Search for magnetic monopoles using the strongest magnetic fields in the Universe with the ATLAS experiment

[ATLAS-CONF-2024-009]

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AGH University of Krakow
on behalf of the ATLAS Collaboration

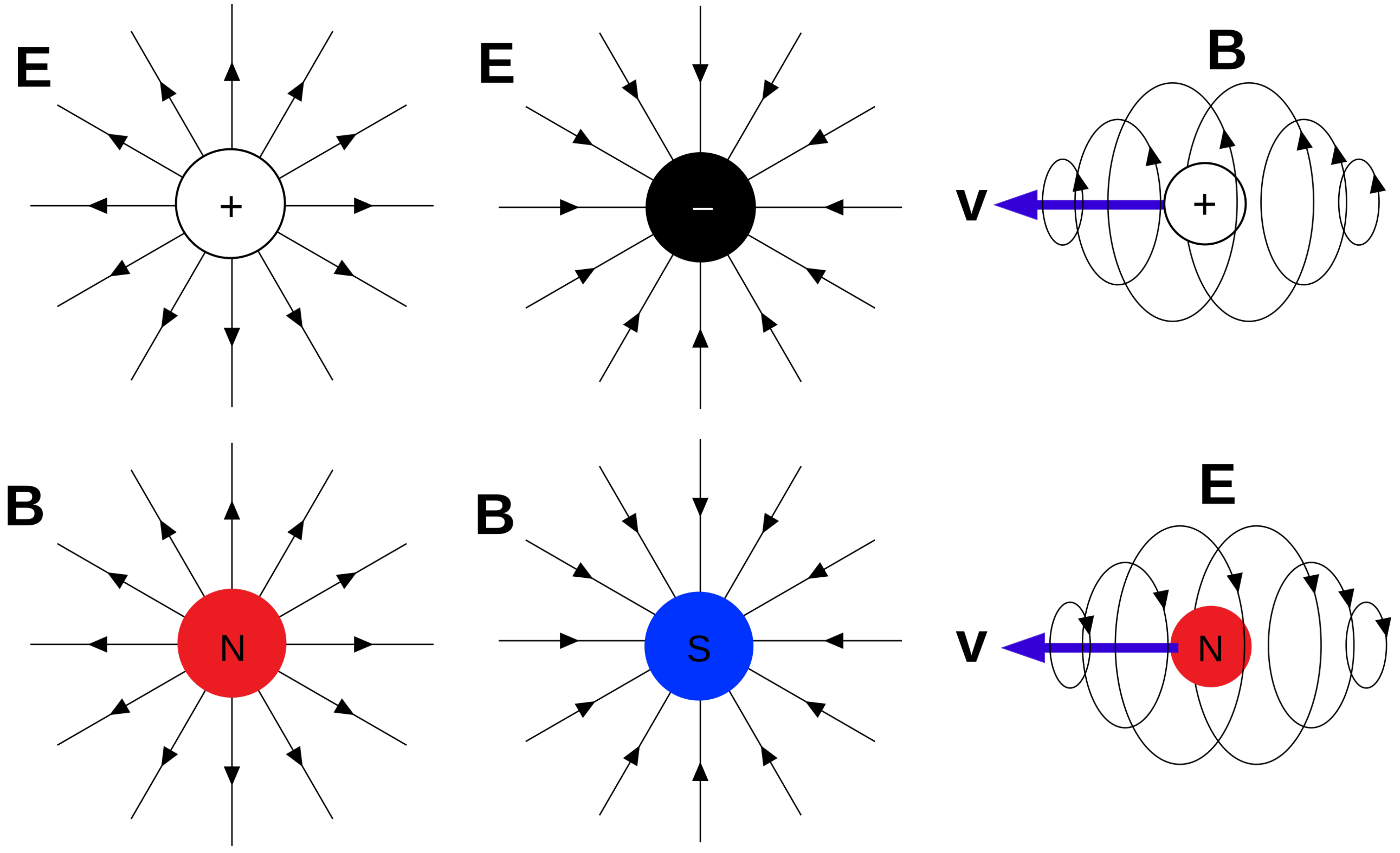
CERN LHC seminar

Magnetic monopoles and the classical physics

MAXWELL'S EQUATIONS
WITH MAGNETIC MONOPOLES

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

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



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.)

- Can be seen by considering a static system of an electric and a magnetic monopoles separated by a distance *r*
  - System possesses angular momentum
  - Quantization of angular momentum → charge quantization

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

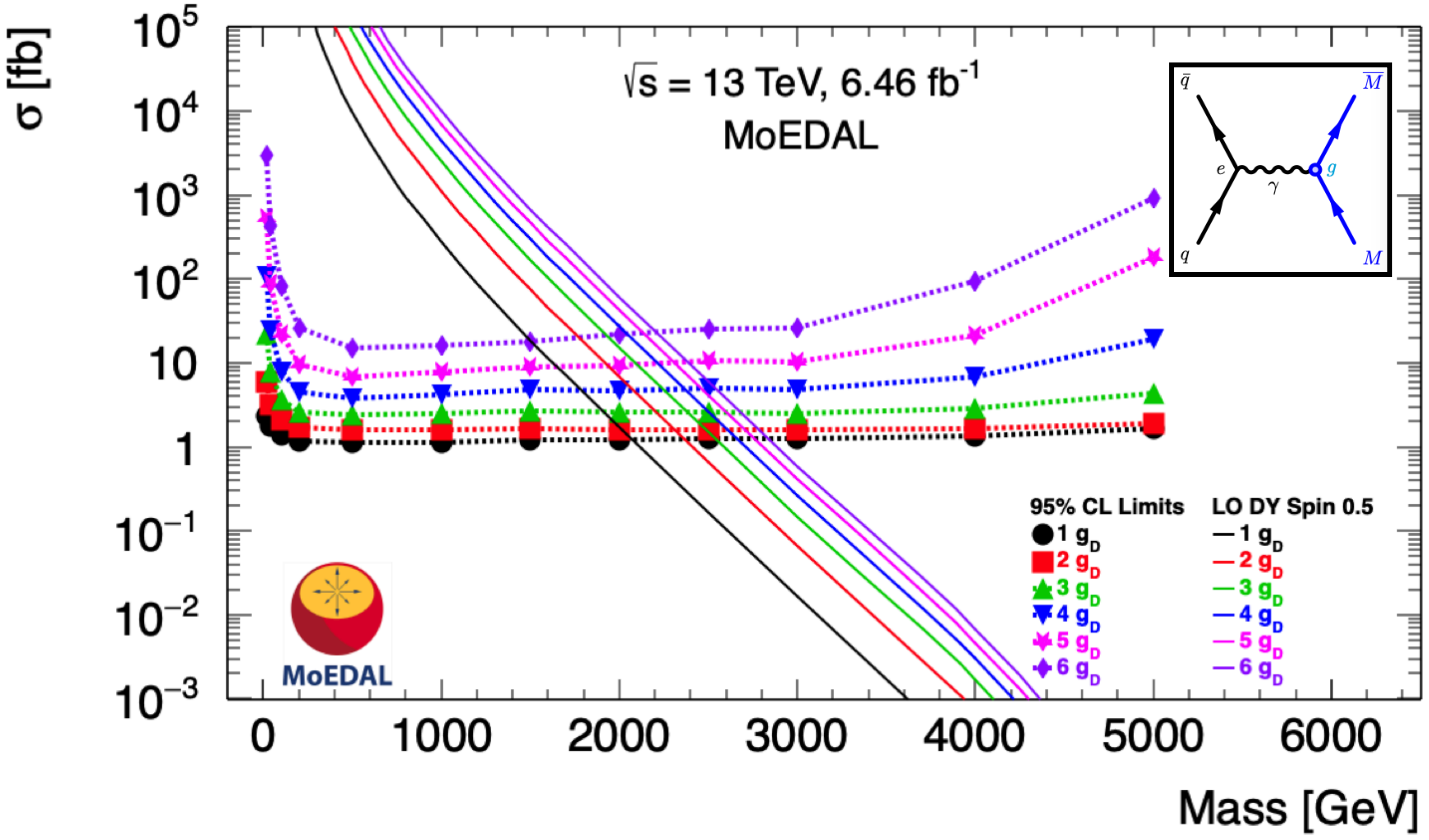
or

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

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

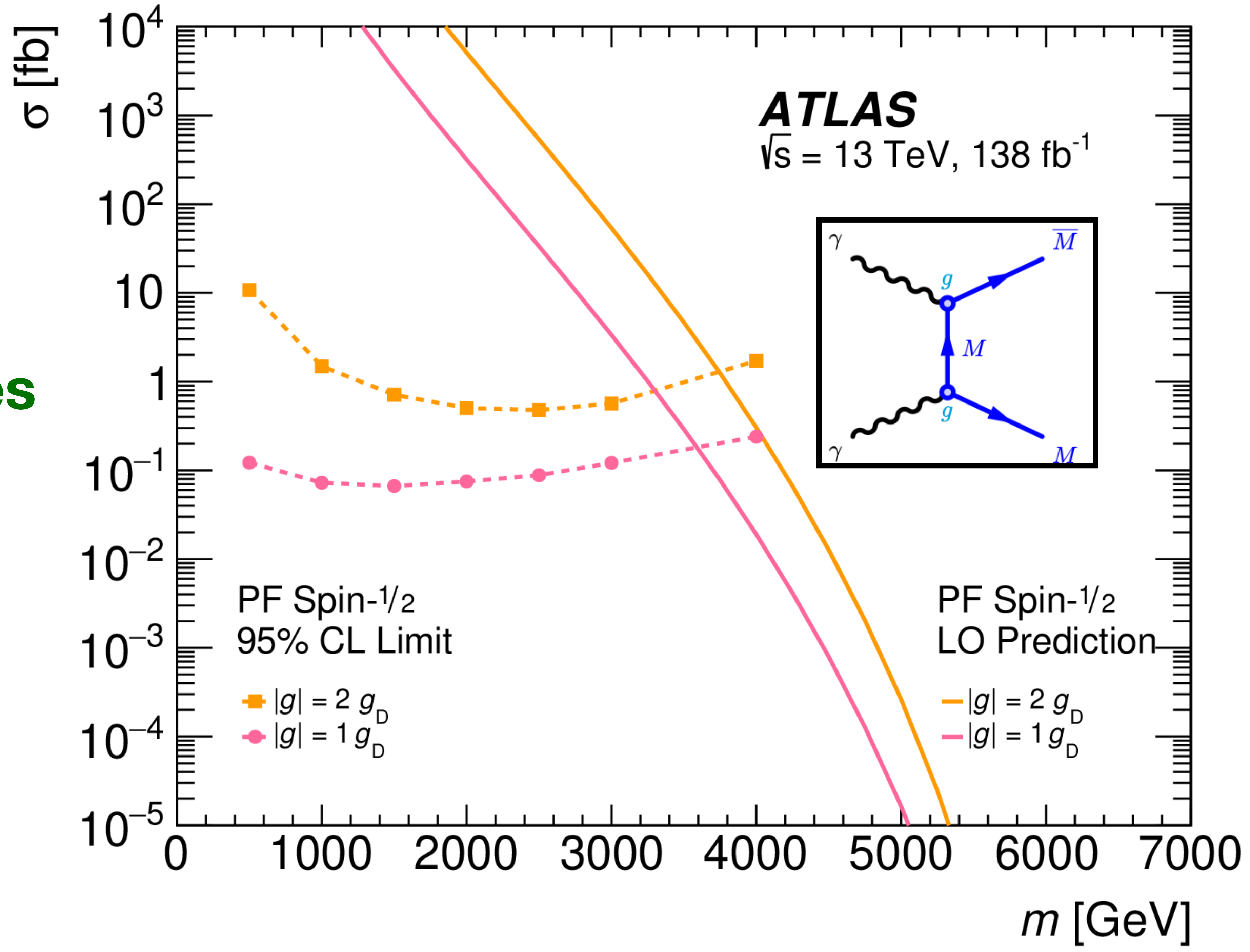
Recent monopole searches at the LHC (pp)

MoEDAL Collaboration, arXiv:2311.06509



complementary detection techniques

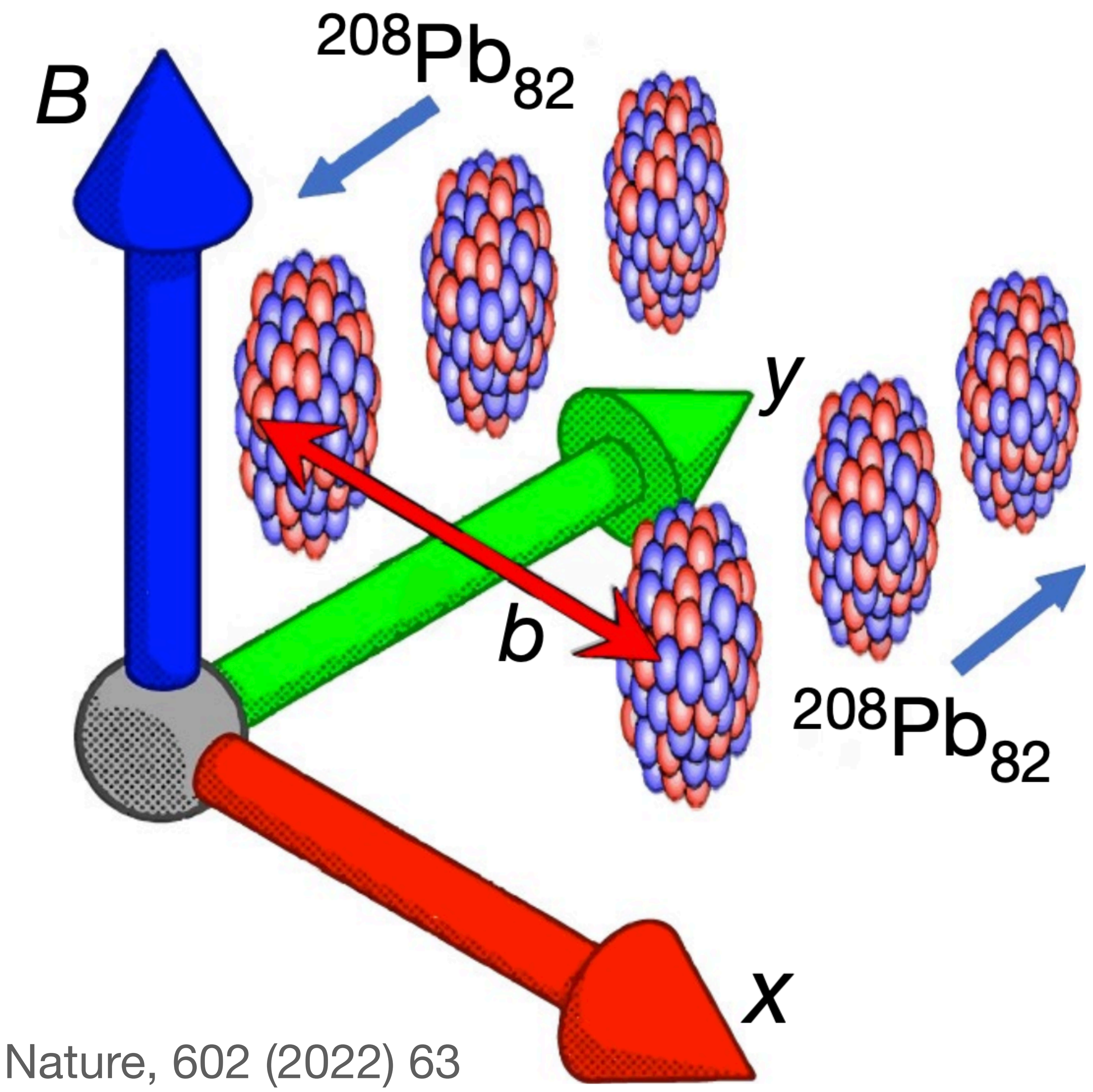
ATLAS, JHEP 11 (2023) 112



- Both searches use production modelled by Drell-Yan or γγ-fusion pair production
  - Derived from ee scattering using naive substitution $\alpha_{EM} \to \alpha_{MM}$
  - But: large γ-MM coupling constant **$\alpha_{MM} \sim 1/(4\alpha_{EM}) \approx 34$** → 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 (impact parameter) b ~ 2R (twice the nuclear radius)**



MoEDAL, Nature, 602 (2022) 63

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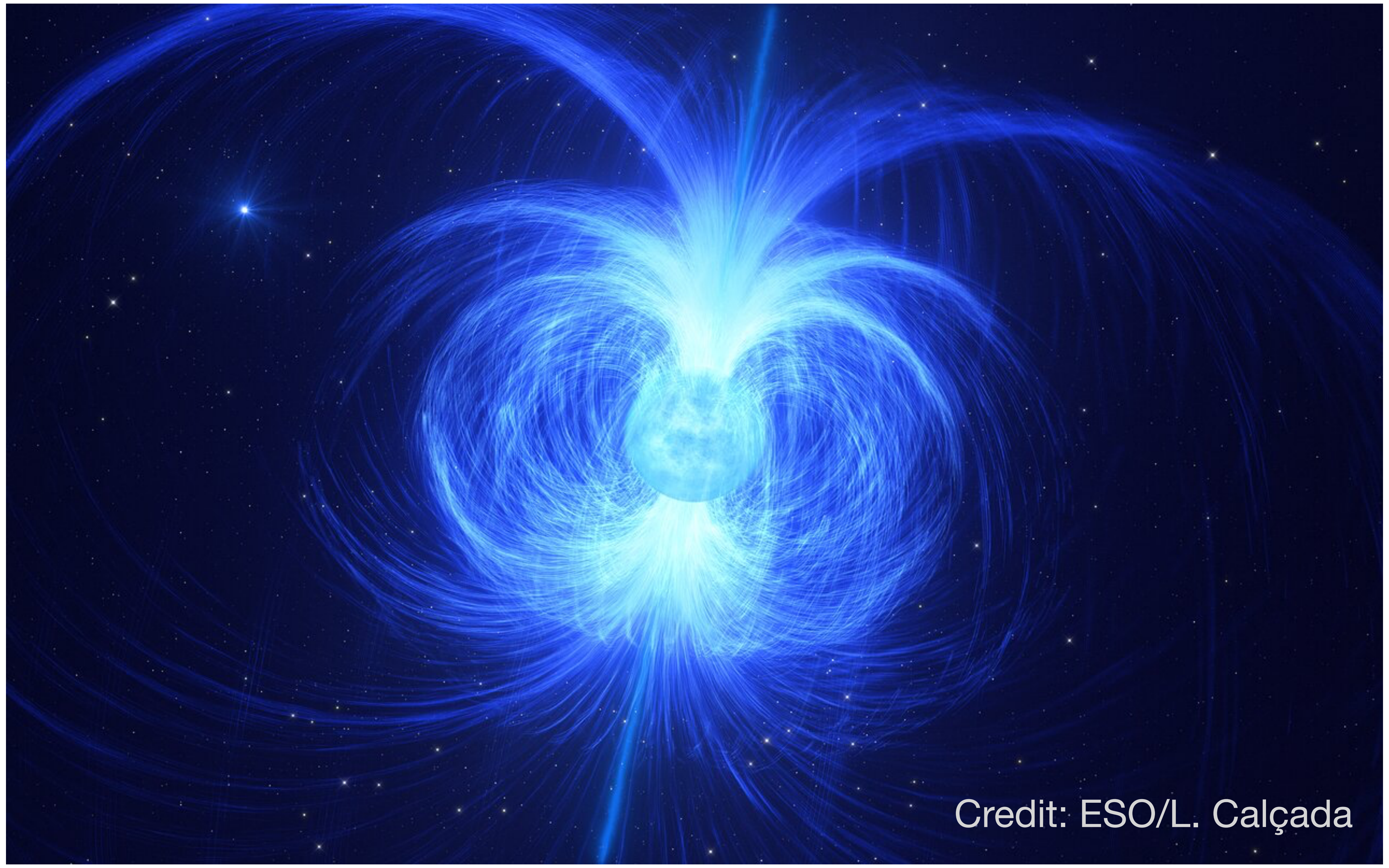
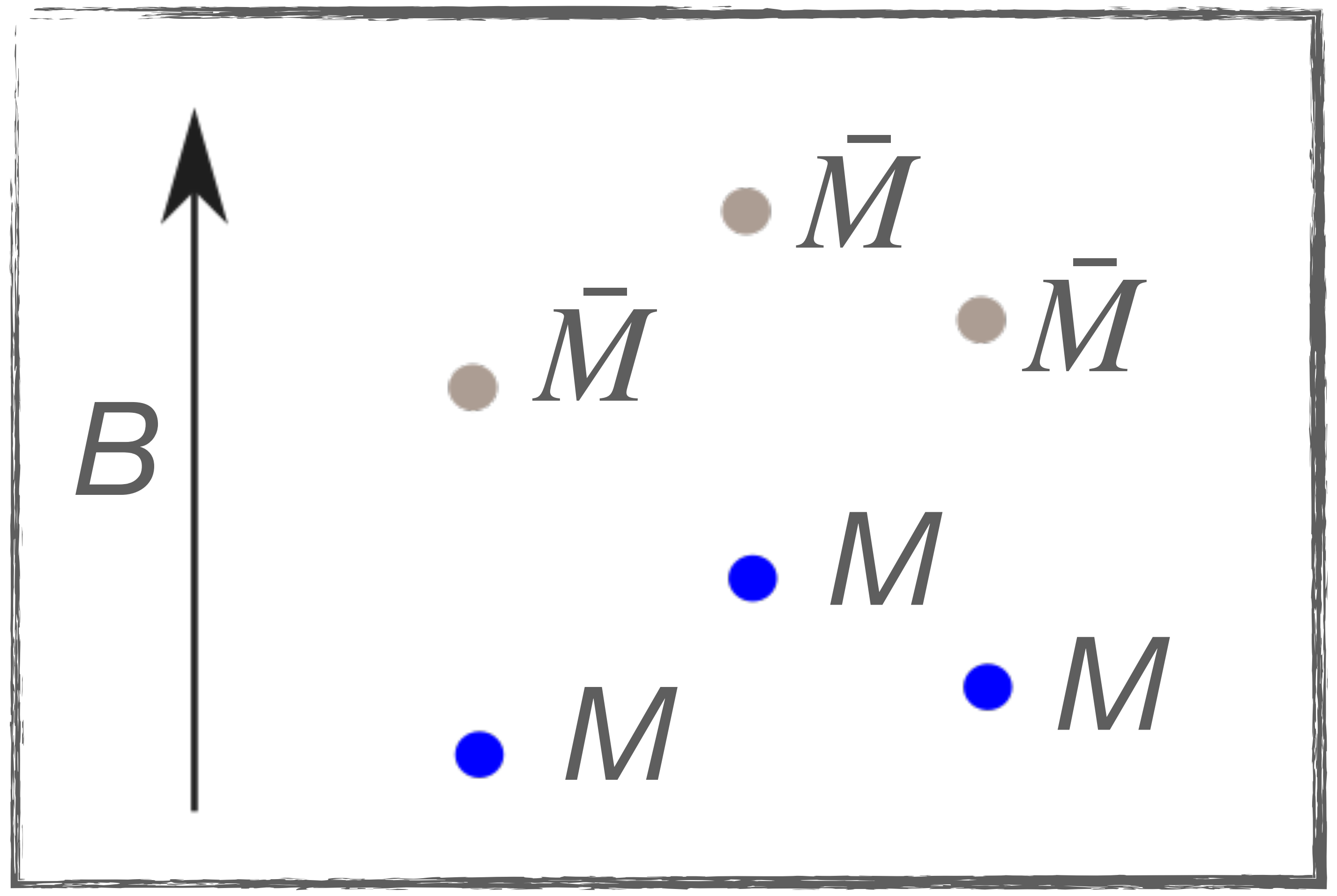


Magnetic monopoles in heavy-ion collisions

- Production via the **Schwinger mechanism** in strong magnetic fields [Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021)]
    - Analogy to originally described spontaneous creation of e+e- pairs in presence of ultra-strong electric field

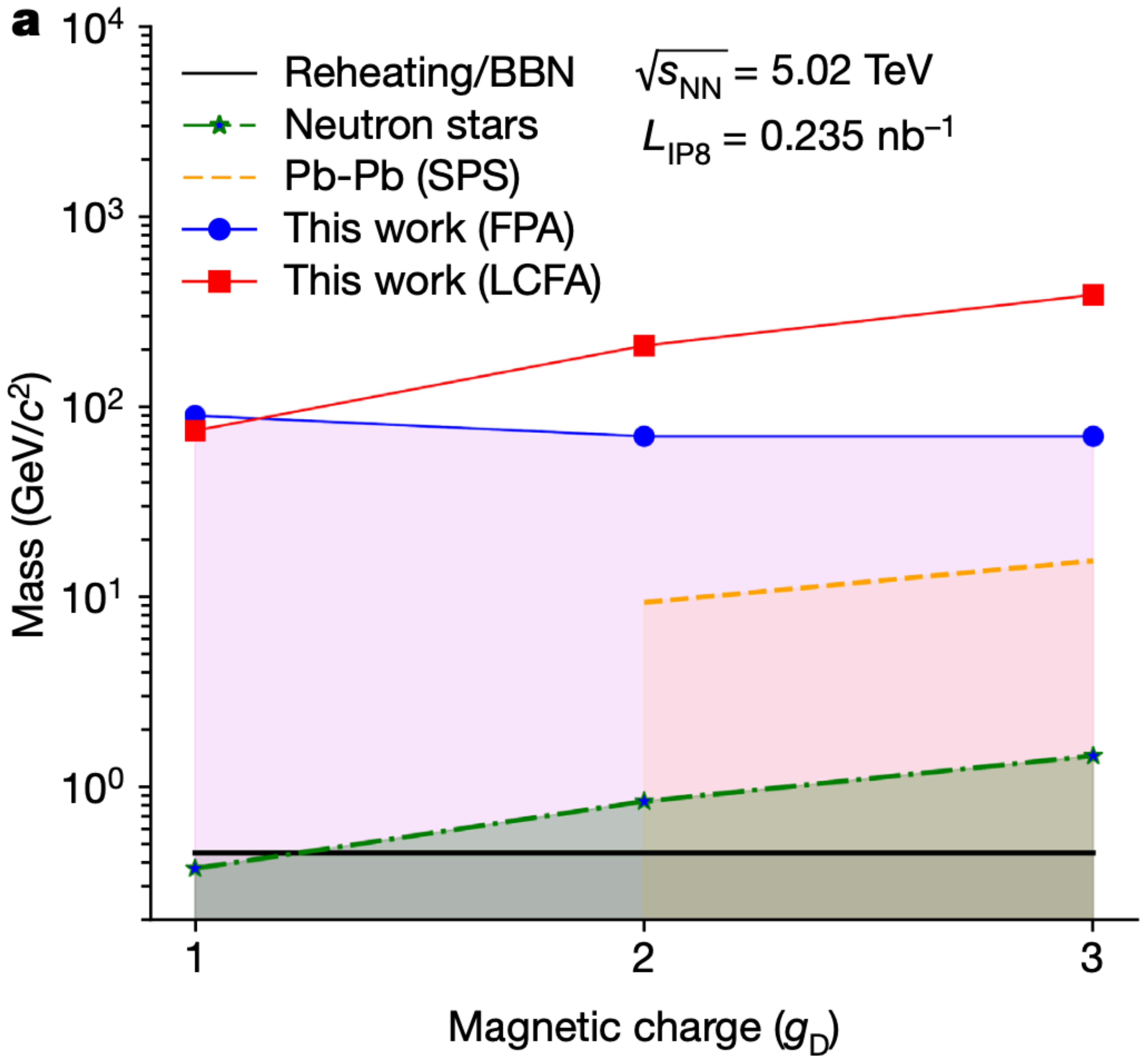


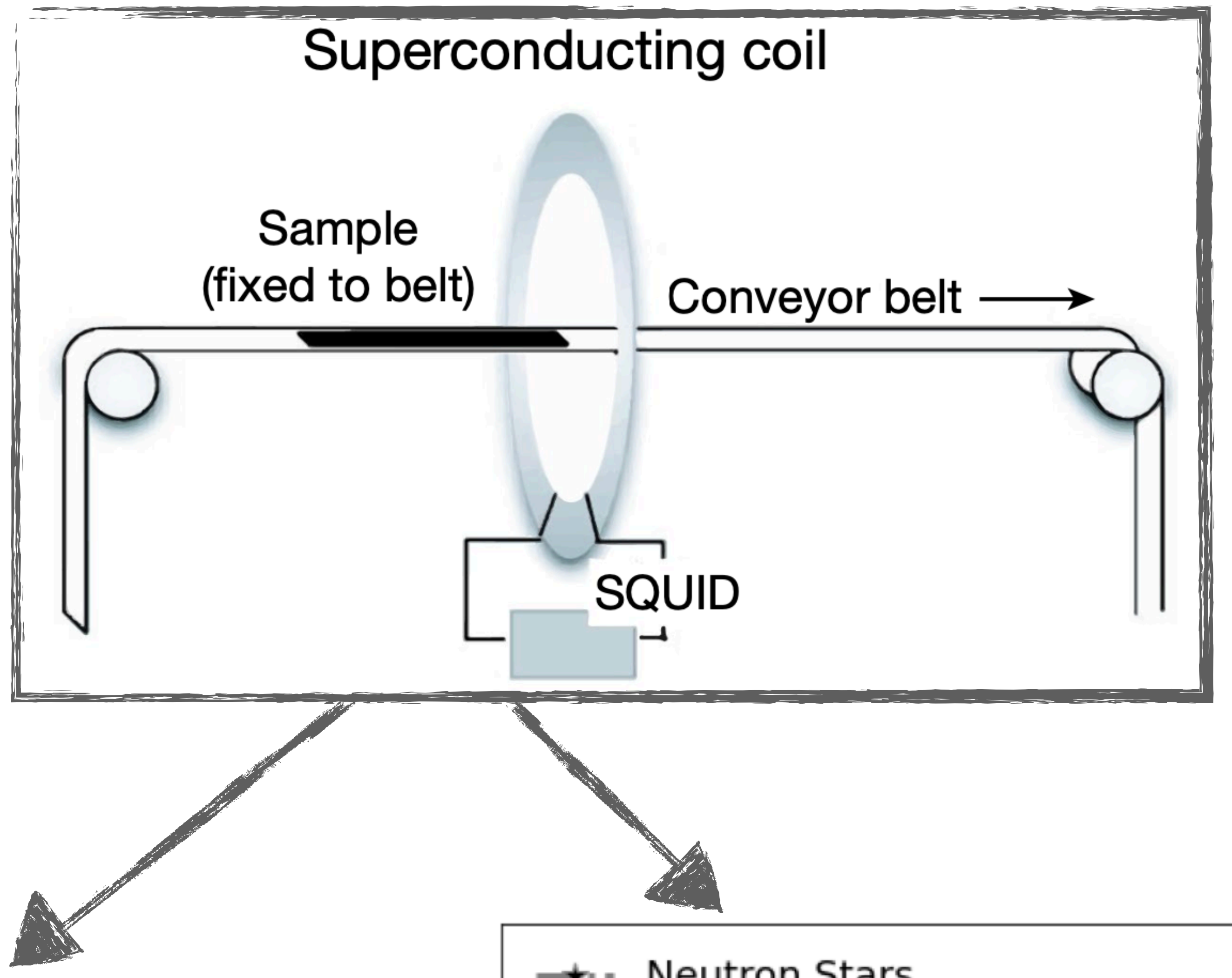
- Advantages over *pp* searches:
    - Cross-sections calculated using **semiclassical techniques** → do not suffer from non-perturbative nature of coupling
    - Composite monopoles enhance the cross section
    - No exponential suppression ($e^{-4/\alpha} \sim 10^{-236}$) for composite monopole models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

Monopole searches in LHC heavy-ion collisions

MoEDAL MMT detectors exposed to 0.235/nb of Run-2 Pb+Pb (IP8) data

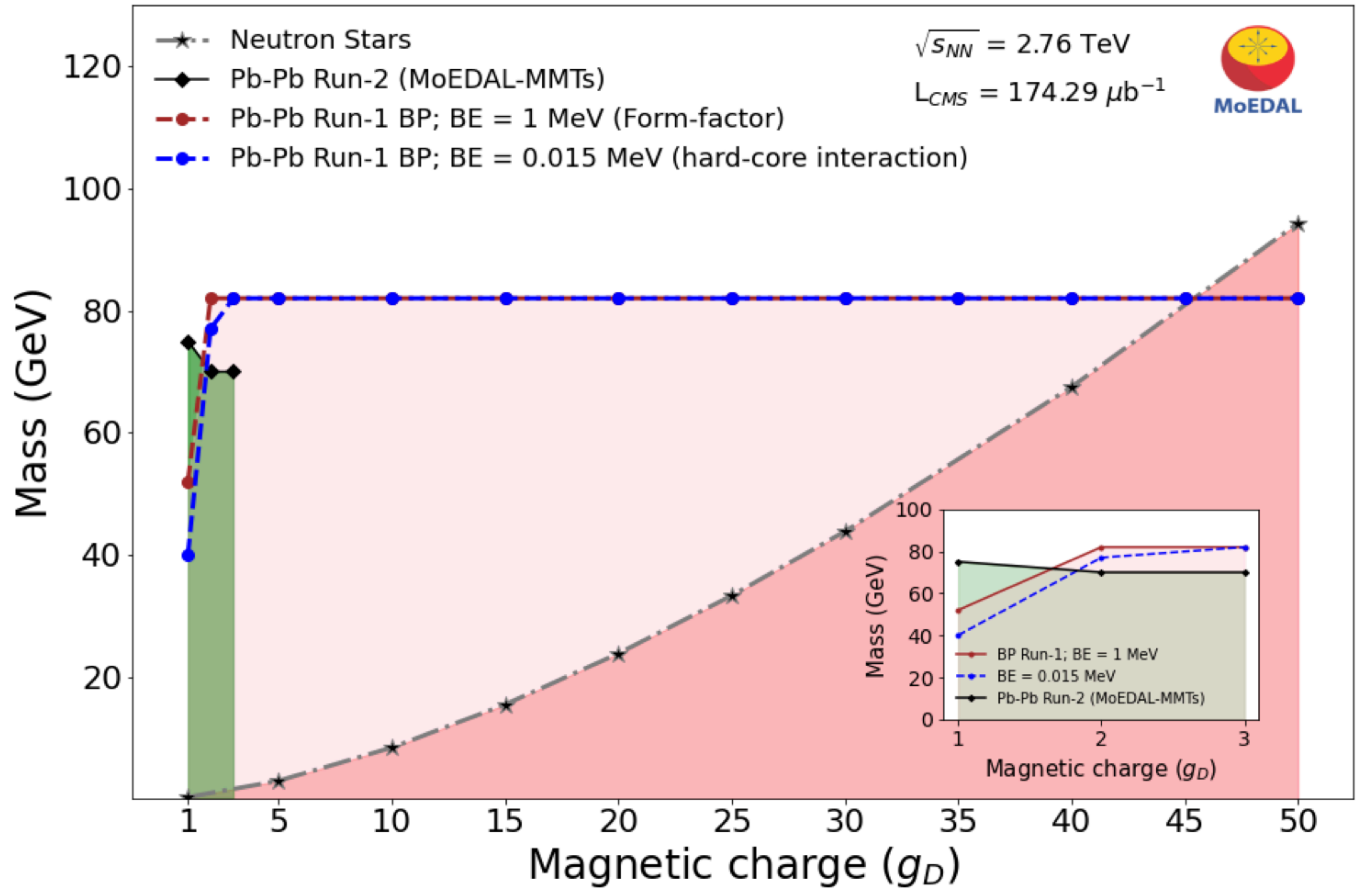
MoEDAL, Nature, 602 (2022) 63





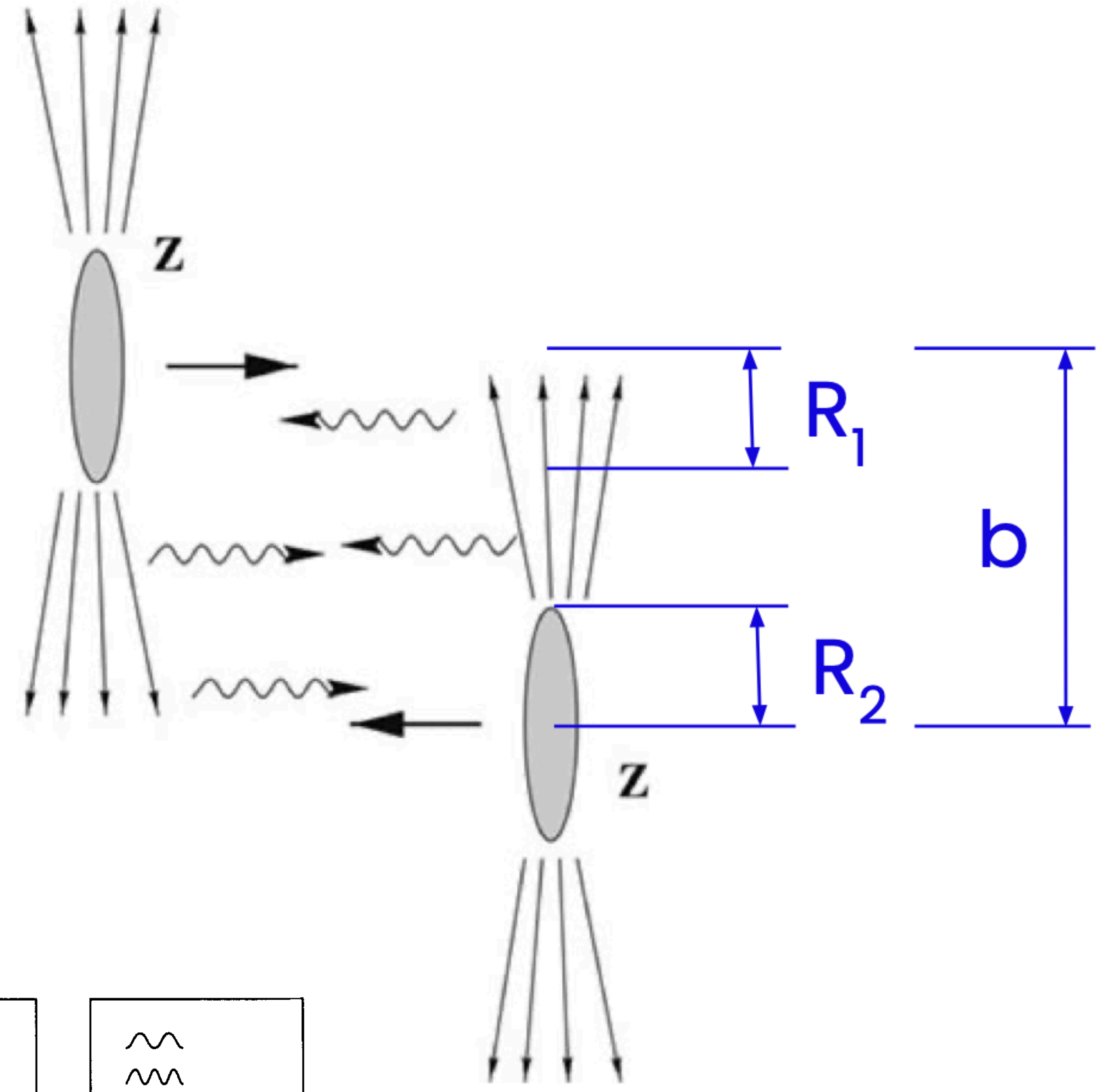
MoEDAL probes CMS Run-1 beam pipe

MoEDAL, arXiv:2402.15682

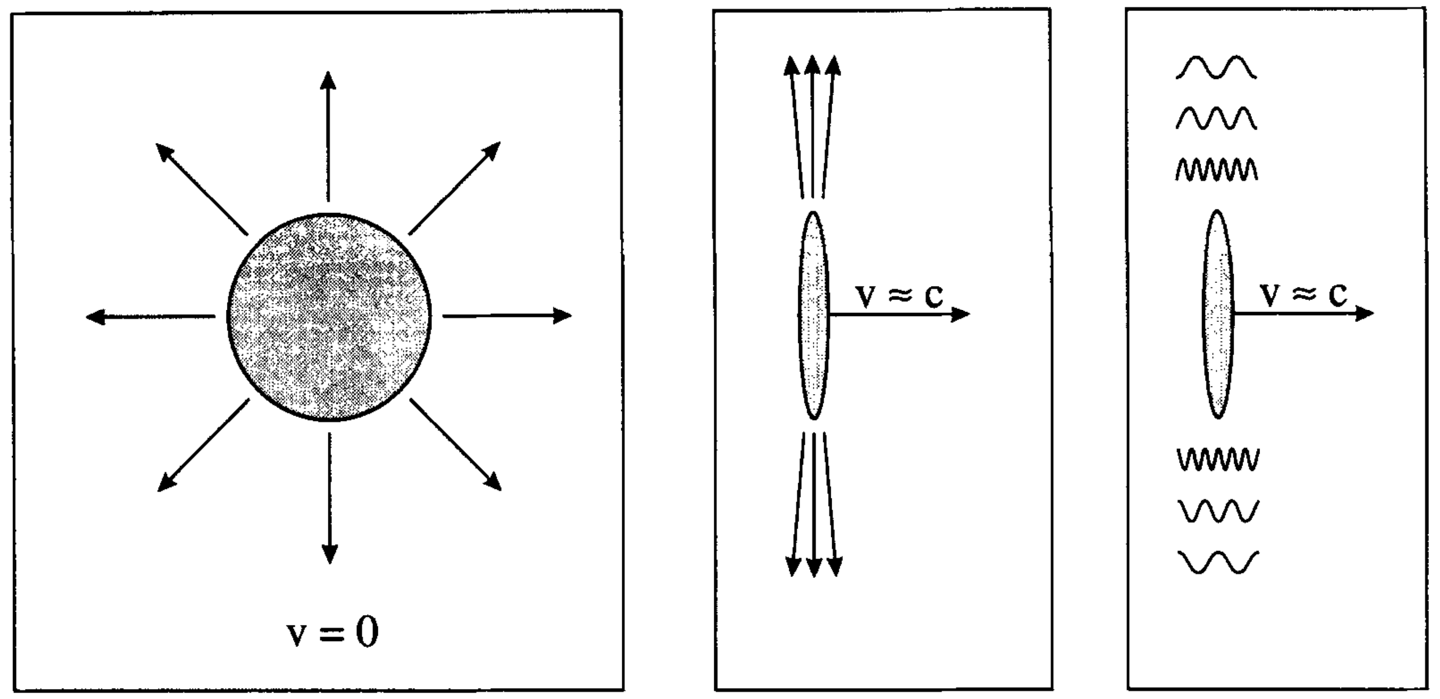


LHC as a photon collider

- 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 **Z^2**

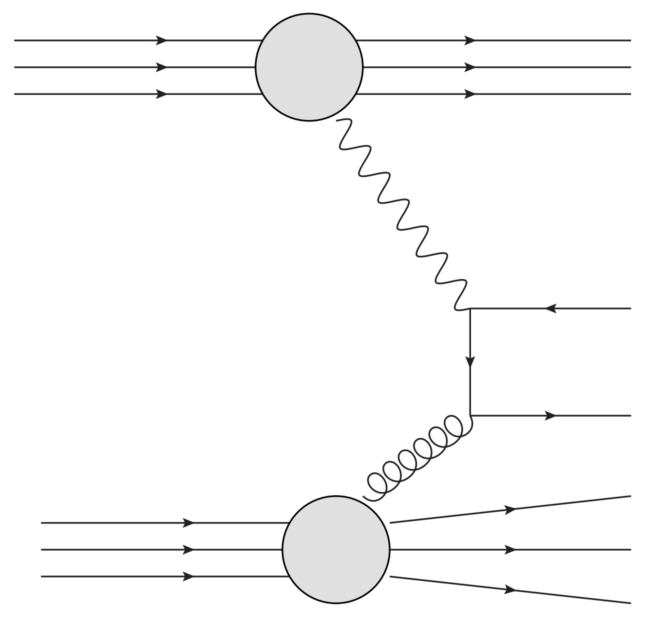


Fermi, Nuovo Cim. 2 (1925) 143



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

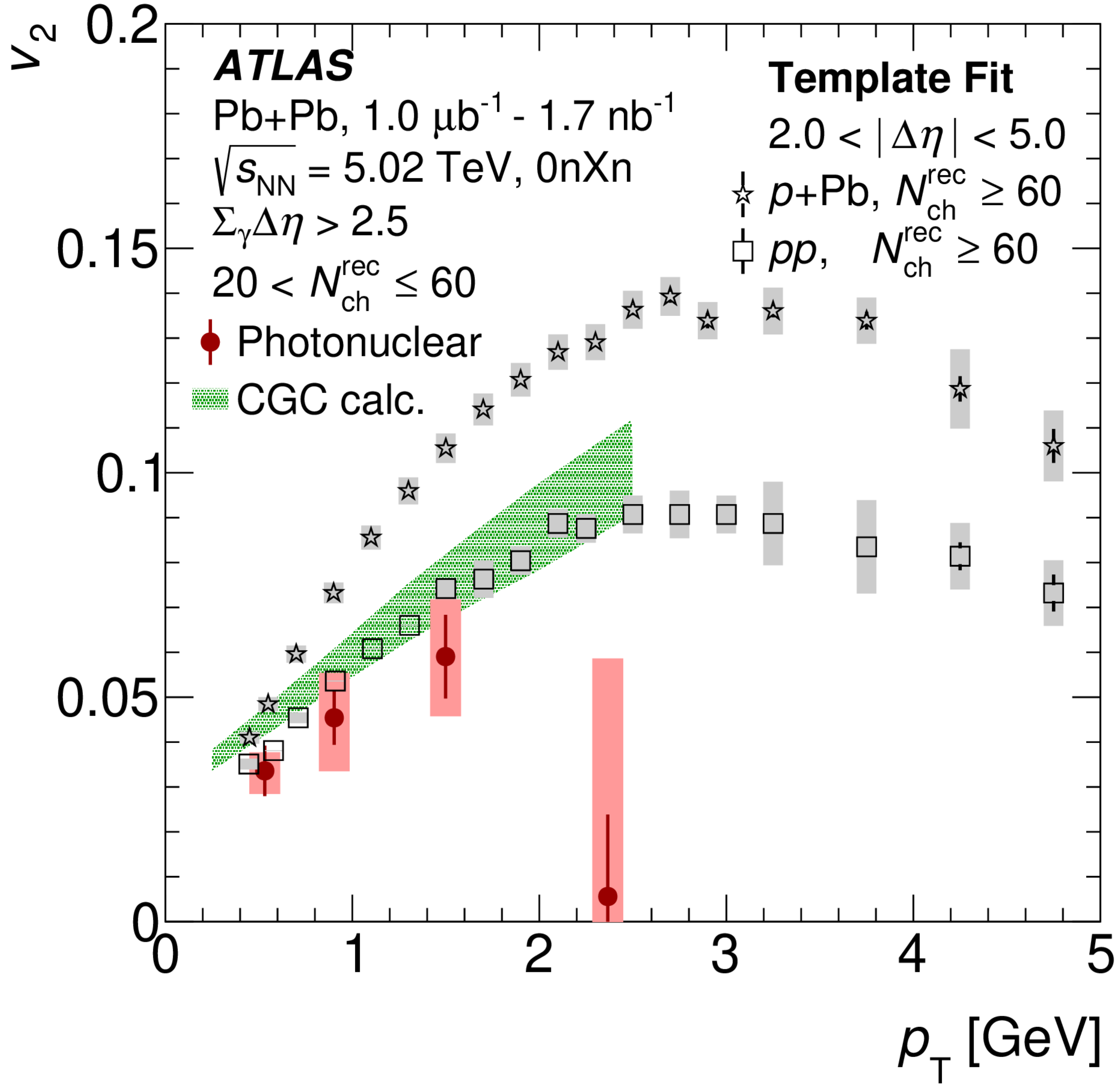
Run2 ATLAS UPC highlights



Characterizing (high-multiplicity) photonuclear interactions

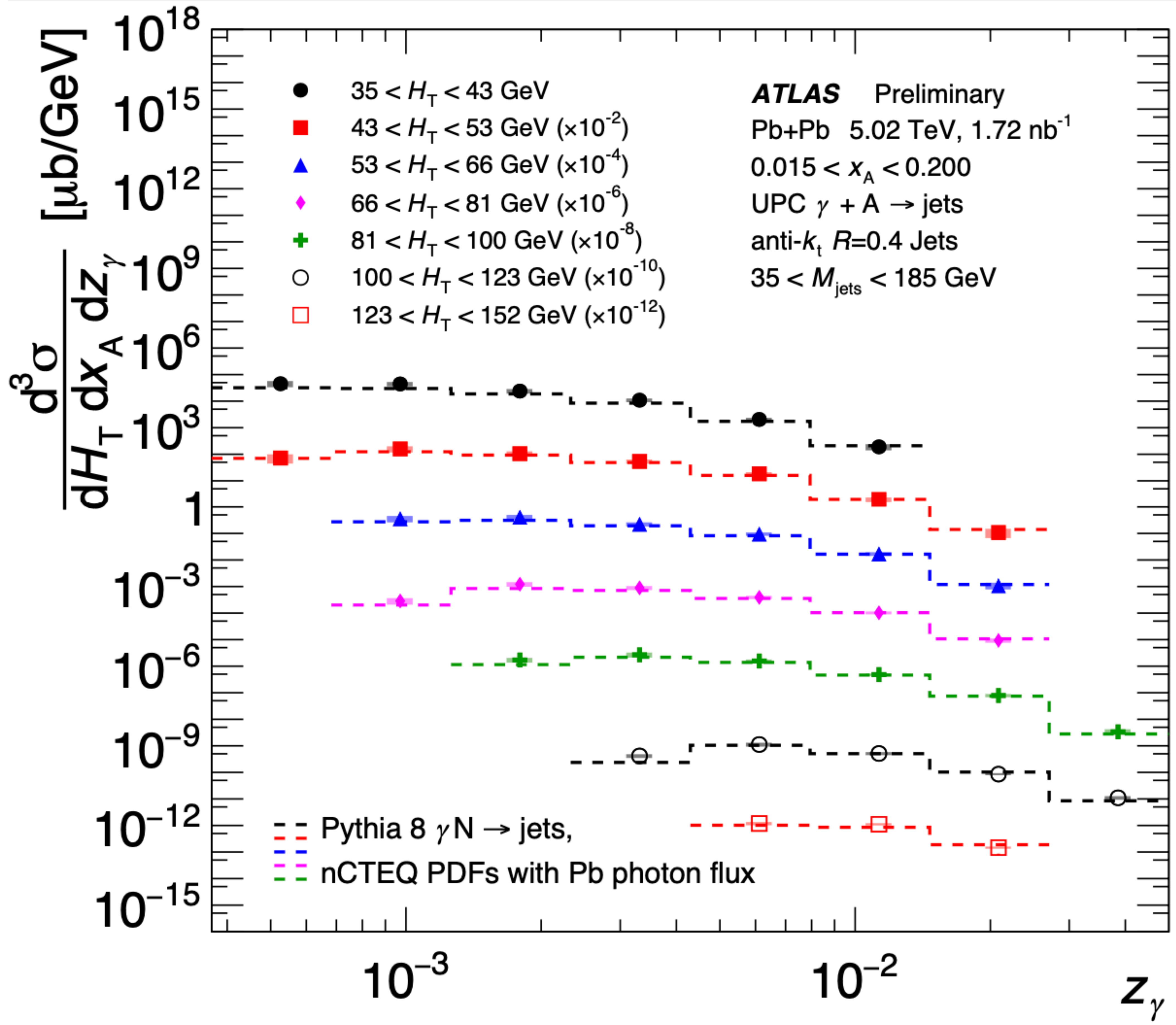
Phys. Rev. C. 104 (2021) 014903

ATLAS-CONF-2023-059

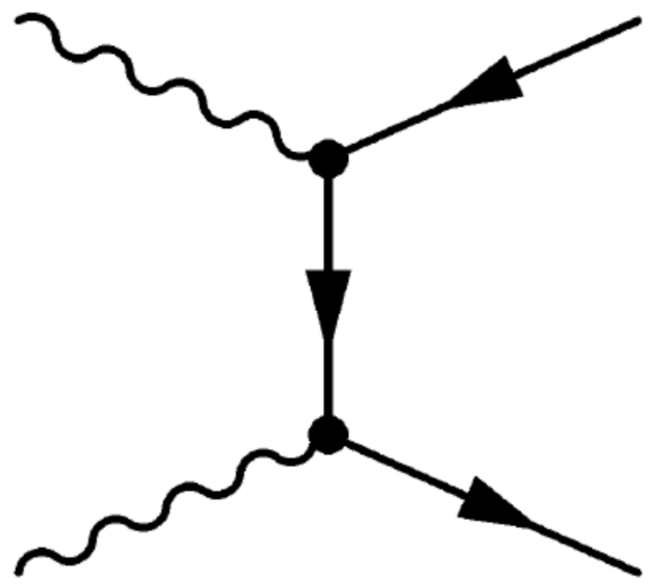


Hard-scale photonuclear collisions with jets

ATLAS-CONF-2022-021

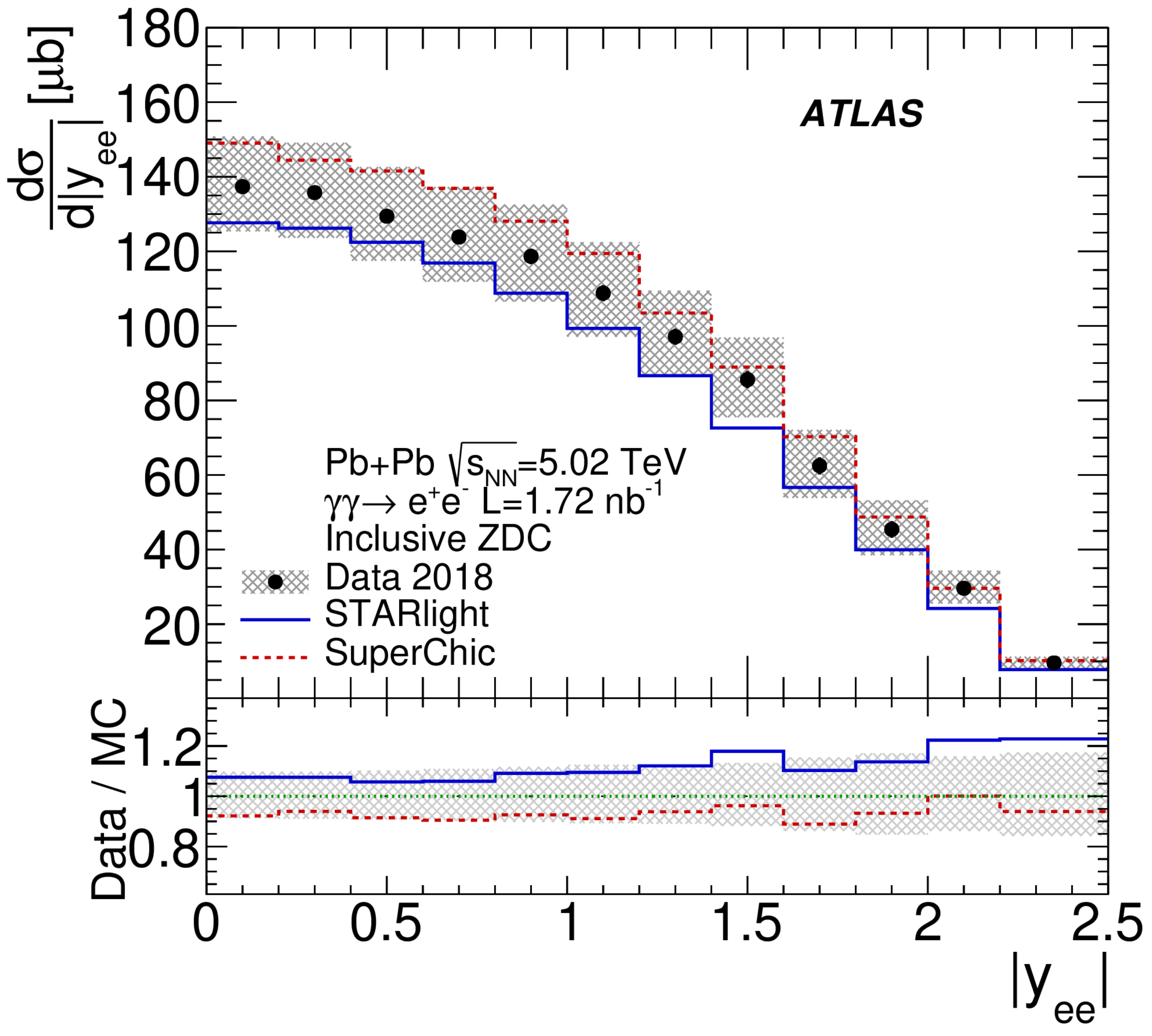


Run2 ATLAS UPC highlights

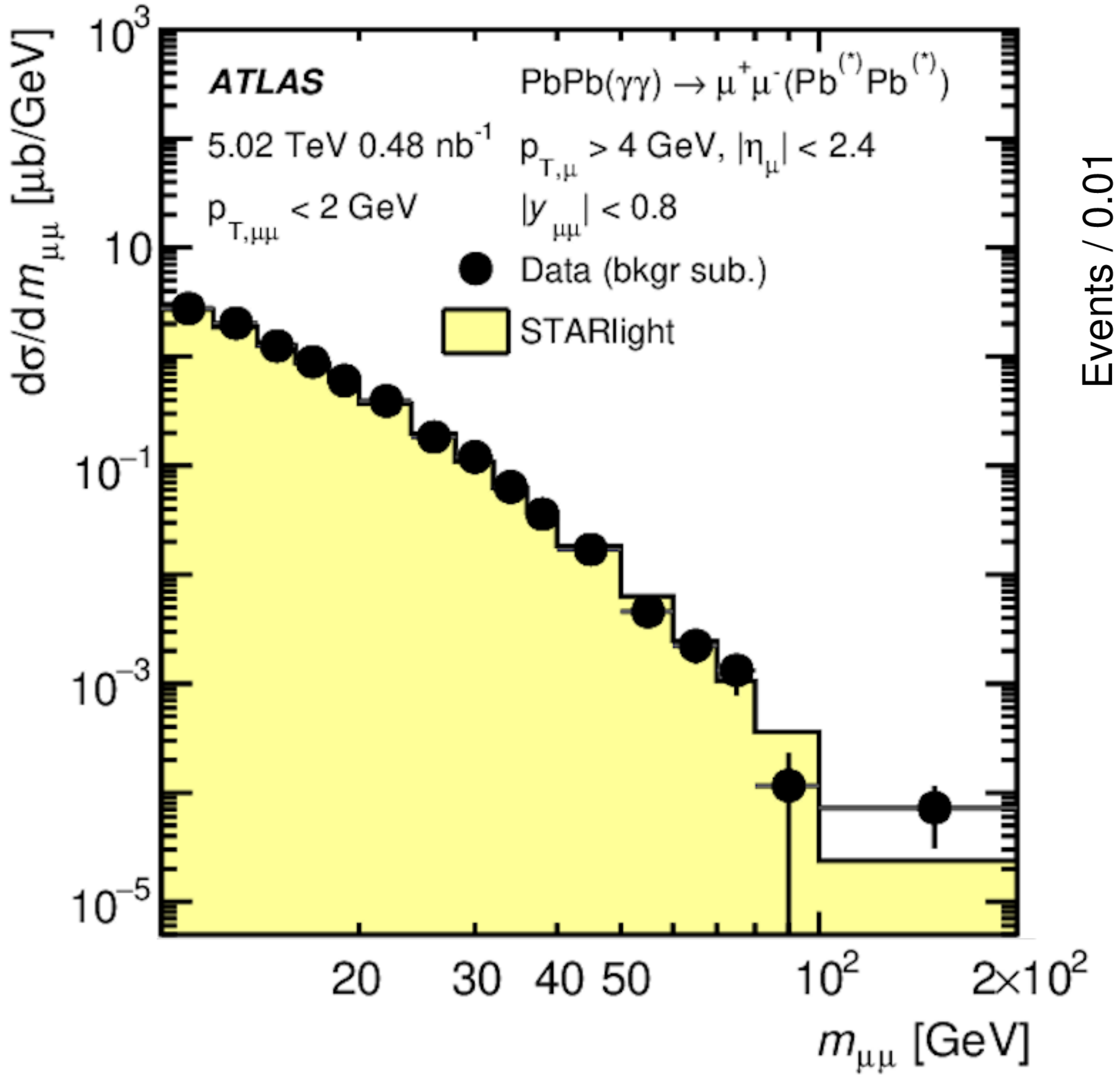


- Precision QED studies with $\gamma\gamma \rightarrow$ ee / $\mu\mu$ / $\tau\,\tau$ production
  - Measured also in non-UPC events by ATLAS [Phys. Rev. C 107 (2023) 054907]

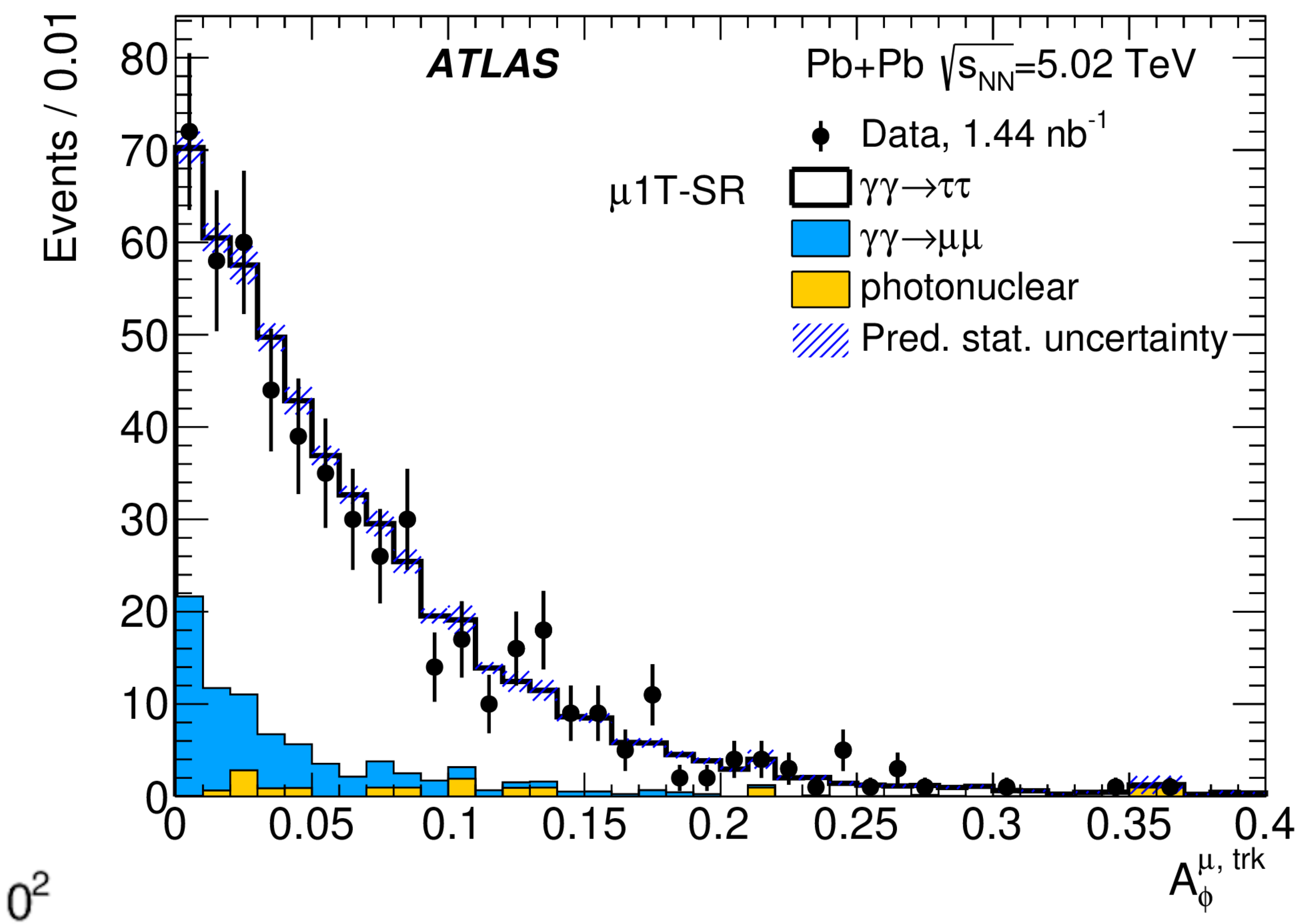
JHEP 06 (2023) 182



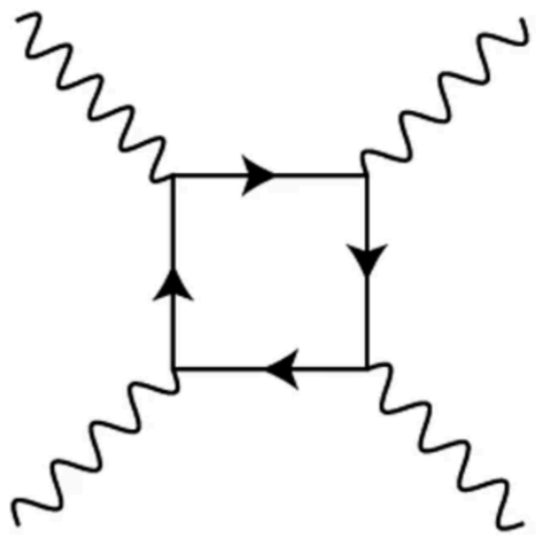
Phys. Rev. C 104 (2021) 024906



Phys. Rev. Lett. 131 (2023) 151802



Run2 ATLAS UPC highlights

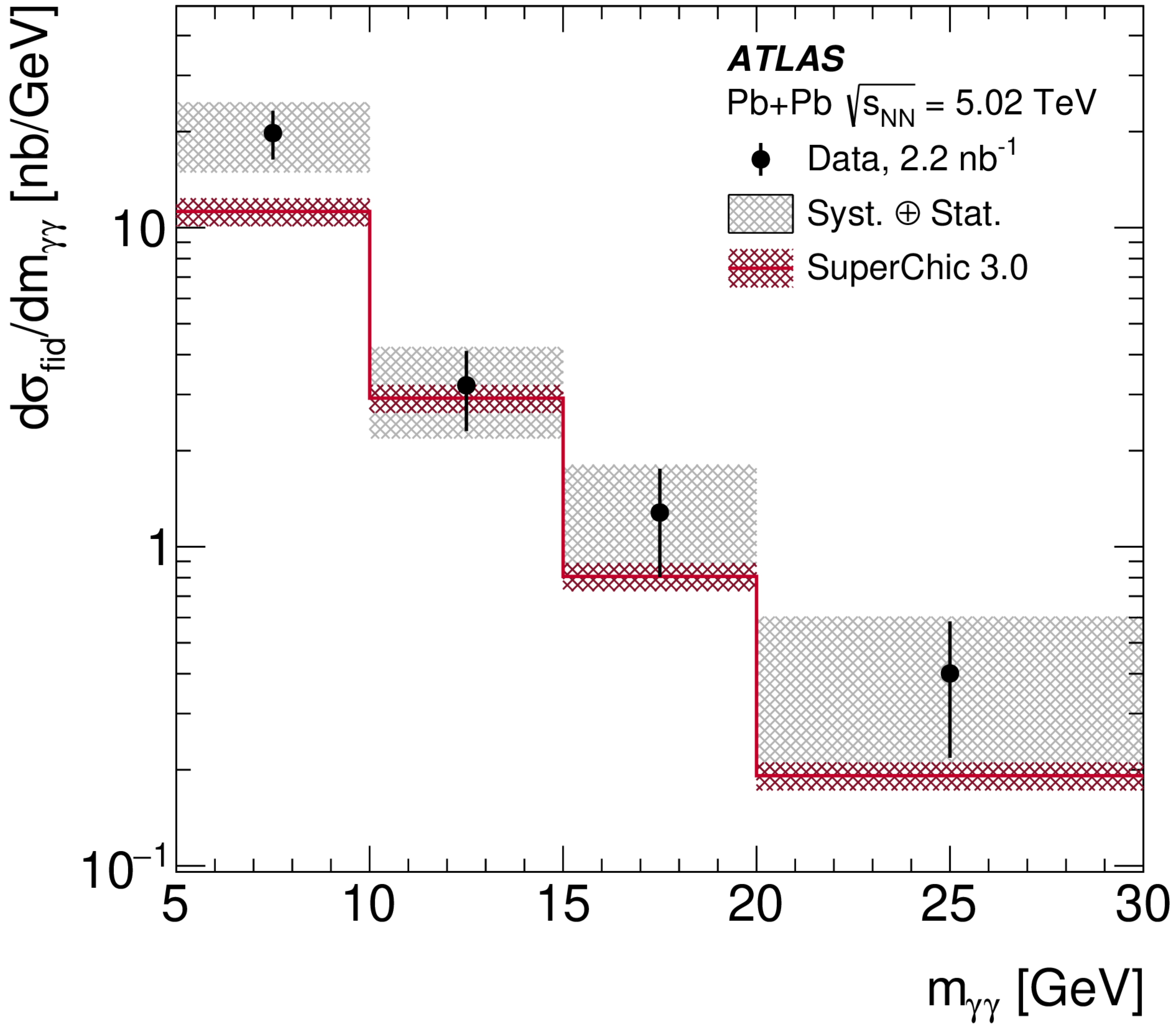


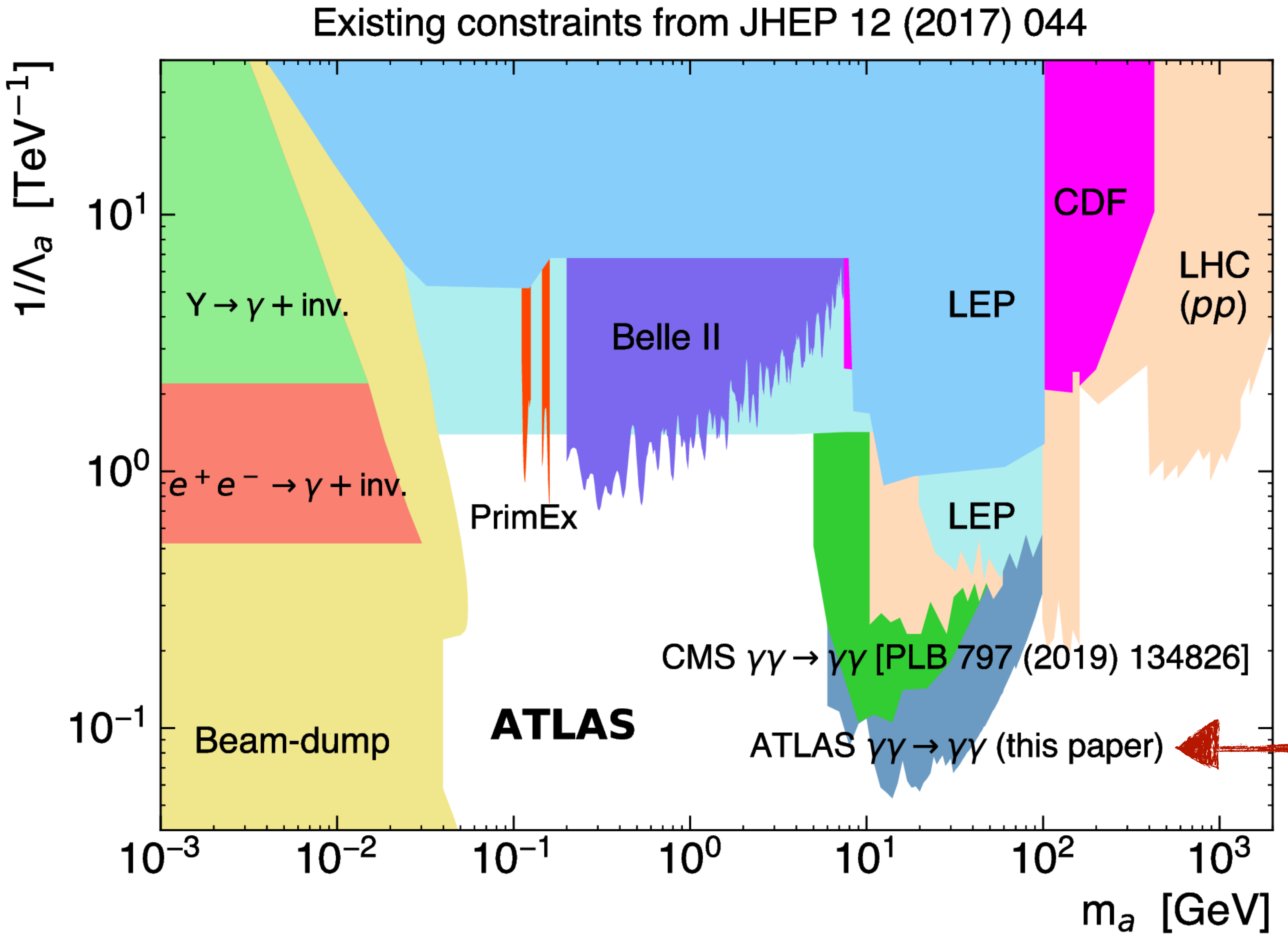
- Series of light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) measurements
  - Incl. analysis interpretations for specific BSM scenario (ALPs)

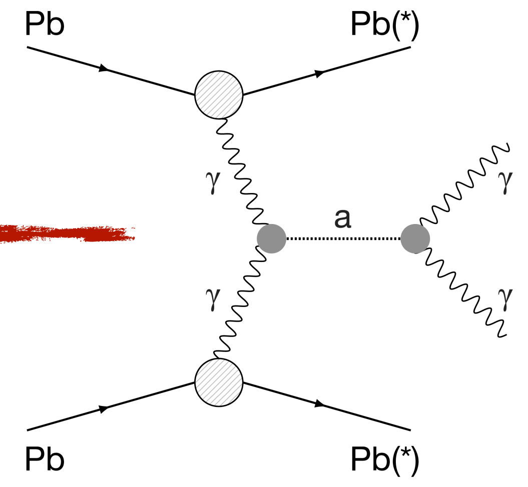
Nature Phys. 13 (2017) 852

Phys. Rev. Lett. 123 (2019) 052001

JHEP 03 (2021) 243



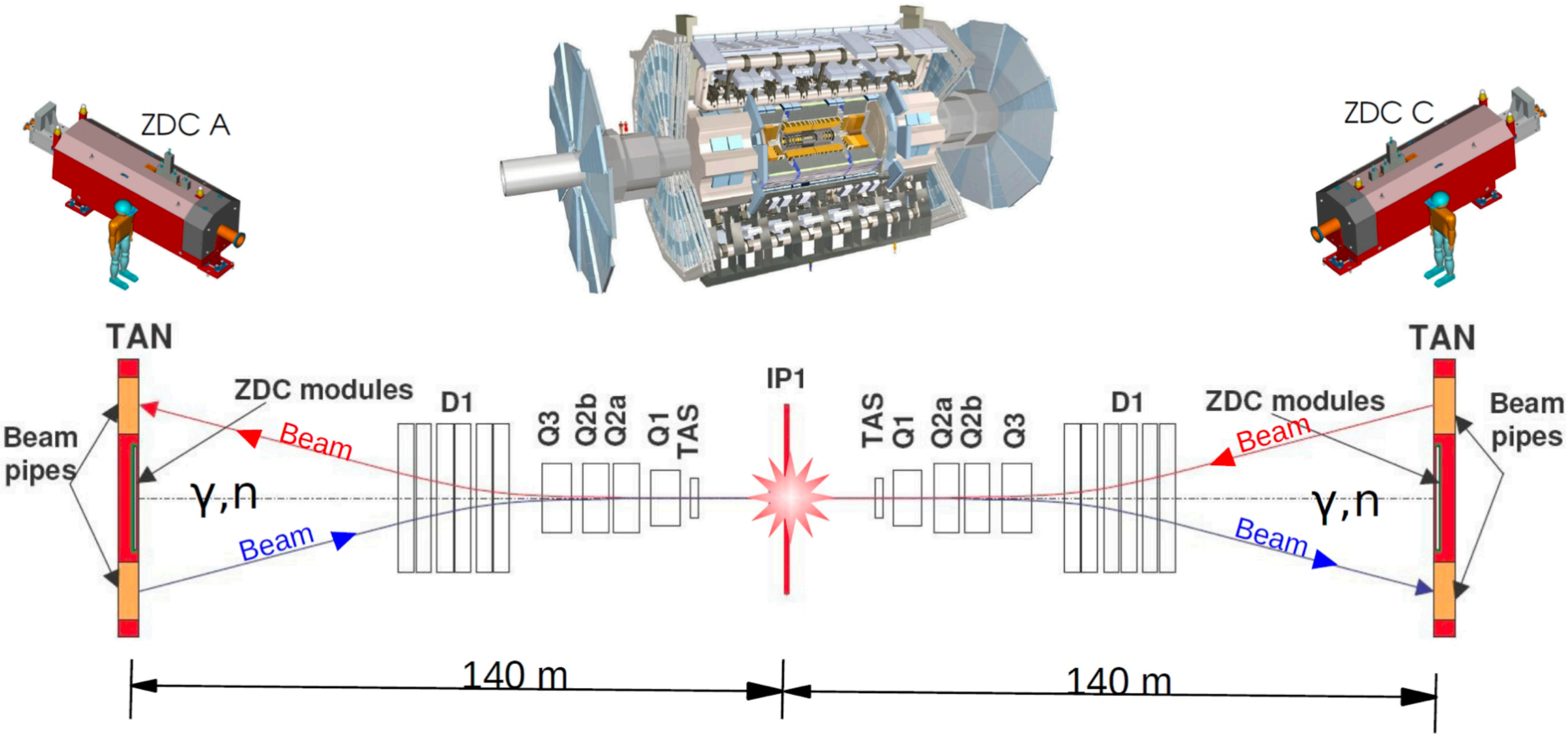




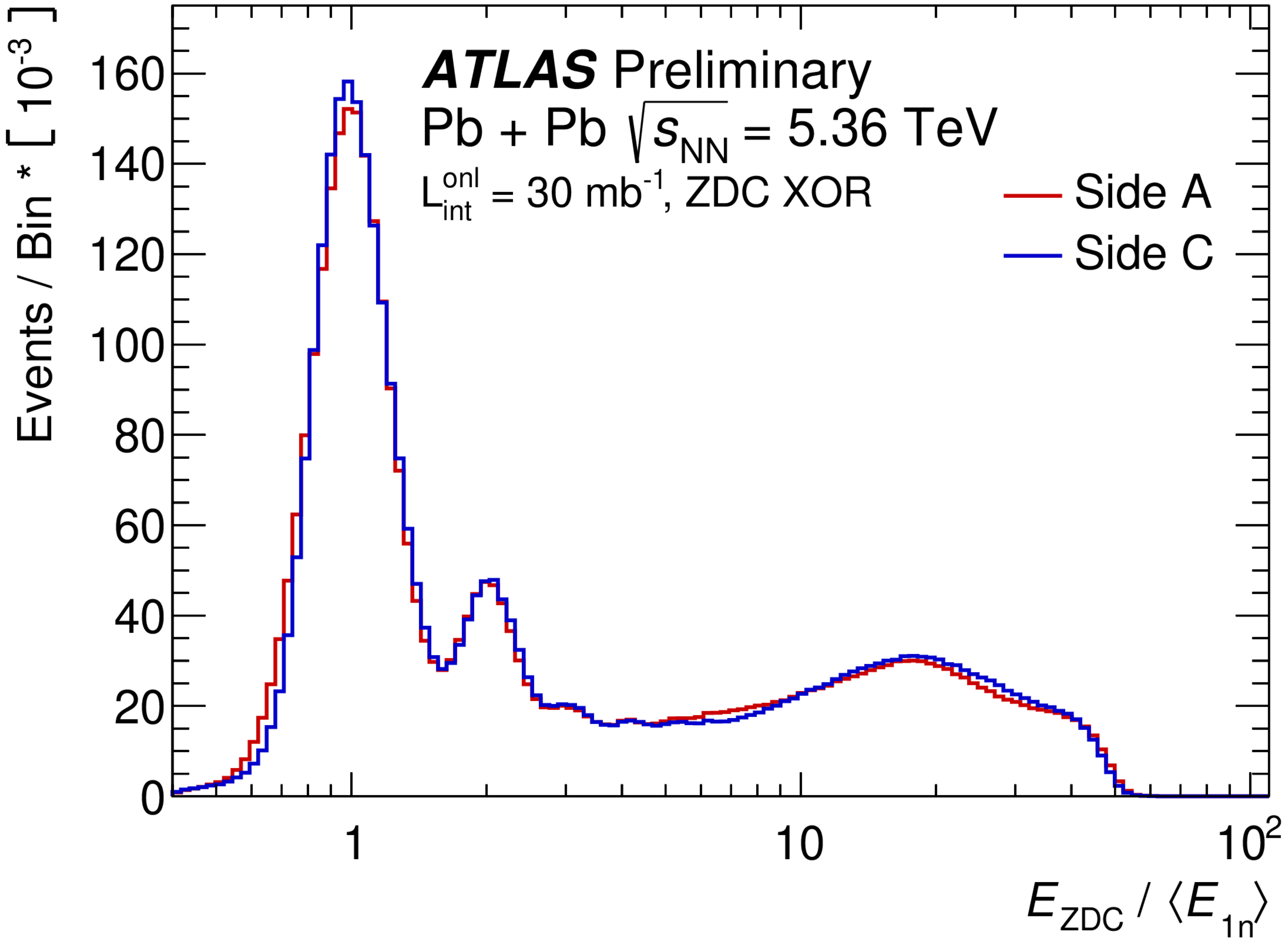

ATLAS
EXPERIMENT
Run: 367321
Event: 755541675
2018-12-01 08:30:26 CEST

Experimental considerations

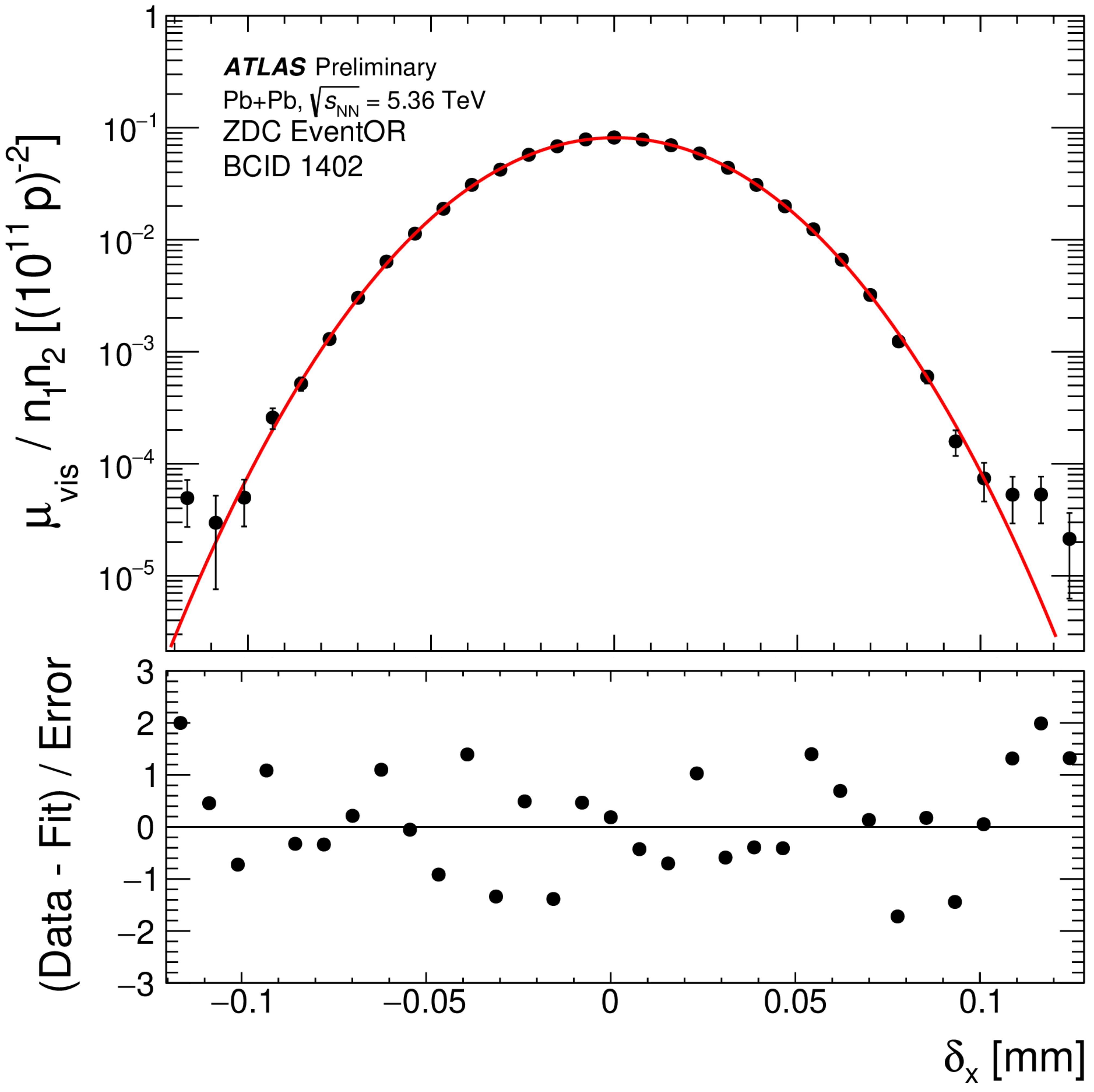
- **UPC = Rapidity gaps, exclusive final states** → veto requirements are essential
  - Many sub-detectors available in ATLAS (|eta|<4.9)
- (Absence of) ion breakup tagged with **Zero Degree Calorimeters (ZDC)**



ATLAS ZDC Run3 performance

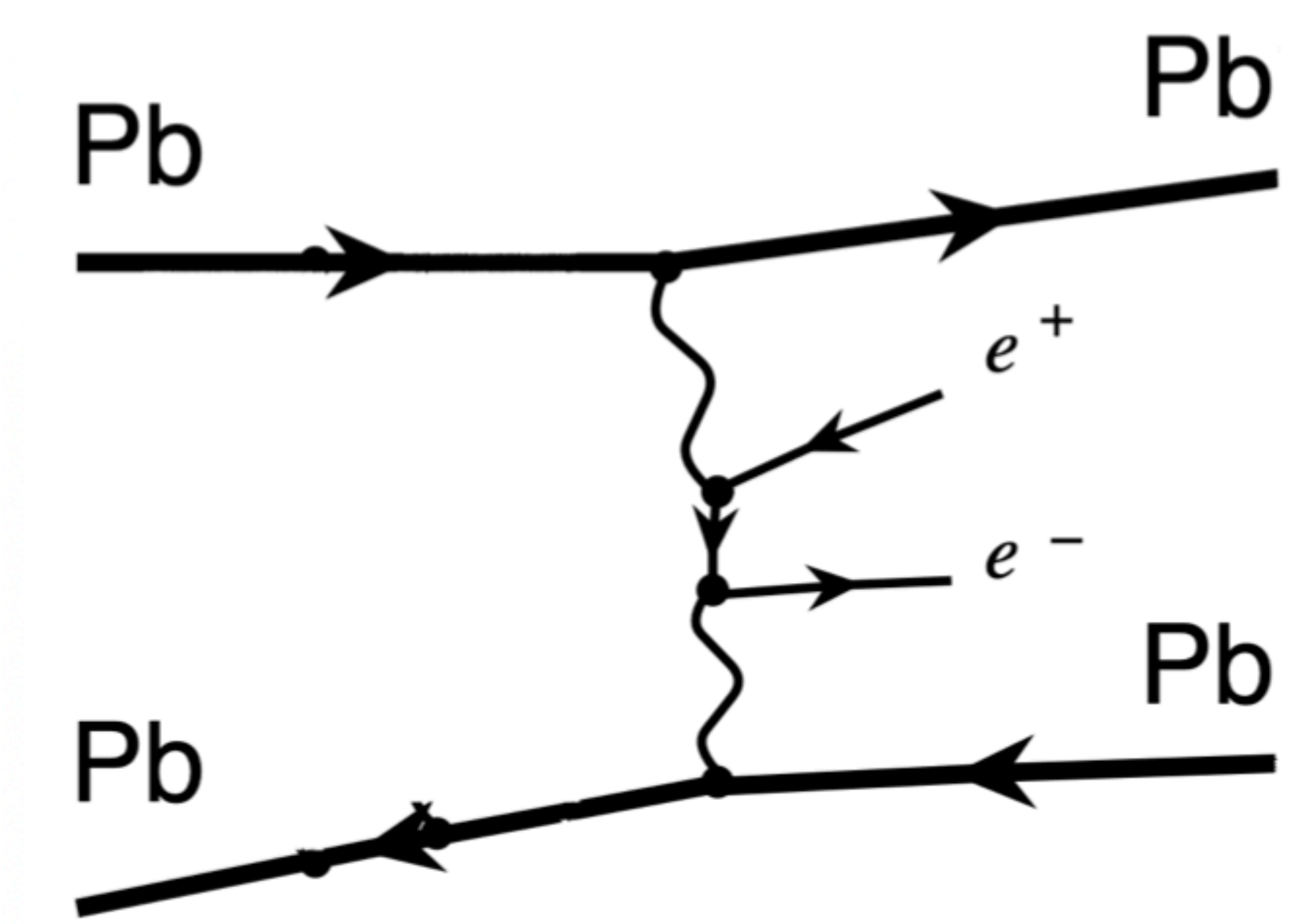


LUMI-2023-09



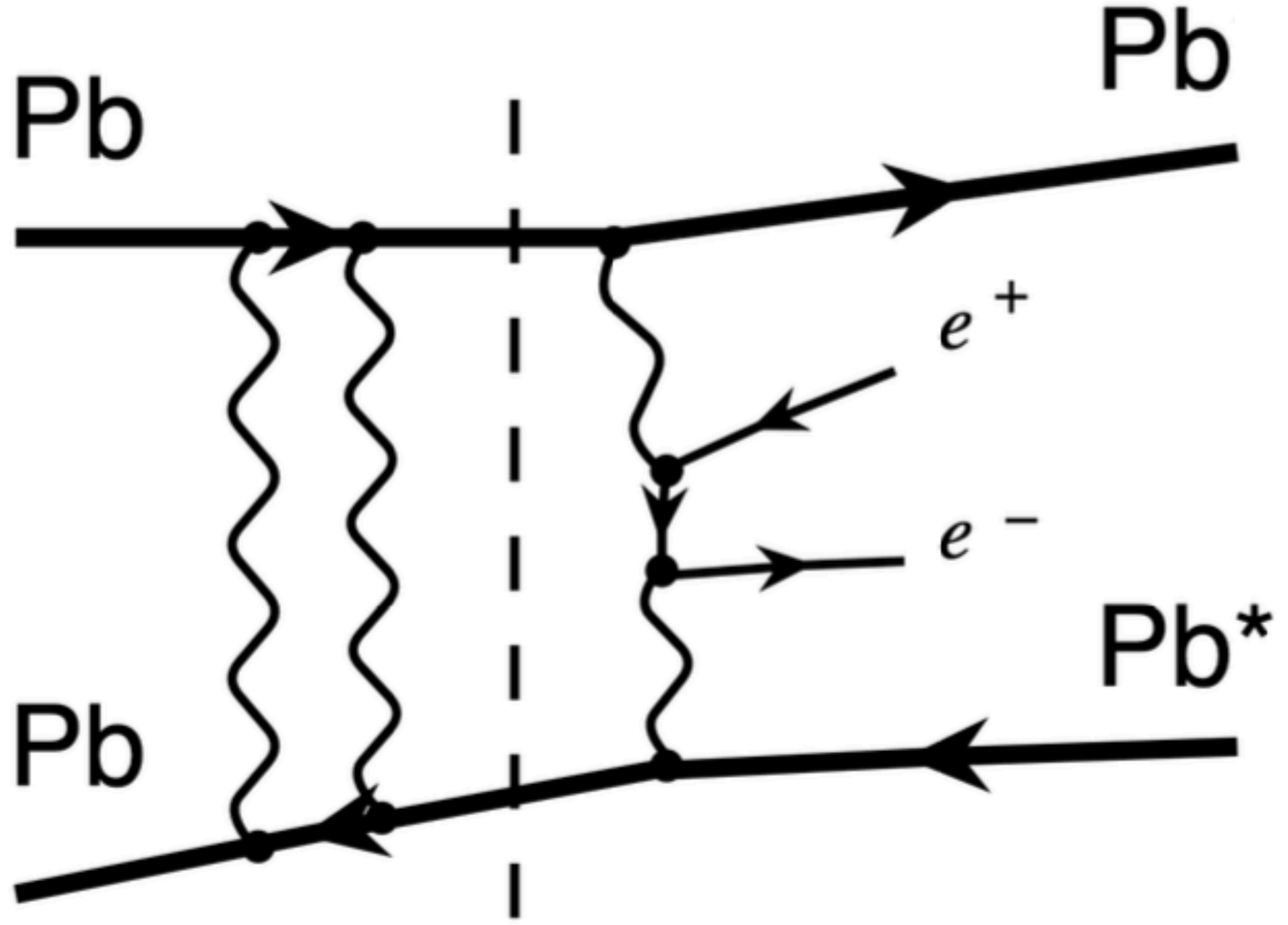
ZDC UPC categories

0n0n



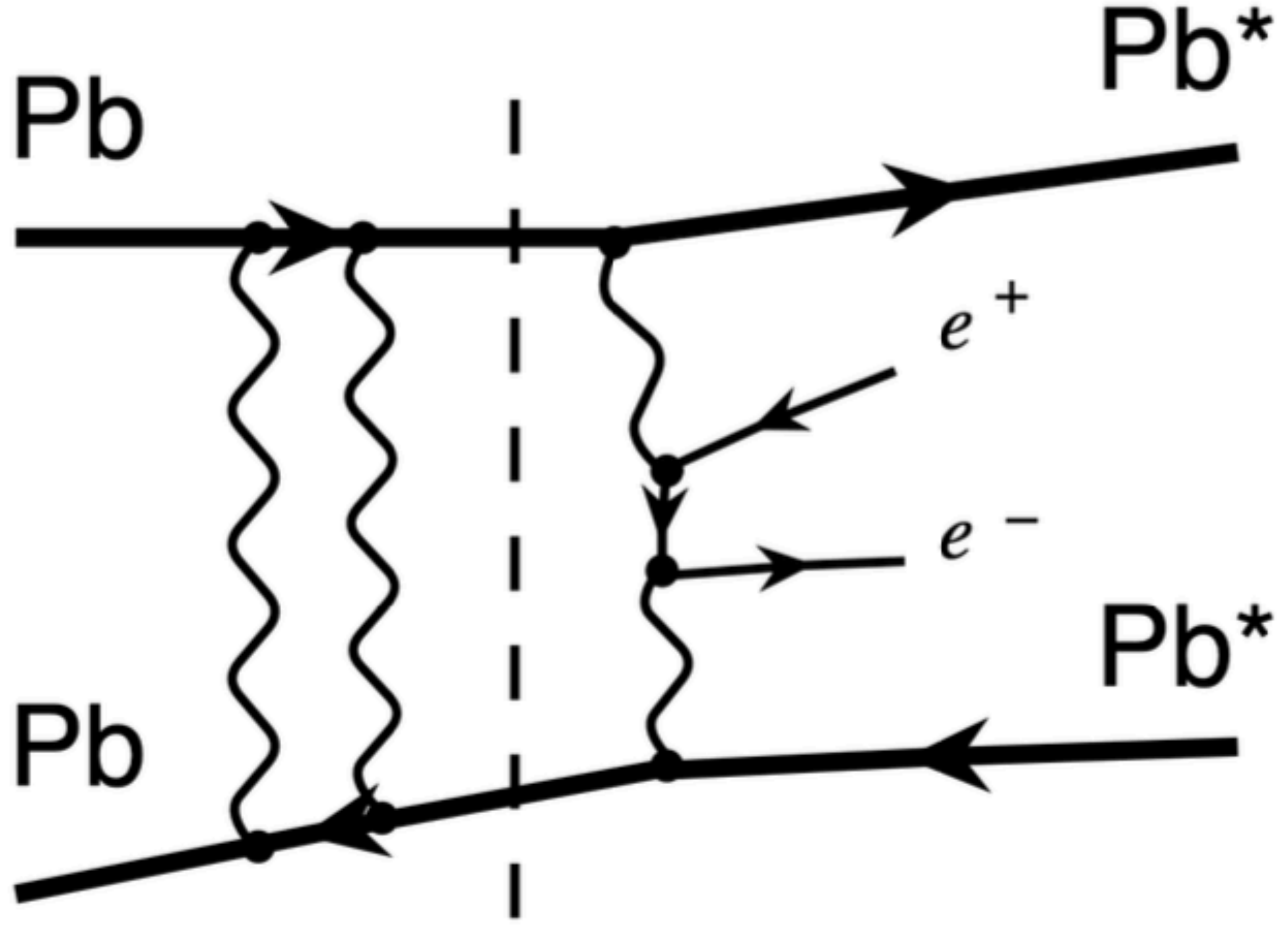
(~60% events @ m_X=30 GeV)

0nXn



(~30% events @ m_X=30 GeV)

XnXn

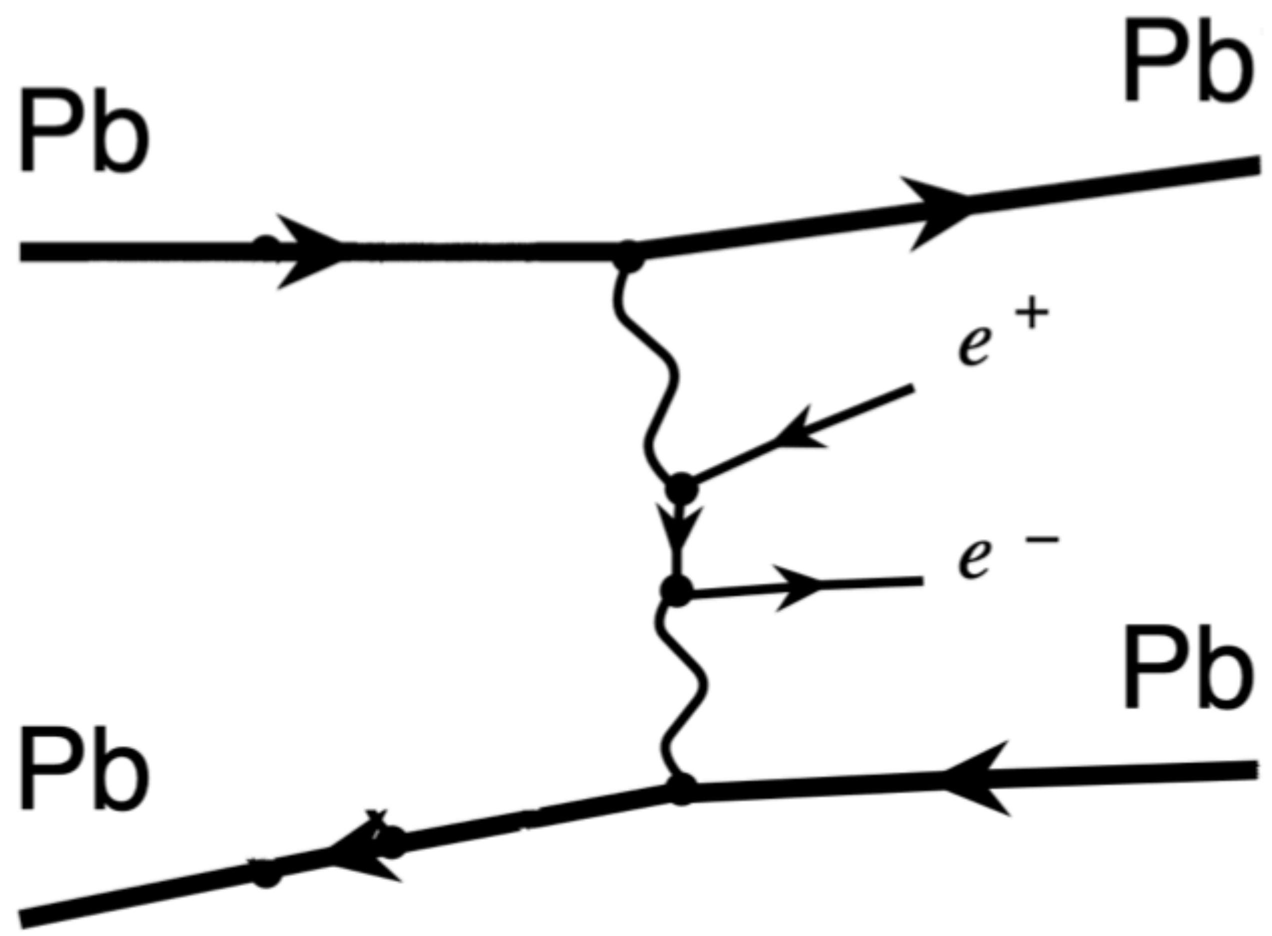


(~10% events @ m_X=30 GeV)

ZDC UPC categories

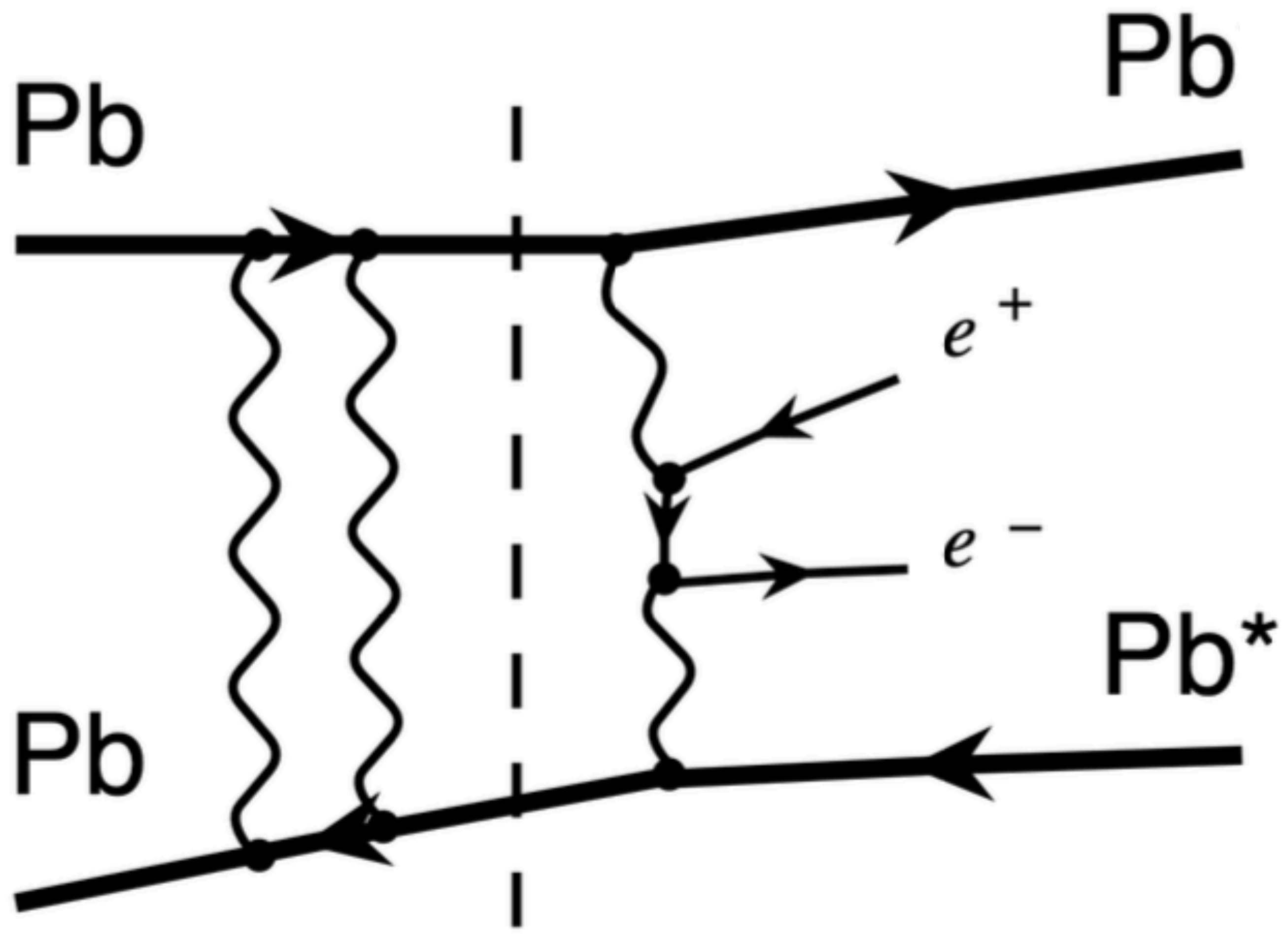
primary signal category for this search*

0n0n



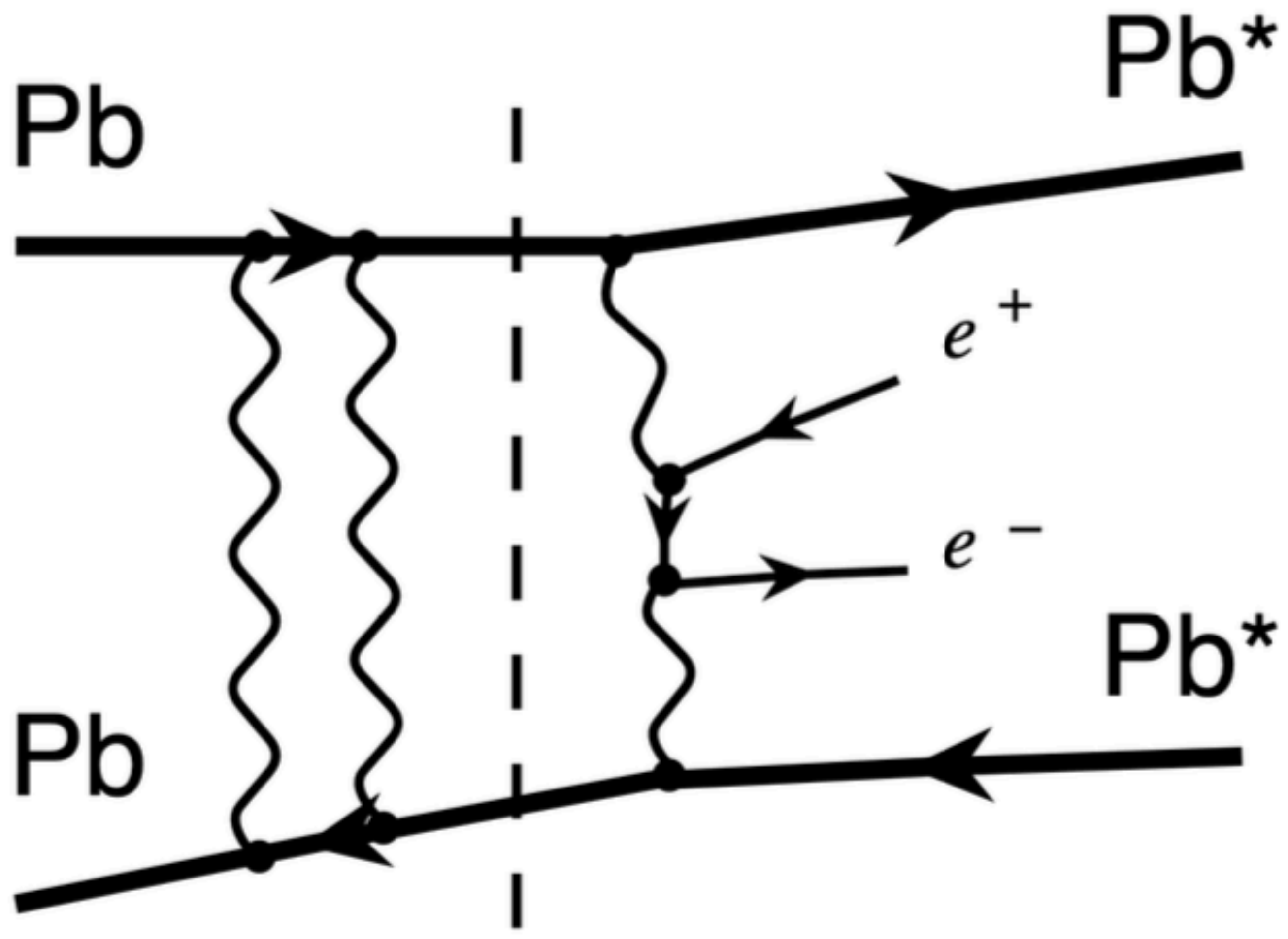
(~60% events @ m_X=30 GeV)

0nXn



(~30% events @ m_X=30 GeV)

XnXn



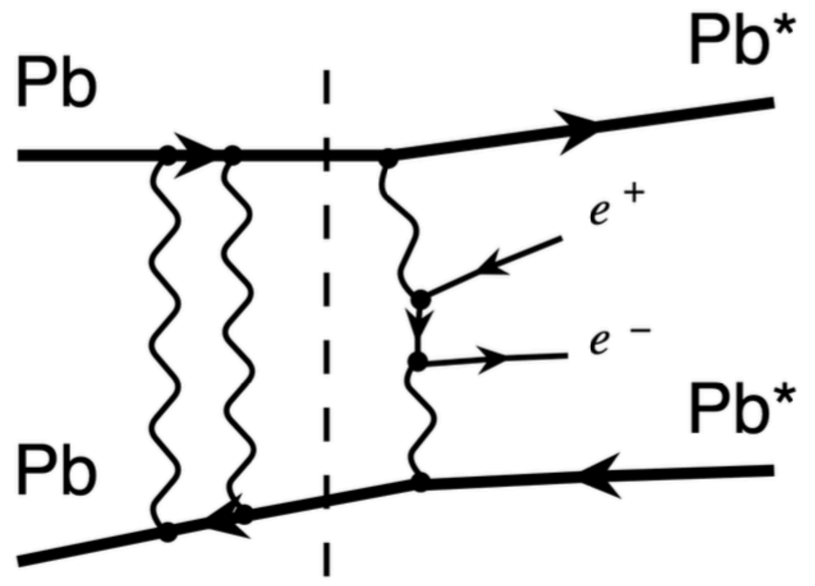
(~10%** events @ m_X=30 GeV)

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

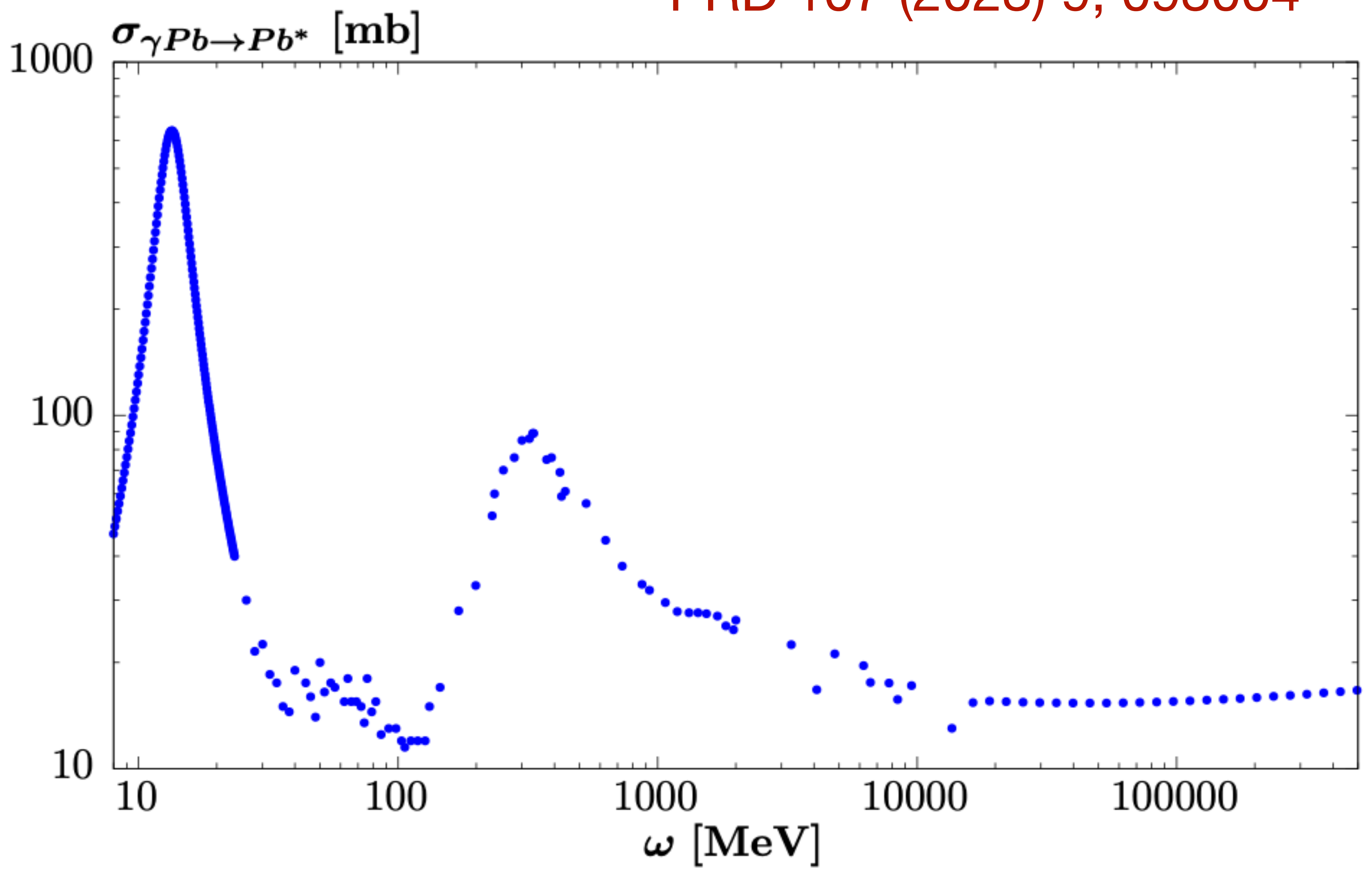
**fraction of XnXn events increases with central system mass m_X

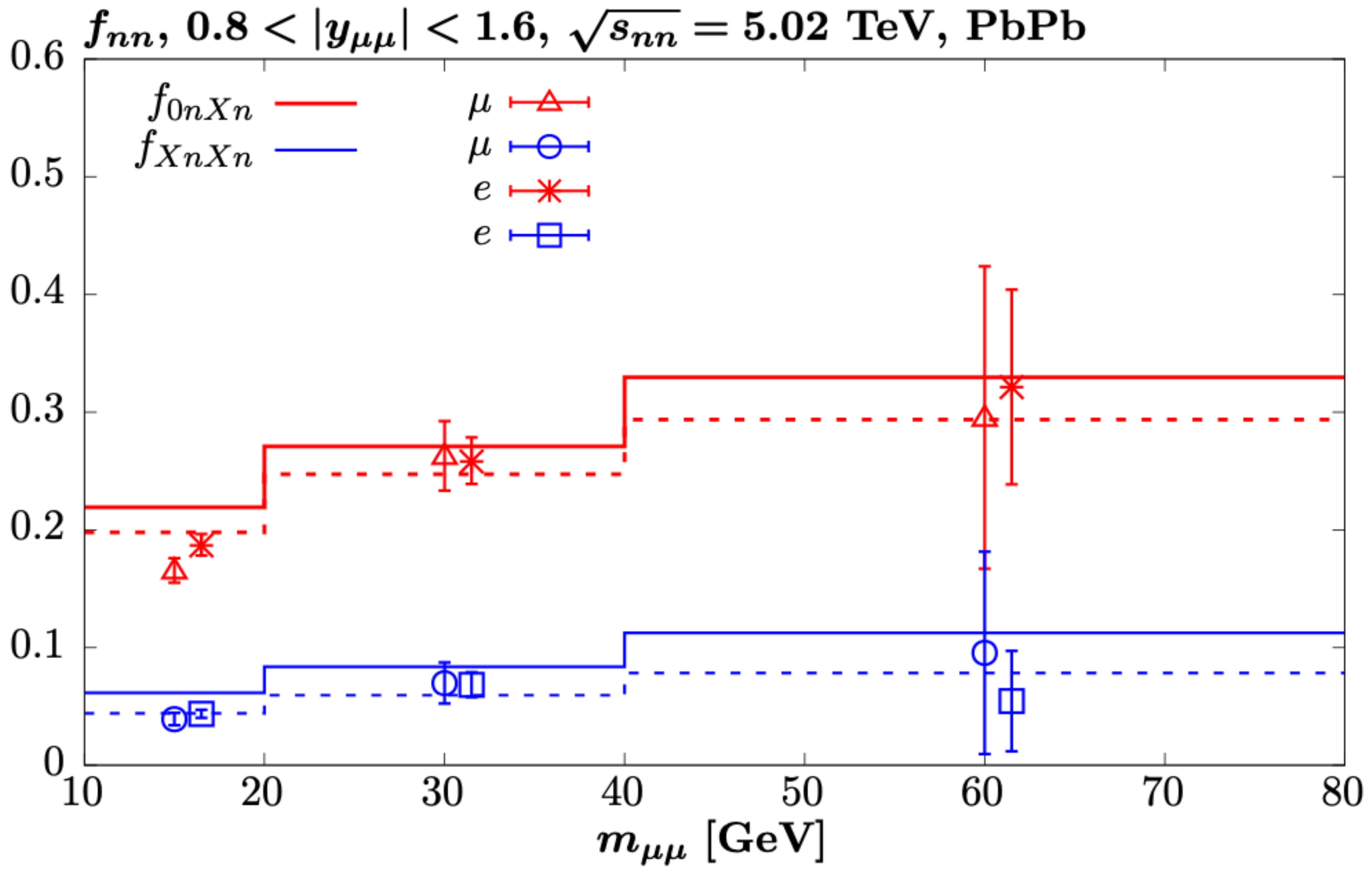
EM breakup modeling

- Models of EM breakup fractions use parameterisations based on low-energy photonuclear scattering data
  - Significant contribution from Giant Dipole Resonanace (GDR)
  - Models can describe LHC data at ~20% level



SuperChic 4.2 MC (Harland-Lang et al.)
EPJC 79 (2019) 1, 39
PRD 107 (2023) 9, 093004



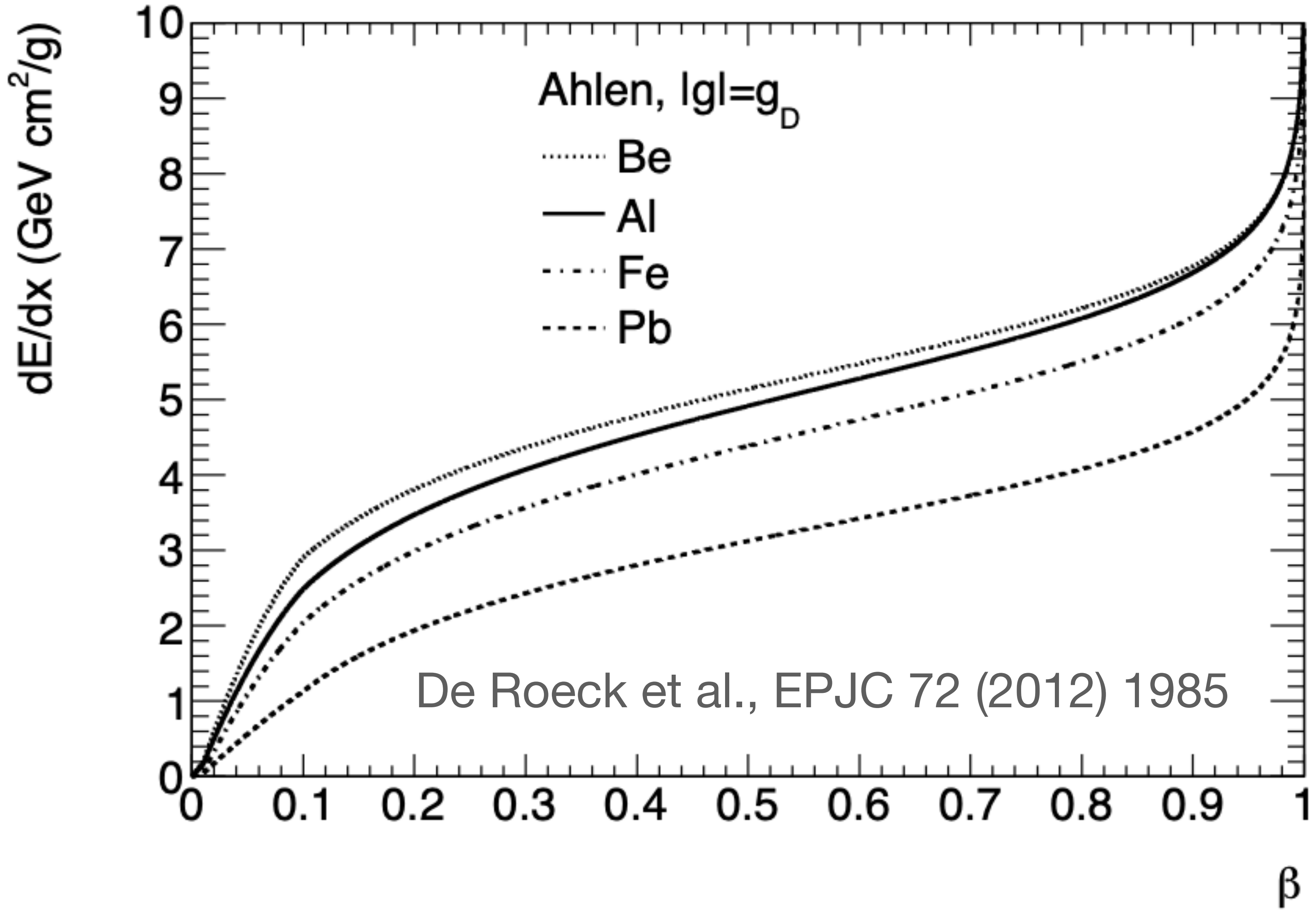


Monopole interactions in the detector

Ahlen, Phys. Rev. D 17 (1978) 229

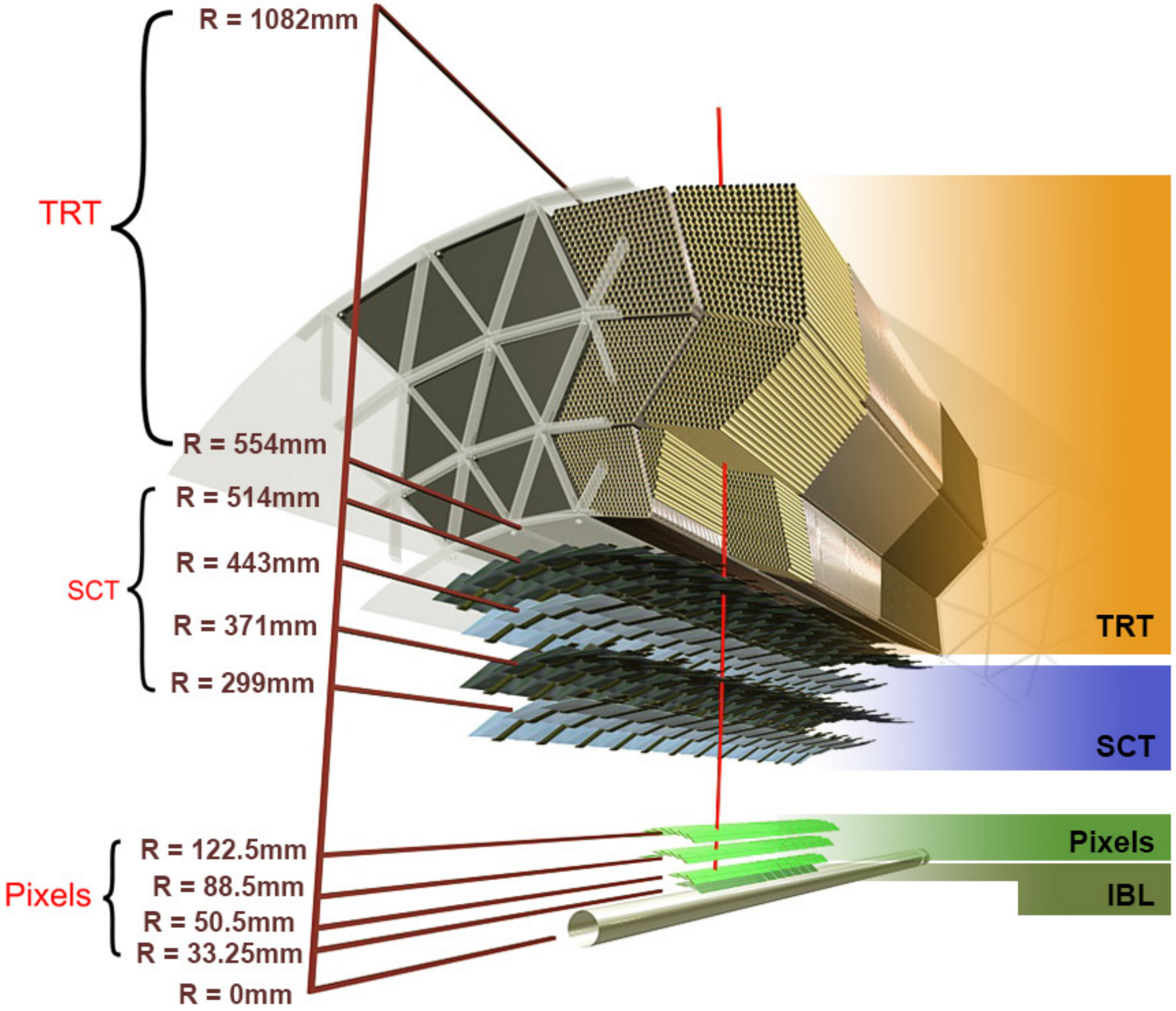
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m} + \frac{K(|g|)}{2} - \frac{1}{2} - B(|g|)\right]$$

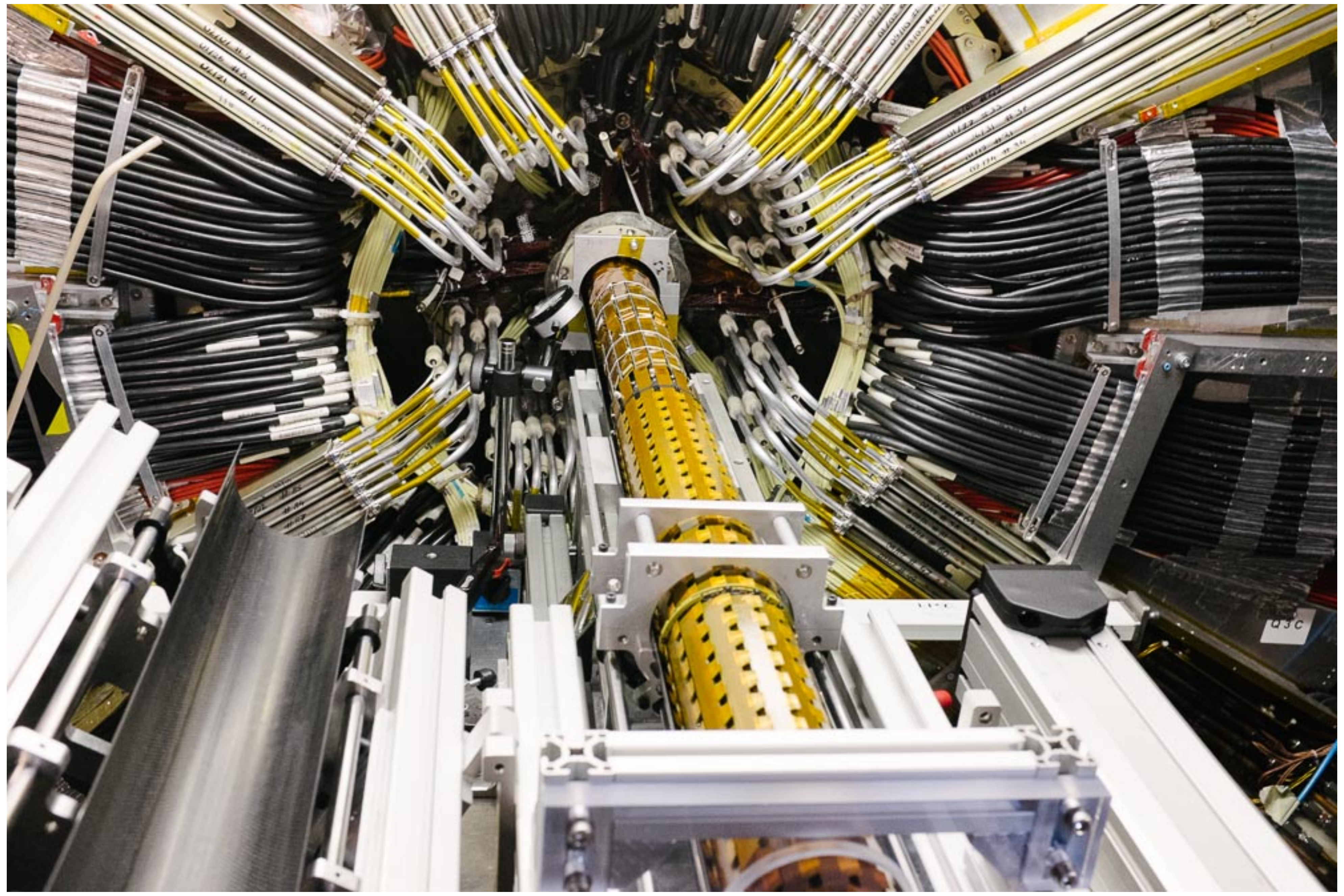
- Energy loss
  - Ionization dominates
  - For $g=1g_D$ and $\beta\sim1$: **$(dE/dx)_{MM} \approx 5000\ (dE/dx)_{MIP}$**
  - Highly ionising particle (HIP) → lots of **δ-rays** near trajectory
  - Slow monopoles → less ionisation



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

The ATLAS Inner Detector (ID)

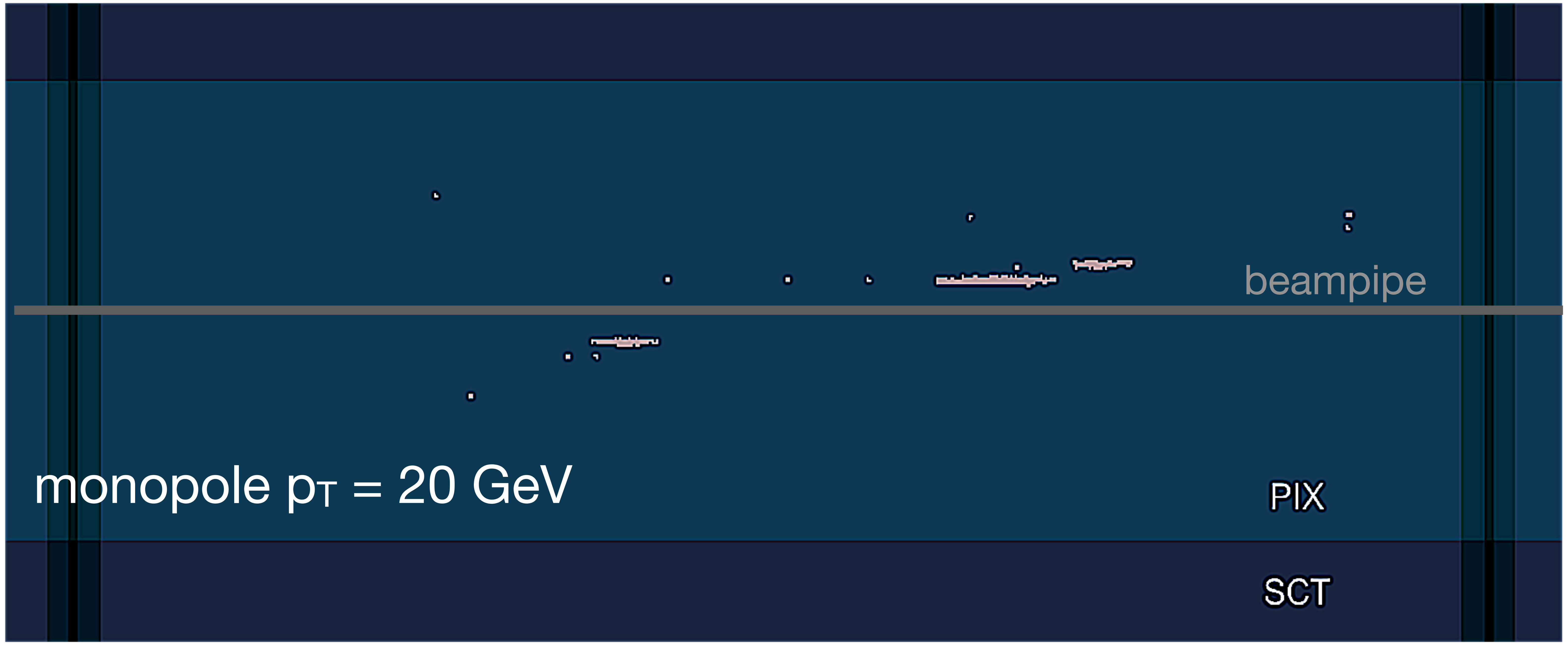




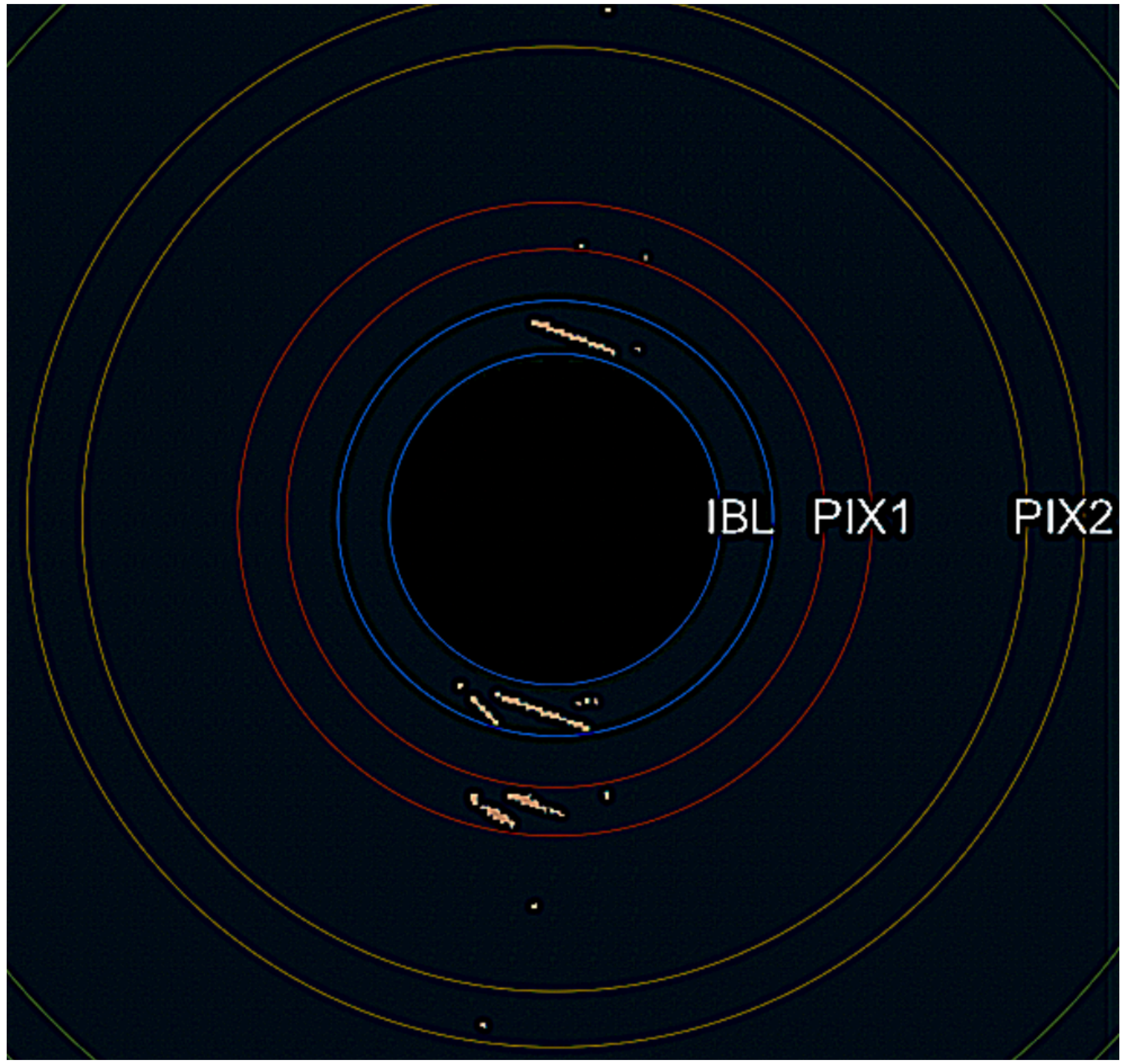
Low-energy monopole interactions in ATLAS

- Simulated pairs of monopoles in UPC (each w/ m=20 GeV)
  - Large activity in the **Pixel detector**
  - Monopoles with p_T <~30 GeV typically do not reach SCT

Longitudinal detector view



Transverse view (Pixel detector only)



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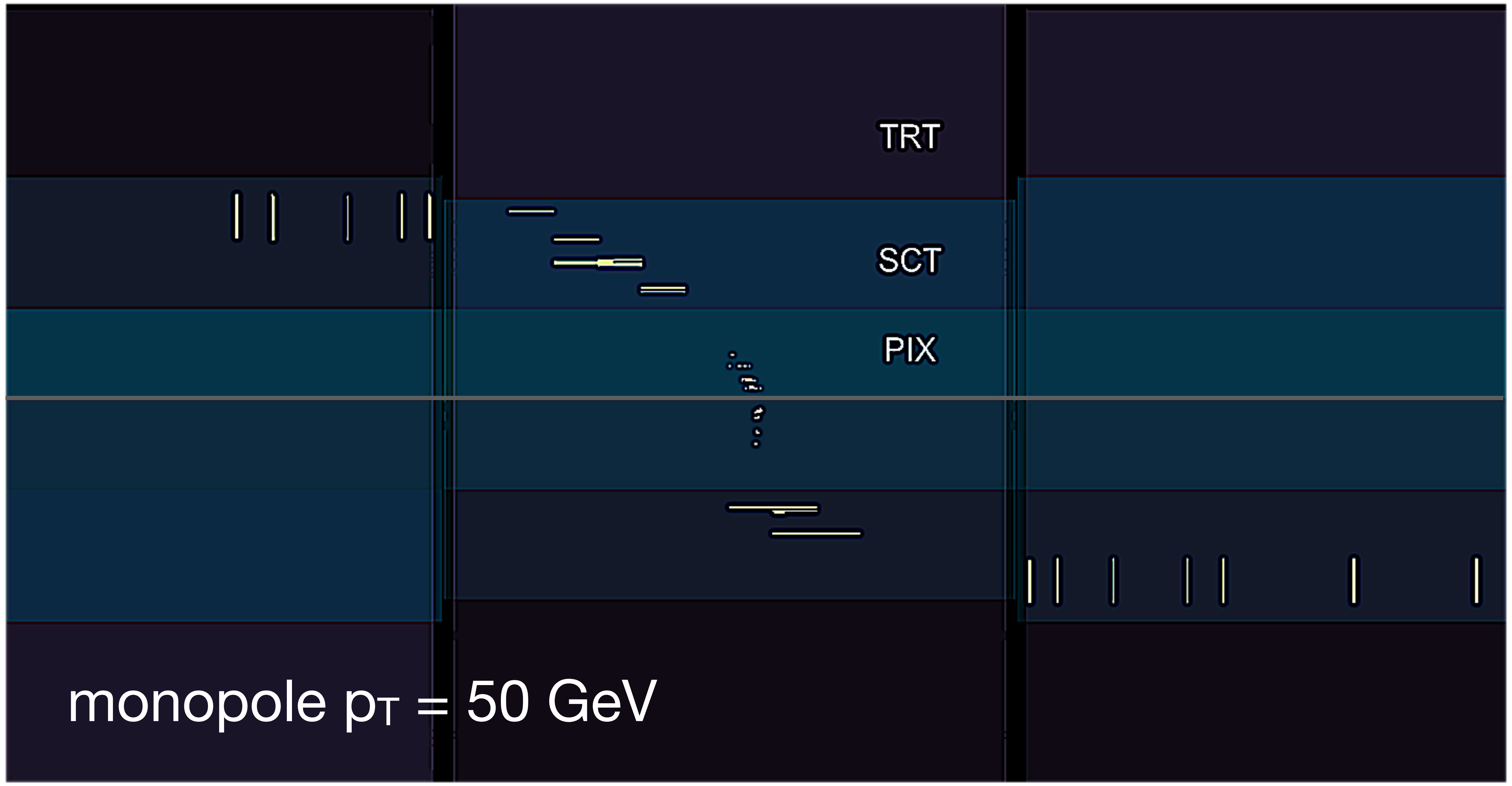

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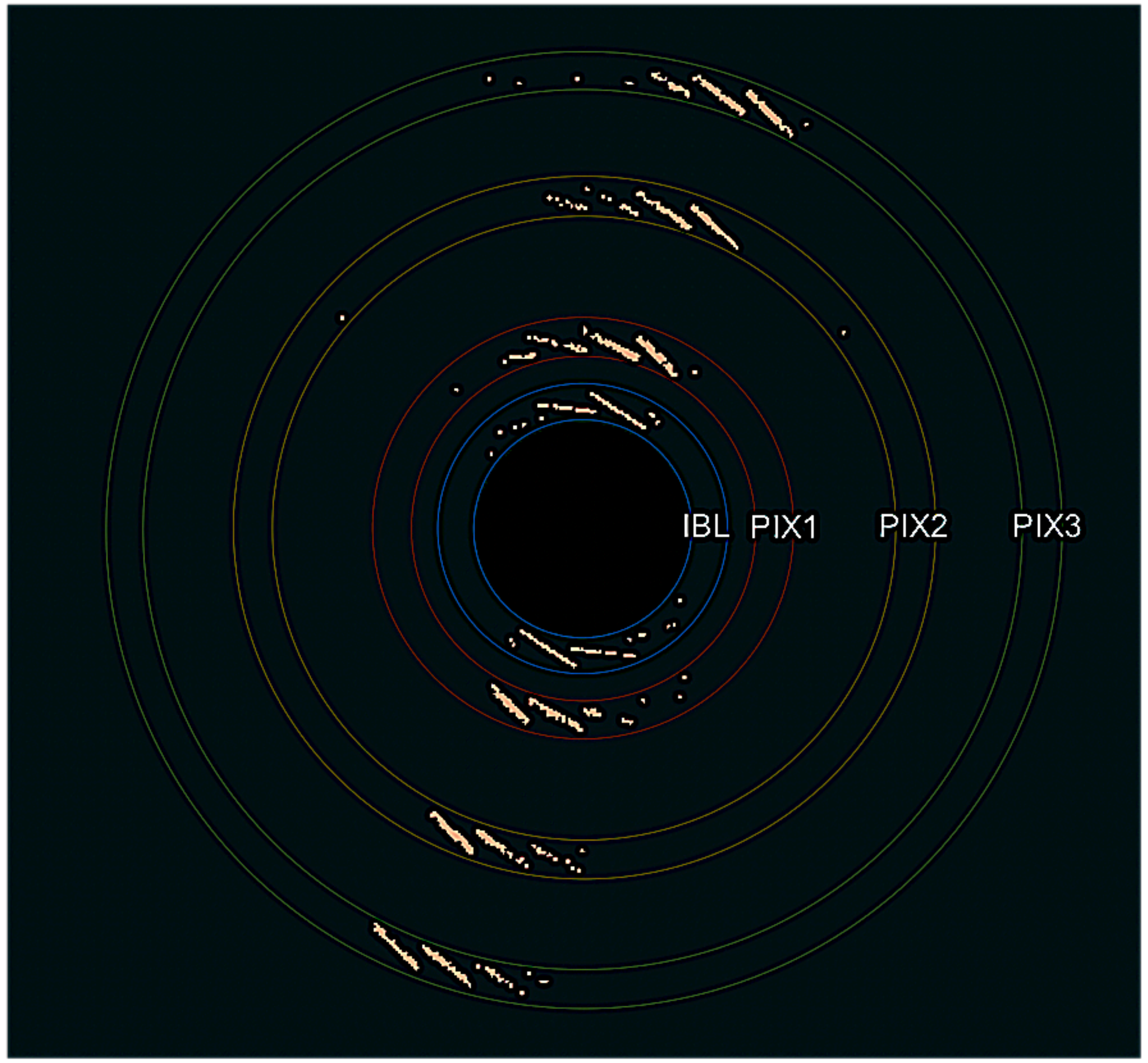

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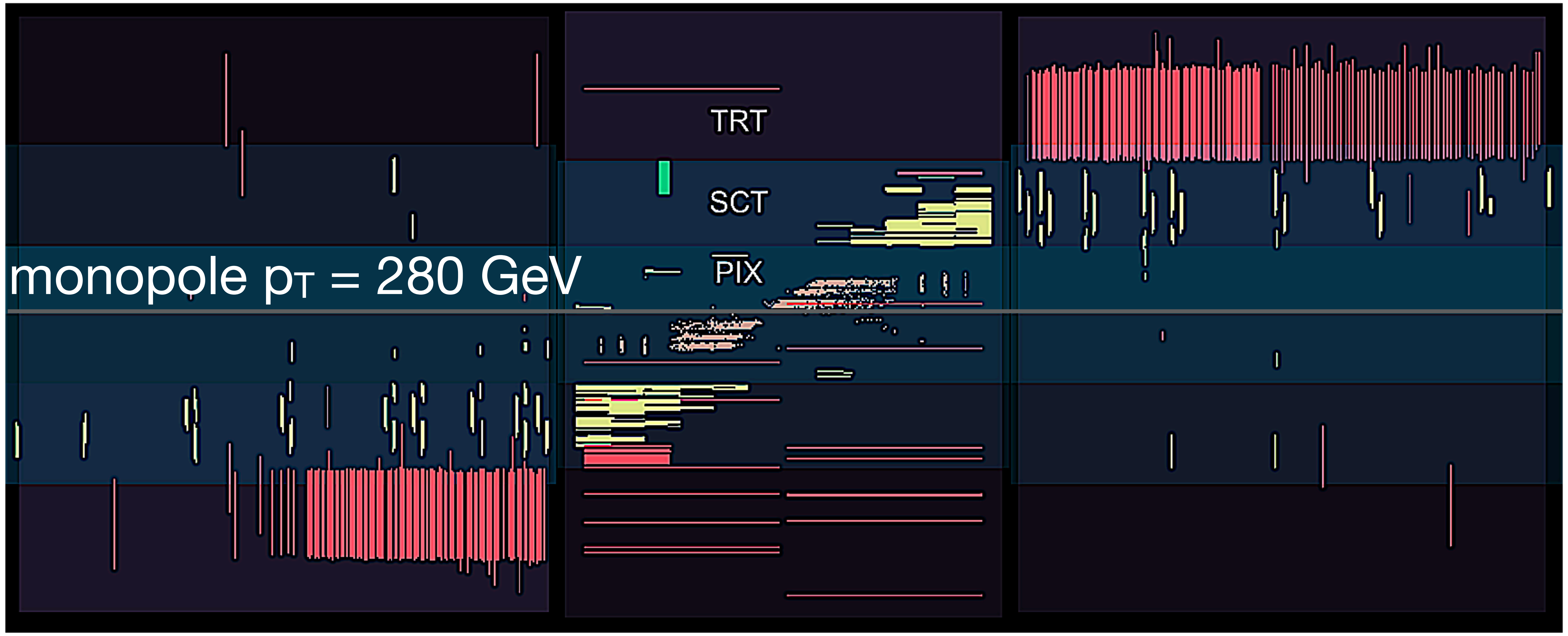
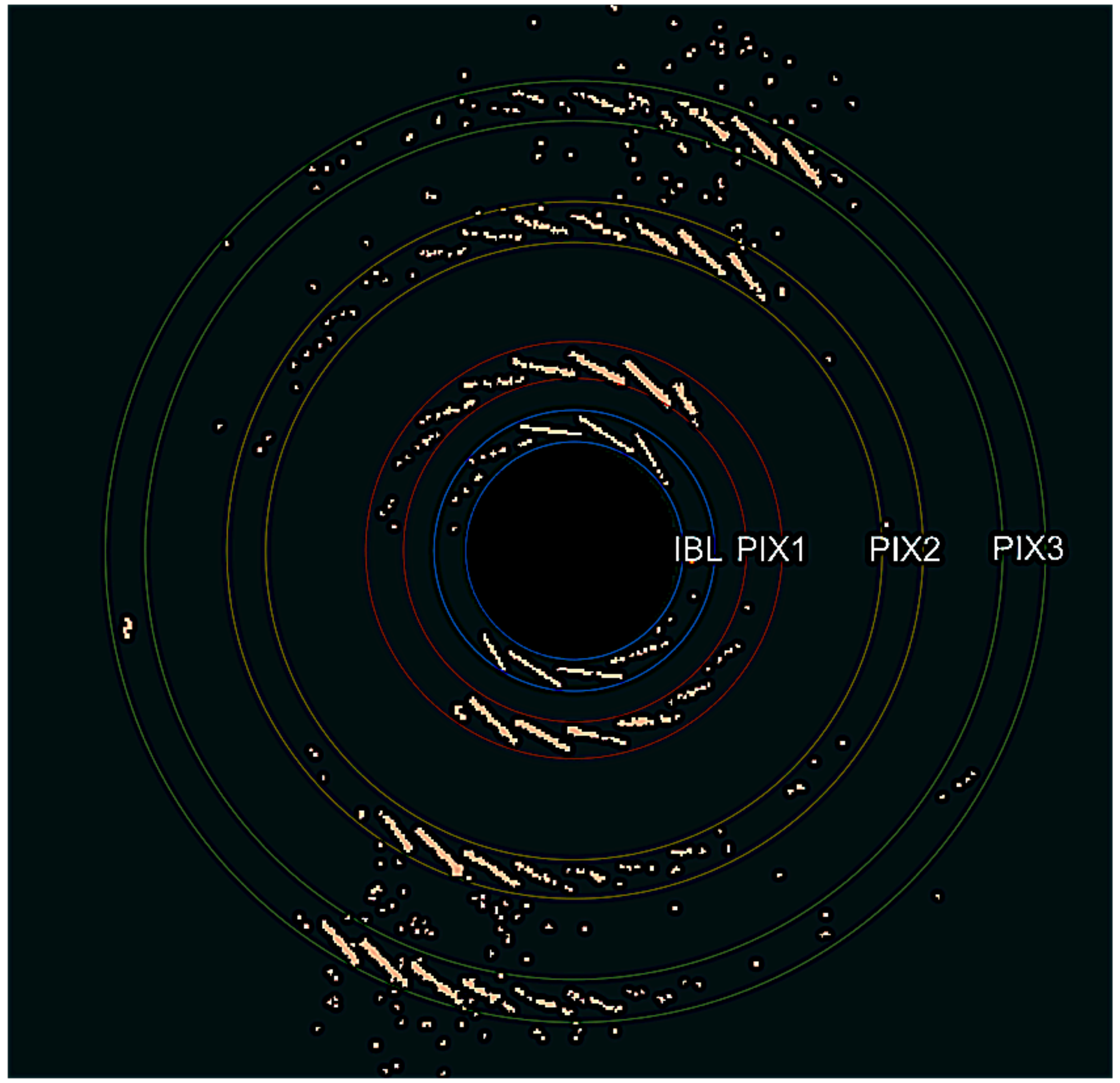
- Simulated pairs of monopoles in UPC (each w/ m=20 GeV)
  - Large activity in the **Pixel detector**
  - Monopoles with p_T <~30 GeV typically do not reach SCT
  - Monopoles with p_T <~300 GeV do not reach calorimeter

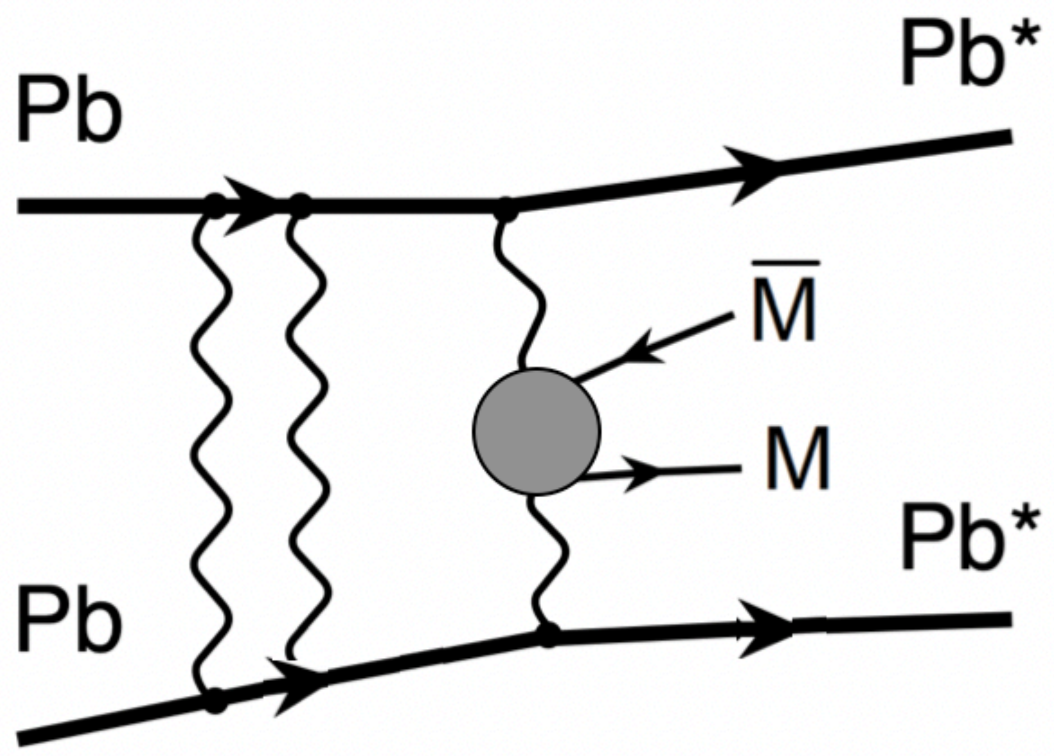
Longitudinal detector view



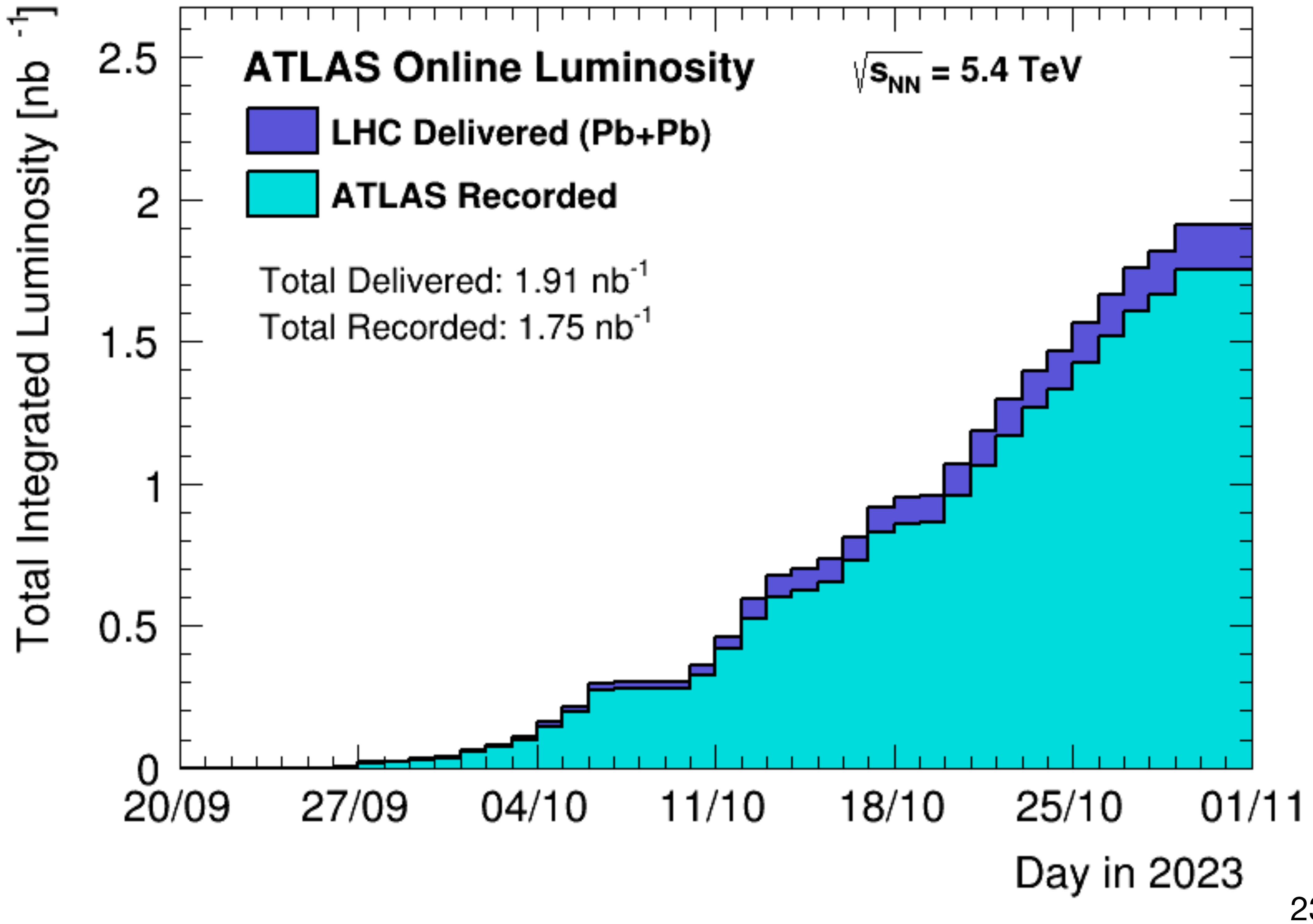
Transverse view (Pixel detector only)



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 + veto on total transverse energy in calo (E_T<10 GeV)
  - **HLT**: **> 100 Pixel clusters** w/o any specific tracking selection
  - 1.7/nb → 0.262/nb due to enormous rate from mutual EM dissociation (L1 trigger prescale)



- **Supporting trigger** (for background estimation):
  - ZDC signal exactly on one side (ZDC_XOR) plus remaining selections as for the signal trigger

Signal simulation

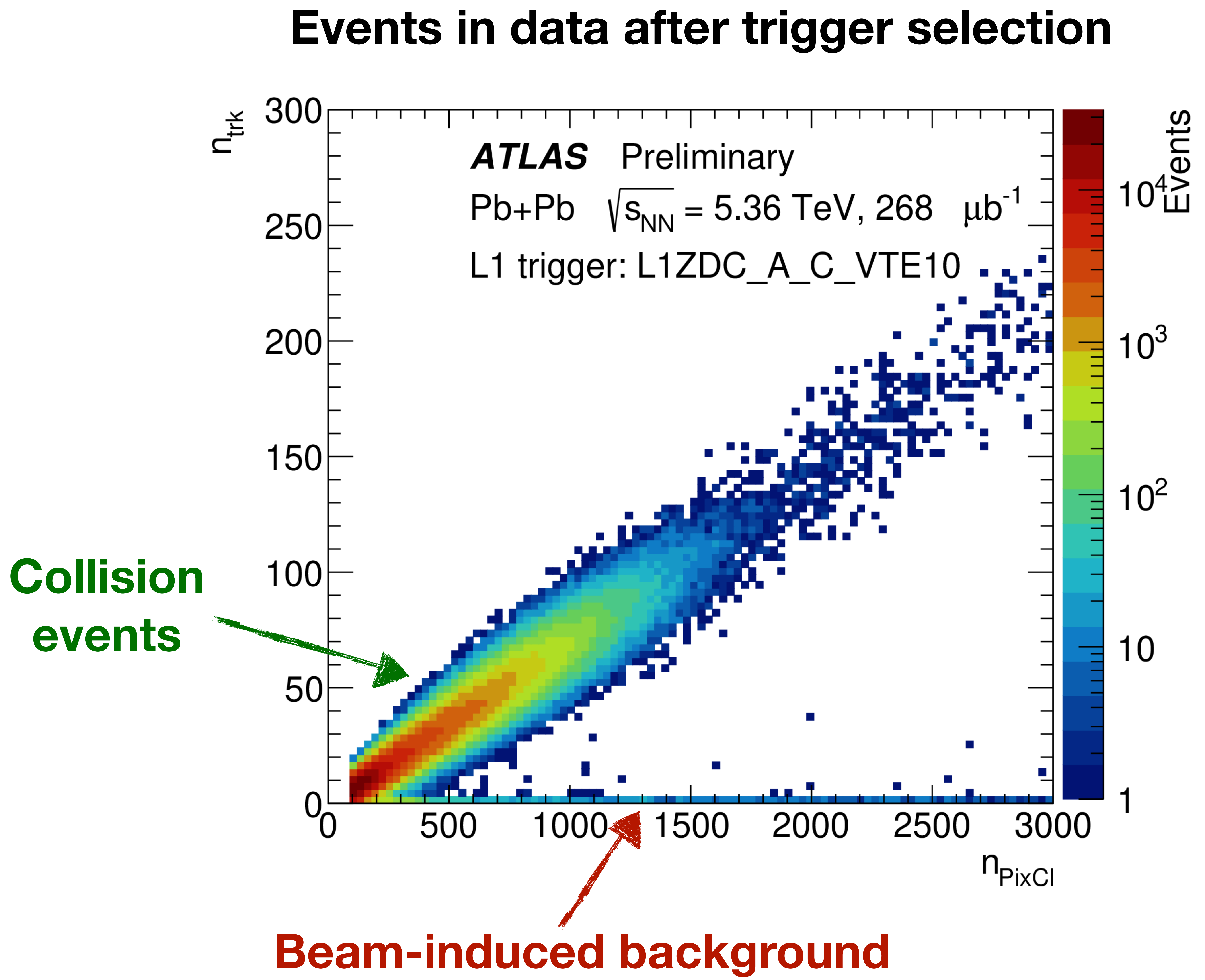
- Use predictions based on the semiclassical model
  - **Free Particle Approximation (FPA)**
    [Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021)]
  - Monopole coupling with initial magnetic fields treated exactly (up to all orders); neglecting possible monopole self-interactions
  - Monopole kinematics based on simplified model with back-to-back monopole production and sampled momentum:

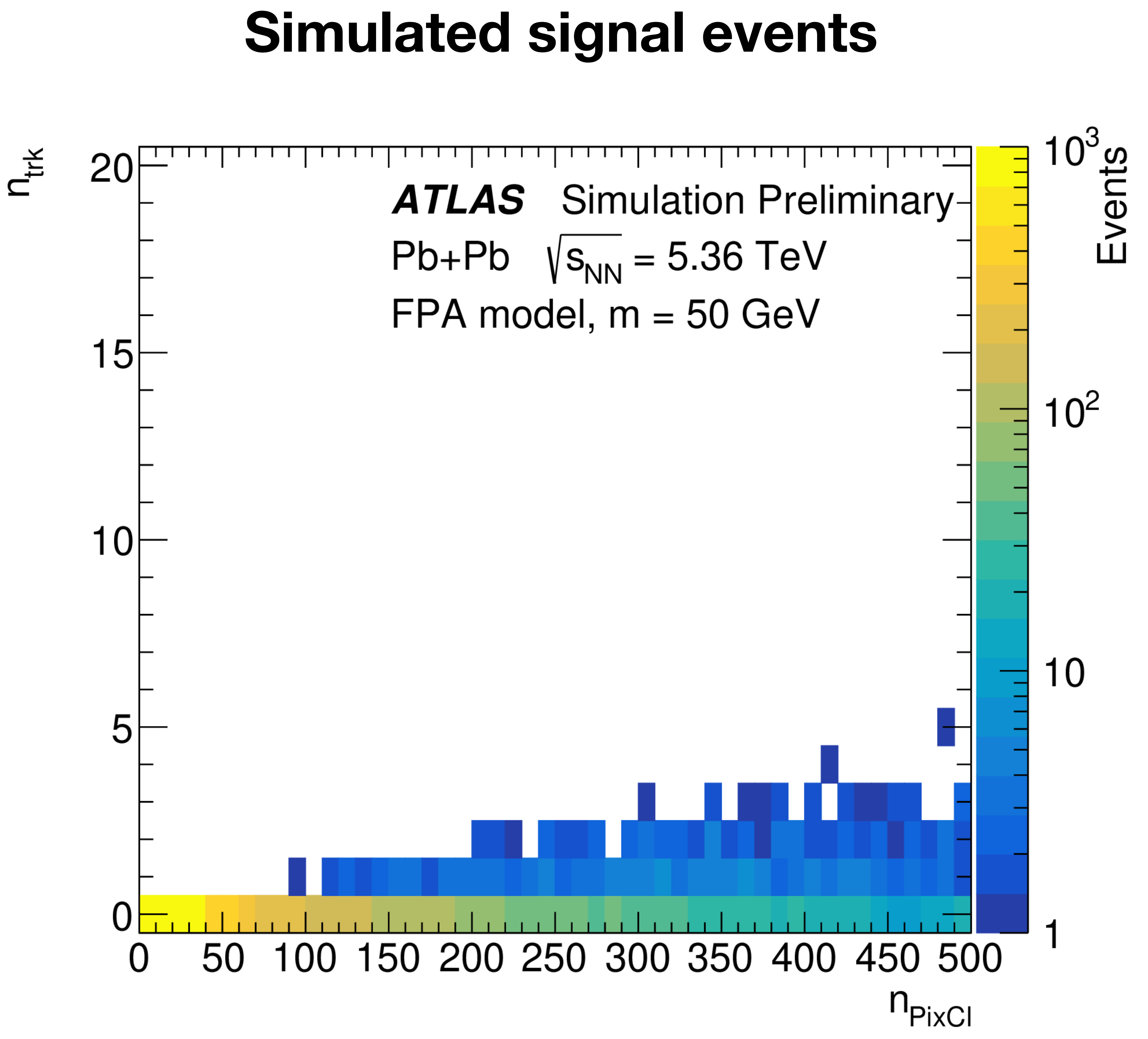
$$d\sigma_{\mathrm{FPA}}(|p|)/d\sigma_{\mathrm{FPA}}(0) = \exp\left[-\frac{4}{\omega}\left(\sqrt{m^2 + |p|^2} - m\right)\right]$$

  - Same model as used by MoEDAL
  - Exploring only **g=1g$_D$**

- Detector simulation
  - Benefits from previous ATLAS pp searches
  - Includes descriptions of **monopole acceleration** in the detector magnetic field, **ionization** energy losses in matter and δ**-electron production** along the monopole trajectory

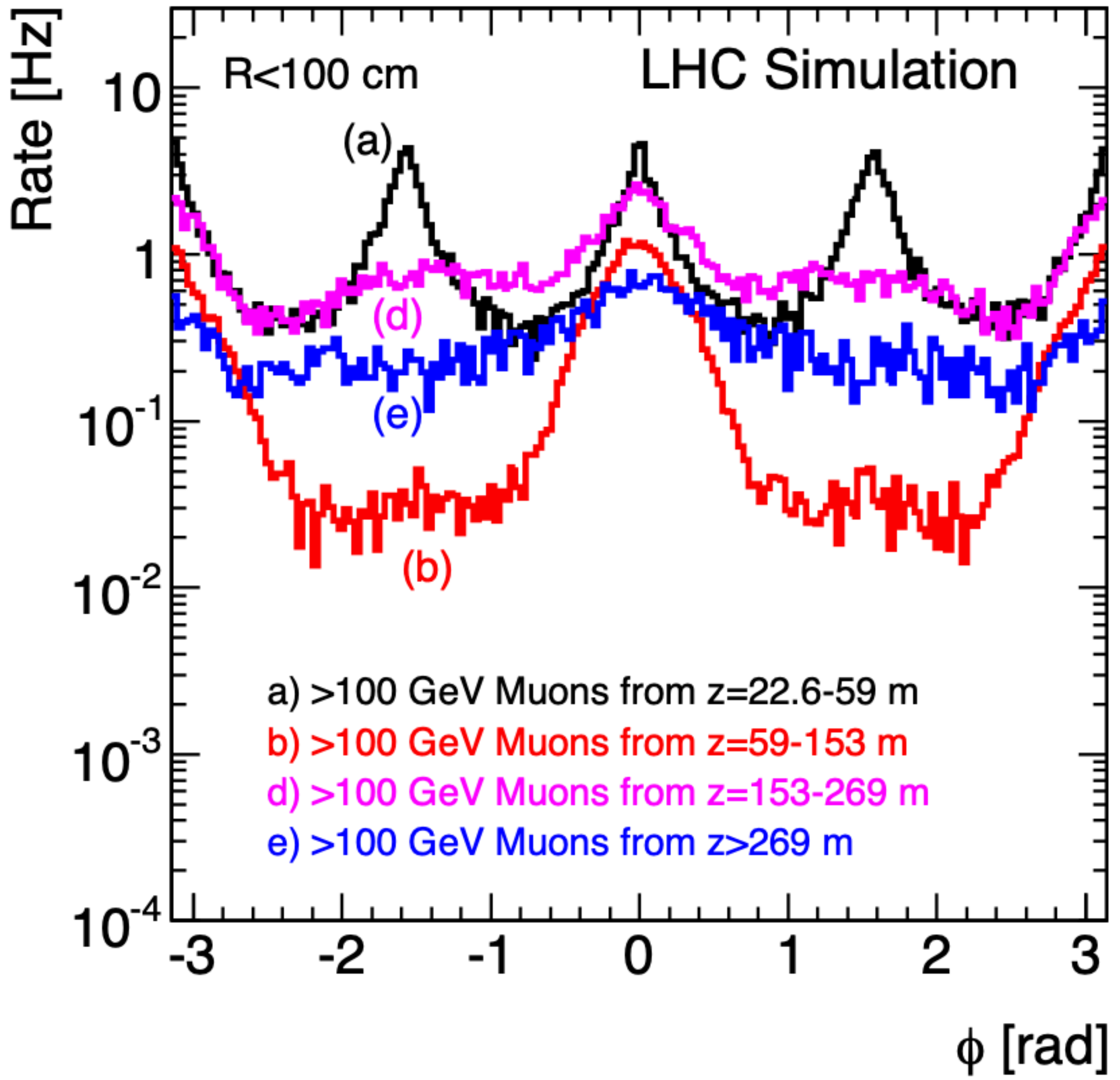
Event properties



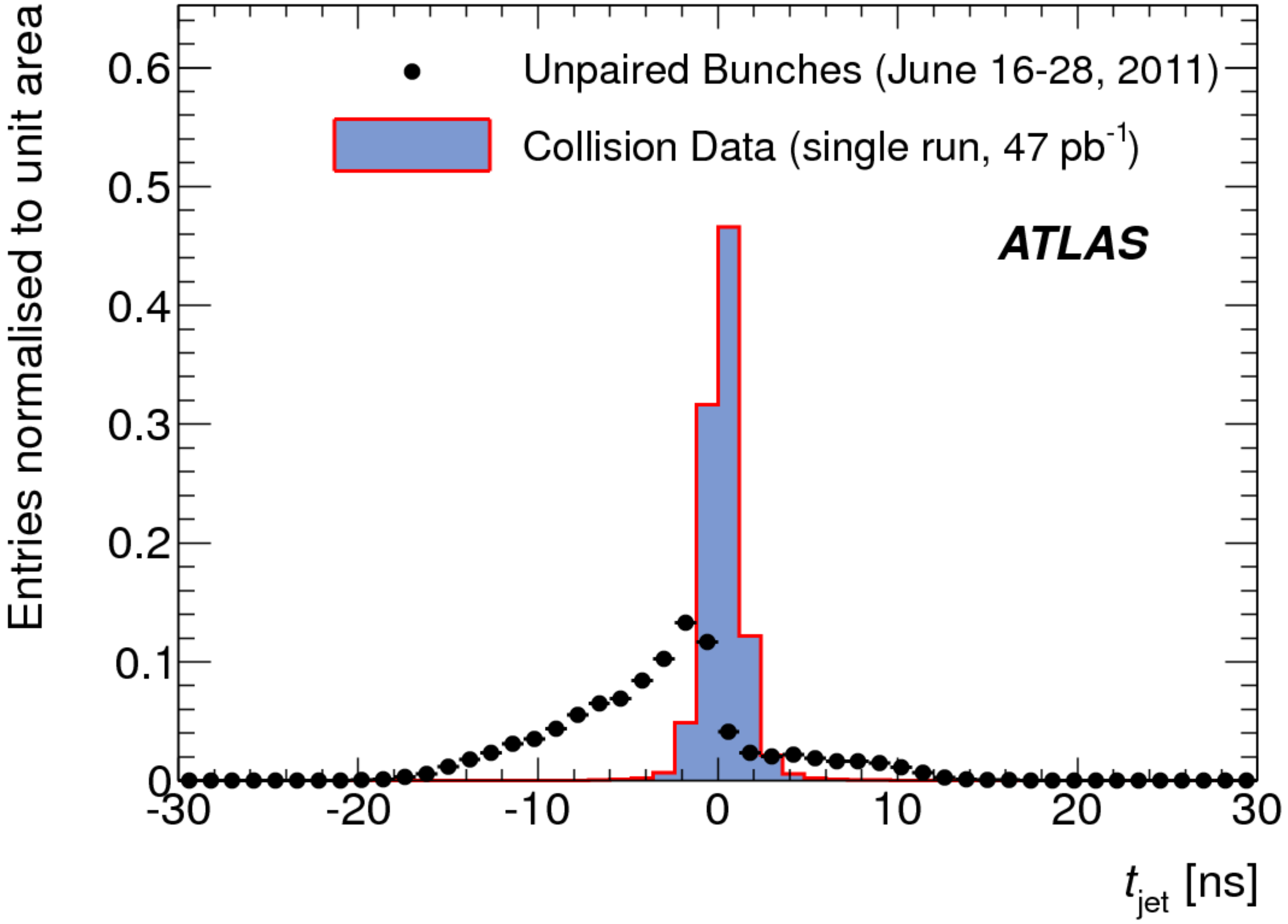


Beam induced background (BIB) characteristics

ATLAS, JINST 8 (2013) P07004



BIB particles largely deflected in the horizontal plane by LHC magnets



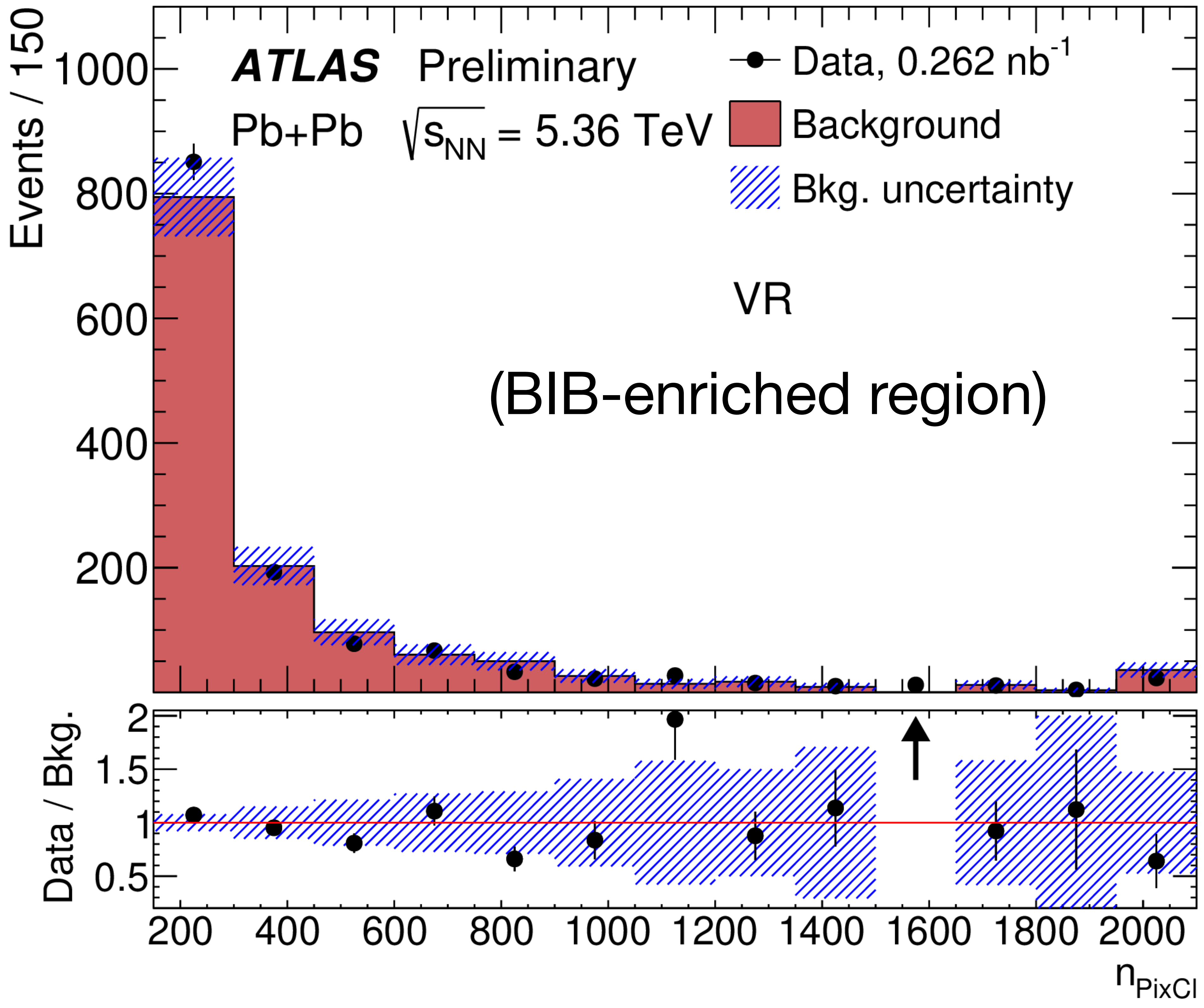
Fake jets from OOT energy deposits

Event selection

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

⇒ to remove **collision bkg**

- $N_{PixelClusters} > 150$, including $N_{IBLclusters} > 50$
  → suppress **BIB**
- Fraction of Pixel clusters from a single module, $f_{leading\text{-}module} < 0.9$
  → to suppress events from **noisy modules**



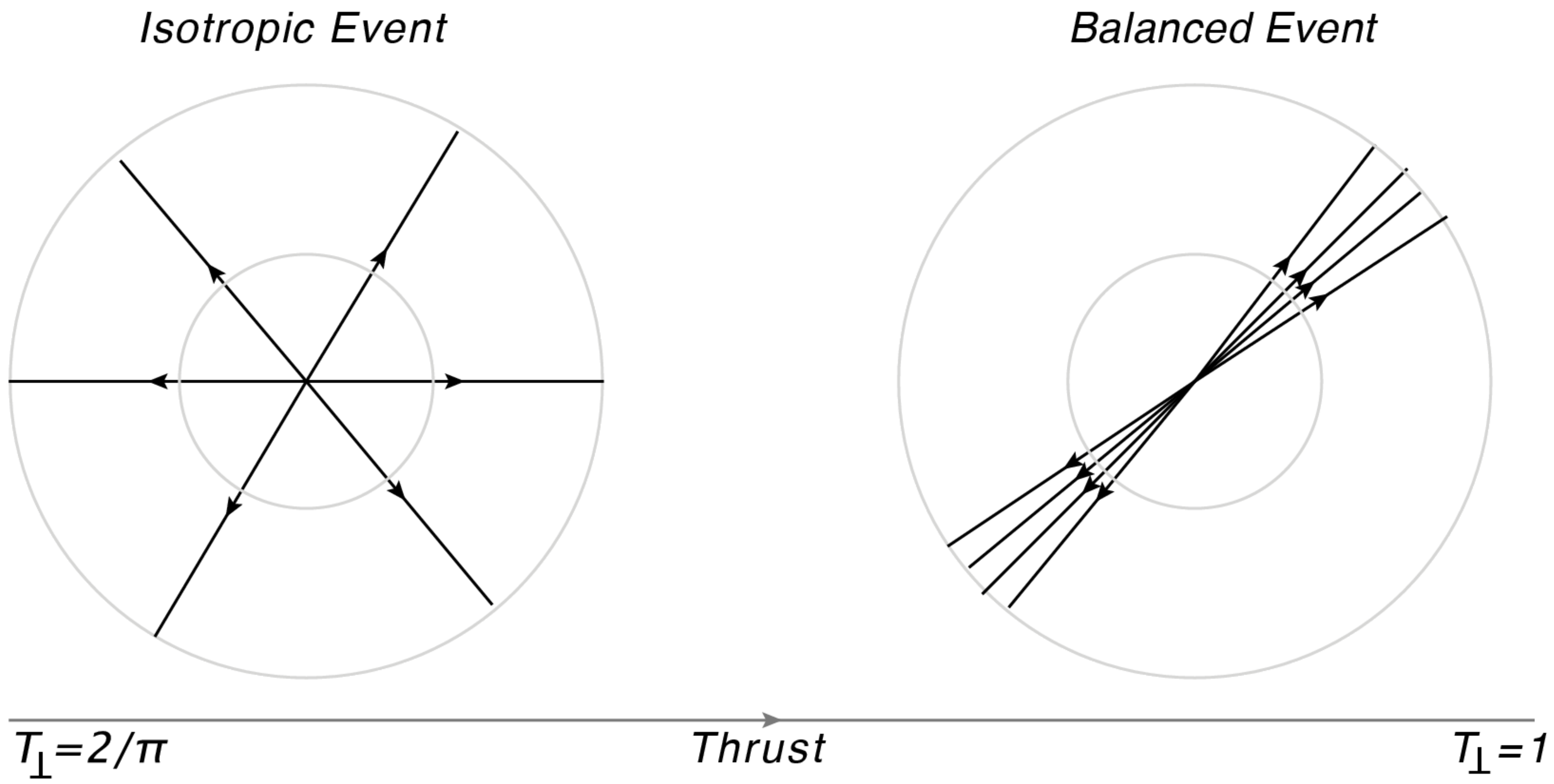
Event selection

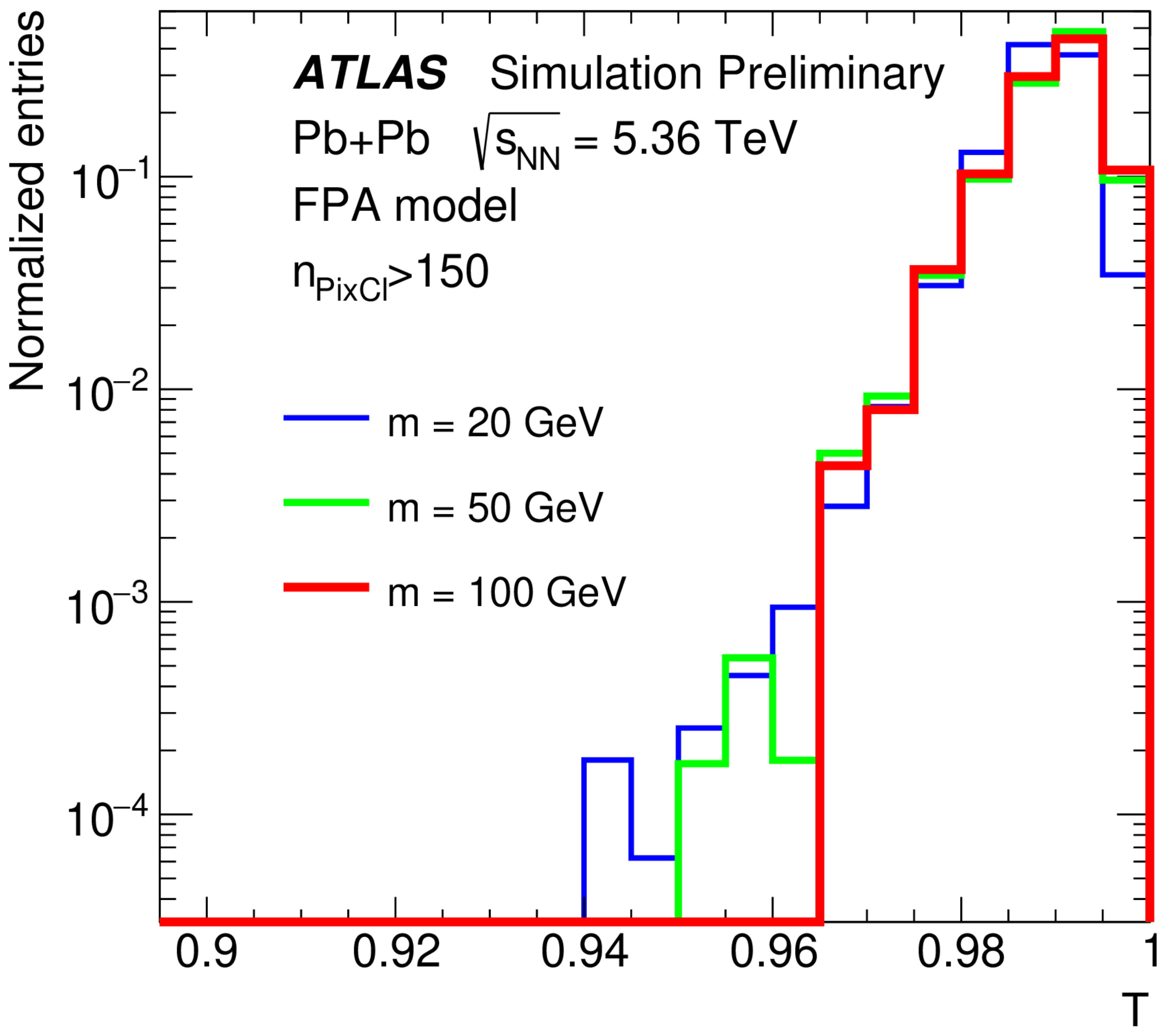
- Final background-discriminating variable based on azimuthal correlations between Pixel clusters
  - Variable inspired by *transverse thrust* used:

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

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

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





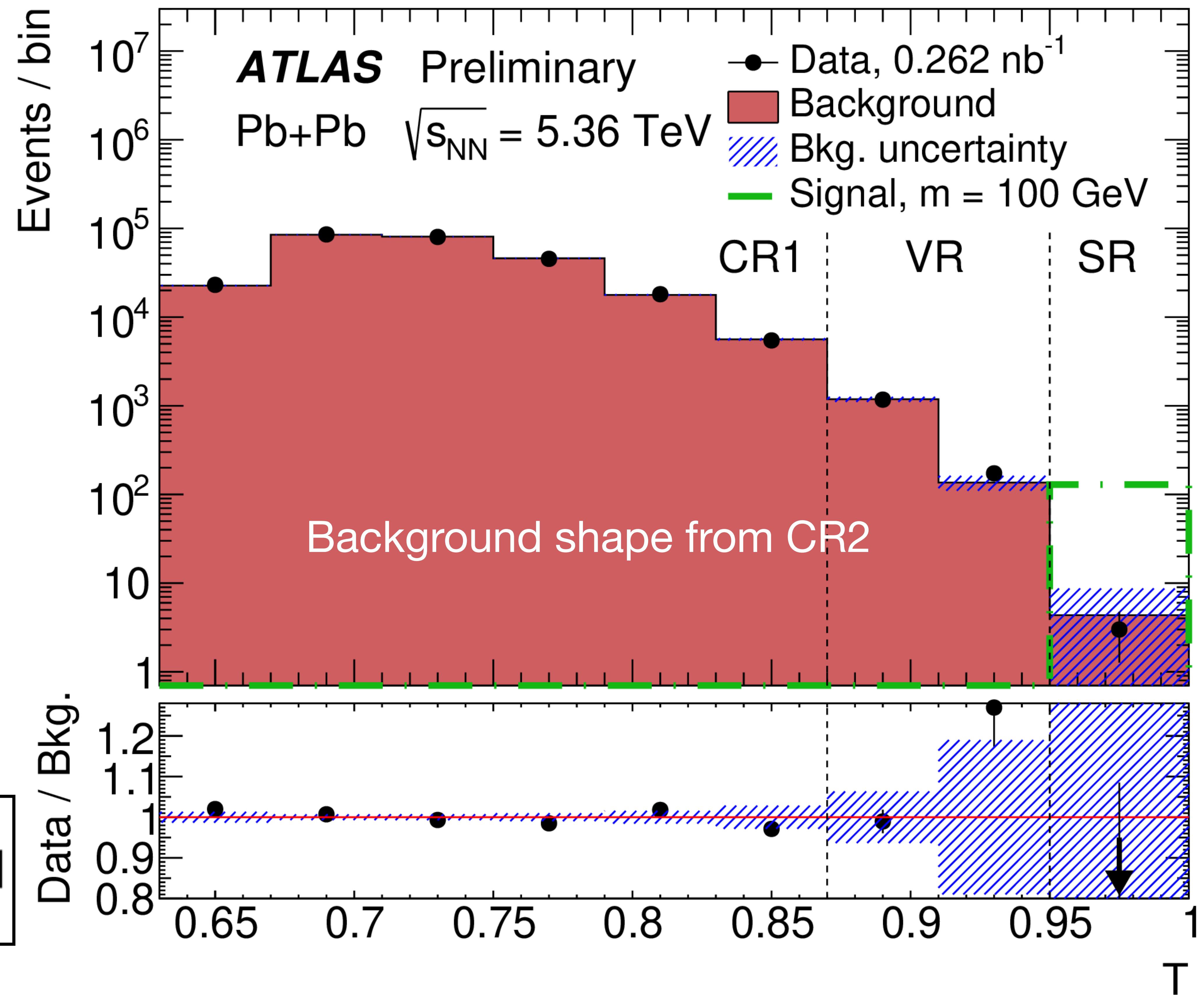
Background estimation

- Define two CRs:
  - **CR1** for events having T<0.87
  - **CR2** from ZDC_XOR-triggered events with 1-3 (soft) topoclusters, incl. at least one out-of time (t<-10 ns)
  - CR2 sample is enriched with BIB events and so

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

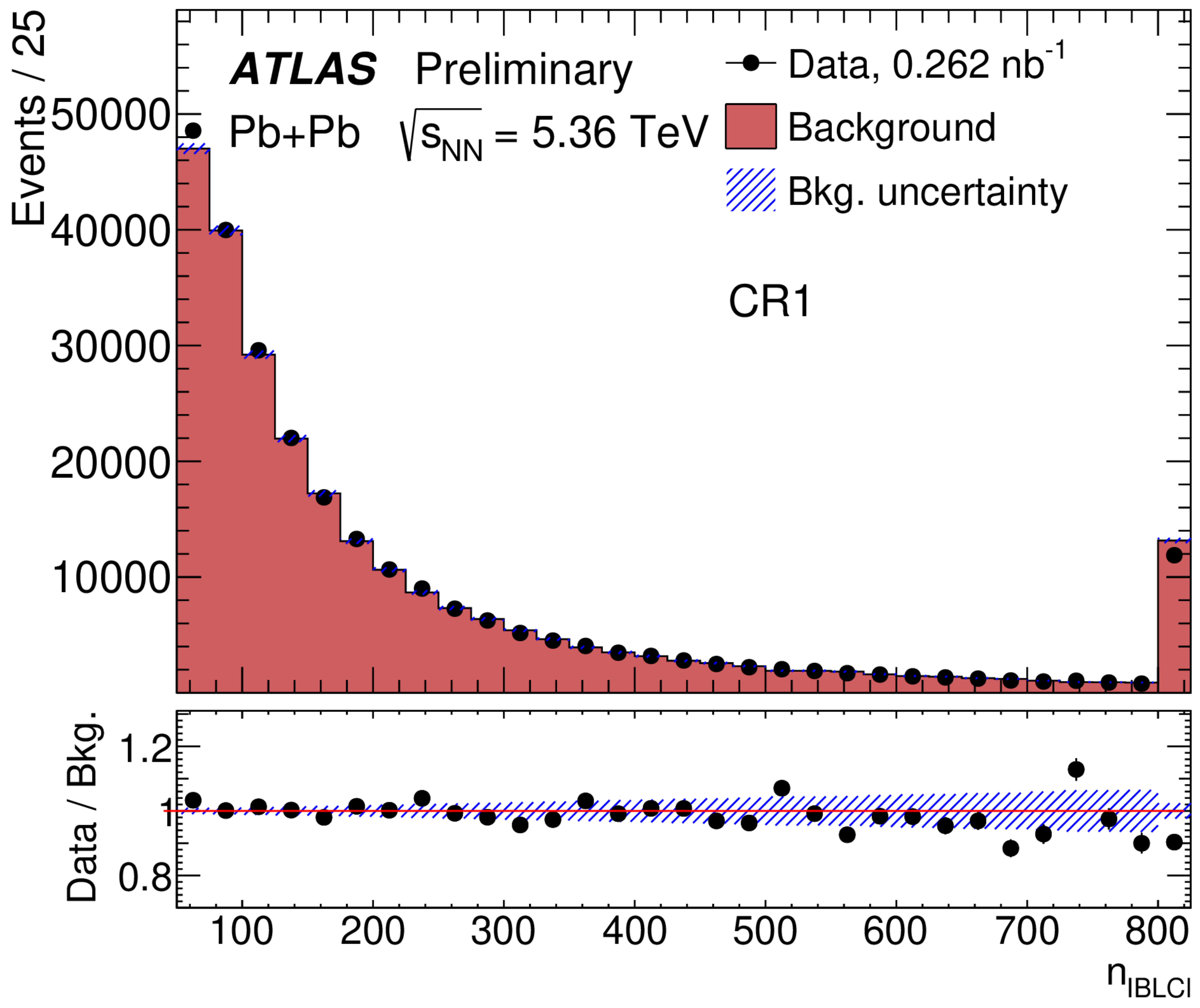
  - Extra reweighting of SCT spacepoint distribution (regulates average radial range of BIB particles) in CR2 for improved background modeling

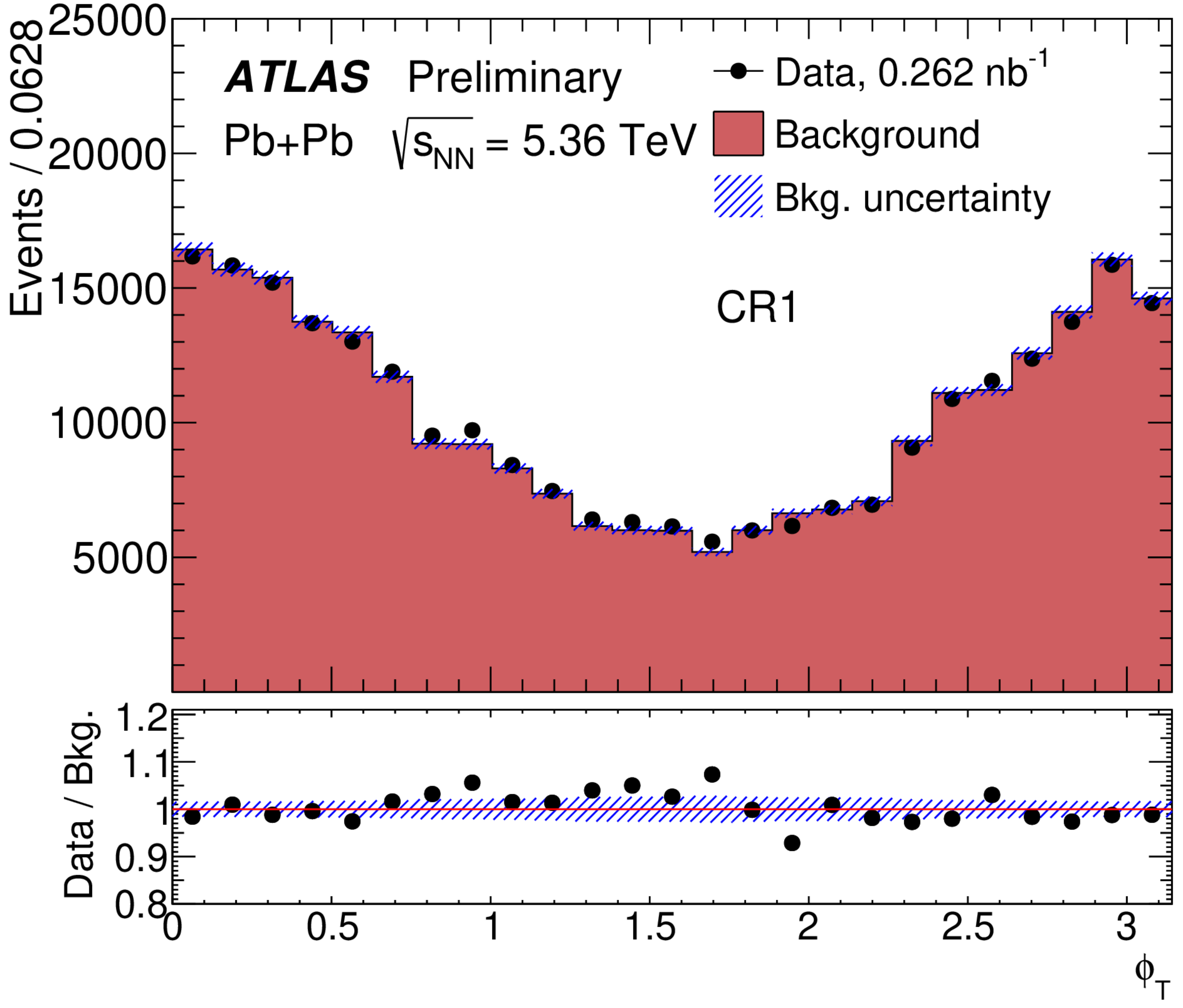
- SR (T>0.95): **4 ± 4** bkg. events expected



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

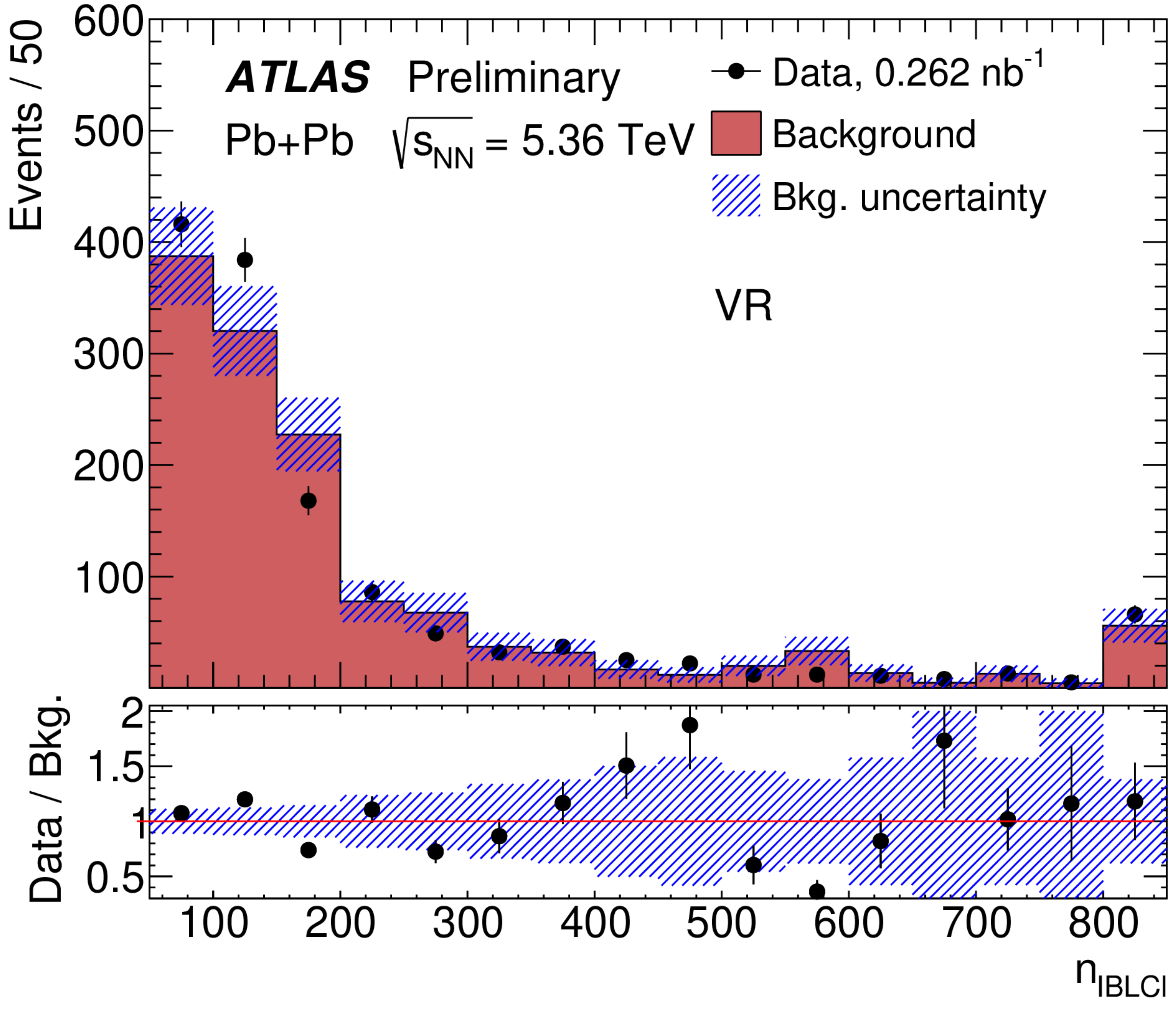
CR1 control distributions

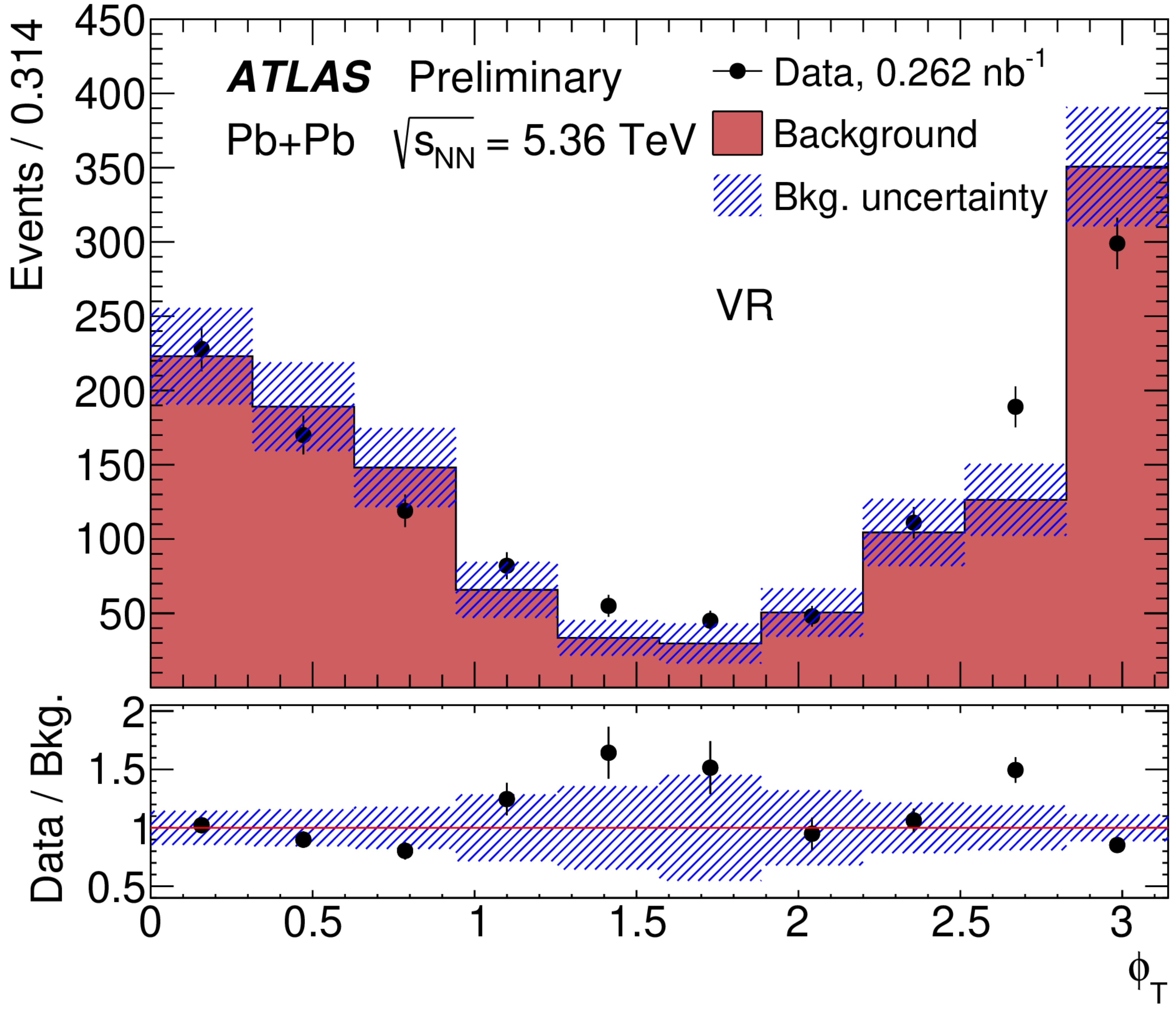




Validation region (VR)

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

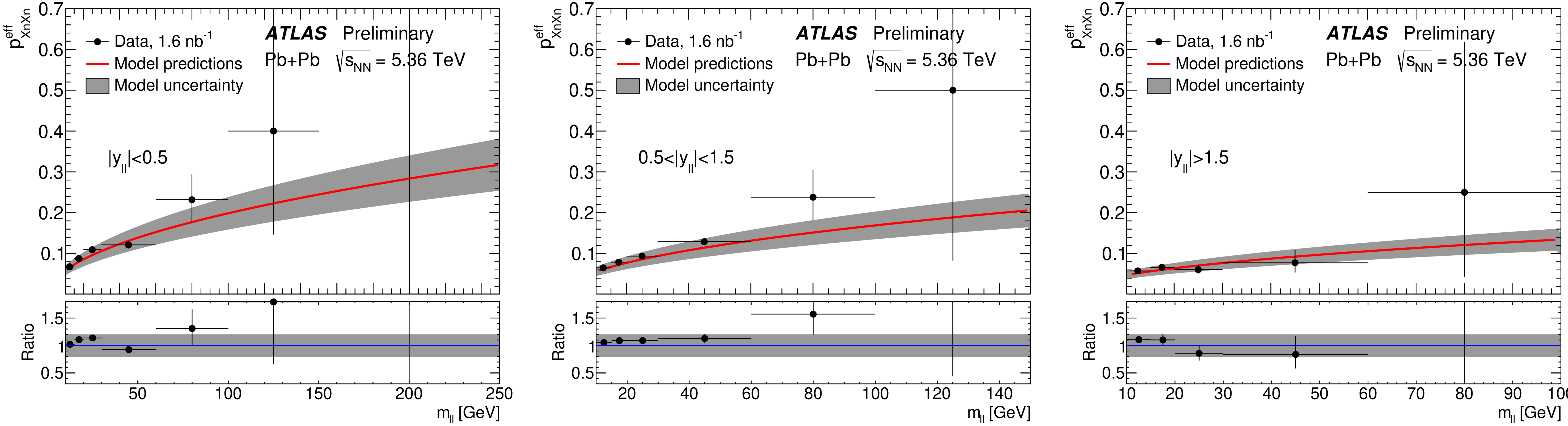




XnXn correction

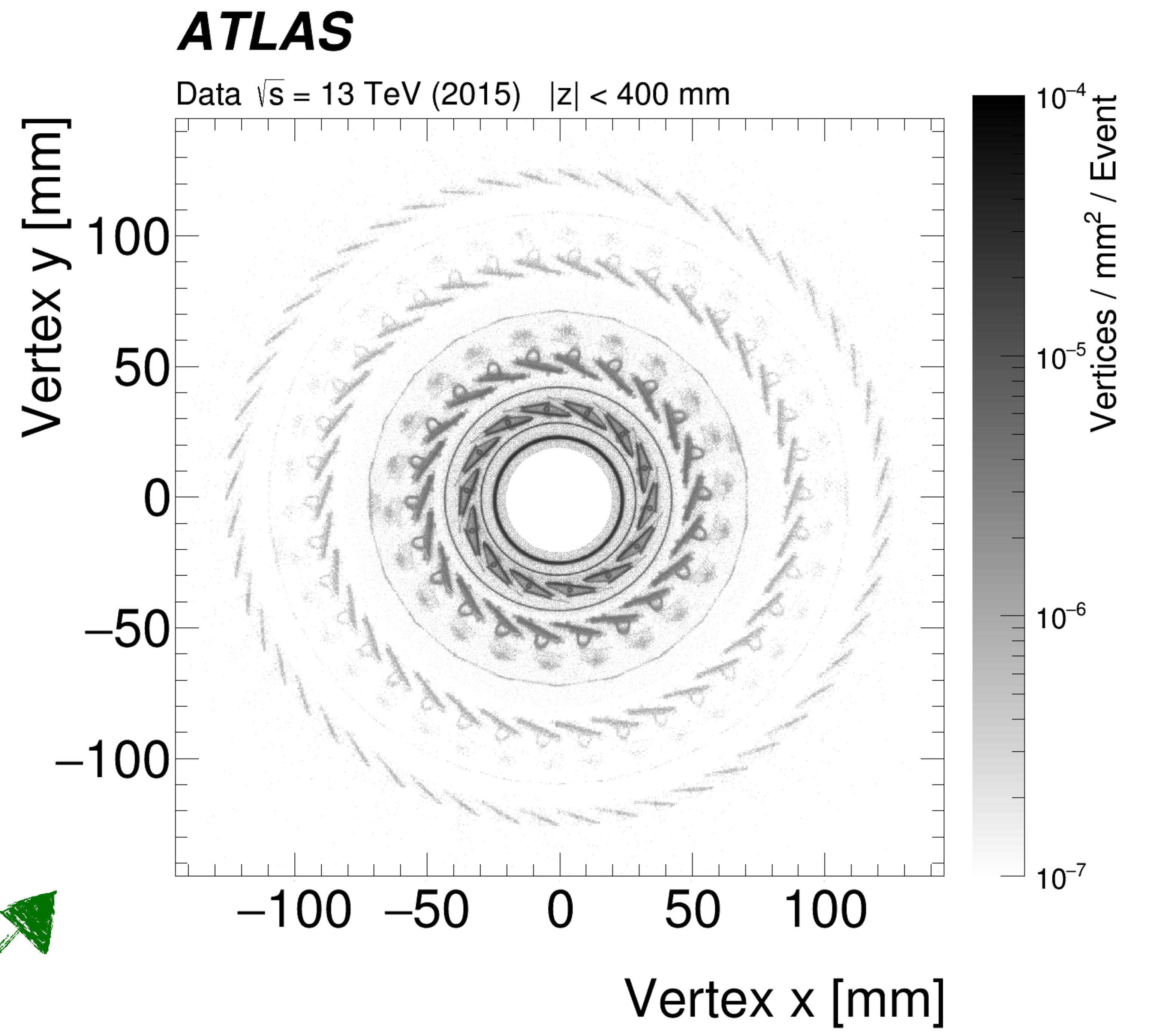
- Signal model has no EM breakup embedded → correcting signal MC for XnXn requirement applied in data
- **Breakup model** based on SuperChic 4.2 MC for γγ → l+l- process is used
- Full model also takes into account:
  - EM pileup (outflow of events primarily from 0nXn class to XnXn)
  - Run-2 UPC γγ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

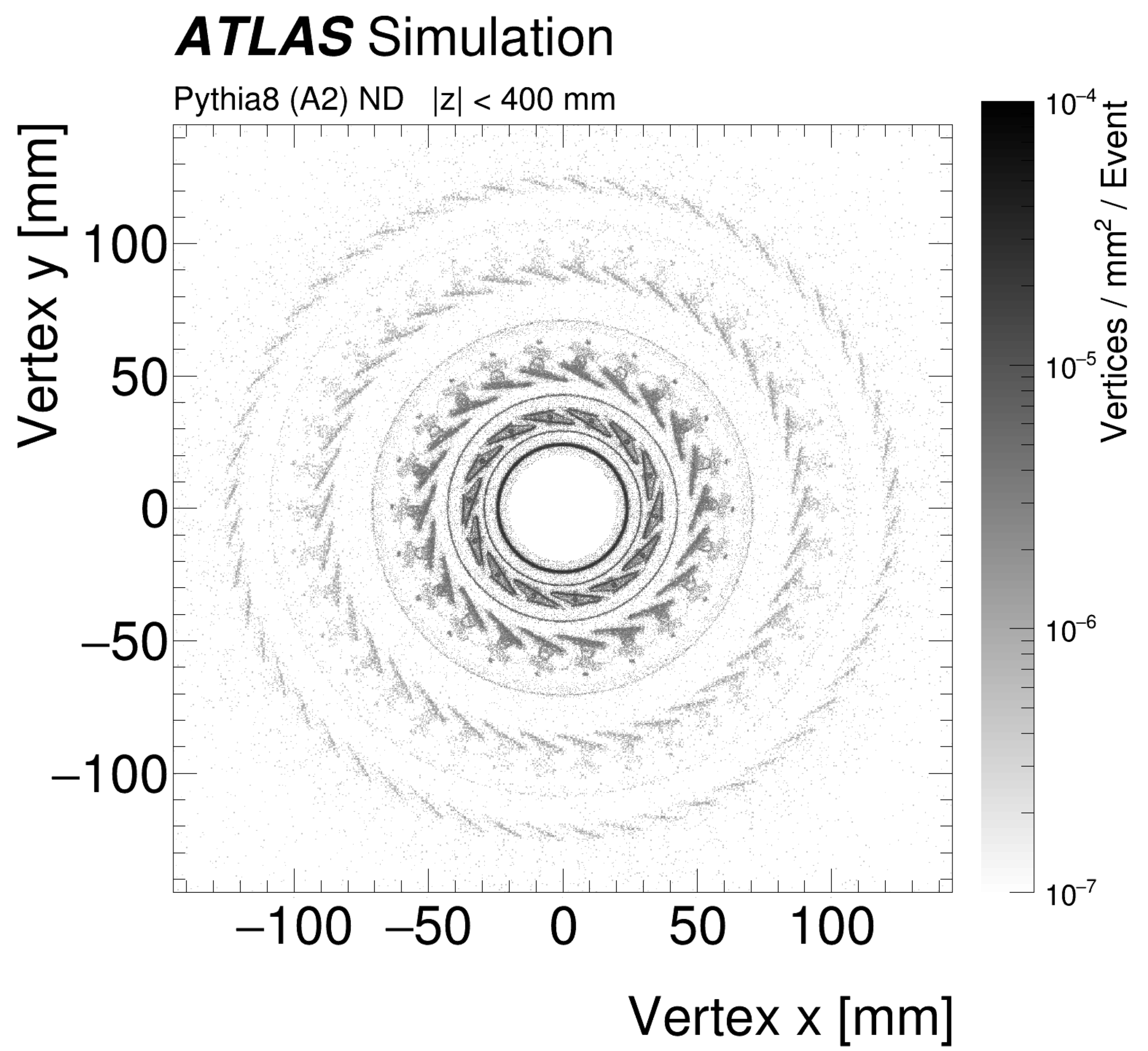
Model validated against γγ → ee (μμ) Run-3 data



Systematic uncertainties

- Dominant source: bkg uncertainty (stat.)
- Also important: detector material modeling
  - Using alternative Geant4 geometries with
    +5% overall Inner Detector (ID),
    +10% IBL,
    +25% services
  - 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)





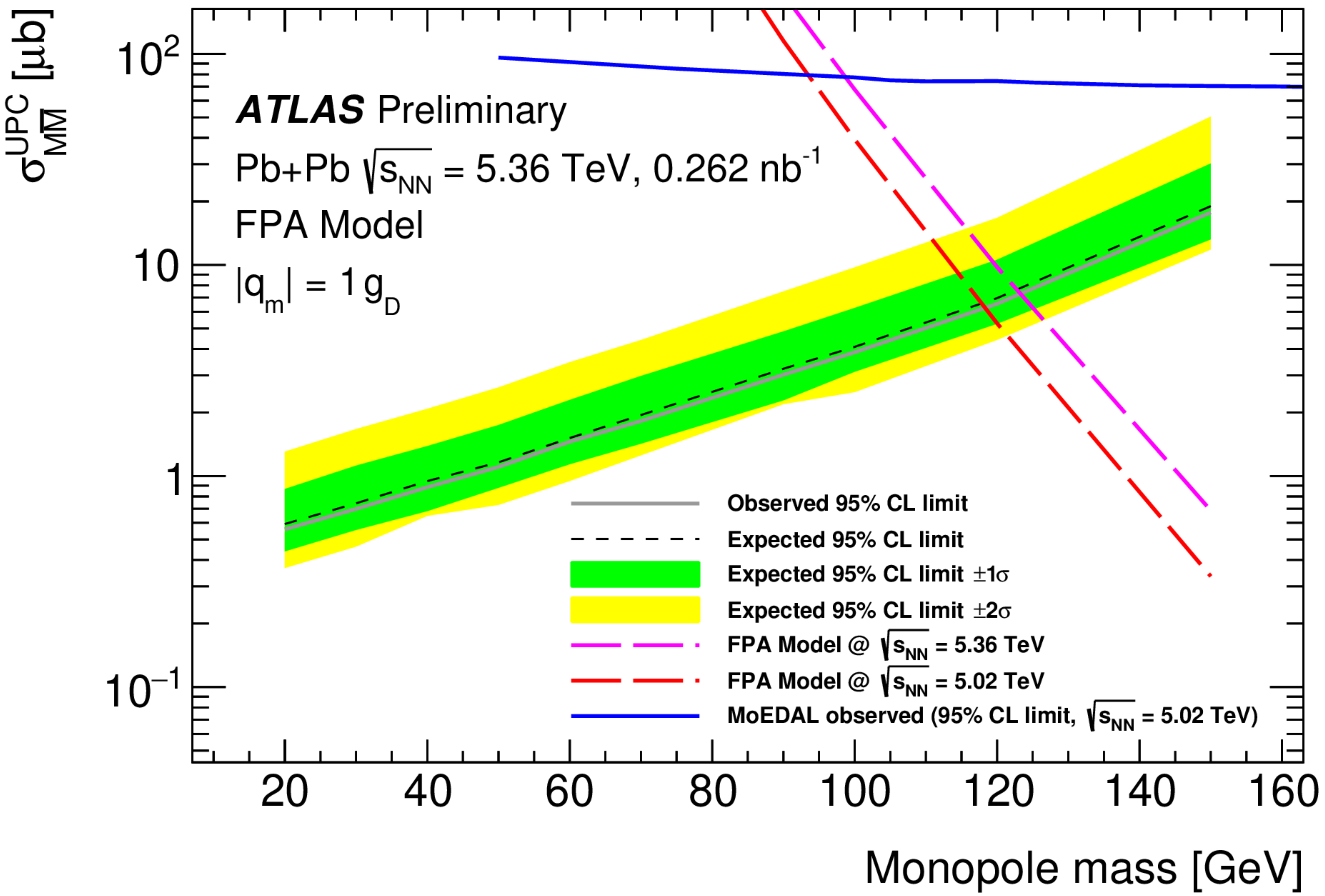
Systematic uncertainties

- XnXn weight modelling (**20%**)
  - Covers data/MC differences observed for $\gamma\gamma \rightarrow l^+l^-$ production
  and differences between nominal (SuperChic) and alternative models (STARlight, gamma-UPC)

- Other sources considered (subdominant)
  - Pixel and calorimeter noise modeling
  - δ-electrons propagation range
  - δ-electrons production modeling
  - Integrated luminosity
  - Background shape systematics

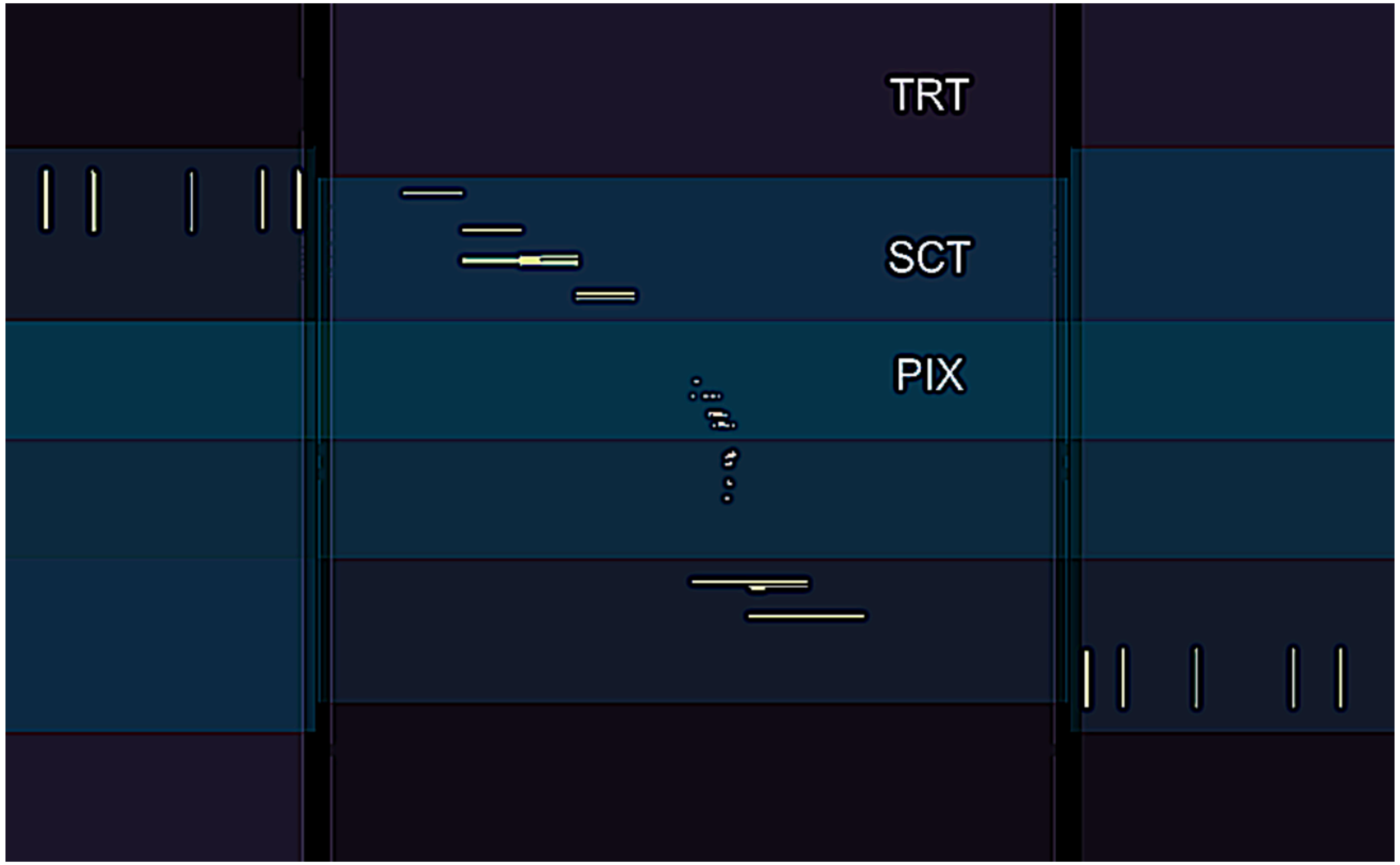
Results

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



Future directions

- Trigger improvements → more data!
- Possible future analysis developments
  - Explore higher magnetic charges
  - MVA methods
  - Unconventional tracking
  - …

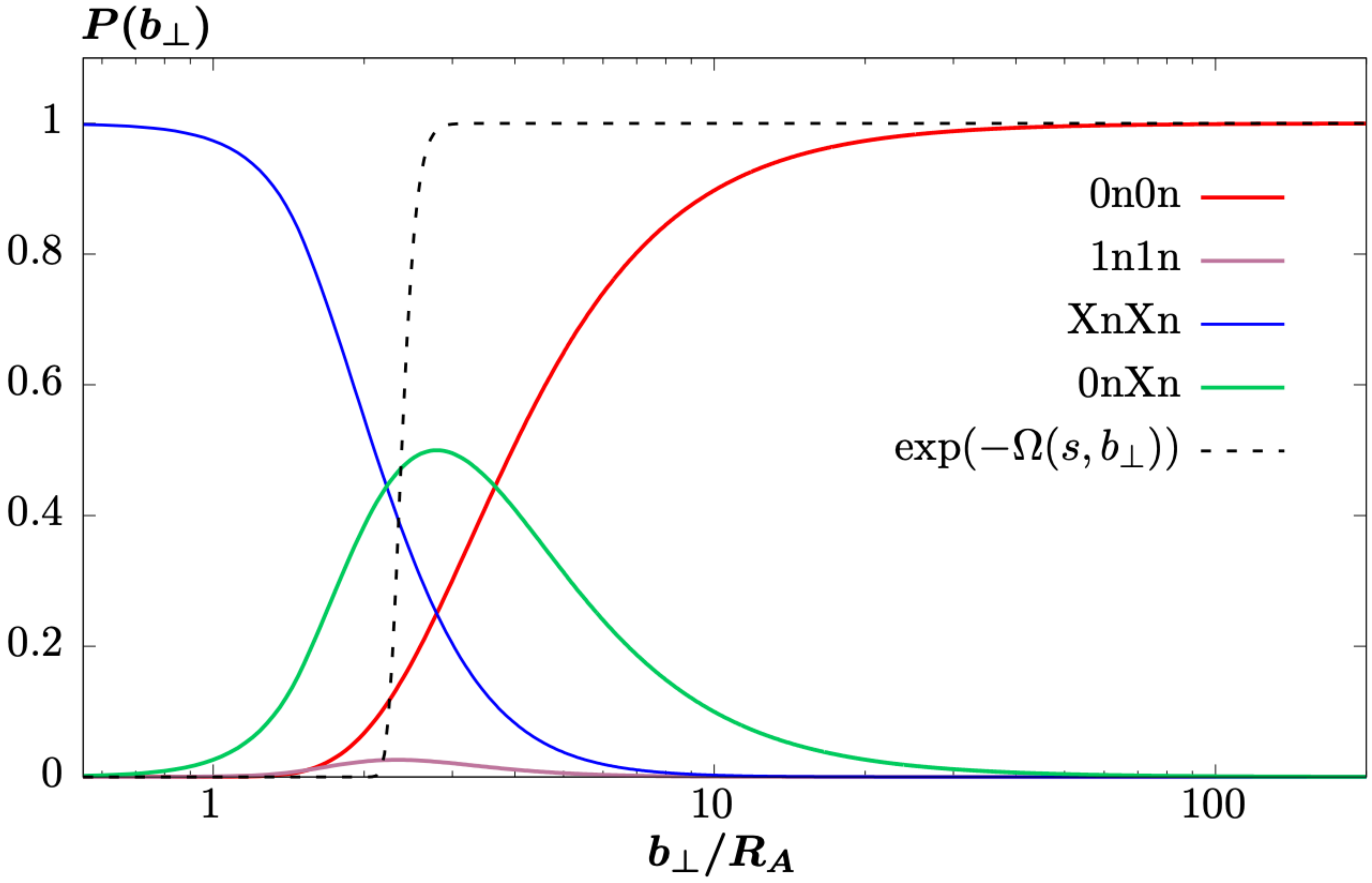


Summary

- The first ATLAS result using Run-3 Pb+Pb data and the first ATLAS search for MM in Pb+Pb collisions
- Analysis relying on non-perturbative FPA model, used previously by MoEDAL
  - Enable to calculate physically valid monopole production cross sections
- Introducing new approach in detecting HIPs at the LHC
  - Main focus on the Pixel detector activity
  - ZDC crucial in data selection (L1 trigger)
  - Best cross-section upper limits for UPC-produced MM for masses 20-150 GeV ($g = 1g_D$)
- This new approach can be extended for other HIP searches in HI data

Backup

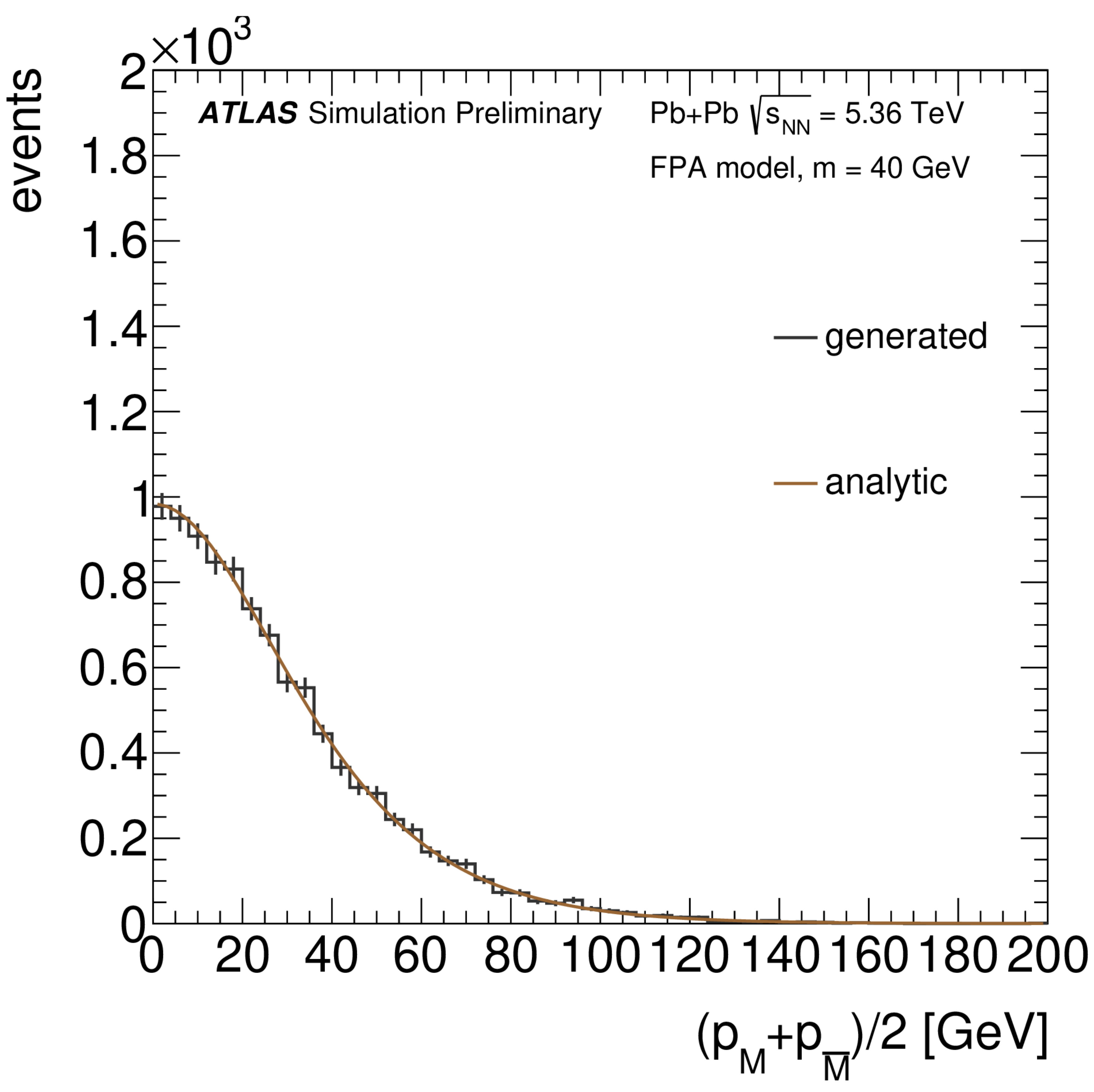
EM breakup fractions

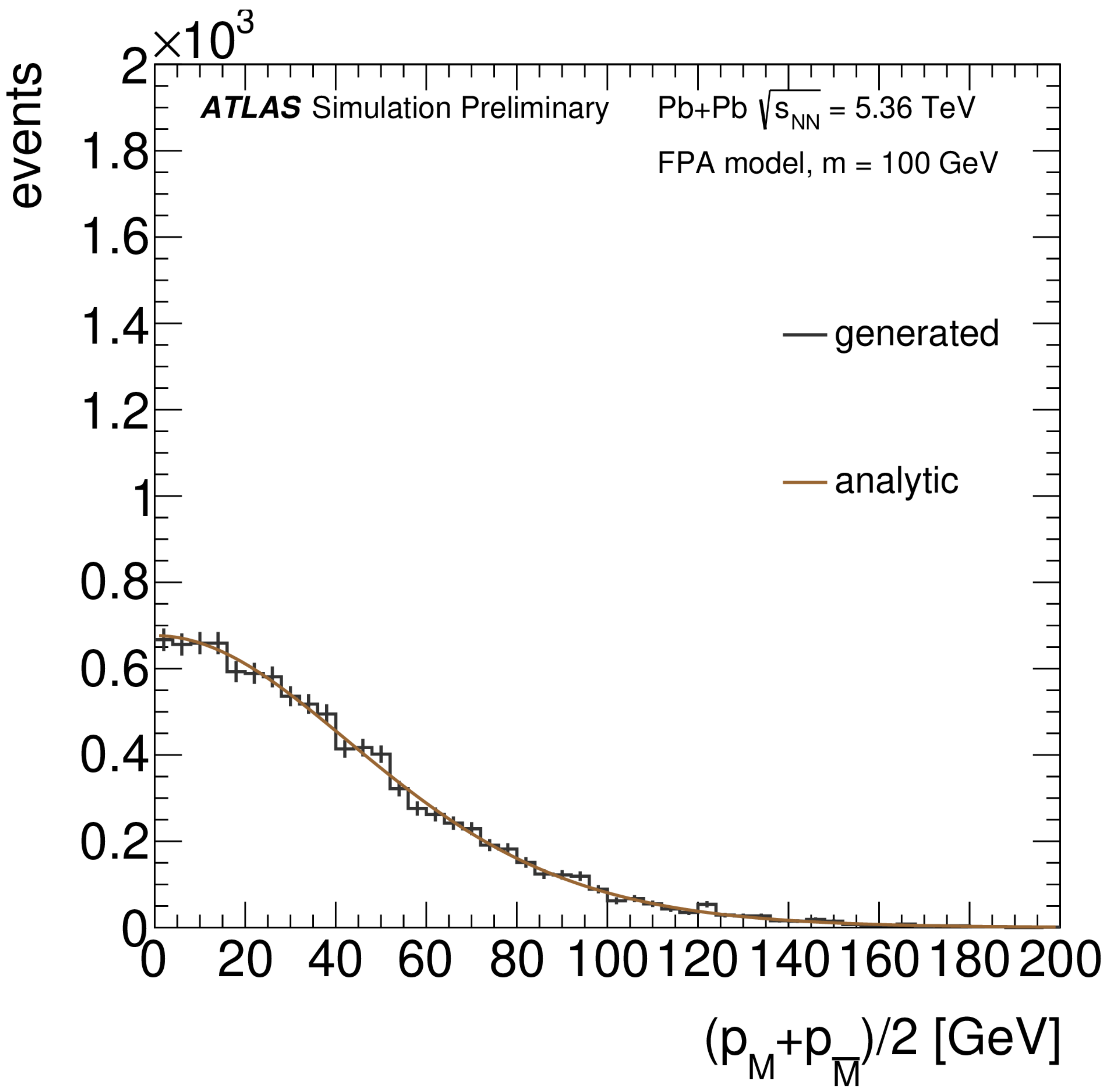


Systematic uncertainties

- 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

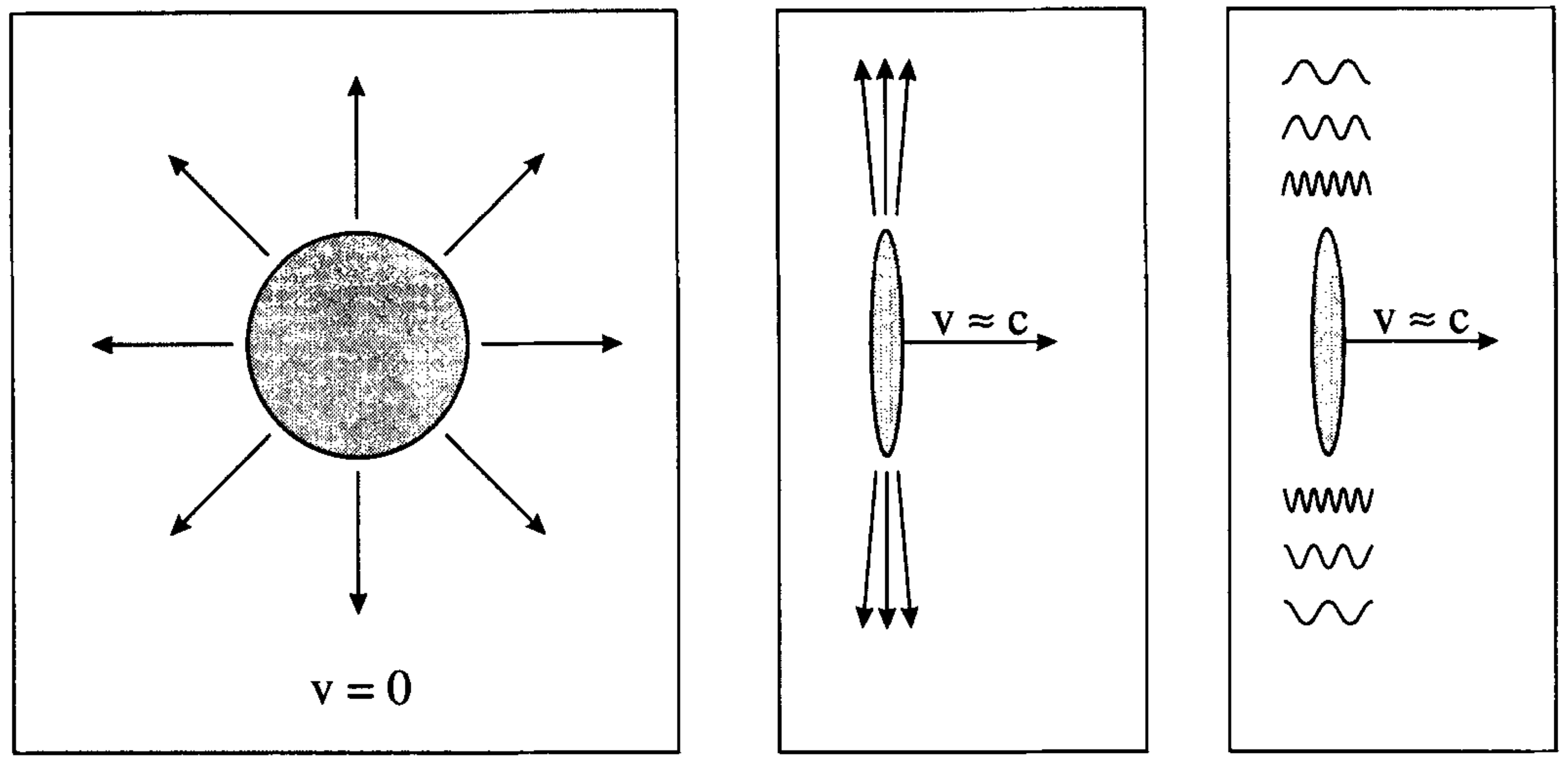
Signal model



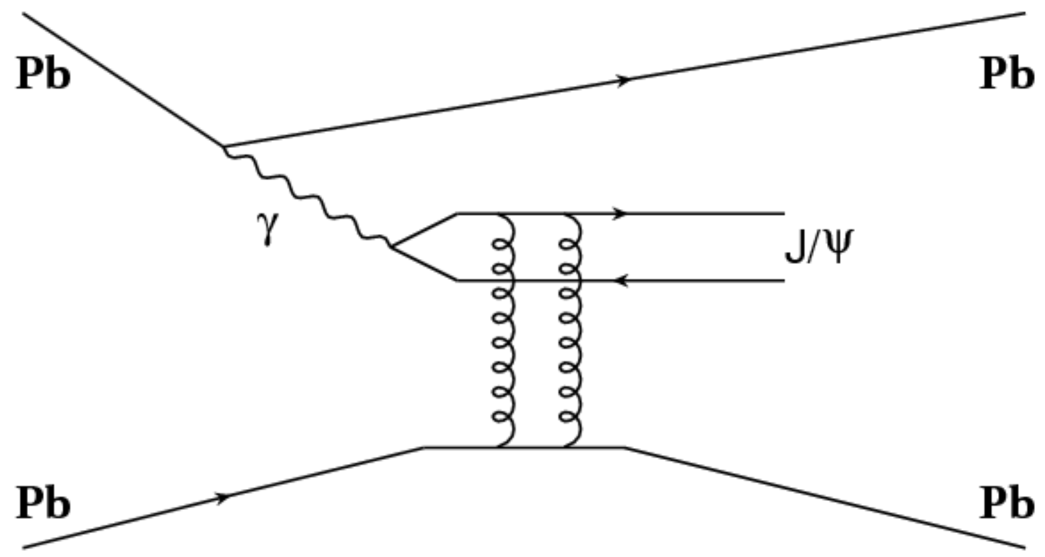


Ultraperipheral collisions at the LHC

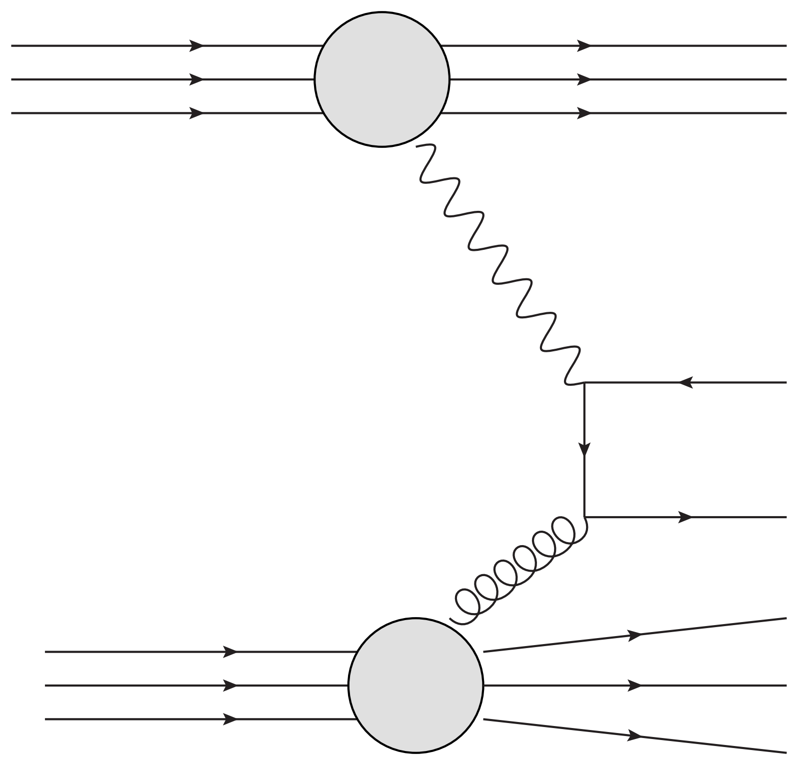
- Boosted nuclei are intense source of quasi-real photons
- **Coherent** photon flux
  - **E_{max} ≲ γ/R ~ 80 GeV** @LHC (**~3 GeV** @RHIC)
  - **Q ~ 1/R ~ 30 MeV** @ LHC/RHIC
  - Each photon flux scales with ~**Z^2**



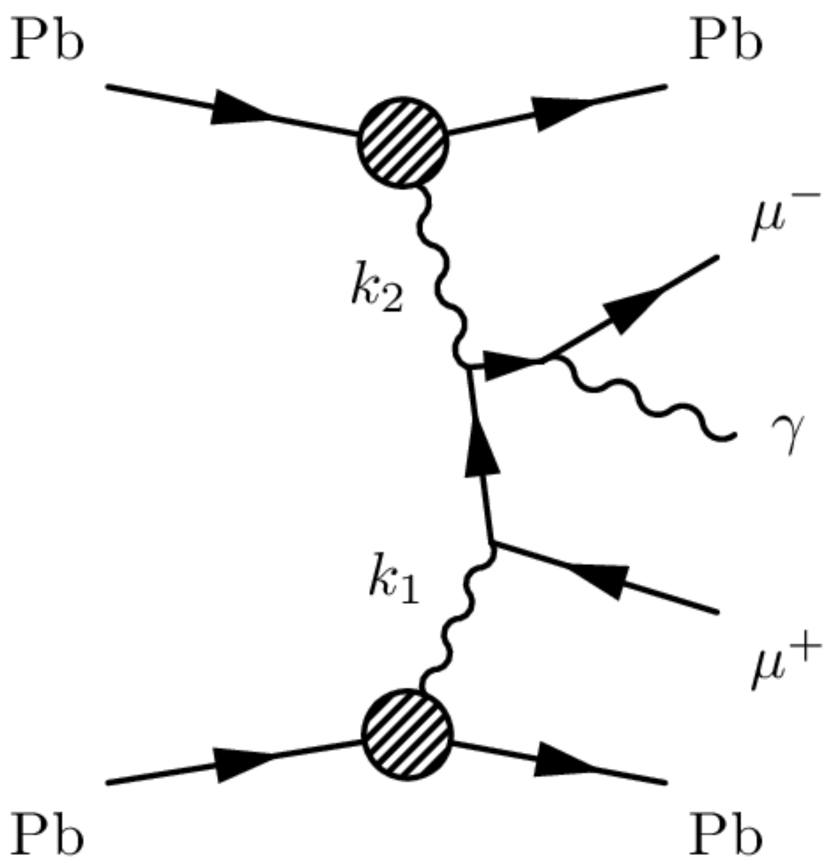
- Various types of interactions possible:



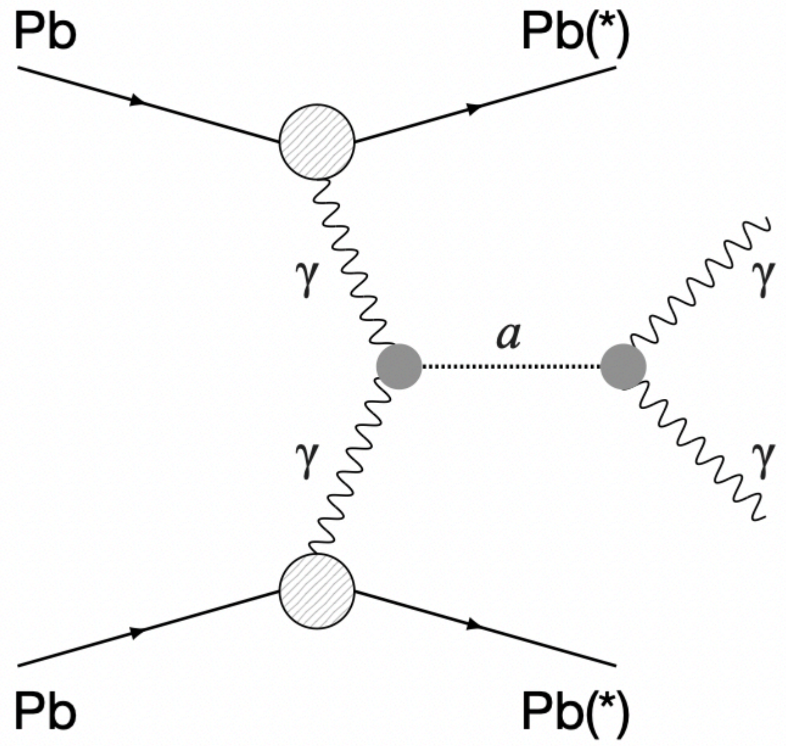
Diffractive Photo-nuclear



(Inelastic) **Photo-nuclear**



(SM) **Photon-photon**



(BSM) **Photon-photon**

Future directions

- A wishlist to theory community
  - Would be nice to have the non-perturbative calculations embedded in a MC generator
  - Could incorporate EM breakup fractions in those calculations
  - Better (more realistic) prescription for theoretical uncertainties