Probing the Transverse Structure of nPDF Modifications in Ultra-Peripheral Collisions with the ATLAS Detector

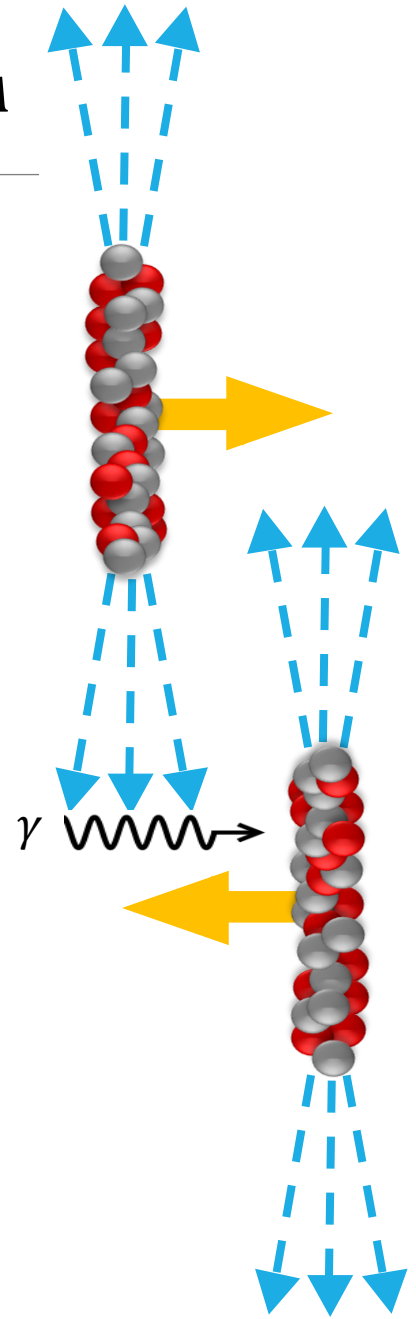
Ben Gilbert, on behalf of the ATLAS Collaboration

arXiv:2604.20559
arXiv:2604.24435

Ultra-Peripheral Collisions (UPCs)

$b > 2R_A$

- In heavy ion collisions, the nuclei generate extremely strong electromagnetic fields.
  - For Z = 82 ions at 5.02 TeV, the field strength is B = O(10^{15}) T.
- These EM fields interact as a flux of nearly real photons. (Equivalent Photon Approximation)
  - The cross-sections for photoproduction are enhanced by Z^2 for each photon emitter.



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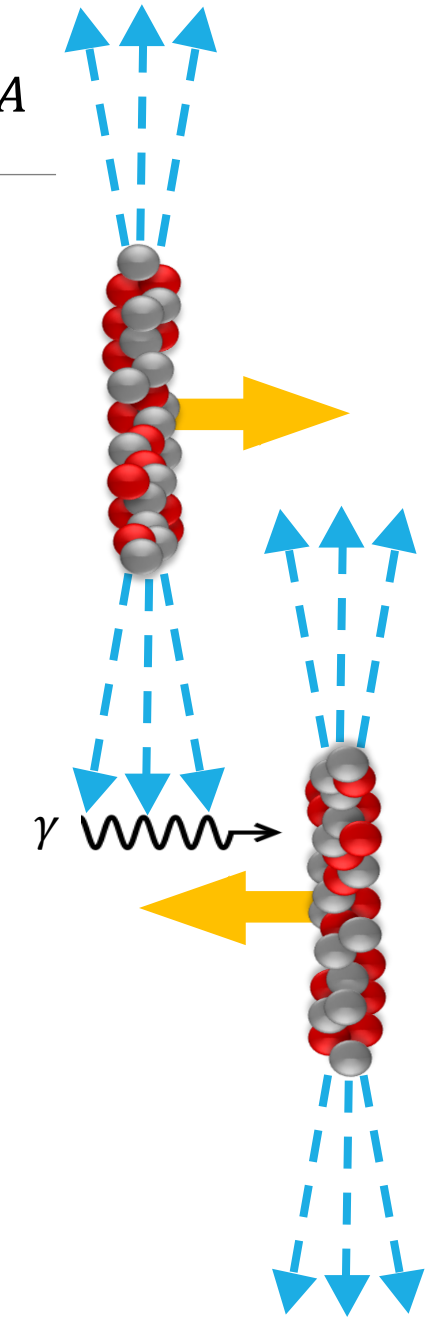

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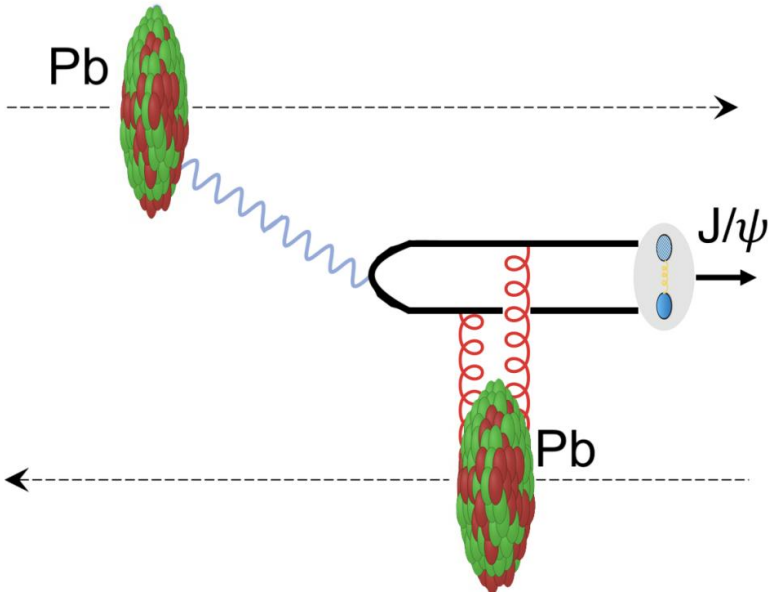
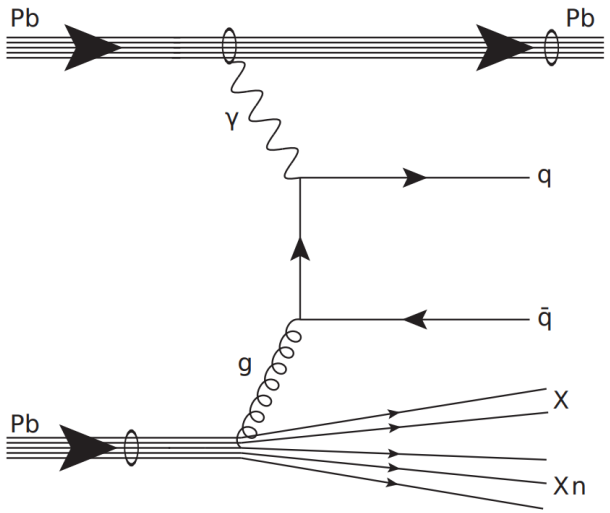
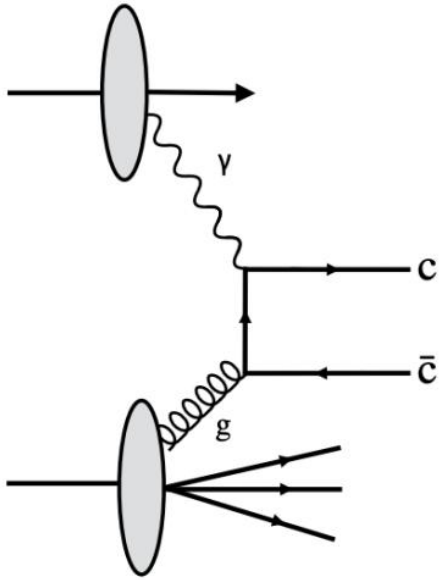


Exclusive Coherent J/ψ
ALICE, ATLAS, CMS, LHCb



Inclusive jets
ATLAS



Inclusive D^0
ALICE (preliminary), CMS

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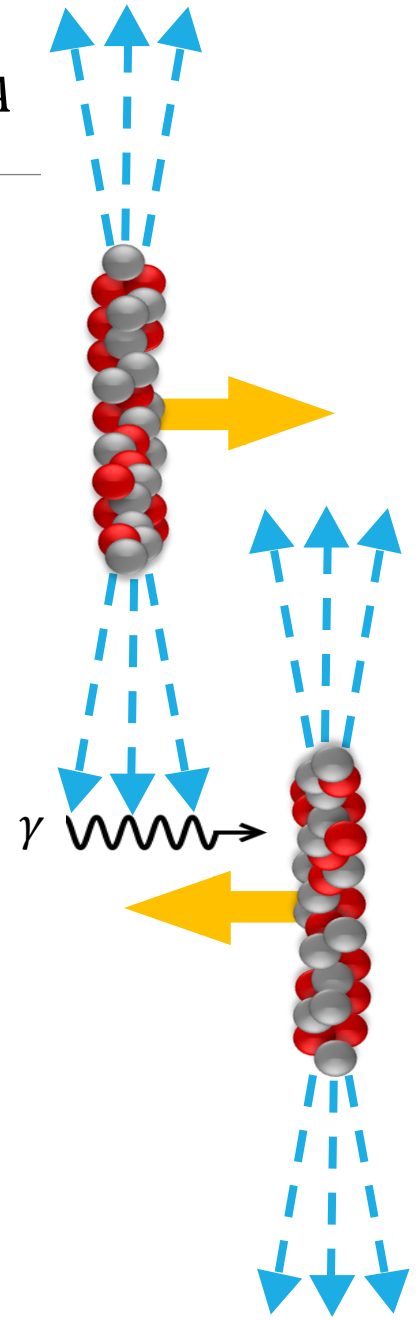

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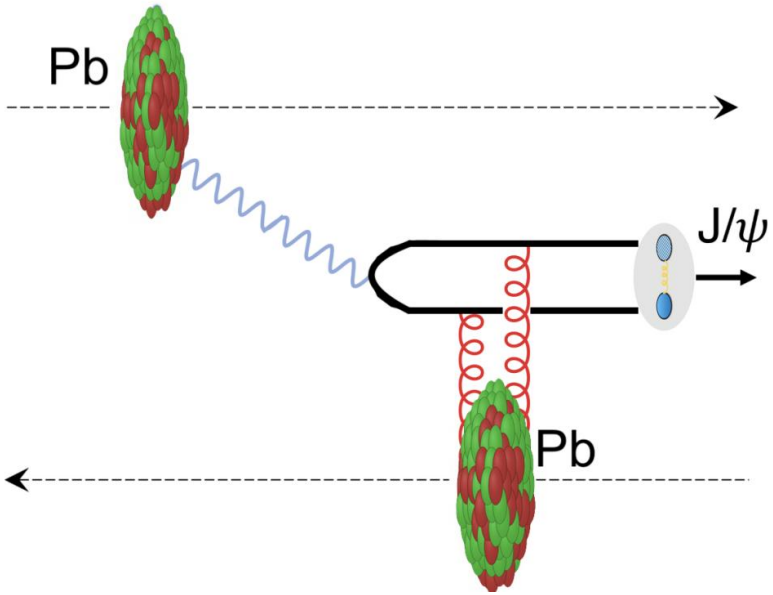

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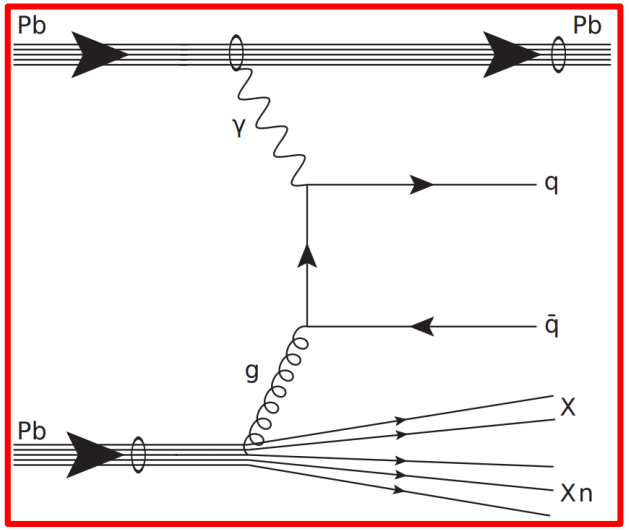

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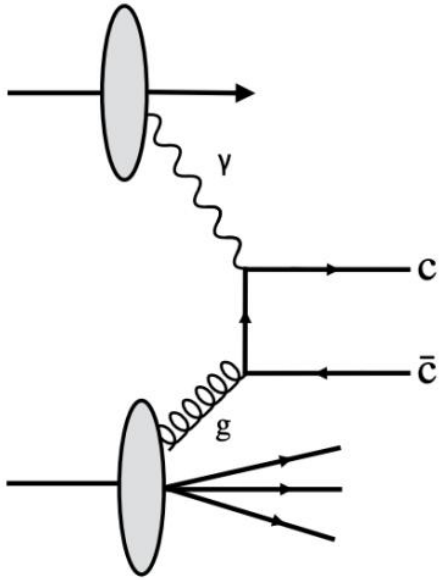

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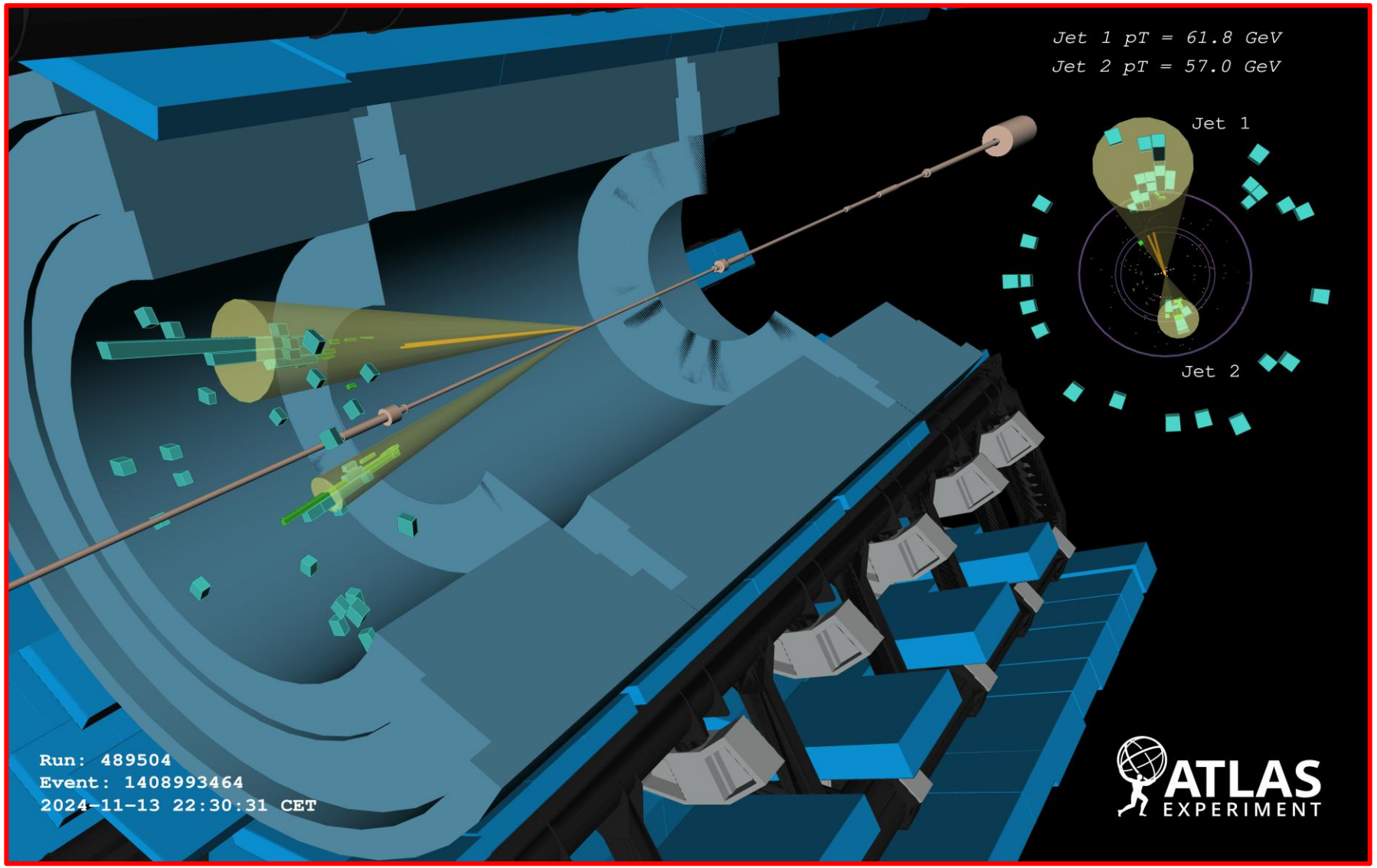
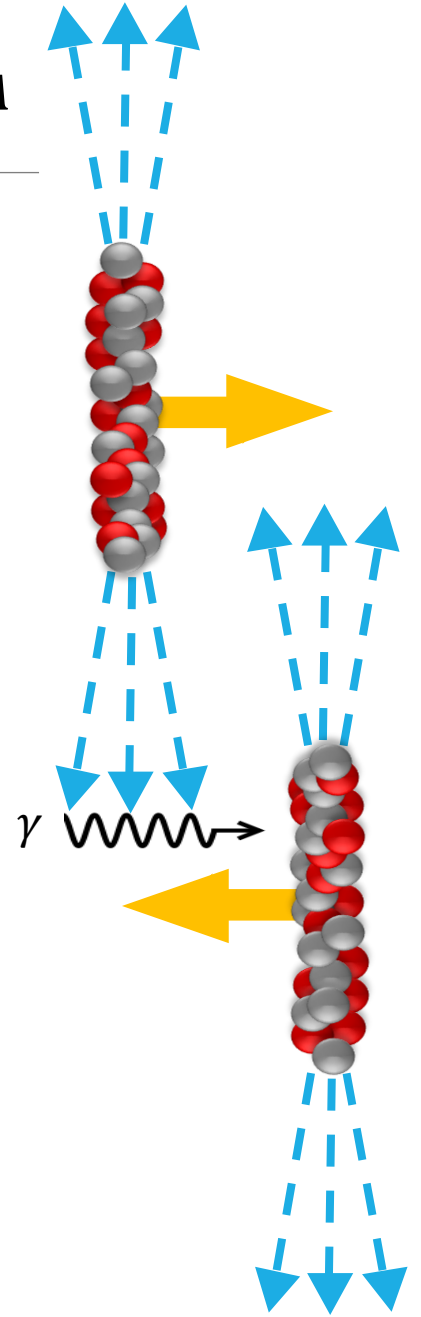




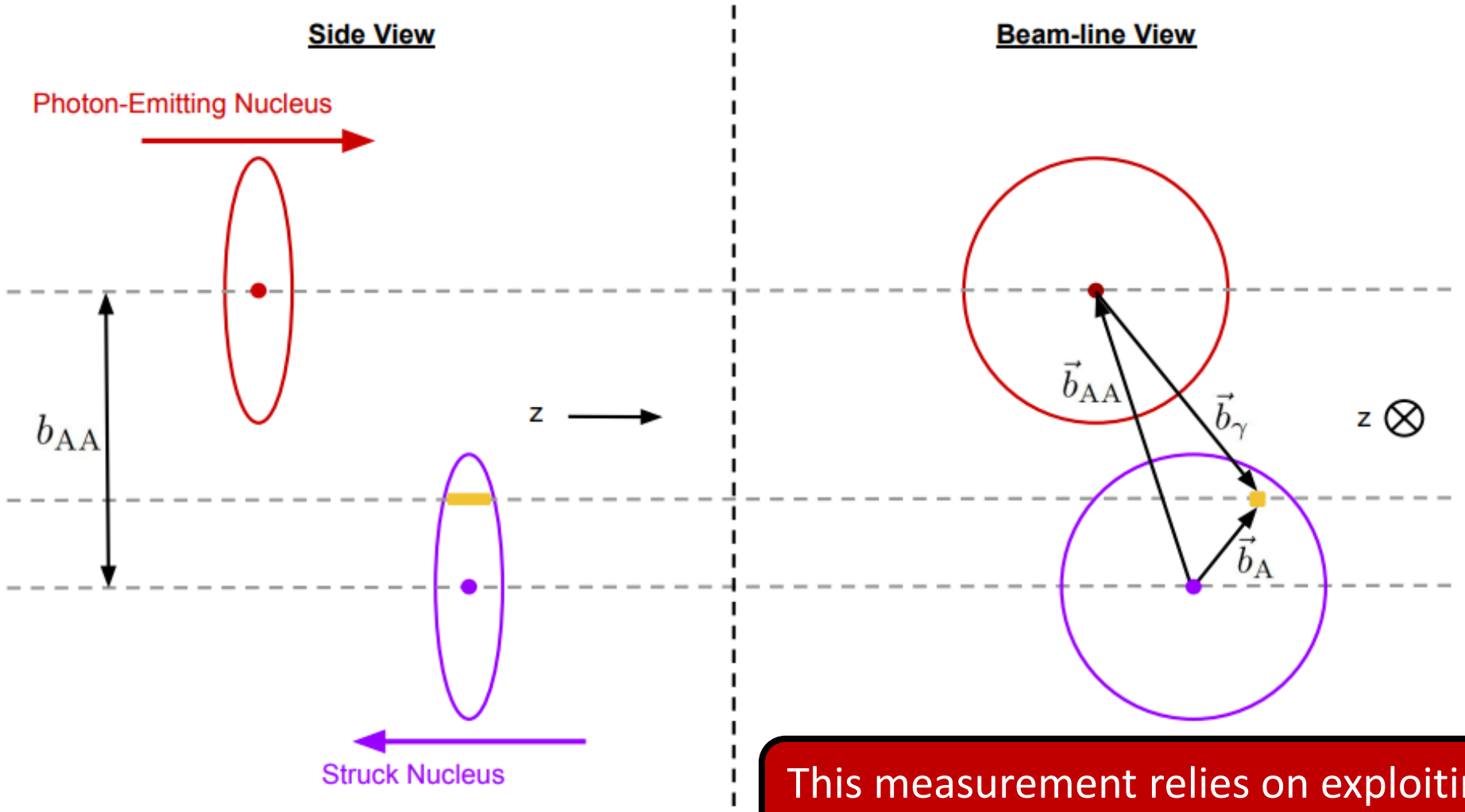
Observing b_A-dependent nPDF Modifications

Measuring parton kinematics in $\gamma + A$ collisions

Selecting a "peripheral" class of $\gamma + A$ collisions

Validating the modified impact parameter

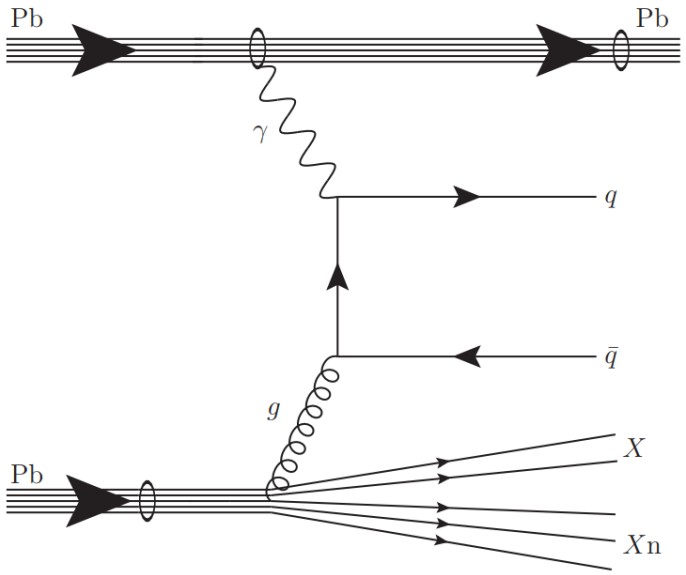
Comparing nPDFs between event classes



This measurement relies on exploiting the unique geometry of UPCs.

Photonuclear Jet Kinematics

Measuring parton kinematics in $\gamma + A$ collisions



Photonuclear Jet Kinematics

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$$H_T = \sum_i p_T^i$$

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

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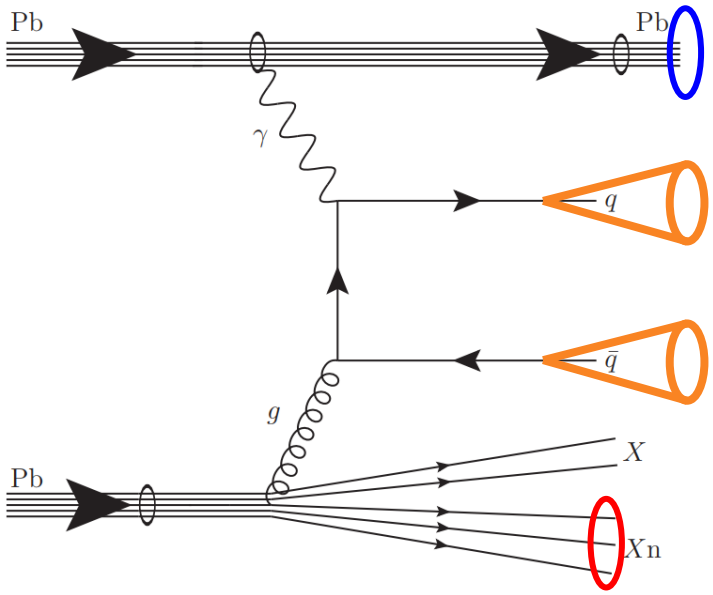

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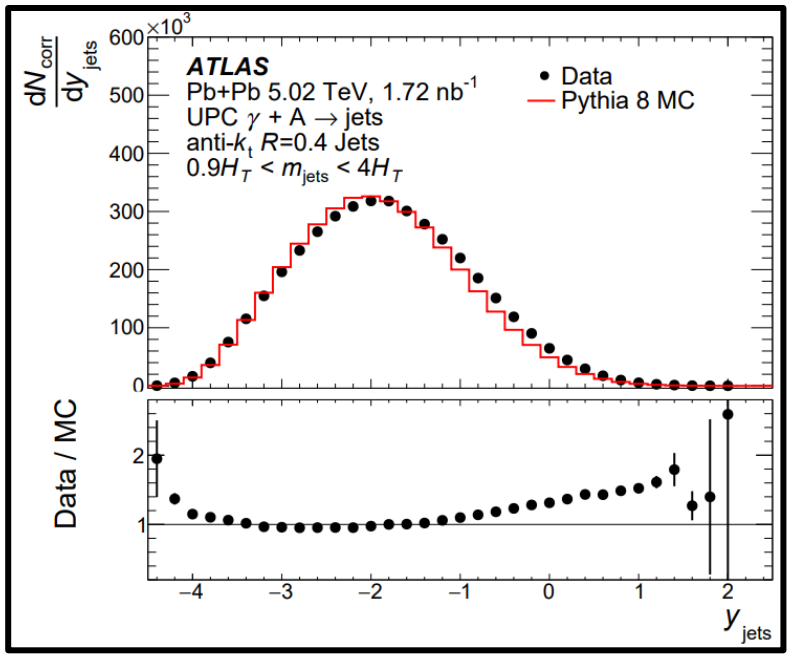

Each event must have 2 jets satisfying $p_T > 13$ GeV and $|\eta| < 4.4$.

Jets provide proxies for:

- Q^2: $Q \sim H_T/2$
- Bjorken-x: x_A at LO
- E_γ: $z_\gamma \sim E_\gamma/E_A$ at LO (Direct)

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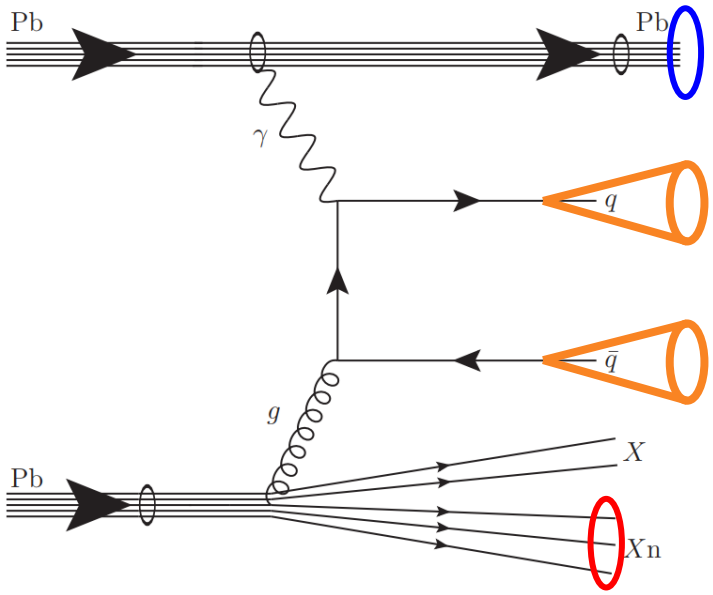
Photon direction

Nucleus direction

0nXn Topology

Sign of y_{jets} is known from forward neutron emission.



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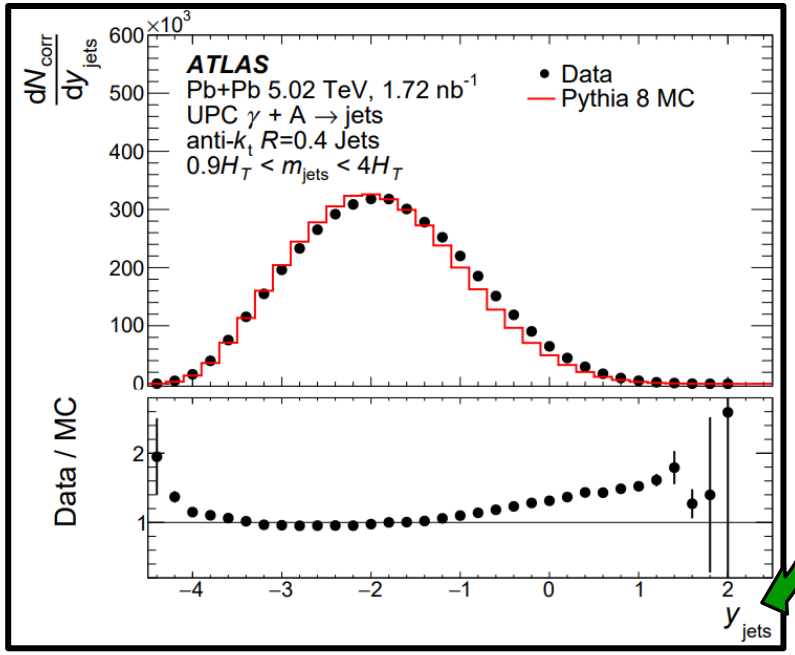

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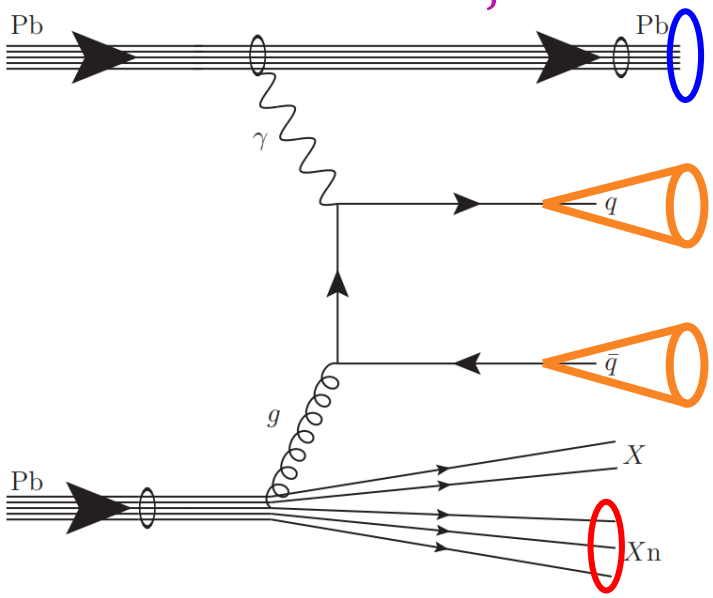
$$z_\gamma = \frac{m_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}} \quad \Rightarrow \quad z_- = \frac{m_{jets} e^{-|y_{jets}|}}{\sqrt{s_{NN}}}$$

For most of the phase space, the sign of y_{jets} can be inferred to near-perfect accuracy.

We can compute proxy parton kinematics without forward neutrons!

Assume $y_{\text{jets}} < 0$



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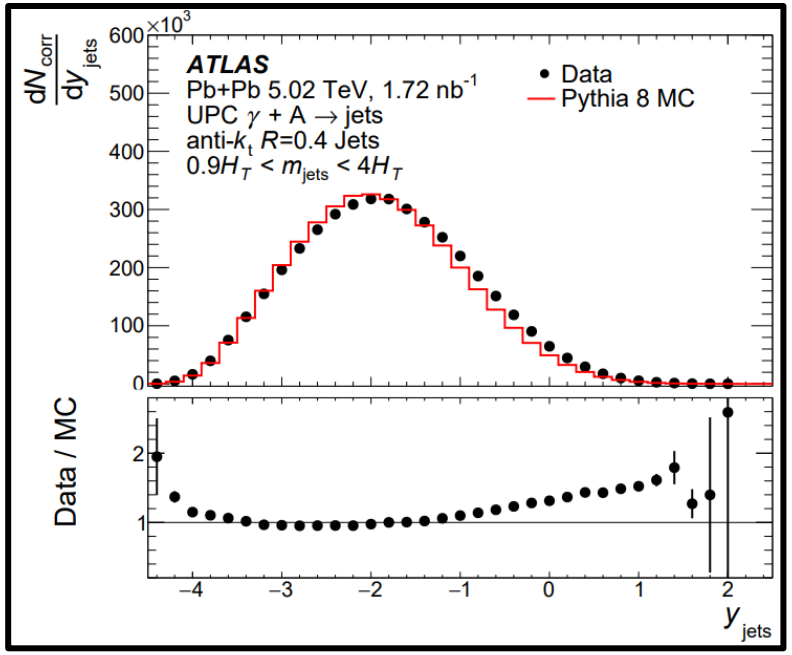

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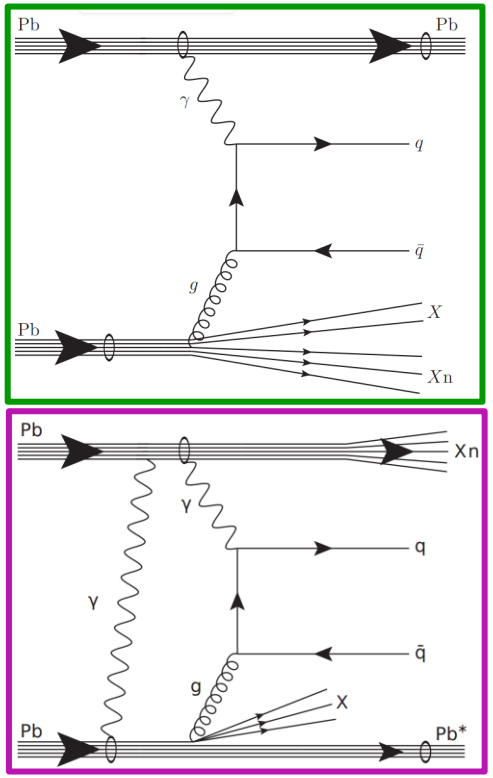
Forward Neutrons

Selecting a "peripheral" class of $\gamma + A$ collisions



- Forward neutrons are measured in the ATLAS ZDCs ($|\eta| > 8.3$) far from the main detector.
- They provide the key handle used to understand impact parameter.
- Two mechanisms can generate forward neutrons, even in the same event!

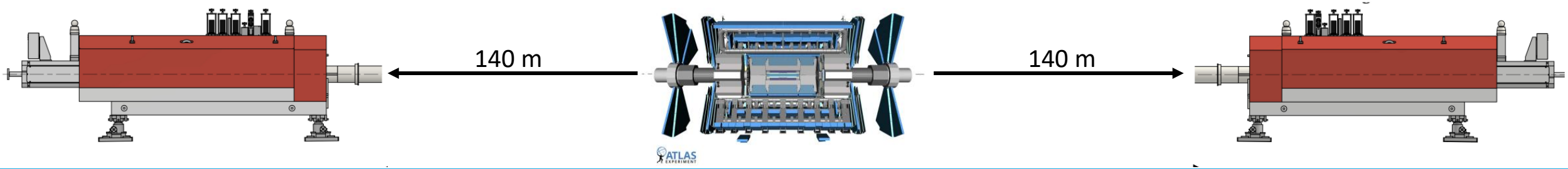
Neutron Production Mechanism	Forward Neutron Topology	Fraction of Events
Hard-scattering nuclear break-up	0nXn (correlated with jet kinematics)	~96%
Electromagnetic Dissociation (EMD)	0nXn or Xn0n (un-correlated with jet kinematics)	10-40%

Fraction of hard-scattering events which also have EMD

Side C ZDC ($\eta < -8.3$)

ATLAS Central Detector

Side A ZDC ($\eta > 8.3$)



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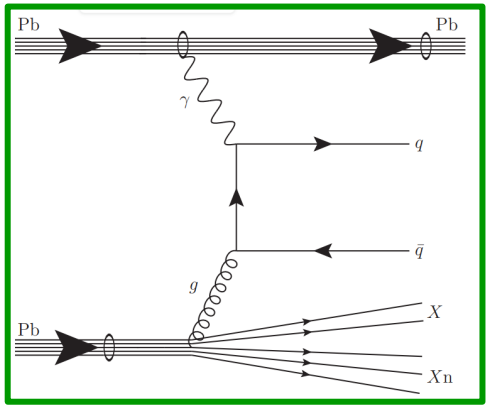

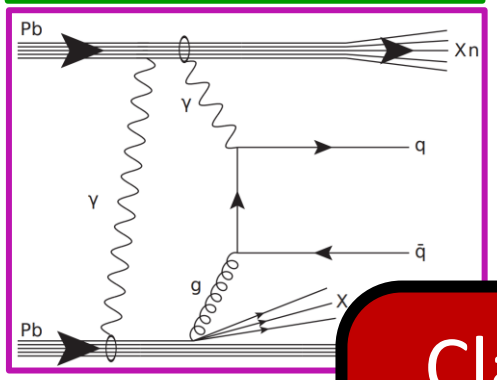

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Fraction of hard-scattering events which also have EMD

Claim: The ~4% of events without hard-scattering nuclear break-up are "peripheral" $\gamma + A$ collisions. [Alvioli et al. (2024), Larionov and Strikman (2020)]

Side C ZDC (

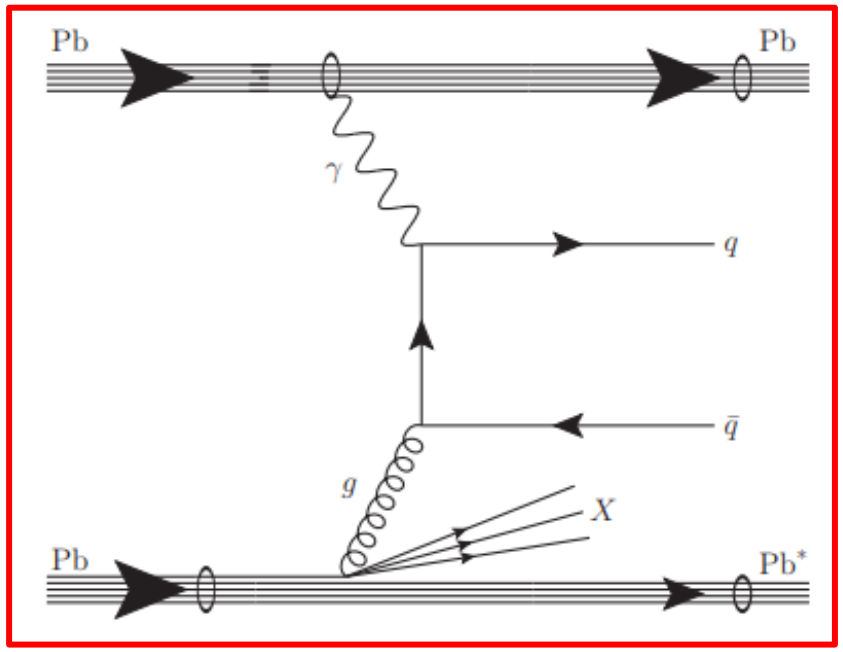
DC ($\eta > 8.3$)

UPC Jets without Forward Neutrons

Selecting a "peripheral" class of $\gamma + A$ collisions

What kinds of UPC events have jets but no forward neutrons?

$\gamma + \mathrm{A} \rightarrow \mathrm{jets}$



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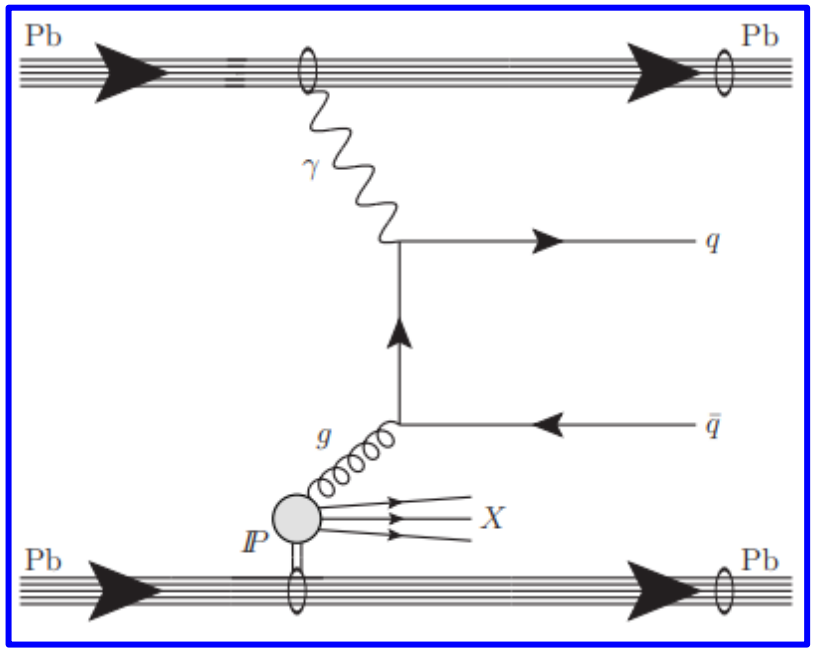

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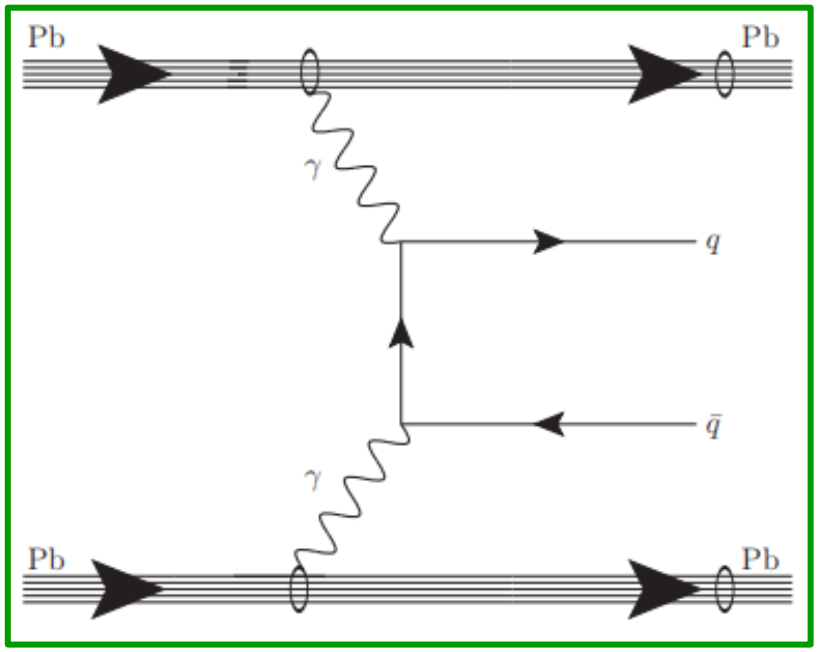

UPC Jets without Forward Neutrons

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Each process has different characteristic particle production!

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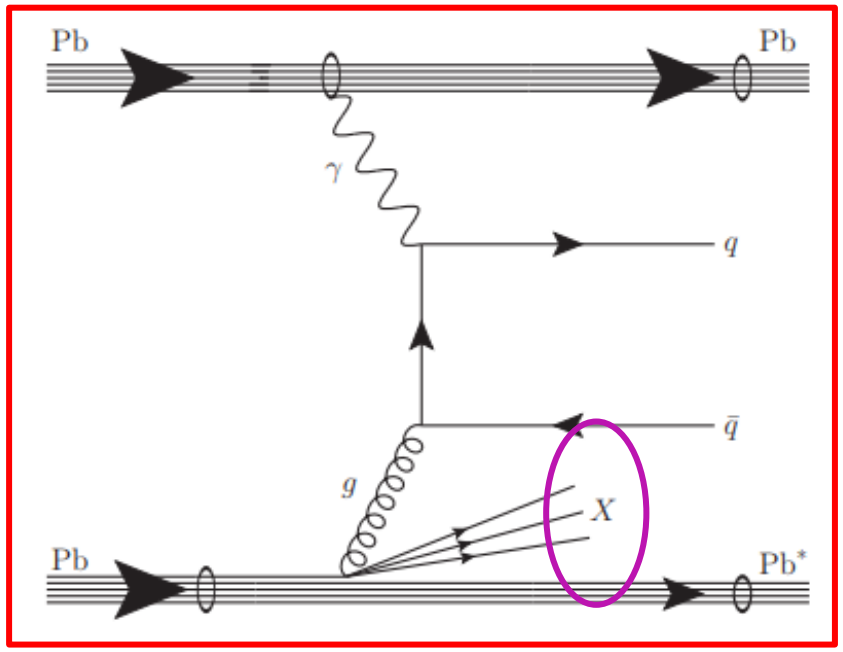

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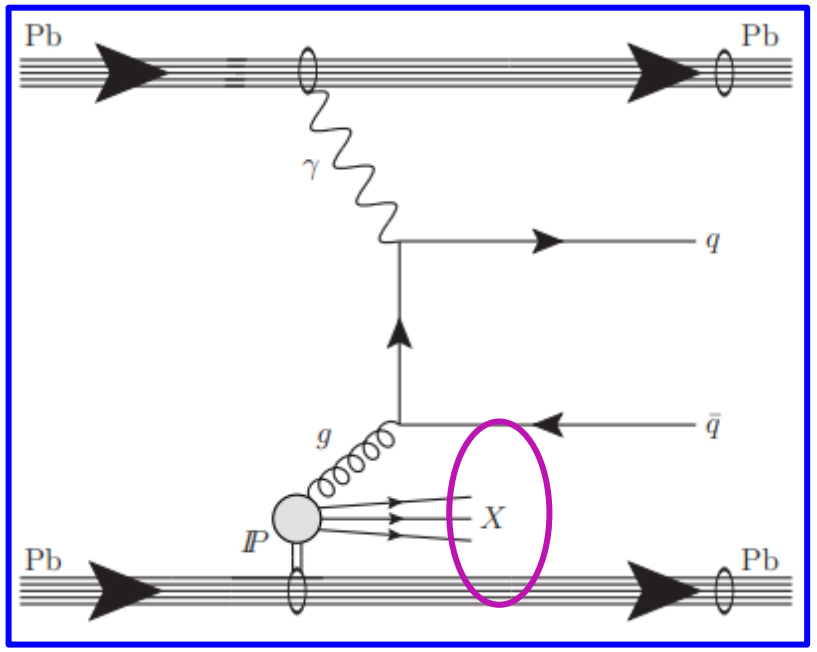

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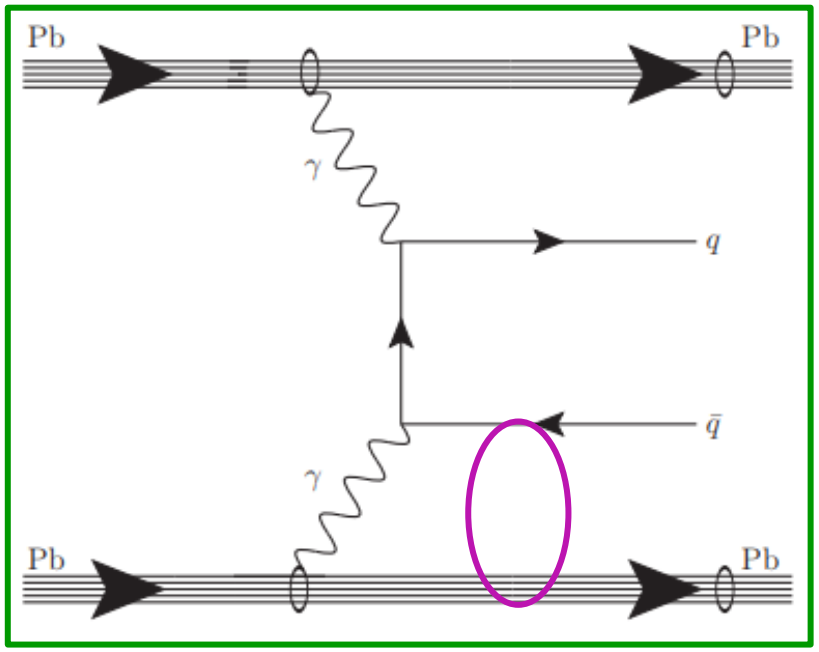
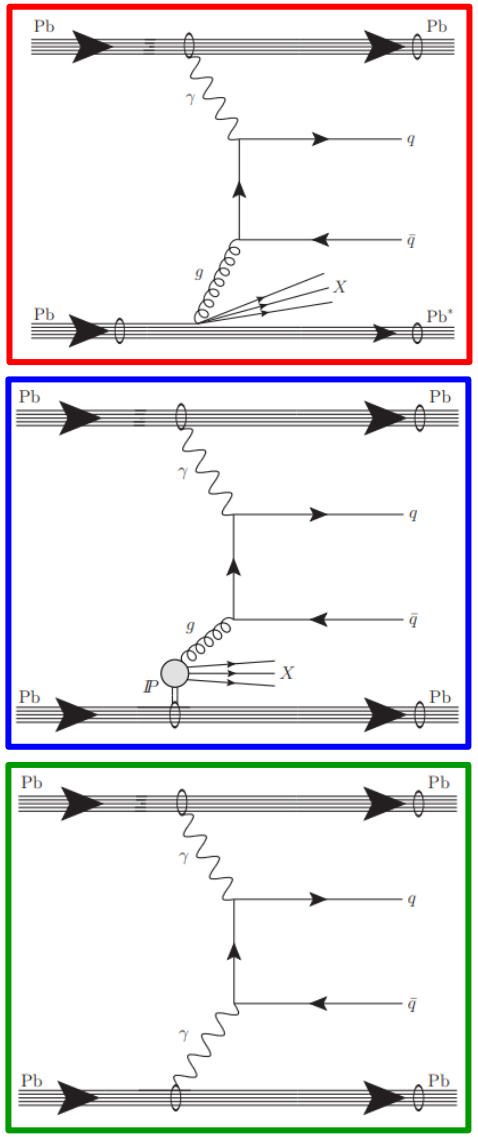
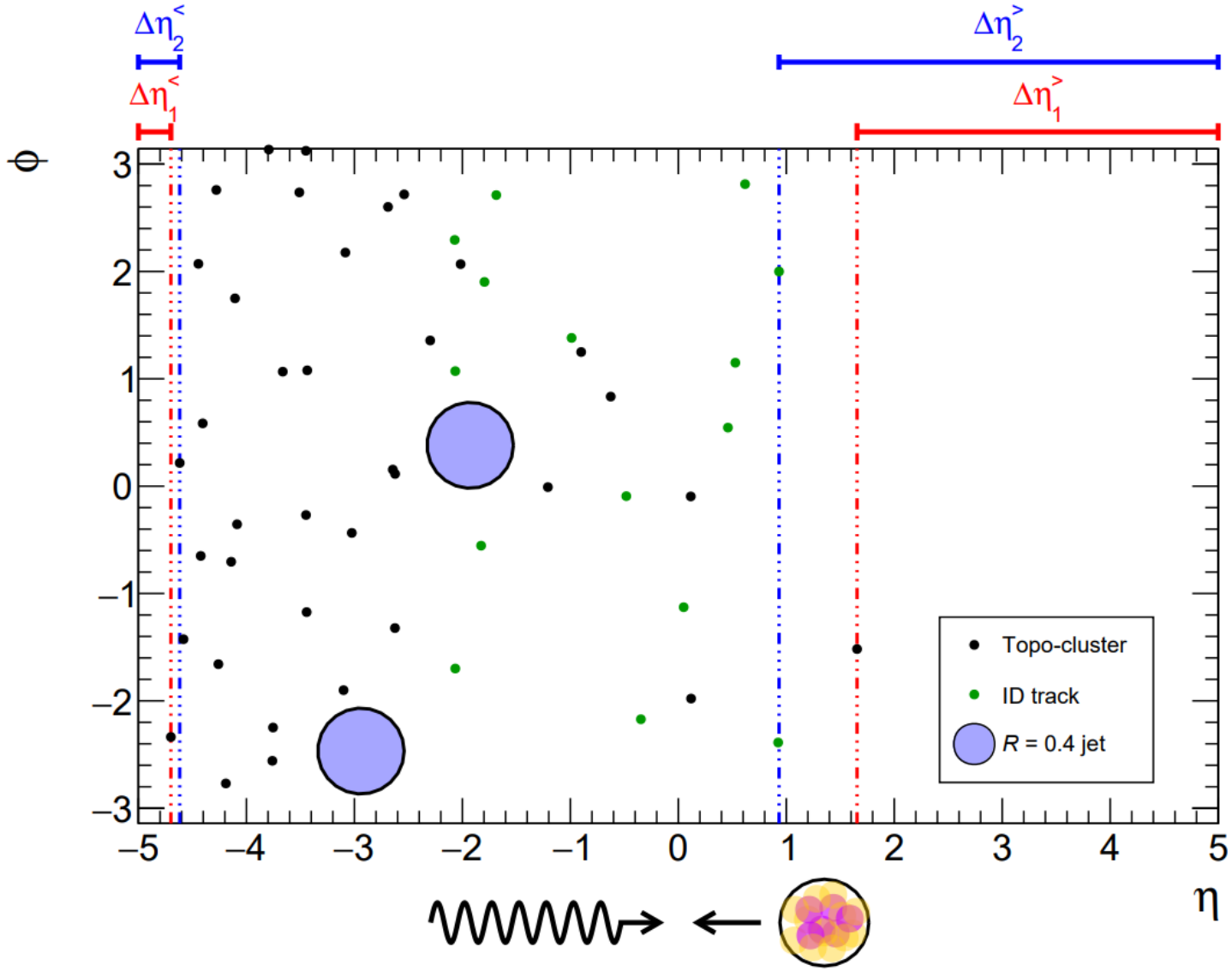


Defining the Rapidity Gap Variable

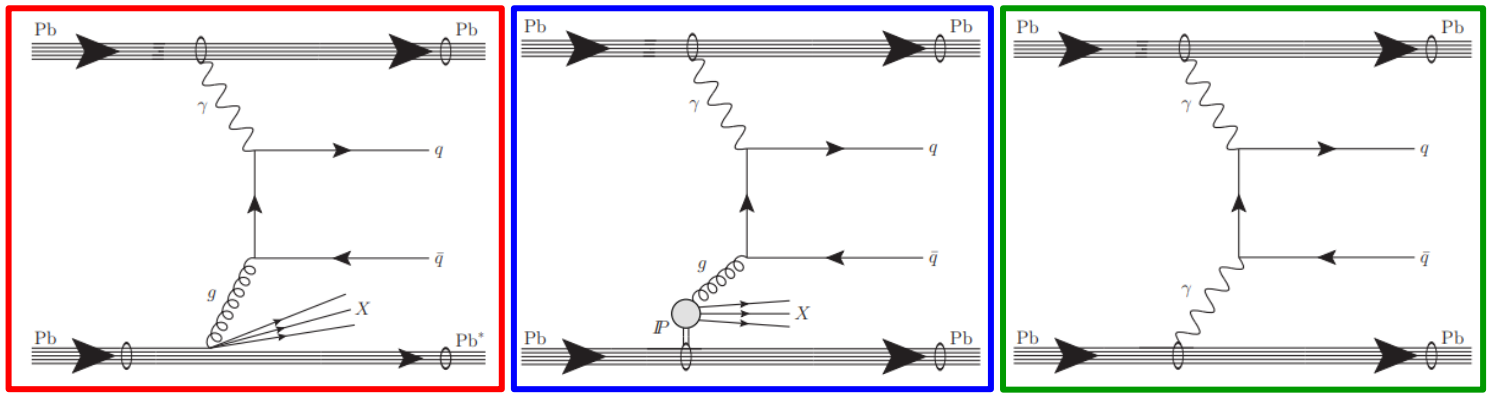
Selecting a "peripheral" class of $\gamma + A$ collisions



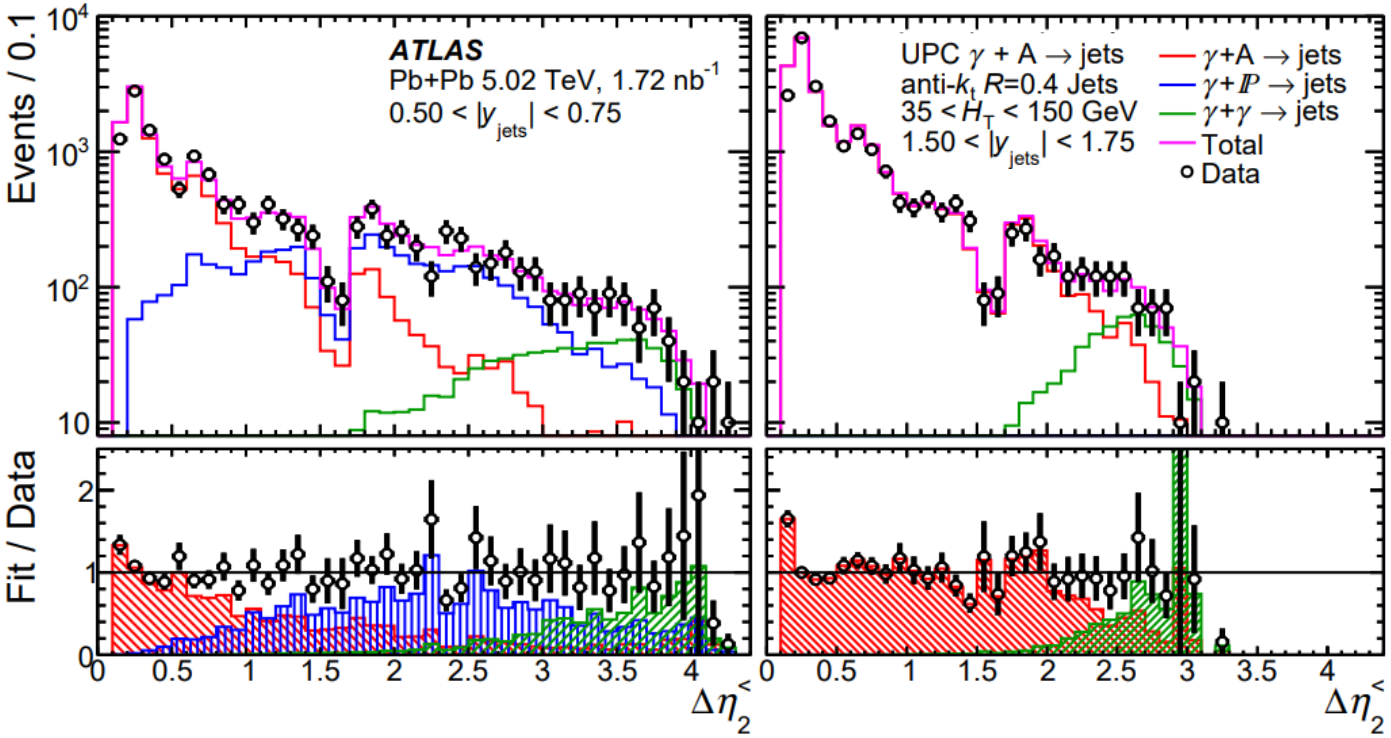


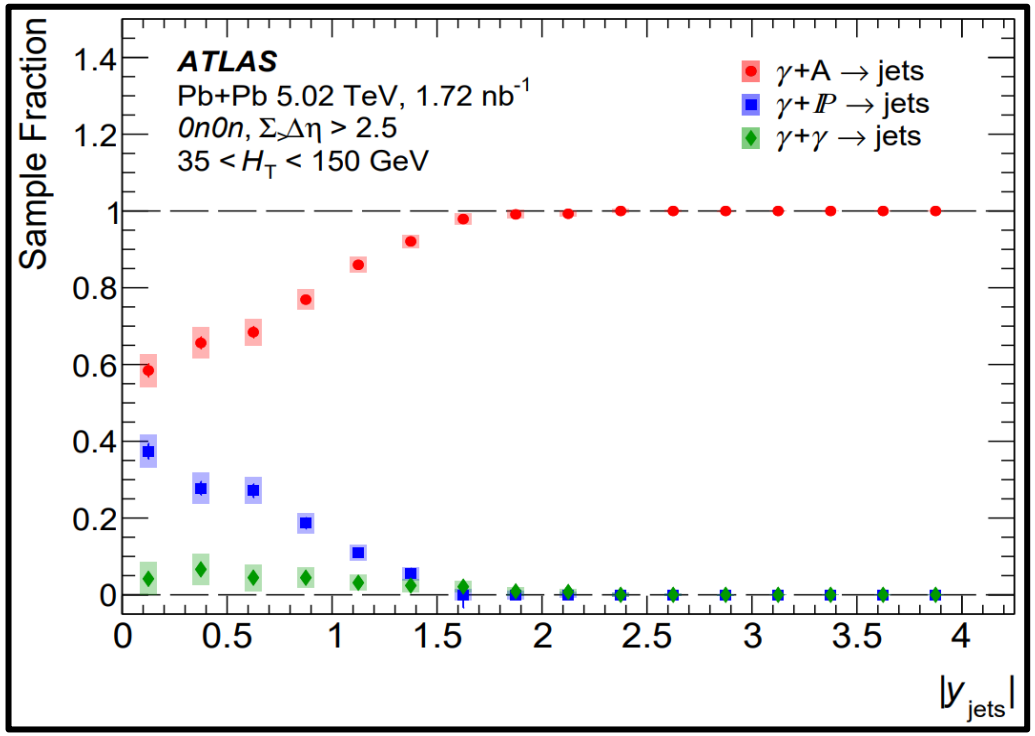
Template Fitting Procedure

Selecting a "peripheral" class of $\gamma + A$ collisions



- The different gap distributions allow us to statistically separate the samples with template fits.





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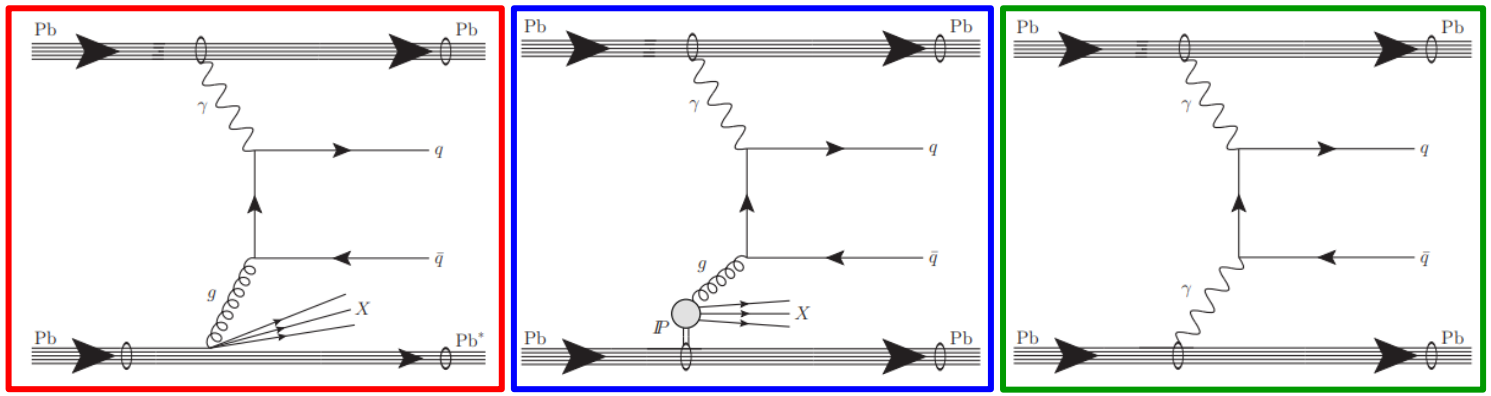
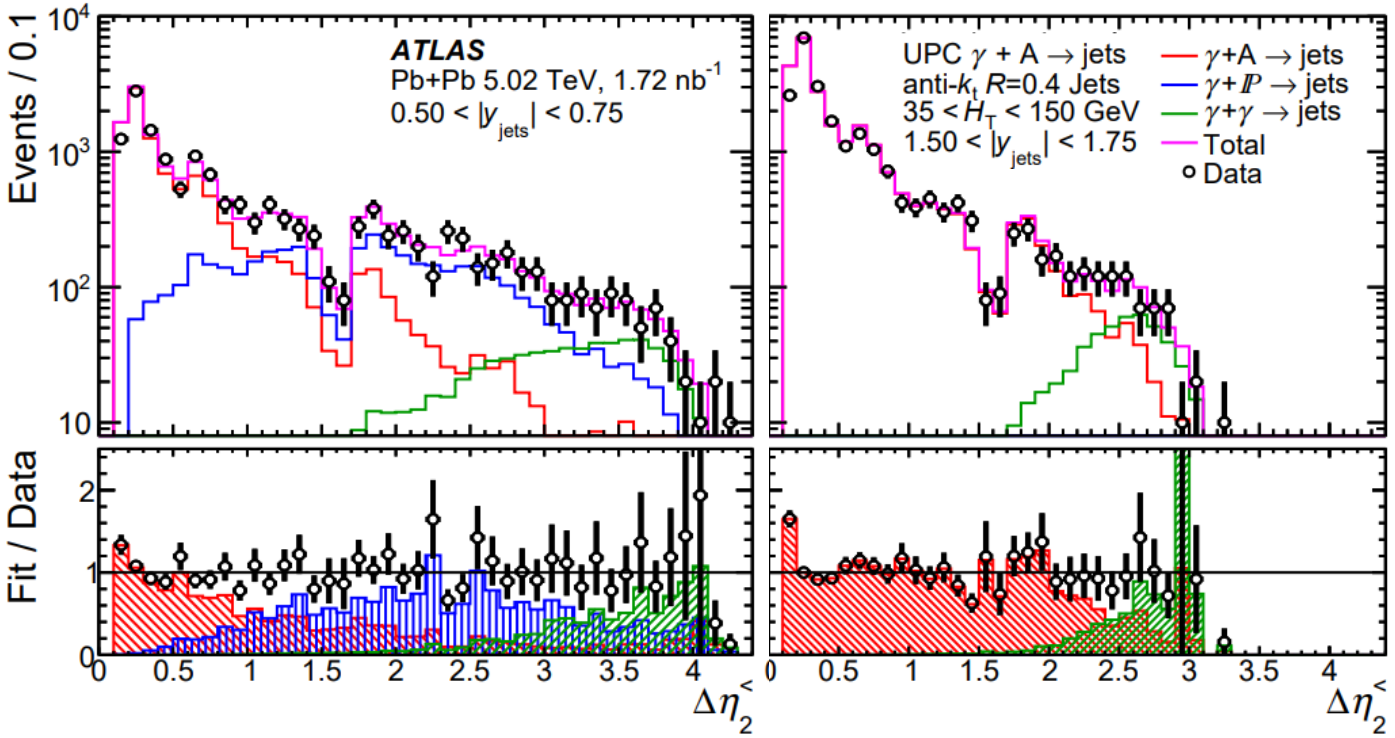
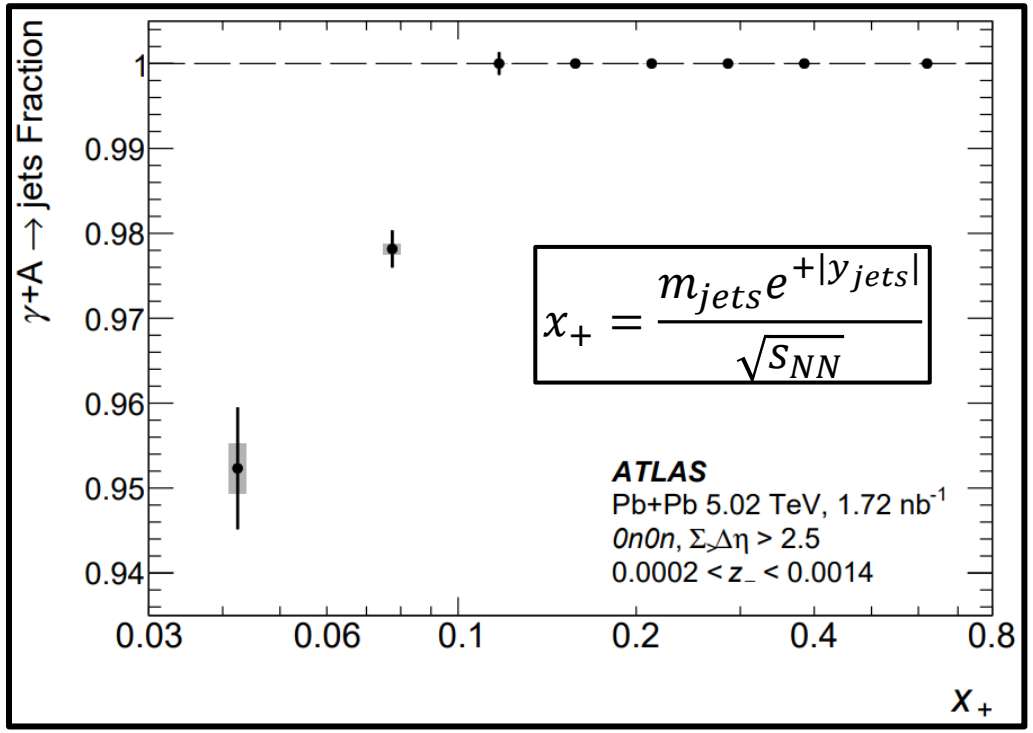


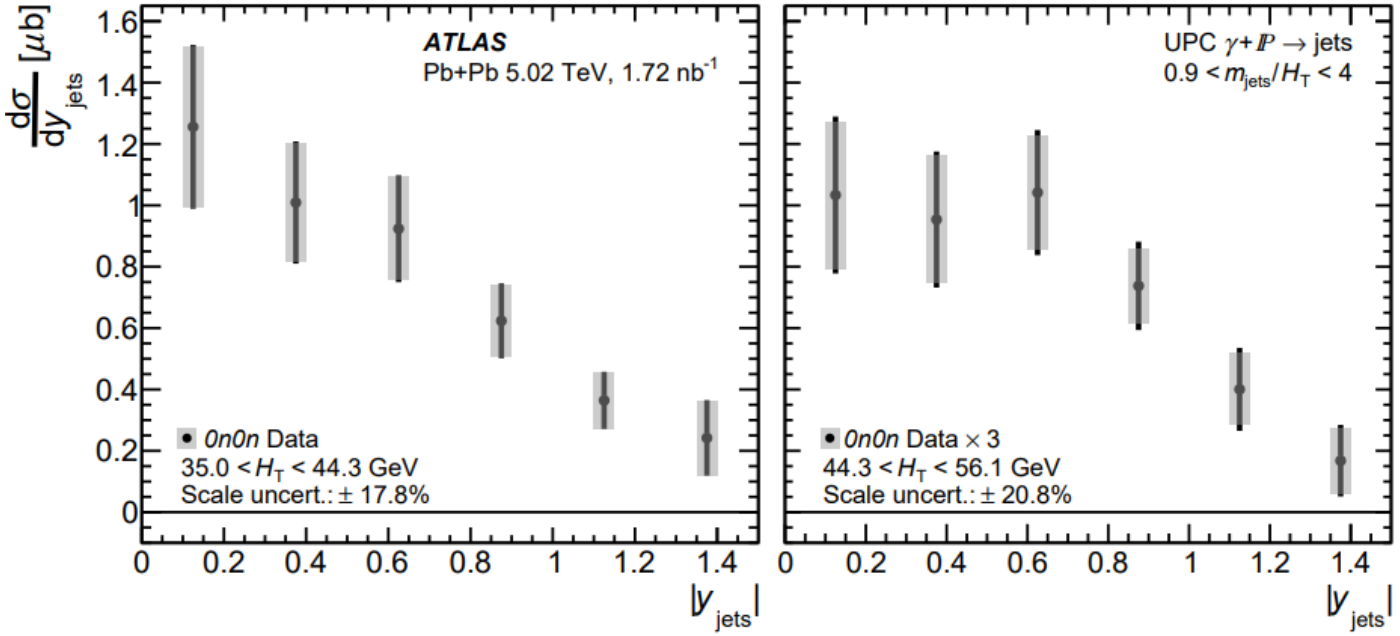
- The different gap distributions allow us to statistically separate the samples with template fits.
- In the forward region, signal events are consistent with >95% photonuclear!

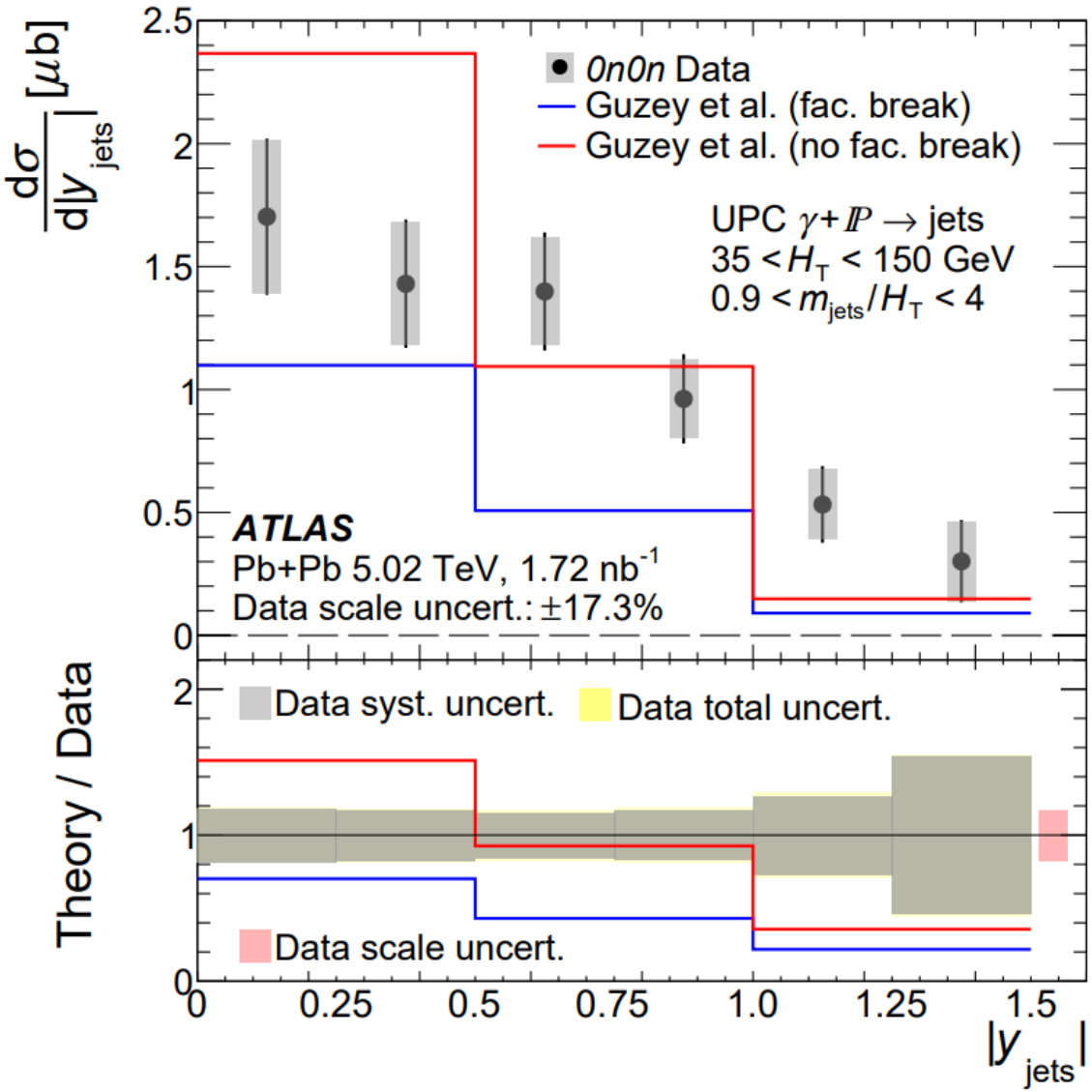




Aside: Diffractive Processes

- The diffractive cross-section is also measured using the template-fitting procedure.
- The H_T-integrated cross-sections (right) are compared to NLO pQCD predictions.
  - While the overall scale of the cross-section is correct, modeling of the shape needs to be improved to extract information.

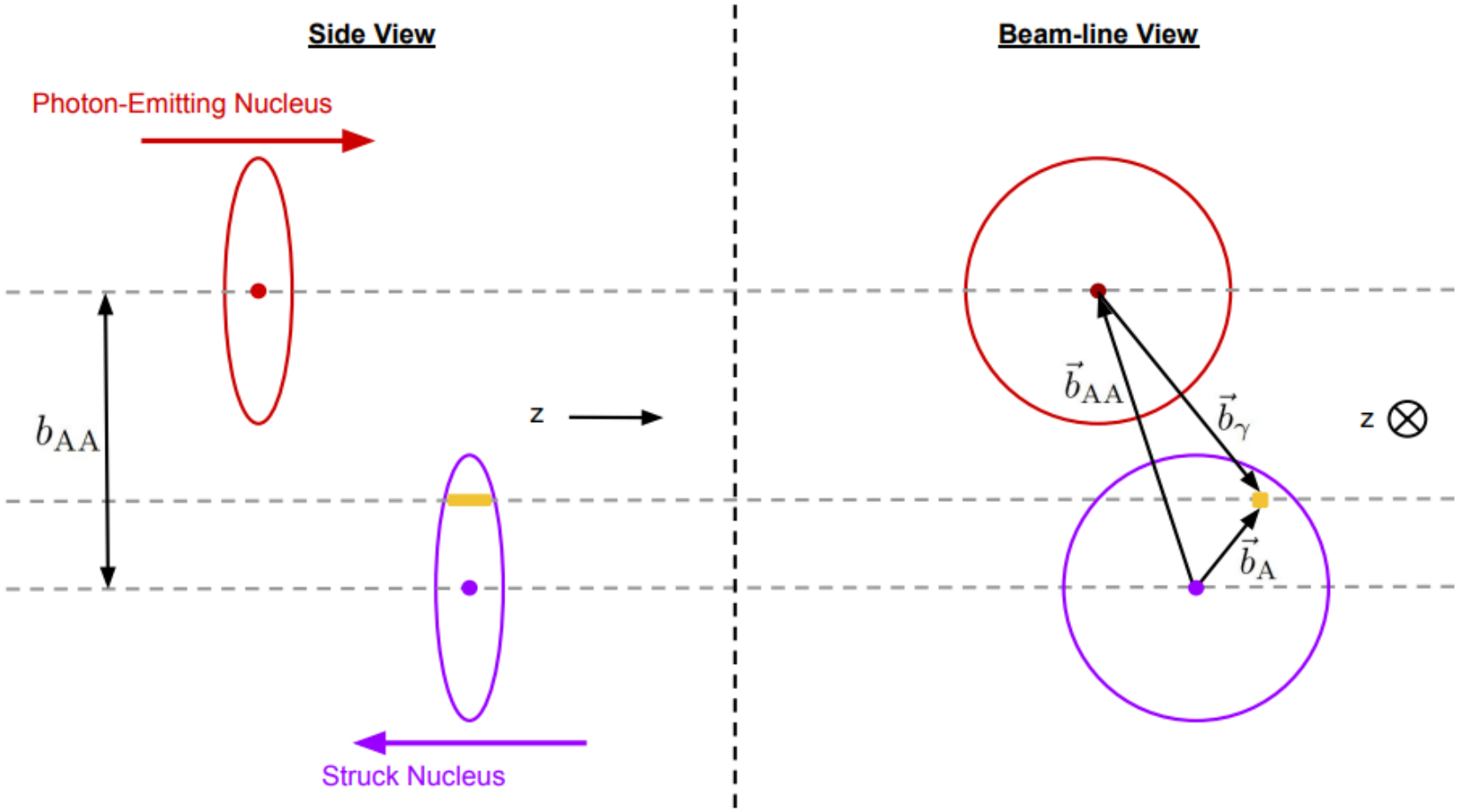


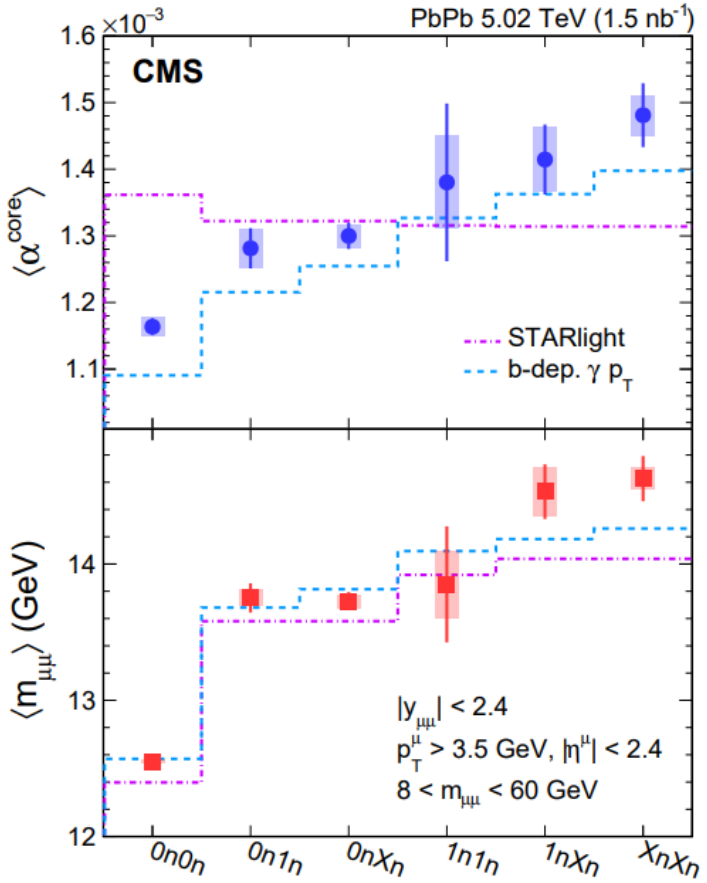


EMD and Impact Parameter

Validating the modified impact parameter

- Closer-passing (smaller b_{AA}) UPCs expose each nucleus to a larger flux of soft photons.
  - This yields a correlation between impact parameter and the rate of EM dissociation.
- Results from CMS (and others) indicate that forward neutrons correlate with b_{AA}.





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EMD and Impact Parameter

Validating the modified impact parameter

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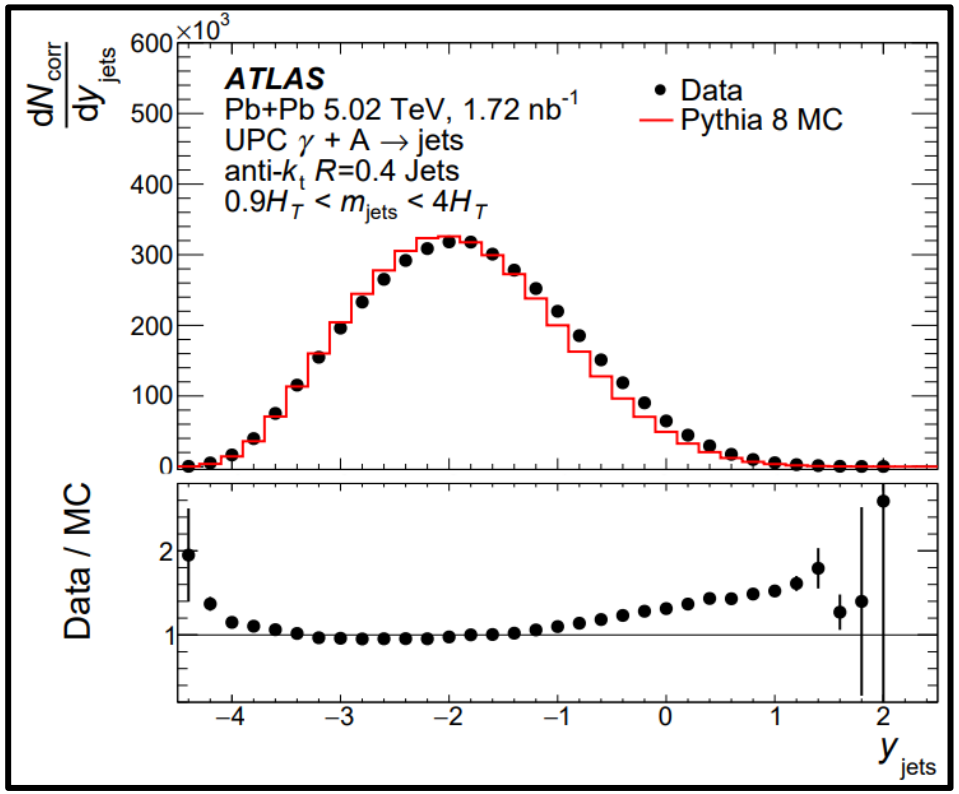

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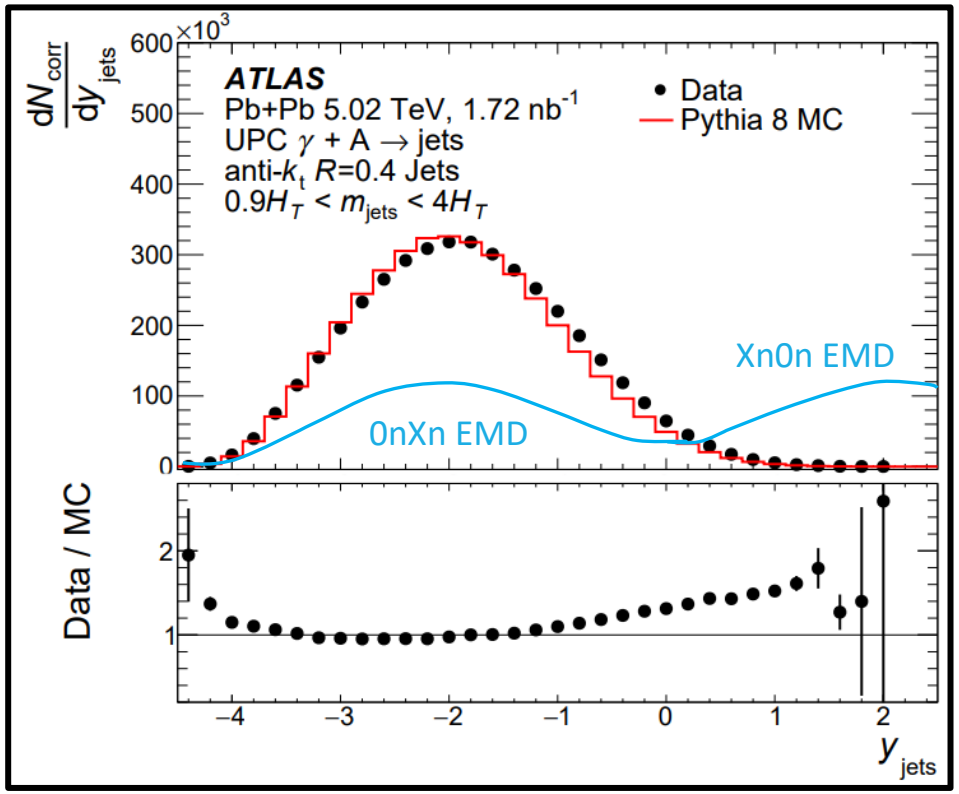
EMD neutrons are un-correlated, so half of the EMD events go the "wrong way"



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Neutron Production Mechanism	Forward Neutron Topology	Fraction of Events
Hard-scattering nuclear break-up	0nXn (correlated with jet kinematics)	~96%
Electromagnetic Dissociation (EMD)	0nXn or Xn0n (un-correlated with jet kinematics)	10-40%

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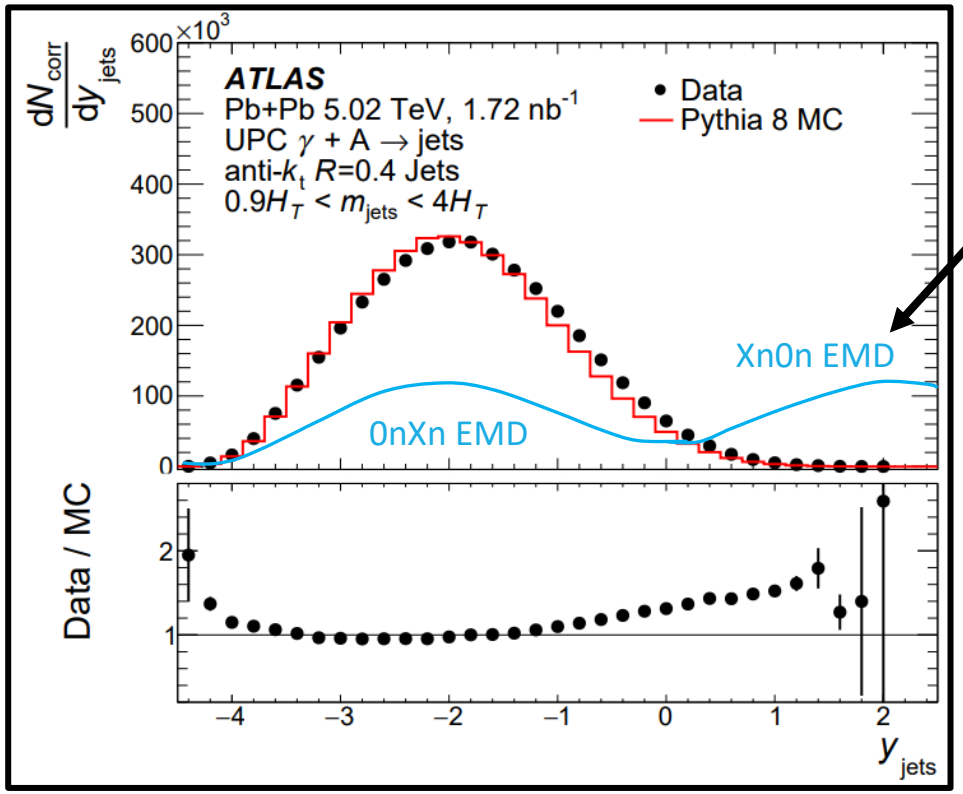

We can select this sample by requiring jets and gaps inconsistent with the forward neutrons!

How is it possible measure 0n0n $\gamma + A$ collisions with EMD? Isn't that identical to 0nXn $\gamma + A$?

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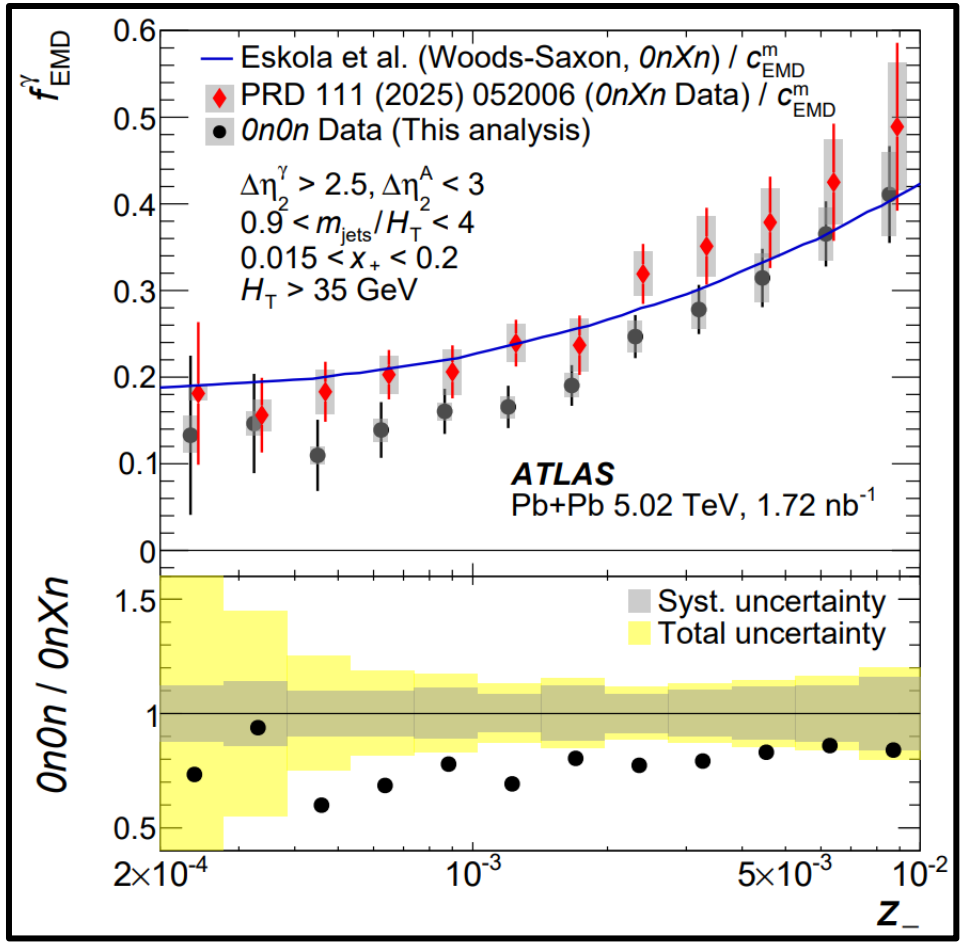
EMD and Impact Parameter

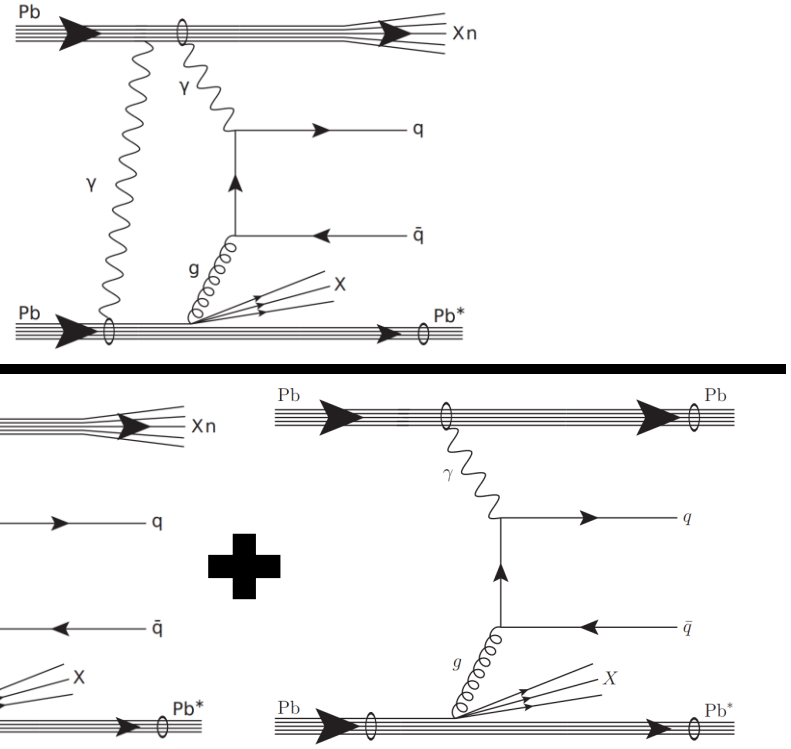
Validating the modified impact parameter

The reduction from 0nXn to 0n0n indicates a modification to b_{AA} (and thus b_A)



$$f^{\gamma}_{\mathrm{EMD}} \equiv \frac{\mathrm{d}\sigma/\mathrm{d}z_-|^{\mathrm{rev.}}_{0nXn}}{\mathrm{d}\sigma/\mathrm{d}z_-|^{\mathrm{rev.}}_{0nXn} + \mathrm{d}\sigma/\mathrm{d}z_-|_{0n0n}}$$

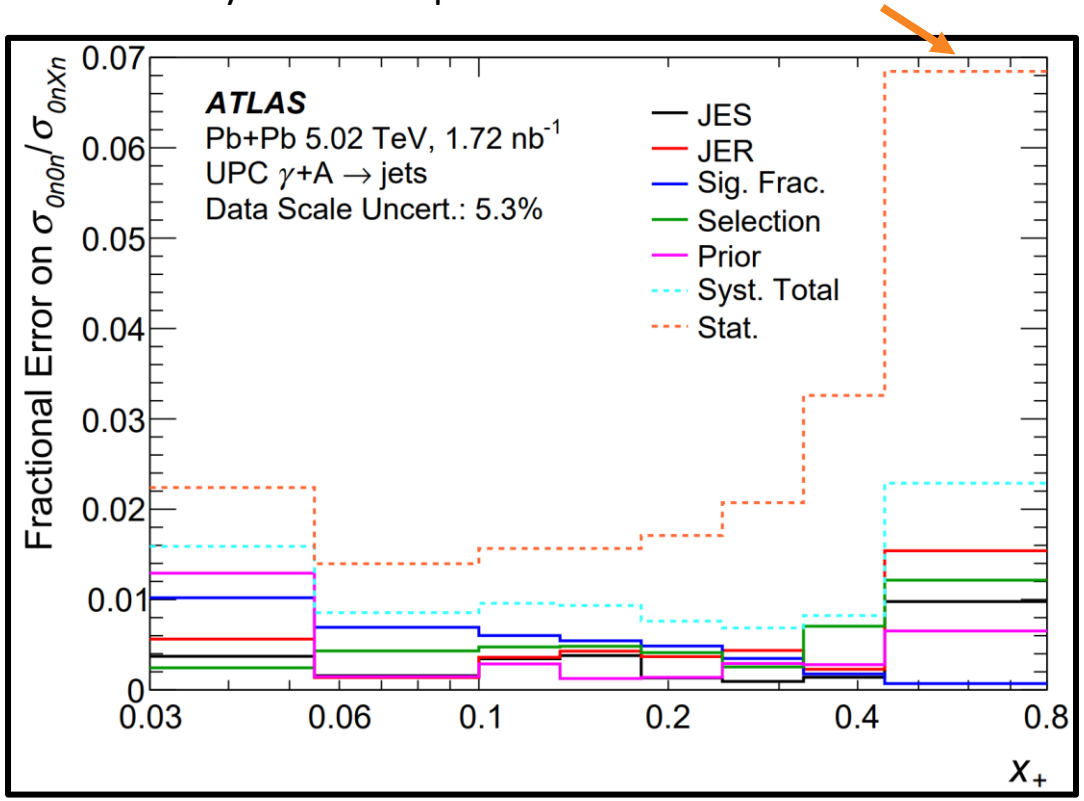
$$f^{\gamma}_{\mathrm{EMD}} = \frac{}{}$$

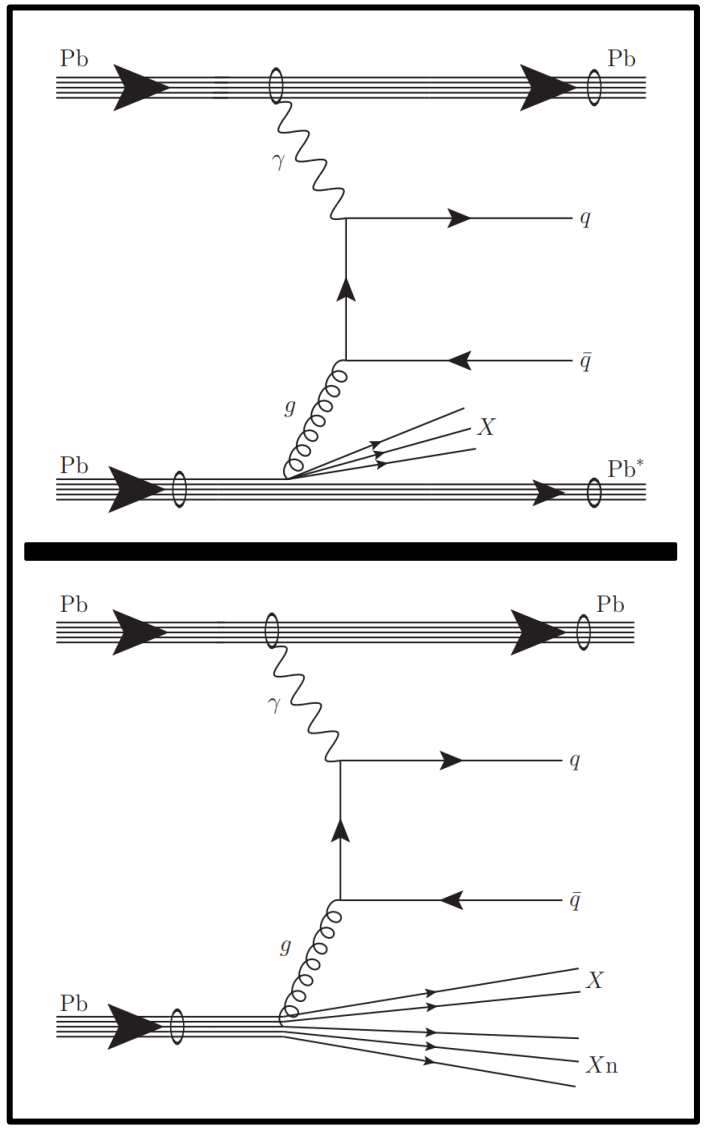


Measuring the 0n0n/0nXn Ratio

Comparing nPDFs between event classes

- The ratio of 0n0n/0nXn events can be measured to very high precision, due to near-complete cancellation of uncertainty from the jet response.
  - The largest point-to-point systematic uncertainty comes from the signal fraction.
  - Uncertainty on the shape of the ratio is statistics-dominated.





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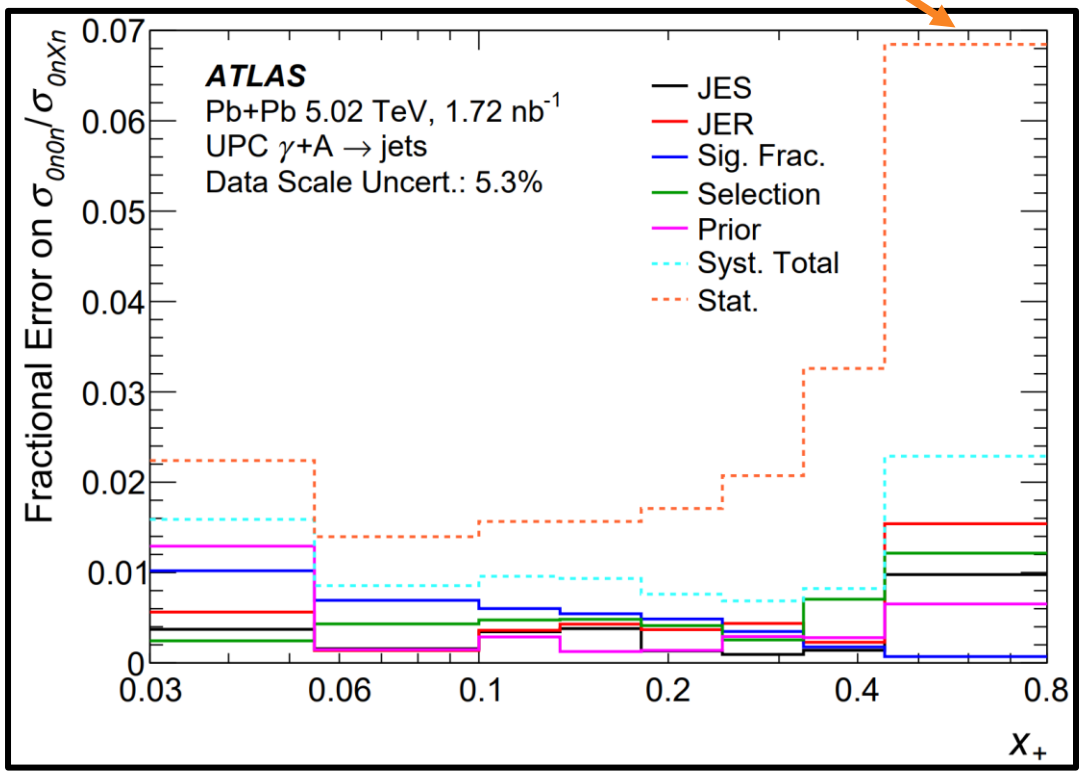

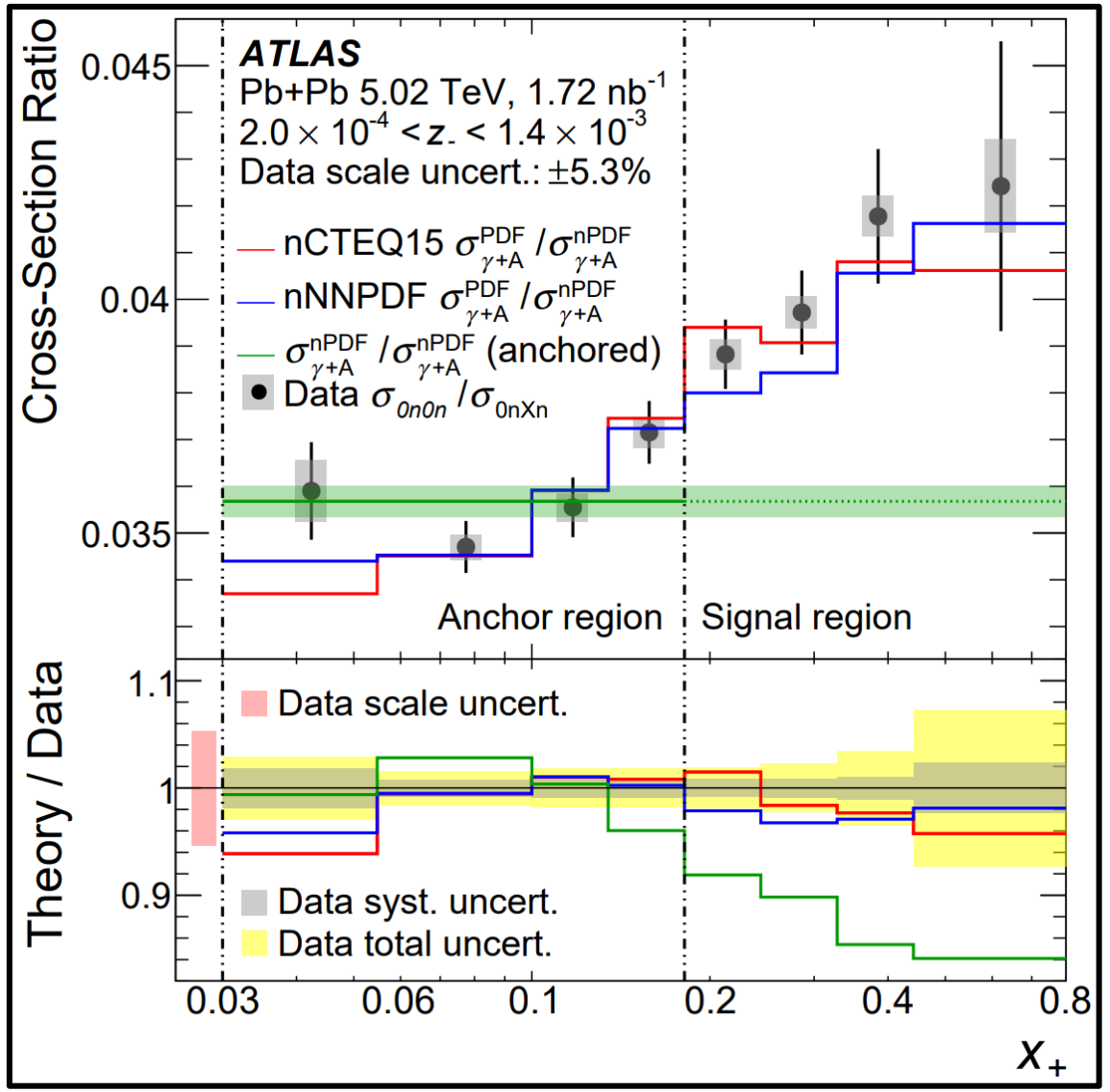

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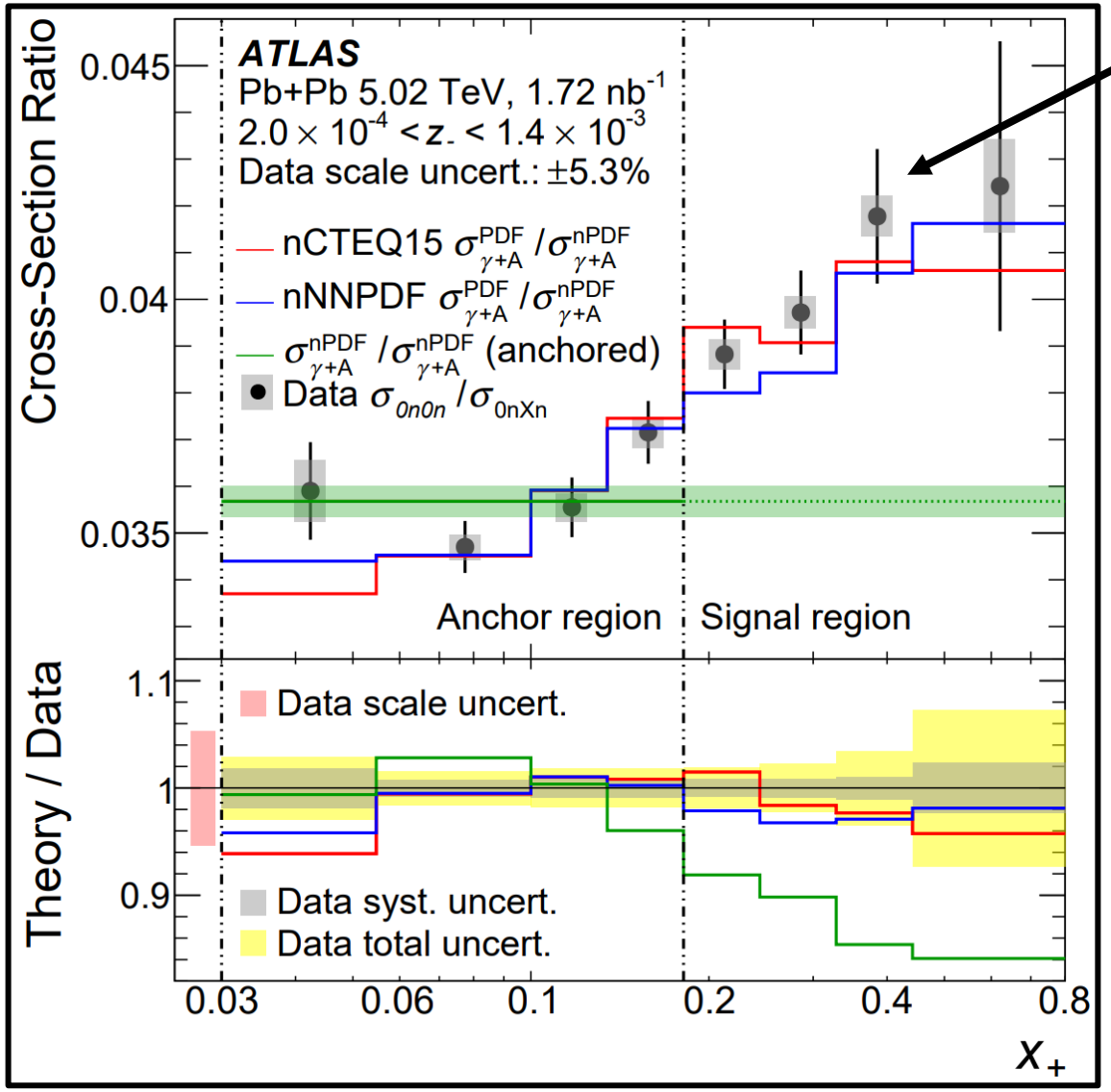

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Data is $\frac{\sigma(\text{peripheral})}{\sigma(\text{inclusive})}$

$$x_+ = \frac{m_{jets} e^{+|y_{jets}|}}{\sqrt{s_{NN}}}$$

Measuring the 0n0n/0nXn Ratio

Comparing nPDFs between event classes

Theoretical comparisons are constructed using nCTEQ and nNNPDF.

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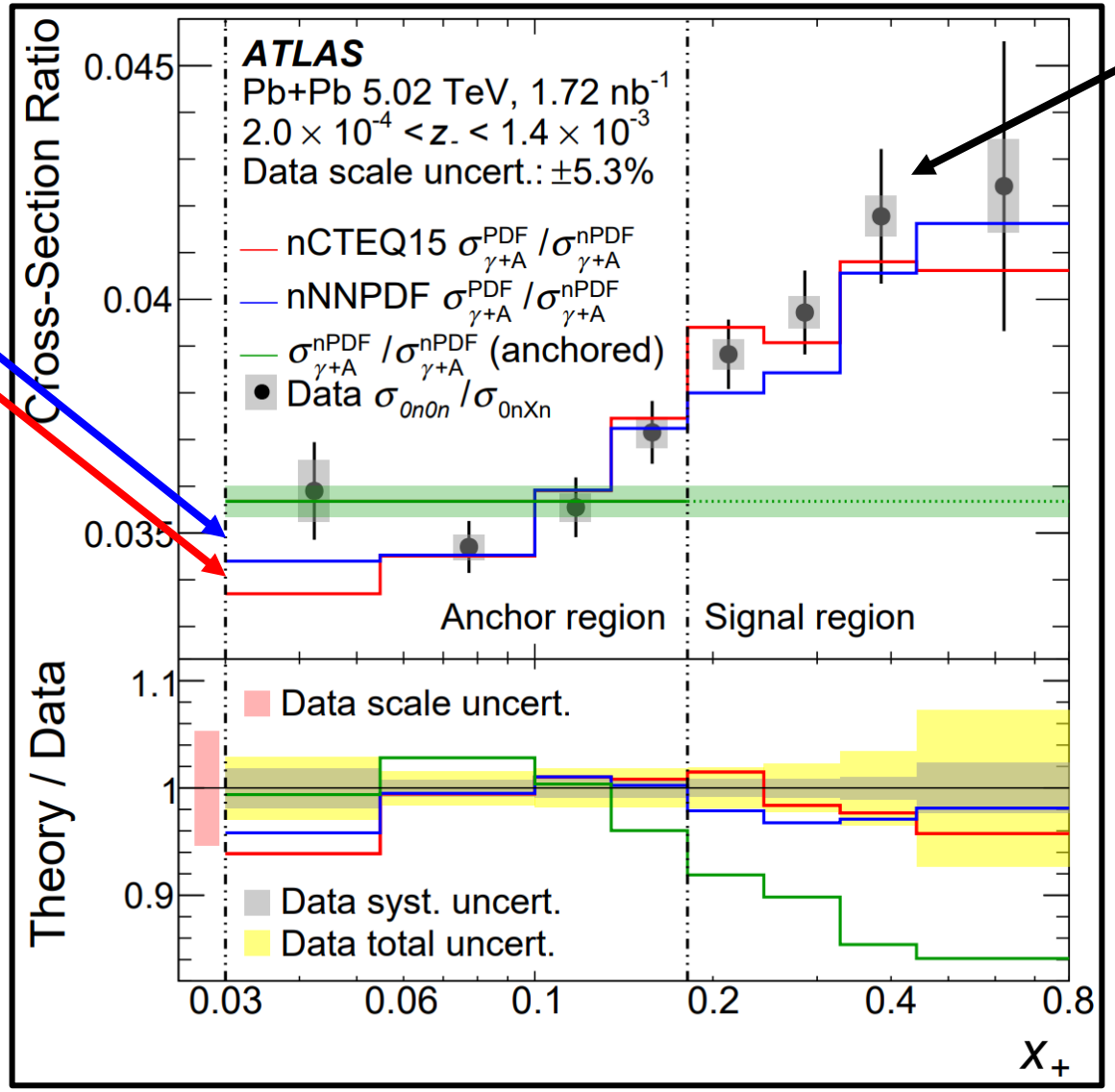

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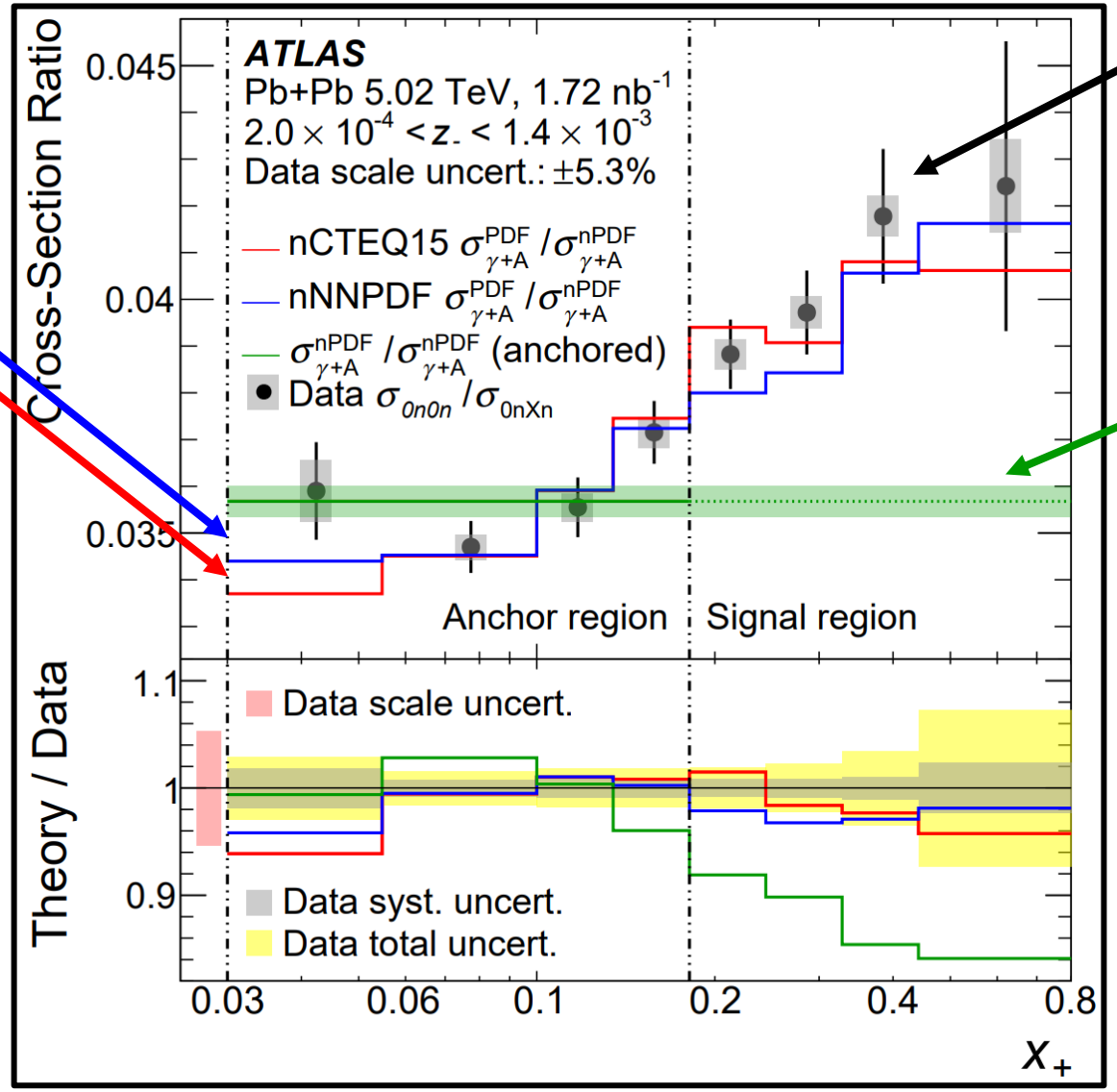

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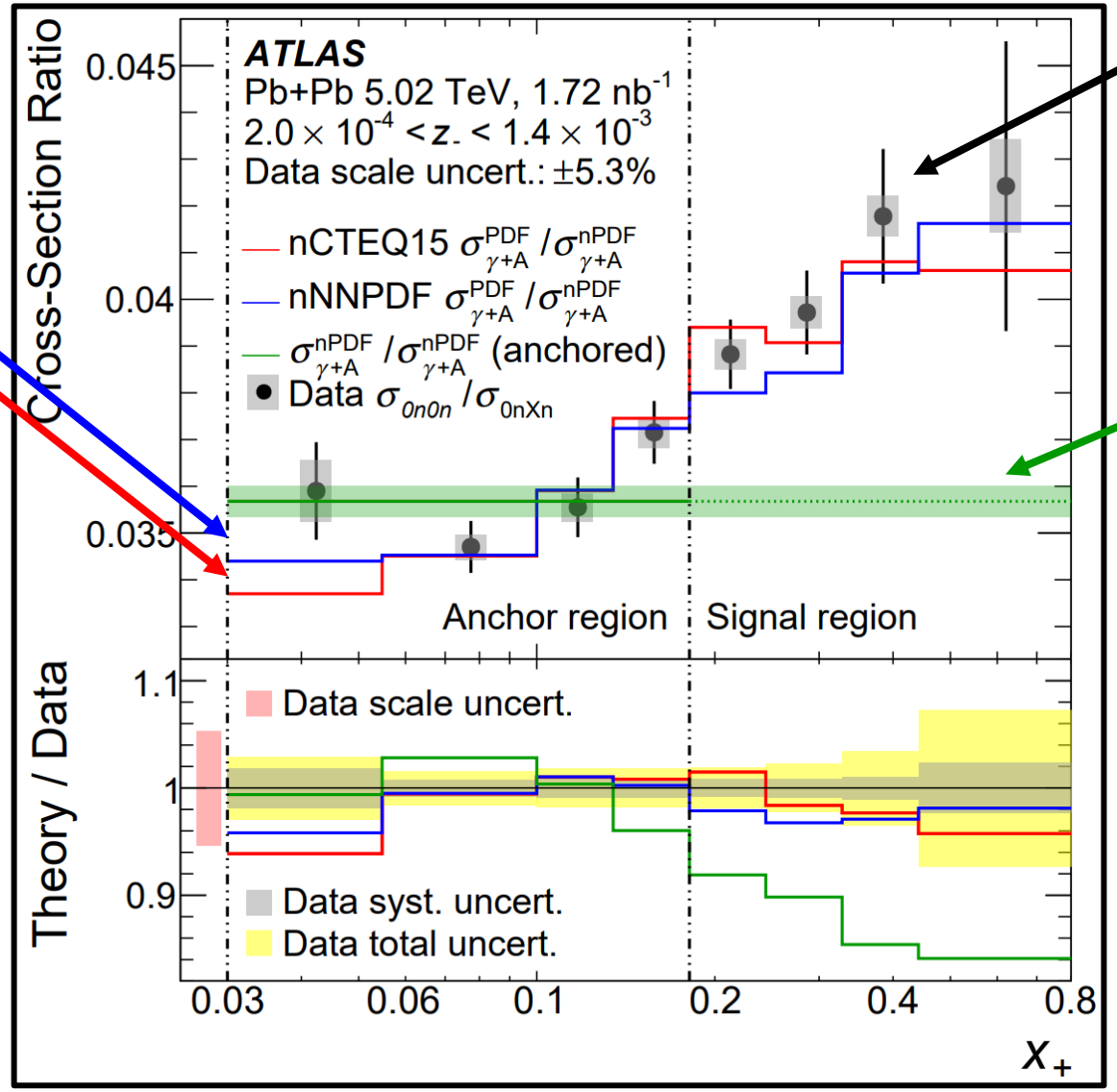

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- The sample is divided into anchor and signal regions, optimized for sensitivity in MC-only studies.
- We integrate the cross-sections and compute the average ratio.
- We compute the statistical significance (S) of the difference.

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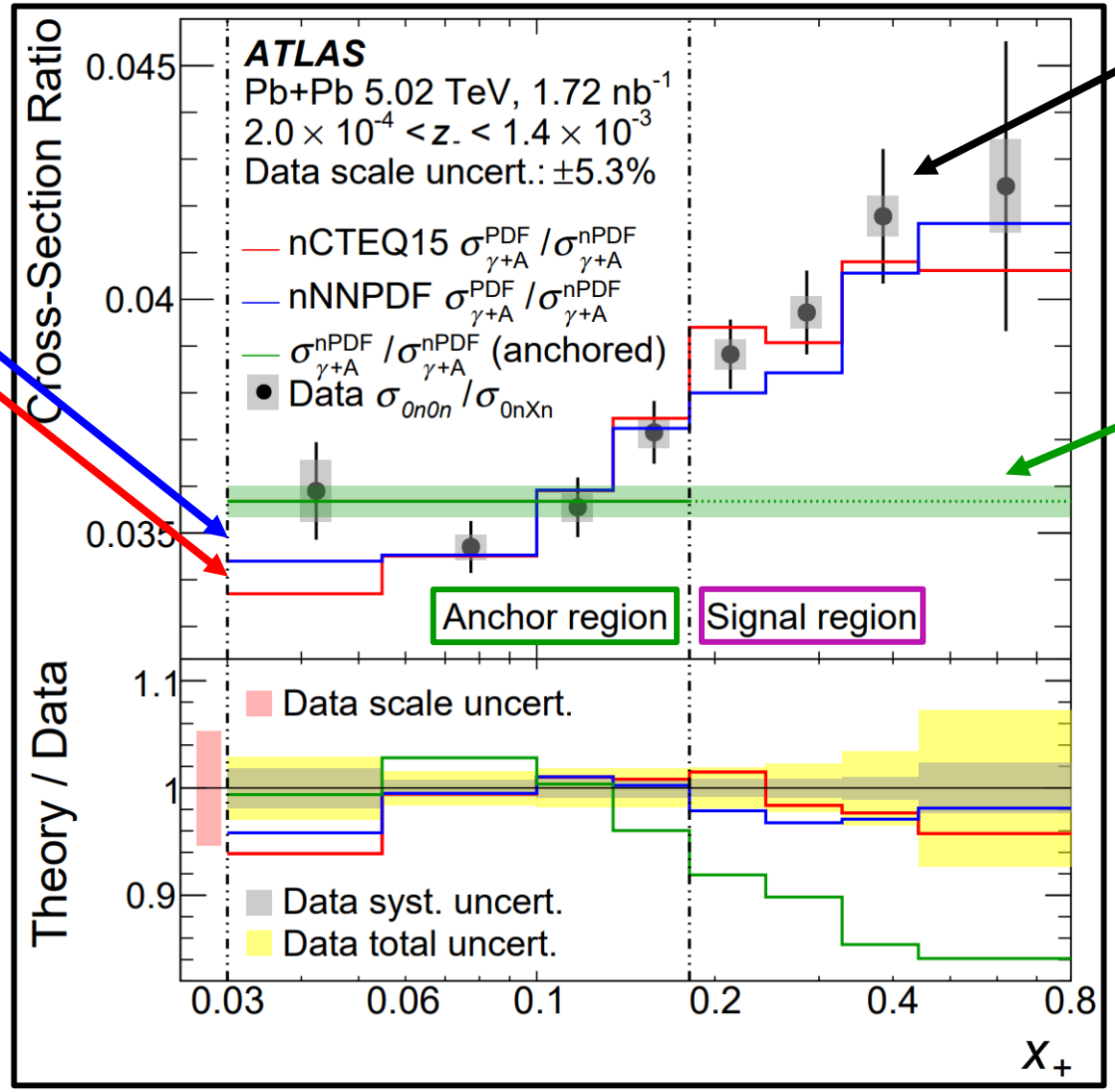

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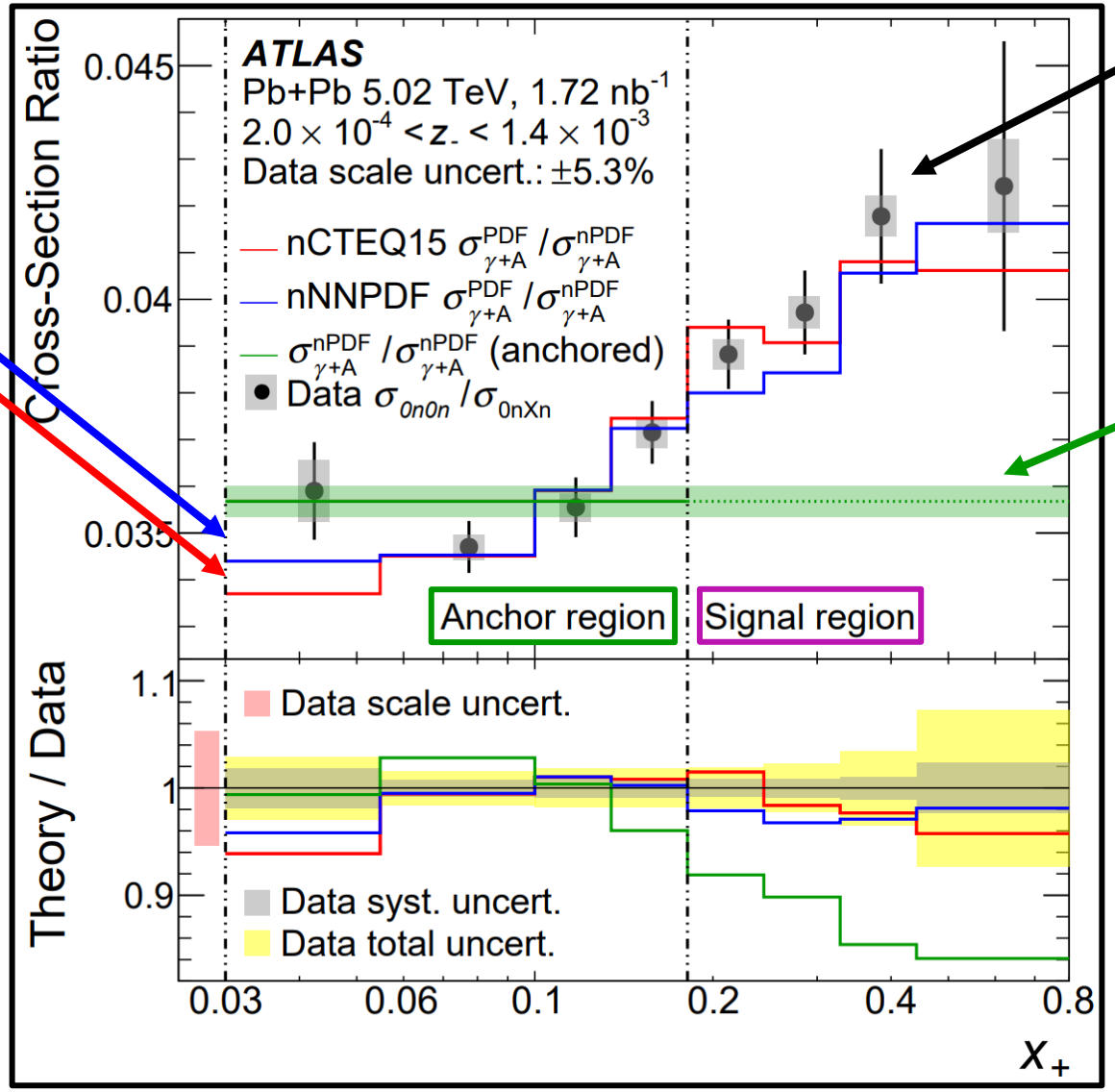

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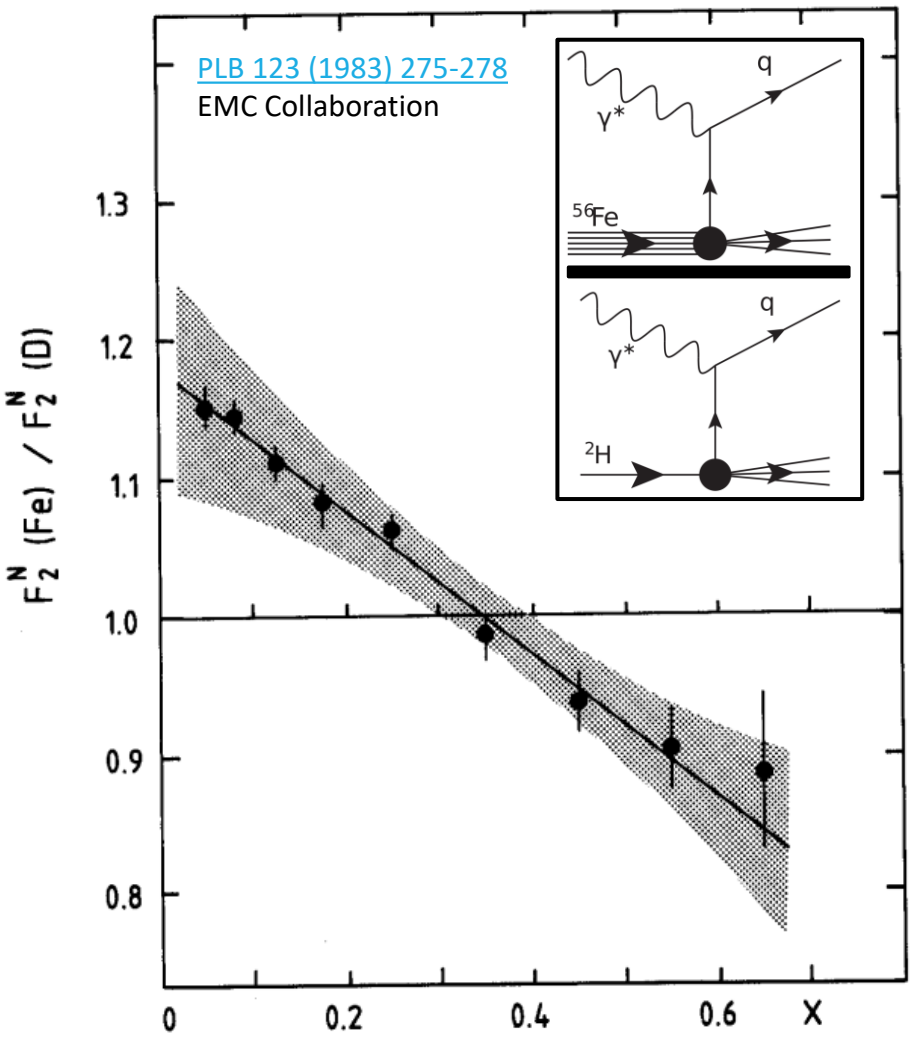
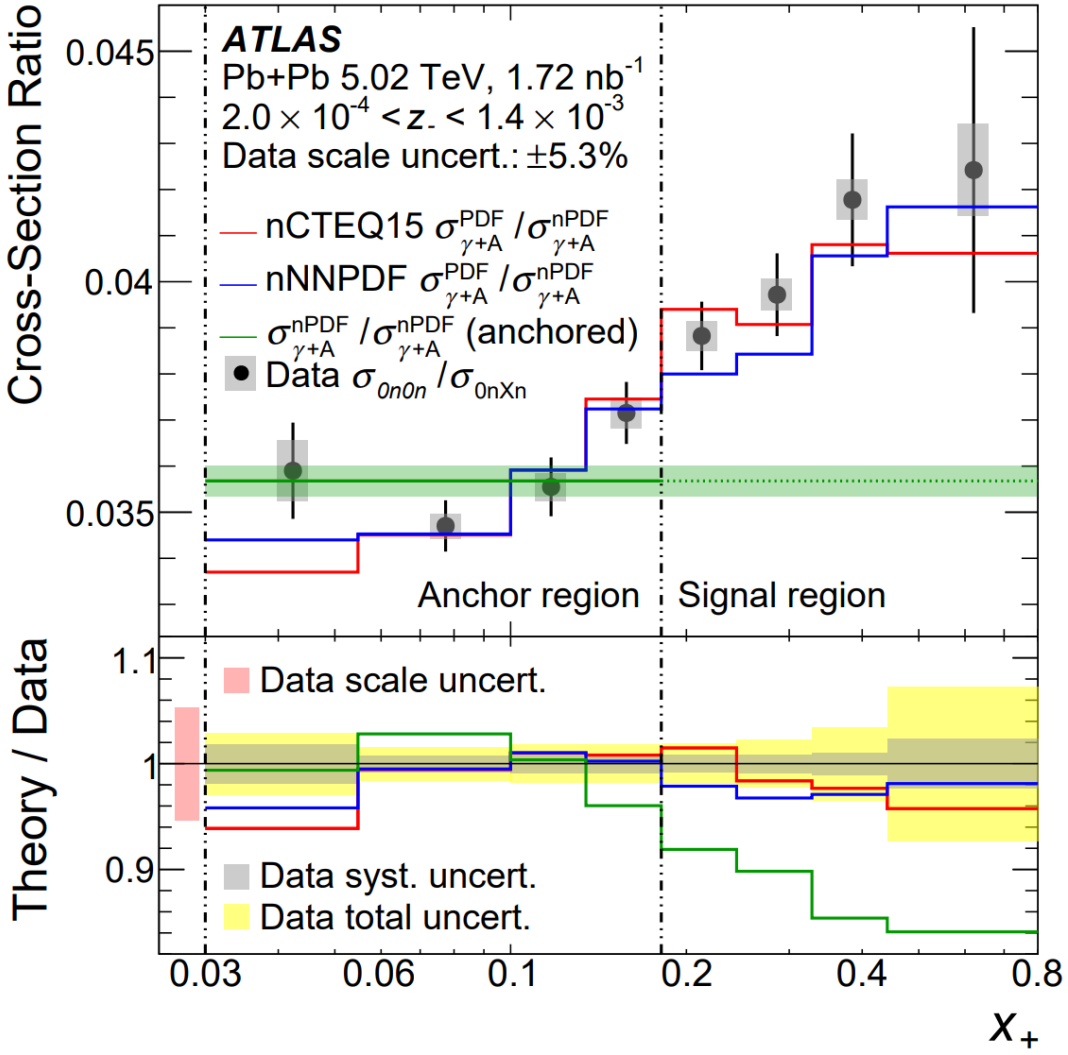
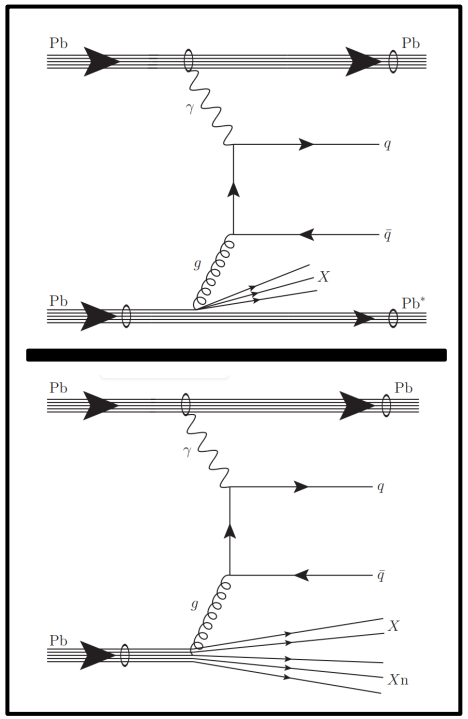
Reversing the EMC Effect

Comparing nPDFs between event classes

- Going all the way back to the discovery of the EMC effect in 1983, we observe the inverse effect in a very different way.







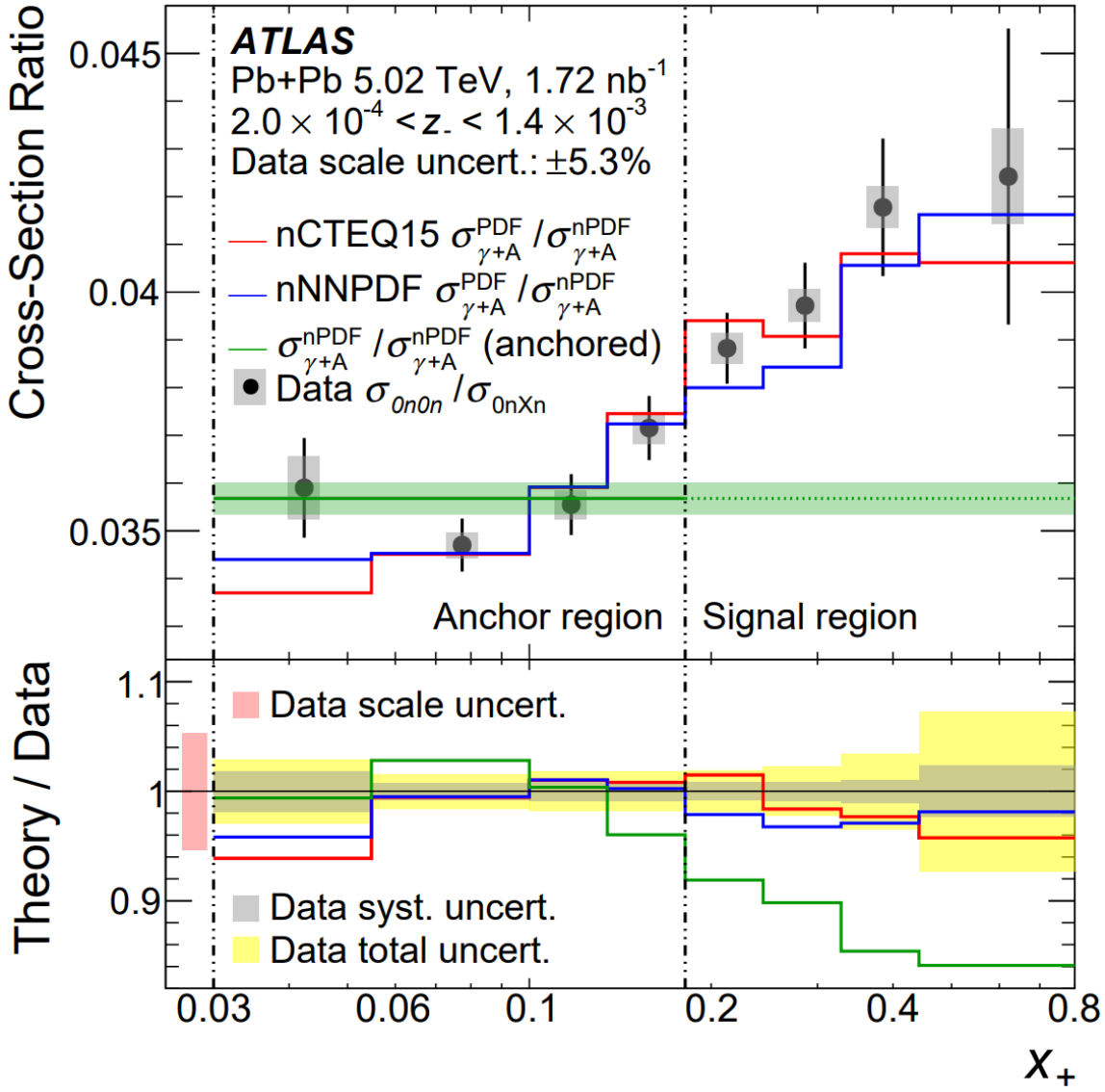
Conclusions and Outlook

- ATLAS has performed measurements of jet photoproduction in Pb+Pb UPCs at 5.02 TeV without nuclear dissociation.
  - The different processes which contribute may be separated via a template-fitting procedure.

- A first measurement of photo-diffractive cross-sections is performed, the scale of which is described by theoretical predictions.

- b_A-dependence of nPDFs is observed for the first time, allowing for:
  - Substantial improvements in modeling many heavy ion observables which depend on impact parameter (centrality)
  - Future studies to map the transverse dimension of nPDFs

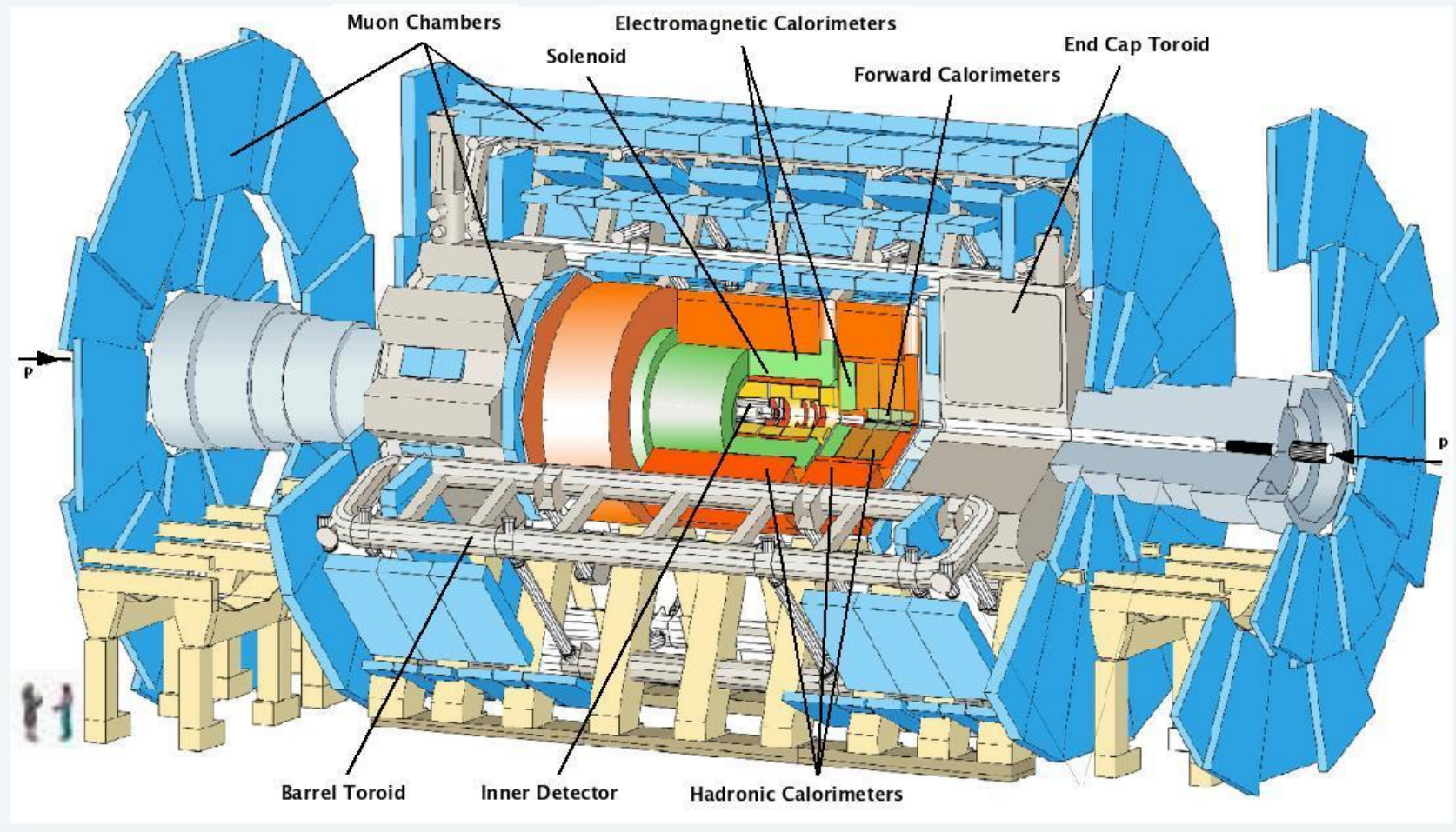
There are many possibilities for further studies using Run 3 LHC, HL-LHC, and EIC data!

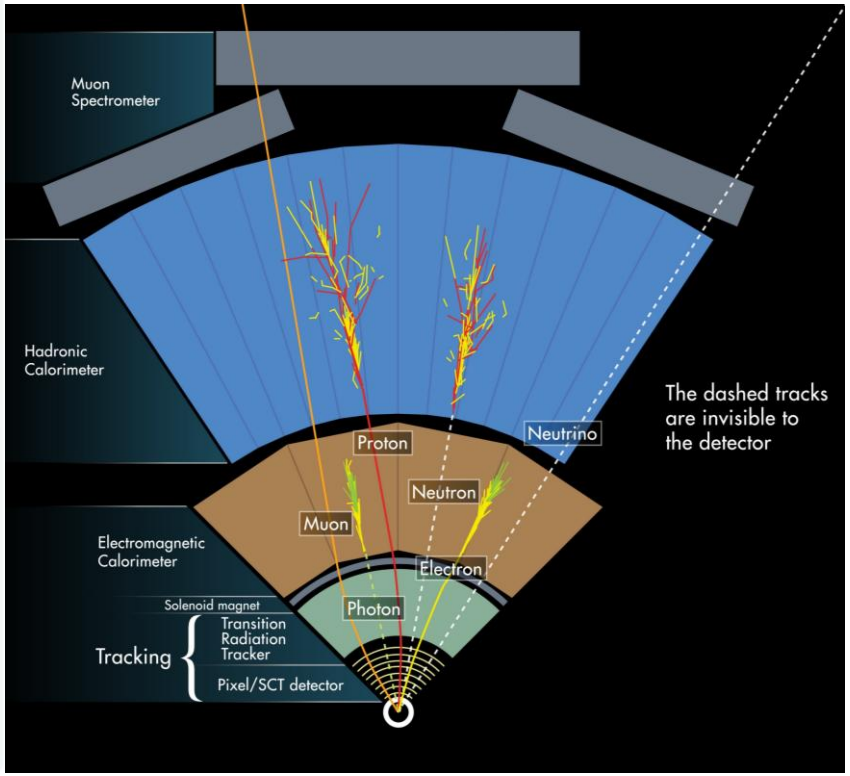


Backup

The ATLAS Detector

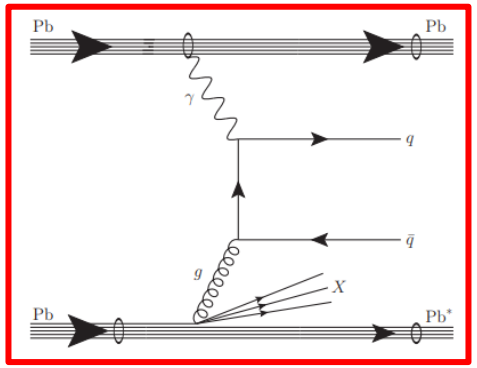
- Photonuclear jet measurements require inputs from nearly every component of the ATLAS detector.
  - Its nearly 10 units of coverage in rapidity are key for distinguishing these events.

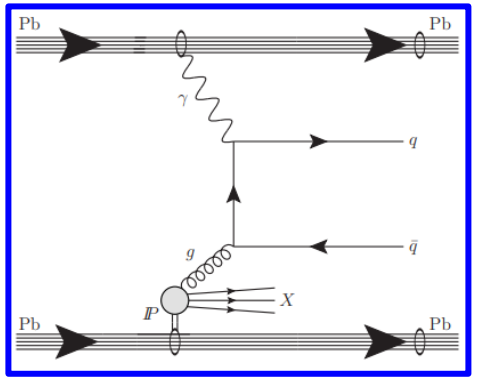


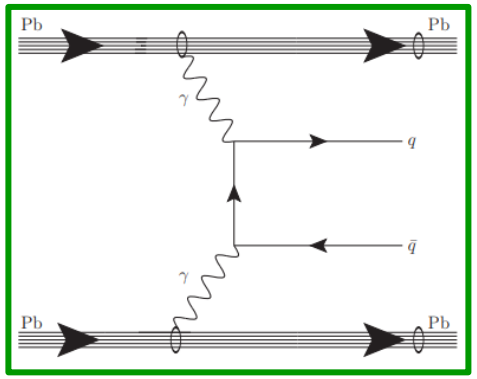


Defining the Rapidity Gap Variable

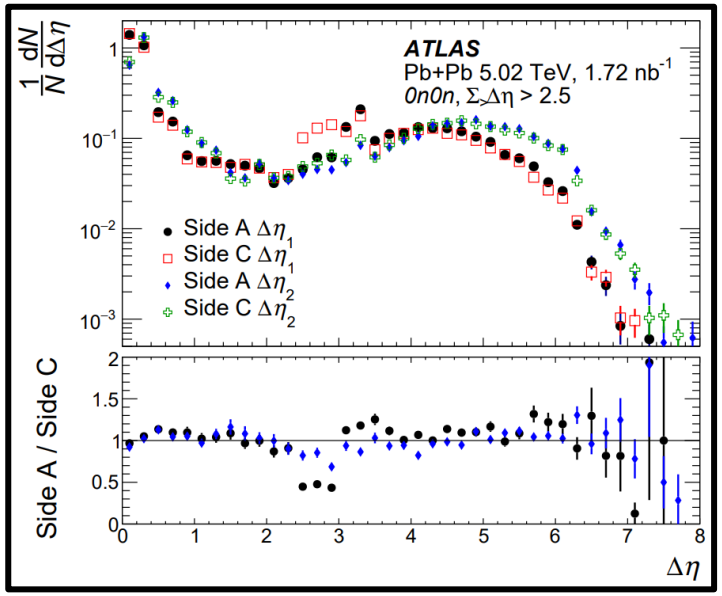
Selecting a "peripheral" class of $\gamma + A$ collisions

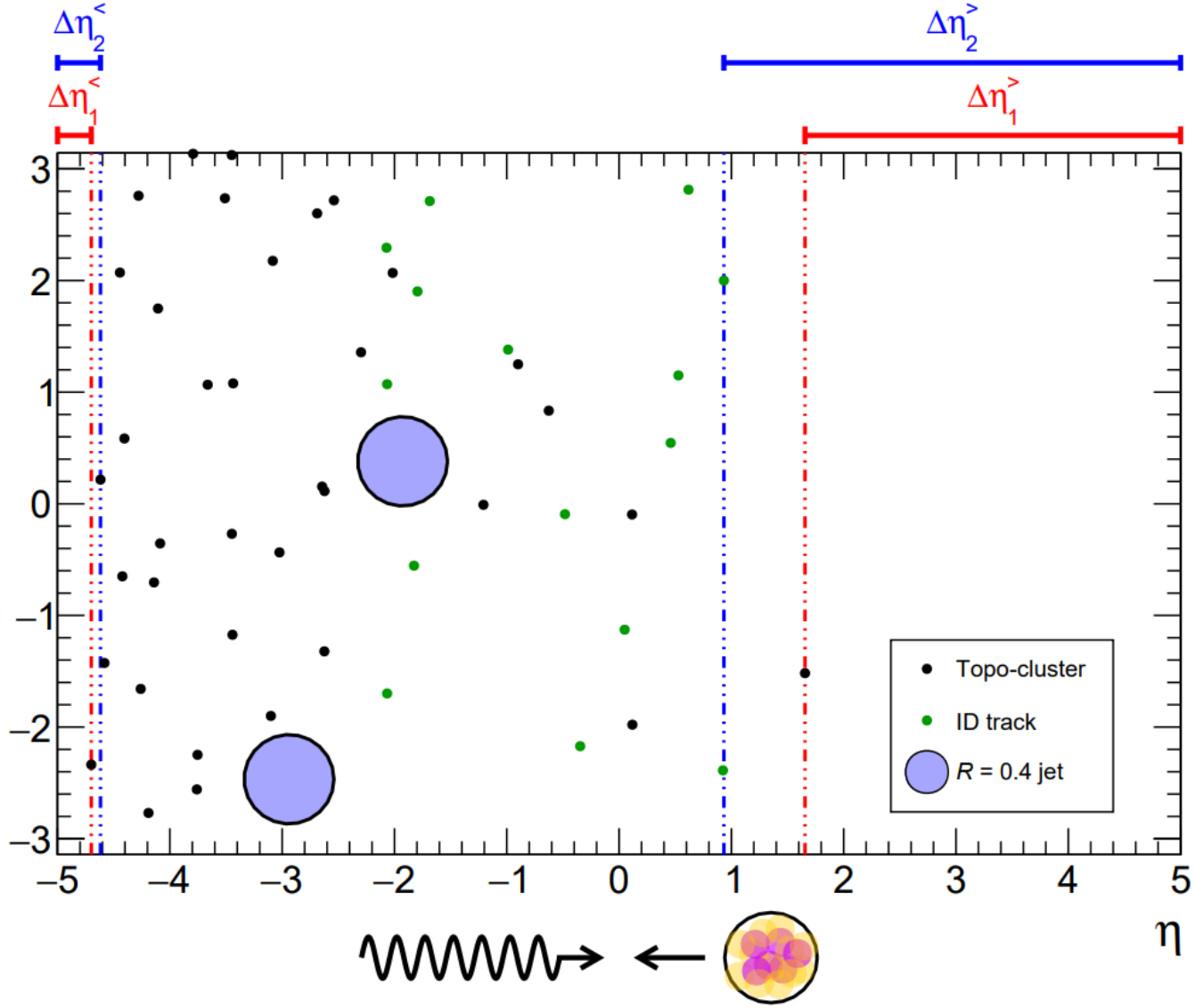






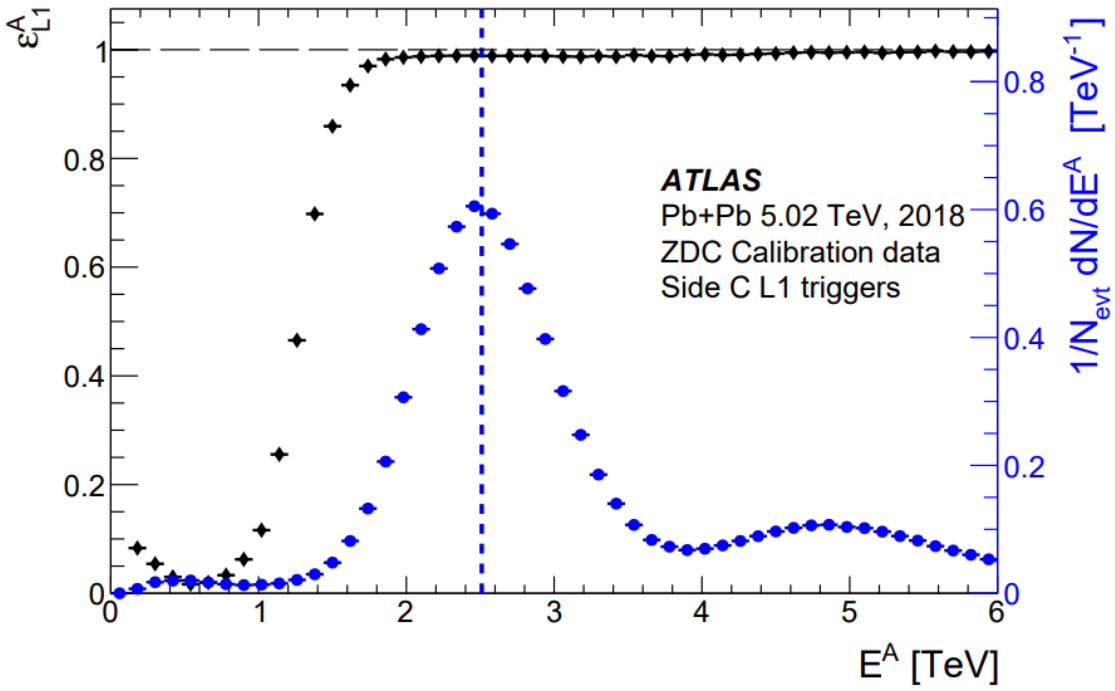
The $\Delta\eta_2$ gap variable is more resilient to detector noise and improves signal modeling!

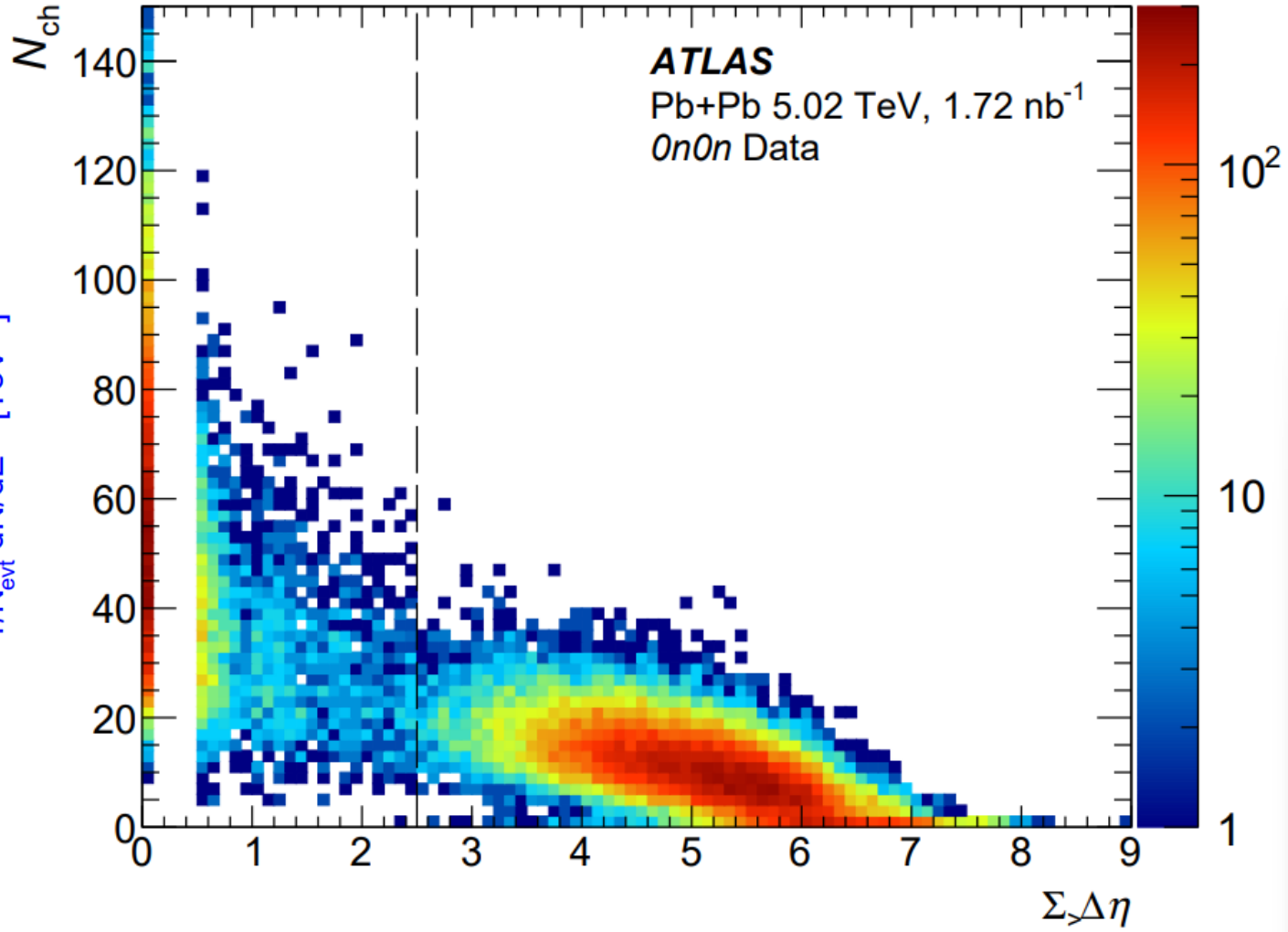




Event Selections

- Photonuclear jet events are selected using both event-level and jet-level requirements.
- Jets are required to satisfy:
  - $p_T > 13$ GeV, $|\eta| < 4.4$
- Events are required to satisfy:
  - $\sum_{>} \Delta\eta > 2.5$, $\Delta\eta_2^{<} < 2.5$
  - $N_{jets} \geq 2$, $0.9 < m_{jets}/H_T < 4$
  - ZDC 0n0n ($E_A < 1$ TeV, $E_C < 1$ TeV)





Correcting for Correlated EMD

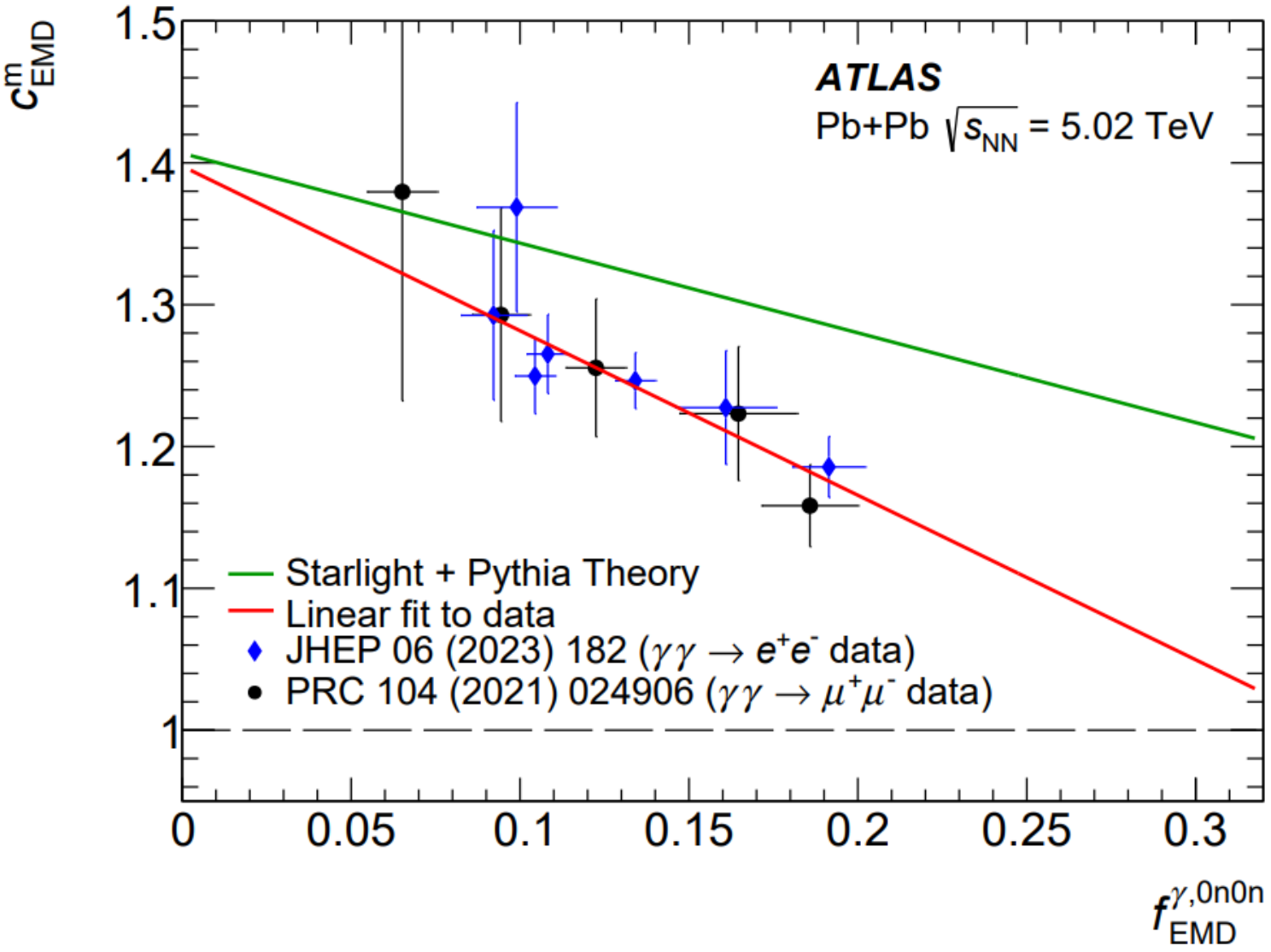
- Correlated EMD is different between the 0n0n and 0nXn measurements.
  - The difference arises due to the inability to distinguish EMD on the nucleus-going side of 0nXn events.
- Corrections are derived from $\gamma + \gamma$ di-lepton production according to:

$$f_{\mathrm{EMD}}^{\gamma,0n0n} = \frac{f_{0nXn}^{\gamma\gamma}}{2 - f_{0nXn}^{\gamma\gamma} - 2f_{XnXn}^{\gamma\gamma}}$$

$$c_{\mathrm{EMD}}^{\mathrm{m}}(f_{\mathrm{EMD}}^{\gamma,0n0n}) = \frac{f_{0nXn}^{\gamma\gamma} + 2f_{XnXn}^{\gamma\gamma}}{2f_{\mathrm{EMD}}^{\gamma,0n0n}}$$

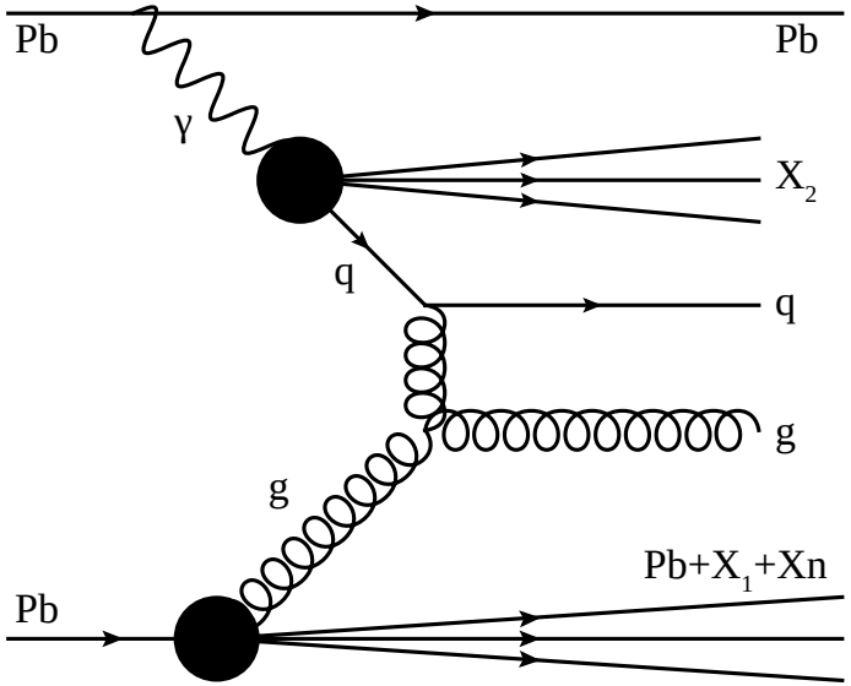
- Then, the correction factors are applied as:

$$f_{\mathrm{EMD}}^{\gamma} = \frac{f_{\mathrm{EMD}}^{\gamma,0nXn}}{c_{\mathrm{EMD}}^{\mathrm{m}}(f_{\mathrm{EMD}}^{\gamma,0n0n})}$$

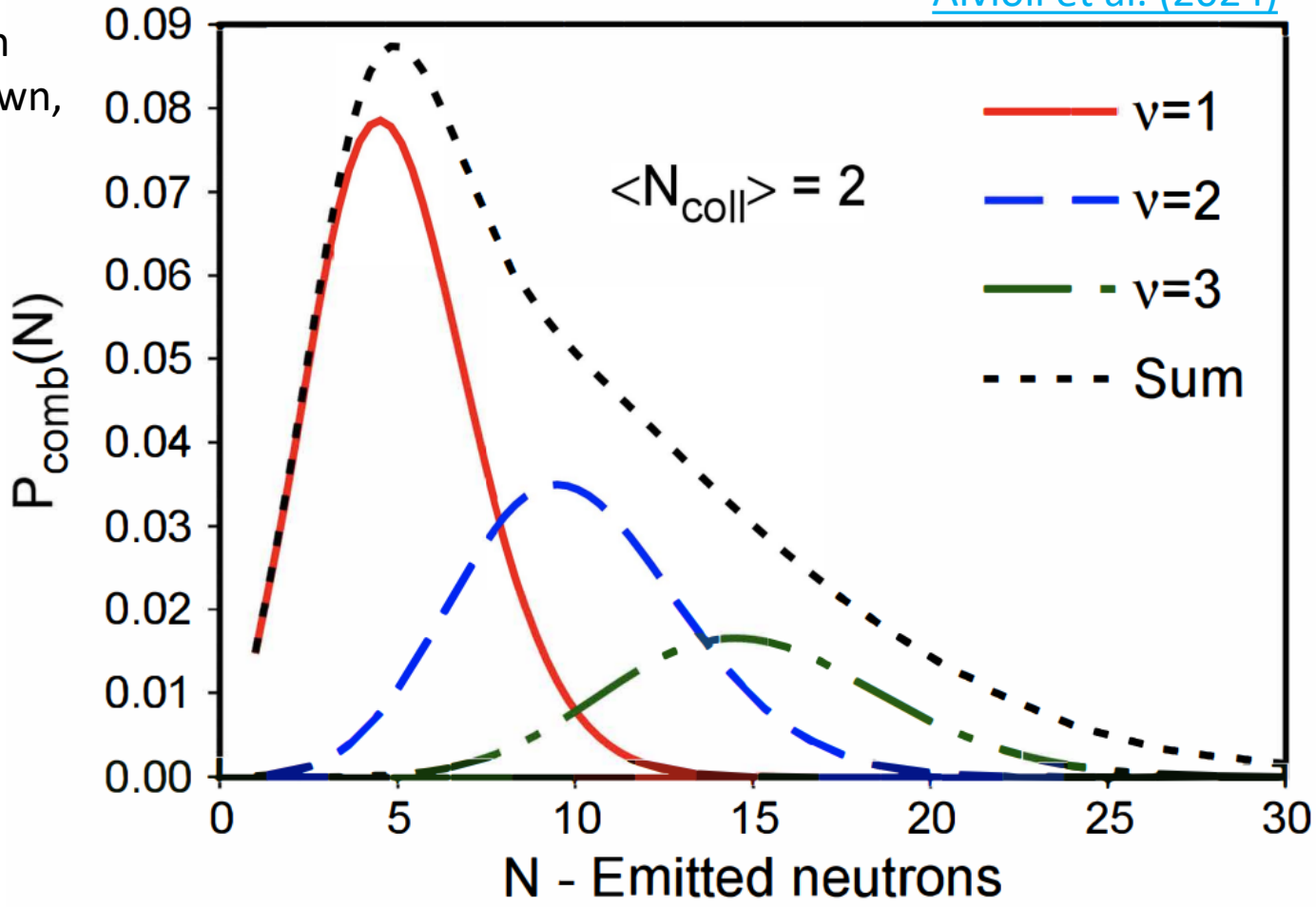


Forward Neutrons and b_A

- For UPC events, resolved photons are able to scatter multiple times from the struck nucleus.
  - The number of produced forward neutrons is highly sensitive to the number of wounded nucleons (ν), (nucleons struck in these multiple interactions).
  - Since the edge of the nucleus has lower nucleon density, the rate for multiple-scattering goes down, with fewer wounded nucleons and thus fewer forward neutrons.



Alvioli et al. (2024)



Photonuclear Jet Kinematics

$$H_T = \sum_i p_T^i$$

$$x_+ = \frac{m_{jets} e^{+|y_{jets}|}}{\sqrt{s_{NN}}}$$

$$z_- = \frac{m_{jets} e^{-|y_{jets}|}}{\sqrt{s_{NN}}}$$

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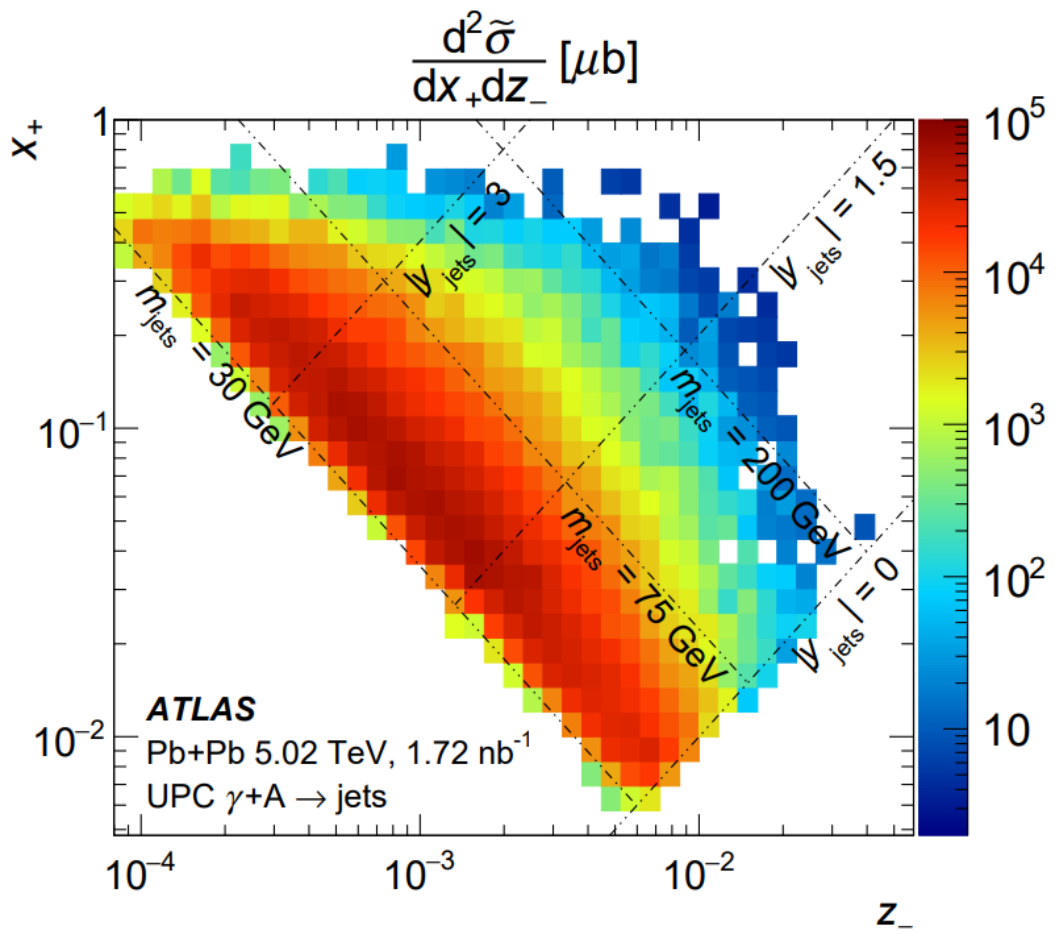
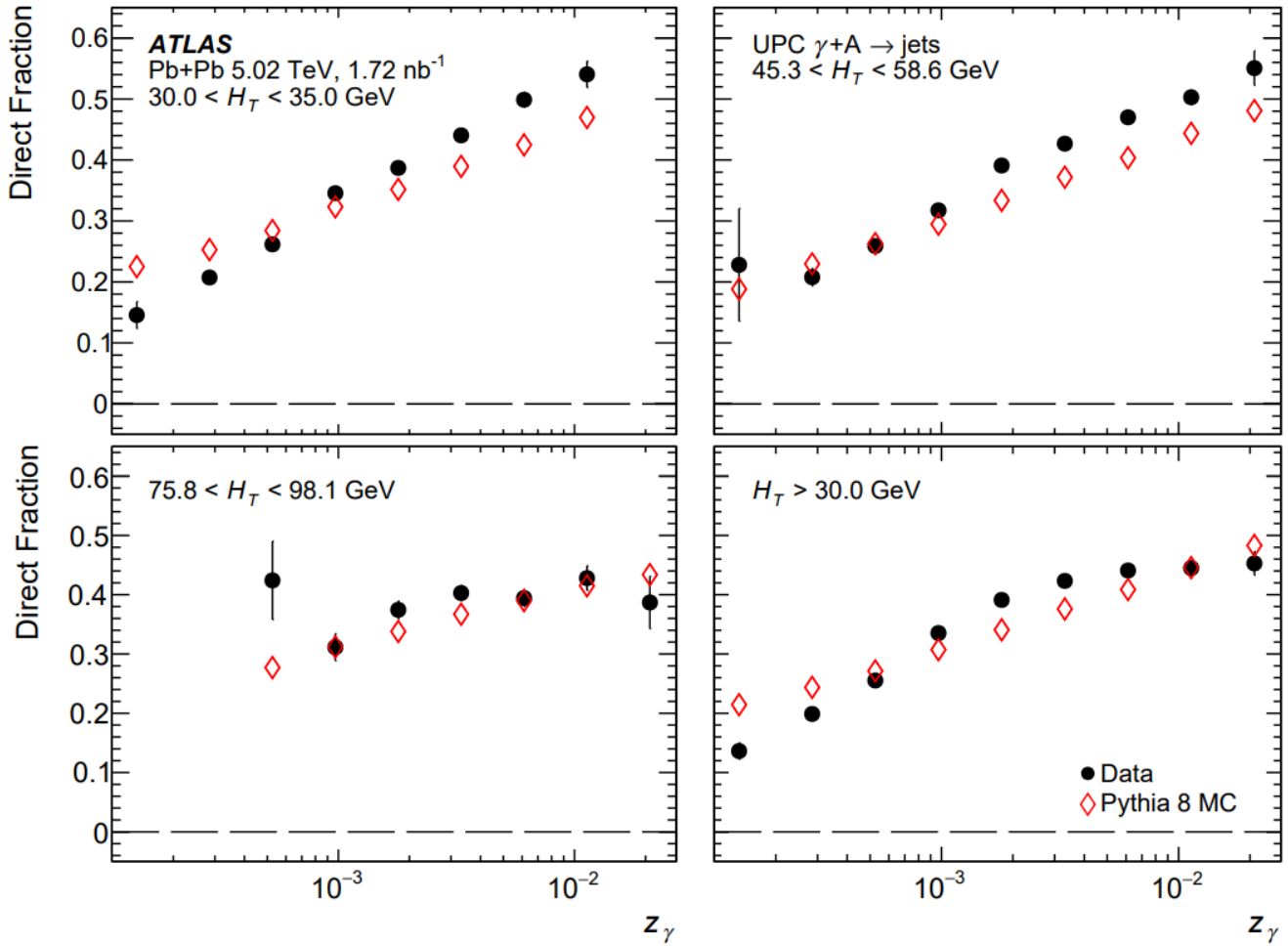
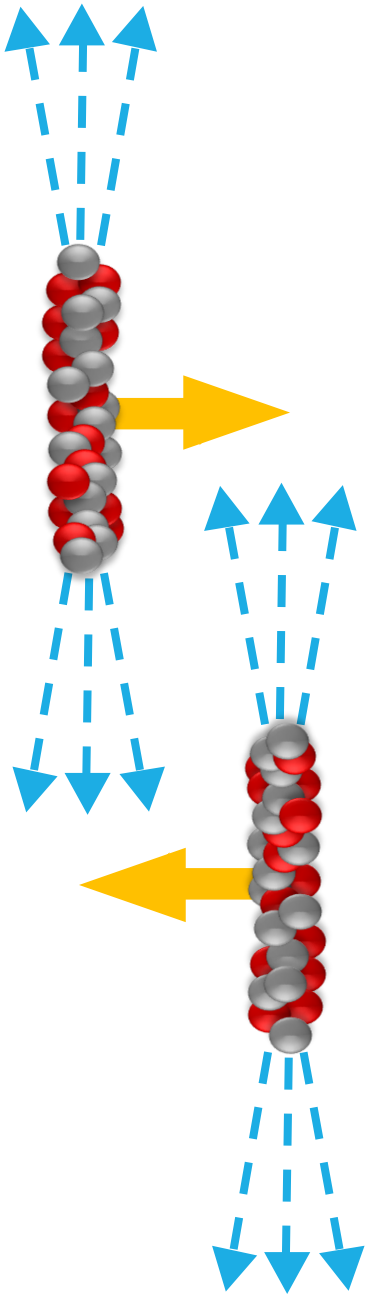


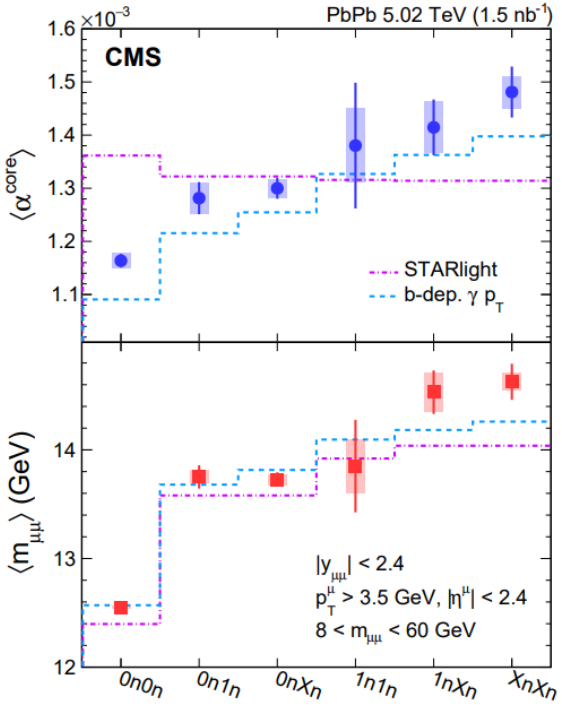


Ultra-Peripheral Collisions (UPCs)

$b > 2R_A$



- In heavy ion collisions, the nuclei generate extremely strong electromagnetic fields.
  - For Z = 82 ions at 5.02 TeV, the field strength is B = O(10^{15}) T.
- These EM fields interact as a flux of nearly real photons. (Equivalent Photon Approximation)
  - The cross-sections for photoproduction are enhanced by Z^2 for each photon emitter.
- We have a strong understanding of the coherent photon flux from previous measurements.



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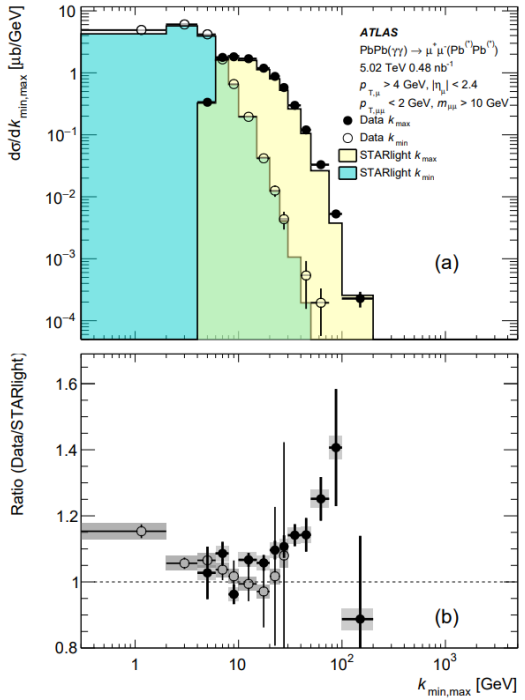

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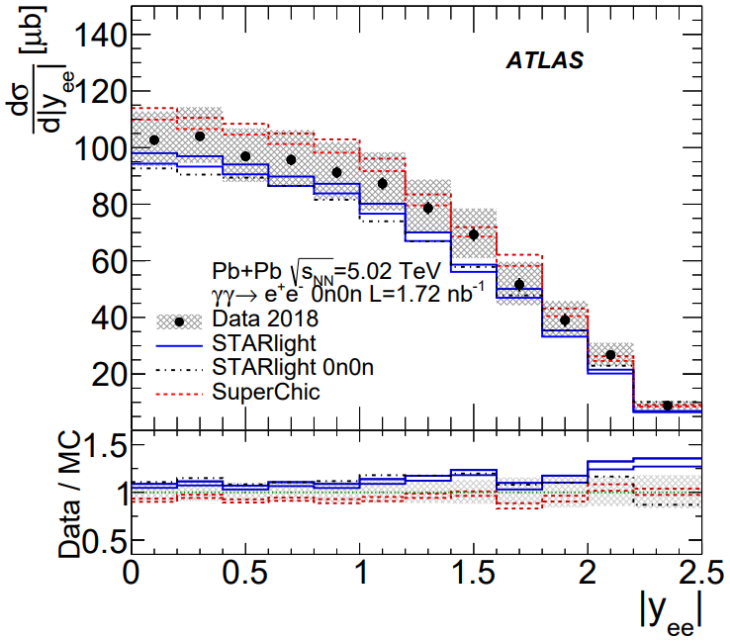

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