Measurements of multi-jet production in ultra-peripheral lead-lead collisions with the ATLAS detector

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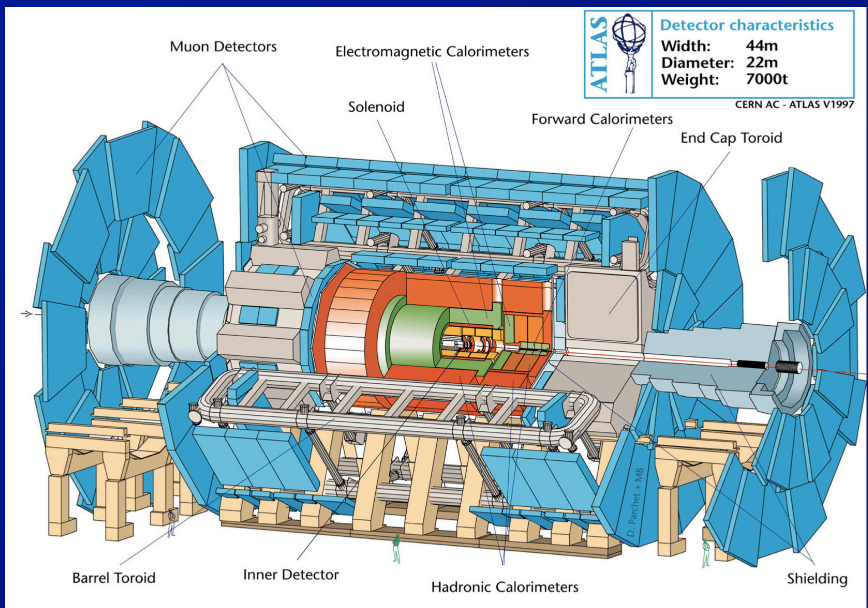
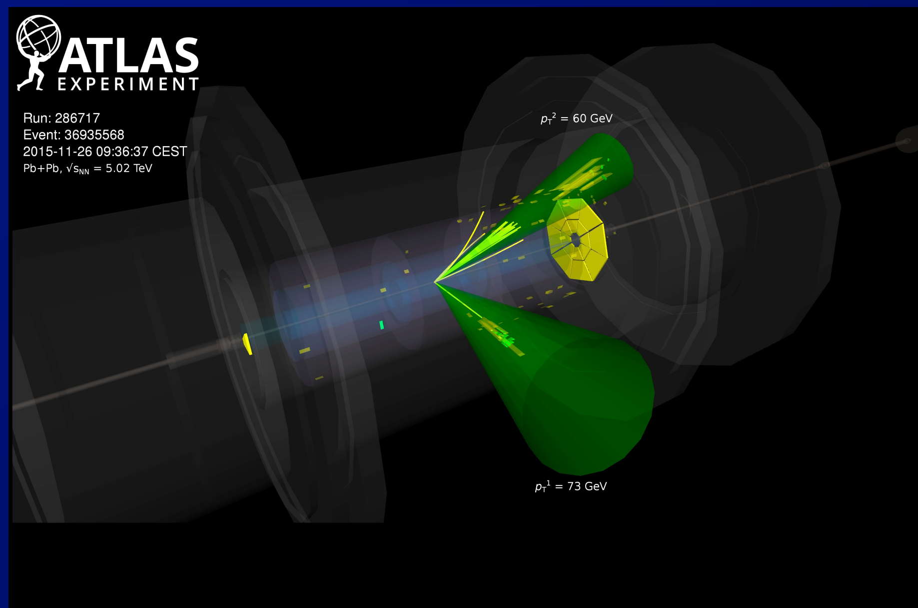
for the ATLAS collaboration





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 recently, not realized by any experiment

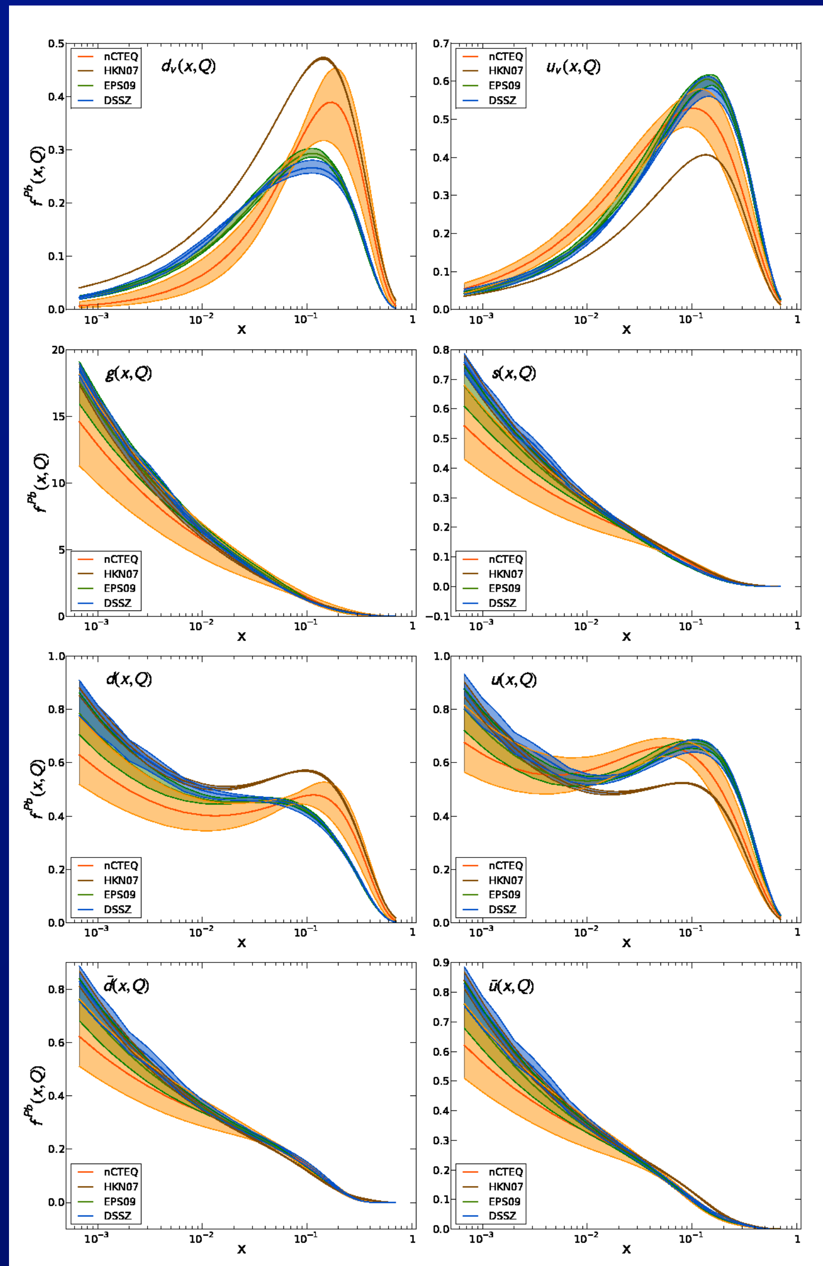
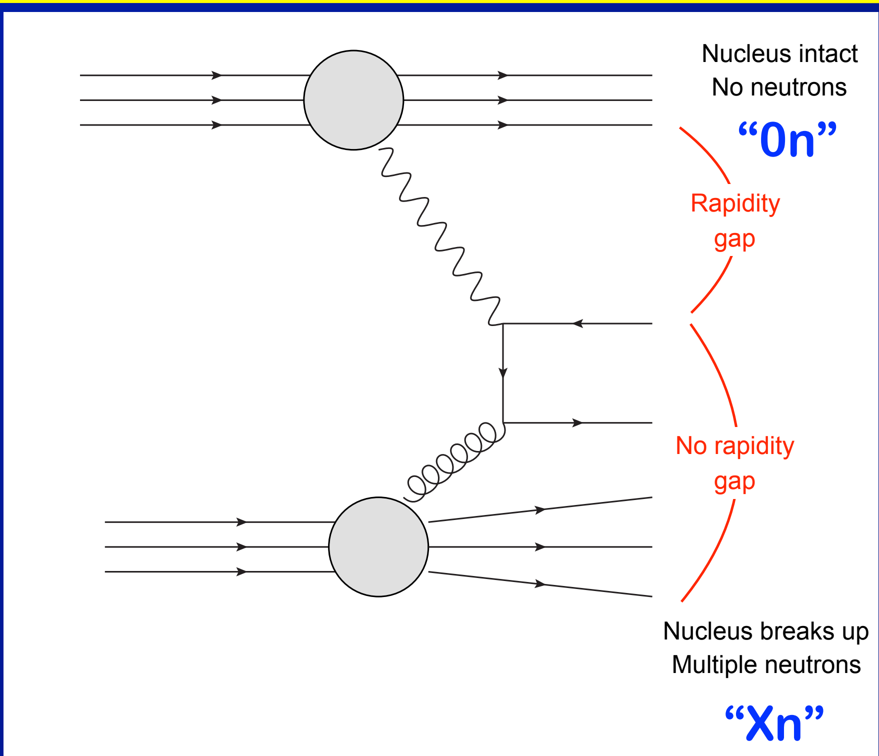
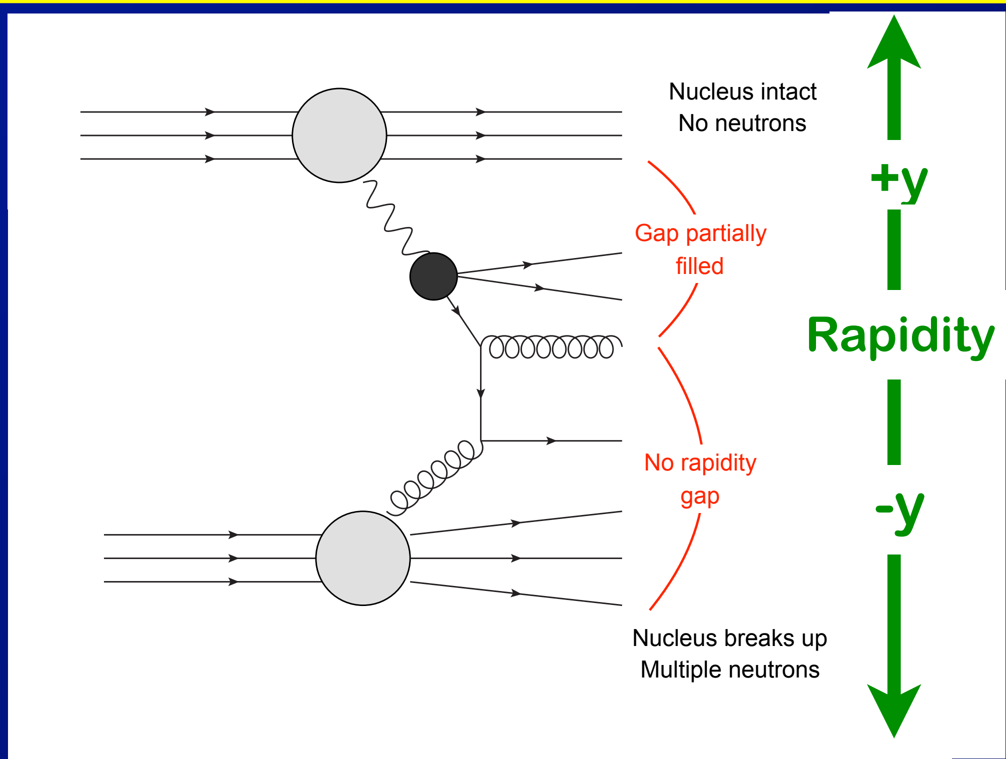


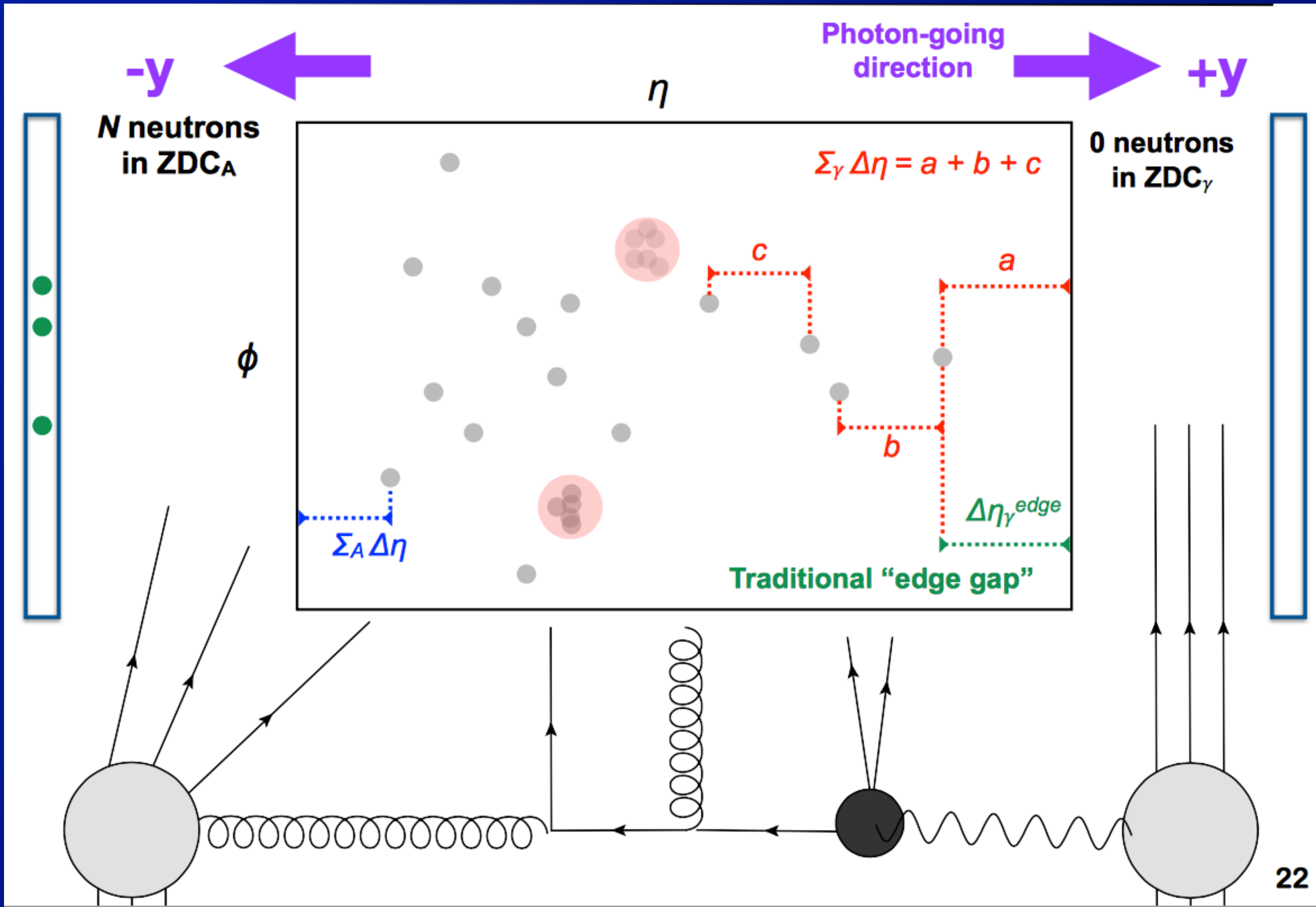
Photo-nuclear processes





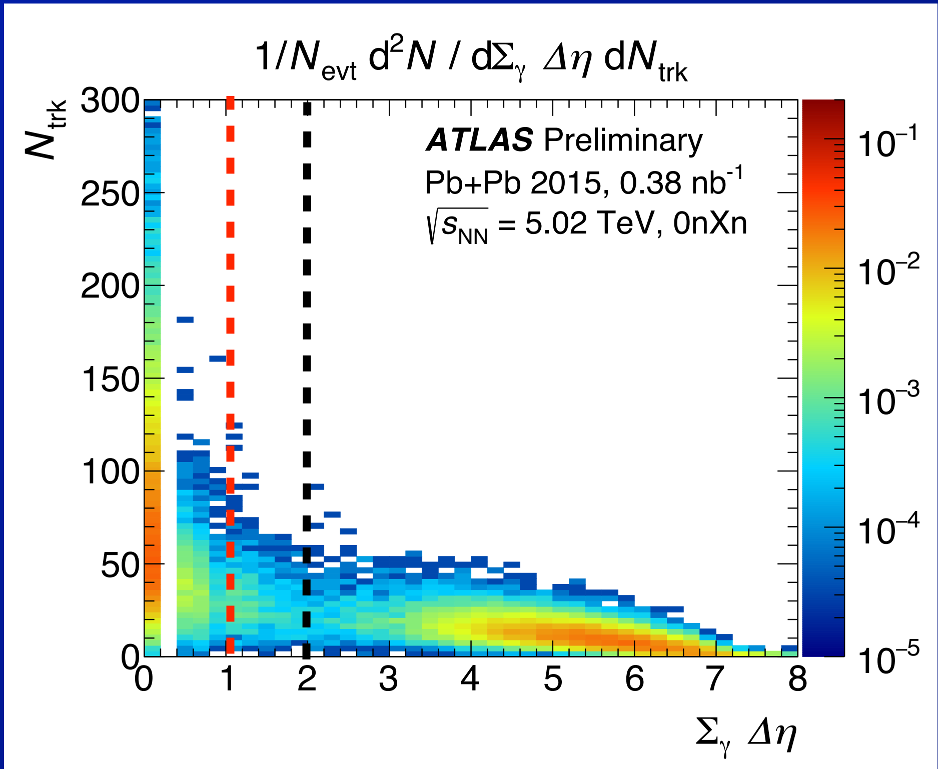
- Two processes:
  - Left: "direct" - photon enters hard scattering
  - Right: "resolved" - photon virtually splits into partons/hadron, which scatters
- Use Zero Degree Calorimeters (ZDCs) to select Pb+Pb 0nXn events
- +gap requirements to select photo-production

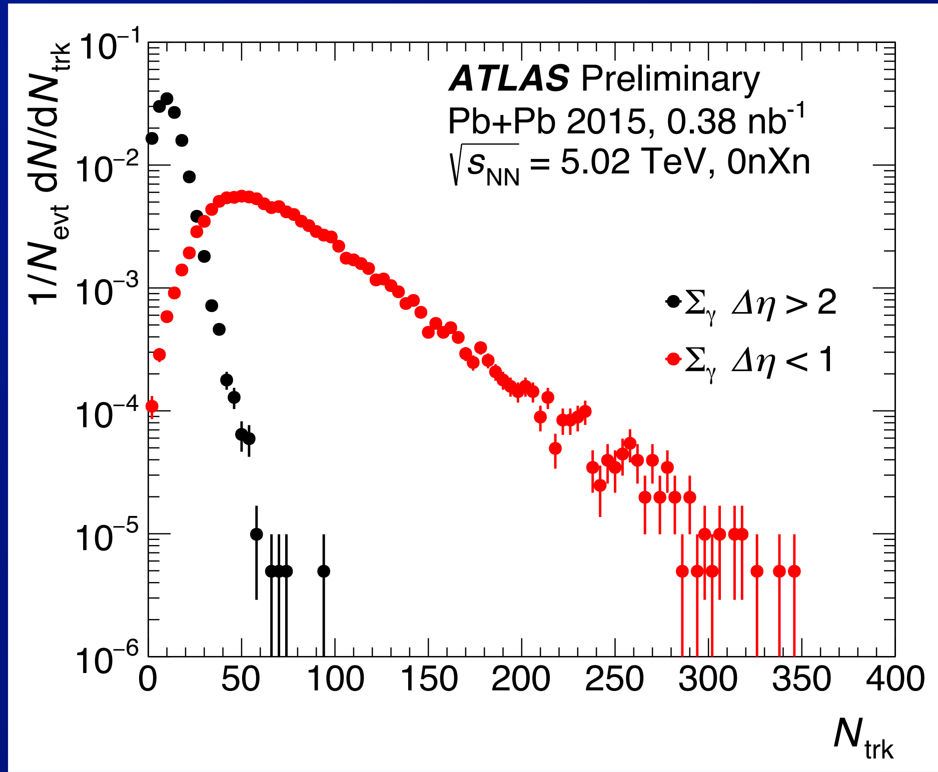
Gap analysis



- 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

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

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

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

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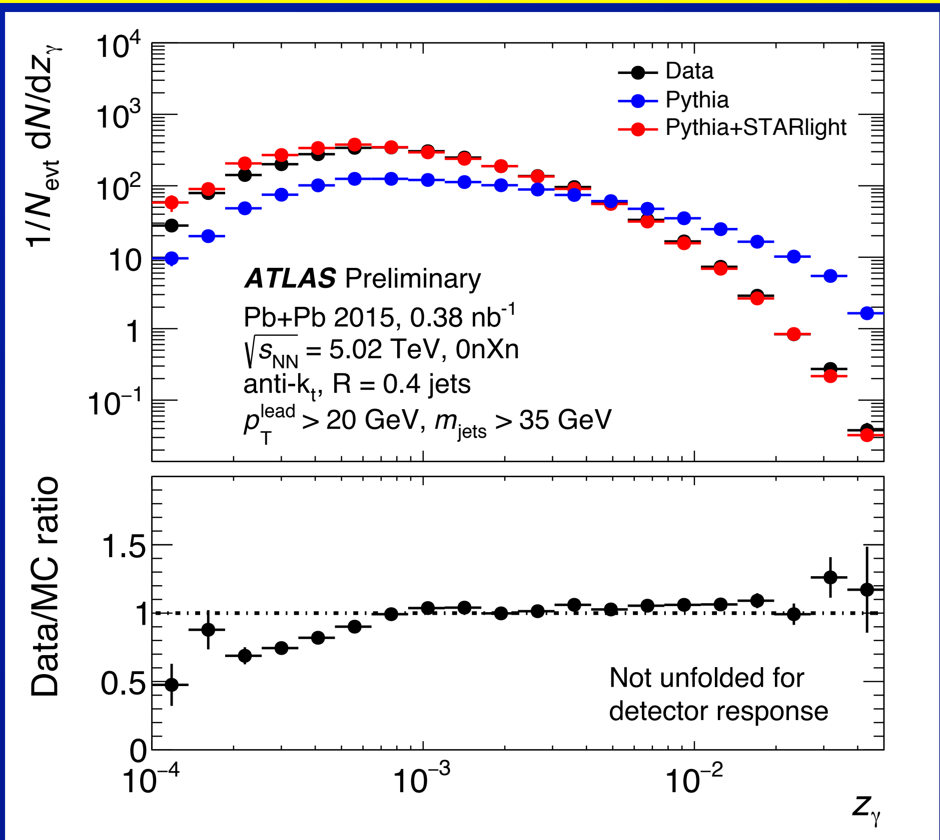
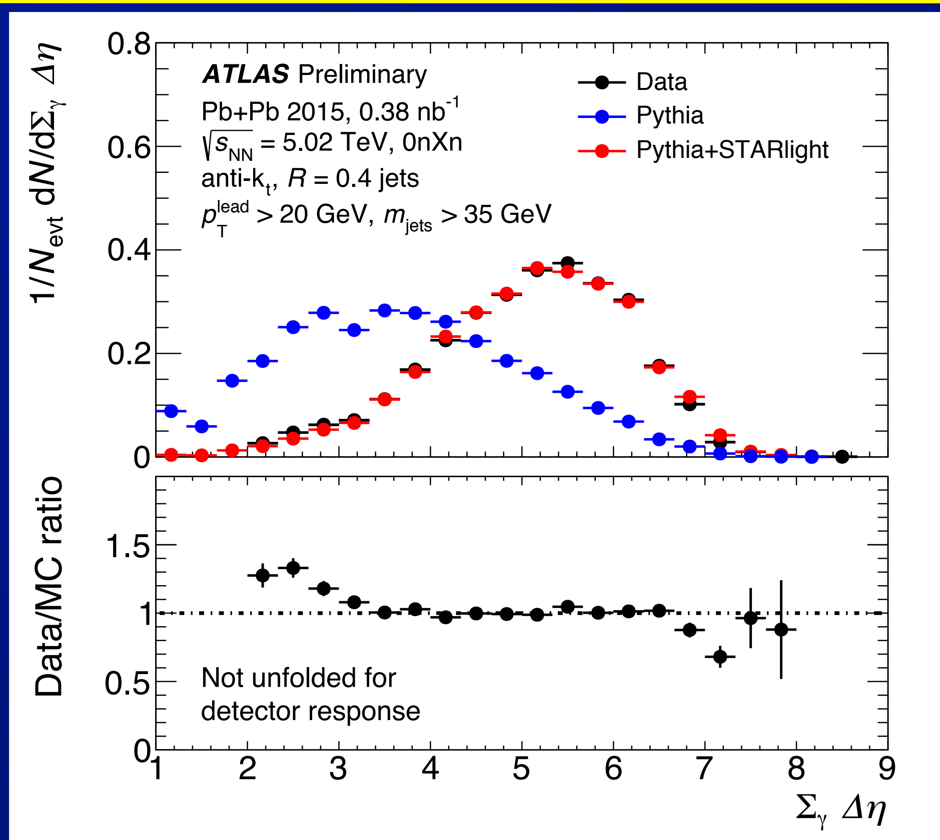
  - ⇒$|\eta_{jet}|$ < 4.4, H_T > 40 GeV
- No unfolding for jet response

Monte Carlo



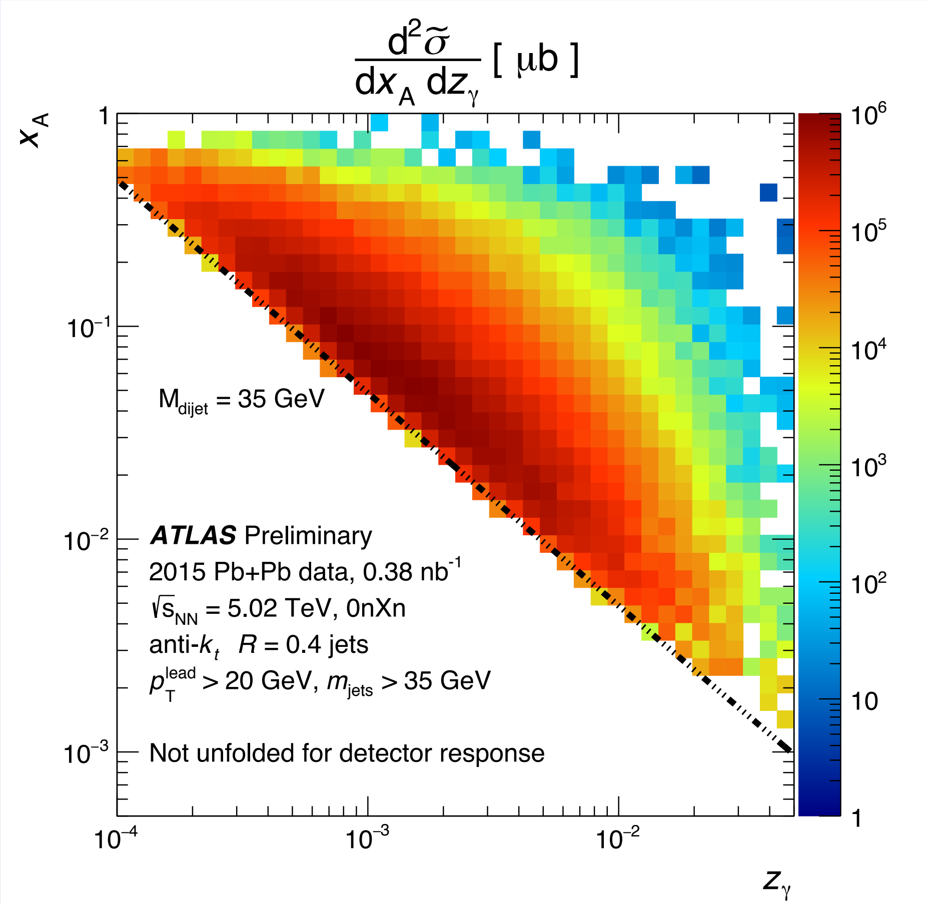


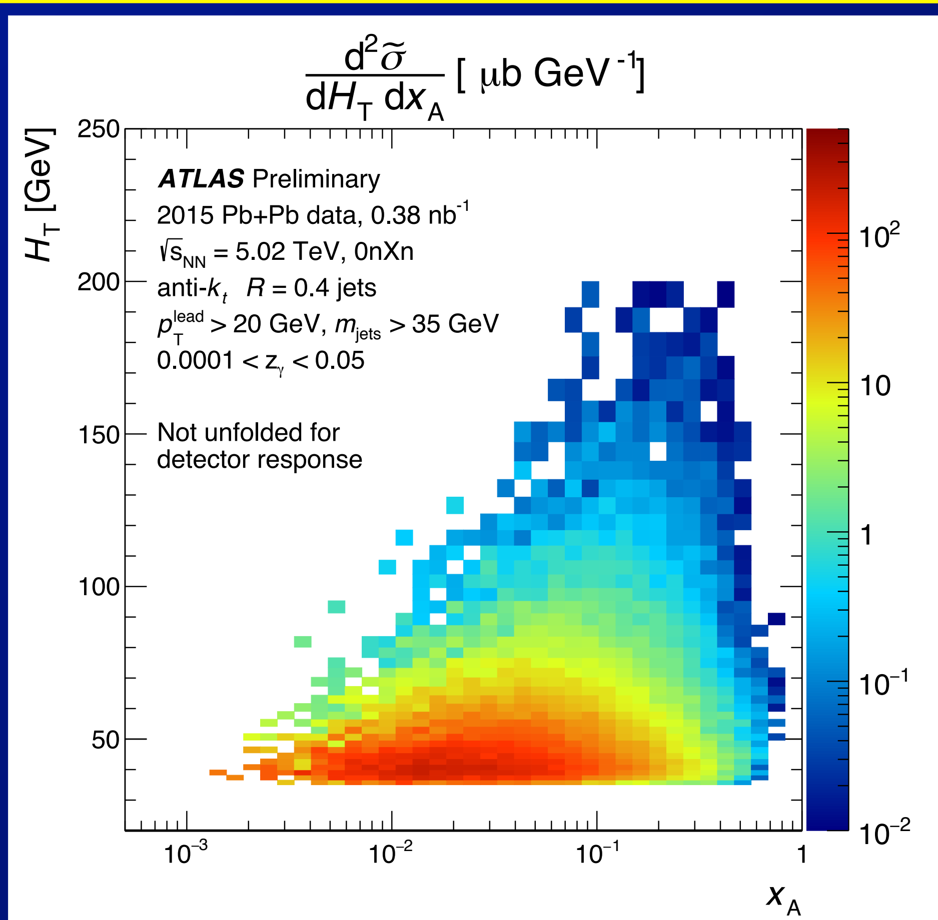
- Pythia 6 photo-production (gamma/mu+p)
  - re-weighted to match STARlight photon spectrum

  ⇒Re-weighted MC agrees well (not perfectly) with data for all topology, kinematic distributions

  ⇒Although ∃ conceptual issues w/ re-weighting

2-D cross-sections

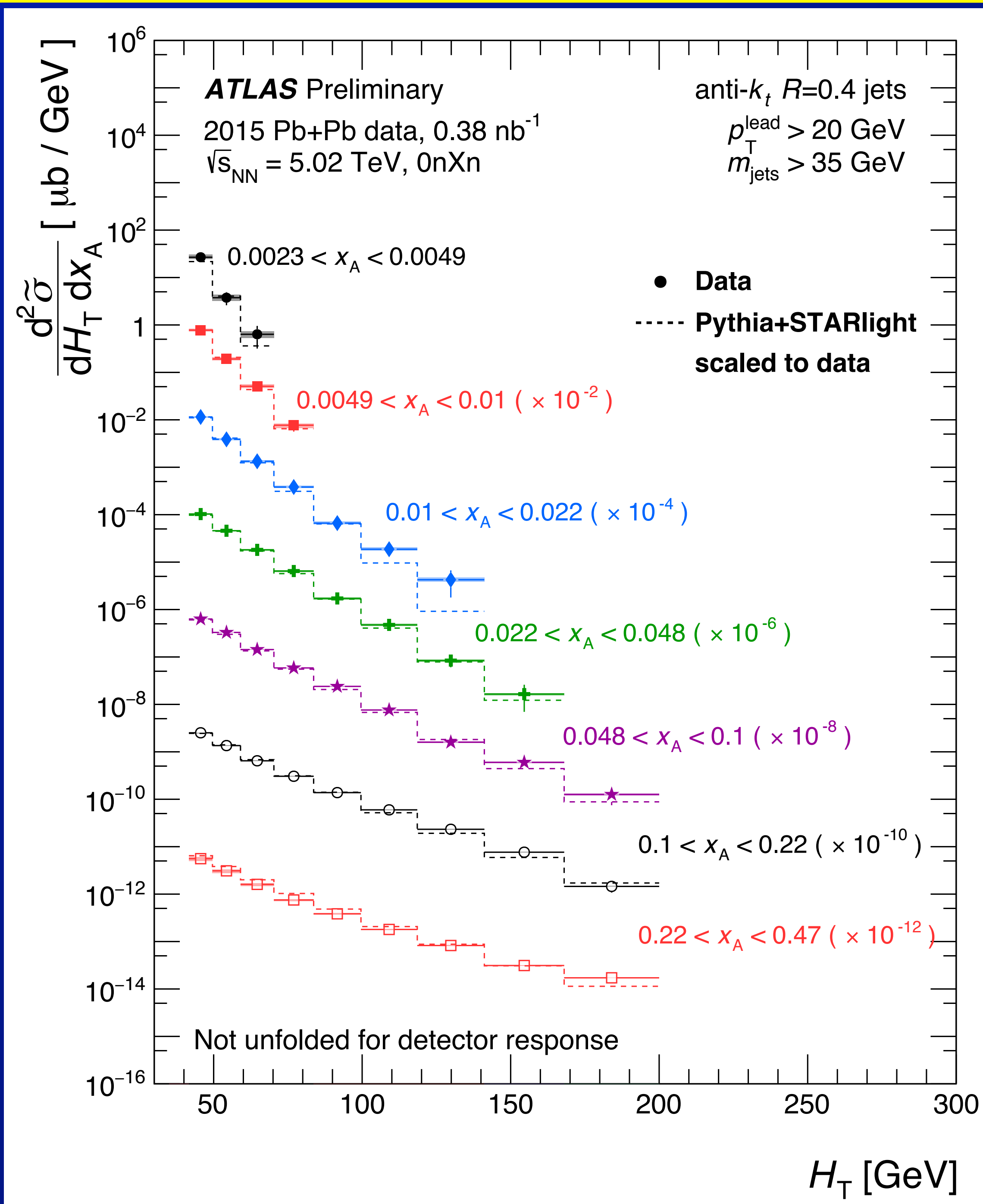




- Acceptance in (zγ, xA) strongly dependent on minimum jet system mass
  - Determined by minimum p_T in analysis

⇒Easiest way to get to low x_A is large z_γ

Results: H_T Dependence



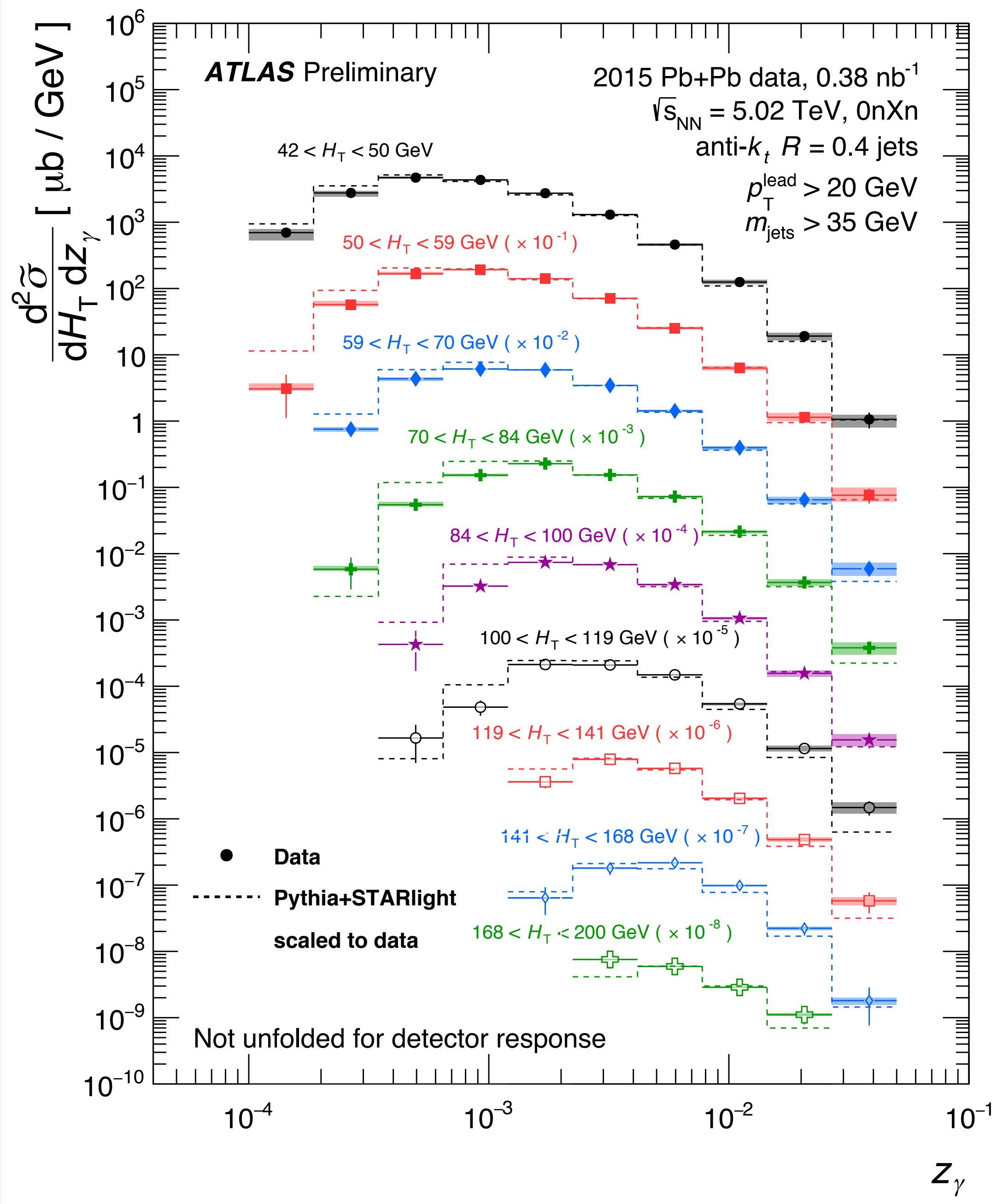
Differential cross-section in slices of x_A

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

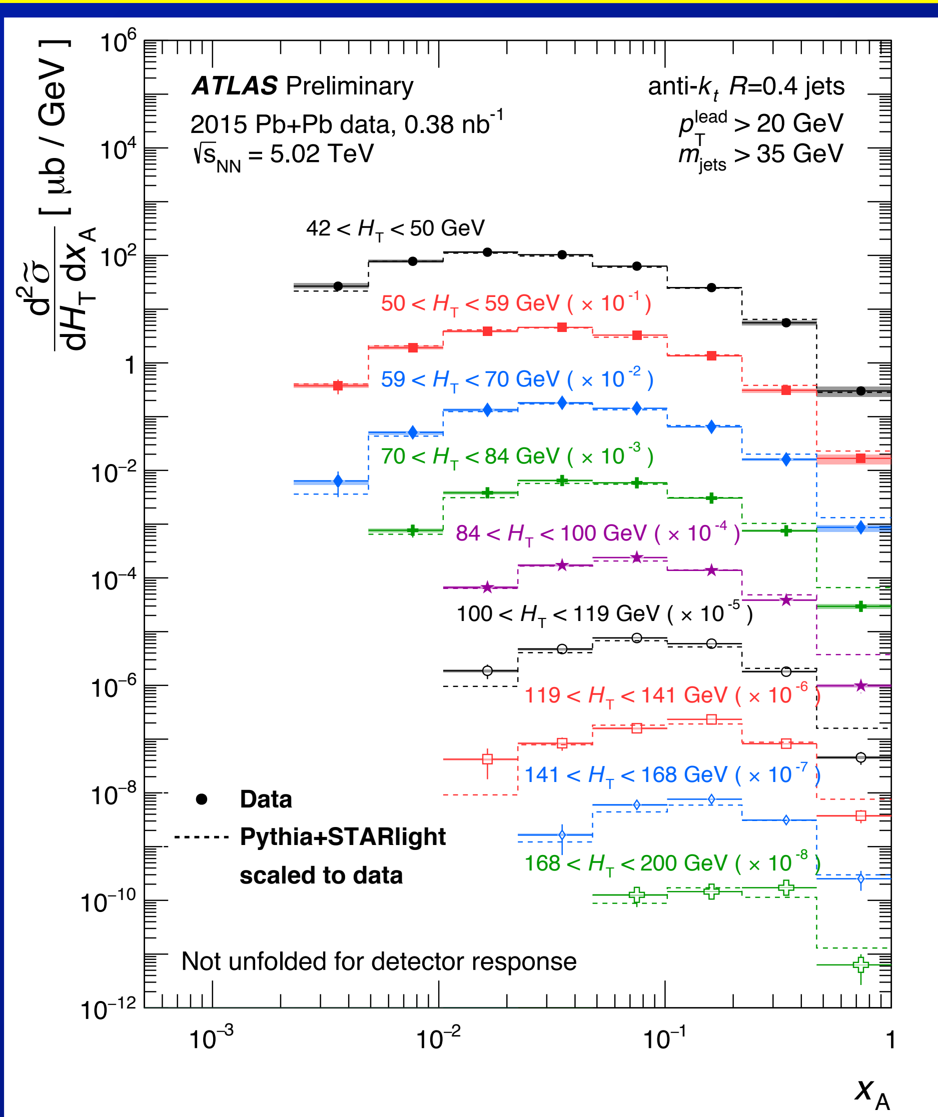


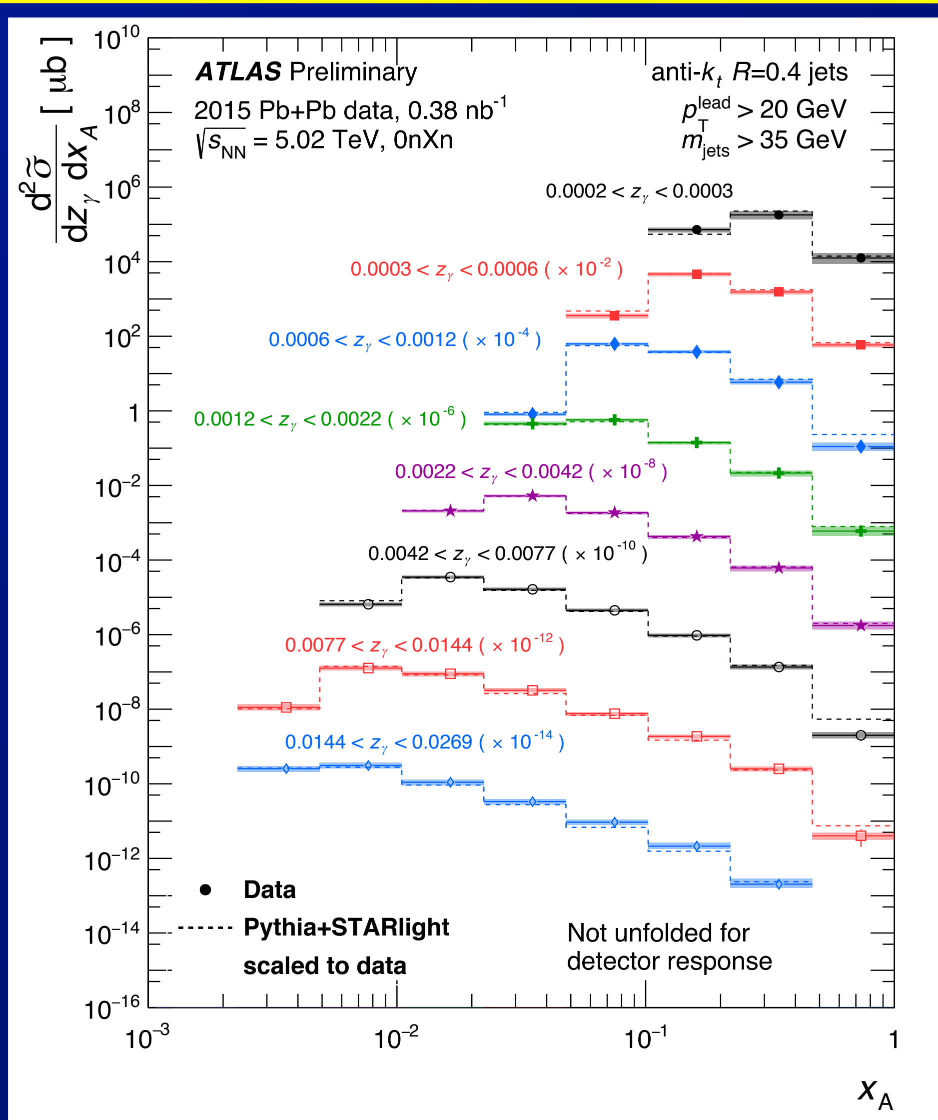
Differential cross-section in slices of H_T

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



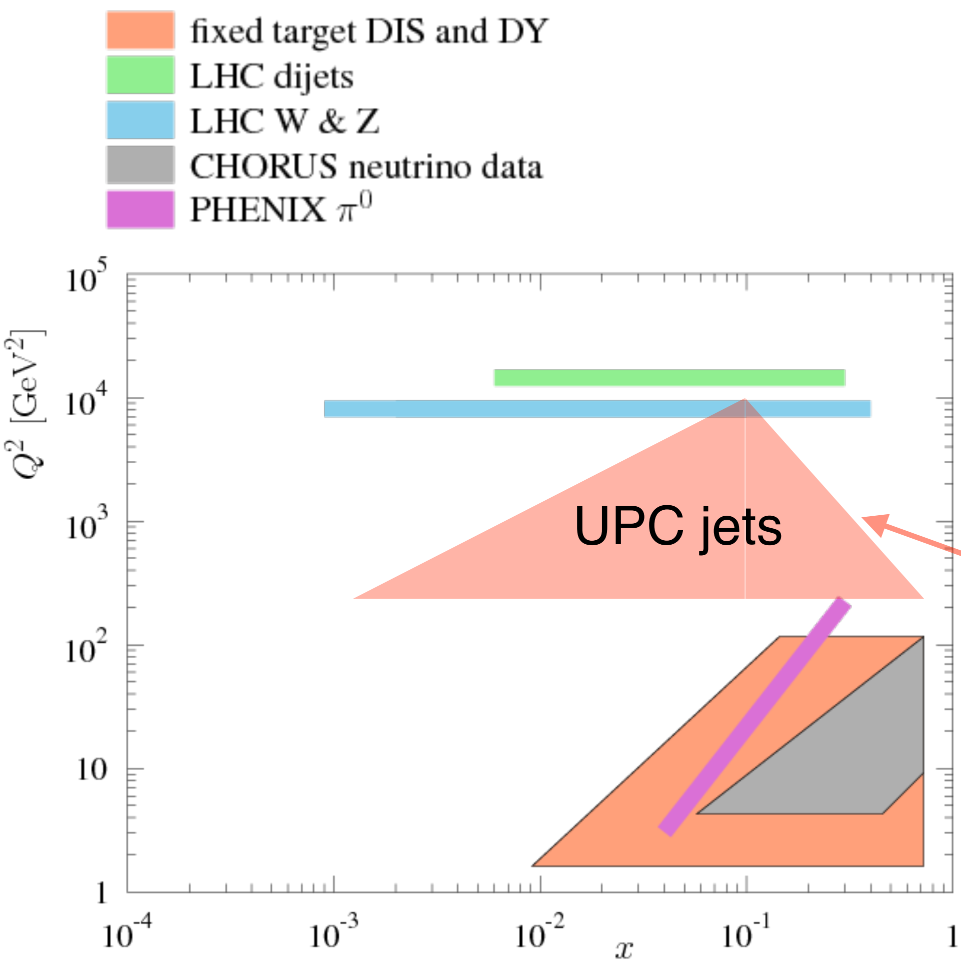


- Data agrees w/ MC over most of acceptance
  - ⇒But limitations in MC sample (e.g. no γ+n, no nPDF)

Summary, conclusions

- Presented a 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
  - Good but not perfect MC-data agreement
  - ⇒ Need MC with Pb+Pb EPA photon flux to avoid re-weighting which has conceptual difficulties
- Proof of principle that photo-nuclear dijet/multi-jet measurements possible in Pb+Pb collisions
  - Can access x_A, Q^2 (H_T) range not covered by existing fixed-target data.
  - ⇒ kinematic coverage primarily constrained by minimum jet p_T, but also $\Sigma_\gamma \Delta\eta > 2$ requirement

Measurement Coverage



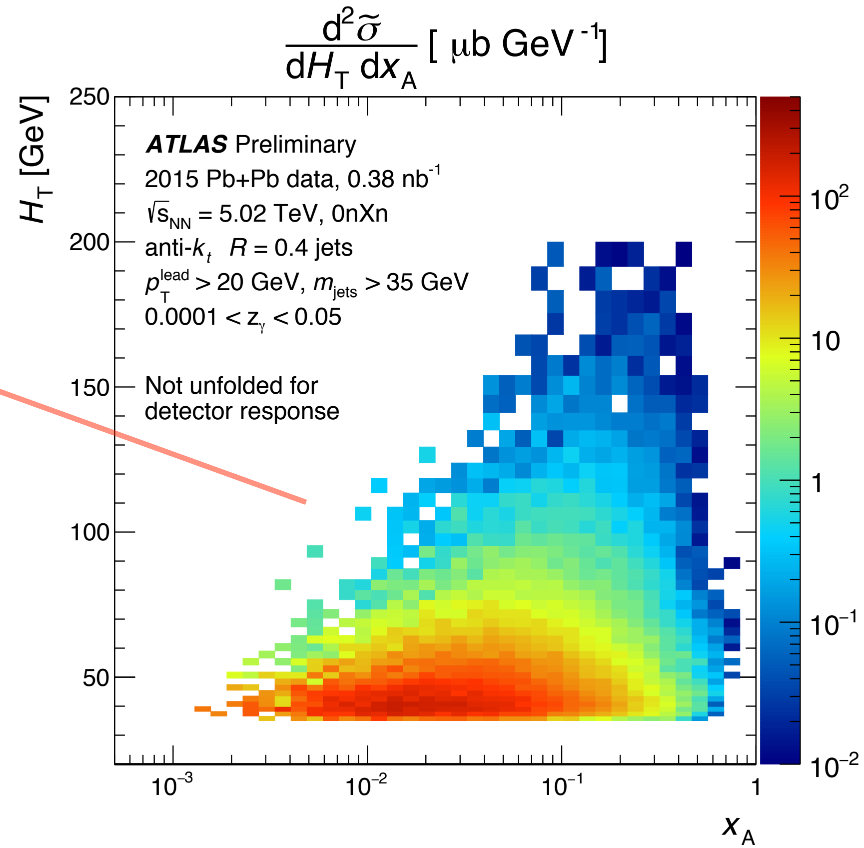


Figure adapted from EPPS16
1612.05741 [hep-ph]

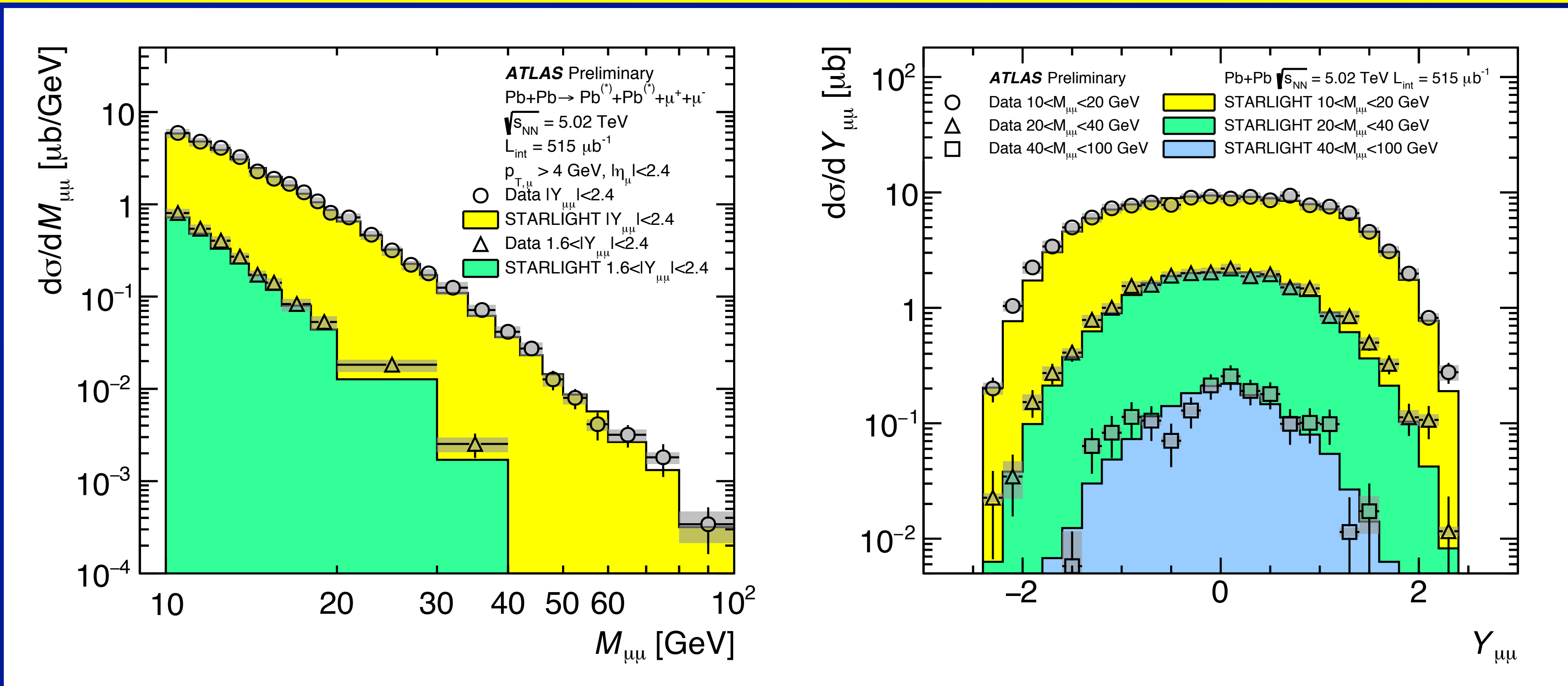
- **ATLAS-CONF-2017-011**

Backup

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

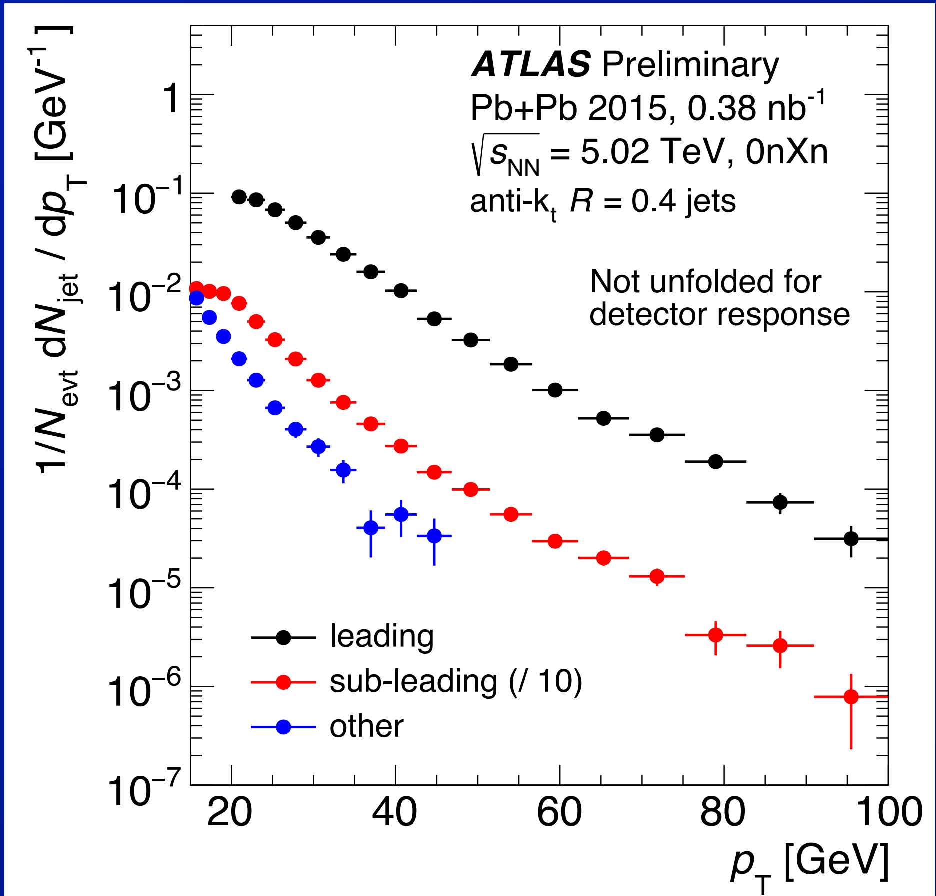
UPC dimuon

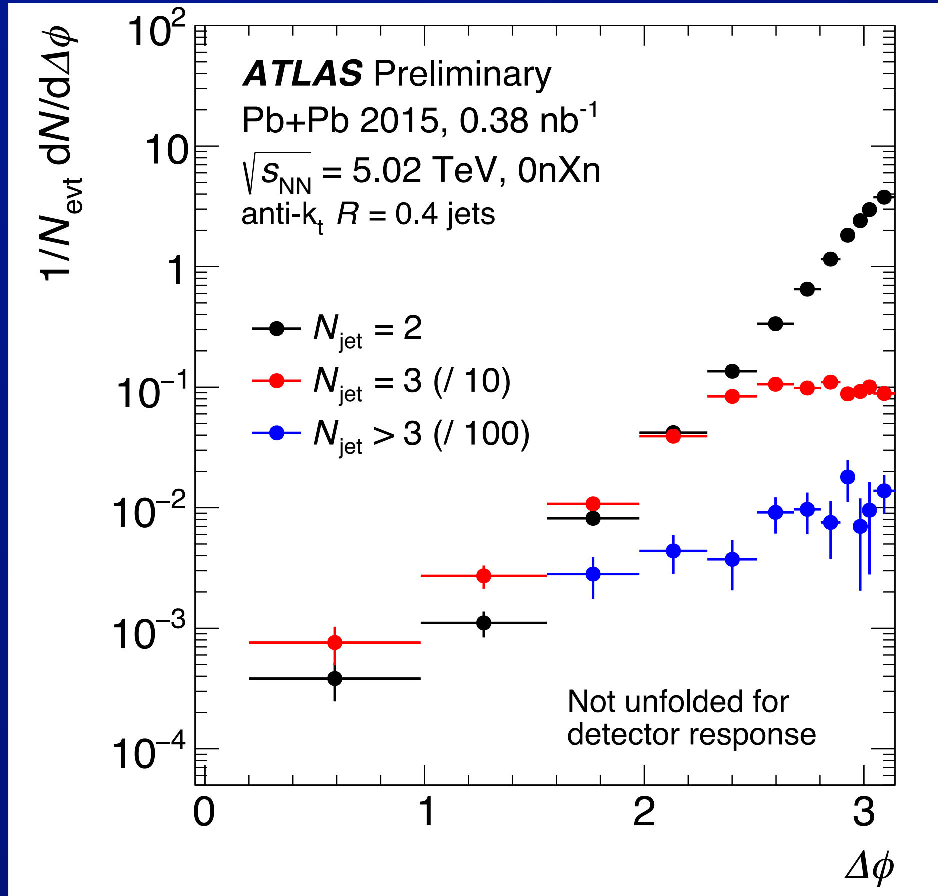


- **Provides valuable estimate/constraint on potential γγ→qqbar backgrounds**
  - **qqbar rate @ given, M, y ~ dimuon**

  ⇒**After gap cuts, negligible background**

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

Triggers & Event selection

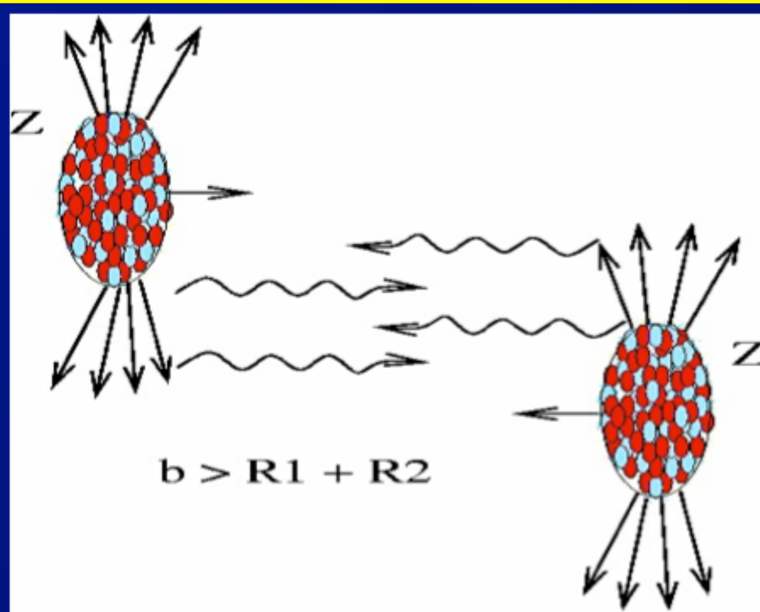
- The base trigger required:
  - $\geq$ 1 neutron in one ZDC, zero neutrons in the other

    ⇒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}

    ⇒Note: Pb+Pb hadronic cross-section is 7.7 b.
- 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

Ultra-peripheral Pb+Pb collisions



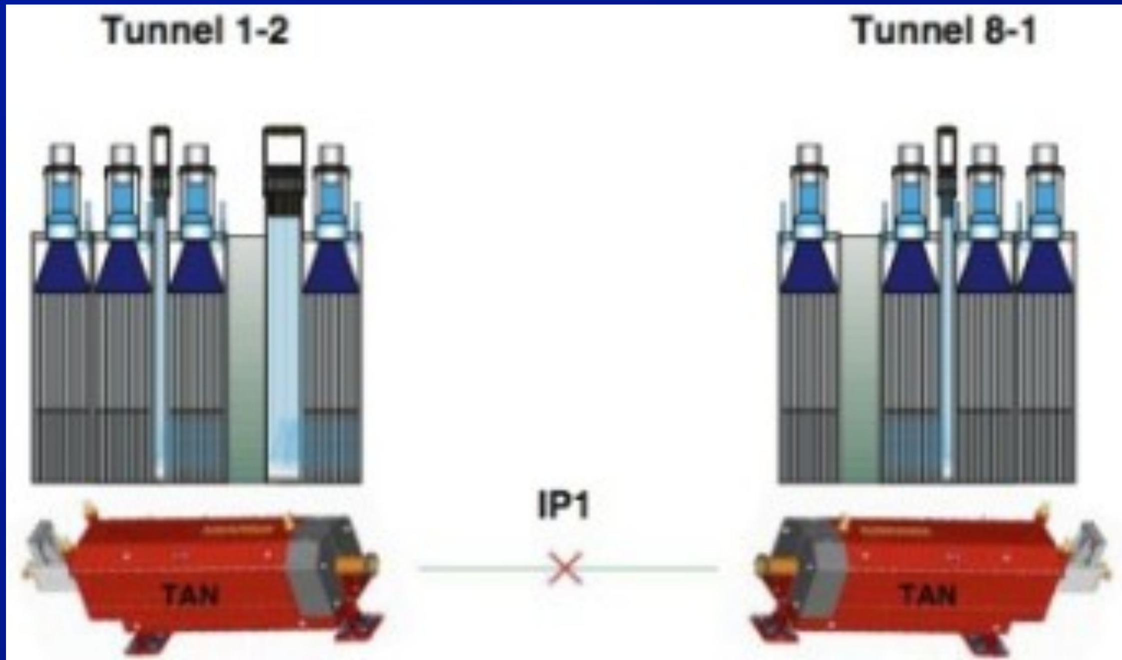
- Ultra-relativistic nuclei source strong EM fields
- Photons coherently emitted by entire nucleus are enhanced by Z2
  - $k\gamma\perp \sim \hbar c$ / 2RA ~ 15 MeV,
  - $k\gamma z$ = γboost x $k\gamma\perp$ ~ 40 GeV

⇒In AA collisions, energetic enough to stimulate hard scattering processes at low x in the target

⇒Cross-section enhanced by Z2A ~ 1.5 x 106 compared to pp collisions at the same √s

- This measurement:
  - Photoproduction of di/multi-jets using 0.38 nb^{-1} of $\sqrt{s_{NN}}$ = 5.02 TeV Pb+Pb data from 2015.

Zero degree calorimeters (ZDCs)

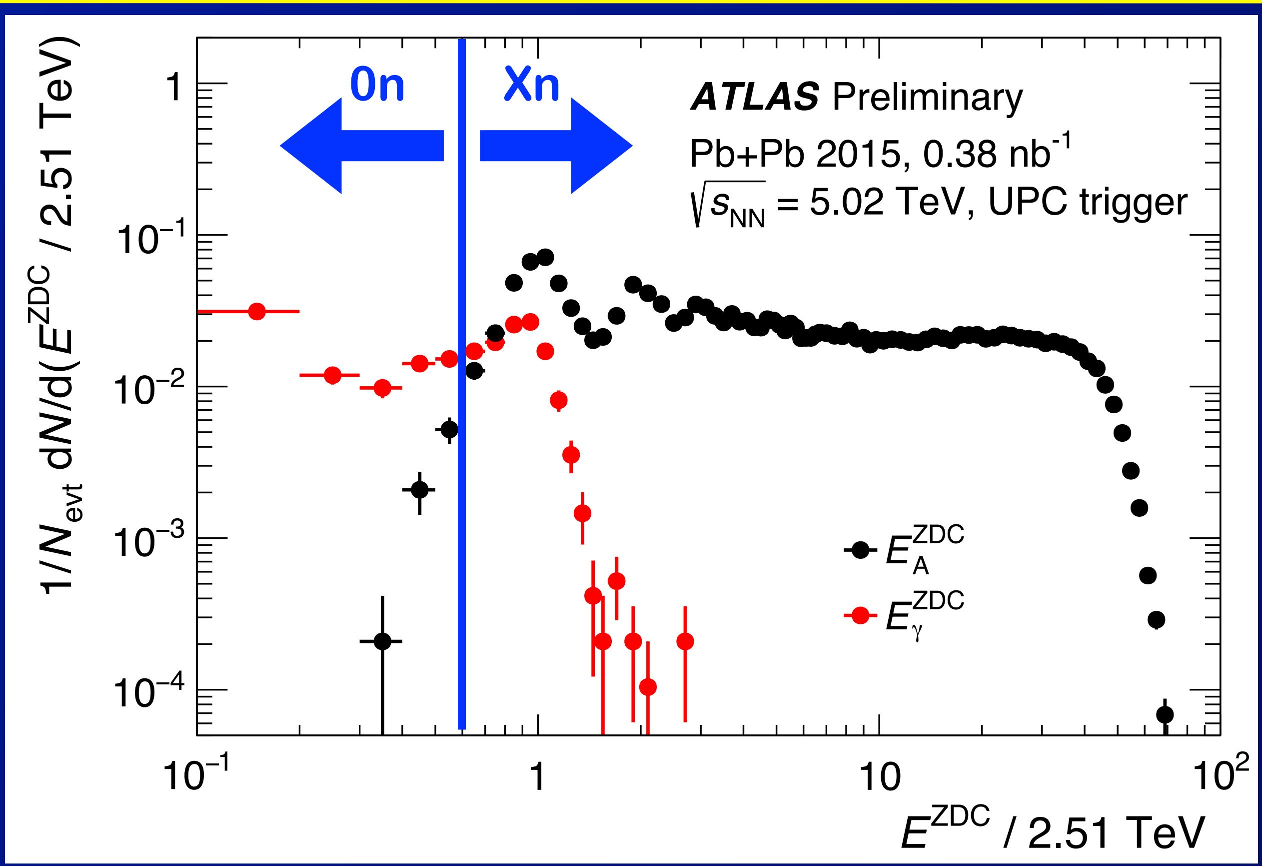


- **ATLAS ZDCs measure beam-rapidity neutrons emitted in Pb+Pb collisions**
  - hadronic collisions in nucleus produce ≥ 1 neutron in target direction with probability ≈ 1
  - photon-emitting nucleus nominally emits 0 neutrons

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

ZDC selection

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



- ZDC used to select 0nXn events (fiducial)
  - ⇒Observe some inefficiency in ZDC trigger rejection due to out-of-time pile-up
- \+ gap requirements to reject hadronic, photo-diffractive, γγ→qqbar backgrounds

Measurement Coverage

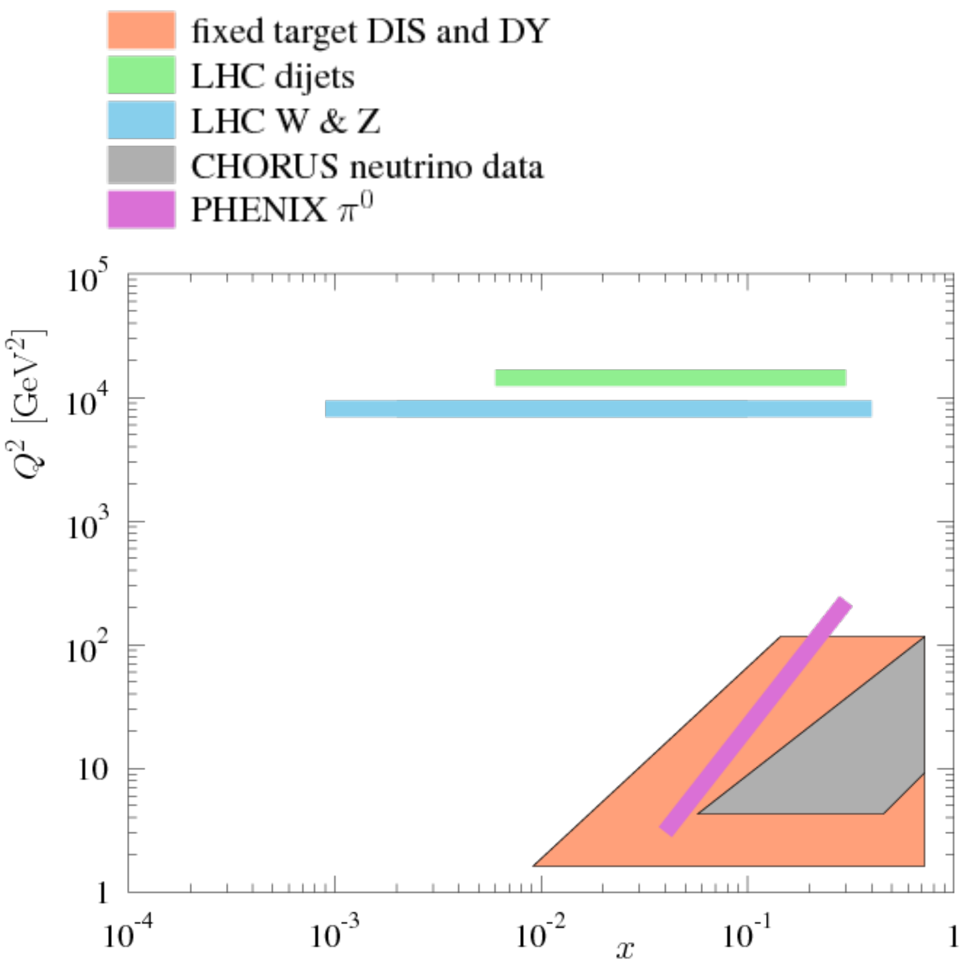


Figure adapted from EPPS16
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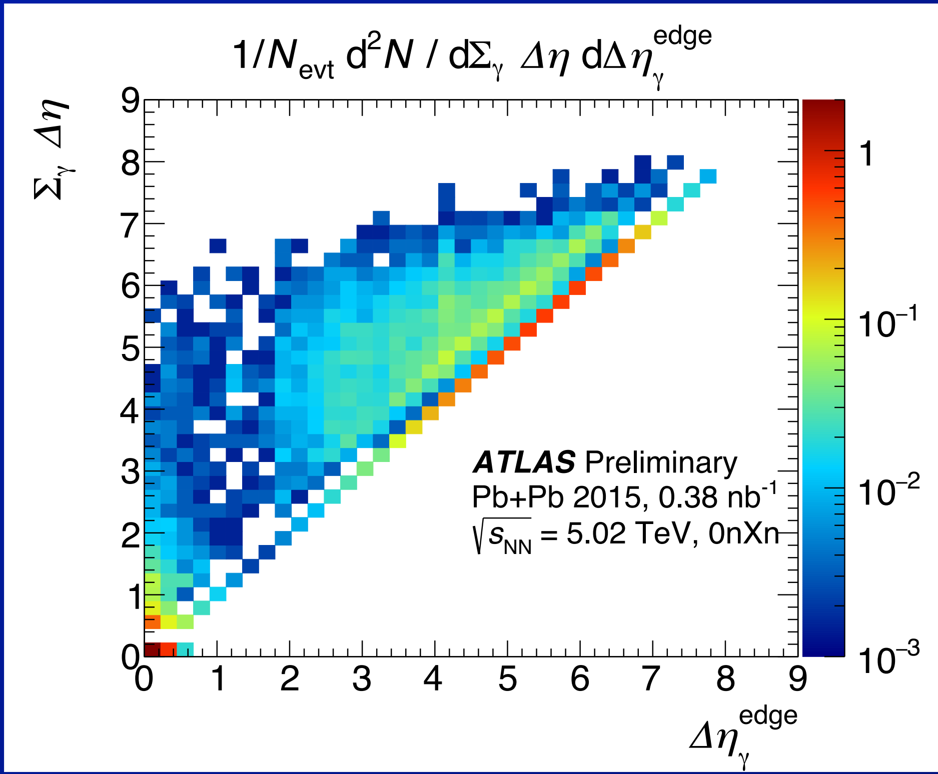
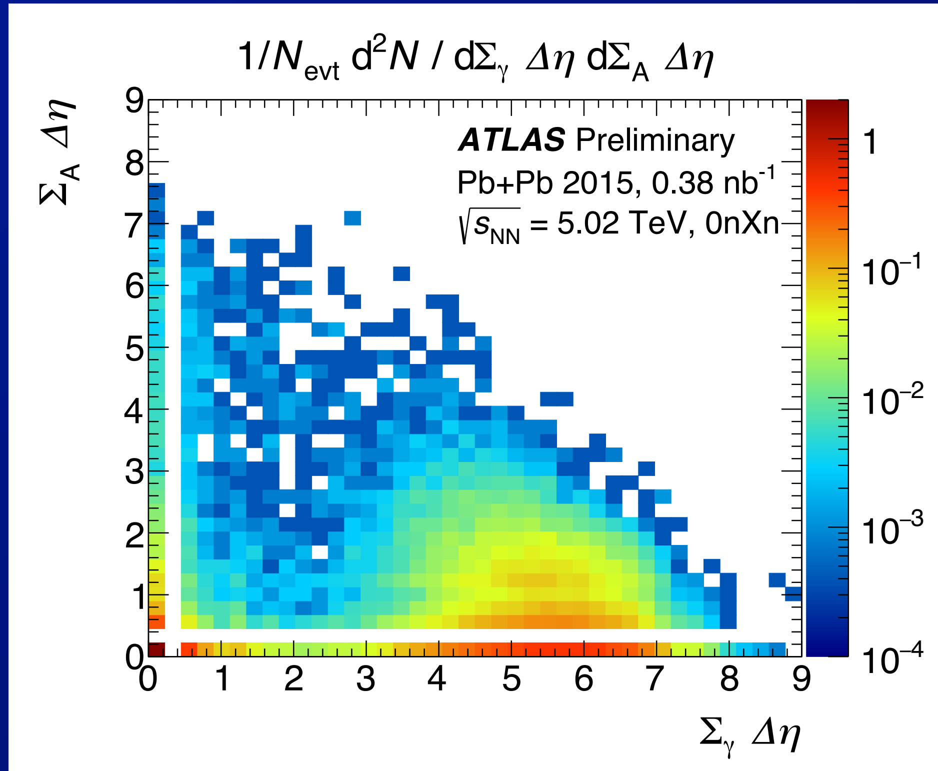
Gap Distributions





- **Left: comparison of traditional (edge) gap and photon-side sum ($\Sigma\gamma\ \Delta\eta$) gaps**

  ⇒off-diagonal events are mostly resolved photons

- **Right: distribution of nucleus ($\Sigma_A\ \Delta\eta$) vs photon ($\Sigma\gamma\ \Delta\eta$) gap sums**

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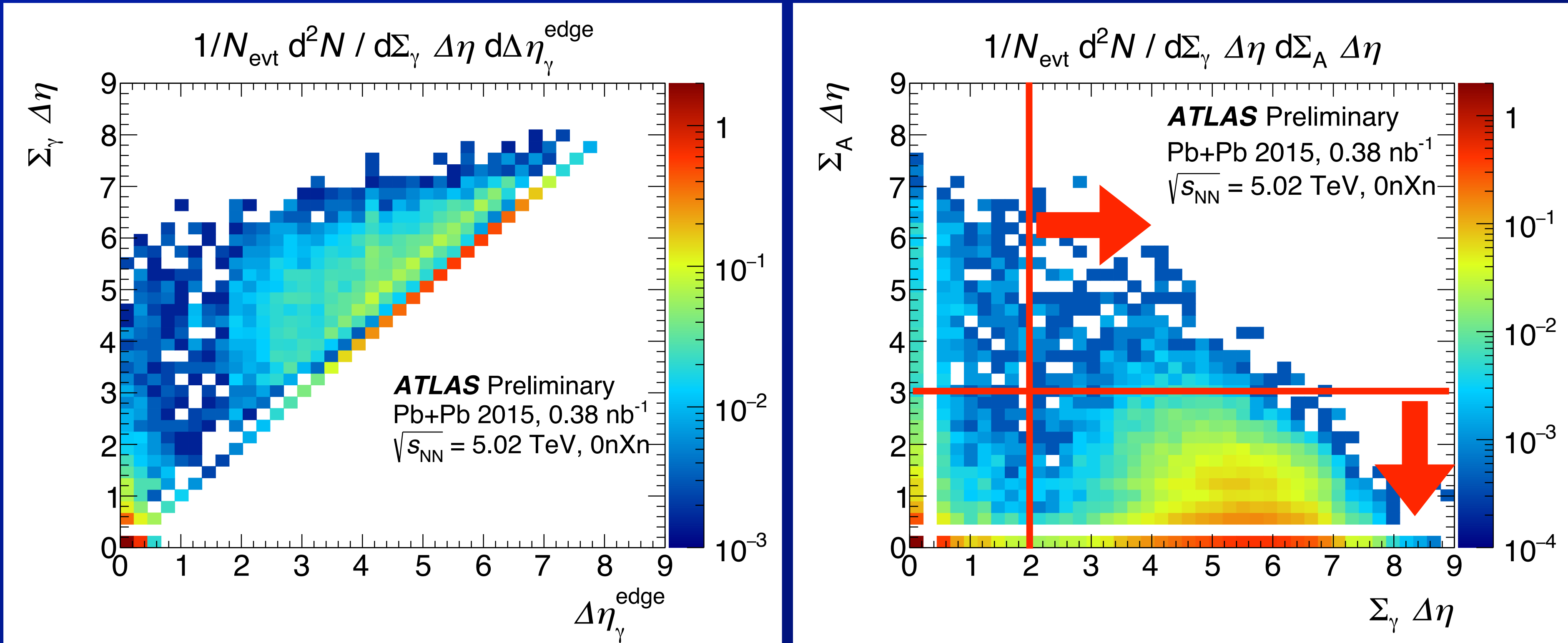

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  - –with selection cuts indicated.

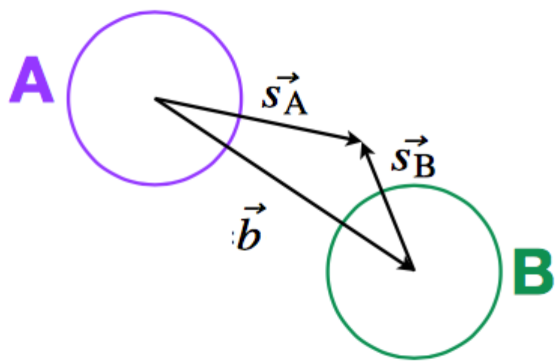
Photo-nuclear Monte Carlo

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

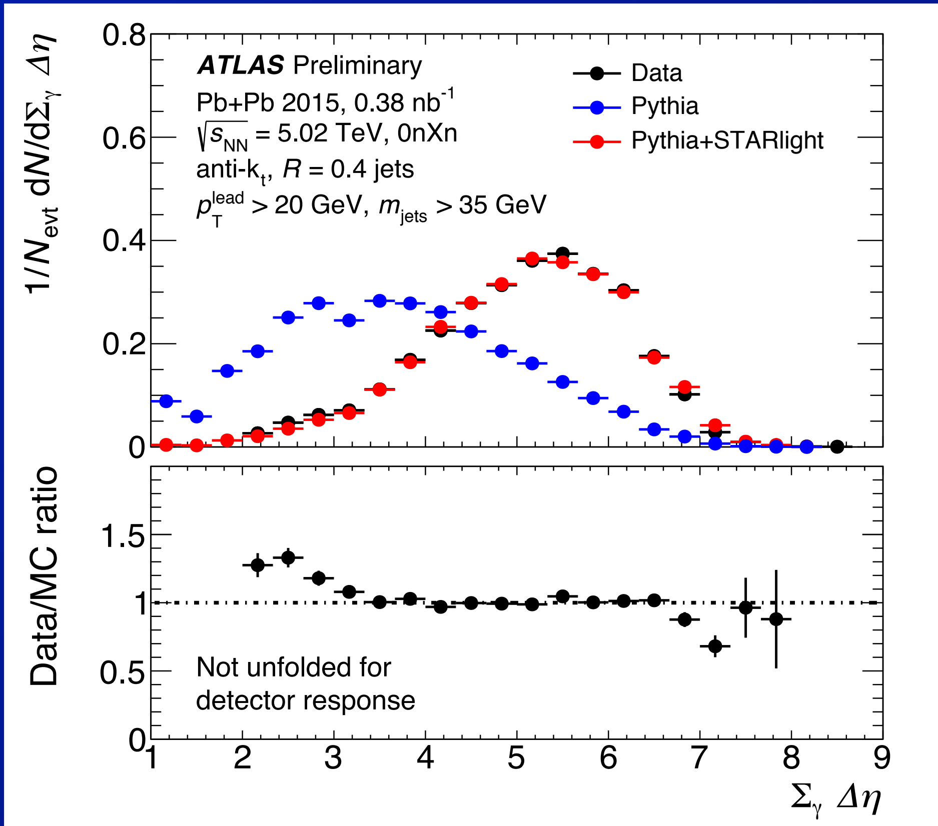
    ⇒Does not have right photon flux
- "STARlight" model describes photon flux in ultra-peripheral nucleus-nucleus collisions
  - Used modified STARlight to calculate weights applied on per-event basis to Pythia sample:

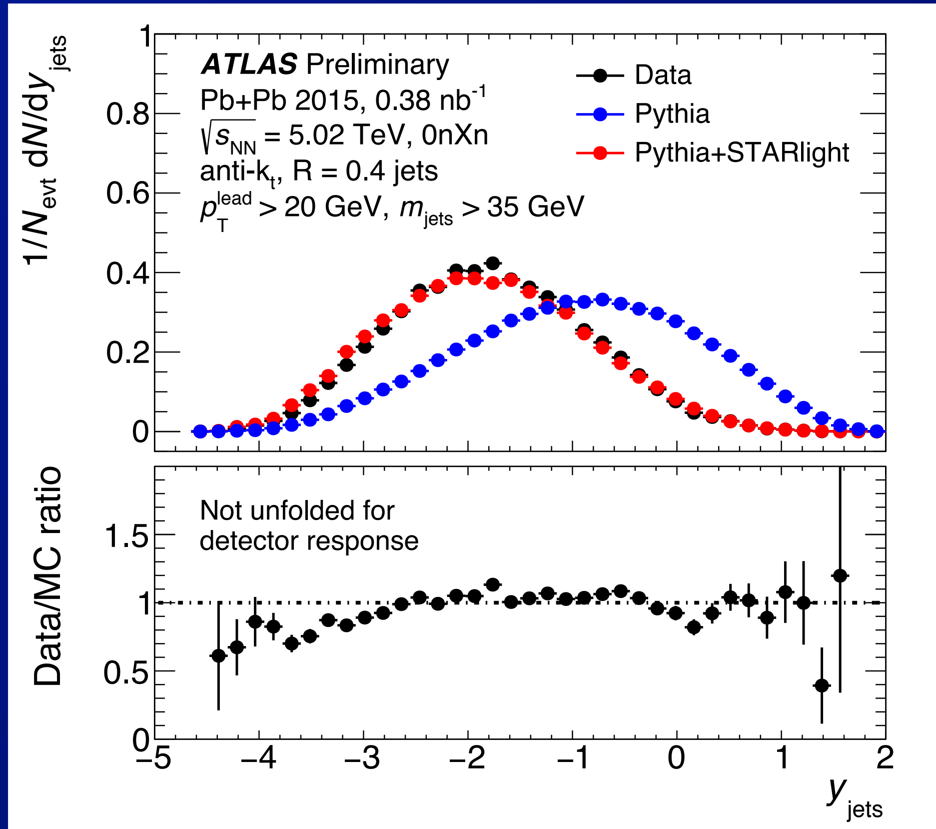
$$\frac{\mathrm{d}\sigma^{\mathrm{Pb+Pb}}_{\mathrm{UPC}}}{\mathrm{d}E} = 2\int \mathrm{d}^2 b\, P_{\mathrm{UPC}}(b) \int \mathrm{d}^2 s_{\mathrm{B}}\, \left.\frac{\mathrm{d}^2 N^{\mathrm{Pb}}_{\gamma}}{\mathrm{d}E\, \mathrm{d}^2 s_{\mathrm{A}}}\right|_{\vec{s}_{\mathrm{A}}=\vec{b}-\vec{s}_{\mathrm{B}}}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

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



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 $z_\gamma < x_A$