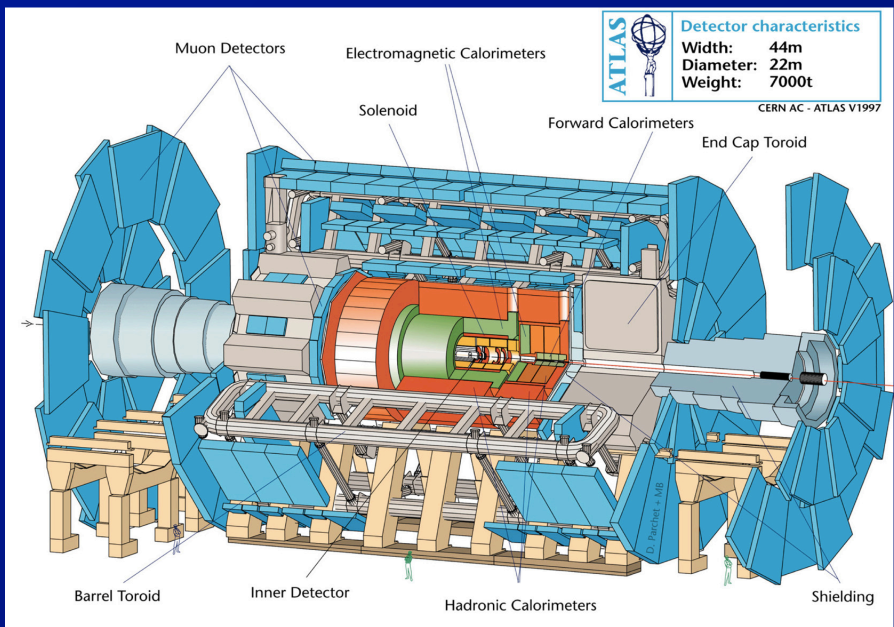
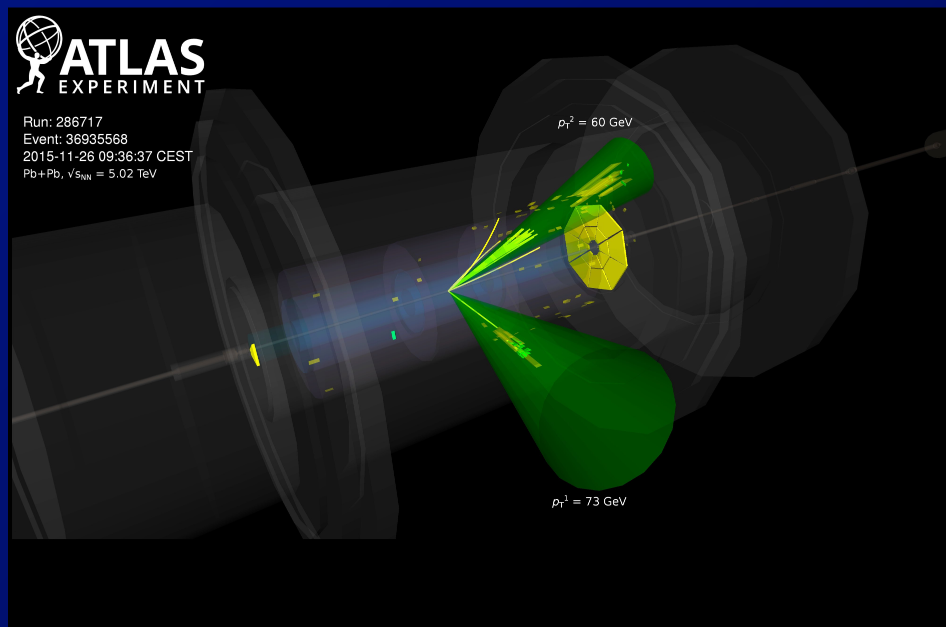
Measurements of dijet production in ultra-peripheral Pb+Pb collisions with the ATLAS detector

Prof. Brian Cole
Columbia University

GHP Meeting, April 11, 2019





Nuclear parton distributions

- Recent CTEQ analysis of nuclear PDFs with comparisons to other fits

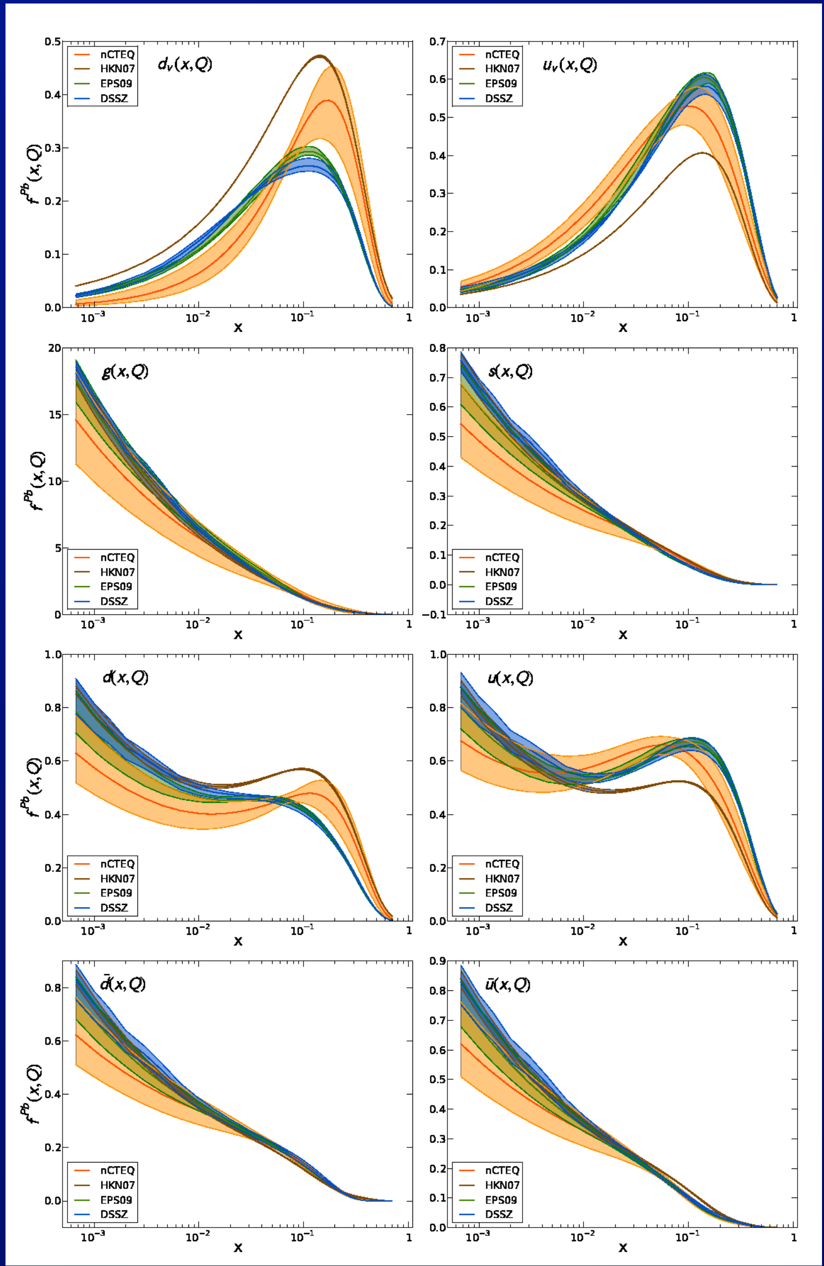
  ⇒Large uncertainties, especially at low x

- New data needed to reduce uncertainties

  – Theoretical proposal by Strikman et al in 2005:

  ⇒measure dijet photo-production in ultra-peripheral nuclear collisions

  ⇒Until now, not realized by any experiment



Measurement Coverage

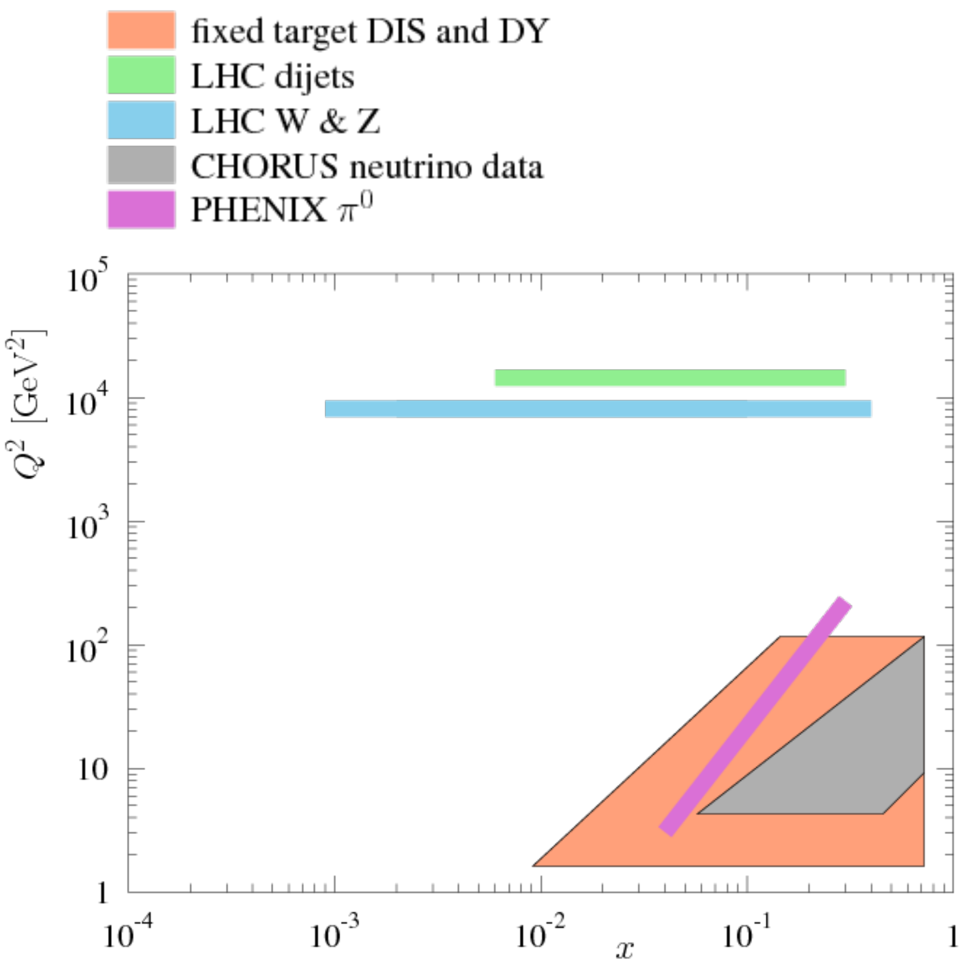


Figure adapted from EPPS16
1612.05741 [hep-ph]

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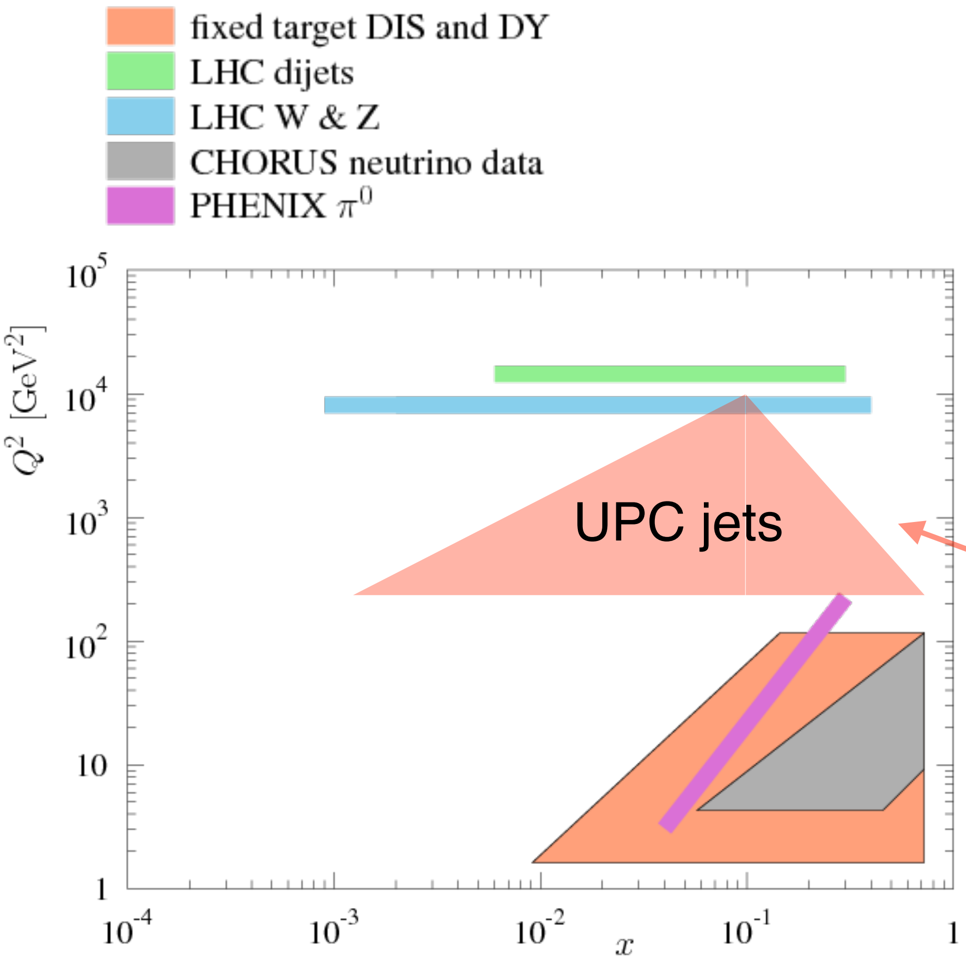

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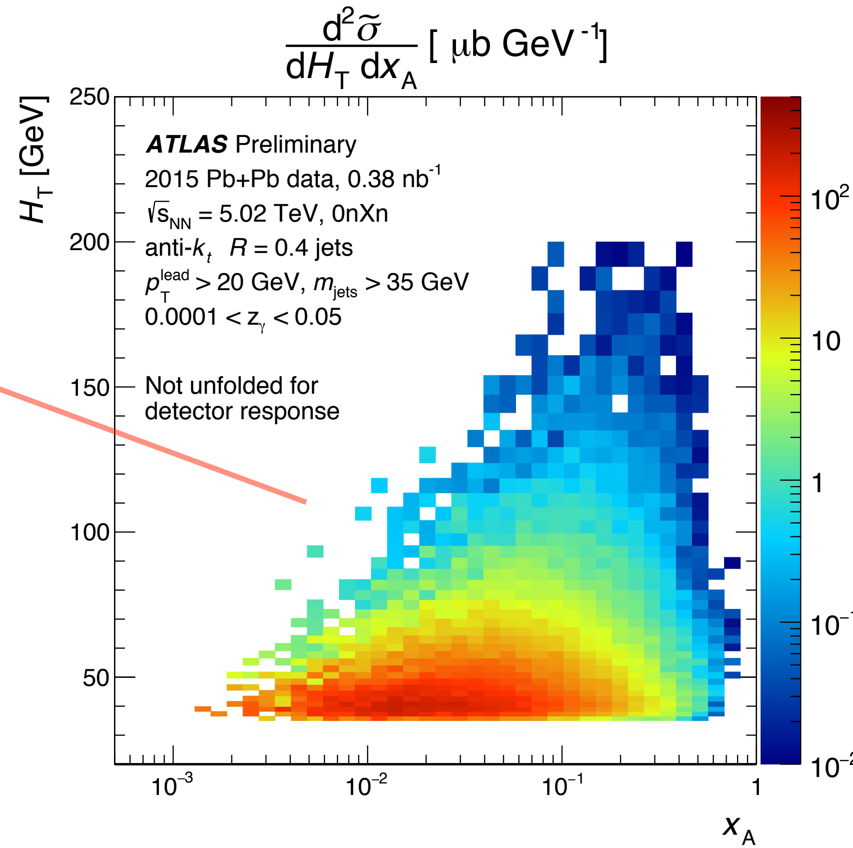
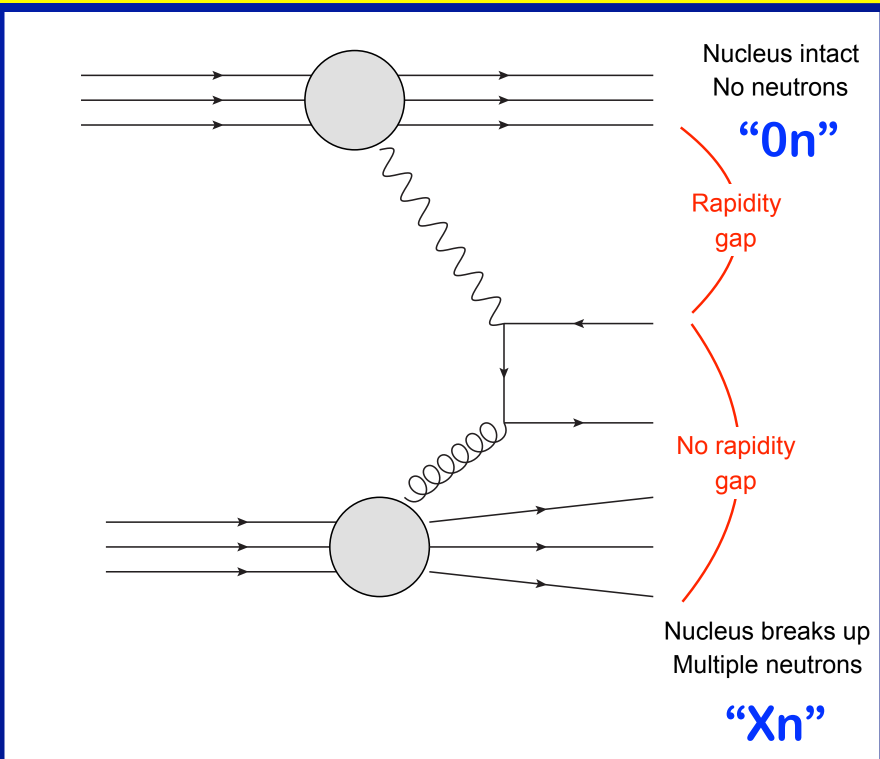
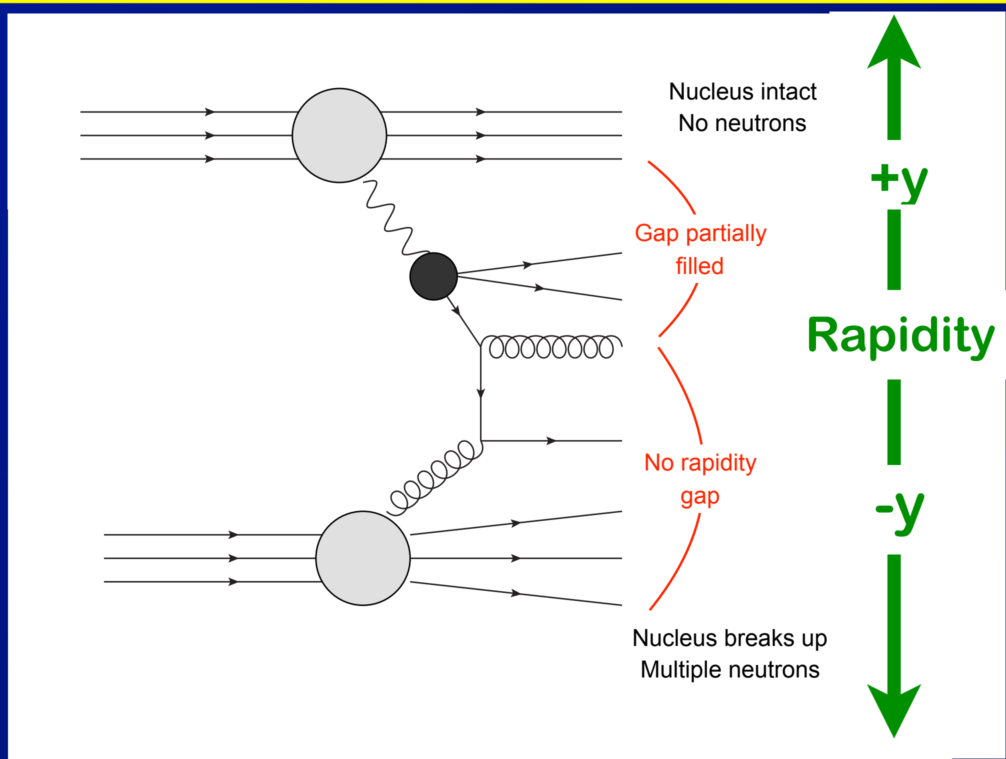


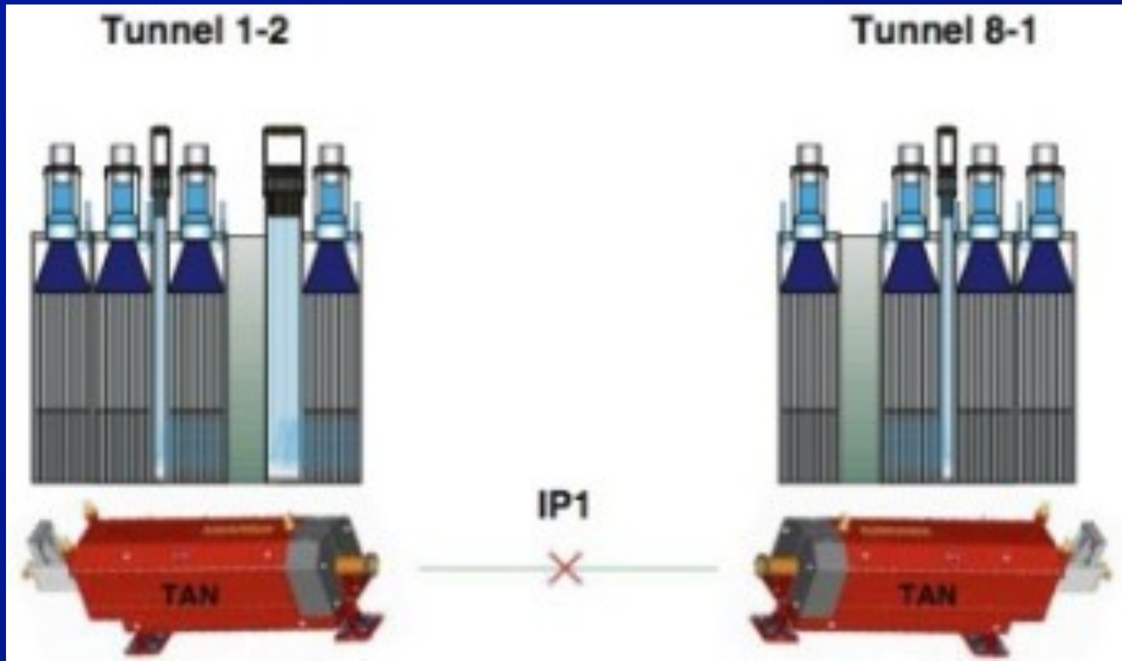
Photo-nuclear processes





- **Left: direct processes**
  - photon couples directly to nuclear parton
- **Right: resolved processes**
  - photon virtually resolved into "hadronic" state which subsequently scatters
- **For both, struck nucleus breaks up**
  - (nominally) photon-emitting nucleus does not

Zero degree calorimeters (ZDCs)



- **ATLAS ZDCs measure beam-rapidity neutrons emitted in Pb+Pb collisions**
  - hadronic collisions in nucleus produce ≥ 1 neutron in target direction with probability ≈ 1
  - photon-emitting nucleus nominally emits 0 neutrons

  ⇒ However, additional soft photon exchanges cause neutron emission ~ 30% of the time.

Triggers & Event selection

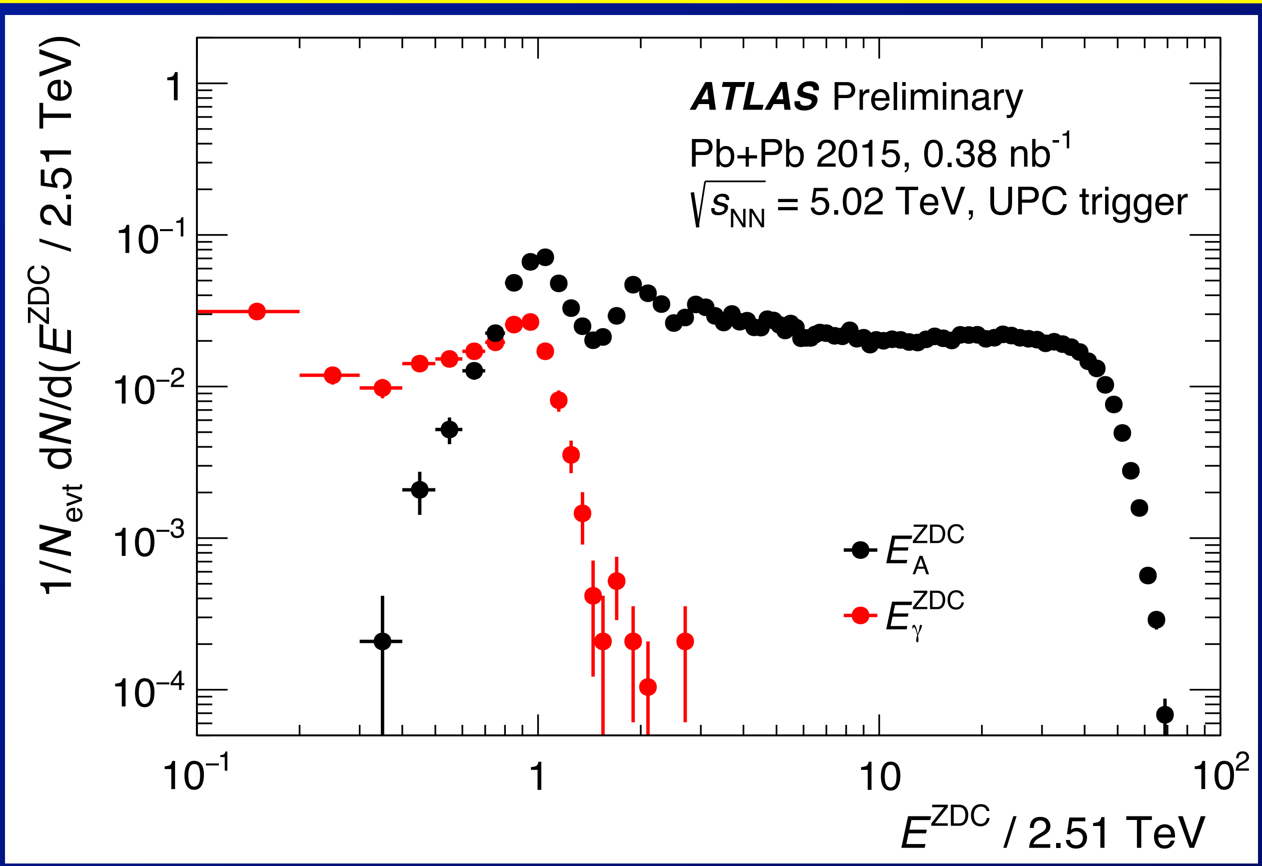
- The base trigger required:
  - $\geq$ 1 neutron in one ZDC, zero neutrons in the other

    ⇒exclusive OR
  - Minimum total transverse energy, $\Sigma E_T > 5$ GeV
  - Maximum total transverse energy, $\Sigma E_T < 200$ GeV
- Two additional triggers were used that required jets with $p_T > 25$ GeV (nominally).
  - Jet triggers sampled total luminosity of 0.38 nb^{-1}
- ZDC used to select 0nXn events (fiducial)

  ⇒no correction for photon emitter breakup
- Additional gap requirements to suppress hadronic, diffractive, $\gamma\gamma \rightarrow$ qqbar backgrounds

ZDC selection

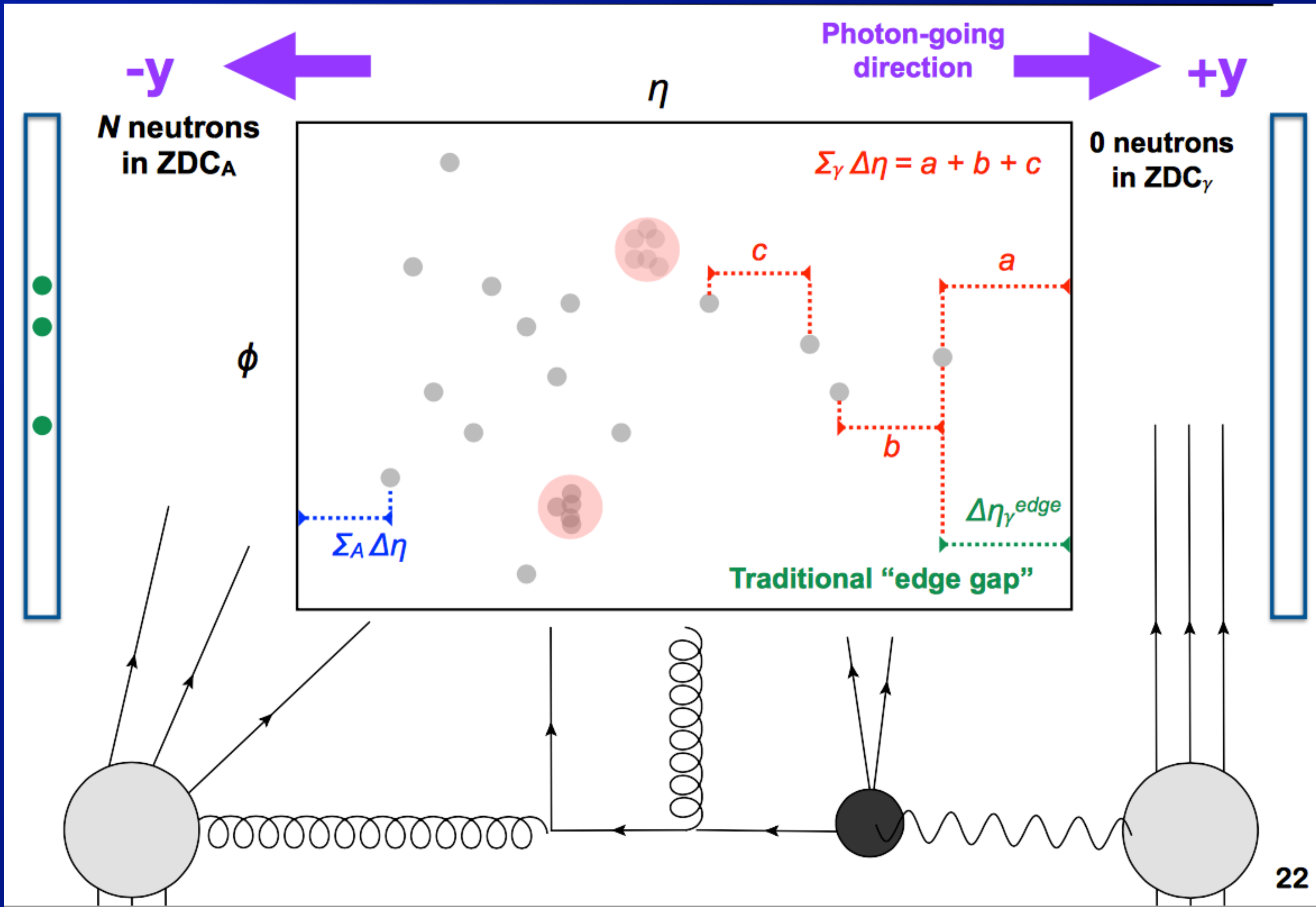
Beware suppressed contribution @ $E_\gamma^{ZDC} = 0$



- Events selected with ZDC "XOR" trigger
  - Red: photon-going direction, 0n

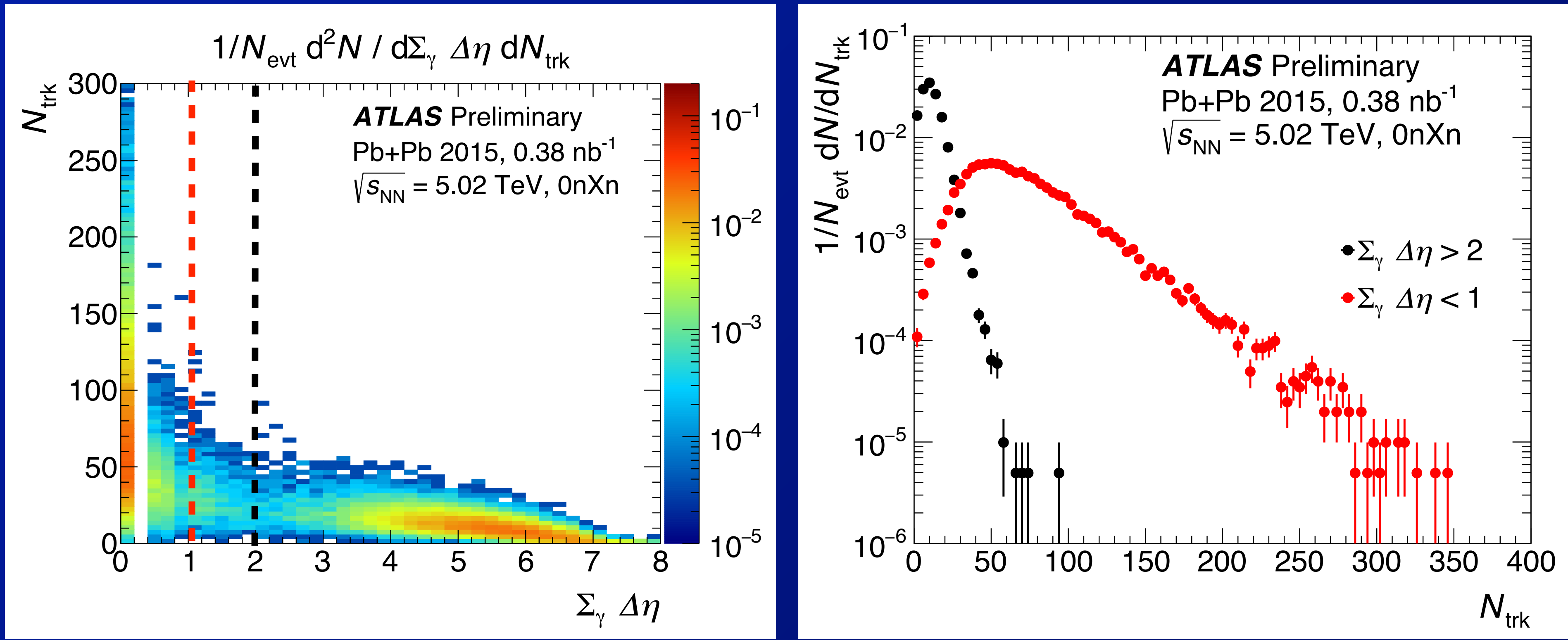
    ⇒ Some inefficiency in ZDC trigger rejection due to out-of-time pile-up (preceding collisions)
  - Black: nuclear direction, Xn

Gap analysis



- Require gap on photon side: $\Sigma_\gamma \Delta\eta > 2$
- Reject large gaps on nuclear side: $\Sigma_A \Delta\eta < 3$

Event Topology: Gaps vs Multiplicity



- **Left: $\Sigma\gamma\Delta\eta$ vs N_{trk} for 0nXn**
- **Right: N_{trk} distributions for events with ($\Sigma\gamma\Delta\eta > 2$) and without ($\Sigma\gamma\Delta\eta < 1$) gaps.**

  ⇒ **clear difference between photo-nuclear and hadronic collision events**

The measurement: jets and kinematics

- Jets reconstructed using anti-k_t algorithm w/ R = 0.4
  - EM+JES calibration + flavor correction
- Measure differential cross-sections vs H_T, x_A, z_γ

$$m_{\mathrm{jets}} \equiv \left(\sum E_i - \left|\sum \vec{p_i}\right|\right)^{1/2} \qquad y_{\mathrm{jets}} \equiv \pm\frac{1}{2}\ln\left|\frac{\sum E_i + \sum p_{z\,i}}{\sum E_i - \sum p_{z\,i}}\right|$$

$$H_{\mathrm{T}} \equiv \sum p_{\mathrm{T}\,i} \qquad x_{\mathrm{A}} = \frac{m_{\mathrm{jets}}}{\sqrt{s}}e^{-y_{\mathrm{jets}}} \qquad z_\gamma = \frac{m_{\mathrm{jets}}}{\sqrt{s}}e^{+y_{\mathrm{jets}}}$$

  - p_z, z_γ, y defined to be positive in photon direction

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  - $x_A \rightarrow$ x of struck parton in nucleus, $z_\gamma \rightarrow x_\gamma\, y_\gamma$, $H_T \rightarrow 2Q$

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- Fiducial acceptance:
  - ⇒ p_T^{lead} > 20 GeV, $p_T^{sub\text{-}lead}$ > 15 GeV
  - ⇒ $|\eta_{jet}|$ < 4.4, H_T > 40 GeV

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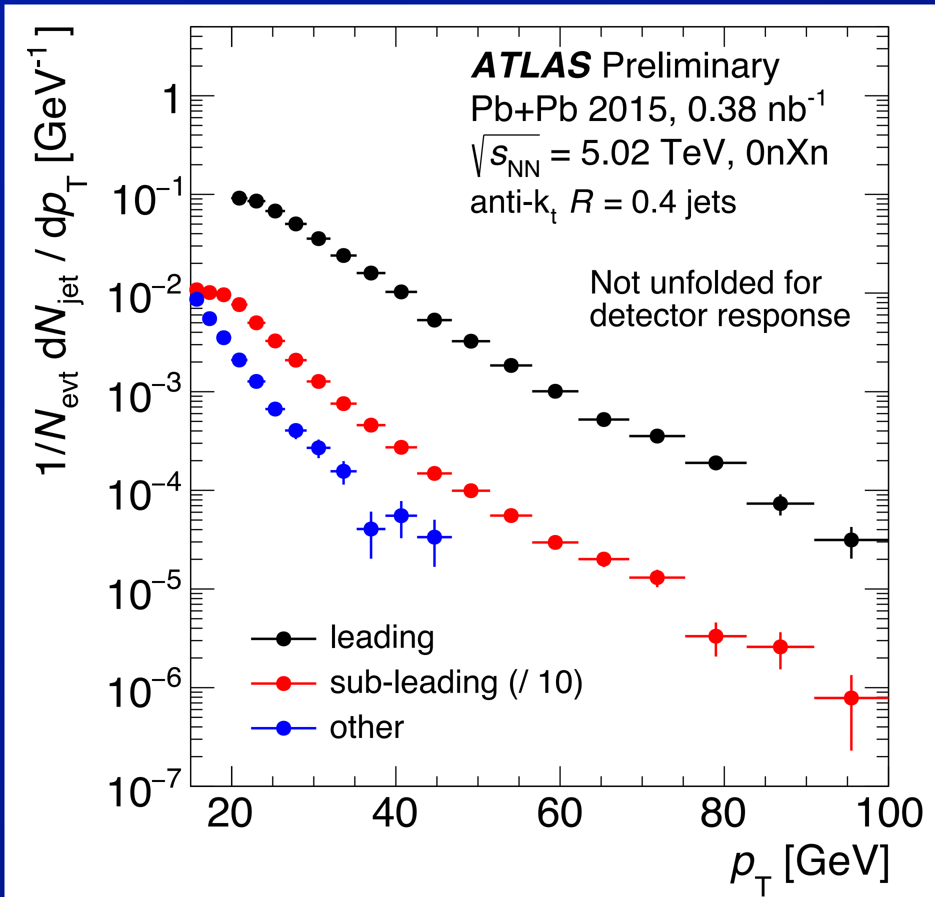
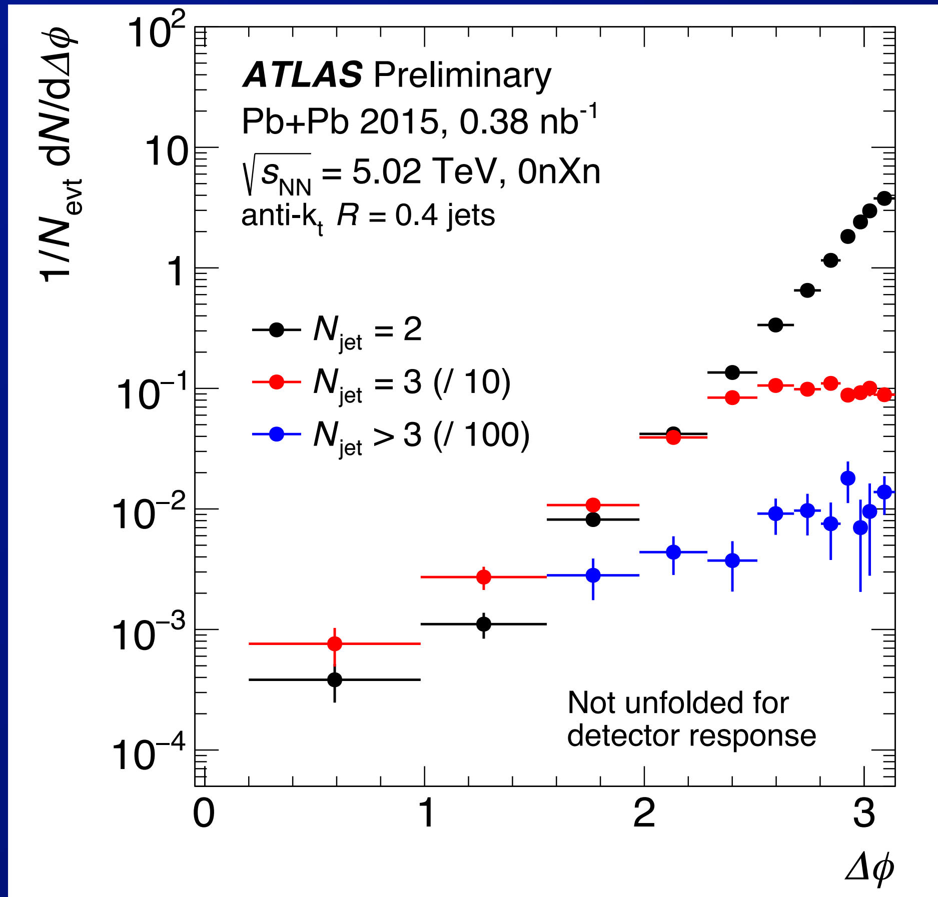
  - ⇒p_T^{lead} > 20 GeV, $p_T^{\mathrm{sub\text{-}lead}}$ > 15 GeV
  - ⇒$|\eta_{\mathrm{jet}}|$ < 4.4, H_T > 40 GeV
- No unfolding for jet response (in progress)

Jet kinematics





- **Left:**
  - single jet p_T for leading, sub-leading, all other jets
- **Right:**
  - dijet $\Delta\varphi$ distributions for 2, 3, >3 jet events

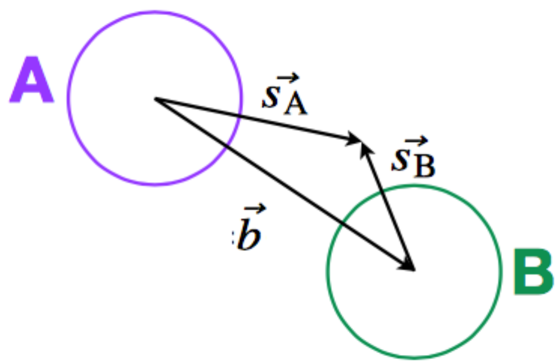
Photo-nuclear Monte Carlo

- Pythia 6 used in "mu/gamma + p" mode to simulate photo-production @ 5.02 TeV
  - Contains mixture of direct and resolved processes

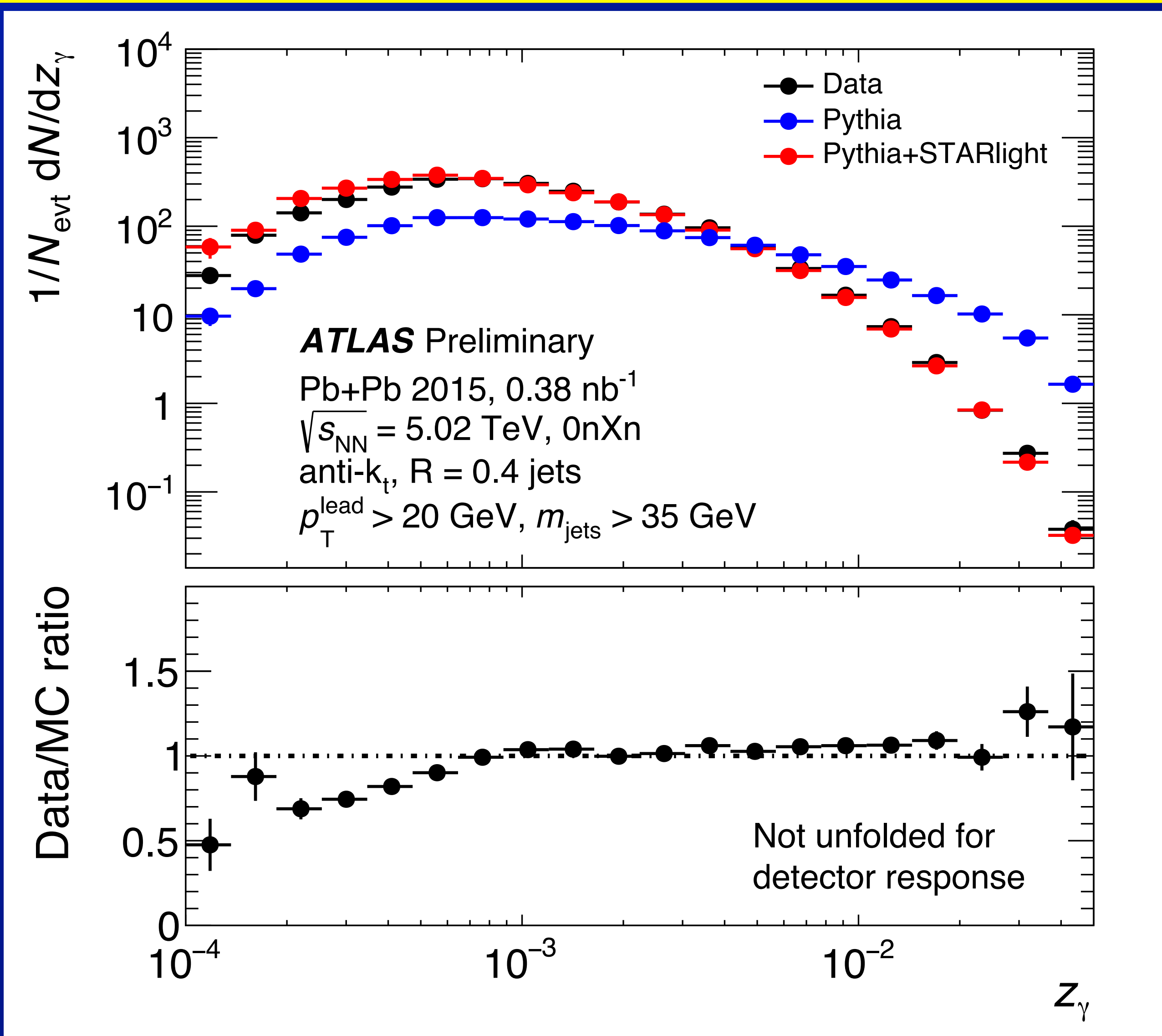
  ⇒But does not have appropriate photon flux
- "STARlight" model describes photon flux in ultra-peripheral nucleus-nucleus collisions
  - Used modified STARlight to calculate weights applied on per-event basis to Pythia sample:

$$\frac{\mathrm{d}\sigma^{\mathrm{Pb+Pb}}_{\mathrm{UPC}}}{\mathrm{d}E} = 2\int \mathrm{d}^2 b\, P_{\mathrm{UPC}}(b) \int \mathrm{d}^2 s_{\mathrm{B}} \left.\frac{\mathrm{d}^2 N^{\mathrm{Pb}}_{\gamma}}{\mathrm{d}E\, \mathrm{d}^2 s_{\mathrm{A}}}\right|_{\vec{s}_{\mathrm{A}}=\vec{b}-\vec{s}_{\mathrm{B}}} T_{\mathrm{Pb}}(s_{\mathrm{B}})\sigma^{\gamma N} \equiv \frac{\mathrm{d}N^{\mathrm{eff}}_{\gamma}}{\mathrm{d}E}\sigma^{\gamma N}$$

$$w(E) \equiv \frac{\mathrm{d}N^{\mathrm{eff}}_{\gamma}}{\mathrm{d}E} \Bigg/ \frac{\mathrm{d}N^{\mathrm{PYTHIA}}_{\gamma}}{\mathrm{d}E}$$



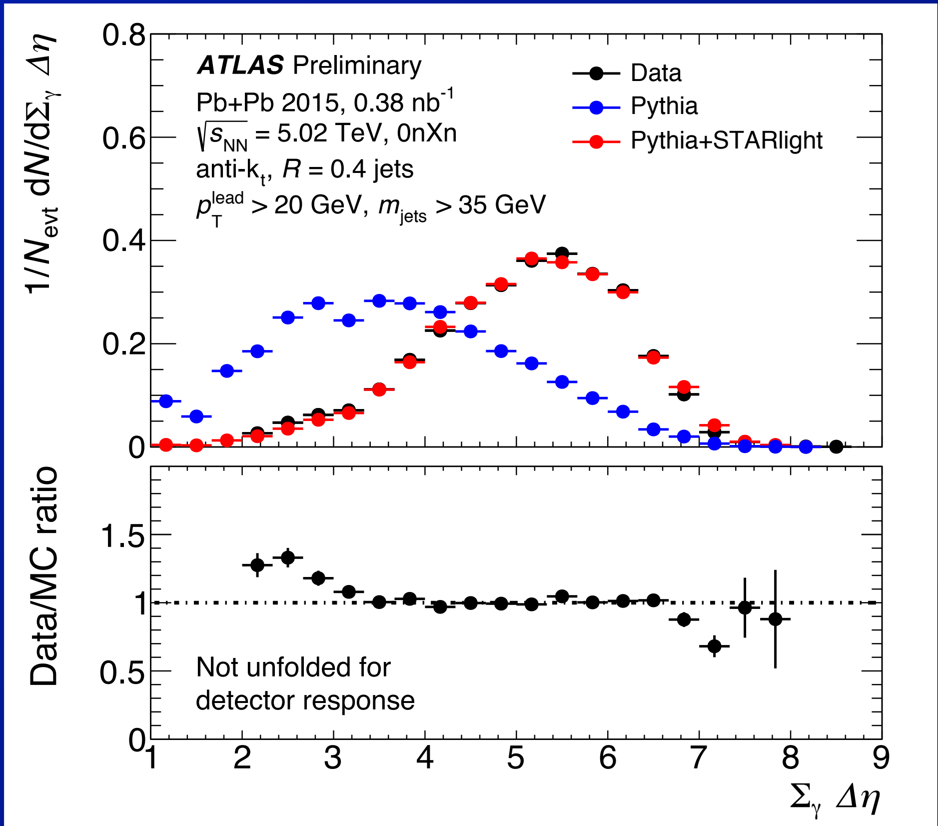
Monte Carlo re-weighting

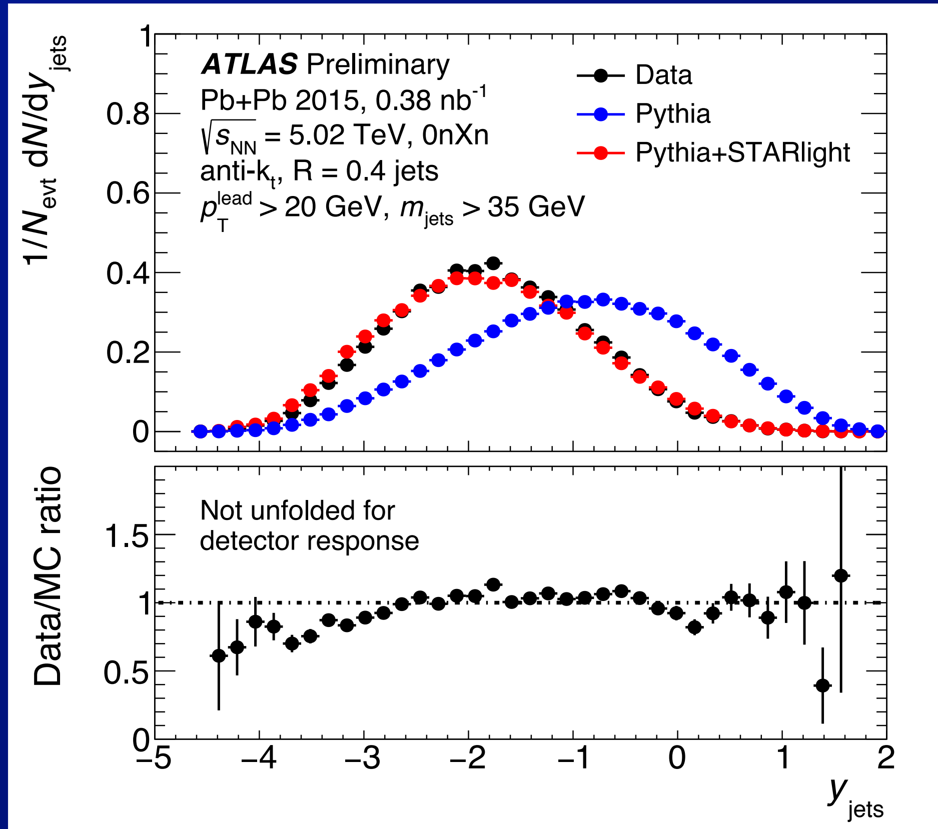


Re-weighted Pythia in good (not perfect) agreement with data

- **Data and MC z_γ distributions and ratio**
  - **with and w/o re-weighting**

Data-MC comparisons

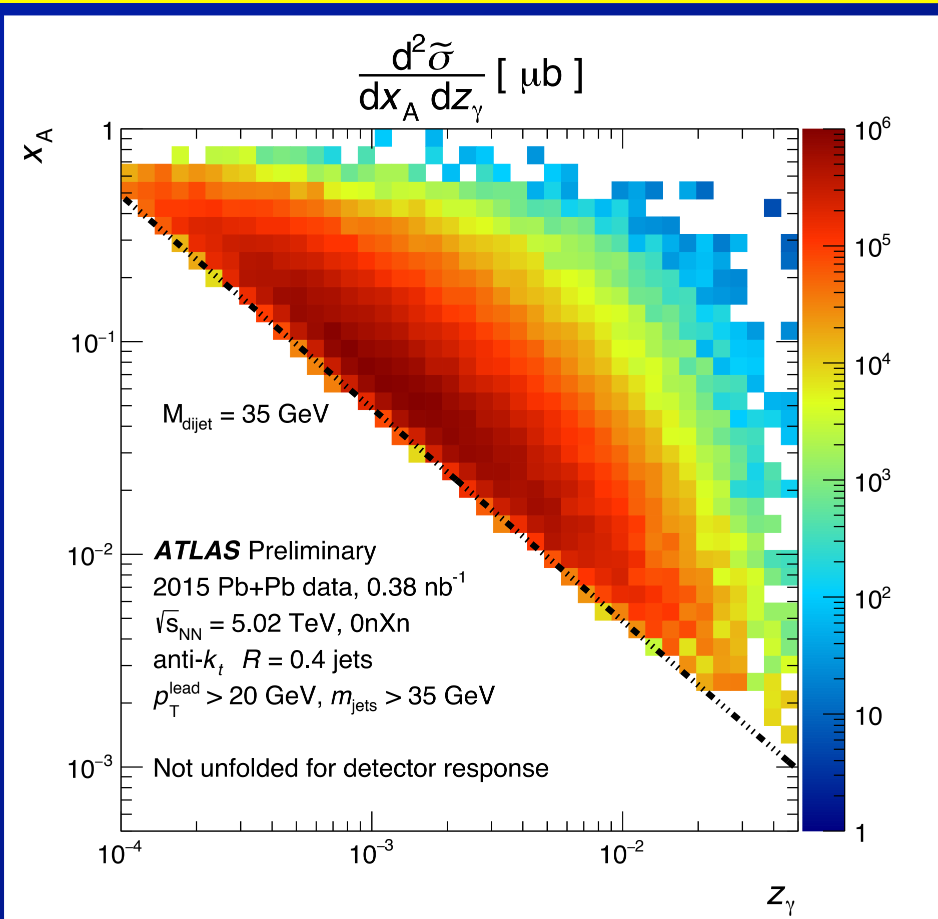


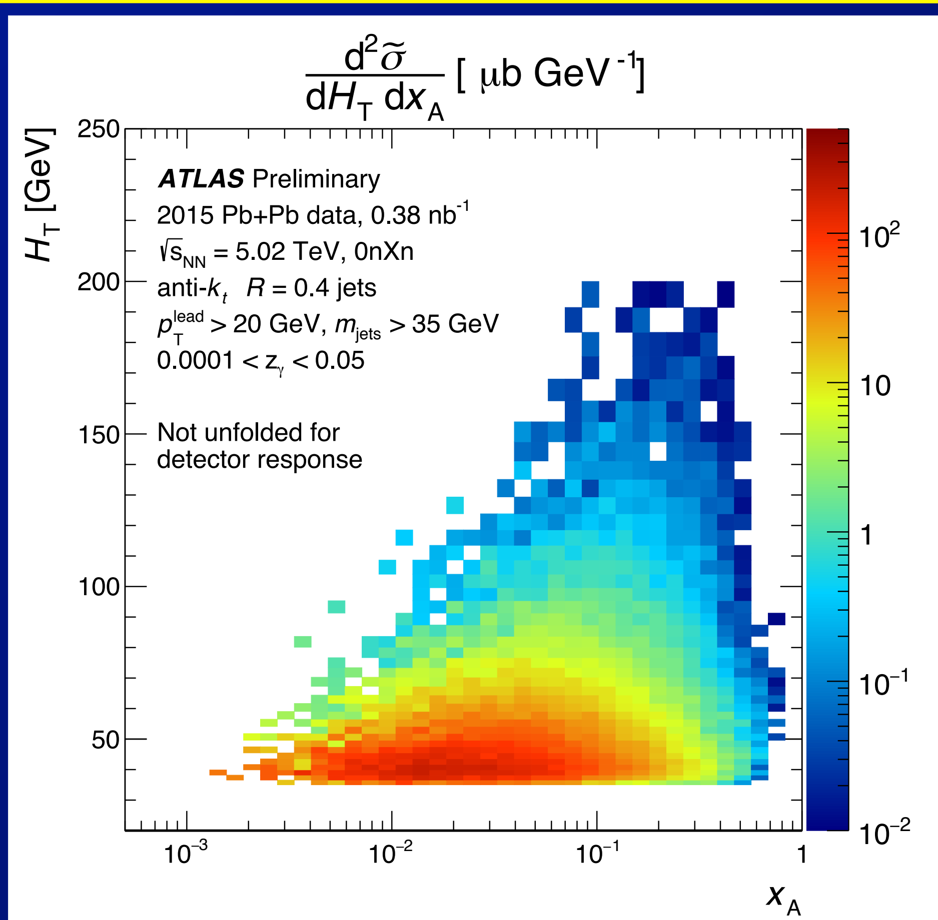


- Good agreement for $\Sigma\gamma$ $\Delta\eta$ after re-weighting
  ⇒ Can trust MC-based corrections for event selection efficiency

- Also good agreement for y_{jets}
  ⇒ See backward shift because $z_{\gamma} < x_{A}$

2-D cross-sections



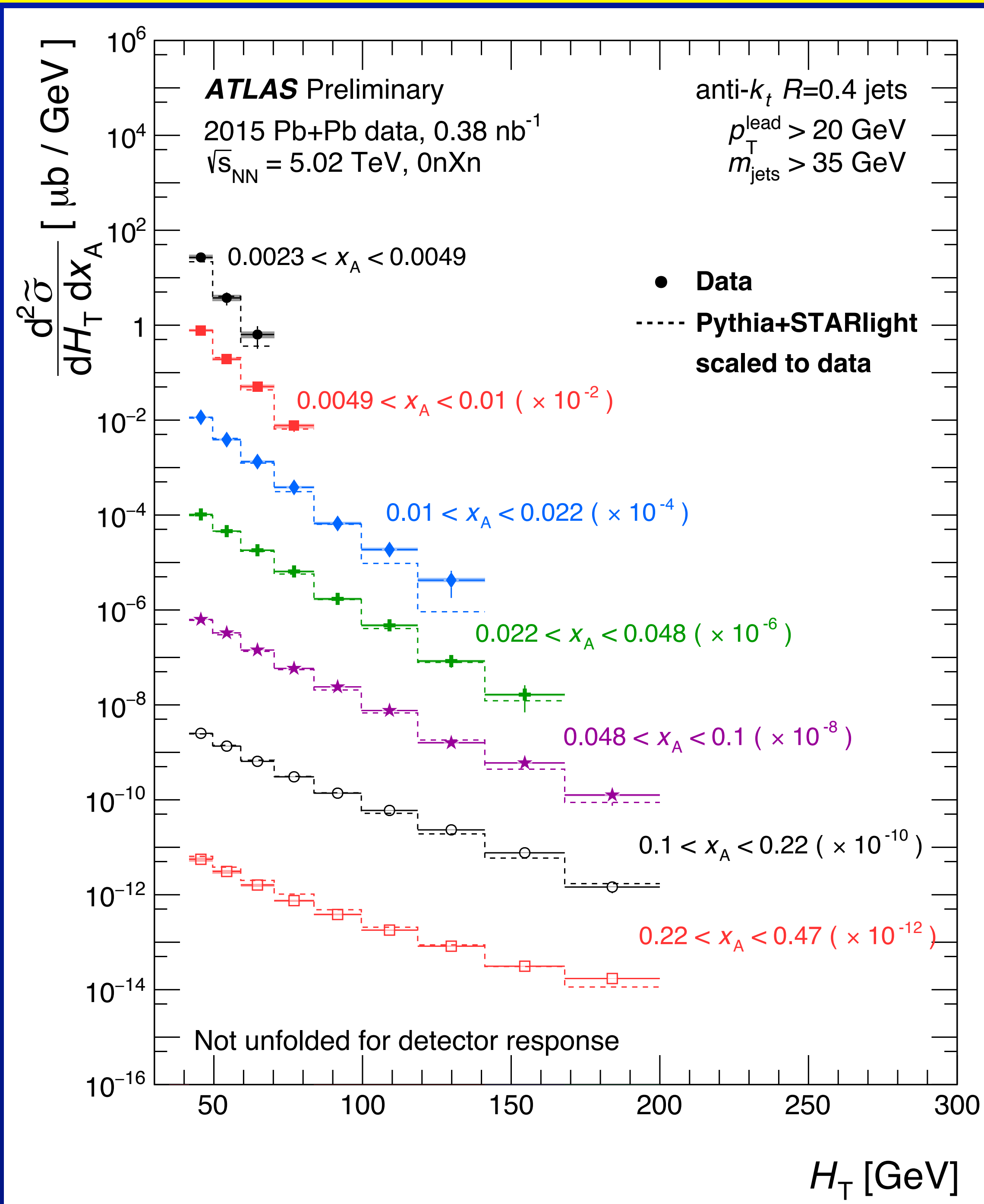


- Acceptance in (z_γ, x_A) strongly dependent on minimum jet system mass
  - Determined by minimum p_T in analysis
  - ⇒ Easiest way to get to low x_A is large z_γ

Corrections and systematics

- Correct for inefficiency introduced by event selection requirements
  - ZDC inefficiency: can lose 0n1n contribution
    ⇒On average: 0.98 ± 0.01
  - "EM pileup": extra neutrons from EM dissociation
    ⇒5 ± 0.5% on overall normalization
  - Signal events removed by gap requirement
    ⇒resulting inefficiency evaluated in MC sample
    ⇒ ~1% correction except at very large z_γ
- Luminosity: 6.1% uncertainty
- Jet response:
  - energy scale and resolution uncertainties
    ⇒ vary with H_T, x_A, z_γ

Results: H_T Dependence



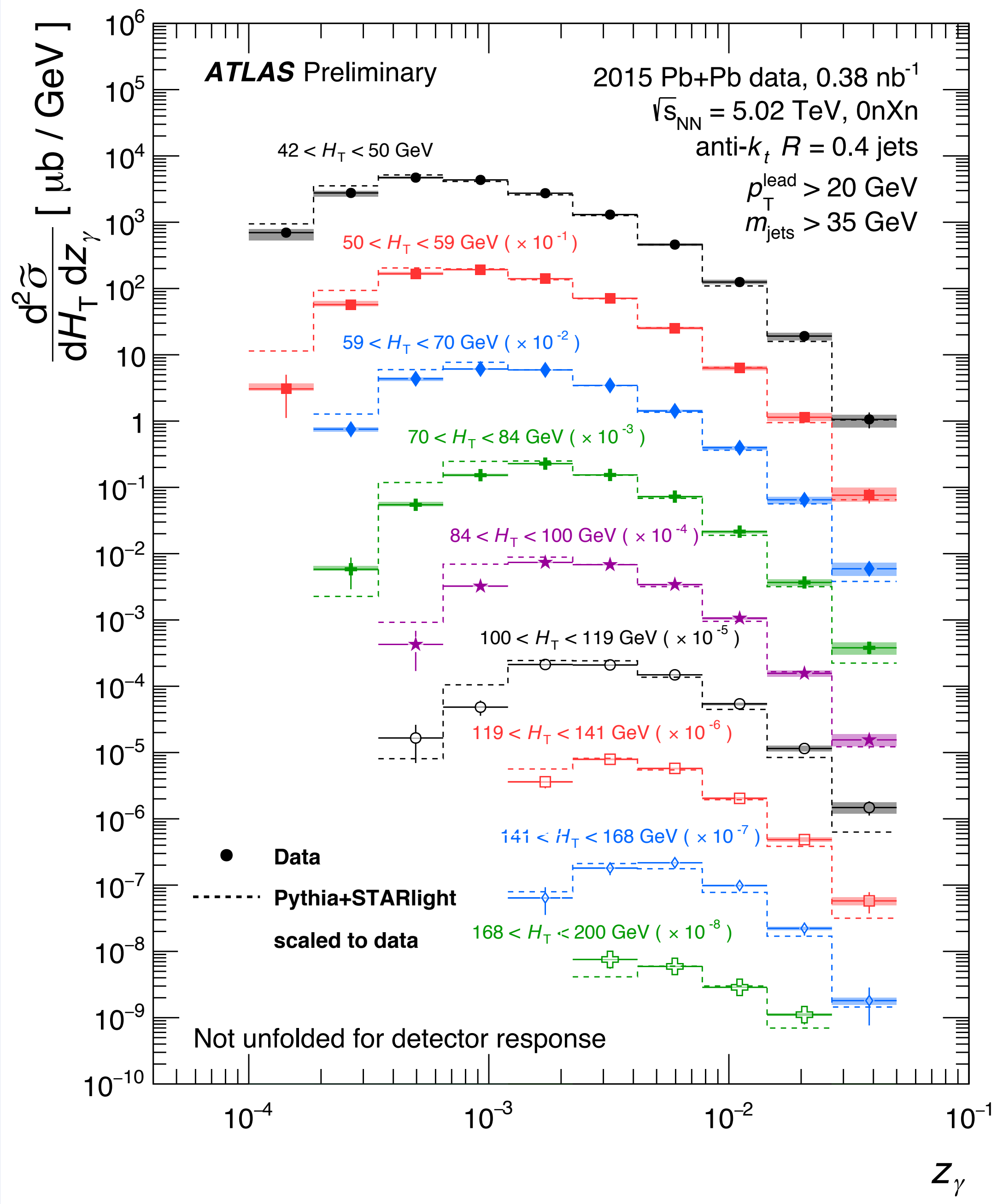
Differential cross-section in slices of x_A

Not in systematic bands: overall normalization systematic of 6.2%

Not exactly same as $F_2(x,Q^2)$

- **Still has ~$1/Q^4$ and z_γ dependence in cross section**
- **Don't expect to see scaling explicitly**

Results: z_γ dependence

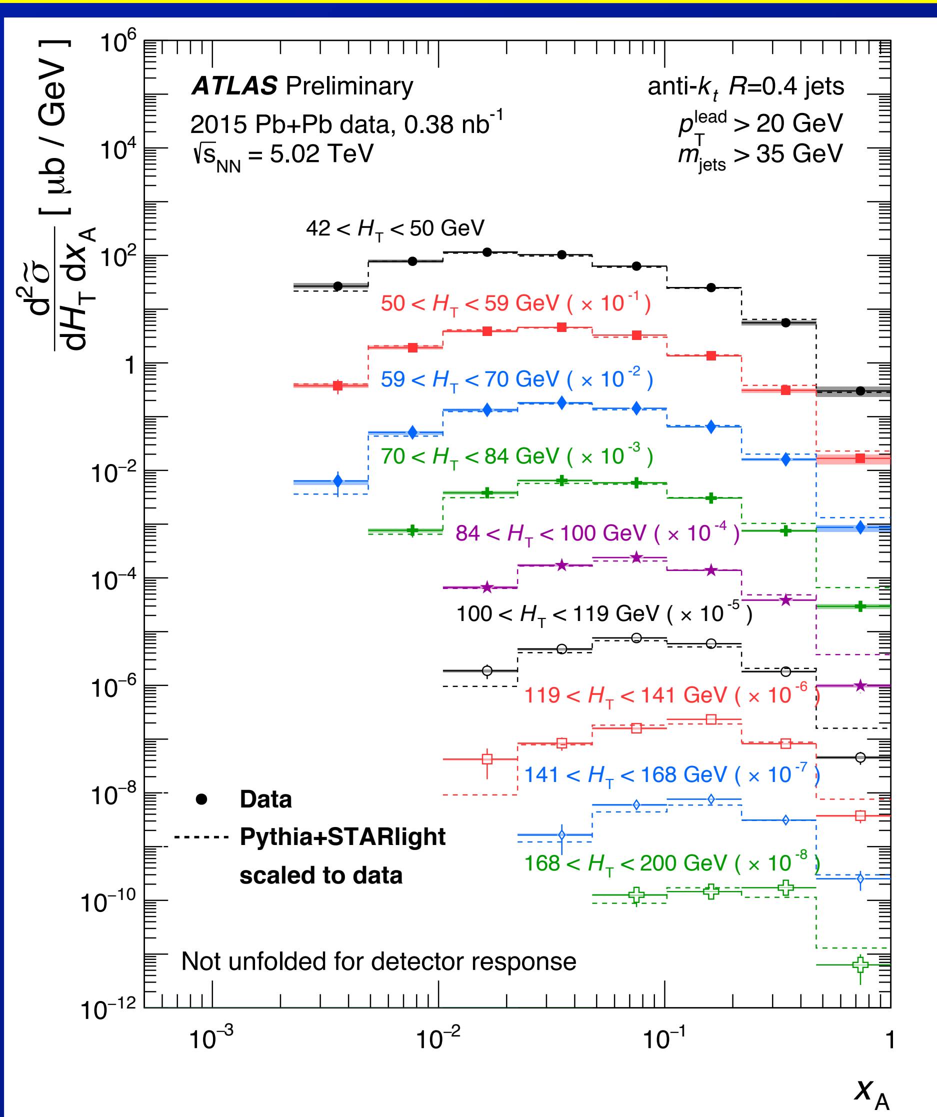


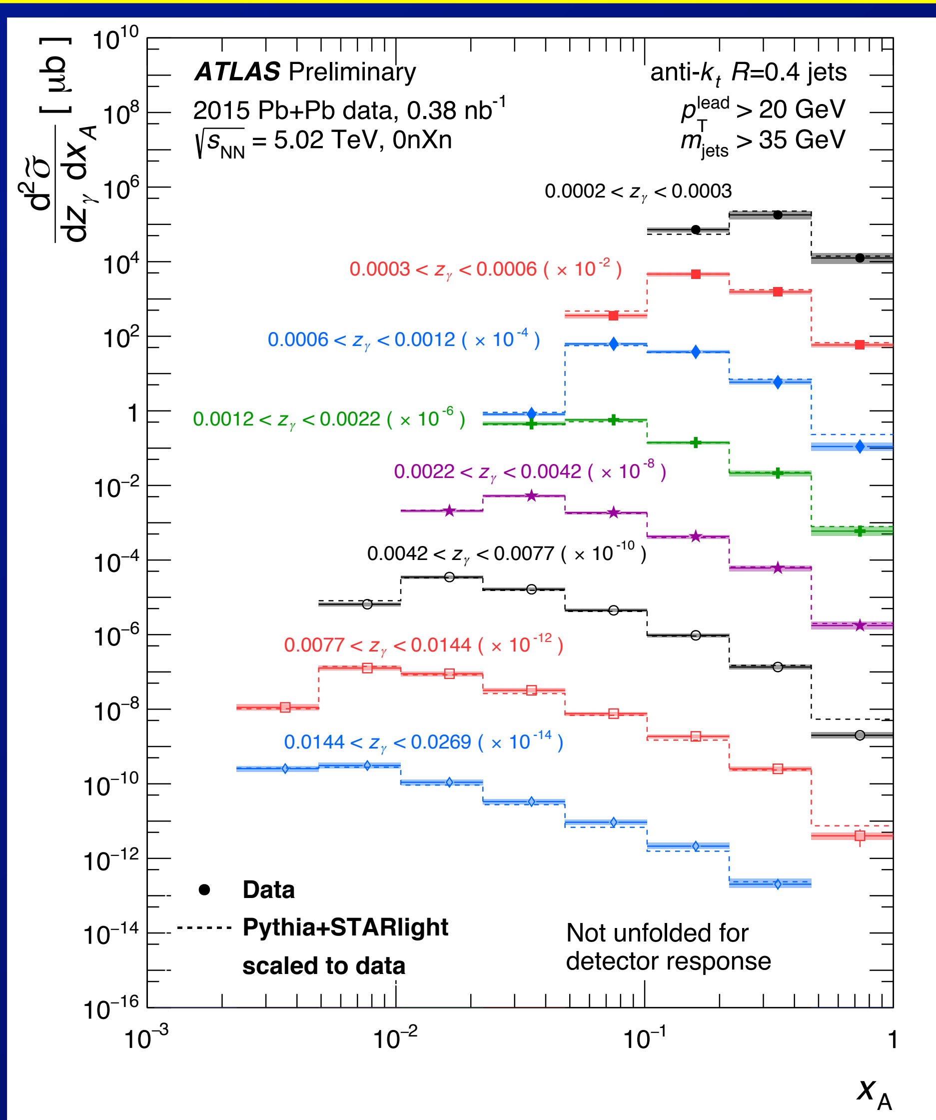
Differential cross-section in slices of H_T

Largest disagreement with model at small z_γ where re-weighted distribution most disagrees with data

Can extend to lower x_A by going to higher z_γ

Results: x_A Dependence





- **Data agrees w/ MC over most of acceptance**
  - ⇒ **But limitations in MC sample (e.g. no γ+n, no nPDF)**

Summary, conclusions

- Presented a preliminary ATLAS measurement of photo-nuclear jet production:
  - Demonstration that original proposal by Strikman can be realized

  ⇒ access a kinematic range not otherwise covered
  - Expected features— rapidity gaps and neutron distributions— observed in the data
  - Good but not perfect MC-data agreement

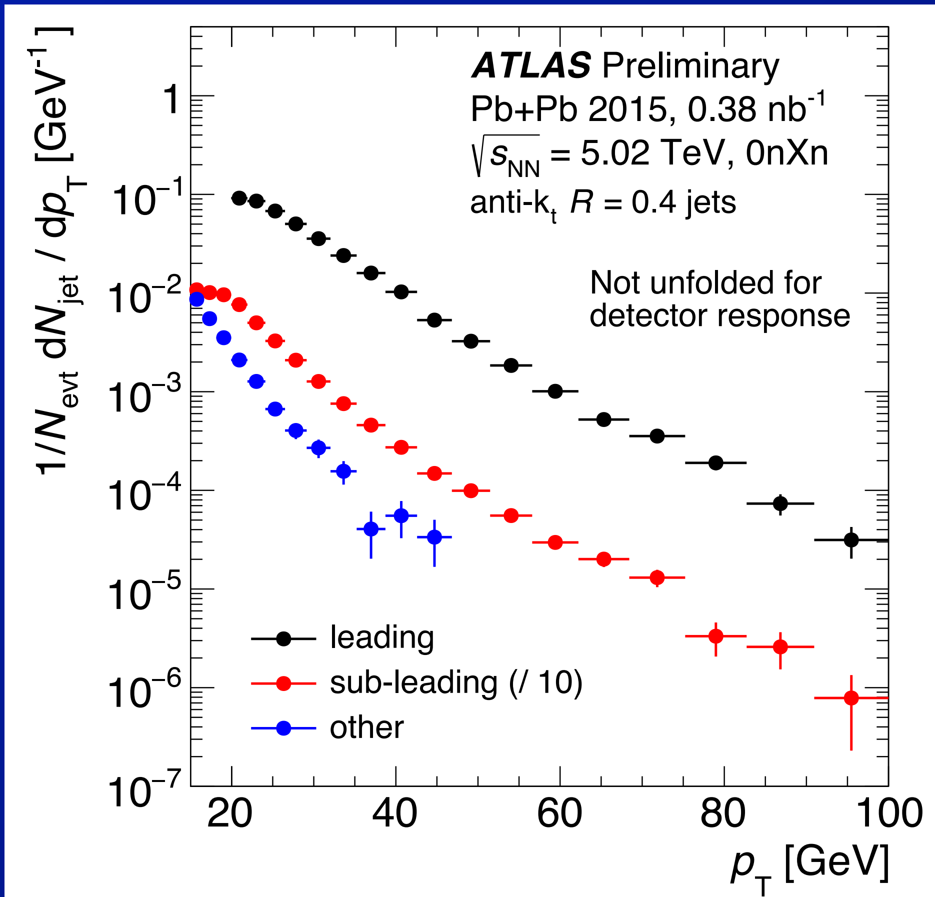
  ⇒ Need MC with Pb+Pb EPA photon flux to avoid re-weighting which has conceptual difficulties

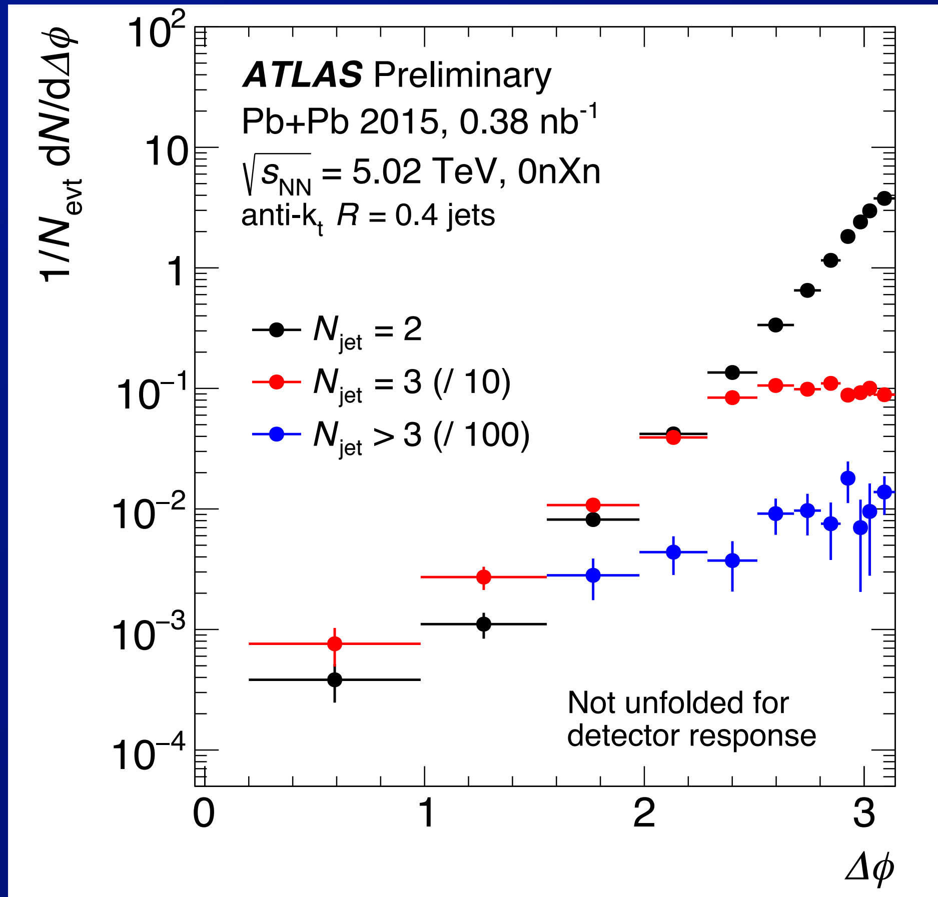
  ⇒ Which we now have (Pythia8 — big advance)
  - Now working on unfolding and controlling the resolved photon contribution.

  ⇒ 3-d unfolding in HT, x_A, z_γ is challenging

Backup

Jet kinematics





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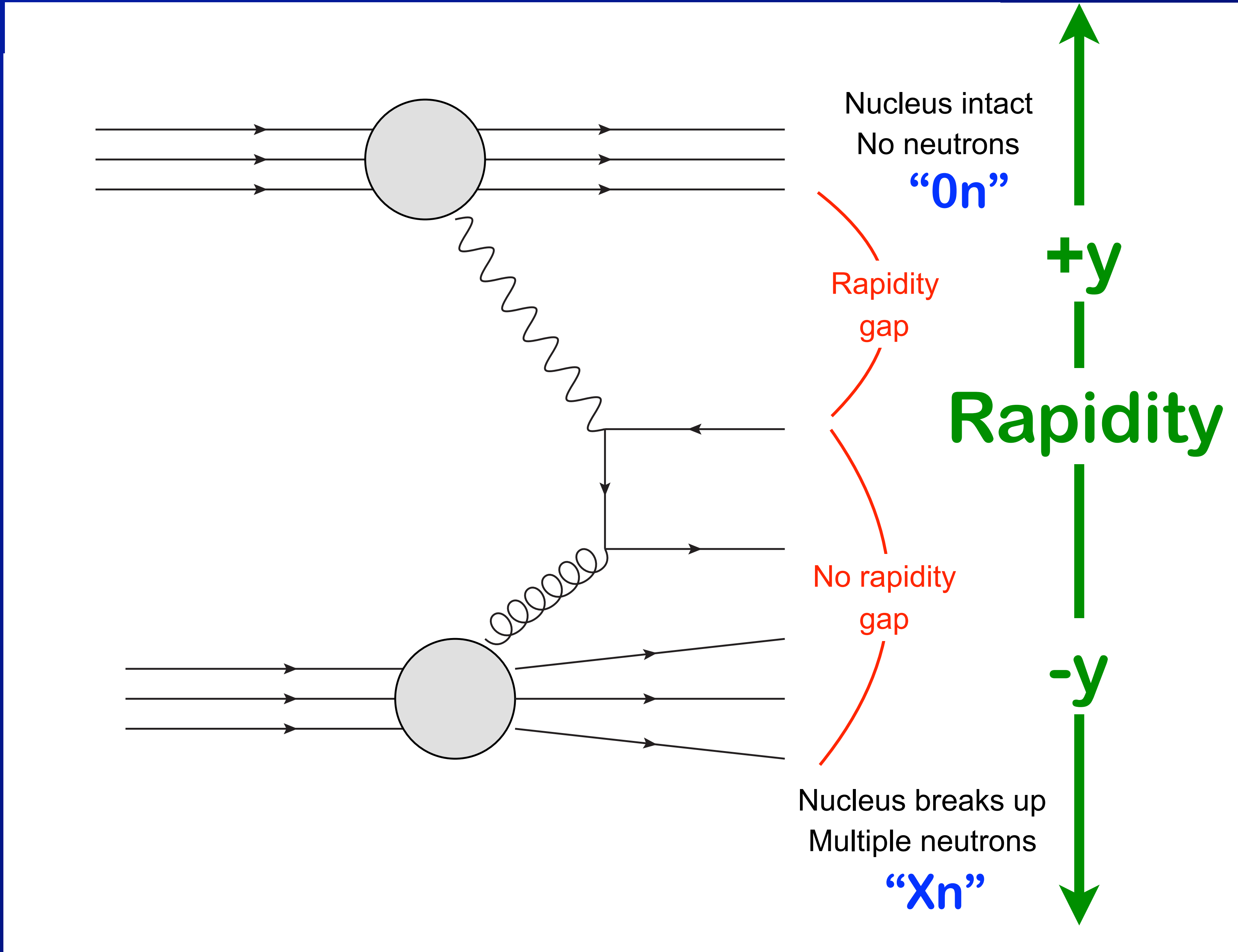
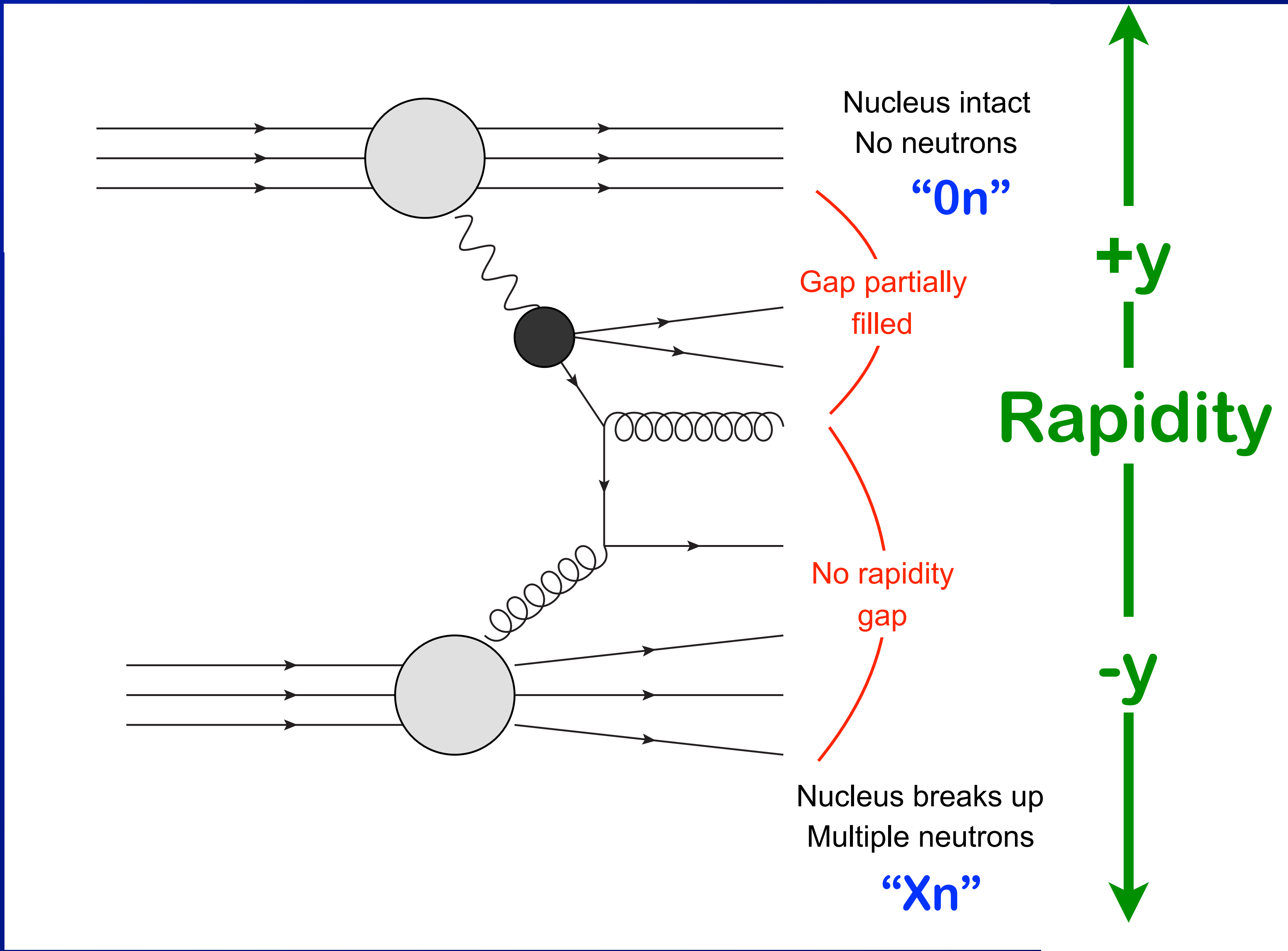
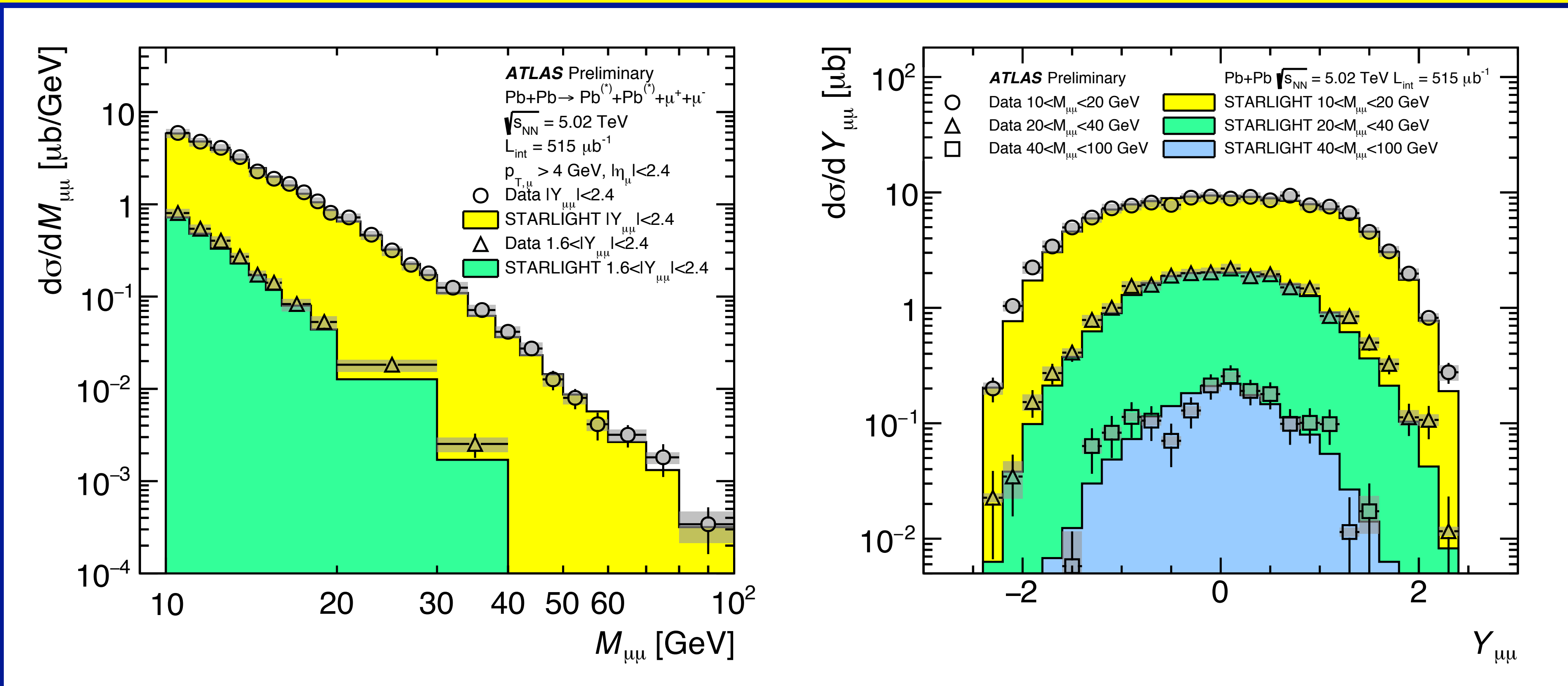
Direct processes



Resolved processes



UPC dimuon



- **Provides valuable estimate/constraint on potential γγ→qqbar backgrounds**
  - **qqbar rate @ given, M, y ~ dimuon**

  ⇒After gap cuts, negligible background