# Probing the Frontiers of QED and QCD in Ultraperipheral Pb+Pb Collisions with ATLAS Using LHC Run 3 Data

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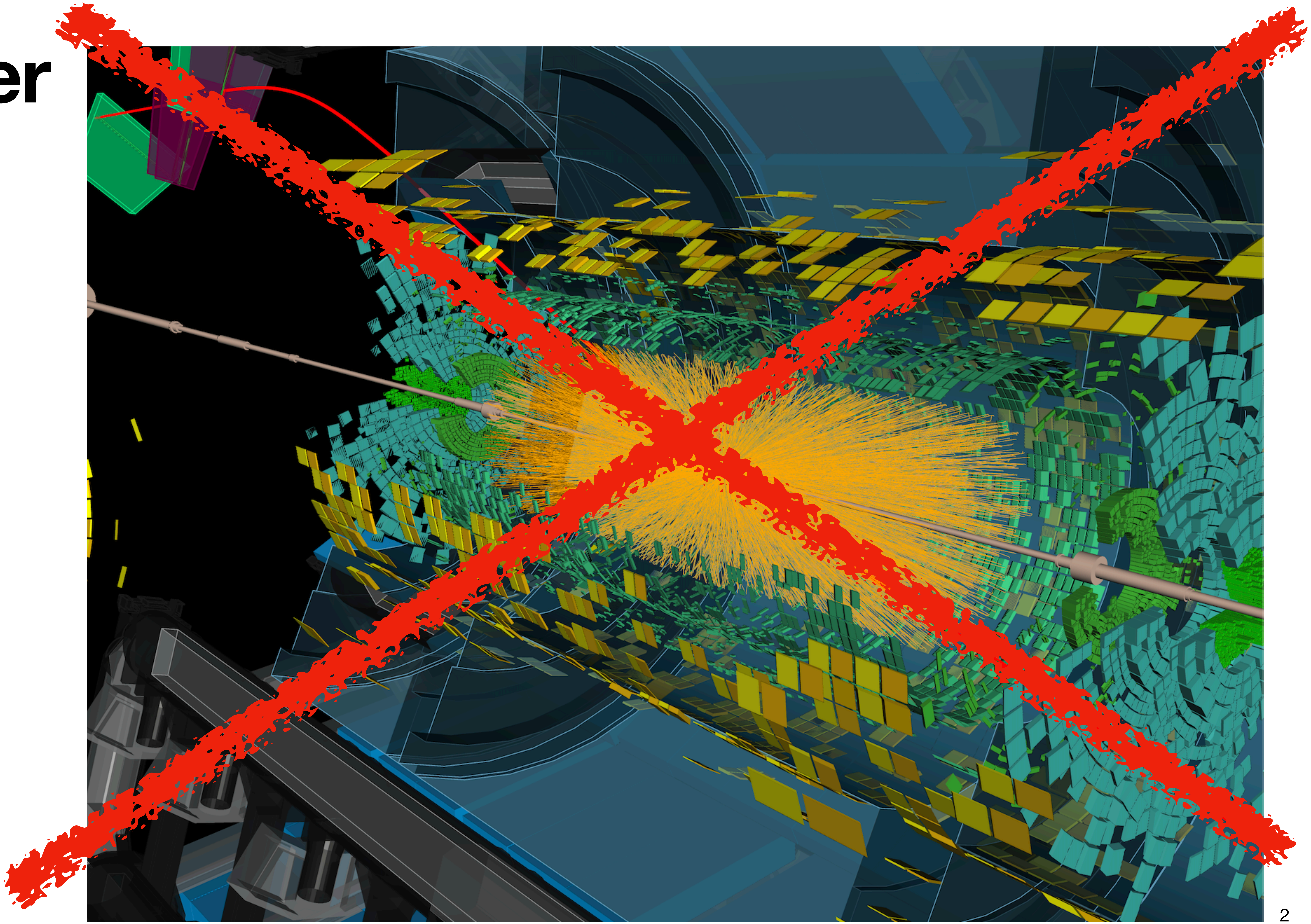
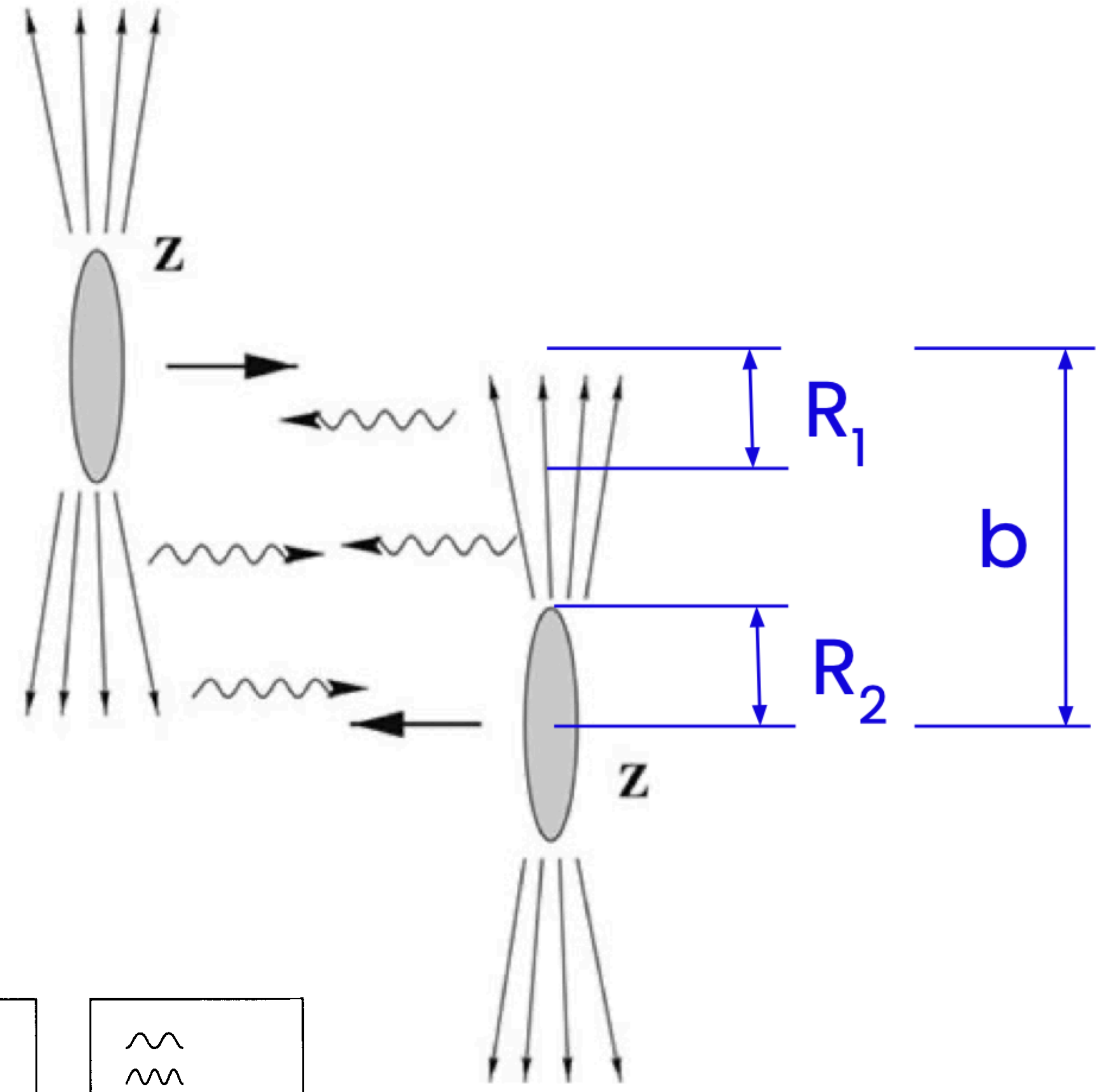
# Disclaimer

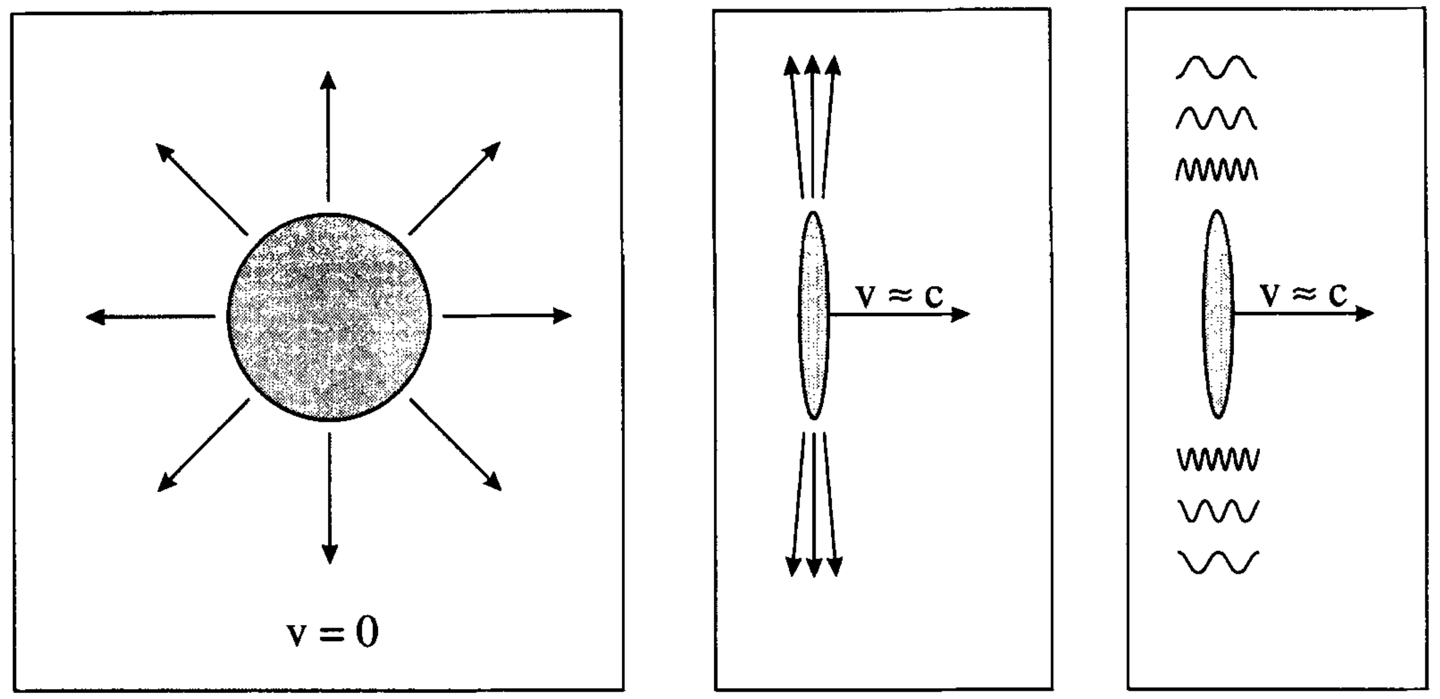


# LHC as a photon collider

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

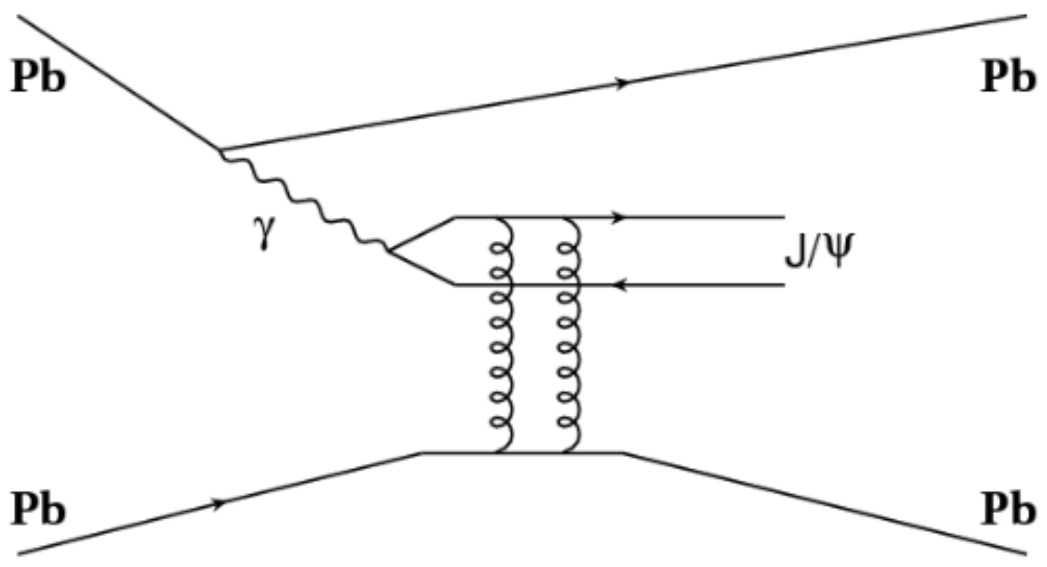



- EM fields
  - Treated as **quasi-real photon** fluxes
  - Each flux ~$\mathbf{Z^2}$

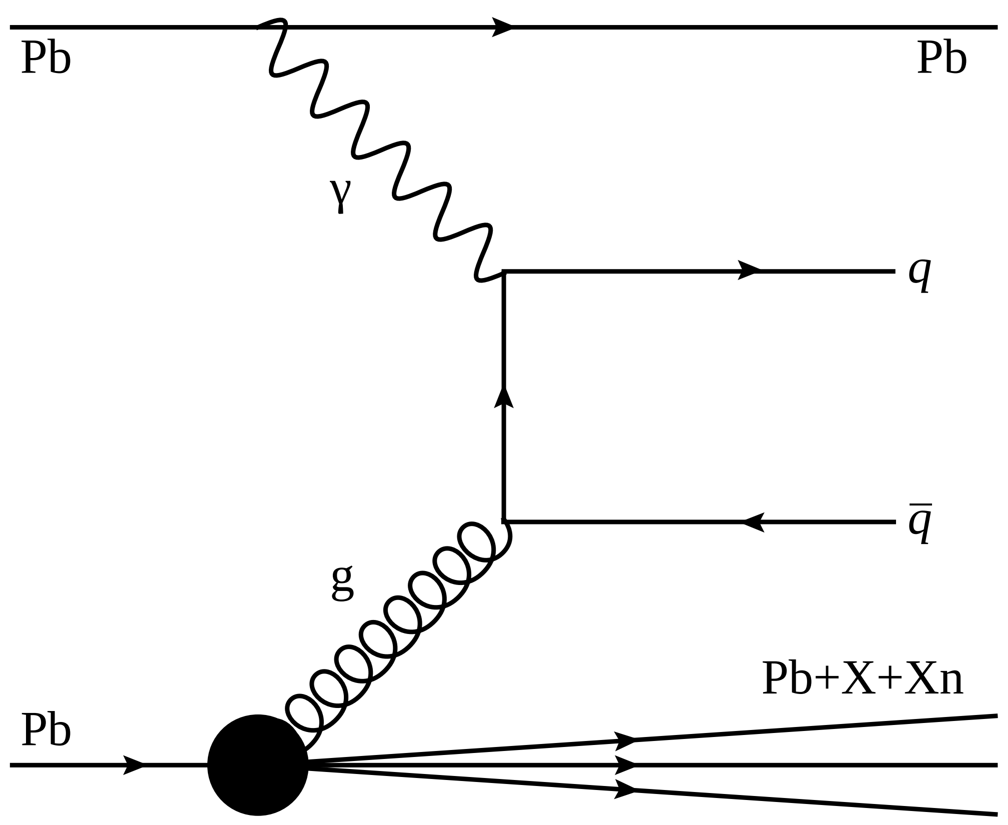



UPC reviews:
Baltz et al., Phys. Rept. 458 (2008) 1-171; Klein & Steinberg, Ann. Rev. Nuclear Part. Sci. 70 (2020) 323

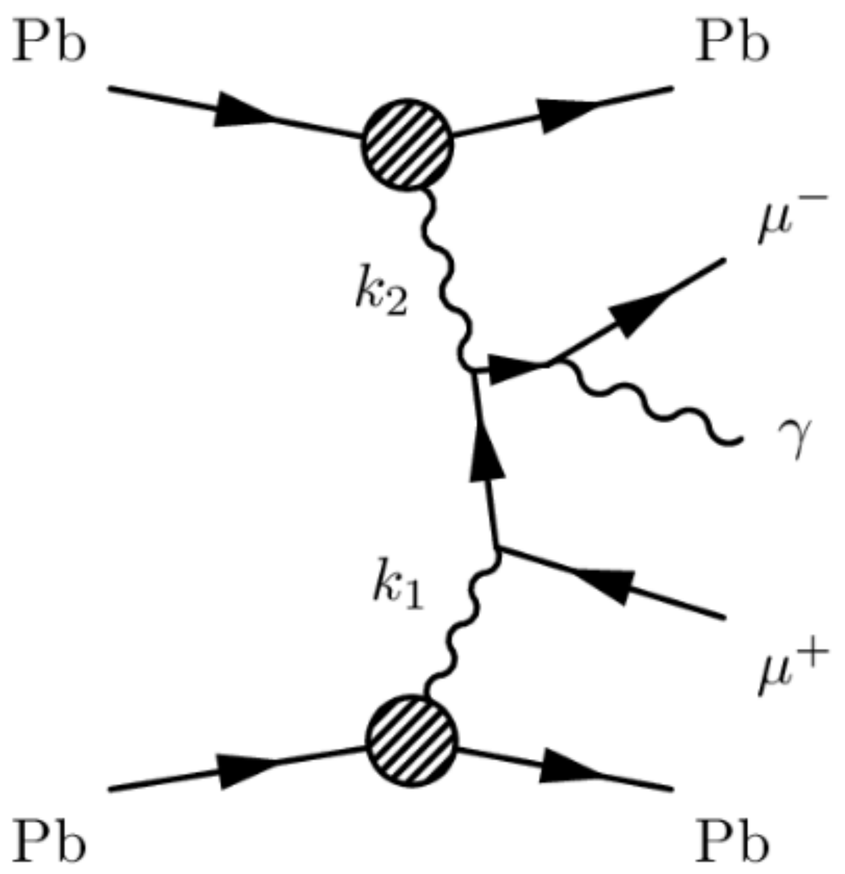
# LHC as a photon collider



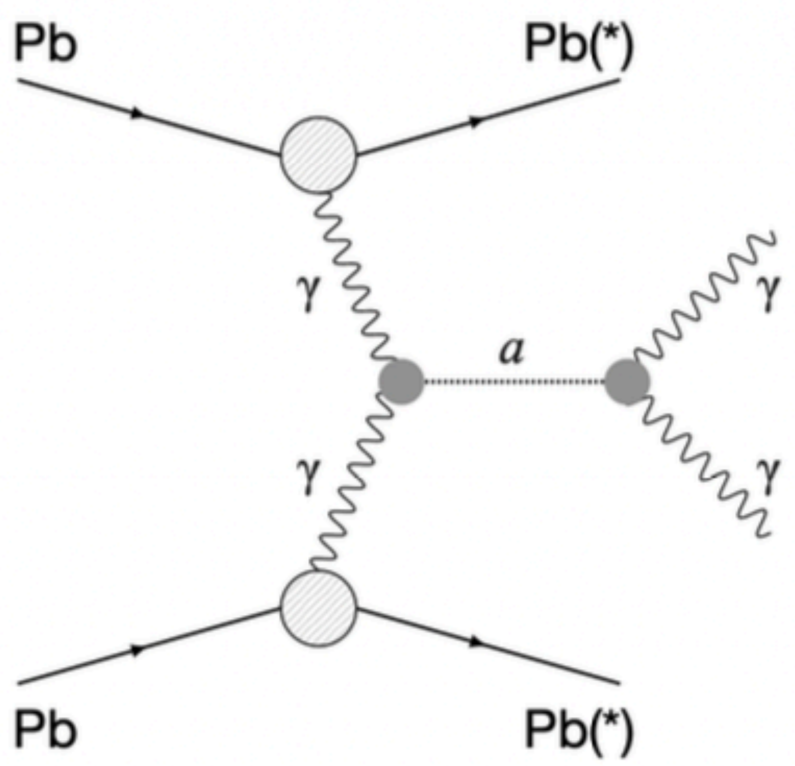

(coherent) **Photo-nuclear**




(Inelastic) **Photo-nuclear**

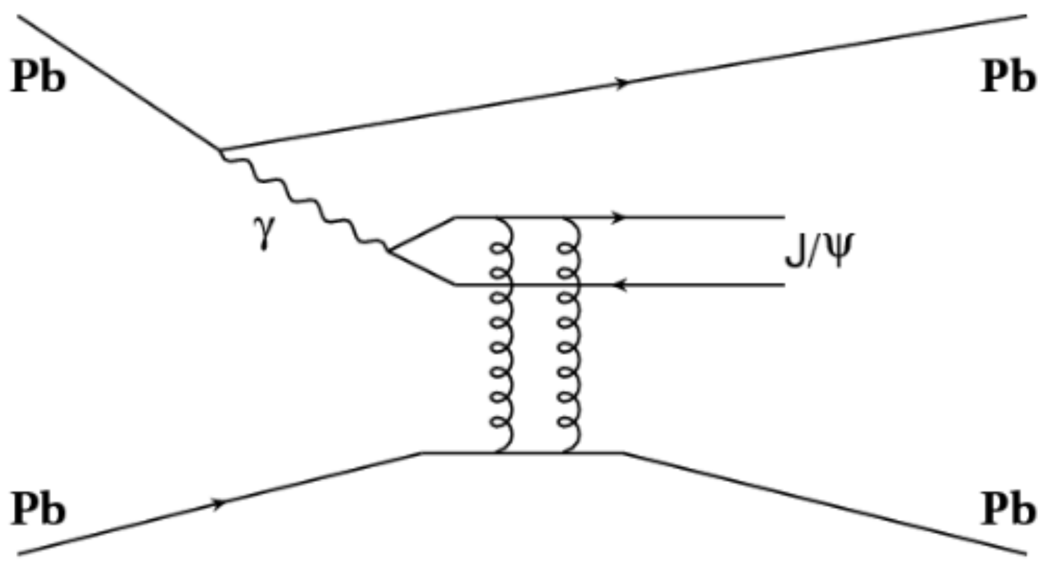



(SM) **Photon-photon**



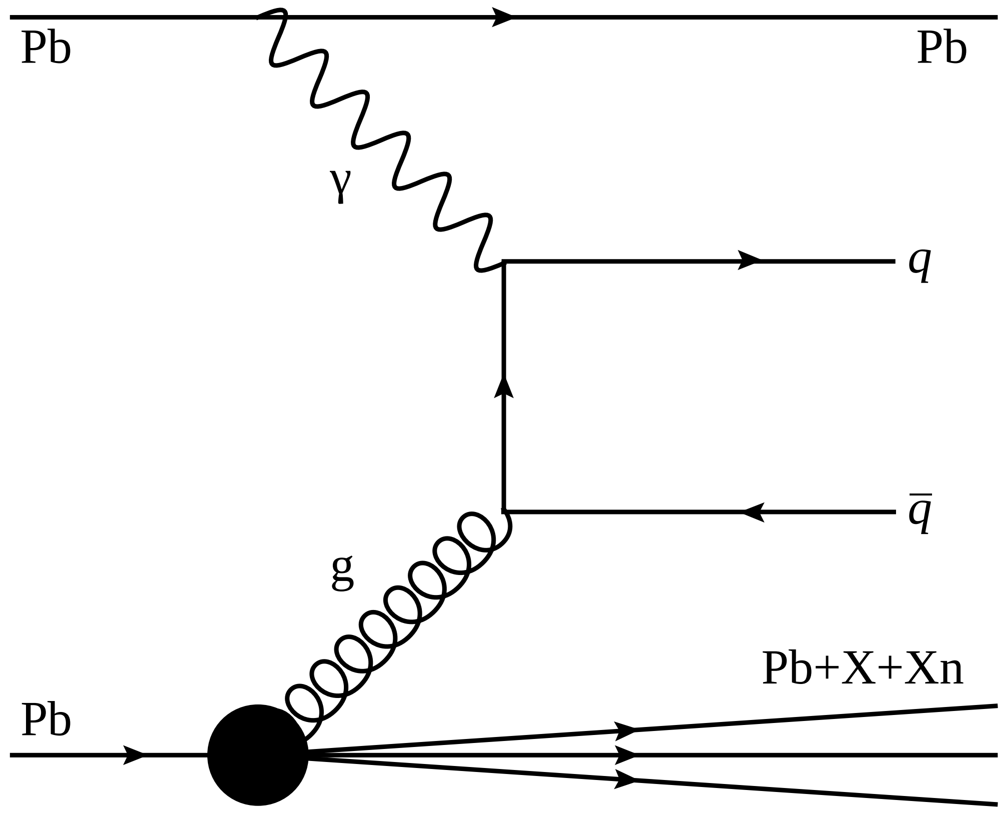

(BSM) **Photon-photon**

# LHC as a photon collider



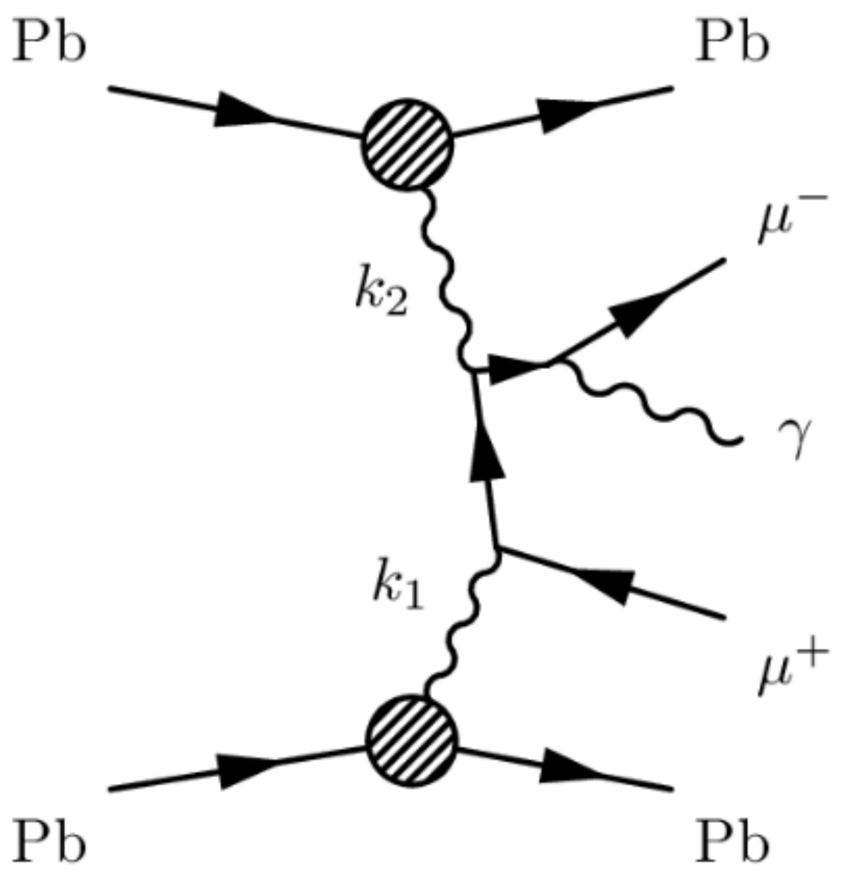

(coherent) **Photo-nuclear**

- Access to low-x QCD phenomena (parton saturation and nuclear shadowing)



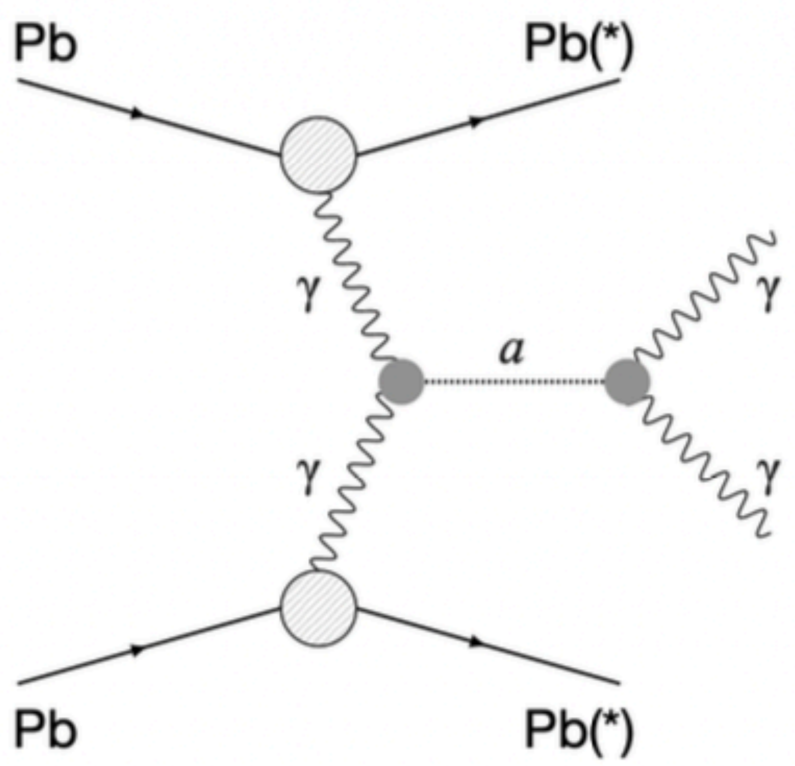

(Inelastic) **Photo-nuclear**

- Probe of nPDFs




(SM) **Photon-photon**

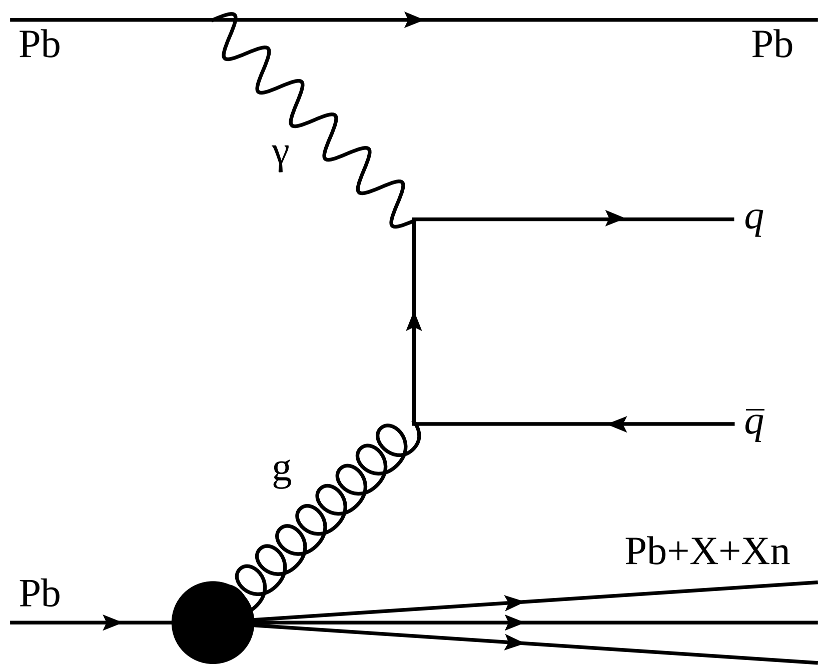
- Tool for precision QED studies at hadron colliders




(BSM) **Photon-photon**

- Novel way for BSM searches

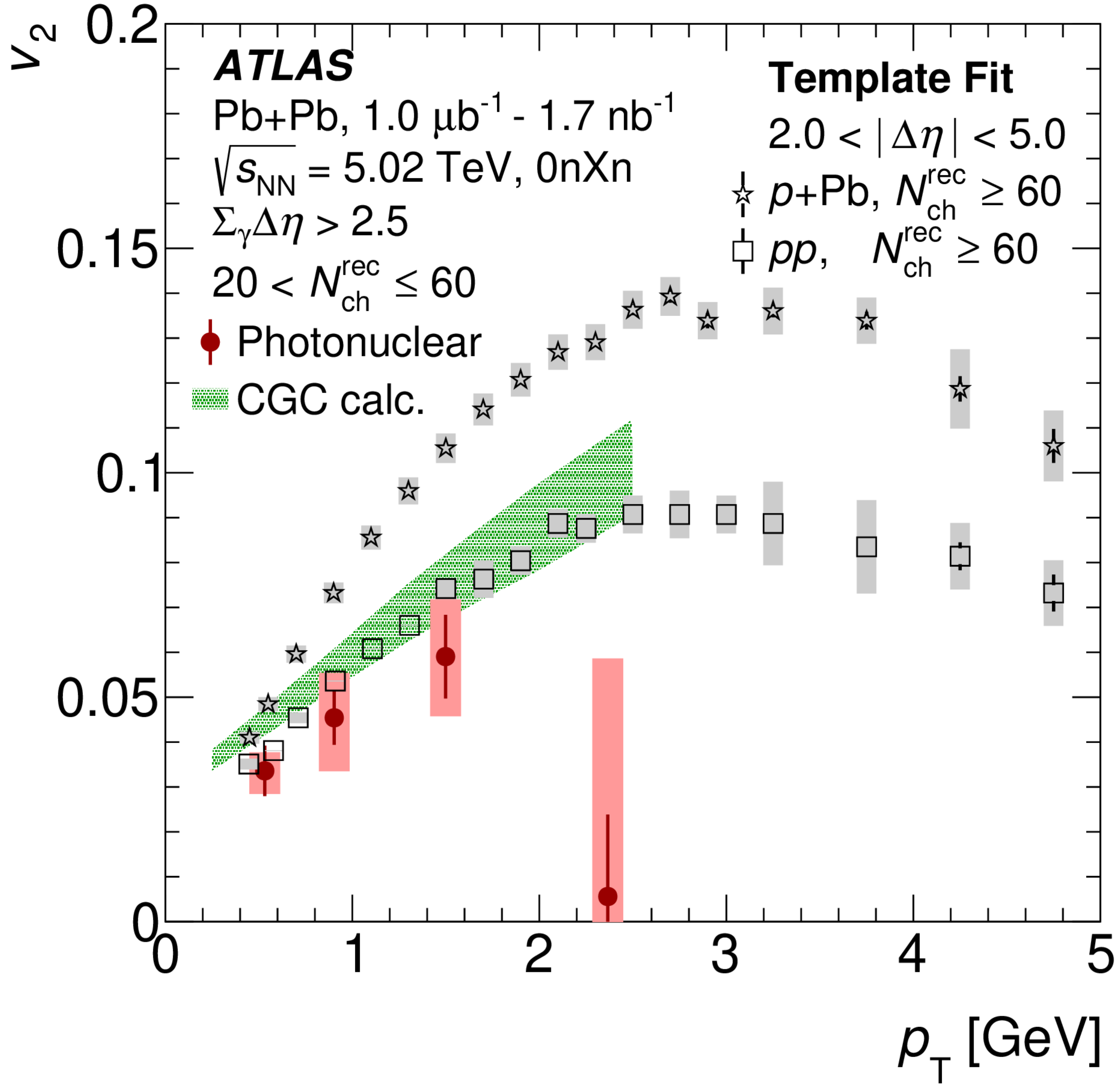
# Run 2 ATLAS UPC highlights




## Characterizing (high-multiplicity) photonuclear interactions

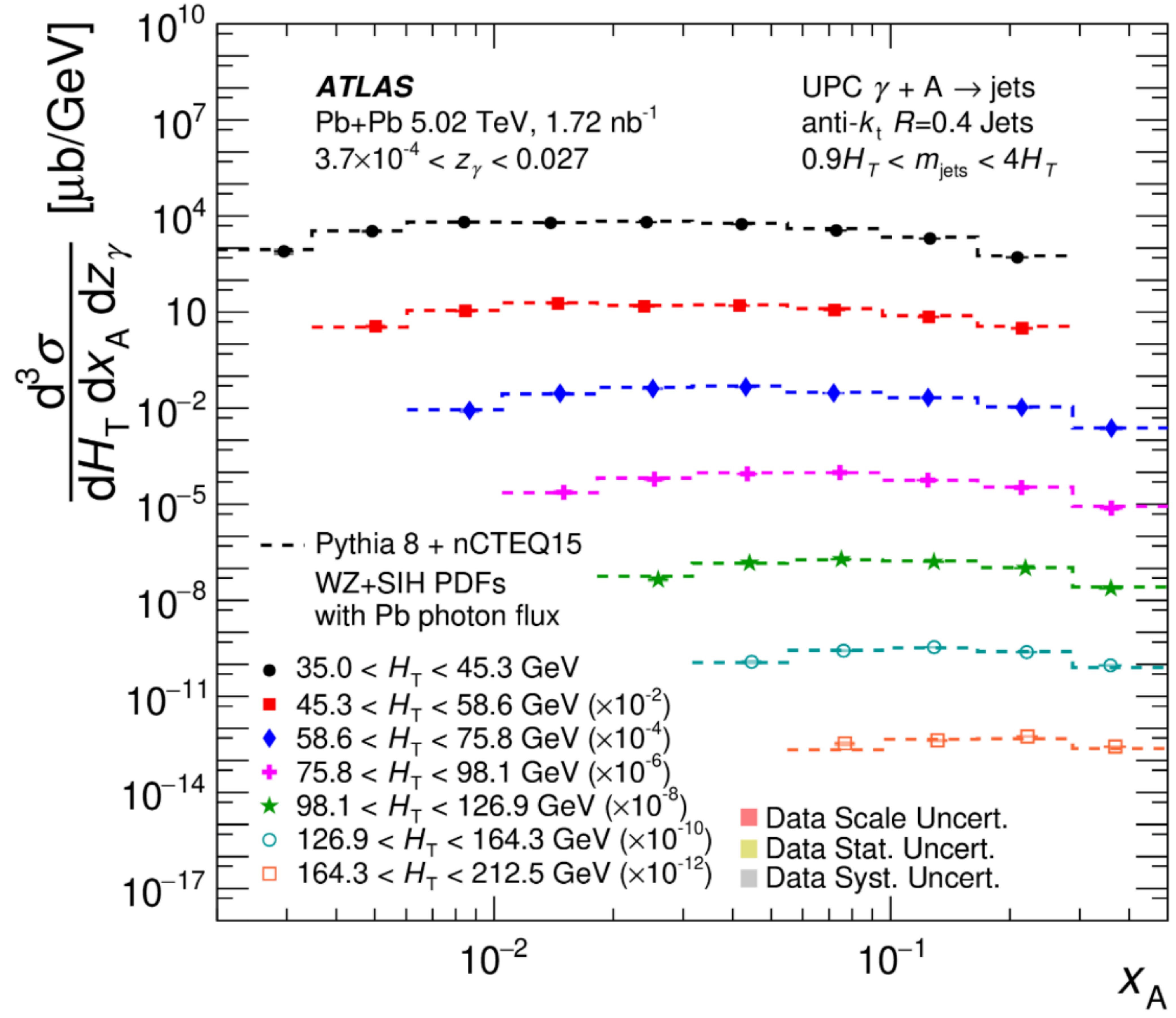
Phys. Rev. C. 104 (2021) 014903

Phys. Rev. C 111 (2025) 064908

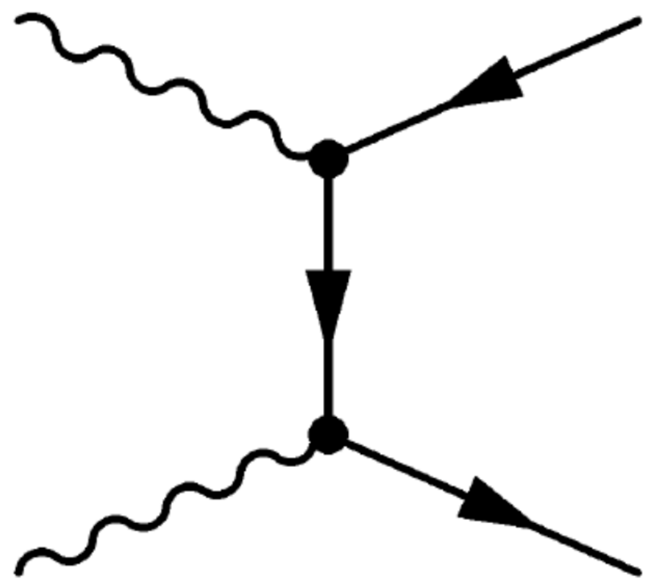



## Hard-scale photonuclear collisions with jets

Phys. Rev. D 111 (2025) 052006

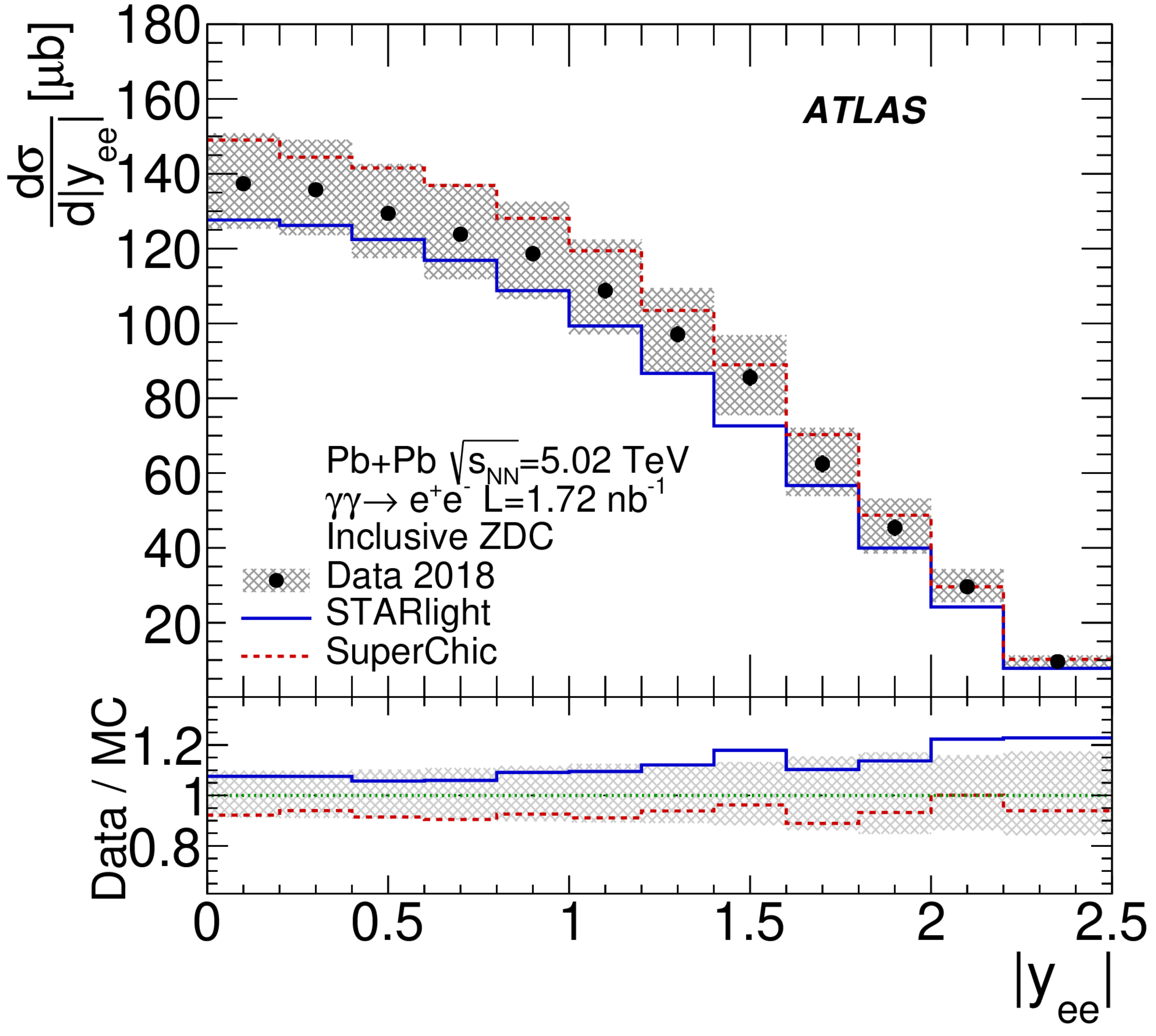


# Run 2 ATLAS UPC highlights

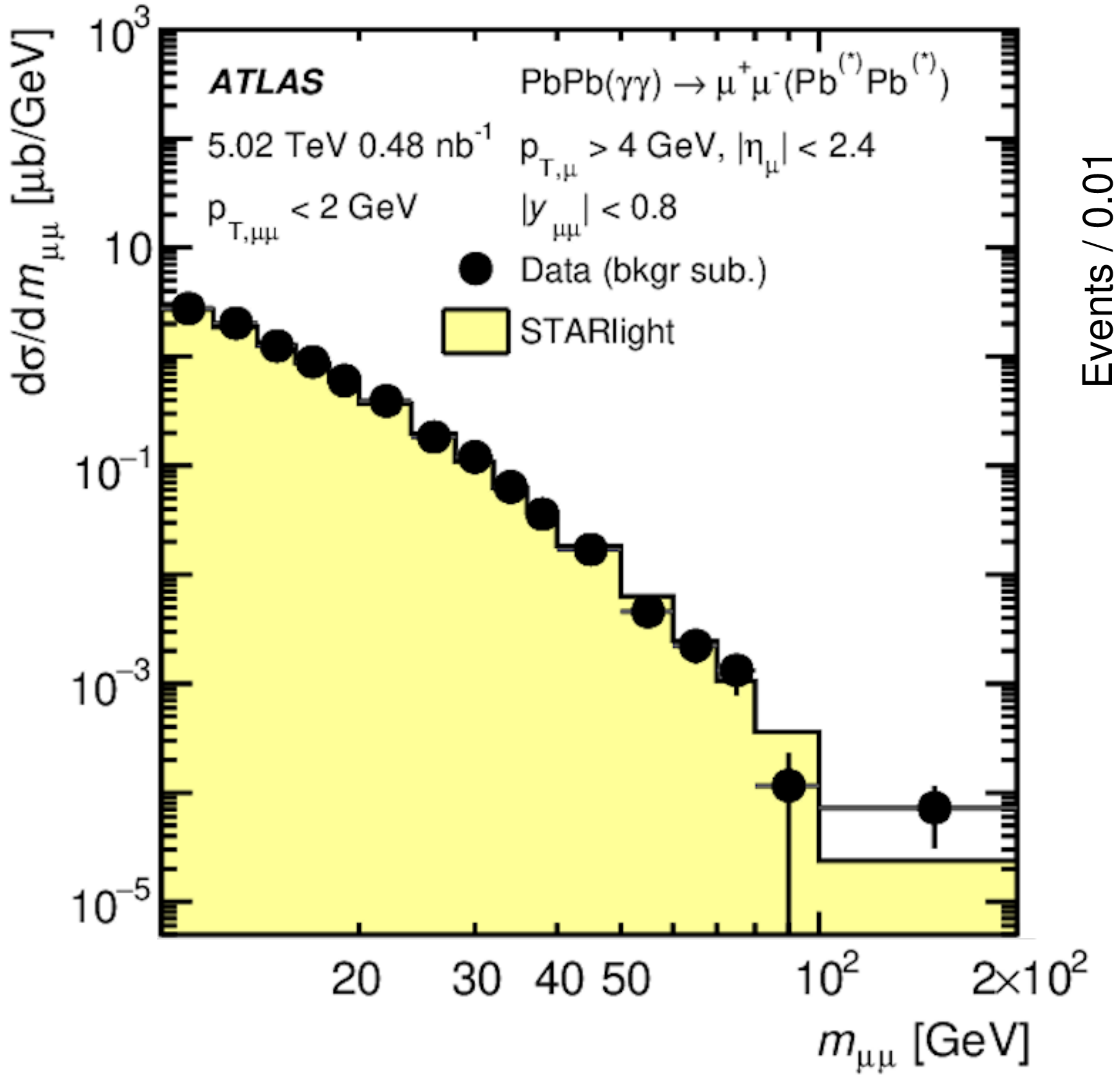


- Precision QED studies with γγ → ee / μμ / τ τ production
  - Di-tau measurement sensitive to tau g-2

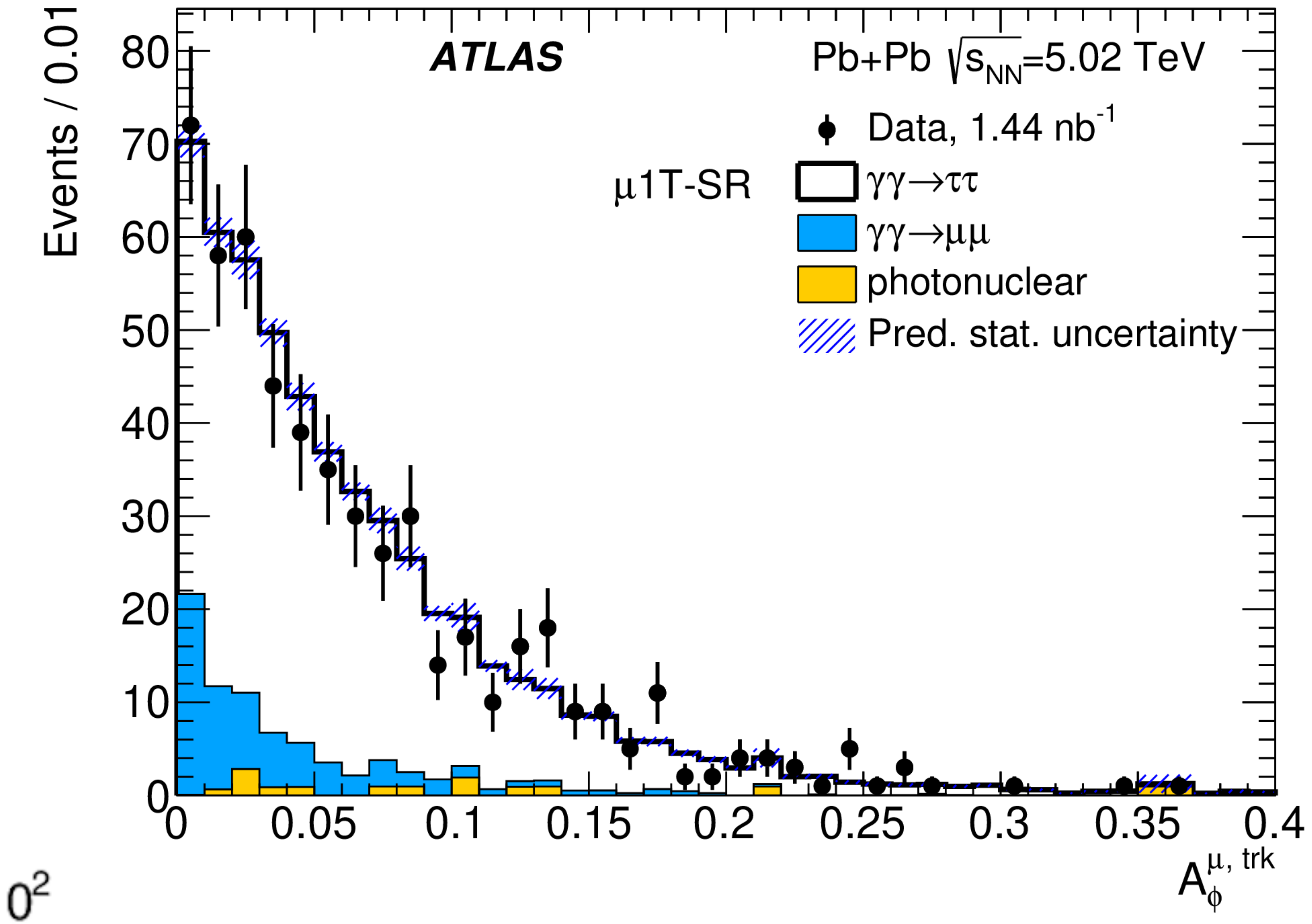
JHEP 06 (2023) 182



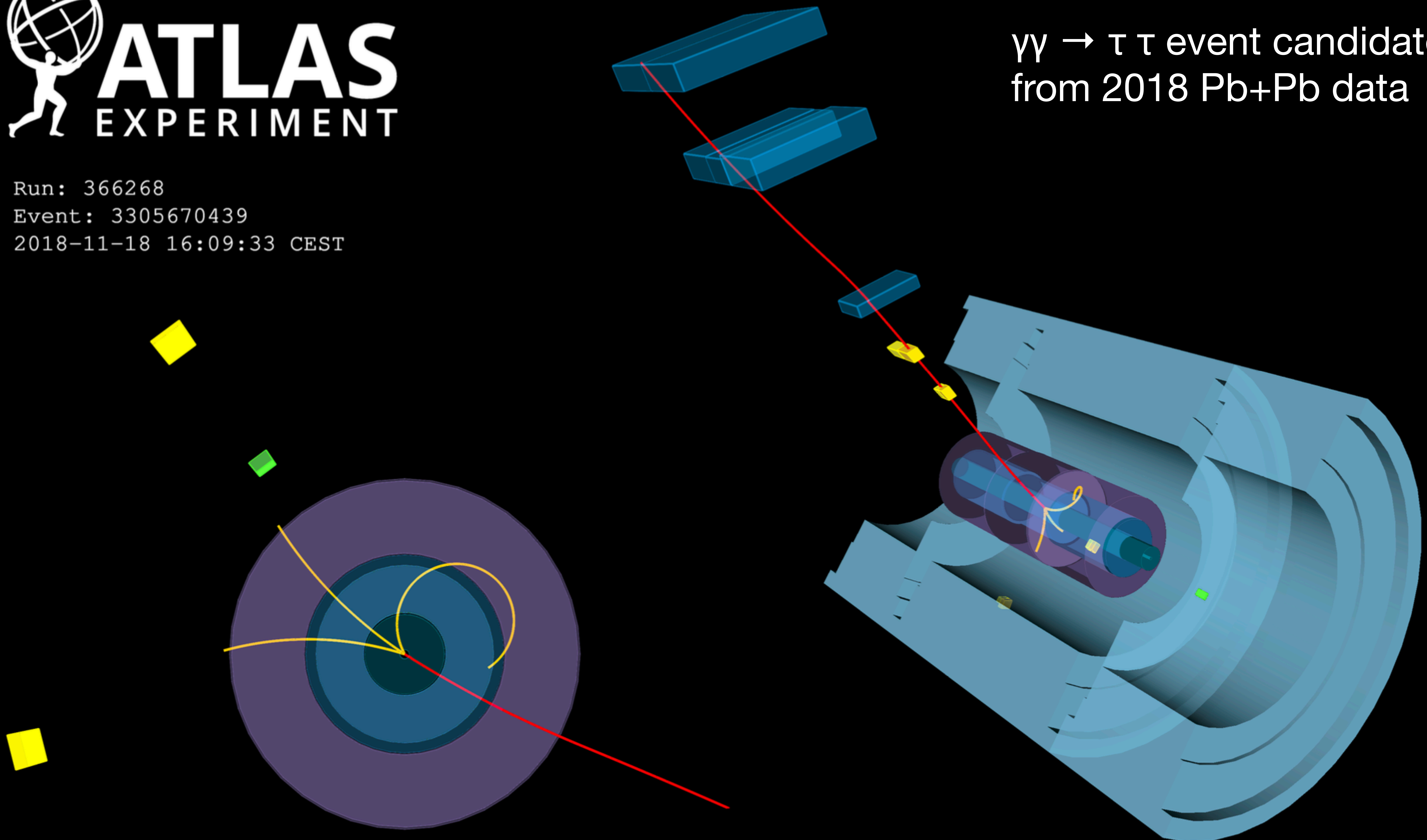

Phys. Rev. C 104 (2021) 024906



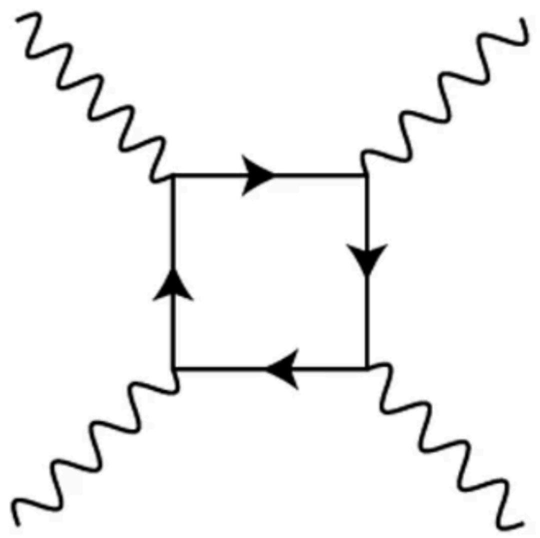

Phys. Rev. Lett. 131 (2023) 151802



γγ → τ τ event candidate from 2018 Pb+Pb data



# Run 2 ATLAS UPC highlights

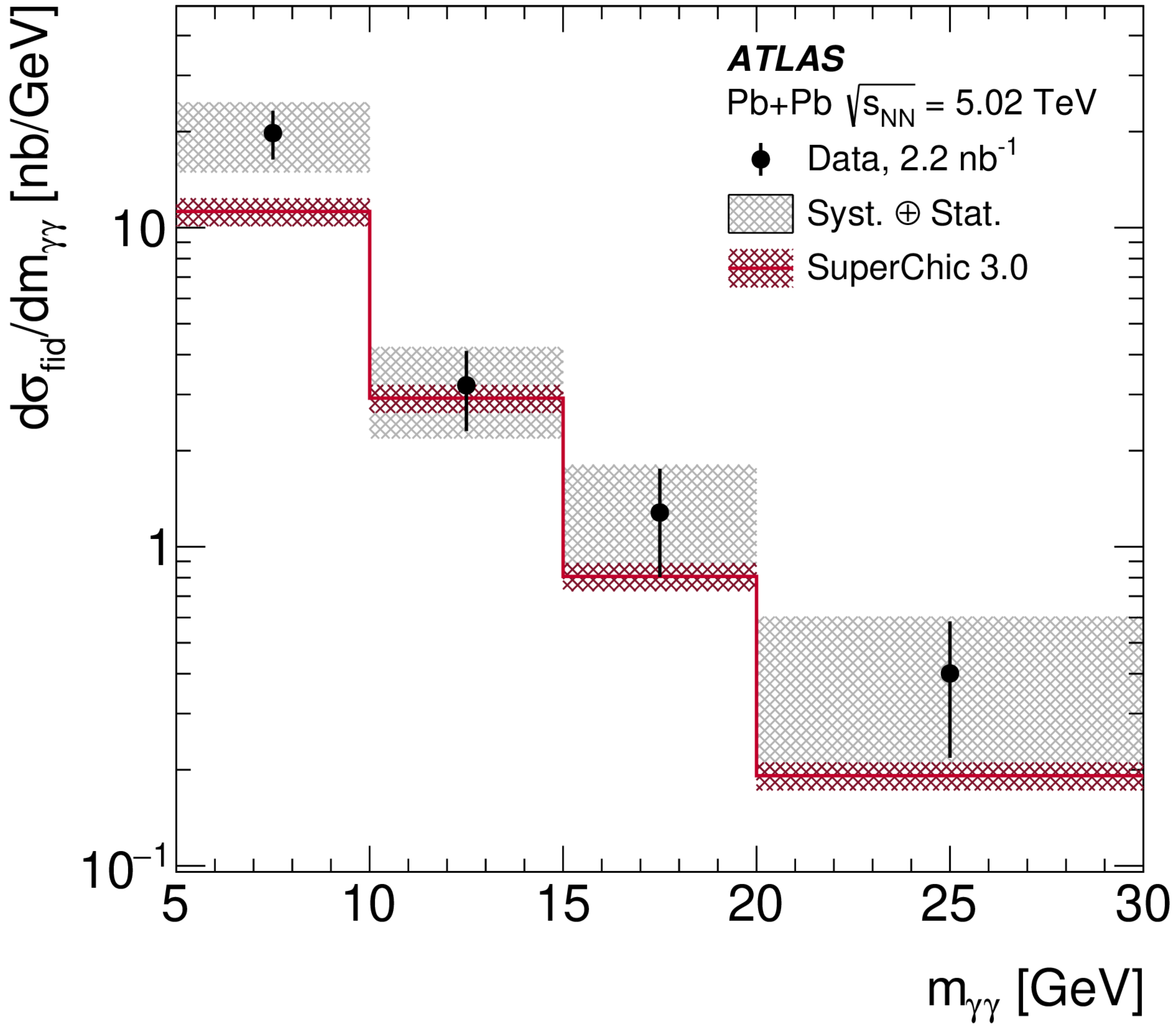


- Series of light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) measurements
  - Incl. analysis interpretations for specific BSM scenario (ALPs)

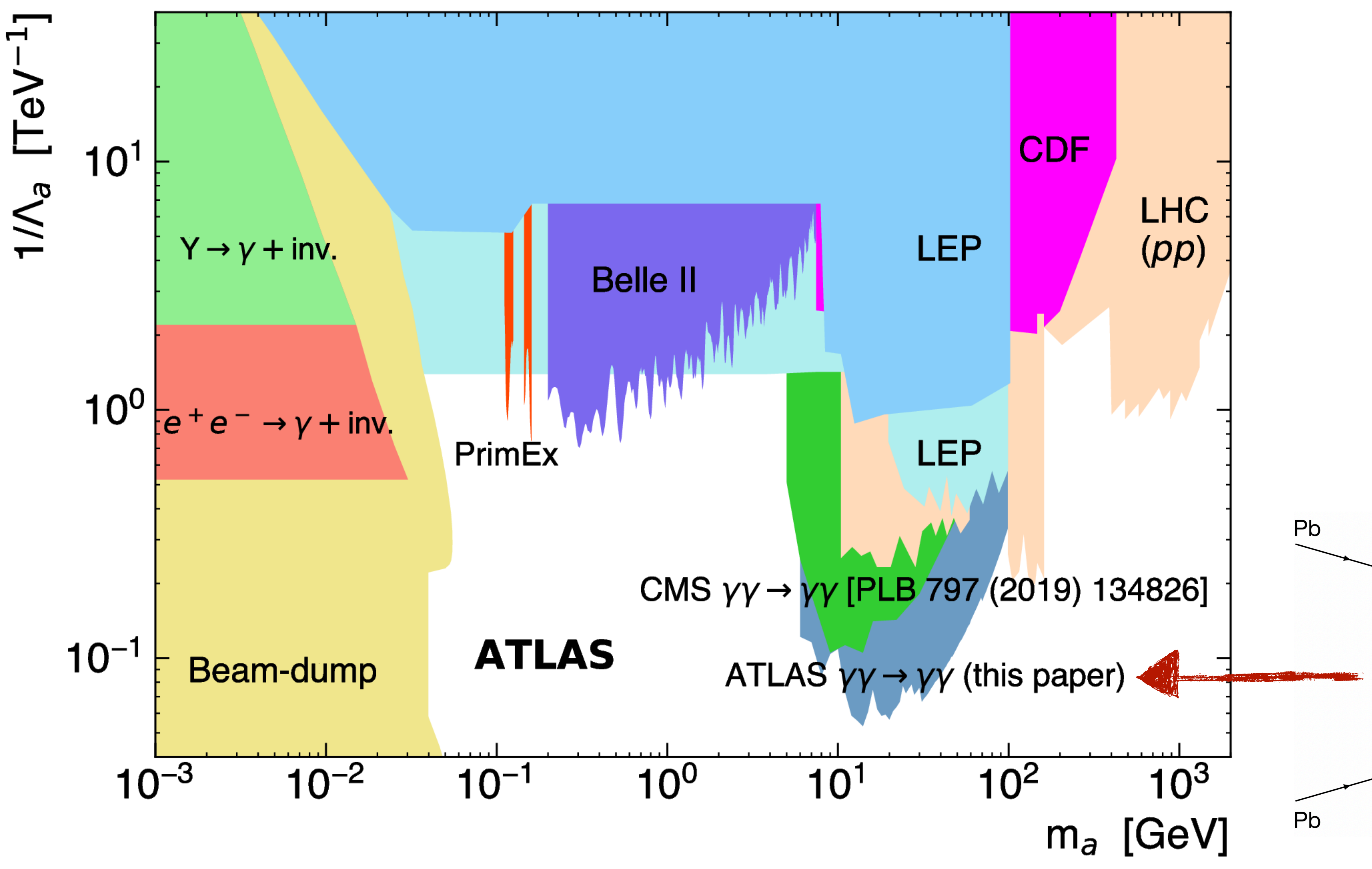
Nature Phys. 13 (2017) 852

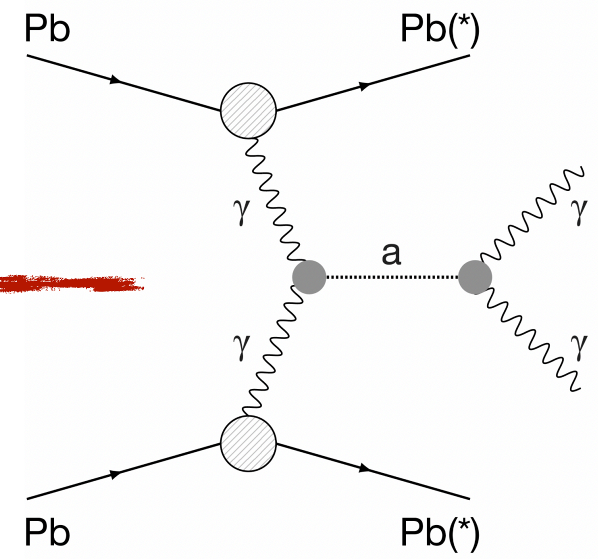
Phys. Rev. Lett. 123 (2019) 052001

JHEP 03 (2021) 243



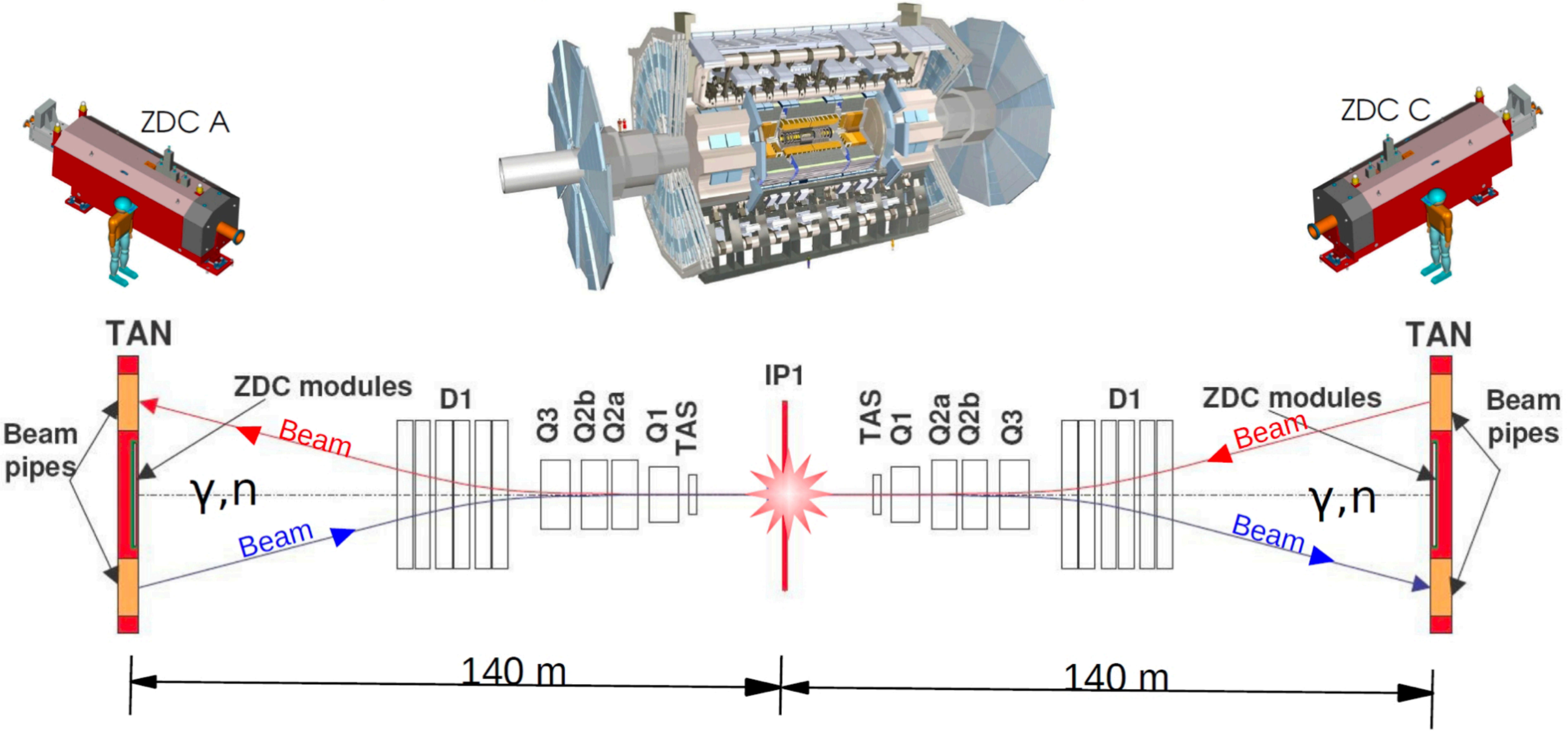

Existing constraints from JHEP 12 (2017) 044



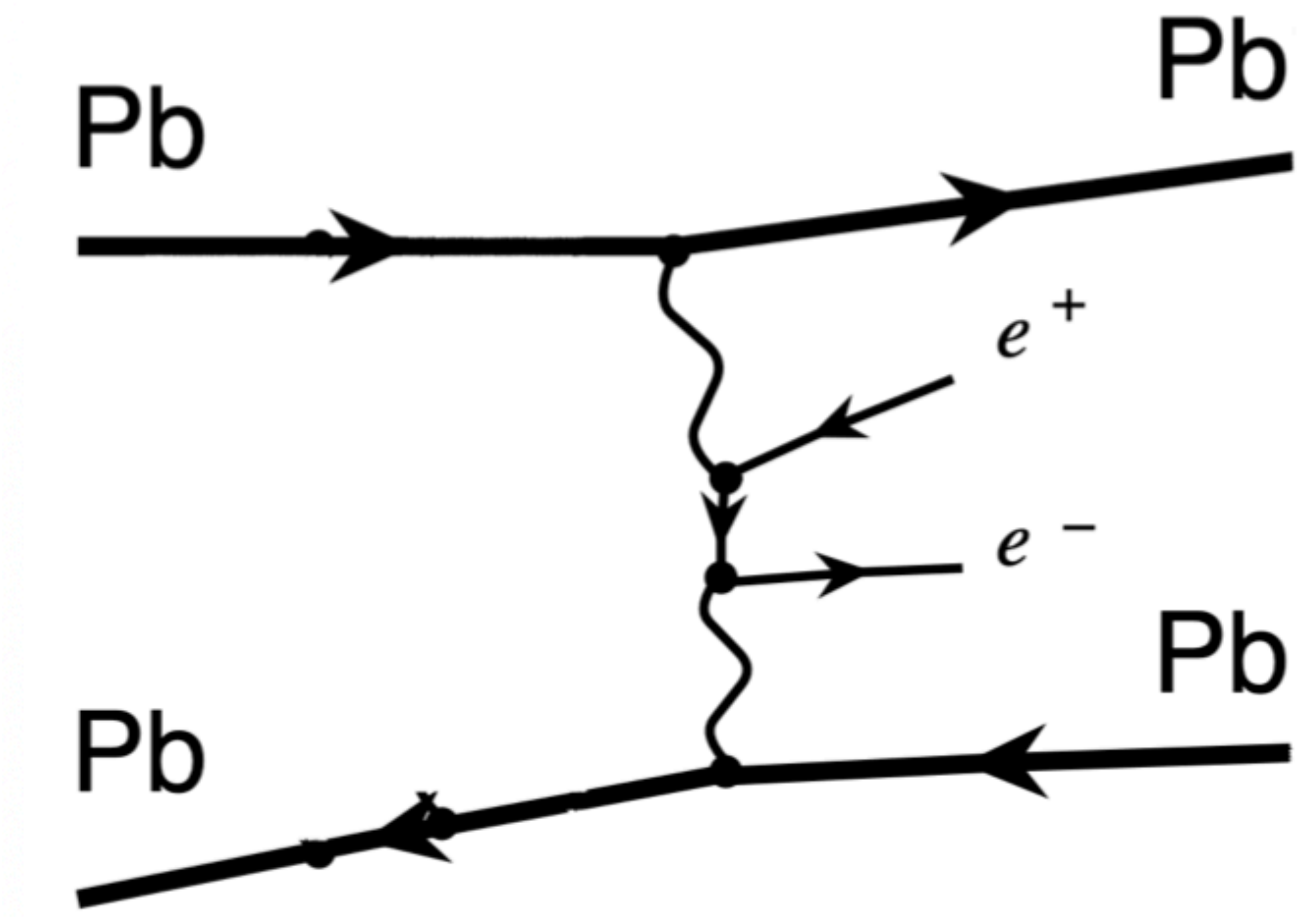
# Experimental considerations

- **UPC == Rapidity gaps, exclusive final states** → veto requirements are essential
  - Many sub-detectors available in ATLAS (**|η|<4.9**)
  - Also: no "pile-up" in LHC Pb+Pb collisions
- (Absence of) ion breakup tagged with **Zero Degree Calorimeters (ZDC)**



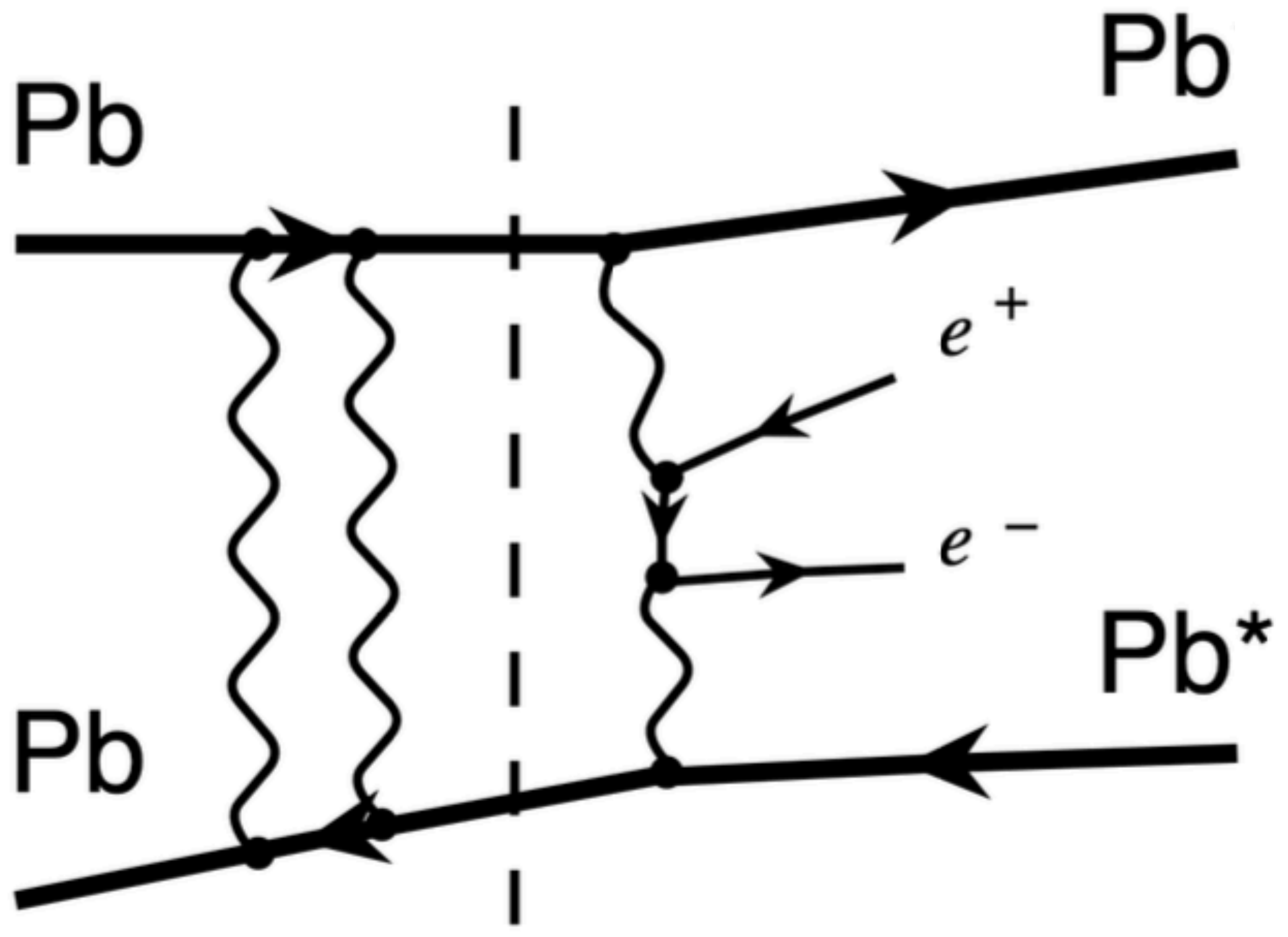
# ZDC UPC categories

**0n0n**



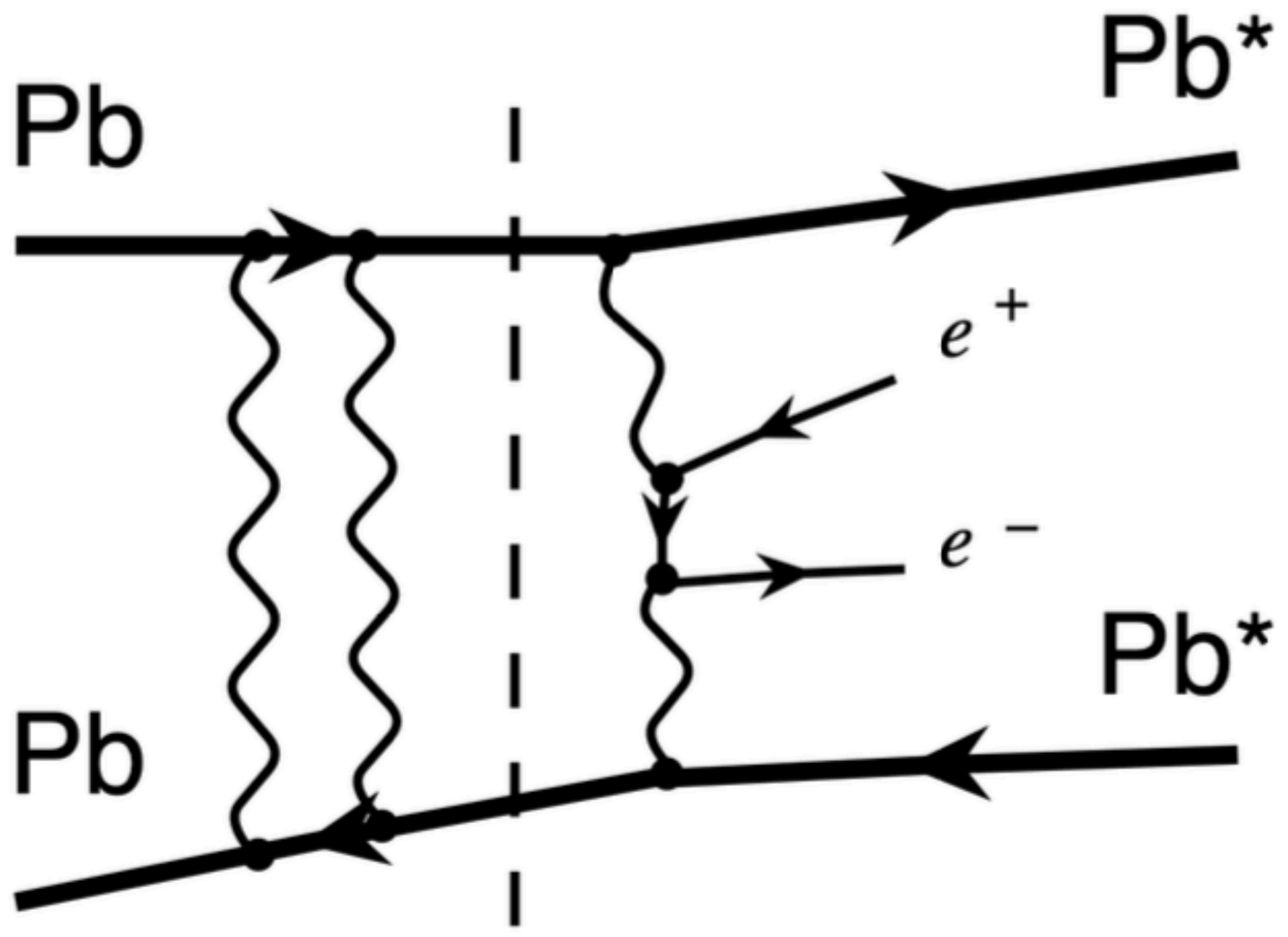

**(~60% events @ $m_{pair}$=30 GeV)**

**0nXn**



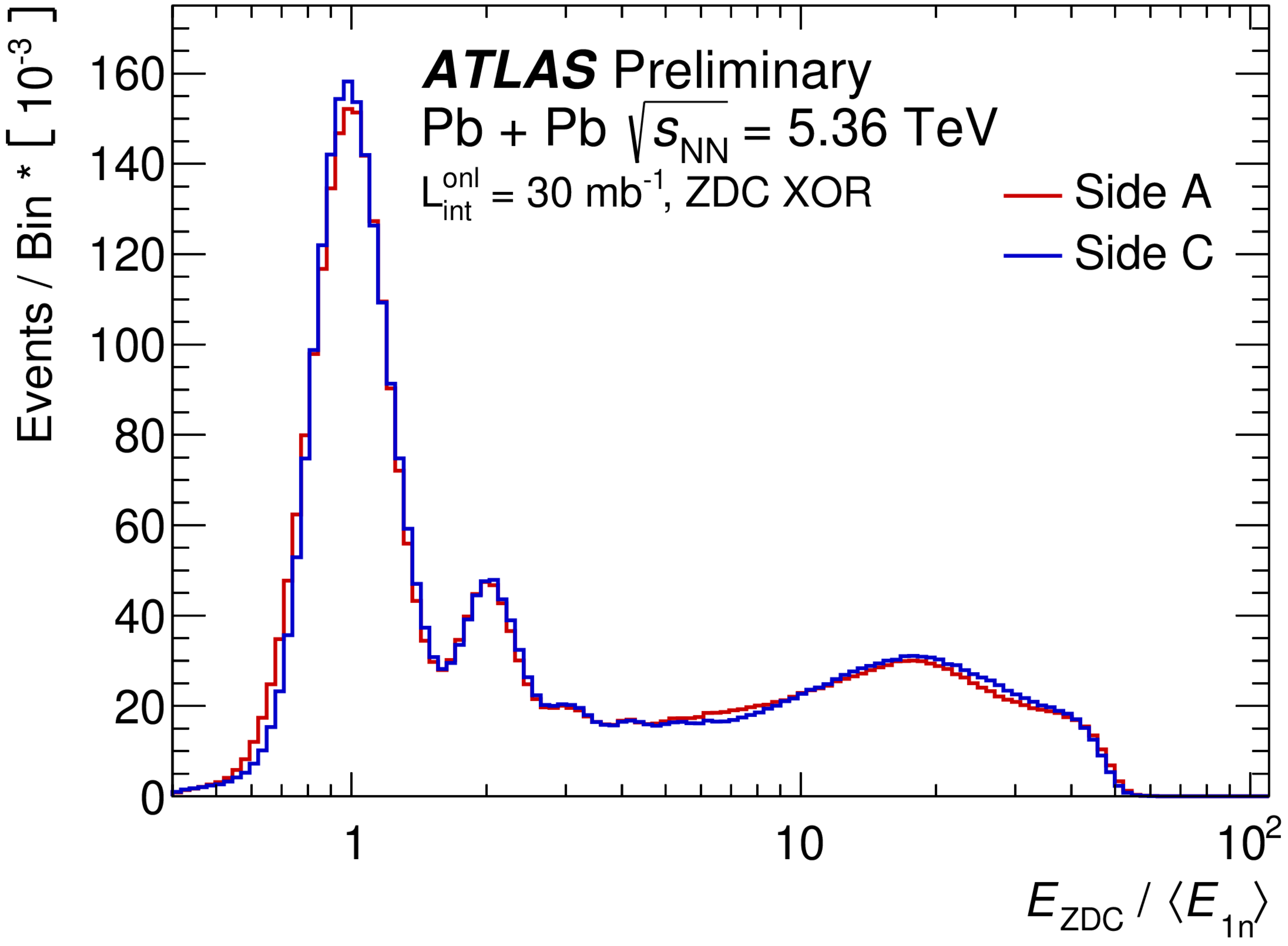

**(~30% events @ $m_{pair}$=30 GeV)**

**XnXn**

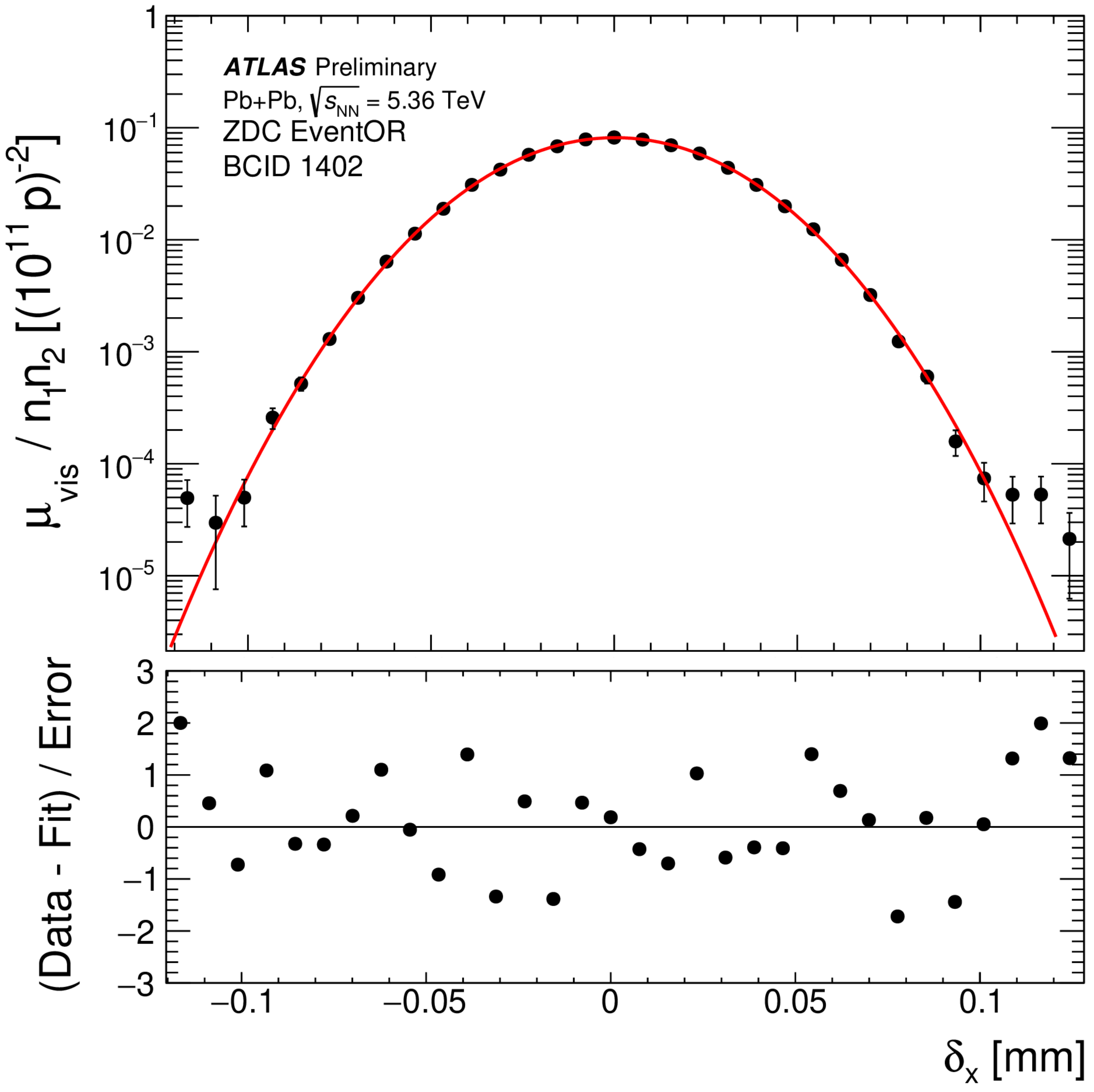



**(~10% events @ $m_{pair}$=30 GeV)**

# ATLAS ZDC performance in Run3



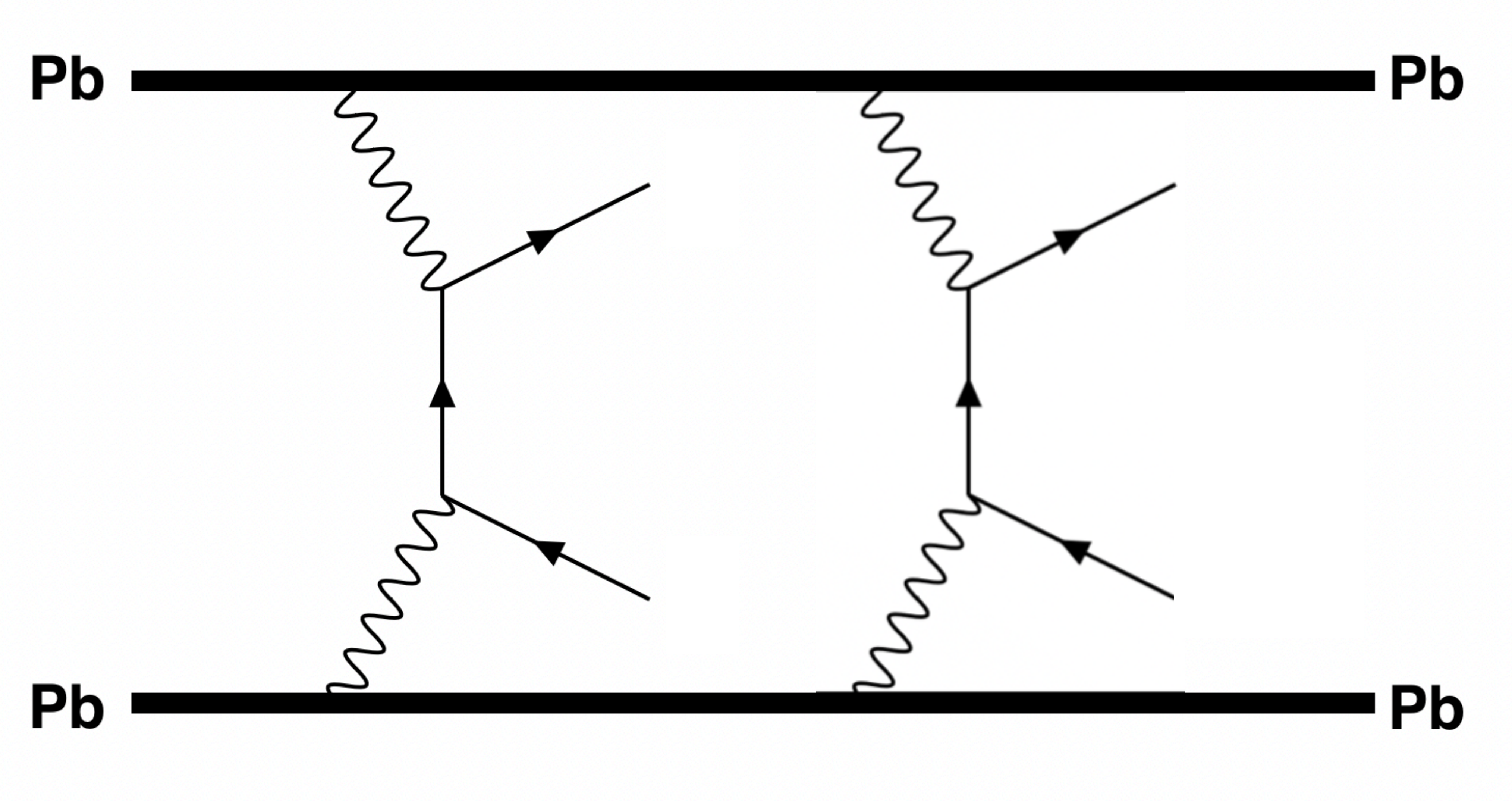

LUMI-2023-09



# Outline

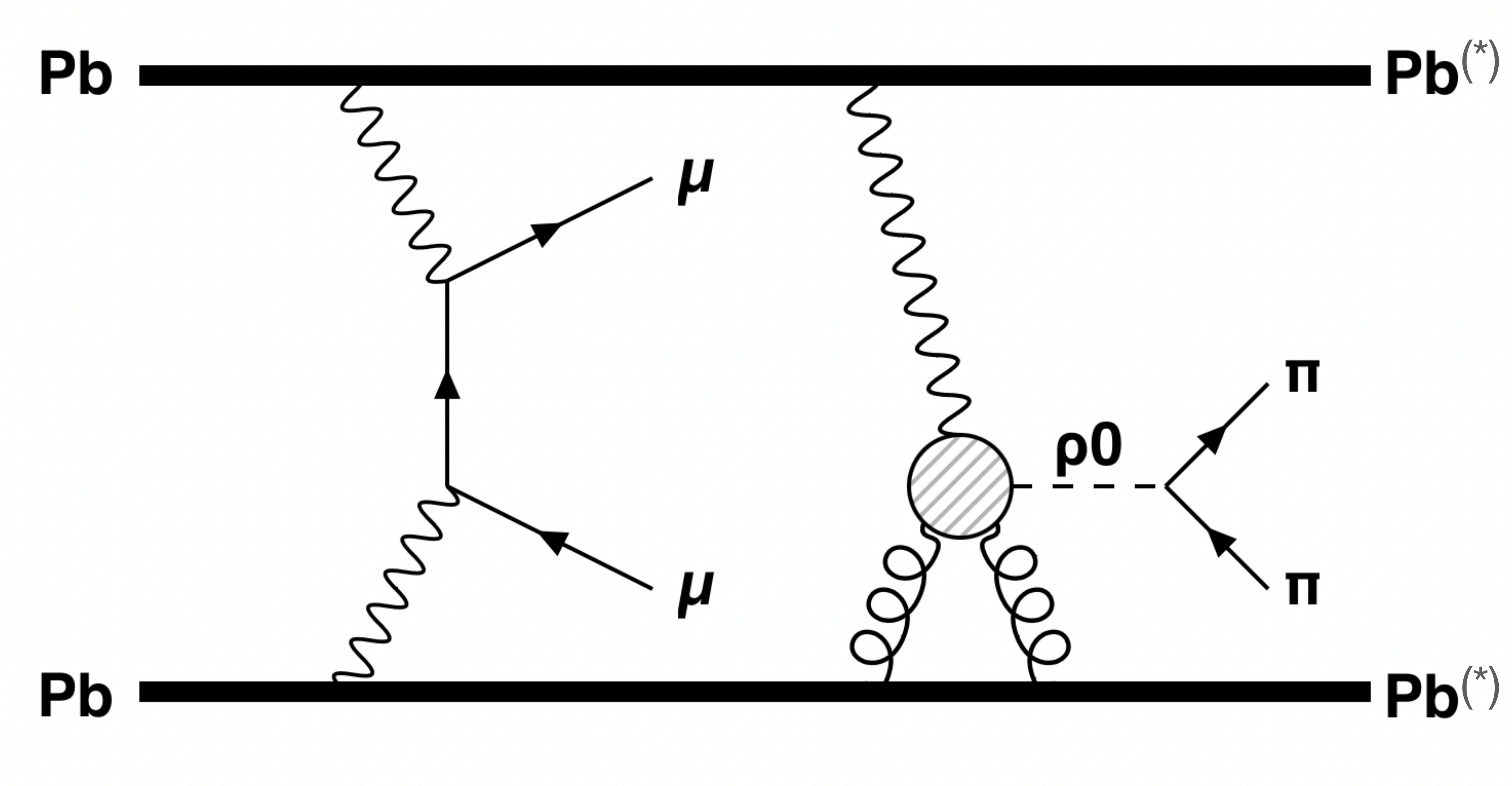
- ATLAS measurements covered in this talk:
  - Measurement of **coincident photon-initiated processes** in ultra-peripheral Pb+Pb collisions with the ATLAS detector, **arXiv:2504.07795**
  - Measurement of **coherent exclusive J/Psi→μμ** production in ultraperipheral Pb+Pb collisions at 5.36 TeV with the ATLAS detector, **arXiv:2509.04135**
  - Search for **magnetic monopole pair production** in ultraperipheral Pb+Pb collisions at 5.36 TeV with the ATLAS detector at the LHC, **Phys. Rev. Lett. 134 (2025) 061803**

# (I) Coincident UPC processes



# Measurement of $\gamma\gamma \rightarrow \mu\mu$ + $\rho^0 \rightarrow \pi\pi$ production in UPC

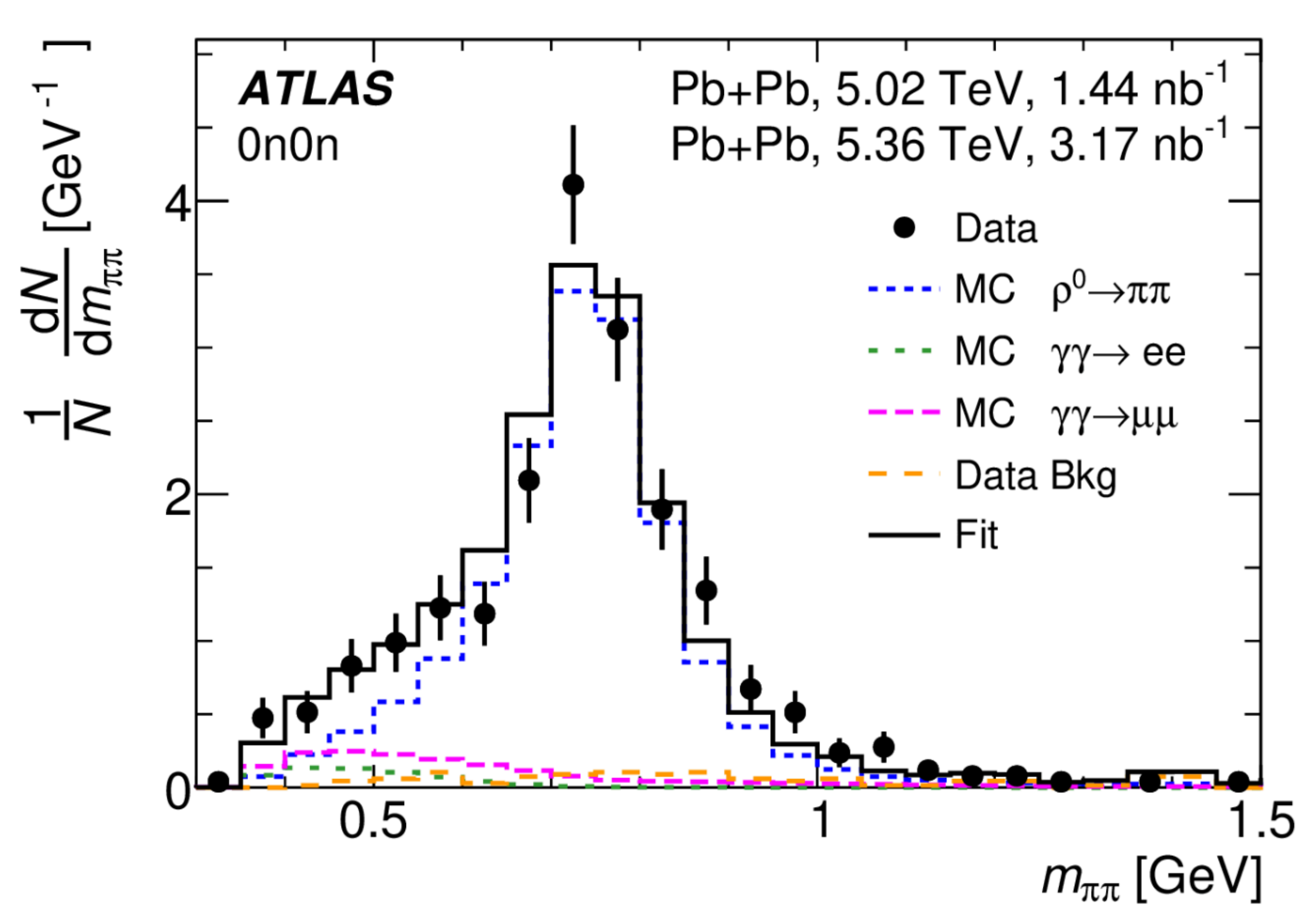
- Extreme EM fields in Pb+Pb UPC @ LHC allow to produce **double photon-induced reactions**
- Aim is to measure the **coincident rate** for $\gamma\gamma \rightarrow \mu\mu$ (higher energy tagged process) + $\rho^0 \rightarrow \pi\pi$ (coincident additional process)

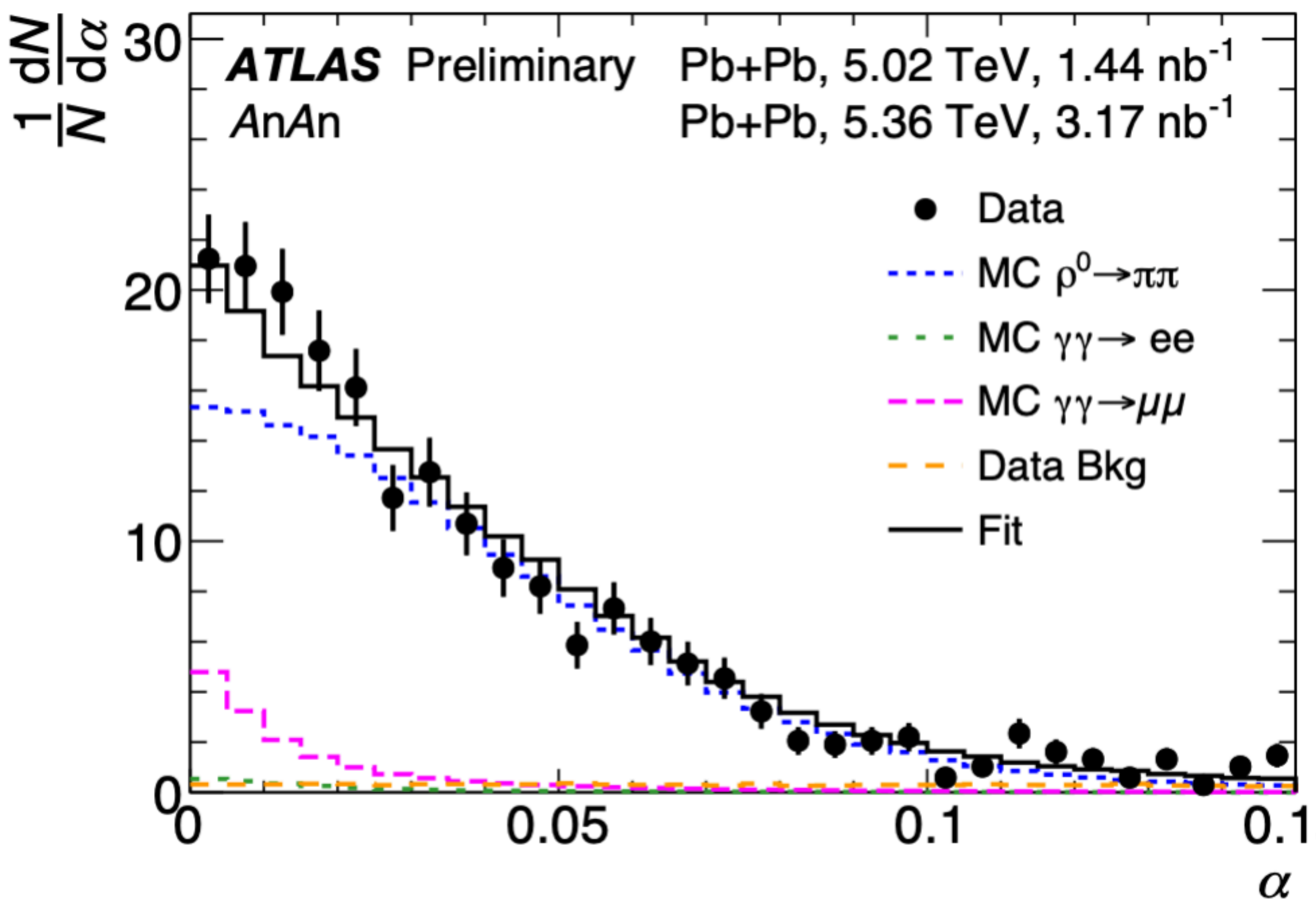


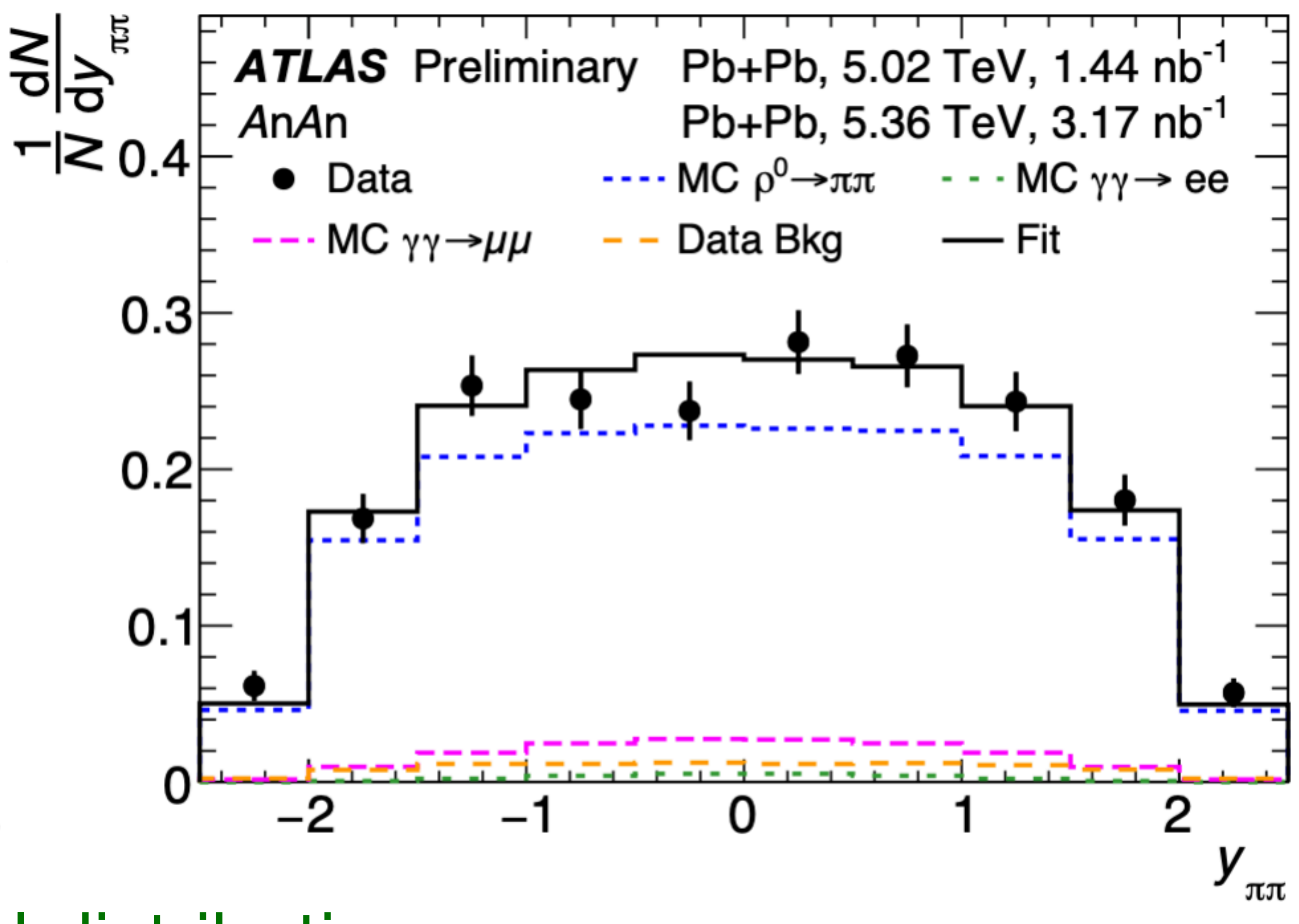

- Analysis strategy:
  - Trigger on muon from the pair
  - Dedicated tracking selection (pixel tracks) to maximise the efficiency for $\rho^0 \rightarrow \pi\pi$
  - Study **relative rate** (not absolute cross-section) over UPC $\gamma\gamma \rightarrow \mu\mu$ process
- Data set
  - Run 2 (2018) + Run 3 ( 2023 and **2024**) Pb+Pb data is used (**~4.5/nb**)

# Measurement of $\gamma\gamma\rightarrow\mu\mu$ + $\rho^0\rightarrow\pi\pi$ production in UPC

- Event selection
  - Two OS muons with $p_T$>4 GeV
  - Small dimuon pair $p_T$
  - Exactly two extra tracks (unassociated w/ muons, but from same vertex)
- Backgrounds
  - Soft $\gamma\gamma\rightarrow ee/\mu\mu$ pairs, combinatorics
- Signal extraction
  - Template fits performed to dipion **mass**
- Signal efficiency corrections
  - Studied using STARlight MC simulated events
- Systematic uncertainties subdominant over stat.



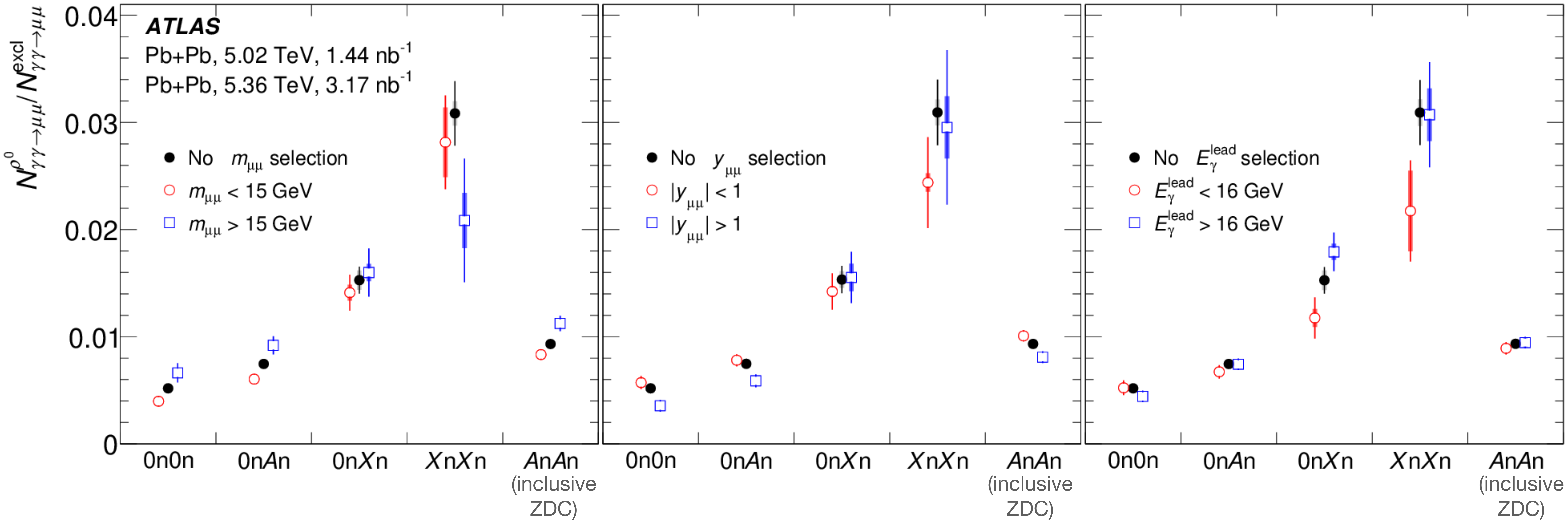



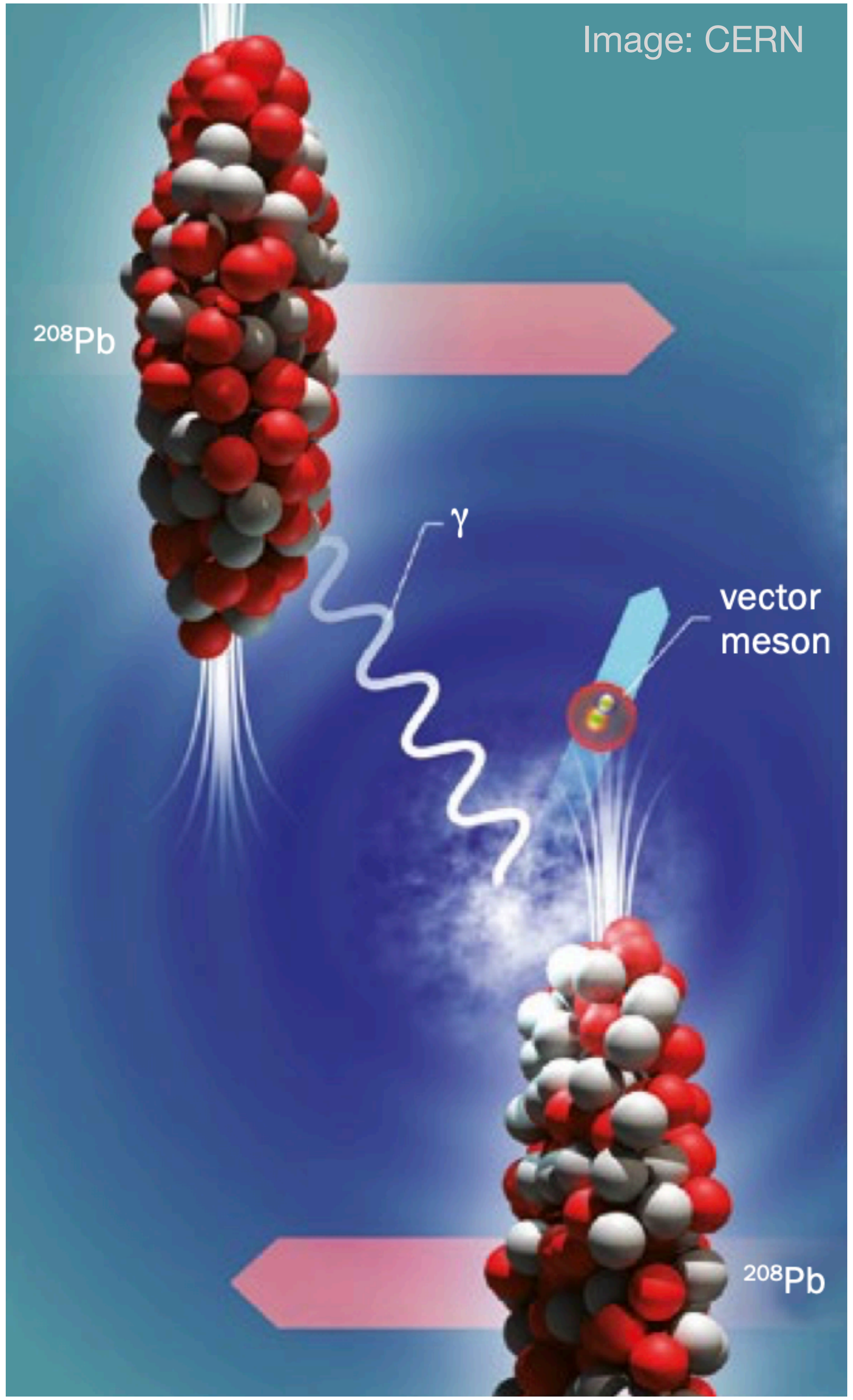

Control distributions

# Measurement of $\gamma\gamma\to\mu\mu$ + $\rho^0\to\pi\pi$ production in UPC

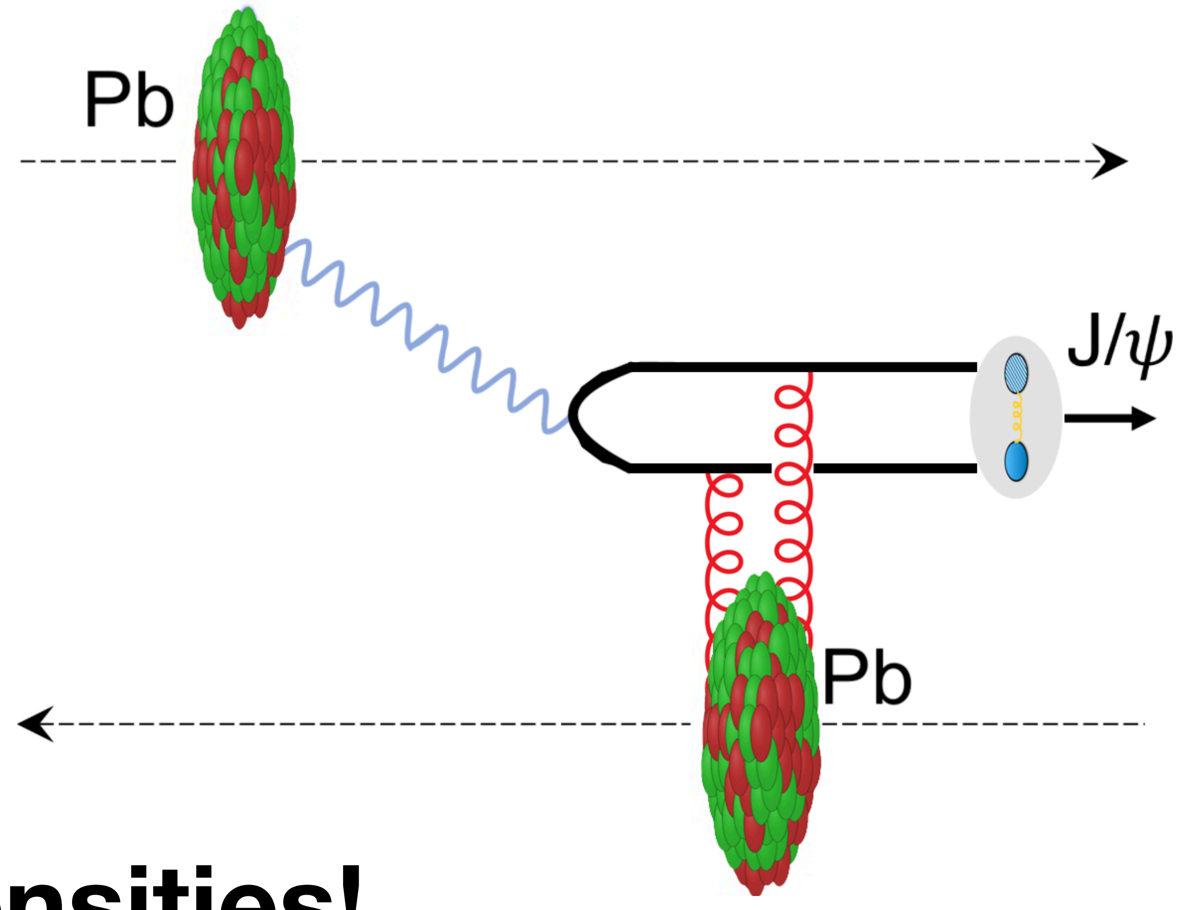
- Dependence of coincidence rate on **ZDC activity** and **dimuon kinematics**
- Coincidence rate **increases**
  - with increasing ZDC activity and/or with increasing dimuon mass (smaller b)
  - Other variables also studied to provide additional constraints on model calculations



# (II) Measurement of coherent J/ψ in UPC

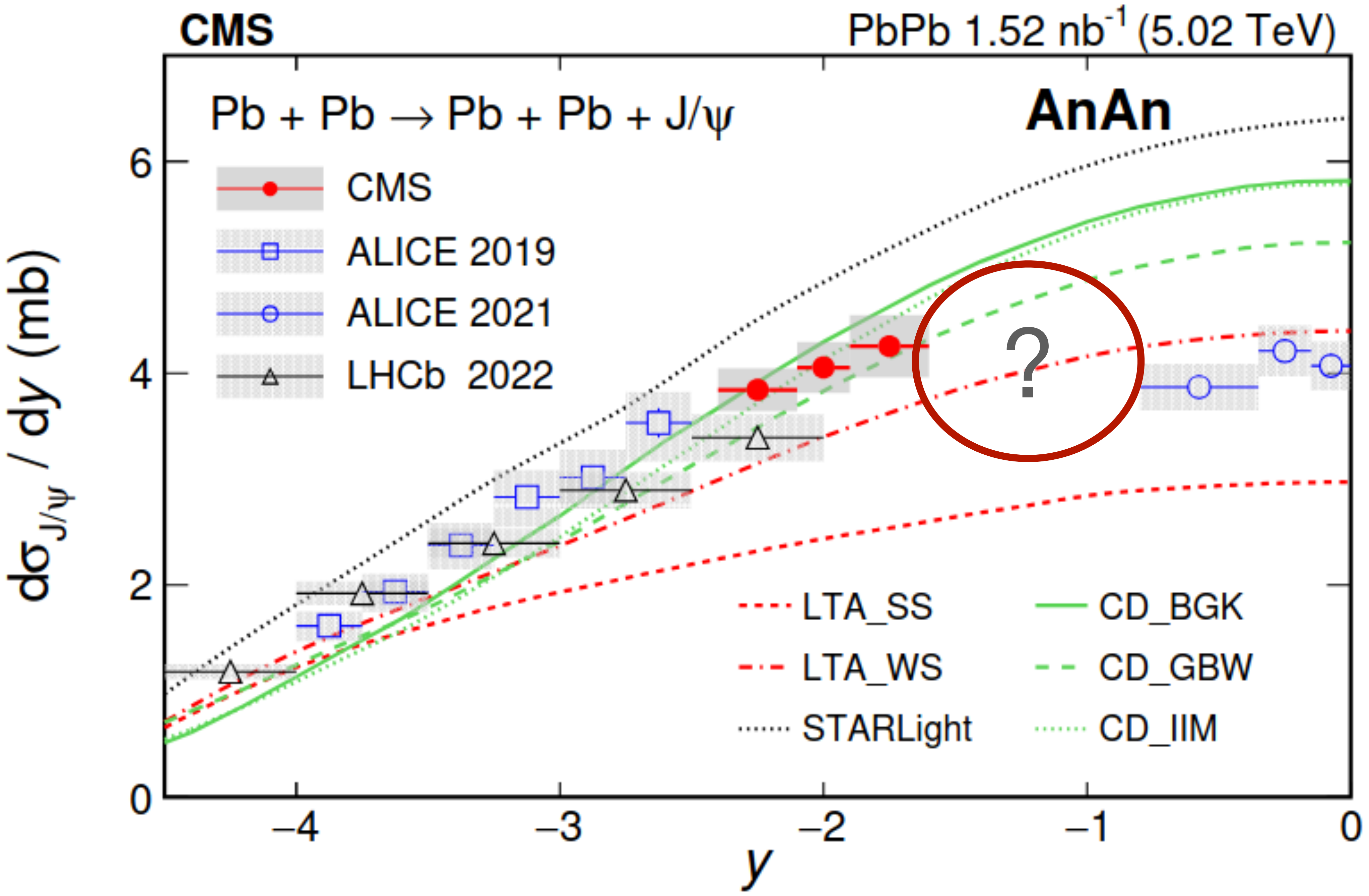


# Measurement of coherent J/ψ in UPC: Motivation




- Process sensitive to nuclear gluon dynamics at low-x
  - (Hard) scale: **$Q^2 = m_V^2/4$**
  - Exclusive process→simple relation: $x = (m_V/\sqrt{s_{NN}})exp(\pm y)$
  - For heavy nuclei at high energy →**probe very large gluon densities!**

CMS collaboration, Phys. Rev. Lett. 131 (2023) 262301




- Filling the gap in measurements for 0.8<|y|<1.6 (uncovered by previous studies)
- Focusing on **dimuon** decay channel
- Key experimental challenge in ATLAS:
  - Trigger on soft (**$p_T$ ~1.5 GeV**) leptons

# ATLAS Run 3 UPC game-changer

**The L1TRT trigger (aka FastOR cosmic trigger): First-ever track-sensitive trigger running at O(MHz) (?)**

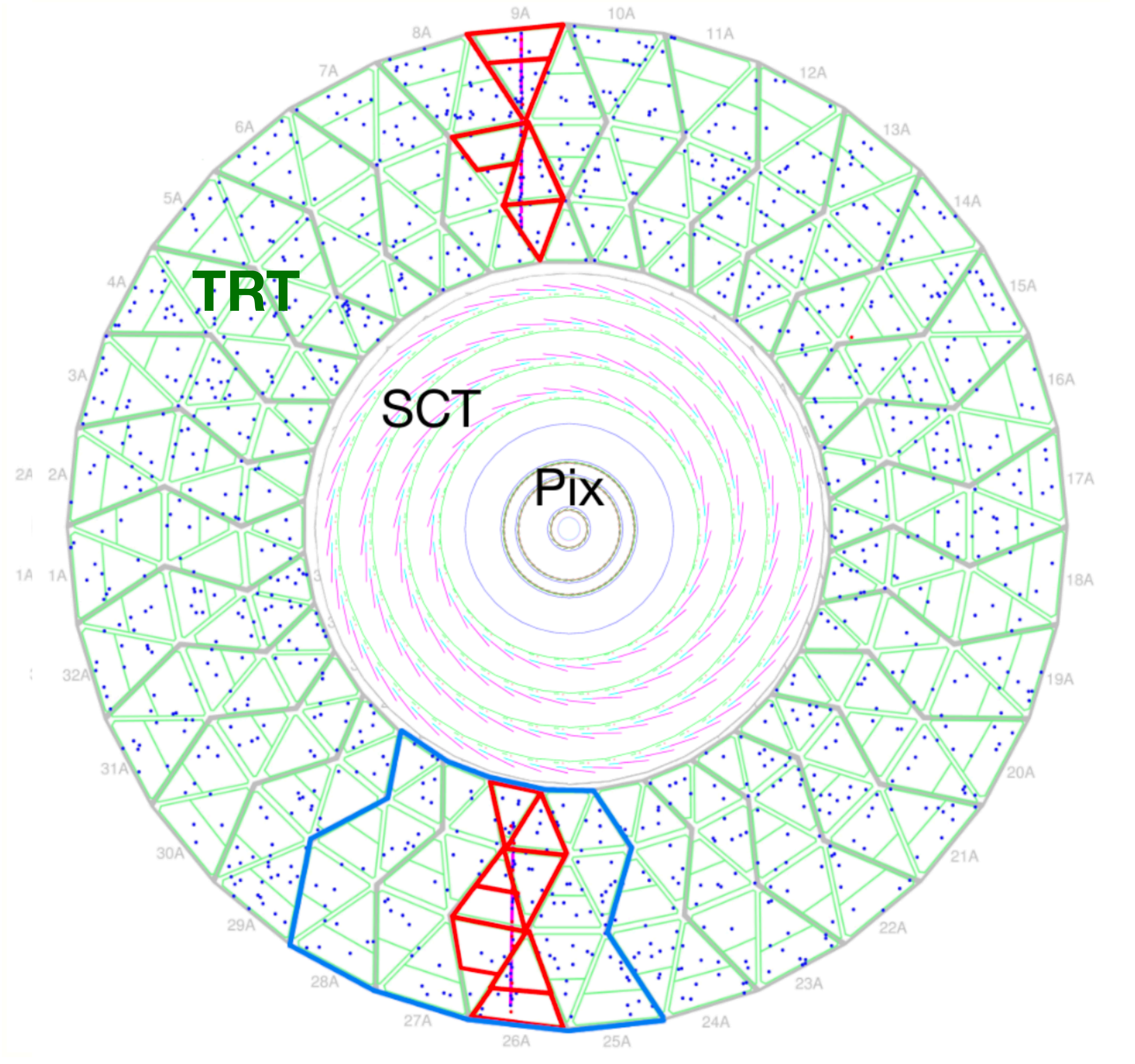
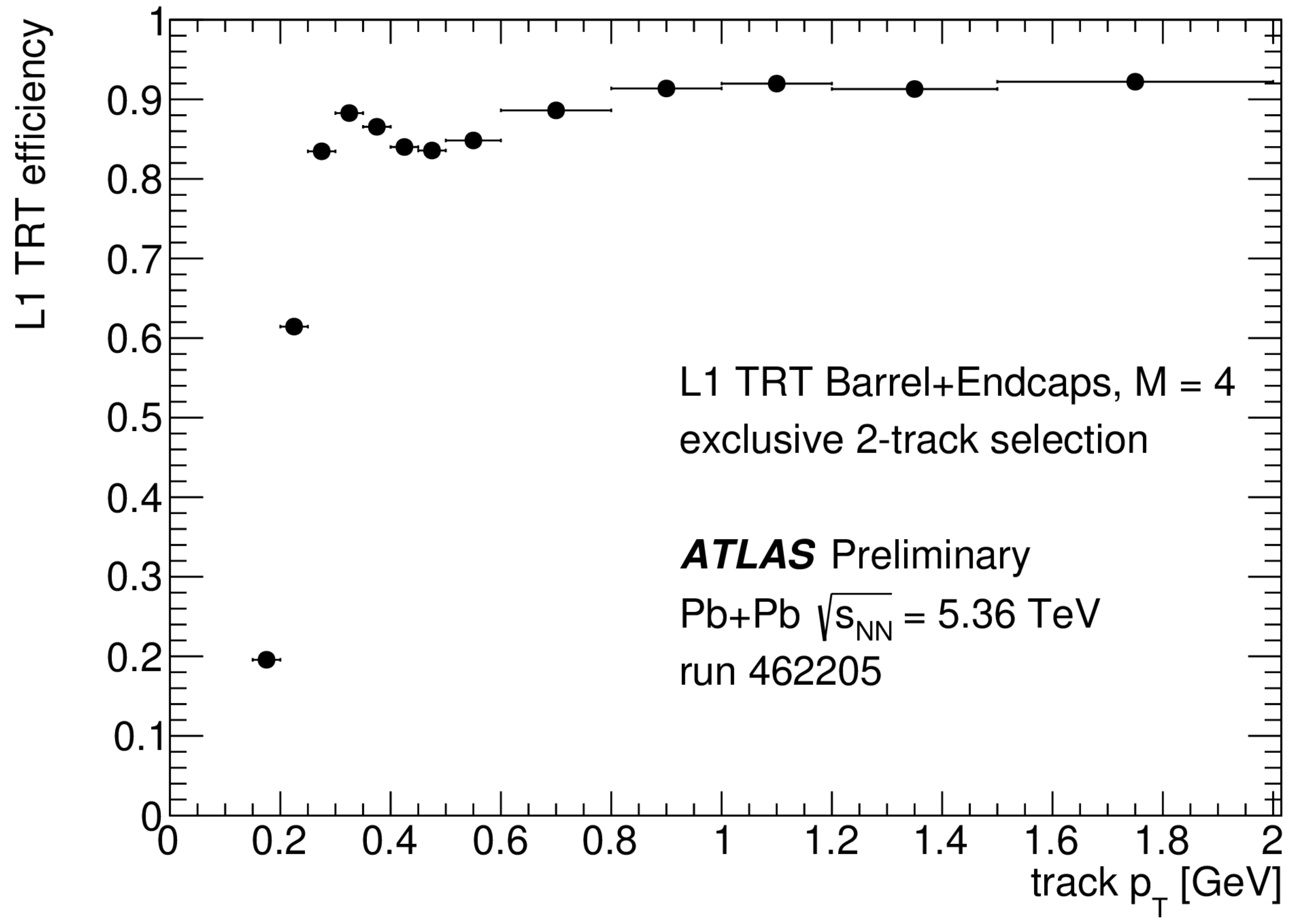



Figure 2.1: The L1TRT FastOR logic in the Barrel A region [17]. The Barrel TRT region is divided into 32 phi sectors (bold gray), each consisting of 9 TRT trigger segments (shown as green triangles/trapezoids). A trigger signal within a segment is formed if the transition radiation threshold is exceeded in any of TRT straws from this segment (shown as red triangles/trapezoids). Then, the trigger logic aggregates signals from all segments in a region formed from 4 adjacent phi sectors (shown in blue for example region), yielding an effective $\phi$ segmentation of 1/8. To form a global trigger decision, a given number of segments (multiplicity) with a trigger signal has to be reached in a given set of four sectors (each set of four sectors = 36 segments).

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDET-2023-01/

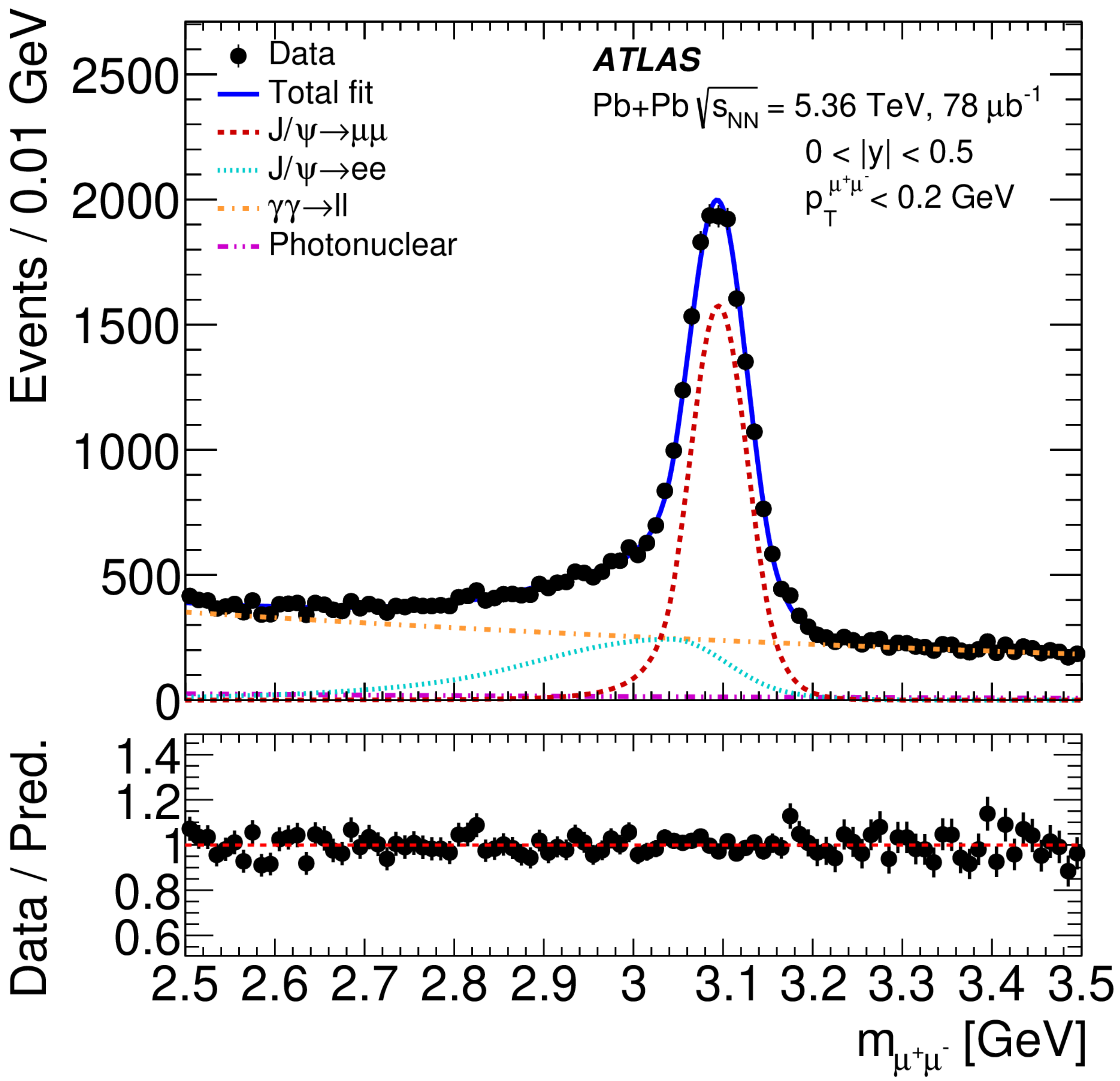


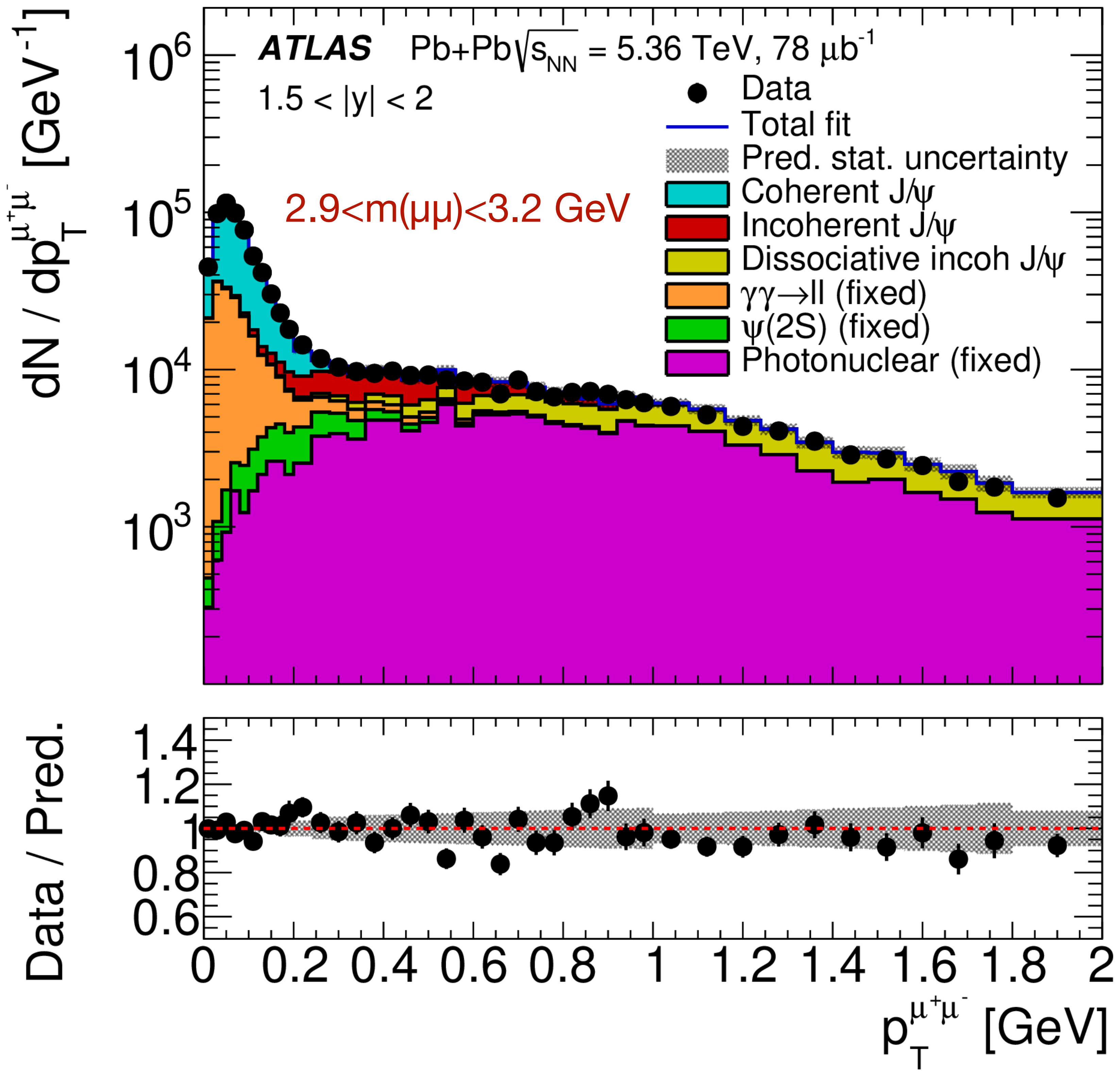

- In 2023, 78/ub of Pb+Pb data at 5.36 TeV was recorded with this trigger

# Measurement of coherent J/ψ in UPC: Analysis

- Event selection
  - Exactly 2 tracks (OS, $p_T$>1 GeV)
  - SR: **$p_T(\mu\mu)$<0.2 GeV, 2.9<m(μμ)<3.2 GeV**
  - No muon ID is used → fits to mass lineshape
- Backgrounds
  - J/ψ→ee, ψ(2S), incoherent J/ψ, combinatorial (pions)
- Signal extraction
  - Template fits to **two-track inv. mass** and **system $p_T$**

Signal and main backgrounds modelled with STARlight MC (+Pythia8 for QED FSR)



# Measurement of coherent J/ψ in UPC: Analysis

- Differential cross section measurement:

$$\frac{d\sigma}{dy} = \frac{N^{coh}_{J/\psi \to \mu^+\mu^-}}{A \times \epsilon_C \times BR \times \mathcal{L}_{int} \times \Delta y}$$

Raw coherent yield from $p_T$ fits

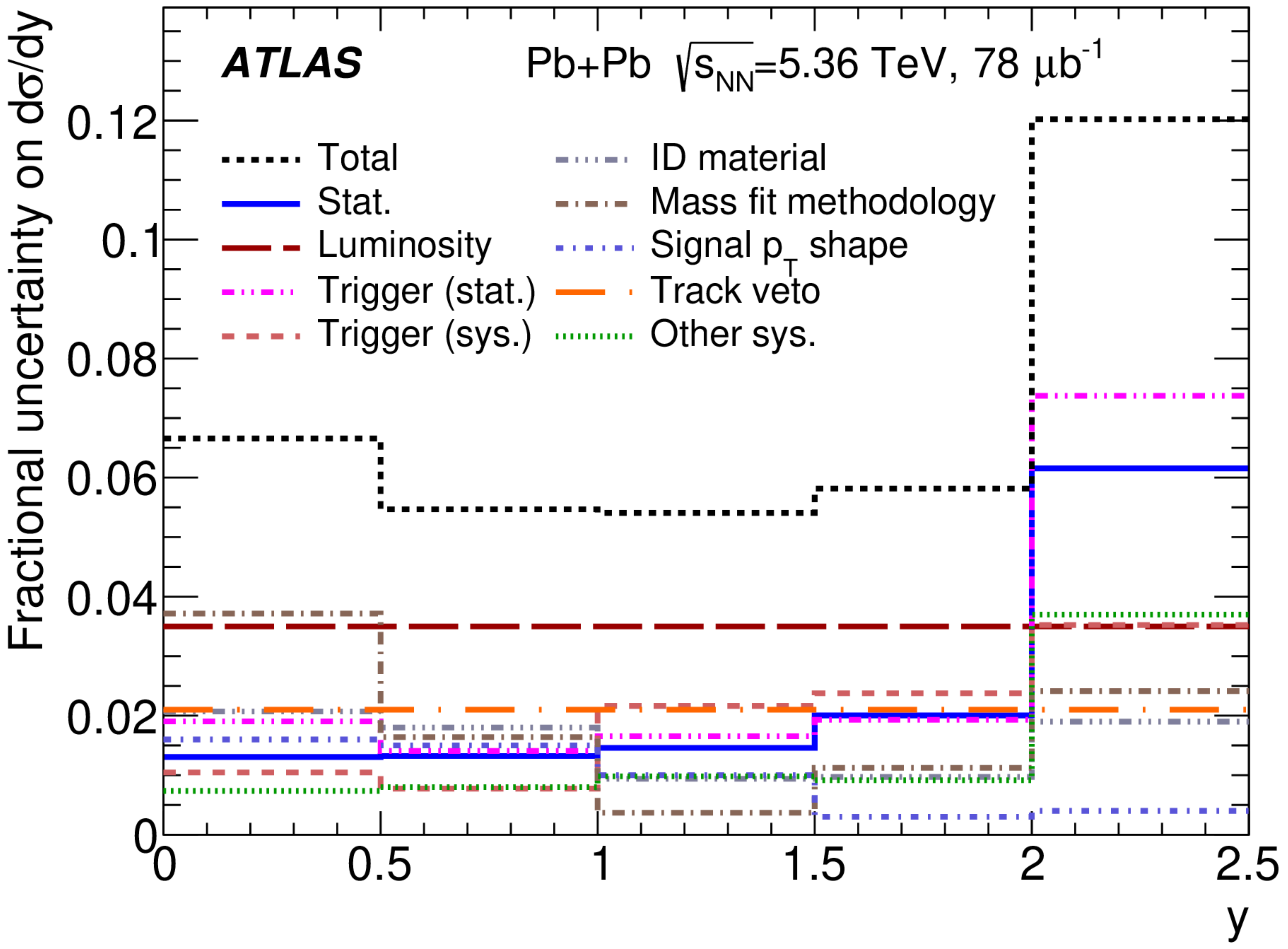
Acceptance correction (from MC)

Efficiency correction (from MC with data-driven correction factors)

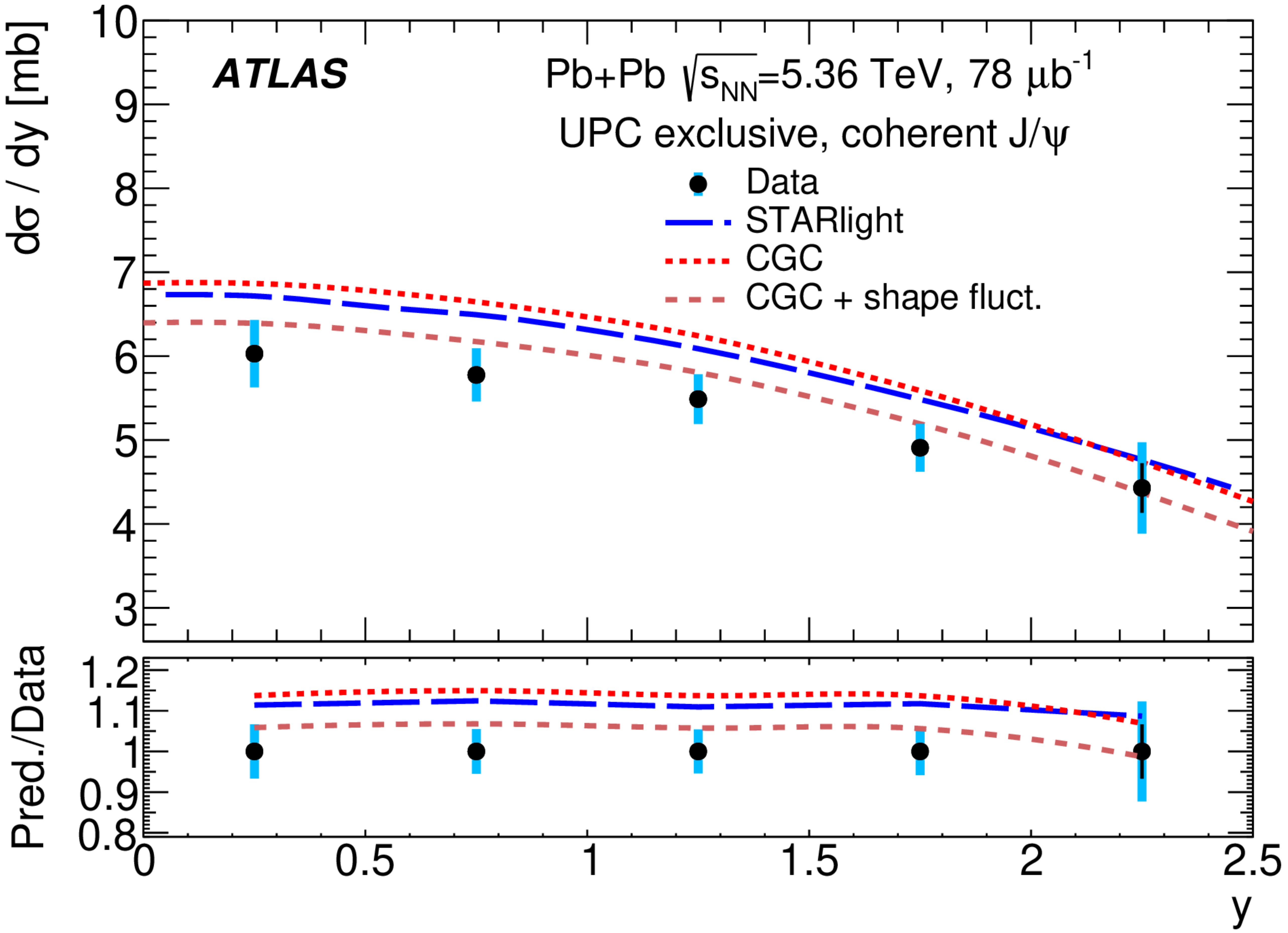
J/ψ →μμ BR

Integrated lumi

- Uncertainties
  - Dominated by **systematics** (lumi, fit methodology, …)



# Measurement of coherent J/ψ in UPC: Results



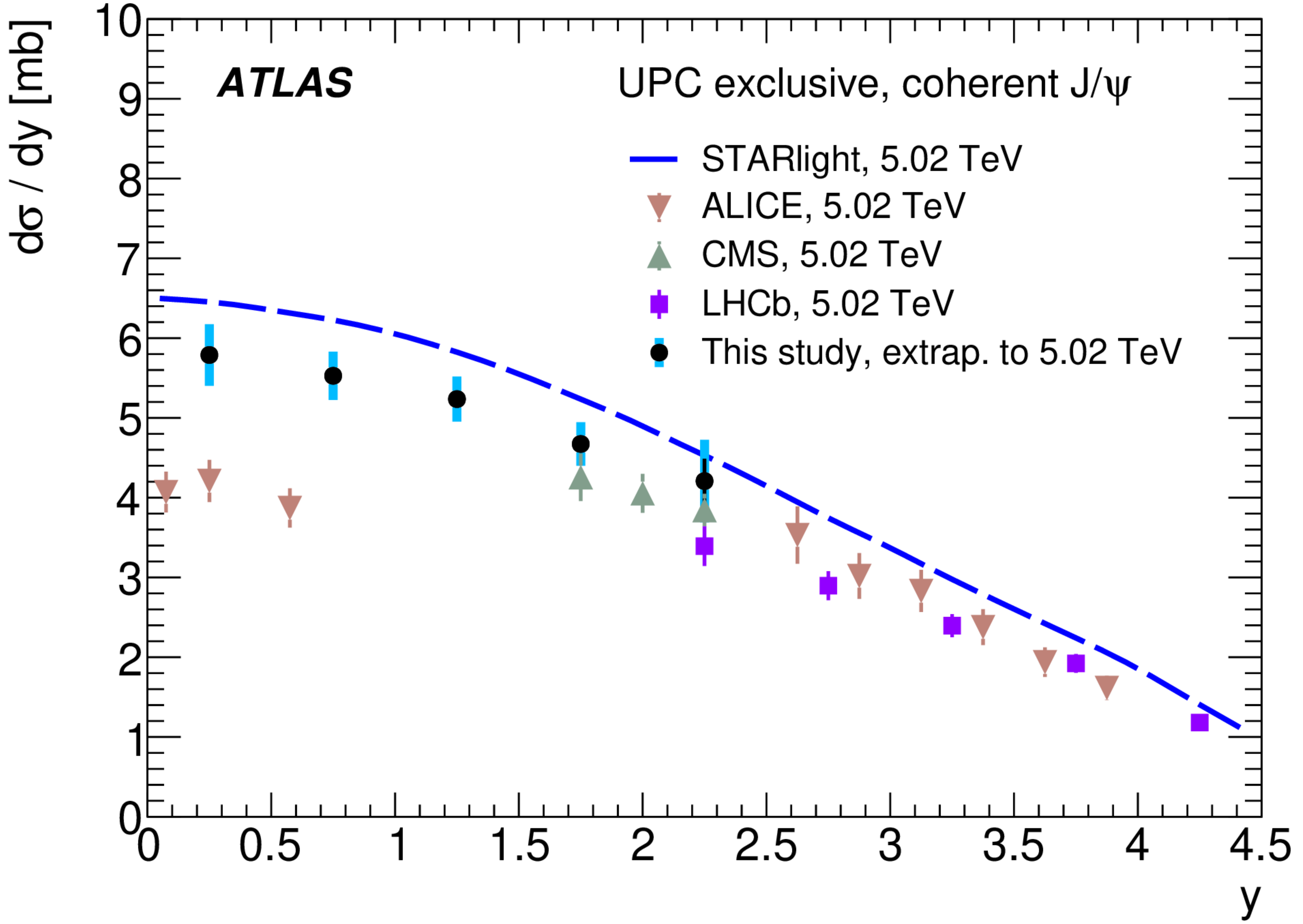

**Blue** vertical bars = total uncertainty

- Comparison with several theory predictions → **Color Glass Condensate (CGC) model w/ shape fluctuations** [Mäntysaari et al, PRD106 (2022)074019] reasonably describe the data

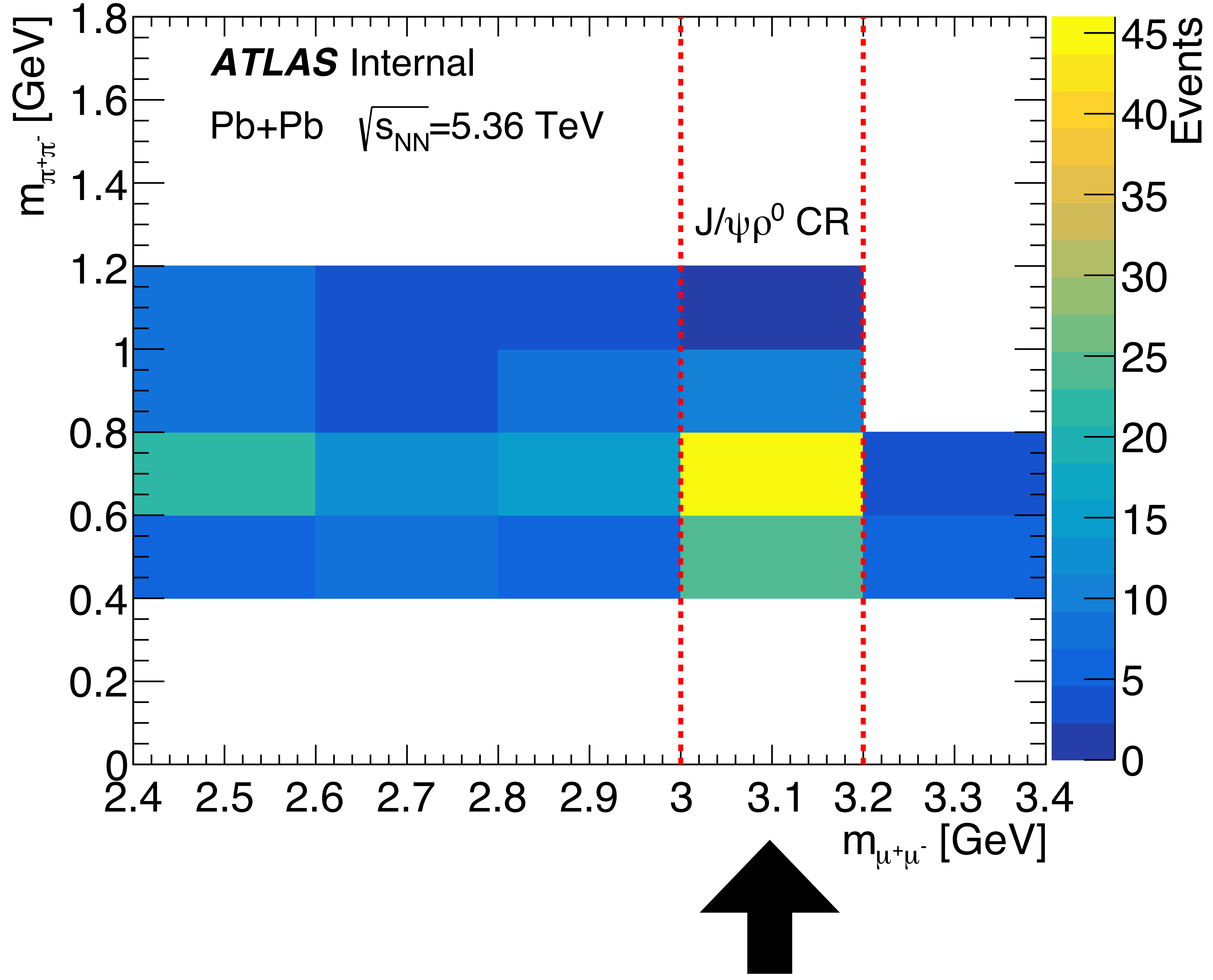
*CGC = effective theory for high gluon densities

# Measurement of coherent J/ψ in UPC: Results

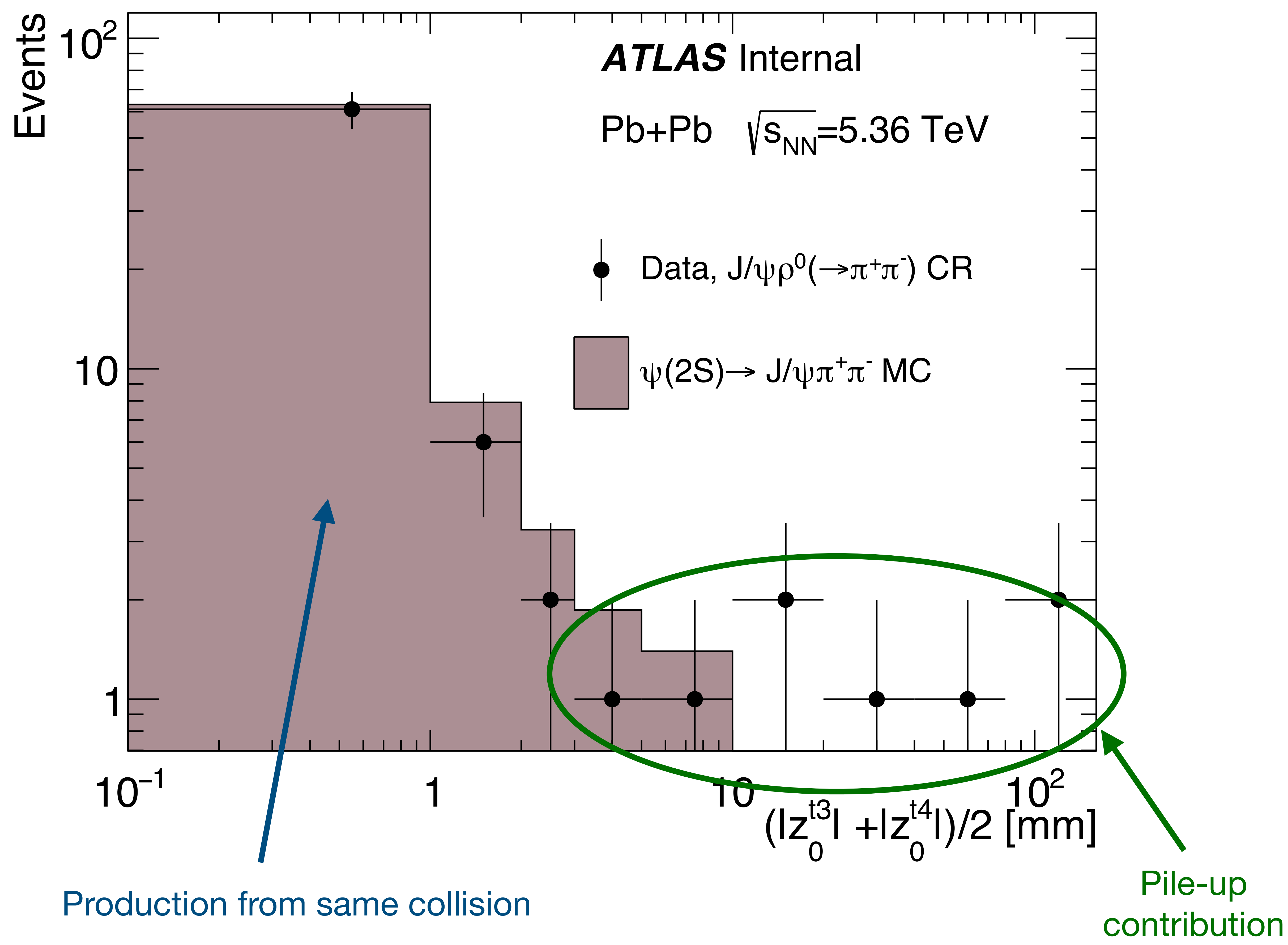
- **Extrapolation** to 5.02 TeV
- Tension w/ previous ALICE mid-rapidity measurement [EPJC 81 (2021)712]
  - ALICE mid-rapidity data requires veto on forward counters (V0 and AD, both in regions well beyond ATLAS acceptance)
  - ALICE publications raise concern that simultaneous forward e+e- pairs (assumed to be pileup) could lead to self-veto
    - Correct for pileup using veto rate measured in an "unbiased" beam-crossing trigger



# Coincident UPC events in coherent J/ψ measurement

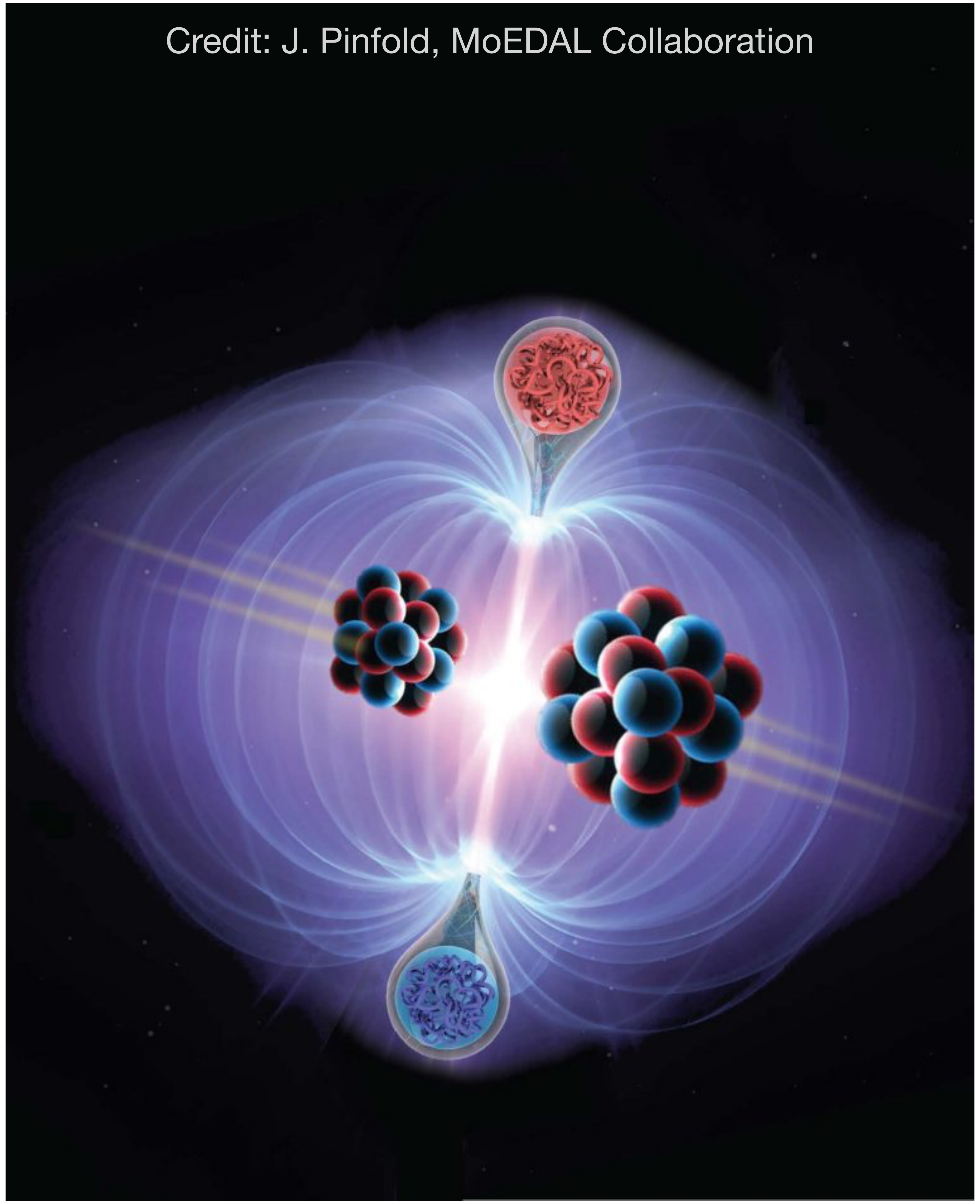



Dedicated CR with 4-tracks in which both J/ψ and $\rho^0$ are produced




**J/Psi + UPC coincident process production is dominated by "same event", and not pileup**

# (III) Search for magnetic monopoles in UPC

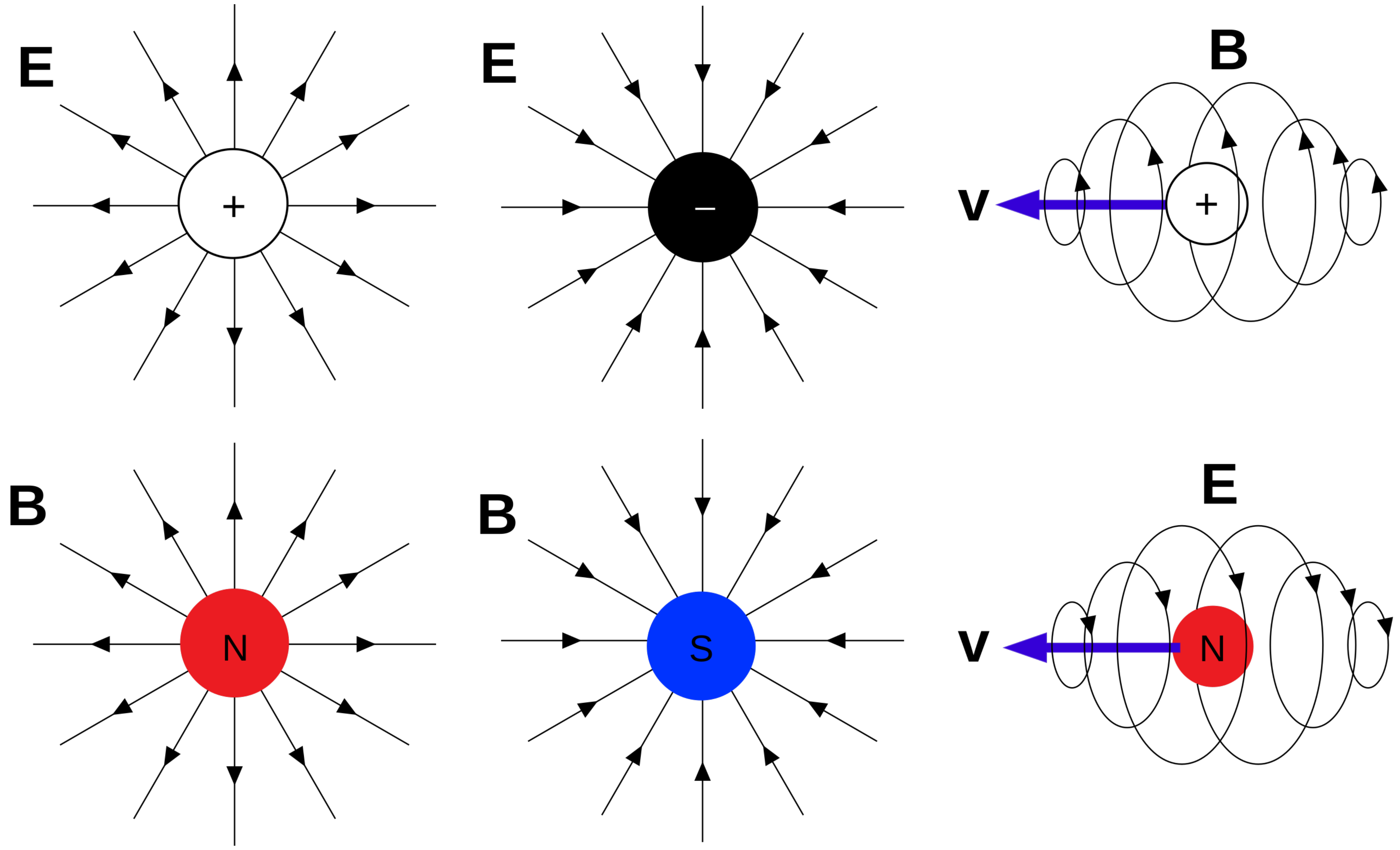


# Magnetic monopoles and the classical physics

**MAXWELL'S EQUATIONS**
**WITH MAGNETIC MONOPOLES**

$$\nabla \cdot \mathbf{E} = \rho_e \qquad \nabla \times \mathbf{E} = -\mathbf{J}_m - \frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = \rho_m \qquad \nabla \times \mathbf{B} = \mathbf{J}_e + \frac{\partial \mathbf{E}}{\partial t}$$




**Duality: E $\Longleftrightarrow$ B**

# Magnetic monopoles and charge quantisation

- Dirac (1931): the existence of magnetic monopole would explain **charge quantization**

*Quantised Singularities in the Electromagnetic Field.*

By P. A. M. Dirac, F.R.S., St. John's College, Cambridge.

(Received May 29, 1931.)

$$\frac{ge}{\hbar c} = \frac{n}{2}; \quad n = 1,2,\ldots$$

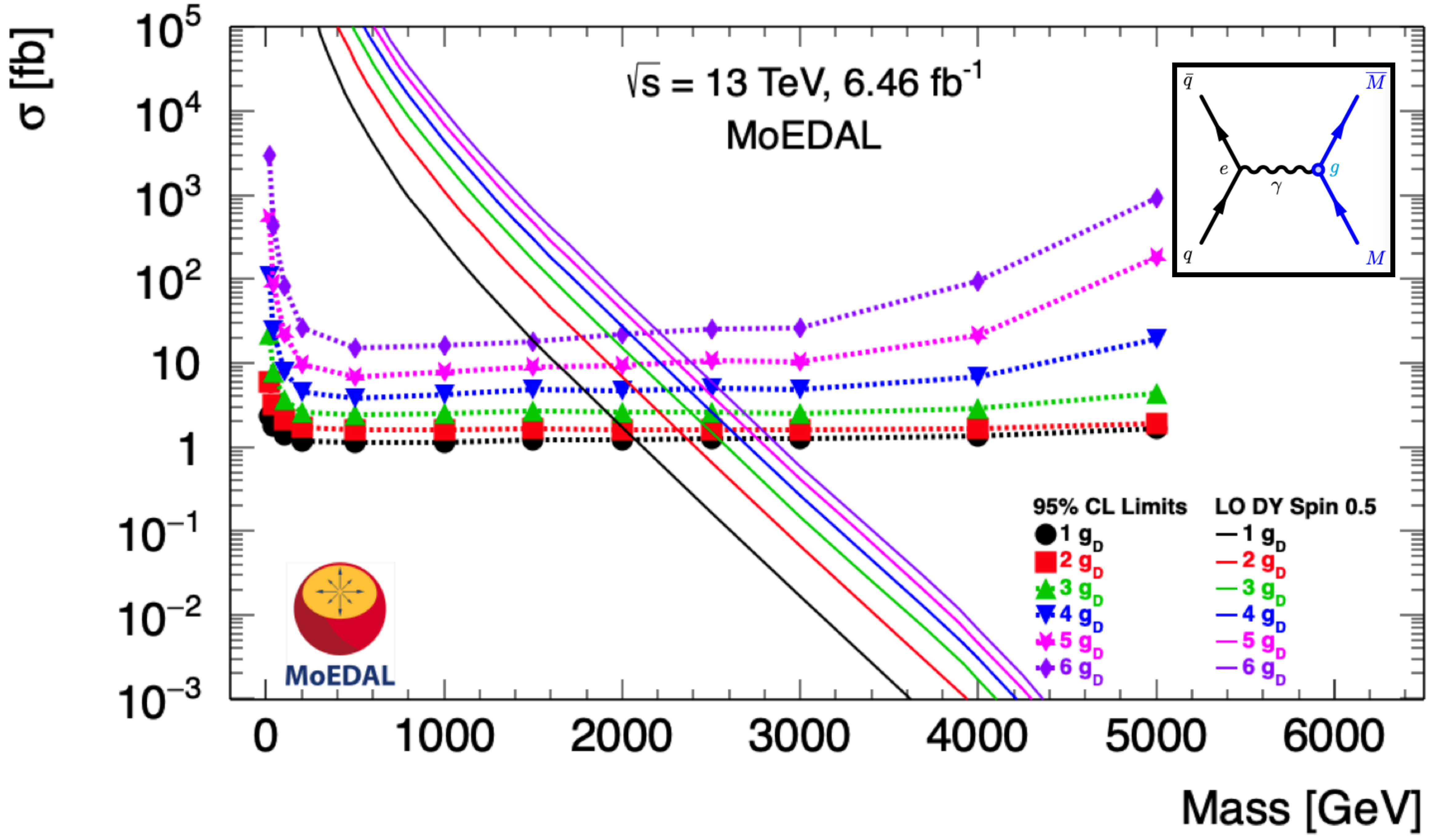
or

$$g = n g_D \Rightarrow \frac{g_D}{e} = \frac{\hbar c}{2e^2} = \frac{1}{2\alpha} \approx 68.5$$

- Dirac monopole = point-like particle (GUT monopoles etc. are composite objects)
    - Monopole **mass** and **spin** are not theoretically fixed

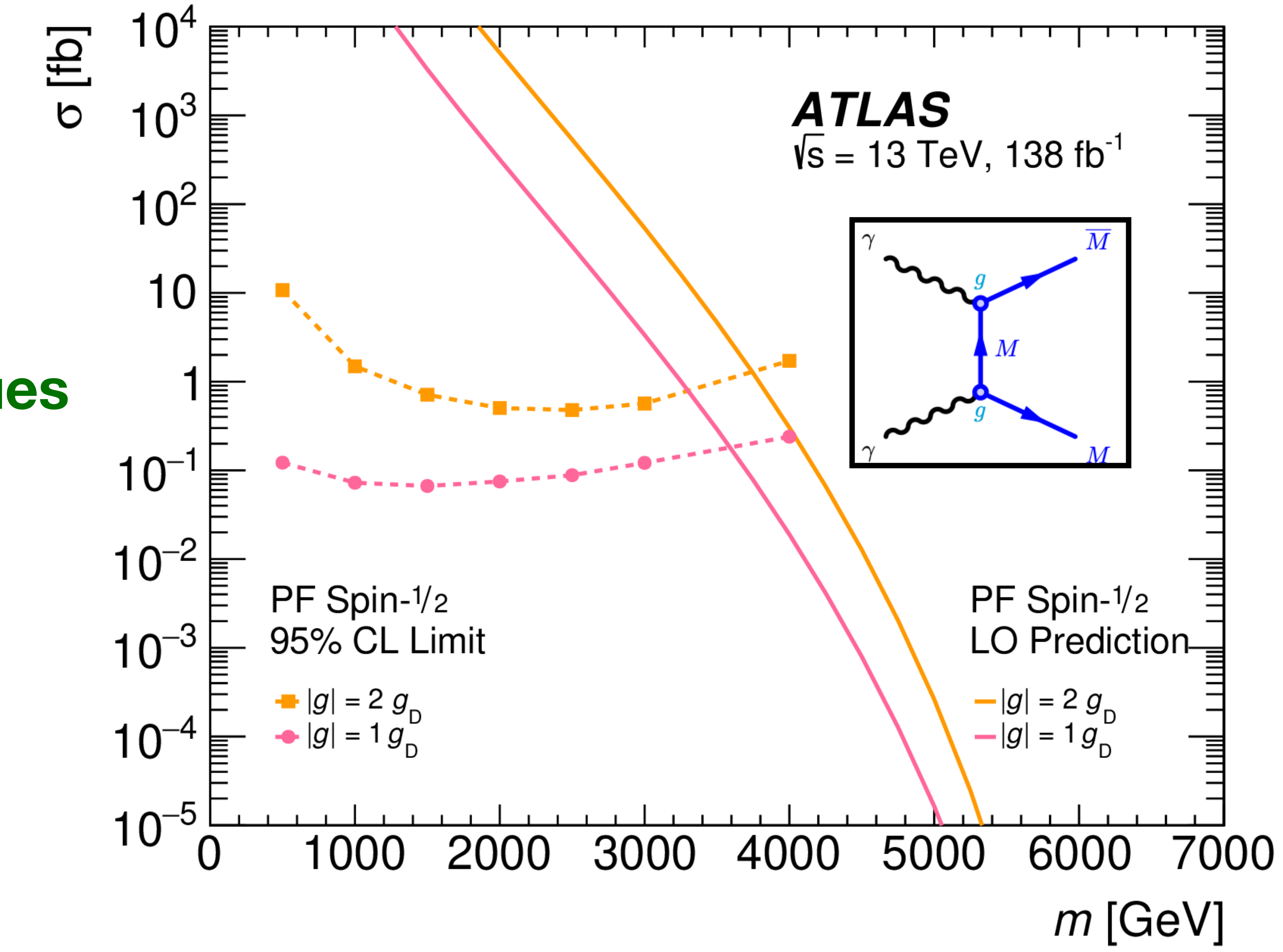
# Recent monopole searches at the LHC (pp)

MoEDAL Collaboration, PRL 134 (2025) 071802




**complementary detection techniques**

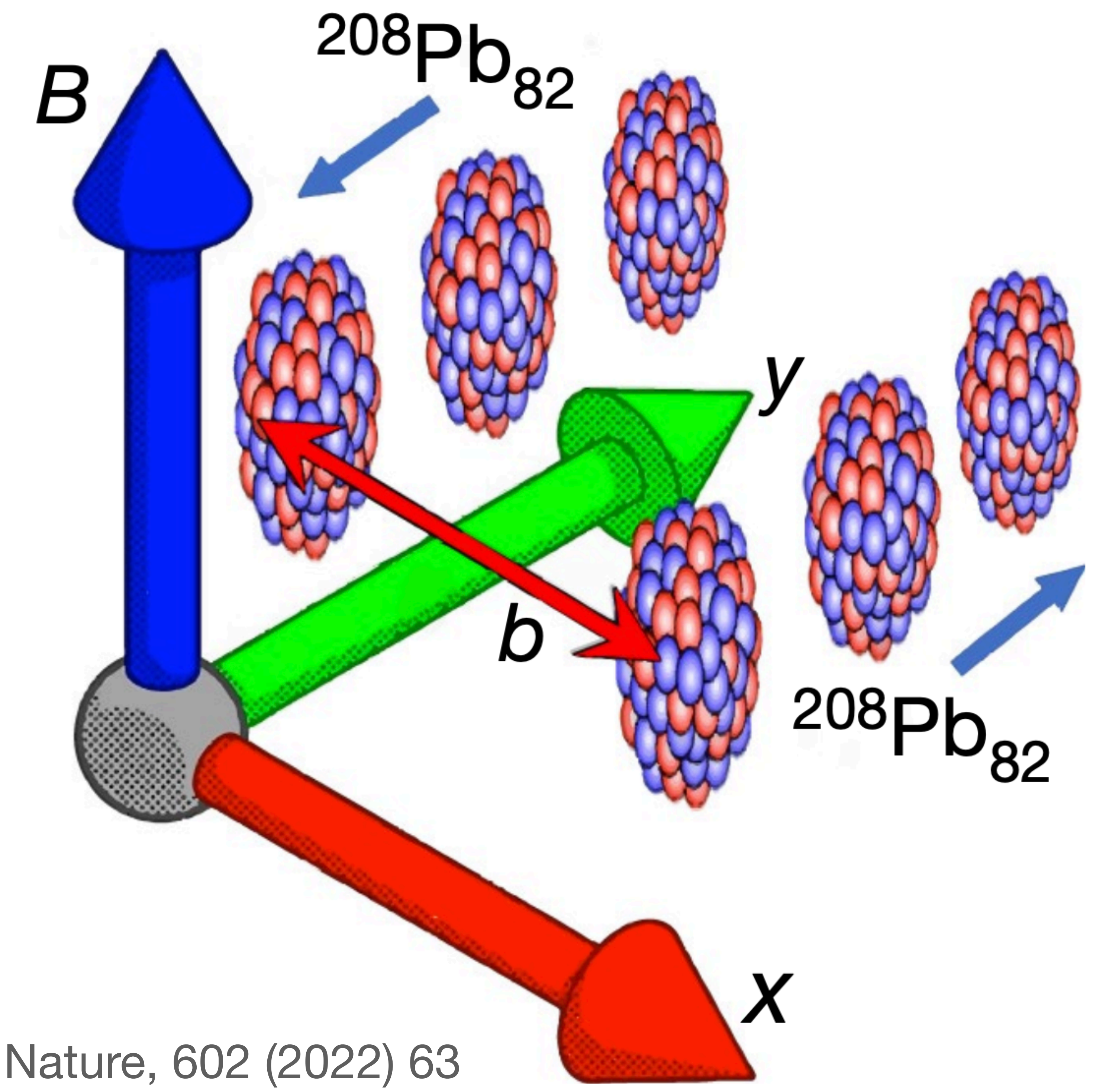
ATLAS, JHEP 11 (2023) 112




- Both searches use production modelled by Drell-Yan or γγ-fusion pair production
  - Derived from ee scattering using naive substitution $\alpha_{EM} \rightarrow \alpha_{MM}$
  - But: large γ-MM coupling: **$\alpha_{MM} \sim 1/(4\alpha_{EM}) \approx 34$** → no perturbative expansion!

# Magnetic monopoles in heavy-ion collisions

- LHC Pb+Pb collisions @ 5.02 TeV → peak **B ~ $10^{16}$ T**
  - **~$10^4$ greater than strongest known astrophysical magnetic fields (magnetars)**
  - **Occurs at distances b ~ 2R -> UPC condition!**




MoEDAL, Nature, 602 (2022) 63

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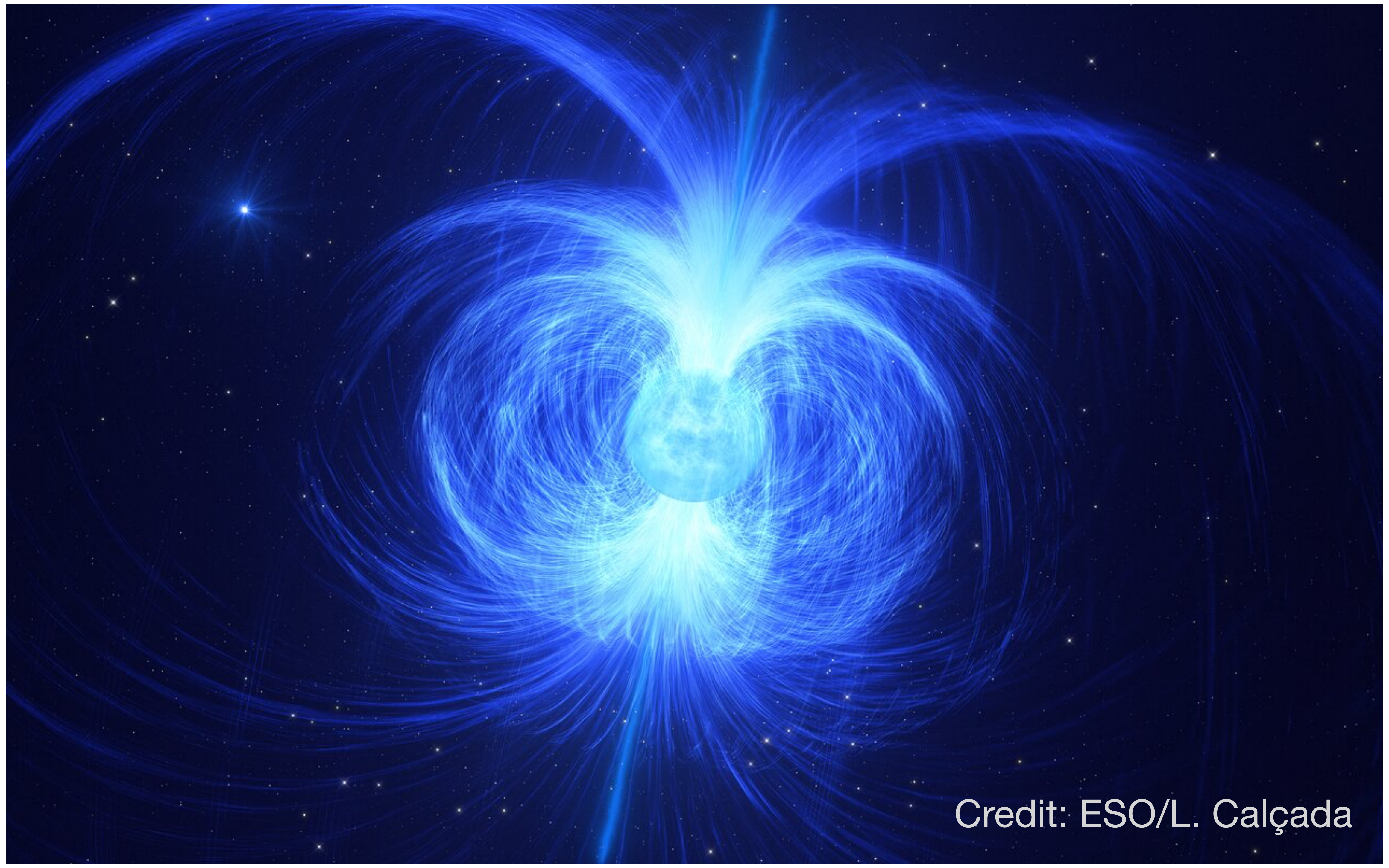
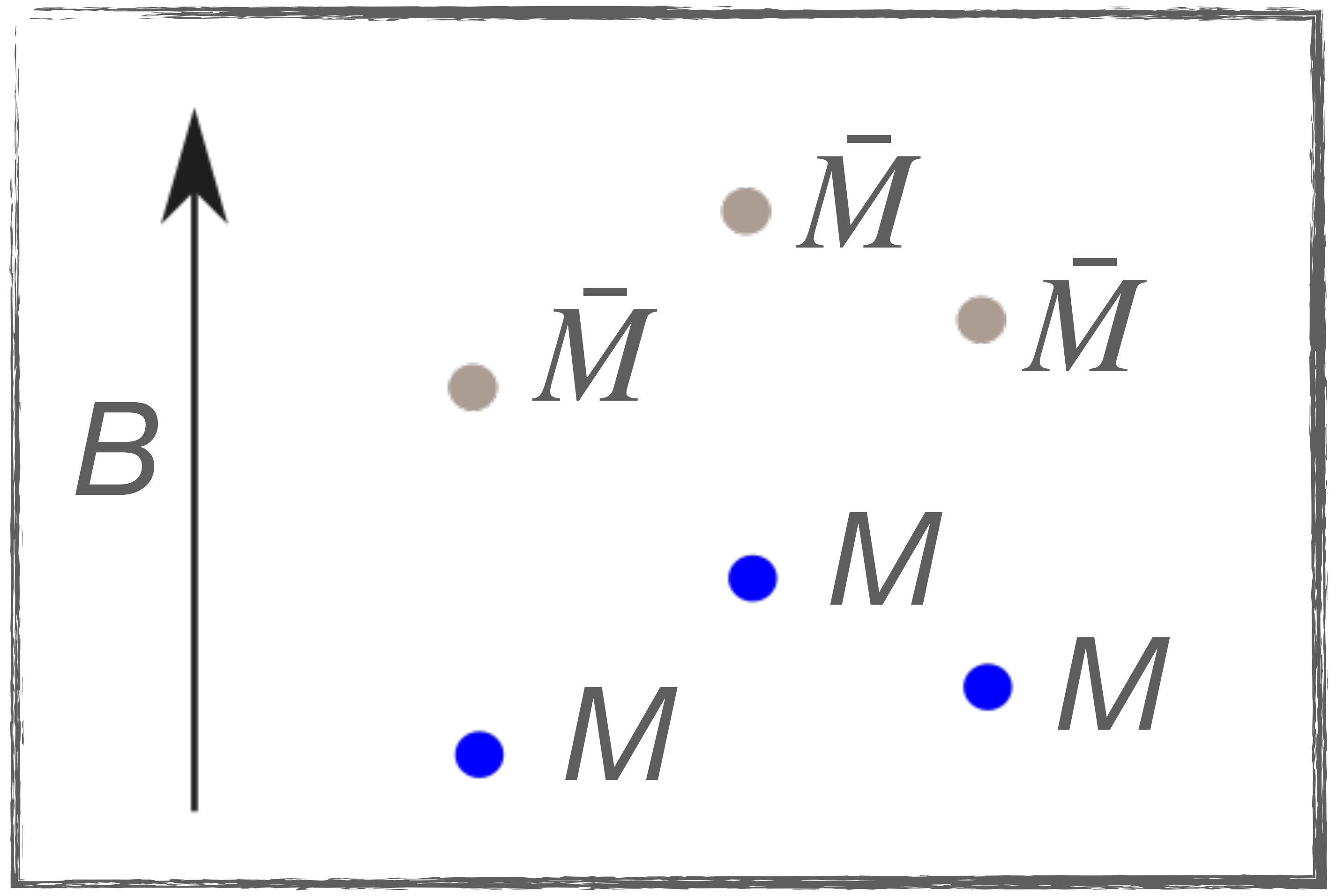


# Magnetic monopoles in heavy-ion collisions

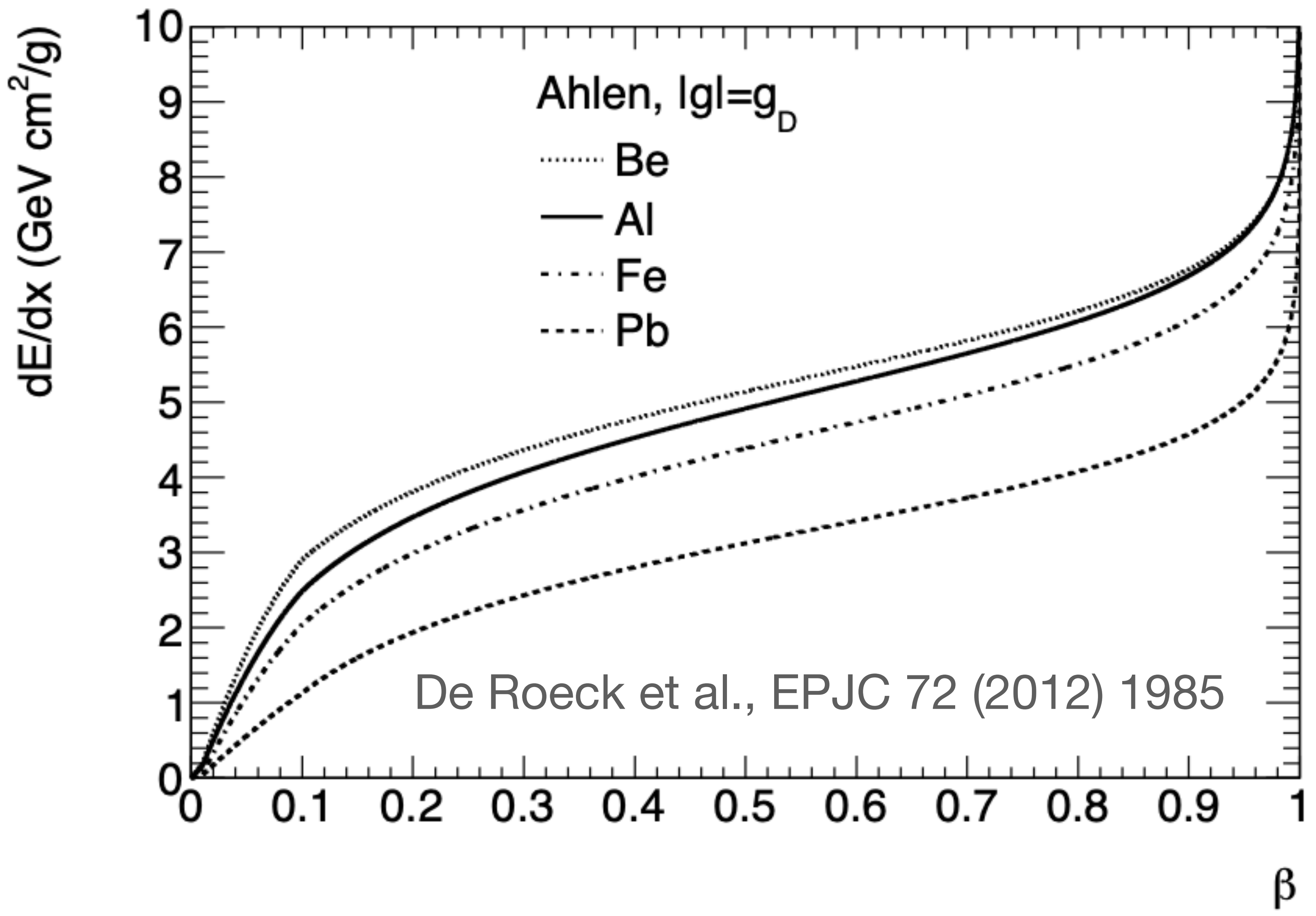
- Production via the **Schwinger mechanism** in strong magnetic fields [Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021)]
    - Analogy to e+e- pairs production




- 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
      [see Drukier & Nussinov, Phys. Rev. Lett. 49 (1982) 102]

# Magnetic monopole interactions in the detector

- Energy loss
  - Ionization dominates
  - For g=1$g_D$ and β~1: **$(dE/dx)_{MM}$ ≈ 5000 $(dE/dx)_{MIP}$**
  - Highly ionising particle (HIP)
    → lots of **δ-rays** near trajectory
  - Slow monopoles → less ionisation

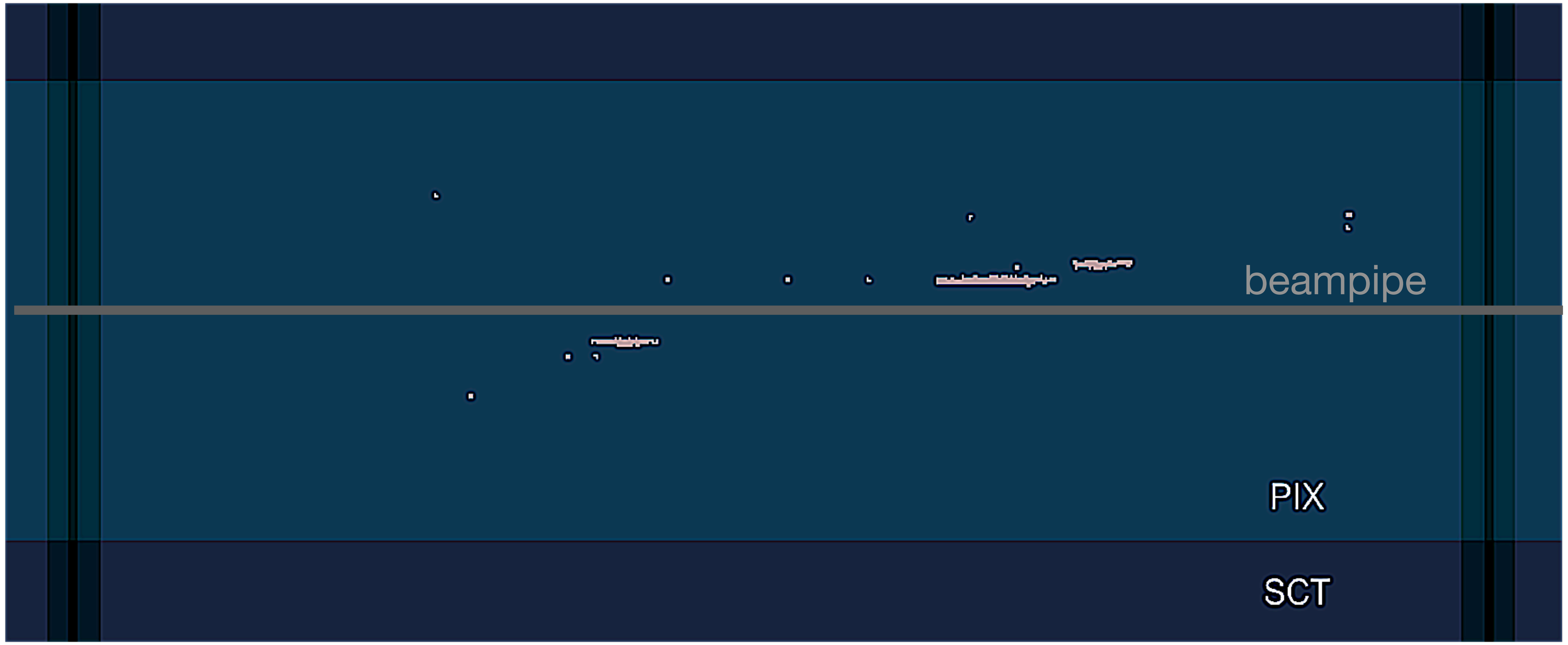



- Equations of motion
  - Monopoles accelerated by magnetic field
  - Trajectory **bends in r-z** plane (**straight in r-ϕ**)

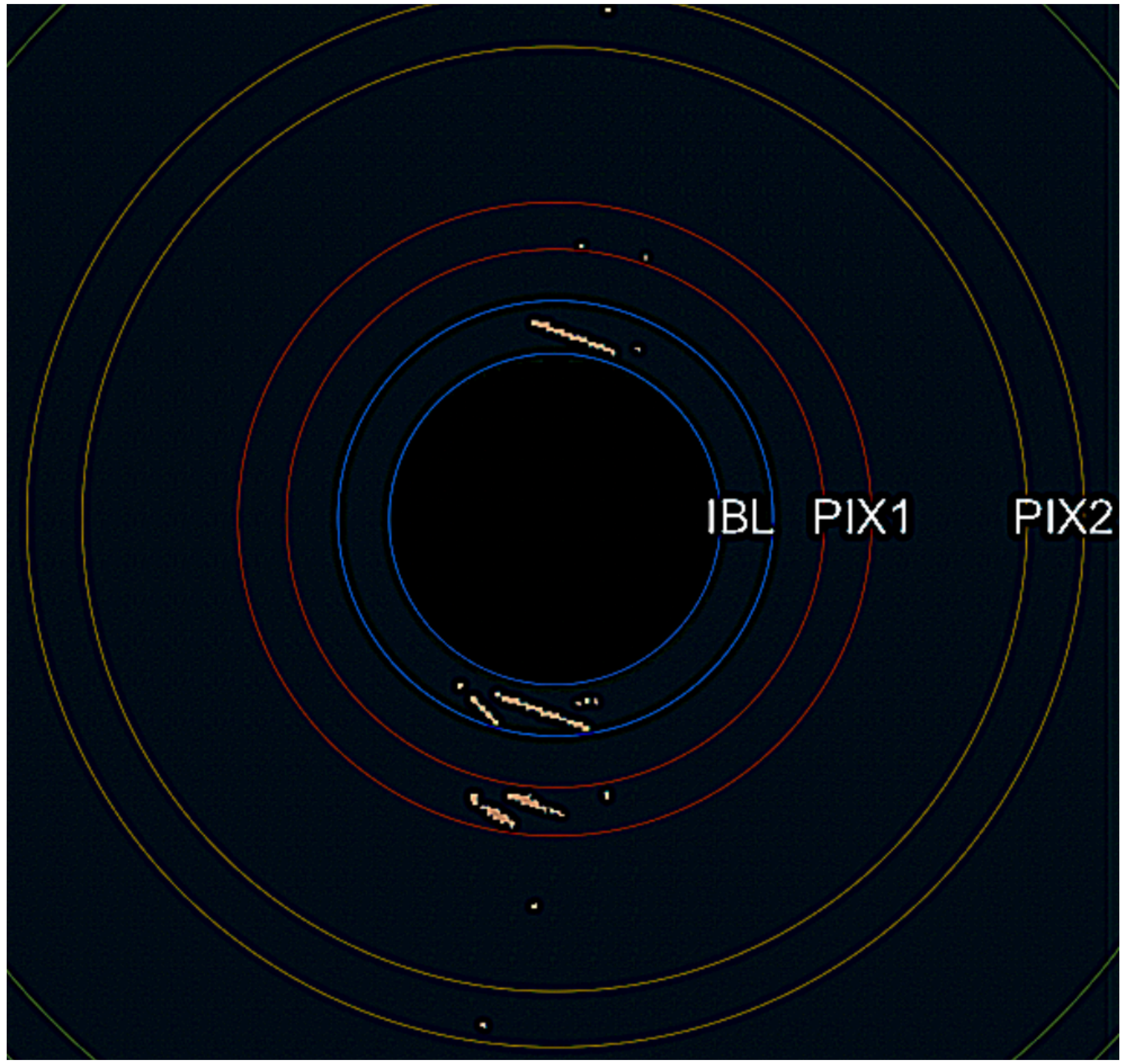
# Low-energy monopole interactions in ATLAS

- Simulated pairs of monopoles in UPC (each w/ m=20 GeV)
  - Monopoles w/ $\mathbf{p_T}$ **= 20 GeV** shown below

Longitudinal detector view



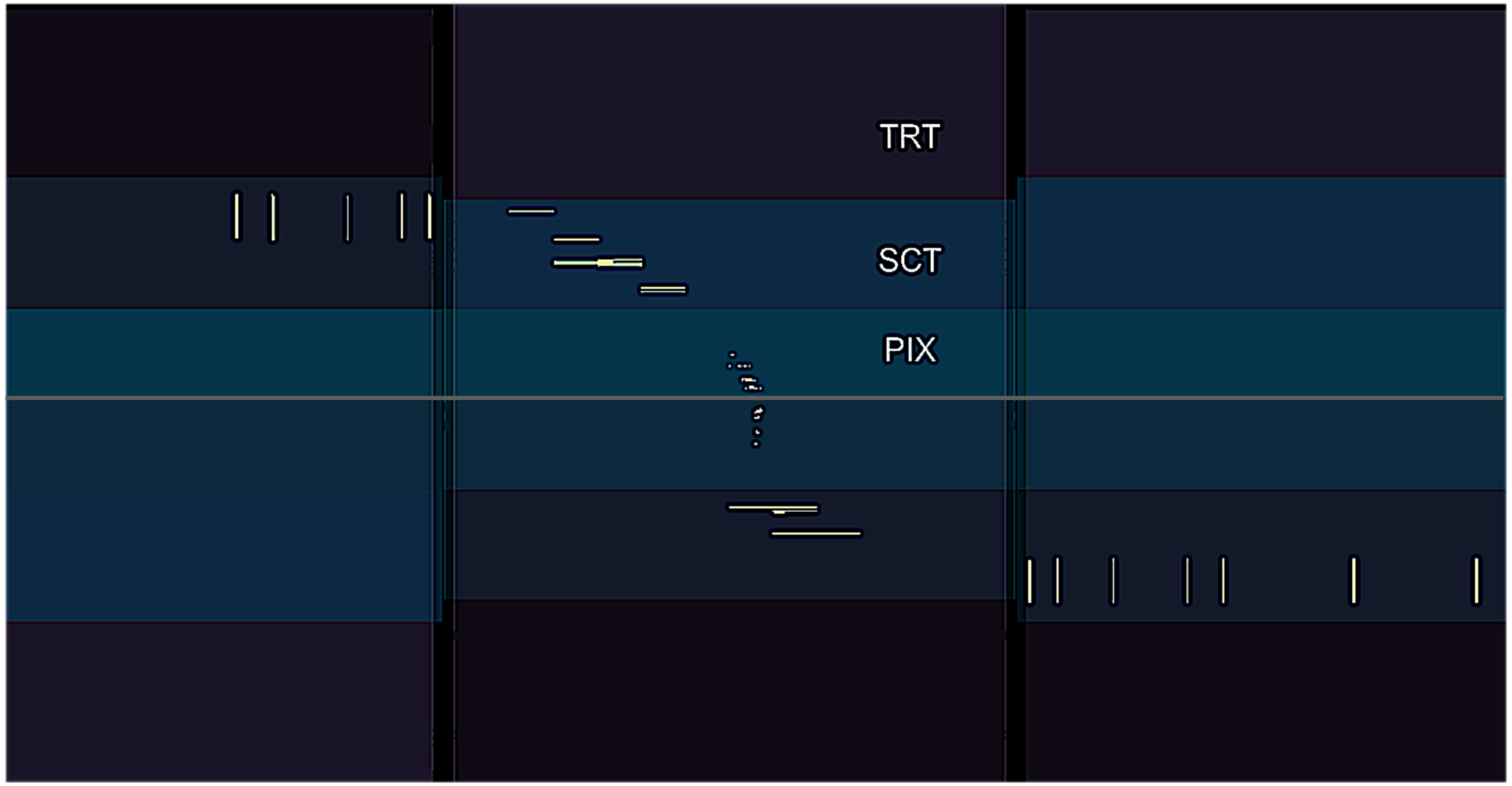

Transverse view (Pixel detector only)



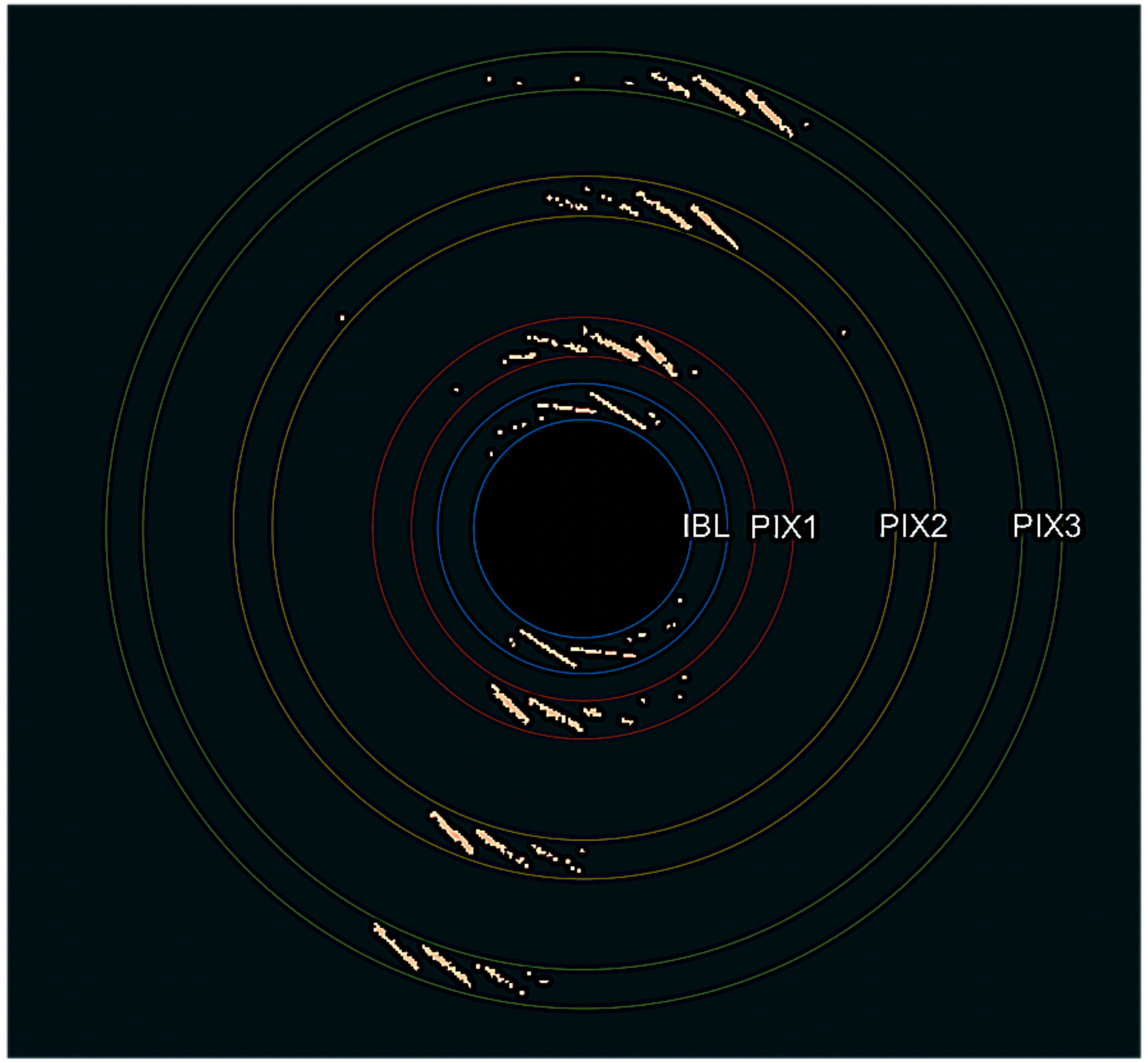
# Low-energy monopole interactions in ATLAS

- Simulated pairs of monopoles in UPC (each w/ m=20 GeV)
  - Monopoles w/ **$p_T$ = 50 GeV** shown below

Longitudinal detector view




Transverse view (Pixel detector only)

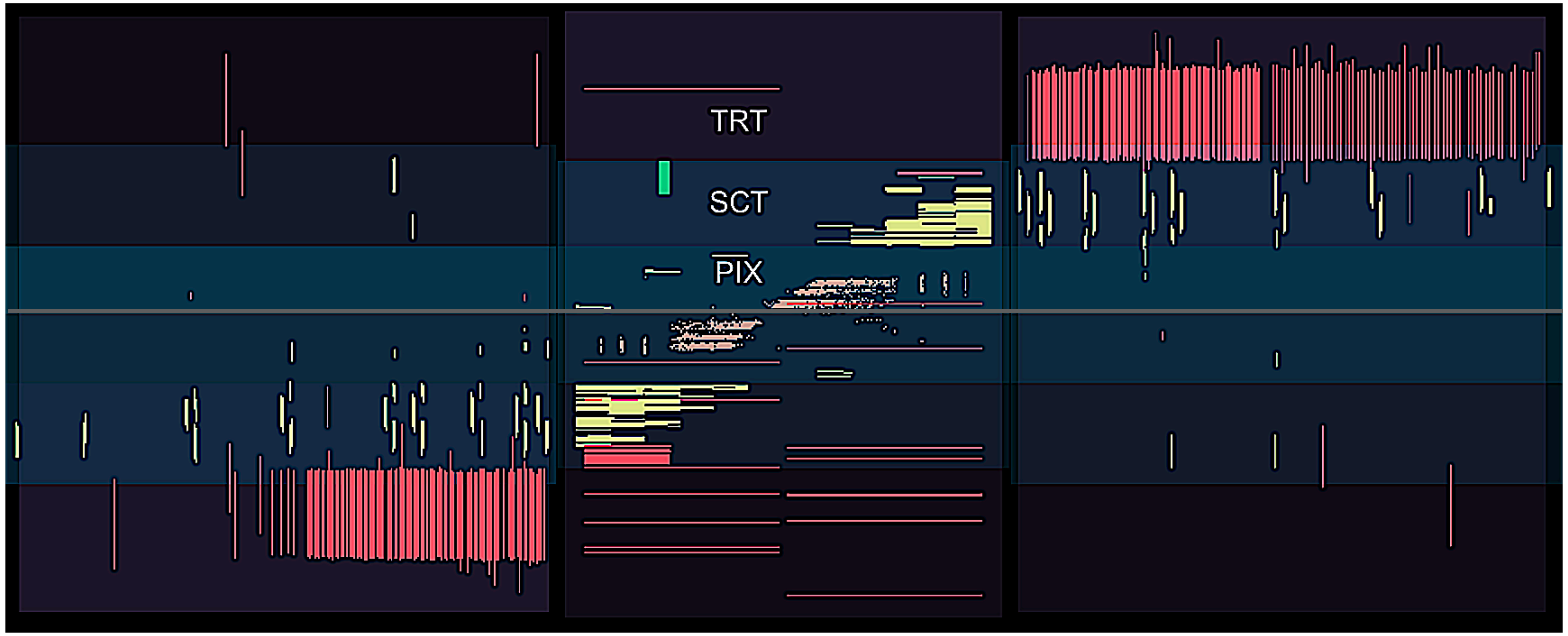


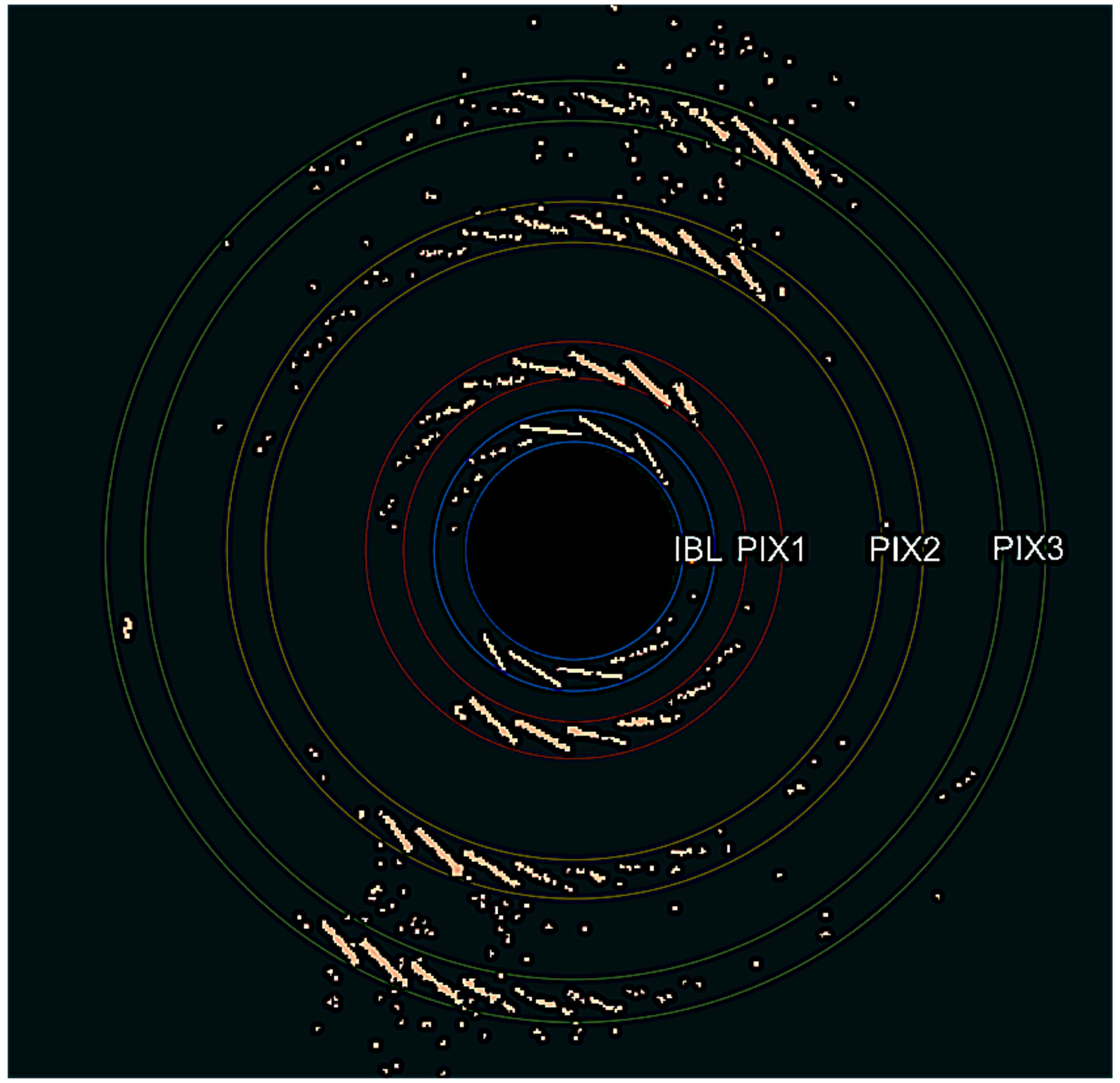
# Low-energy monopole interactions in ATLAS

- Simulated pairs of monopoles in UPC (each w/ m=20 GeV)
  - Monopoles w/ $\mathbf{p_T = 280}$ **GeV** shown below (unphysical scenario for Pb+Pb EM fields)

Transverse view (Pixel detector only)

Longitudinal detector view

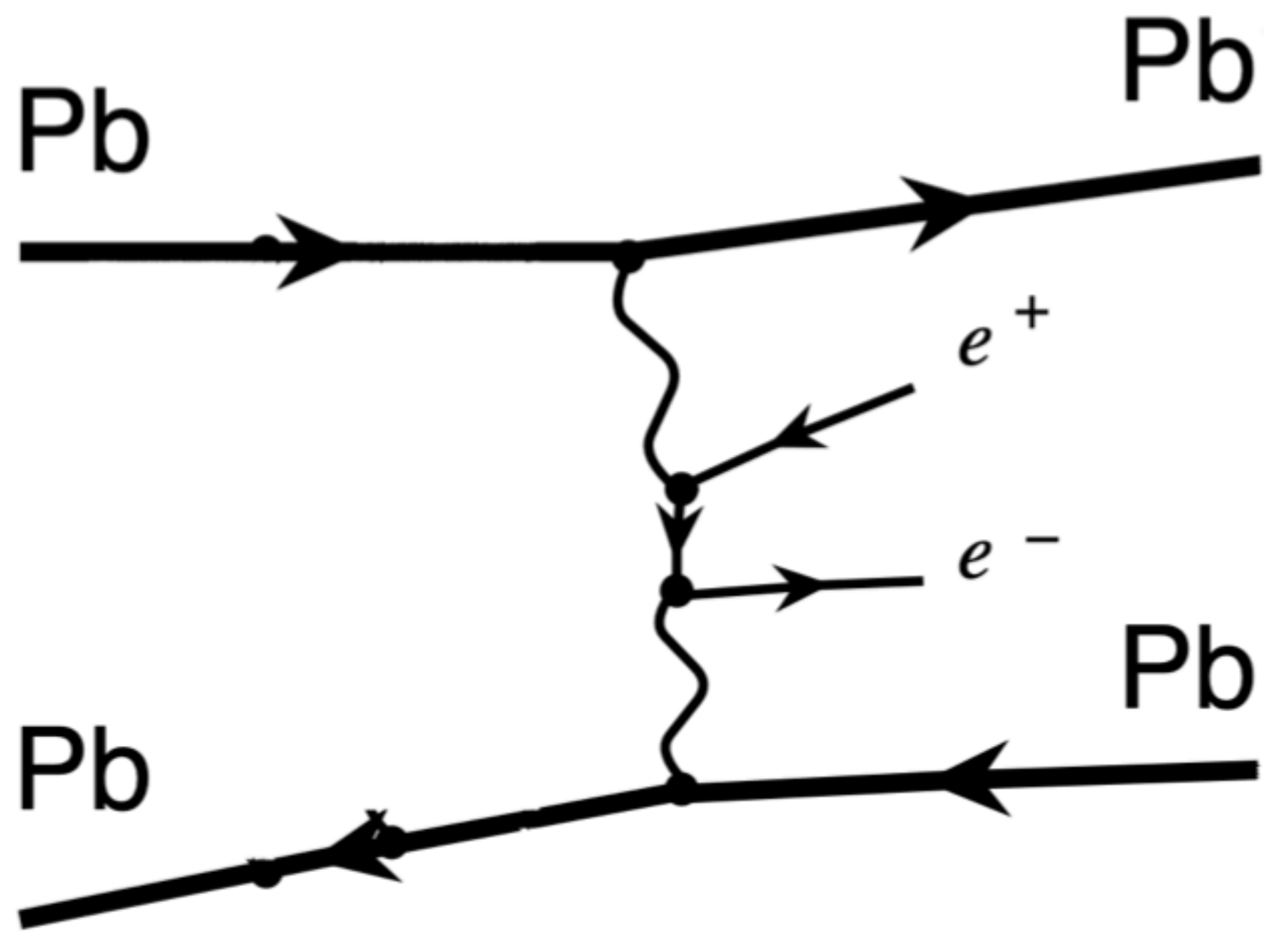


# Magnetic monopoles in UPC: how to trigger?

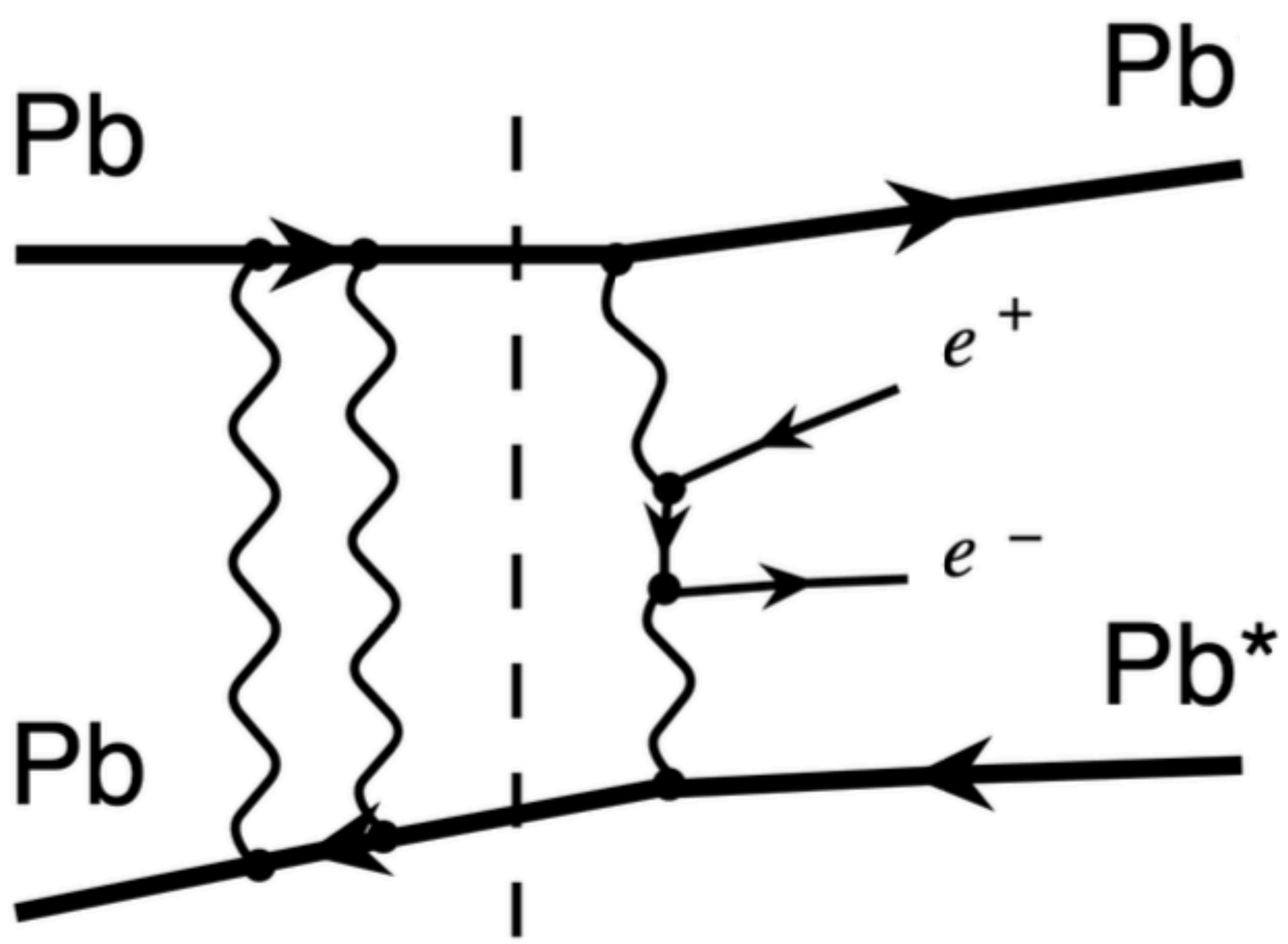
primary signal category for this search*

## 0n0n



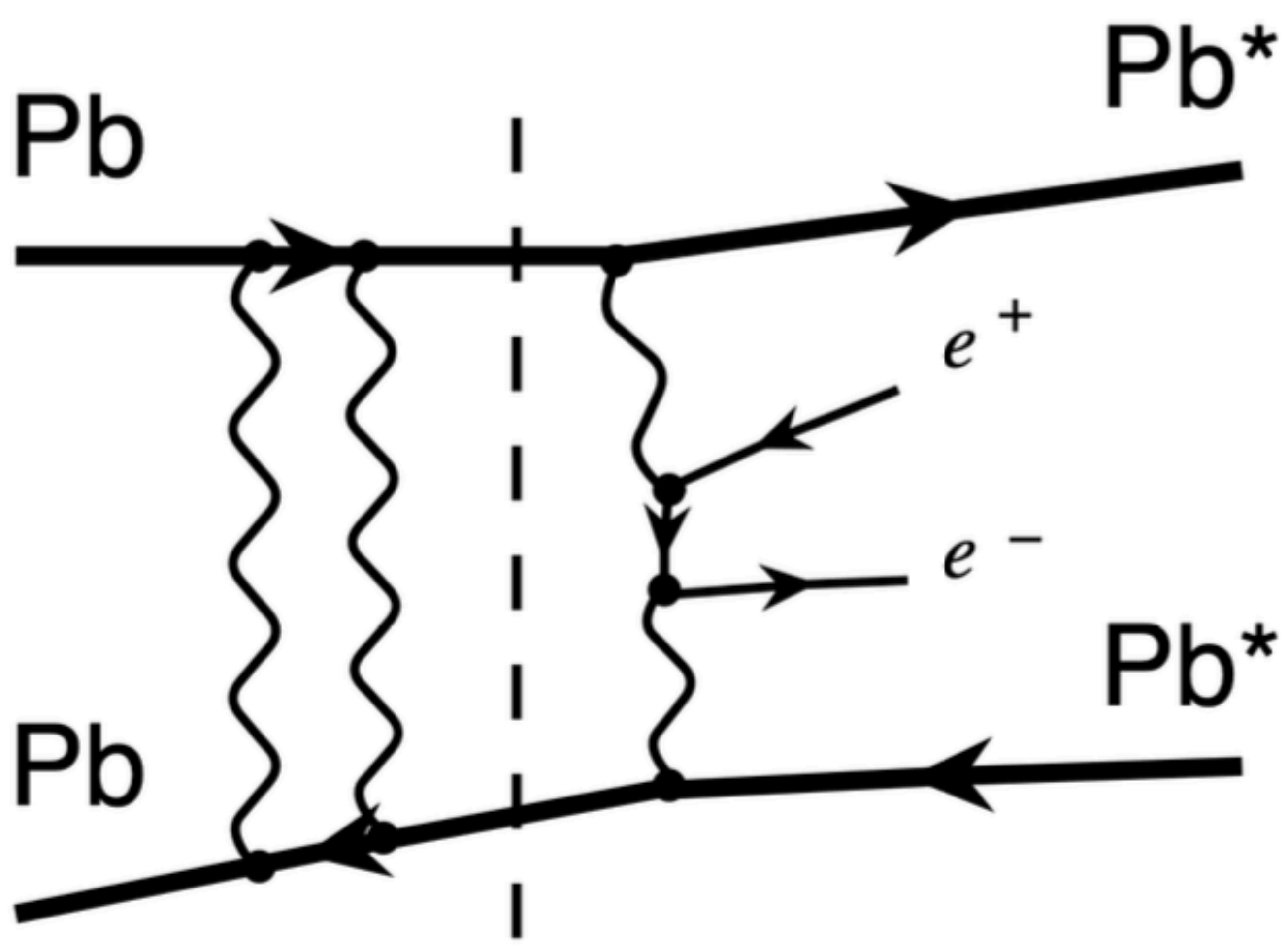

(~60% events @ $m_{pair}$=30 GeV)

## 0nXn




(~30% events @ $m_{pair}$=30 GeV)

## XnXn




(~10%** events @ $m_{pair}$=30 GeV)

*mainly due to trigger limitations (empty events @ L1)

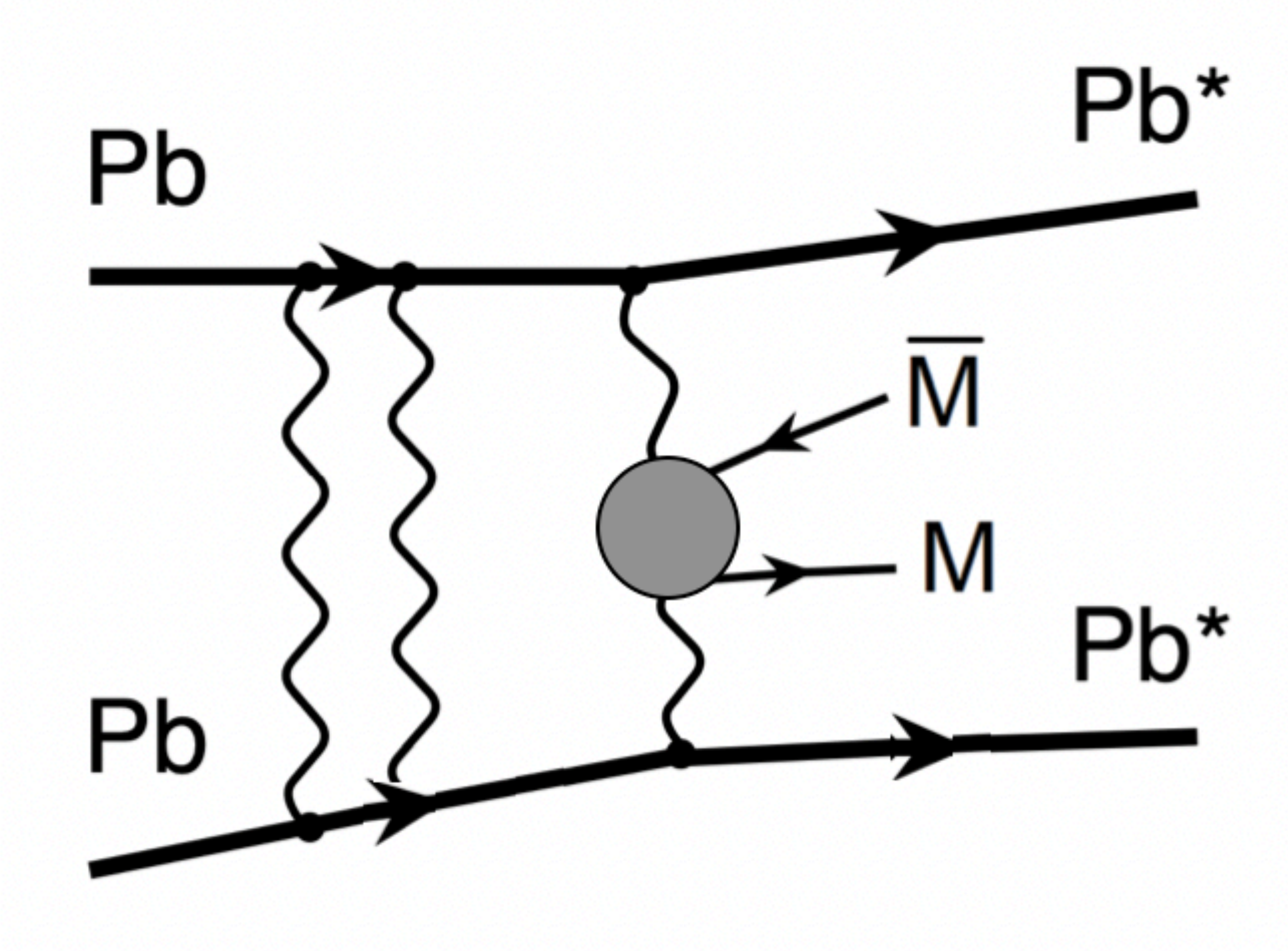
**fraction of XnXn events increases with central system mass $m_X$

# Magnetic monopoles in UPC: Data set and trigger

- Use 0.262/nb of 2023 Pb+Pb data at 5.36 TeV

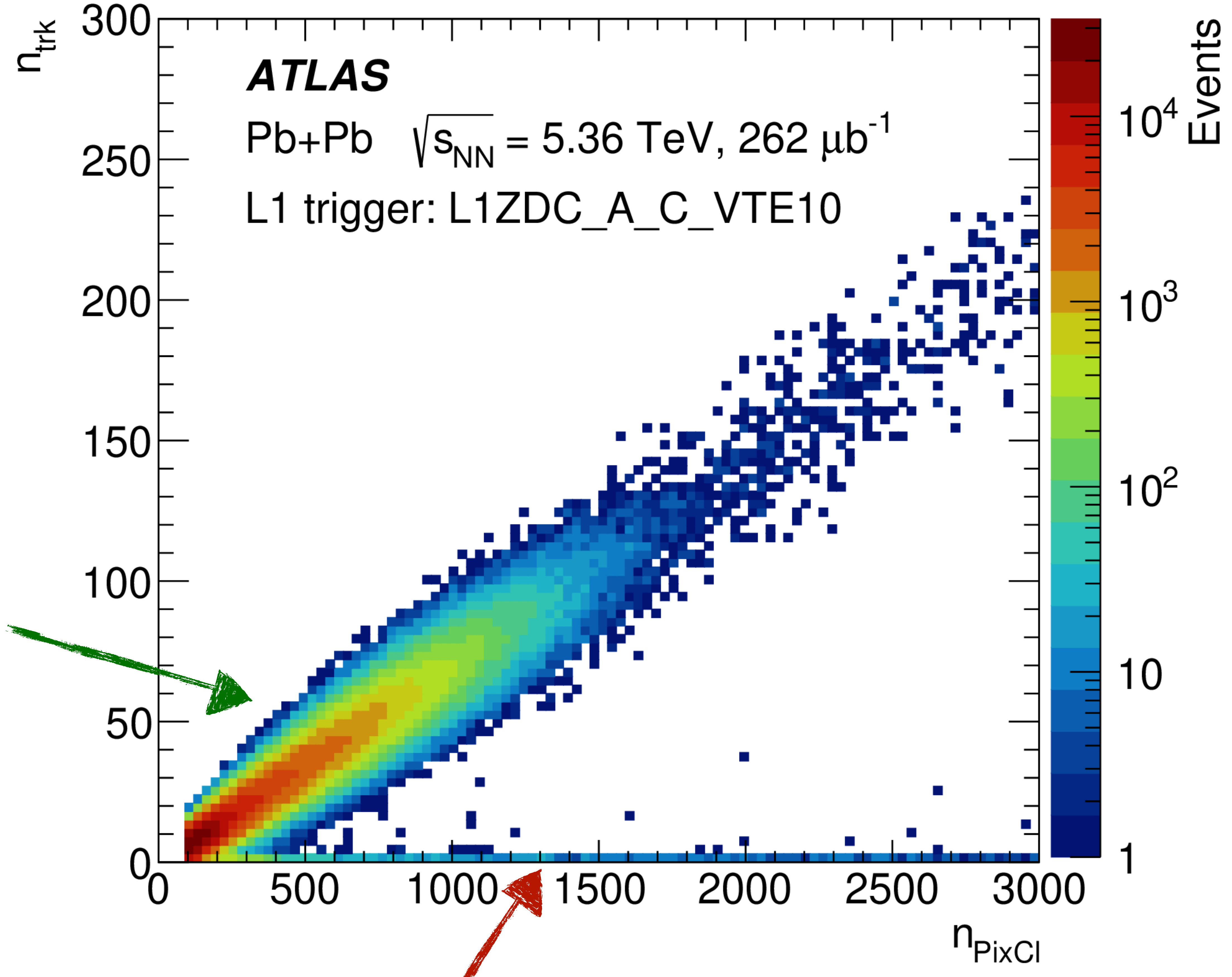
- **Signal trigger**
  - **L1**: coincidence of **ZDC A+C** signals
  - **HLT**: **> 100 Pixel clusters** w/o any specific tracking selection

- **Supporting trigger** (for background estimation):
  - ZDC signal exactly on one side (ZDC_XOR)



# Magnetic monopoles in UPC: Event properties

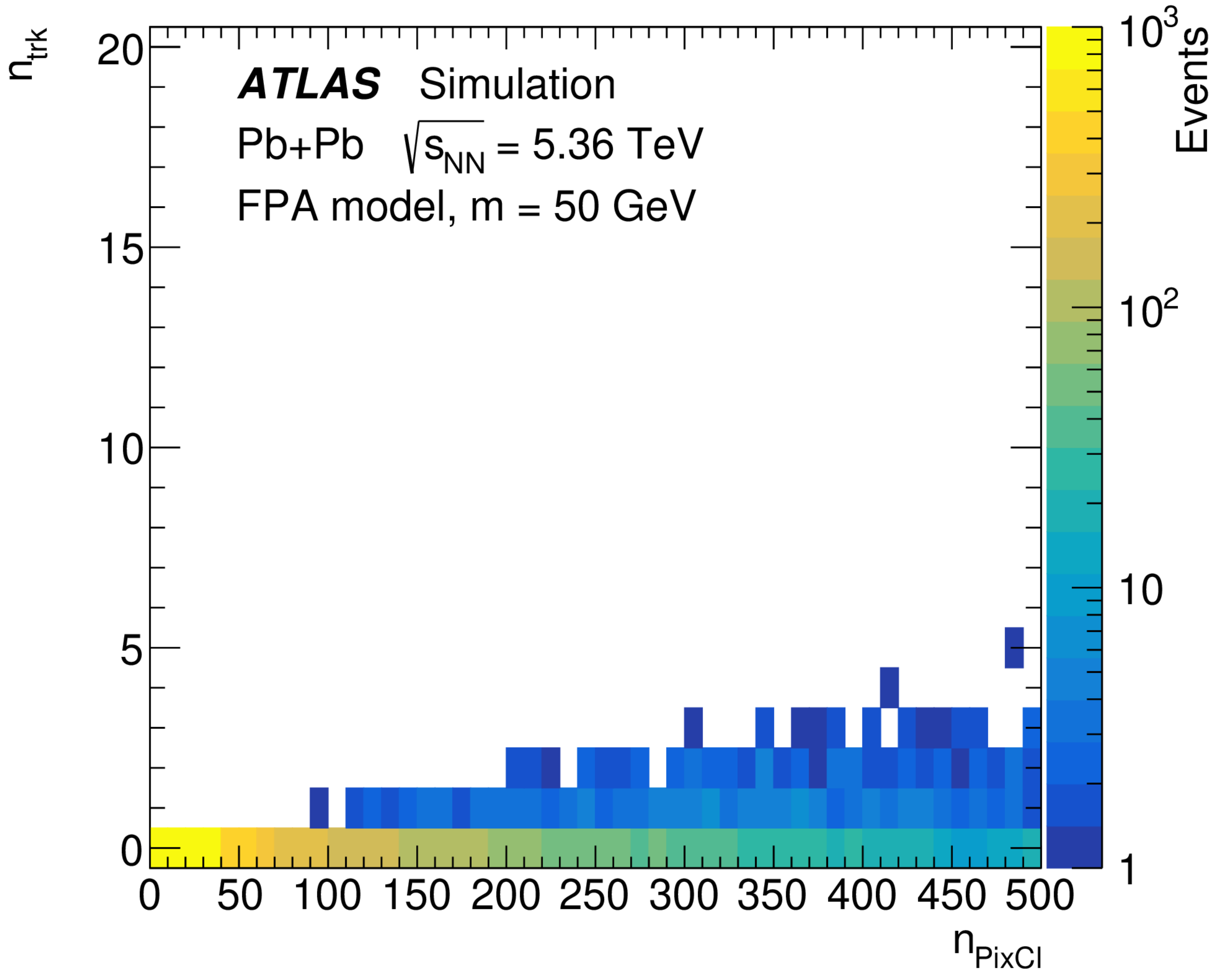
**Events in data after trigger selection**




**Collision events**

**Beam-induced background (BIB) - dominant bkg in this search**

**Simulated signal events**



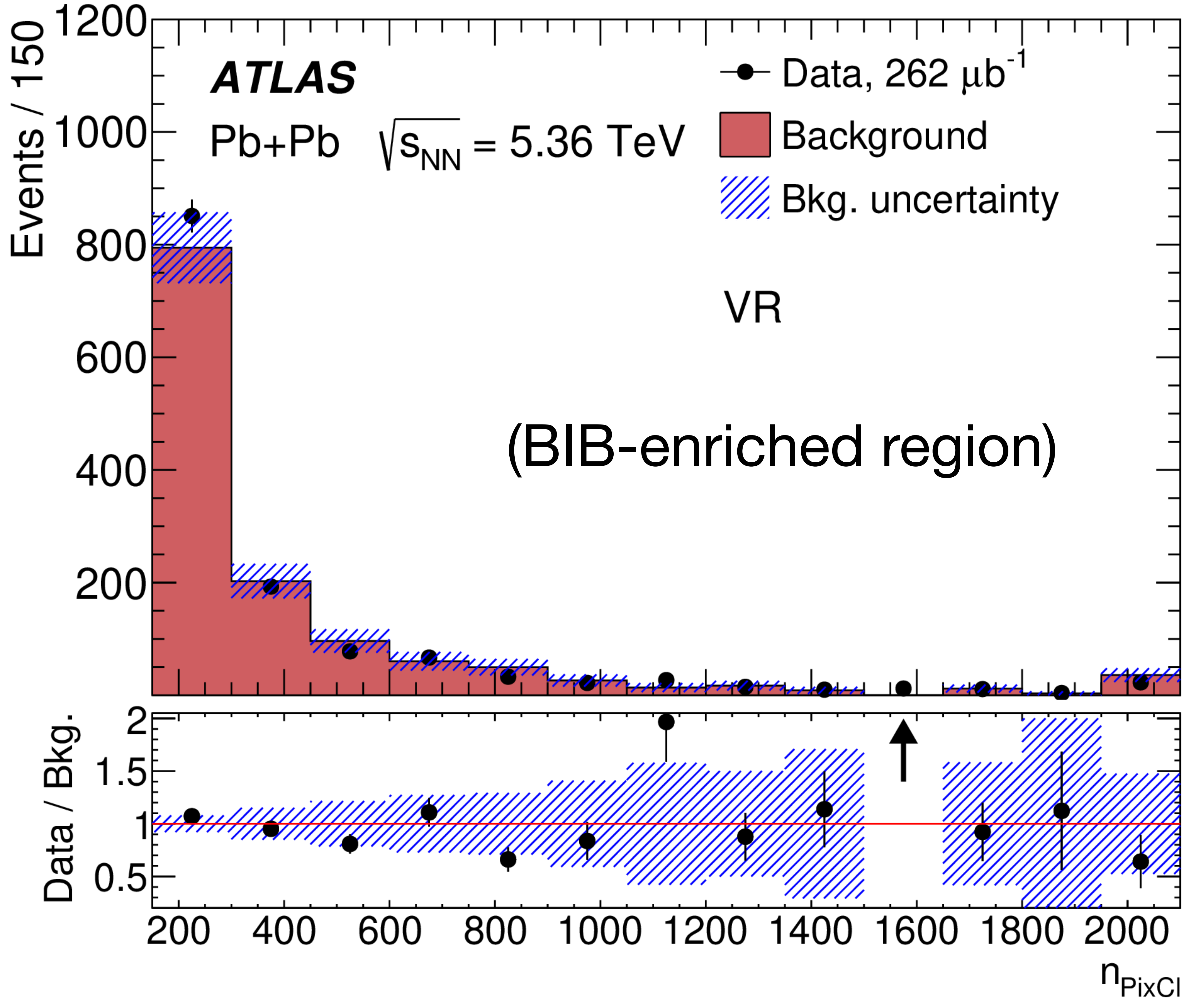
# Magnetic monopoles in UPC: Event selection

- $N_{tracks} \leq 1$
- $N_{topoclusters} \leq 1$

⇒ to remove **collision bkg**

- Fraction of Pixel clusters from a single module, $f_{leading\text{-}module} < 0.9$
  → to suppress events from **noisy modules**

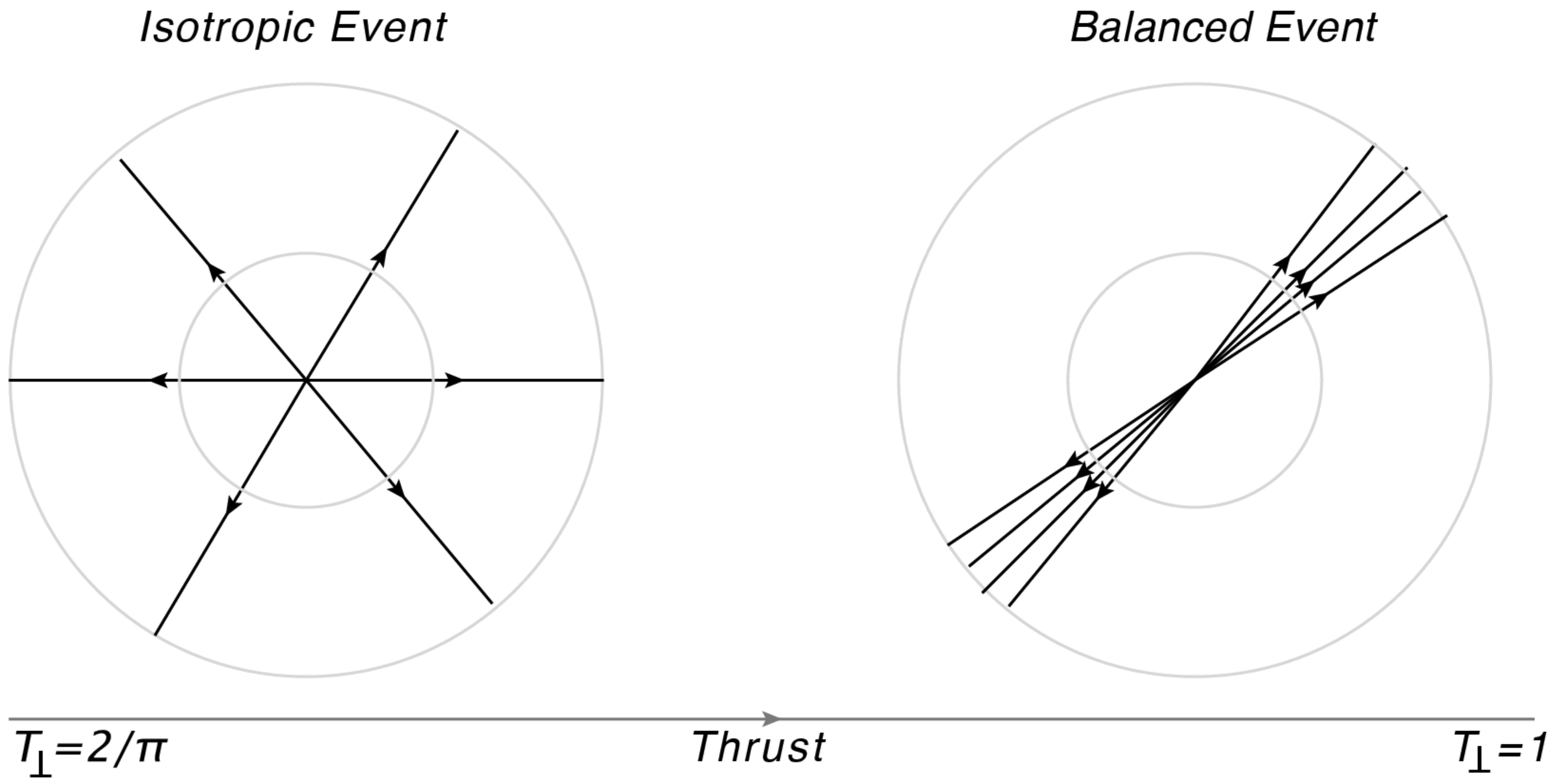
- $N_{PixelClusters} > 150$, including $N_{IBLclusters} > 50$
  → suppress beam-induced backgrounds **(BIB)**

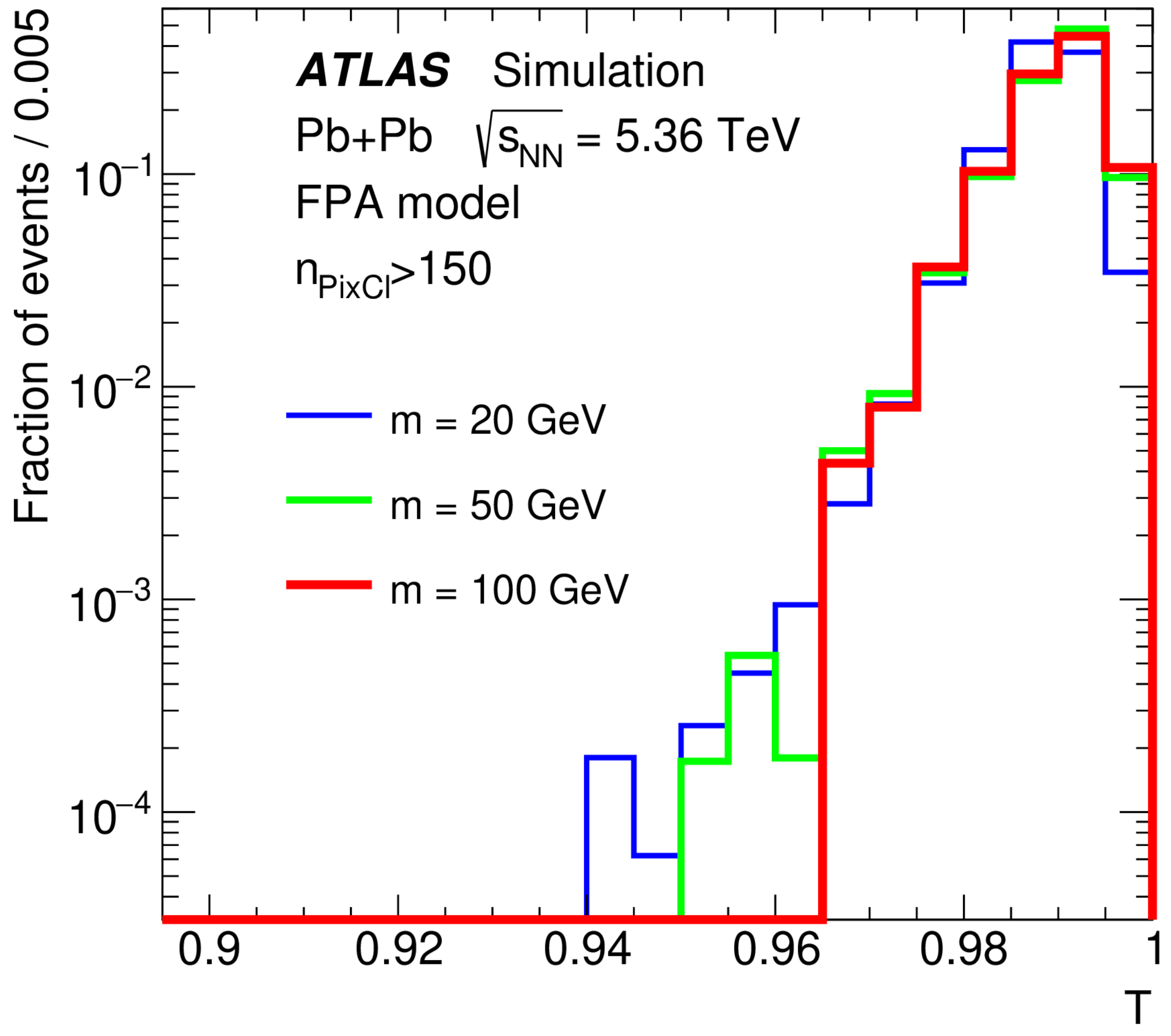


# Magnetic monopoles in UPC: Event selection

- Final background-discriminating variable based on azimuthal correlations between Pixel clusters
  - Variable inspired by *transverse thrust* used:

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




- Require **T>0.95** (SR definition)

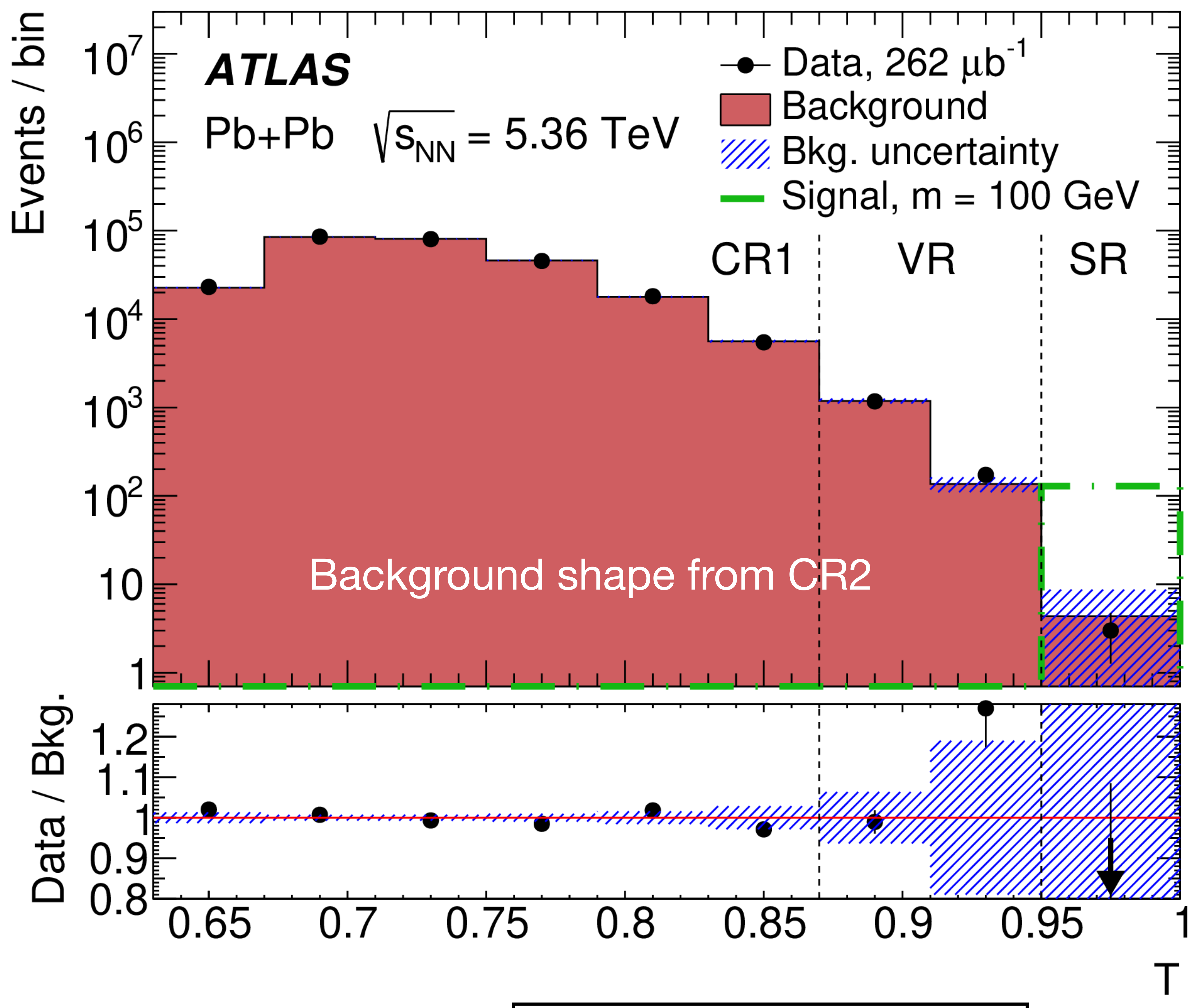
- Signal efficiency varies from **4%** (m=20 GeV) to **0.2%** (m=150 GeV)

# Magnetic monopoles in UPC: Background estimation

- Define two CRs:
  - **CR1** for events having **T<0.87**
  - **CR2** from ZDC_XOR-triggered events with extra selections to purify BIB sample
  - CR2 sample is enriched with BIB events and so:

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

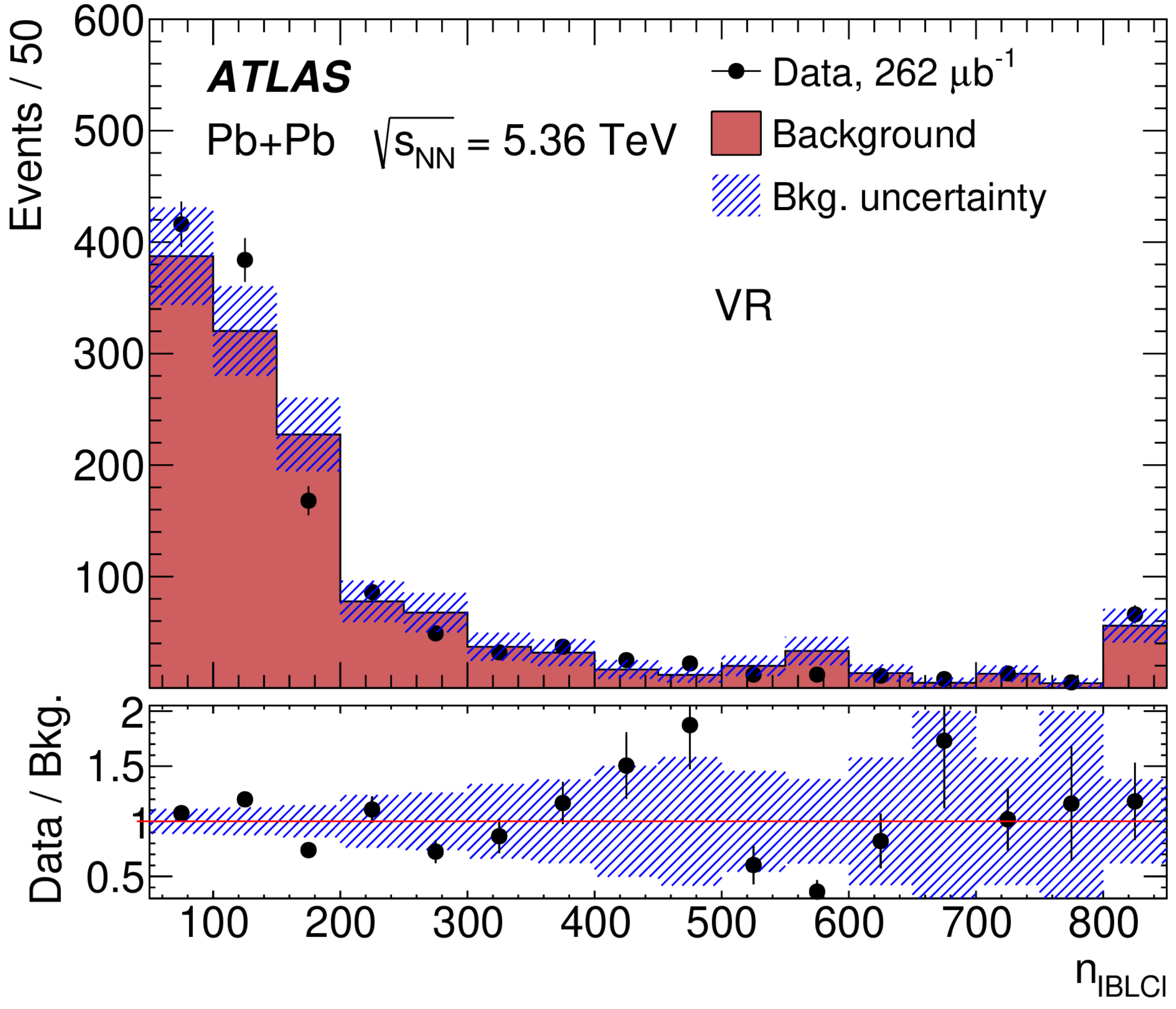
- SR (T>0.95): **4 ± 4** bkg. events expected

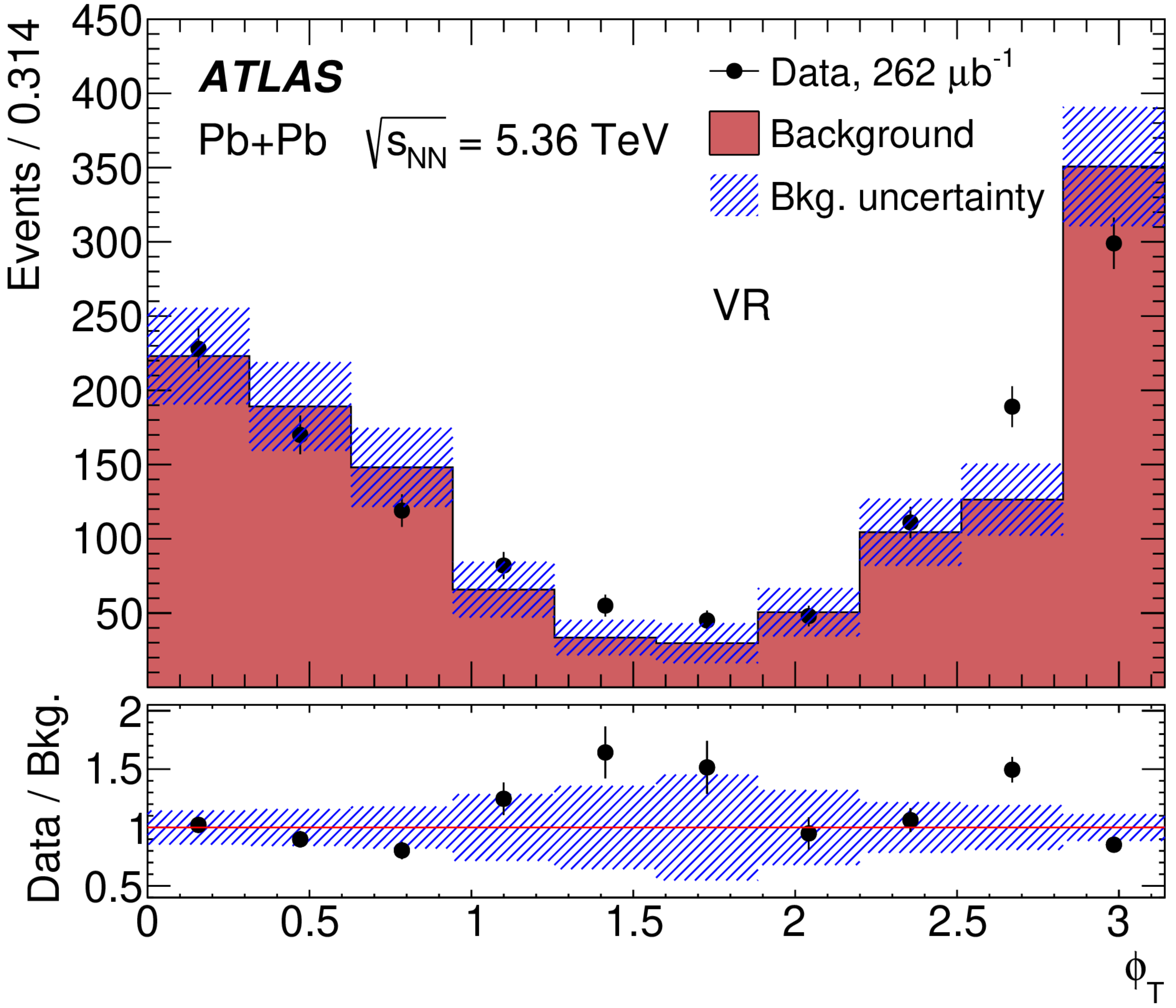



$$T = 1/n_{\text{PixCl}} \sum_{i=1}^{n_{\text{PixCl}}} |\hat{r}_i \cdot \hat{n}|$$

# Magnetic monopoles in UPC: Validation region (VR)

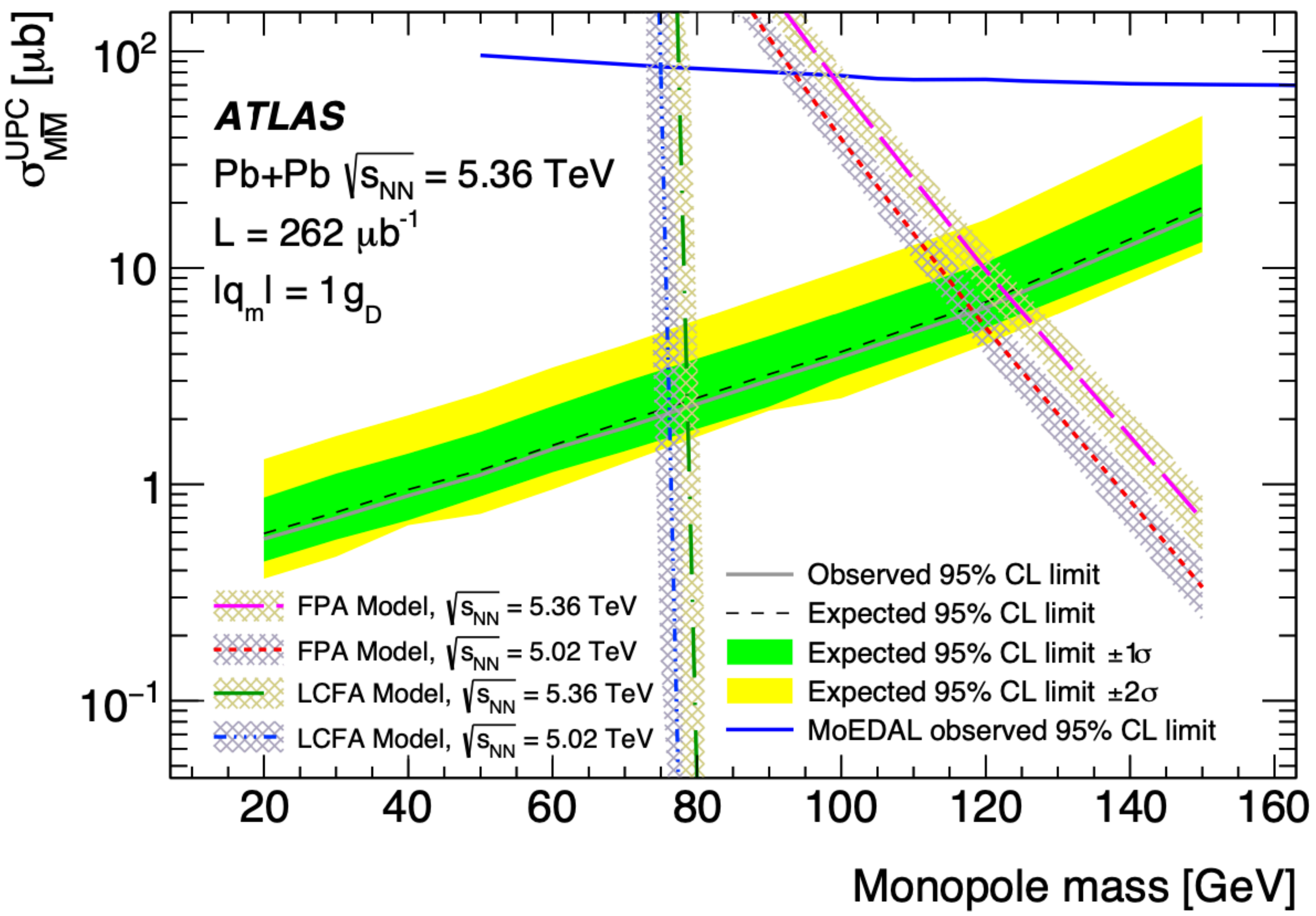
- Formed using events close to the SR (0.87<T<0.95)



# Magnetic monopoles in UPC: Results

- **3** events in SR, consistent with background estimate (4 ± 4)
- Cross-section upper limits for 20 < m < 150 GeV ($g=1g_D$)
- Better sensitivity compared to MoEDAL
- Depending on the model, excluded magnetic monopoles with mass < 120 GeV (FPA model) or < 80 GeV (LCFA model)



# Summary

- Ultraperipheral collisions (UPC): excellent tool to probe QED & QCD theories under their extremes

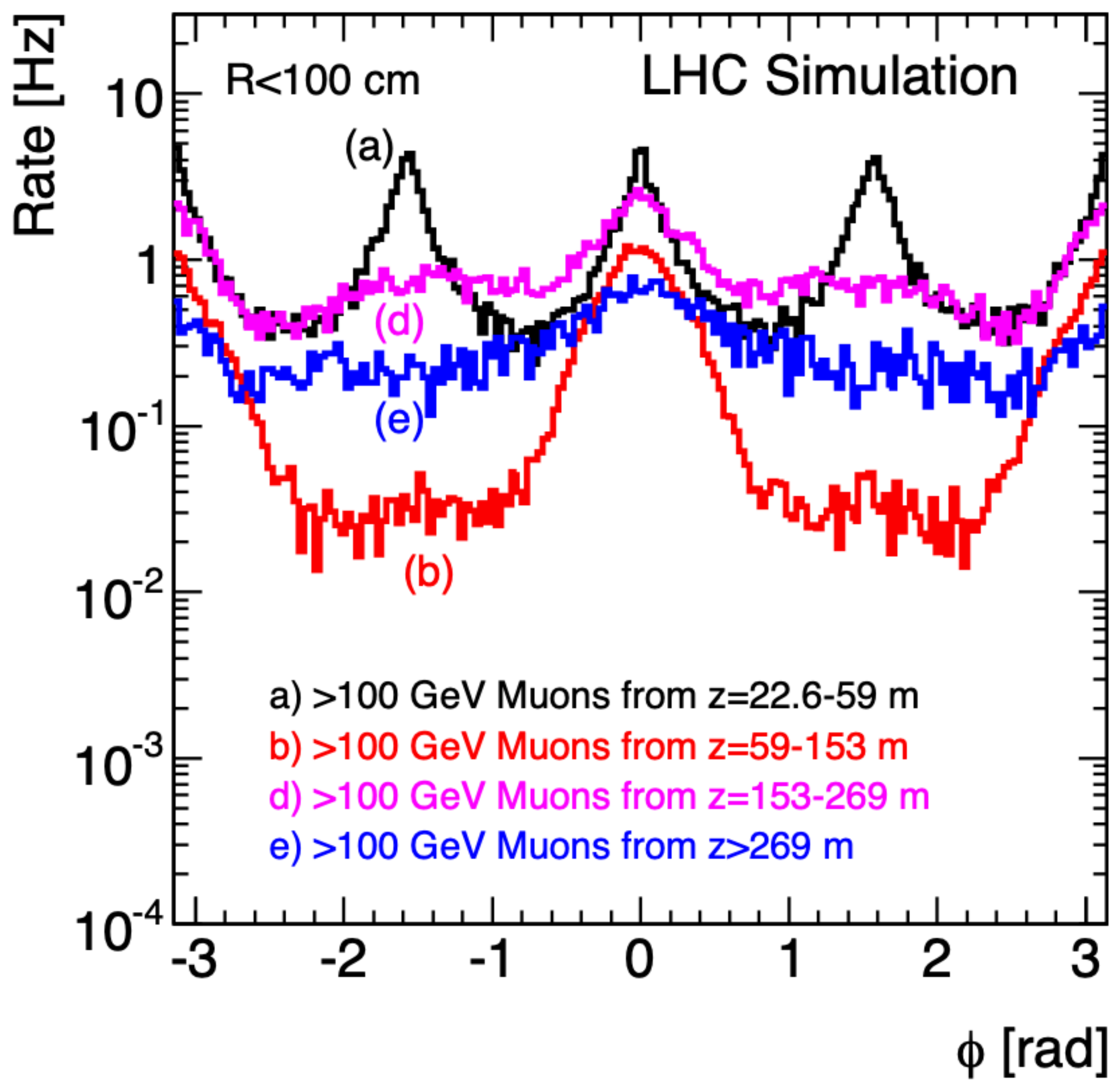
- Coherent J/ψ production in UPC measured for the first time in ATLAS
  - Large event sample collected in Run 3 thanks to track-sensitive trigger at L1 (TRT FastOR)
  - Differential cross sections measured in the range $|y| < 2.5$
  - ALICE vs ATLAS tension at mid-rapidity observed -> impact of coincident UPC processes on exclusivity requirements?

- Introducing new approach in detecting highly-ionising particles (HIPs) at the LHC
  - Best cross-section upper limits for UPC-produced monopoles for masses **20-150 GeV** ($g = 1g_D$)
  - This new approach can be extended for other HIP searches in HI data

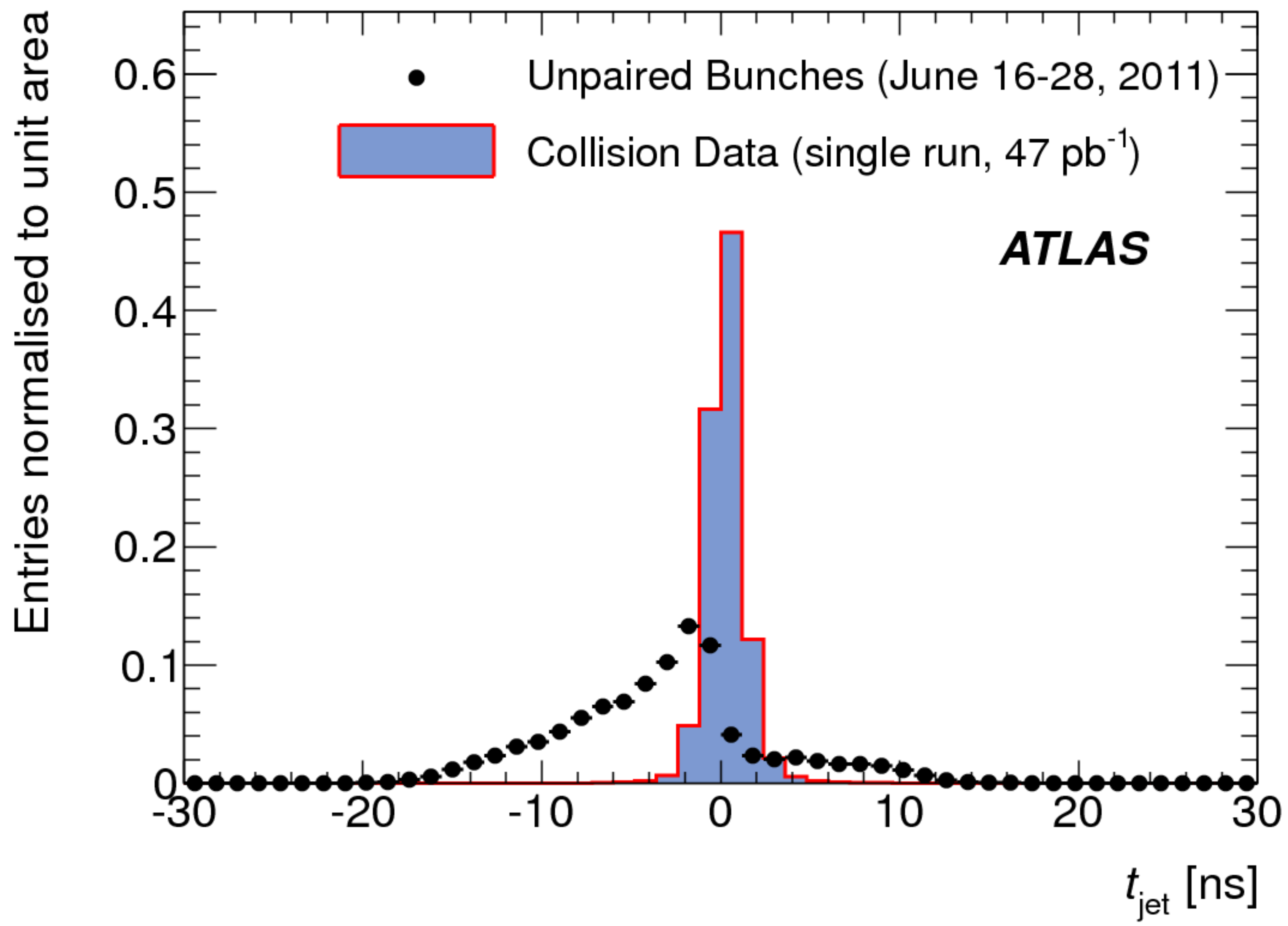
# Backup

# Beam induced background (BIB) characteristics

ATLAS, JINST 8 (2013) P07004




BIB particles largely deflected in the horizontal plane by LHC magnets

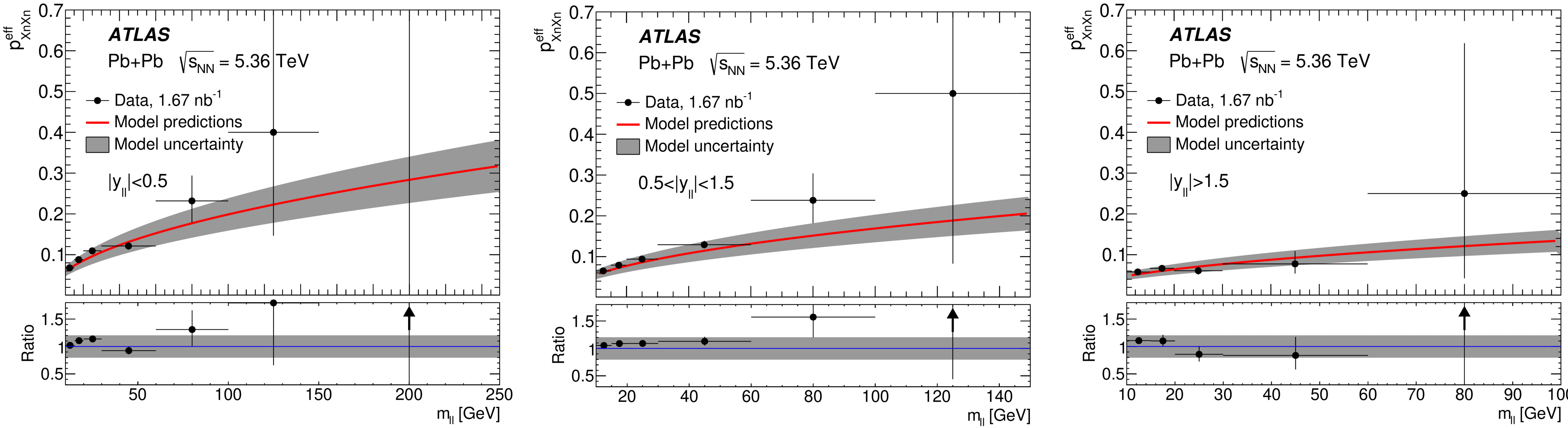



Fake jets from OOT energy deposits

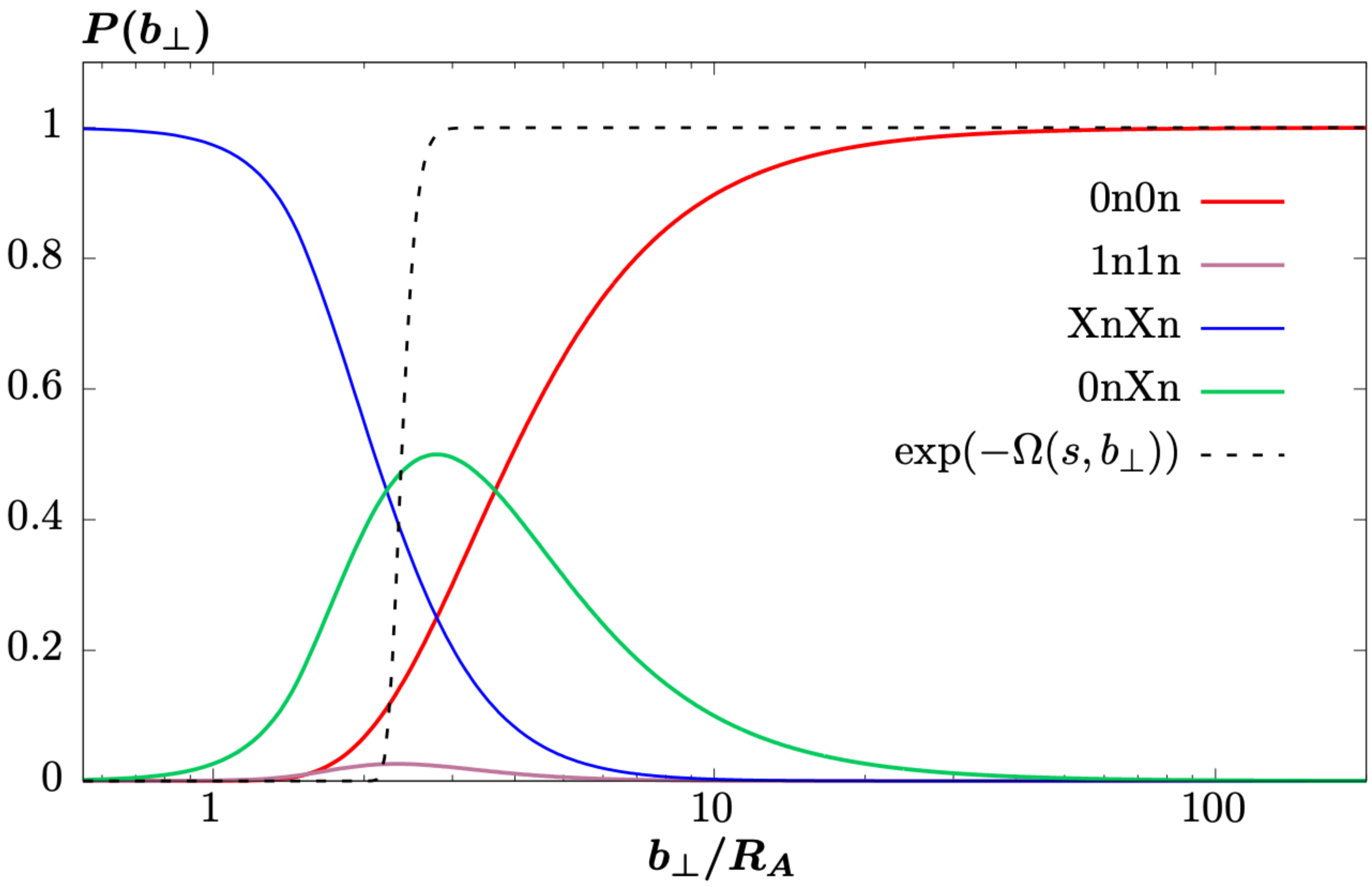
# XnXn correction

- 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**

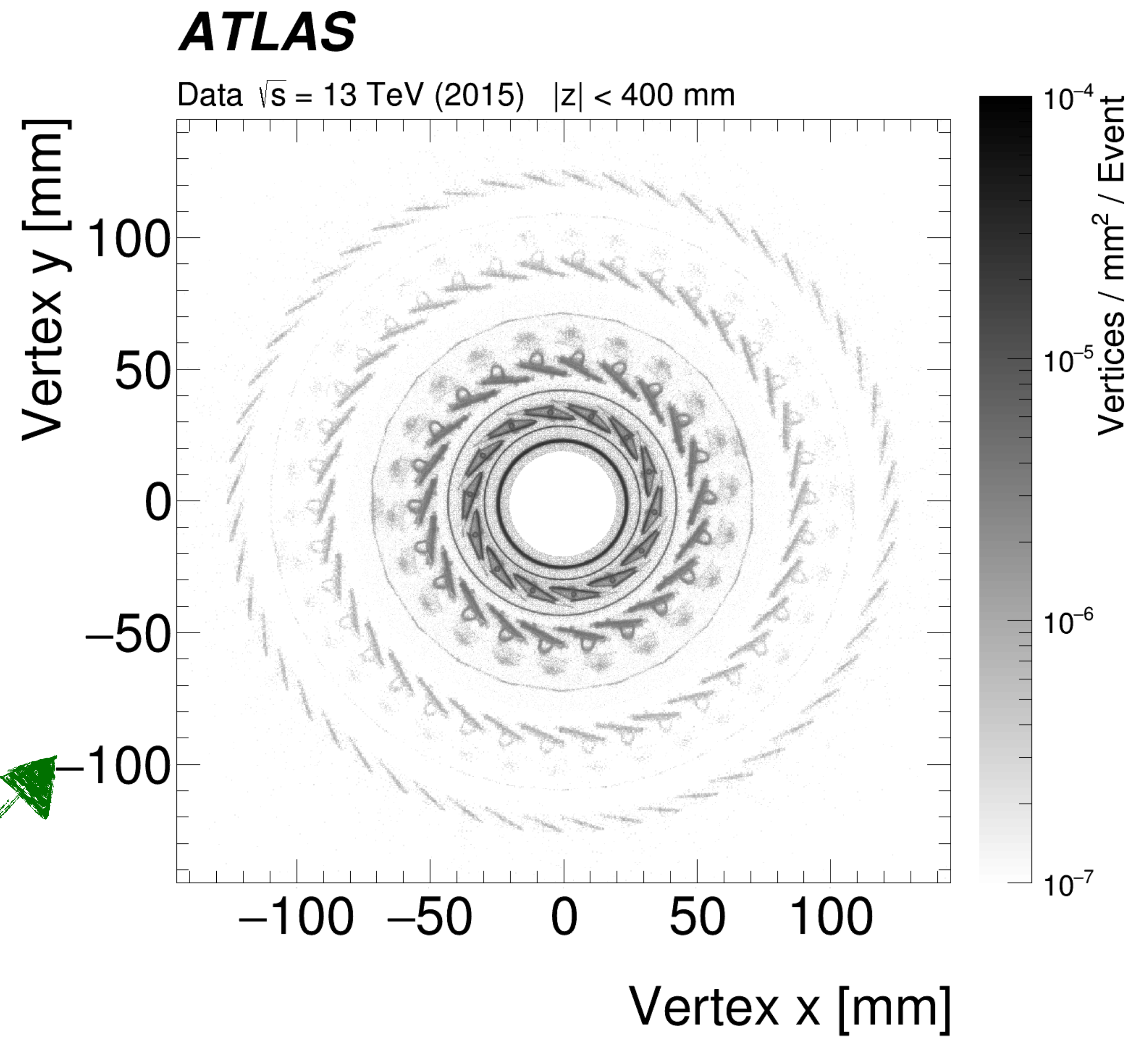


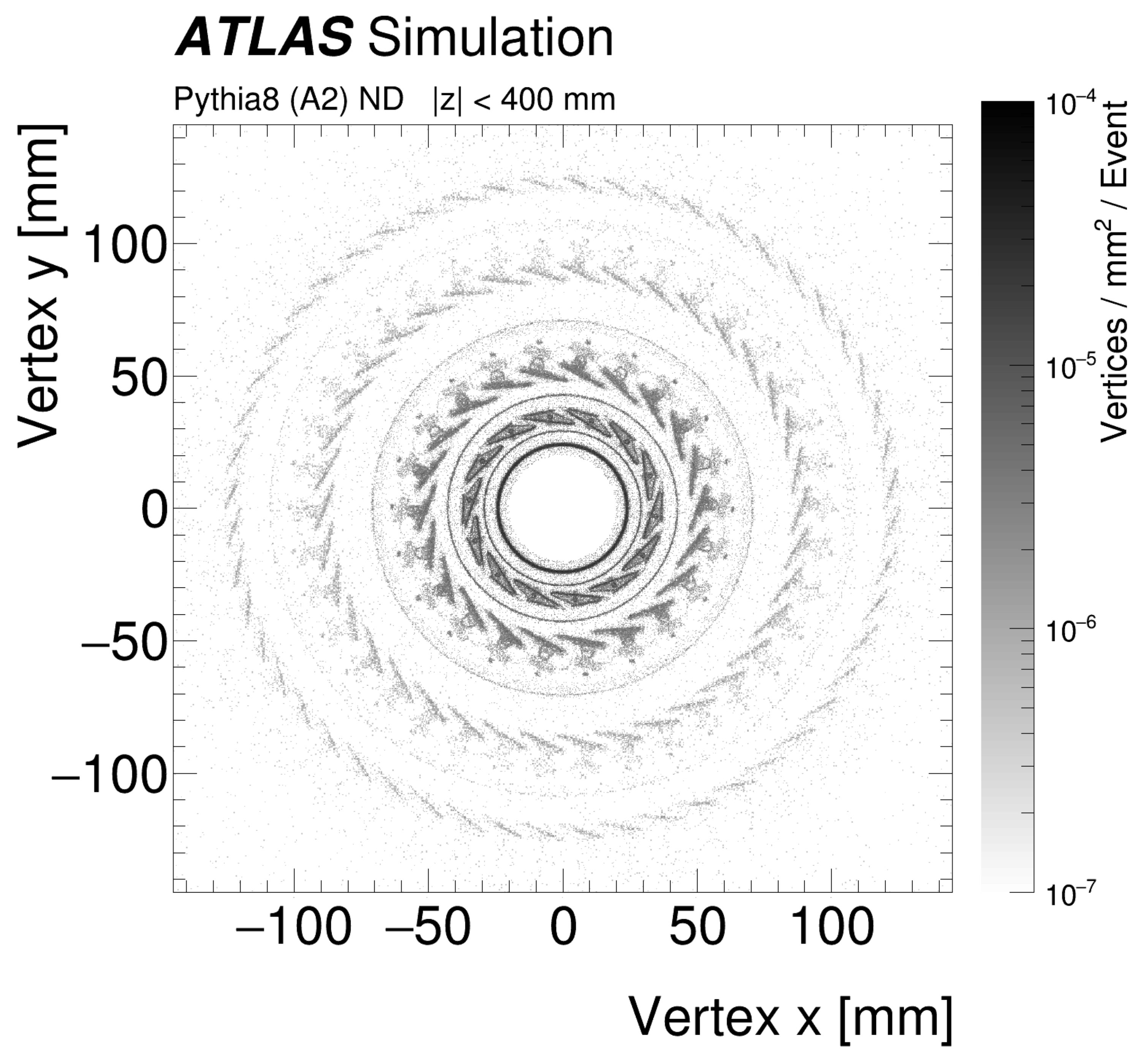
# EM breakup fractions



# Systematic uncertainties

- Dominant source: background uncertainty (stat.)
- Also important: detector material modeling
  - Using alternative Geant4 geometries with varied ID material
  - Variations capture the full range of data-MC differences observed in dedicated studies of the ID material [ATLAS, JINST 12 (2017) P12009]
  - Combined effect on the signal varies from **4%** (low masses) to **28%** (highest mass)



# Systematic uncertainties

- δ-electrons propagation range
  - Low energy δ-electrons evolution simulated only down to some kinetic energy threshold
  - Change from 0.05 to 0.01 mm
  - Less than 3% effect

- δ-electrons production modeling
  - dE/dx formulas for ionisation by monopoles have ±3% uncertainty in analysis kinematic region
  - Reducing δ-electrons production rate by 3% in the simulation
  - About 2-5% signal yield reduction