COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

ATLAS EXPERIMENT

Measurements of Ultra-Peripheral Collisions with ATLAS

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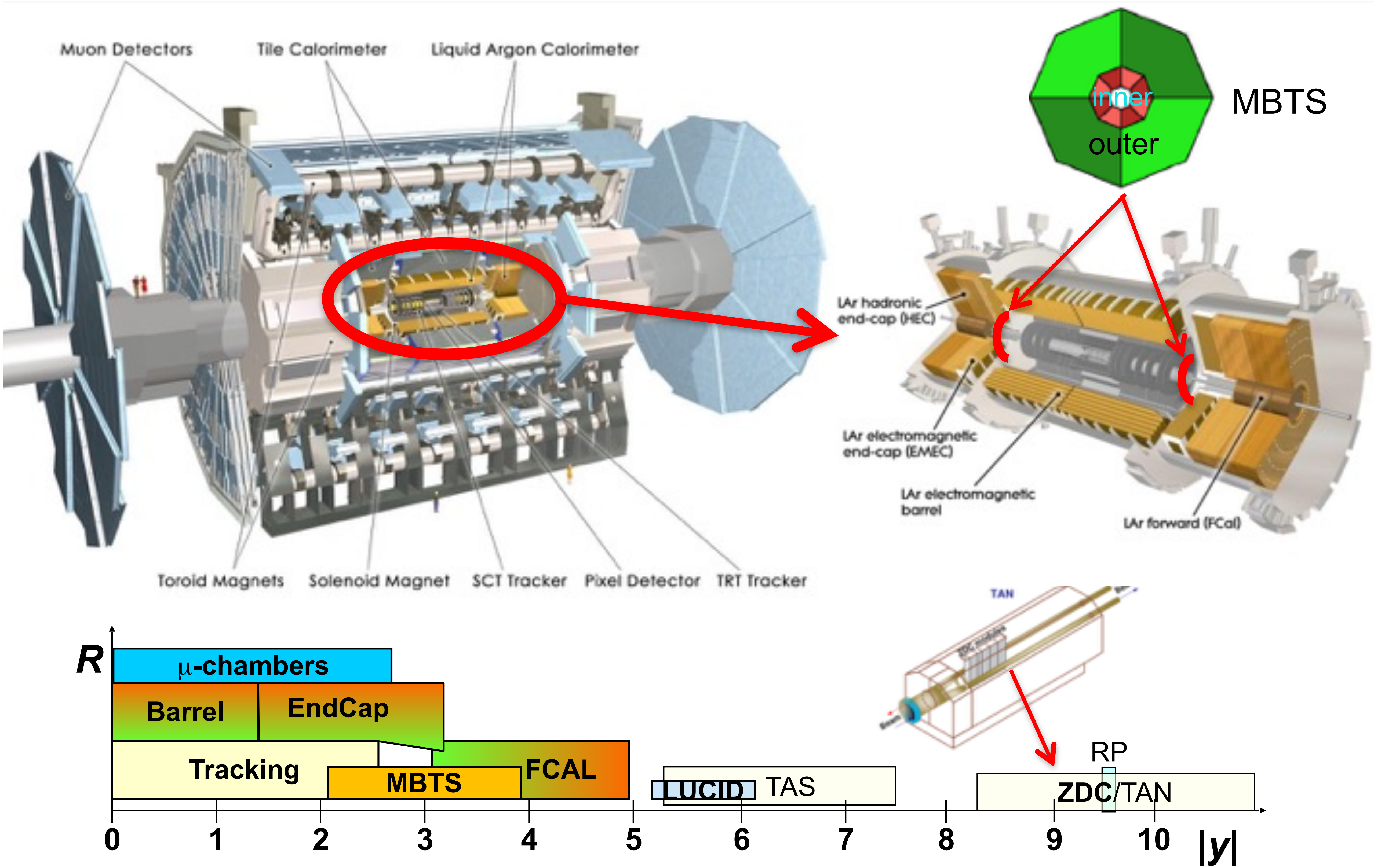
Ultra-Peripheral Collisions

- 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
    - ▸ $k_{\perp\,\gamma} \sim \hbar c\, /\, 2R_{\mathrm{N}} \sim$ 15 MeV, $k_{z\,\gamma} = \gamma_{\mathrm{boost}} \times k_{\perp\,\gamma} \sim$ 40 GeV
- Reactions possible at large impact parameter
  - Event characteristics are qualitatively different than usual AA collisions
- Substantial rate for two photon reactions
  - Mostly exclusive processes
  - Opportunity to study light-by-light scattering
- 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

ATLAS Detector



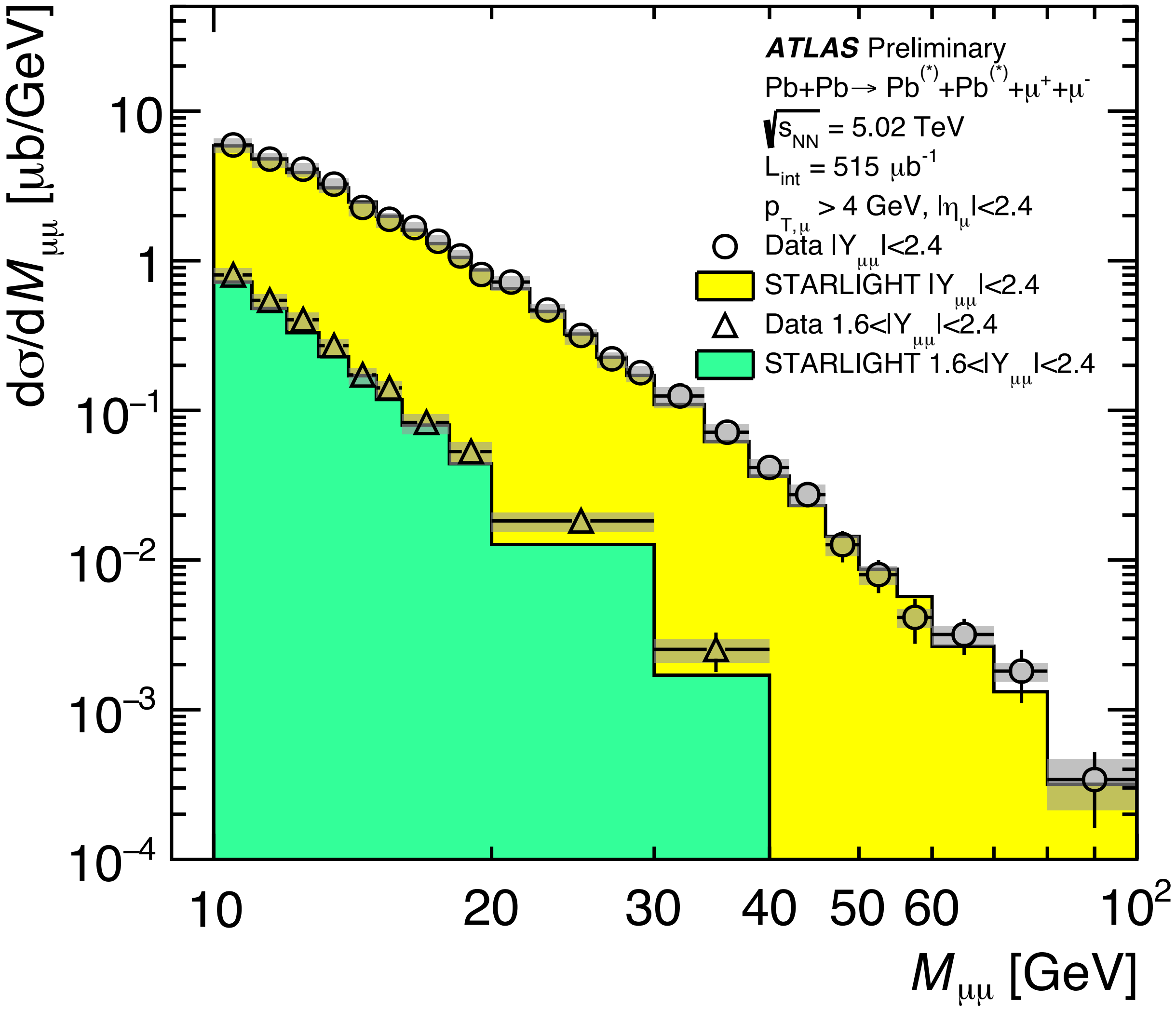
Slide from M. Dyndal's QM2017 talk

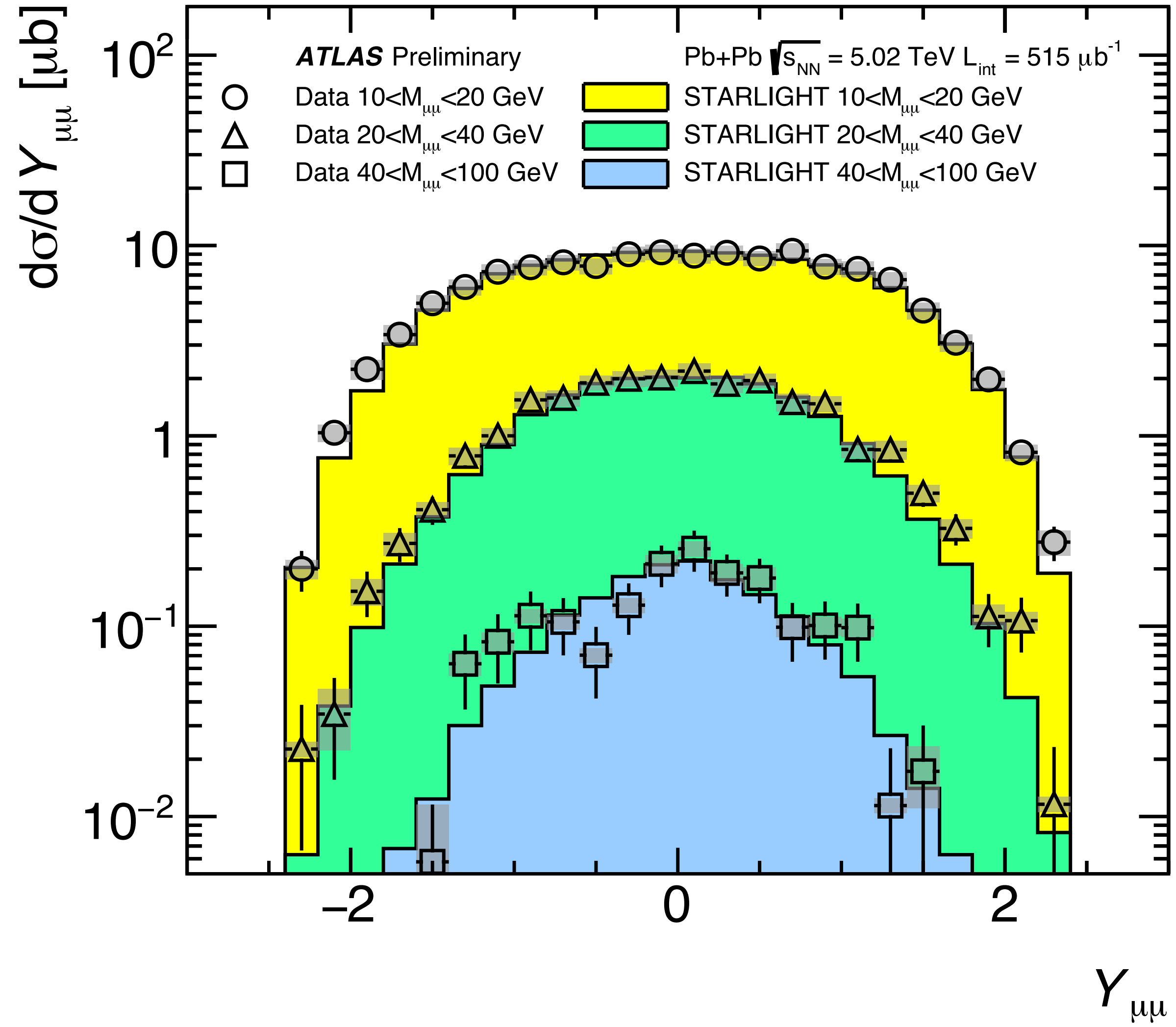
$\gamma\gamma \to \mu^+\mu^-$: Measurement

- Important baseline for other UPC measurements
  - Control over photon flux and its relationship to nuclear breakup modes
- Analysis: ATLAS-CONF-2016-025
  - Two opposite signed muons $p_T > 4$ GeV, $|\eta| < 2.4$ and $m_{\mu\mu} > 10$ GeV
  - Reconstructed vertex with zero additional tracks
  - 12069 total di-muon pairs
- Comparison to STARlight 1.1 (EPA+LO QED)
- Total cross section:
  - $\sigma_{meas.} = 32.2 \pm 0.3\ (stat.) \pm 4.0\ (syst.)\ \mu b$
  - $\sigma_{starlight} = 31.6\ \mu b$

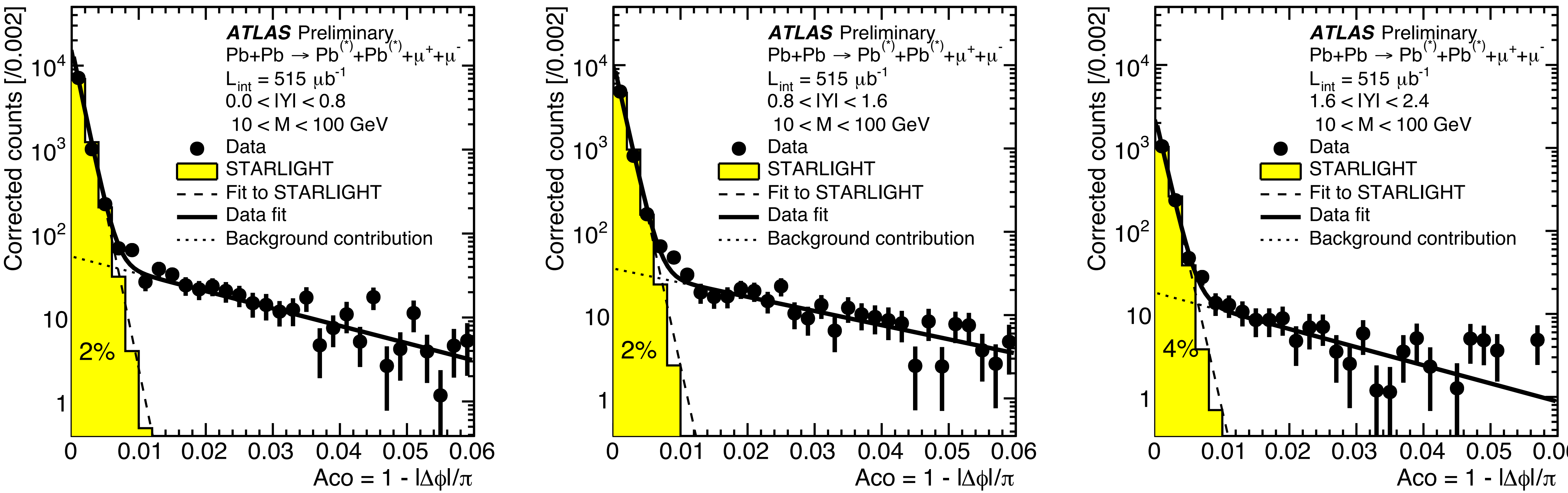
$\gamma\gamma \rightarrow \mu^+\mu^-$: Cross Sections

- **Both $d\sigma/dM_{\mu\mu}$ and $d\sigma/dY_{\mu\mu}$ in reasonably good agreement with prediction**





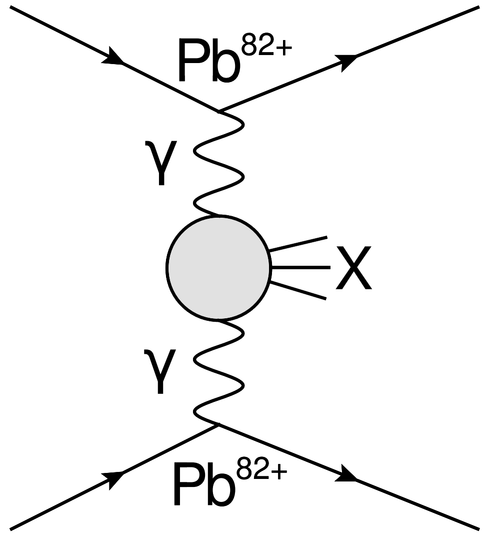
$\gamma\gamma \rightarrow \mu^+\mu^-$: Acoplanarity

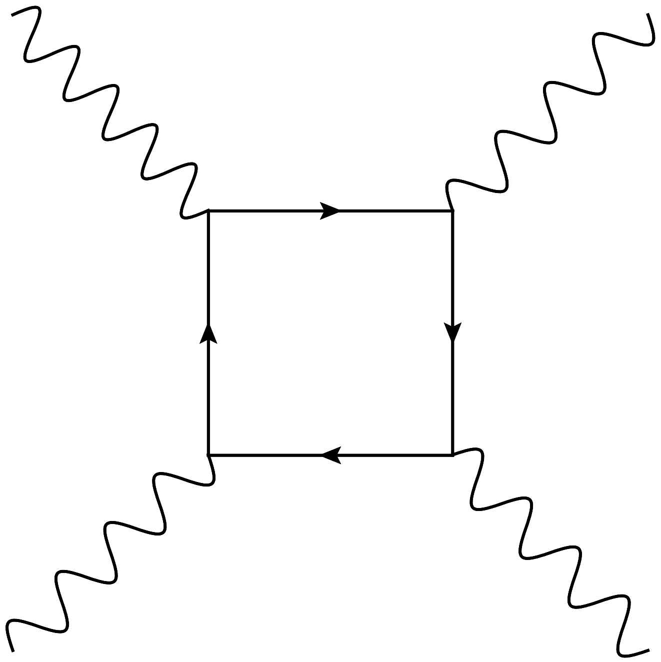


- **Background or QED radiation?**
  - **Influences systematics**
- **Could use theoretical input for how much of broadening comes from radiation**

$\gamma\gamma \to \gamma\gamma$: Measurement

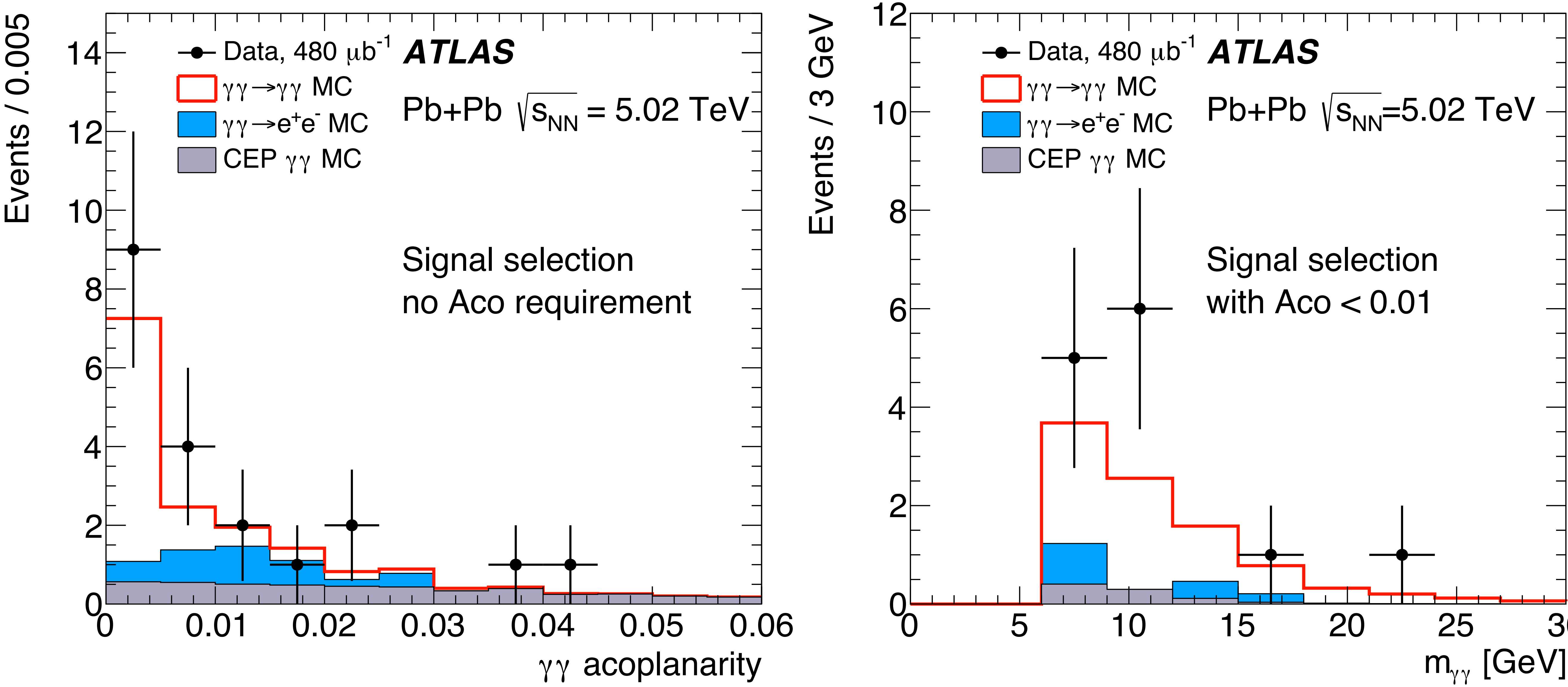
- **Process is forbidden in classical electrodynamics but is a basic prediction of QED**
- **Has not been directly observed***
  - **As particle-like scattering of two photons of well-defined momenta**
- **Process also sensitive to quartic gauge couplings and potentially new BSM particles**





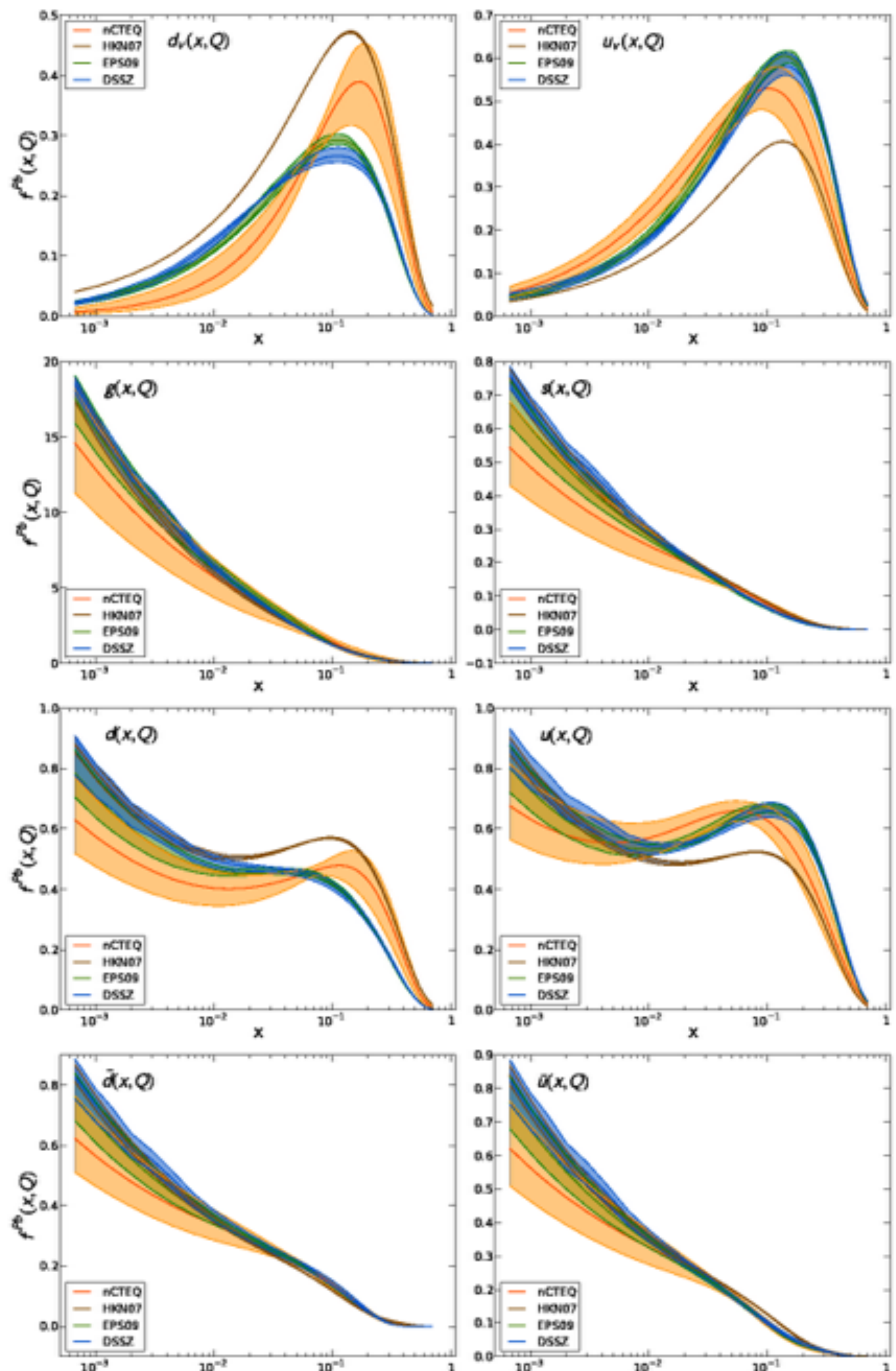
$\gamma\gamma \rightarrow \gamma\gamma$: Results

- **ATLAS paper: arxiv:1702.01625, 4.4σ obs (3.8 SM)**
- **Cross section: $\sigma_{meas.}$=70 ± 20 (stat.)±17(syst.) nb**
  - **$E_{T\gamma}$ > 3 GeV, $|\eta_{\gamma}|$ < 2.37**
  - **$m_{\gamma\gamma}$ < 6 GeV, $p_{T\gamma\gamma}$ < 2 GeV, Aco = 1-$\Delta\phi/\pi$ < 0.01**



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**



Measurement Coverage

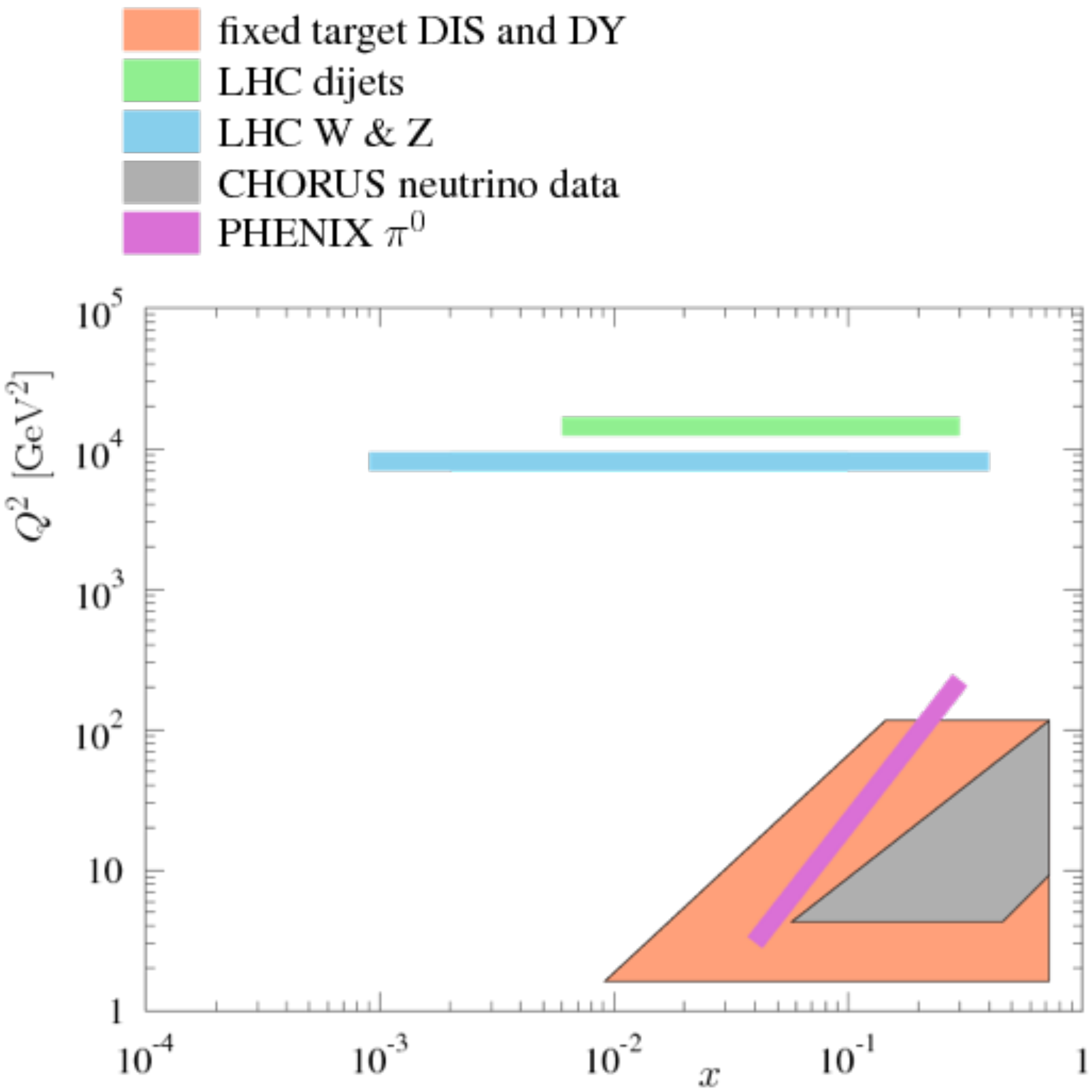
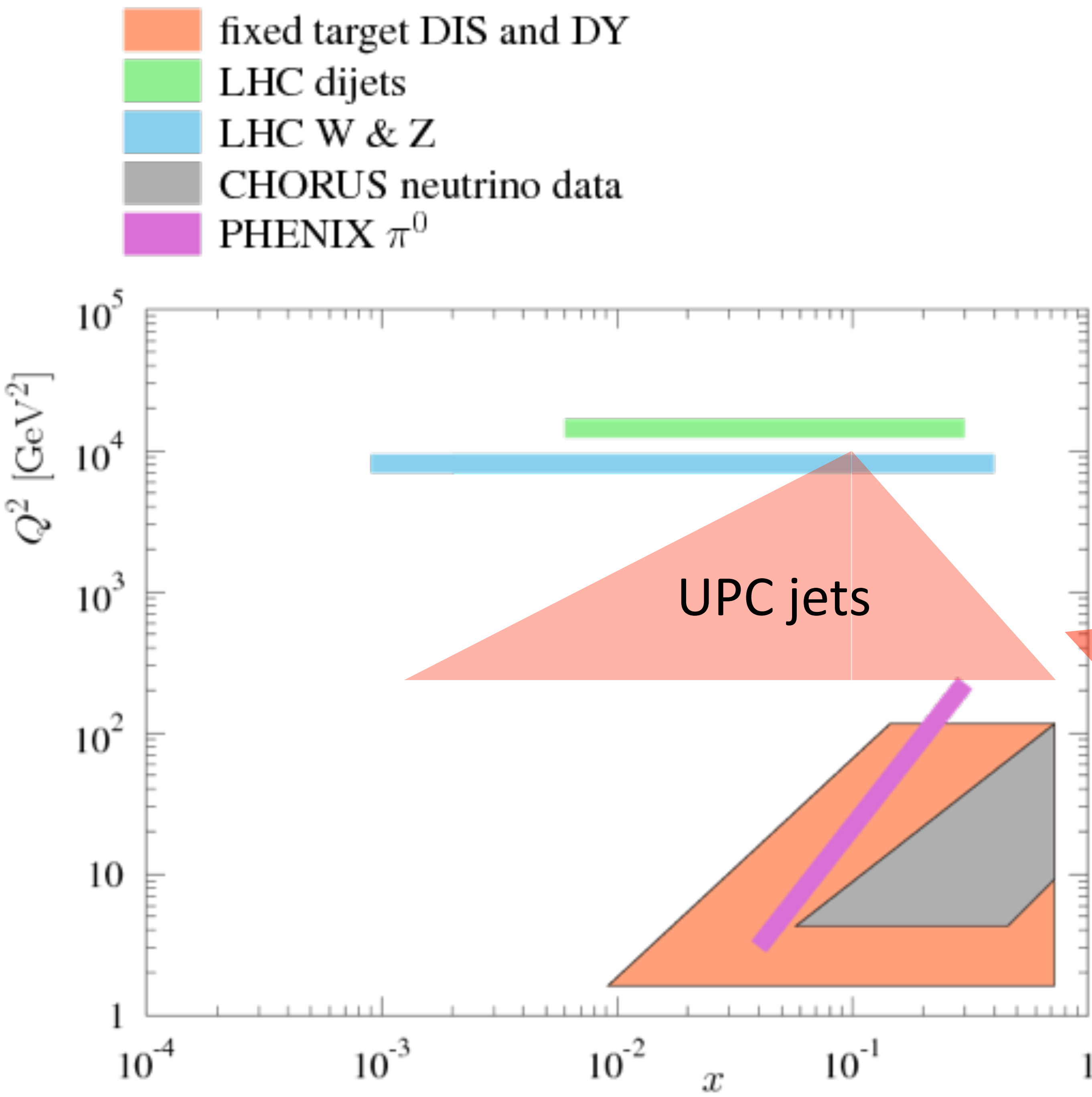


Figure adapted from EPPS16
1612.05741 [hep-ph]

Measurement Coverage



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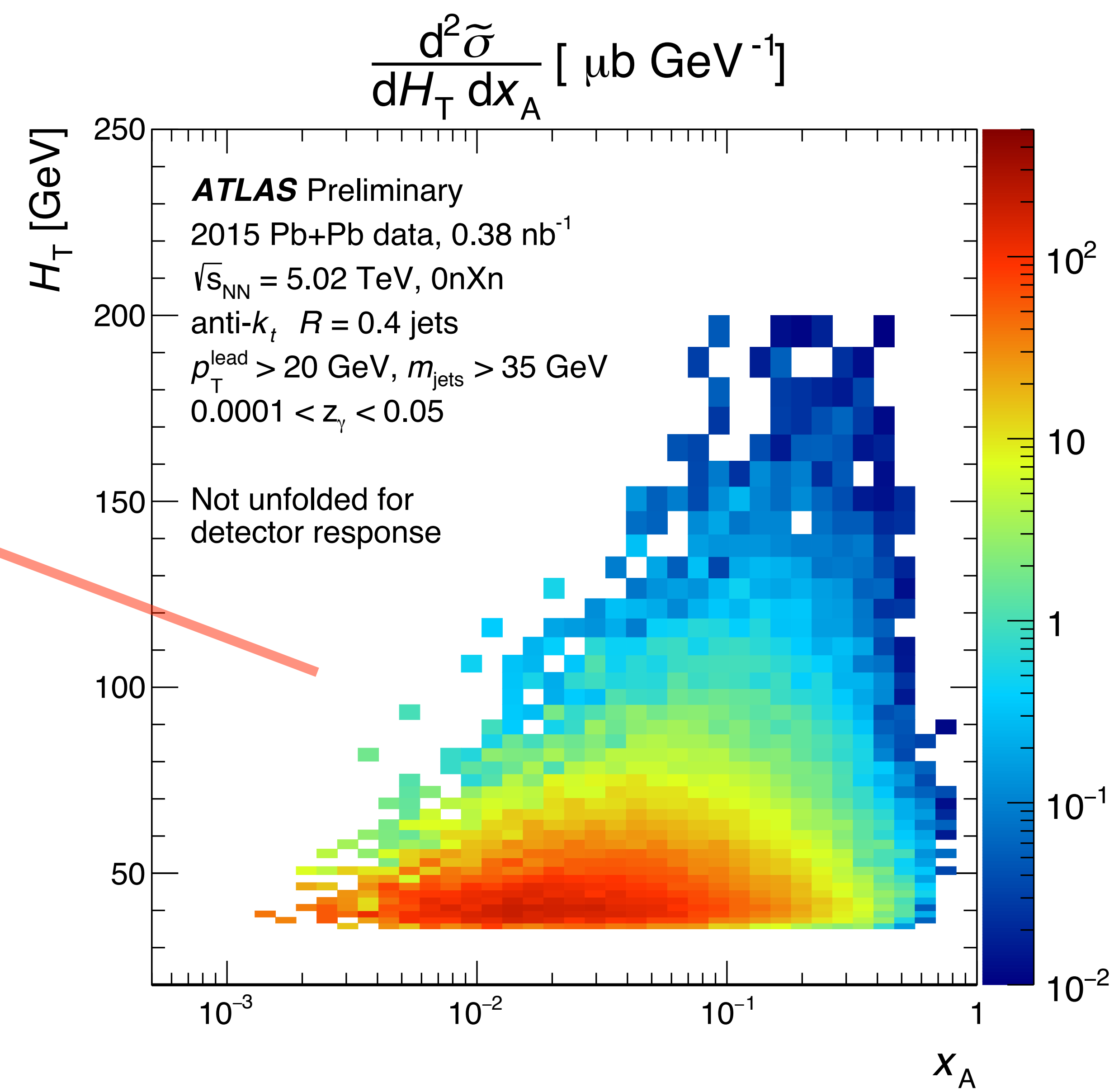
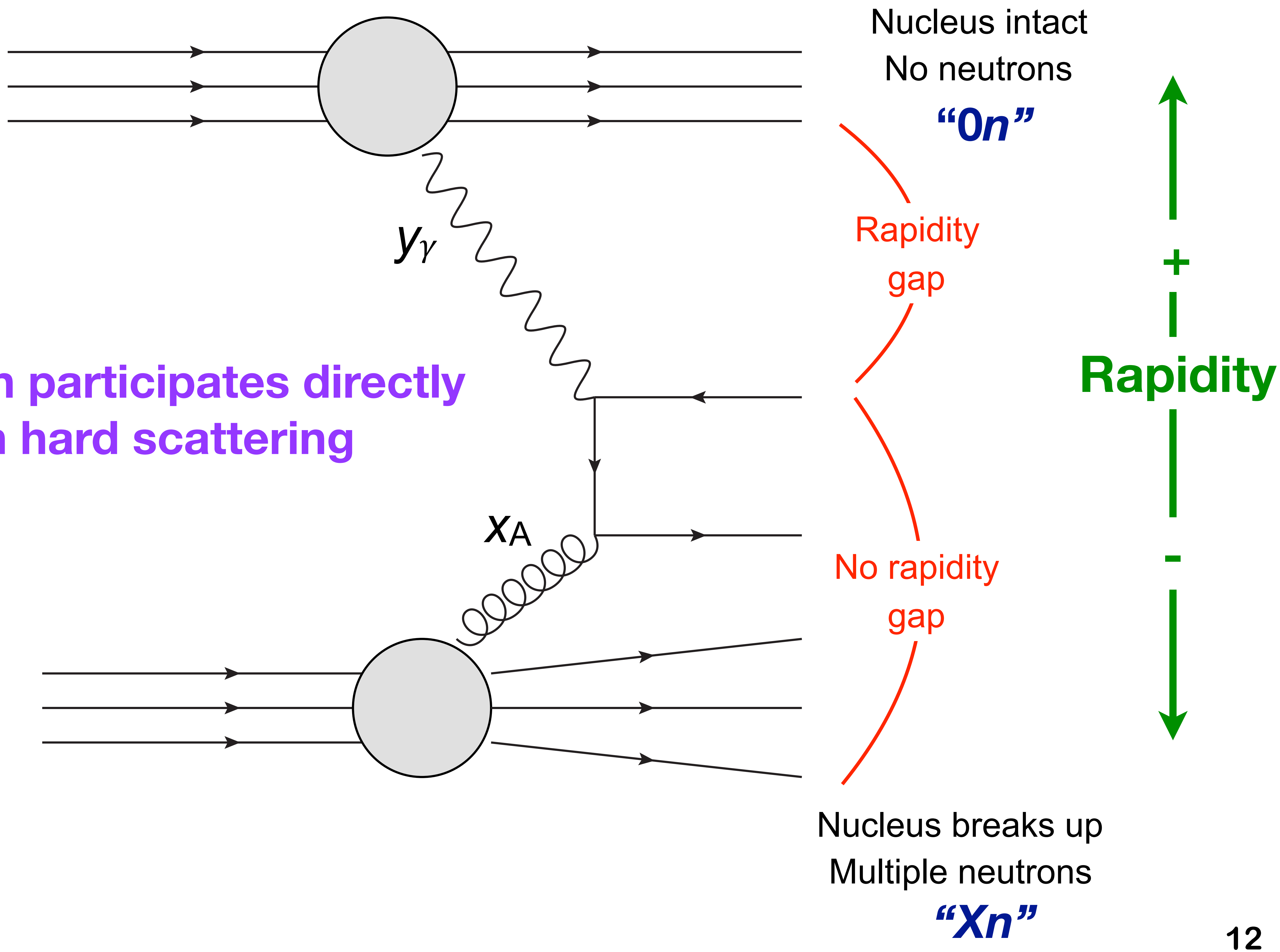


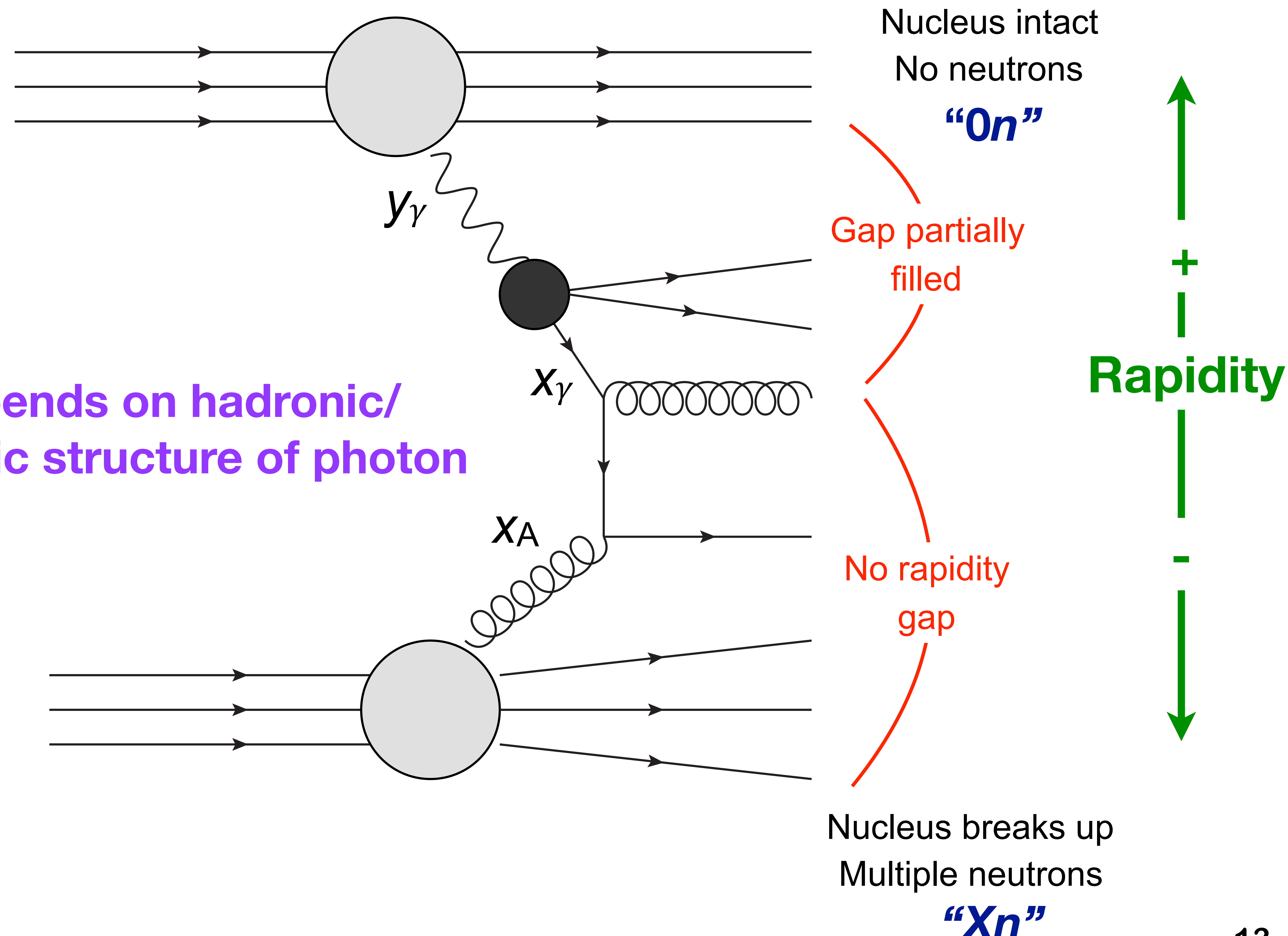
- **ATLAS-CONF-2017-011**

Event Topology: “Direct”

Photon participates directly in hard scattering



Event Topology: “Resolved”

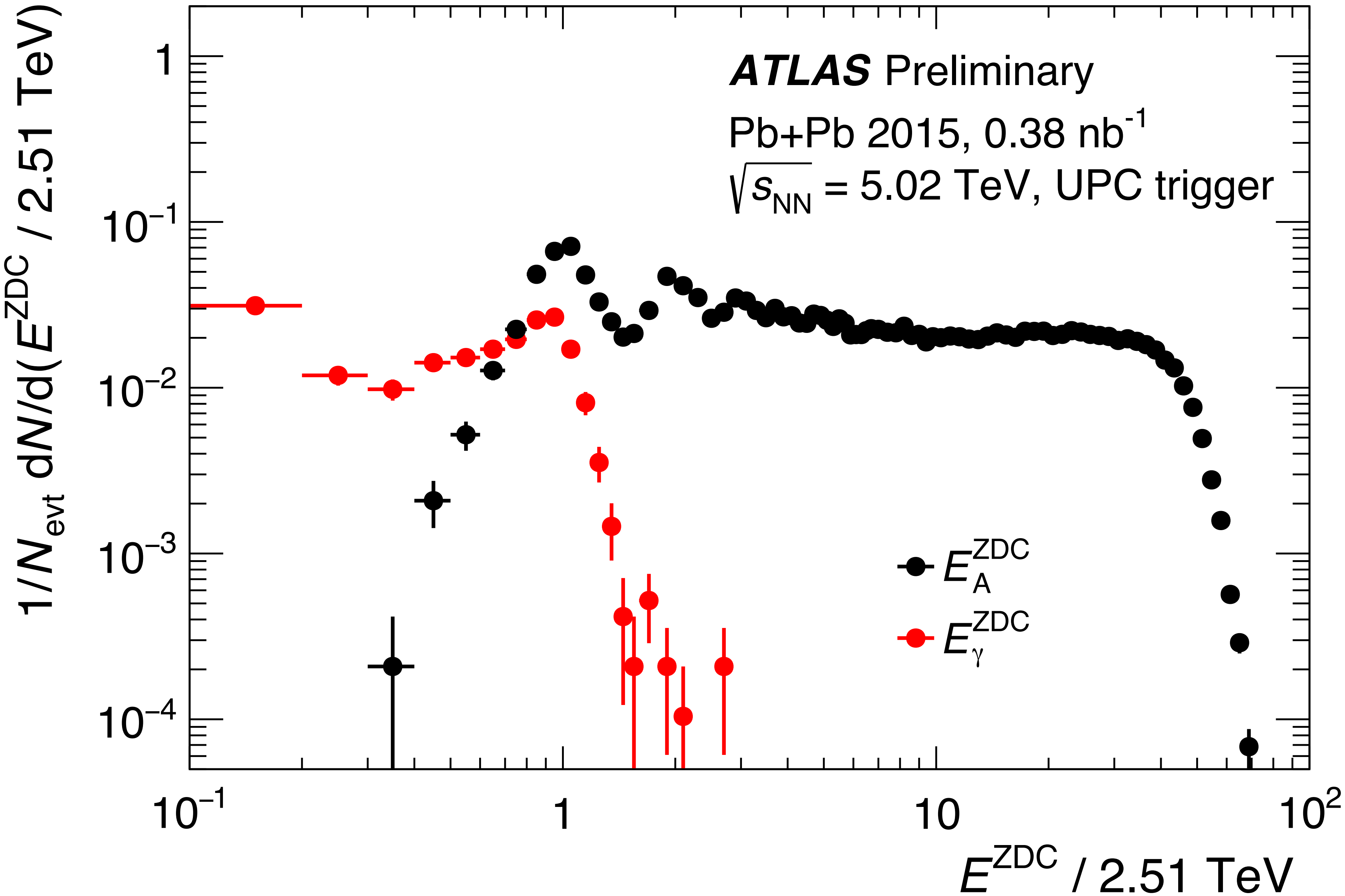


Depends on hadronic/ partonic structure of photon

The Measurement: Event Selection

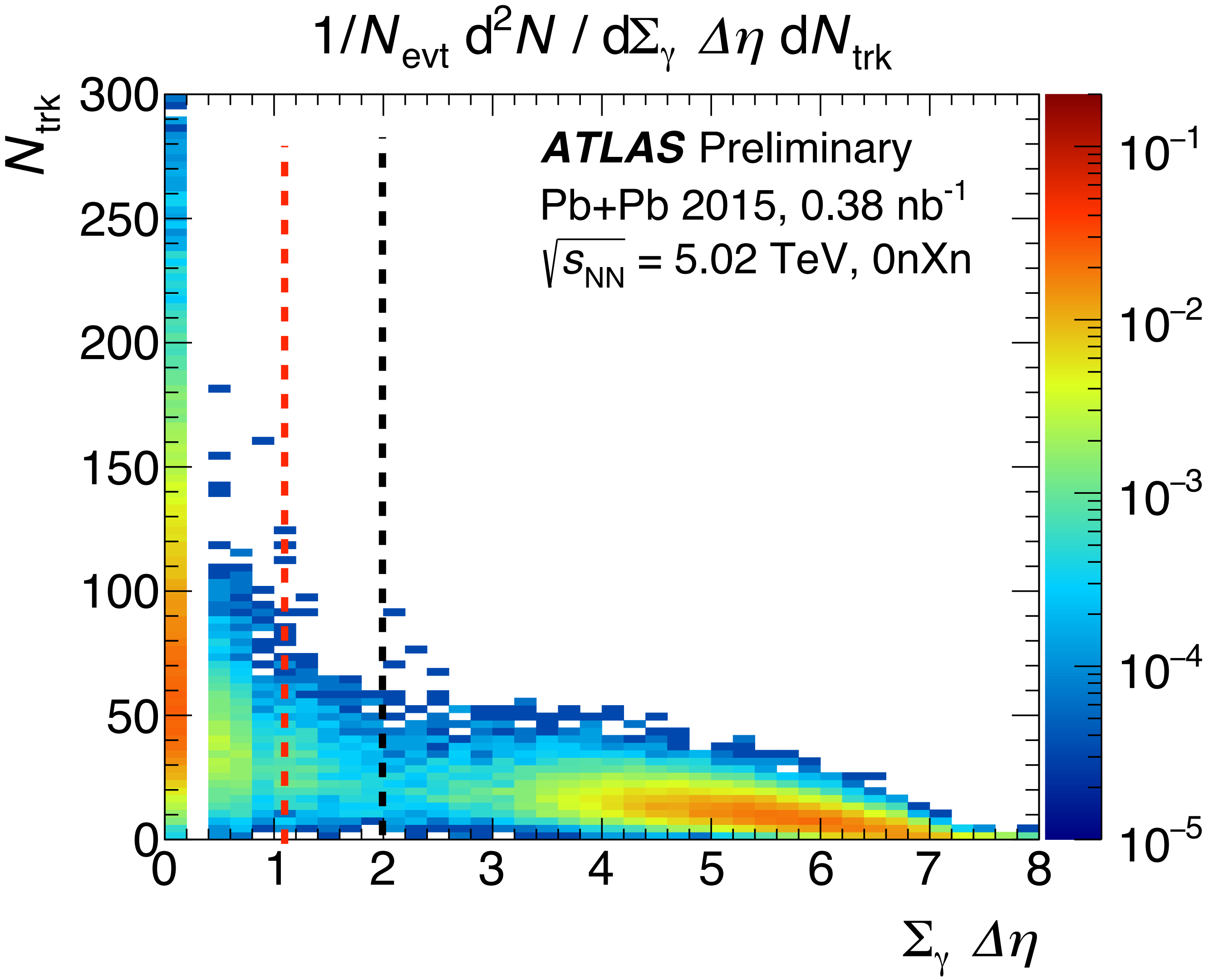
- Using 2015 Pb+Pb data; $\sqrt{s_{NN}}$=5.02 TeV
  - Events selected with ZDC (+jet) triggers, 0.38 nb^{-1}
- Use ZDC to select "*0nXn*" events (fiducial)
  - No correction for photon emitter breakup
- Physics backgrounds
  - Ordinary Pb+Pb jet production
    - ▸ Remove with minimum gap requirement 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 maximum gap requirement in A direction: $\Sigma_{A}\Delta\eta < 3$
  - Cross sections corrected for inefficiency introduced by gap requirements

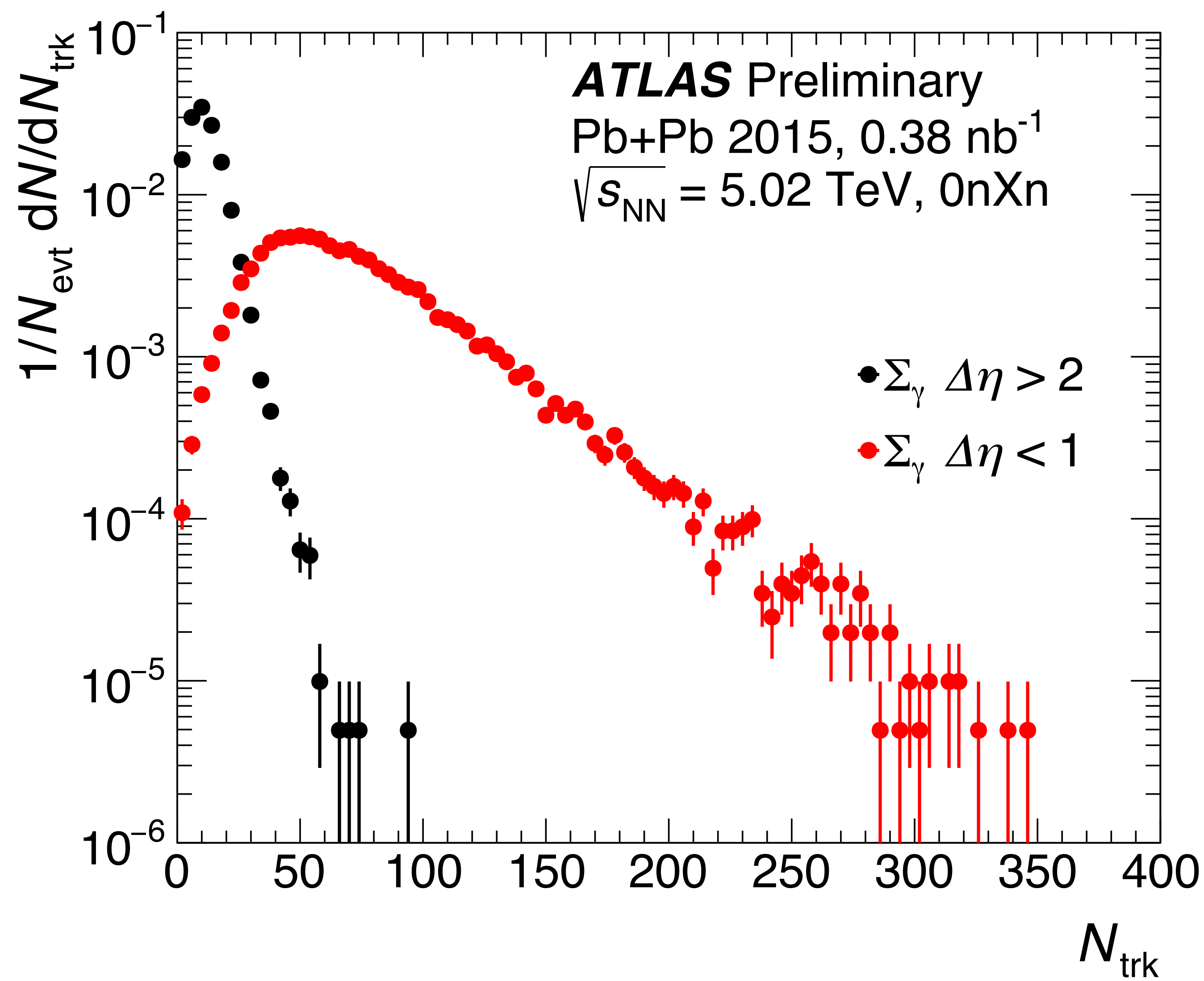
Event topology: 0*n*X*n*



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

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:

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

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

Sign of *z*/*η*/*y* defined to be positive in *γ* direction

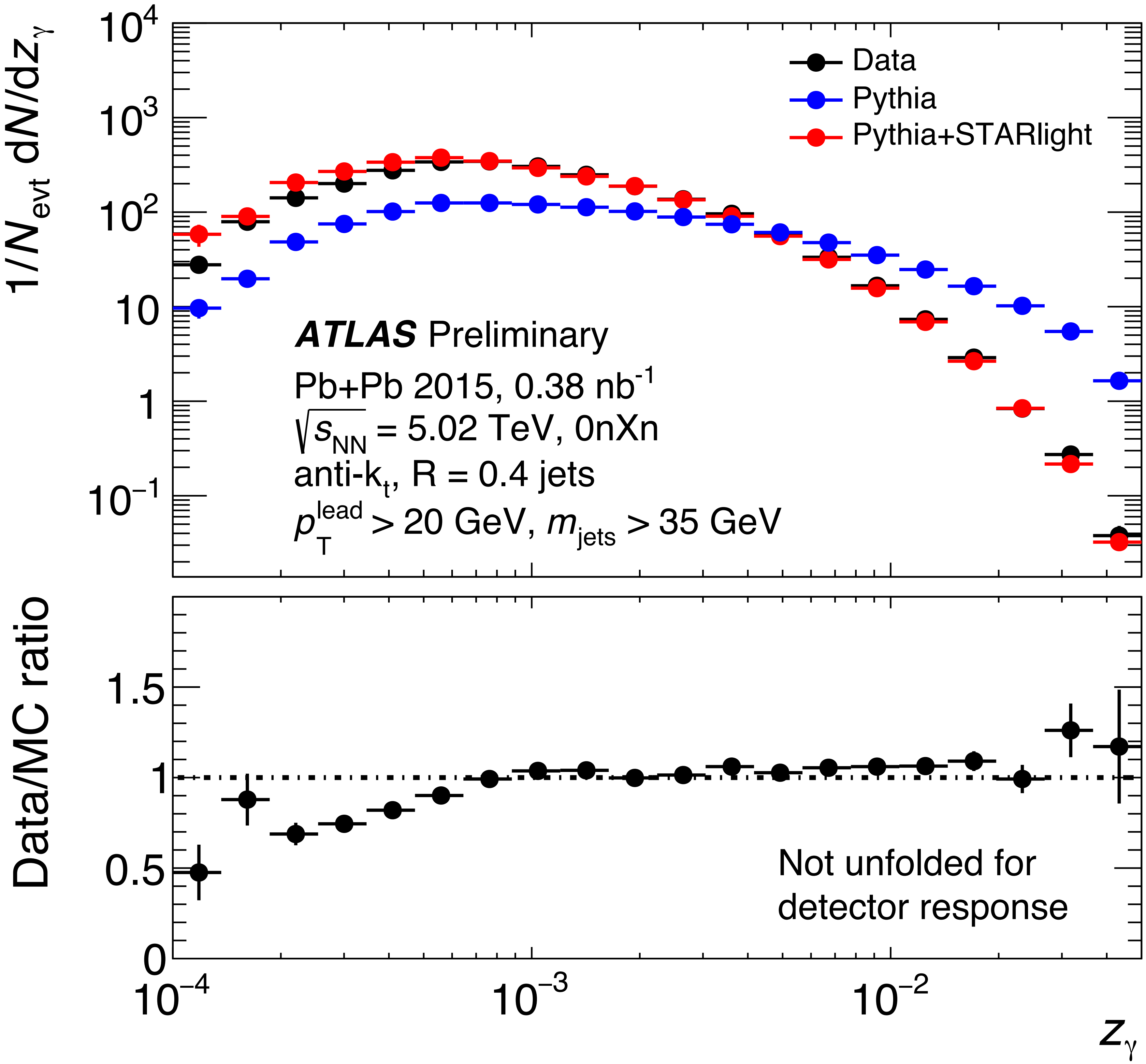
- $p_{\rm T\ lead} > 20$ GeV
- $|\eta| < 4.4$
- $p_{\rm T\ sublead} > 15$ GeV
- $m_{\rm jets} > 35$ GeV

- 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)

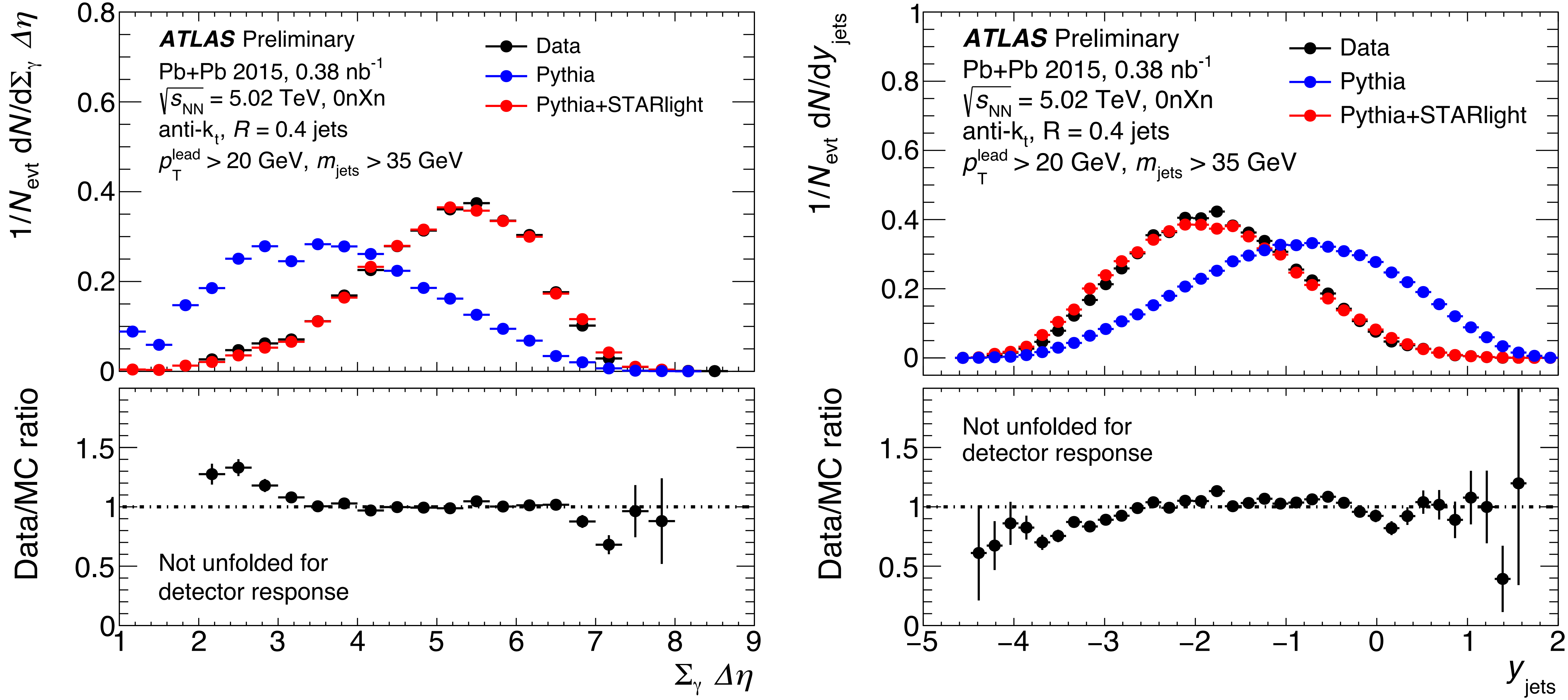
- Pythia 6 can be used in “mu/gamma p” mode to simulate photo-nuclear processes
  - Contains mixture of direct and resolved processes
    - Does not have right photon flux
- STARlight capable of providing nuclear photon flux
  - Needs to be integrated over target
  - For small *b*, additional hadronic 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



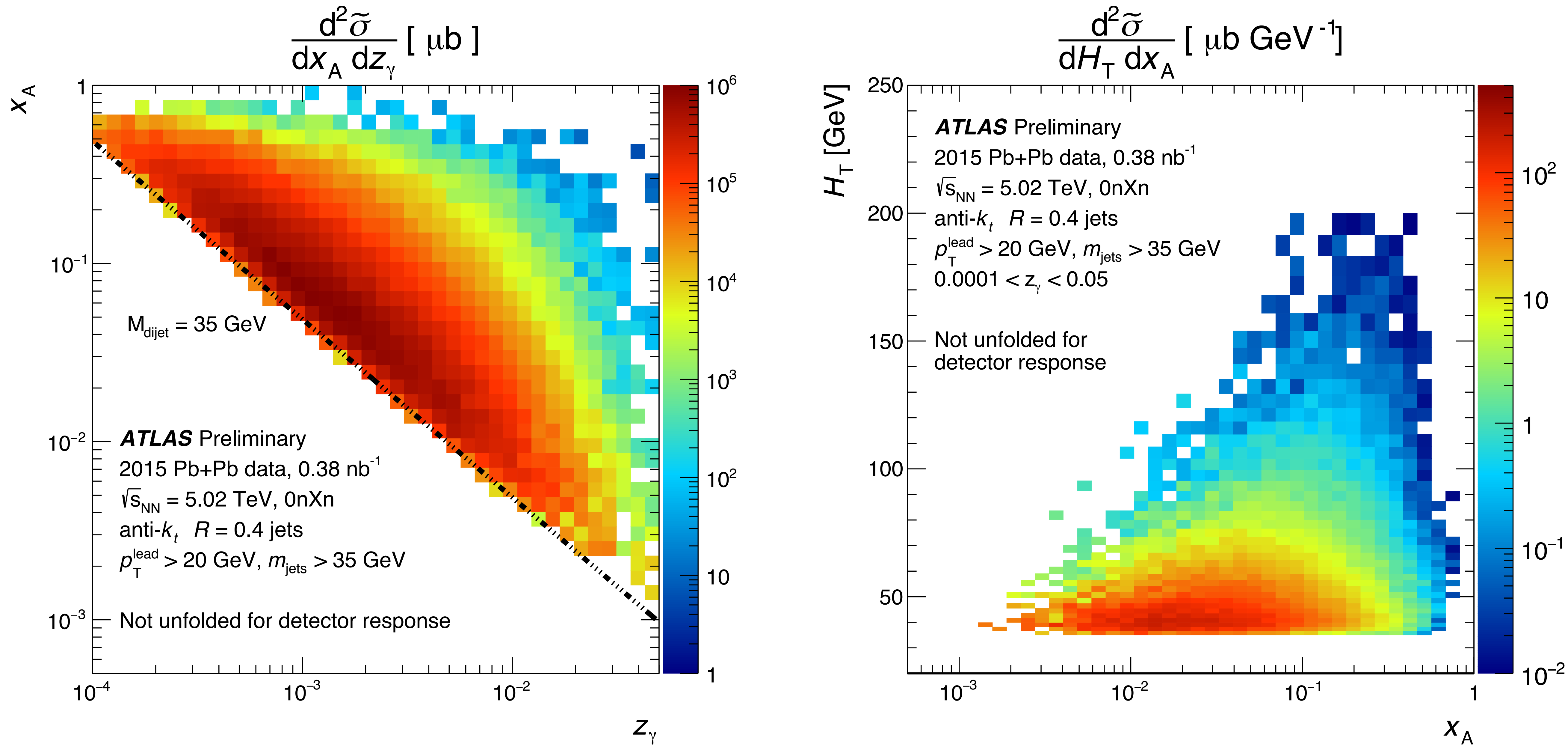
- **Re-weighted Pythia in good (not perfect) agreement with data**

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

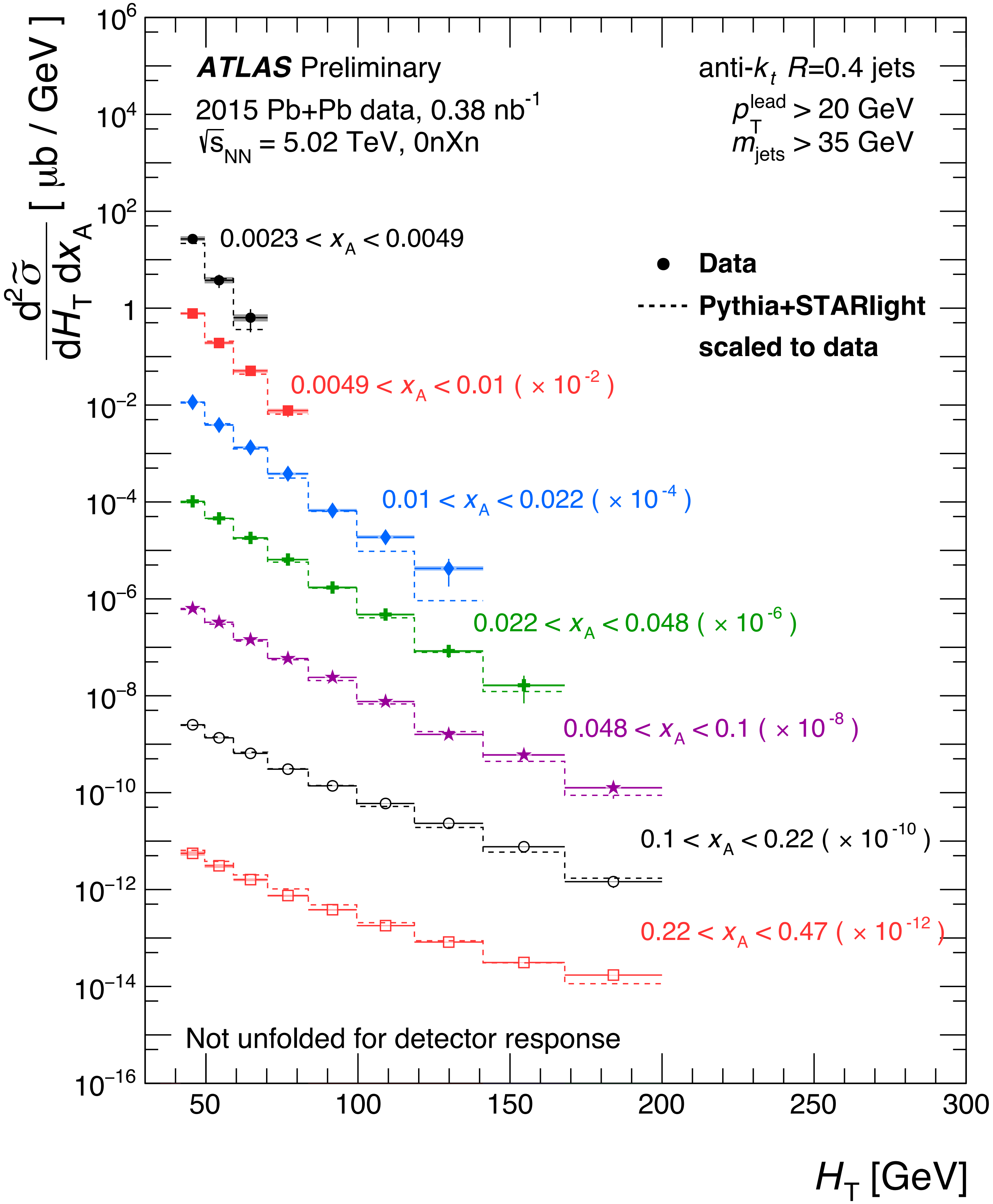


- **Acceptance in (z_γ, x_A) strongly dependent on minimum jet system mass**
  - **Determined by minimum p_T in analysis**
  - **Easiest way to get to low x_A is large z_γ**

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

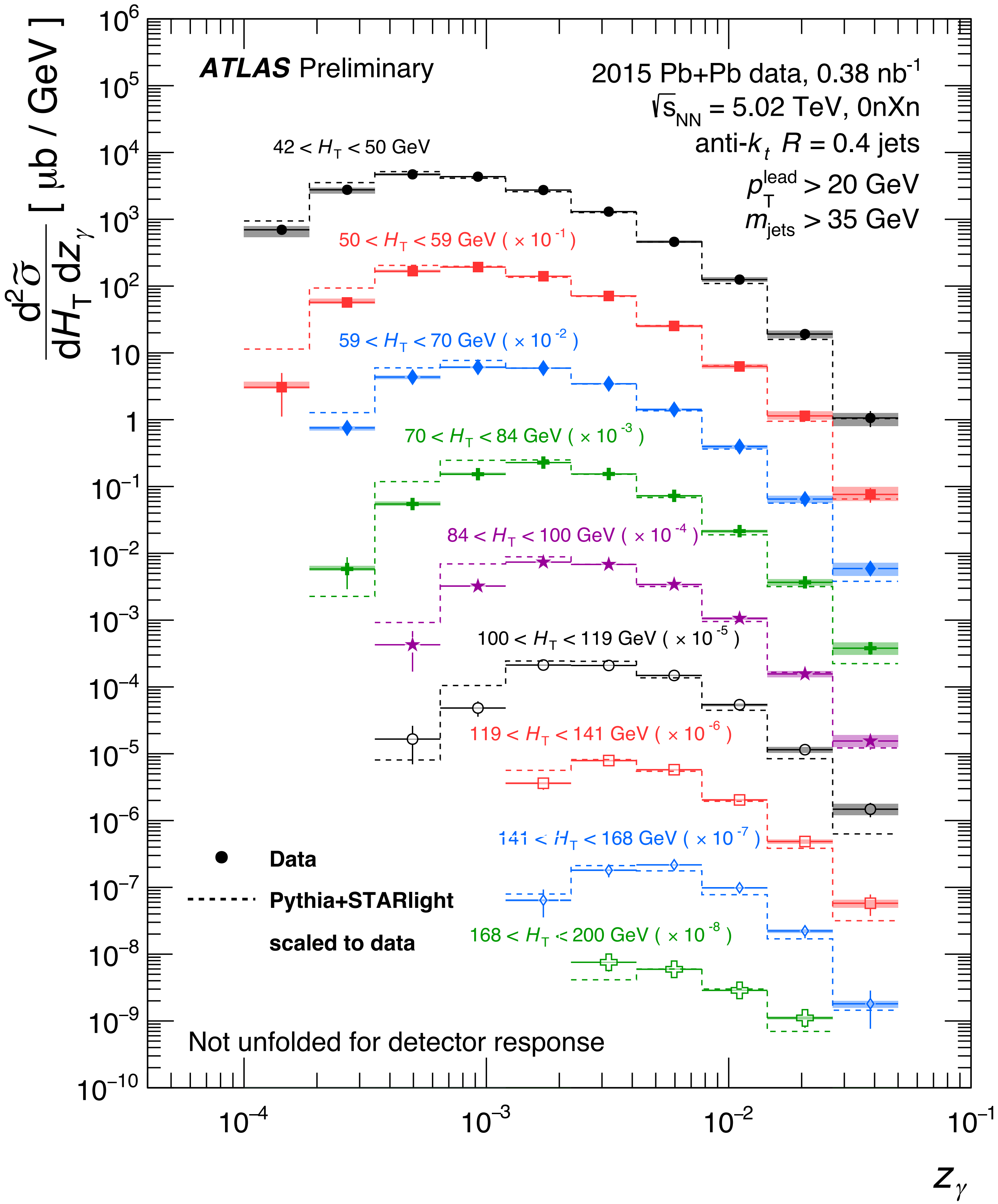
Results: H_T Dependence



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**

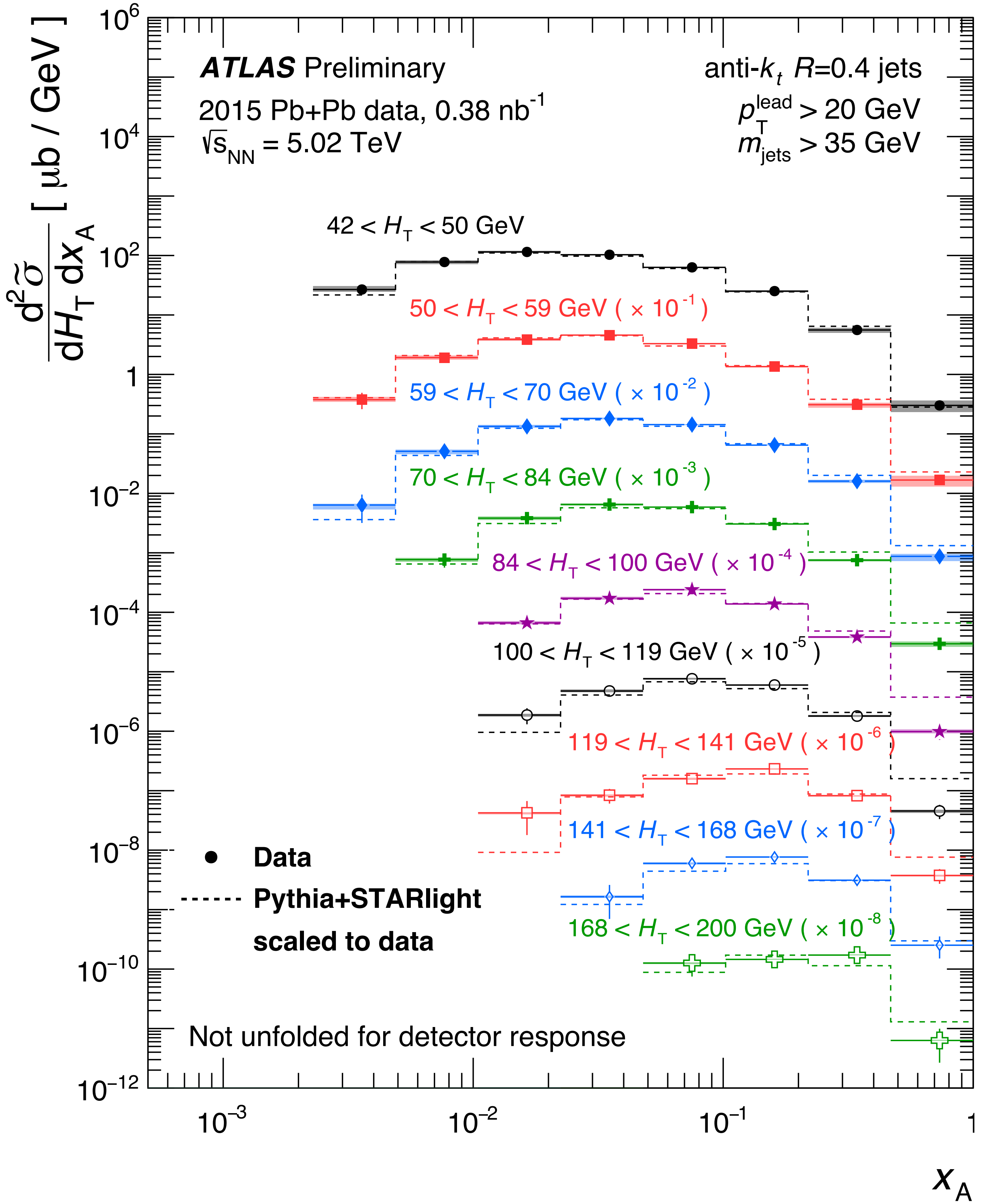
Results: z_γ Dependence

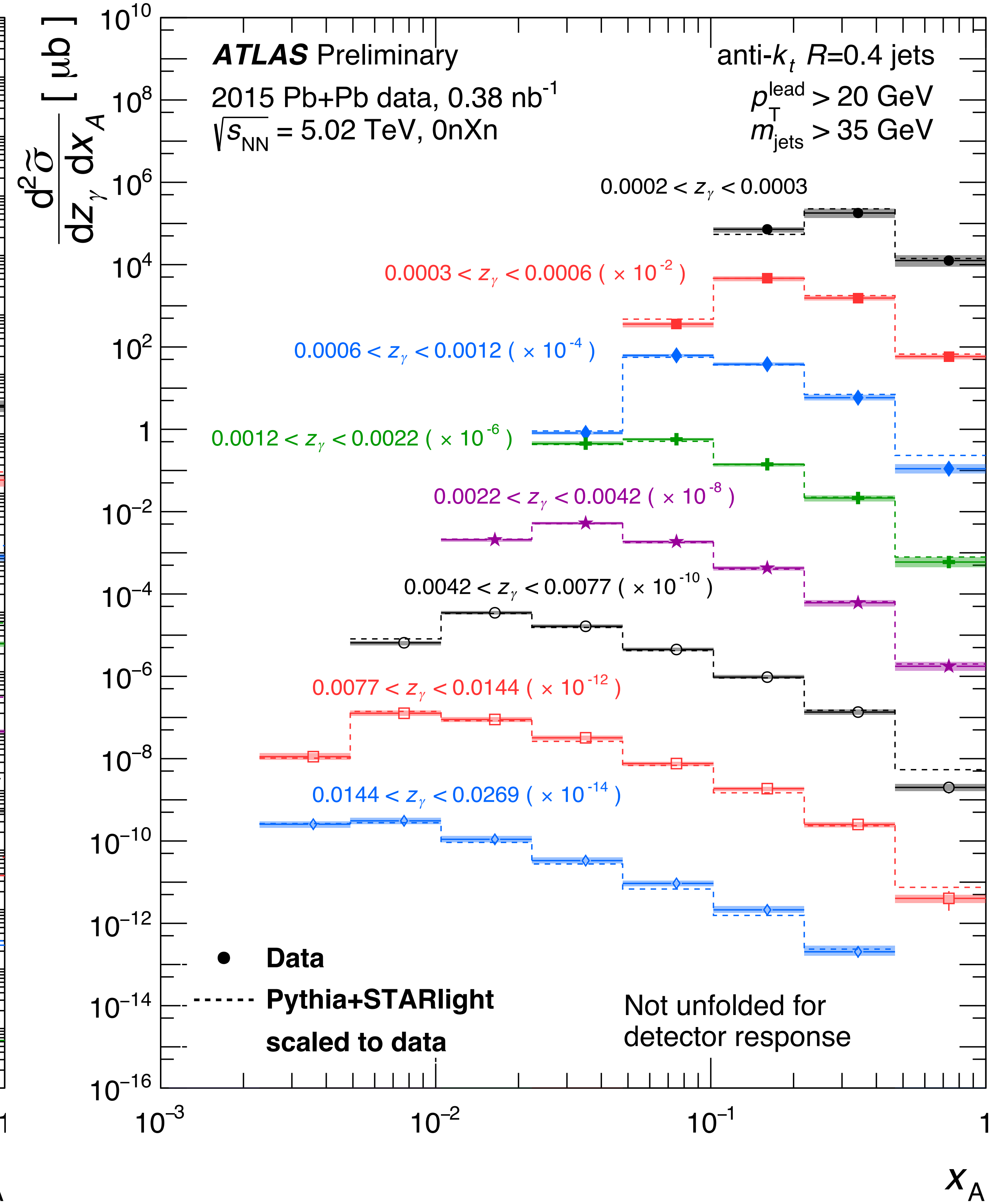


Slices of H_T

- **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**

UPC Jet Production: Conclusions

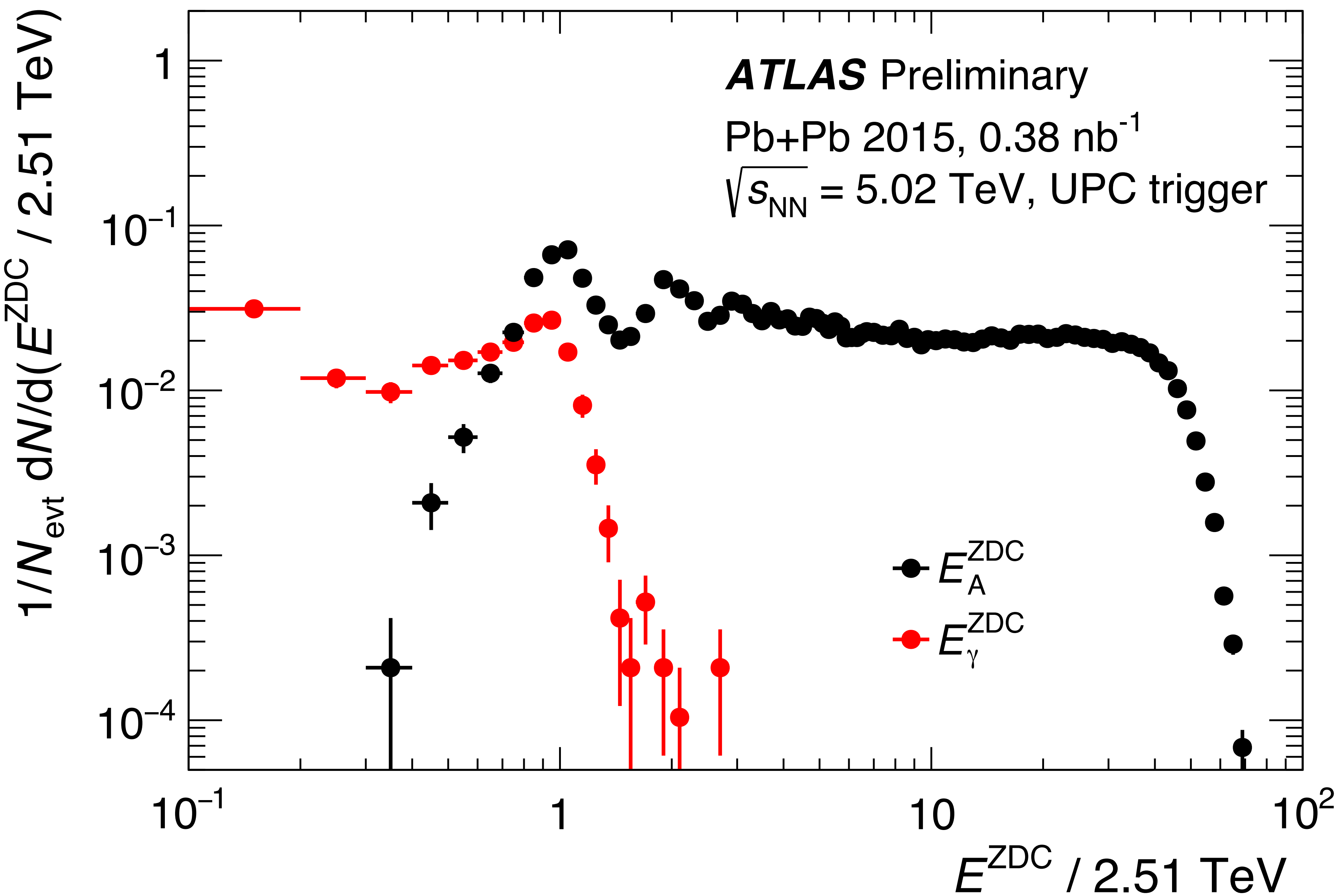
- Presented a measurement of photo-nuclear jet production
  - Qualitatively different than normal jet production in hadronic collisions
  - Expected features— rapidity gaps and neutron distributions— observed in the data
- Measurement needs to be unfolded
  - Lots of experience with this
- More rigorous 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

Questions/Remarks

- Given recent nPDF analyses, would this data actually be used in a fit?
  - e.g. recent EPPS16 analysis ignores potentially useful data like inclusive jet production
- Should we be presenting measurements of (e.g. unfolding) something closer to the structure function?
- Role of direct vs resolved photon contributions
  - Description of photon structure required for extraction of nPDF
  - How should this be handled in measurement?

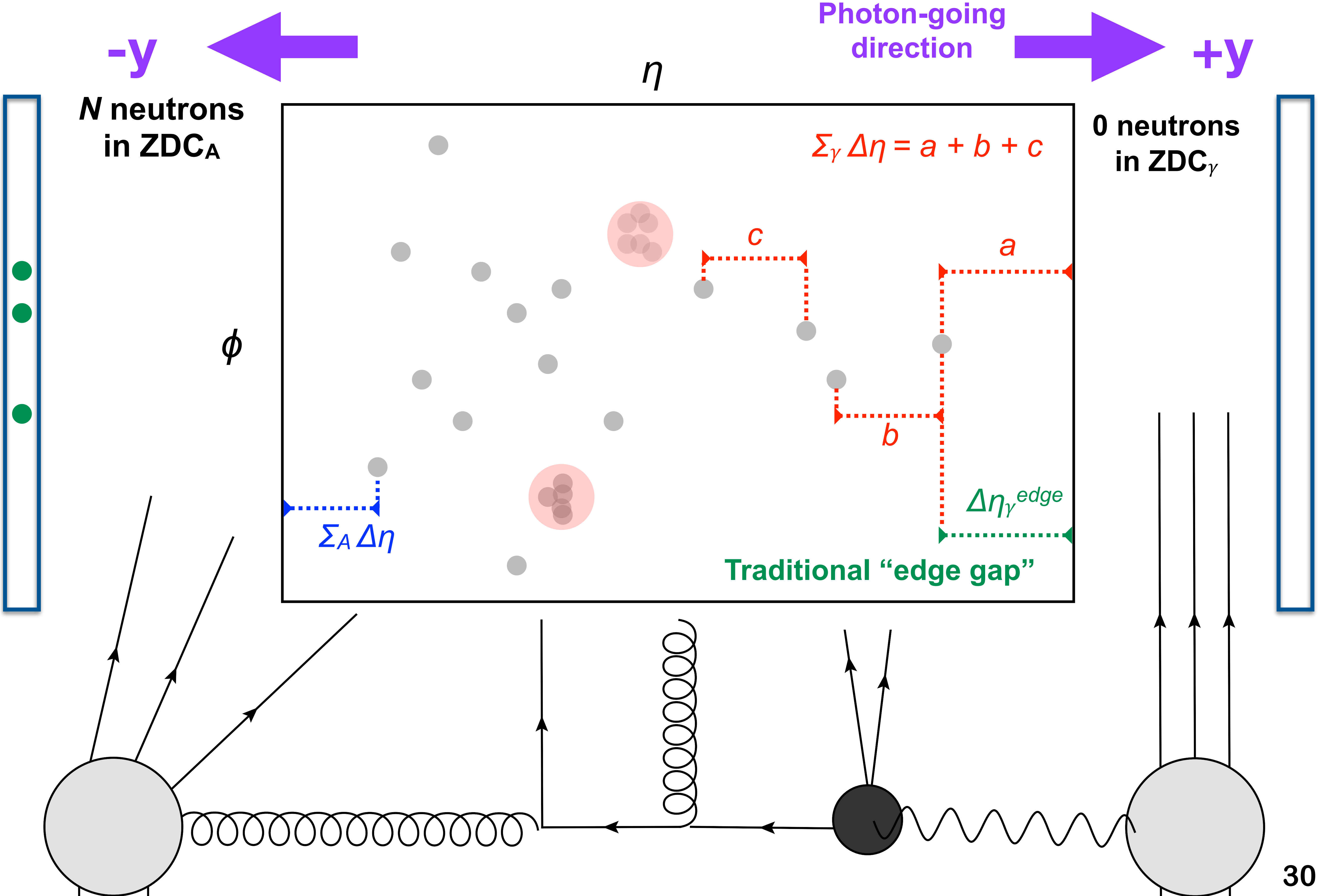
Extras

Event topology: 0*n*X*n*

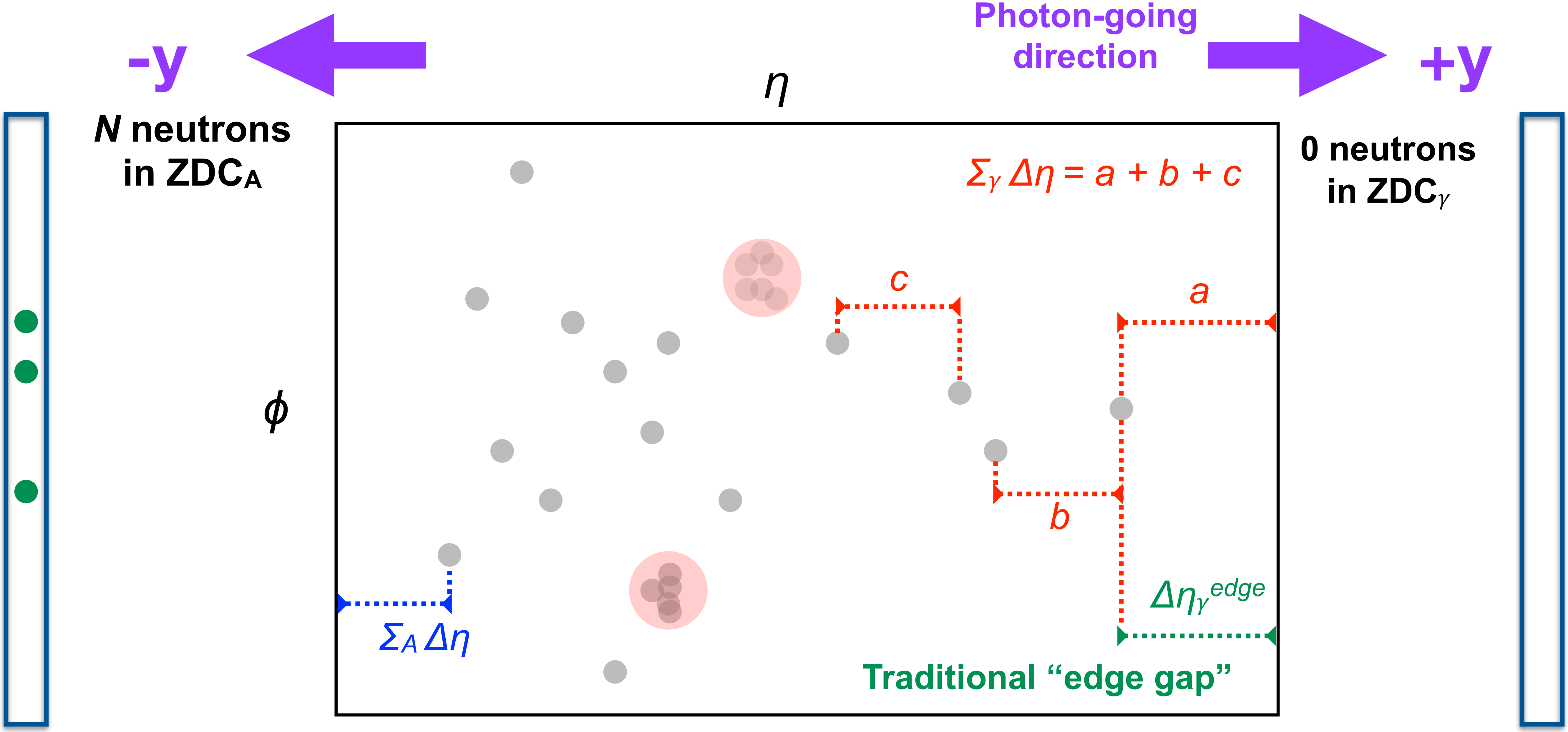


- **Events selected ZDC "XOR" trigger**
- **Red: photon-going direction, 0*n***
- **Black: nuclear direction, X*n***

Event topology (experimental)

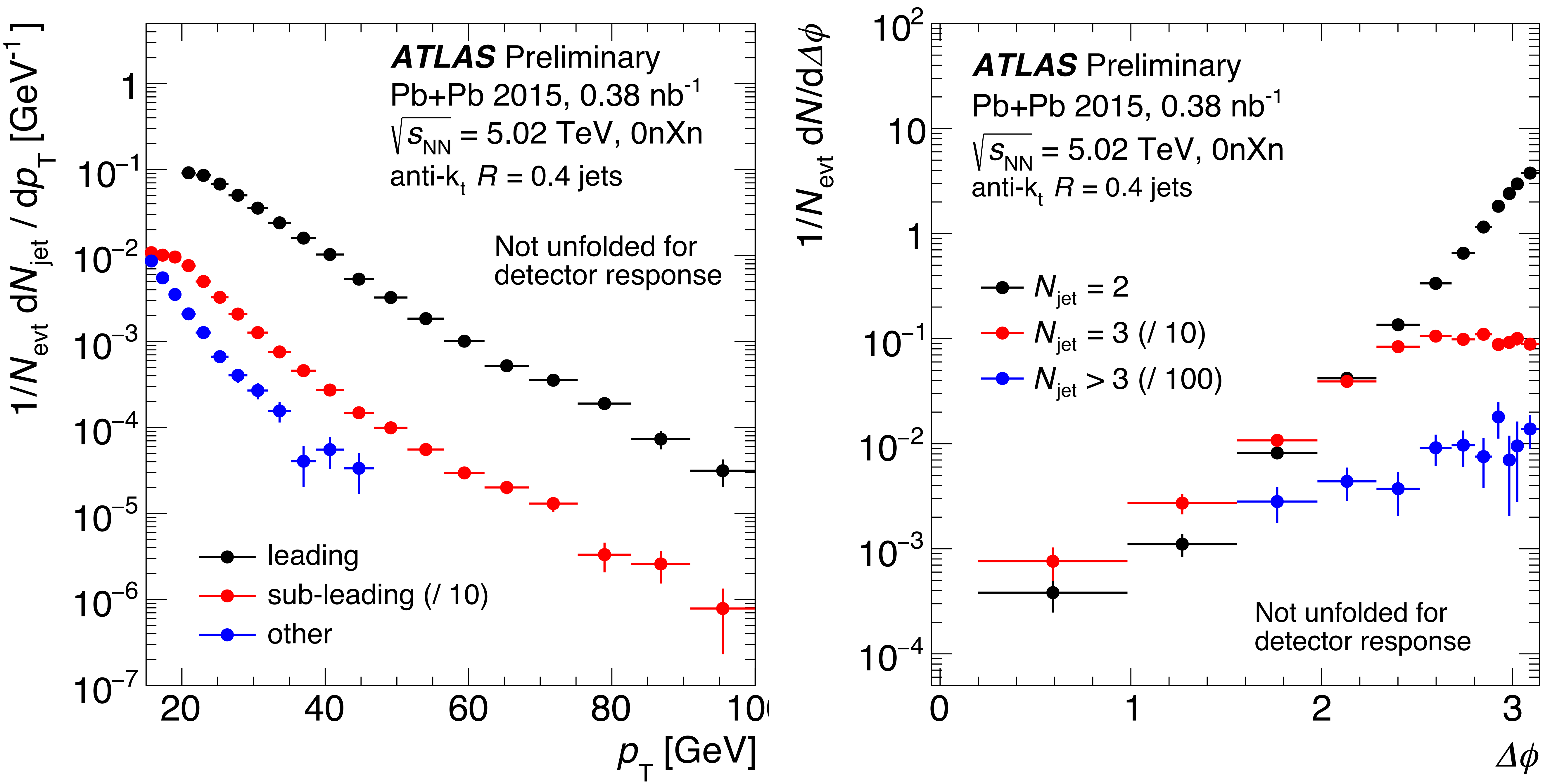


Event topology (experimental)



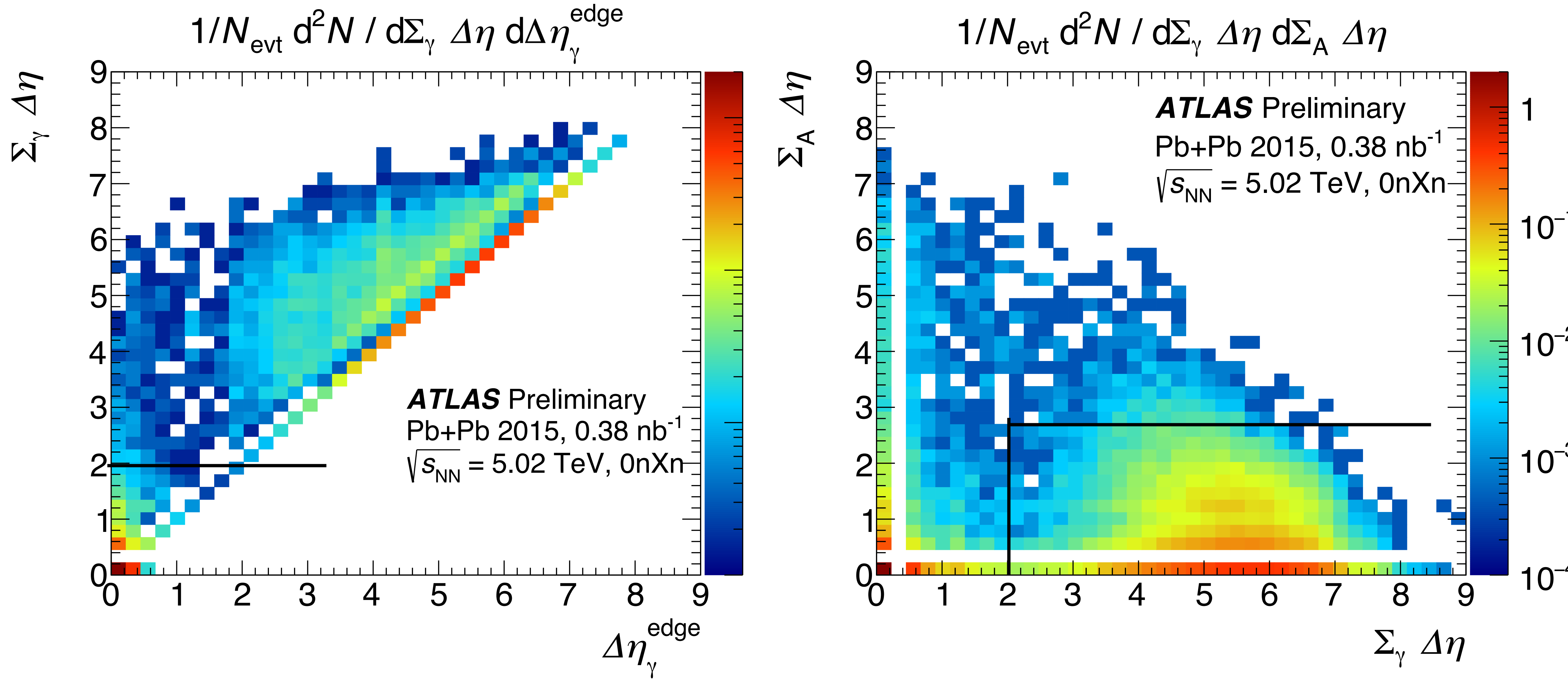
- ZDC requirement: "*0nXn*" topology
- Minimum $\Sigma_\gamma\ \Delta\eta$ requirement: $\Sigma_\gamma\ \Delta\eta_> > 2$
- Maximum $\Sigma_A\ \Delta\eta_<$ requirement: $\Sigma_A\ \Delta\eta < 3$

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**

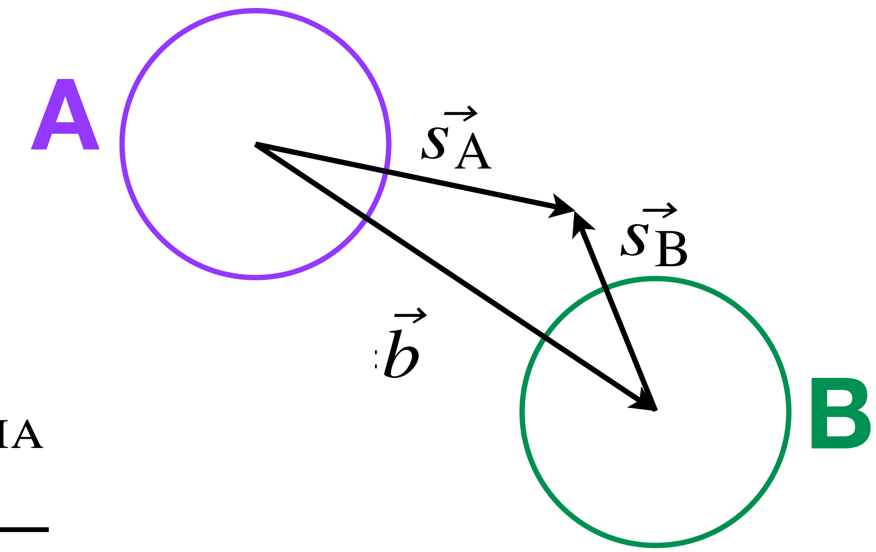
    ➡ $\Sigma_\gamma\Delta\eta > \Delta\eta^{edge}$
- **Right: $\Sigma_\gamma\Delta\eta$ vs $\Sigma_A\Delta\eta$**

  ➡ **backgrounds (e.g. $\gamma\gamma\rightarrow e^+e^-$) for large $\Sigma_\gamma\Delta\eta$**

Theoretical model (II)

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

From STARlight

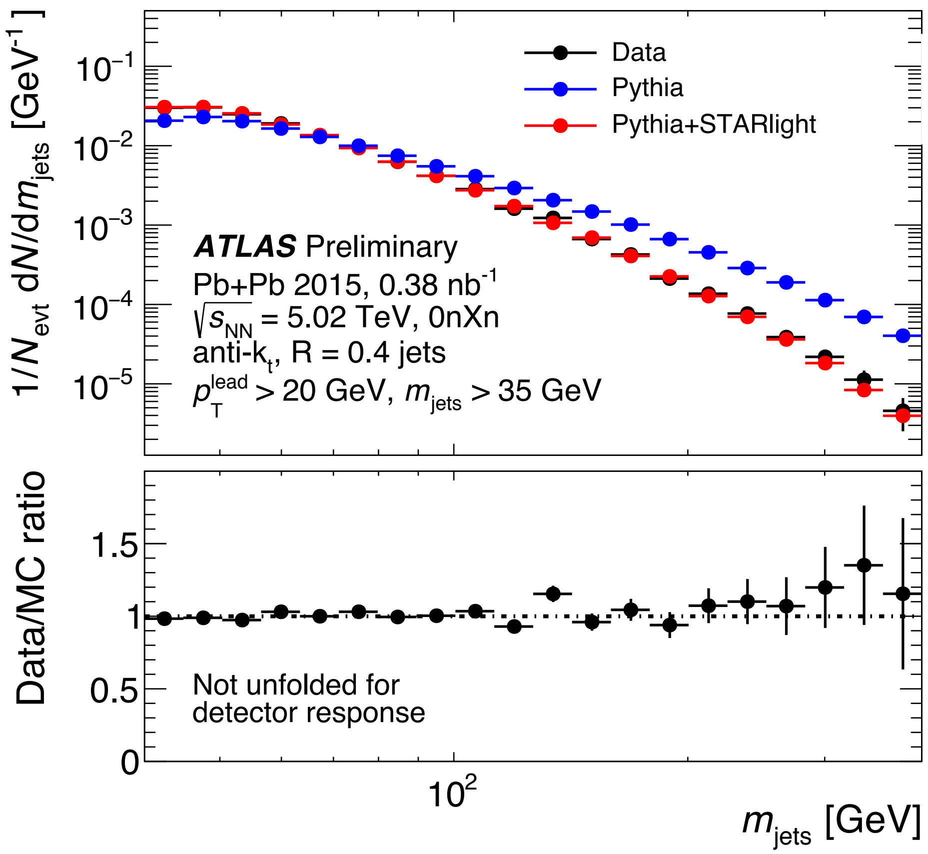


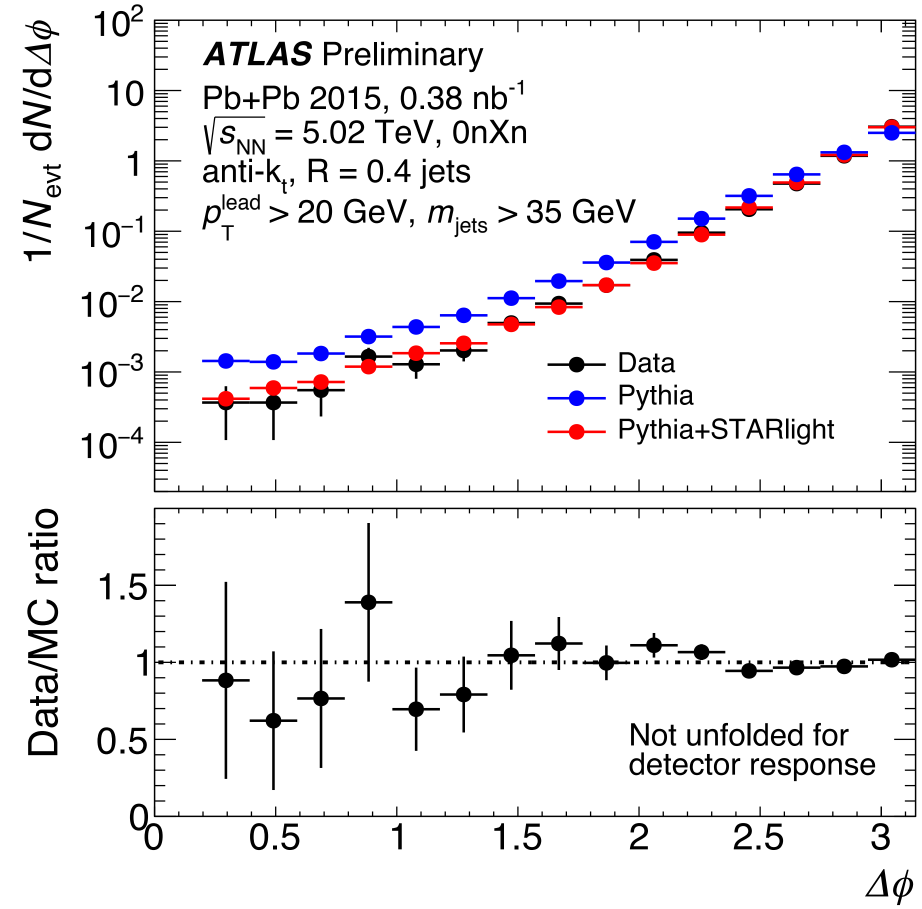
Apply per-event weight to Pythia sample

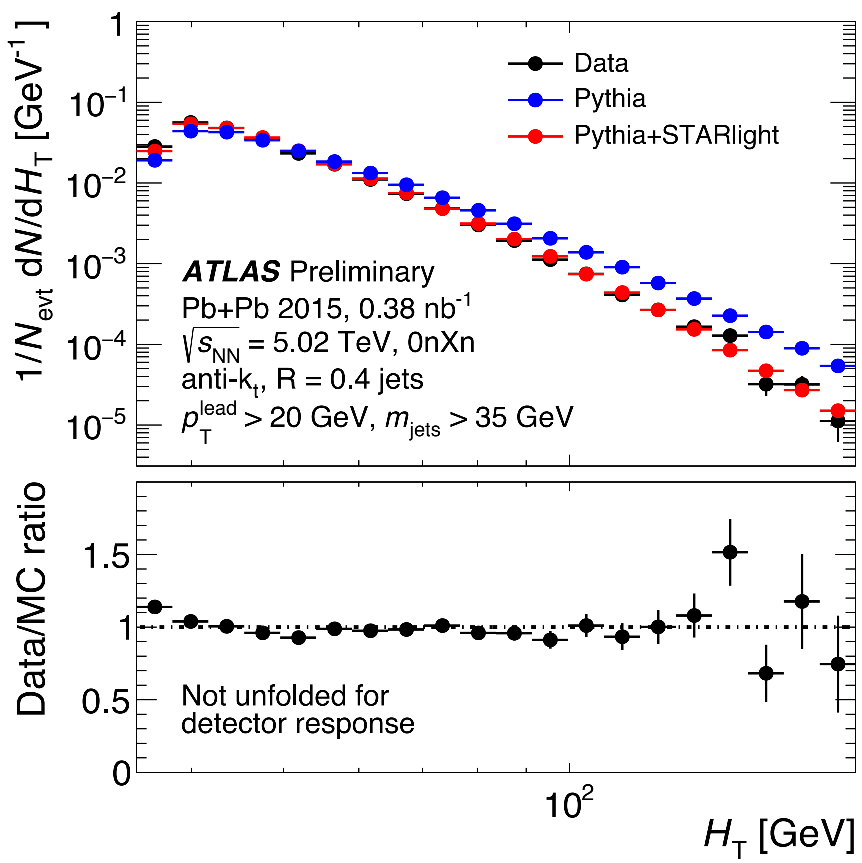
$$w(E) \equiv \frac{dN_\gamma^{\text{eff}}}{dE} \Big/ \frac{dN_\gamma^{\text{PYTHIA}}}{dE}$$

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)