Ultra-peripheral collisions and Zero-degree calorimeters
An ATLAS-centric perspective

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Columbia University and ATLAS collaboration

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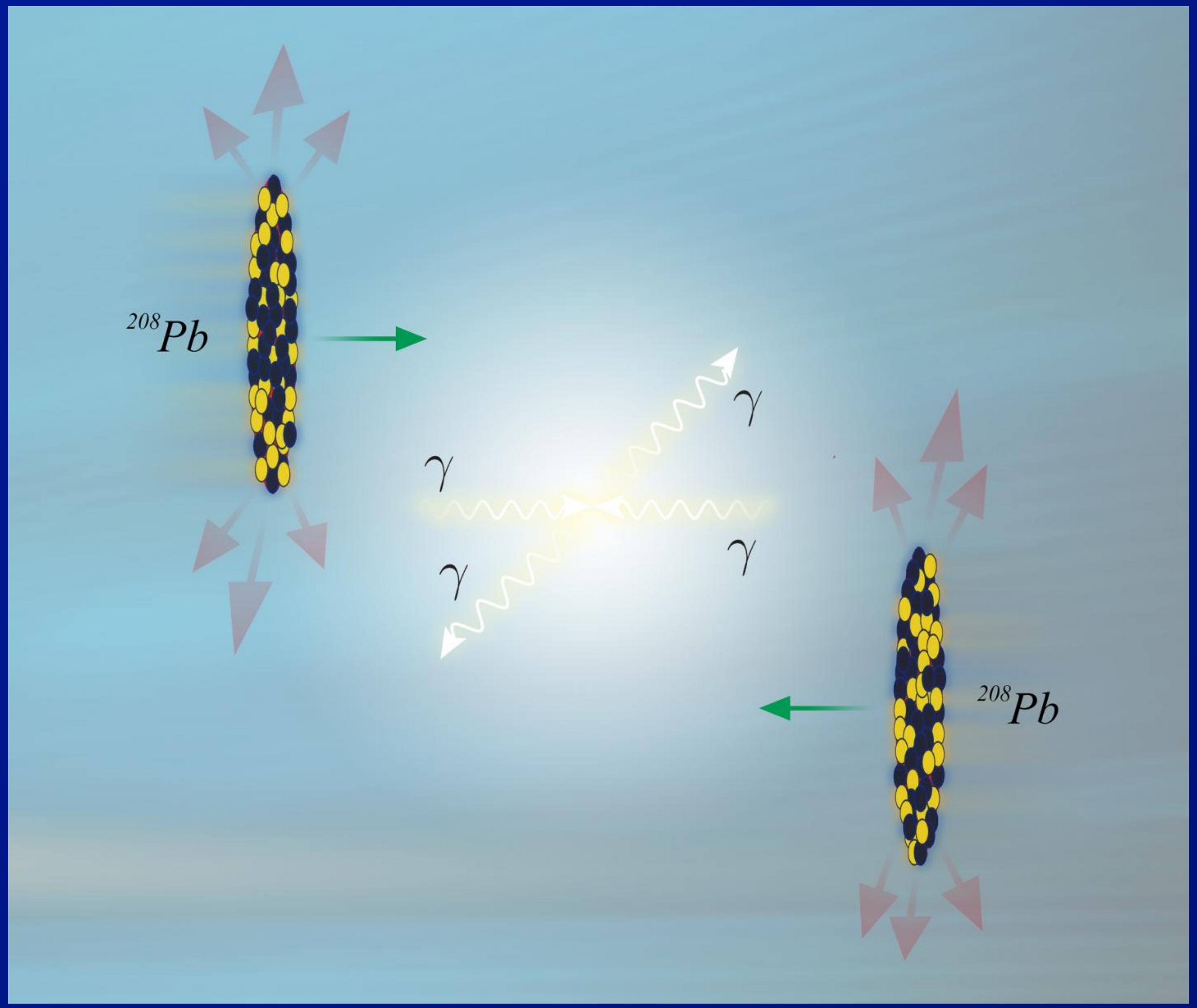
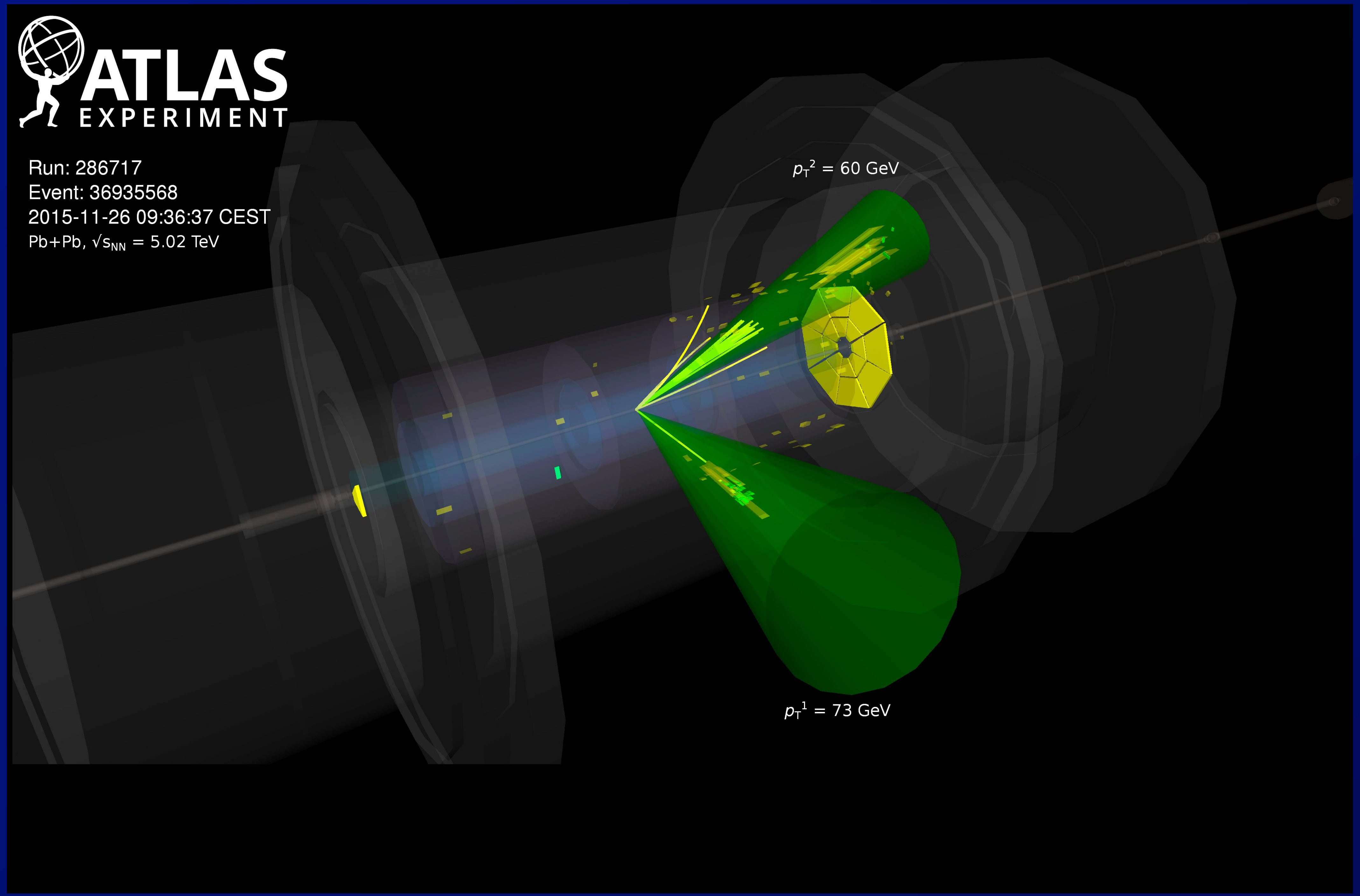
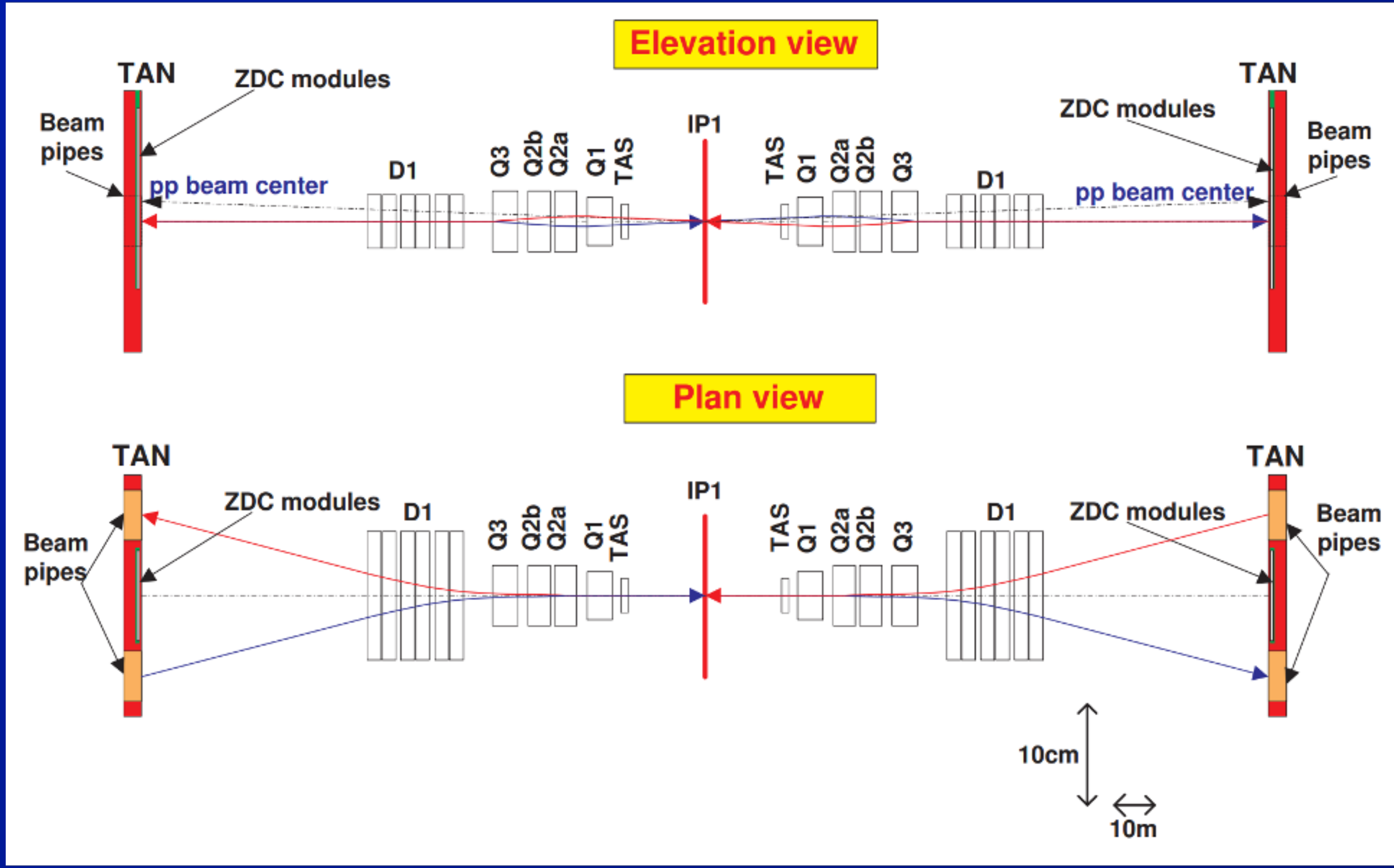
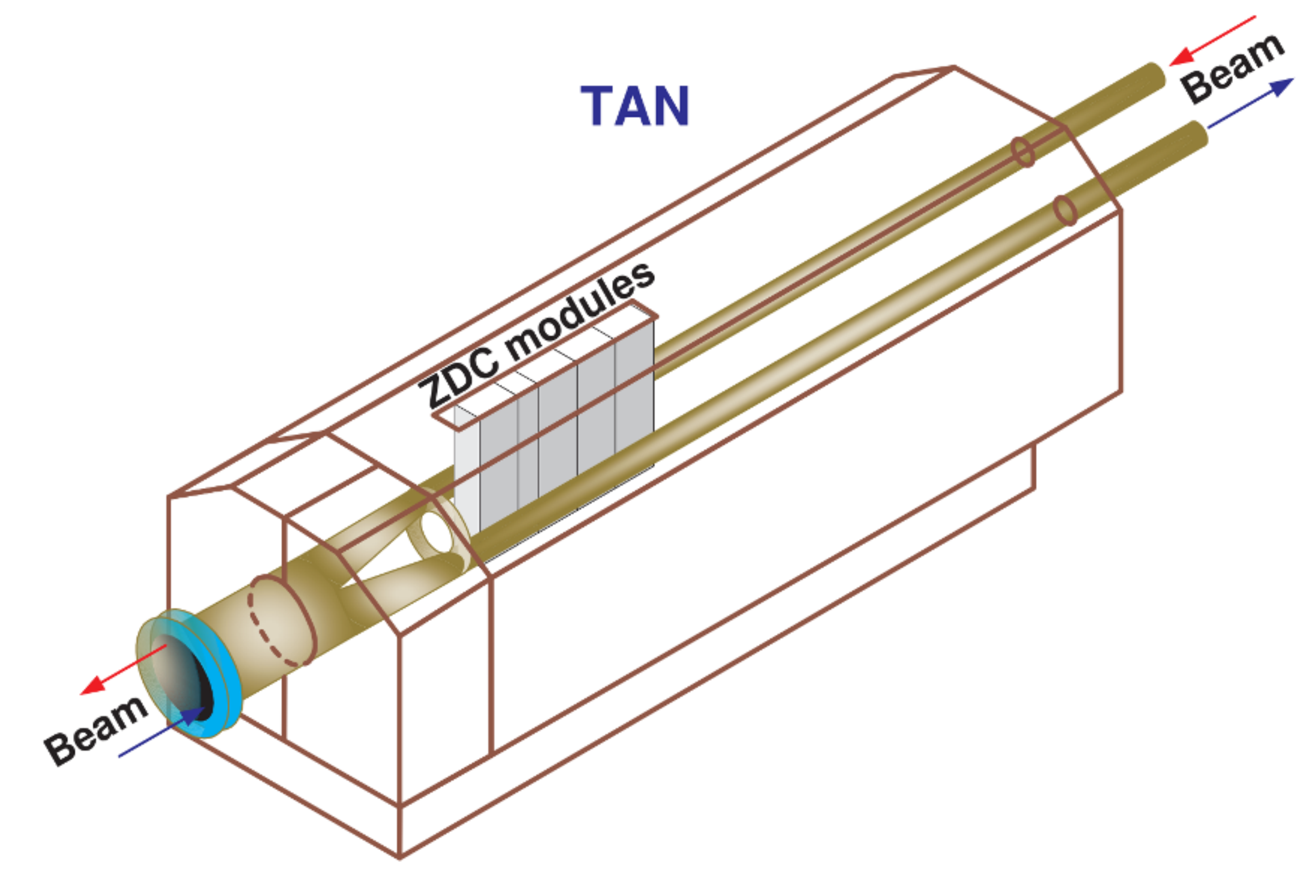




ATLAS zero degree calorimeters

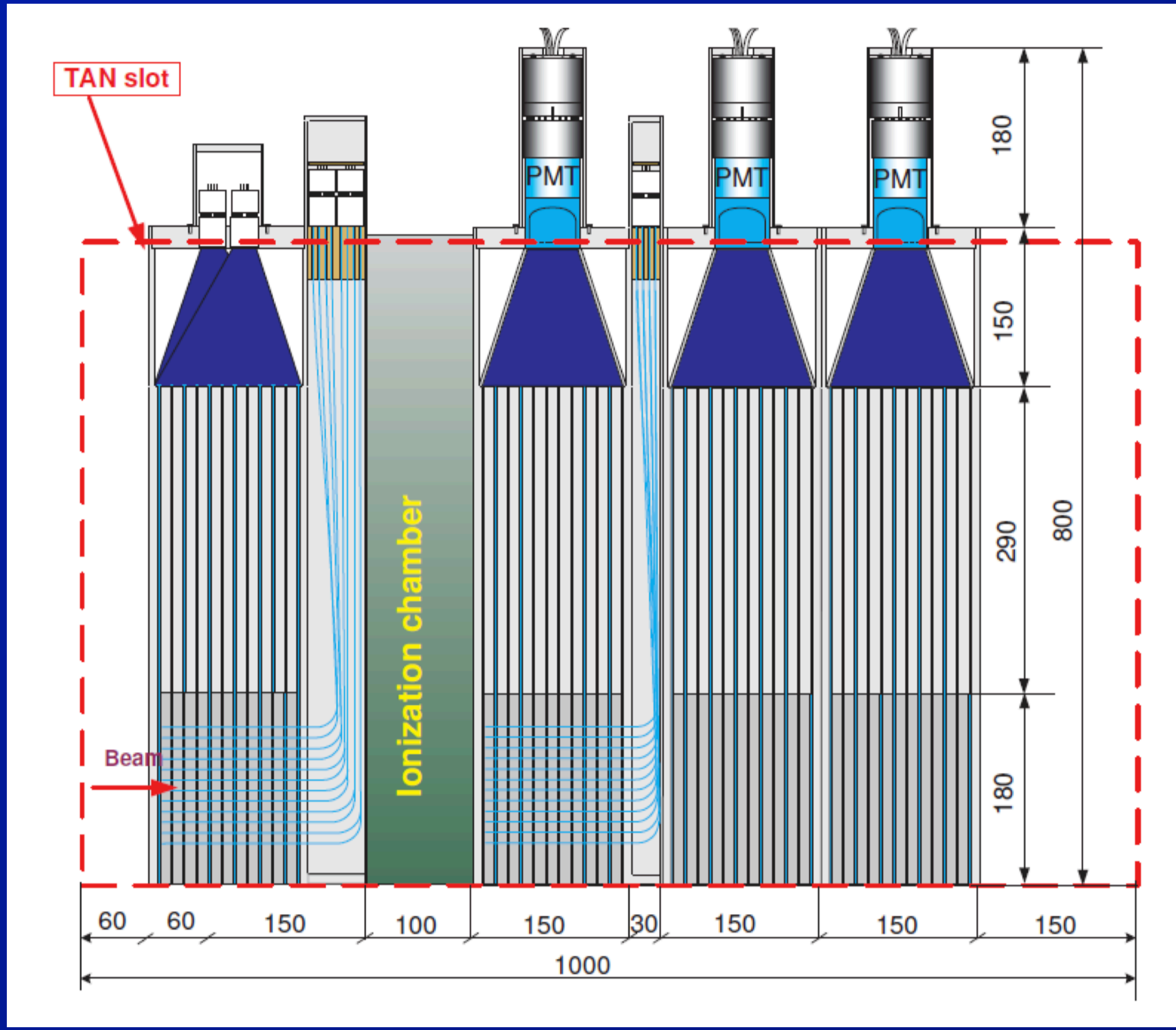


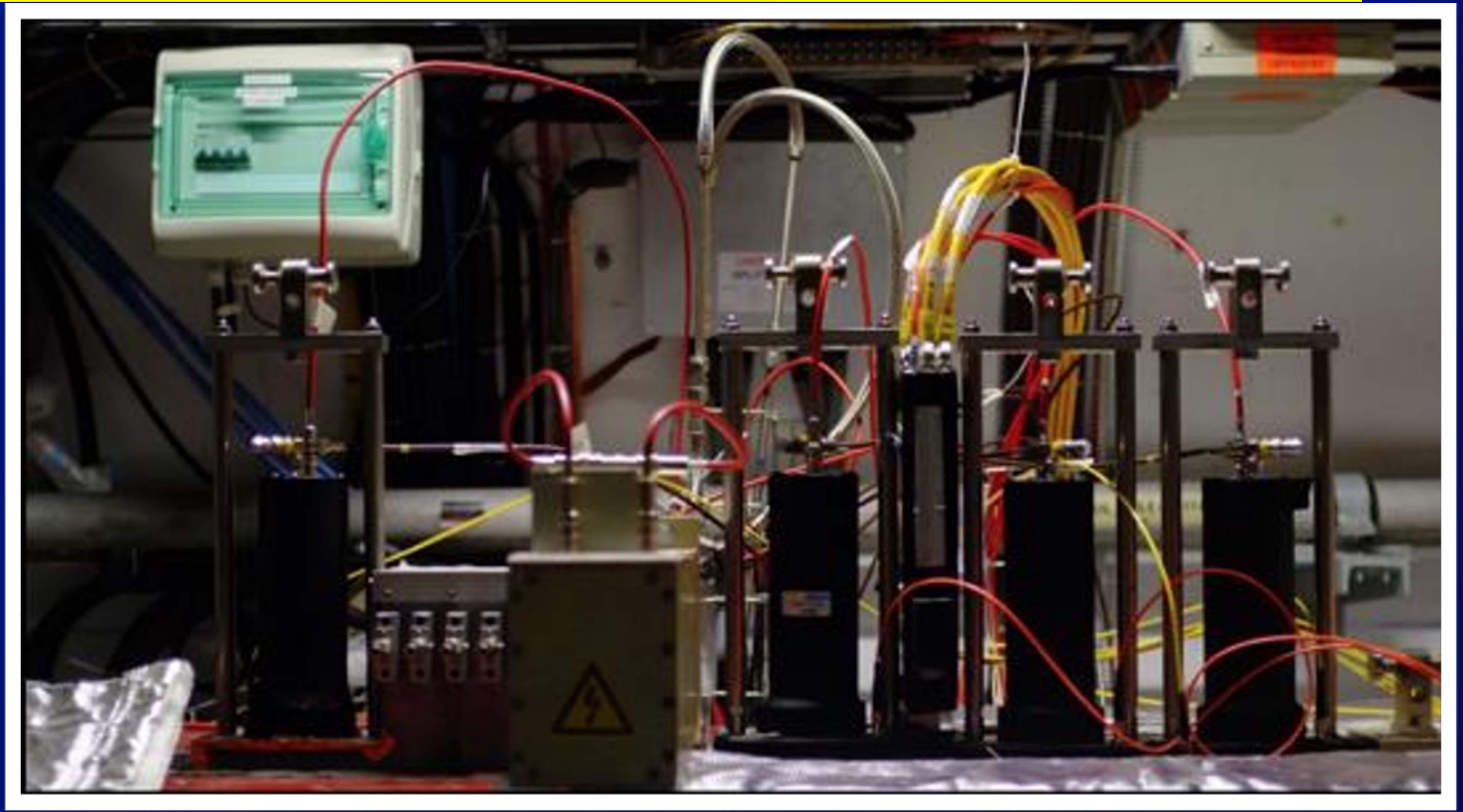


- Located 140 m from center of ATLAS, in LHC TAN
- Measures neutral particles in $|\eta| > 8.3$
- 4.5 interaction lengths of tungsten absorber (plates)
- Quartz fiber Cherenkov radiators

$\Rightarrow$ ~ 16% sampling fraction

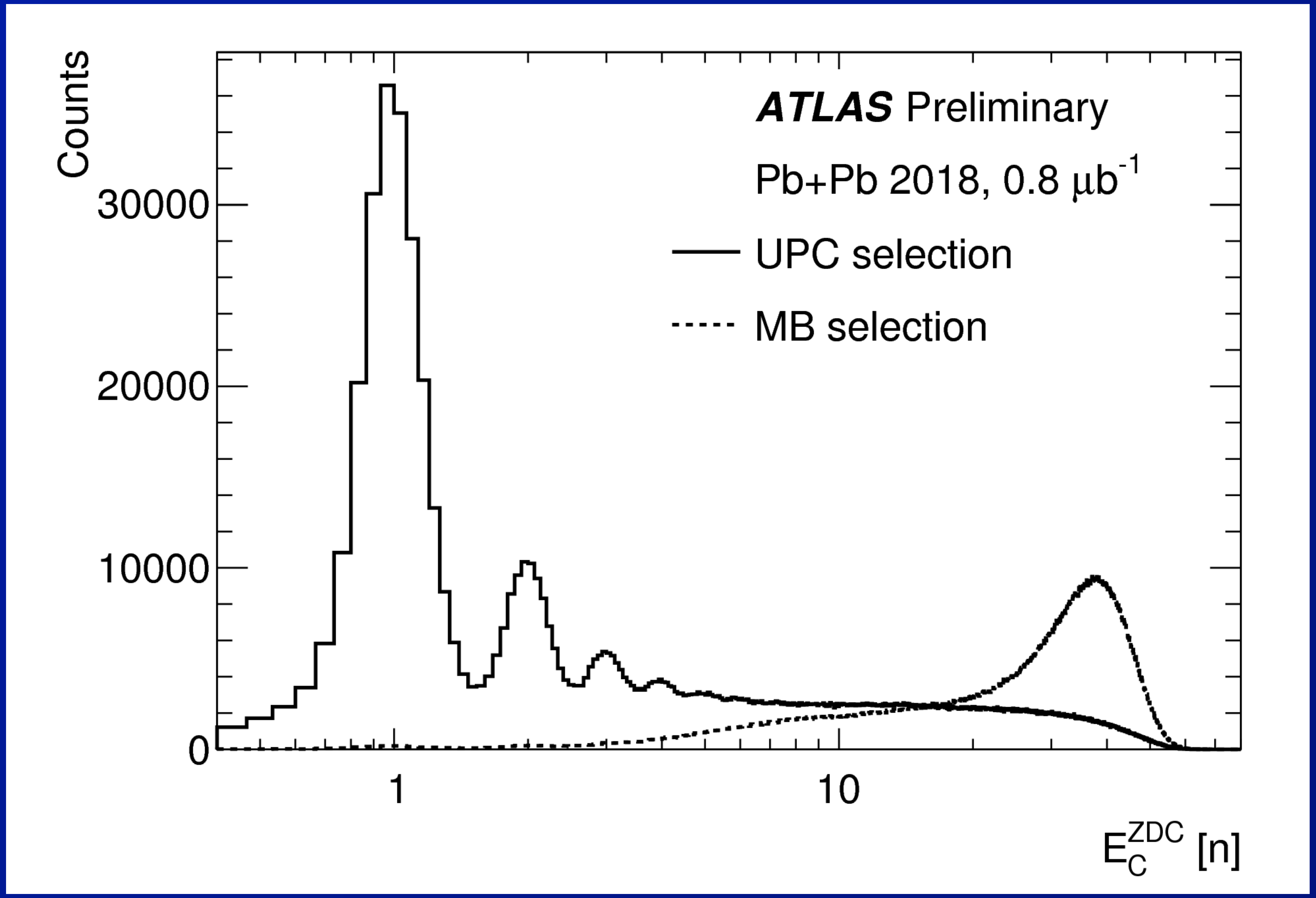
ATLAS zero degree calorimeters

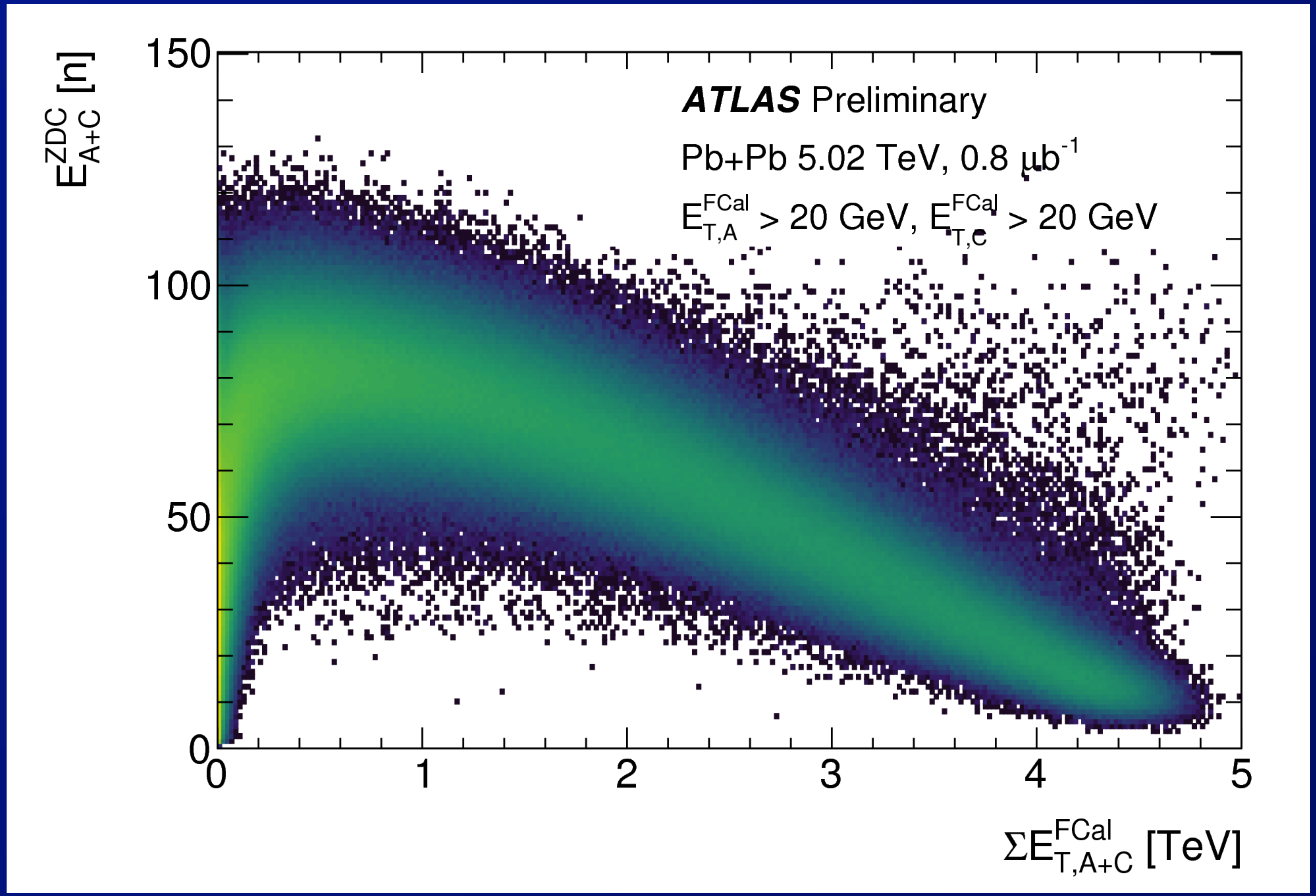




- Four-fold longitudinal segmentation, 11 quartz layers each
  - With LHC BRAN detector after first module
- Read out via four PMTs operated with dynode boosters
- Signals sent over ~200 m of cable to USA15 cavern

Inclusive ZDC measurements (2018)



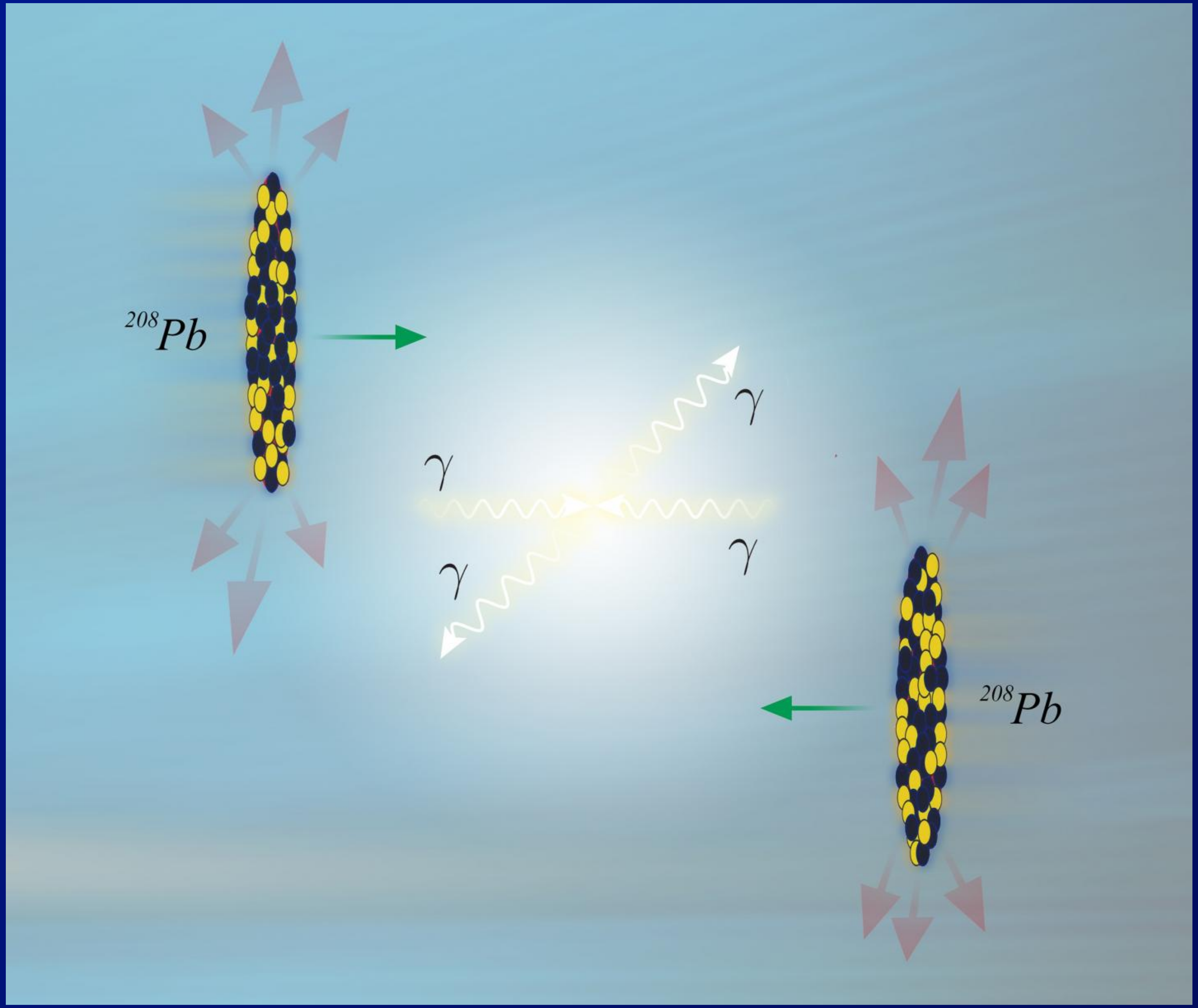


- ZDC energies calibrated using 1 neutron peak
- Large dynamic range in Pb+Pb collisions
  - few neutrons in (ultra)peripheral Pb+Pb collisions
  - up to ~50 neutrons in Pb+Pb collisions

⇒ centrality dependence reflects # spectators + clustering (peripheral)

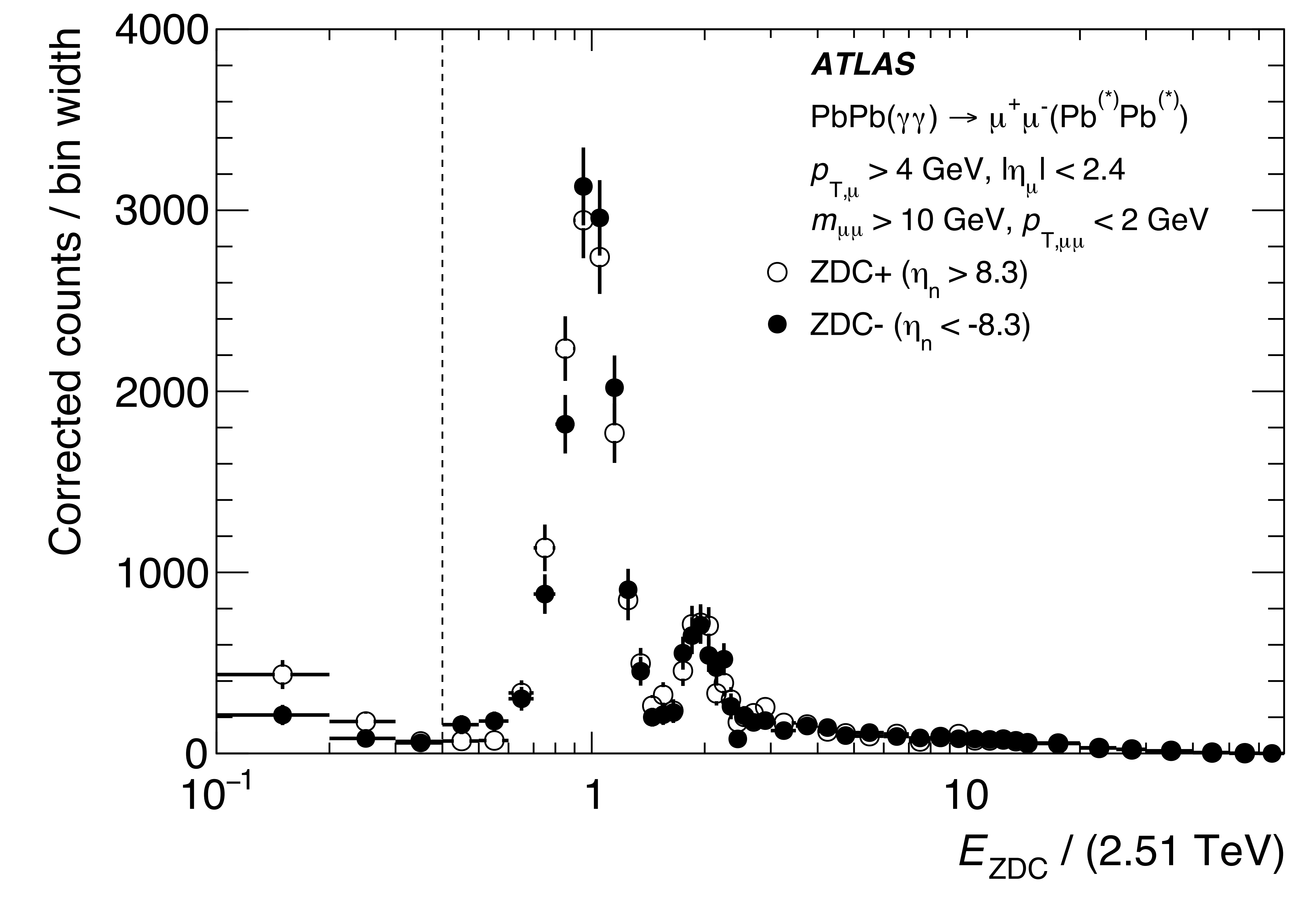
Ultra-peripheral collisions

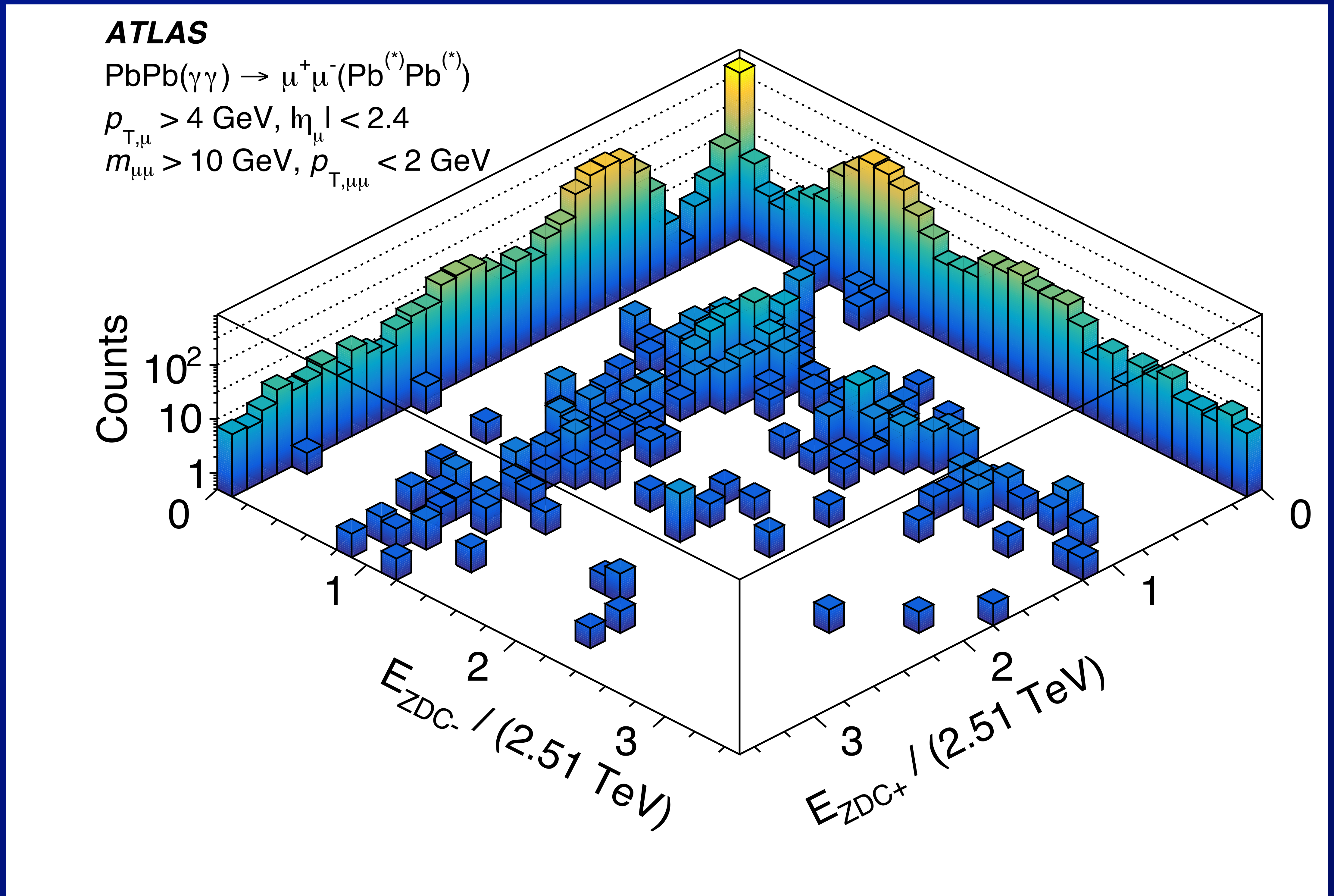
- In UPC events, in principle use ZDCs to tag whether/ which nucleus emitted photon
  - e.g. in (coherent) $\gamma+\gamma$ processes neither nucleus breaks up (nominally)
  - ⇒ "0n0n" topology
  - in γ+A scattering one nucleus breaks up (nominally)
  - ⇒"0nXn" topology
- But, coulomb excitation can cause photon emitter to also break up w/ ~ few neutrons
  - ⇒Spencer's talk
  - ⇒More on this later



UPC dilepton production

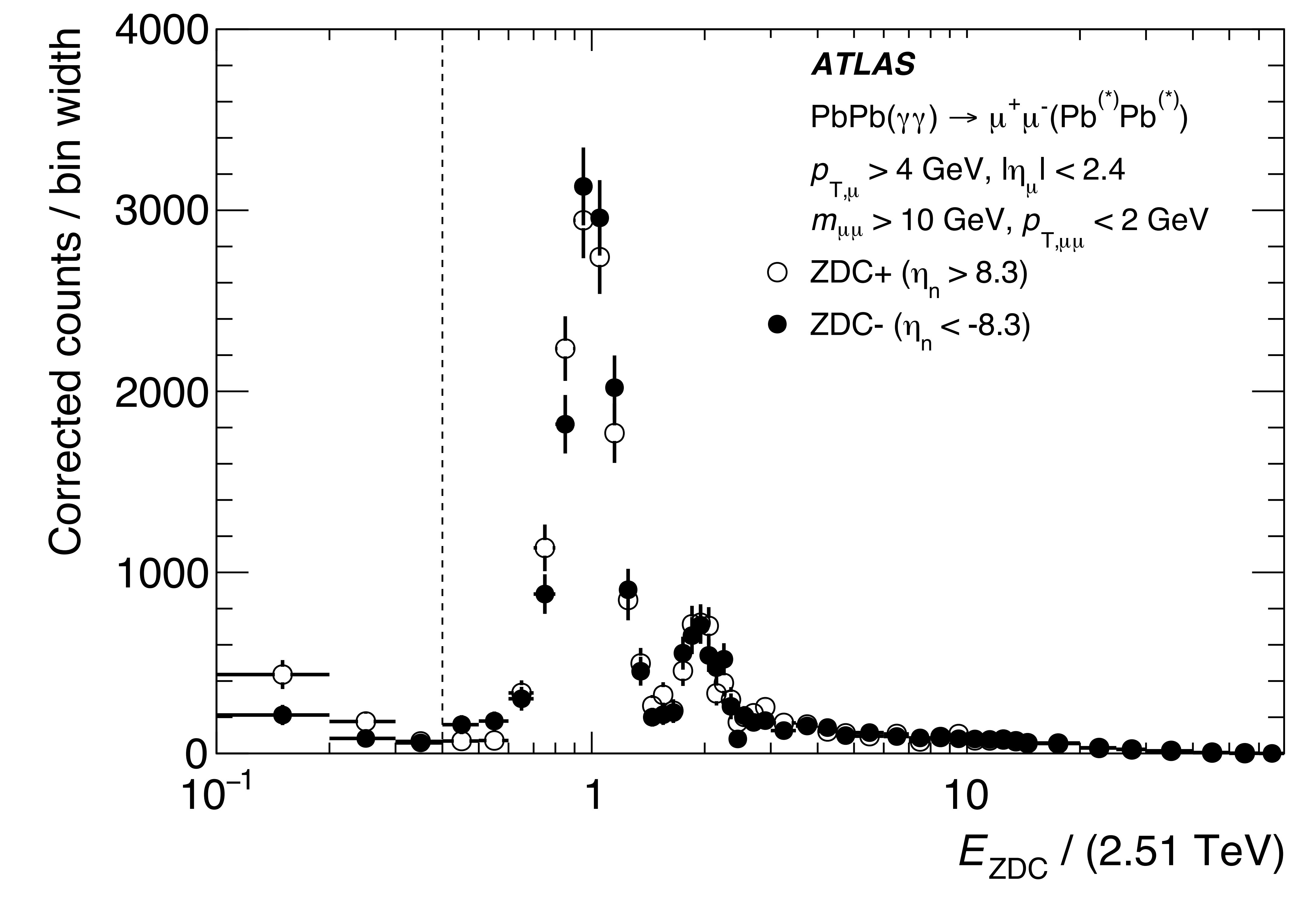
Dimuon production in UPC γ+γ, nuclear breakup

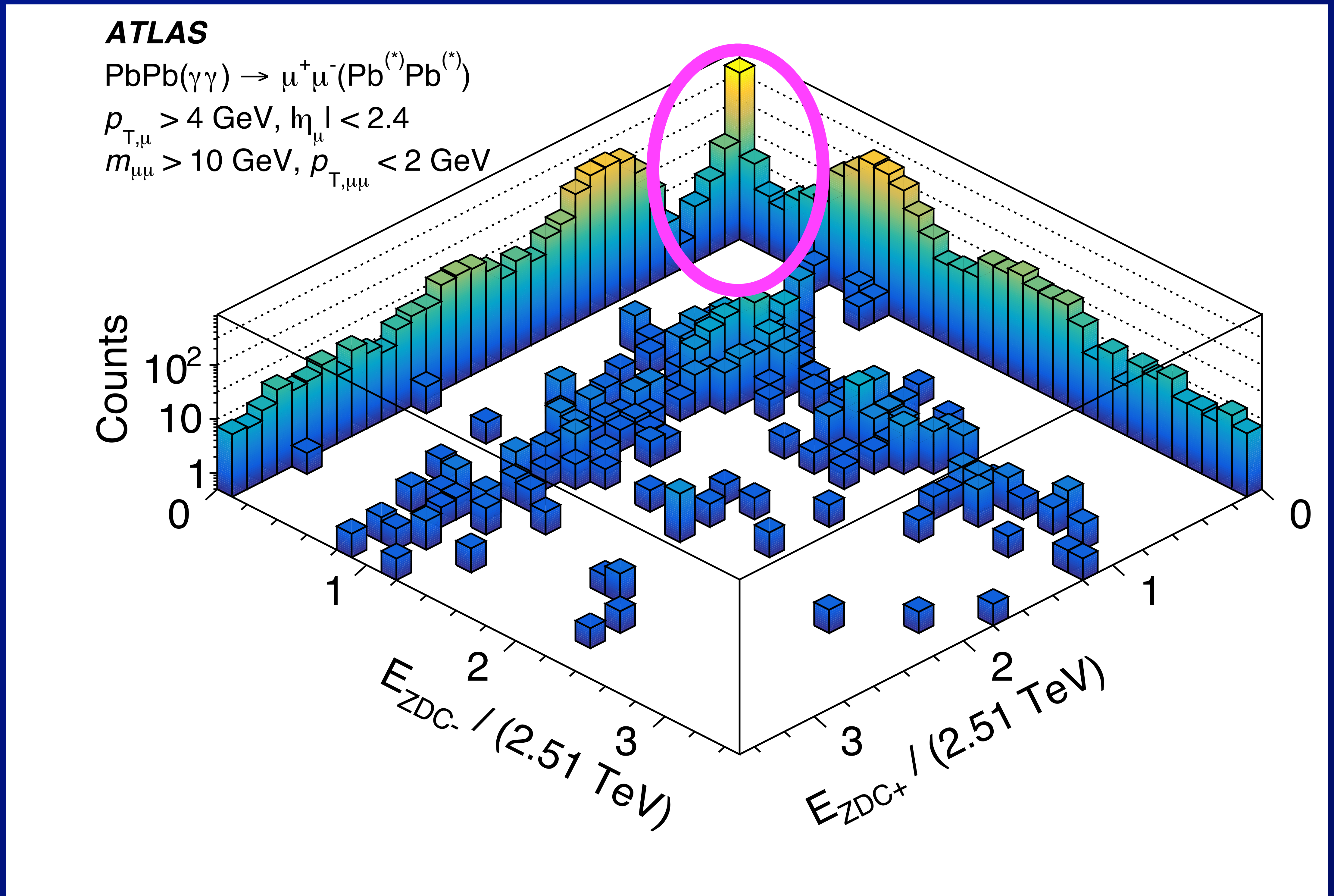




- Event "topology" as seen in the two ZDCs

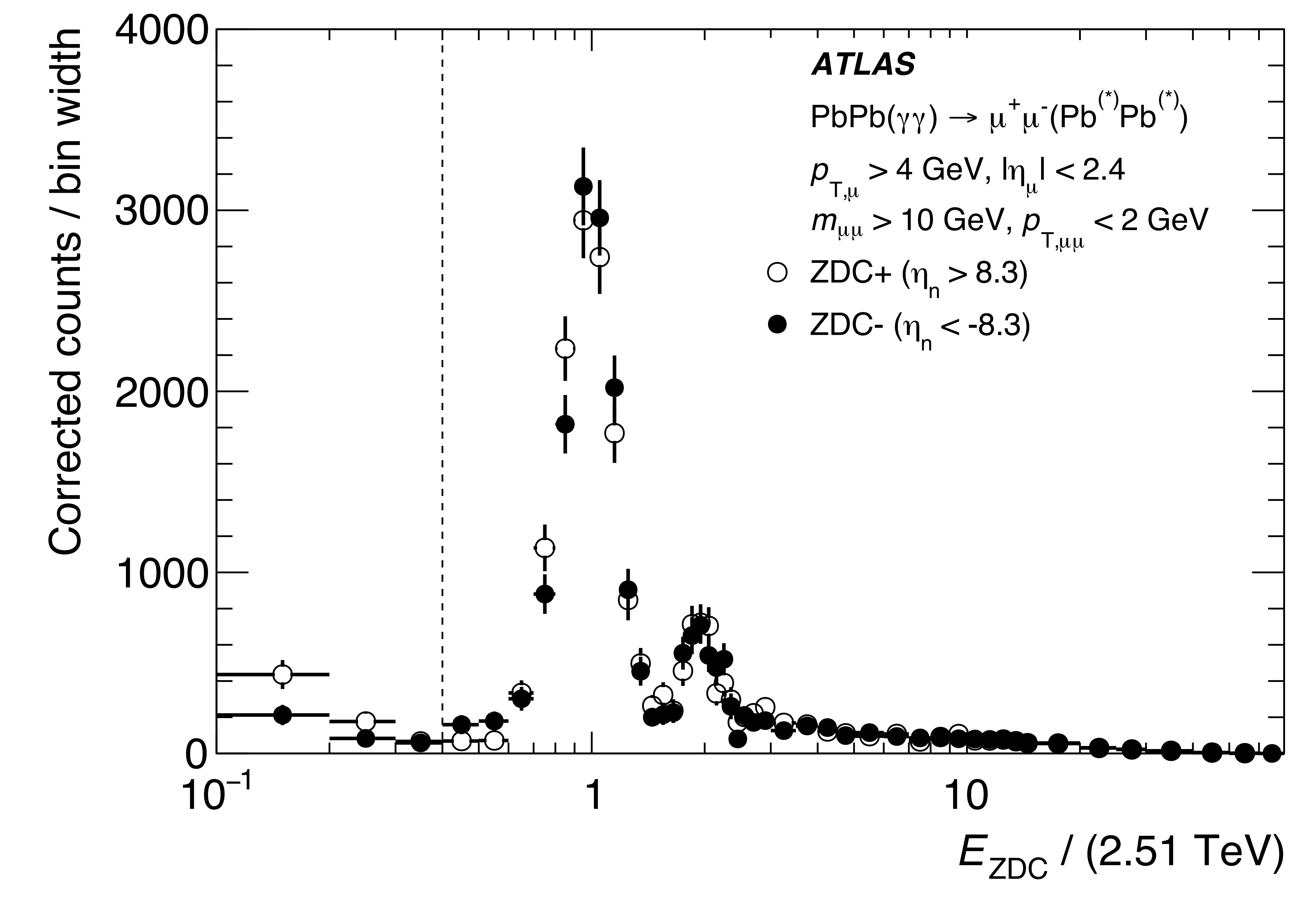
Dimuon production in UPC γ+γ, nuclear breakup

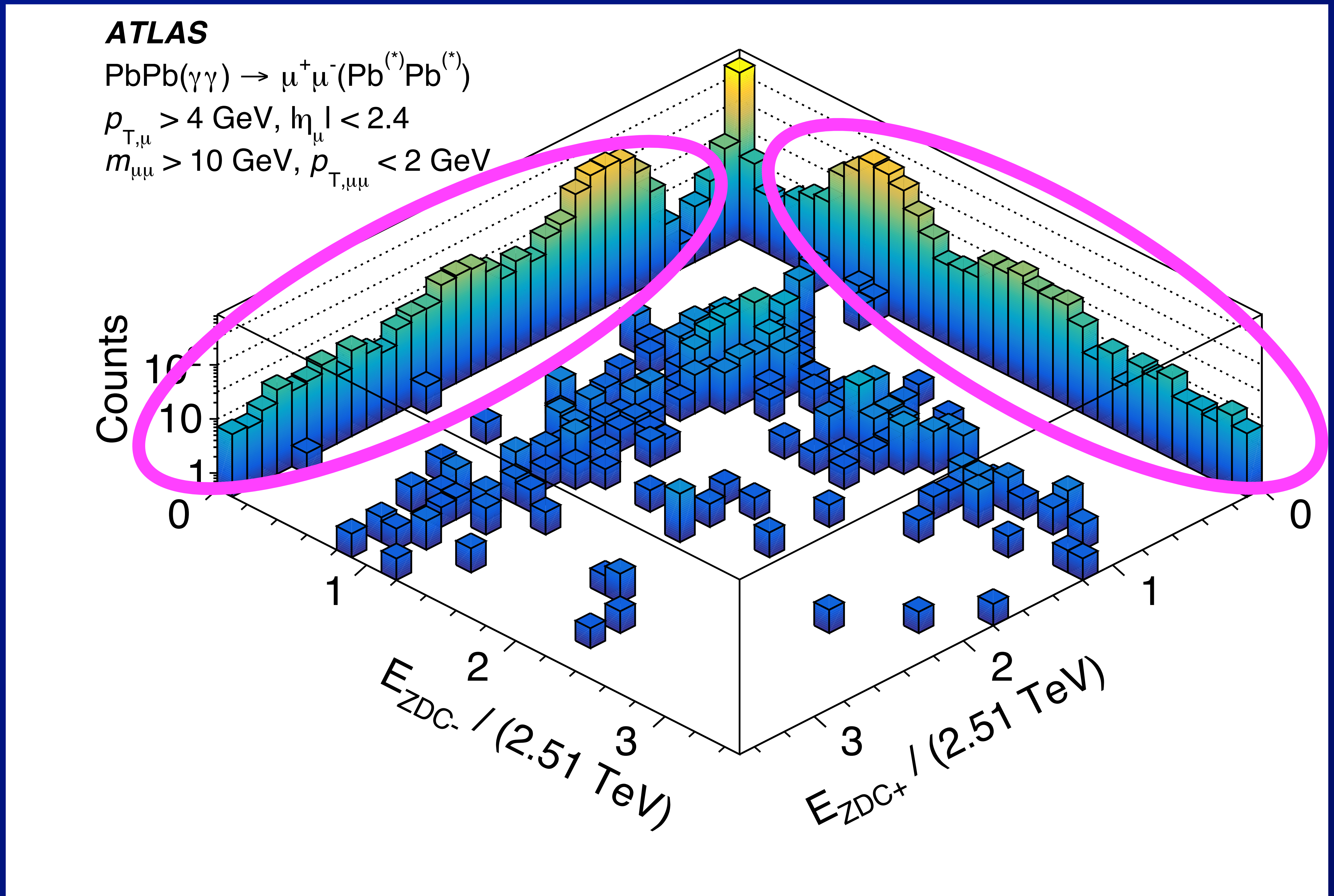




- Event "topology" as seen in the two ZDCs
  - 0n0n - no neutrons in either

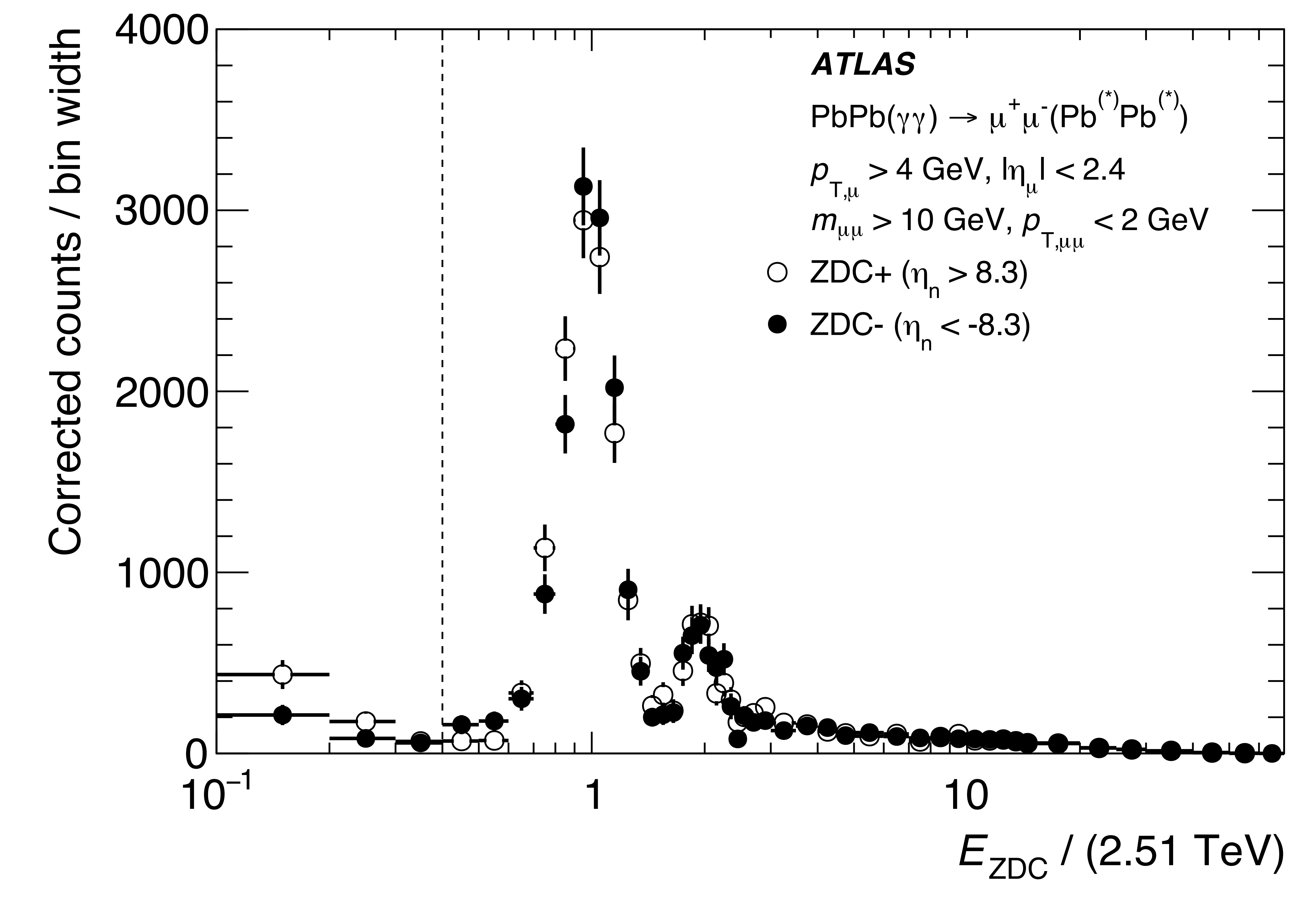
Dimuon production in UPC γ+γ, nuclear breakup

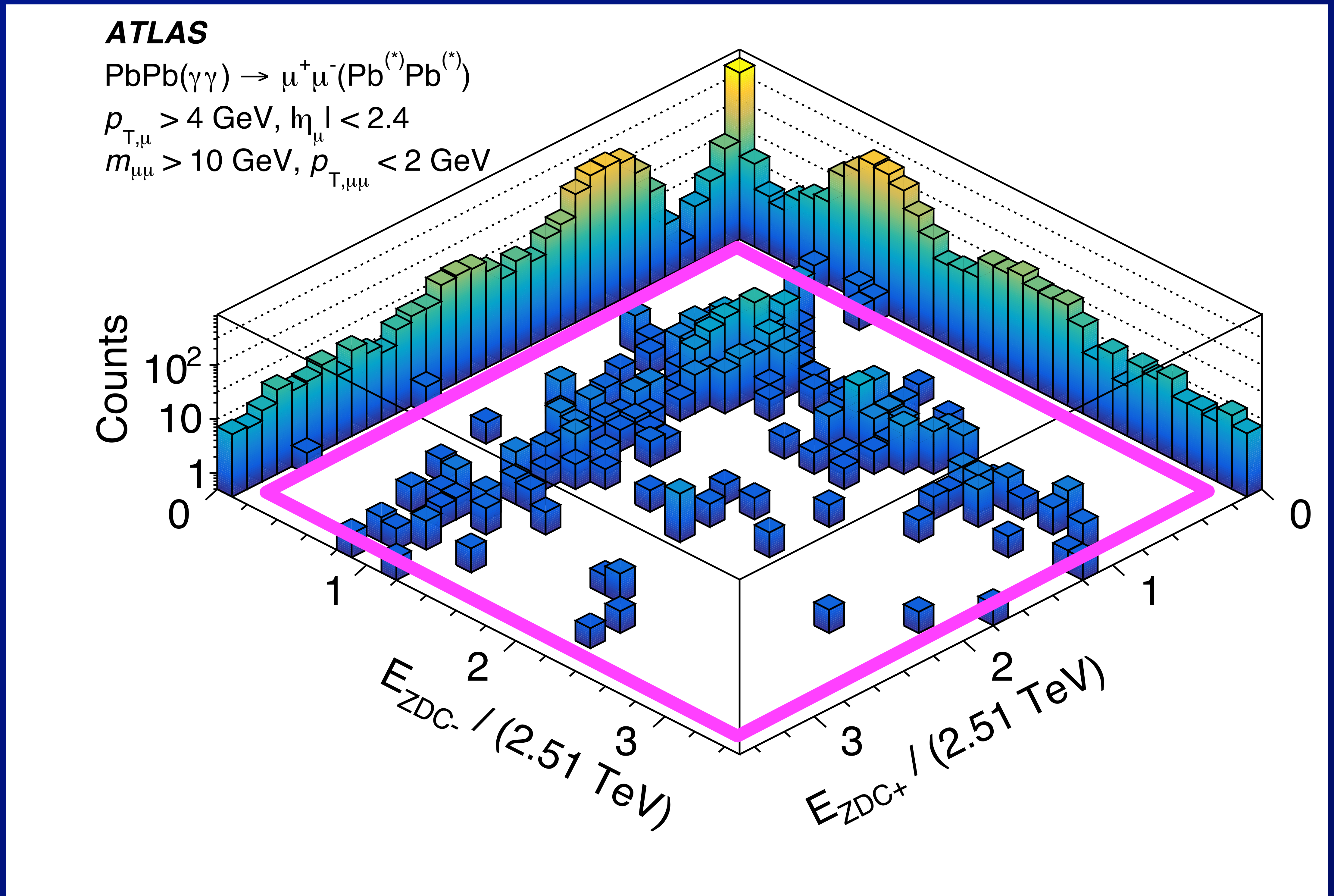




- Event "topology" as seen in the two ZDCs
  - 0nXn
  - ⇒ 0 neutrons in one
  - ⇒ ≥ 1 in the other

Dimuon production in UPC γ+γ, nuclear breakup

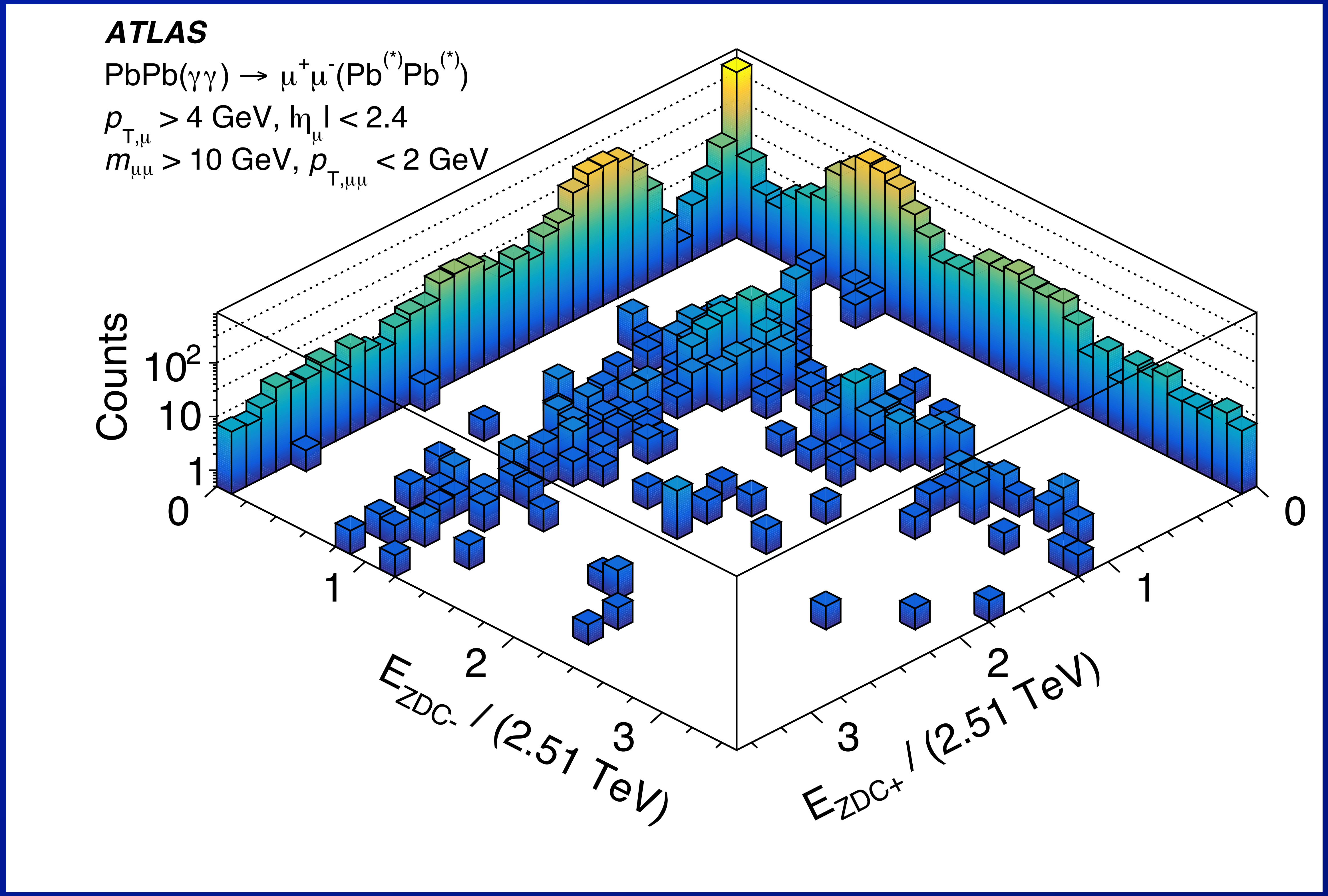


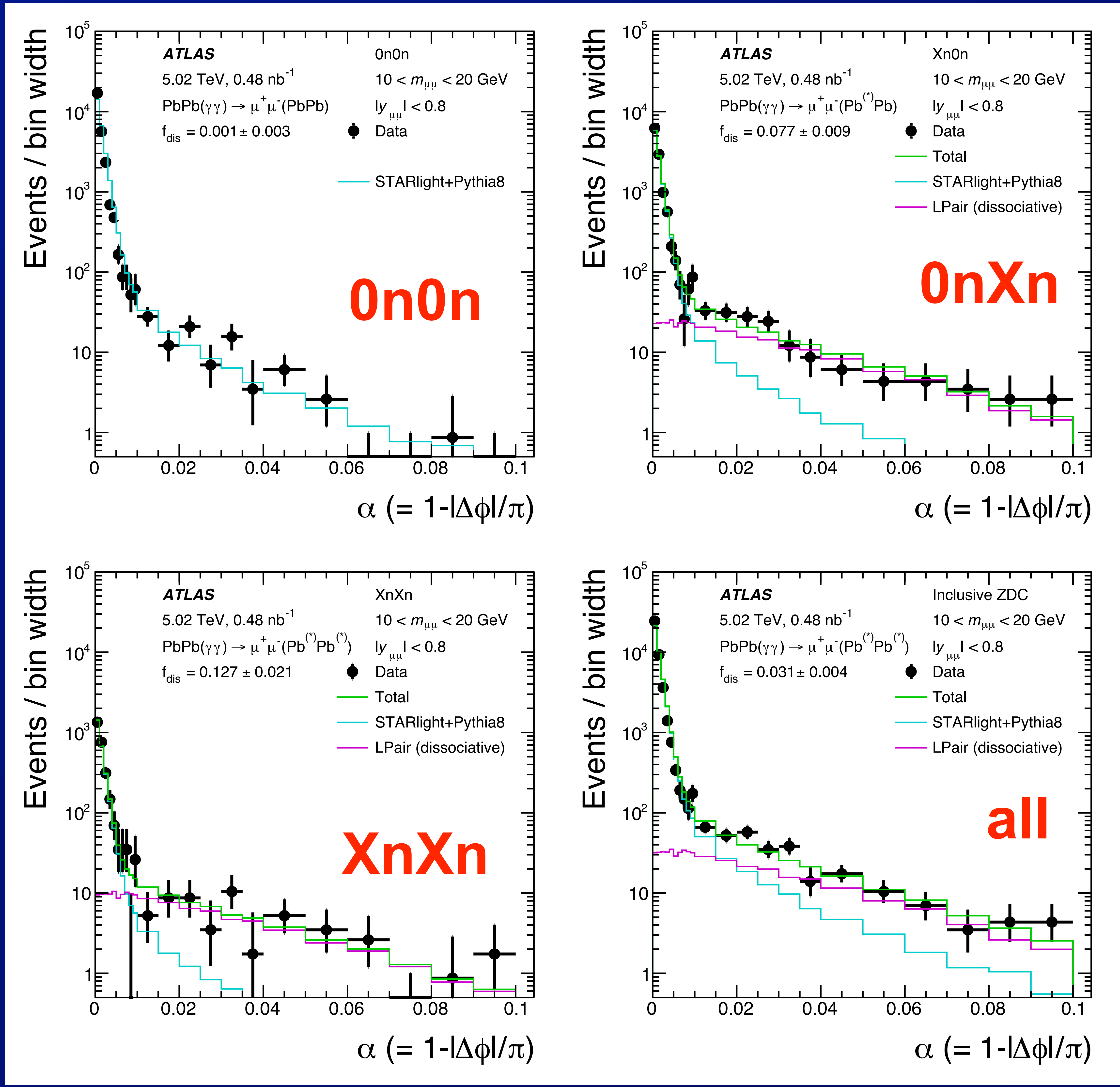


- Event “topology” as seen in the two ZDCs
  - XnXn

    ⇒≥ 1 neutrons in both

Dimuon production in UPC γ+γ, nuclear breakup





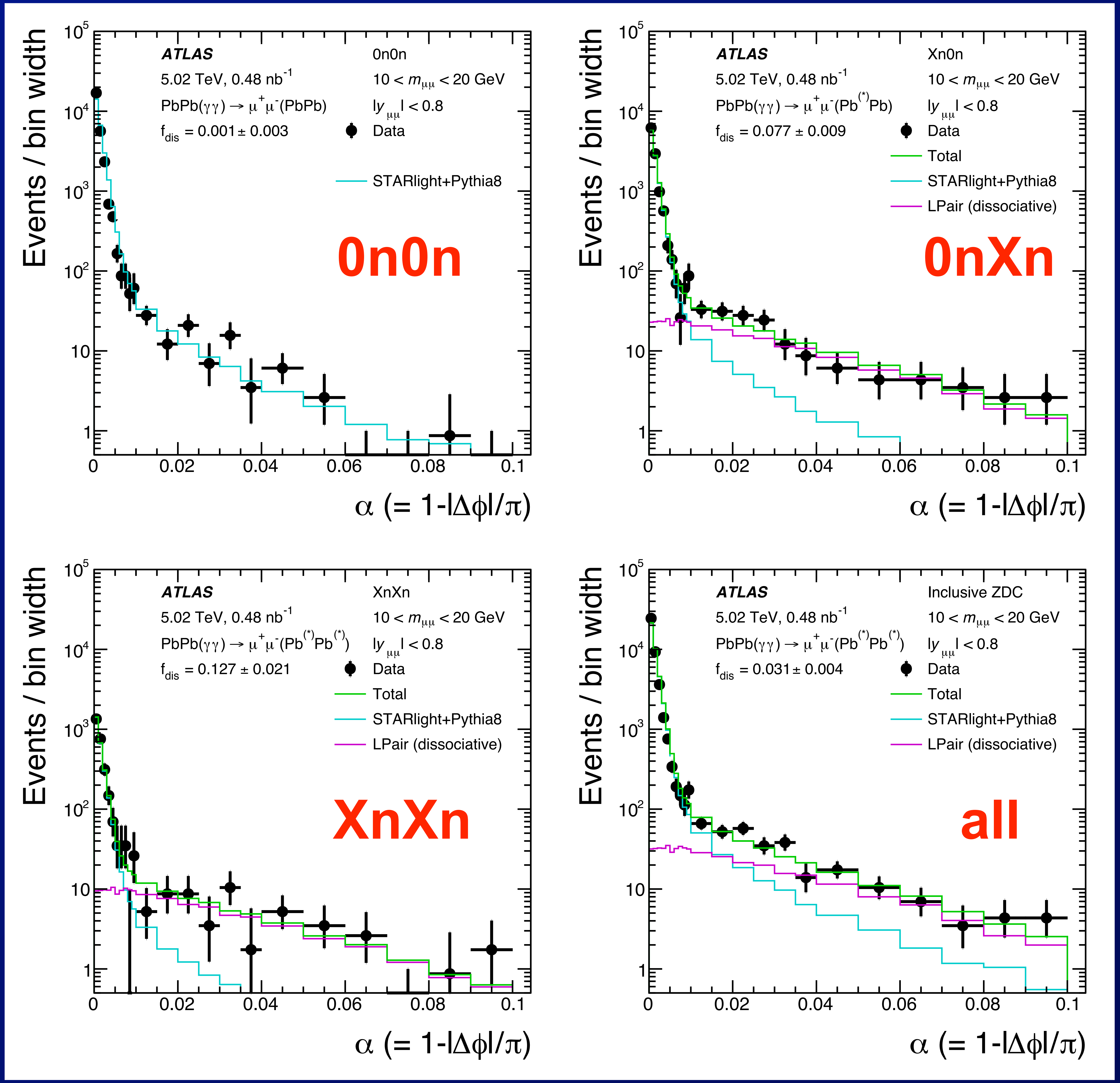
- **Dimuon acopolanarity distributions** $\alpha = 1 - \frac{\Delta\phi}{\pi}$
  - for different neutron topologies

⇒Large-acoplanarity tails change shape for different neutron topologies

Dimuon production in UPC γ+γ, nuclear

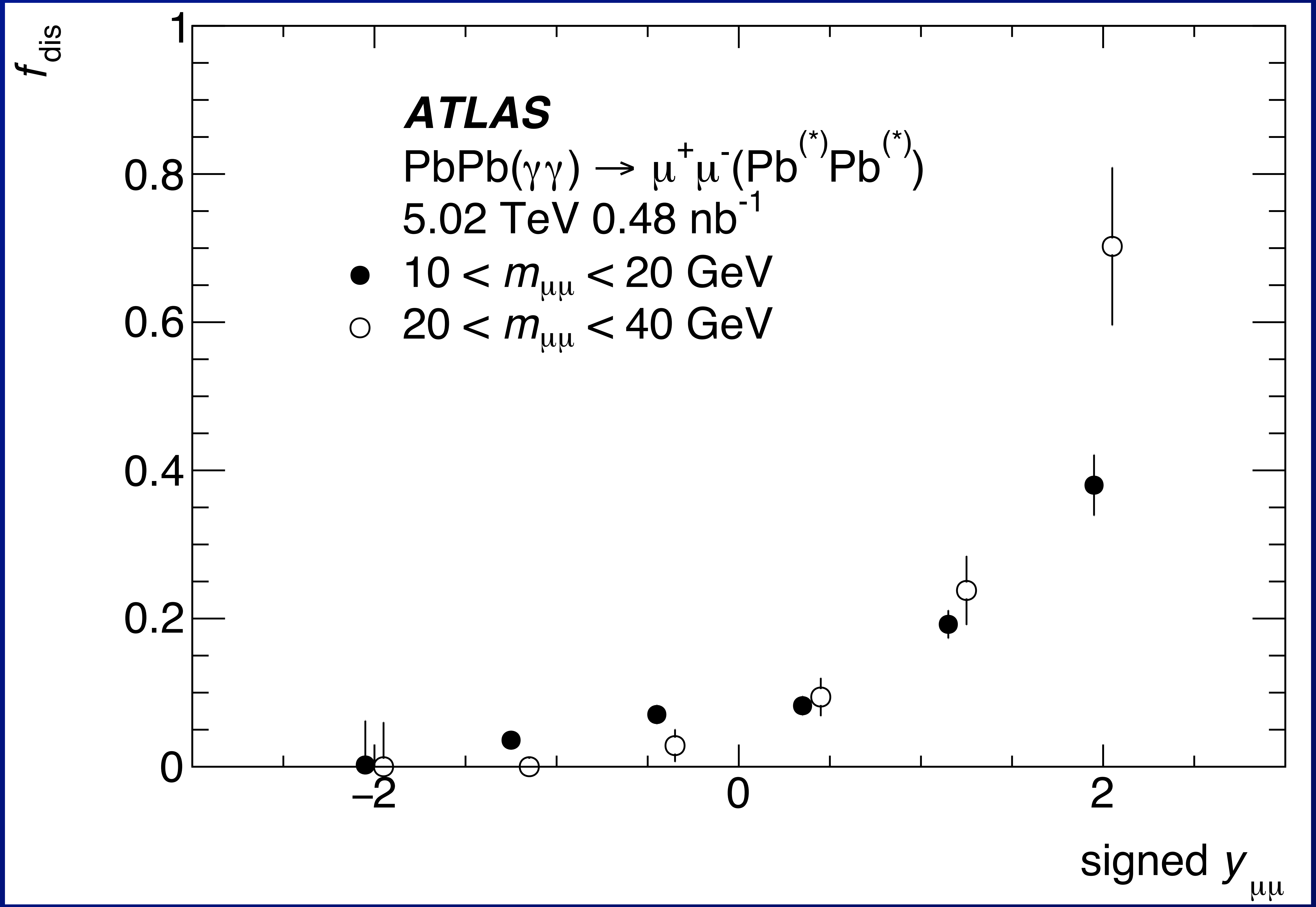
- Template fit using
  - –STARlight+Pythia8 for BW+QED,
  - –LPair for dissociative
  - ⇒0n0n well described by STARlight+Pythia8
  - ⇒Tails on 0nXn and XnXn dominated by dissociative

ATLAS, 2011.12211 [nucl-ex]



Dimuon production in dissociative UPC $\gamma+\gamma$,

- Select 0nXn and use the asymmetric topology to study:
  breakup $\Longleftrightarrow$ dissociation
- use signed $y_{\mu\mu}$ relative to Xn direction
  – larger $y_{\mu\mu}$ means more energetic photon emitted by nucleus that breaks up
- See *large* breakup fractions for large $y_{\mu\mu}$



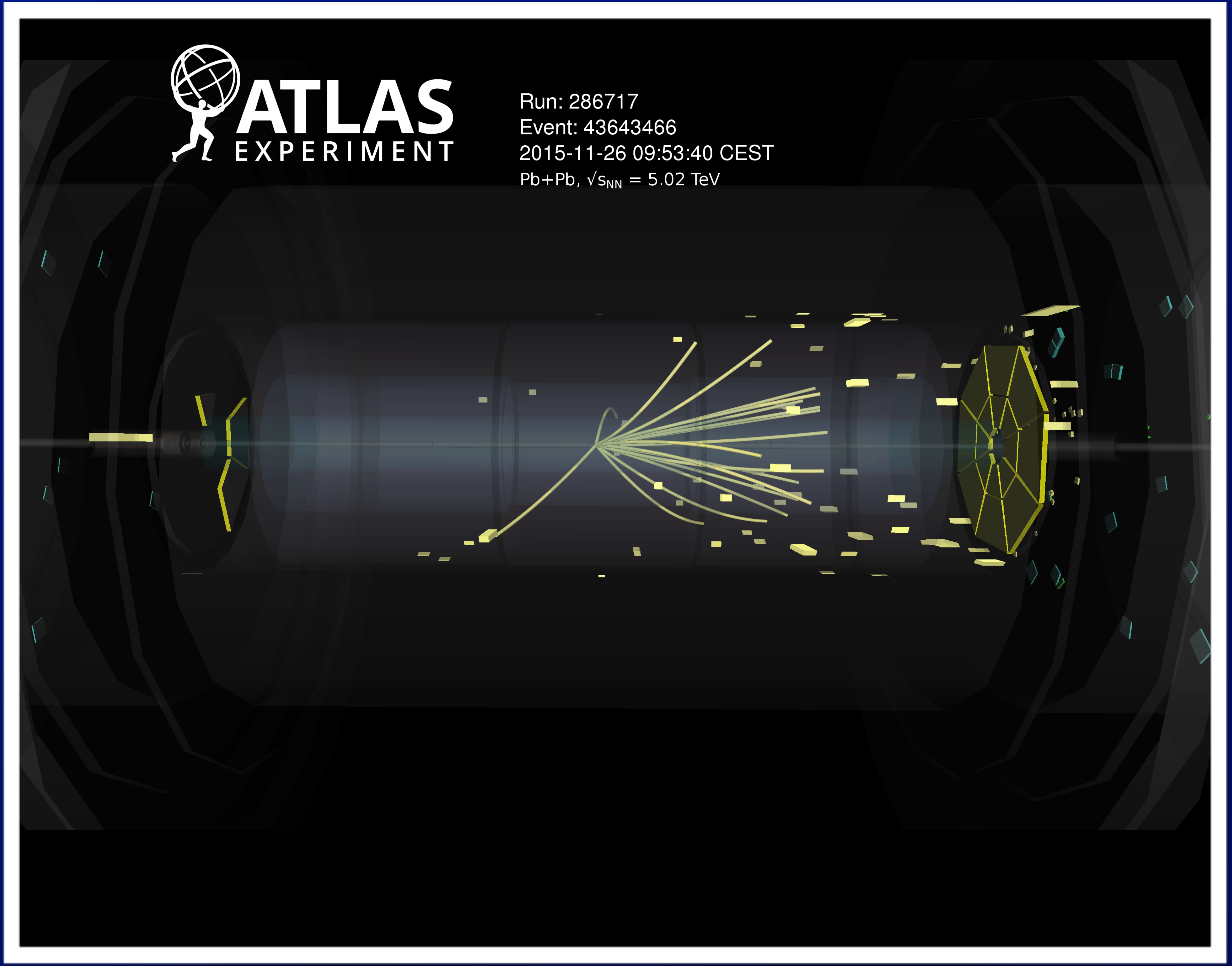
ATLAS, 2011.12211 [nucl-ex]

Photonuclear jet production

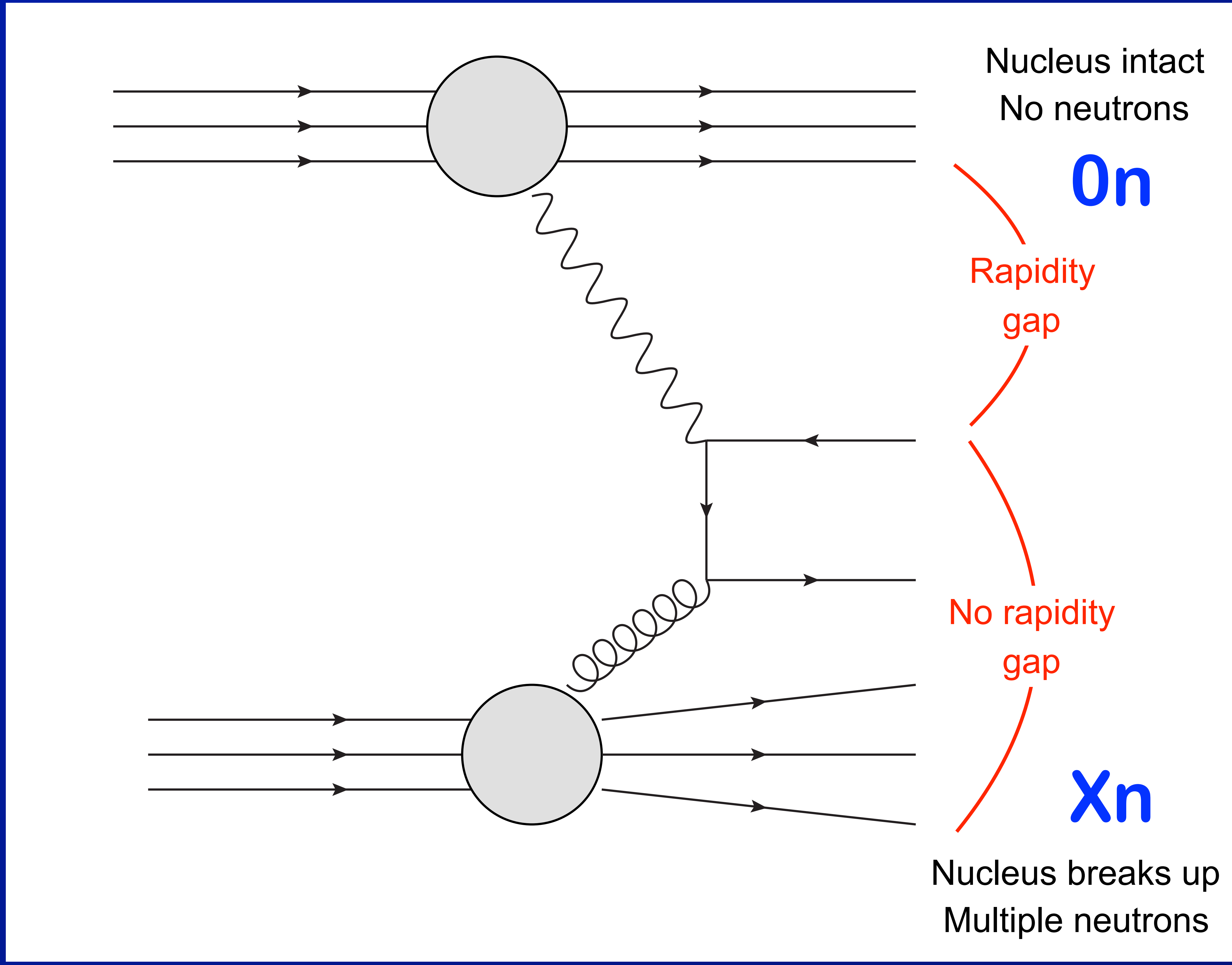
Pb+Pb inclusive photonuclear processes

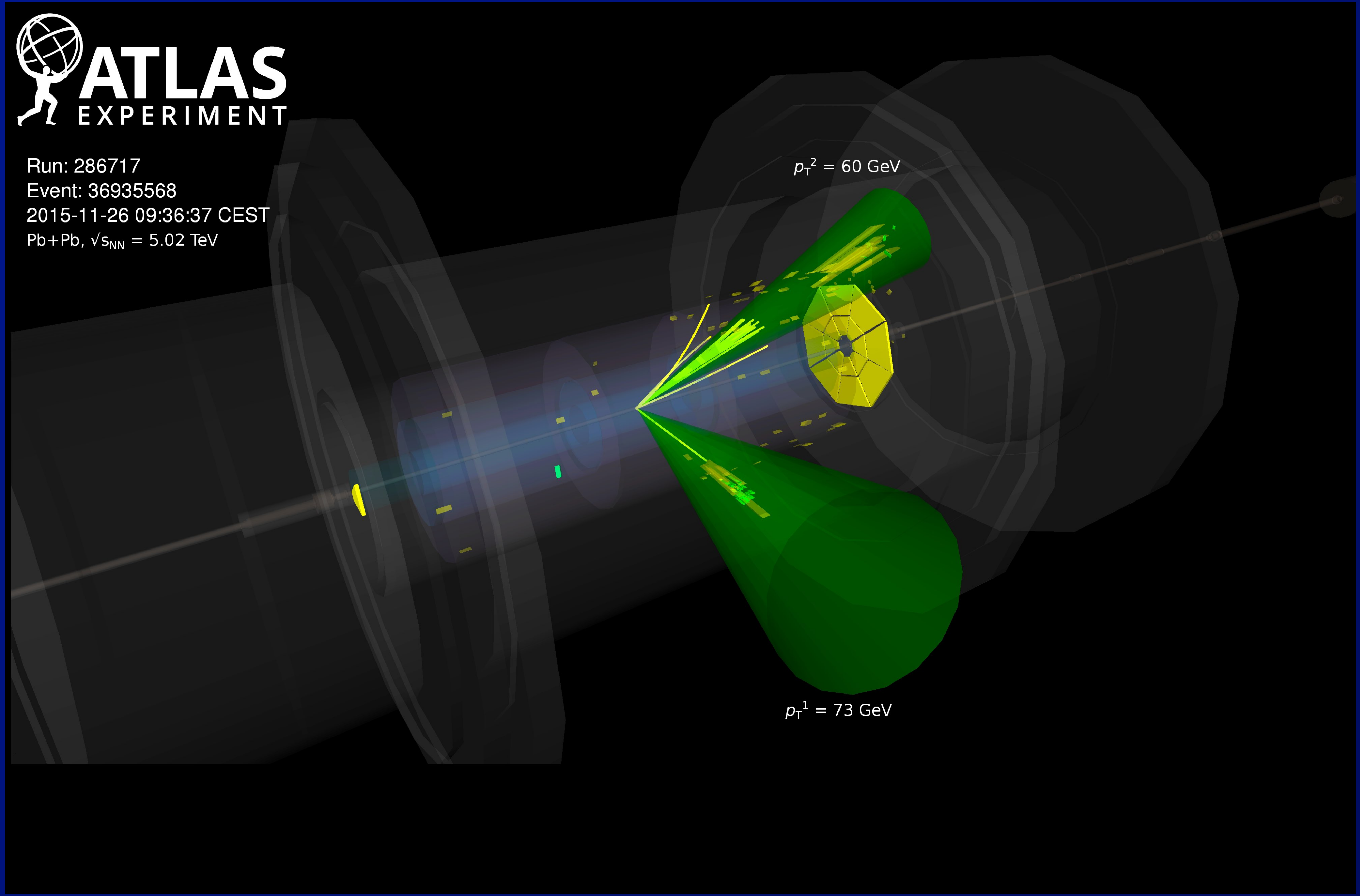
- In ATLAS, so far, triggering and selection of γ+A collisions starts from ZDC 0nXn topology
  - Additional gap selections to suppress hadronic collisions
- Example event shown to right
  - rapidity asymmetry self-evident
- ATLAS has published an analysis of two-particle correlations in inclusive γ+A
  - dominated by VDM-like scattering

  ⇒ further inclusive γ+A measurements under consideration



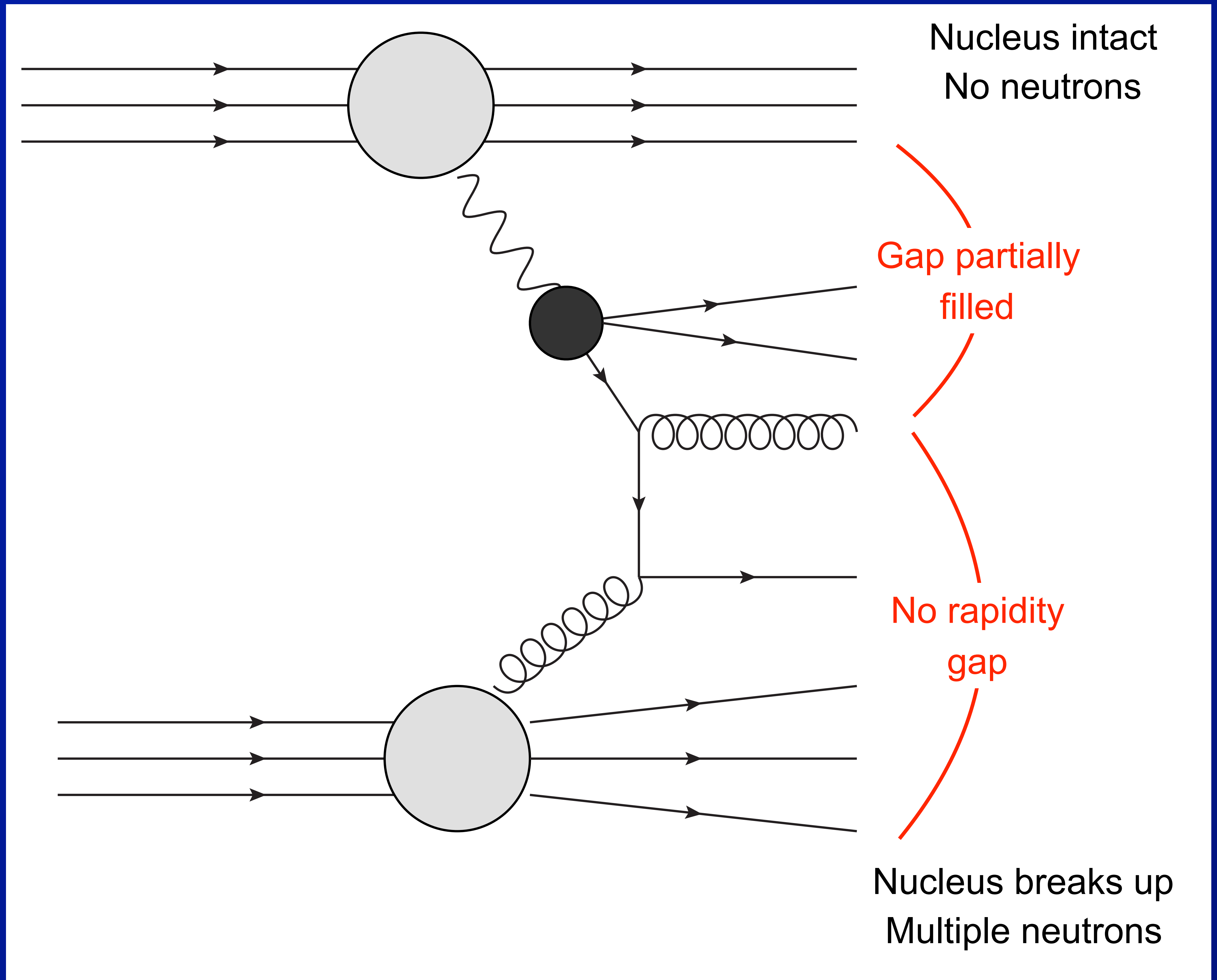
Jet photo production

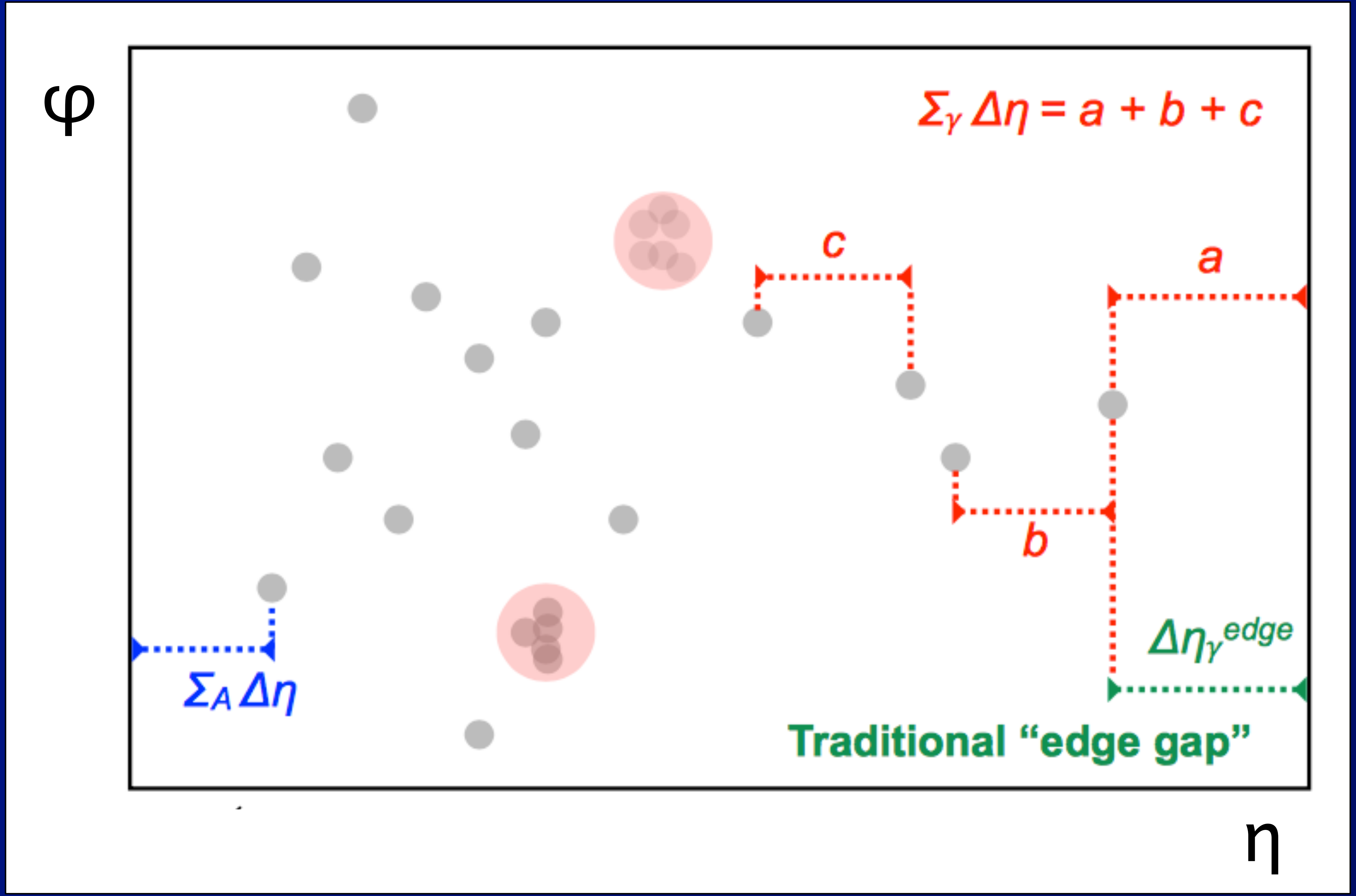




- **In ATLAS, primary trigger based on 0nXn + jet trigger**
  - in 2018, sampled full luminosity for jet p_T > 20 GeV
    - ⇒However, misses contribution from soft breakup of photon emitter
    - ⇒Also lose ~ 5% of cross-section due to “EM pileup”

Jet photo production, gap analysis



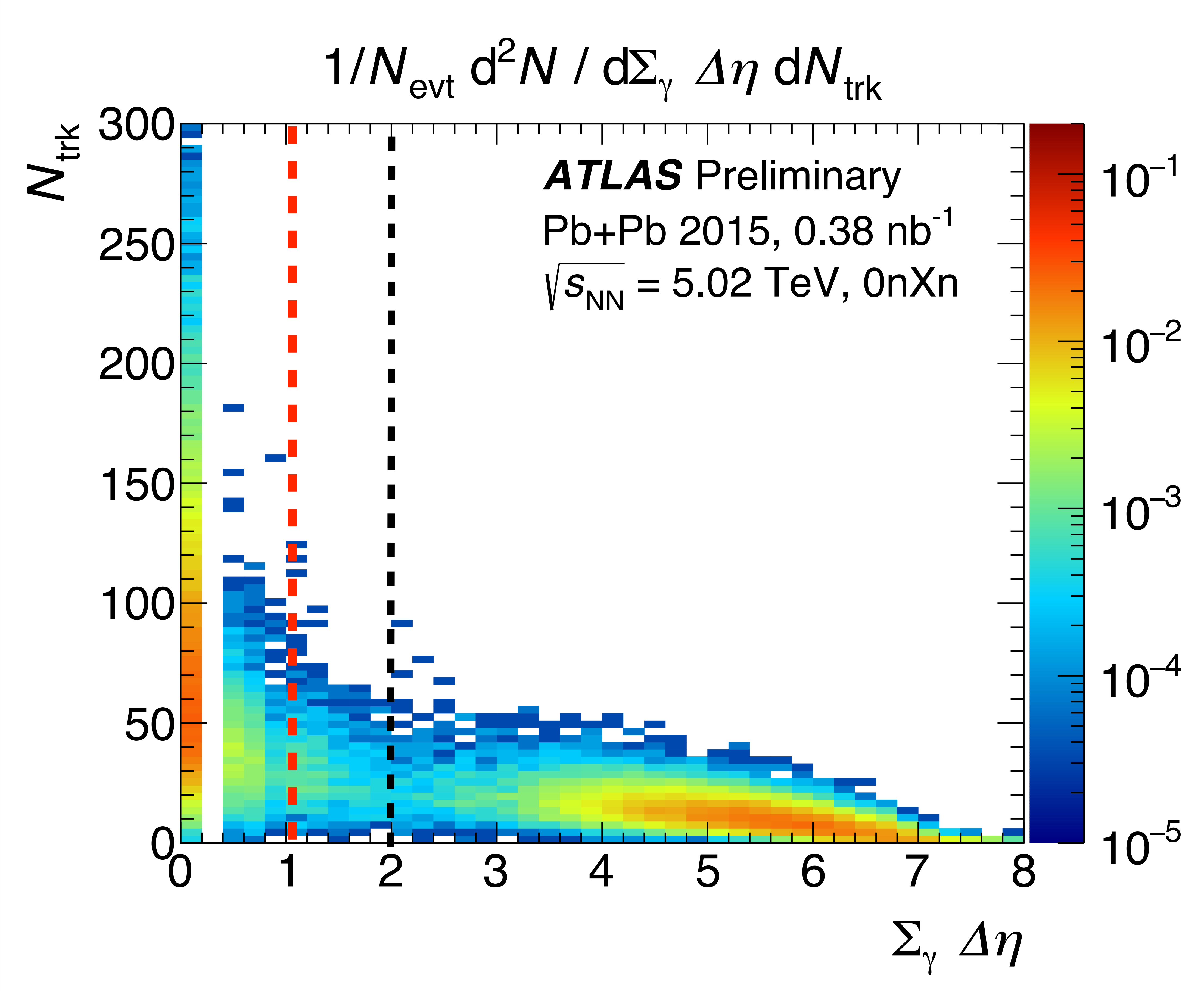


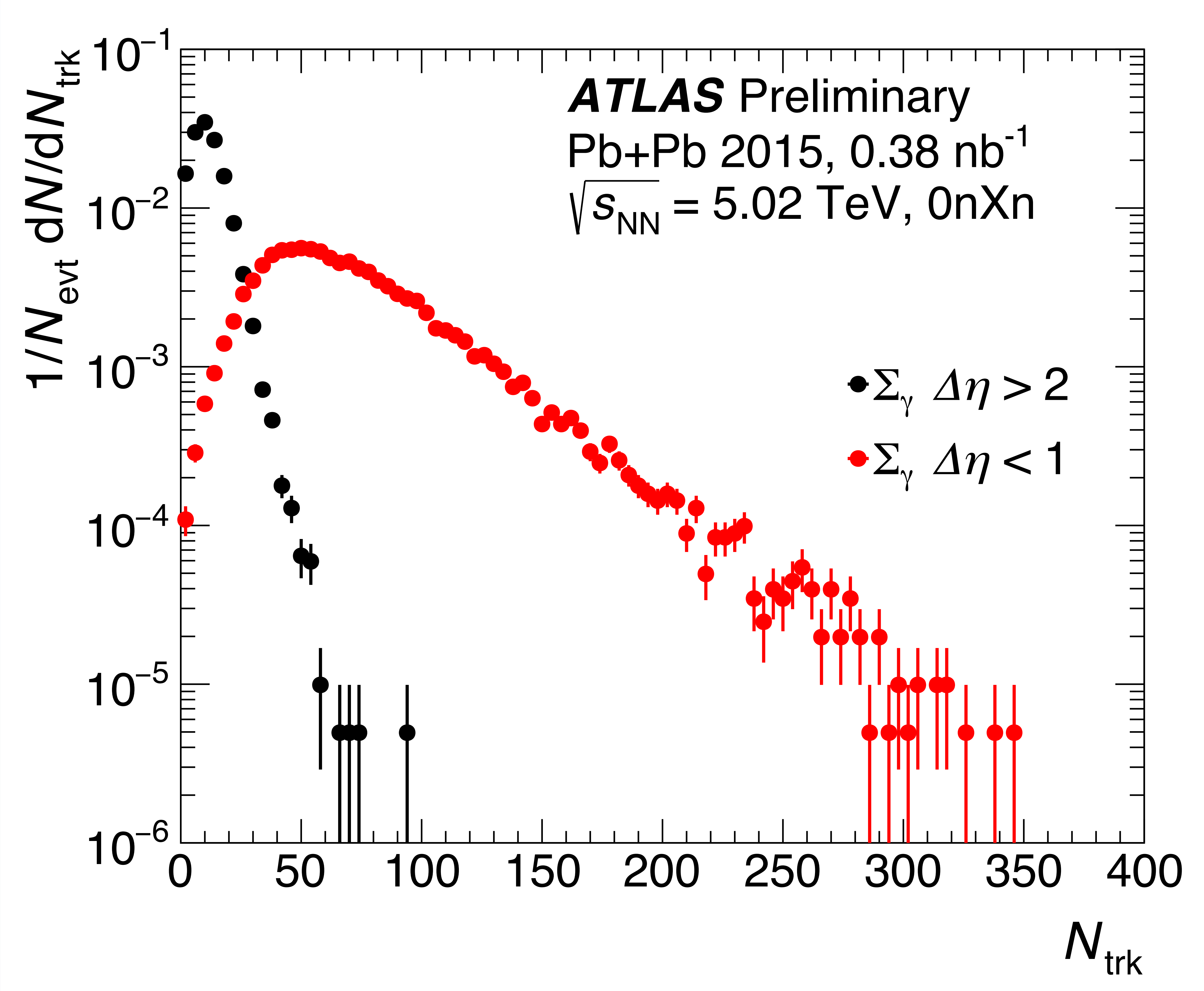
- **Resolved photons partially fill the gap in photon direction**
  - In ATLAS, sum gaps of $\Delta\eta > 0.5$ separately forward (γ) and backward (A)

$\Rightarrow$ in preliminary analysis of 2015 Pb+Pb data required $\Sigma\gamma\Delta\eta > 2$

$\Rightarrow$ in analysis of 2015+2018 underway, $\Sigma\gamma\Delta\eta > 2.5$

Jet photo production, gap analysis



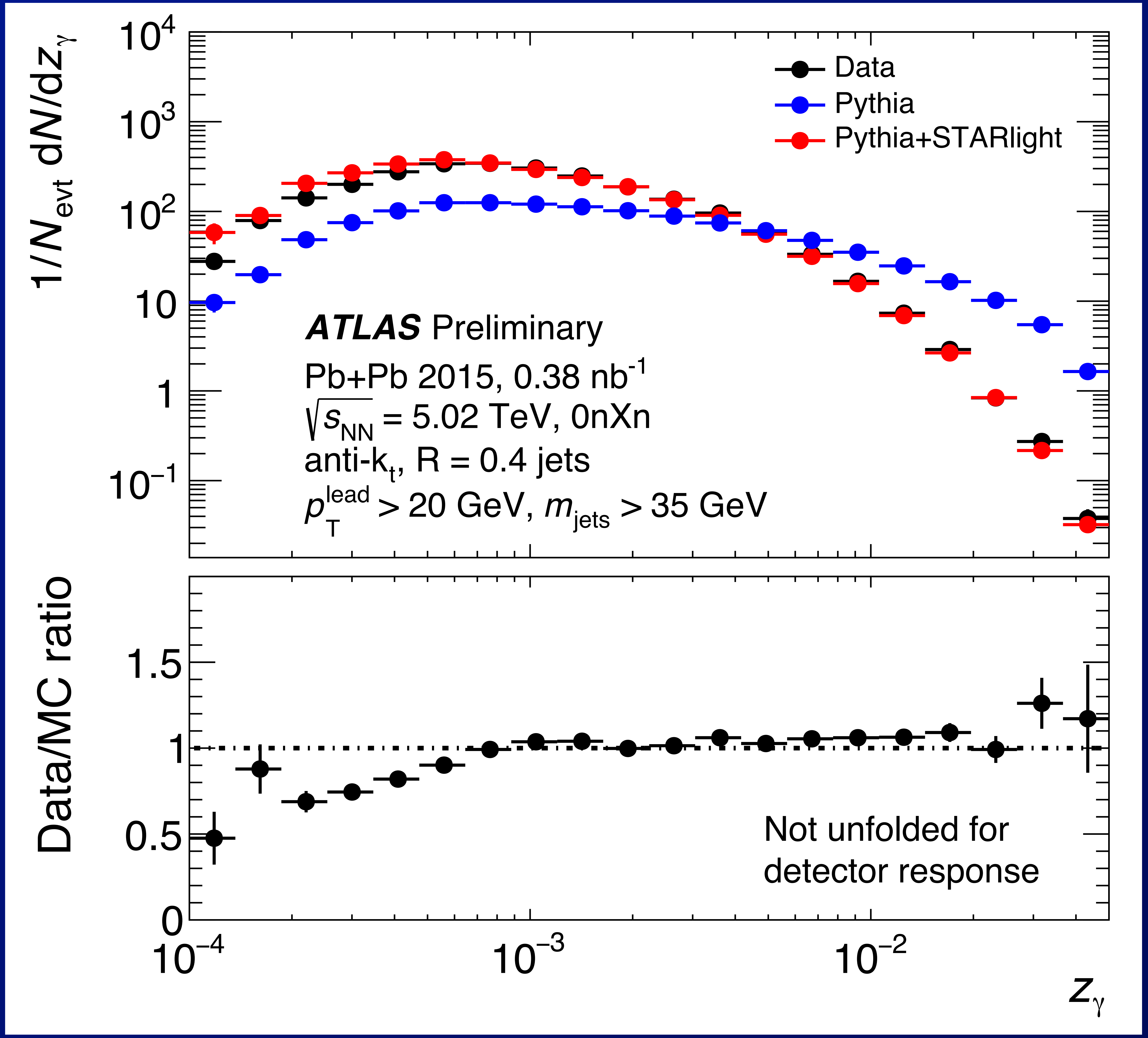


- Good (not perfect) separation between hadronic and γ+A events

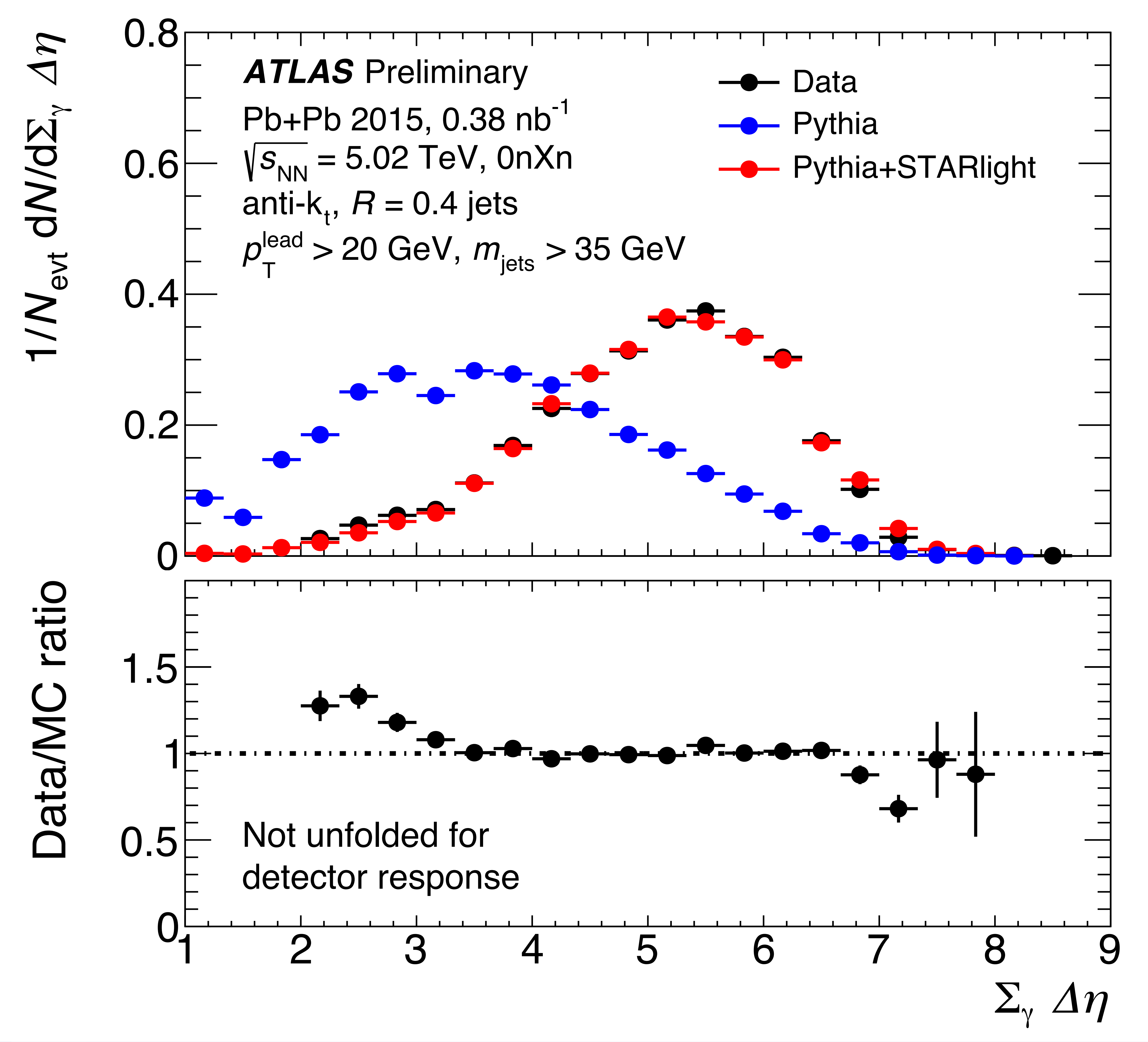
⇒e.g. completely different charged particle multiplicity distributions

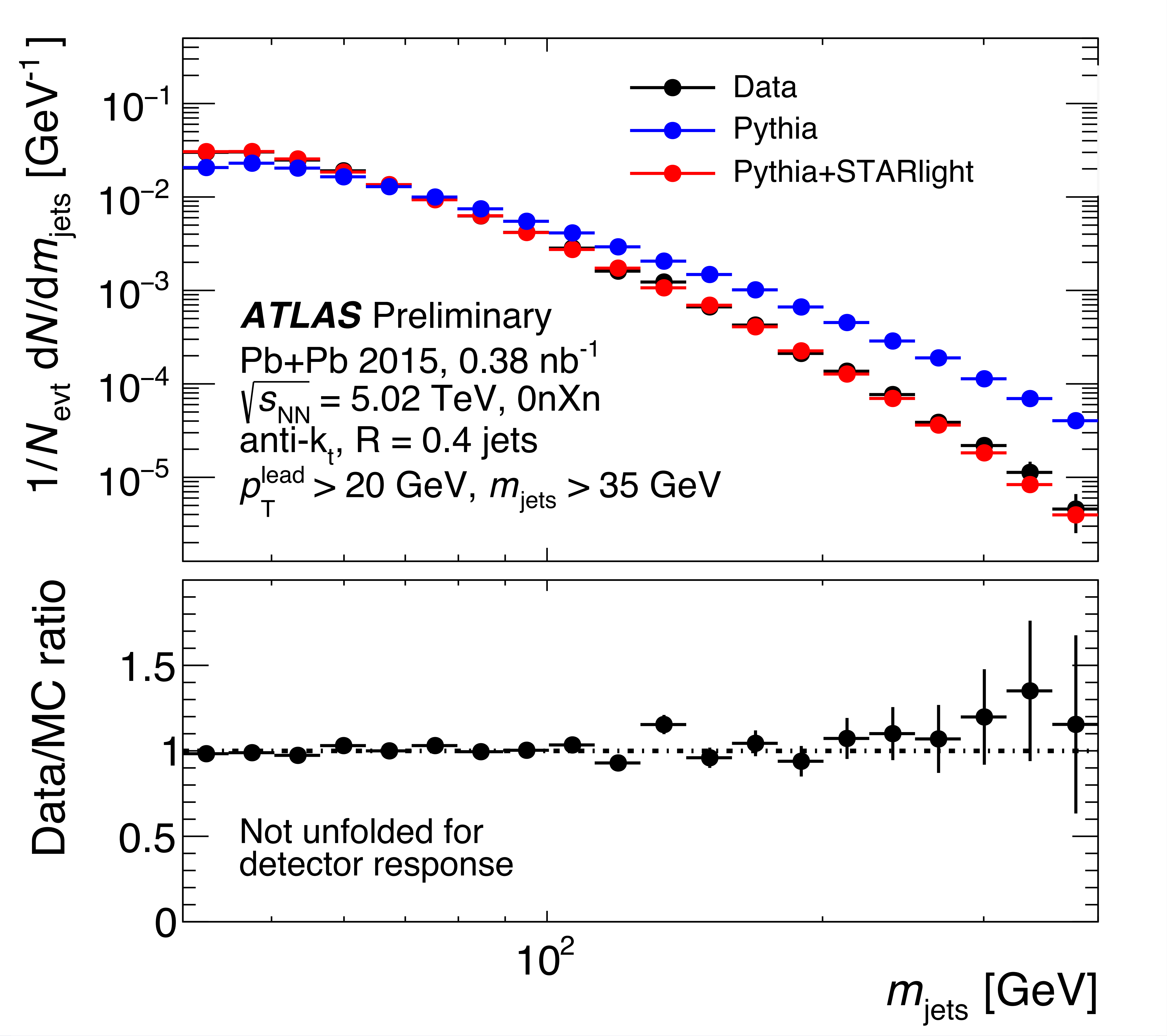
Photonuclear MC: Pythia 6 -> Pythia 8

- Preliminary measurement used Pythia6 to generate MC sample needed to corrections
  - photon flux from muon
  - ⇒ very different from Pb flux
- Re-weighted MC sample as a function of y to account for difference
  - see e.g. the z = x*y distribution
- But the re-weighting created a number of technical problems
  - ⇒ Introduction of nuclear photon flux in Pythia8 a game changer



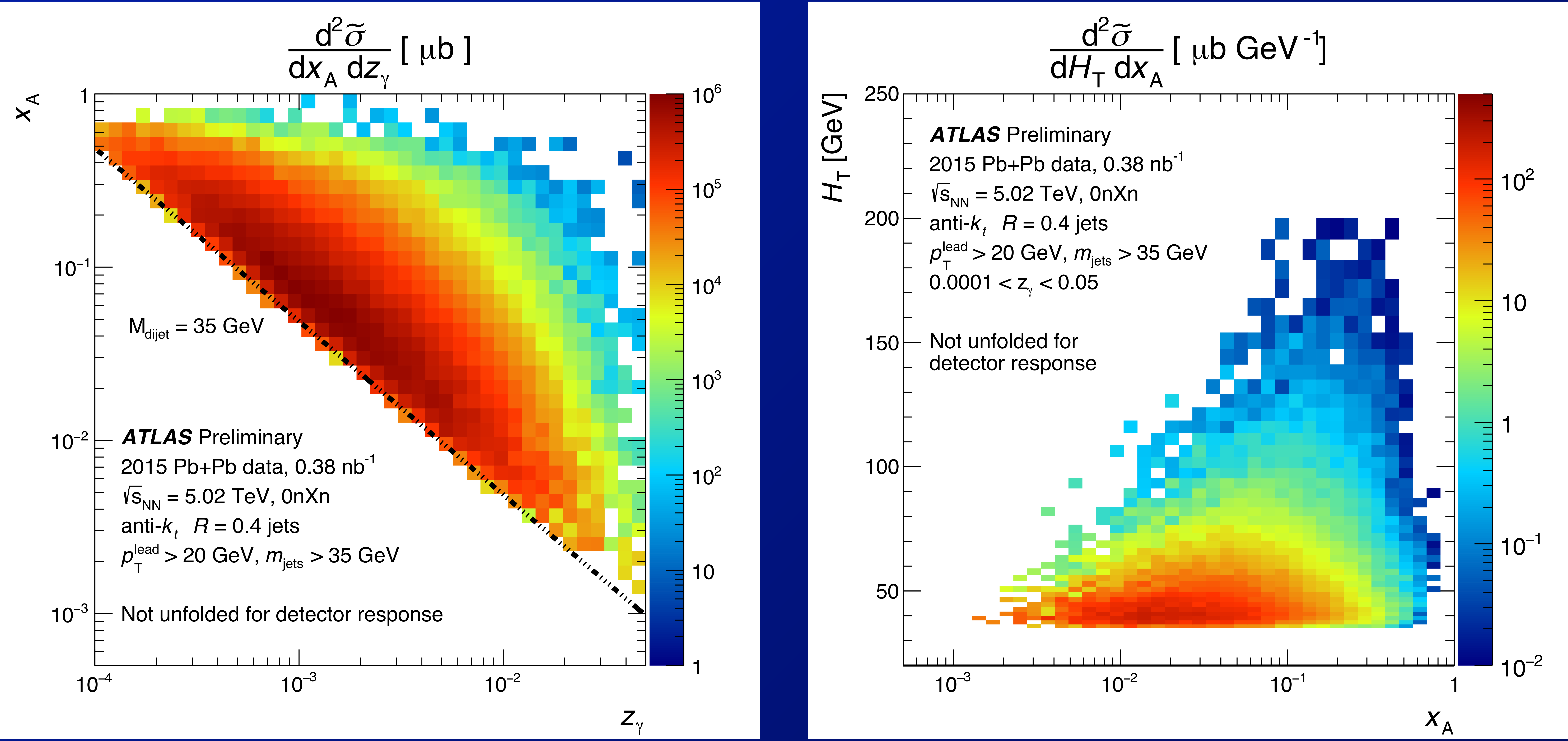
Data / Pythia 6 comparisons





- **Re-weighted Pythia 6 reasonably described data:**
  - e.g. gap and mass distributions

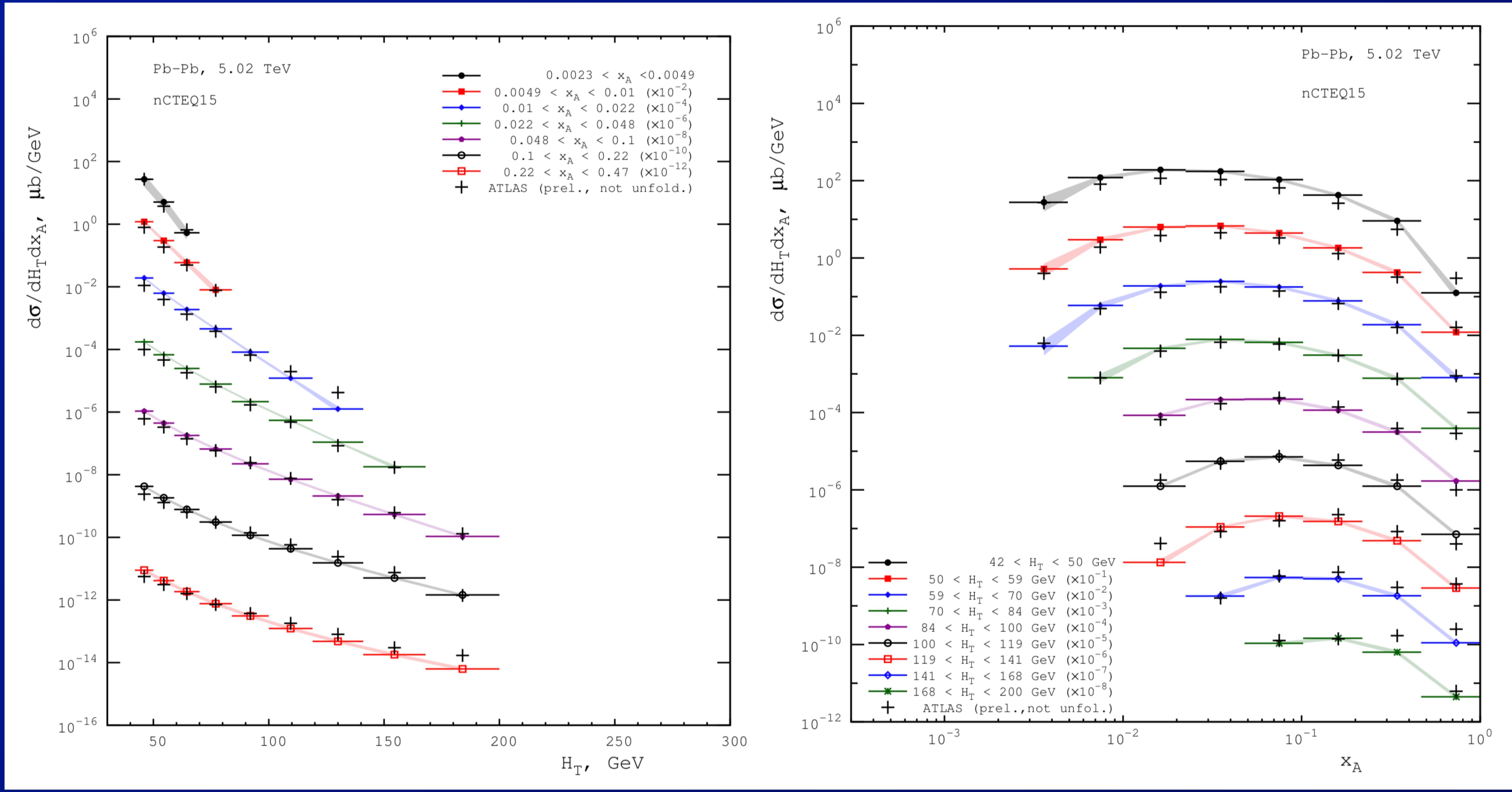
ATLAS di/multi-jet kinematic coverage



- Constrained by jet minimum p_T (20 GeV) and y range ($|y_{jet}|$ < 4.4)

Preliminary, γ+A → jets cross-sections

from Guzey, Klasen
arXiv:1909.08954



- Comparison of NLO predictions to preliminary ATLAS data
  - qualitatively excellent agreement, but some systematic differences
  - lack of unfolding for jet resolution/response

⇒BUT ALSO: data has 0nXn requirement — γ-dependent loss of σ

Photonuclear jet production: target fragmentation

- ATLAS analysis of 2015+2018 data will be presented this spring
  - better statistics, use of particle-flow jets, better MC, …
- But, primary result will be based on 0nXn selection
  - loss of cross-section due to soft nuclear breakup

    ⇒process dependent

    ⇒appears to be larger in γ+A → jets than (e.g.) $\gamma+\gamma \to \mu\mu$
  - Correct data? Rely on theory to predict 0xXn?
- We do have an alternative trigger that allows lower-statistics measurement of (e.g.) 1nXn, 2nXn

  ⇒In Run 3, will include 1-4nXn ZDC triggers to include soft breakup events
- Is there a contribution from (coherent) diffraction?

  ⇒ nuclear breakup in emission of coherent pomeron?

Photonuclear jet production: target fragmentation

- ATLAS is also measuring jet production in 0n0n events
  - both γ+γ and coherent photo-diffraction
  - photo-diffraction cross-section significantly larger

  ⇒Depends on gap requirement / factorization breaking

  ⇒With full factorization breaking, γ+γ > diffractive

- Events are clearly distinct from photo nuclear jet production
  - rapidity distributions symmetric around mid-rapidity
- No event generator implements Pb coherent pompon flux?

  ⇒would be good to solve this problem
- 0n0n selection even more sensitive to soft breakup
  - in fact, coherent diffraction + breakup may create non-negligible background to the photo nuclear measurement!

ZDCs in ATLAS (and CMS)

- ATLAS has made significant upgrades to ZDCs for Run 3
  - Installed “air core” (no dielectric) cables between TANs and USA15
  - signal fall times decreased by ~ factor of 2
  - ⇒ substantial reduction in out-of-time pileup
  - Replaced radiation damaged quartz with new, more rad-hard fibers
  - ⇒also factor of 2 better light yield
  - New readout and trigger electronics
  - ⇒fully digital trigger with multiple thresholds implemented via LUTs
  - ⇒will allow, for example, Level-1 triggers like: 1-4nXn
- For HL-HLC/Run 4 ATLAS and CMS are collaborating on construction of new ZDCs (JZCapa)
  - adapt to different LHC constraints
  - better sampling, better radiation hardness