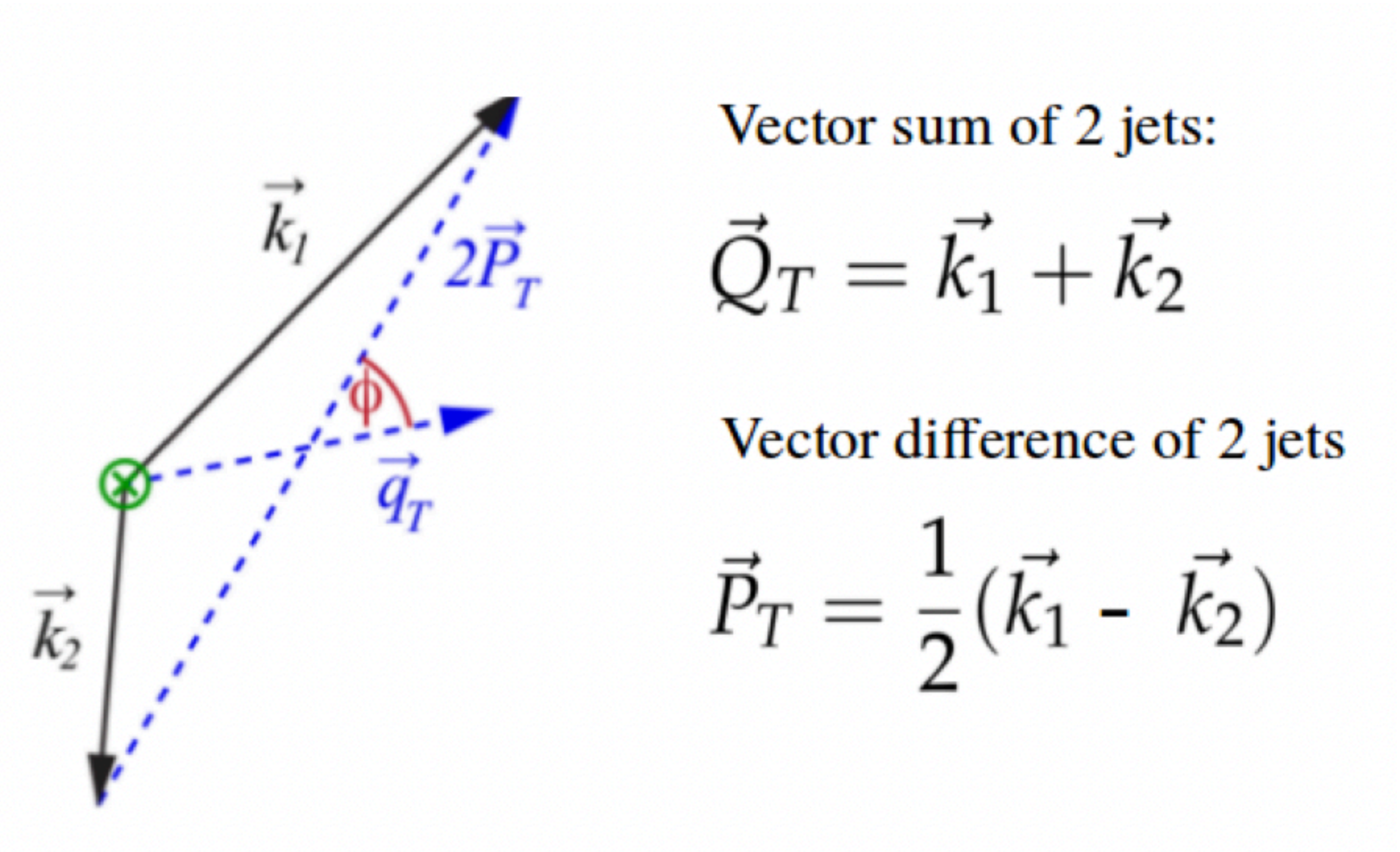


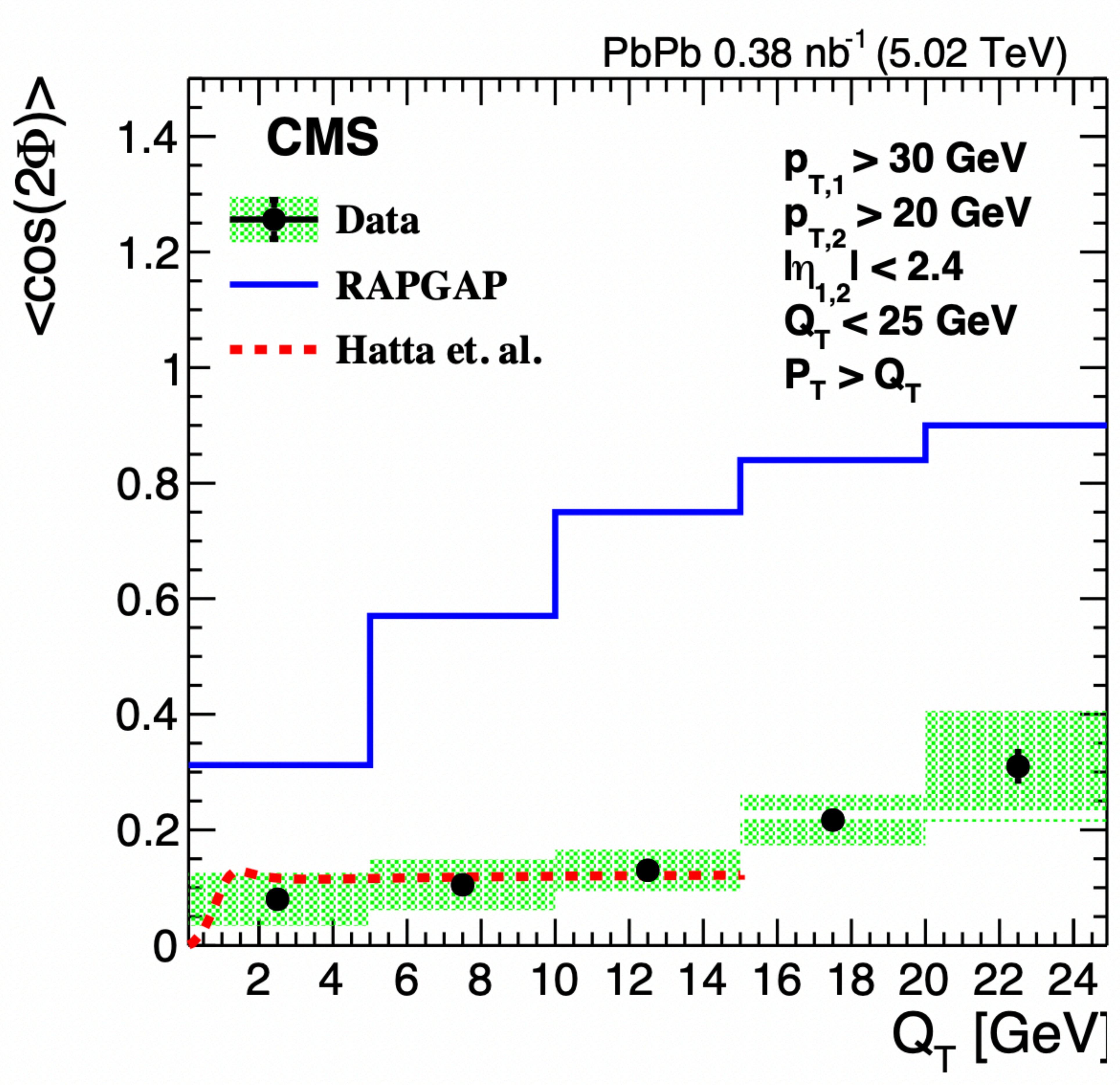


Diffractive photo-nuclear dijets in Pb+Pb

CMS, arXiv:2205.00045

- Azimuthal angular decorrelation of dijets (2nd Fourier harmonic)
  - Potentially sensitive to elliptic gluon Wigner distribution

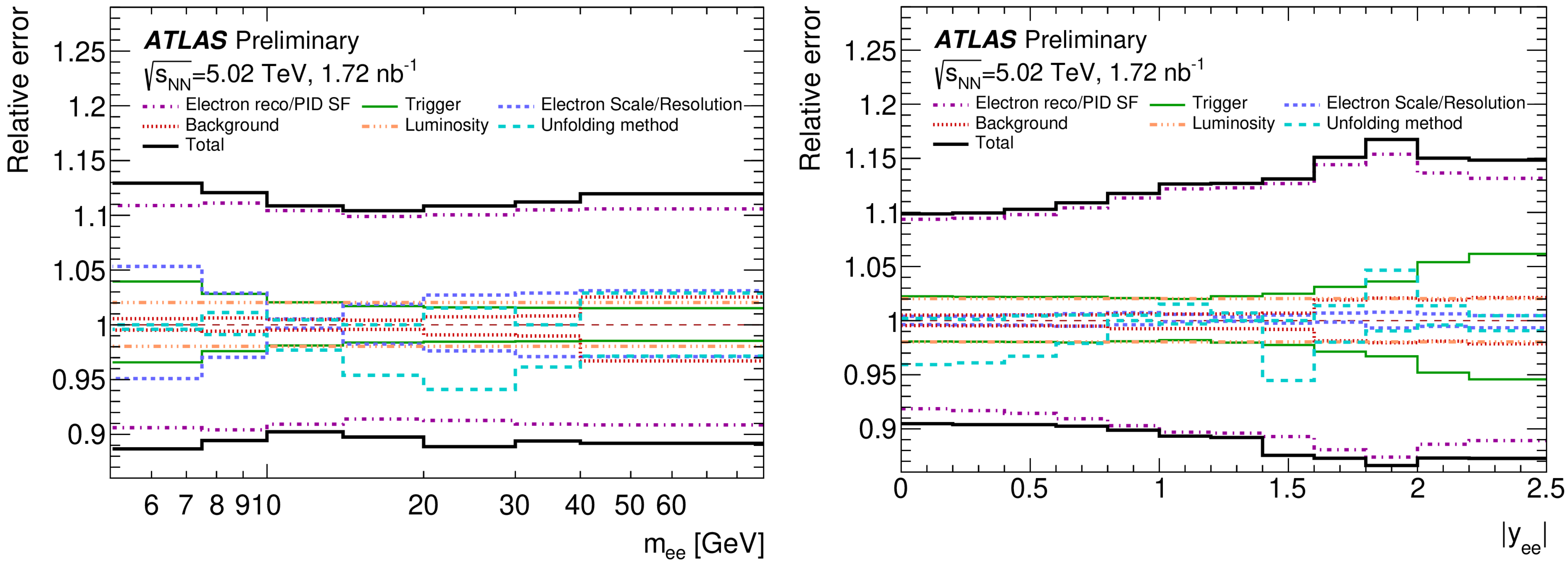




QT is the proxy for recoil momentum of Pb target

Exclusive dielectron production in Pb+Pb UPC

- Systematic uncertainties
  - Dominated by the knowledge of electron reco+identification efficiency



a_τ parameterisation

- Elementary $\gamma\gamma \rightarrow \tau\,\tau$ cross section has explicit dependence on photon-τ vertex function:

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

$F_2(q^2)$: $=a_\tau\ (q^2=0)$

$F_3(q^2)$: $=d_\tau * 2m_\tau / e\ (q^2=0)$