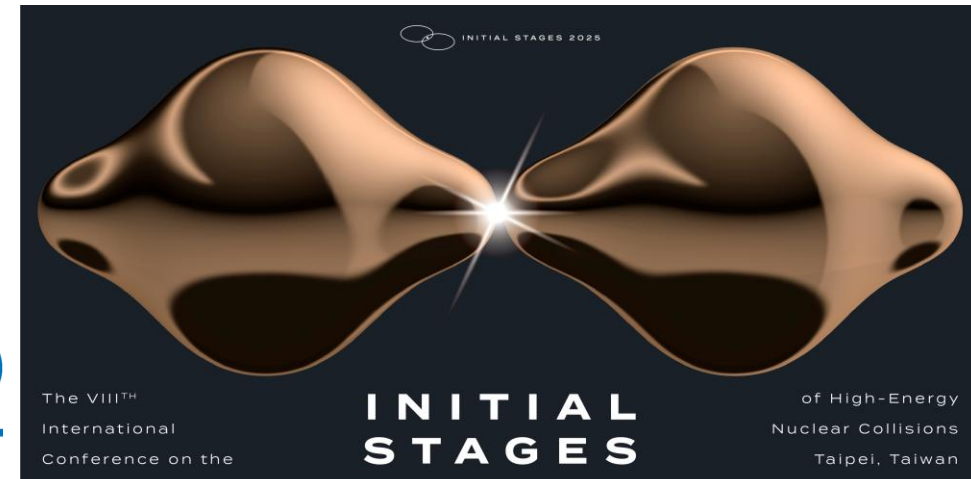


# UPC Jet and Top Quark probes of nuclear PDF effects with the ATLAS detector

Ben Gilbert, on behalf of the ATLAS Collaboration

[PRD 111 \(2025\) 052006](#)

[JHEP 11 \(2024\) 101](#)



# Introduction: Nuclear PDFs

- The kinematic coverage of world data constraining nuclear Parton Distribution Functions (nPDFs) has expanded massively with contributions from the LHC.
- Gaps still remain in the data determining nPDFs, leaving large stretches of phase space un-constrained.
  - We must currently rely on interpolation and miss the finer details of their evolution.
- The EIC will provide more coverage, but it is years away.
  - It still will not extend as high in  $Q^2$  as measurements from the LHC.

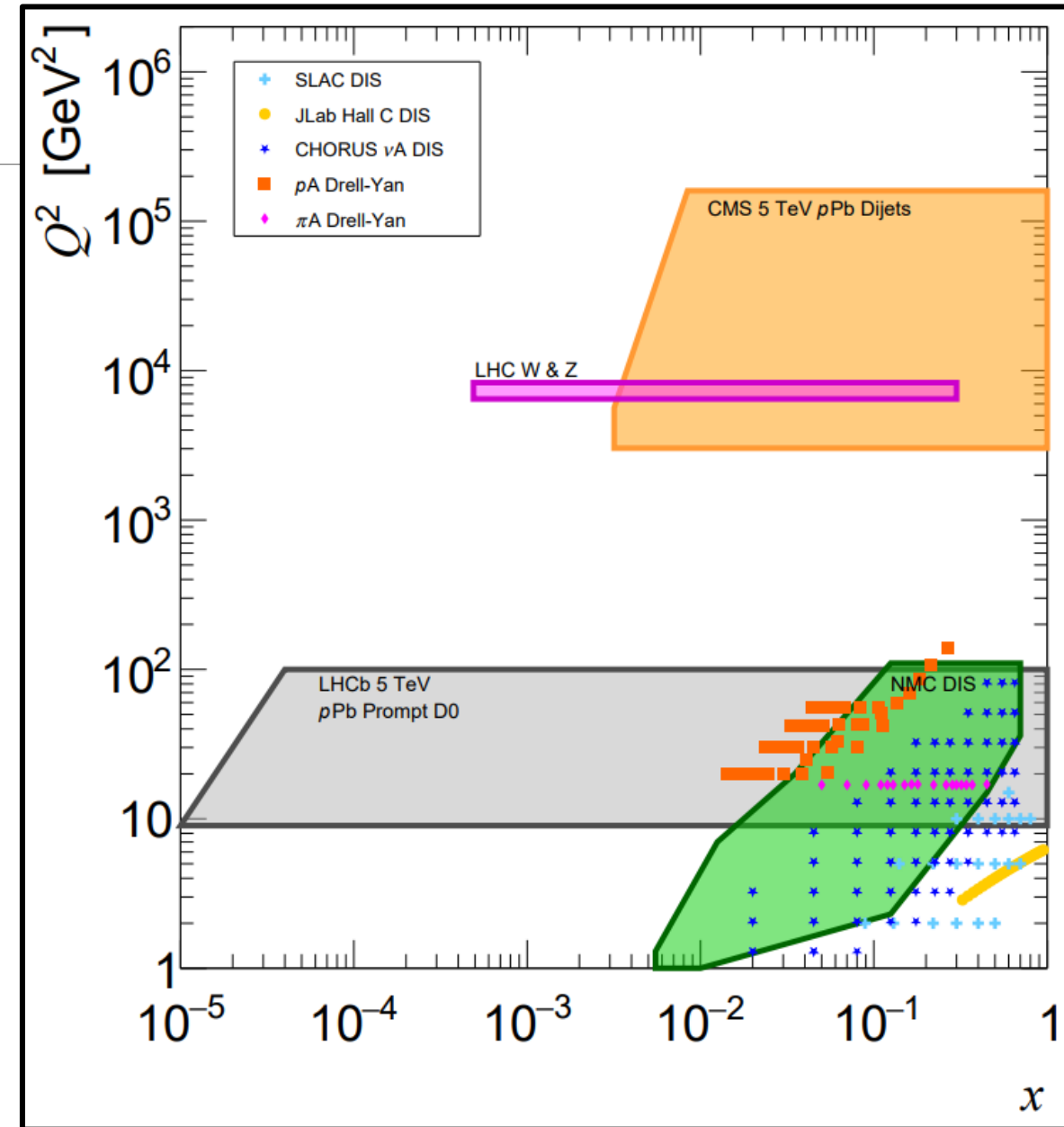


Figure inspired by [arXiv:2112.12462](https://arxiv.org/abs/2112.12462)

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  - We must currently rely on interpolation and miss the finer details of their evolution.
- The EIC will provide more coverage, but it is years away.
  - It still will not extend as high in  $Q^2$  as measurements from the LHC.
- Two recent ATLAS measurements will help to constrain a large region of this phase-space:
  - Top quark pair production in 8.16 TeV p+Pb collisions
  - Dijet production in 5.02 TeV ultra-peripheral Pb+Pb collisions

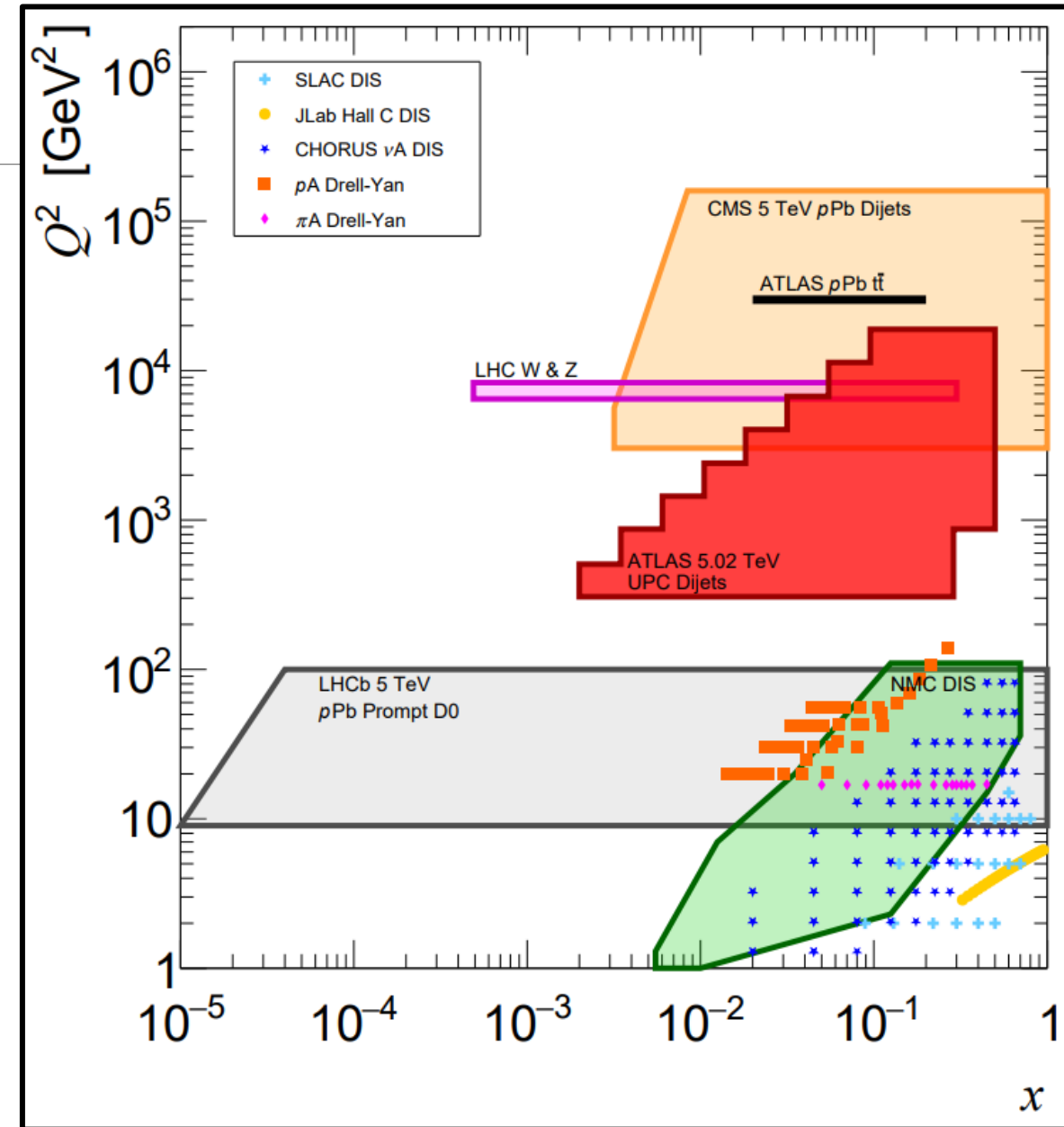
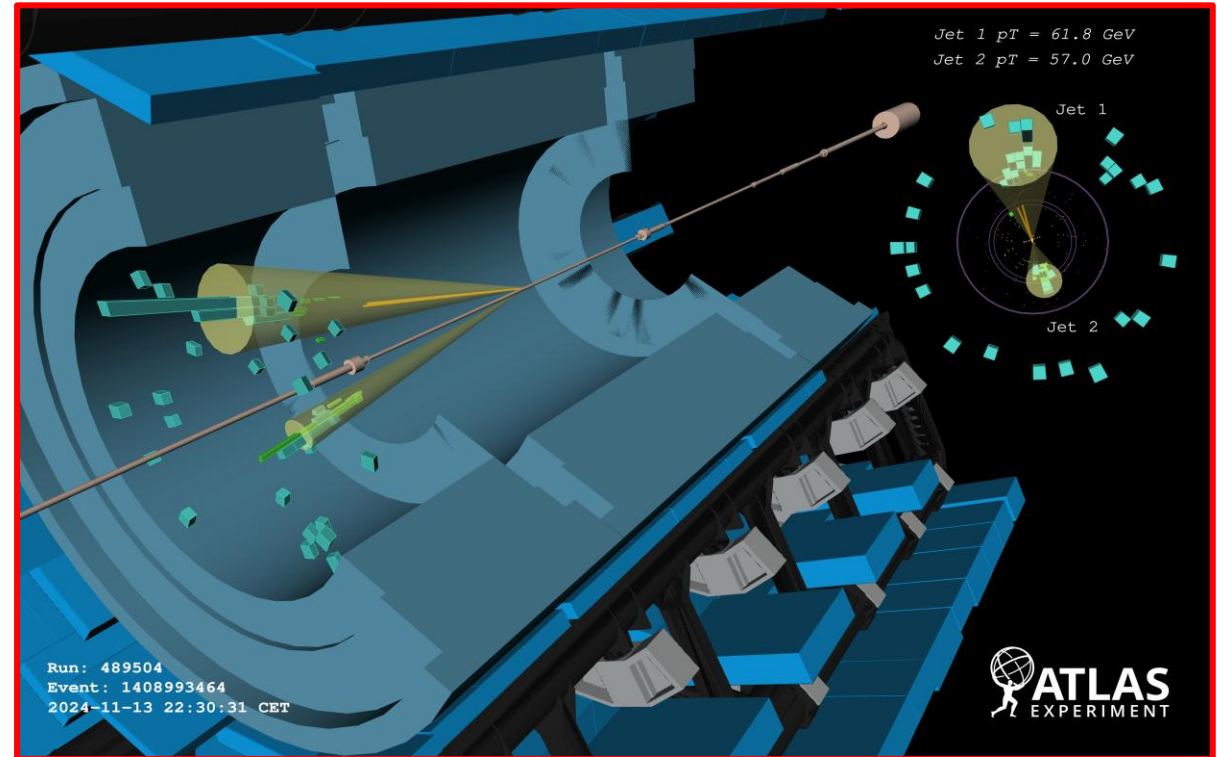
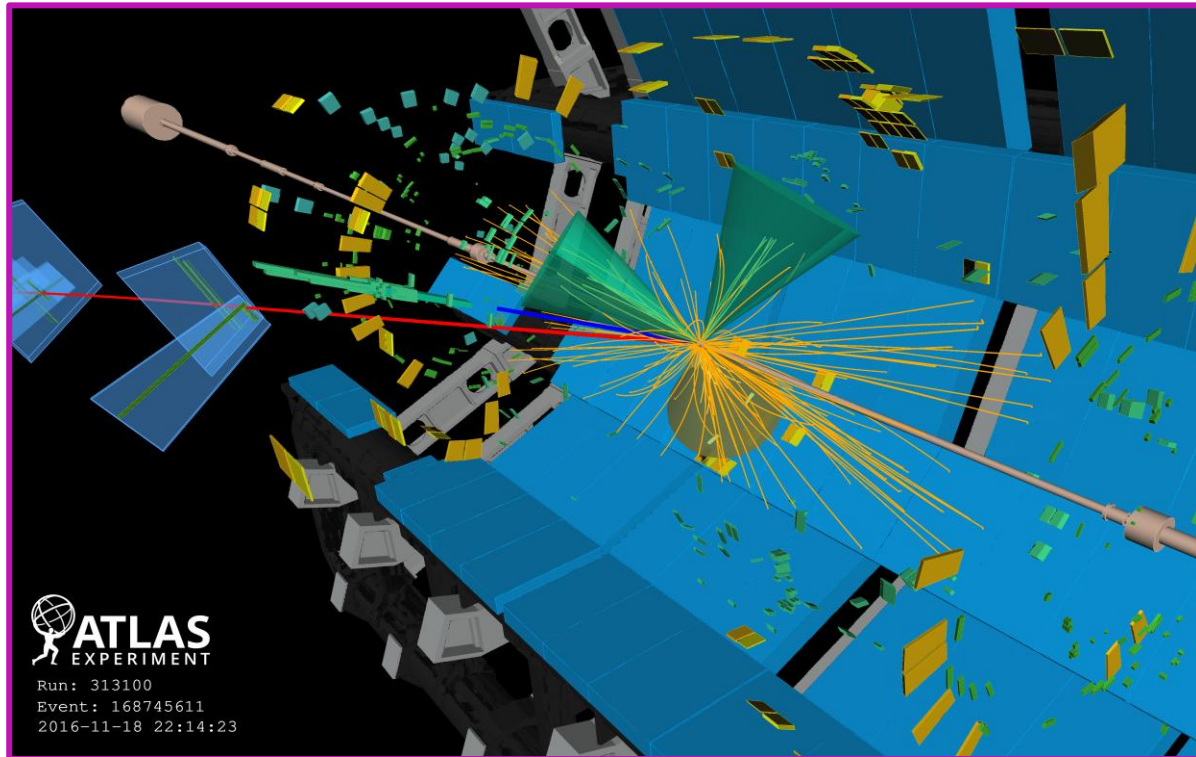
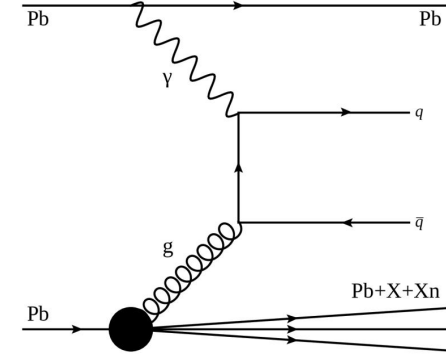
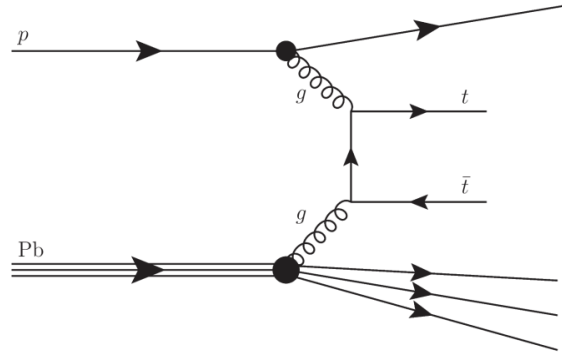


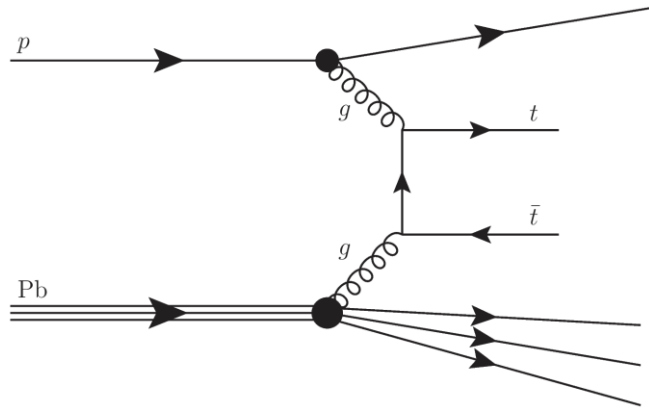
Figure inspired by [arXiv:2112.12462](https://arxiv.org/abs/2112.12462)

# Measurement Strategies



# Top Quark Measurement Channels

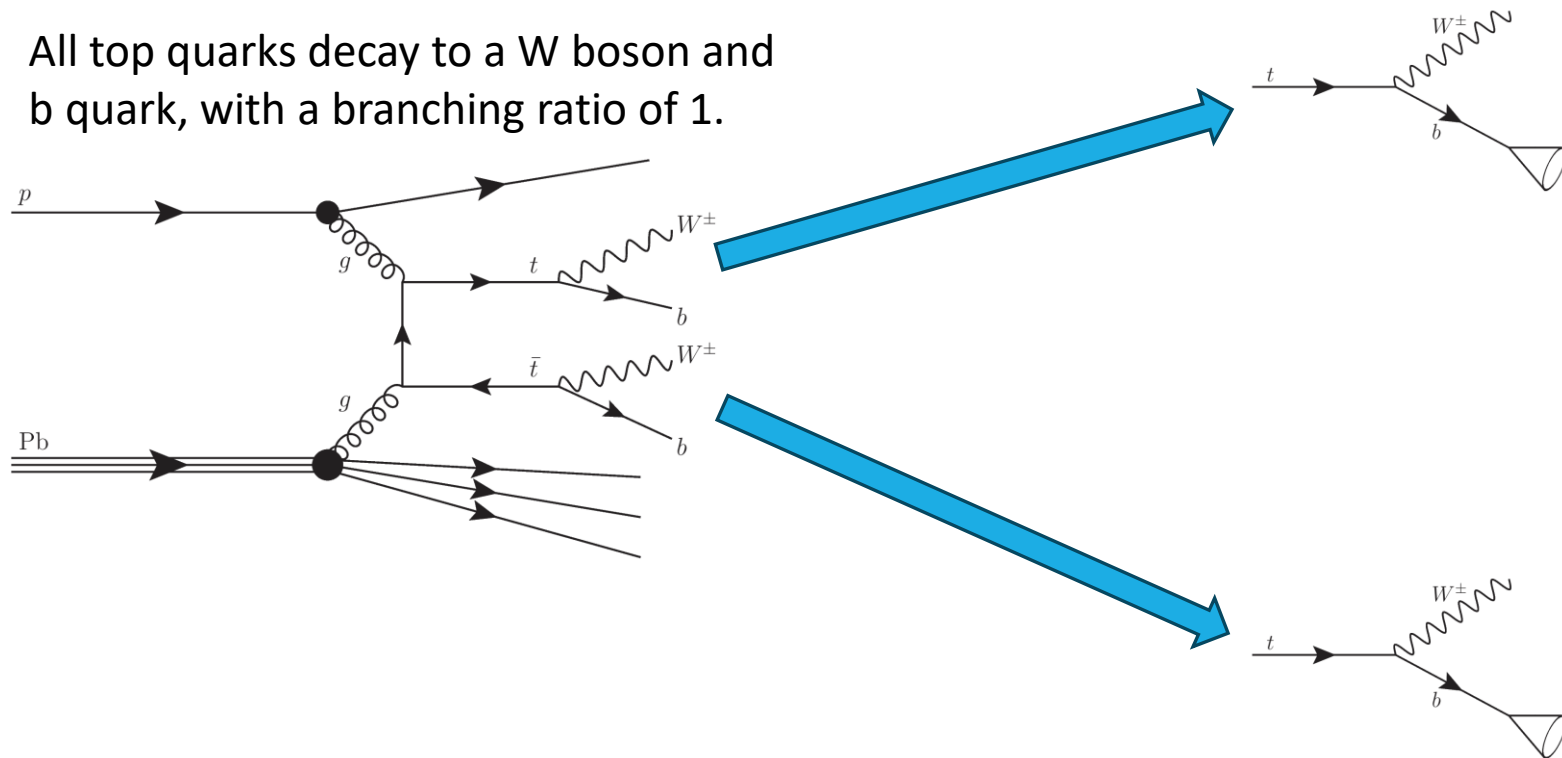
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# Top Quark Measurement Channels

All top quarks decay to a W boson and b quark, with a branching ratio of 1.

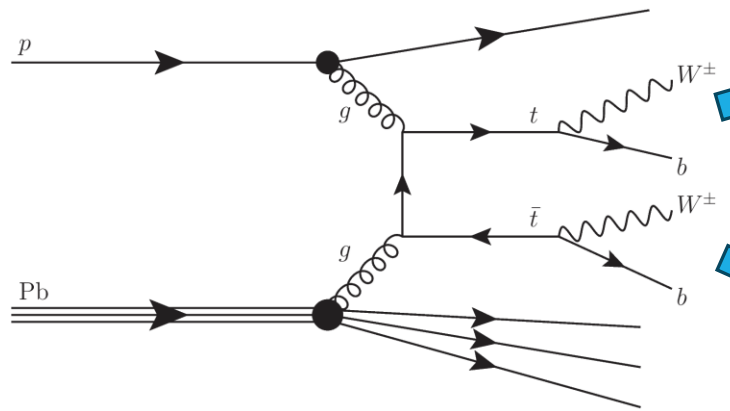
Each b quark produces a jet in the final state.



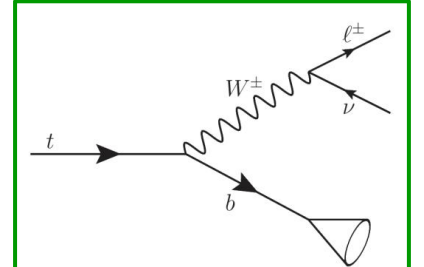
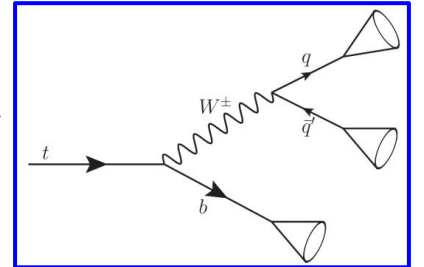
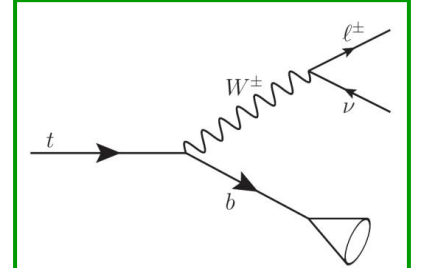
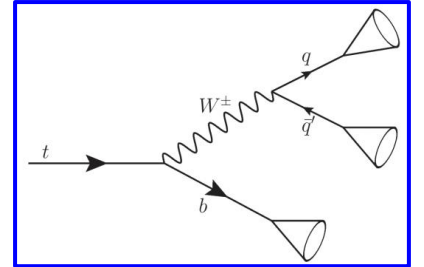
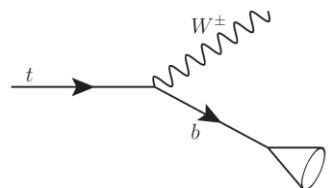
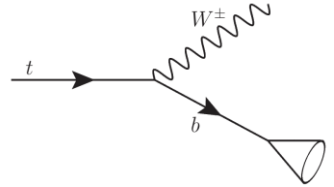
# Top Quark Measurement Channels

W bosons are detected via their **hadronic** or **leptonic** decays.

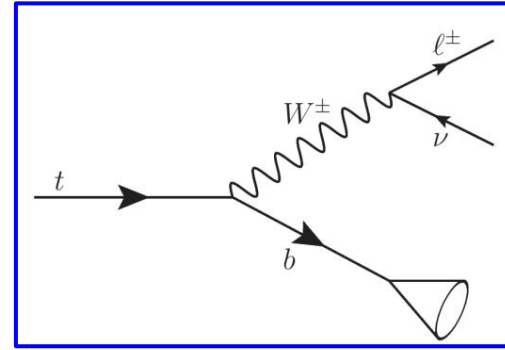
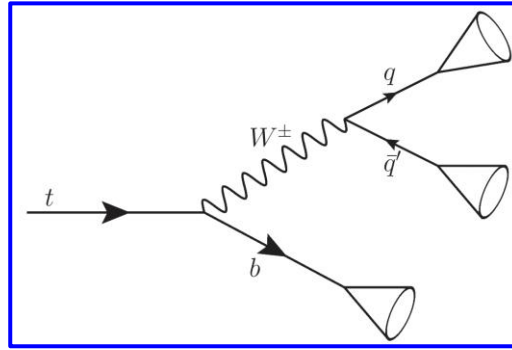
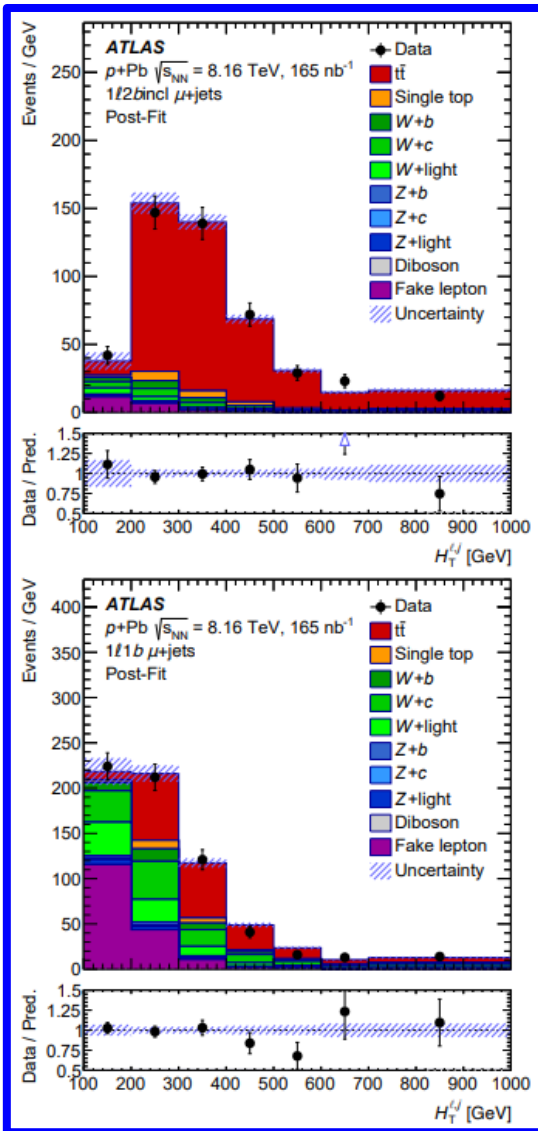
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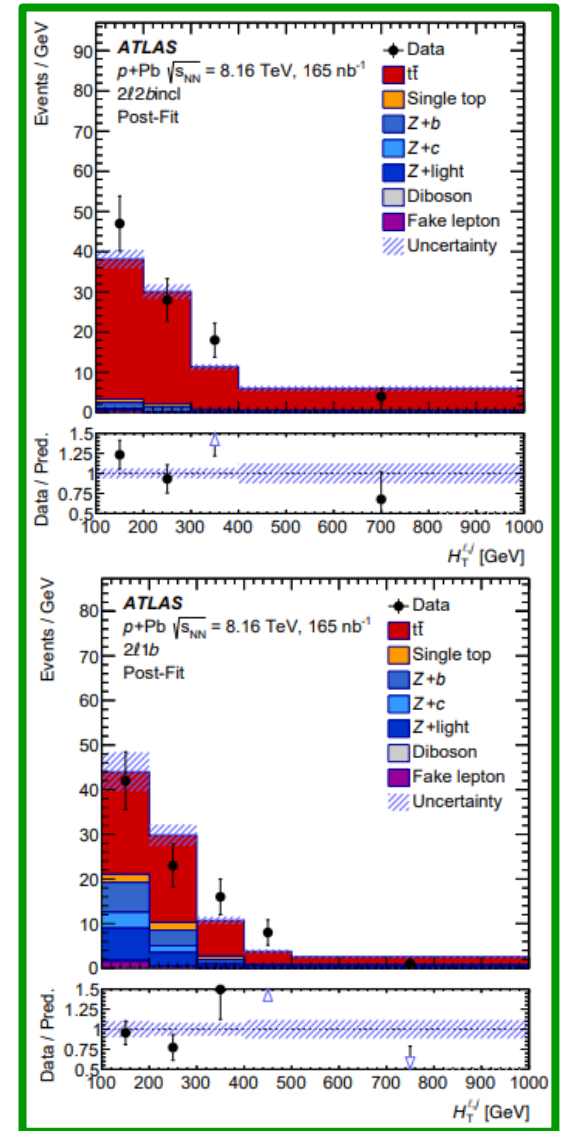
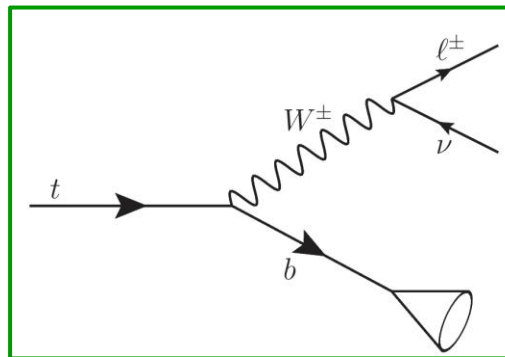
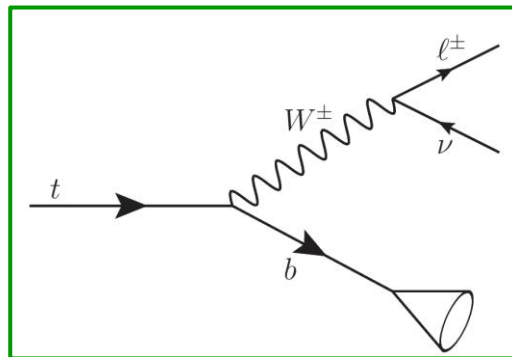


# Top Quark Measurement Channels



Channels with both b-jets identified (upper) have a higher purity.  
 Signal strength is constrained using a fit in  $H_T^{l,j}$  for 6 SRs.  
 All channels require at least 1 leptonic decay and at least 1 b-jet.

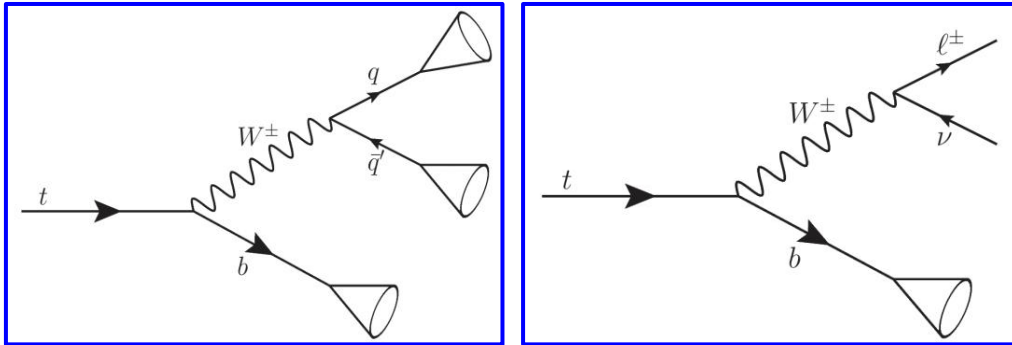
$$H_T^{l,j} = \sum_{l,j} p_T$$



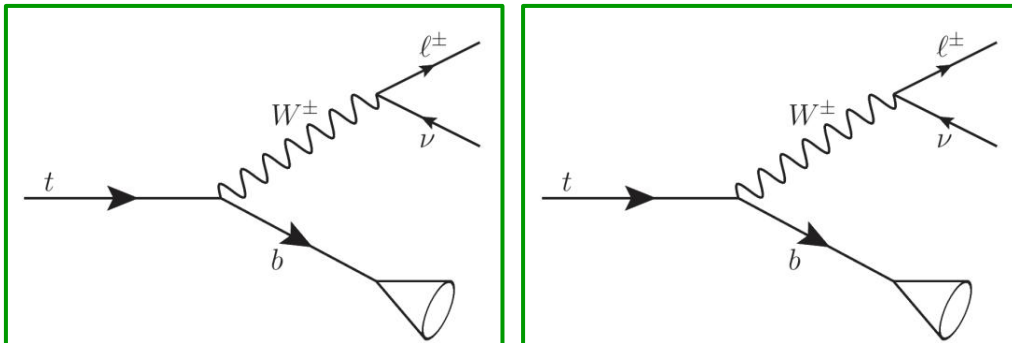
# Sources of Systematic Uncertainty

- No single systematic uncertainty dominates the measurement, but some of the largest come from:
  - Jet energy scale – Uncertainty on the in-situ calibration of the jet energy
  - $t\bar{t}$  generator – Sensitivity of the extraction to changes in the  $t\bar{t}$  signal shape from MC

Lepton+jet channels were dominated by systematic uncertainties.



Di-lepton channels were dominated by statistical uncertainties.

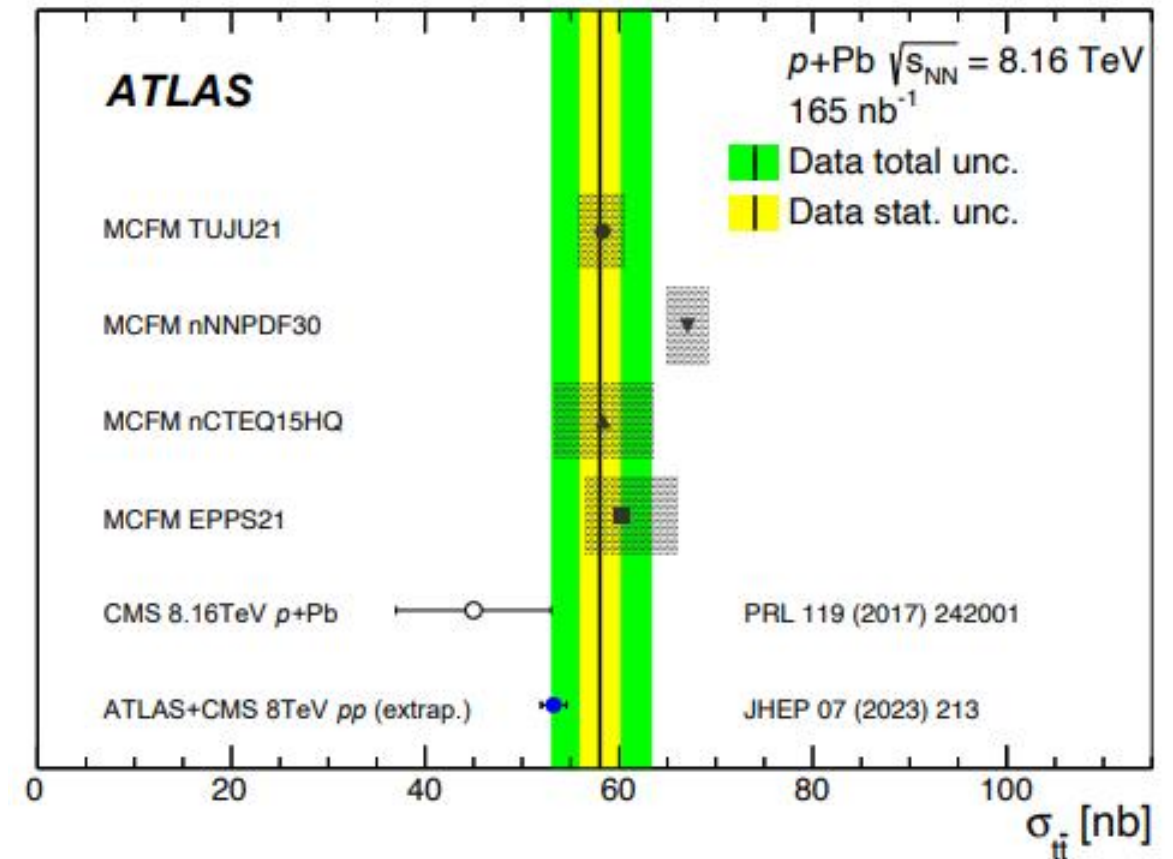
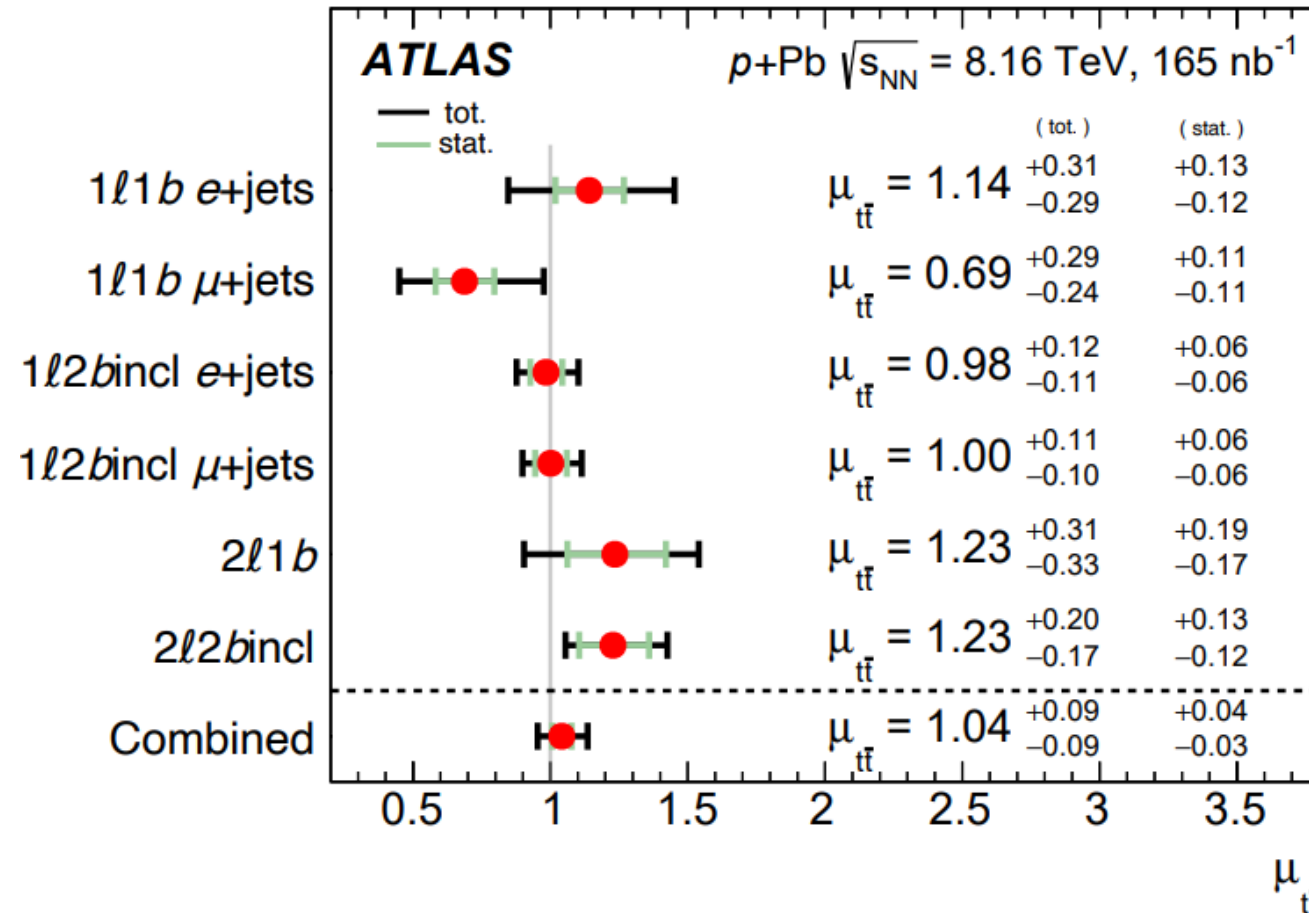


Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$	
	unc. up [%]	unc. down [%]
Jet energy scale	+4.6	-4.1
$t\bar{t}$ generator	+4.5	-4.0
Fake-lepton background	+3.1	-2.8
Background	+3.1	-2.6
Luminosity	+2.8	-2.5
Muon uncertainties	+2.3	-2.0
W+jets	+2.2	-2.0
b-tagging	+2.1	-1.9
Electron uncertainties	+1.8	-1.5
MC statistical uncertainties	+1.1	-1.0
Jet energy resolution	+0.4	-0.4
$t\bar{t}$ PDF	+0.1	-0.1
<b>Systematic uncertainty</b>	<b>+8.3</b>	<b>-7.6</b>

# Top-Quark Production: nPDF Interpretation

- The signal regions are combined to maximize precision.
- Top production is observed at  $> 5\sigma$  in both the  $2\ell$  and  $\ell + \text{jets}$  channels separately, as well as combined.

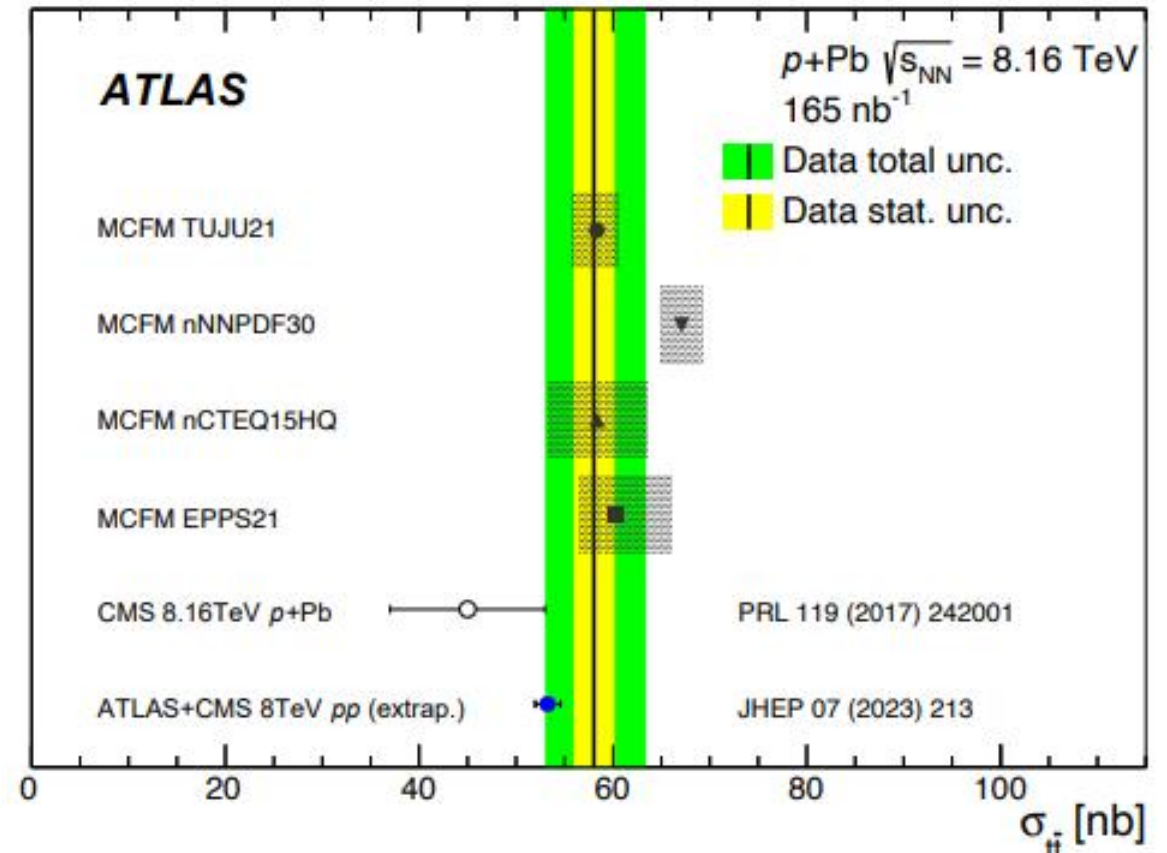
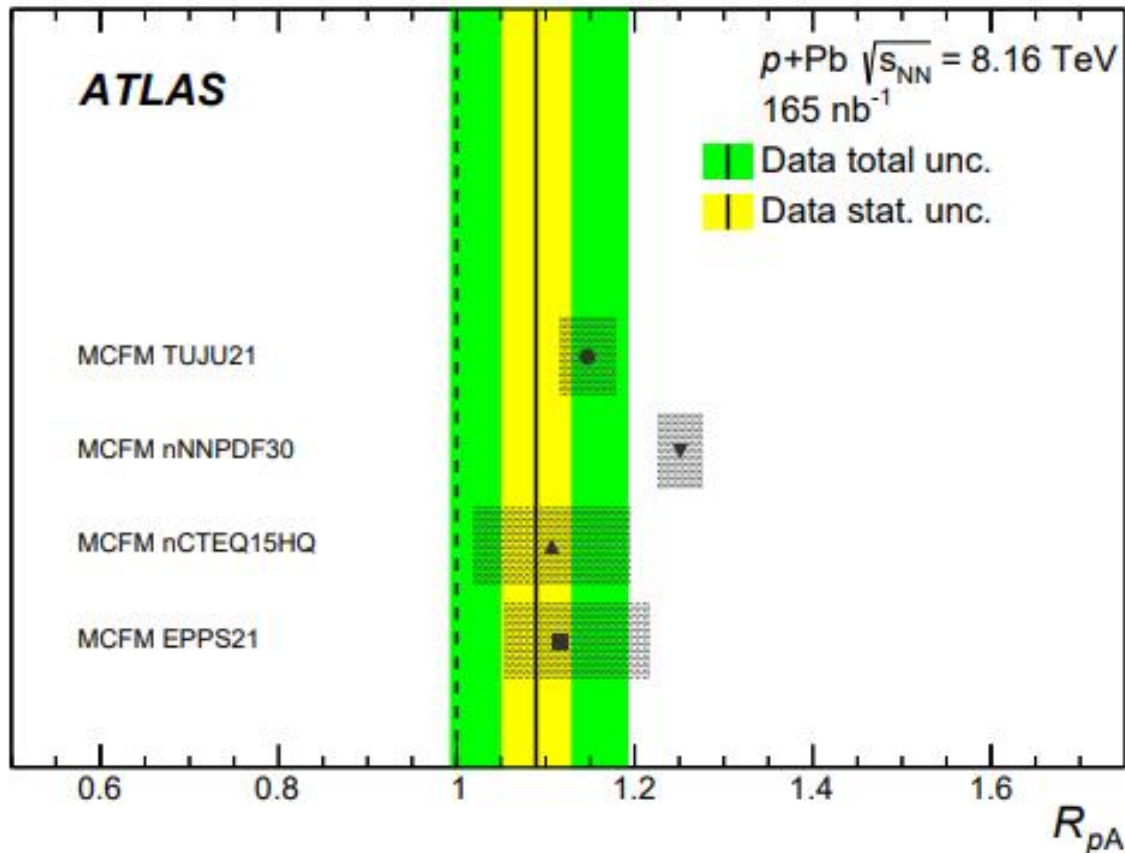
$$\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{Pb} \cdot \sigma_{t\bar{t}}^{th} = 58.1_{-4.9}^{+5.2} \text{ nb}$$



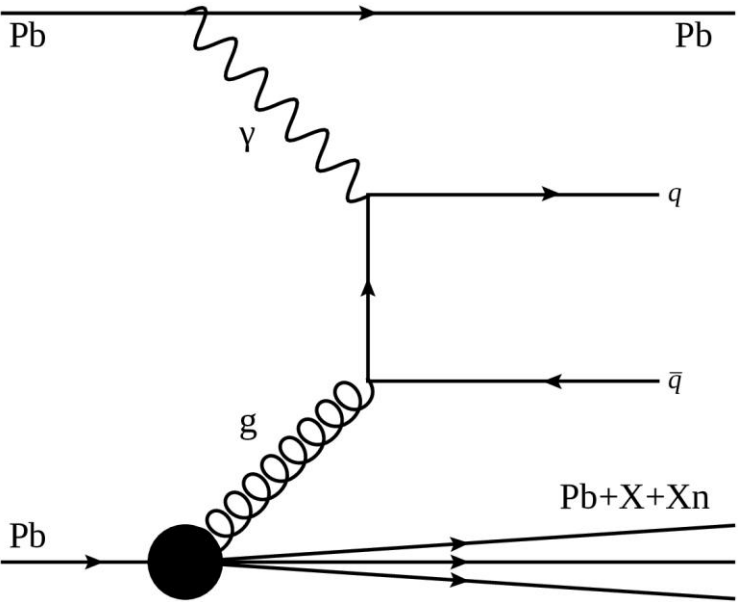
# Top-Quark Production: nPDF Interpretation

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+Pb}}{A_{Pb} \cdot \sigma_{t\bar{t}}^{pp}} = 1.090 \pm \underbrace{0.039}_{\text{statistical}} \overset{+0.094}{\underset{-0.087}{\text{systematic}}}$$

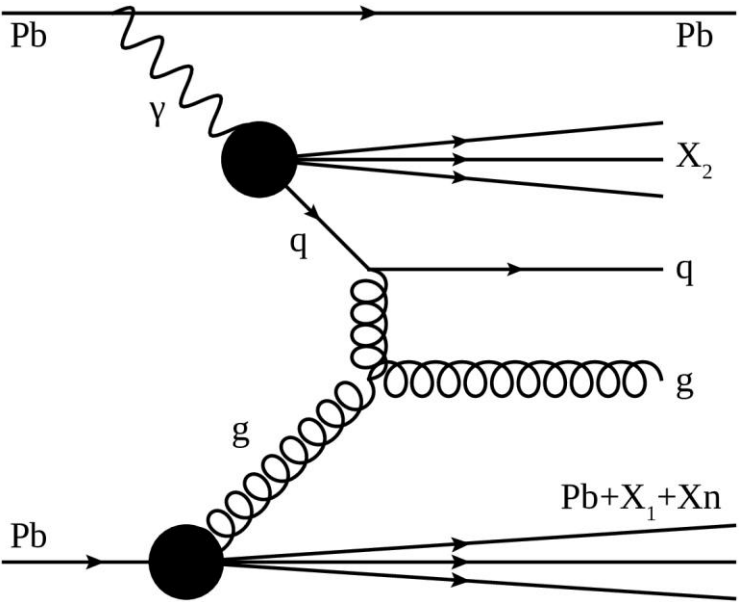
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# An Overview of Photonuclear Jet Production



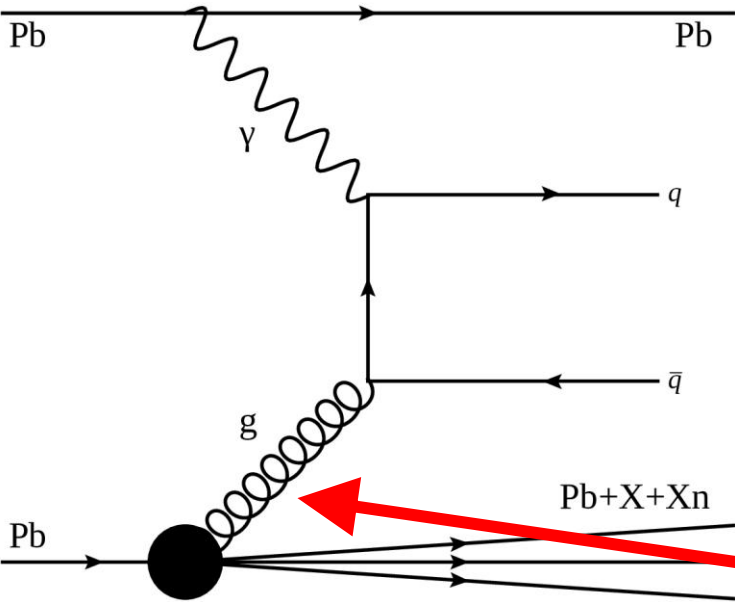
Direct



Resolved

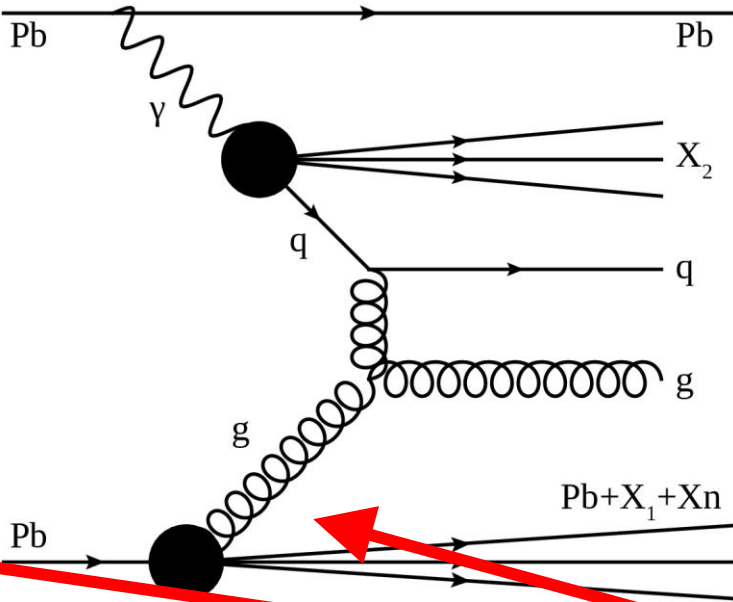
# An Overview of Photonuclear Jet Production

“Direct” photons scatter off the nucleus.



Direct

“Resolved” photons scatter hadronically through a virtual fluctuation of the photon.



Resolved

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

# An Overview of Photonuclear Jet Production

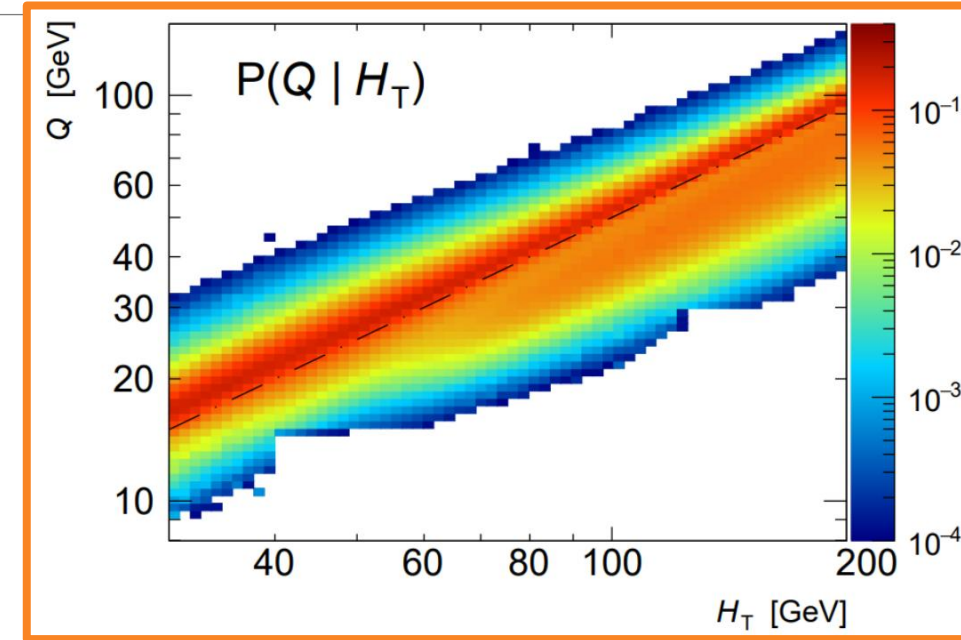
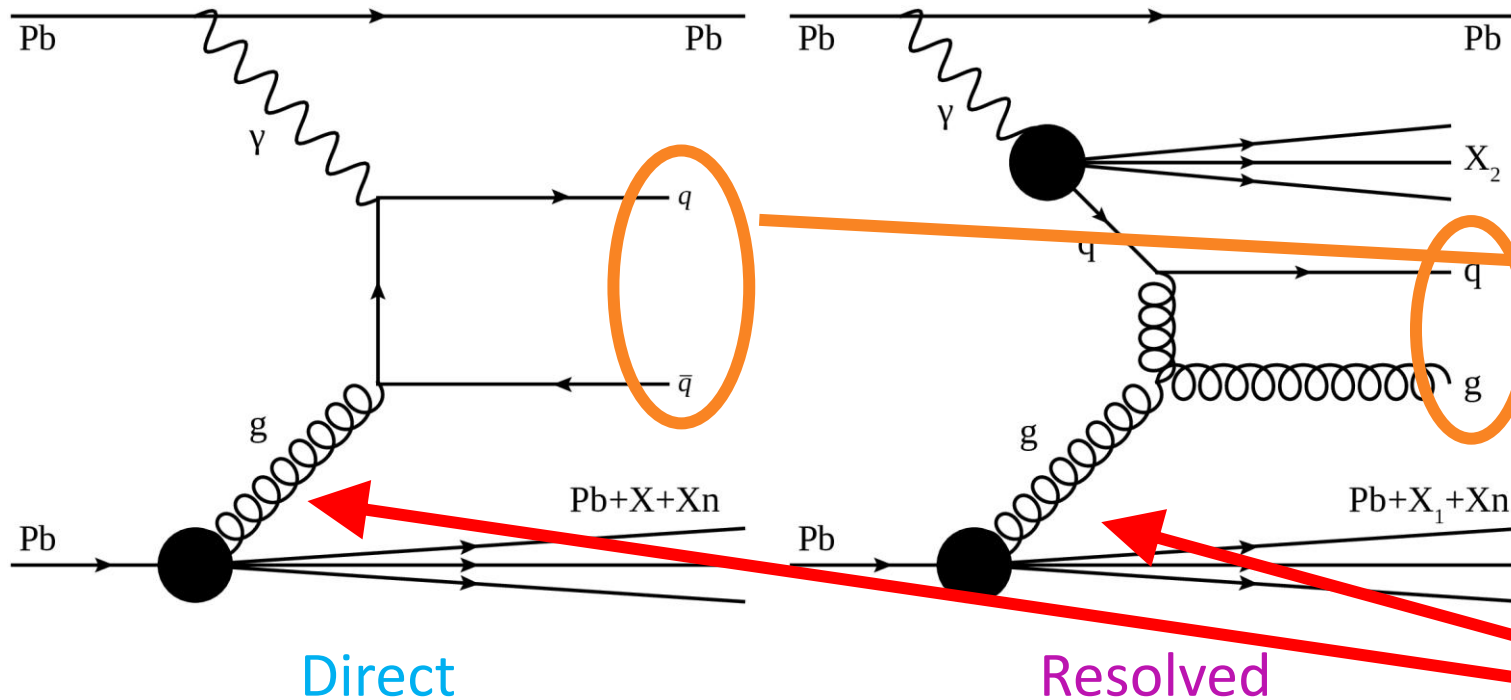
$$H_T = \sum_i p_T^i$$

$$x_A = \frac{M_{jets} e^{-y_{jets}}}{\sqrt{S_{NN}}}$$

$$z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{S_{NN}}}$$

“Direct” photons scatter off the nucleus.

“Resolved” photons scatter hadronically through a virtual fluctuation of the photon.



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

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

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Unique kinematic coverage!

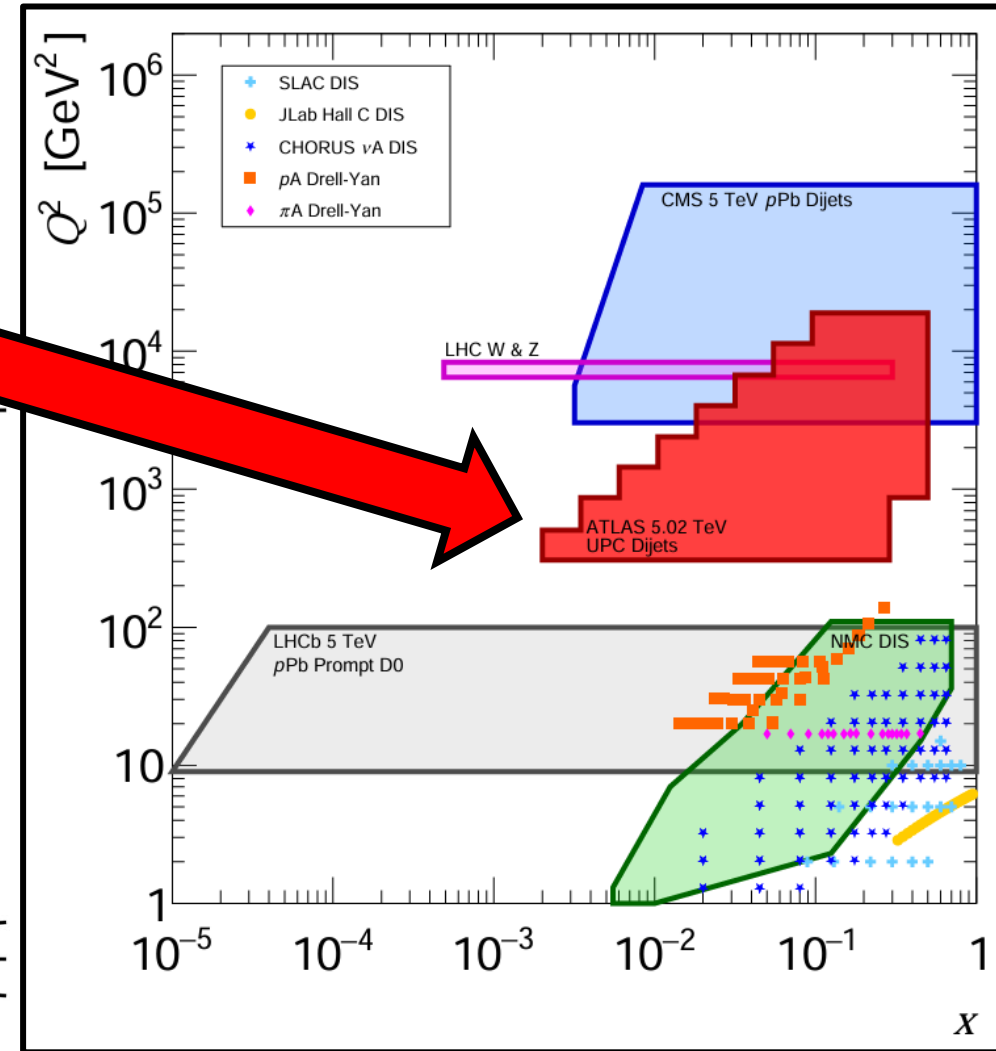
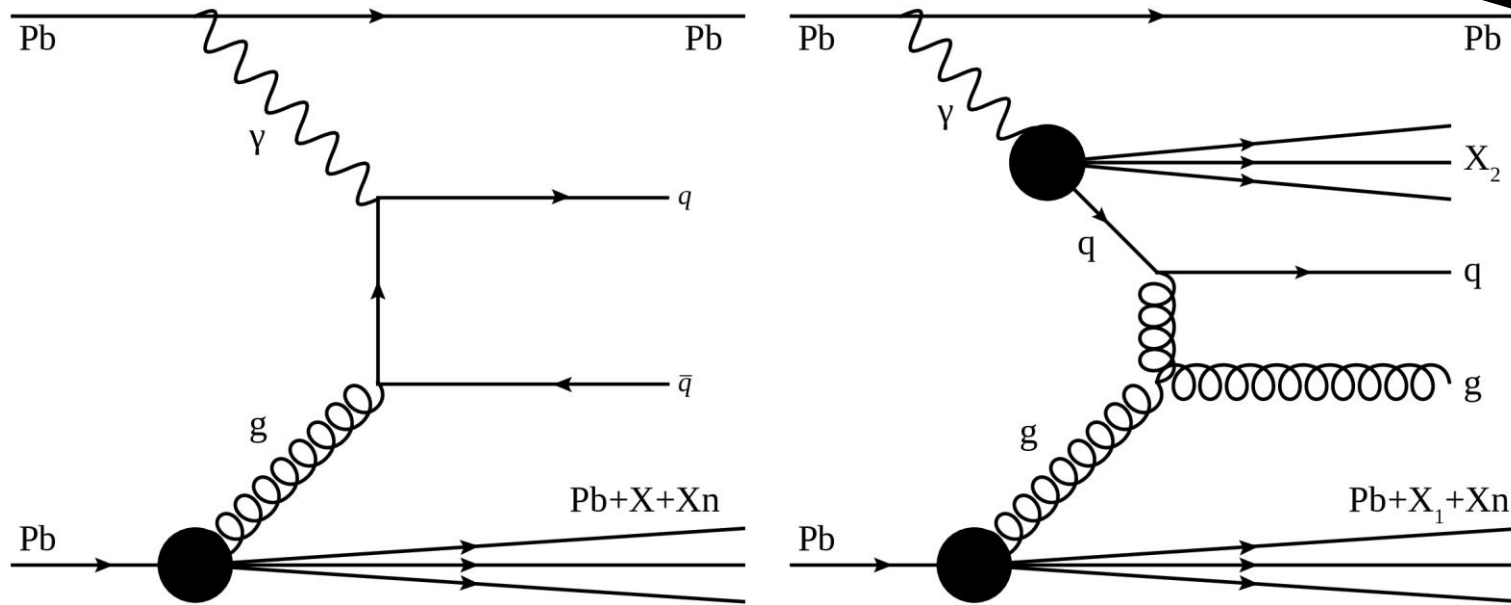
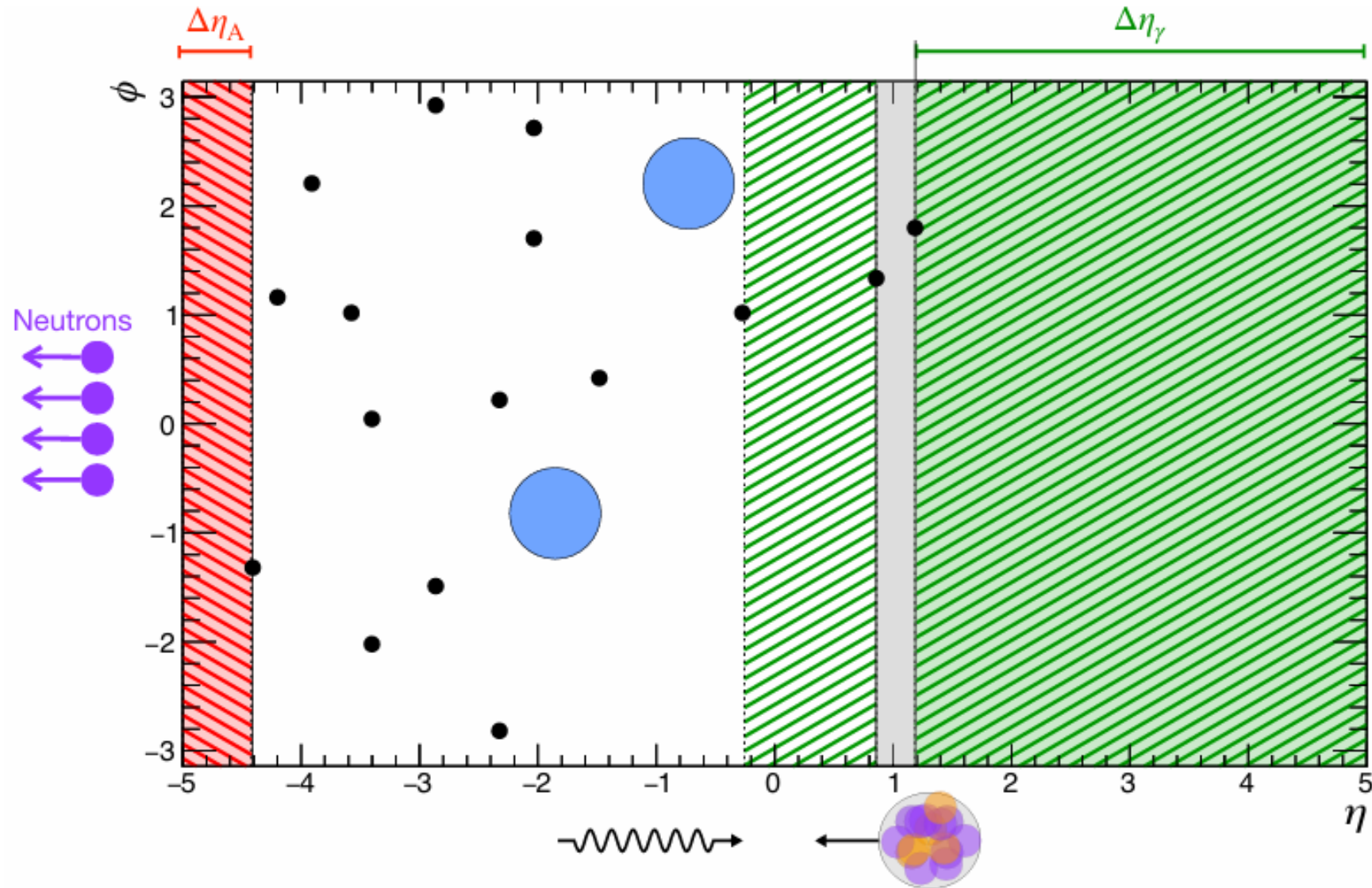
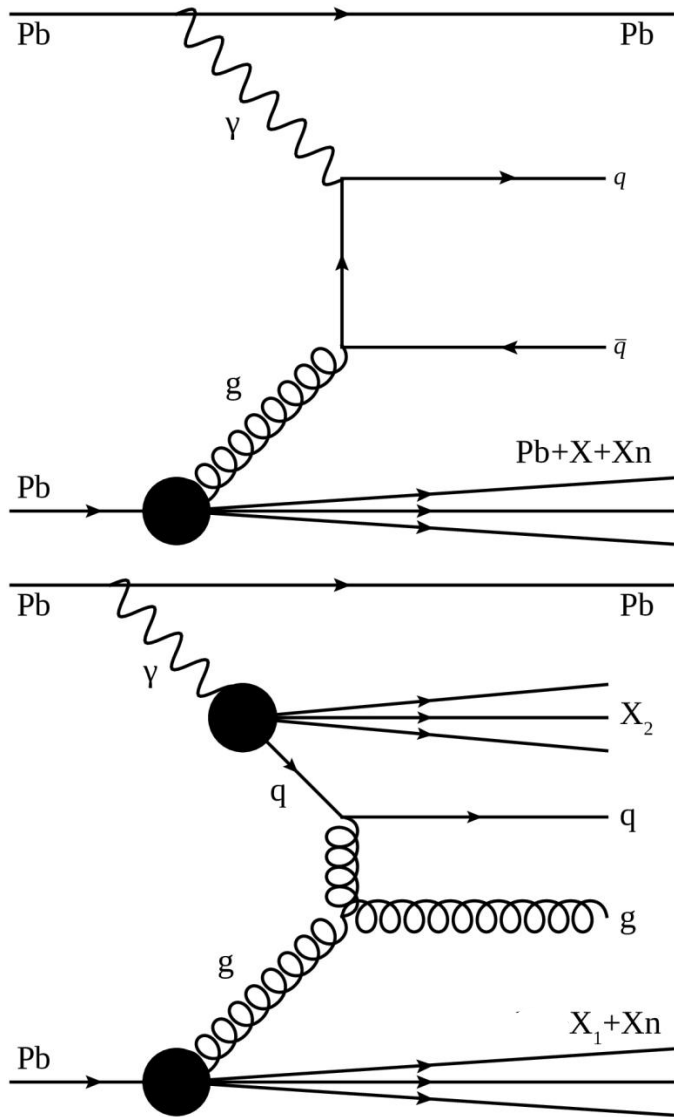
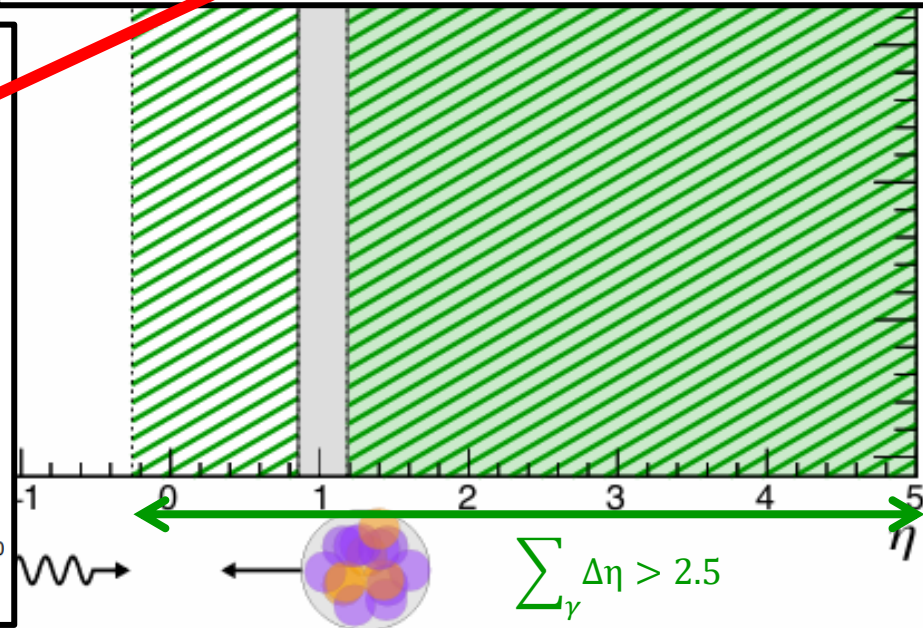
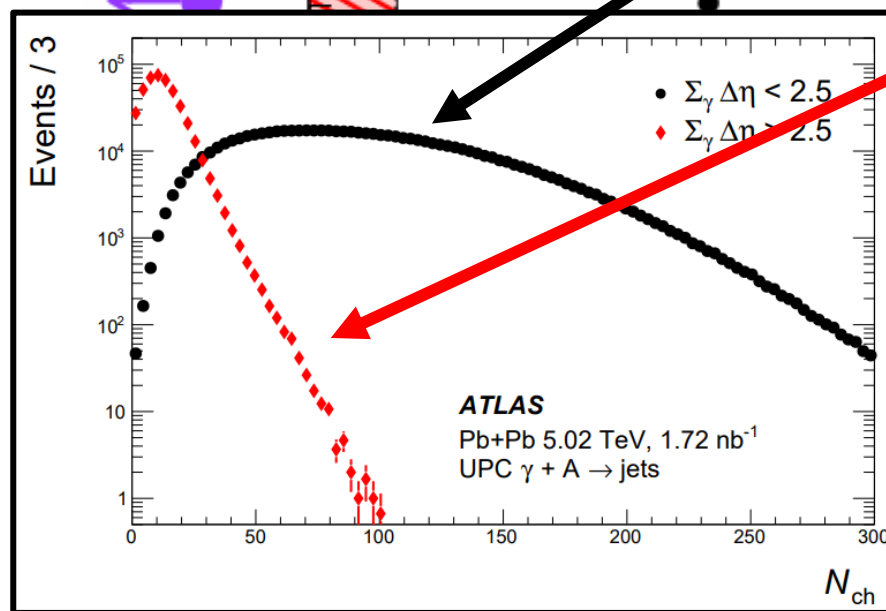
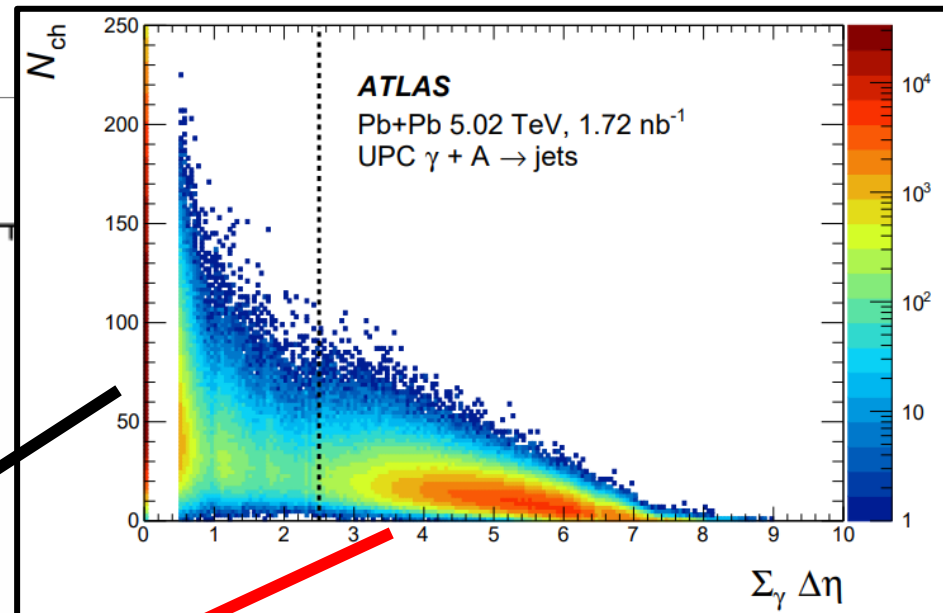
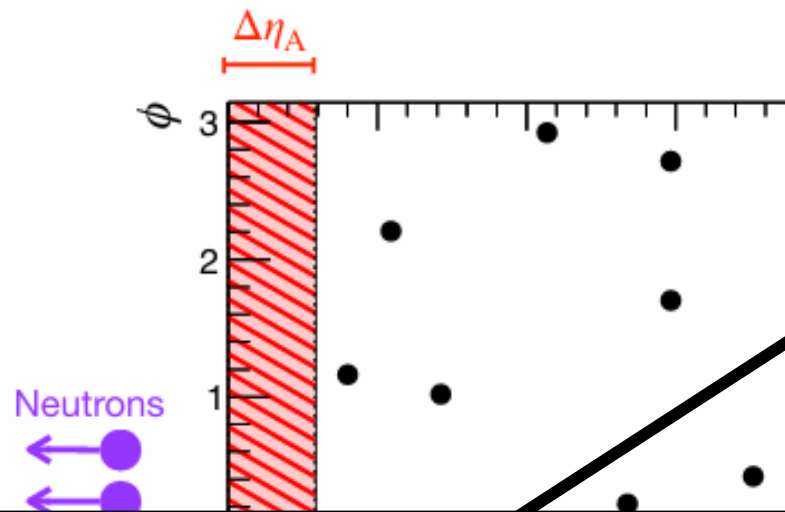
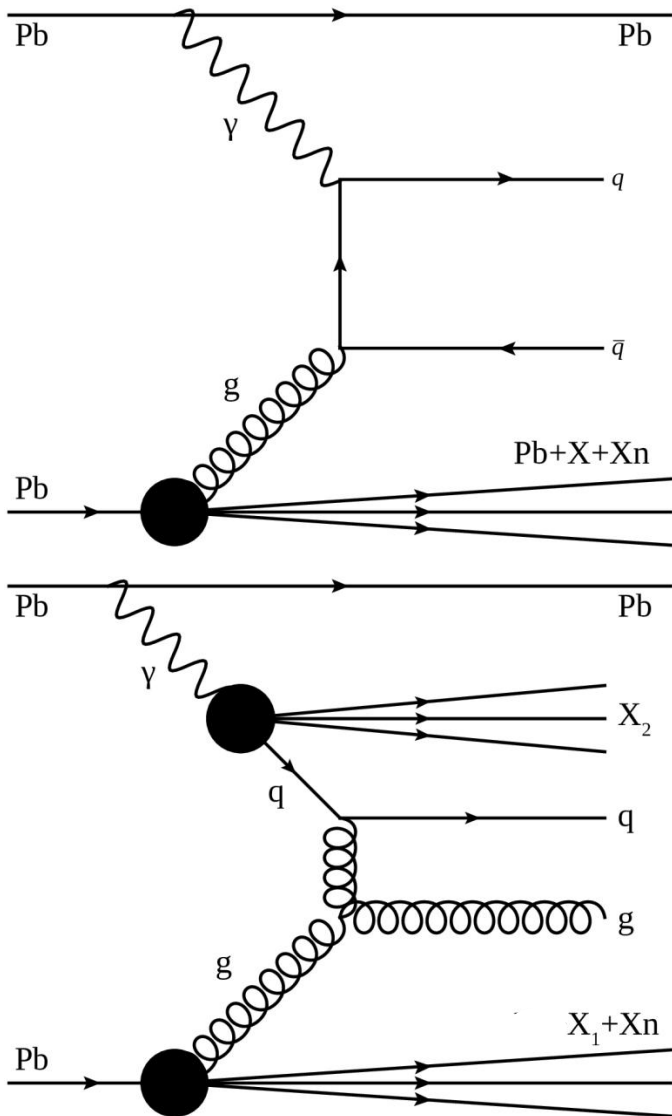


Figure inspired by [arXiv:2112.12462](https://arxiv.org/abs/2112.12462)

# Selecting Photonuclear Jet Events



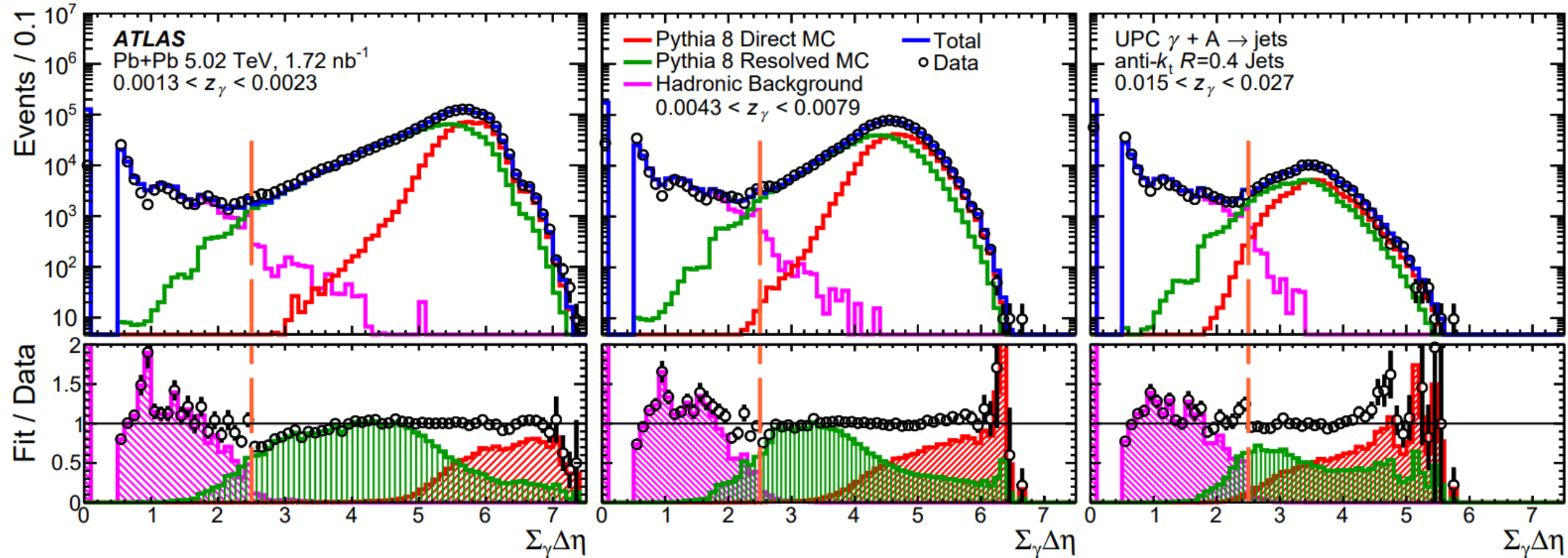
# Selecting Photonuclear Jet Events



# Gap Selections and Photon Structure

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

Template fits of the gap distributions can constrain backgrounds and provide information on photon structure.

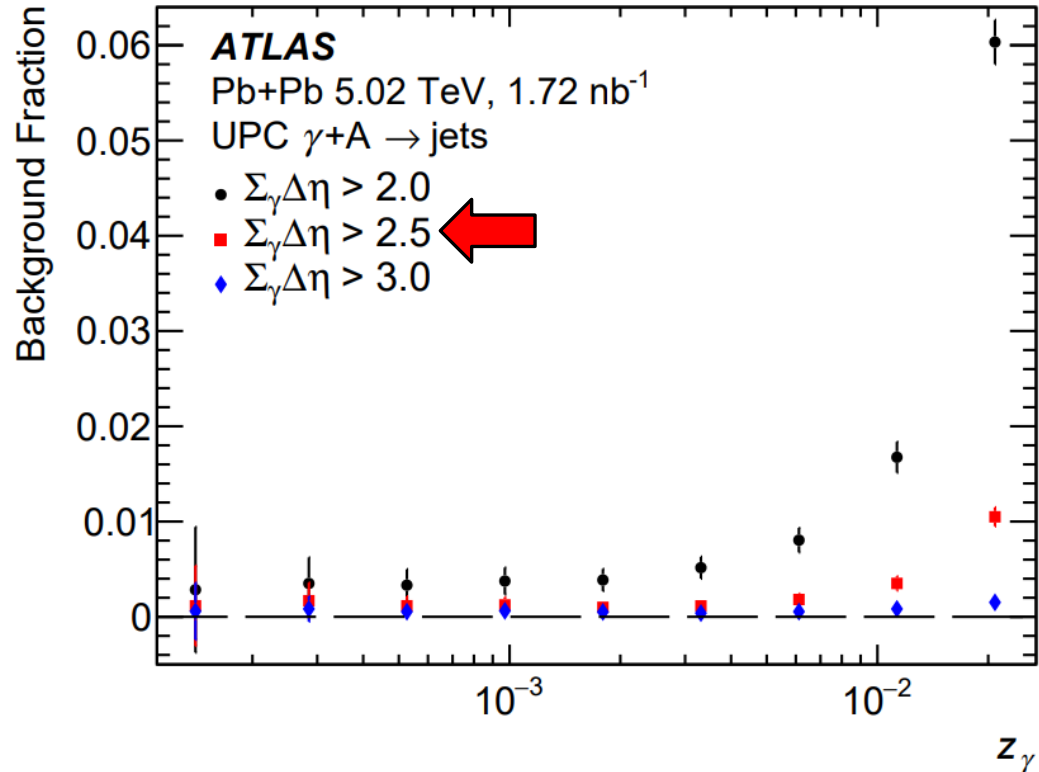


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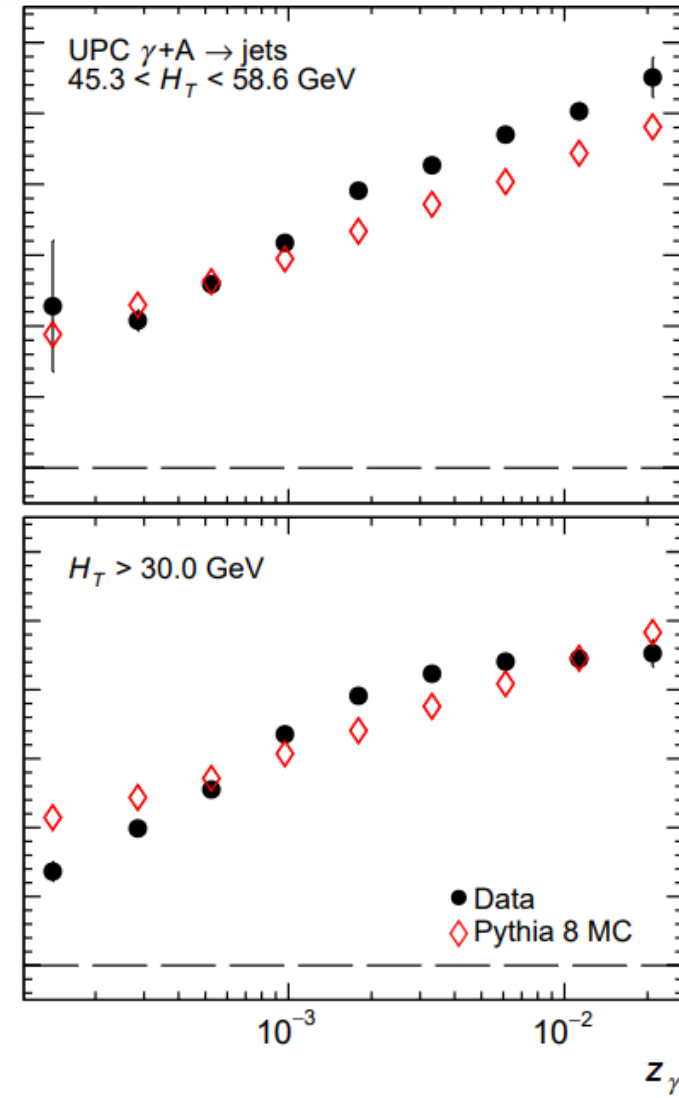
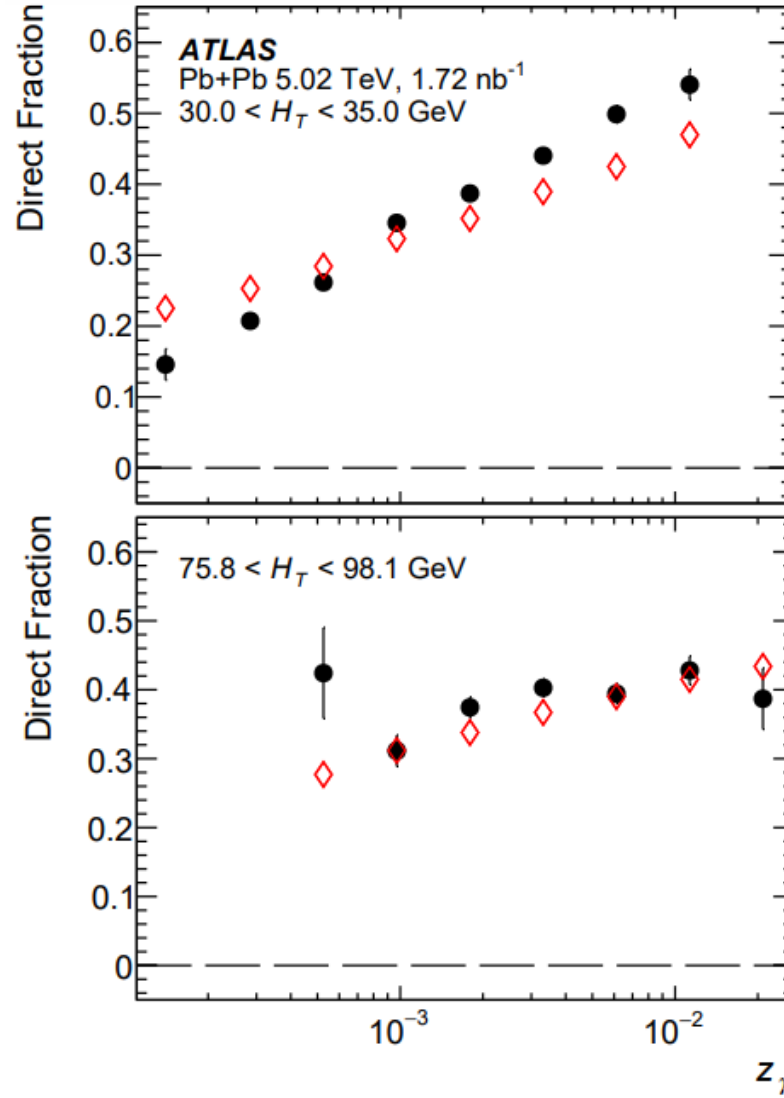
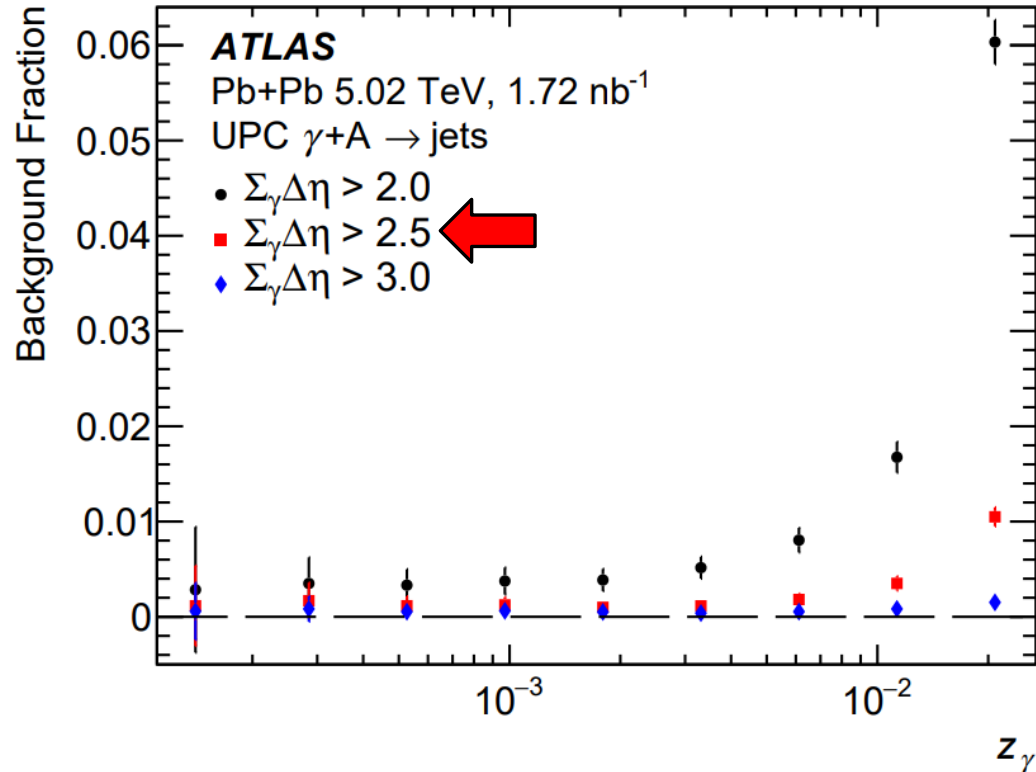
- The selection we apply (red) maintains a sufficient level of signal purity.



# Gap Selections and Photon Structure

$$H_T = \sum_i p_T^i \quad z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{S_{NN}}}$$

- The selection we apply (red) maintains a sufficient level of signal purity.
- The direct fraction differs between data and theory at low  $H_T$  but is modeled well at high  $H_T$ .

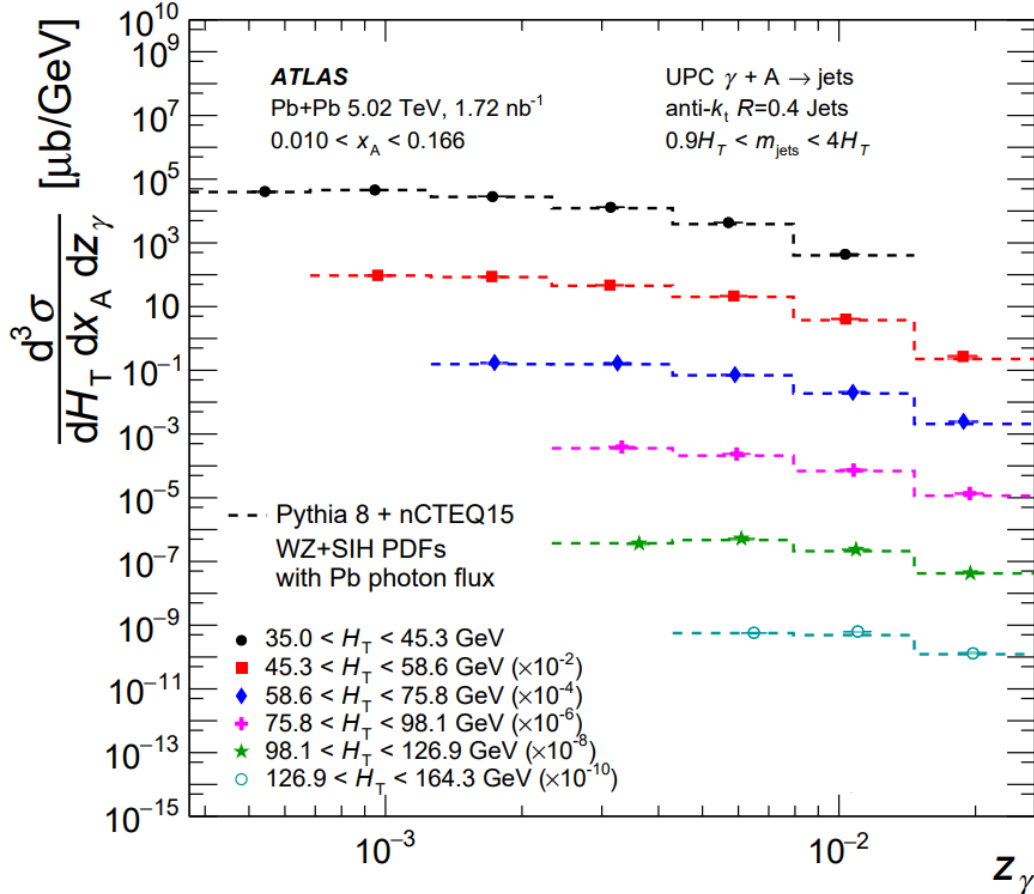


# Scanning in Photon Energy

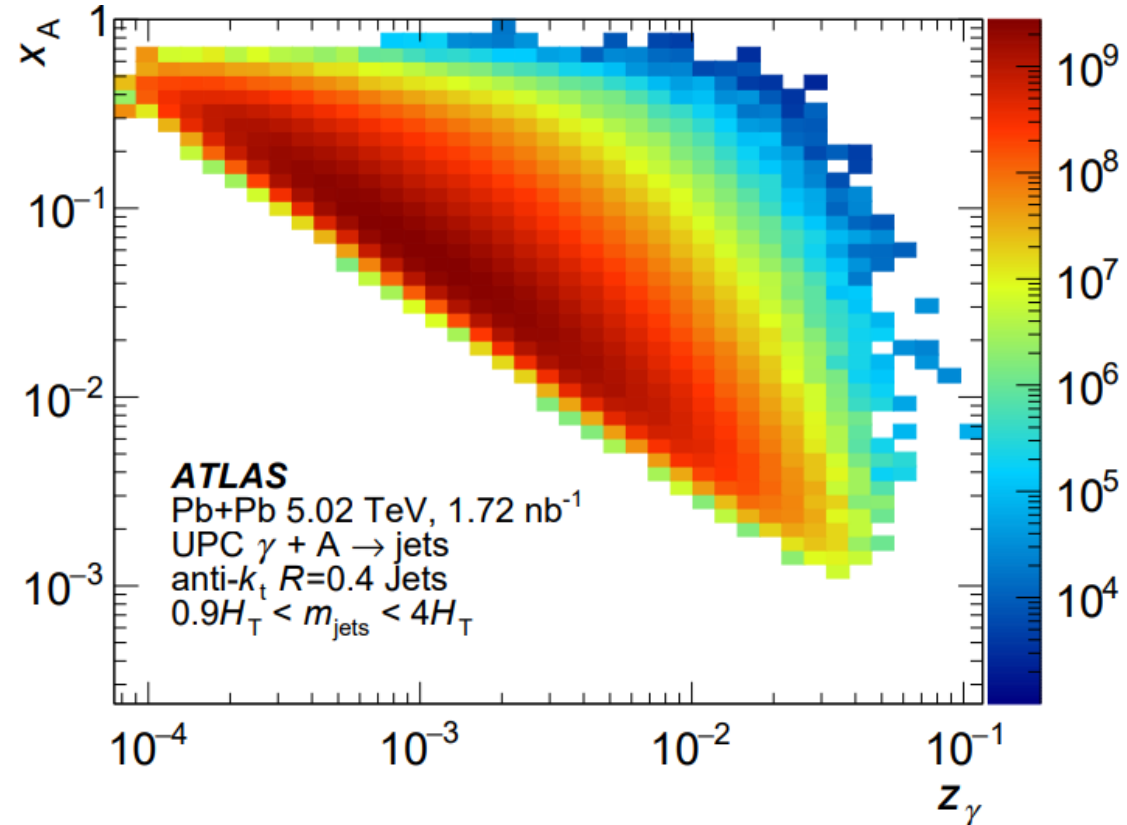
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Selecting on photon energy allows for a more un-biased measurement sensitive to nPDFs.

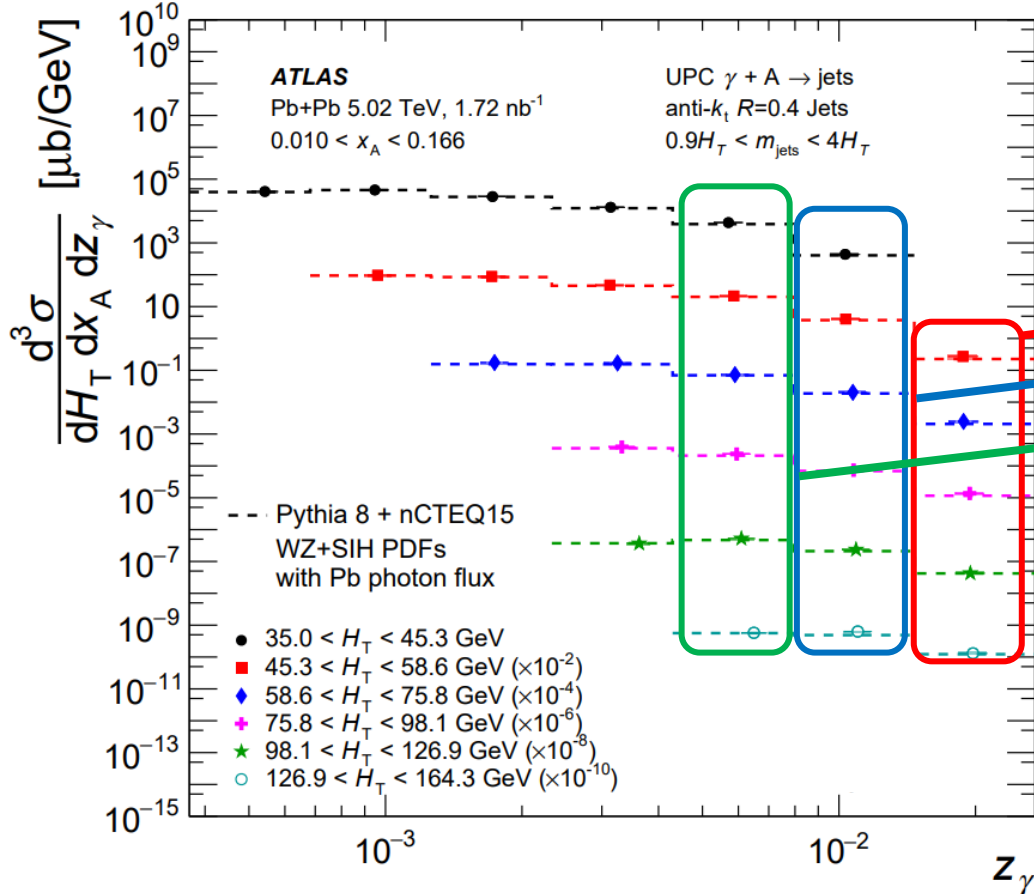


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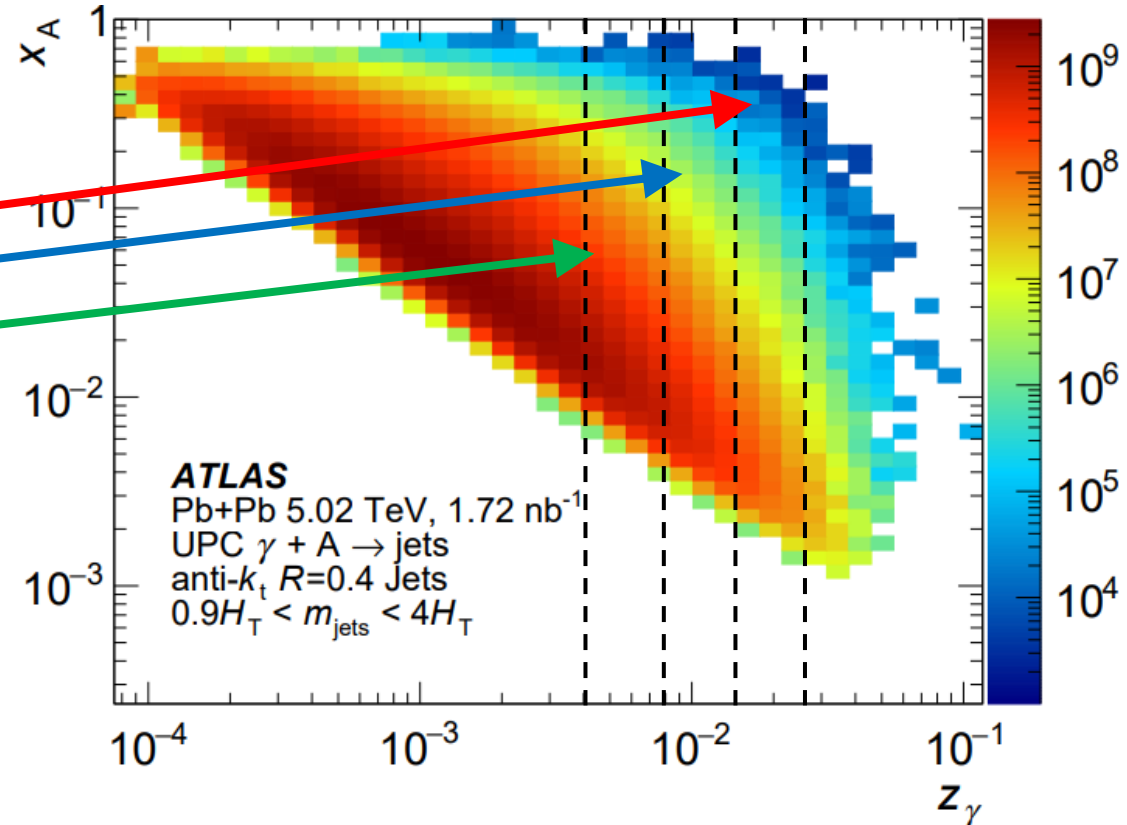
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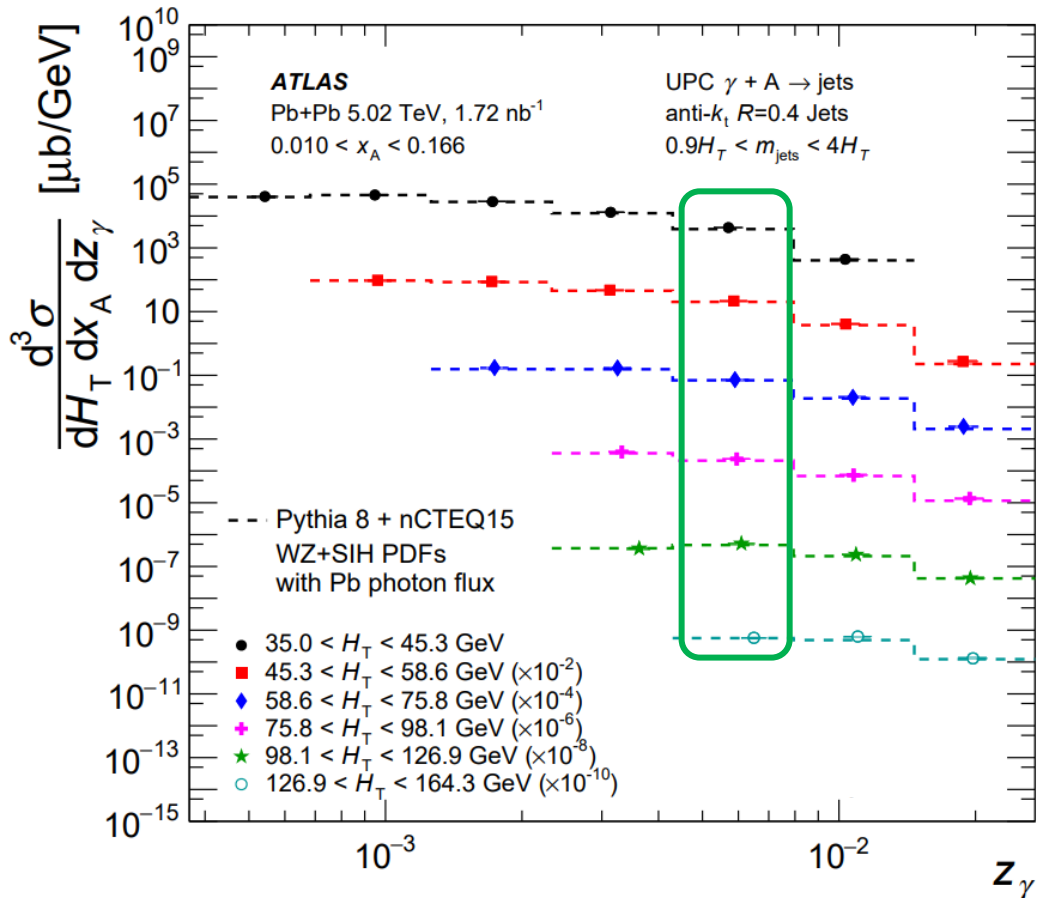


# Measured Cross-Sections

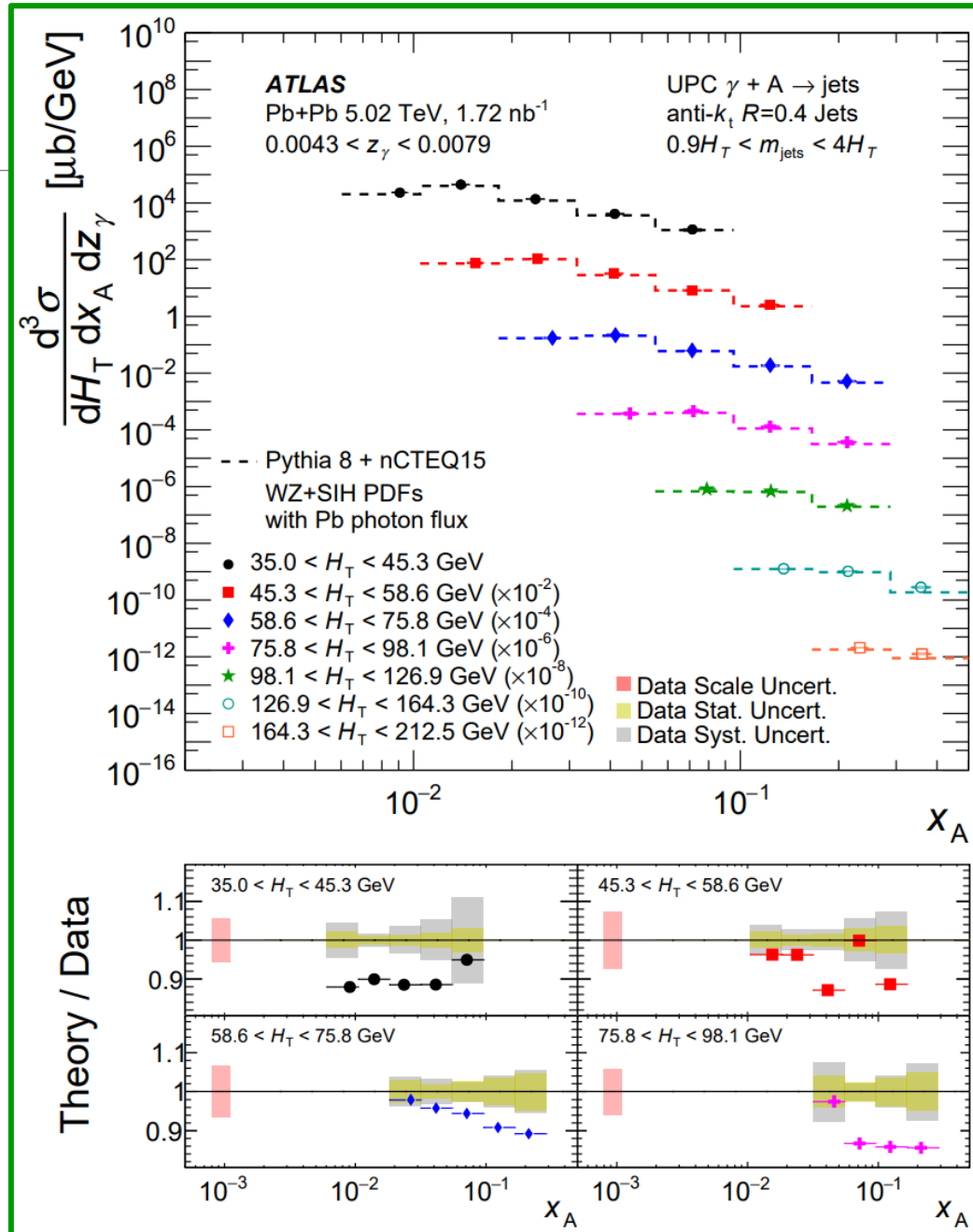
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Photon Energy  
0.004 < z<sub>γ</sub> < 0.008

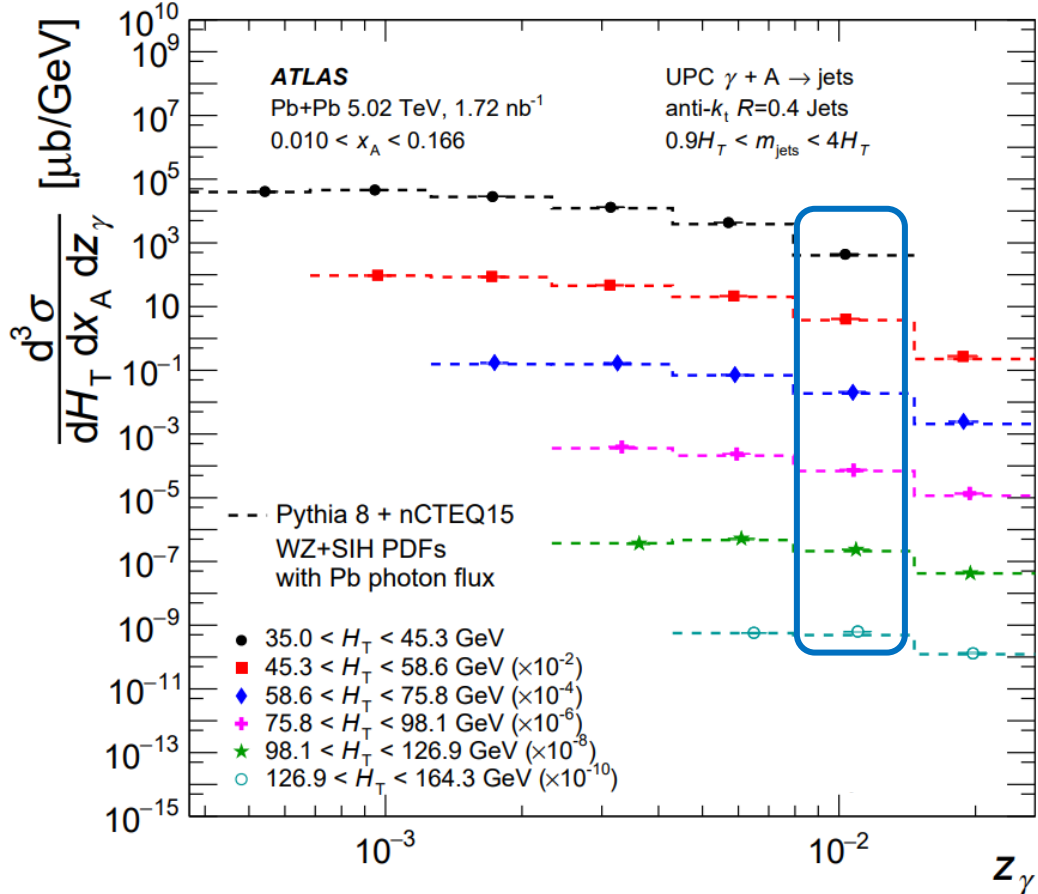


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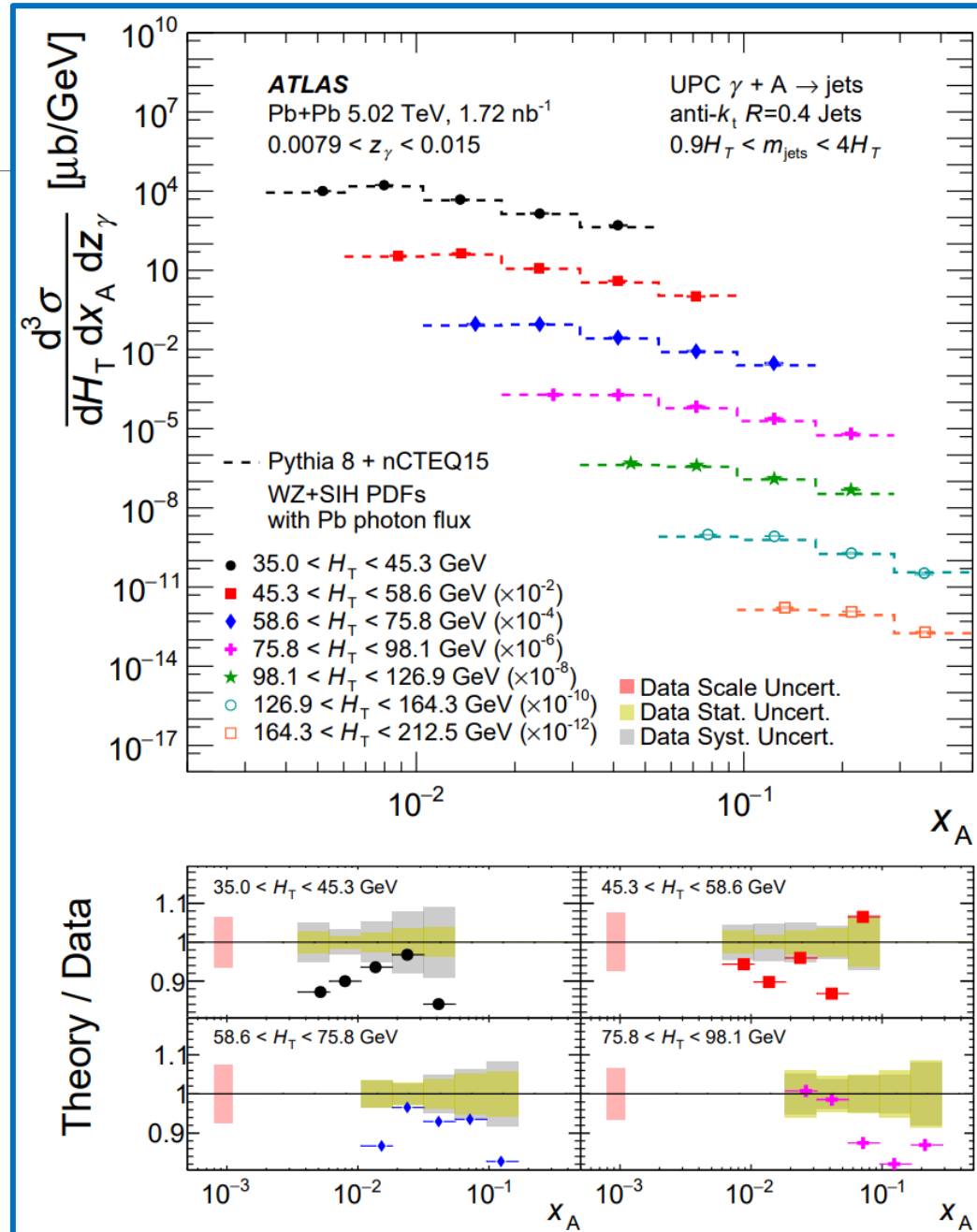
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Photon Energy  
0.008 < z<sub>γ</sub> < 0.015

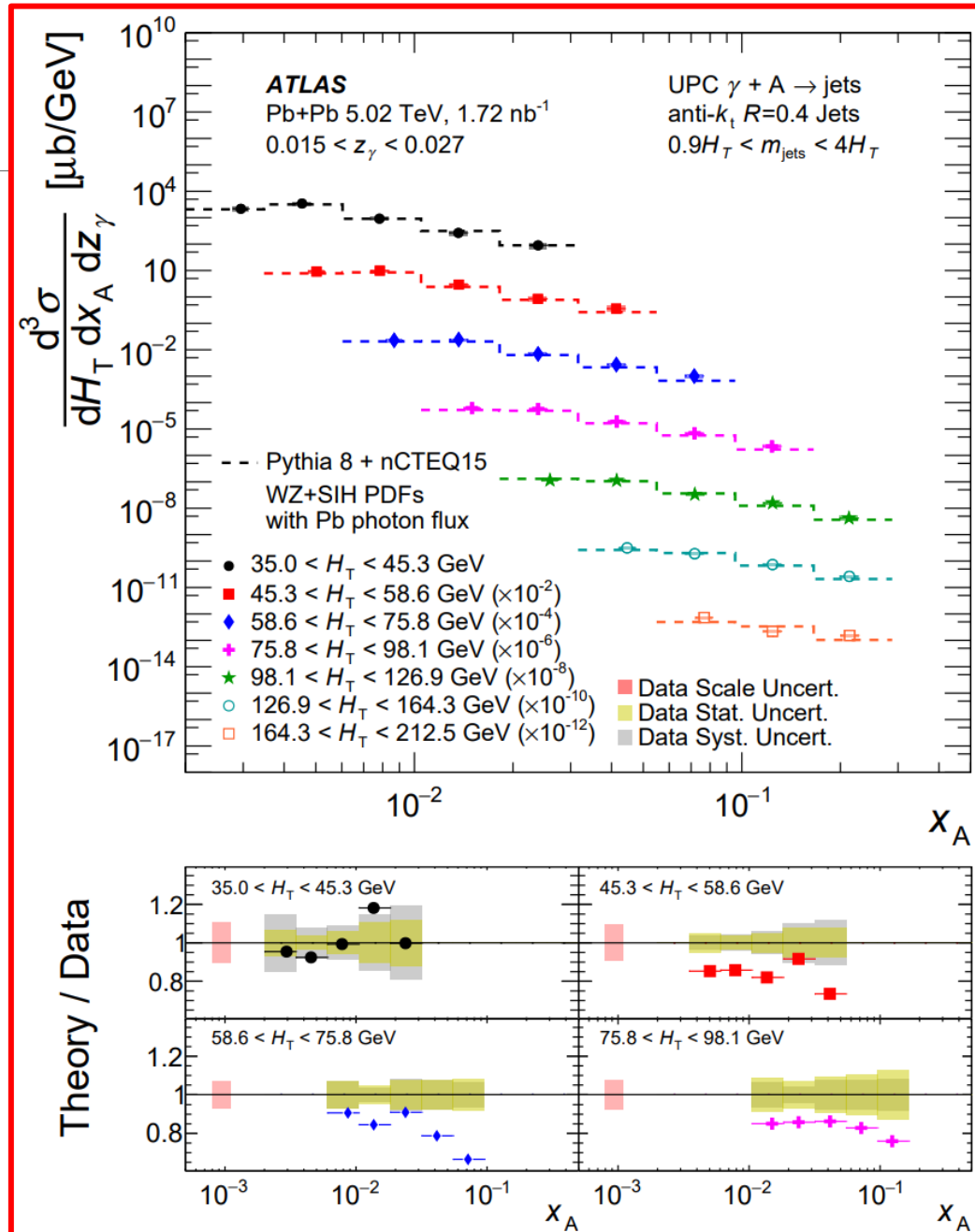
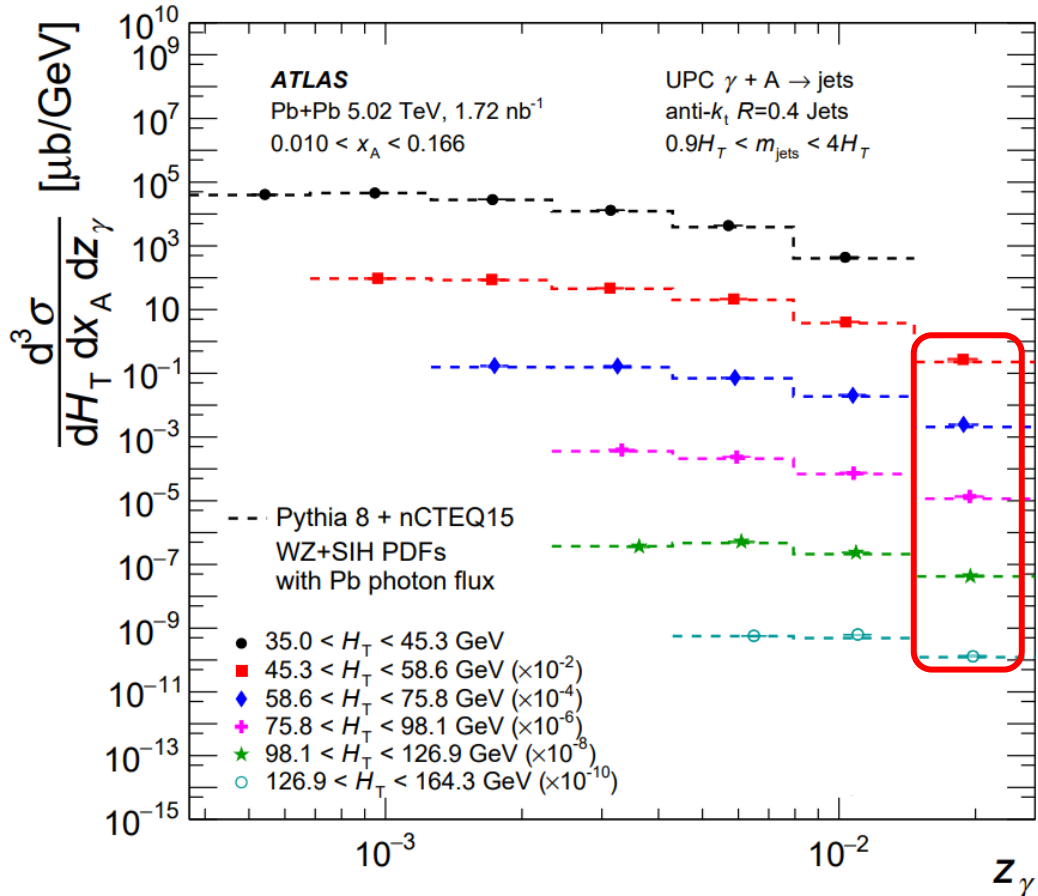


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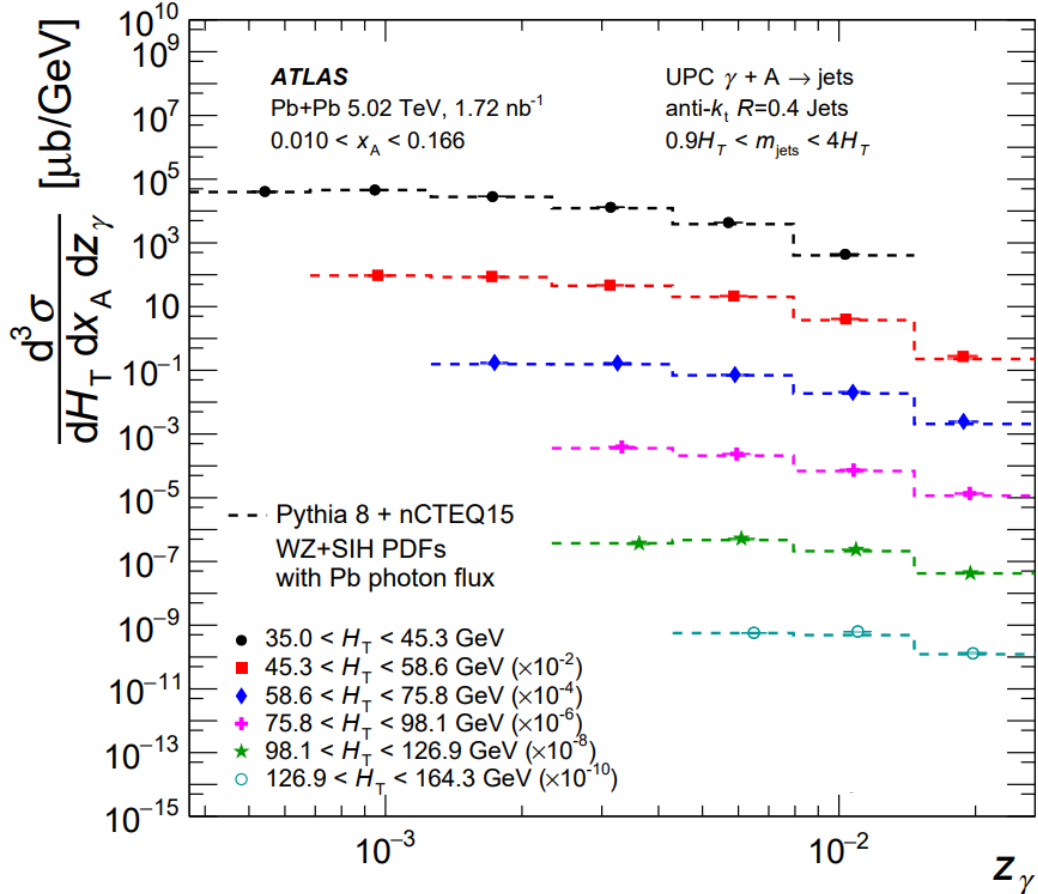


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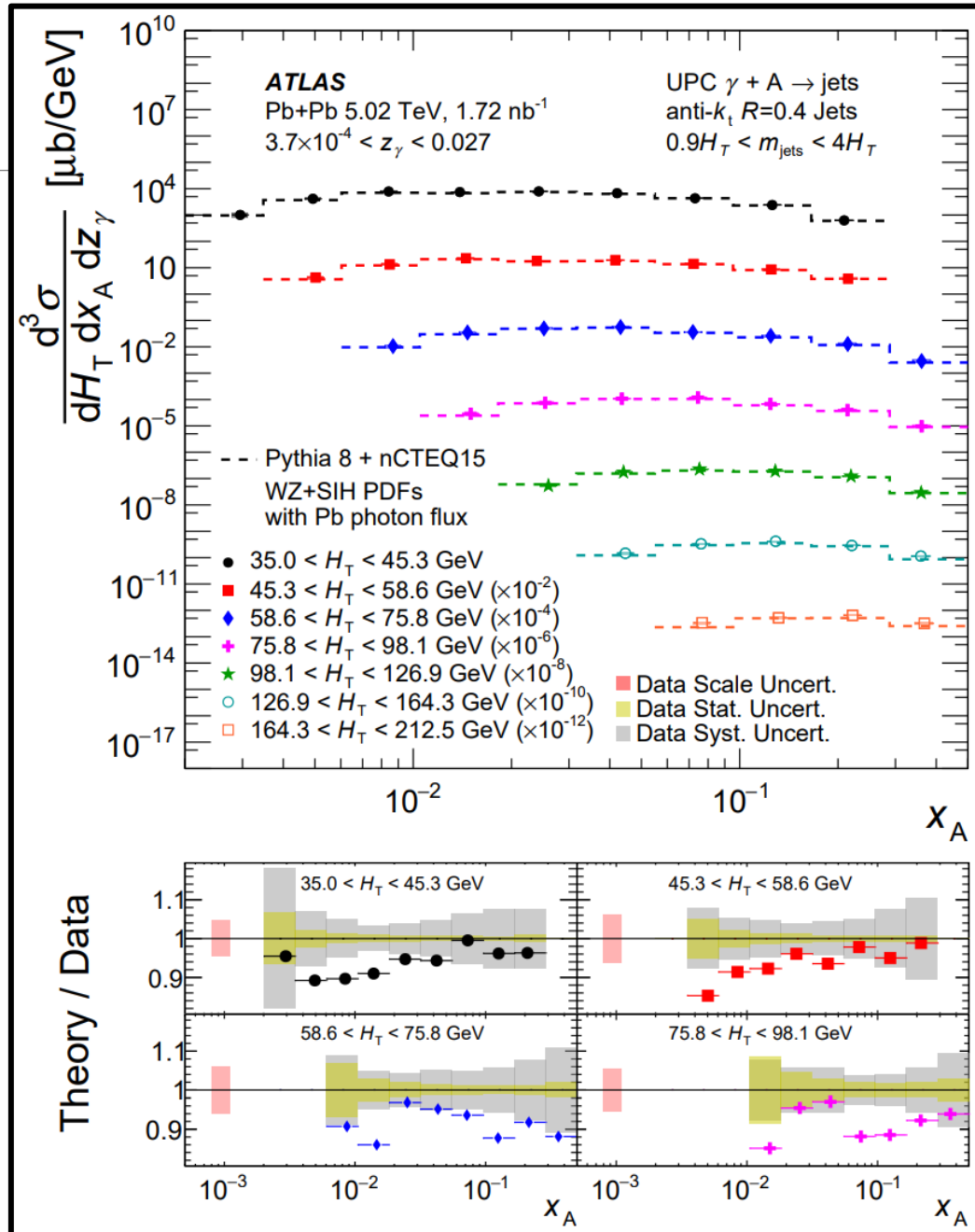
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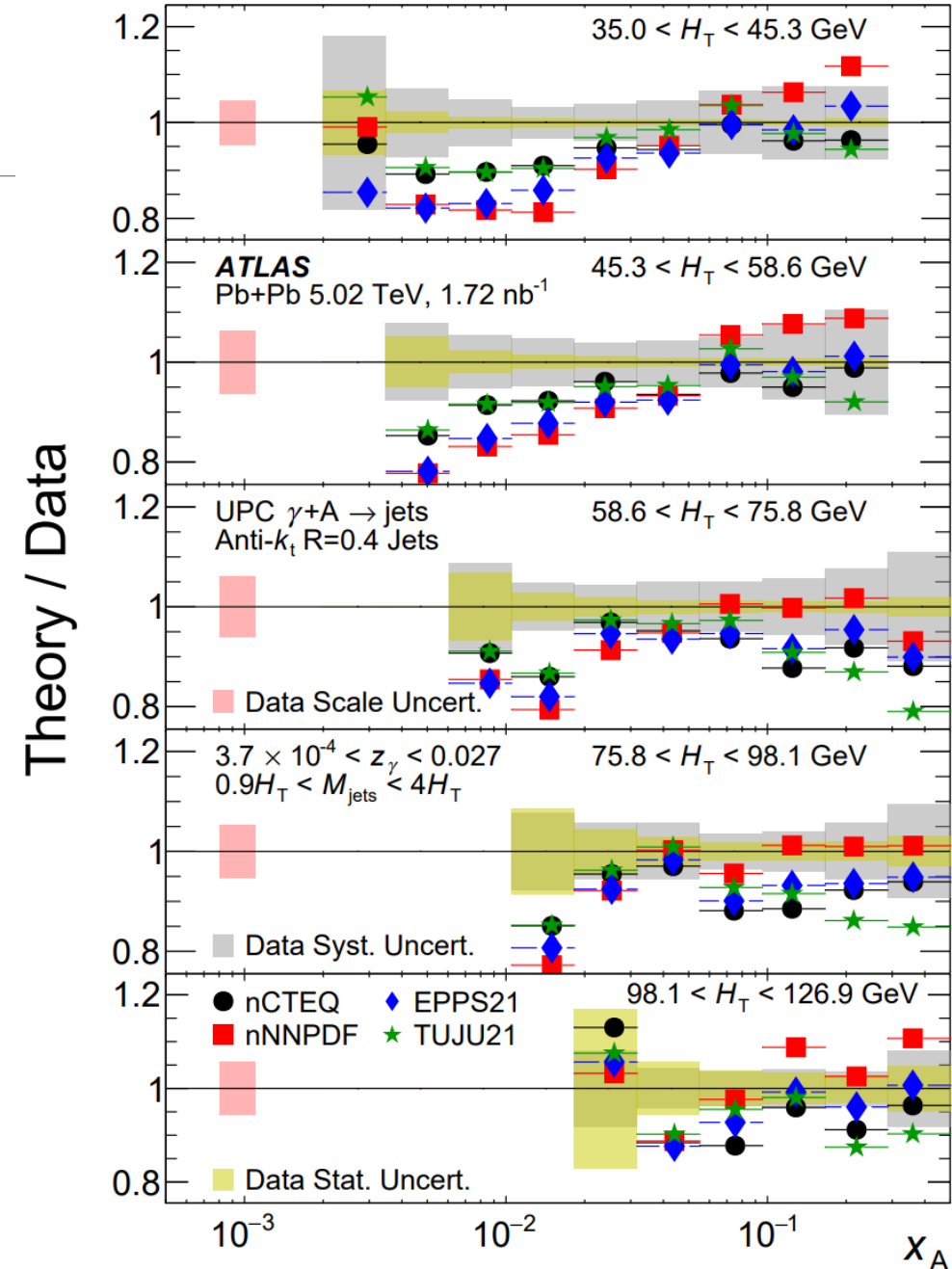


Photon Energy  
 $3.7 \times 10^{-4} < z_\gamma < 0.027$



# Comparing to nPDF Fits

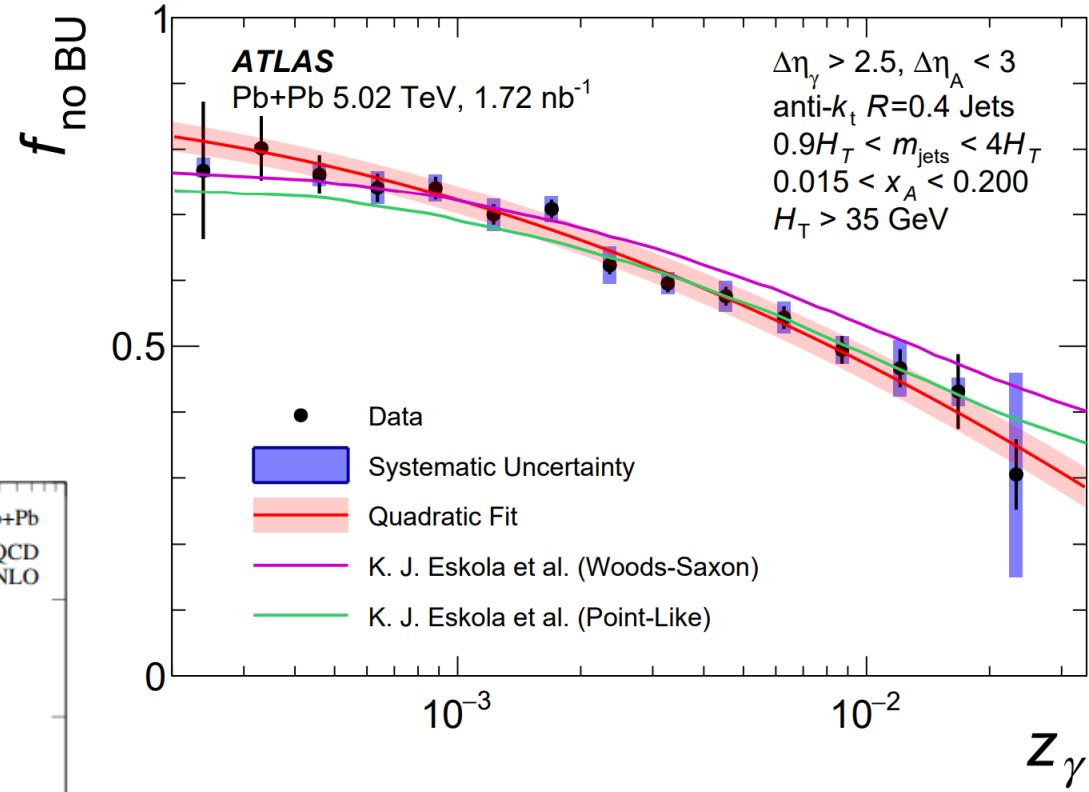
- Comparing to a larger set of nPDFs, we can see the influence this data may have on nPDFs.
  - The different sets studied are nCTEQ15 WZ+SIH, [EPPS21](#), [nNNPDF 3.0](#), and [TUJU21](#).
  - Before drawing strong conclusions, it is important to remember that NLO corrections will likely increase the total cross-section.
- The separation of correlated systematic uncertainties is even more robust when looking at smaller intervals in  $z_\gamma$ .
- We see a clear tension between the shadowing and anti-shadowing regions.
  - Both cannot be in agreement with the data, and models which include high- $p_T$  LHC pPb data ([nNNPDF](#), [EPPS21](#)) tend to have larger modifications.



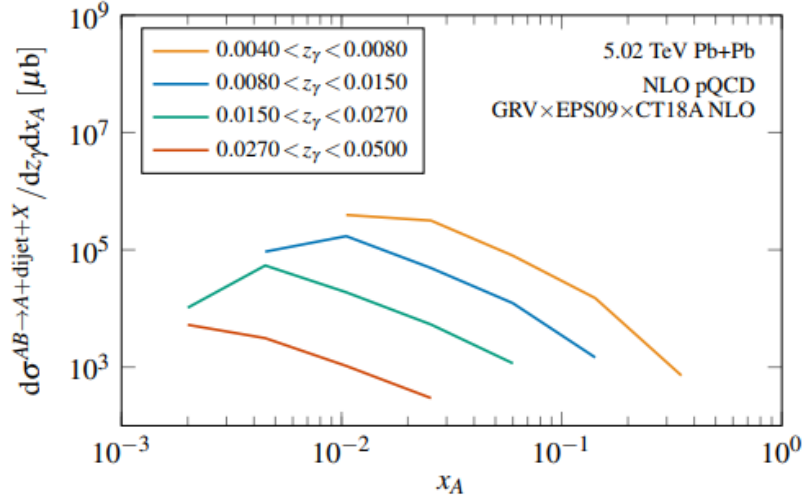
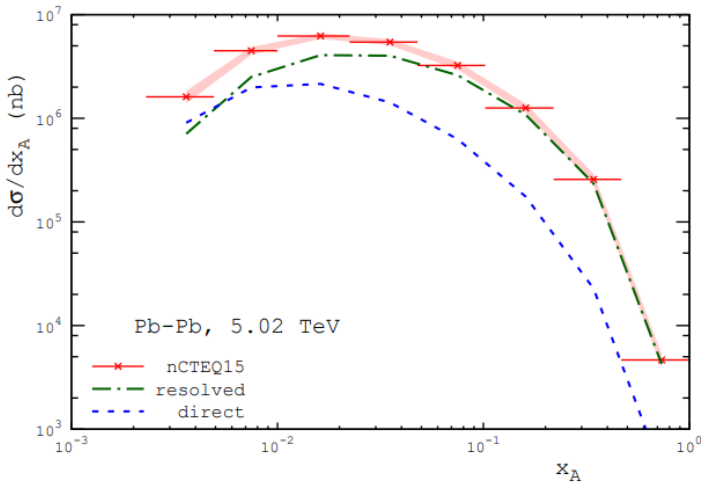
# Including UPC Jet Data in nPDF Fits

- NLO calculations for jet photoproduction in UPC have been well-understood for years.
  - Test of nPDF constraining power: [PRC 99 \(2019\) 065202](#)
  - Recent results considering EMD: [PRC 110 \(2024\) 054906](#)
- After extracting correlated effects, bin-to-bin uncertainties are on the order of a few percent for a wide range of kinematics.
- Effects of EMD are large, but they are well-understood from data.
  - Uncertainties are  $\sim$ fully correlated within a  $z_\gamma$  bin.
  - Corrections using theory are sensitive to model differences.

Cross-sections with a full decomposition of correlated systematic uncertainties are [available!](#)

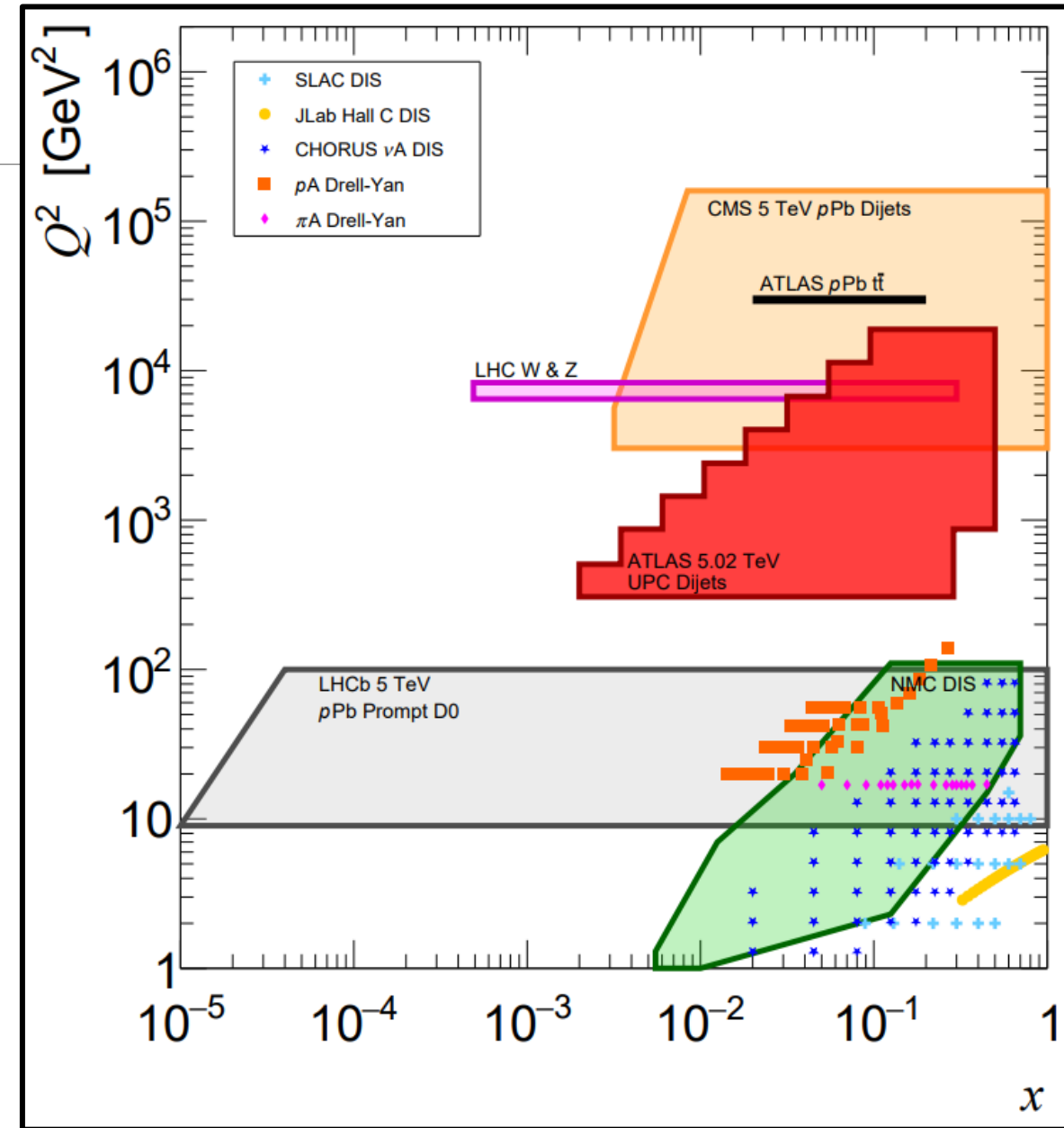


Extraction also relies on knowledge of photon PDFs. See [Madhav's talk](#) yesterday.



# Conclusions

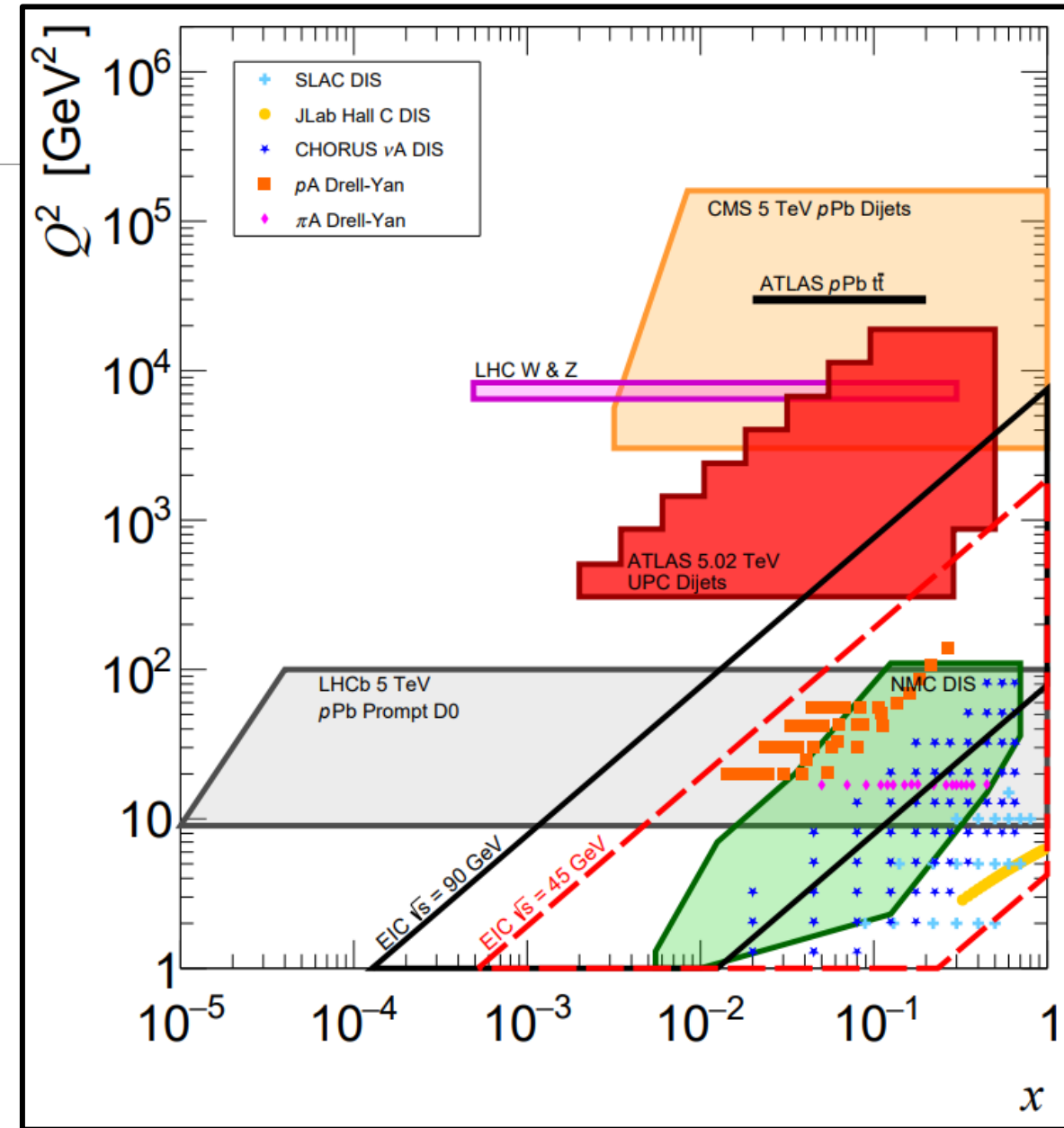
- The results from this measurement provide substantially improved coverage of the intermediate and high  $Q^2$  regions, for a wide range of  $x$  values.
- The top-quark cross-section in p+Pb collisions provides a  $> 5\sigma$  observation of the process and constrains anti-shadowing effects.
- The UPC results are fully inclusive, and after correction for nuclear break-up, the measured cross-sections agree well with existing nPDFs using LO+PS calculations.
- These data will have substantial constraining power for nPDFs in multiple kinematic regions.



# Conclusions

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- These data will have substantial constraining power for nPDFs in multiple kinematic regions.

These results are closely related to early physics goals of the EIC!

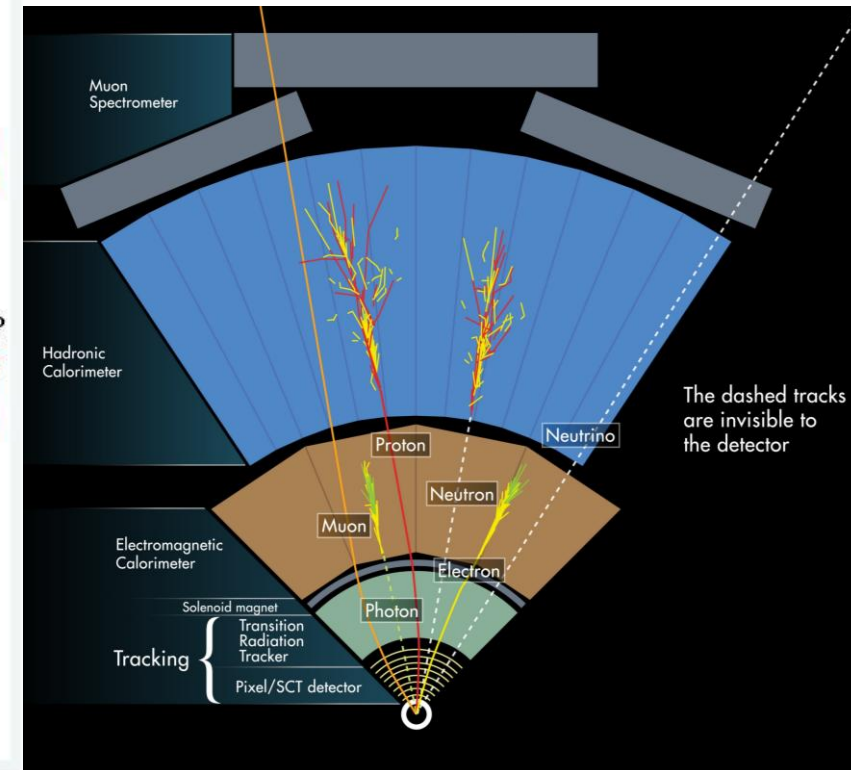
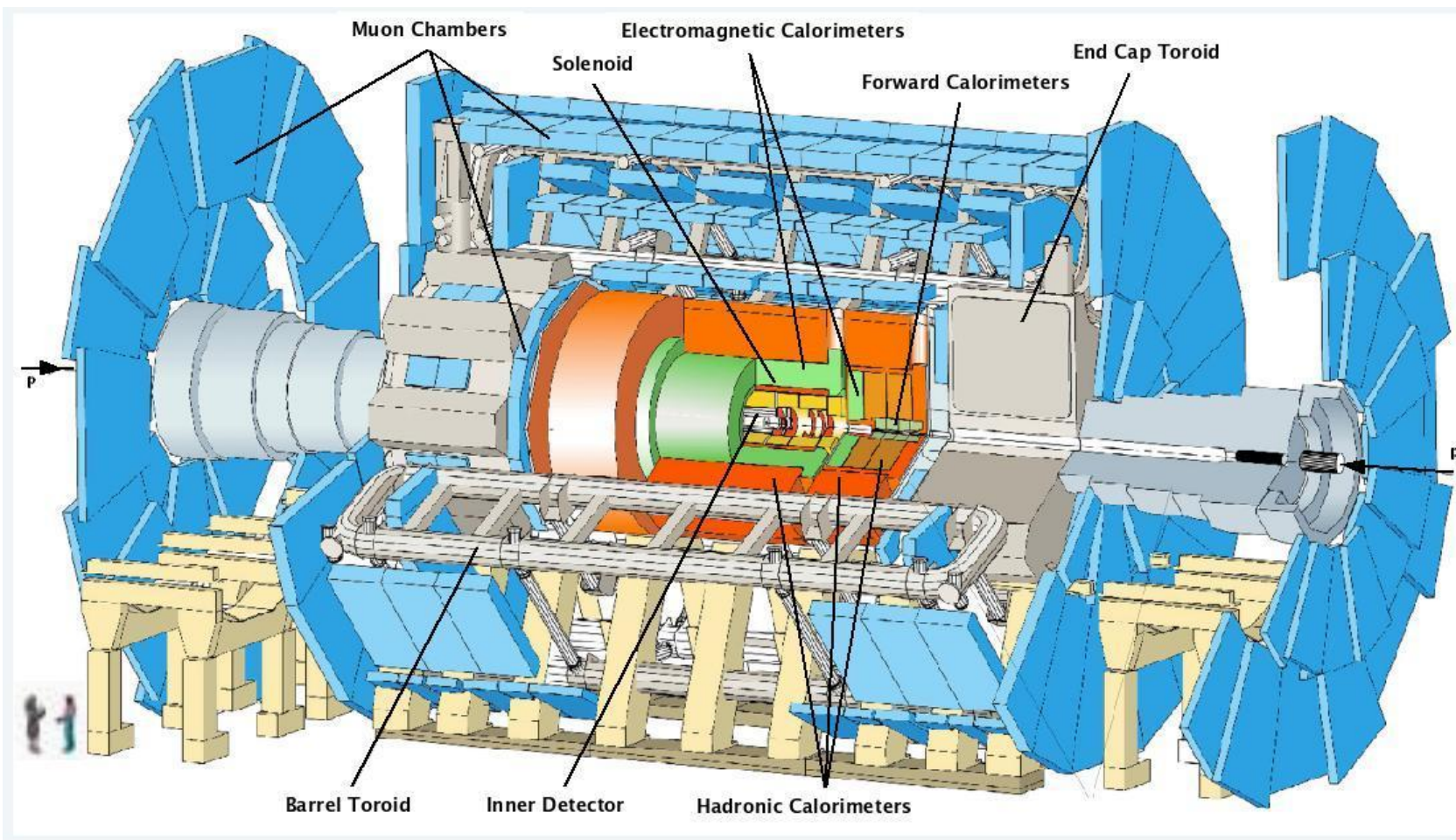


# Backup

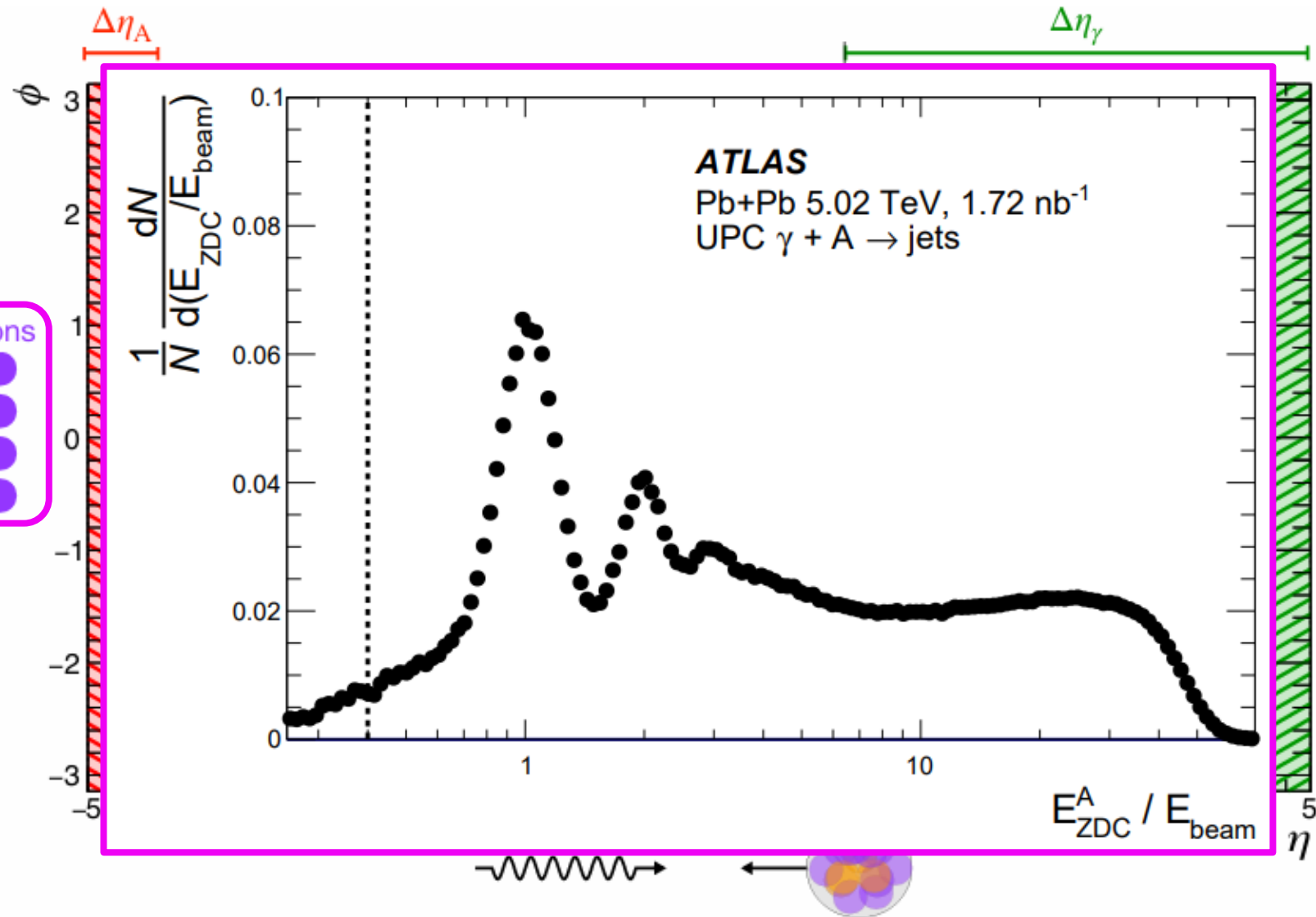
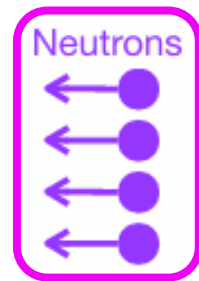
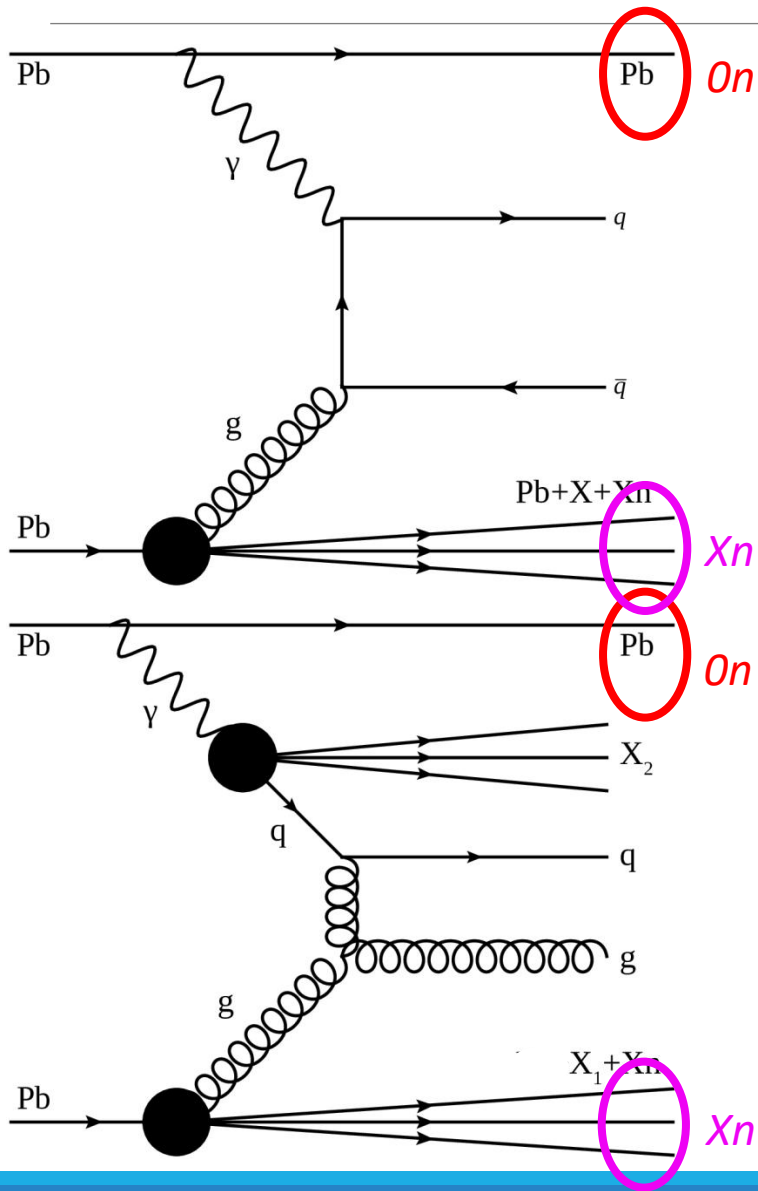
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# The ATLAS Detector

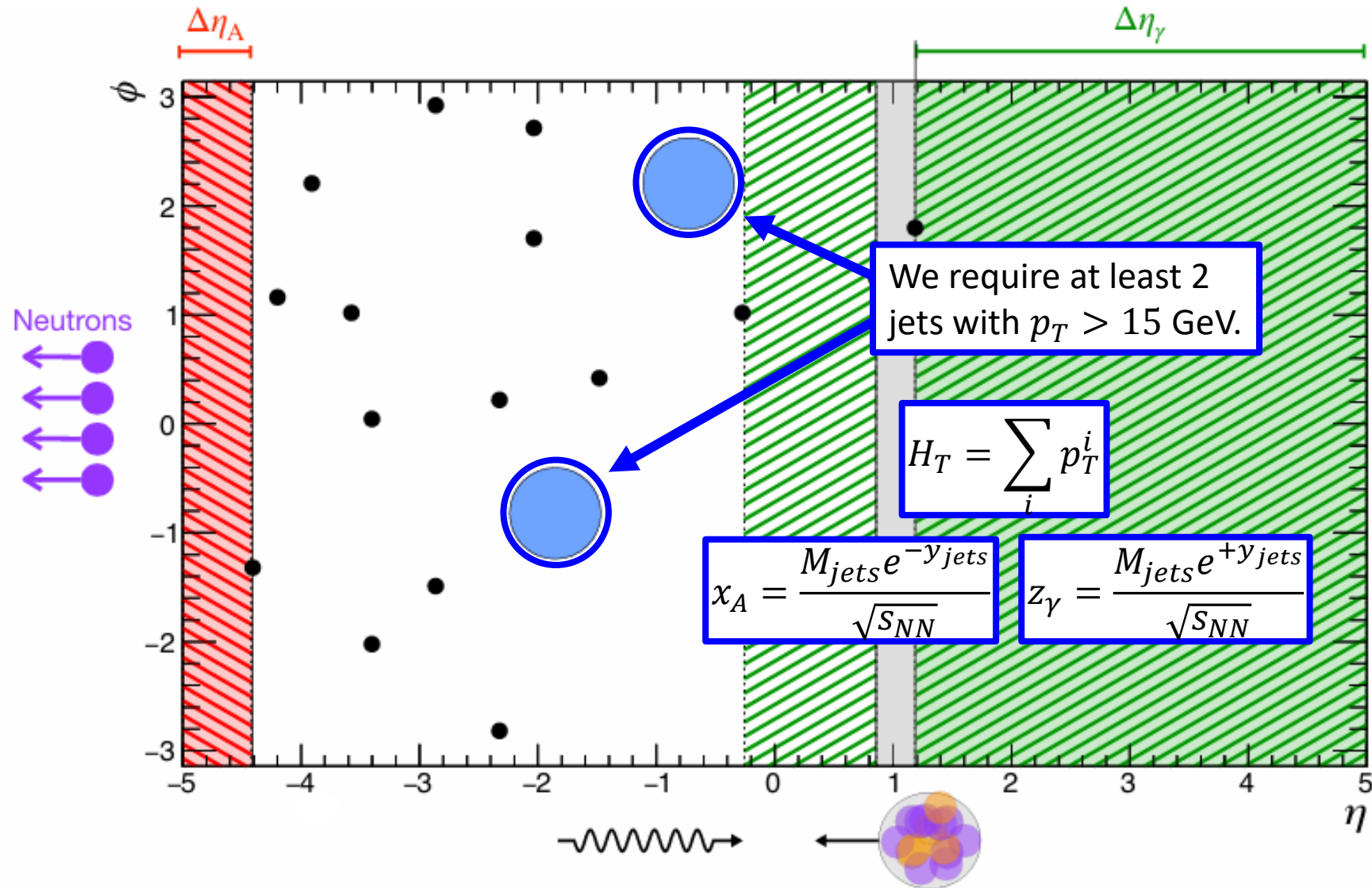
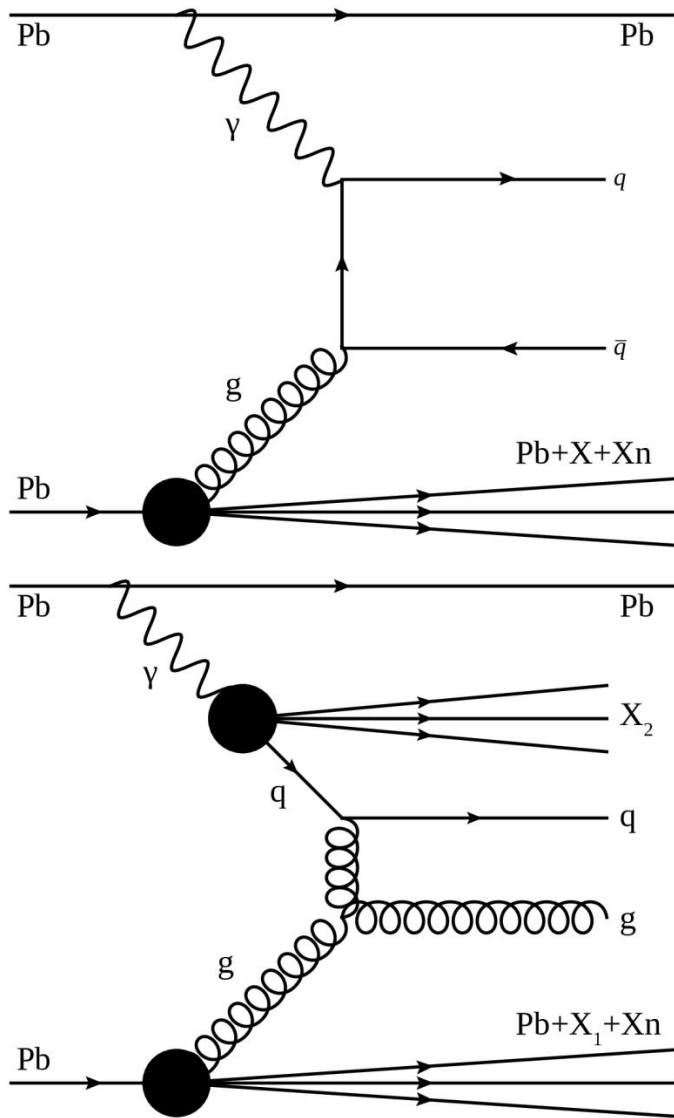
- Photonuclear jet measurements require inputs from nearly every component of the ATLAS detector.
  - Its nearly 10 units of coverage in rapidity are key for distinguishing these events.



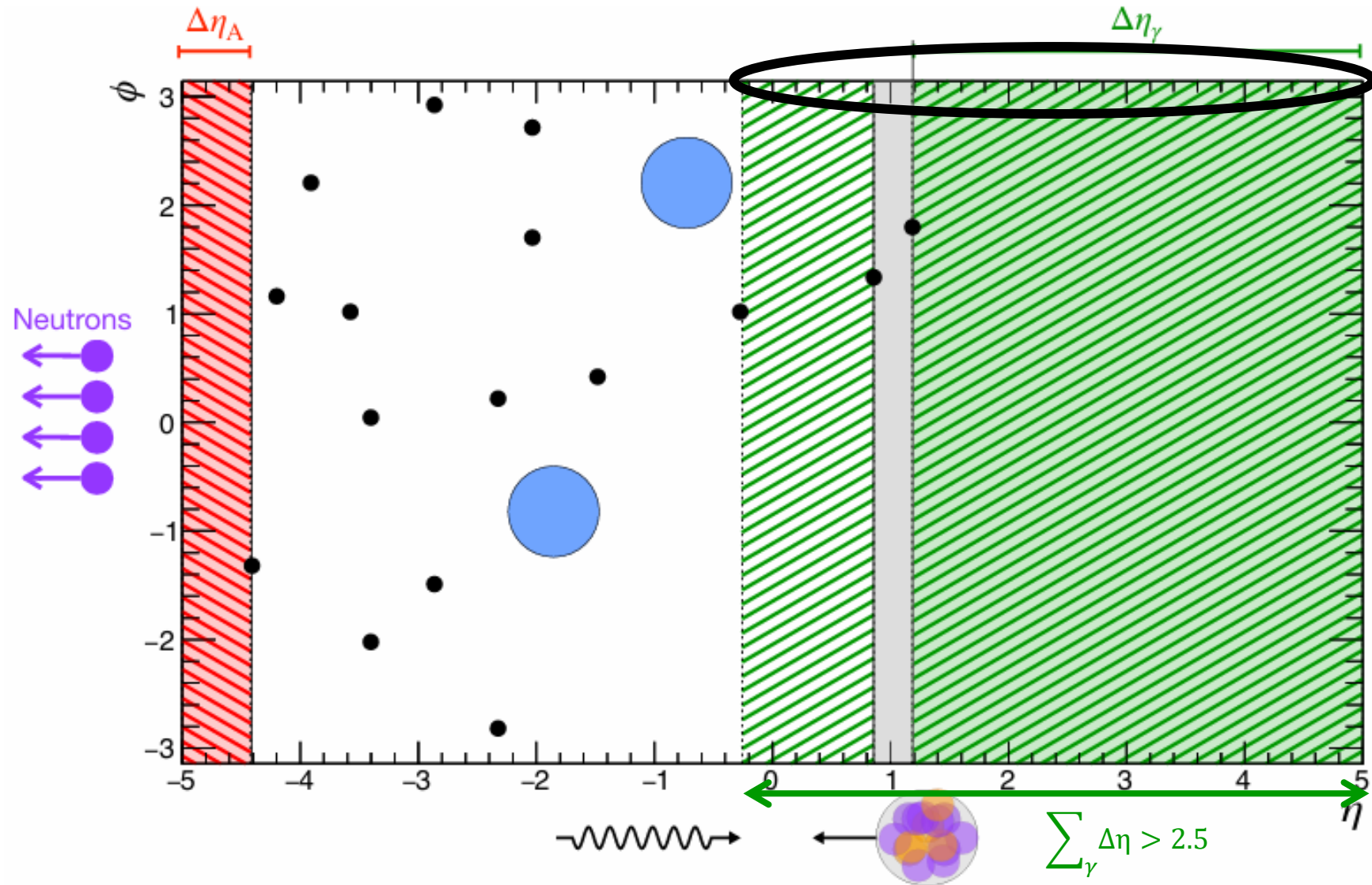
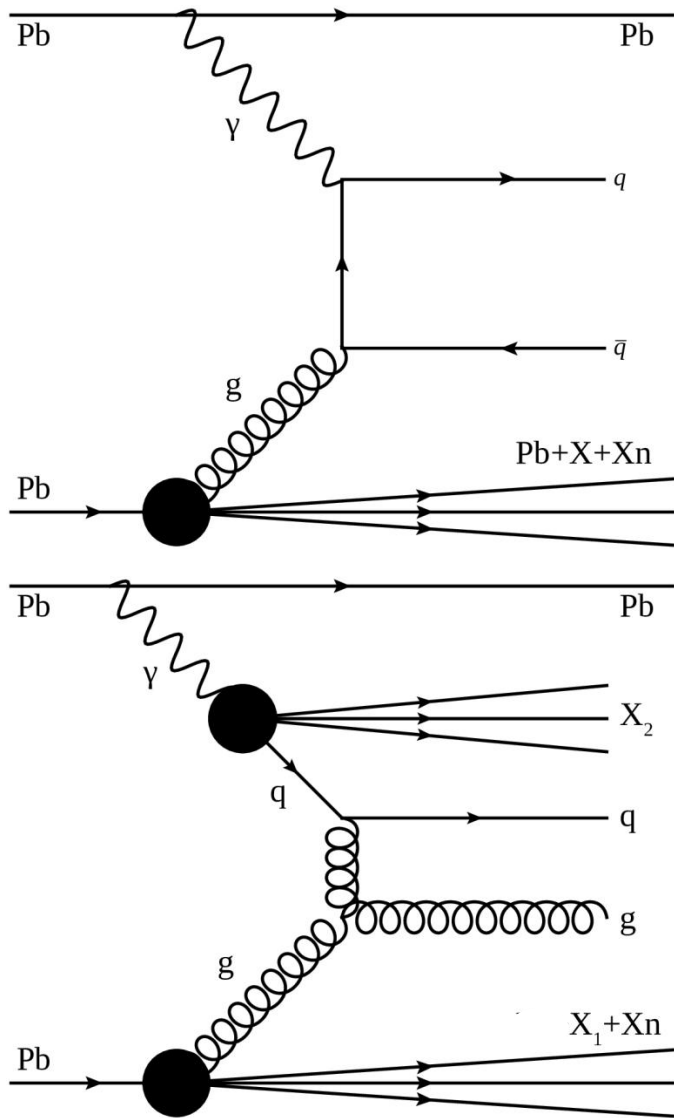
# Selecting Photonuclear Jet Events



# Selecting Photonuclear Jet Events

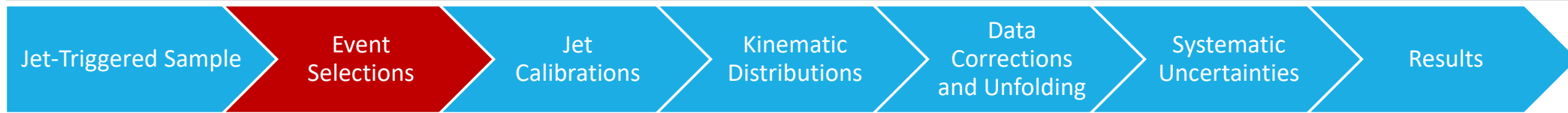


# Selecting Photonuclear Jet Events

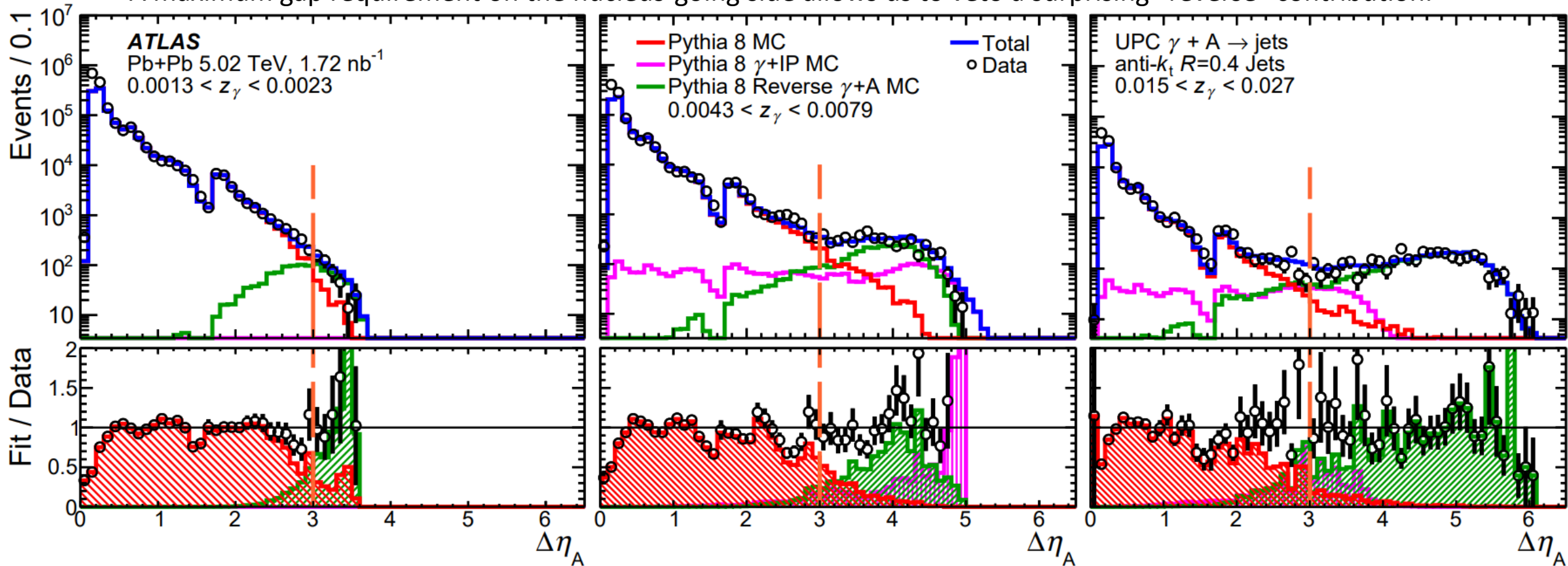


# Gap Selections: Nuclear Side

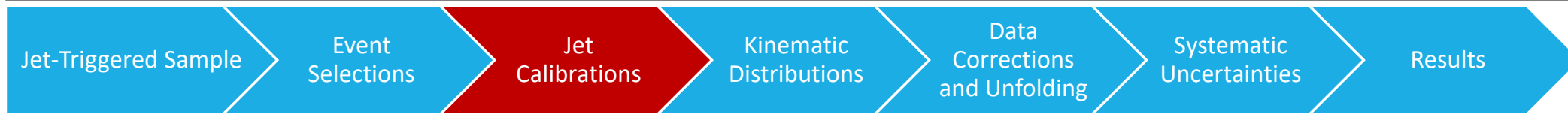
$$H_T = \sum_i p_T^i \quad z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{S_{NN}}}$$



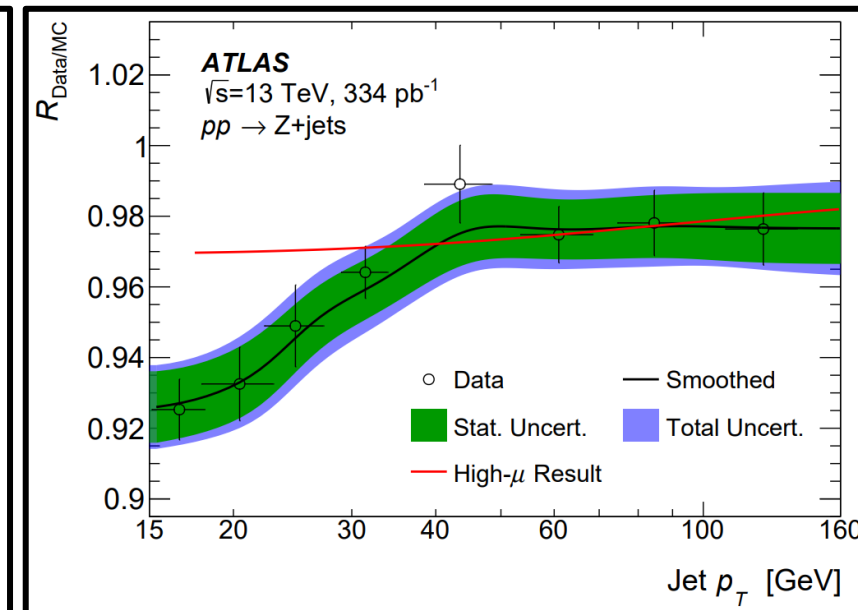
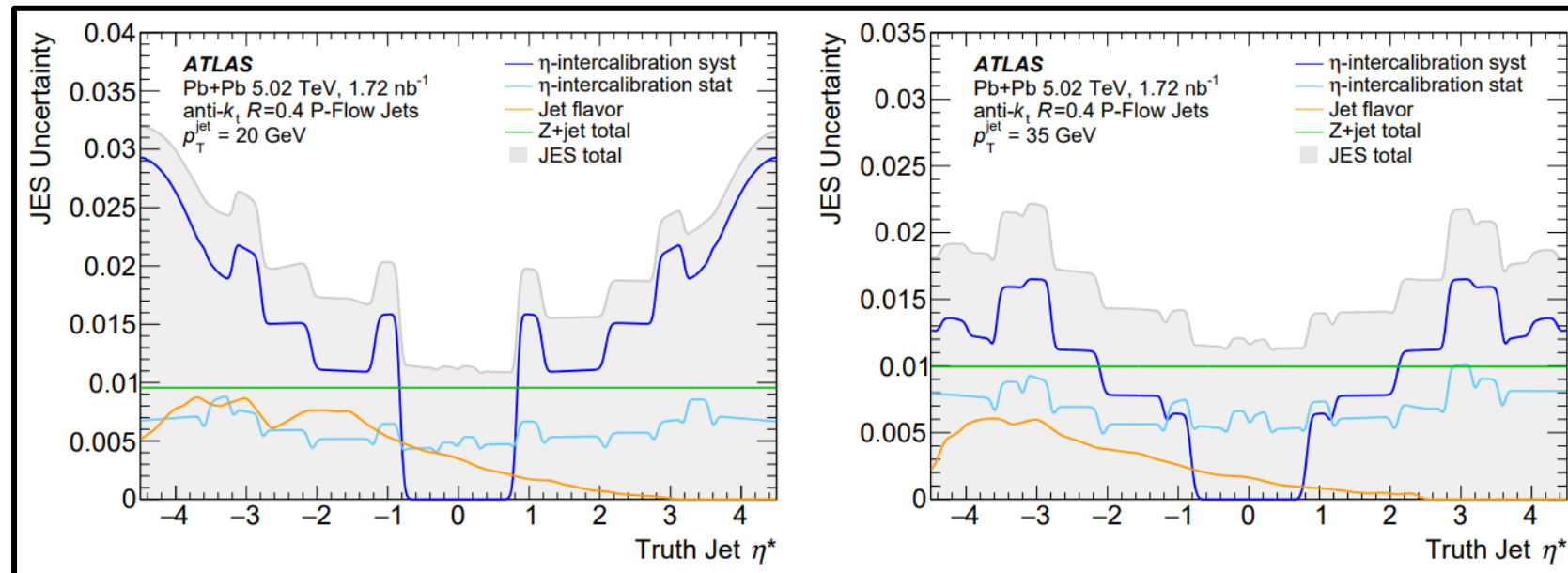
A maximum gap requirement on the nucleus-going side allows us to veto a surprising “reverse” contribution.



# Jet Reconstruction and Response



- Due to the unique environment of UPCs, an entirely new jet calibration was derived specifically for this measurement.
- This result extends lower in jet  $p_T$  than any previous ATLAS measurement.
  - This coverage was made possible through new techniques for studying the absolute energy scale at low  $p_T$ .
- Methodology for measuring jets in UPC is useful for the EIC program, and some dominant uncertainties are shared!



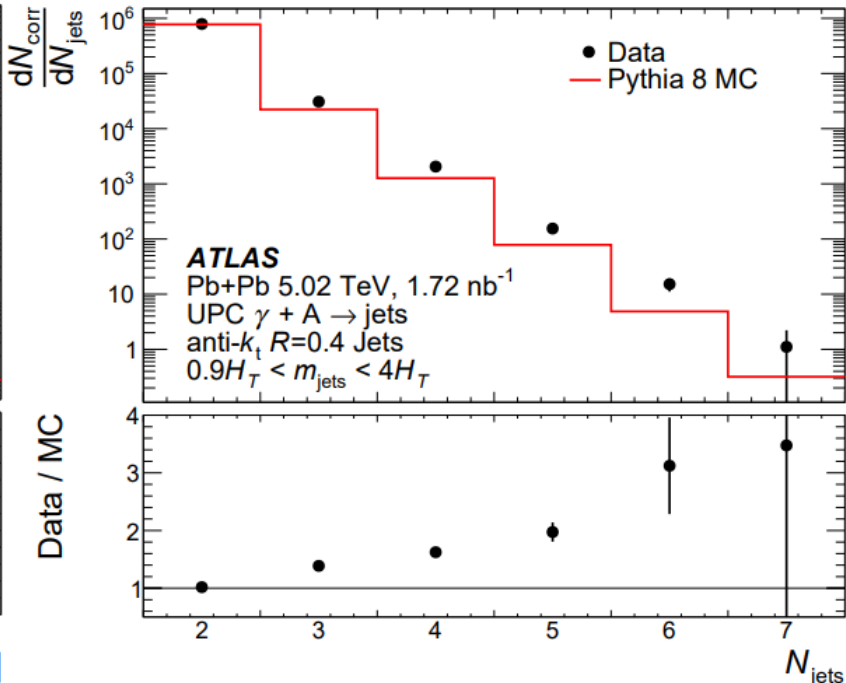
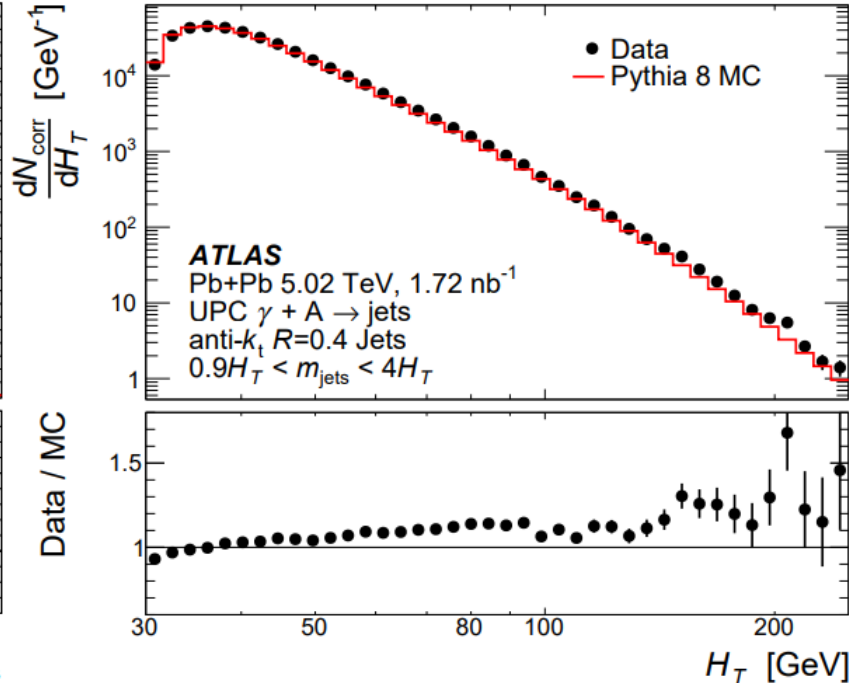
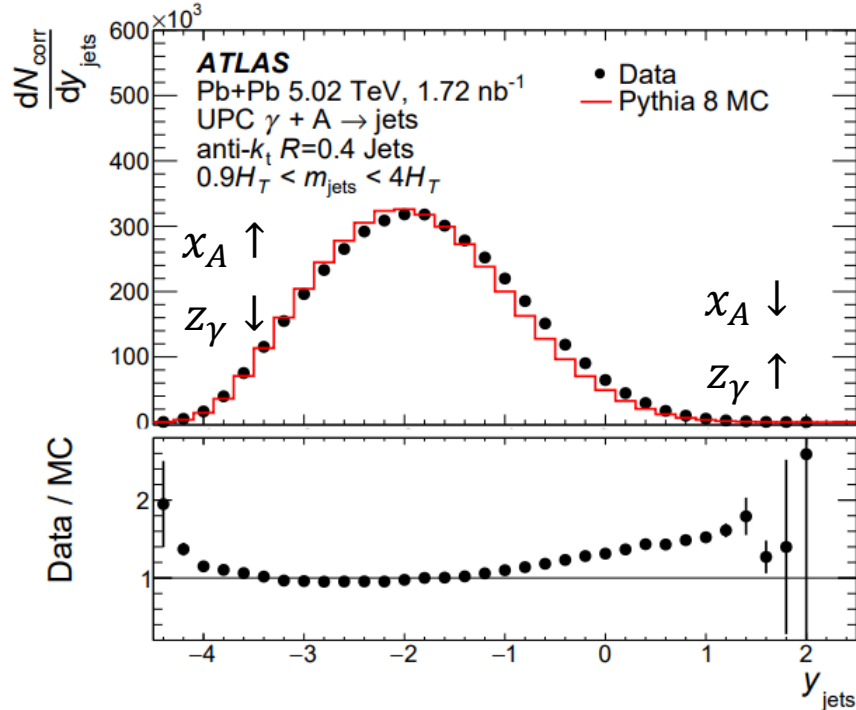
# Comparing Data to MC Before Unfolding

$$x_A = \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}$$

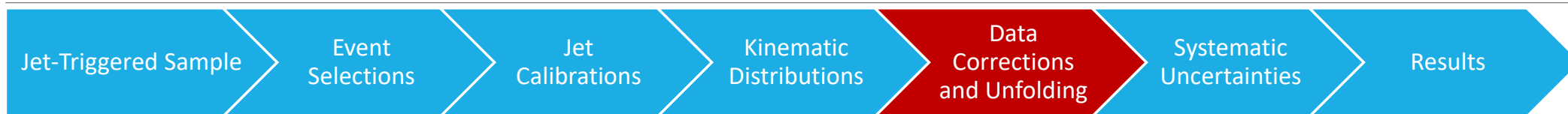
$$z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$



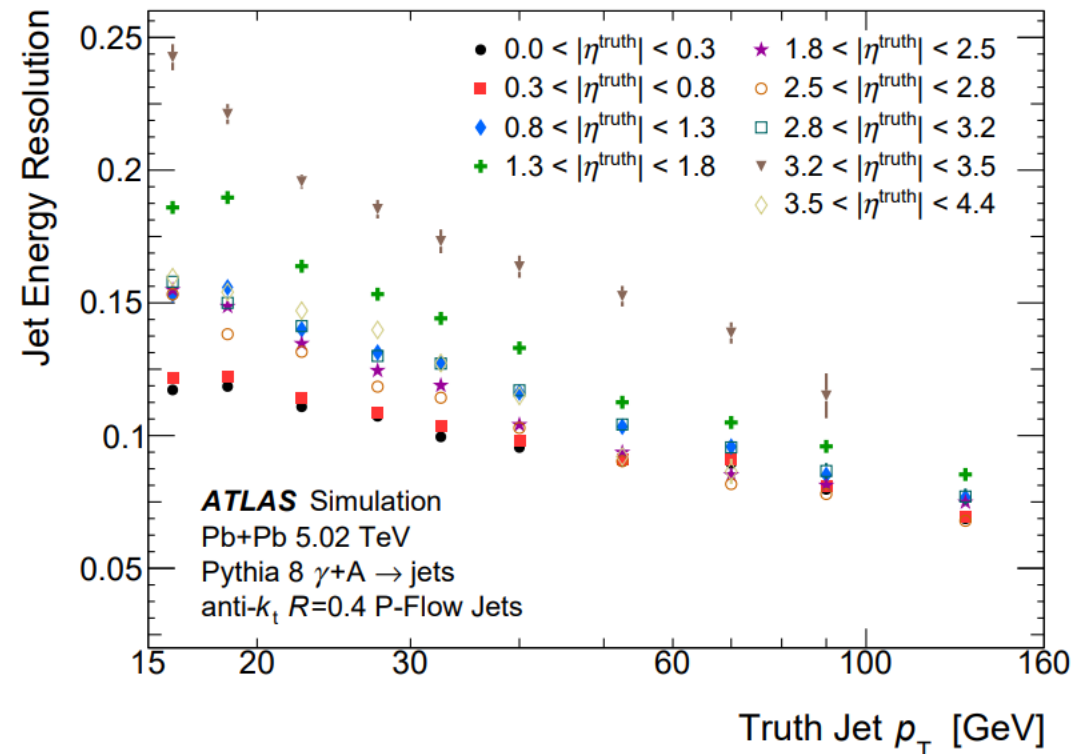
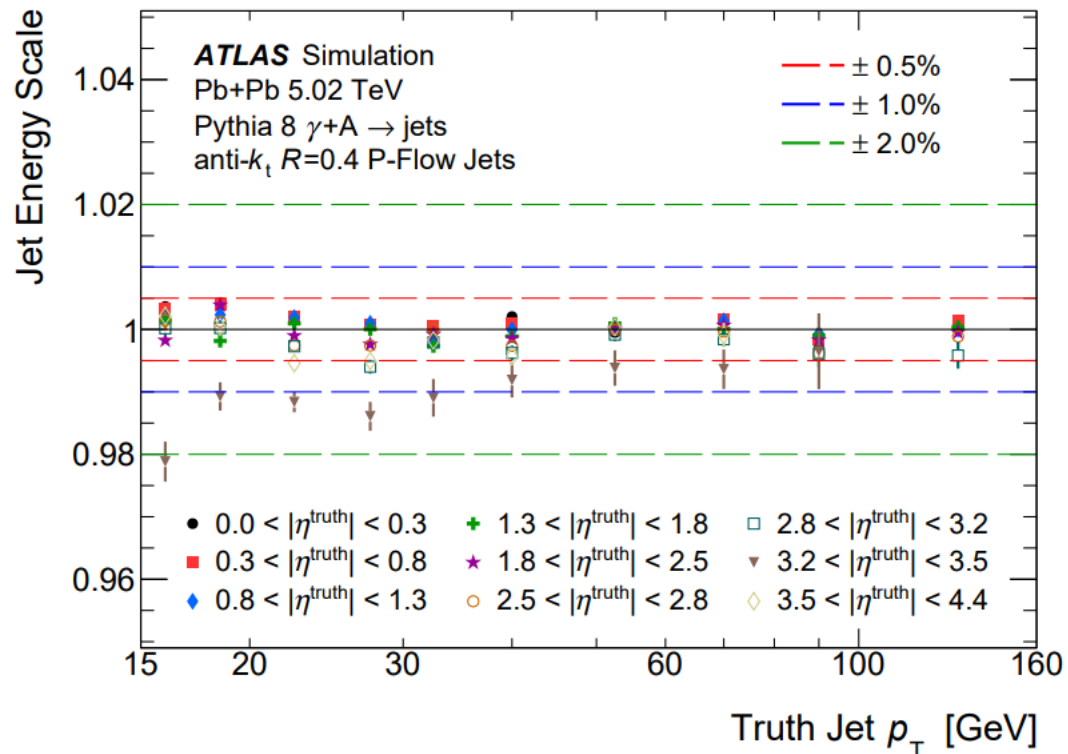
- Comparing reconstructed MC to data, we see broad agreement, with a few key features:
  - Effects at large positive  $y_{jets}$  are in the region most sensitive to nPDF shadowing effects.
  - The discrepancies for larger jet multiplicities are indicative of missing higher-order effects in the LO Pythia comparison.



# Unfolding for Jet Reconstruction



- The dominant correction applied to the data is the unfolding, which accounts for effects of the jet response:
  - The mean jet response is typically closed, but certain regions exhibit non-closure which is corrected.
  - The resolution is remarkably good given the jet  $p_T$  range, but it still requires a substantial unfolding correction.



# Kinematics of Photonuclear Jet Production

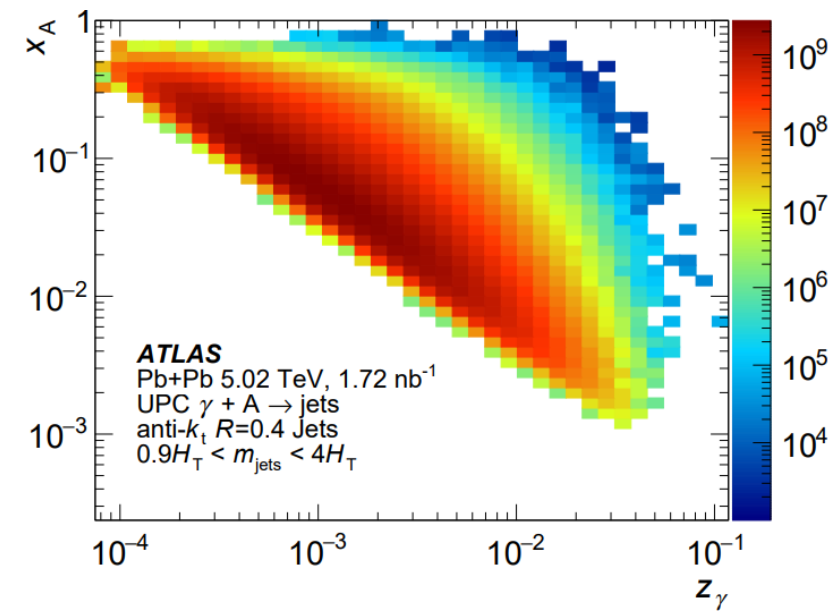
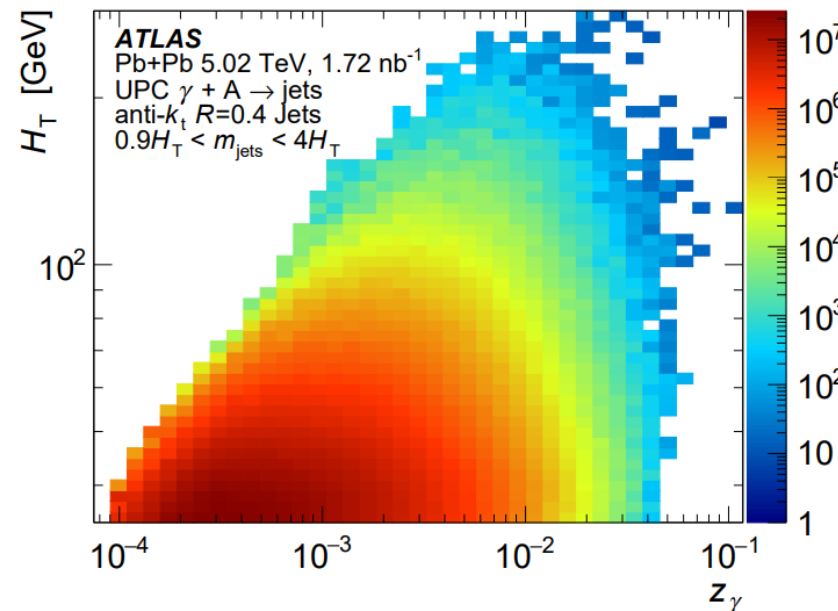
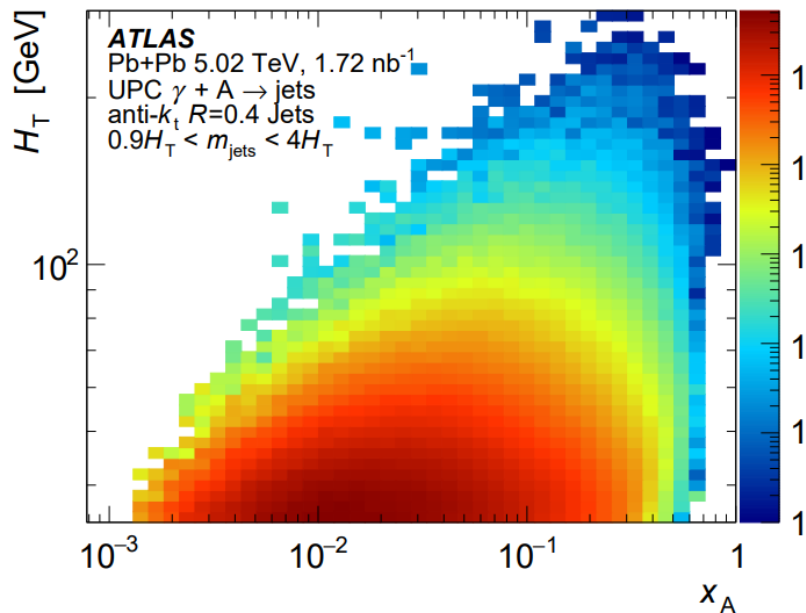


$$H_T = \sum_i p_T^i$$

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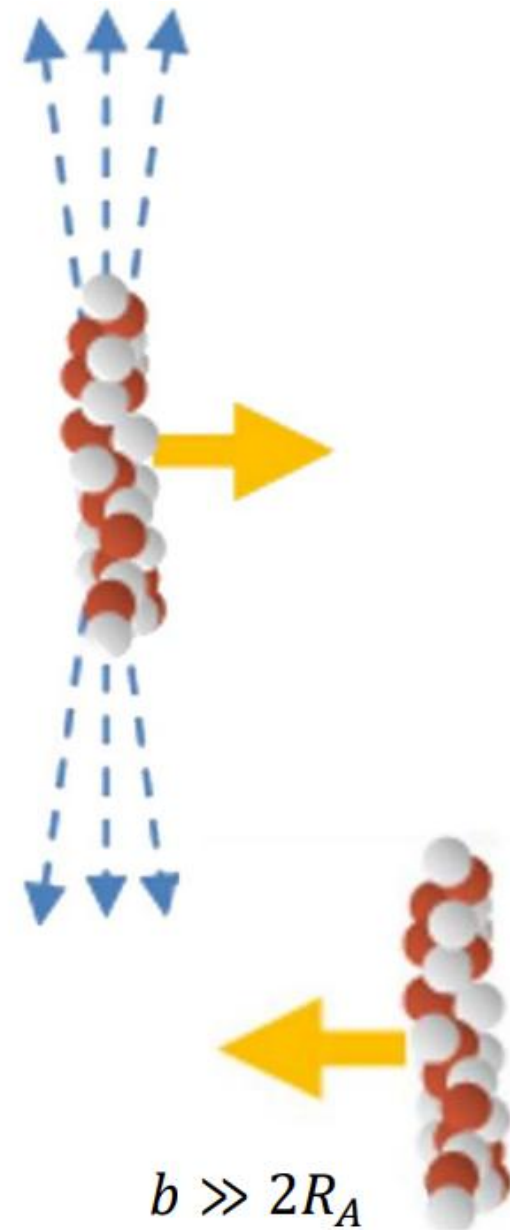
$$z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{S_{NN}}}$$

- The measurement is performed in two different variable sets:
  - $H_T$ ,  $y_{jets}$ , and  $m_{jets}$ : Kinematics of the jet system
  - $H_T$ ,  $x_A$ , and  $z_\gamma$ : Proxy variables for the kinematics of the hard-scattering process



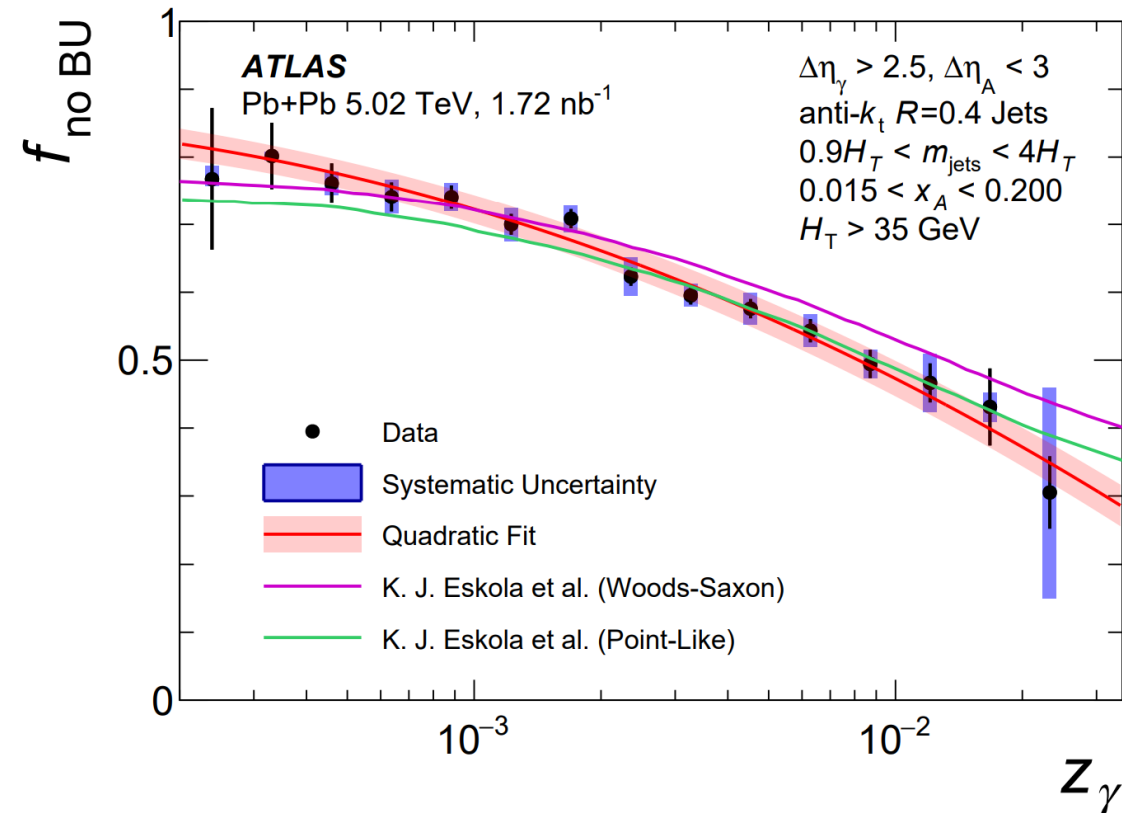
# An Aside: Nuclear Break-up

- Our typical picture of an ultra-peripheral heavy-ion collision involves two nuclei with some large separation,  $b > 2R_A$ .
- $E_\gamma \propto 1/b \rightarrow$  Biases towards lower impact-parameter collisions
- Higher probability of breakup of the photon-emitting nucleus due to additional EM interactions



# An Aside: Nuclear Break-up

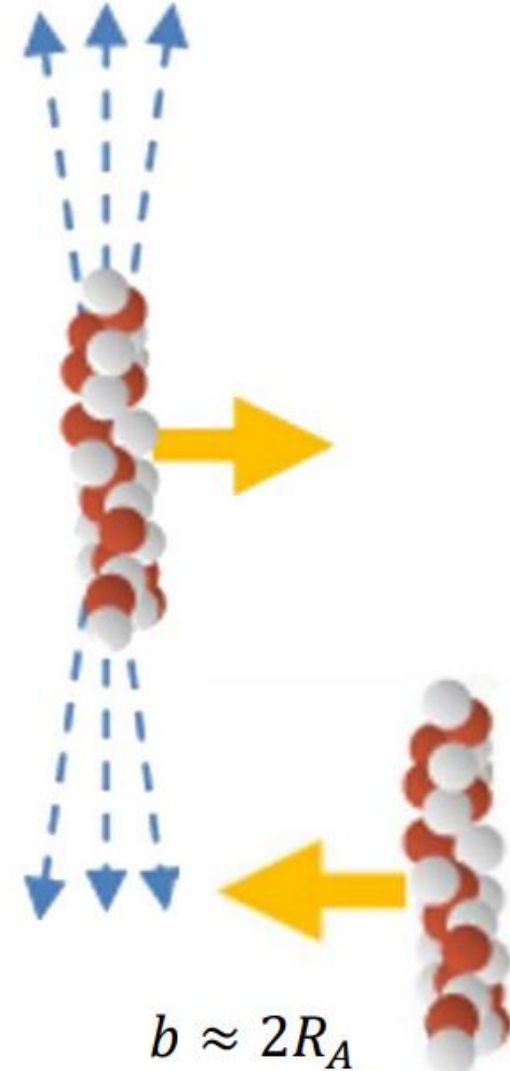
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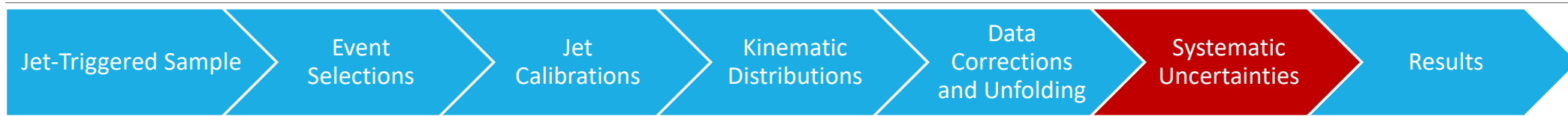
$$f_{\text{no BU}} \equiv \frac{d\sigma/dz_\gamma|_{0nXn}}{d\sigma/dz_\gamma|_{XnXn} + d\sigma/dz_\gamma|_{0nXn}}$$

The measured breakup is used to correct the theory predictions when comparing to data.

Theoretical modeling predicts the rate quite well! (arXiv:2404.09731)



# Systematic Uncertainty

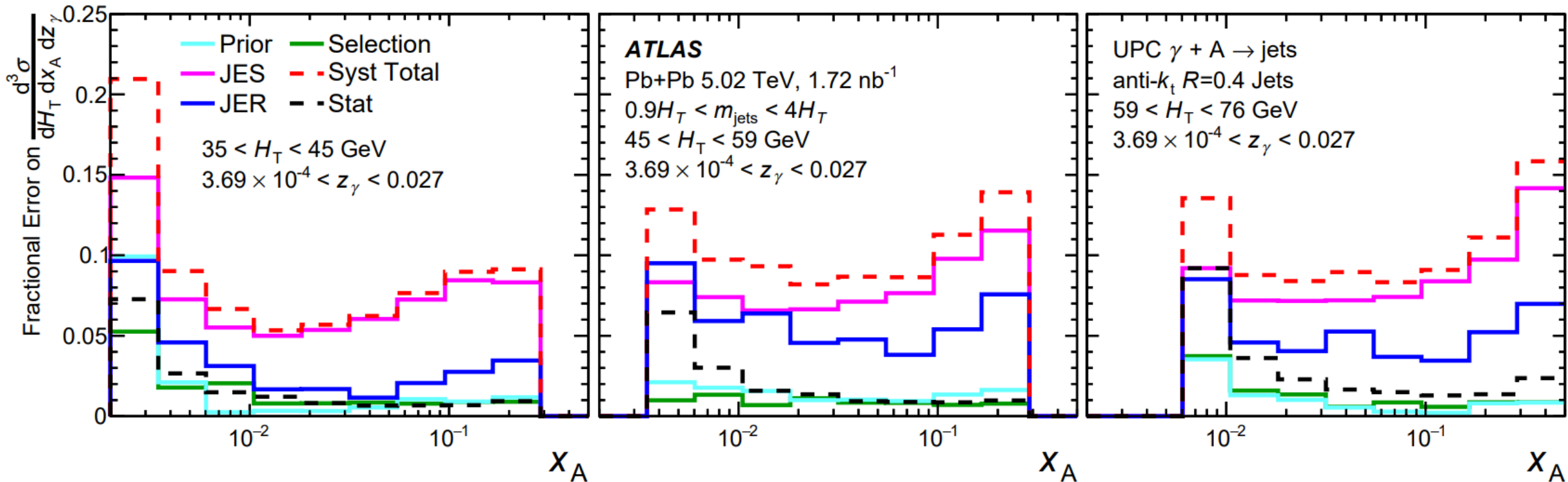


Systematic uncertainties are the limiting factor in sensitivity to nuclear PDFs.

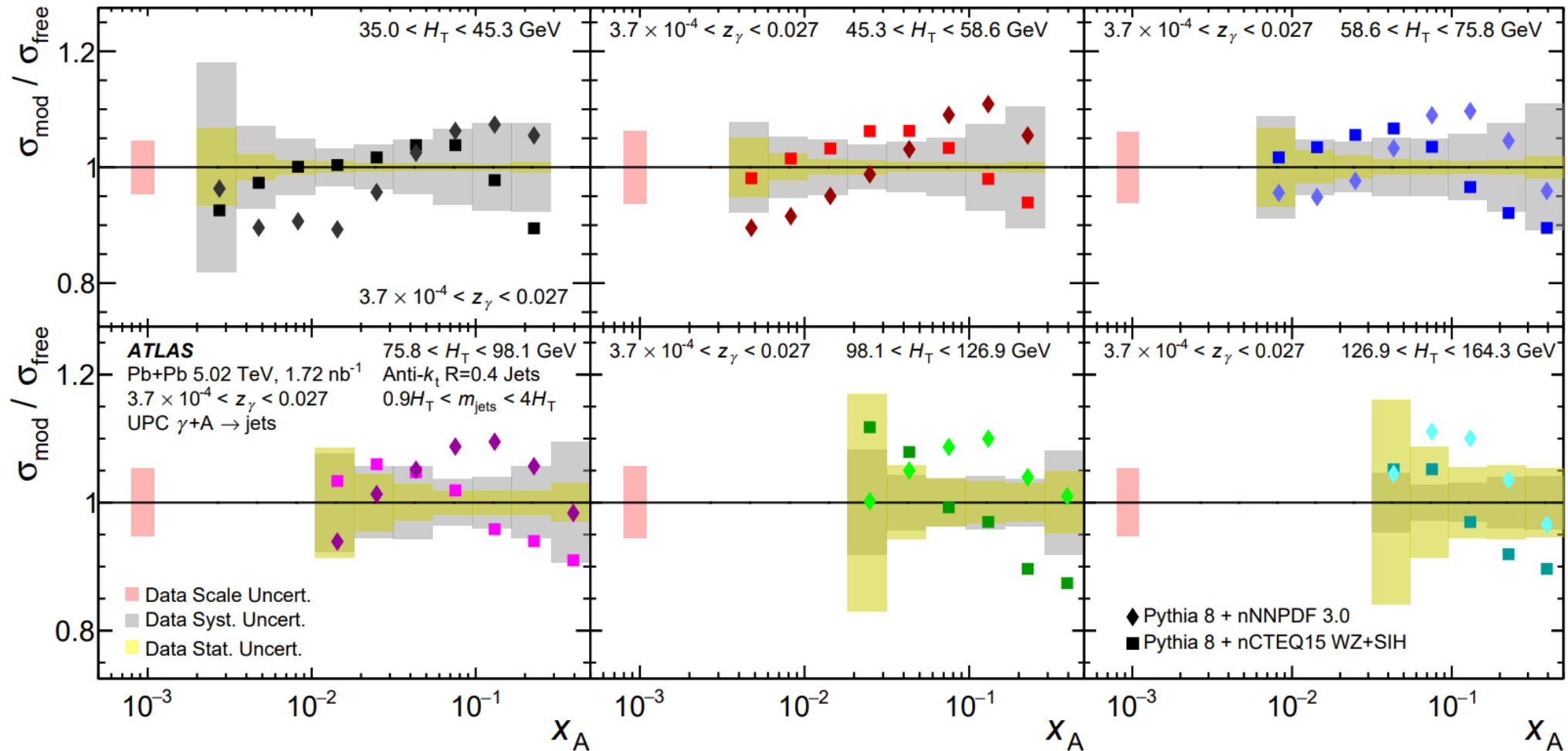
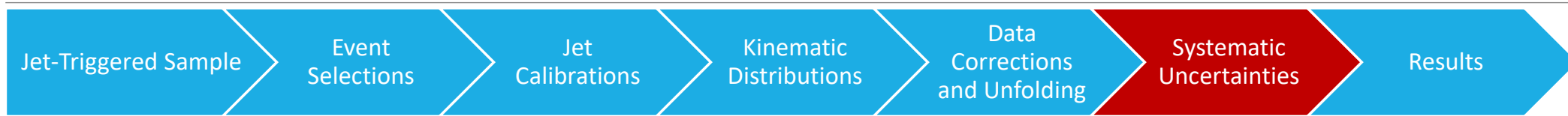
The jet energy **scale** and **resolution** uncertainties are typically 5-10%.

Systematic uncertainties also arise due to the **unfolding** and **event selections**.

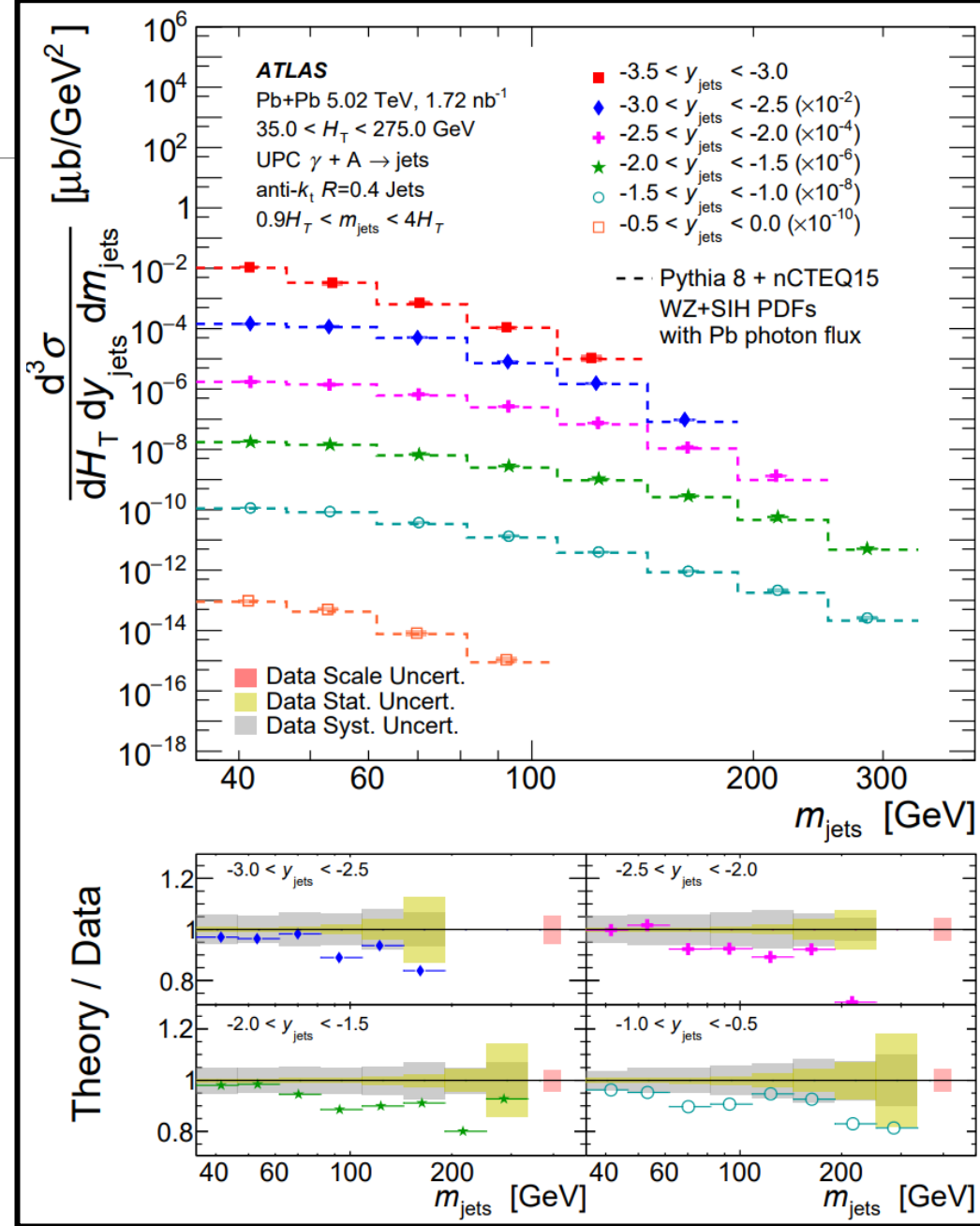
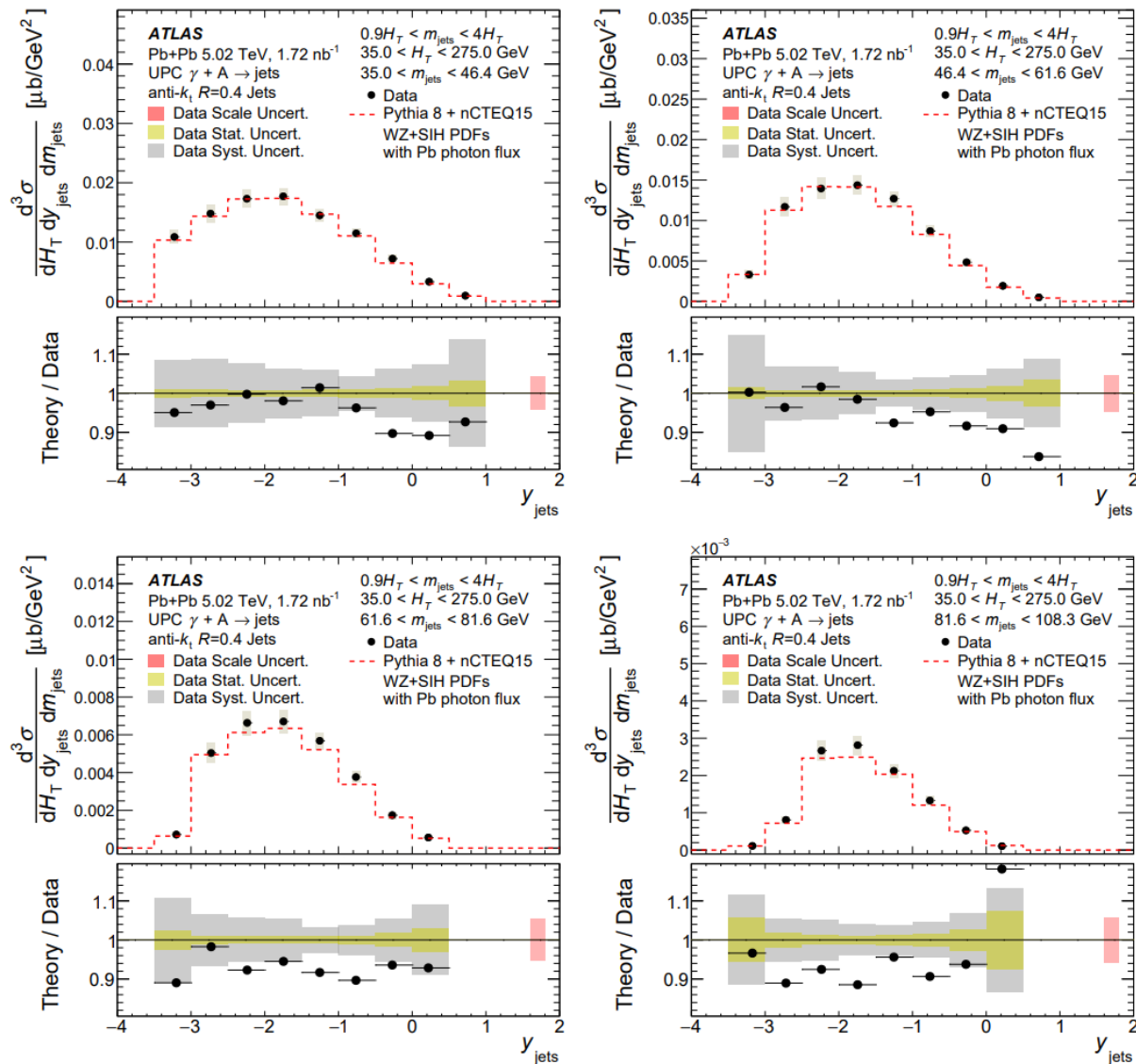
Full treatment of correlated uncertainties provides substantially more constraint.



# Sensitivity to nPDF Effects



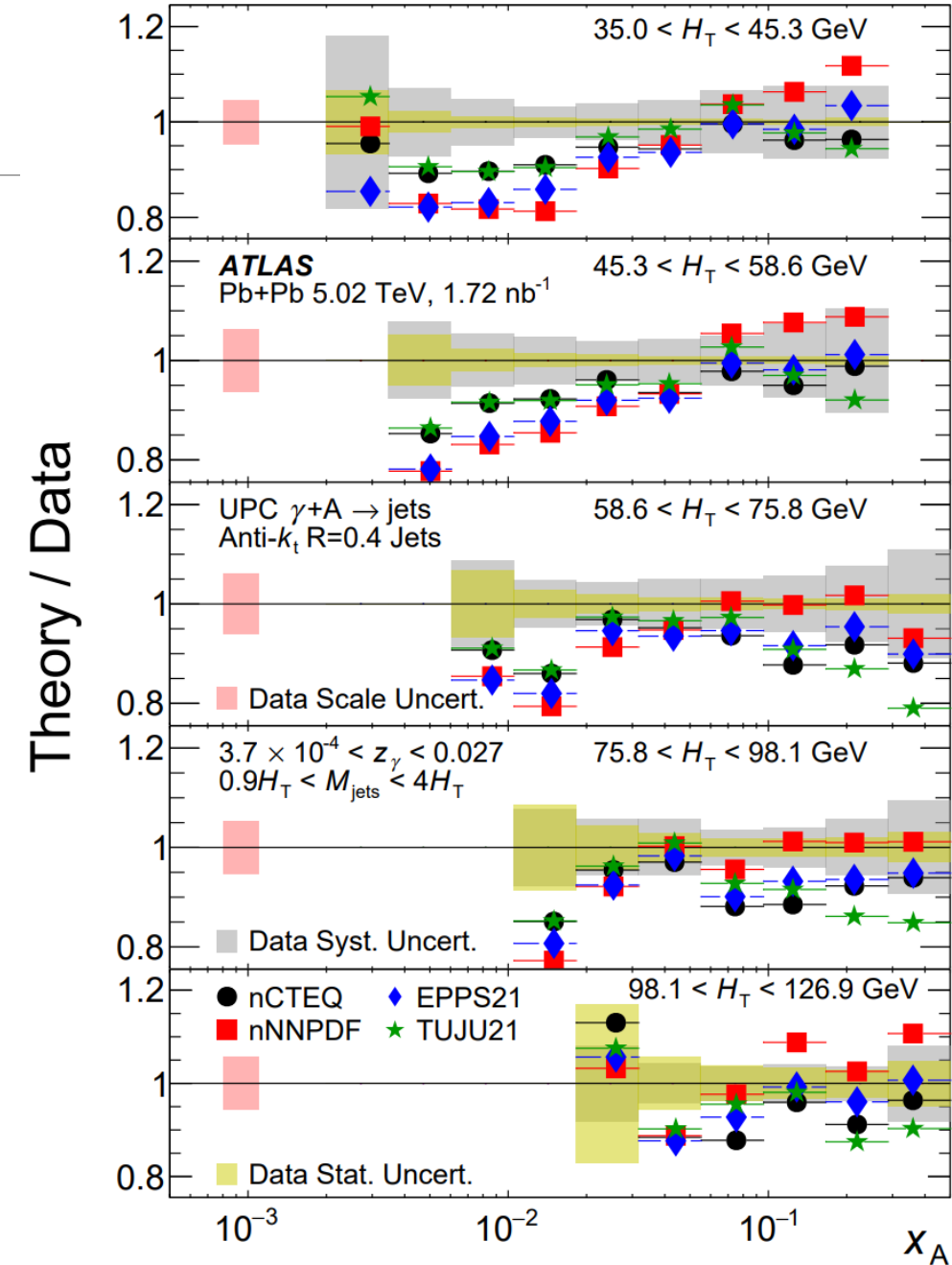
# Results: Jet System Kinematics



# nPDF Comparisons

- The key difference between these results is that EPPS and nNNPDF include the CMS pPb dijet results.
  - These tend to have a higher cross-section in the anti-shadowing region and lower in the shadowing region.

Dataset Description	nCTEQ15WZ+SIH	EPPS21	nNNPDF 3.0	TUJU21
SLAC/FNAL/CERN/Hermes DIS	✓	✓	✓	✓
JLab CLAS+Hall C $eA$ DIS	✓	✓		
CHORUS/CDHSW $\nu A$ DIS	✓	✓	✓	✓
NuTeV/CCFR $\nu A$ DIS	✓		✓	
FNAL $pA$ Drell-Yan	✓	✓	✓	
FNAL/NA3/NA10 $\pi A$ Drell-Yan		✓		
STAR+PHENIX Inclusive $\pi^0$	✓	✓		
STAR+PHENIX $\eta, \pi^\pm$	✓			
PHENIX $K^\pm$	✓			
LHC $Z^0$ Bosons	✓	✓	✓	✓
CMS+ALICE $W^\pm$ Bosons	✓	✓	✓	✓
ALICE $\pi^0, \eta, \pi^\pm, K^\pm$	✓			
CMS $pPb$ Dijets		✓	✓	
ATLAS $pPb$ Prompt Photons			✓	
LHCb $pPb$ Prompt $D^0$	✓	✓	✓	
ALICE $pPb$ Prompt $D^0$	✓			



# Photo-Diffractive Jet Production

ATLAS measurements of dijets without break-up (0n0n) suggest a substantial photo-diffractive jet cross-section at the LHC.

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  $\gamma\gamma \rightarrow \text{jets}$ , estimated by Pythia or comparison to  $\gamma\gamma \rightarrow \mu^+\mu^-$  studies.

