Measurements of photo-nuclear jet production in Pb+Pb collisions with ATLAS

Aaron Angerami

on behalf of the ATLAS Collaboration

Columbia University

Quark Matter 2017

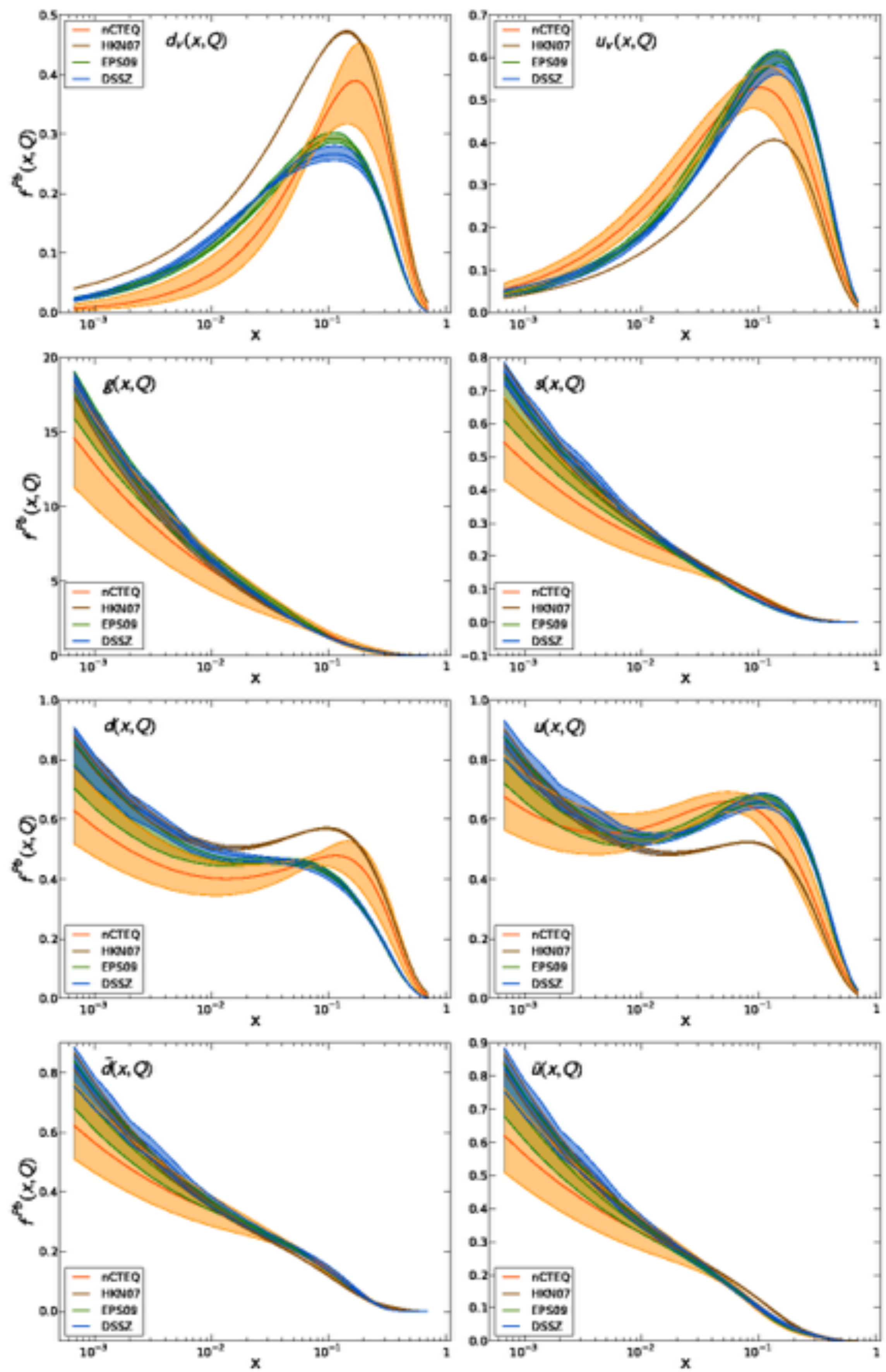
Chicago, IL, USA

Tuesday February 7, 2017

Parallel Session 1.1: Initial State Physics and Approach to Equilibrium

Nuclear Parton Distributions

- Recent CTEQ analysis of nuclear PDFs with comparisons to other fits
- “Old” problem of the low-*x* behavior
  - Large uncertainties
  - Not so much progress because little/no new data



Ultra-Peripheral Collisions

- At the LHC, ion beams are accompanied by large equivalent photon flux
  - Photons that can be emitted by entire nucleus are enhanced by Z^2
    - $k_{\perp\gamma} \sim \hbar c / 2R_N \sim 15$ MeV, $k_{z\gamma} = \gamma_{boost} \times k_{\perp\gamma} \sim 40$ GeV
  - In AA collisions, energetic enough to stimulate hard scattering processes at low *x* in the target
    - Enhanced by $Z^2 A \sim 10^6$ compared to *pp*
- Reactions possible at large impact parameter
  - Event characteristics are qualitatively different than usual AA collisions
- Can study nPDFs with photo-nuclear jet production
  - Proposal by Strikman, Vogt and White: hep-ph/0508296
  - Very clean probe of target, a la DIS

Measurement Coverage

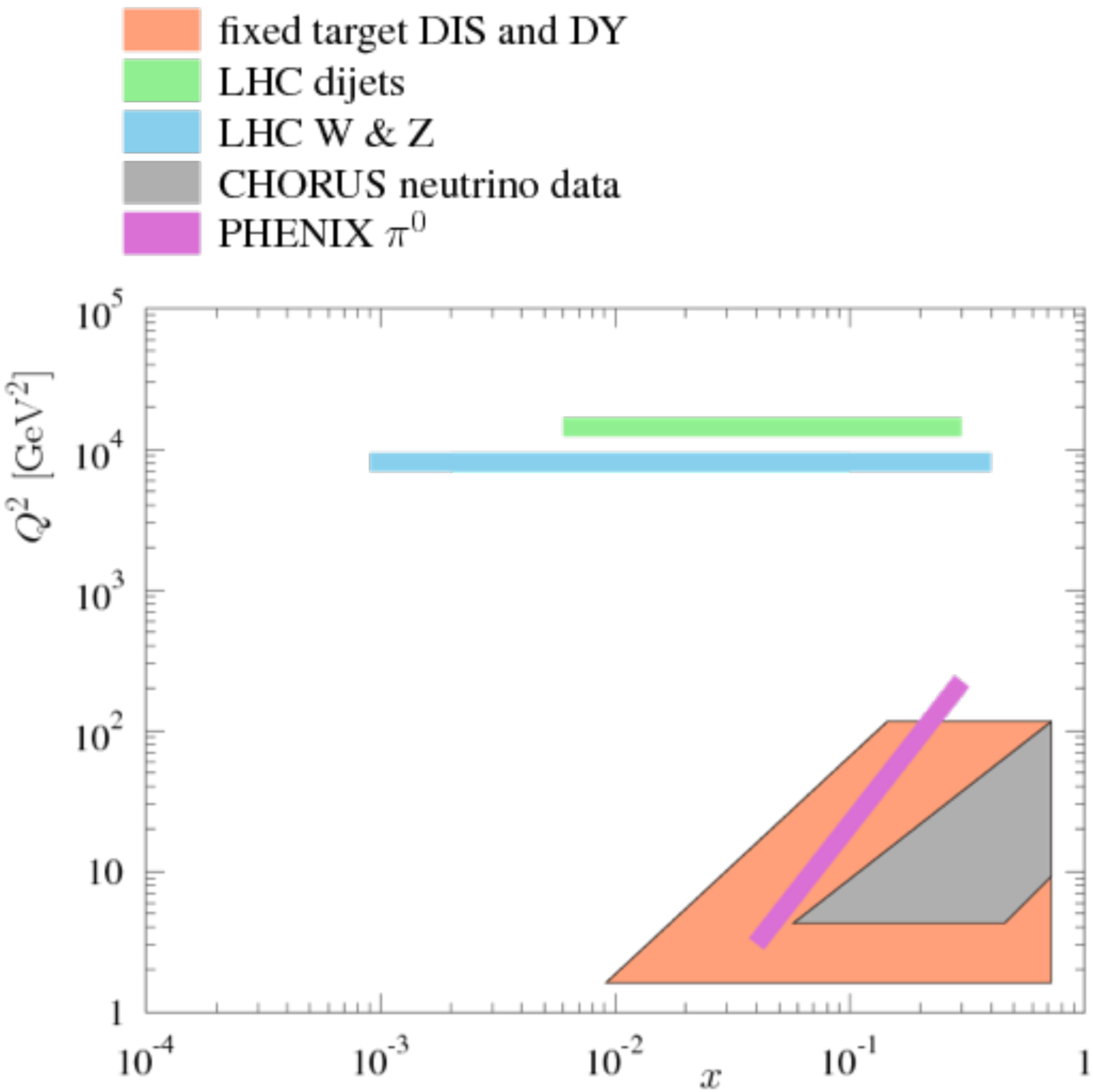
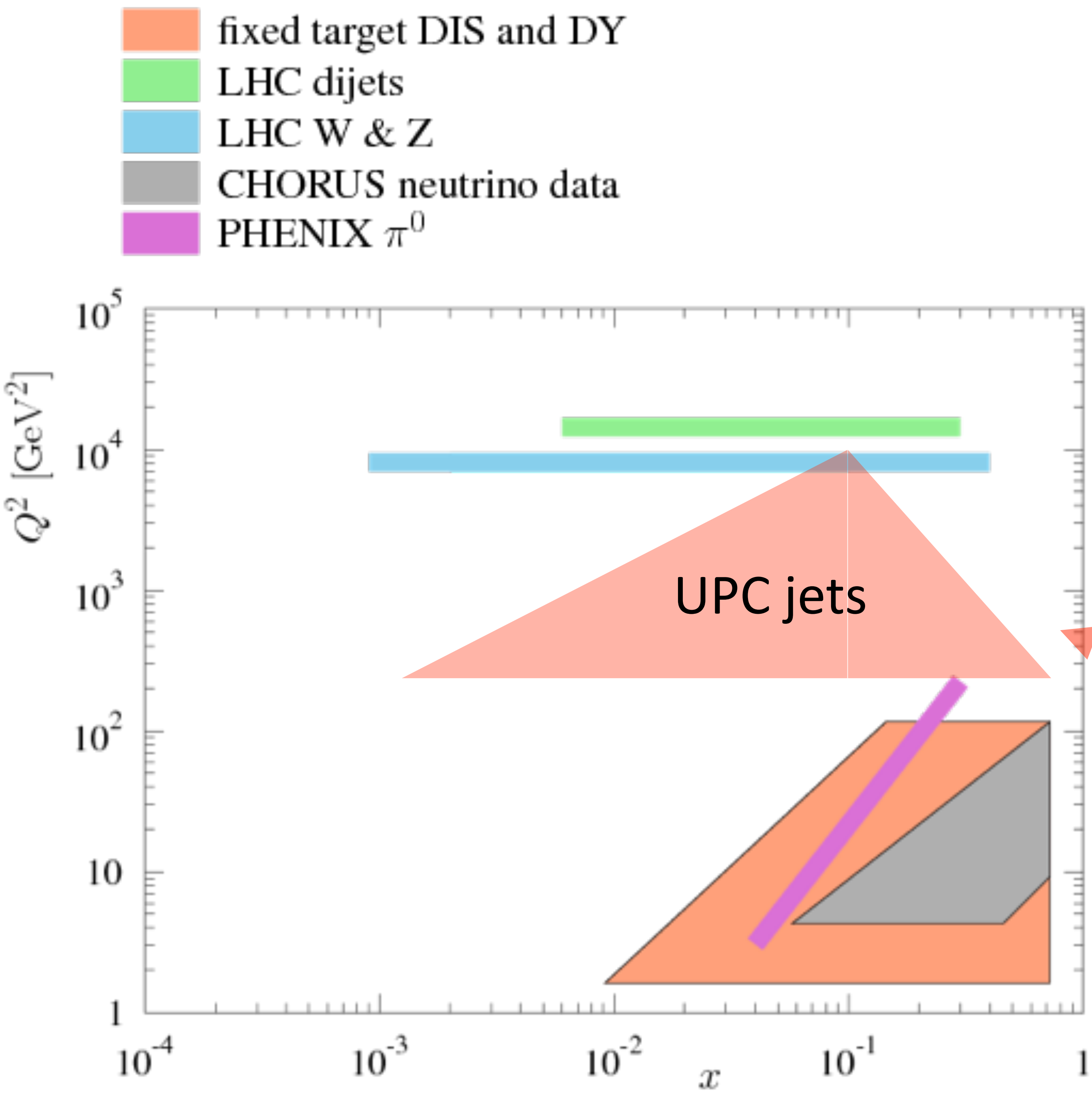
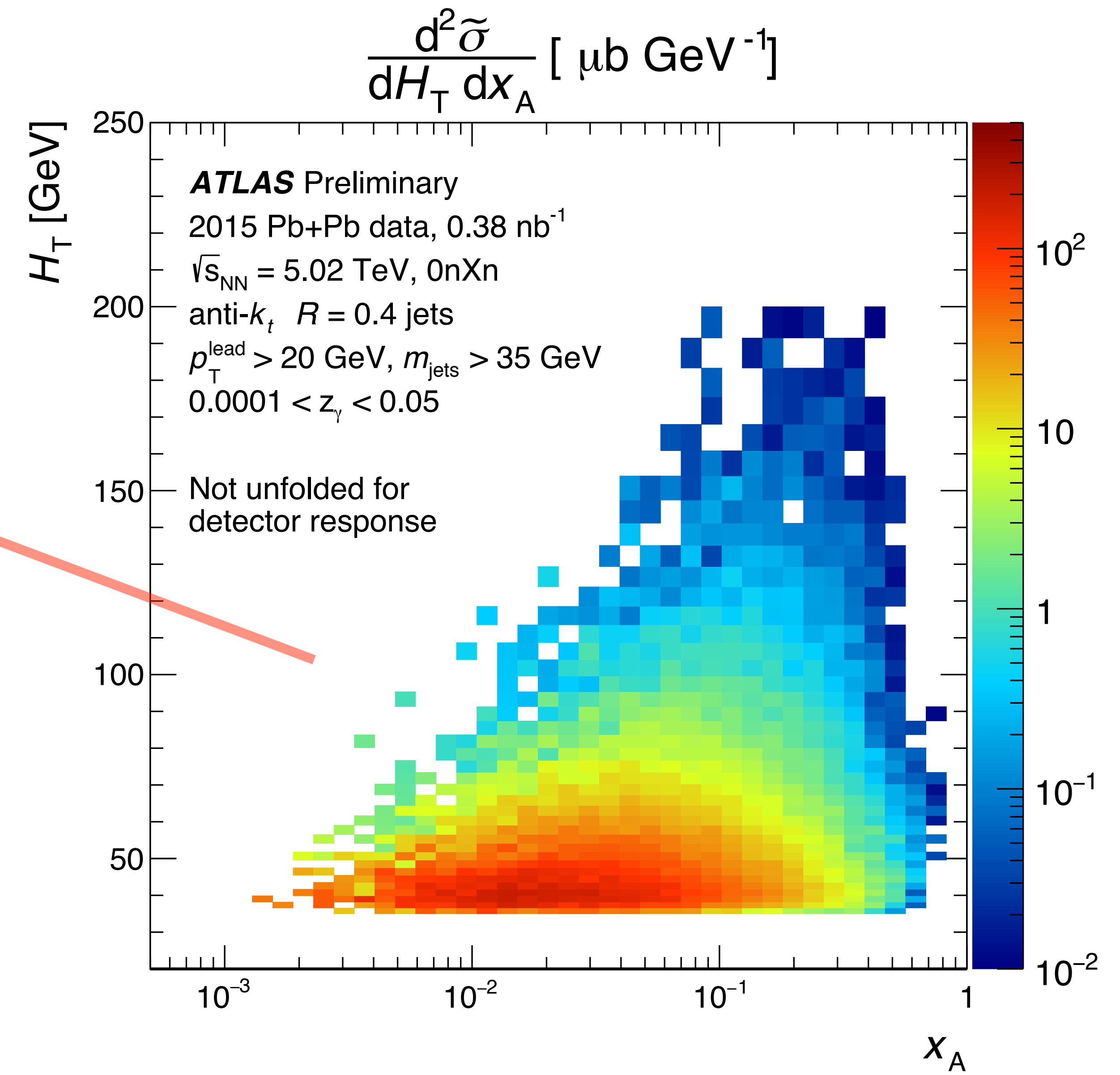


Figure adapted from EPPS16
1612.05741 [hep-ph]

Measurement coverage





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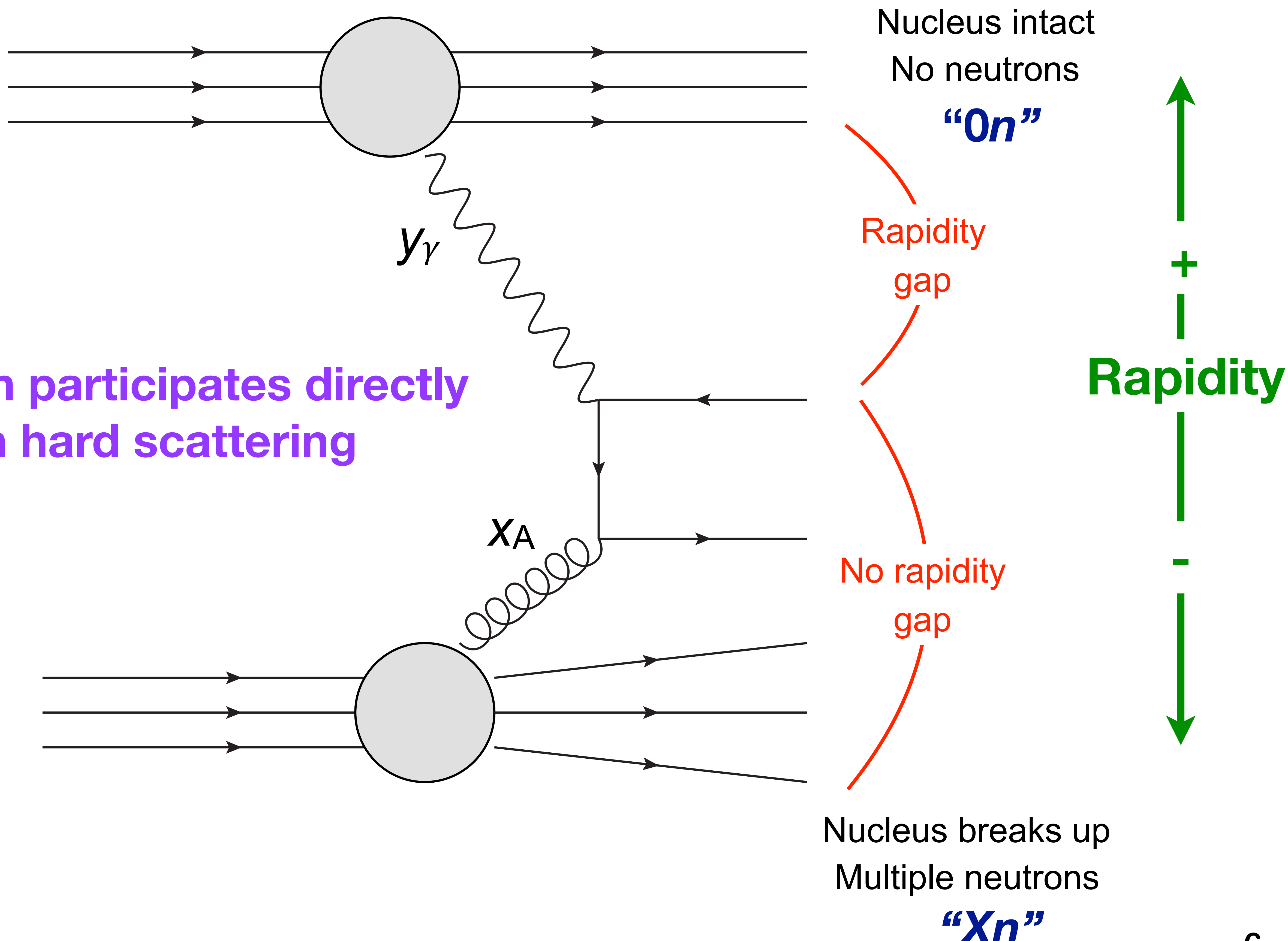
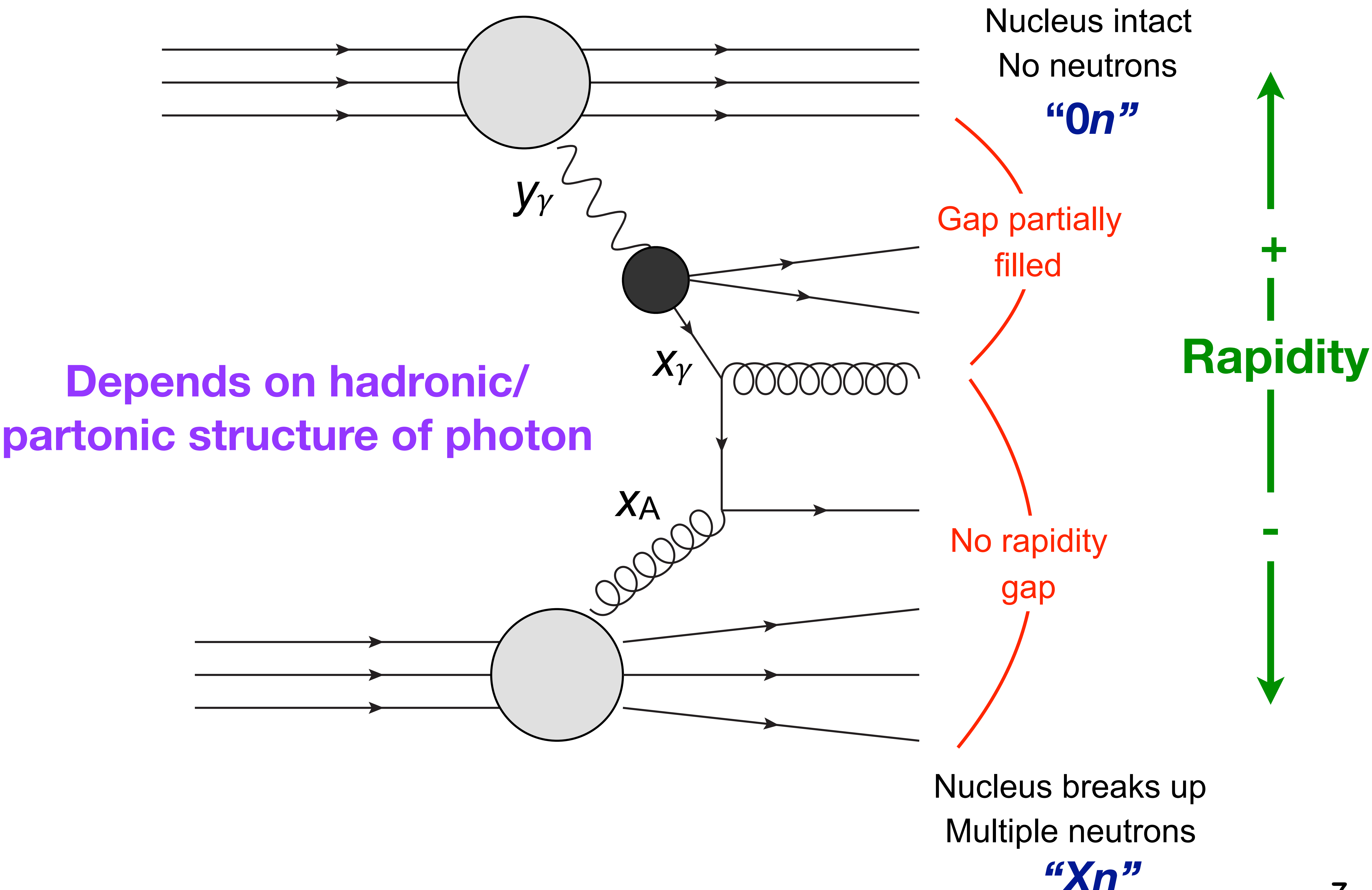
Event Topology: "Direct"

Photon participates directly in hard scattering



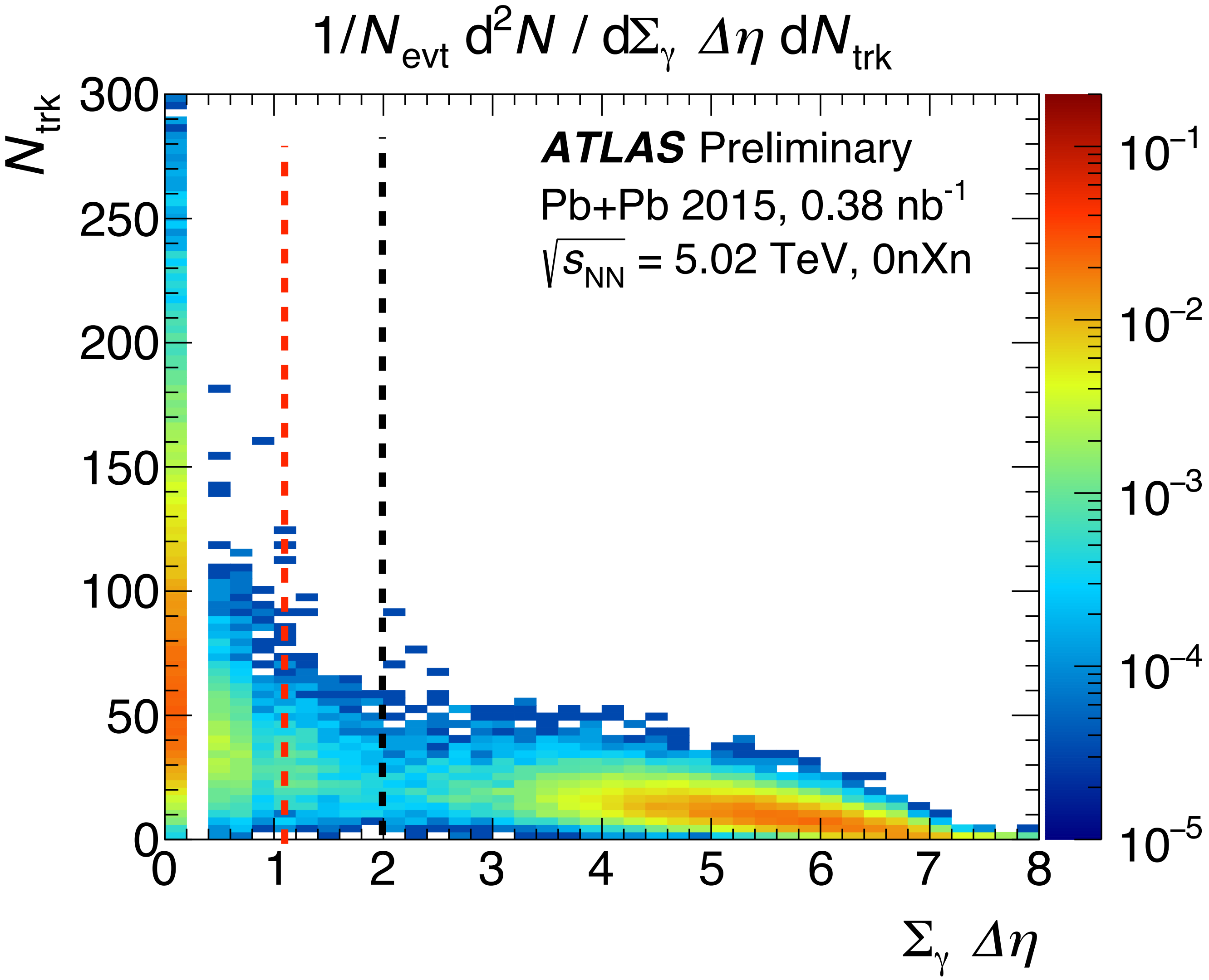
Event Topology: “Resolved”

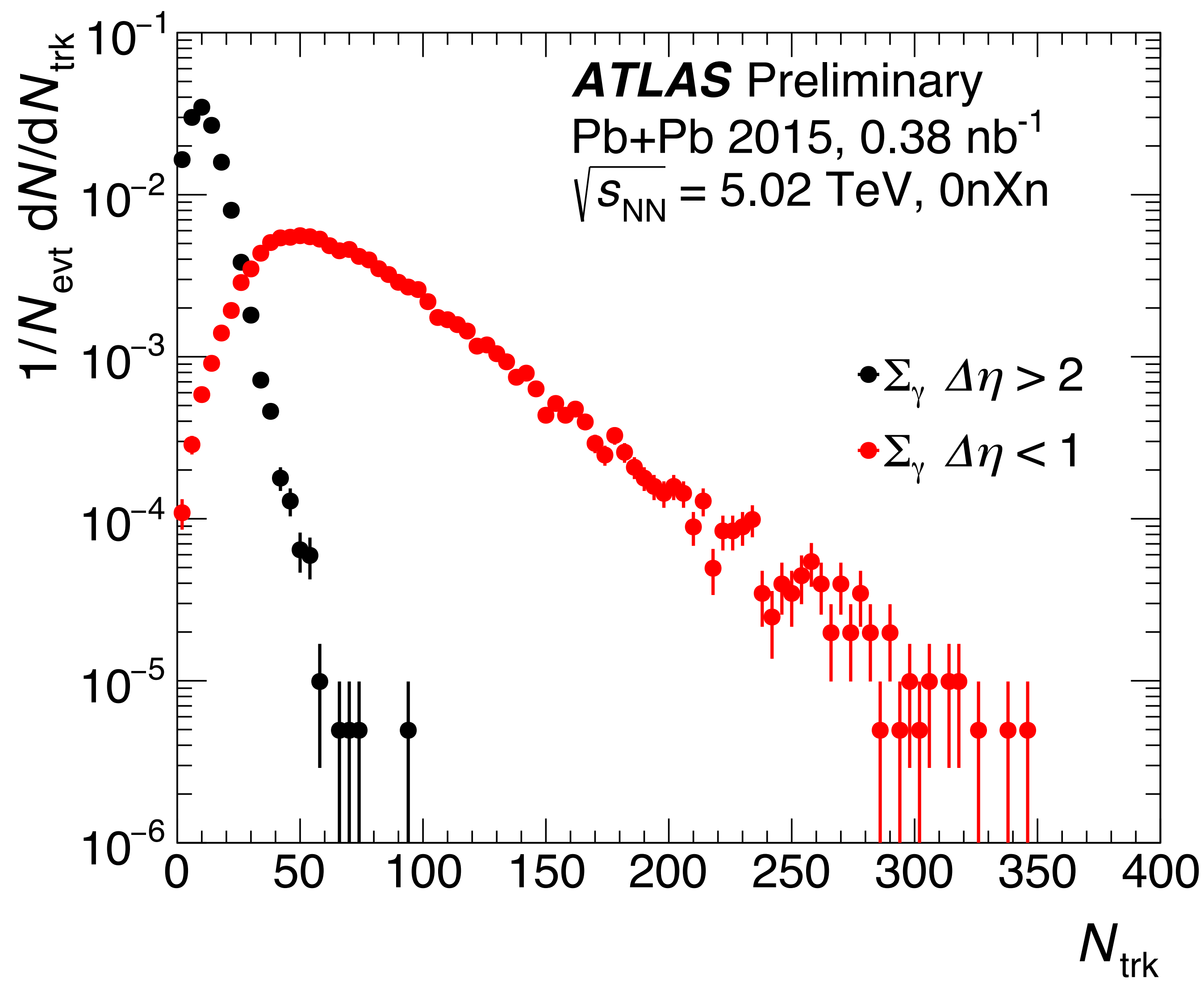


The Measurement: Event Selection

- Using 2015 Pb+Pb data; $\sqrt{s_{NN}}$=5.02 TeV
  - Events selected with ZDC (+jet) triggers, 0.38 nb^{-1}
- Use ZDC to select "*0nXn*" events (fiducial)
  - No correction for photon emitter breakup
- Physics backgrounds
  - Ordinary Pb+Pb jet production
    - Remove with <u>minimum</u> gap requirement in γ direction: $\Sigma_{\gamma}\Delta\eta > 2$
  - Central diffraction, $\gamma\gamma \rightarrow e^{+}e^{-}, \tau^{+}\tau^{-}, q\bar{q}$
    - Not usually *0nXn*
    - Remove with <u>maximum</u> gap requirement in A direction: $\Sigma_{A}\Delta\eta < 3$
  - Cross sections corrected for inefficiency introduced by gap requirements

Event Topology: Gaps vs Multiplicity





- **Left: $\Sigma_\gamma \Delta\eta$ vs N_{trk} for *0nXn***
  - **See clear difference between events with, w/o gaps**
- **Right: comparison of N_{trk} distributions for events with ($\Sigma_\gamma \Delta\eta > 2$) and without ($\Sigma_\gamma \Delta\eta < 1$) gaps.**

The Measurement: Jets and Kinematics

- Measure differential cross sections as vs of H_T, x_A and z_γ:

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

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

Sign of $z/\eta/y$ defined to be positive in γ direction

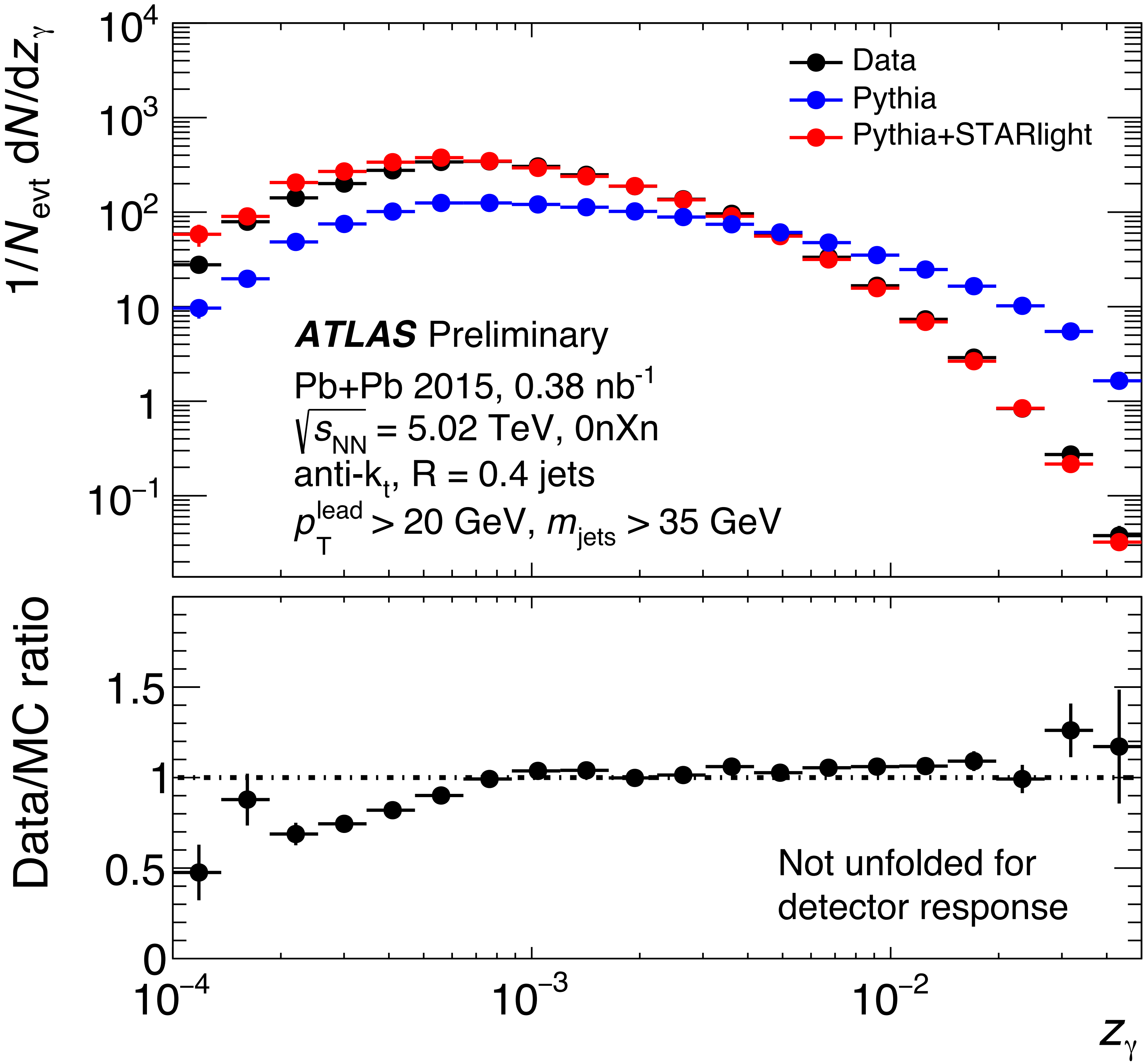
- $p_{\text{T lead}} > 20$ GeV
- $p_{\text{T sublead}} > 15$ GeV
- $|\eta| < 4.4$
- $m_{\text{jets}} > 35$ GeV

- Event-level observables generalize to *n* jet final states
- In 2 → 2 scattering limit:
  - $x_A \rightarrow$ x of struck parton in nucleus
  - $z_\gamma \rightarrow x_\gamma y_\gamma$
  - $H_T \rightarrow 2Q$
- No unfolding; measured cross sections compared to MC
  - Use symbol $\tilde{\sigma}$

Theoretical Model (I)

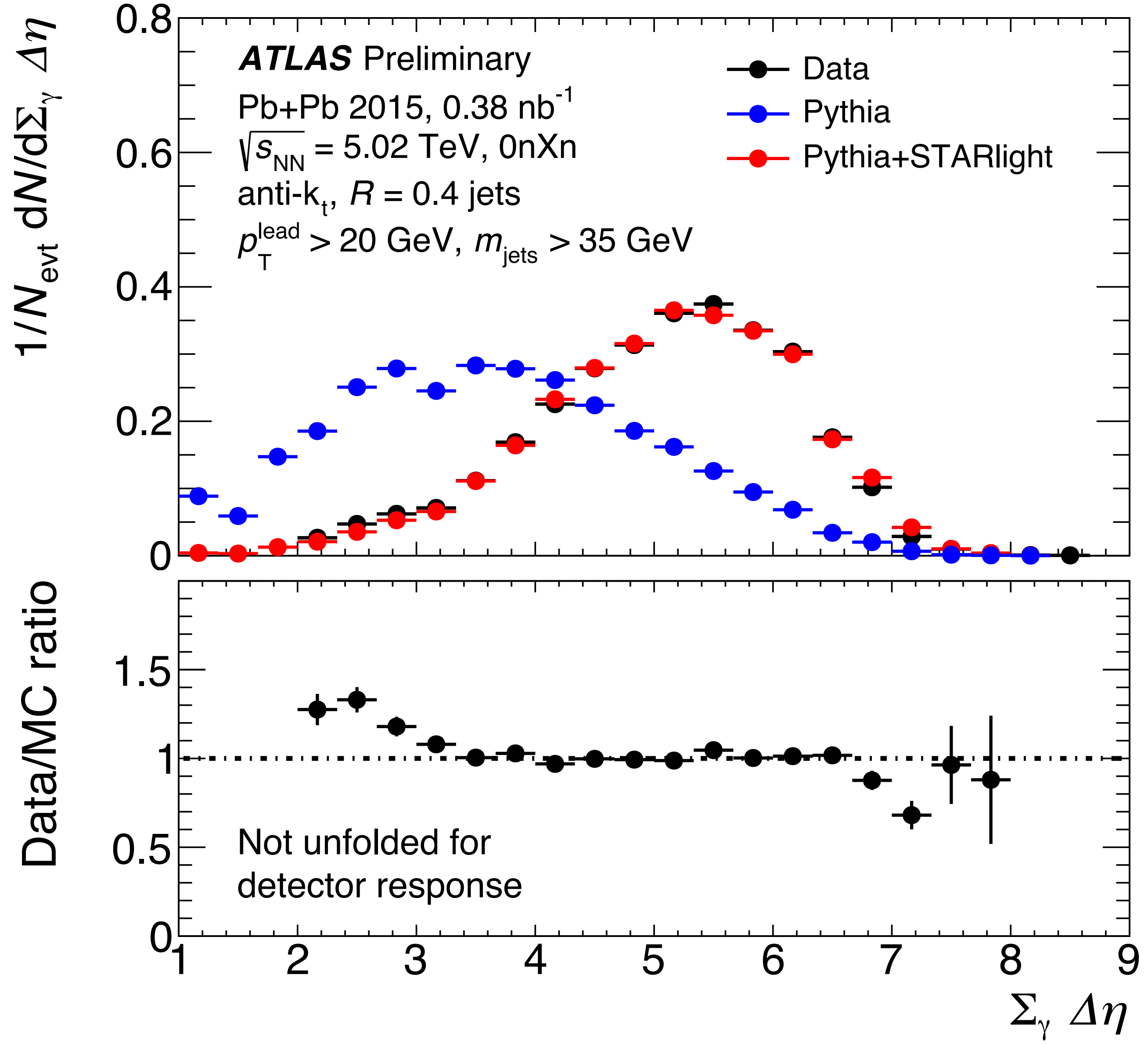
- **Pythia 6 can be used in "mu/gamma p" mode to simulate photo-nuclear processes**
  - **Contains mixture of direct and resolved processes**
    - **Does not have right photon flux**
- **STARlight capable of providing nuclear photon flux**
  - **Needs to be integrated over target**
  - **For small *b*, additional hadronic interactions cause nuclei to break up**
    - **No longer UPC events**
    - **Cannot separate photo-nuclear processes from "normal" AA collisions**
- **Used modified STARlight to calculate weights applied on per-event basis to Pythia sample**

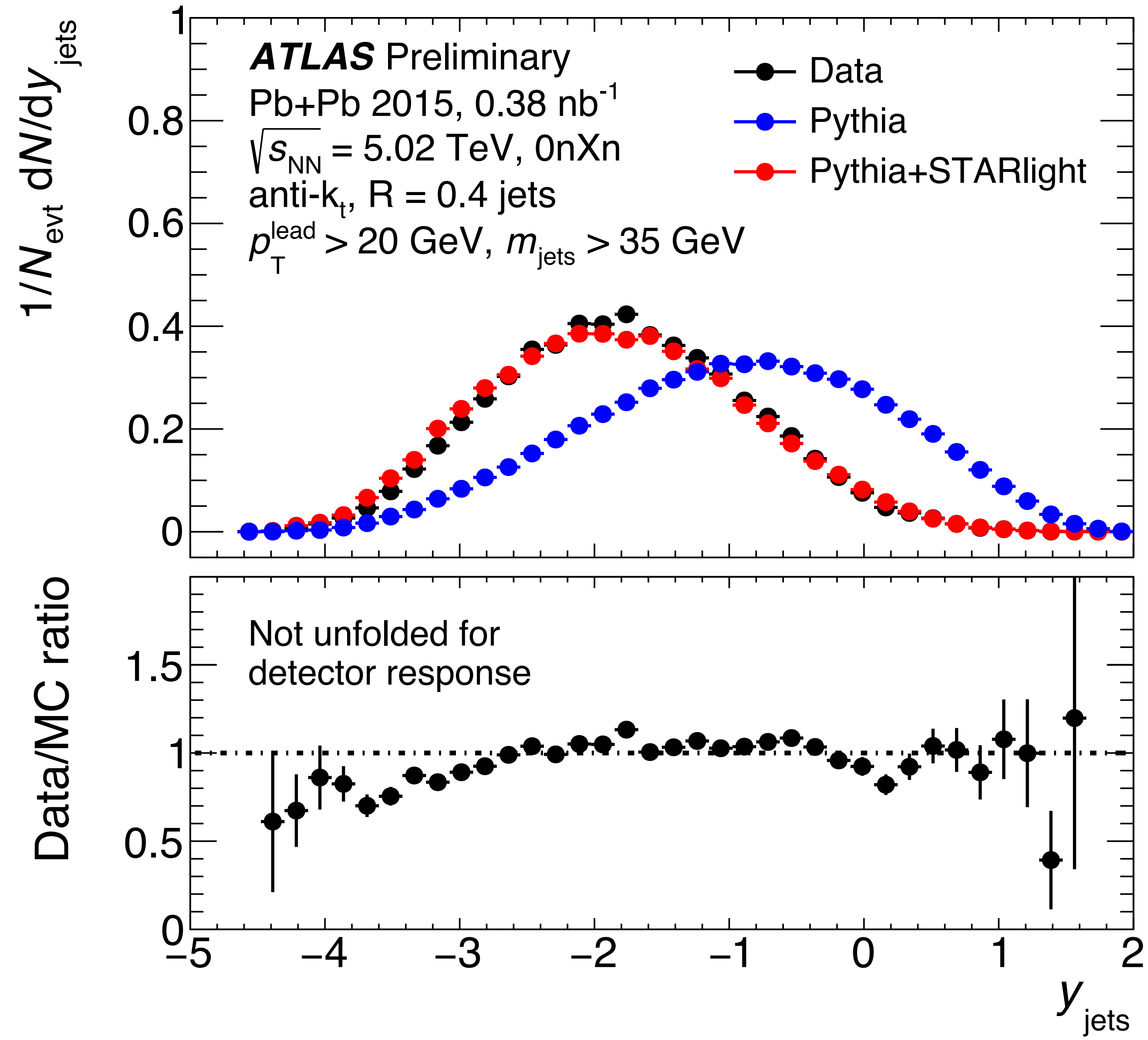
Monte Carlo Re-weighting



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

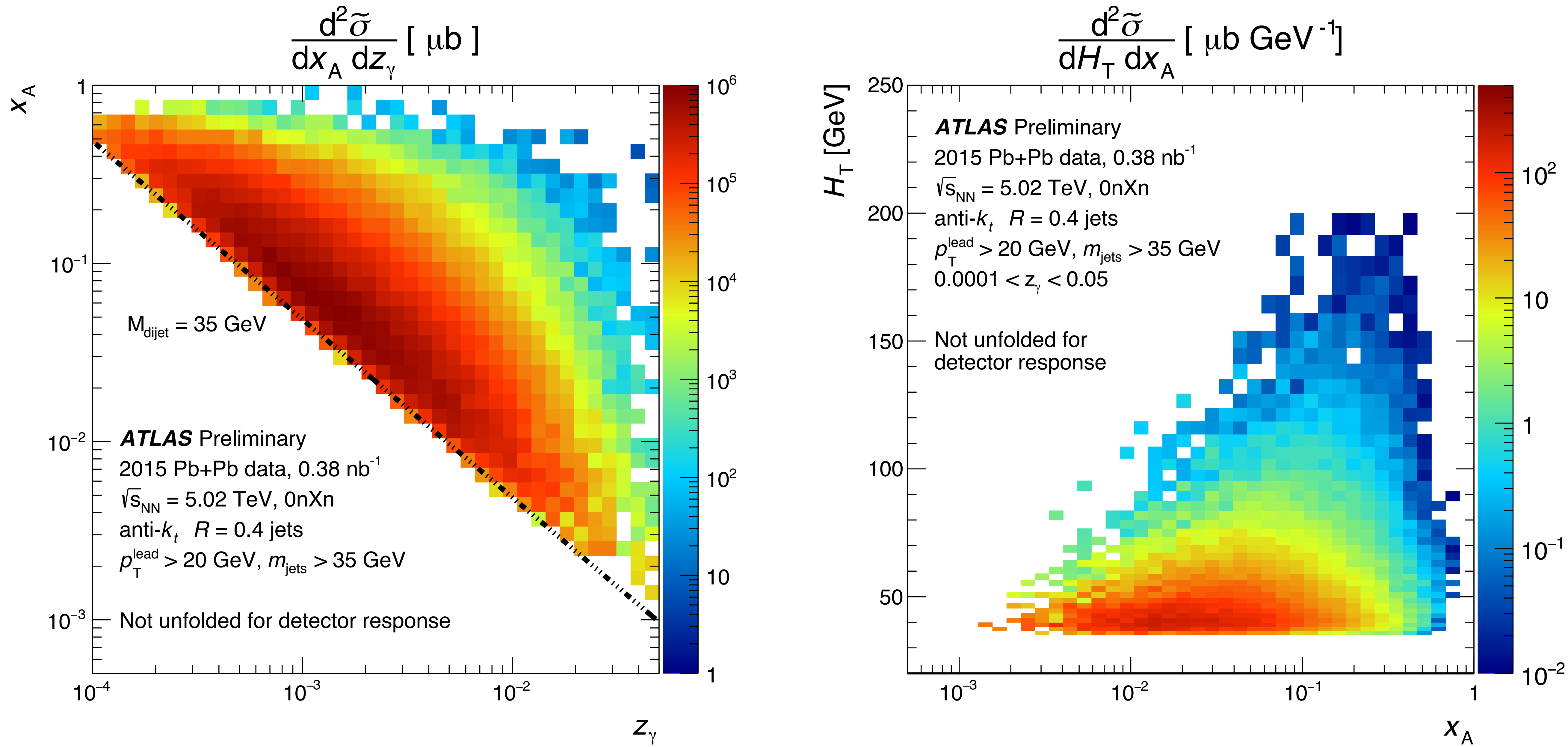
Data-MC Comparisons





- **Good description of gap quantity**
  - **Comfortable w/ MC-based corrections**
- **Positive rapidity in photon direction**
  - **See backward shift because $z_\gamma < x_A$**

2-D Cross Sections

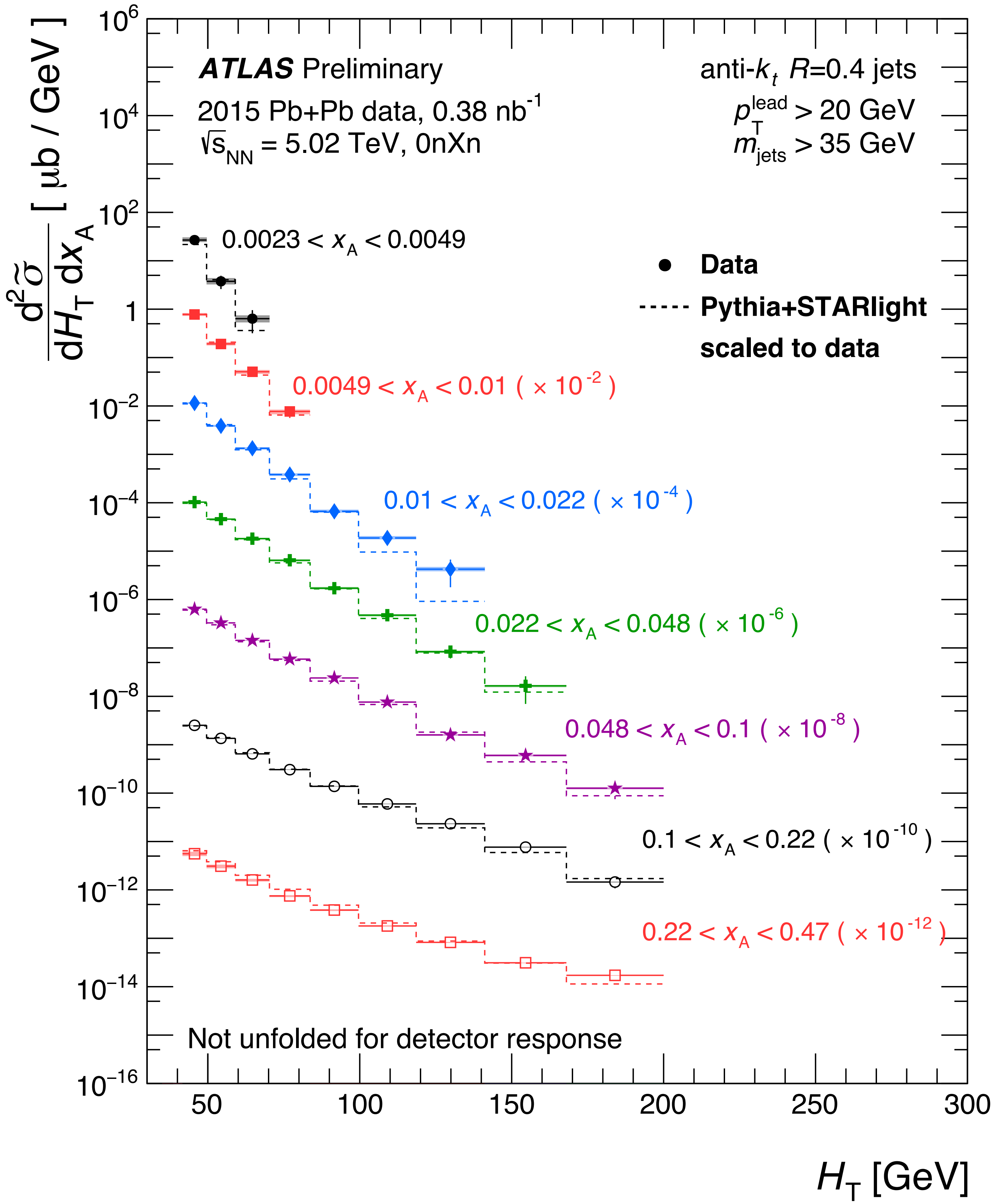


- **Acceptance in (z_γ, x_A) strongly dependent on minimum jet system mass**
  - **Determined by minimum p_T in analysis**
  - **Easiest way to get to low x_A is large z_γ**

Corrections and Systematics

- Correct for inefficiency introduced by event selection requirements
  - ZDC inefficiency: can lose 0*n*1*n* 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
    - Evaluated in MC sample
    - ~1% effect except at very large z_γ
- Luminosity: 6.1% uncertainty
- Jet response: energy scale and resolution uncertainties

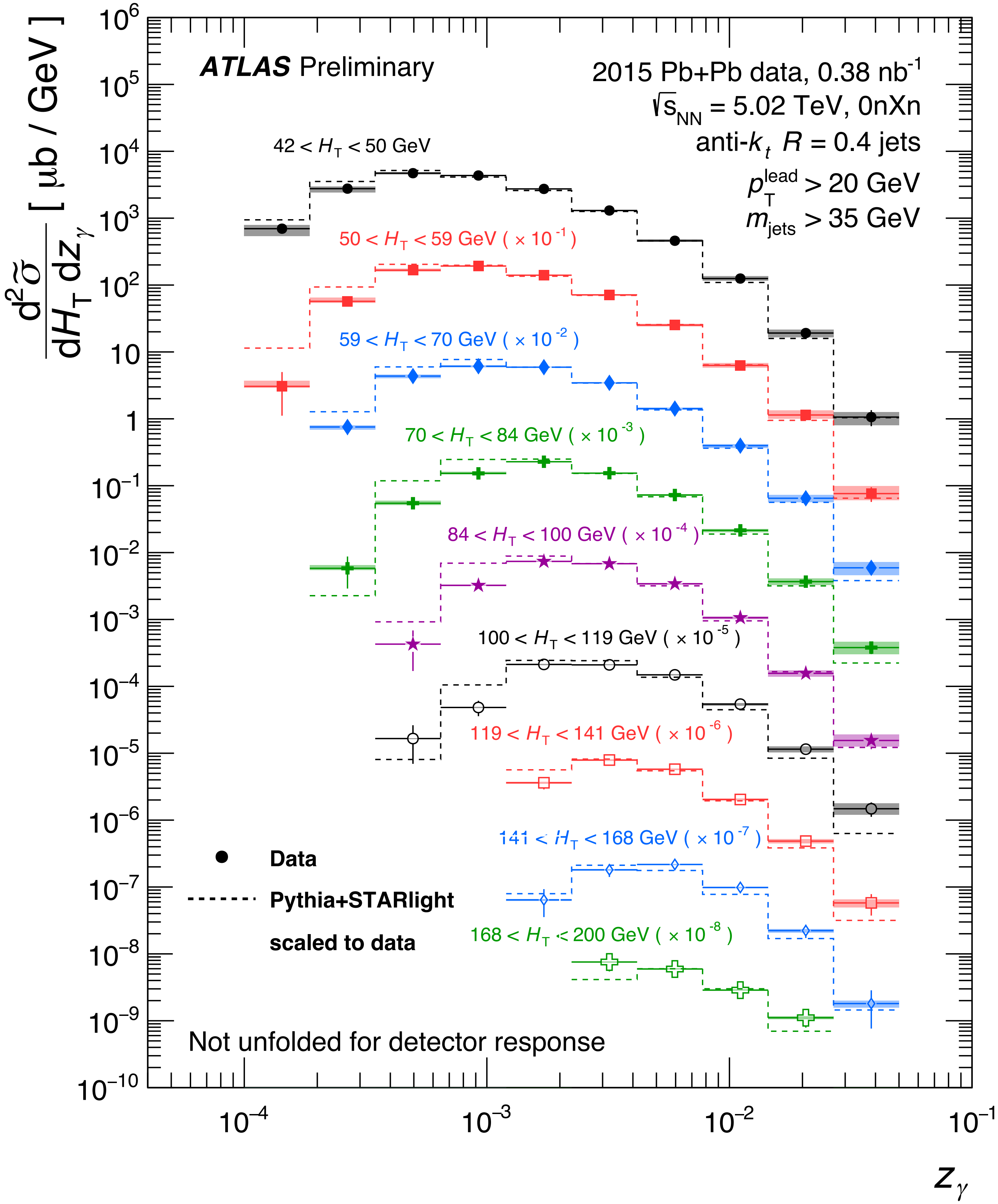
Results: H_T Dependence



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**

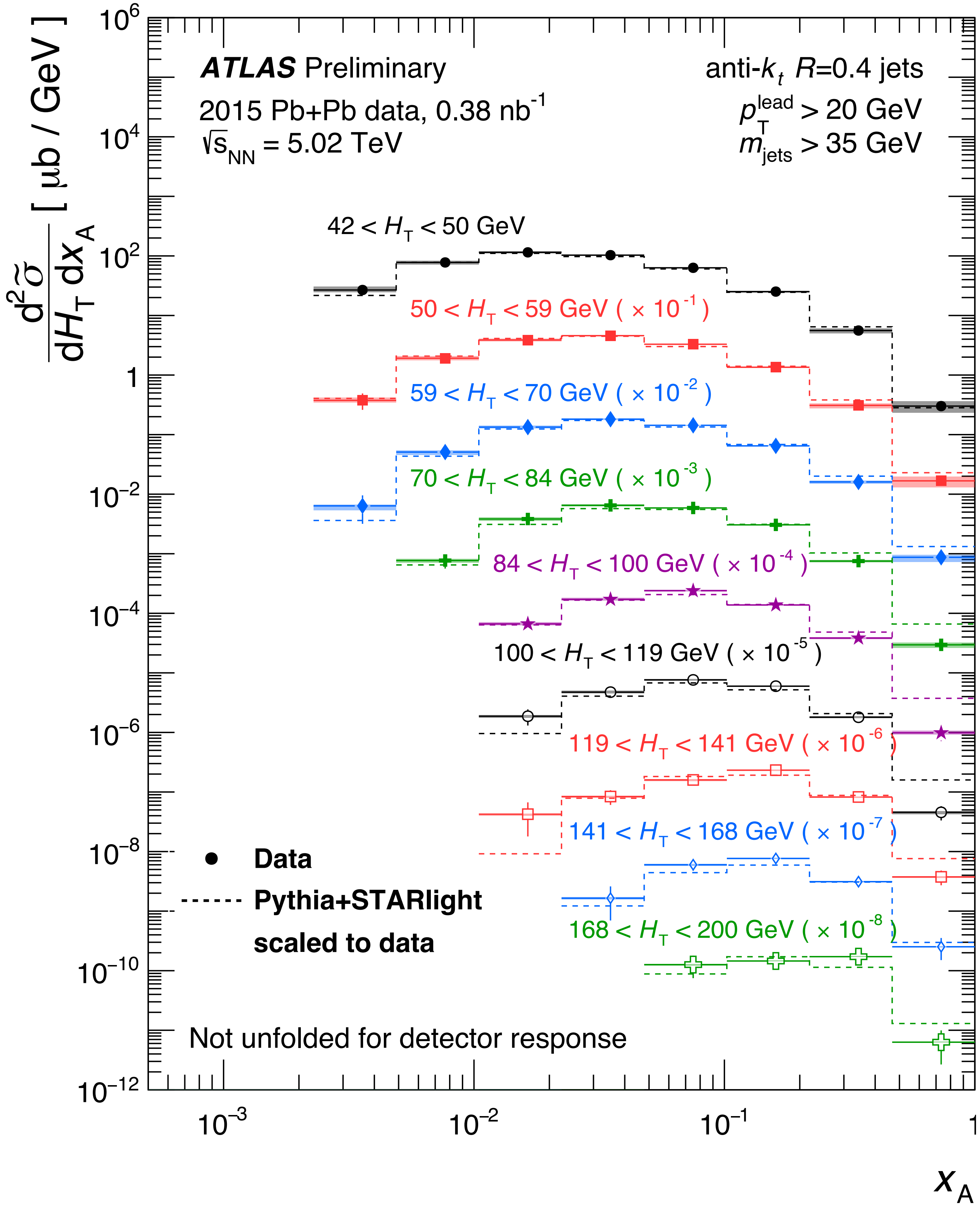
Results: z_γ Dependence



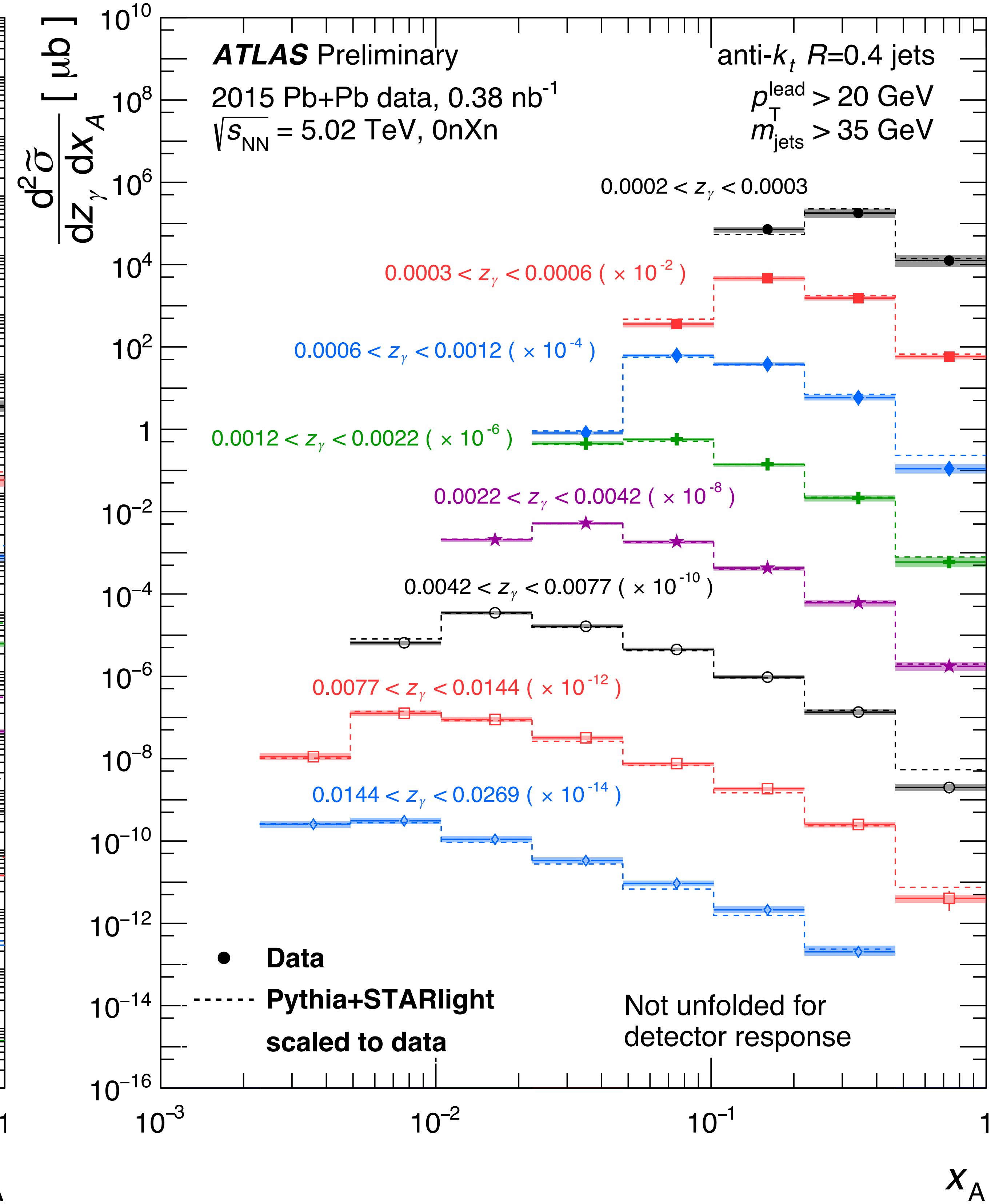
Slices of H_T

- **Largest disagreement with model at large and small z_γ where reweighting is most significant**
- **Can extend to lower x_A by going to higher z_γ**

Results: x_A Dependence



Slices of H_T



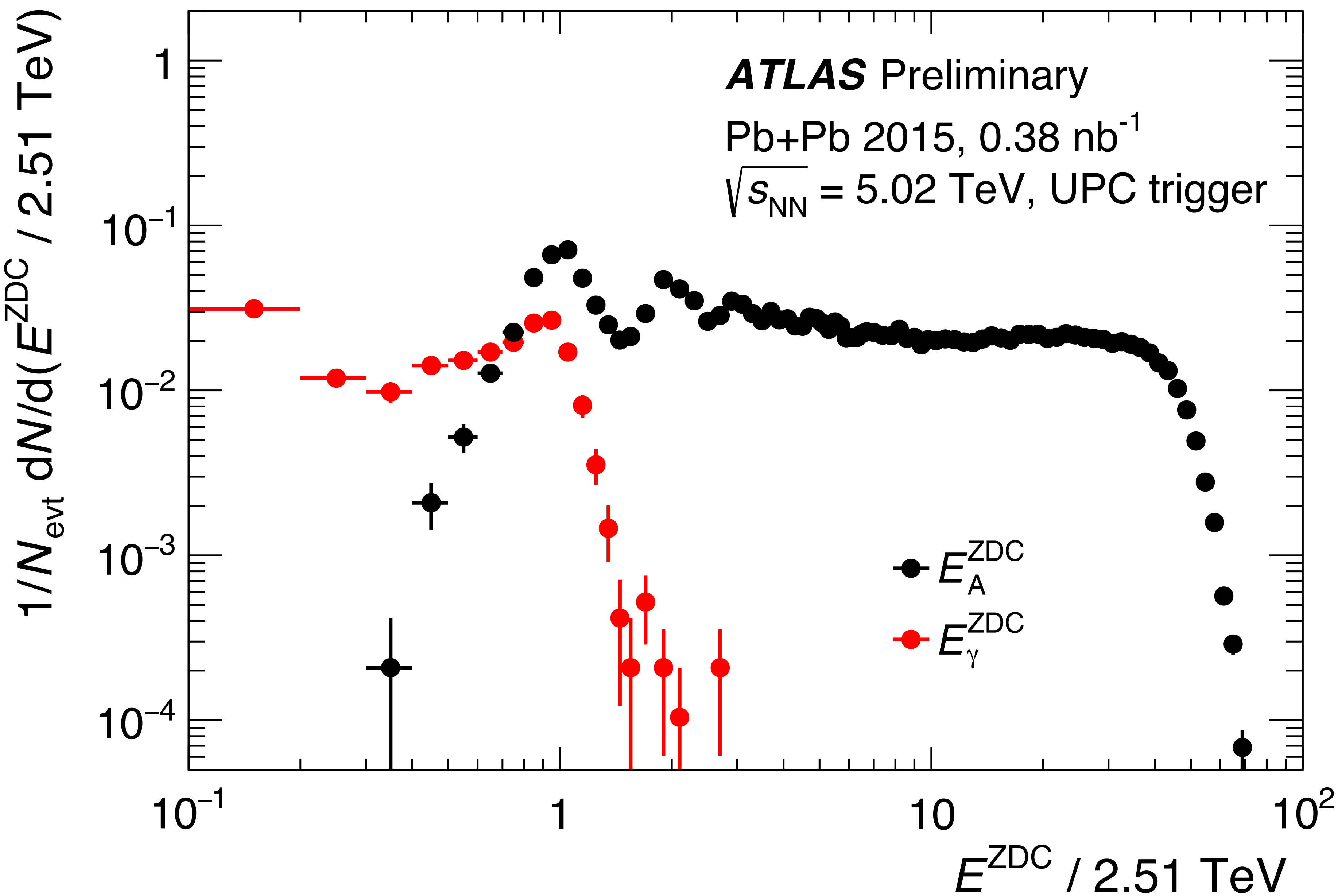
Slices of z_γ

Summary and Conclusions

- Presented a measurement of photo-nuclear jet production: ATLAS-CONF-2017-011
  - Qualitatively different than normal jet production in hadronic collisions
  - Expected features— rapidity gaps and neutron distributions— observed in the data
- Measurement needs to be unfolded
  - Lots of experience with this
- More rigorous comparisons to theory
- Input into new nPDF analyses
  - Domain of x/Q^2 not covered by previous data
- Connects to day 1 measurements at EIC

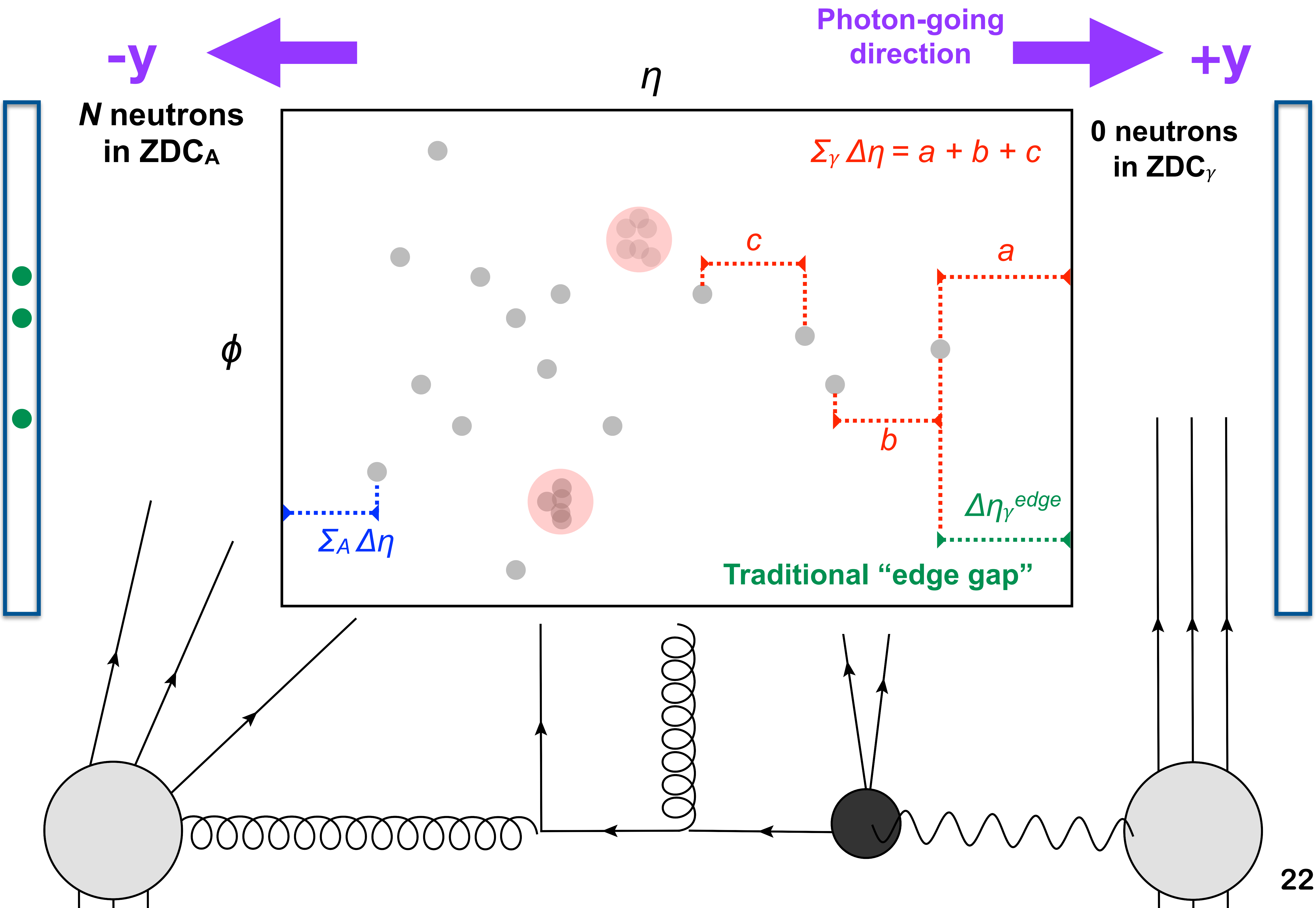
Extras

Event topology: 0*n*X*n*

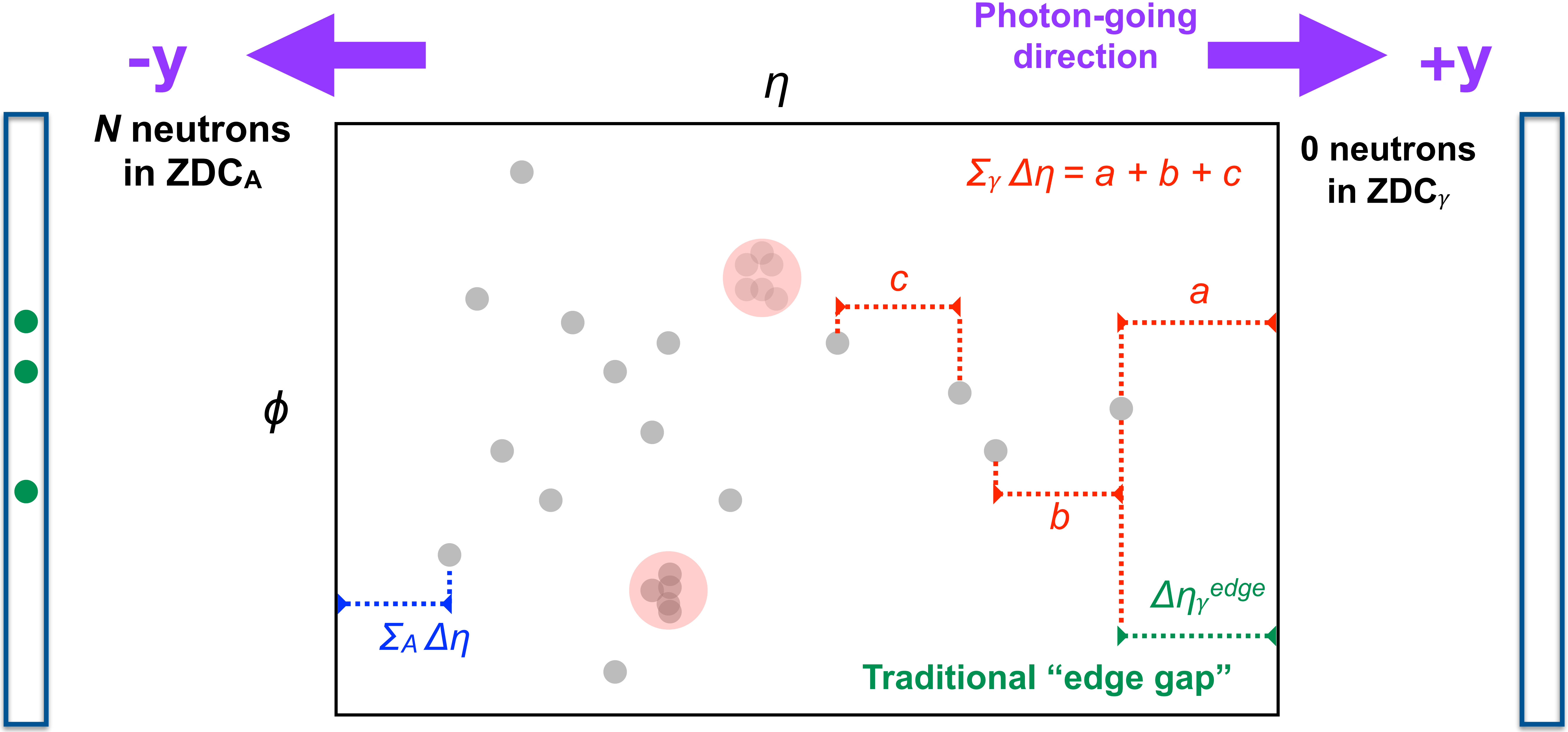


- **Events selected ZDC "XOR" trigger**
- **Red: photon-going direction, 0*n***
- **Black: nuclear direction, X*n***

Event topology (experimental)

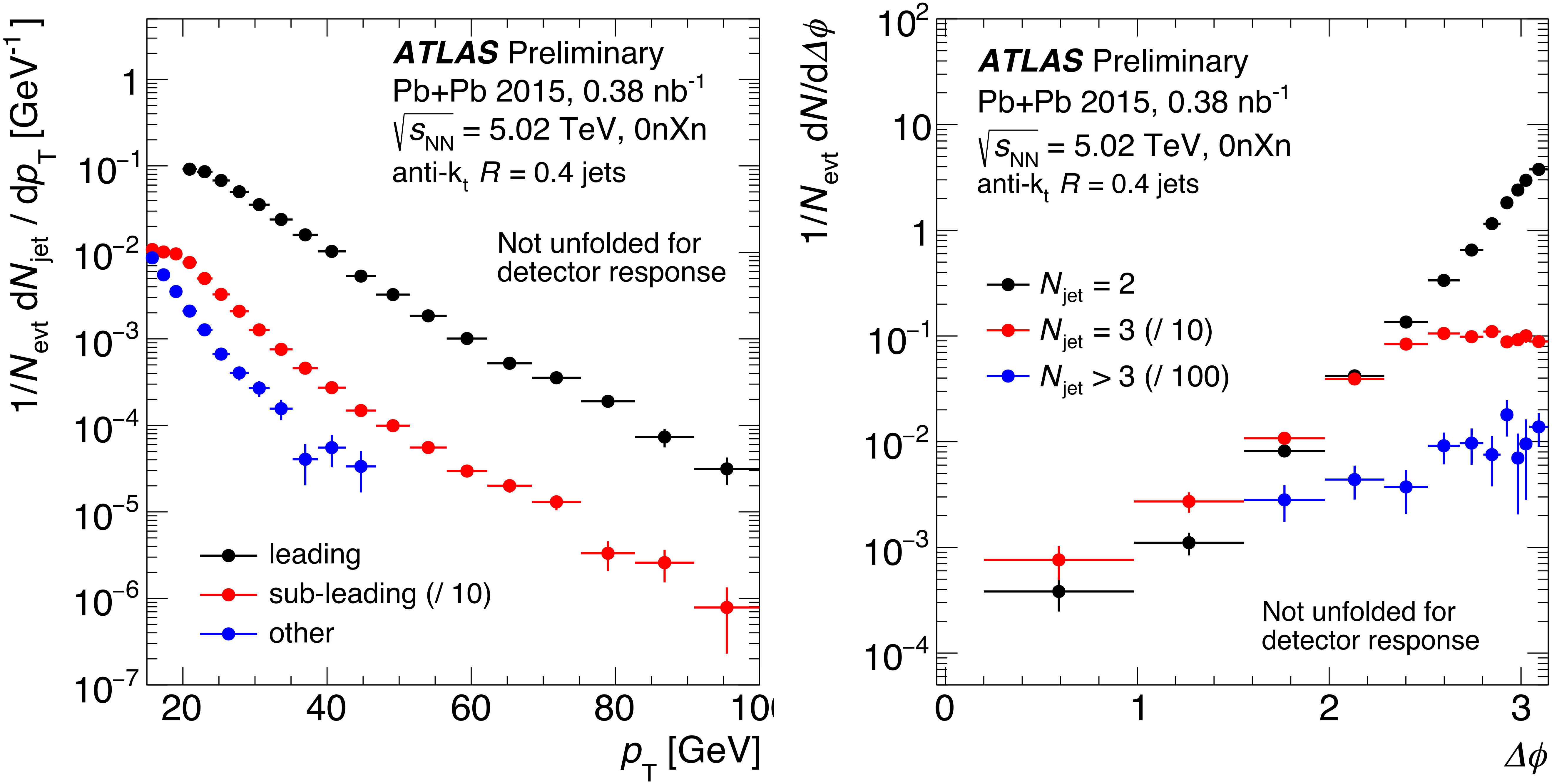


Event topology (experimental)



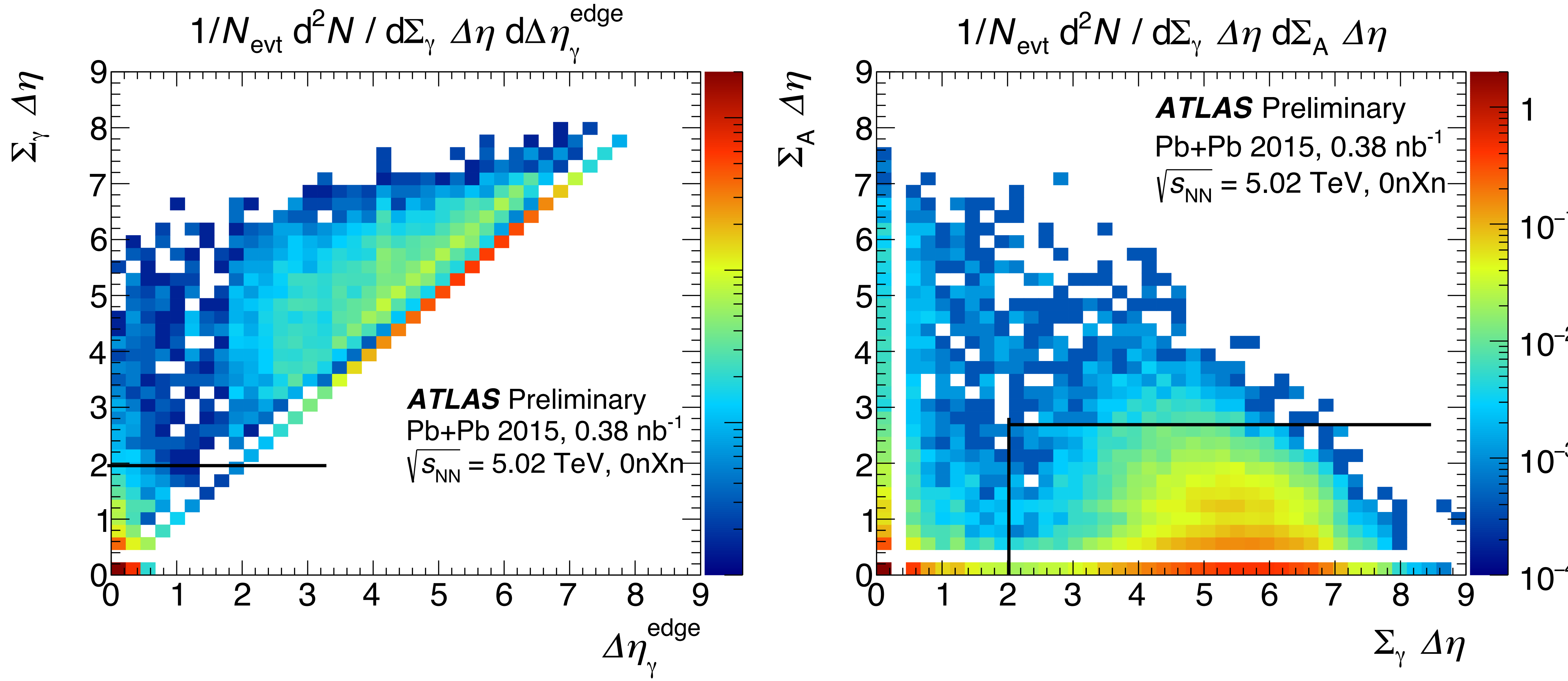
- ZDC requirement: "*0nXn*" topology
- Minimum $\Sigma_\gamma\ \Delta\eta$ requirement: $\Sigma_\gamma\ \Delta\eta_> > 2$
- Maximum $\Sigma_A\ \Delta\eta_<$ requirement: $\Sigma_A\ \Delta\eta < 3$

Jet kinematic distributions



- **Left: jet p_T spectra**
- **Right: leading - sub-leading Δϕ distributions for different numbers of jets**

Event topology: gaps

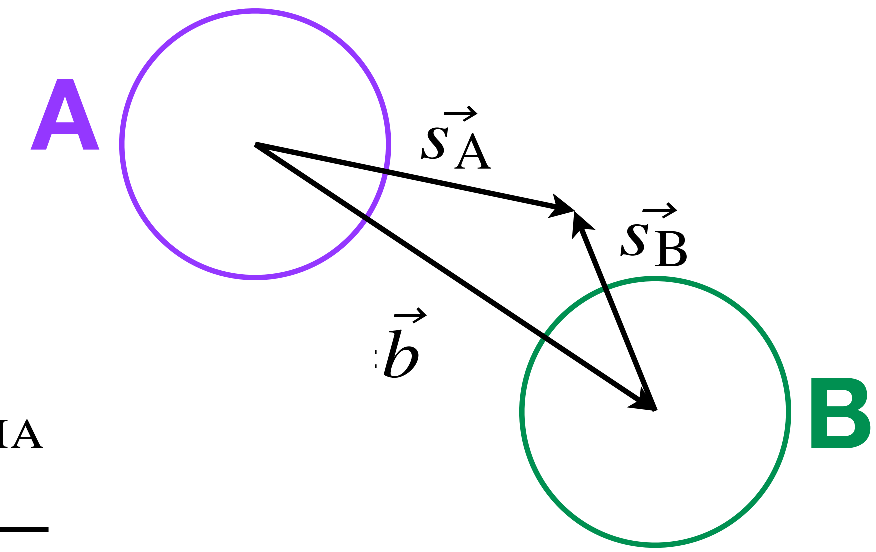


- **Left: compare $\Sigma_\gamma\Delta\eta$ to forward edge gaps**
  - **See effect of resolved photons in split gaps**
    - ➡ **$\Sigma_\gamma\Delta\eta > \Delta\eta^{edge}$**
- **Right: $\Sigma_\gamma\Delta\eta$ vs $\Sigma_A\Delta\eta$**
    - ➡ **backgrounds (e.g. $\gamma\gamma \rightarrow e^+e^-$) for large $\Sigma_\gamma\Delta\eta$**

Theoretical model (II)

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

From STARlight

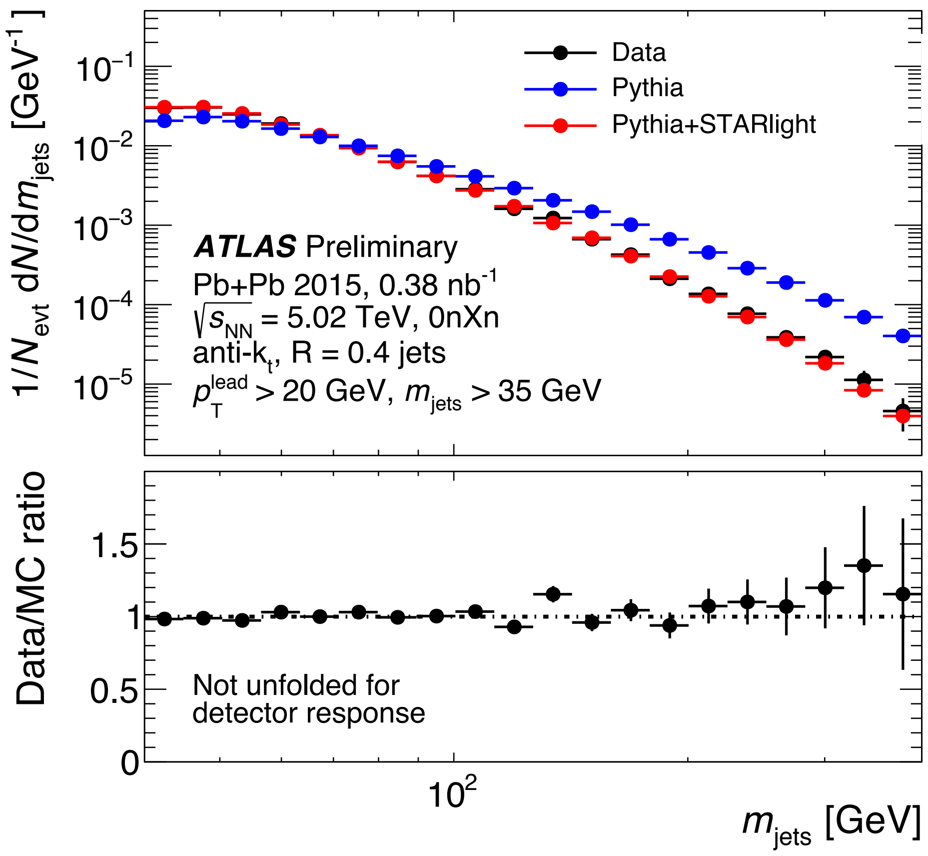


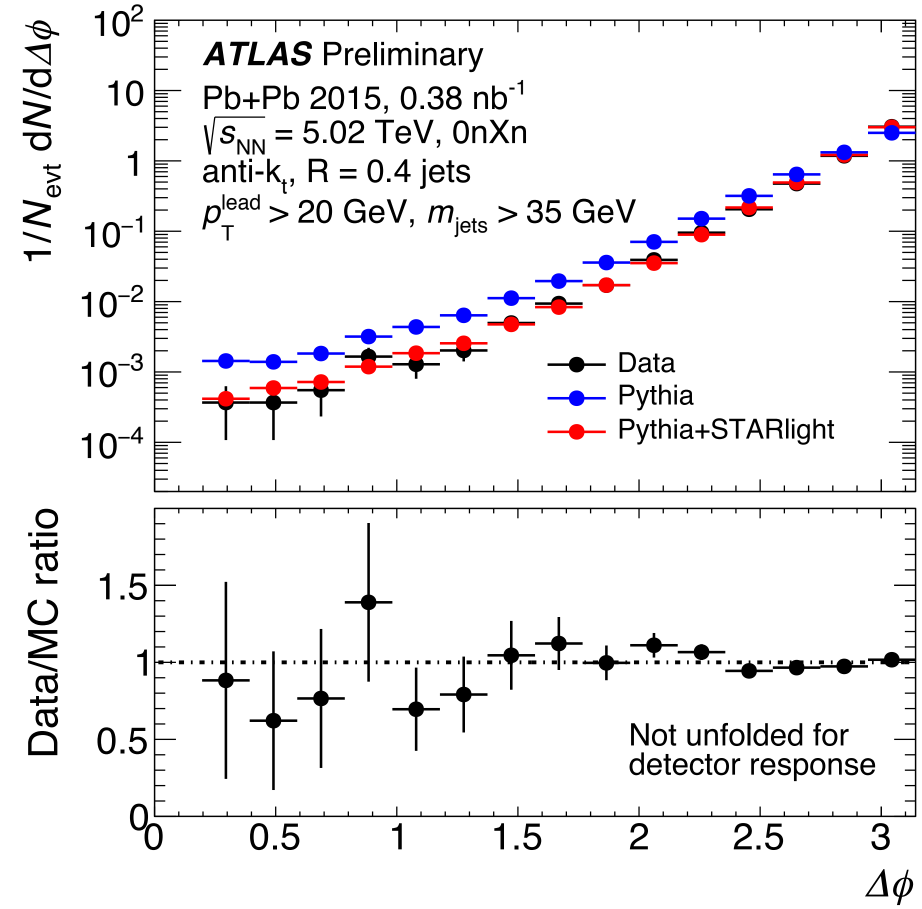
Apply per-event weight to Pythia sample

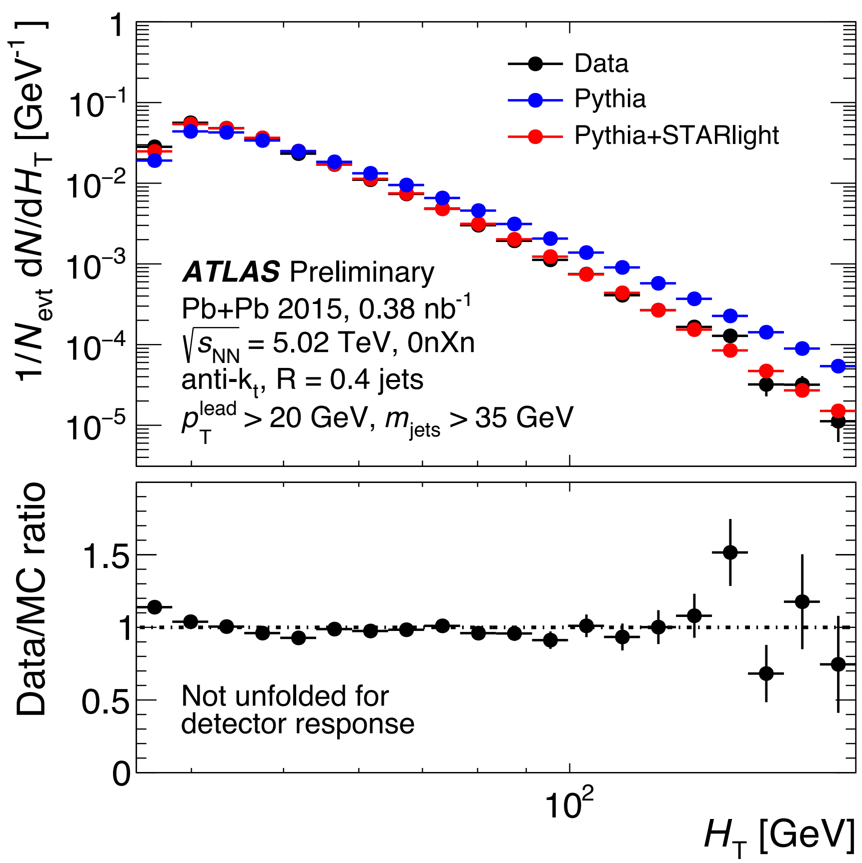
$$w(E) \equiv \frac{\mathrm{d}N_\gamma^{\mathrm{eff}}}{\mathrm{d}E} \Big/ \frac{\mathrm{d}N_\gamma^{\mathrm{PYTHIA}}}{\mathrm{d}E}$$

Flux used by Pythia

Jet system distributions







- **Distributions of the primary ingredients to the kinematic variables used in cross-section**
- **Data-MC description very good for variables sensitive to transverse dynamics**

Event topology (idealized)