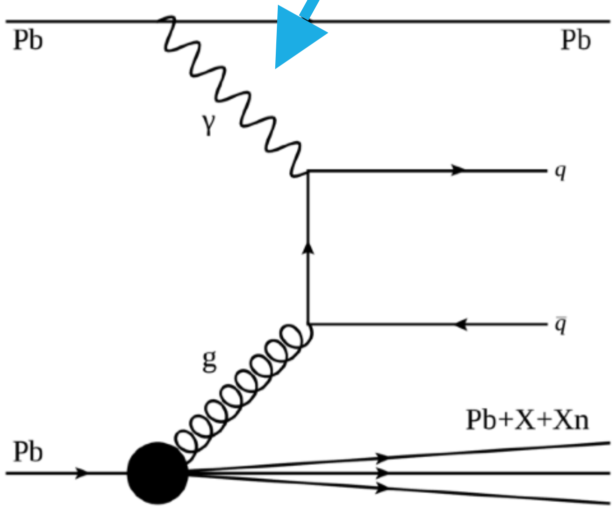
Photo-nuclear Jet Production in Ultra-Peripheral Pb+Pb Collisions at 5.02 TeV with the ATLAS Detector

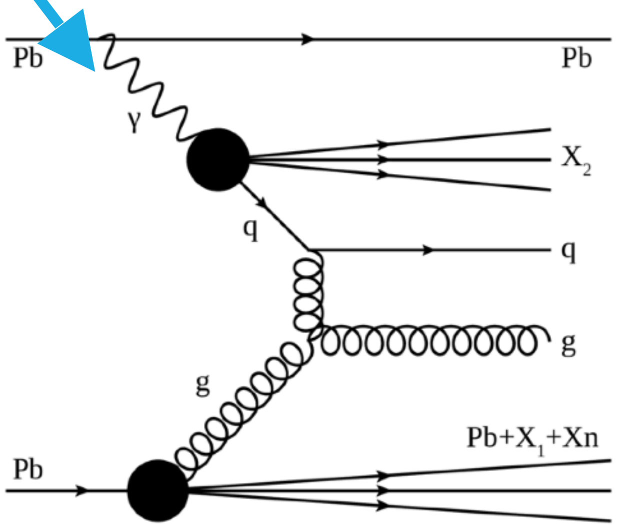
Peter Steinberg
Brookhaven National Laboratory

Introduction: Photo-nuclear Jet Production

In ultra-relativistic heavy ion collisions, the intense electromagnetic fields provide a flux of quasi-real photons.



Direct



Resolved

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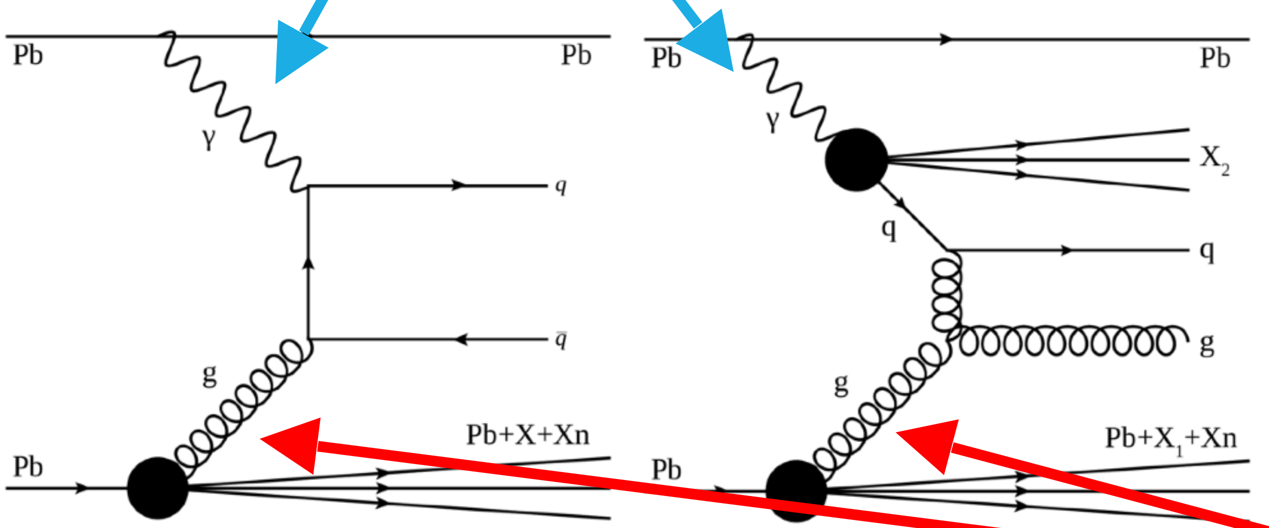

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Resolved

Those photons can scatter off of partons in the other (target) nucleus.

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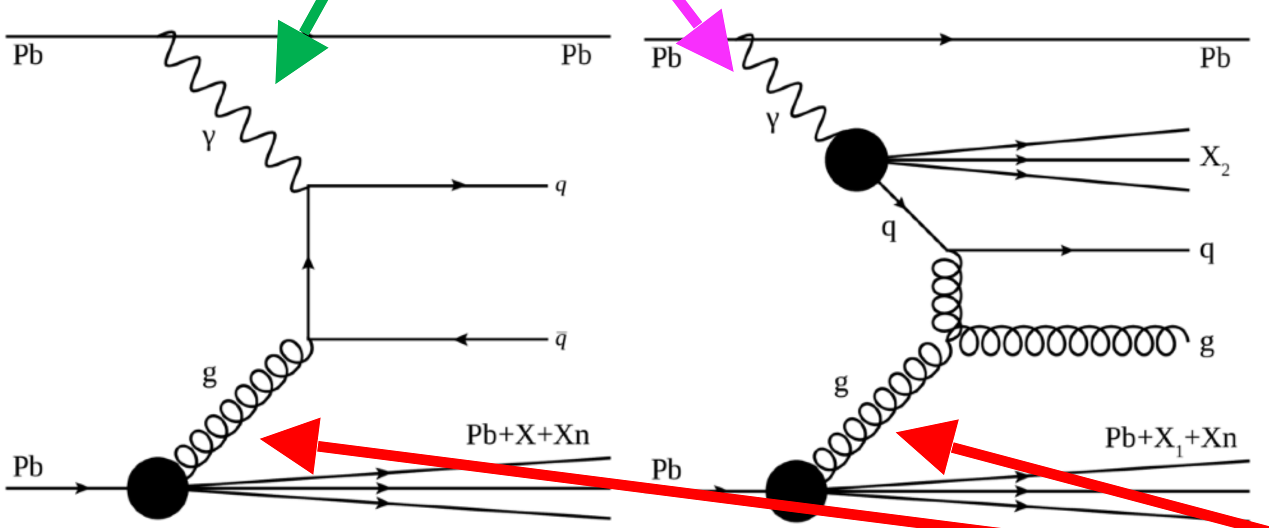
“Direct” photons scatter off nuclear partons

“Resolved” photons scatter via a virtual qq excitation (+ Fock states) of photon.



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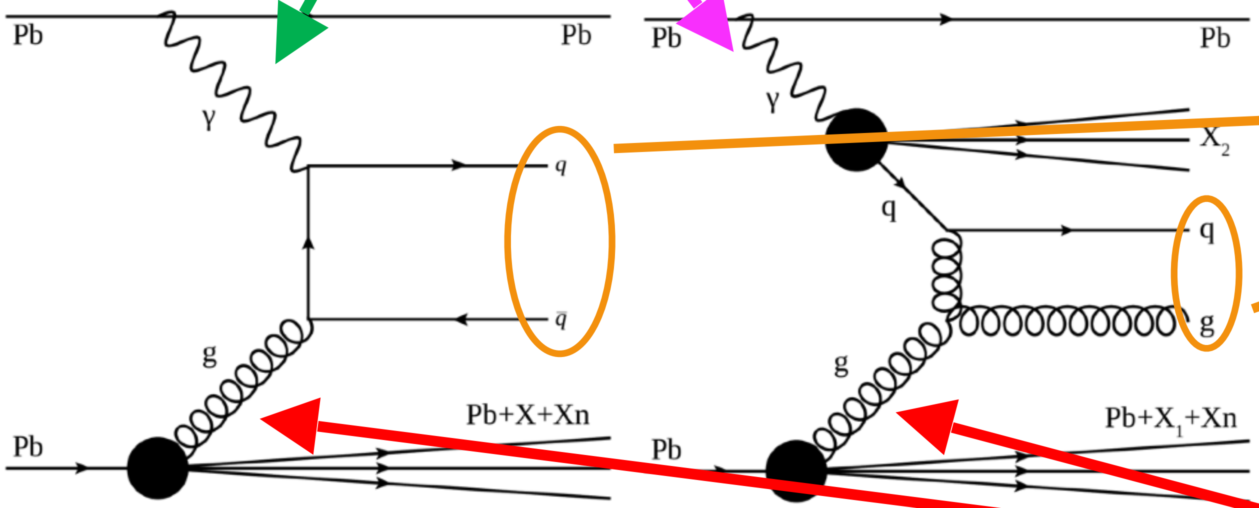
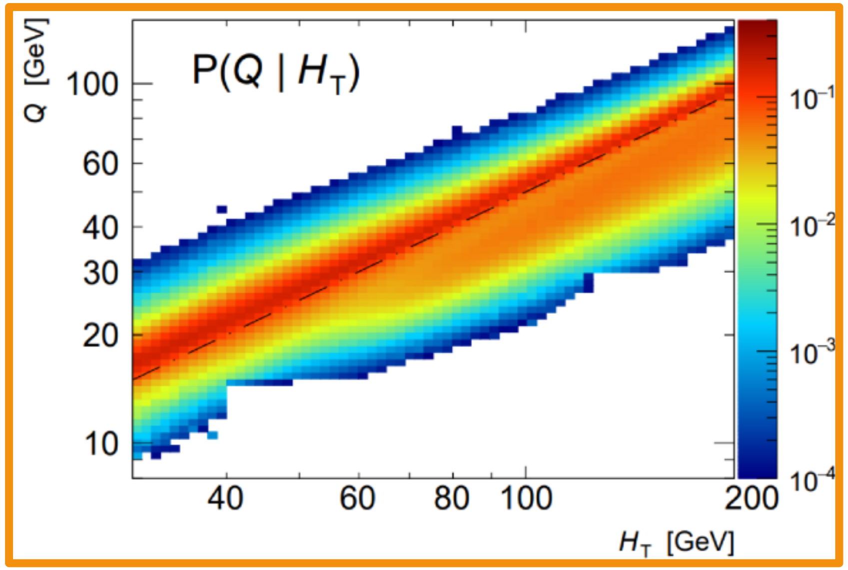


Pythia8 generator level



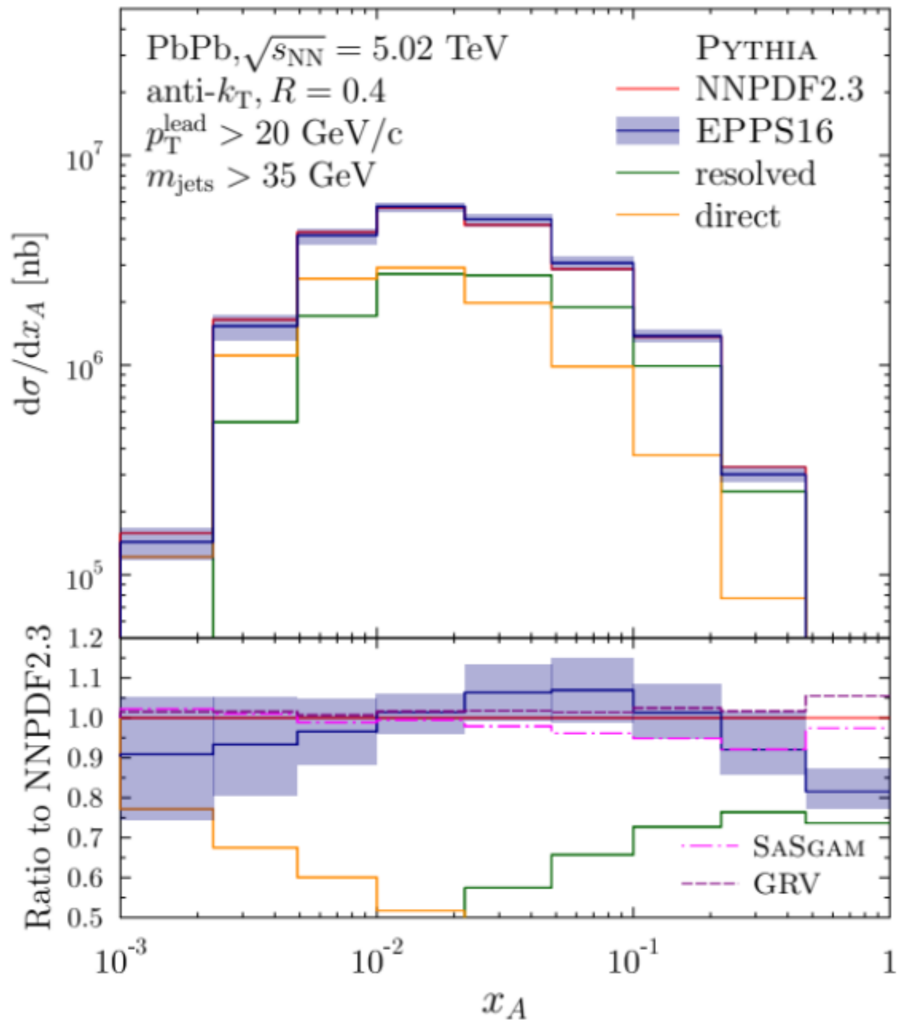
Jet kinematics provide access to hard-scattering kinematics, directly probing nuclear PDF effects.

$$H_T = \sum_i p_T^i \qquad x_A = \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}} \qquad z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

Those photons can scatter off of partons in the other (target) nucleus.

Introduction: Nuclear PDFs at Low-x

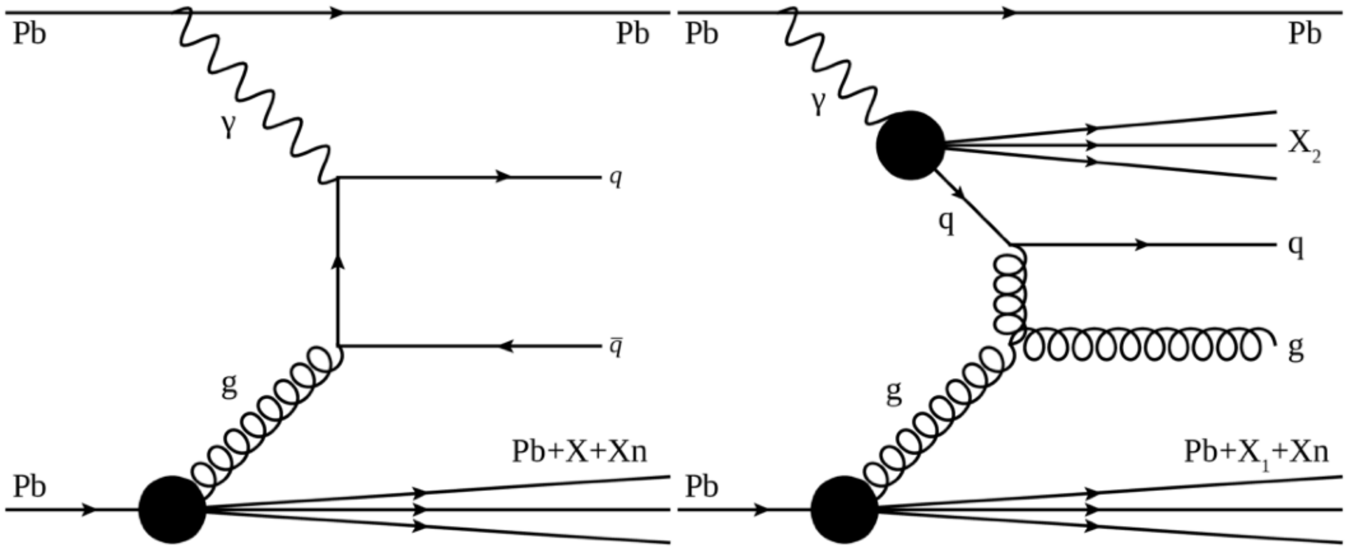
- Nuclear Parton Distribution Functions (nPDFs) are important for precision measurements of a number of physical observables.
- They are poorly constrained at low-x and intermediate Q^2 due to a lack of available data.
  - 100 GeV² $< Q^2 <$ 1000 GeV² has very little constraint.
  - Nuclear shadowing at low-x in this region is of particular theoretical interest.
- Photo-nuclear jet production provides a clean probe of this kinematic region, similar to DIS:
  - Proposal by Strikman, Vogt, and White (2005)
  - Test of sensitivity (right) by Helenius (2018)

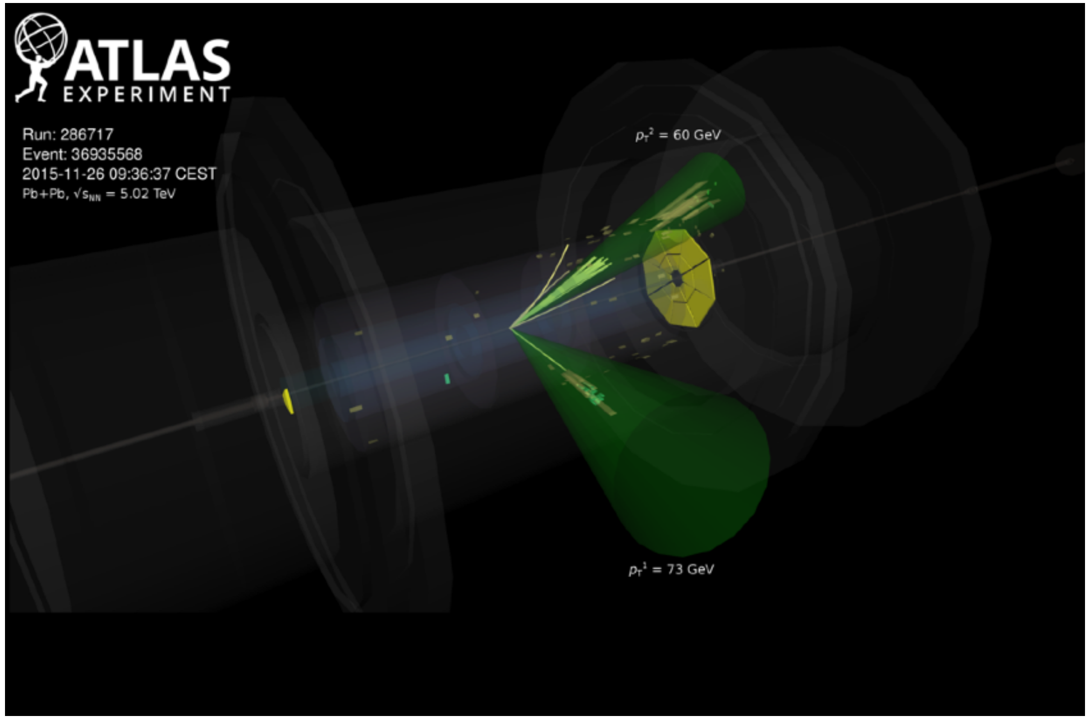


Selecting Photo-nuclear Jet Events

Event Selections | Raw Yields | Unfolding | Systematic Uncertainty | Final Results

Event Selections





Selecting Photo-nuclear Jet Events

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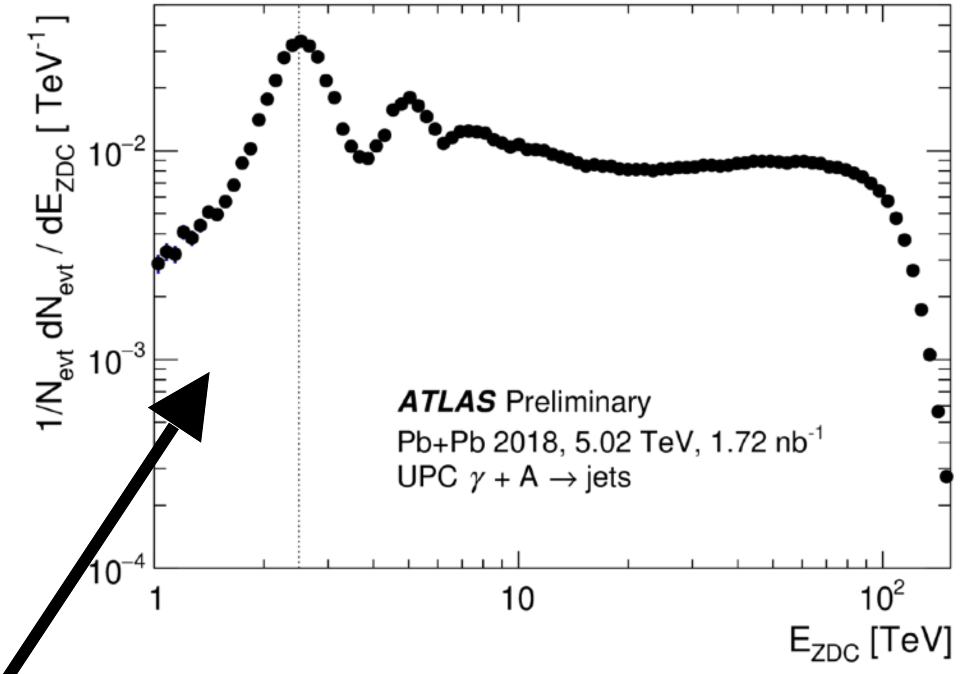
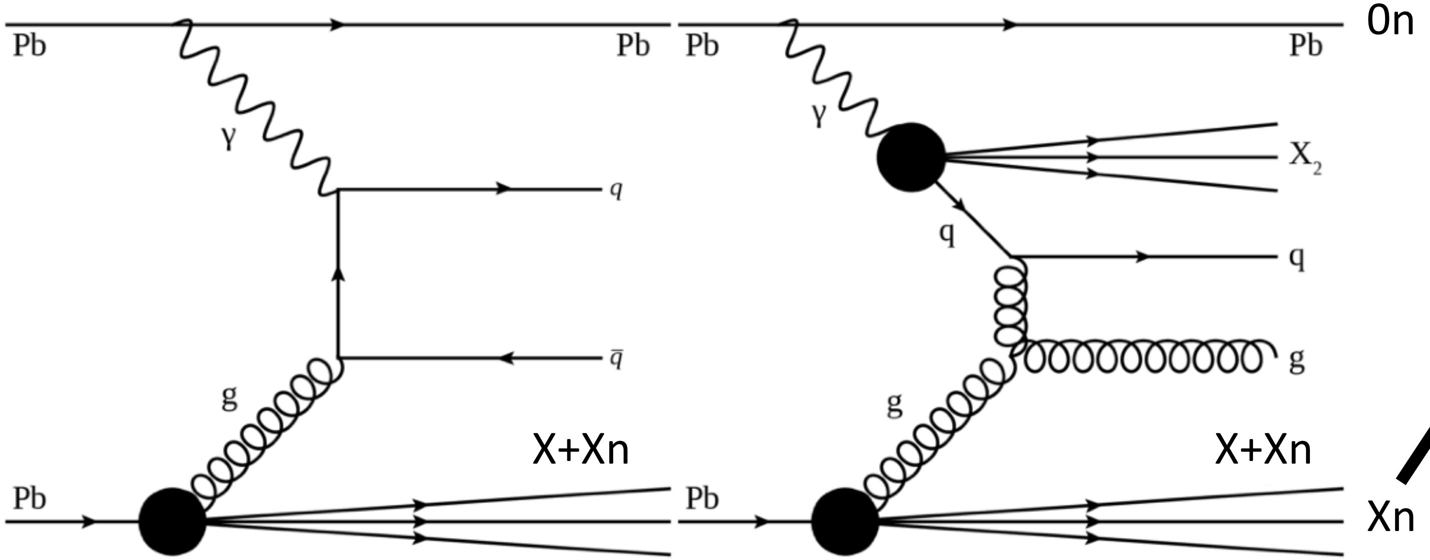
<u>Event Selections</u>

- 0nXn requirement for nuclear breakup in exactly <u>one</u> ATLAS Zero-Degree Calorimeter (ZDC)





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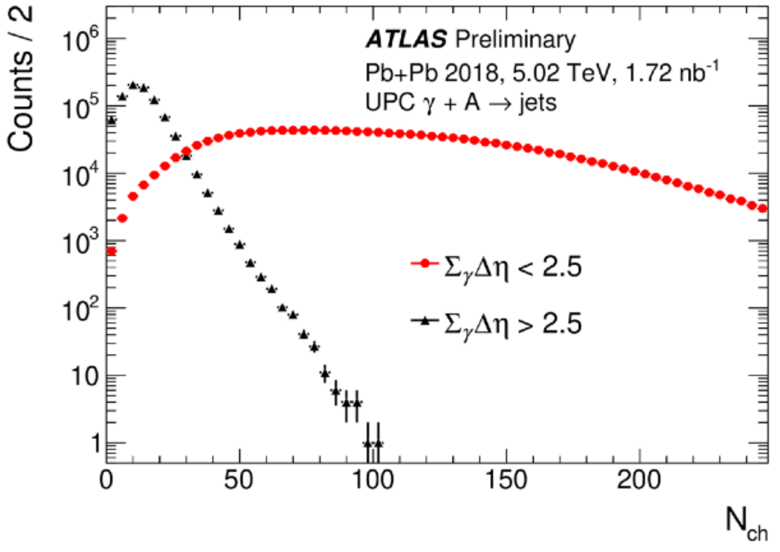

Event Selections

- 0nXn requirement for nuclear breakup in exactly one ATLAS Zero-Degree Calorimeter (ZDC)
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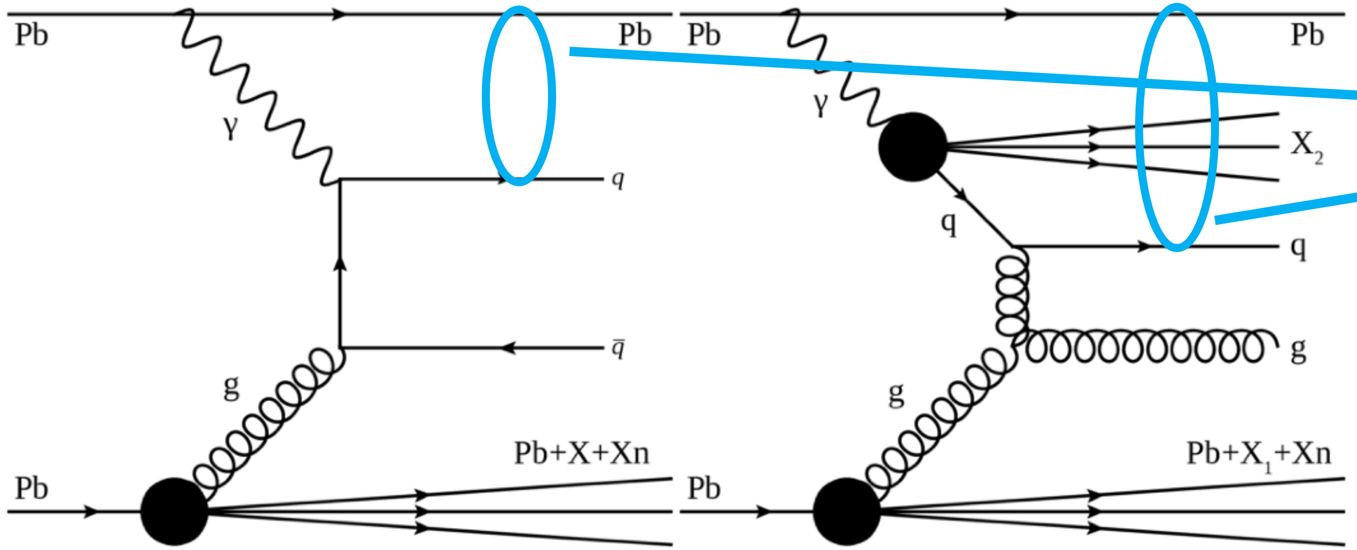
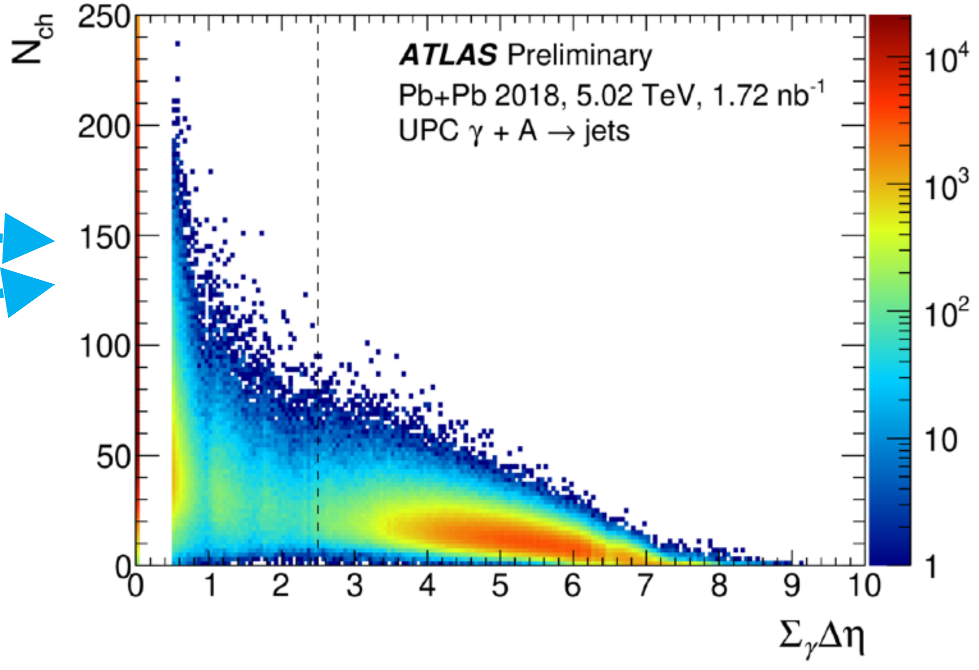
  - To veto $\gamma\gamma \rightarrow q\bar{q}$, also require $\Delta\,\eta_A^{edge} < 3$.





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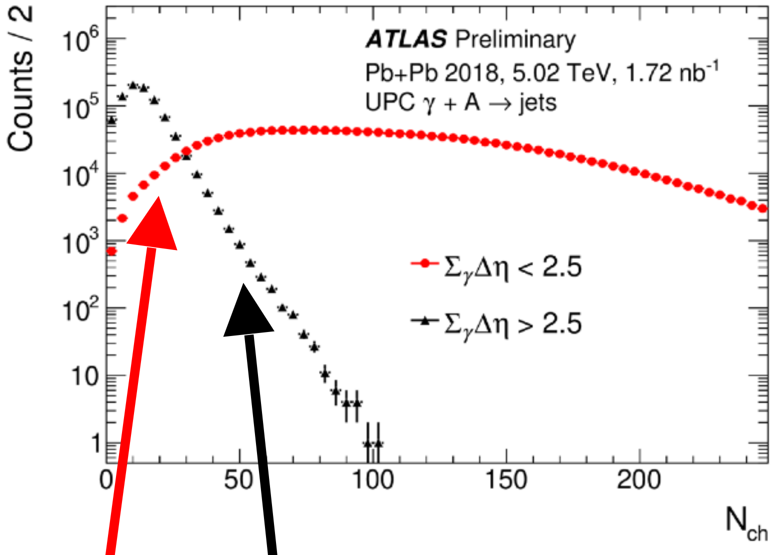

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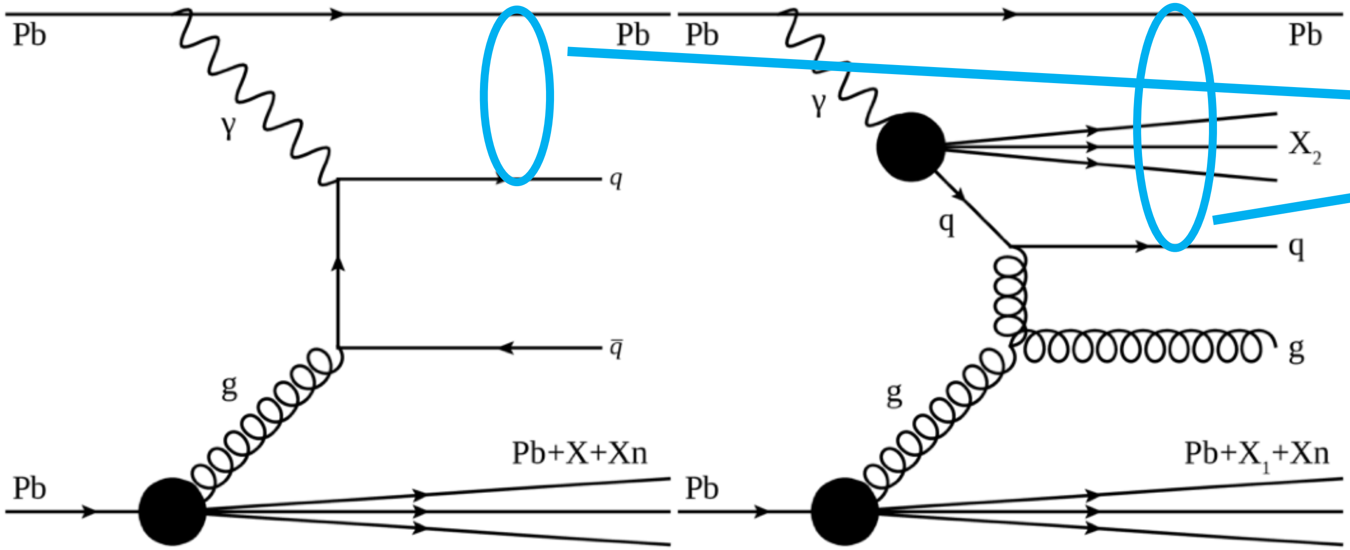

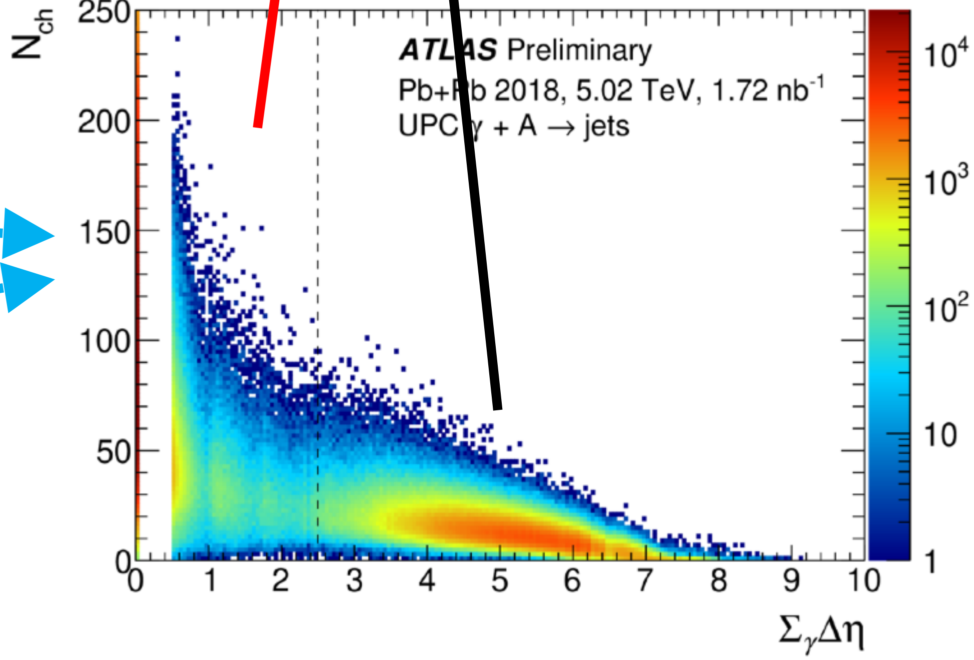

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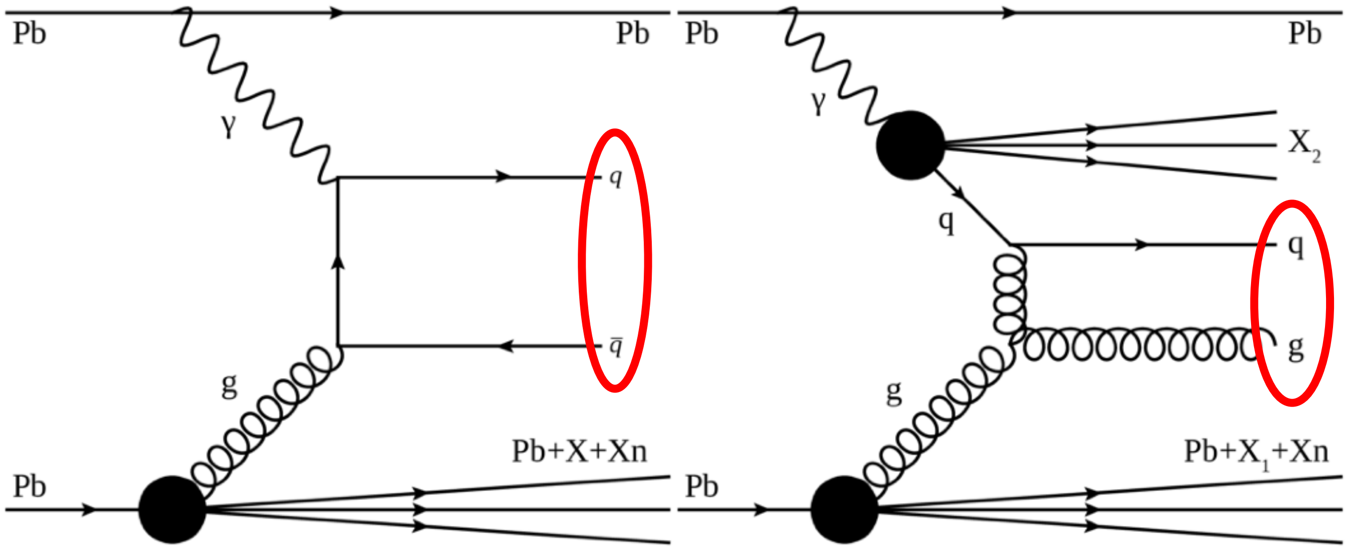
  - To veto $\gamma\gamma \rightarrow q\bar{q}$, also require $\Delta\,\eta_{A}^{edge} < 3$
- At least two Particle-Flow jets with $p_T > 15$ GeV.

Selecting at least two jets allows access to the hard-scattering kinematics



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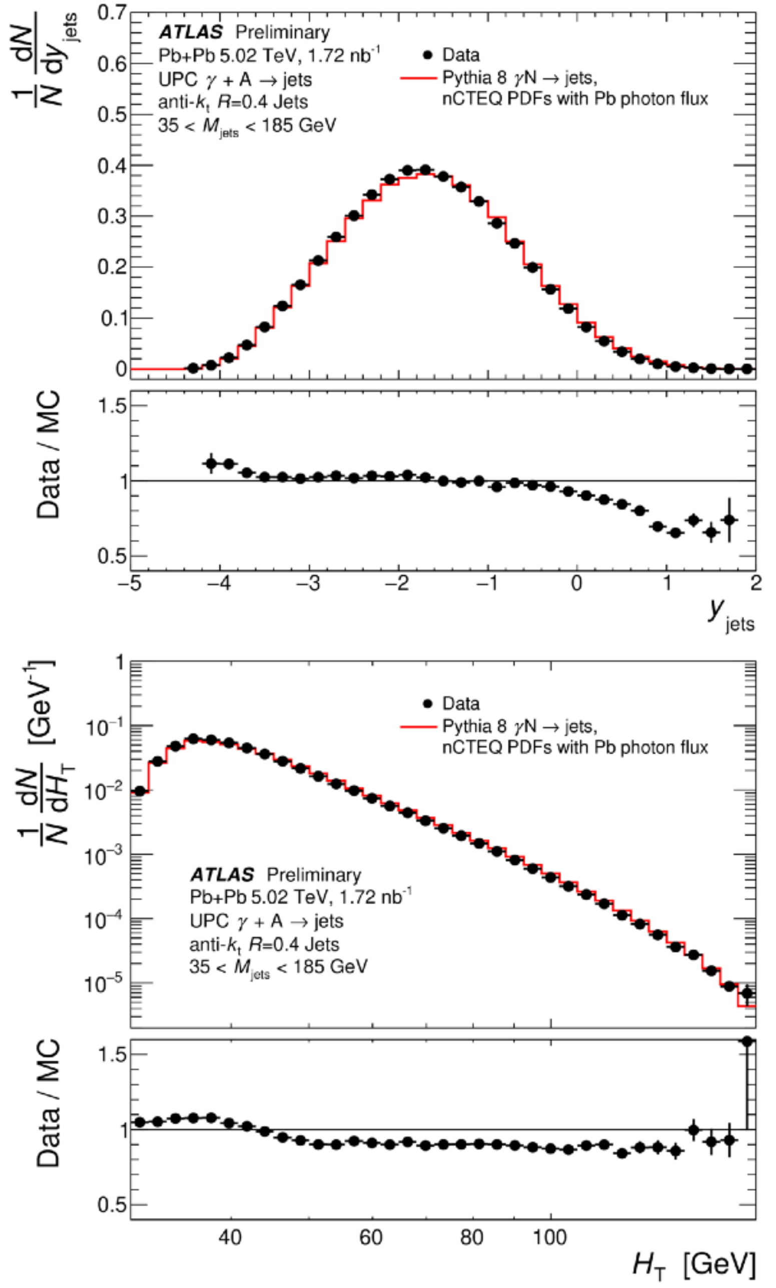
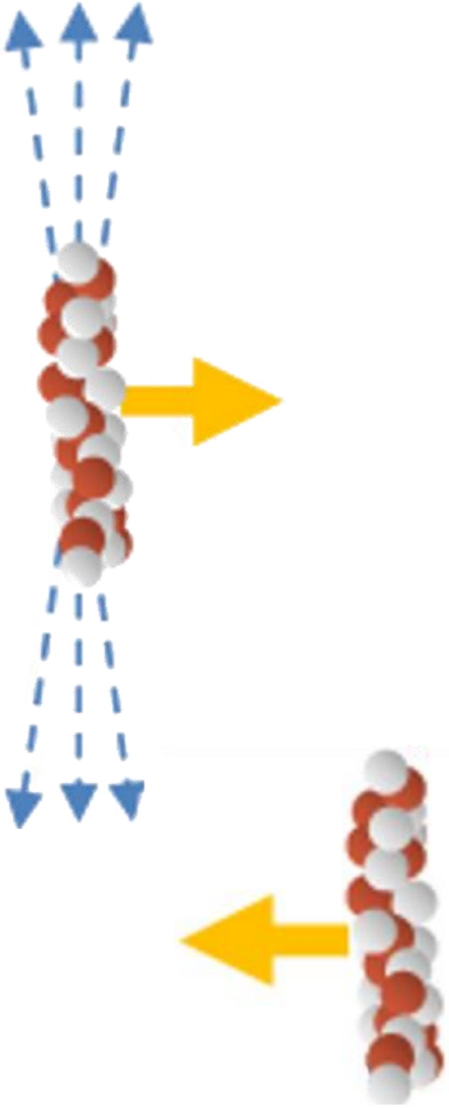


Importance of Forward Neutrons: *XnXn* Events

The photo-nuclear jet requirements select events with very high-energy photons.



Importance of Forward Neutrons: *XnXn* Events

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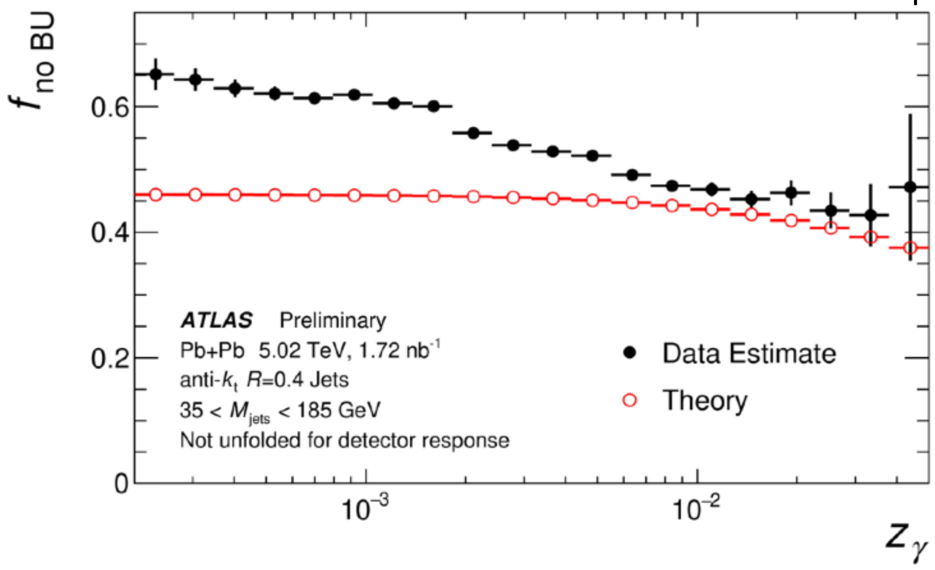
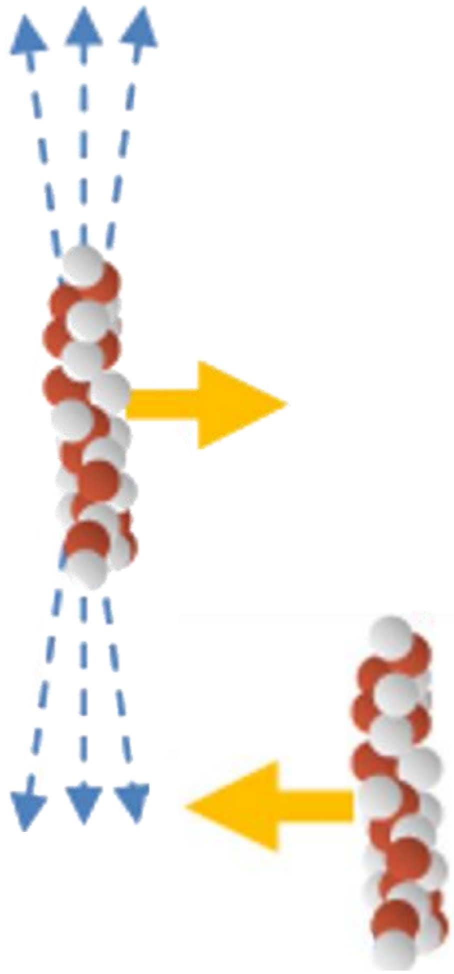
The photo-nuclear jet requirements select events with very high-energy photons.

- $E_\gamma \propto 1/b \rightarrow$ Biases towards lower impact parameter collisions
- Much higher probability of breakup due to additional EM interactions

fraction of events with no breakup





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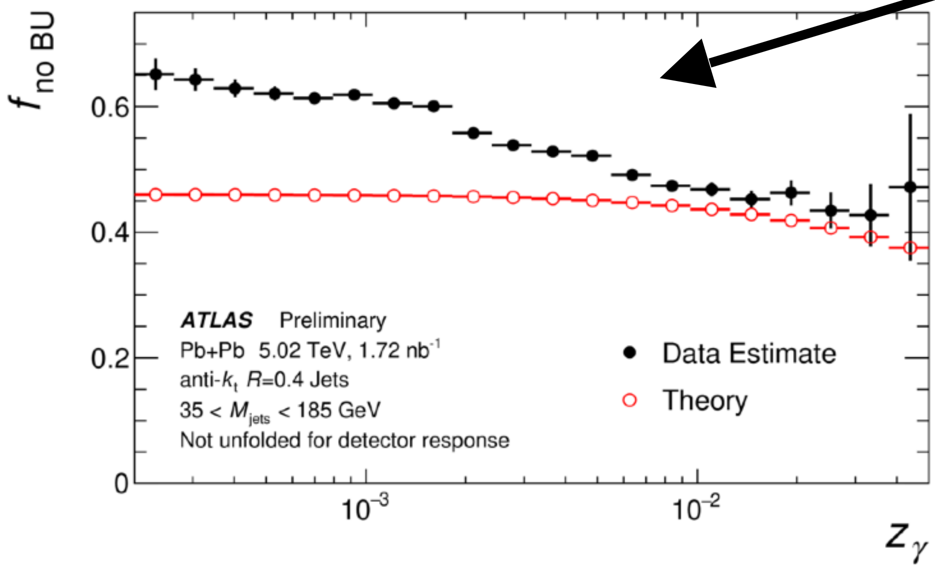
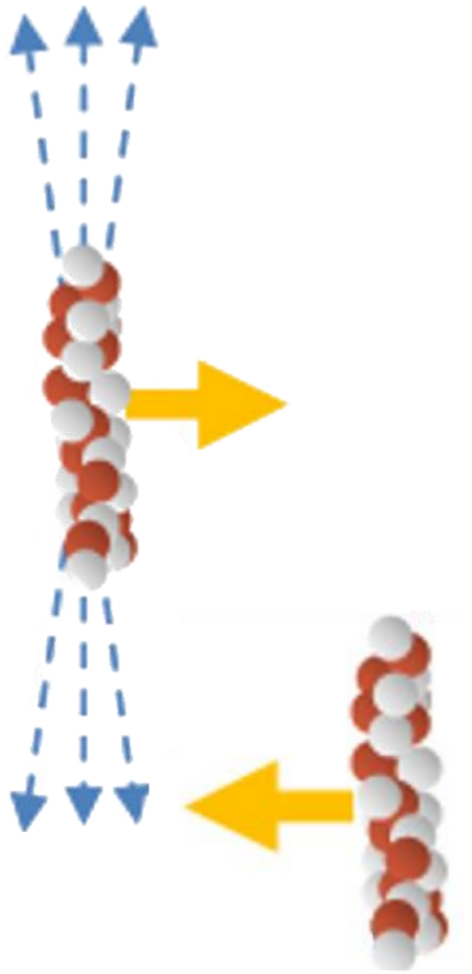


Studies of dijet events with large gaps on one side estimate about 50% of photo-nuclear jet production breaks up both nuclei!



Importance of Forward Neutrons: *XnXn* Events

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This theoretical model for breakup is used to compare theory to data.

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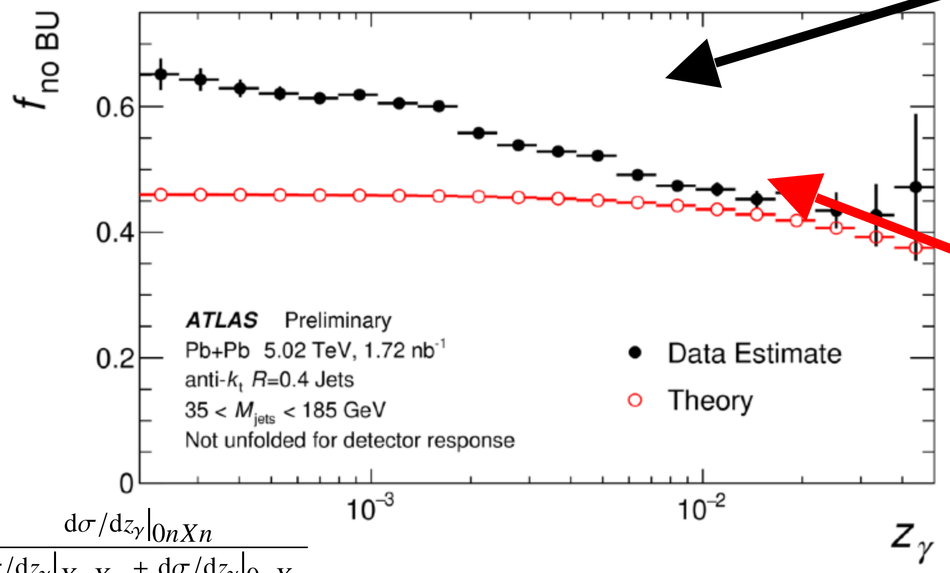
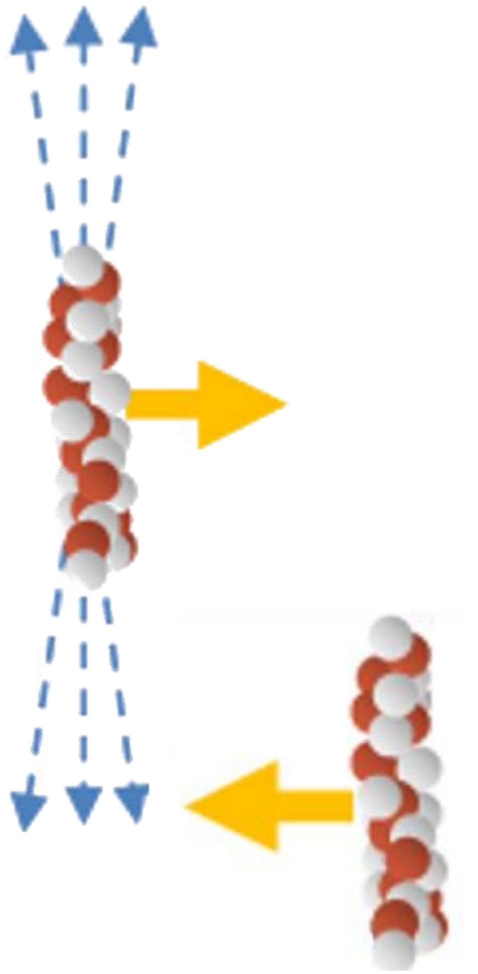


$$f_{\text{no BU}} \equiv \frac{d\sigma/dz_\gamma|_{0nXn}}{d\sigma/dz_\gamma|_{XnXn} + d\sigma/dz_\gamma|_{0nXn}}$$

Studies of dijet events with large gaps on one side estimate about 50% of photo-nuclear jet production breaks up both nuclei (i.e. XnXn)!

Simple theoretical model (based on STARlight formalism) predicts an even higher breakup rate.

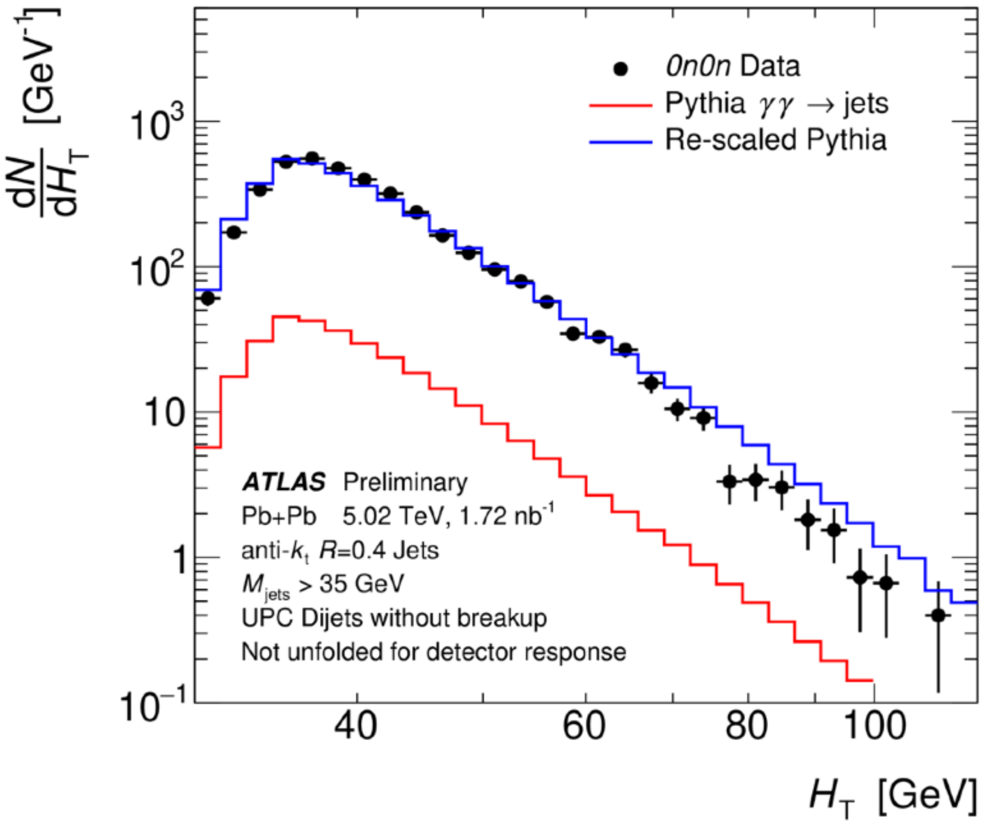


Importance of Forward Neutrons: *0n0n* Events

ATLAS has observed jet production in UPCs without nuclear breakup (0n0n) - cf. CMS arXiv:2205.00045

Gaps are required on both sides of the detector: $\sum \Delta\,\eta > 2.0$

A factor of 10 more events are observed in data than are predicted from $\gamma\gamma \rightarrow$ jets, estimated by Pythia or comparison to $\gamma\gamma \rightarrow \mu^{+}\mu^{-}$ studies.



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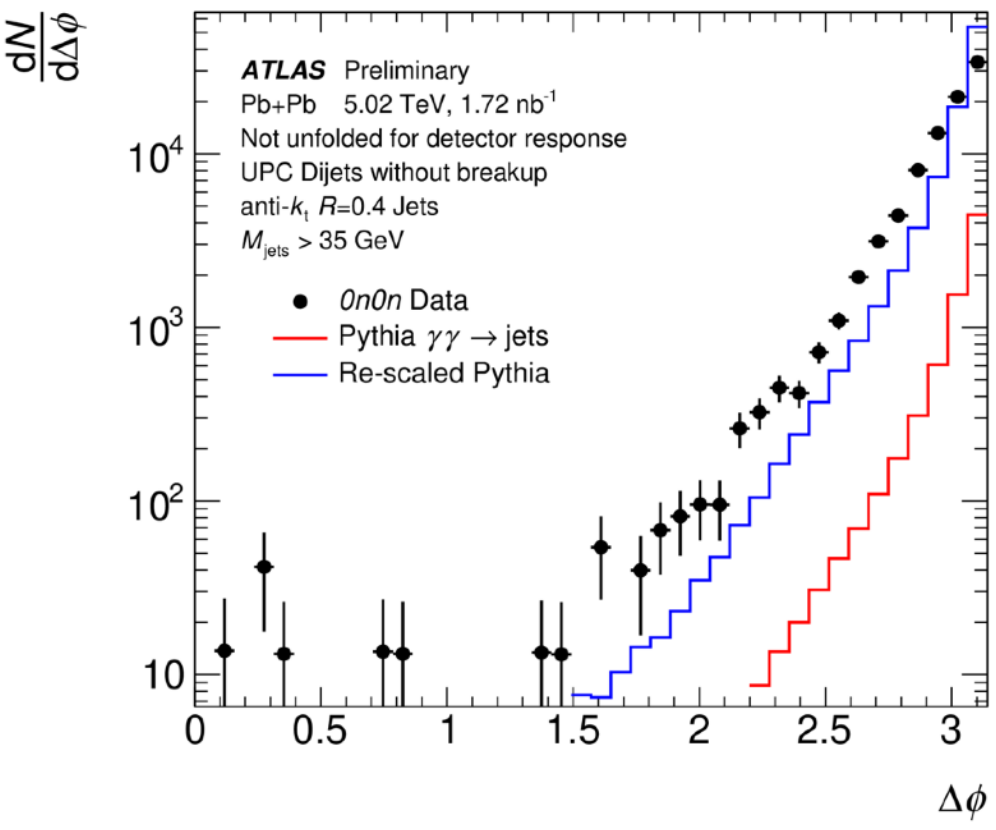
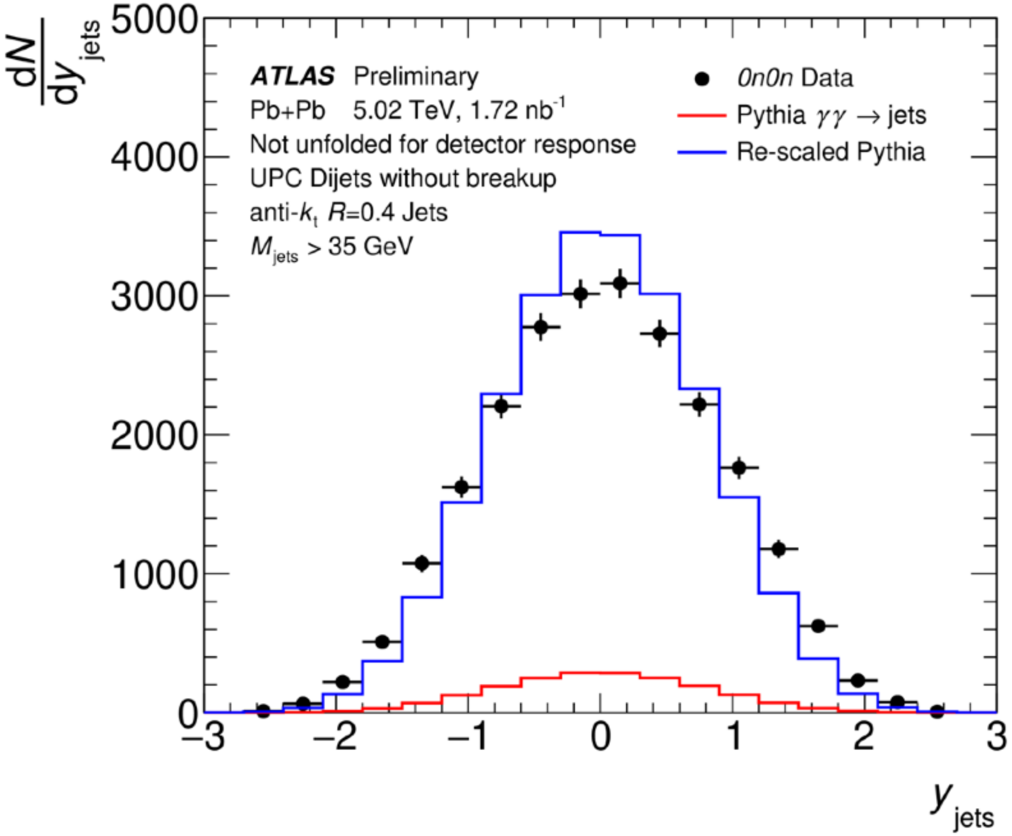
The distribution shapes look different than Pythia 8 $\gamma\gamma \rightarrow$ jets.

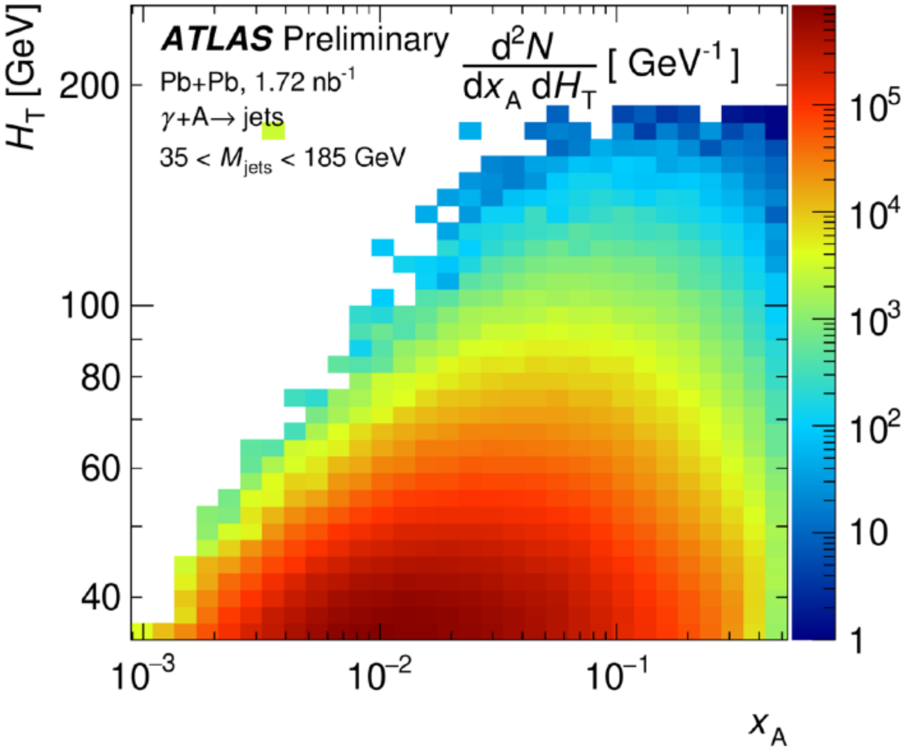




Constructing the Cross-Section

$$\frac{d^3\sigma}{dH_T dx_A dz_\gamma} = \frac{1}{\mathscr{L}} \frac{\Delta Y}{\Delta H_T \Delta x_A \Delta z_\gamma}$$

Event Selections → **Raw Yields** → Unfolding → Systematic Uncertainty → Final Results



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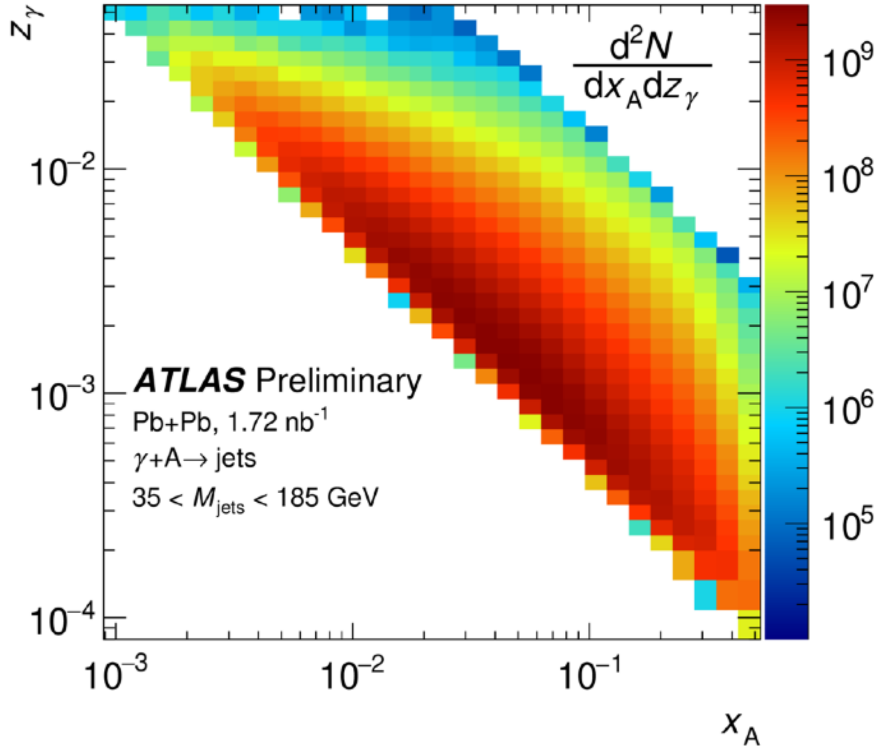

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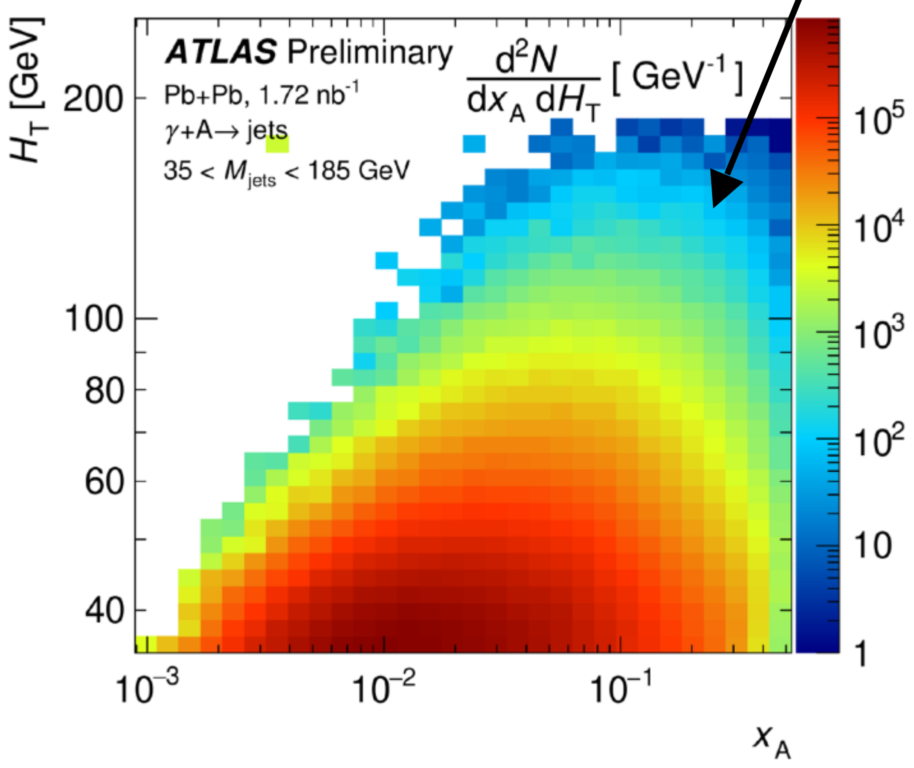
H_T does not depend strongly on x_A or z_γ.



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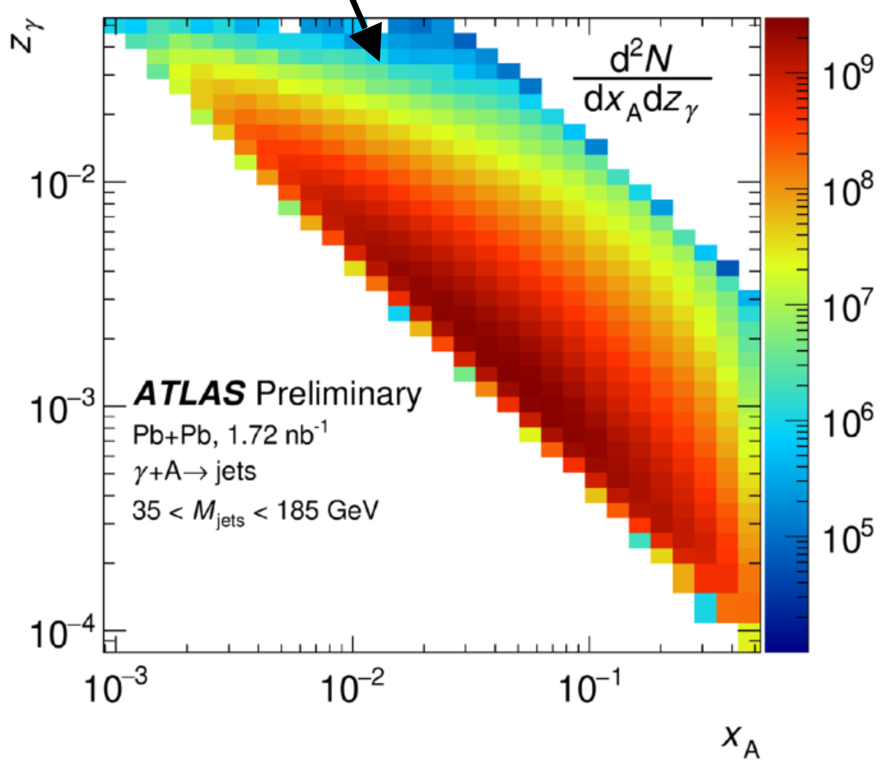
Acceptance in x_A is strongly dependent on the photon energy, z_γ.



Unfolding Measured Cross-Sections

Event Selections → Raw Yields → **Unfolding** → Systematic Uncertainty → Final Results

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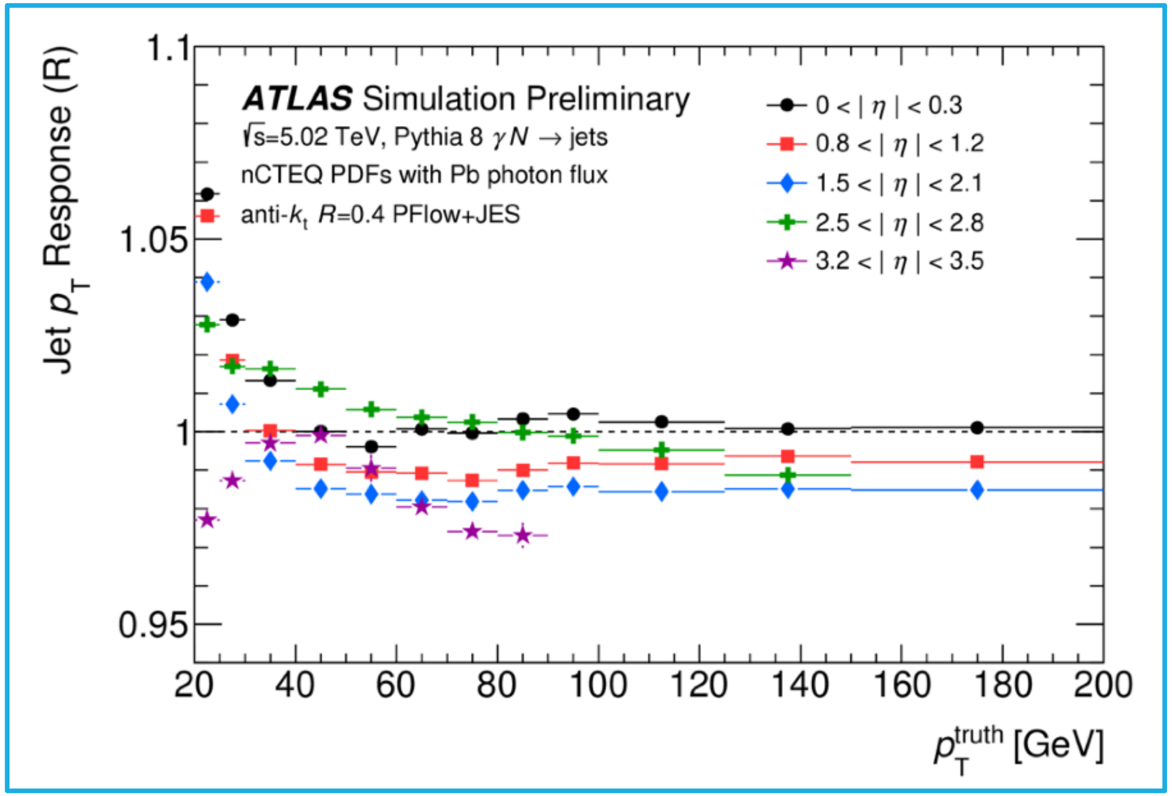
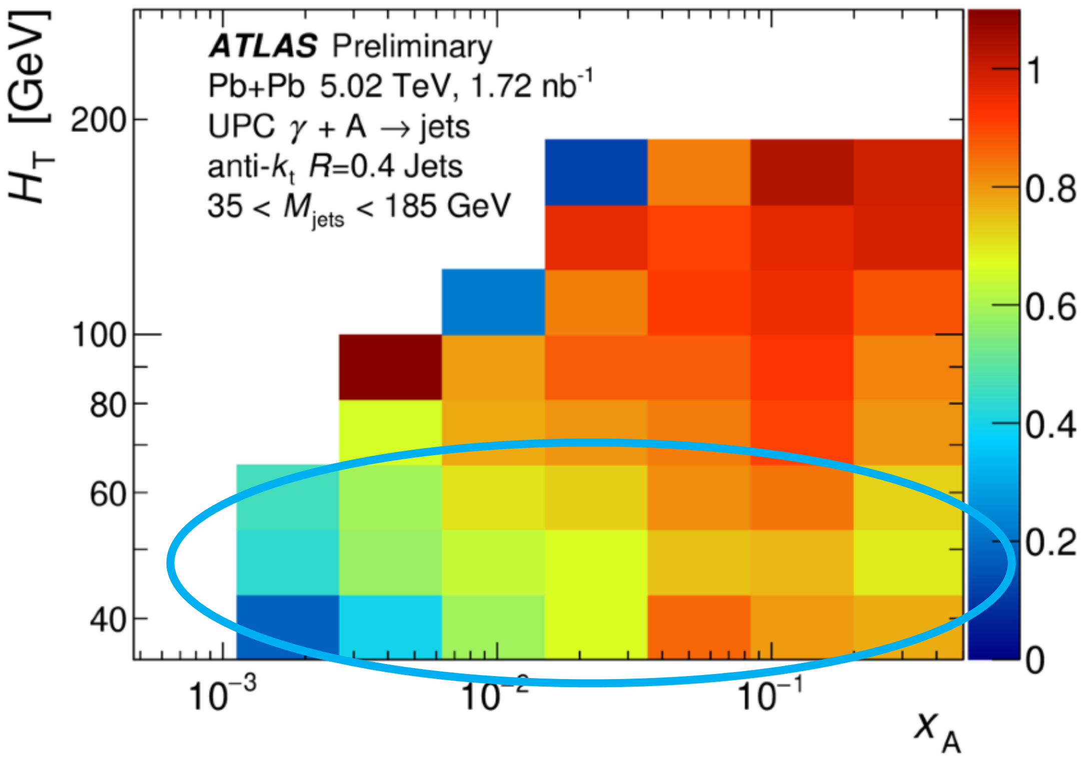
The measured cross-sections are then unfolded in 3 dimensions to correct for detector effects.

- Low-p_T flavor effects are the largest correction.



Unfolded / Measured



Systematic Uncertainties

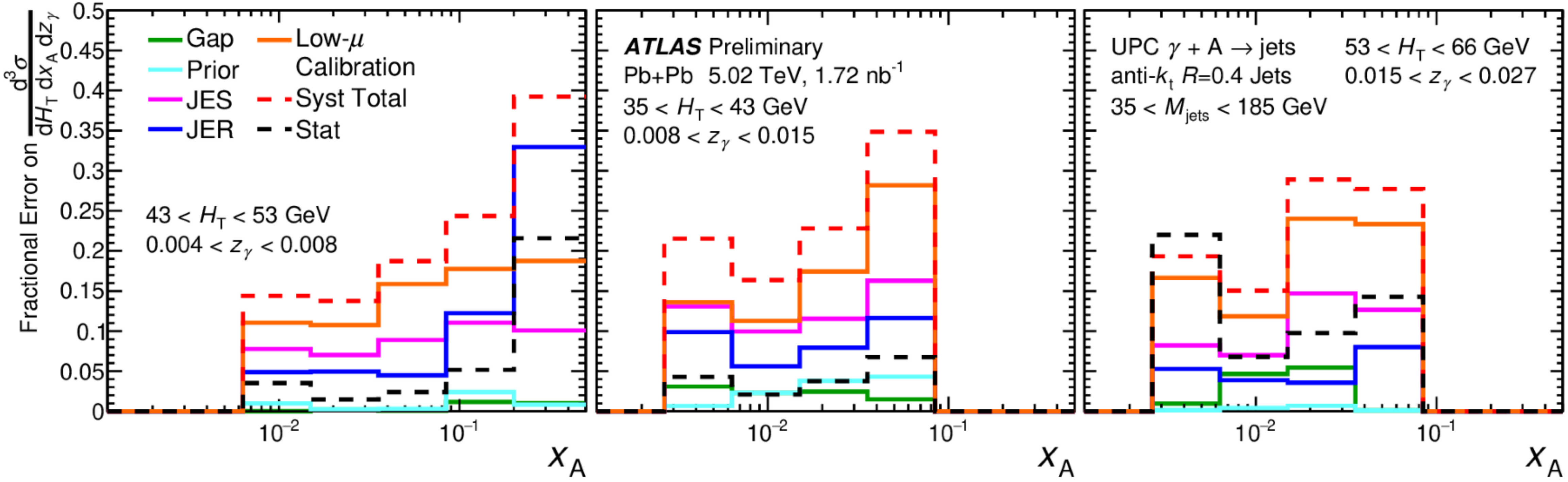
Event Selections → Raw Yields → Unfolding → **Systematic Uncertainty** → Final Results

Systematic uncertainties are the key limiting factor in our sensitivity to nuclear PDFs.

The jet energy scale and resolution uncertainties are typically 5-10%.

Control over the preliminary low-μ calibration currently provides the dominant source of uncertainty.

Systematic uncertainties are also evaluated on the unfolding and event selections.



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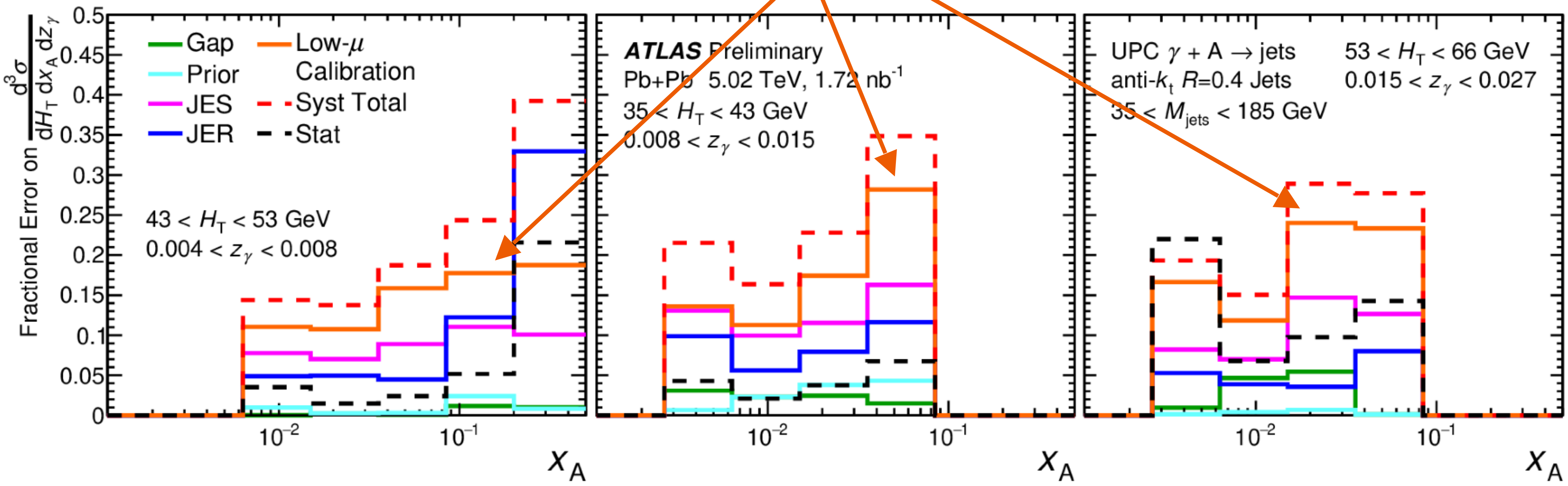
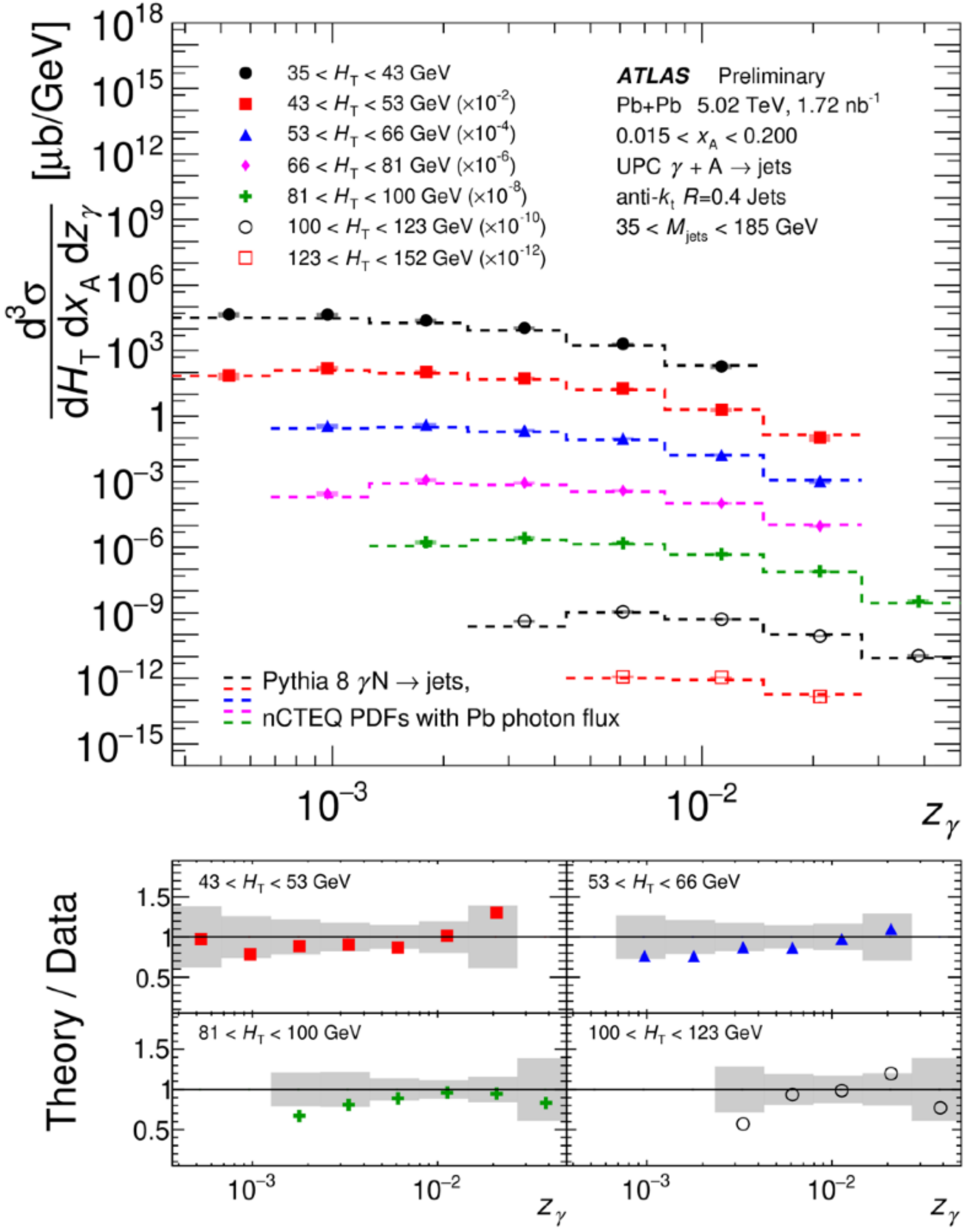


The Measured Photon Flux

Event Selections → Raw Yields → Unfolding → Systematic Uncertainty → **Final Results**

- The distribution of z_γ values for large x_A in bins of H_T (right) reflects the photon flux.
  - The breakup model performs well within systematic uncertainties.
  - Disagreements appear to arise at low z_γ, where the breakup model tends to over-correct.



Scanning in Photon Energy

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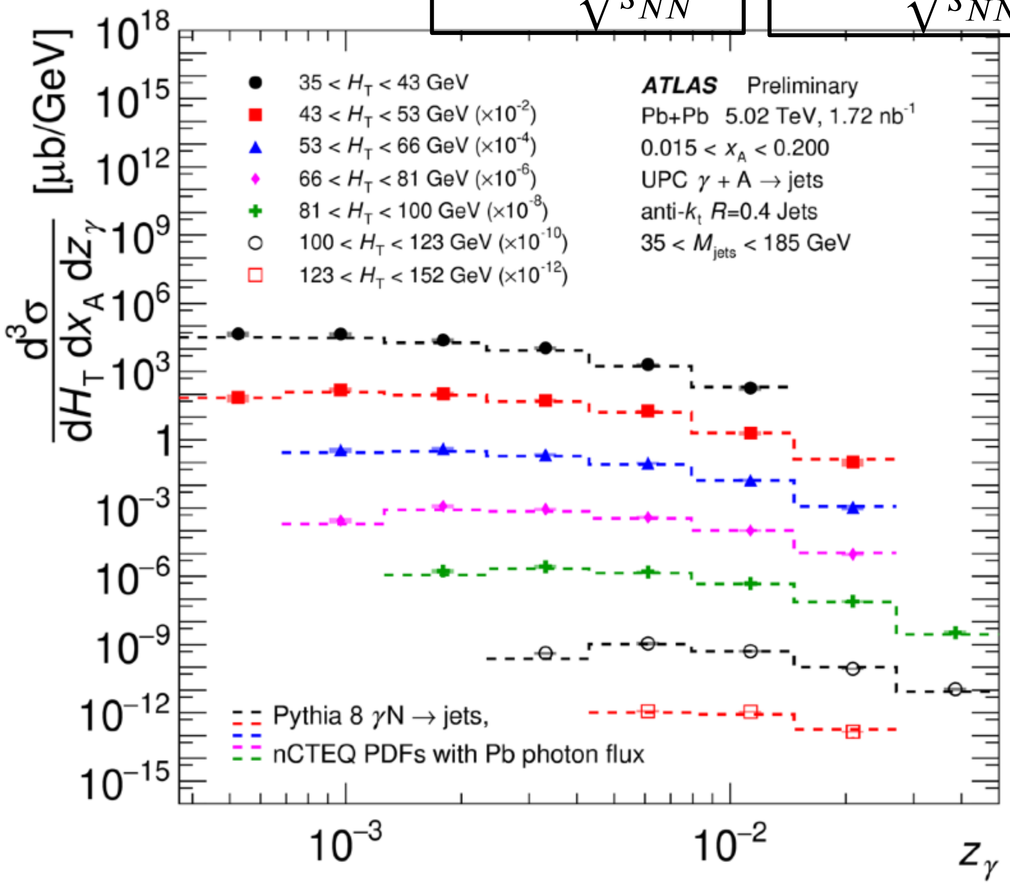
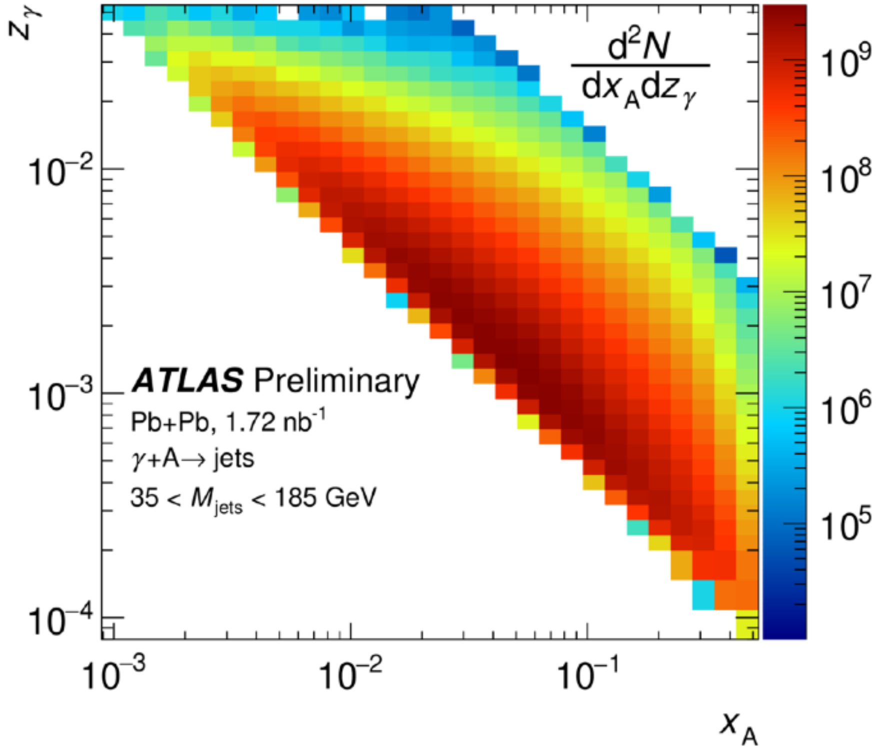


The x_A distribution has substantial acceptance effects in z_γ.

Selecting on photon energy removes this bias, allowing a more direct measurement of nPDFs.



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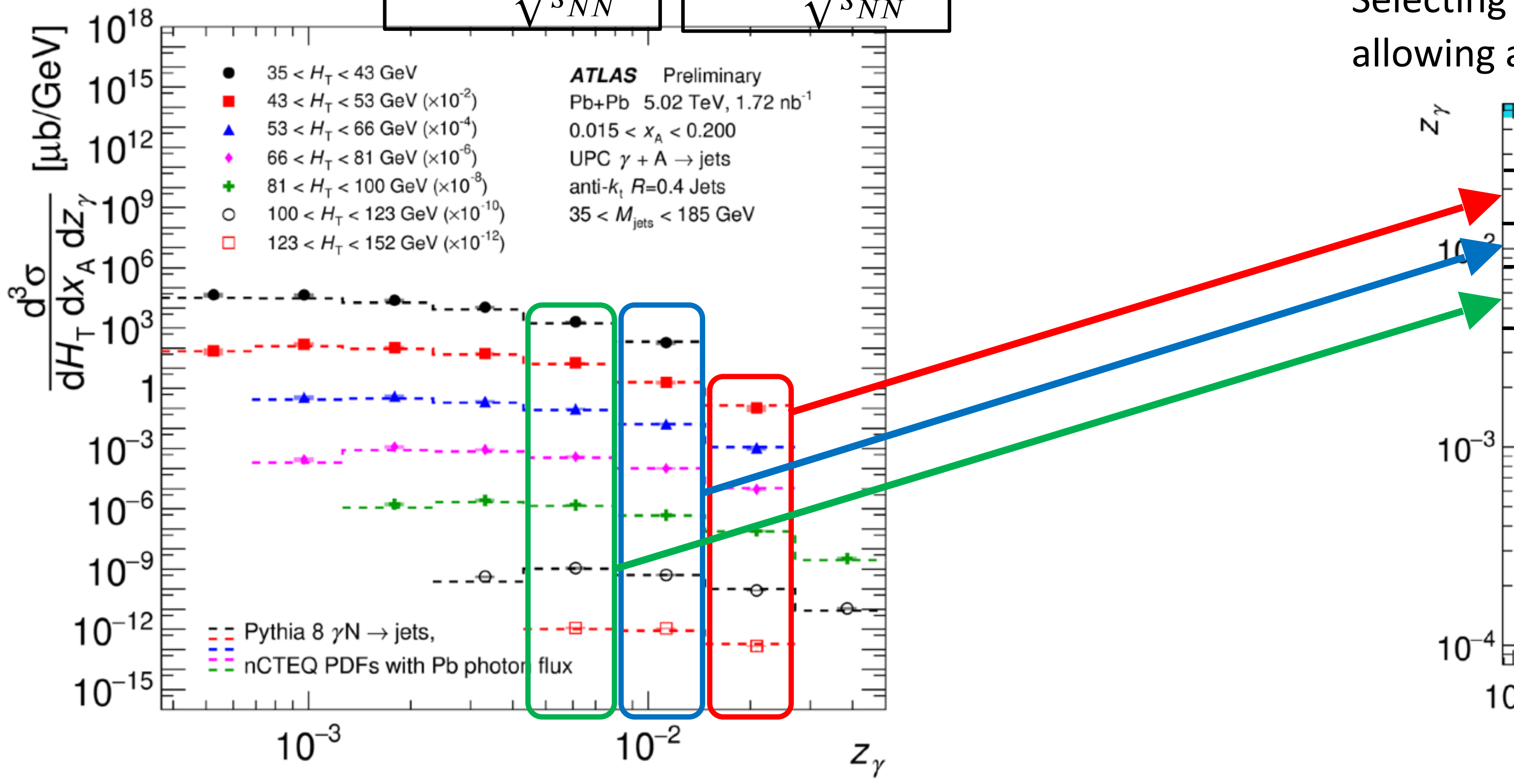

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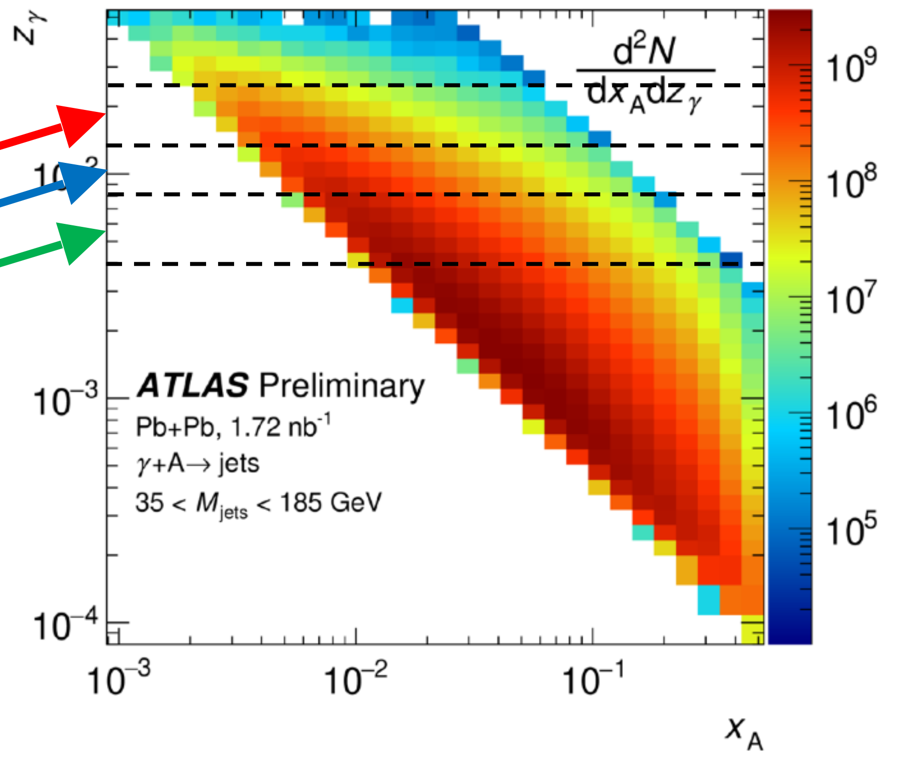
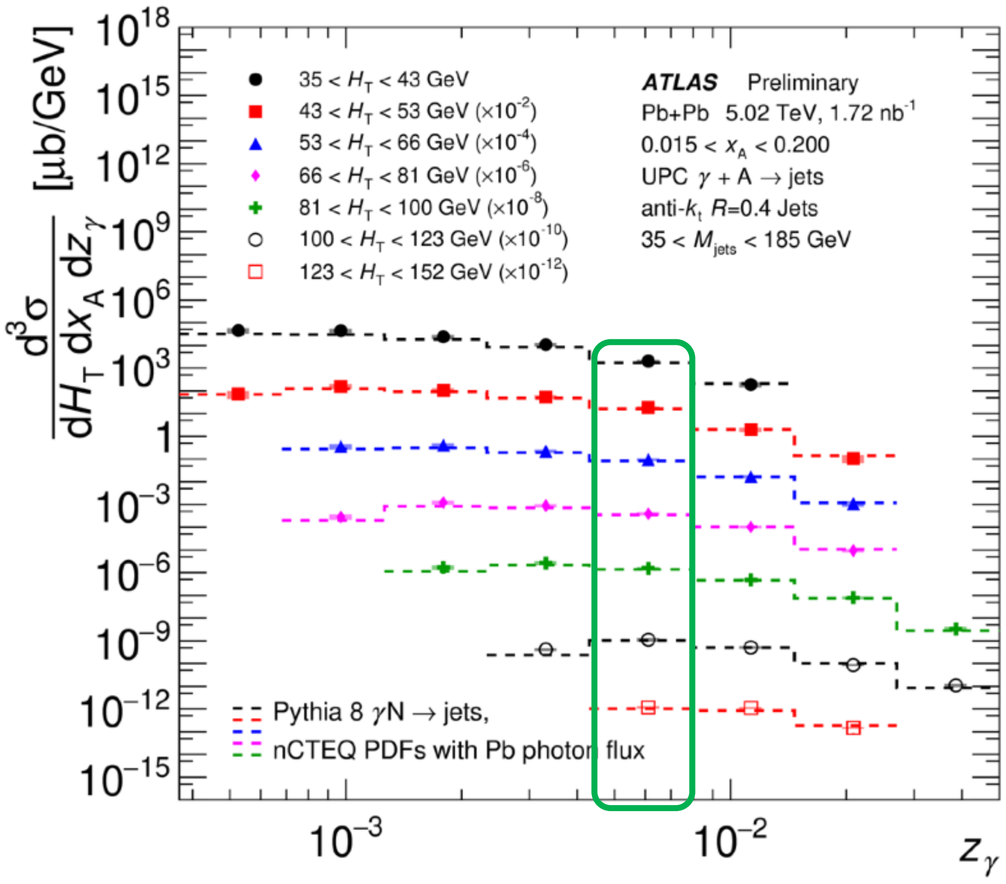


Measured Cross-Sections

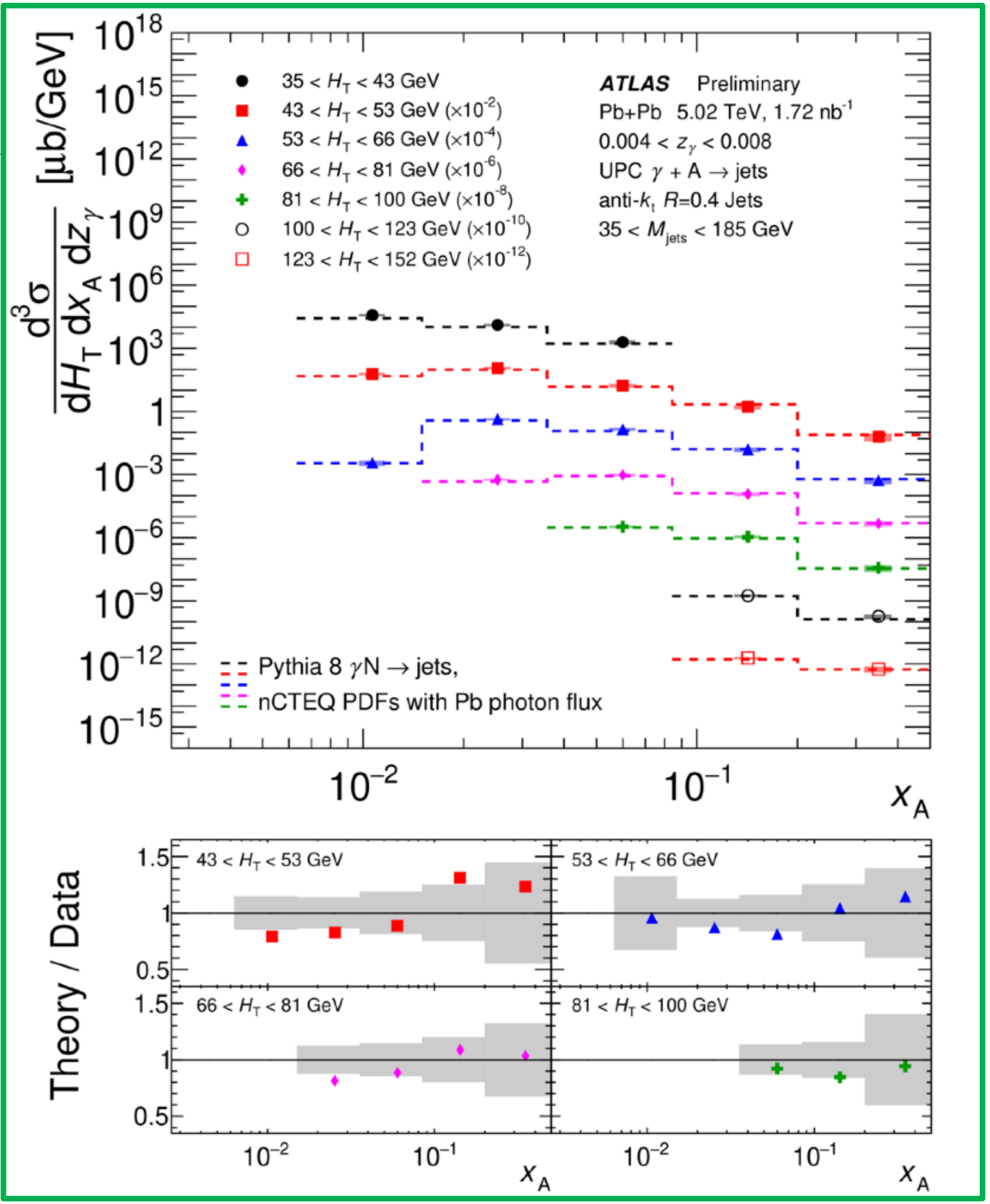
Event Selections → Raw Yields → Unfolding → Systematic Uncertainty → Final Results

- At intermediate photon energies, we can access higher-x partons.



Photon Energy

$0.004 < z_\gamma < 0.008$



Measured Cross-Sections

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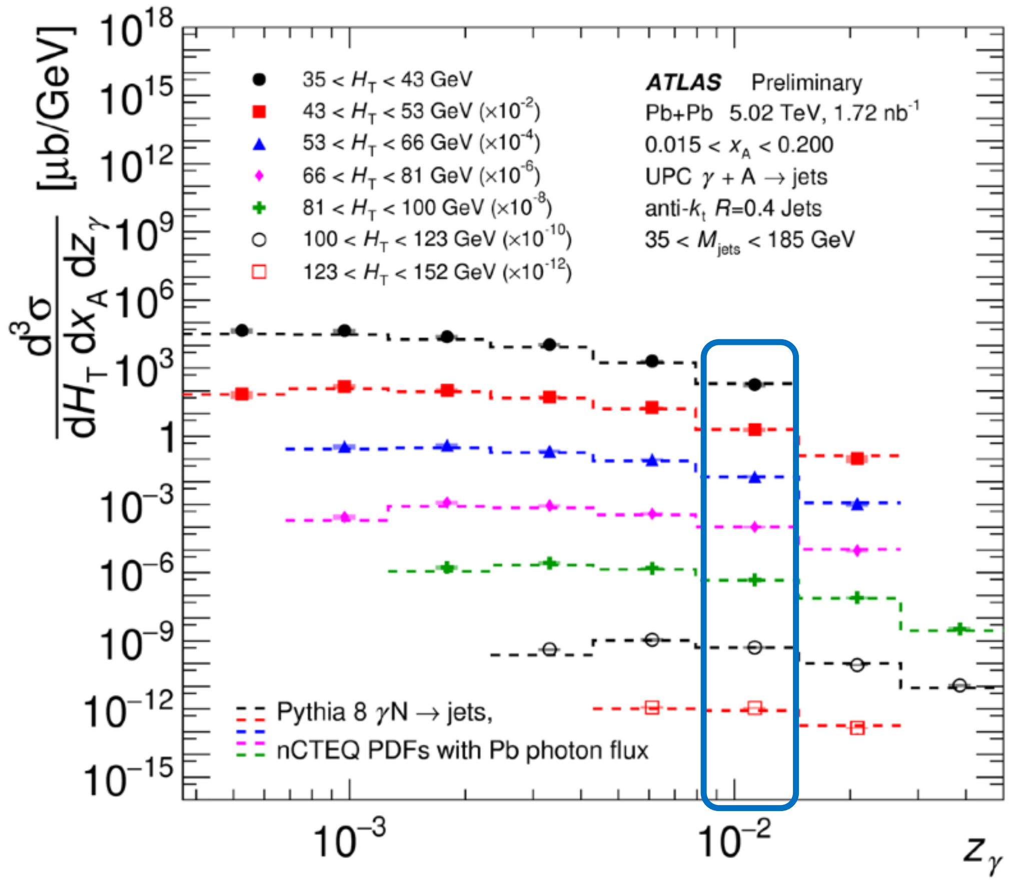
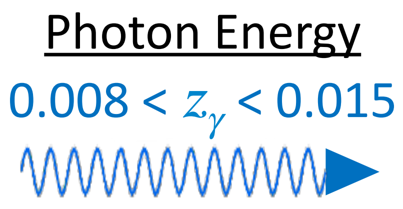
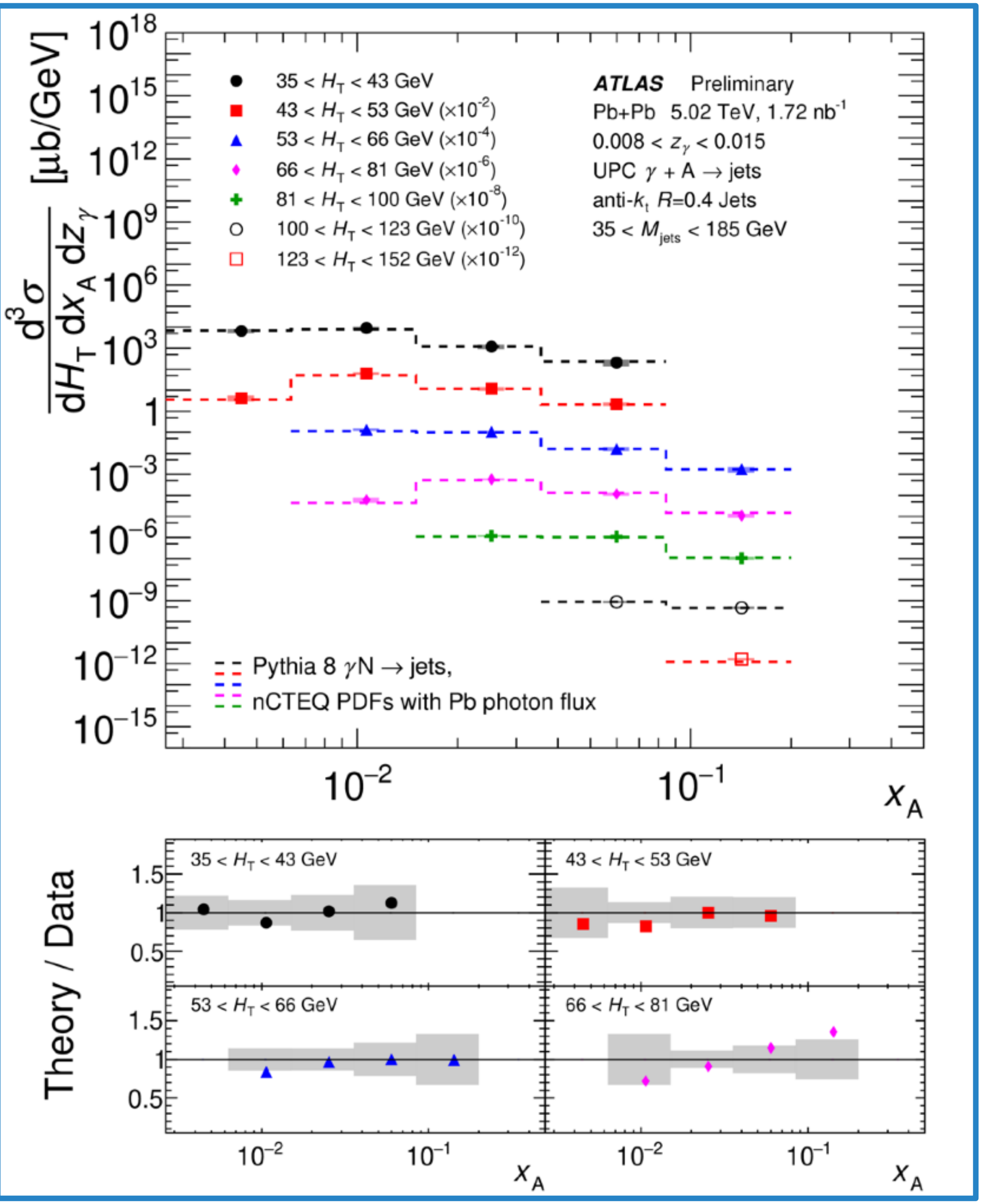
- Higher photon energy opens up the low-x shadowing region.
- Results are quite consistent with the theoretical model.



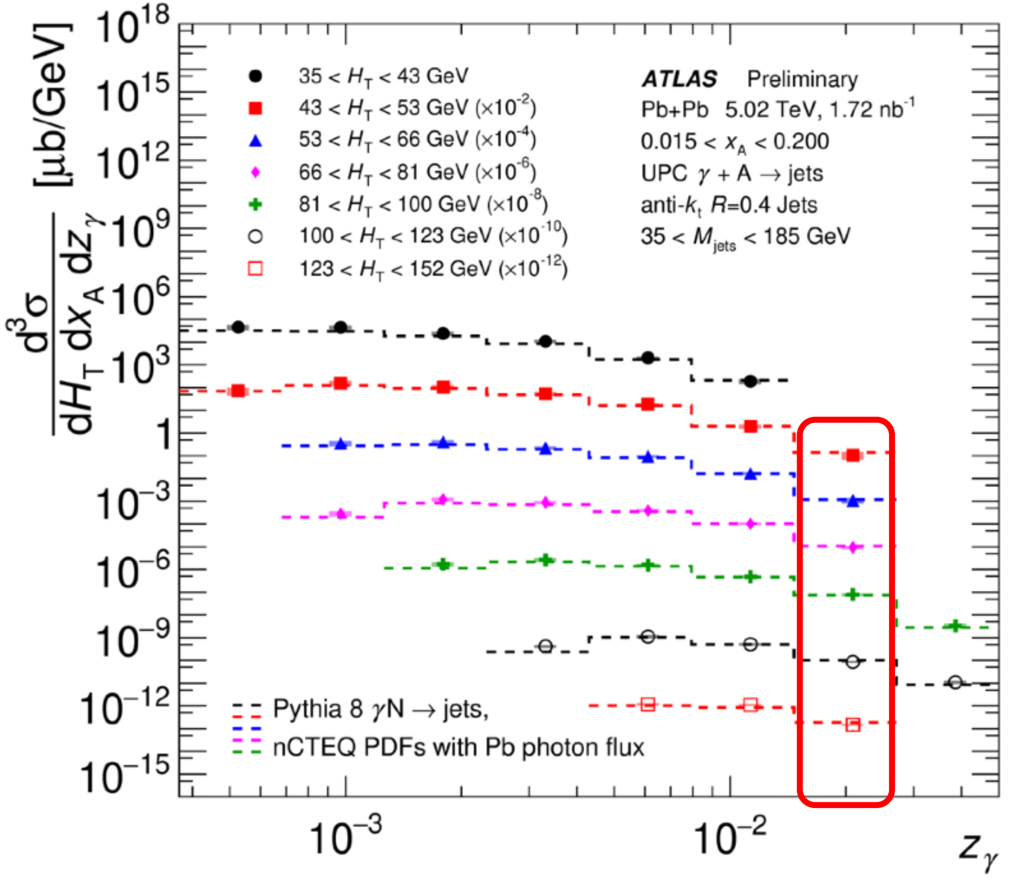




Measured Cross-Sections

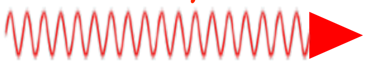
Event Selections → Raw Yields → Unfolding → Systematic Uncertainty → **Final Results**

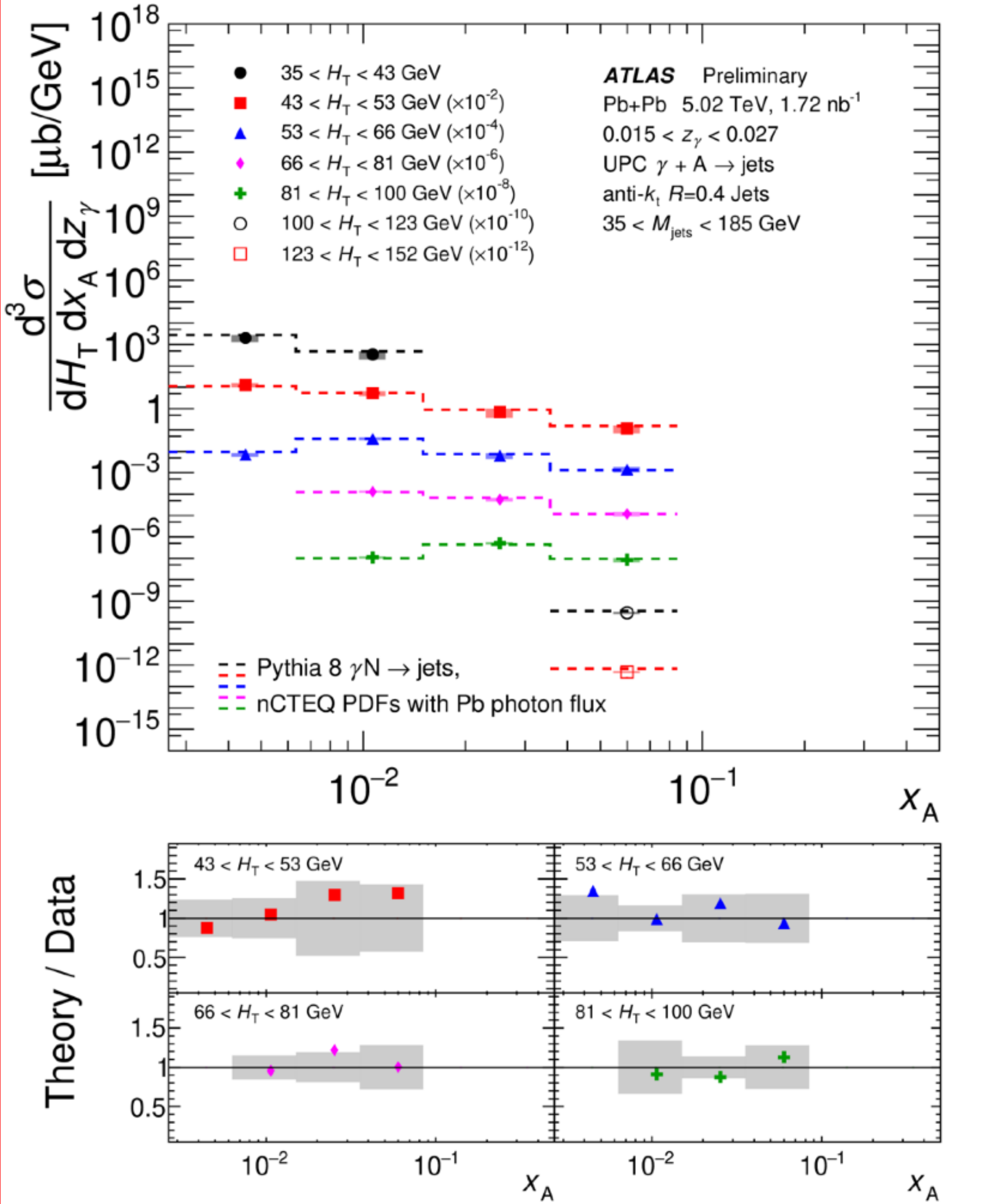
- The highest photon energy allows the most access to low x.
- Systematic control is more challenging near acceptance edges.



Photon Energy

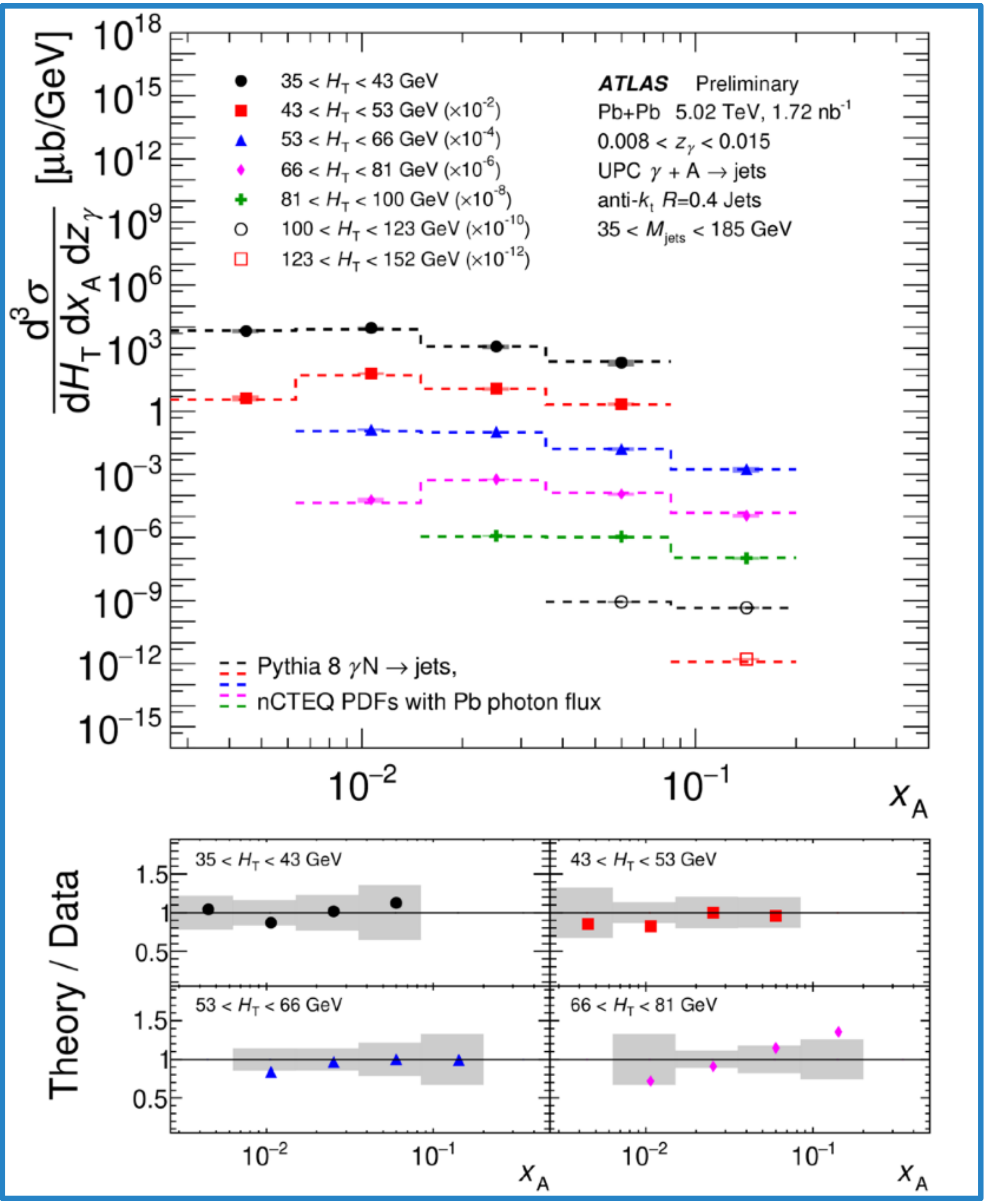
$0.015 < z_\gamma < 0.027$





Conclusions and Next Steps

- Photo-nuclear jet production was measured by ATLAS in 5.02 TeV Pb+Pb collisions with 2018 data.
  - Particle-Flow jets allow for the measurement to be extended even lower in jet p_T while maintaining systematic control.
  - This measurement has been fully unfolded for detector response for the first time.
- The overall normalization of the cross-section is well-predicted by theoretical comparisons.
  - A theoretical model of nuclear breakup is necessary to understand the total cross-section.
- This study is sensitive to nuclear PDF effects with a precision of up to 10% in some bins.
  - Once final studies of low-μ jet response in ATLAS can be completed, substantial gains in systematic control are possible.
- These results should offer helpful input for preparations for early results at the EIC.



Backup

Theoretical Modeling of Nuclear Breakup

- The photon flux available through Pythia makes certain overly-simplified assumptions which we correct via modeling with STARlight.

Integrate over A-A impact parameter (b) and the impact parameter relative to the photon-emitting nucleus (s_A).

Correction for the probability of breakup due to additional EM interactions

Nuclear thickness function

$$F^{\mathrm{eff}}_{\gamma/A}(E_\gamma) \equiv \int \mathrm{d}^2 b \mathrm{d}^2 s_A P_{\mathrm{no\ had}}(b) P_{\mathrm{no\ EM}}(b) f_{\gamma/A}(E_\gamma, s) T_B(\vec{s}_A - \vec{b})$$

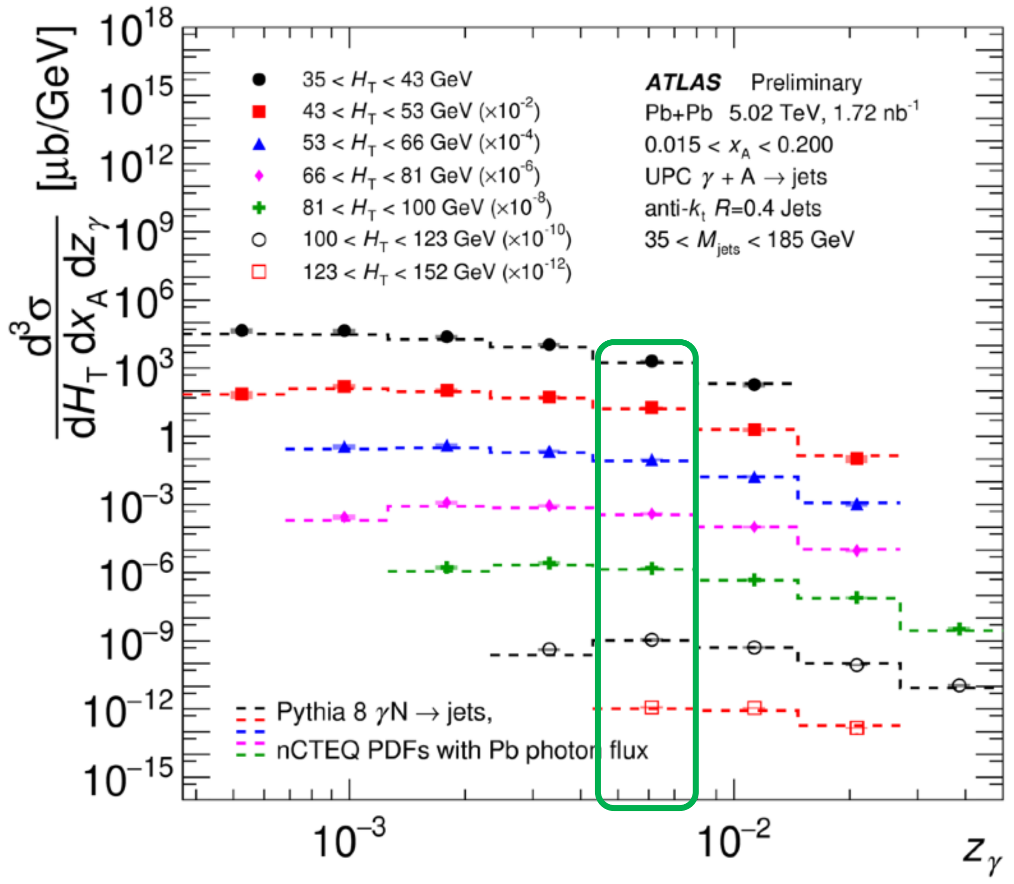
Correction for the probability of breakup due to hadronic interactions (overlap veto)

The photon flux from Pythia uses a point source, so this term corrects for coherent nuclear emission.

Measured Cross-Sections

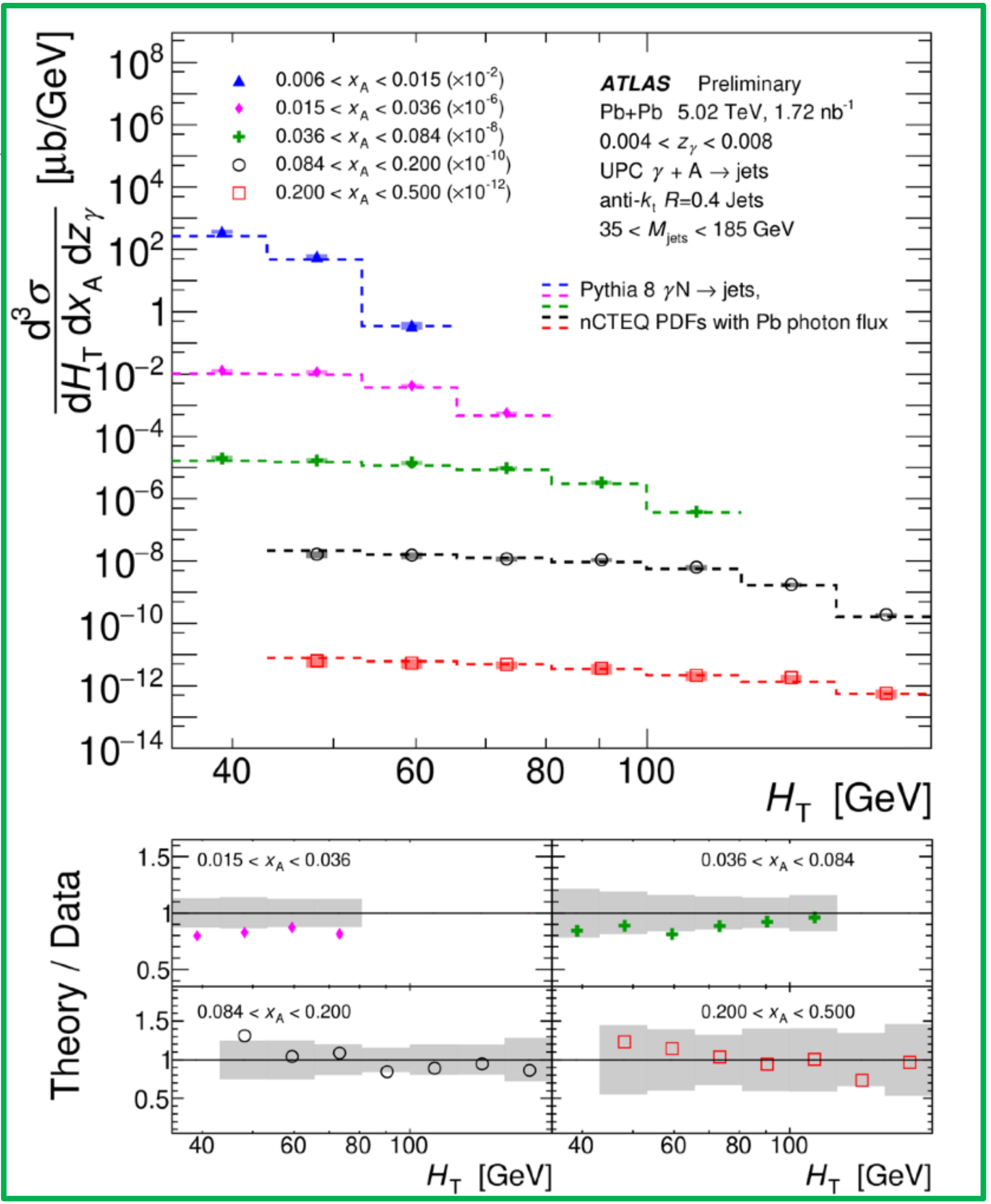
Event Selections → Raw Yields → Unfolding → Systematic Uncertainty → **Final Results**

- At intermediate photon energies, we can access higher-x partons.



Photon Energy

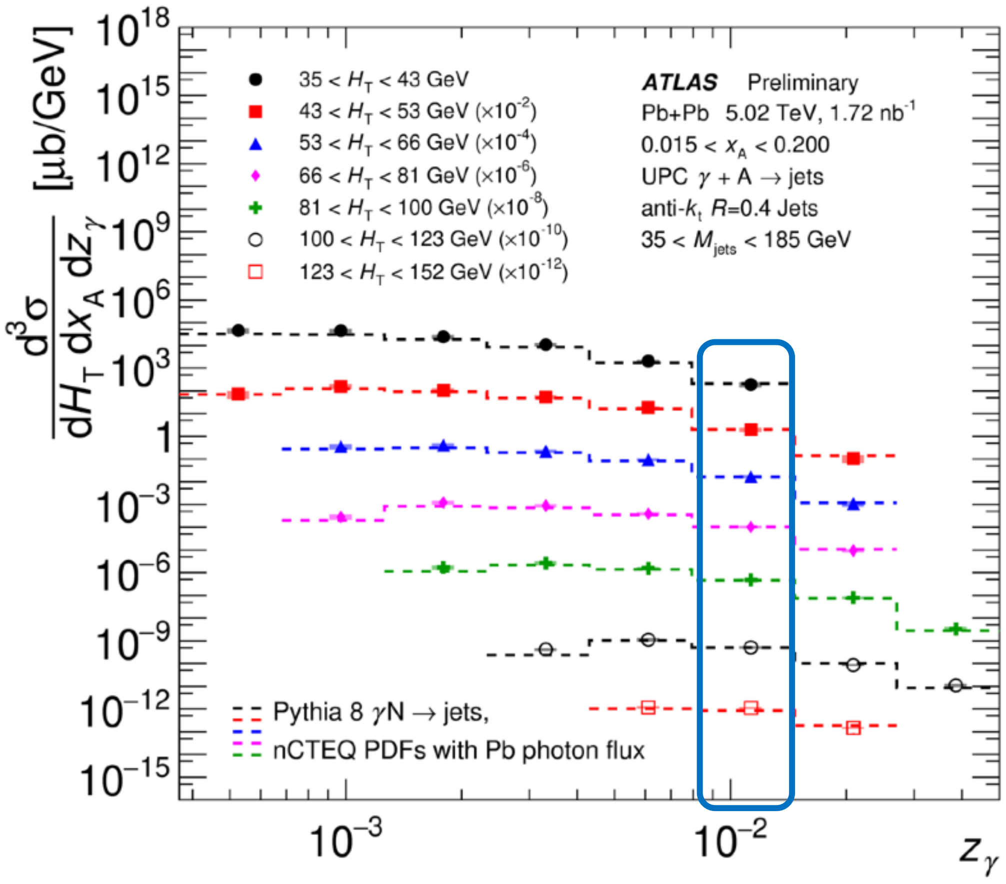
$0.004 < z_\gamma < 0.008$



Measured Cross-Sections

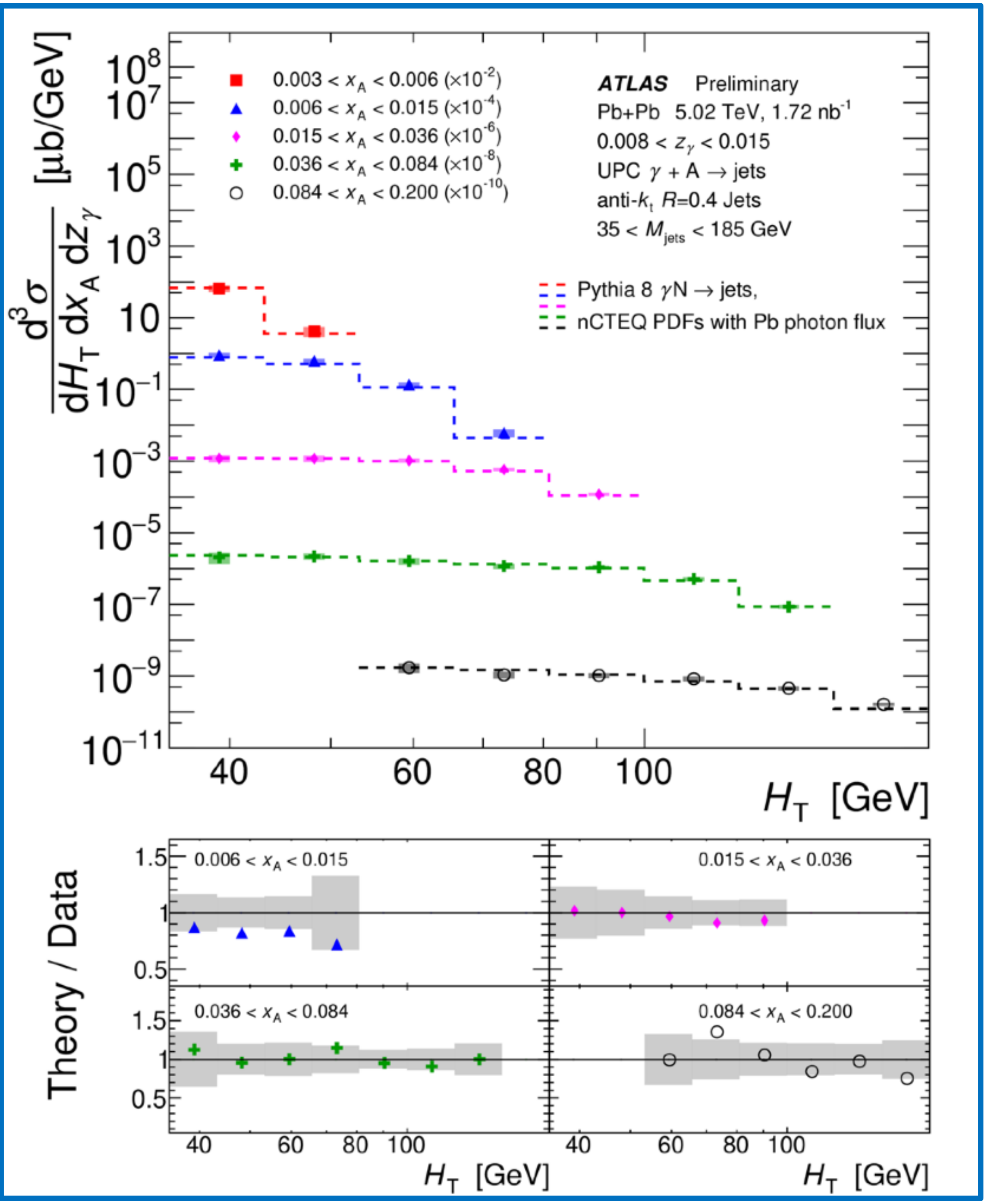
Event Selections → Raw Yields → Unfolding → Systematic Uncertainty → **Final Results**

- Higher photon energy opens up the low-x shadowing region.
- Results are quite consistent with the theoretical model.



Photon Energy

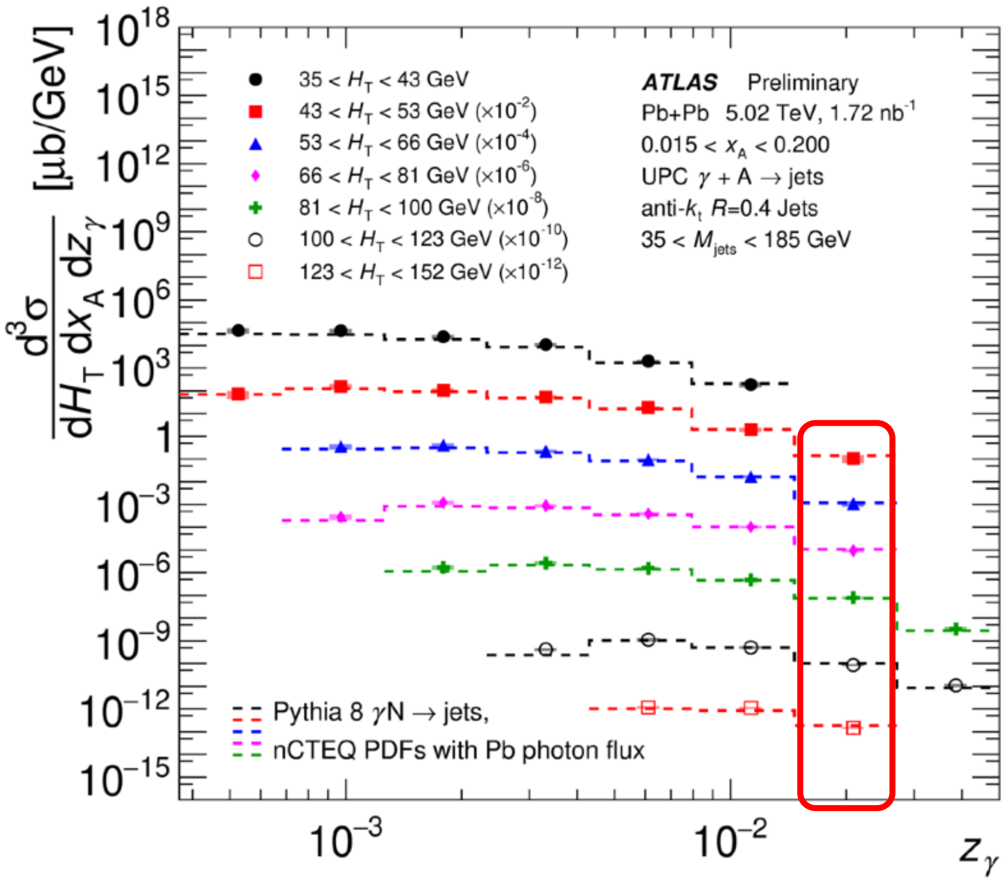
$0.008 < z_{\gamma} < 0.015$



Measured Cross-Sections

Event Selections → Raw Yields → Unfolding → Systematic Uncertainty → **Final Results**

- The highest photon energy allows the most access to low x.
- Systematic control is more challenging near acceptance edges.



<u>Photon Energy</u>

$0.015 < z_\gamma < 0.027$