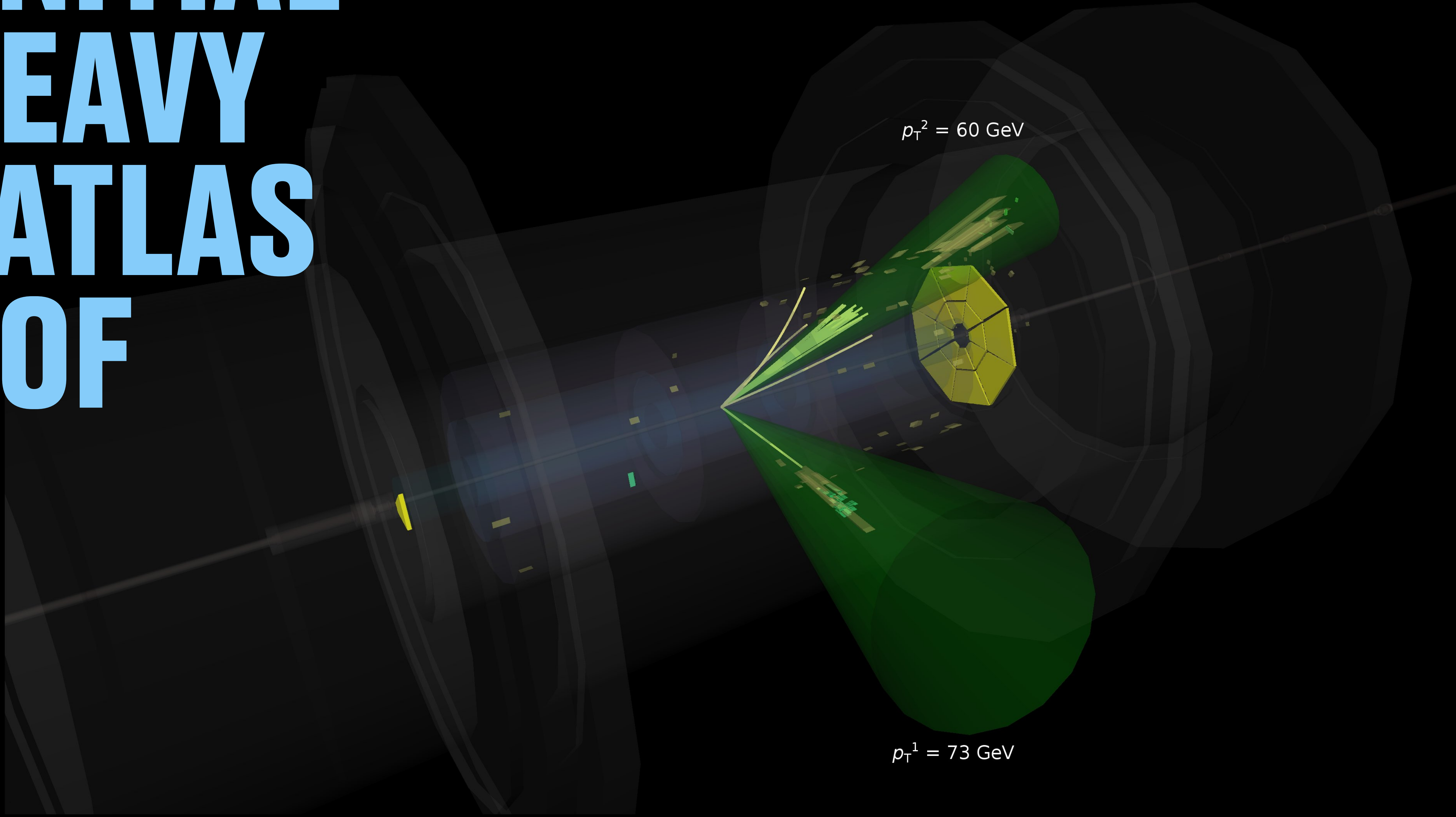
INVESTIGATION OF INITIAL STATE EFFECTS IN HEAVY ION COLLISIONS AT ATLAS VIA MEASUREMENT OF DIJET PRODUCTION



Riccardo Longo
On behalf of the ATLAS Collaboration

20th June 2023
IS2023, Copenhagen

2023 IS INITIAL STAGES

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

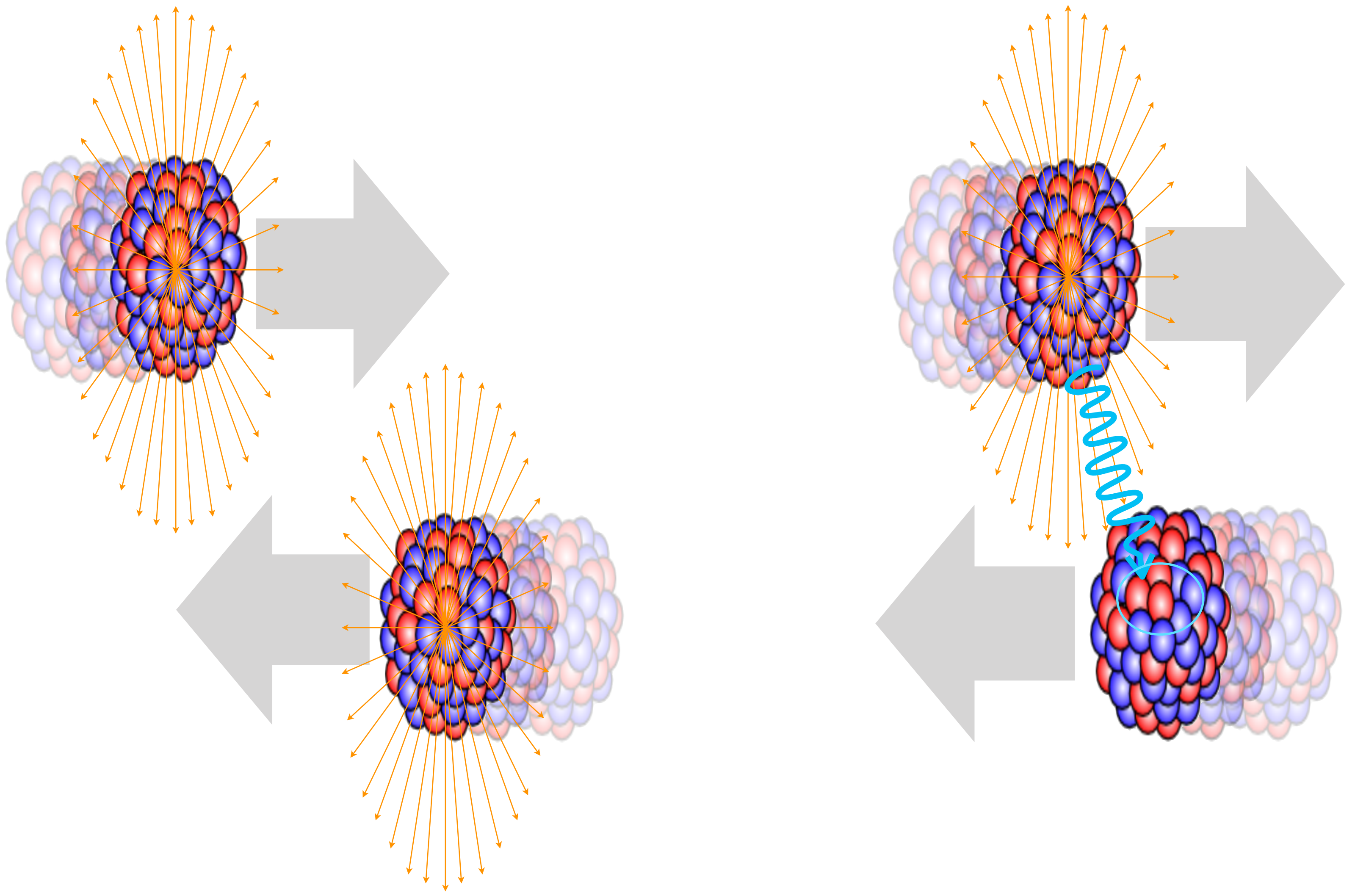
ATLAS EXPERIMENT

PROBING INITIAL STATE EFFECTS IN HI

- Different probes can be used to investigate the nuclear structure and the QCD nature of nuclear collisions.

  In this talk:

  - **Photons emitted in Ultra-Peripheral Collisions (UPC)**
    - Intense EM fields provide a flux of quasi-real photons
    - A photon from one nucleus can interact strongly with the other, effectively probing the nuclear structure



  - **Proton-ion collisions**
    - Strongly interacting probe
    - Can be used to investigate QCD and nuclear structure

- **Dijet events provide direct access to the hard scattering kinematics**
  - Detailed mapping of IS nuclear (nPDFs) and QCD (color transparency) effects
  - Measurements span remarkable kinematic phase space for such measurements thanks to the acceptance of the ATLAS Calorimeter

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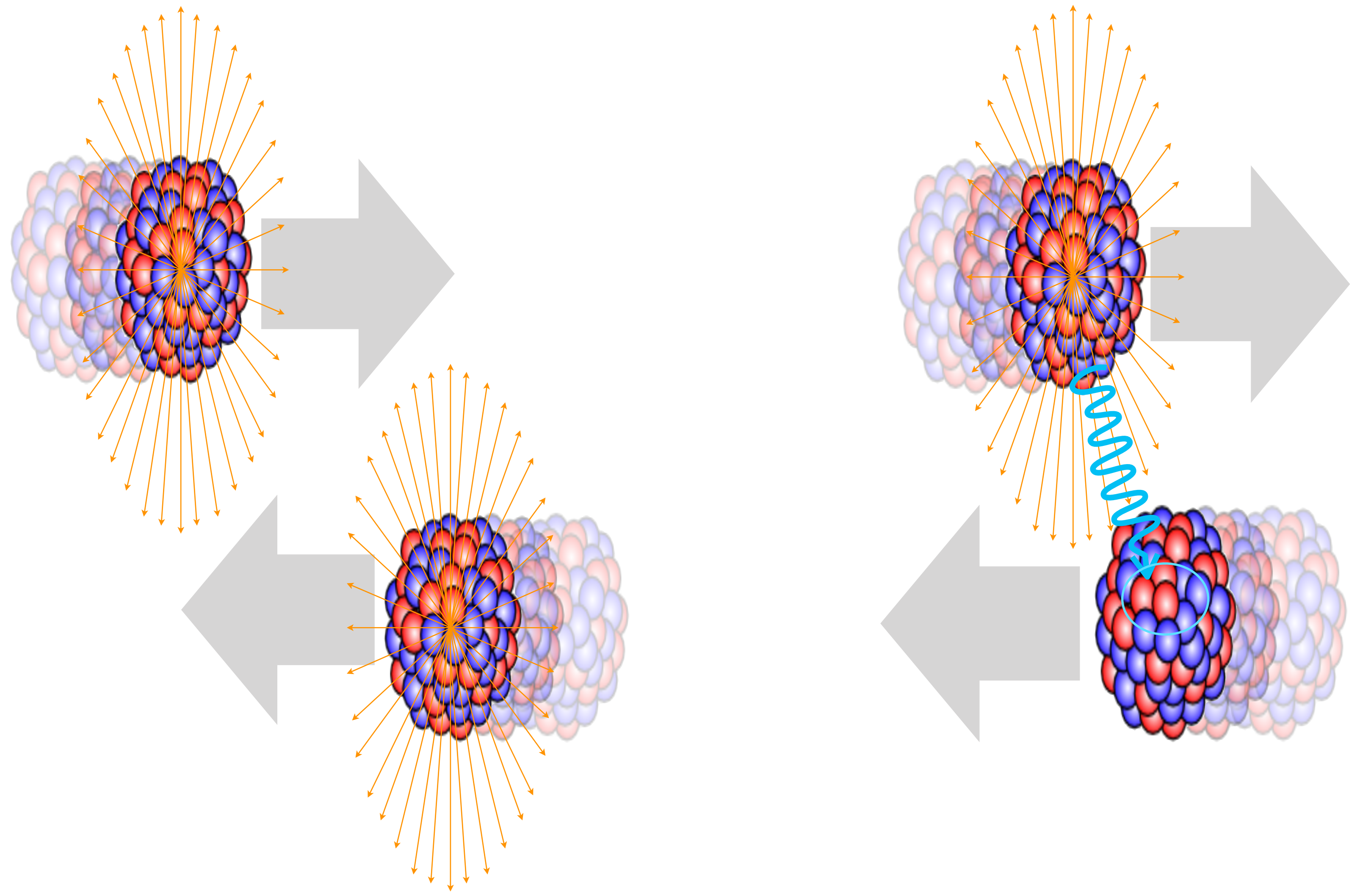

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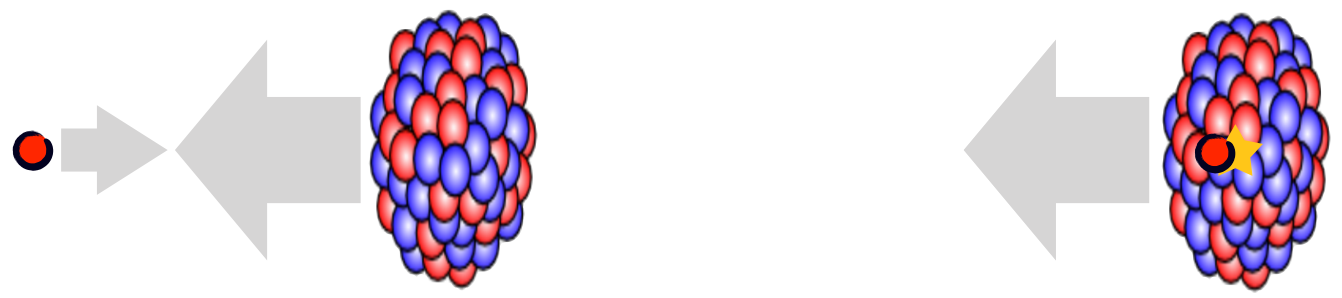

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DIJET PROBES FOR INITIAL STATE EFFECTS

- Different probes can be used to investigate the nuclear structure and the QCD nature in nuclear collisions.

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  - **Proton-ion collisions**

    ATLAS CONF 2023-011

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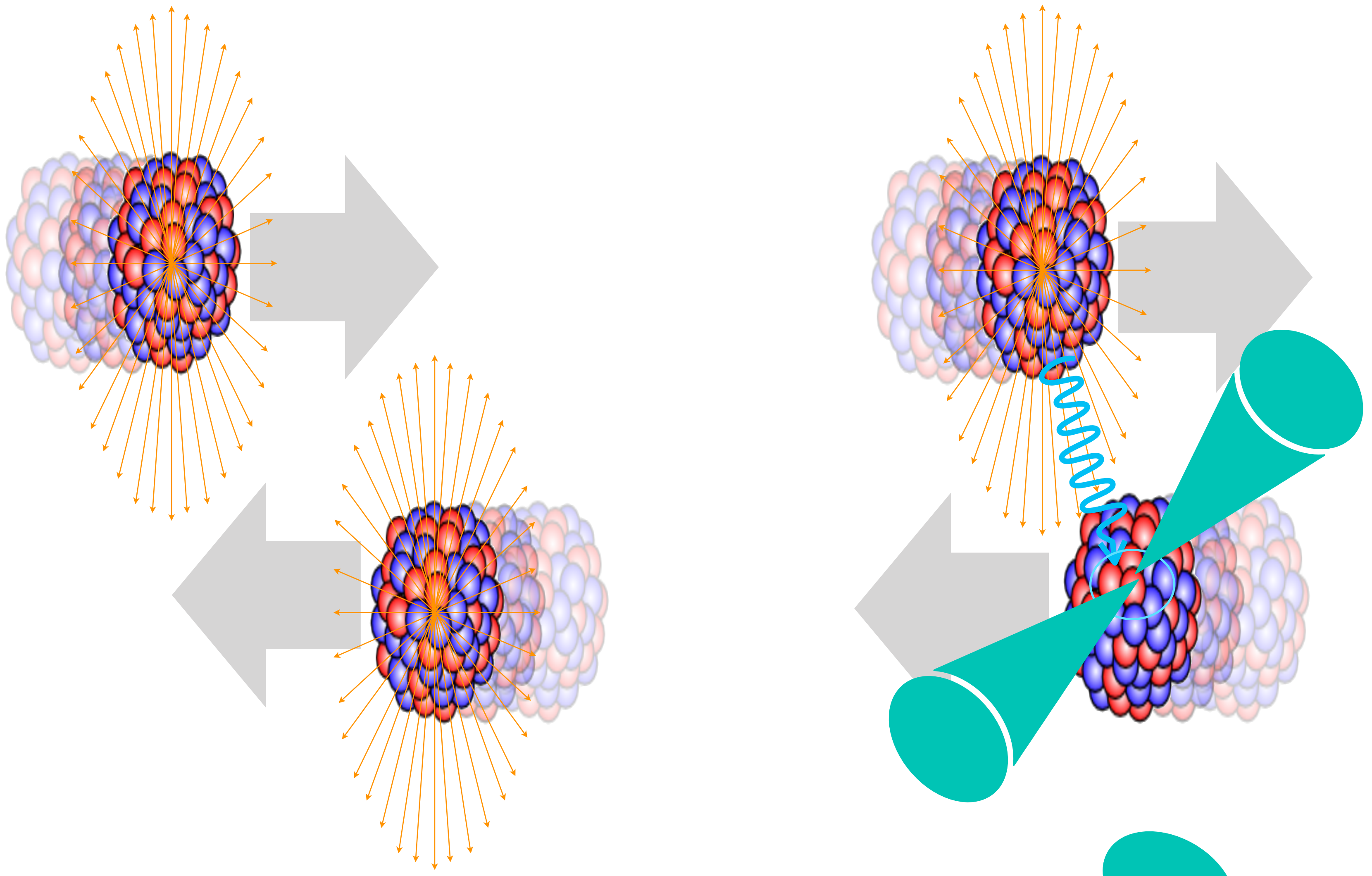

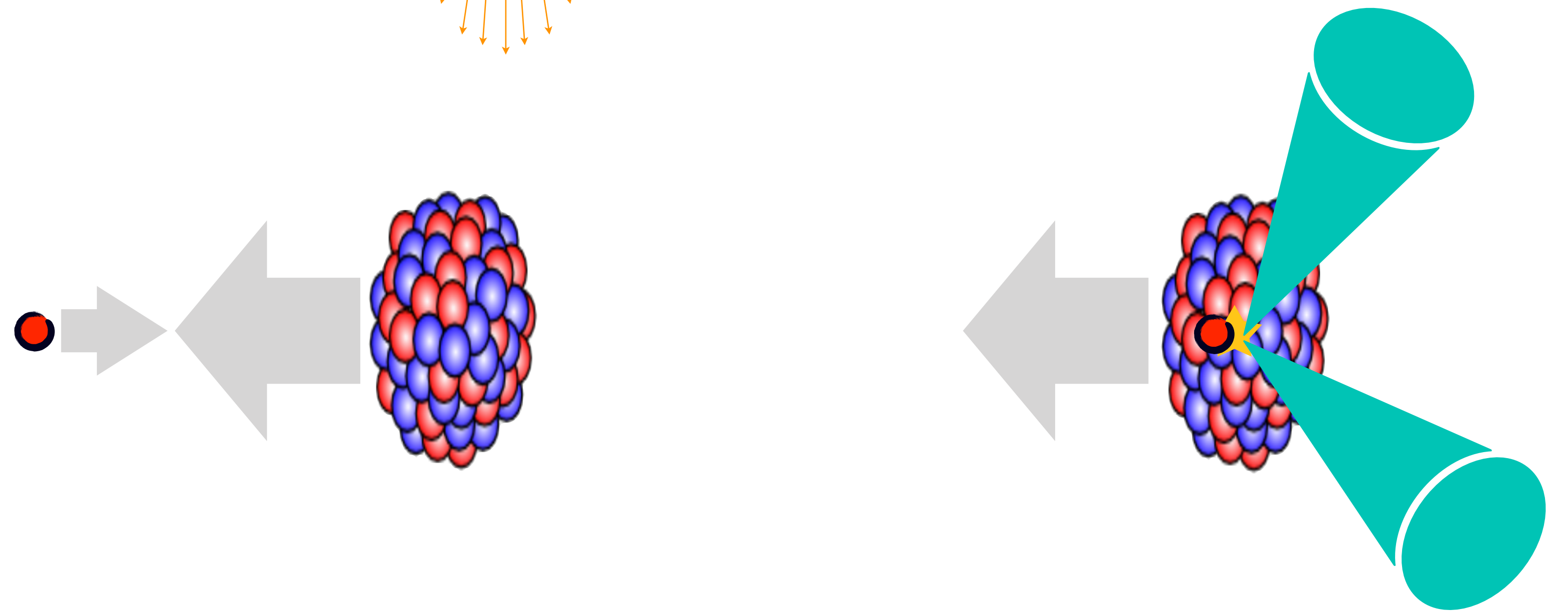

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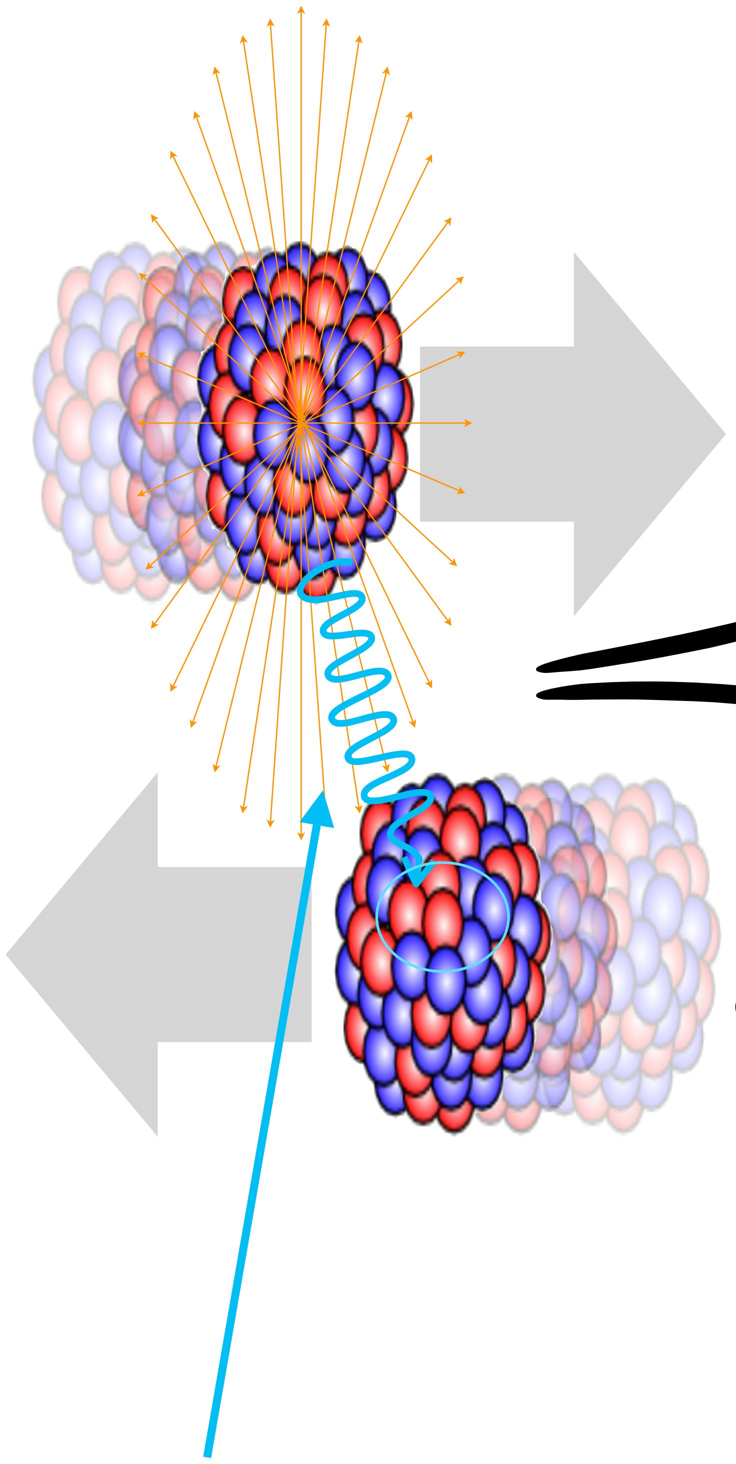
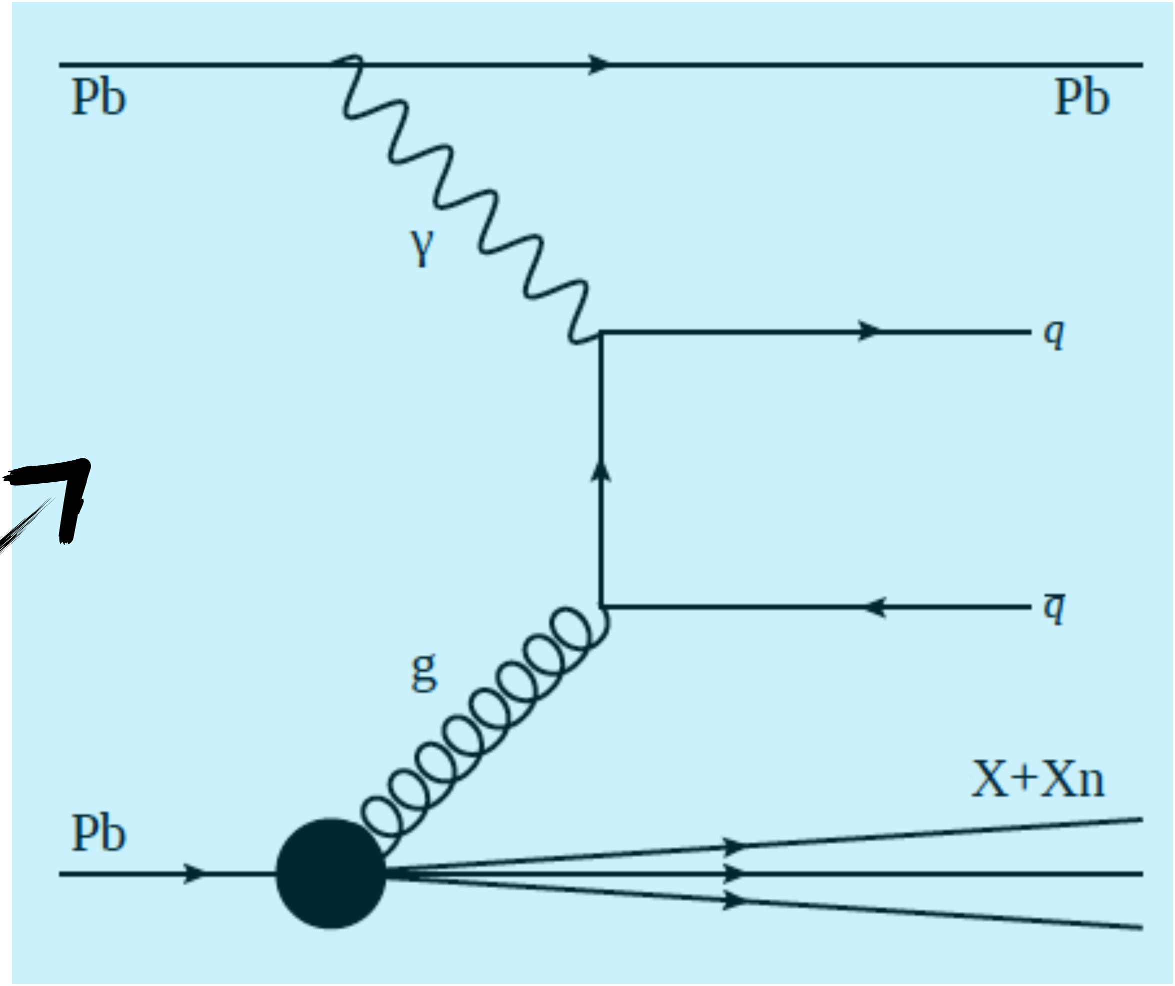
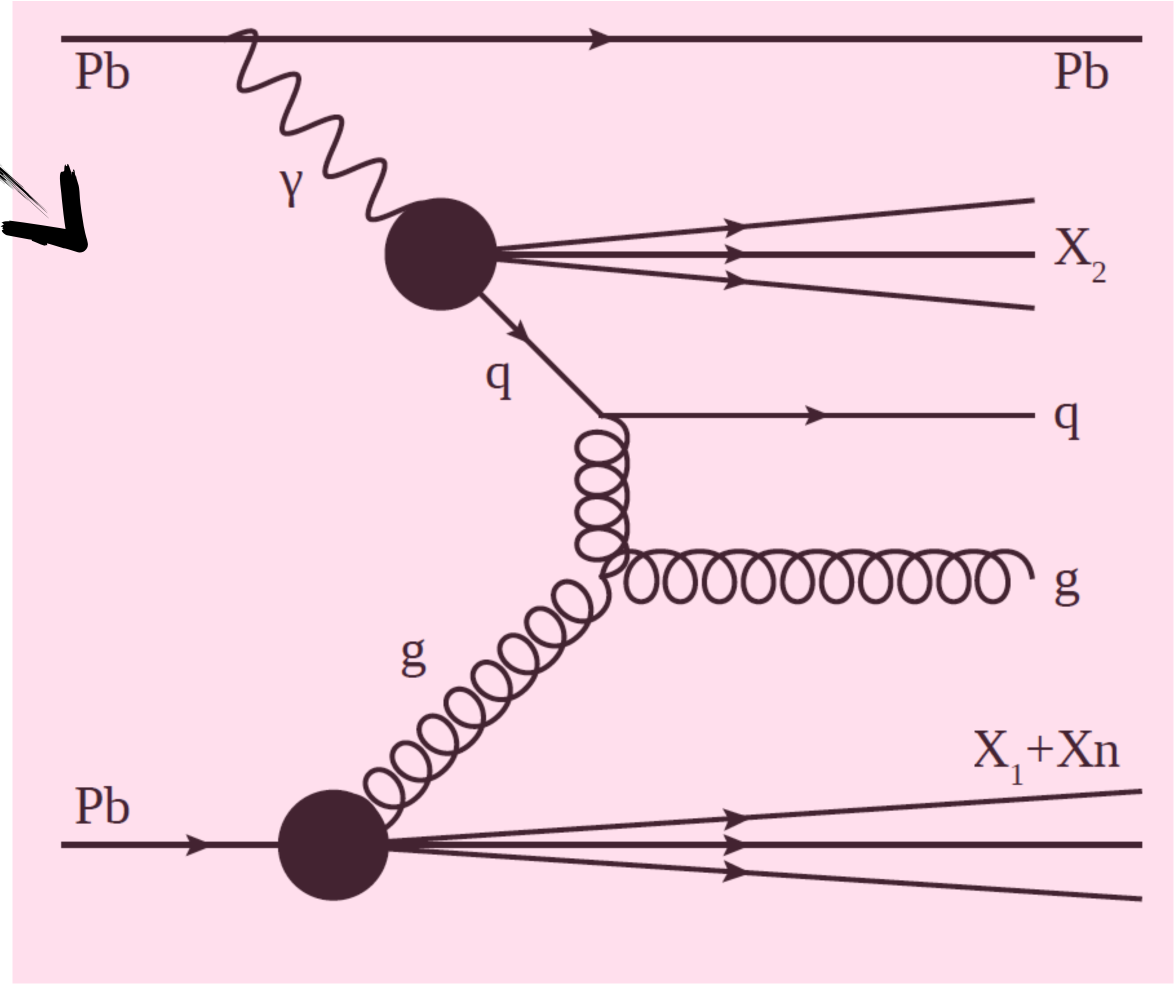
PHOTO-NUCLEAR EVENTS



"**Direct**" photons scatter off the nucleus

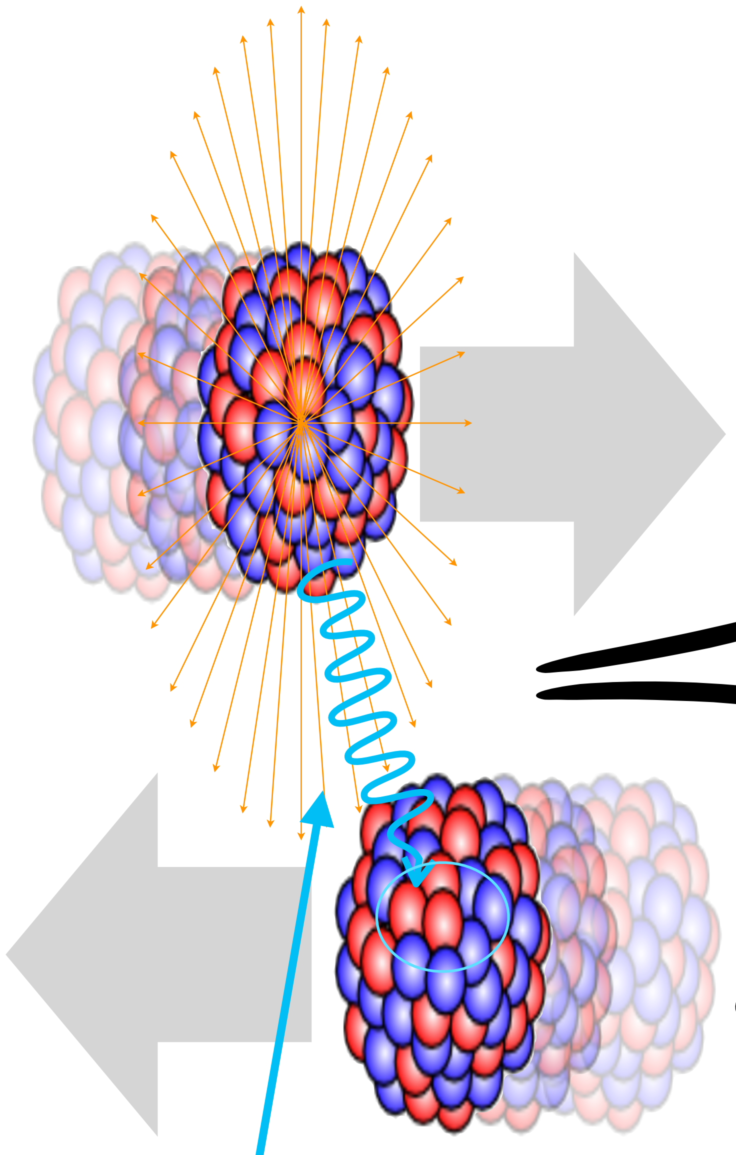
"**Resolved**" photons scatter through a virtual hadronic excitation of the photon





These photons can scatter off the nucleus and resolve nuclear partons!

DIJET PRODUCTION IN PHOTO-NUCLEAR EVENTS



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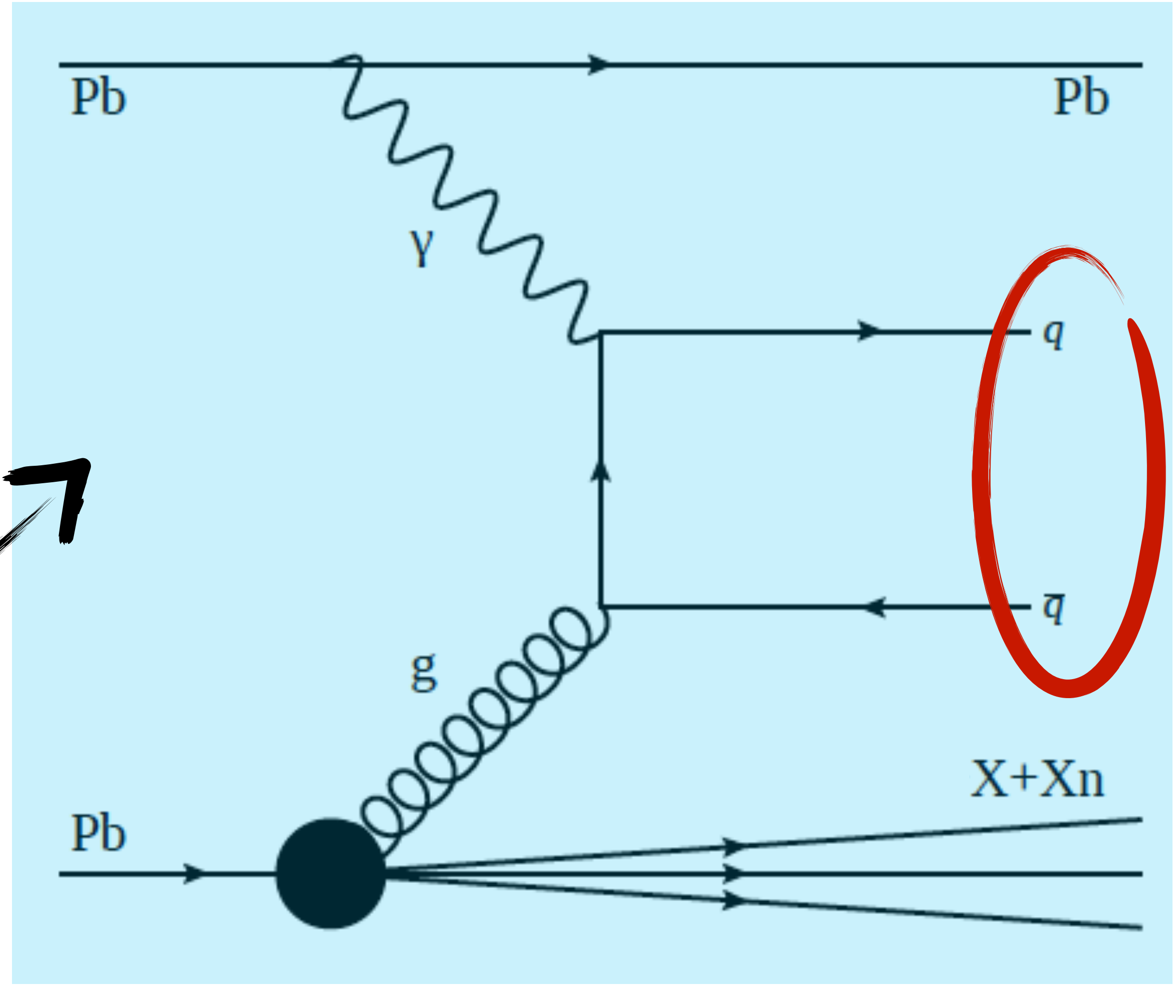

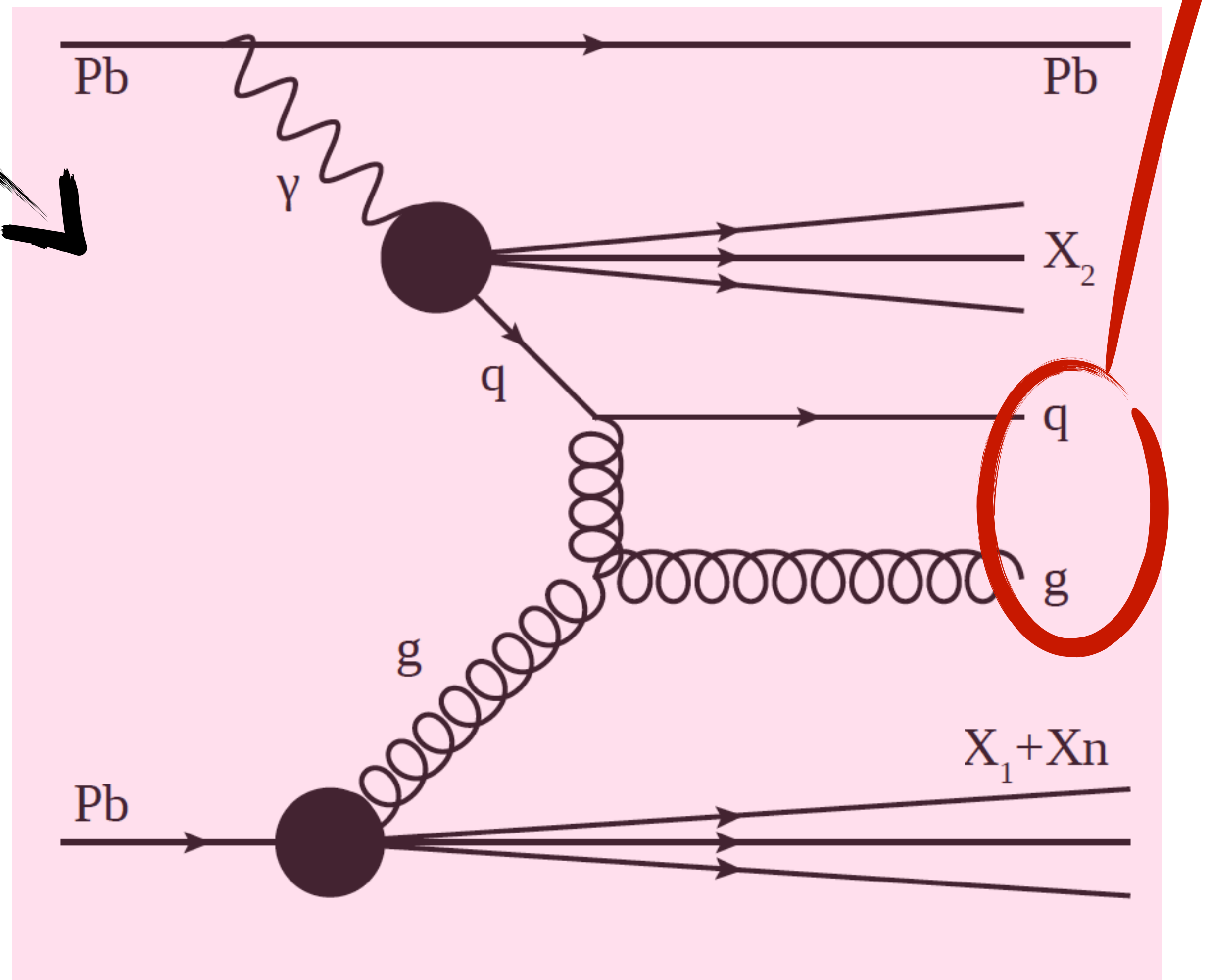

Jet kinematics are proxy to hard-scattering kinematics

$$H_T = \sum_i p_T^i$$

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

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

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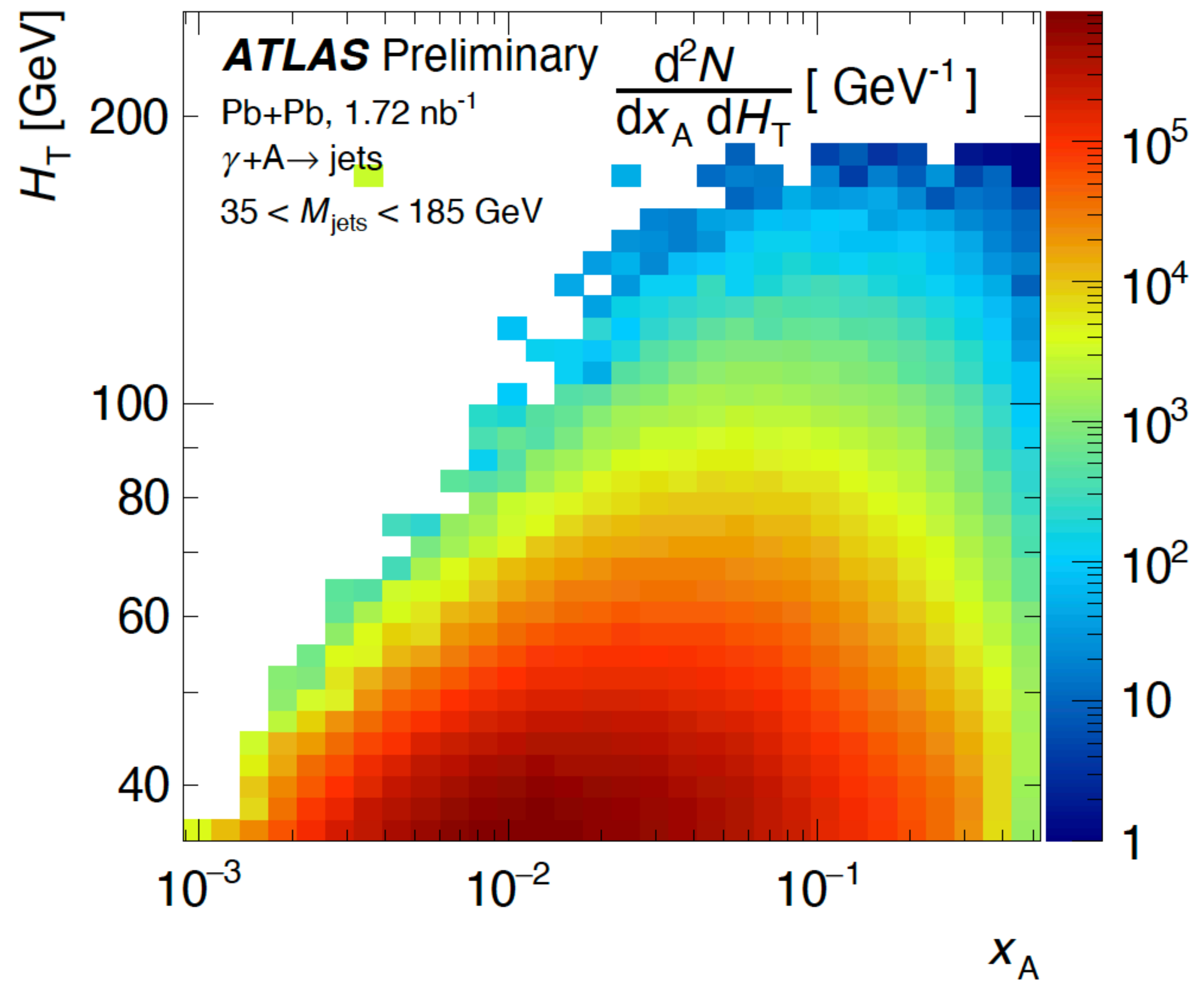
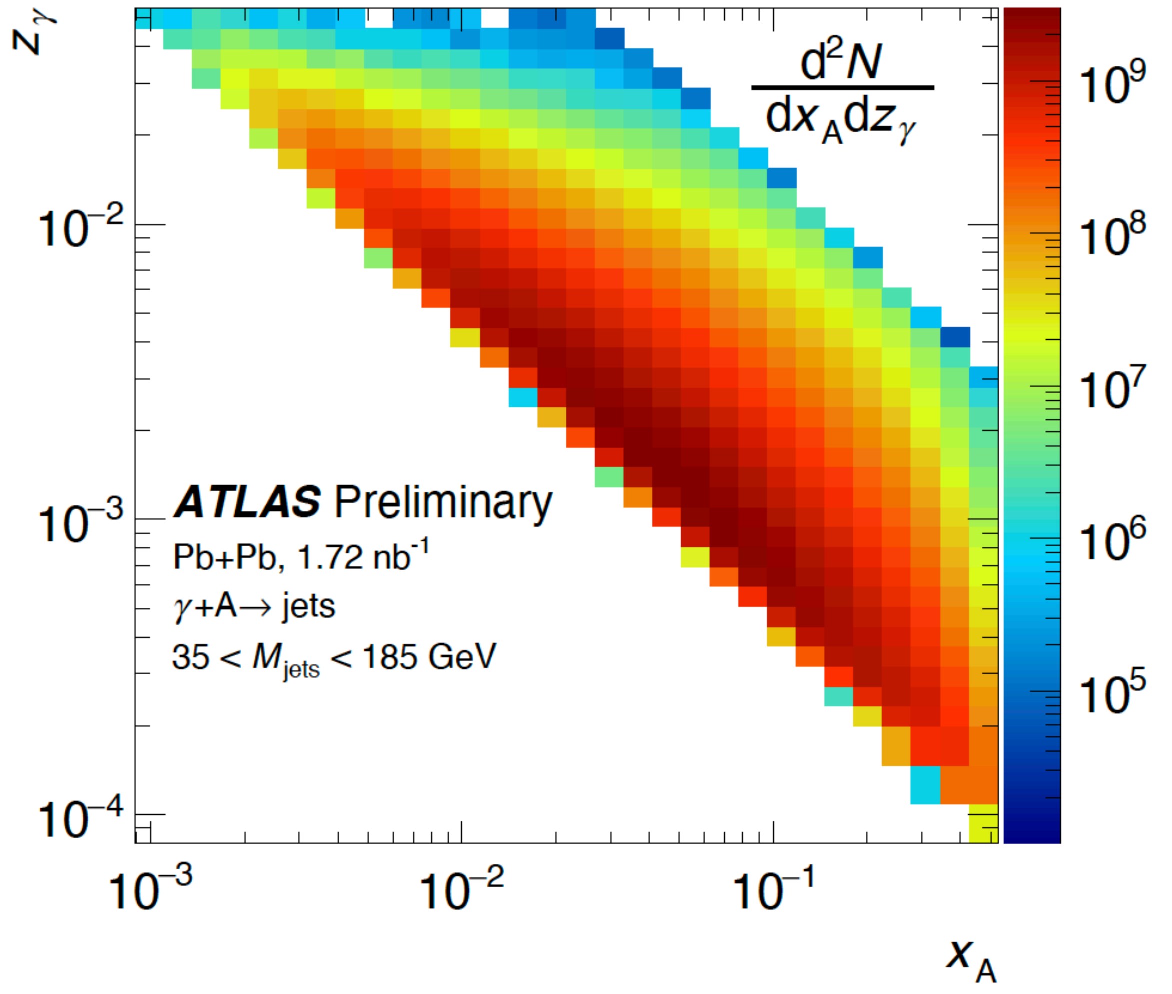
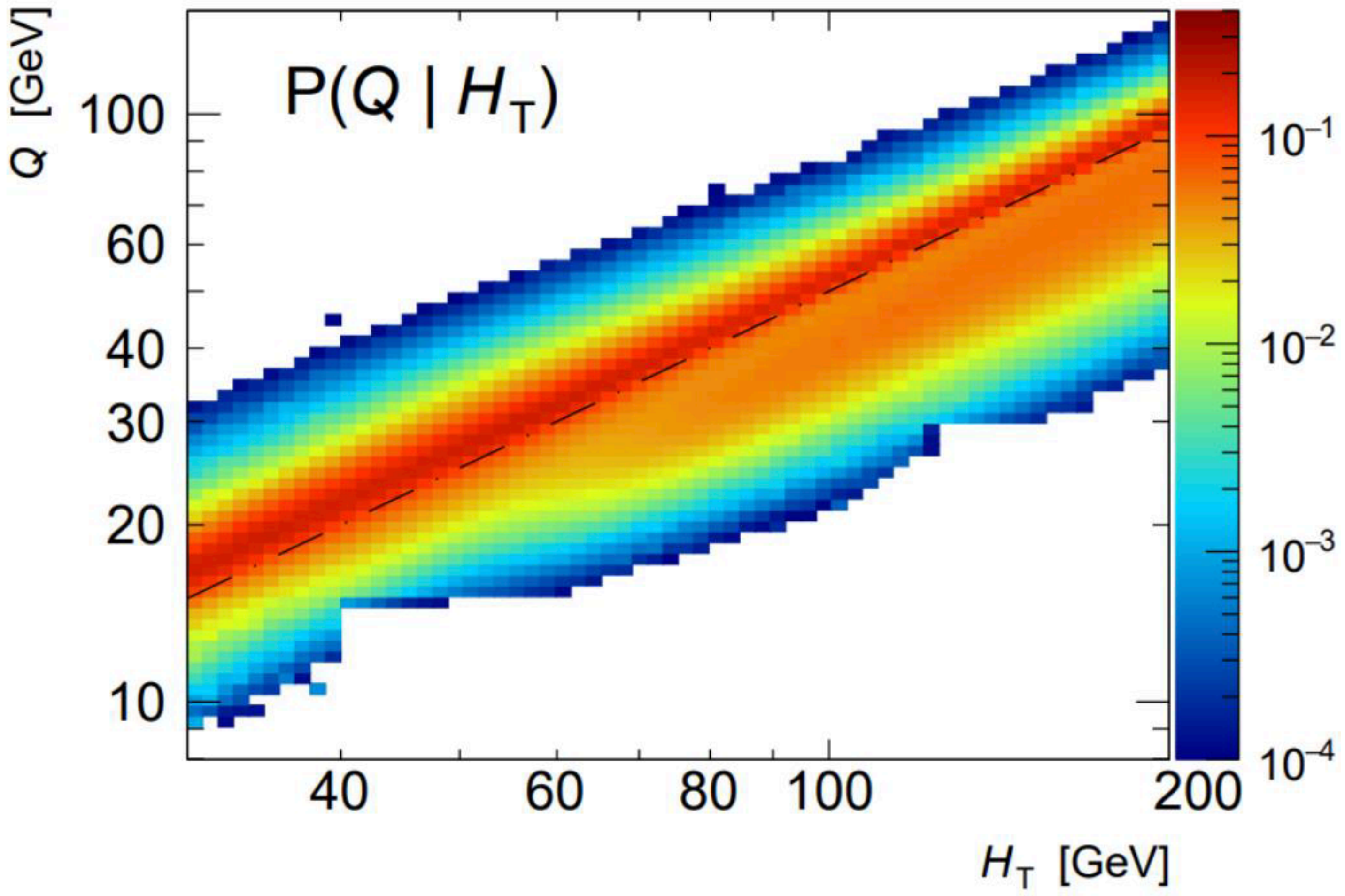
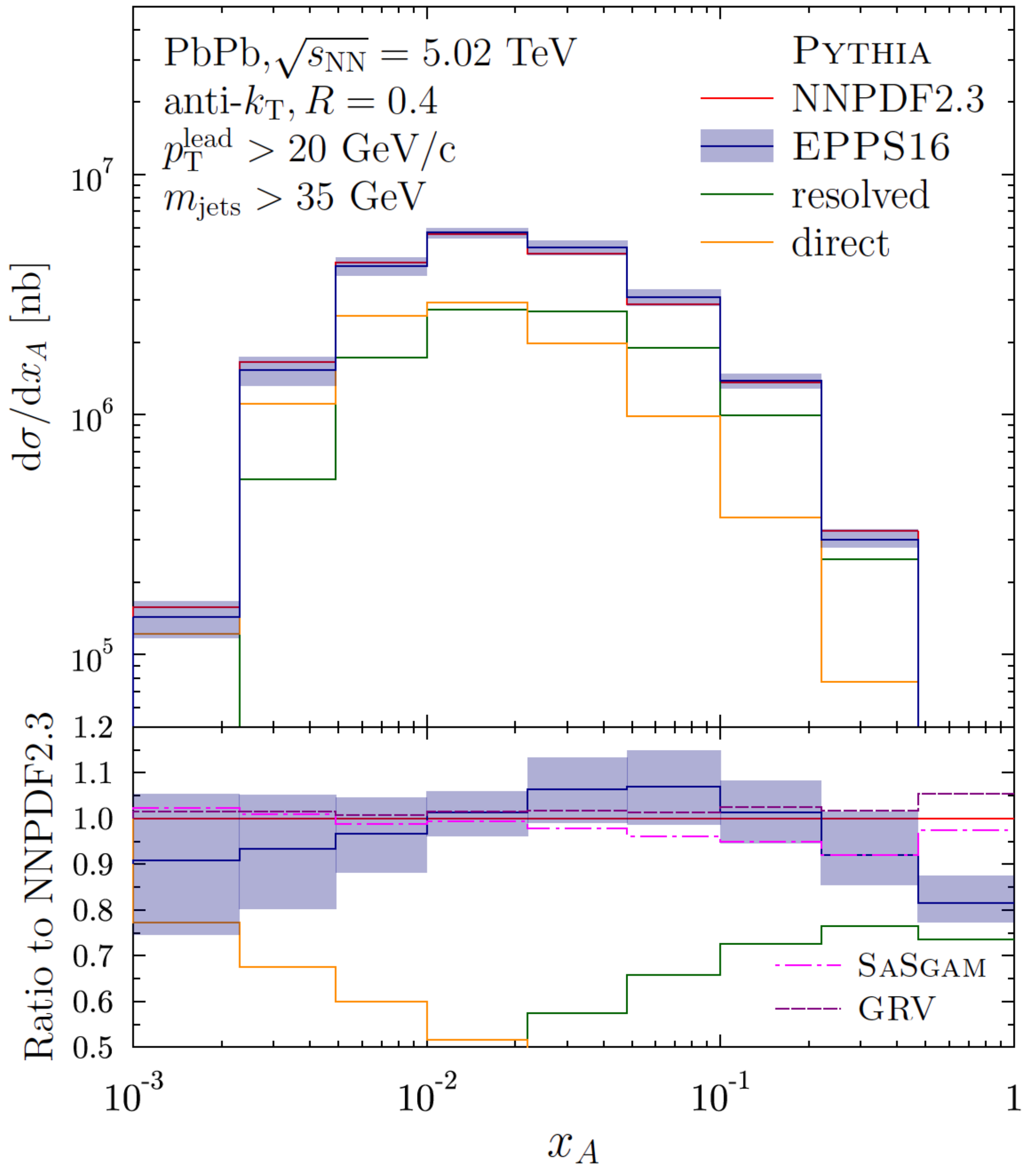




CONSTRAINING nPDFs

- nPDFs are a key ingredient for several **precision measurements**
- **Poorly constrained** at intermediate Q² and low-*x*
  - $100 < Q^2/\text{GeV}^2 < 1000$ region has very little input from data
  - Nuclear shadowing at low-x draws particular theoretical interest
- Test of sensitivity [Helenius, 2018]





Jet kinematics are proxy to hard-scattering kinematics, directly probing nuclear PDF (nPDF) effects.

$$H_T = \sum_i p_T^i$$

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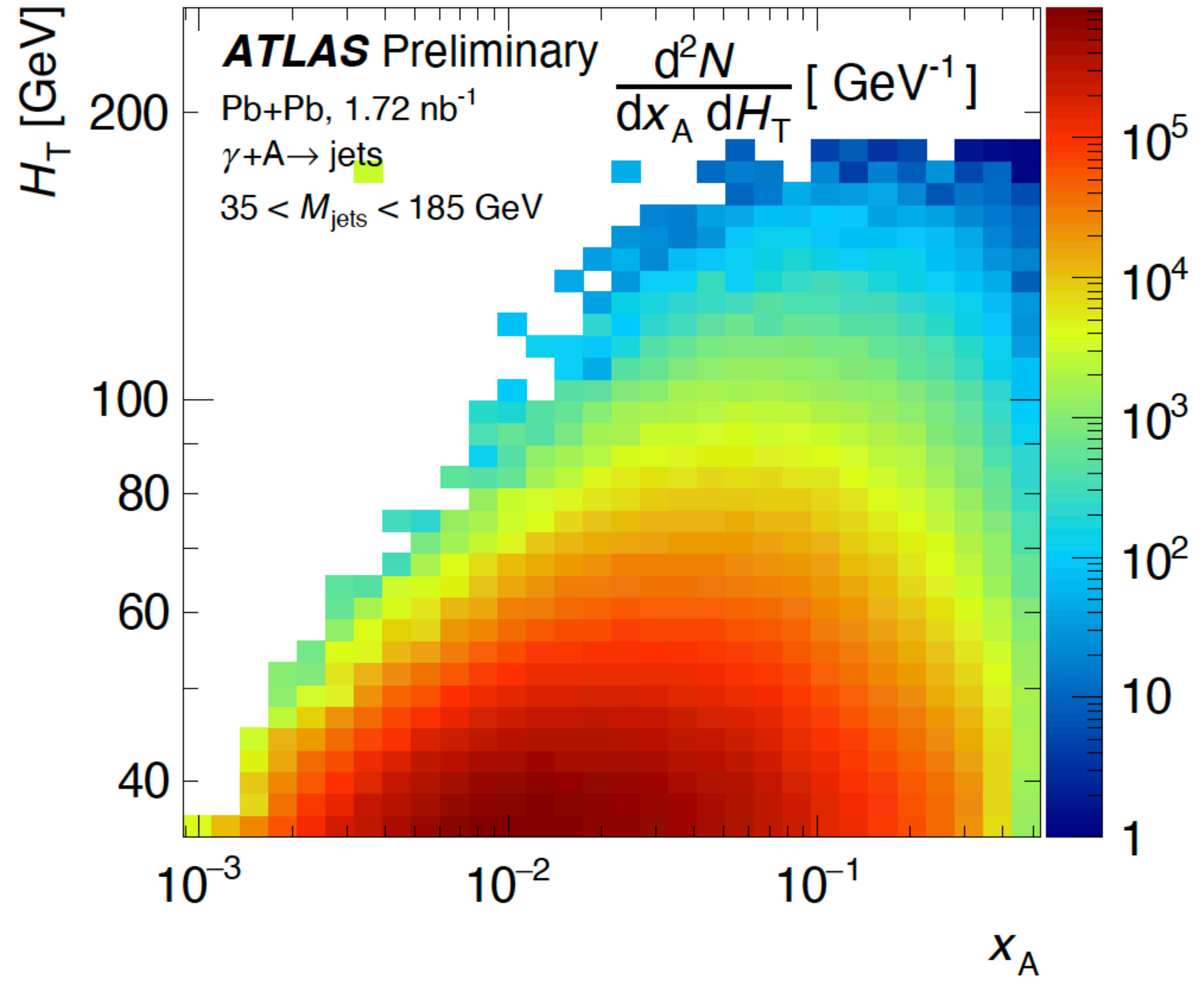

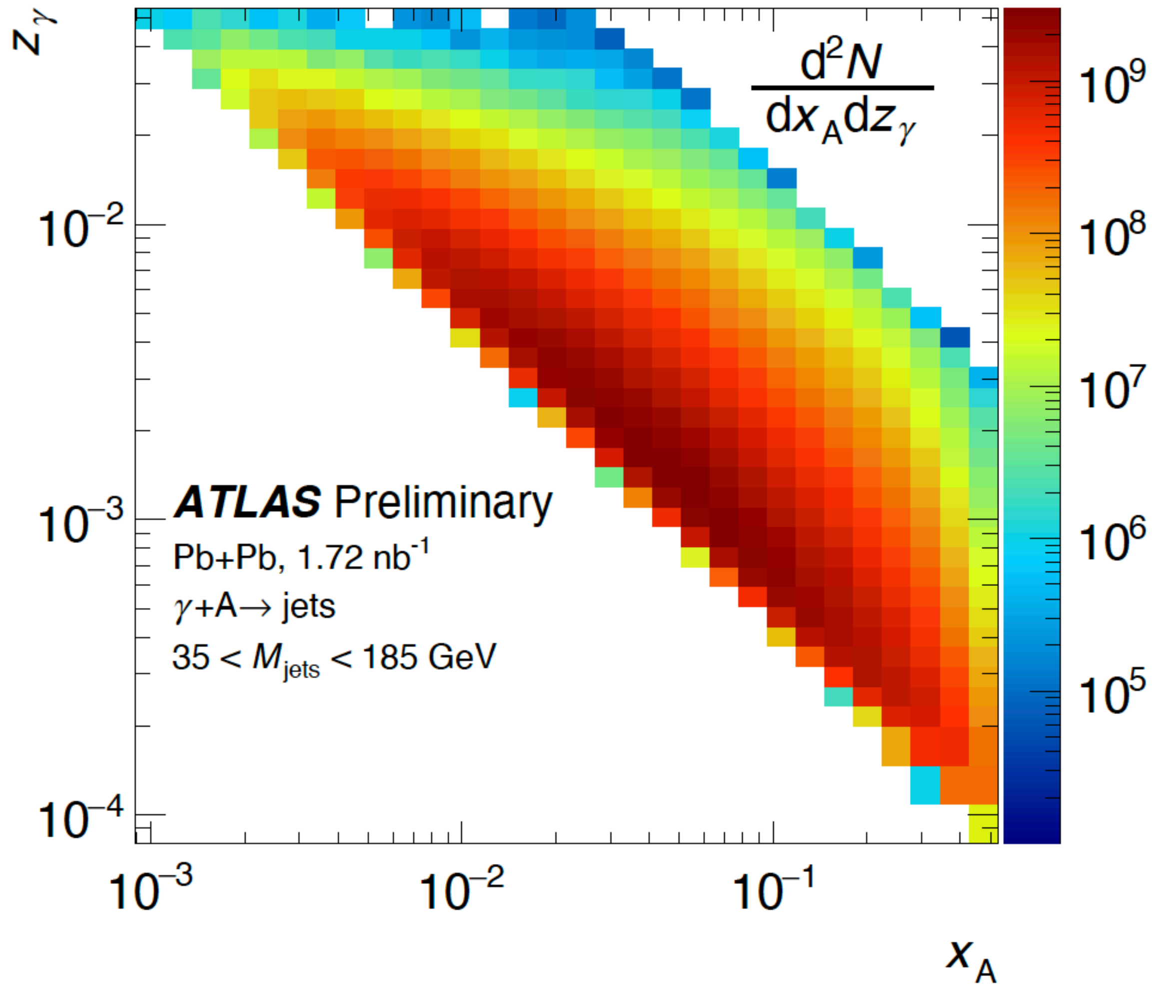

EVENT SELECTION

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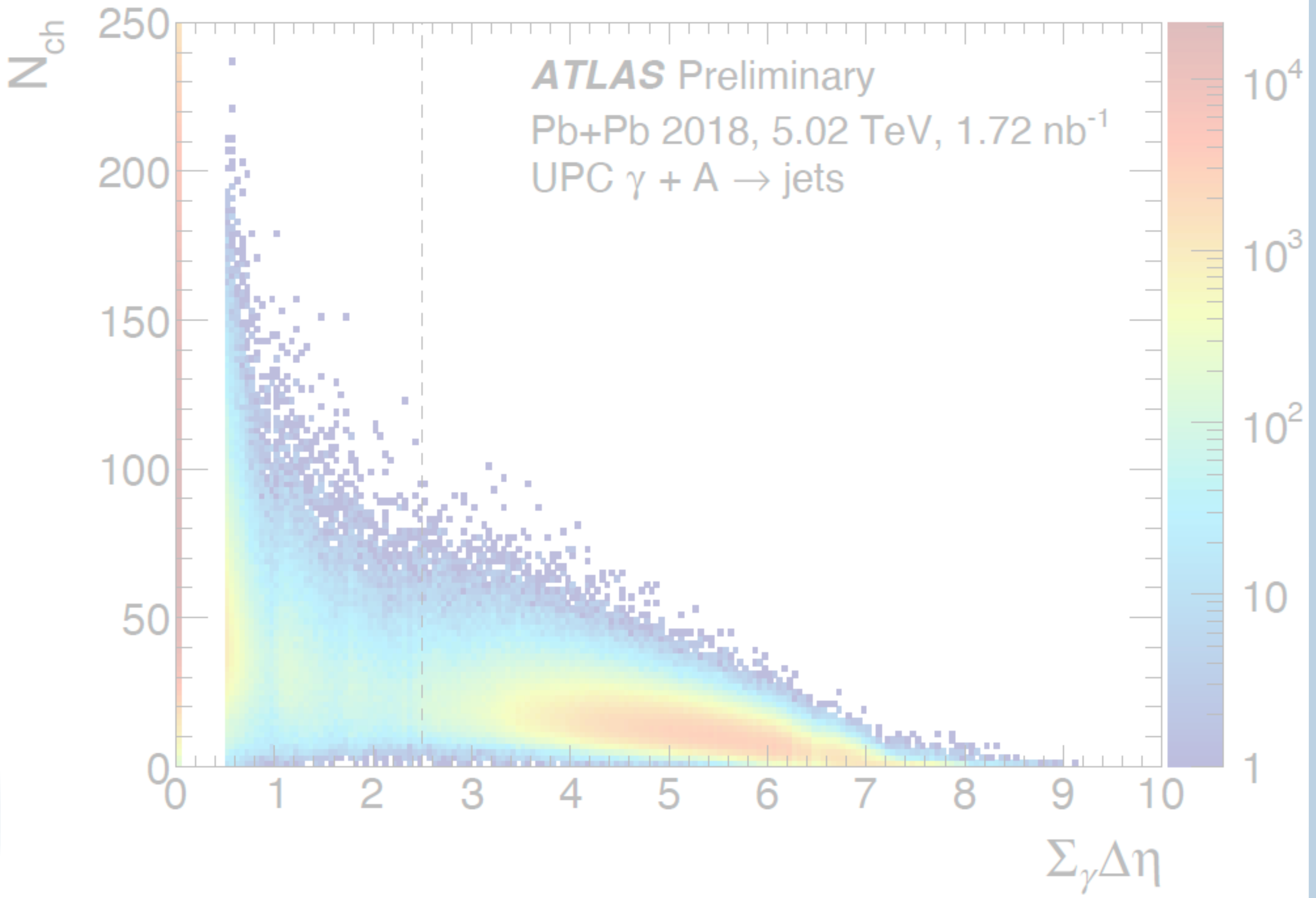
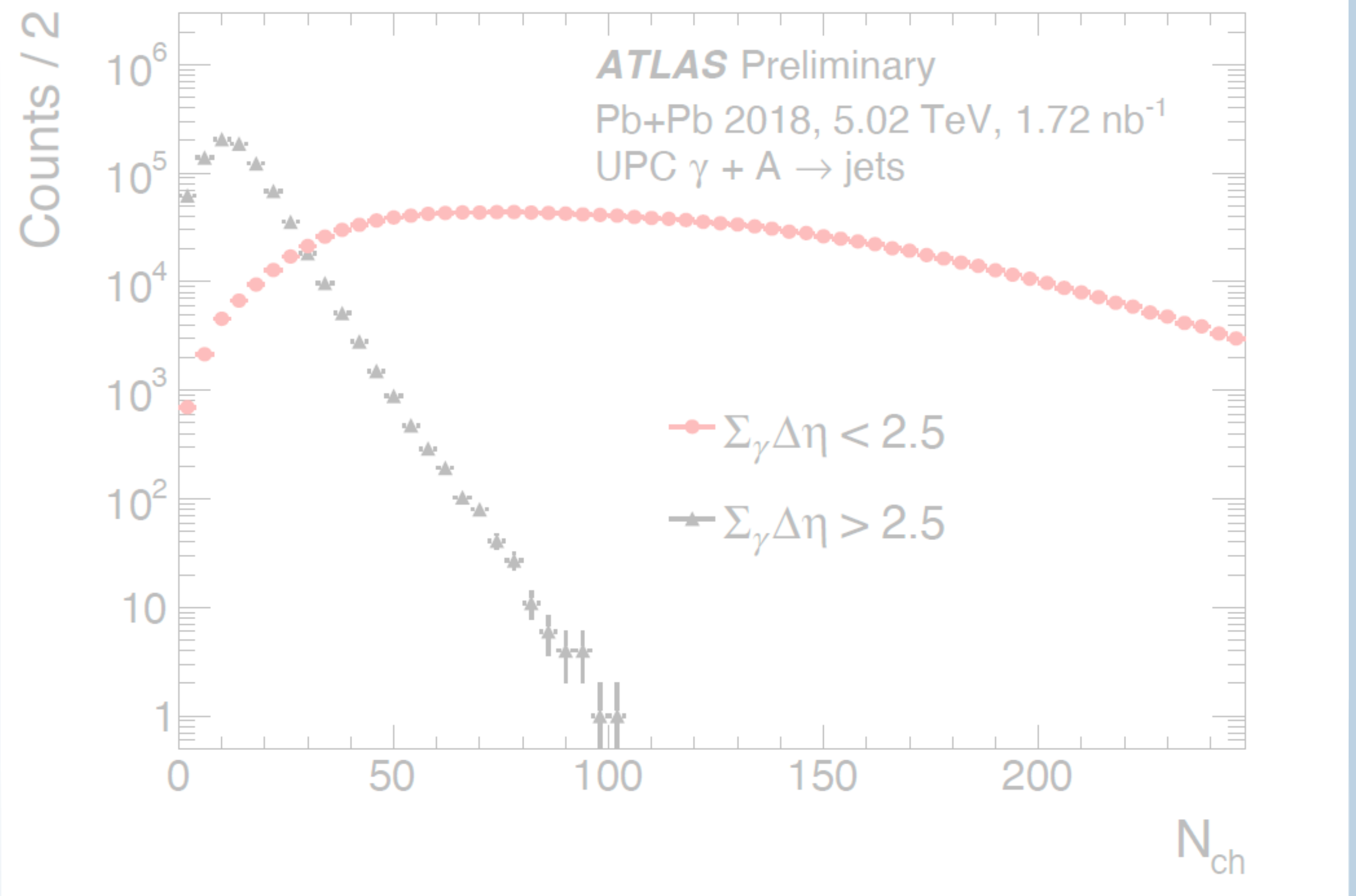
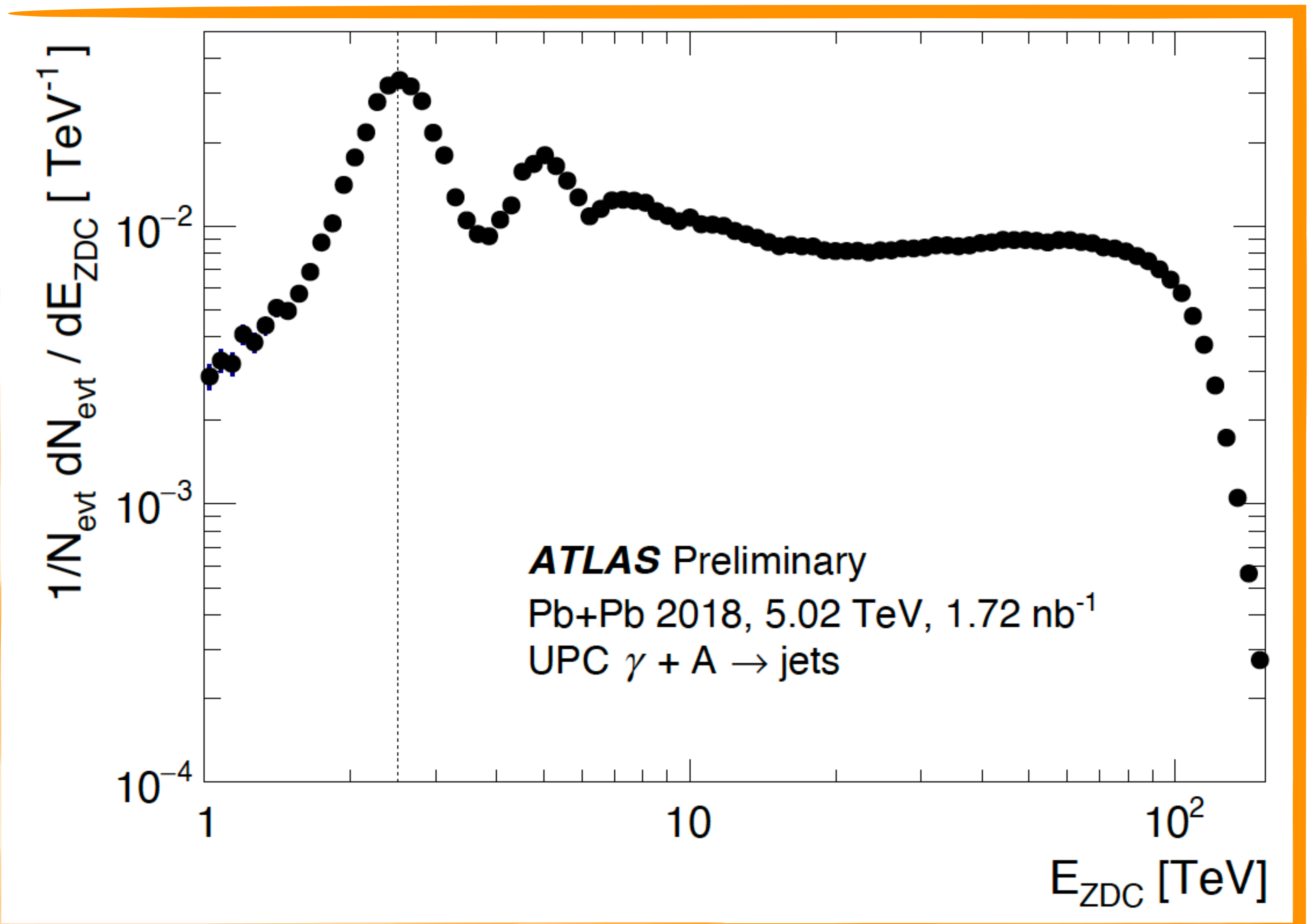




- **0nXn requirement for nuclear breakup** in exactly one ATLAS Zero-Degree Calorimeter (ZDC)
- Further cleaning from hadronic interactions, $\gamma\,\gamma$ and diffractive photo-production by applying **rapidity gap cuts**, e.g. $\sum_\gamma \Delta\eta > 2.5$ and $\Delta\eta_A < 3$
- **At least two particle-Flow jets** with $p_T > 15$ GeV to access the full kinematics of the hard-scattering



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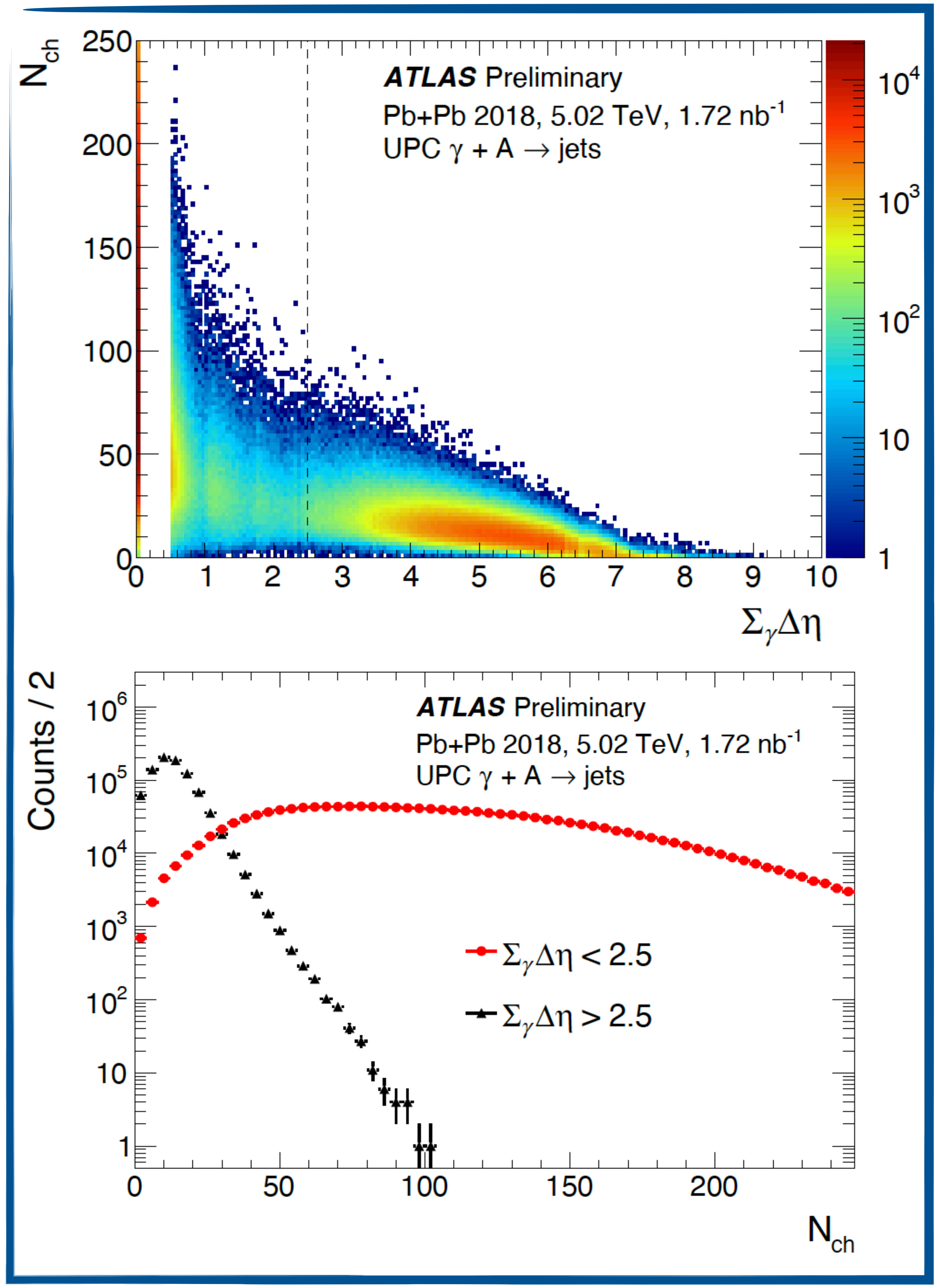

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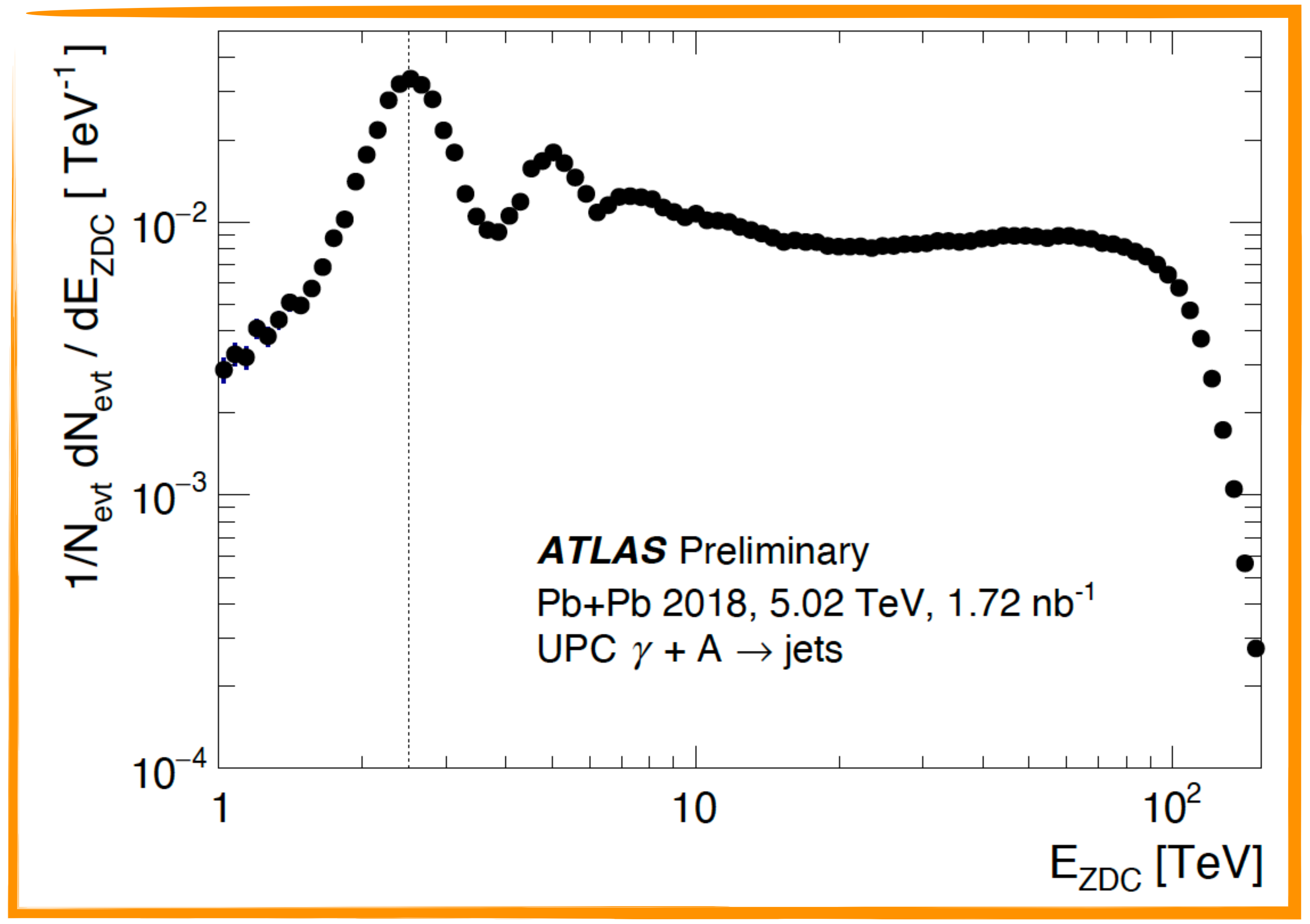

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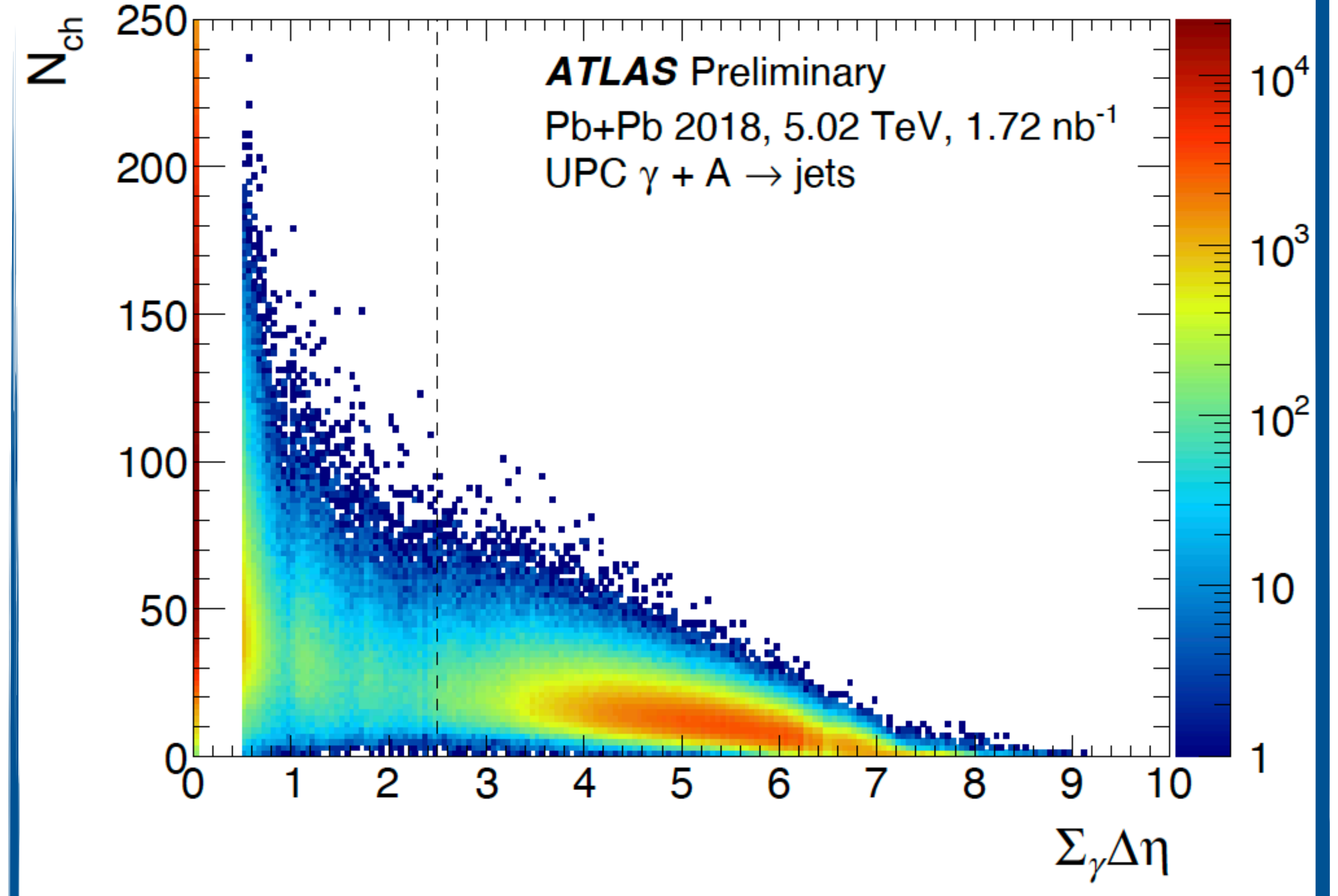

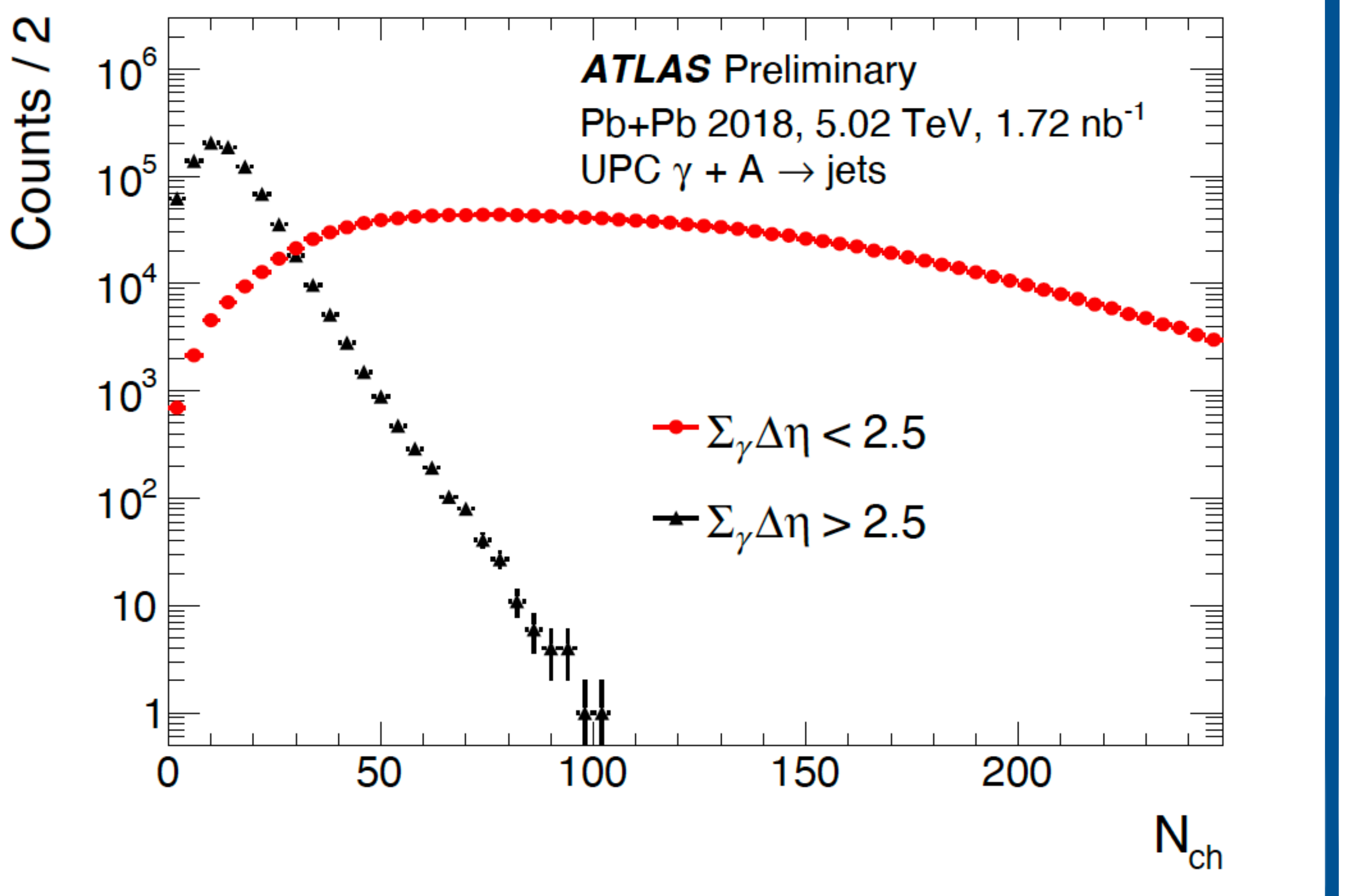

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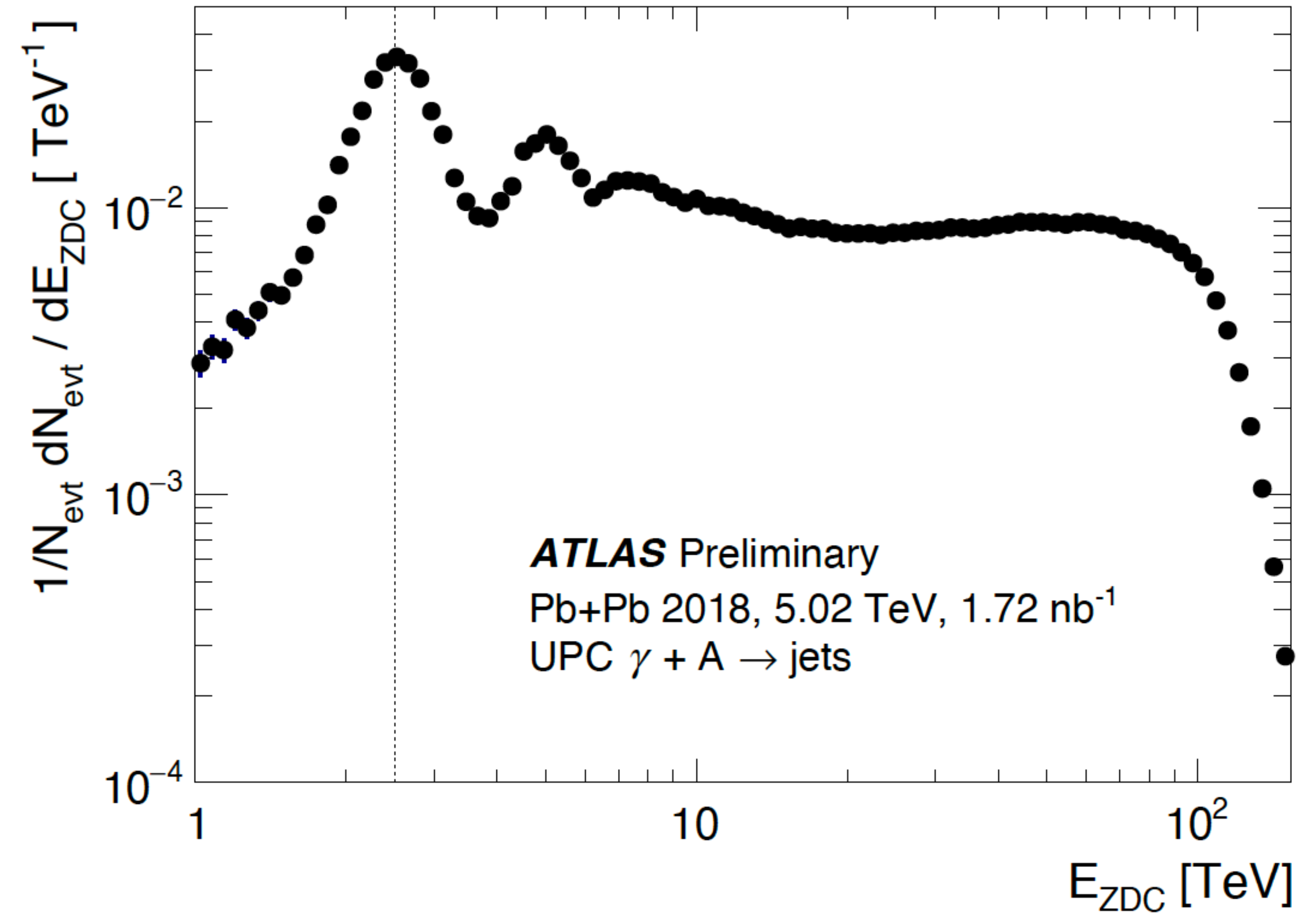

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SYSTEMATICS

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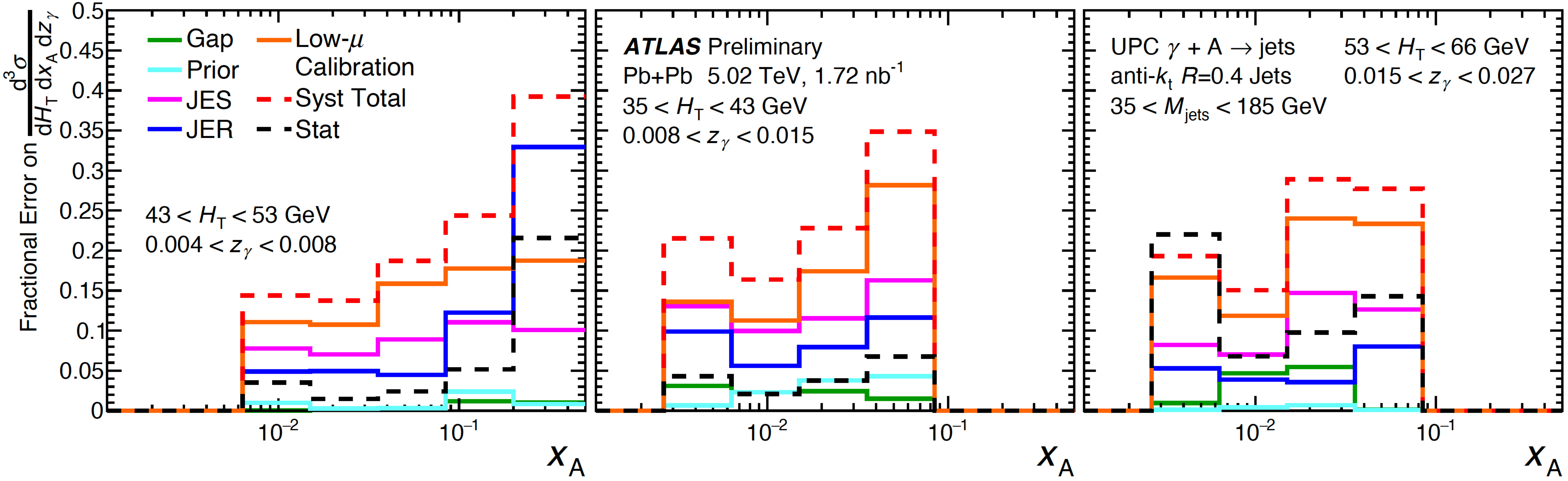

- Systematic uncertainties are the current main limiting factor in our sensitivity to nPDFs
- **Jet Energy Scale** and **Jet Energy Resolution** ~ 5-10%
- **Control over the low-μ calibration** is currently the dominant source of uncertainty
- Additional systematic uncertainties are assigned for the **unfolding procedure** and **event selection**

RESULTS: PHOTON FLUX

$$H_{\mathrm{T}} = \sum_i p_{\mathrm{T}}^i, \quad x_{\mathrm{A}} = \frac{M_{\mathrm{jets}} e^{-y_{\mathrm{jets}}}}{\sqrt{S_{\mathrm{NN}}}}, \quad z_\gamma = \frac{M_{\mathrm{jets}} e^{+y_{\mathrm{jets}}}}{\sqrt{S_{\mathrm{NN}}}}$$

- The measured cross-sections are **unfolded in 3 dimensions** to correct for detector effects
- z_γ dependence of the cross-section over a narrow x_A interval (0.015-0.2) should be primarily determined by the photon flux
- These results provide input to constrain theoretical models of both photon flux and breakup probability for the photon-emitting nucleus
  - The breakup model performs well within systematic uncertainties
  - Disagreements appear to arise at low z_γ, where the model seems to overcorrect

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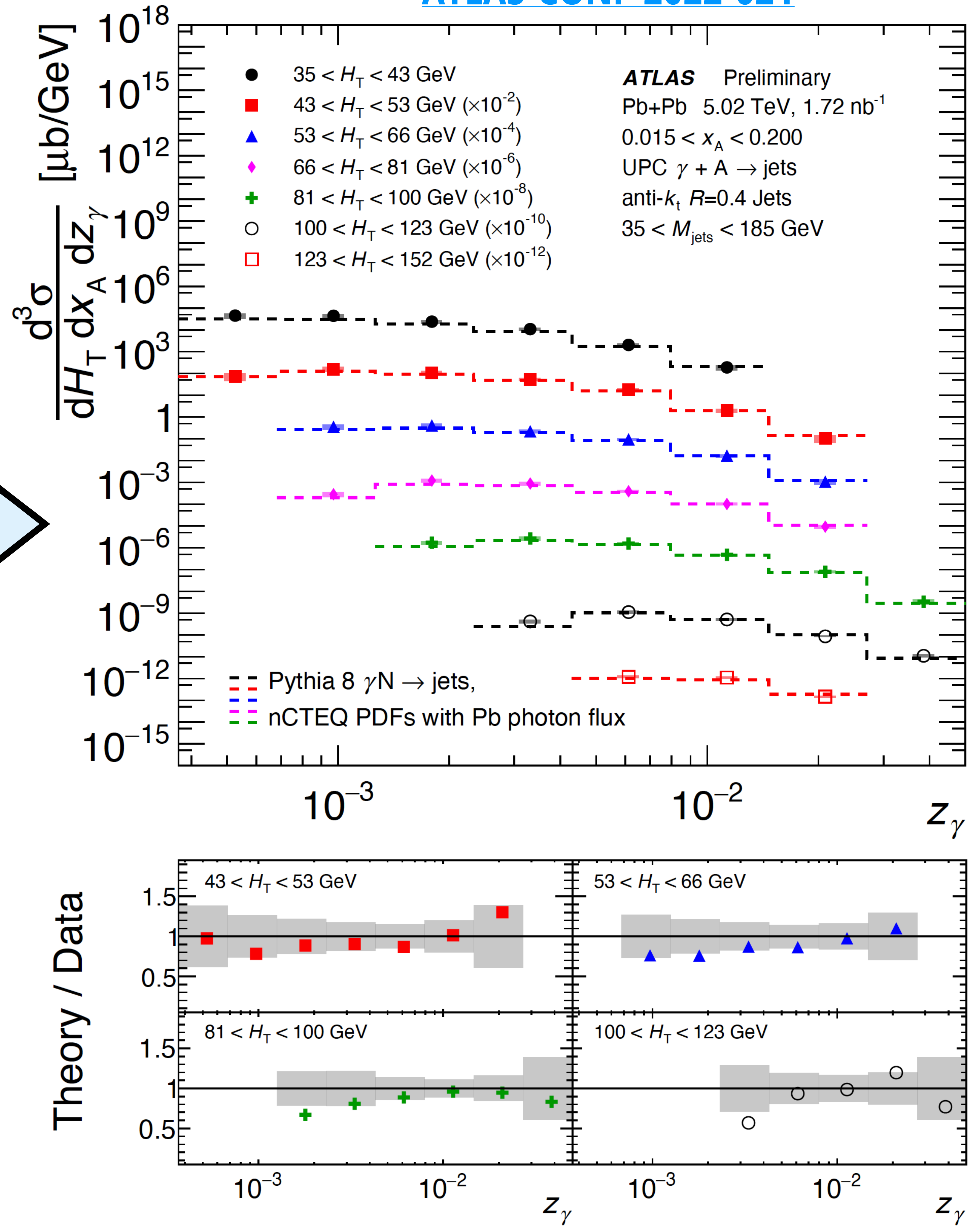
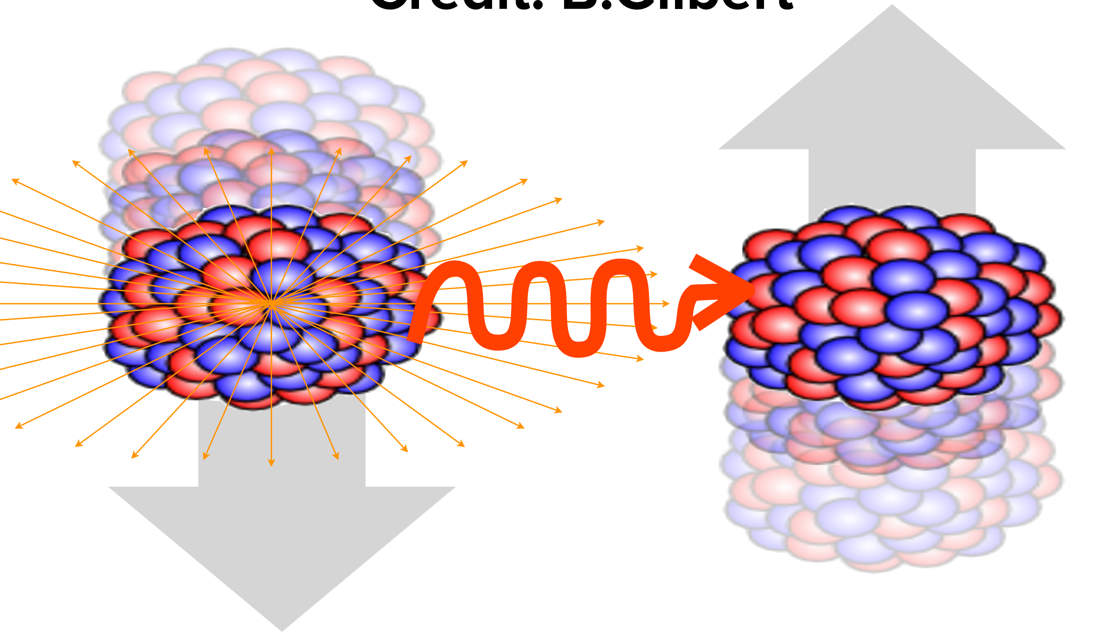


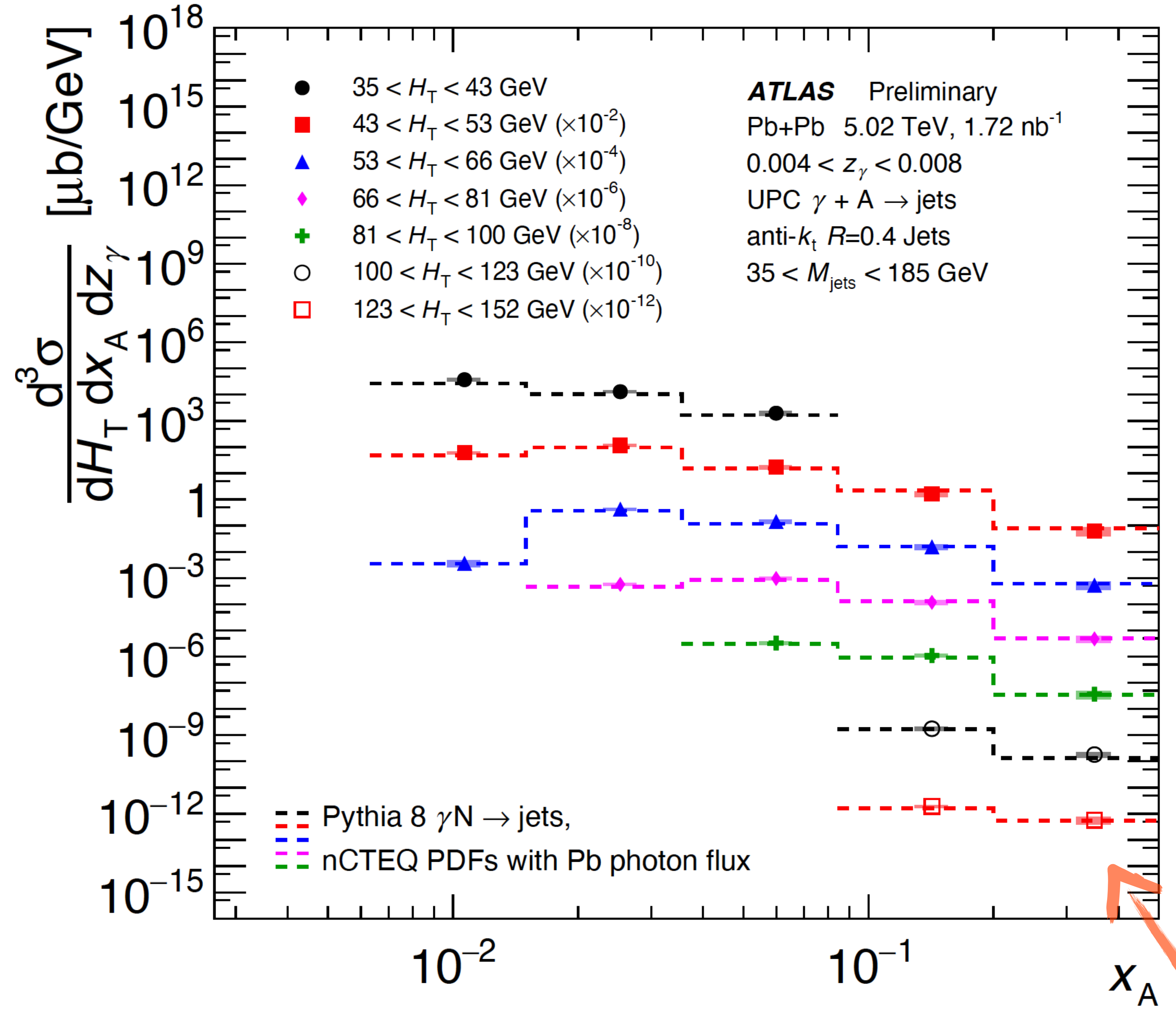
RESULTS: SCAN IN PHOTON ENERGY

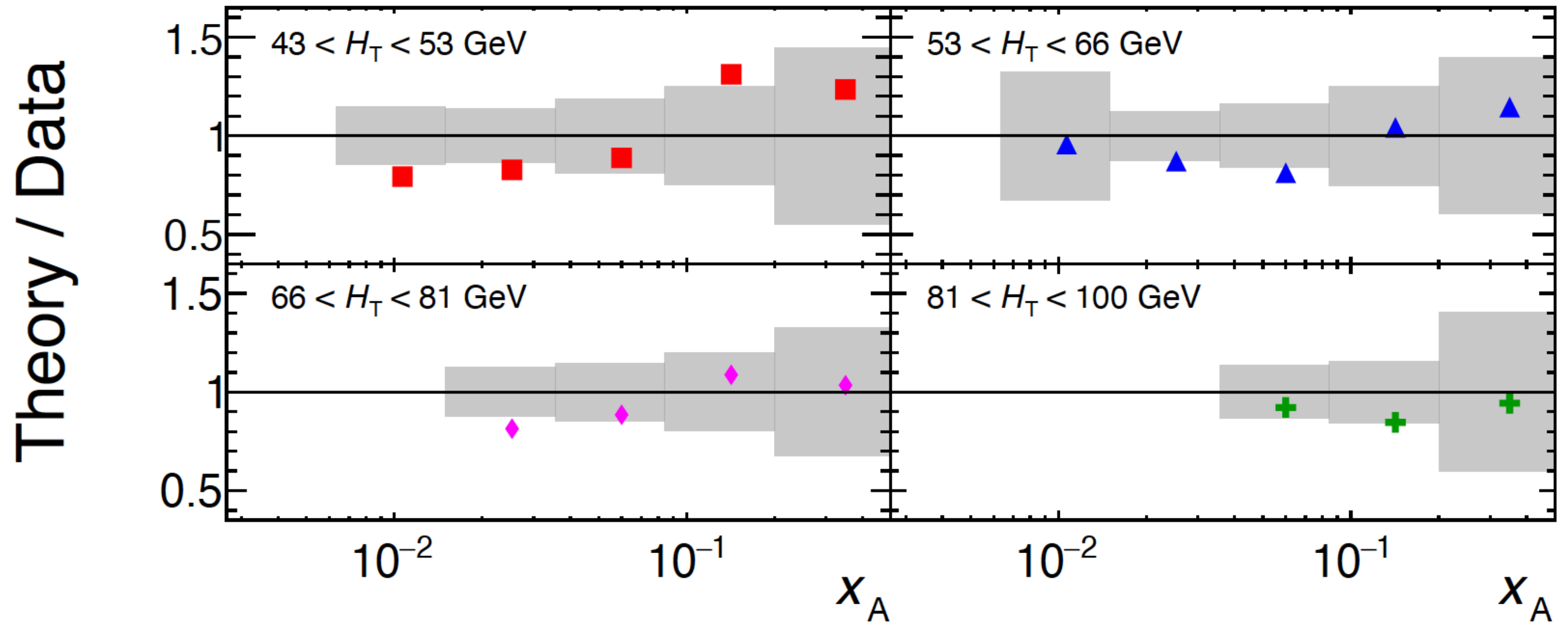
Credit: B.Gilbert

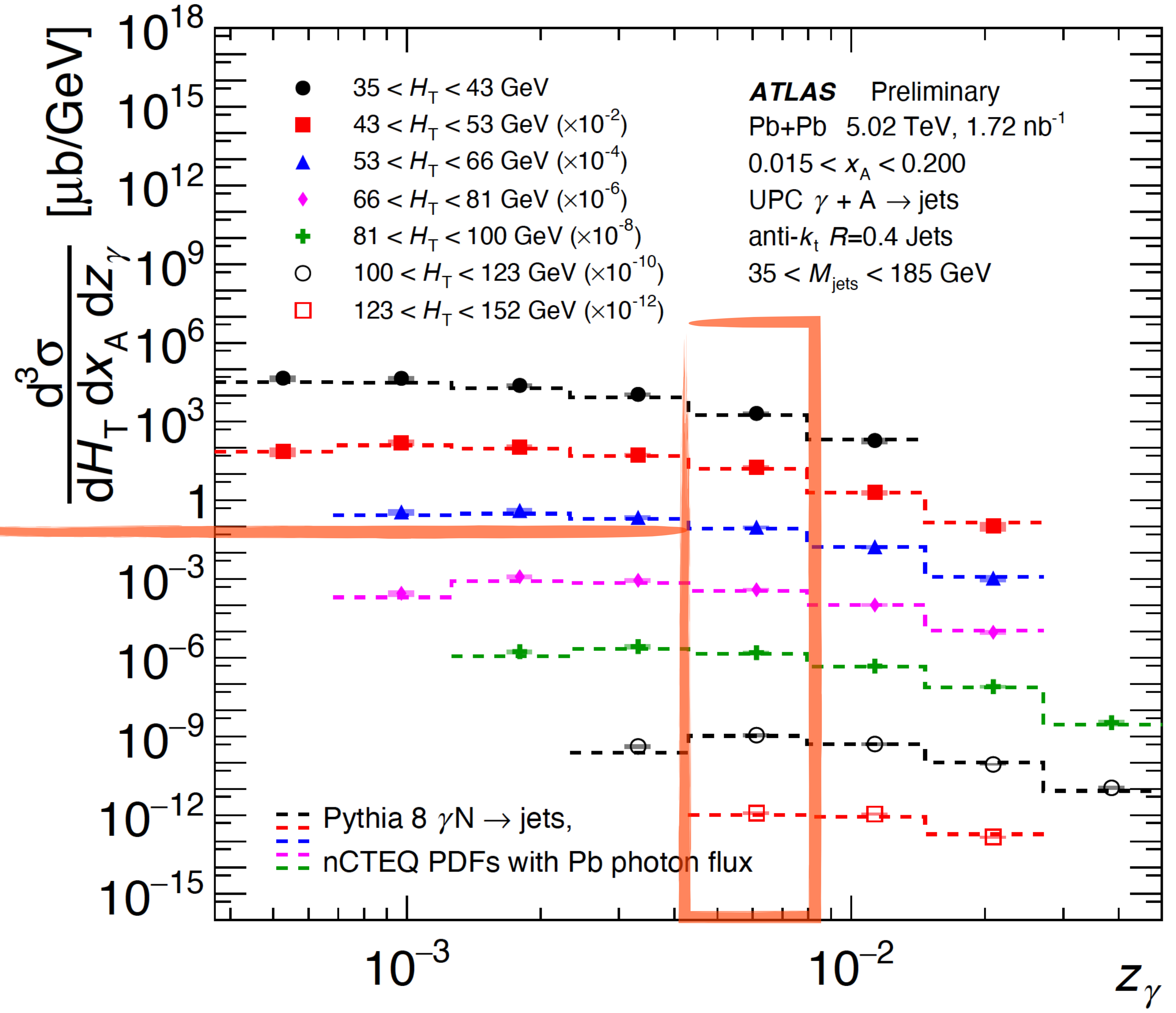


$0.004 < z_\gamma < 0.008$

- Scanning results in terms of the photon energy allows one to resolve different partonic kinematic regimes
- Provides new input to constrain nPDFs







Intermediate photon energies provide access to higher-x parton in the nucleus

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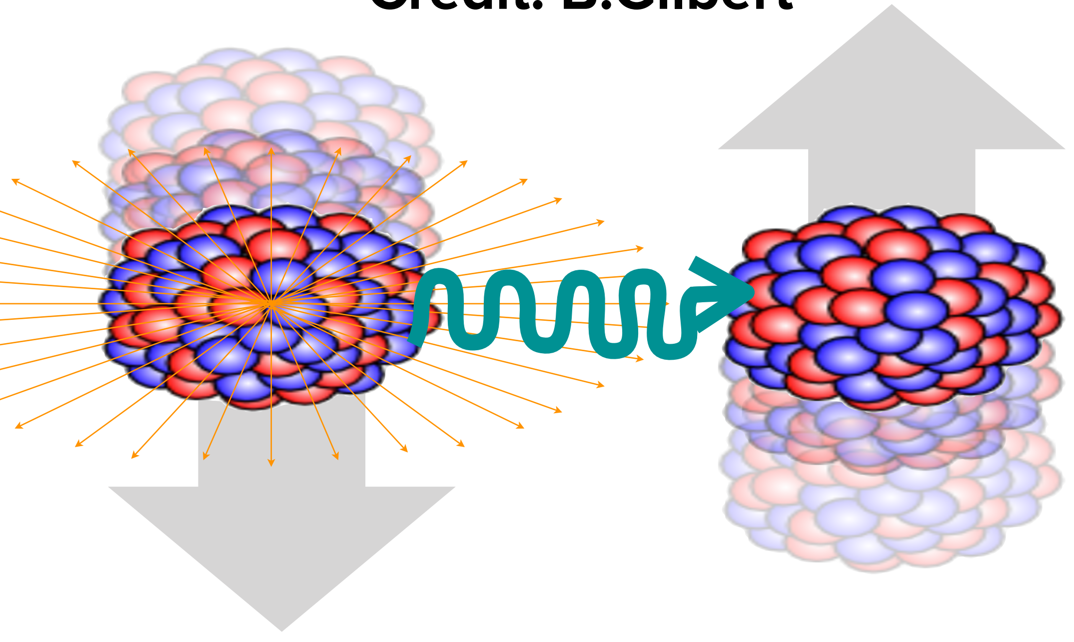
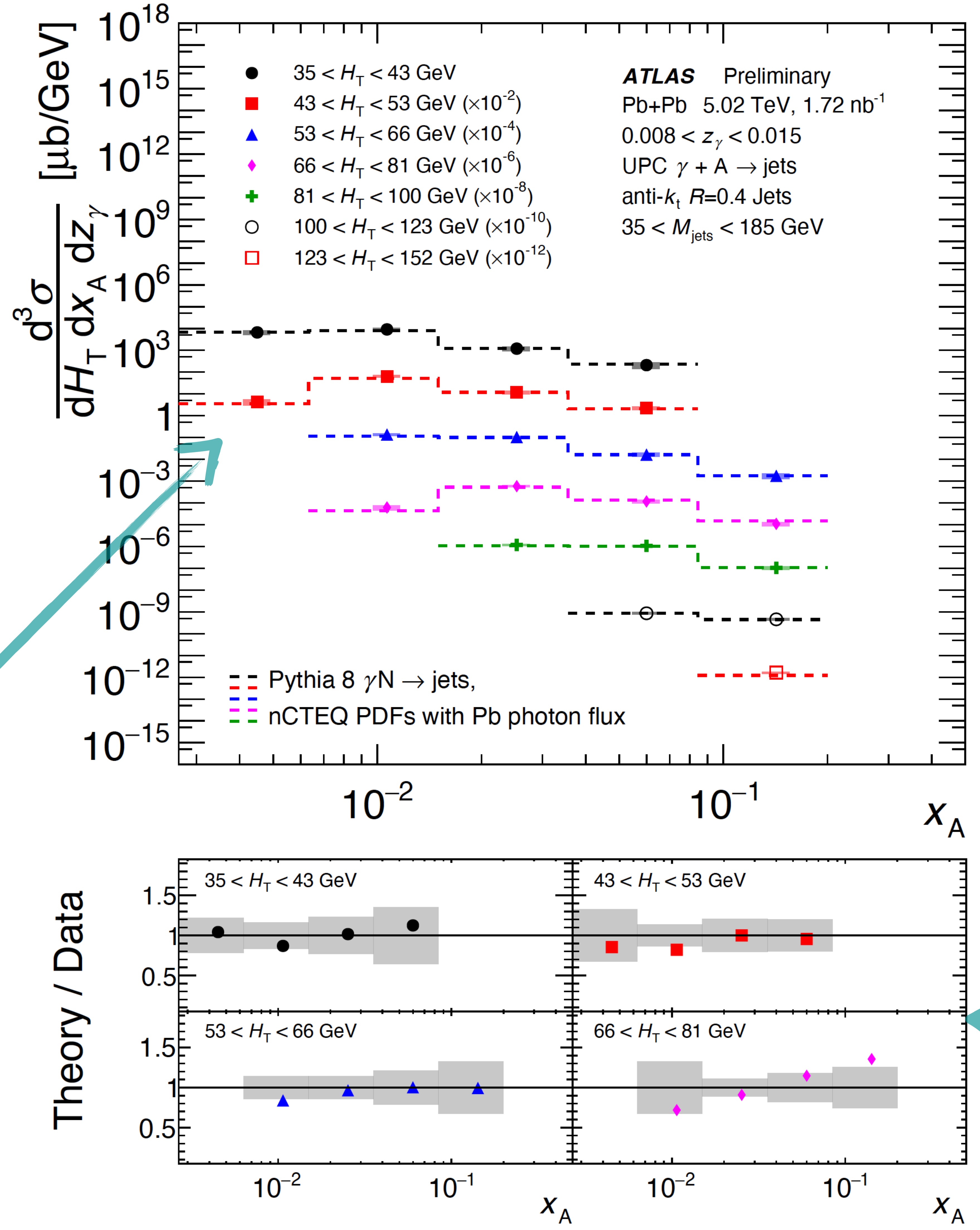
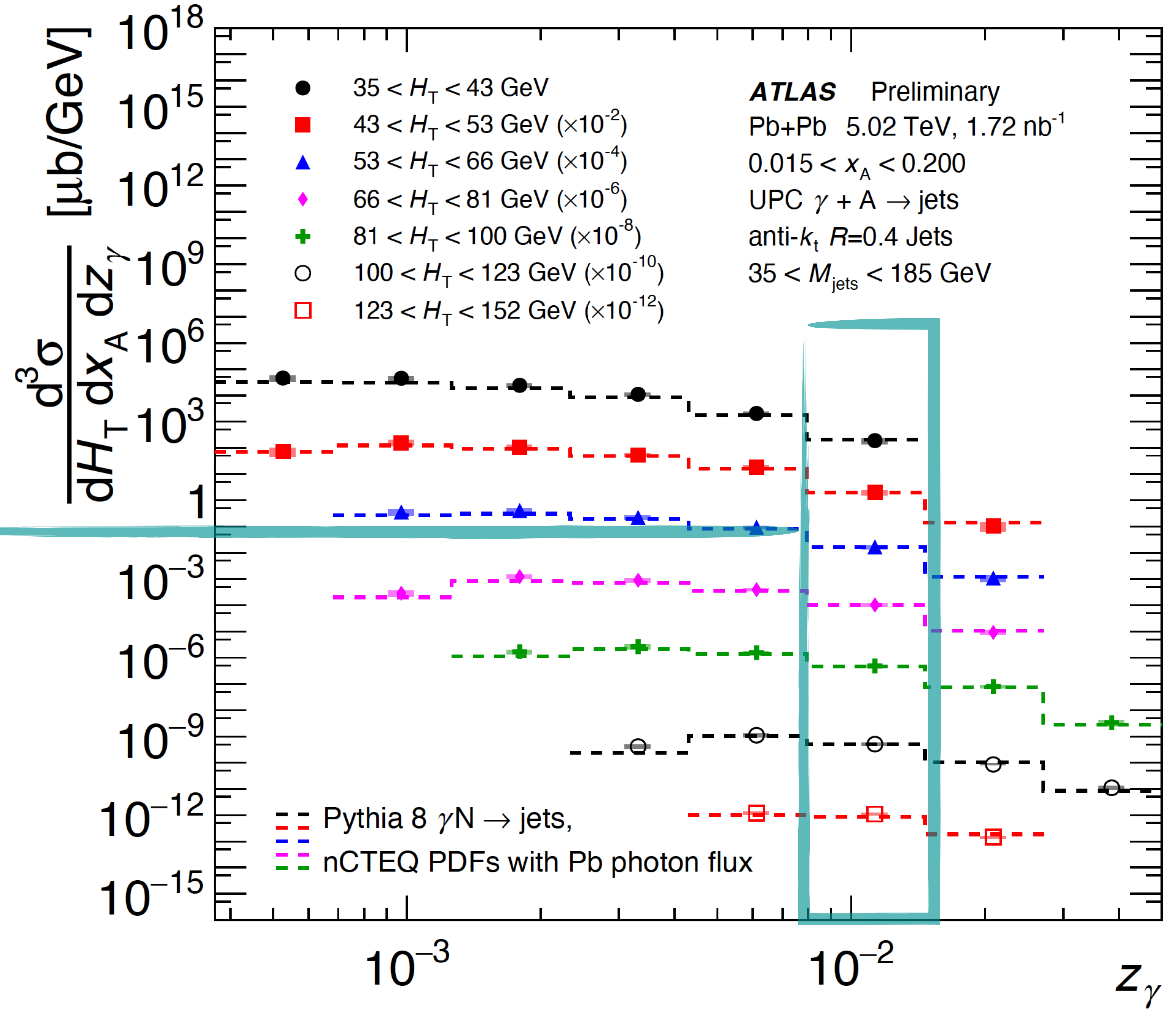


0.008 < z_γ < 0.015



Increasing the photon energy enhances the resolution power and probes the low-x shadowing region



Results show quite good consistency with theoretical model

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RESULTS: SCAN IN PHOTON ENERGY

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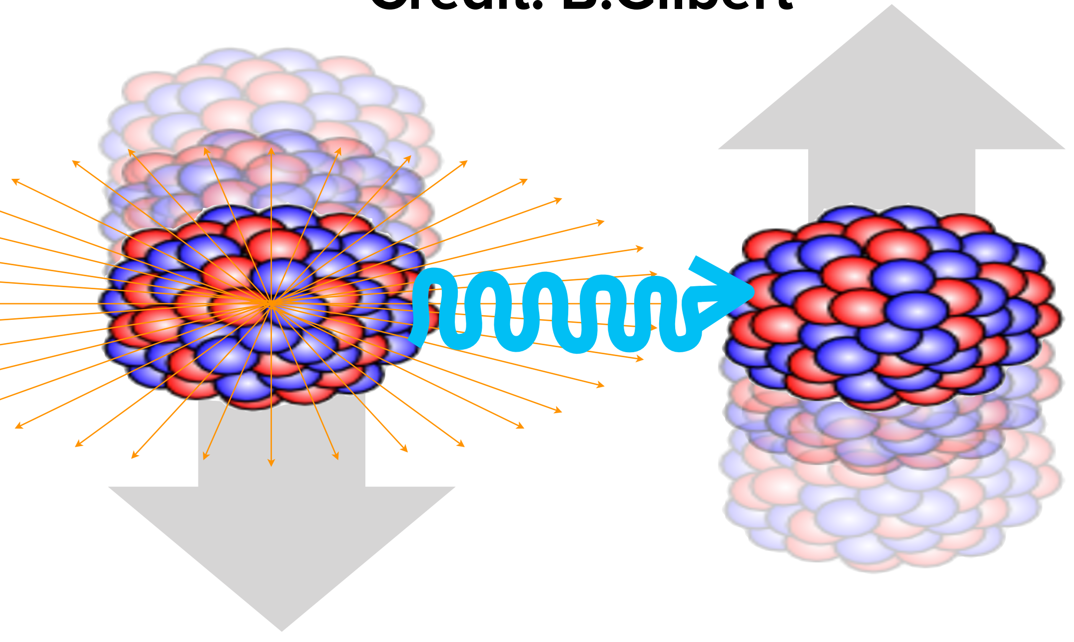
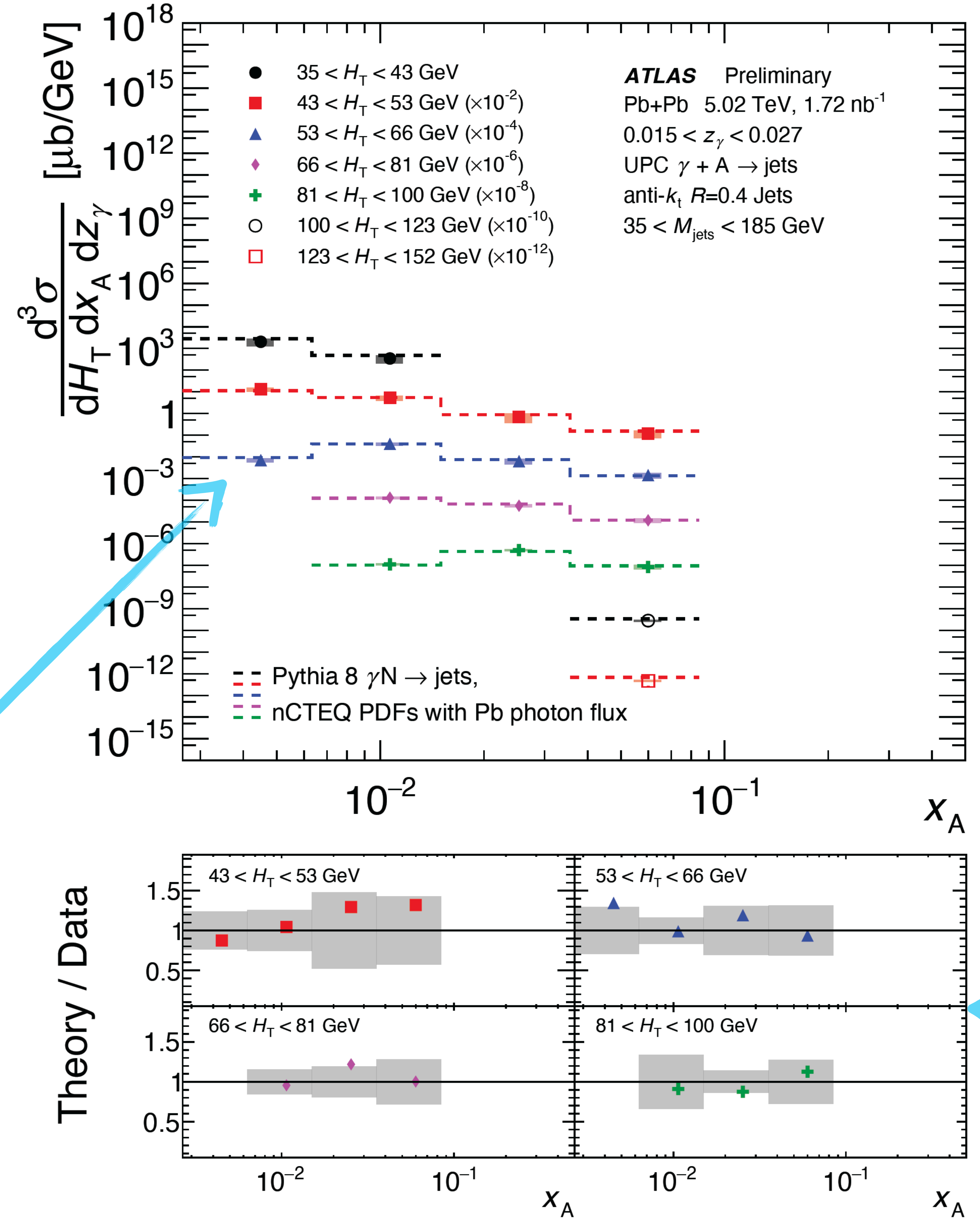
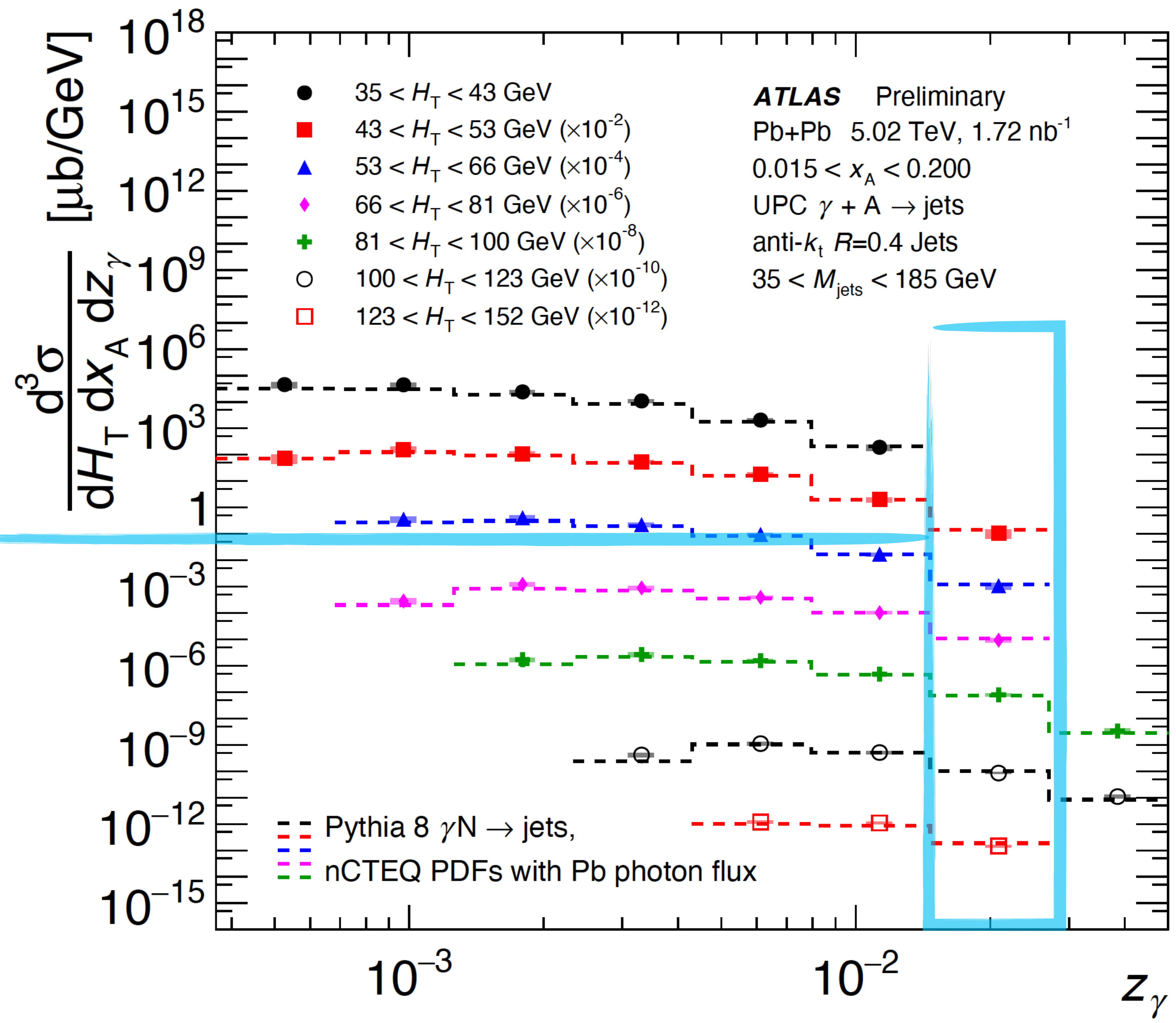


$0.015 < z_\gamma < 0.027$





Highest photon energies allow for exploration of the lowest x region ($\sim 10^{-3}$)

Systematic control more challenging when approaching acceptance edges

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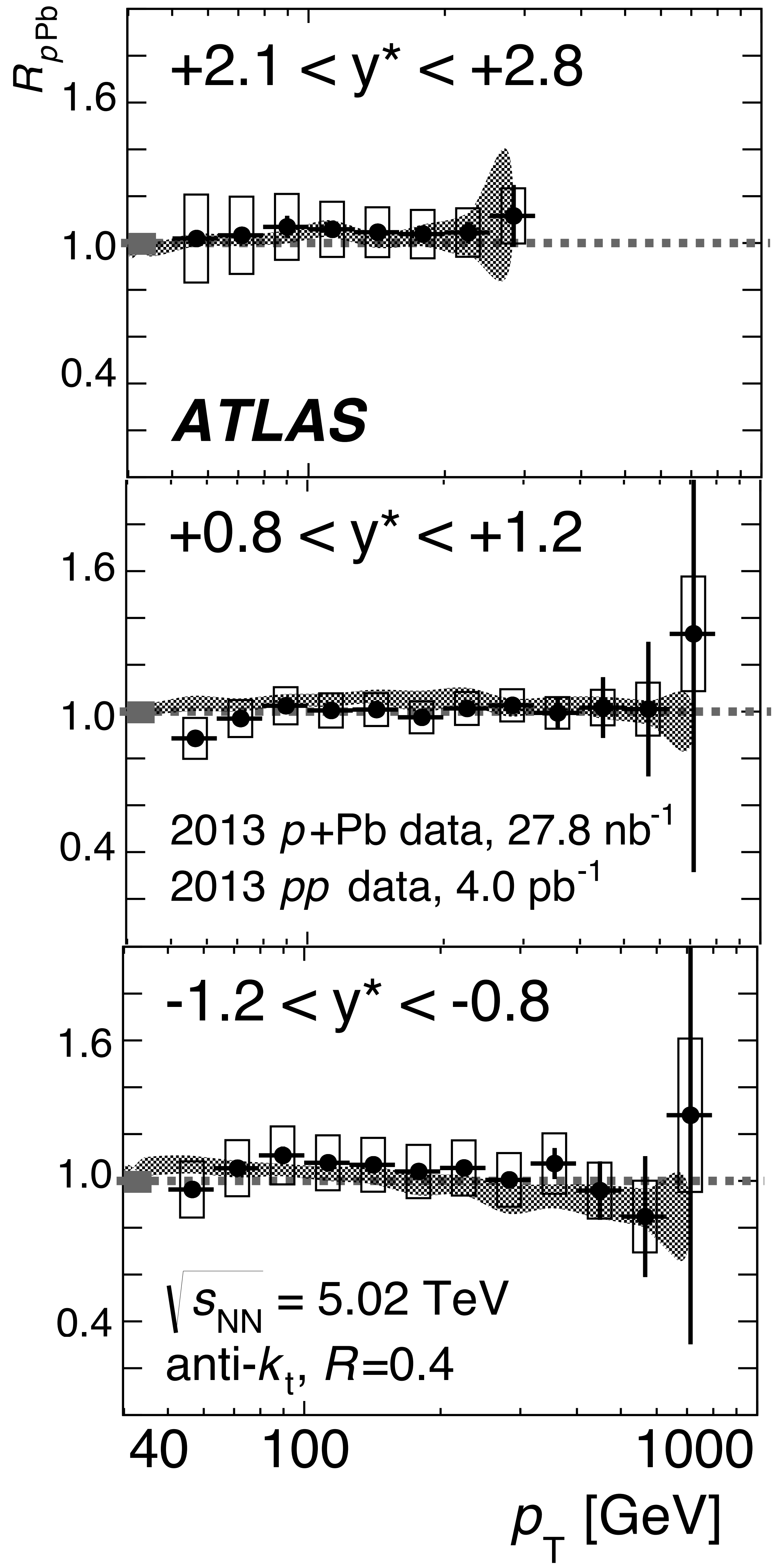
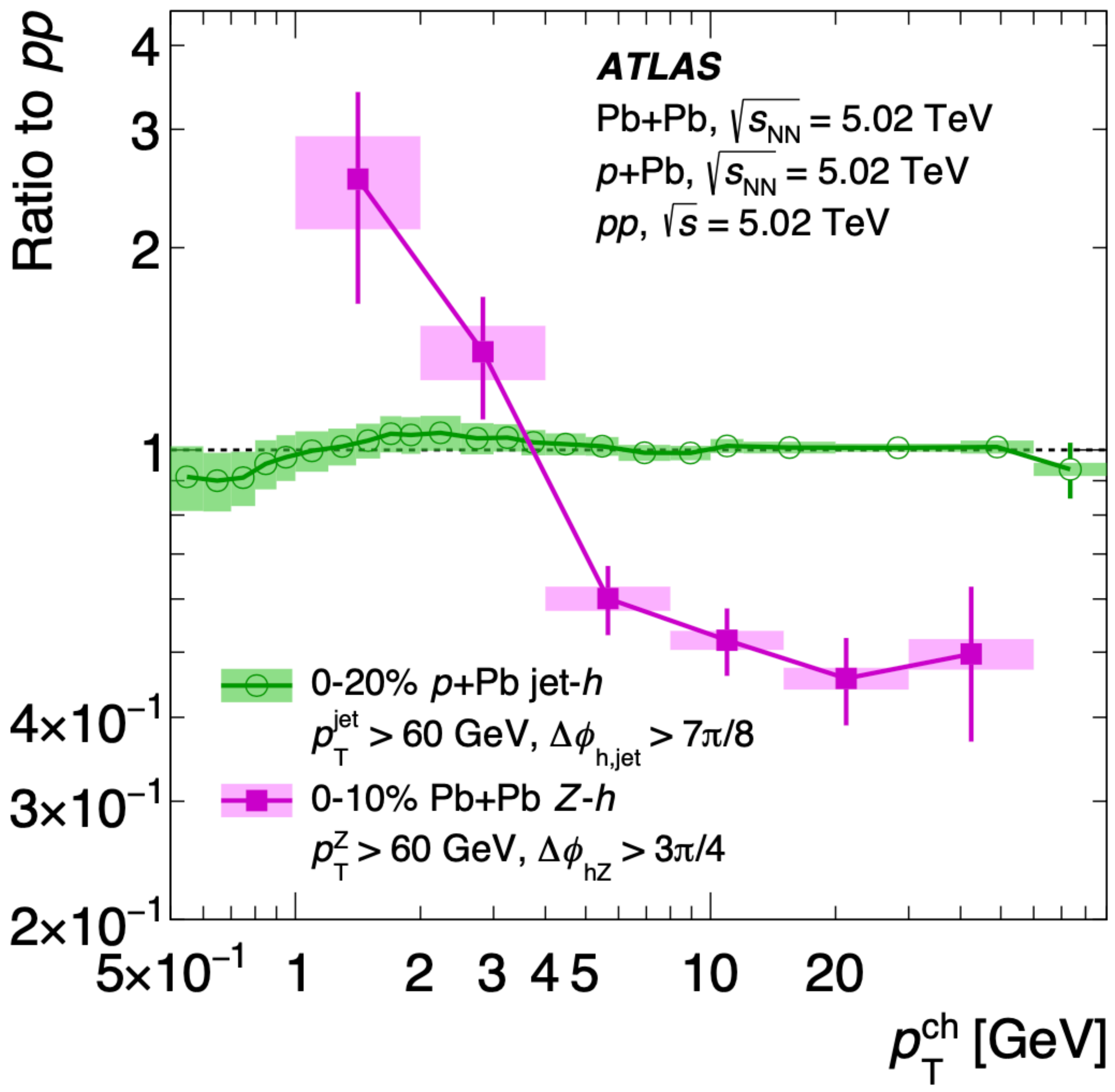
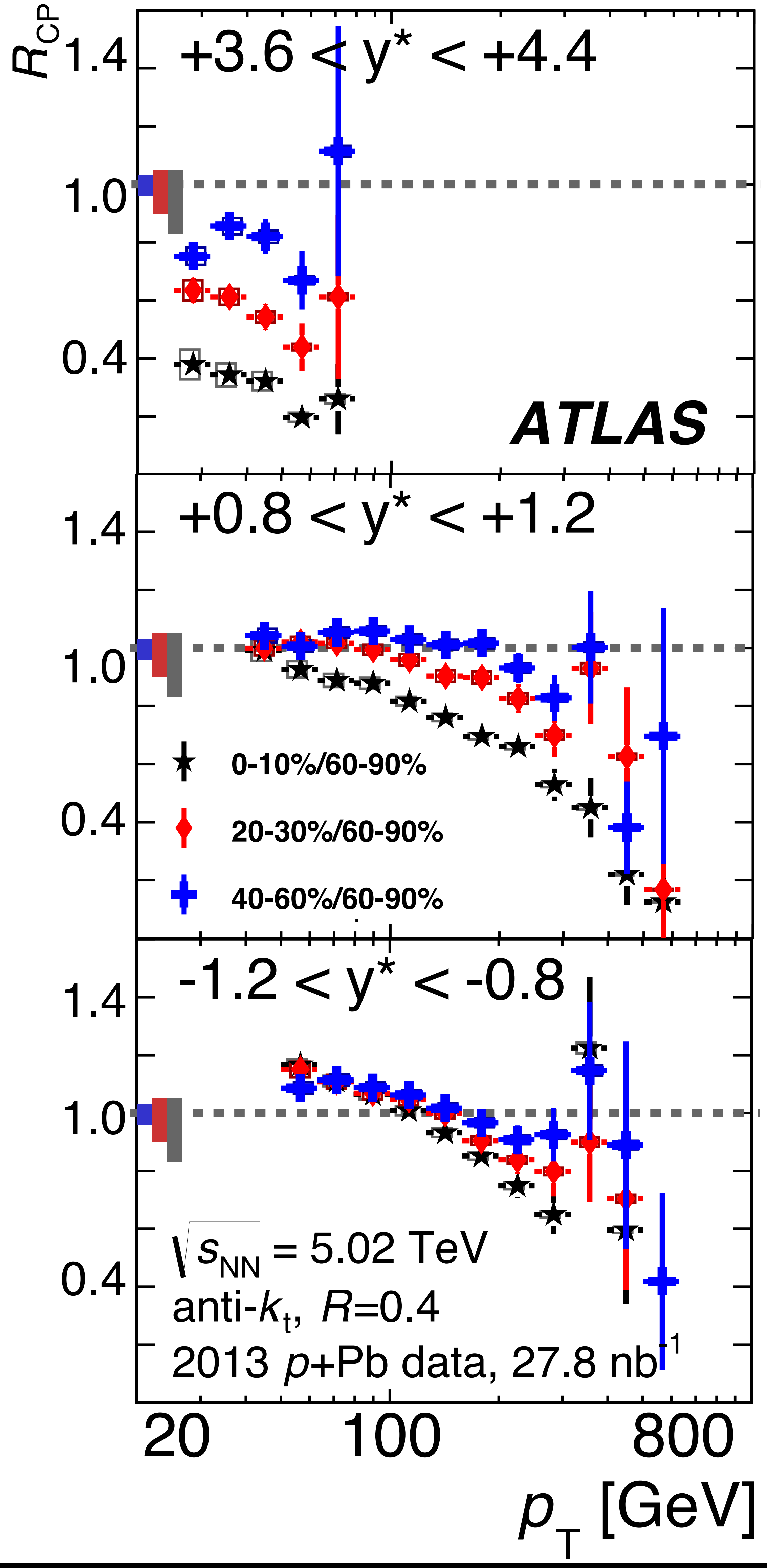
CHANGING THE PROBE: p+Pb COLLISIONS

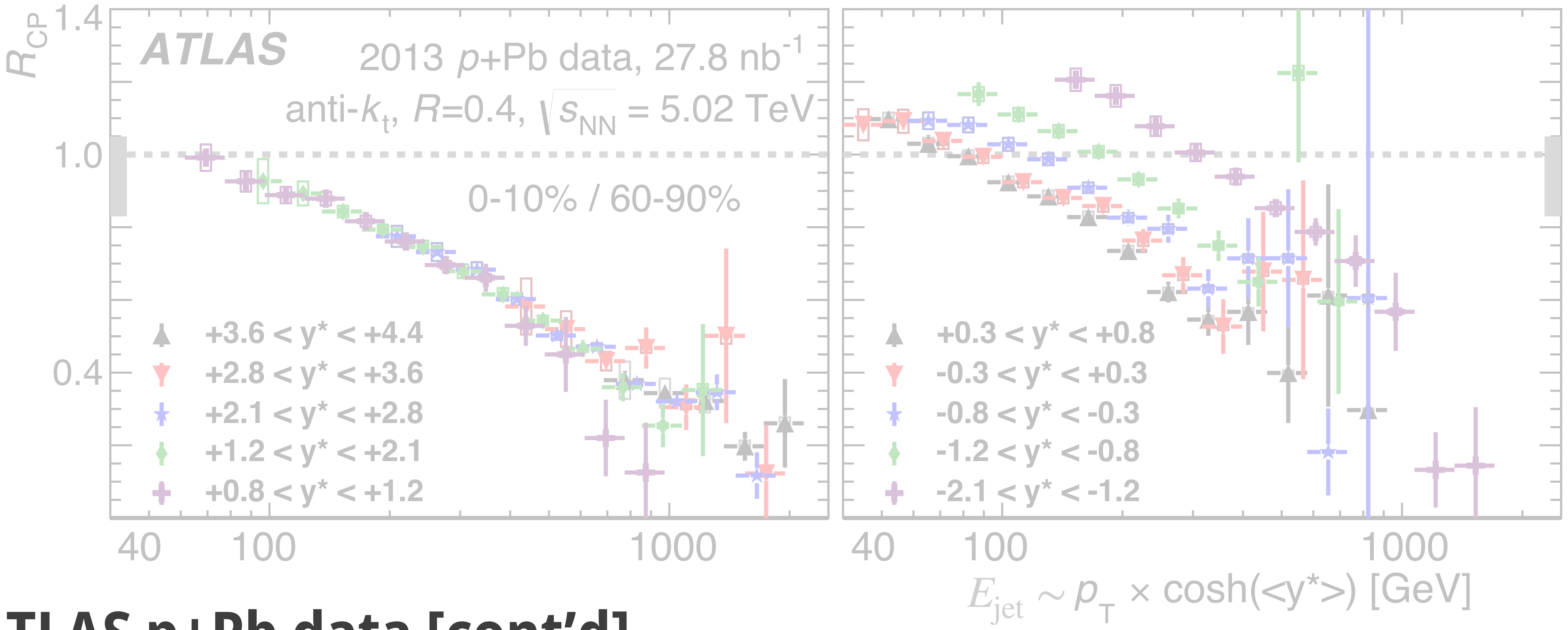


- Measurement of inclusive **jets in p+Pb** collisions also provide input to **nPDF studies**
- **5.02 TeV ATLAS p+Pb data**
  - R_{pPb}: no evidence for large modification of the total yield of jets relative to the geometric expectation observed **PLB 748 (2015) 392–413**
  - Also, **no jet quenching** evidence in p+Pb - new strong constraints reported by ATLAS **Arxiv:2206.01138, accepted PRL**
    - Observed deviation in jet production should be attributed to different effects



CENTRALITY DEPENDENCE OF JET PRODUCTION





- **5.02 TeV ATLAS p+Pb data [cont'd]**
  - Intriguing results from the measurement of centrality dependence of inclusive jet production
  - R_{CP} results - suppression of the jet production in central events compared to peripheral events at all p_T at forward rapidities and for large p_T at mid-rapidity, **PLB 748 (2015) 392–413**

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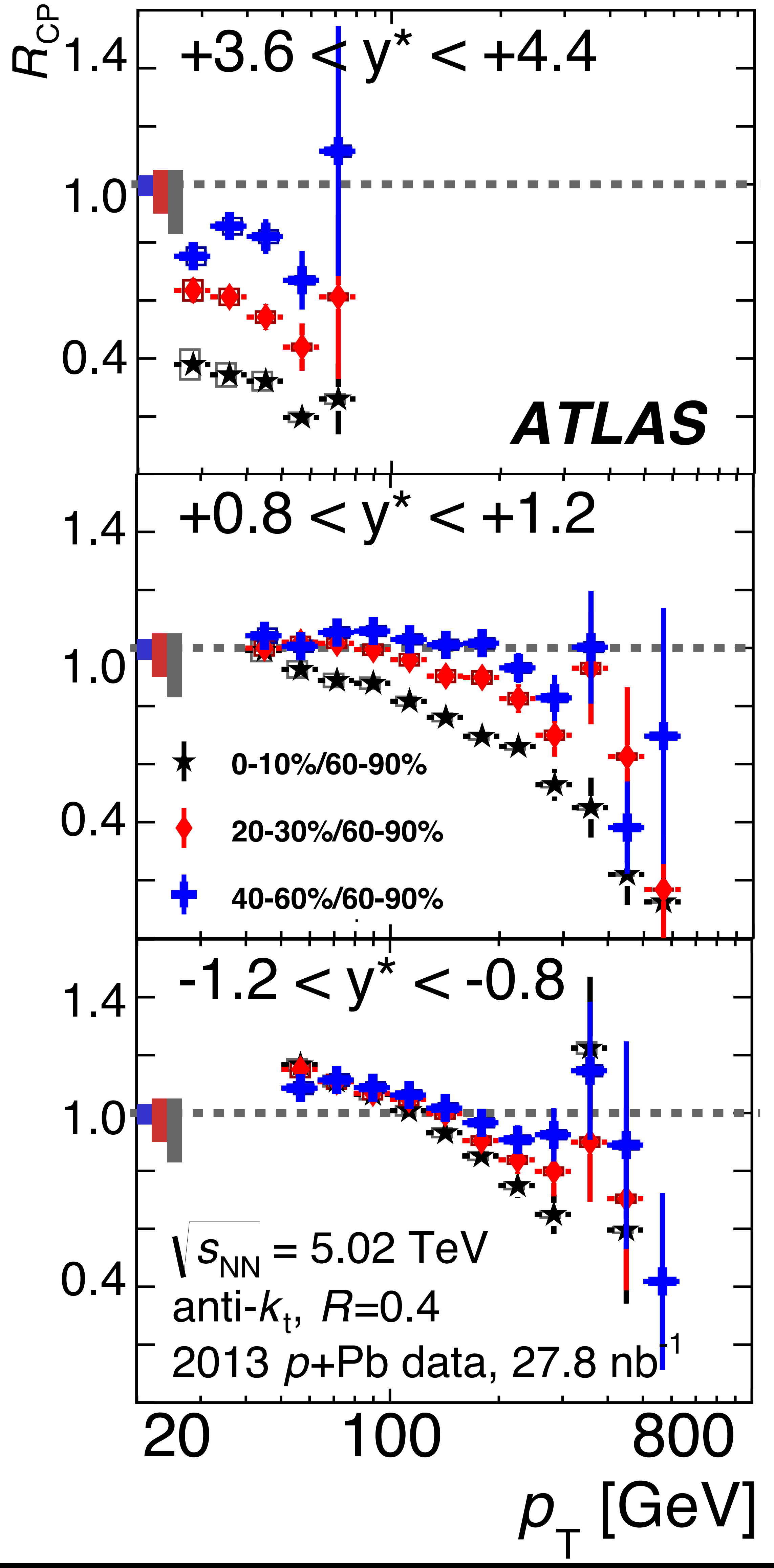

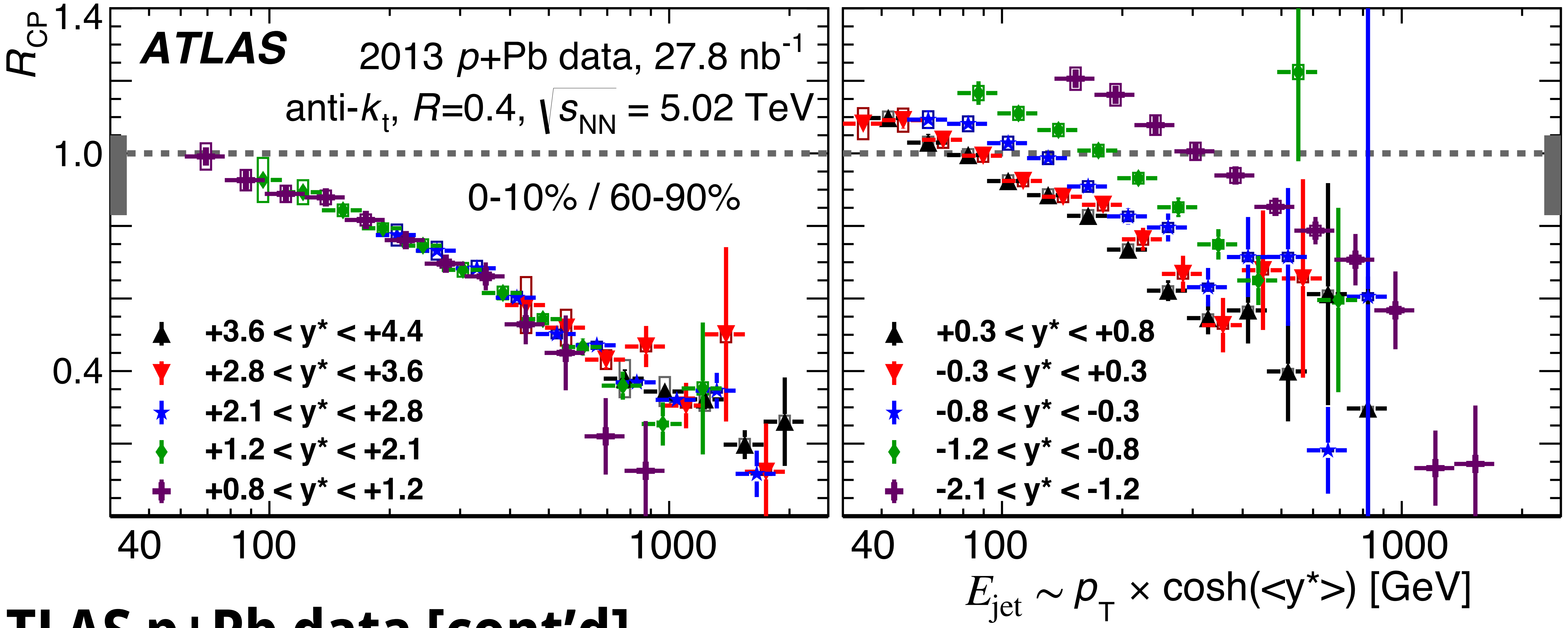

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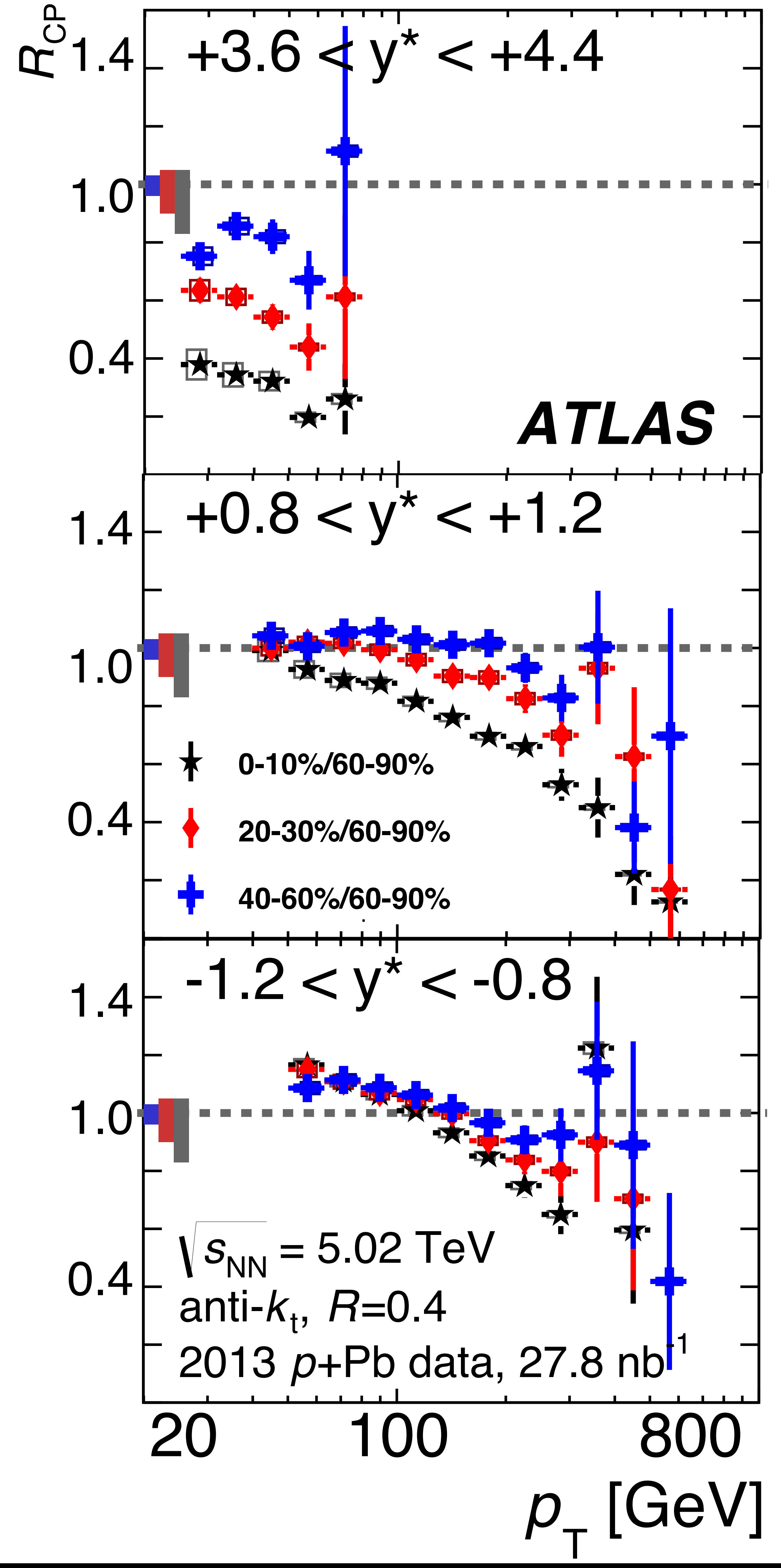
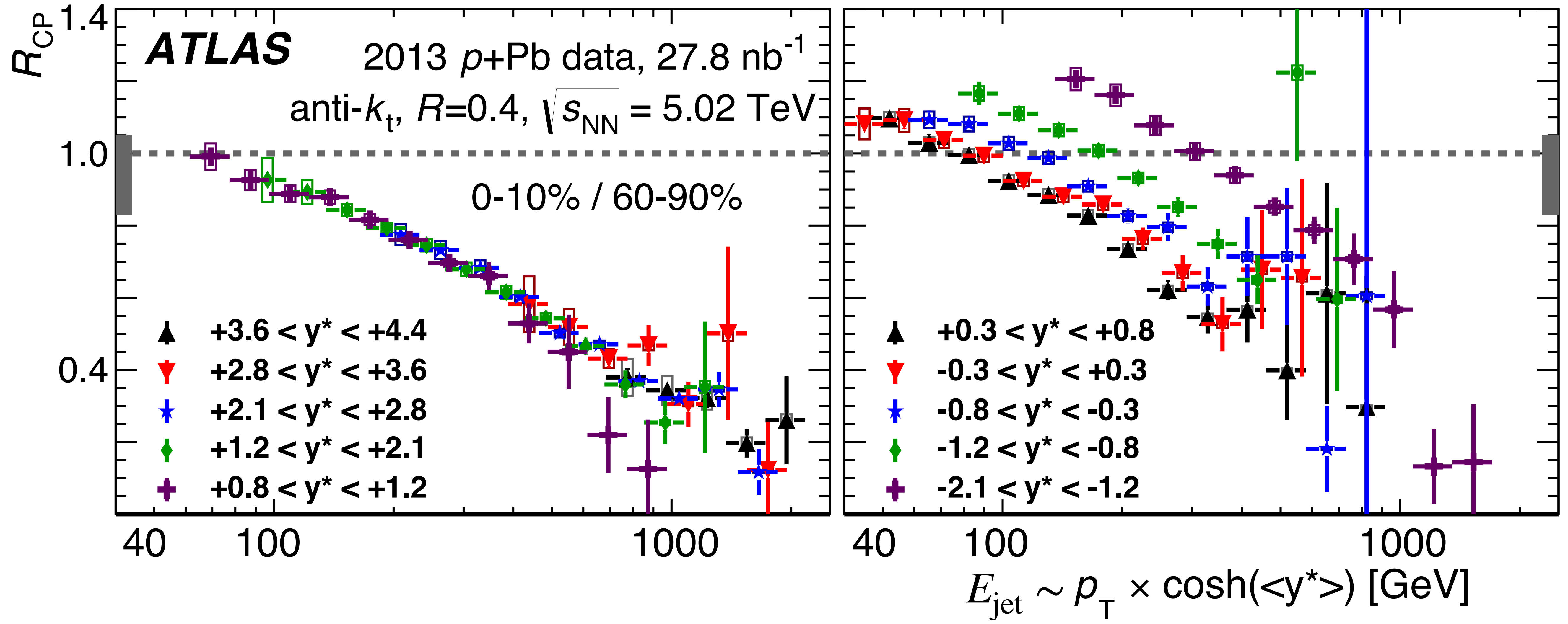
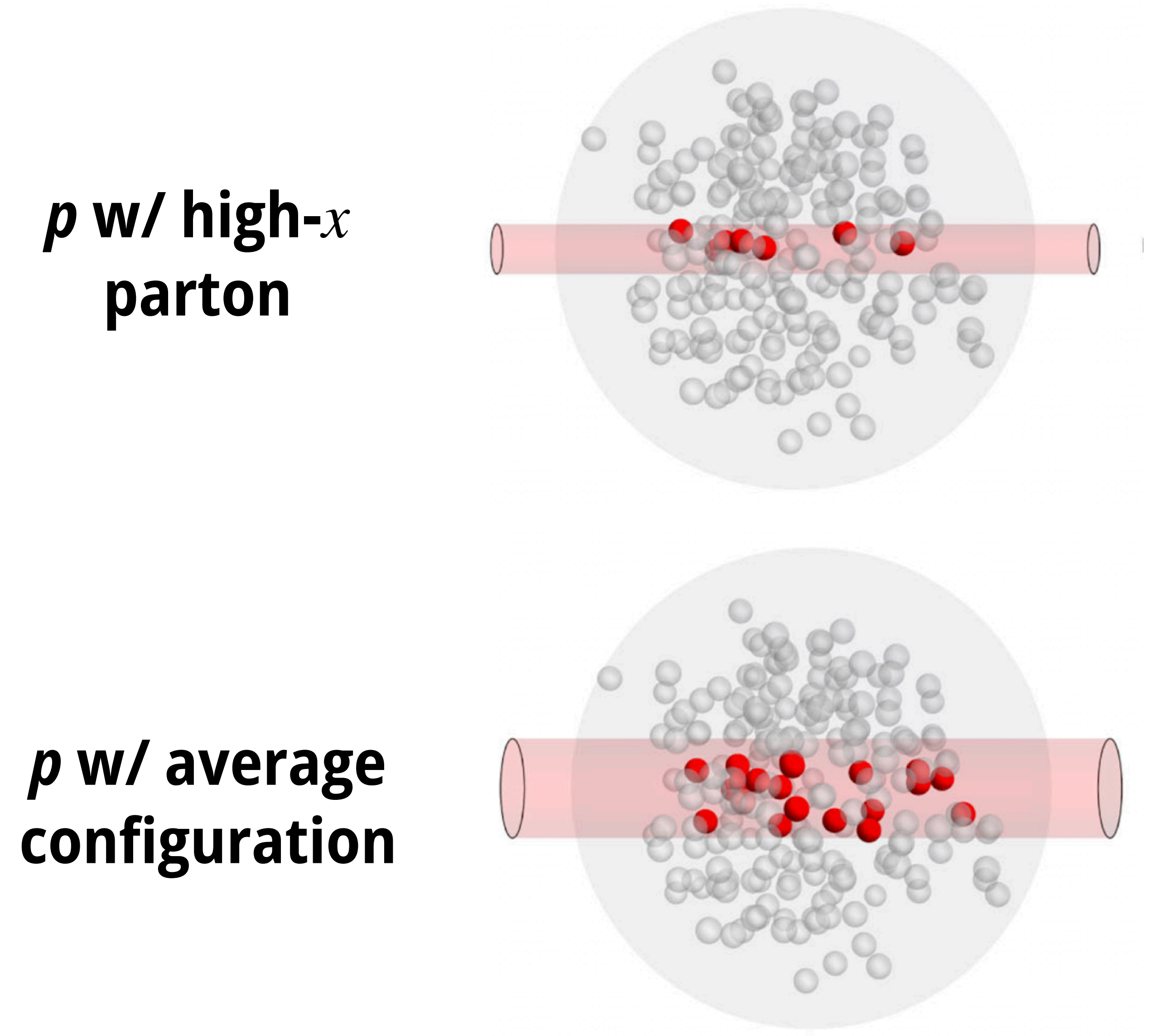
  - R_{CP} results - suppression of the jet production in central events compared to peripheral events at all p_T at forward rapidities and for large p_T at mid-rapidity, **PLB 748 (2015) 392–413**
  - Found to be a **function of the total jet energy** only - suggesting direct relation with the hard parton-parton scattering.

CENTRALITY DEPENDENCE OF JET PRODUCTION



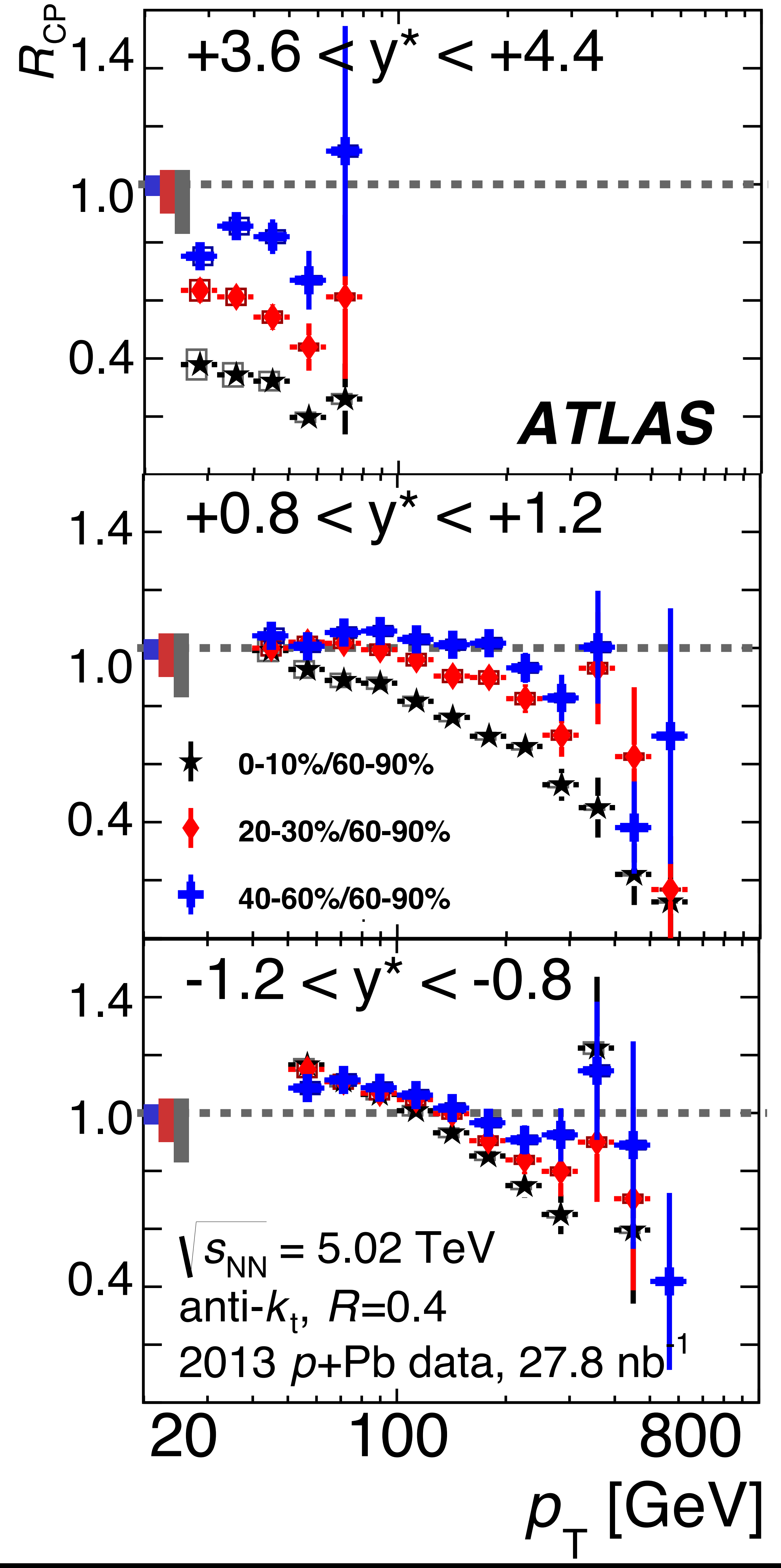


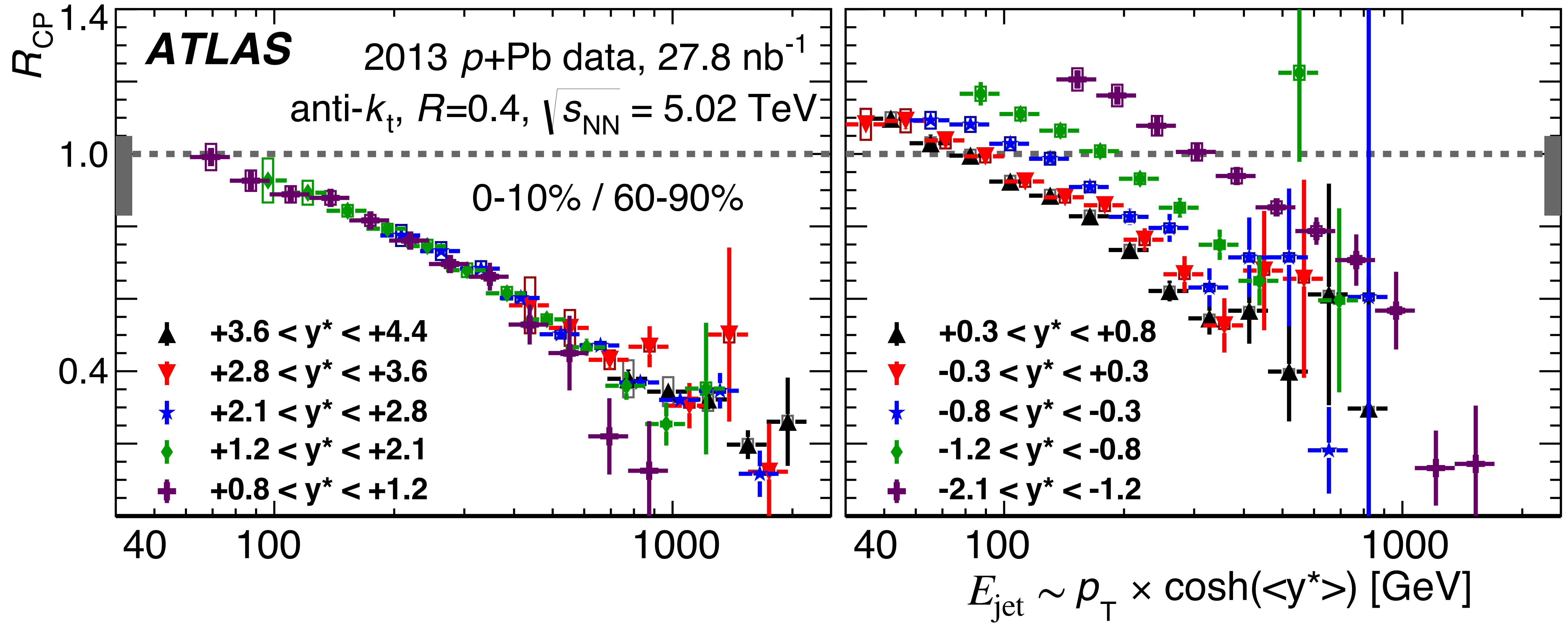


Sketch from Alvioli et al., **PRD 98 (2018) 071502**

p containing a parton with large *x* interacts with a nuclear target with smaller than average cross-section and smaller than average size (*manifestation of color fluctuations - example of* ***color transparency***)

CENTRALITY DEPENDENCE OF DIJET PRODUCTION





The study of dijets in p+Pb collisions at 8.16 TeV offers unique opportunity to advance the understanding of the centrality dependence of jet production in p+Pb collisions

CENTRALITY DEPENDENCE OF DIJET PRODUCTION

- 165 nb^{-1} of *p*+Pb data collected in 2016 (Largest *p*+Pb dataset collected to date by ATLAS)
- Anti-k_t R = 0.4 calorimeter jets
- Enough luminosity for measurement of the centrality-dependence of the **triple differential** per-event dijet yield →

$$\frac{1}{N_{\mathrm{evt}}^{\mathrm{cent}}} \frac{\mathrm{d}^3 N_{\mathrm{dijet}}^{\mathrm{cent}}}{\mathrm{d}p_{\mathrm{T,Avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^*}$$

  - Average transverse momentum: $p_{\mathrm{T,Avg}} = \frac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2}$
  - Boost of Dijet System: $y_{\mathrm{b}} = \frac{1}{2}(y_1^{\mathrm{CM}} + y_2^{\mathrm{CM}})$
  - Dijet Half Rapidity Separation: $y^* = \frac{1}{2}|y_1^{\mathrm{CM}} - y_2^{\mathrm{CM}}|$
- 3D measurement provides **access to partonic system kinematics** →

$$m_{1,2} = \sqrt{\hat{s}} = \sqrt{x_{\mathrm{p}} x_{\mathrm{Pb}} s},$$

$$x_{\mathrm{p}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{y_{\mathrm{b}}} \cosh y^*,$$

$$x_{\mathrm{Pb}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{-y_{\mathrm{b}}} \cosh y^*$$

KINEMATIC DOMAIN

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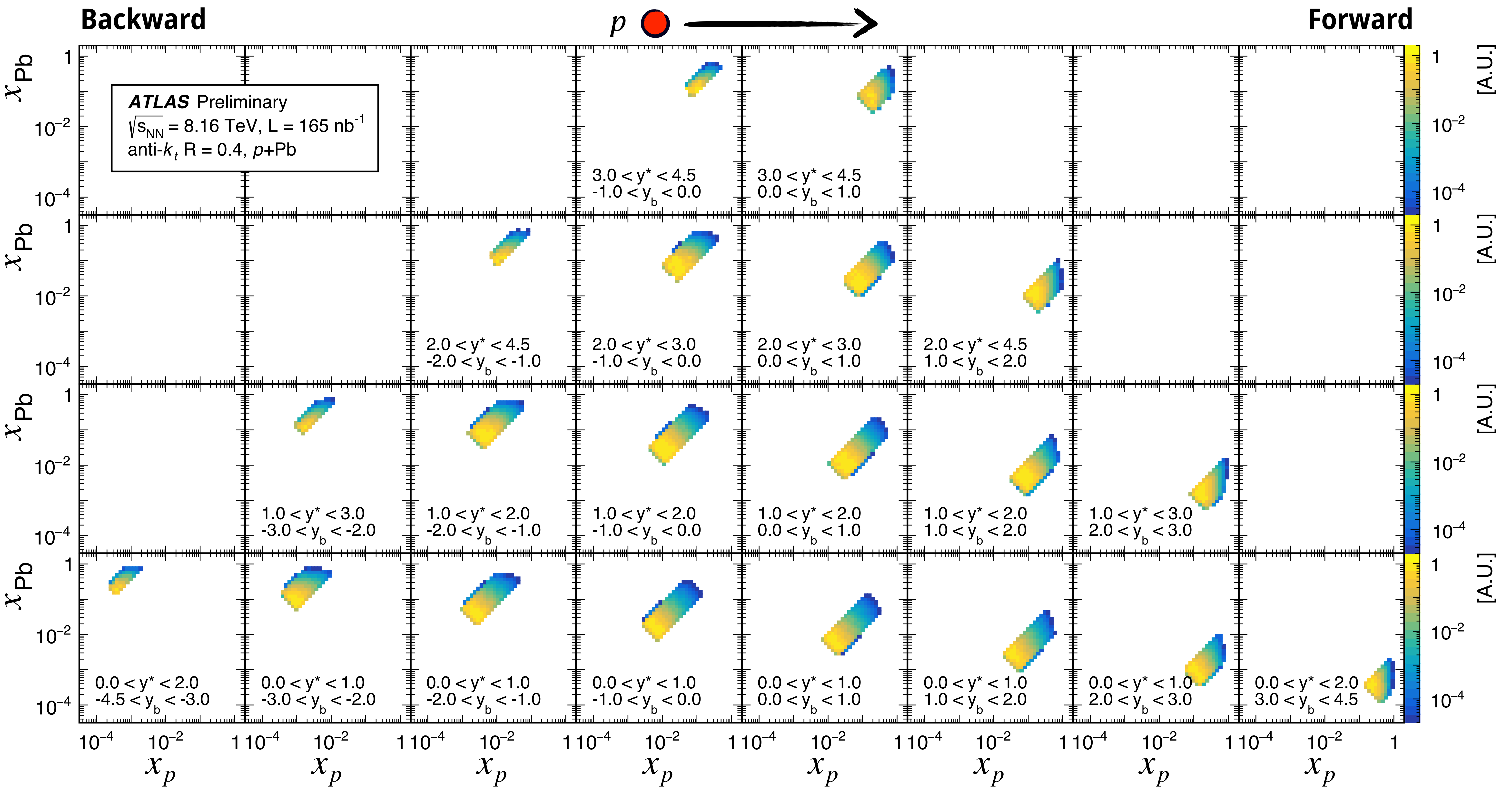
$$30\,\text{GeV} < p_{\text{T,Avg}} < 10^3\,\text{GeV}$$
$$-4.5 < y_\text{b} < 4.5$$
$$0 < y^* < 4.5$$

- Measurement that scans the internal structure of the *p* and the Pb over four orders of magnitude
- Unfolding of detector effects in $p_{\text{T,Avg}}$ distributions using 1D bayesian approach
- Allowed by limited migration in y_b and y^* (accounted for w/ an efficiency correction)
- The measurement is **not directly carried out in parton system kinematic variables**



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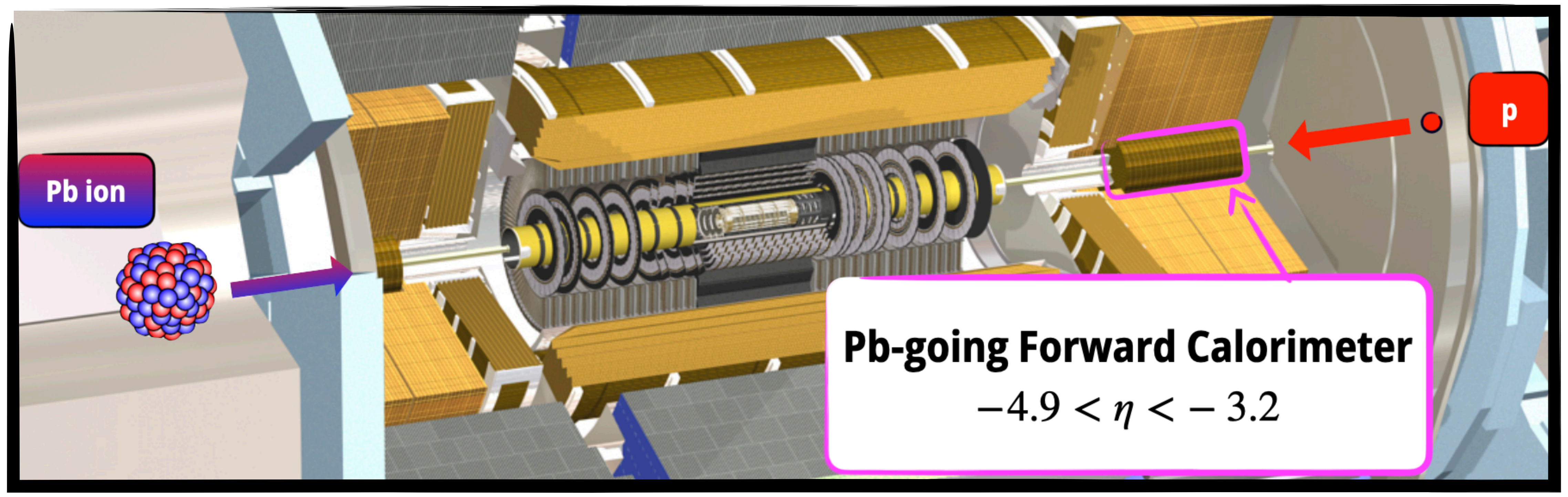
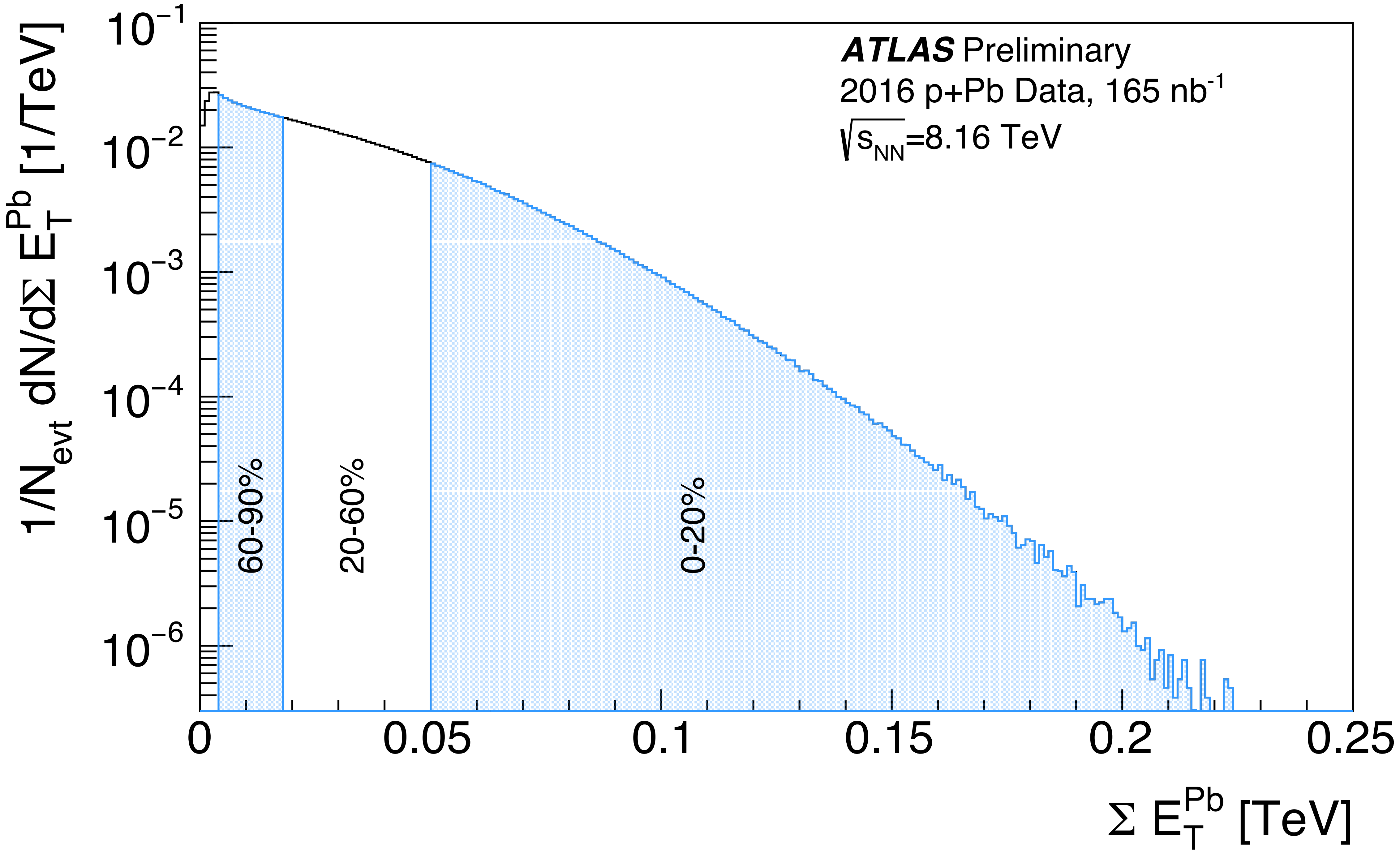
CENTRALITY DETERMINATION IN p+Pb

- Centrality determined using ΣE_T in the Pb-going arm of the FCal (see **Eur. Phys. J. C 76 (2016) 199**)
  - Best sensitivity to collision geometry
  - Method successfully applied in former ATLAS *p*+Pb Analyses (**PLB 748 (2015) 392–413**)





- Centrality determination fully separated from the analysis thanks to fiducial cut on η of leading and sub-leading jet
- Two centrality classes considered in the analysis:
  - 0-20% → **Central events**
  - 60-90% →**Peripheral events**

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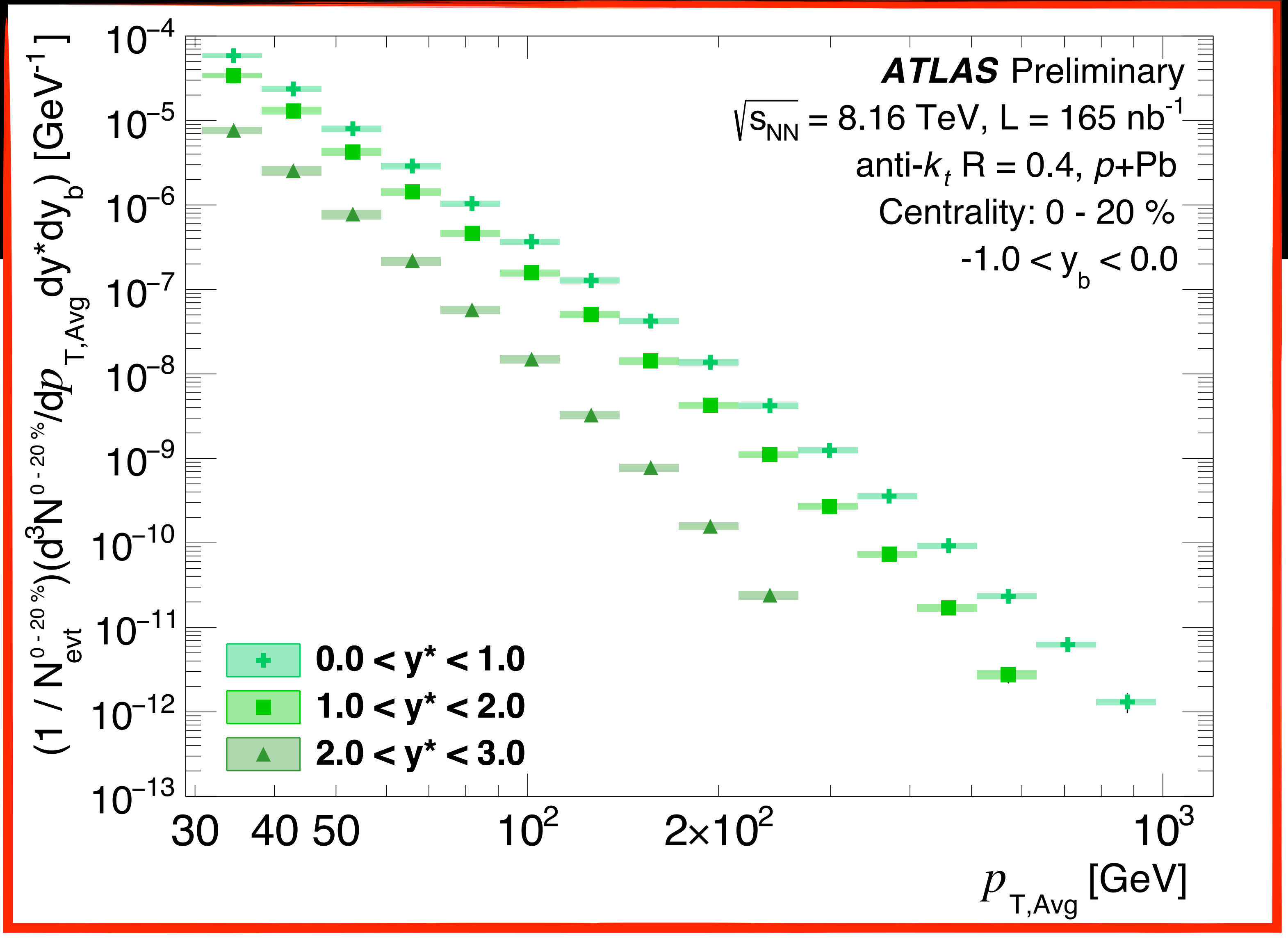
RATIO CENTRAL TO PERIPHERAL

- Constructed to study the centrality dependence of the dijet production in *p*+Pb collisions
- Partial cancellation of correlated systematics in the ratio

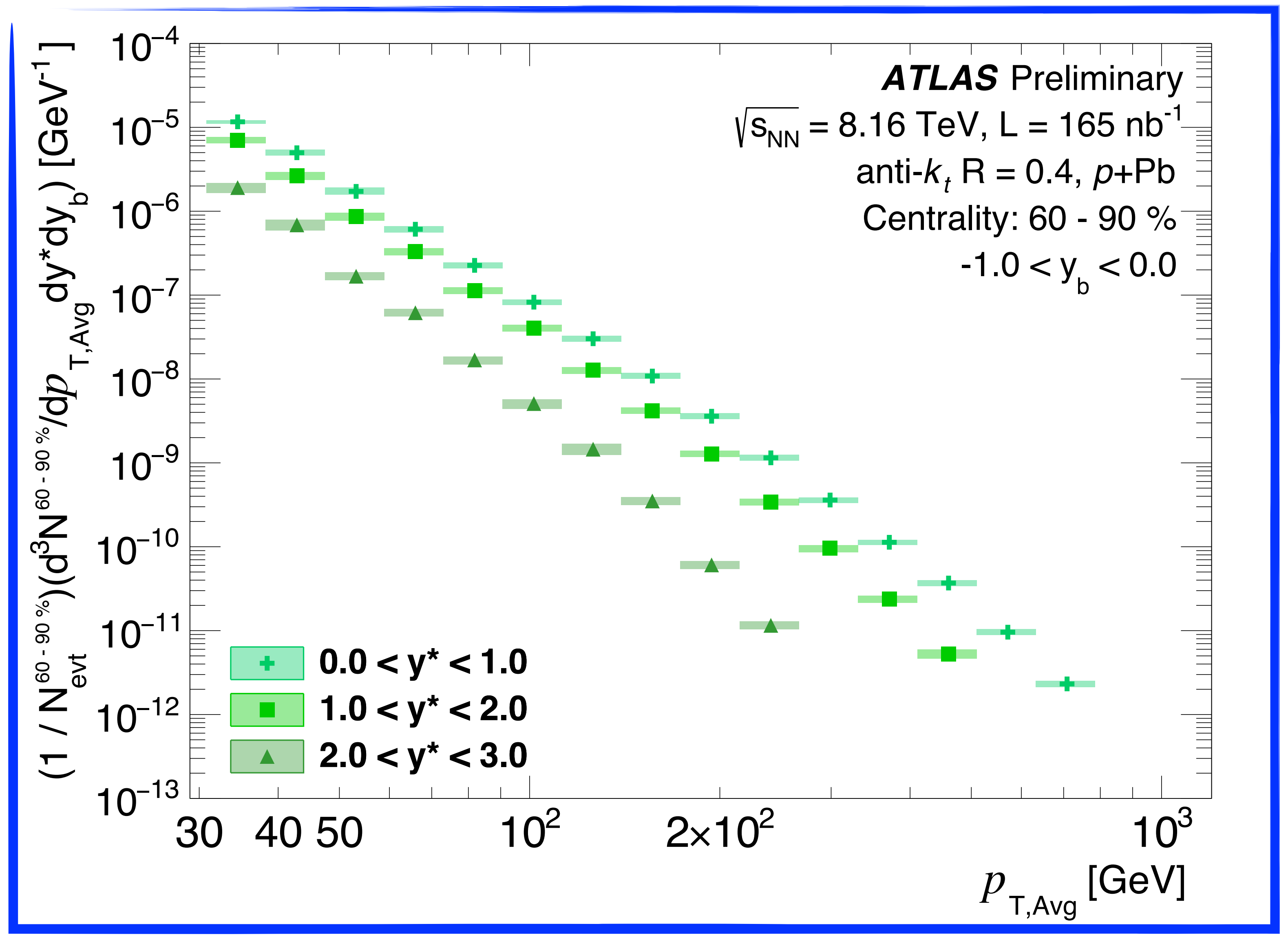
R_{CP} definition

$$R_{CP}^{\frac{0-20\%}{60-90\%}}(p_{T,Avg}, y_b, y^*) = \frac{\frac{1}{\langle T_{AB}^{0-20\%}\rangle}\frac{1}{N_{evt}^{0-20\%}}\frac{dN_{dijet}^{0-20\%}}{dp_{T,Avg}dy_b dy^*}}{\frac{1}{\langle T_{AB}^{60-90\%}\rangle}\frac{1}{N_{evt}^{60-90\%}}\frac{dN_{dijet}^{60-90\%}}{dp_{T,Avg}dy_b dy^*}}$$

Central dijet yield



Peripheral dijet yield



Nuclear overlap function

- Standard Glauber Monte Carlo techniques [**SoftwareX 1-2 (2015) 13-18**] to determine the relation between the mean number of participants and the event geometry

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PER-EVENT DIJET YIELD R_{CP} ($p_{T,Avg}$)

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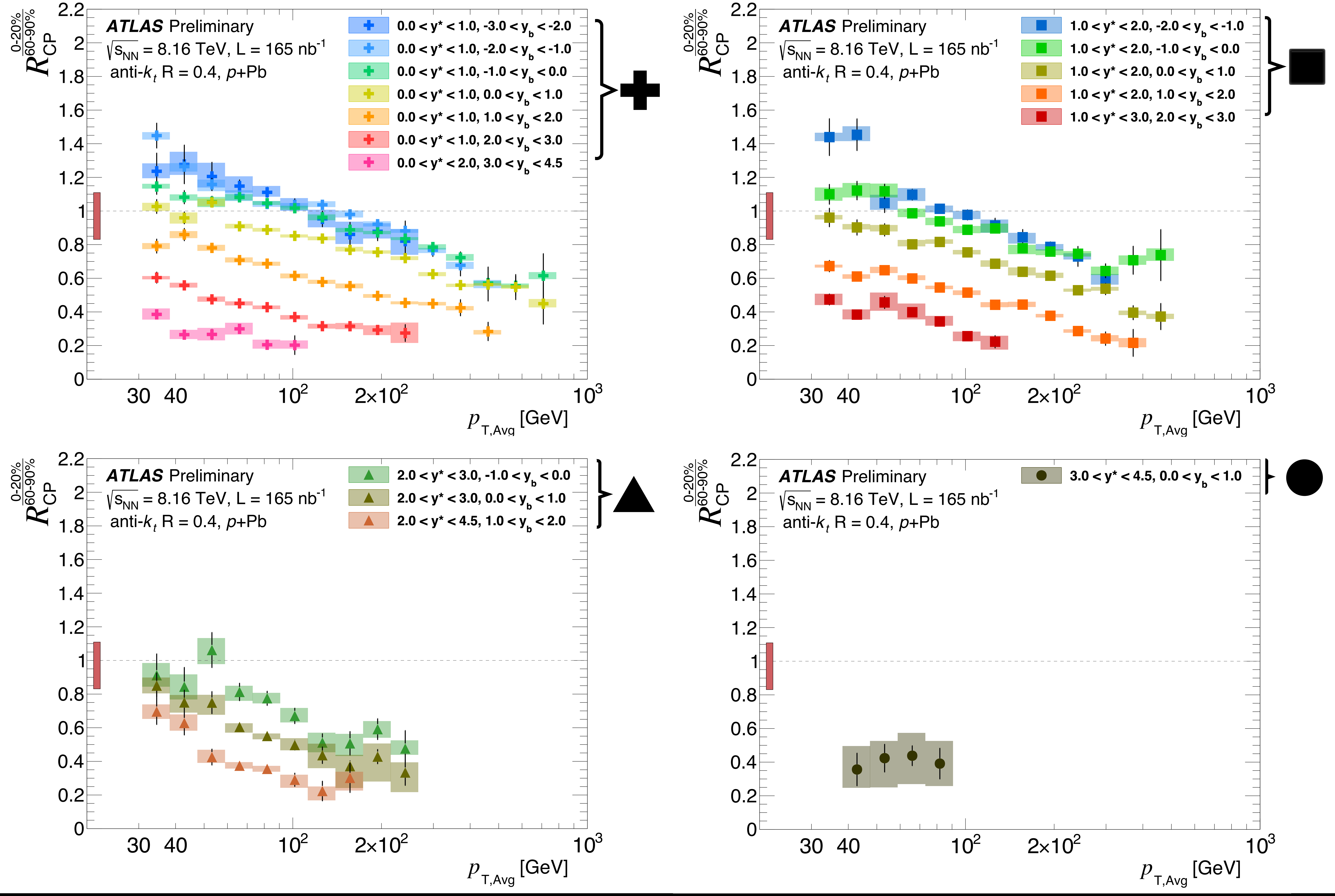
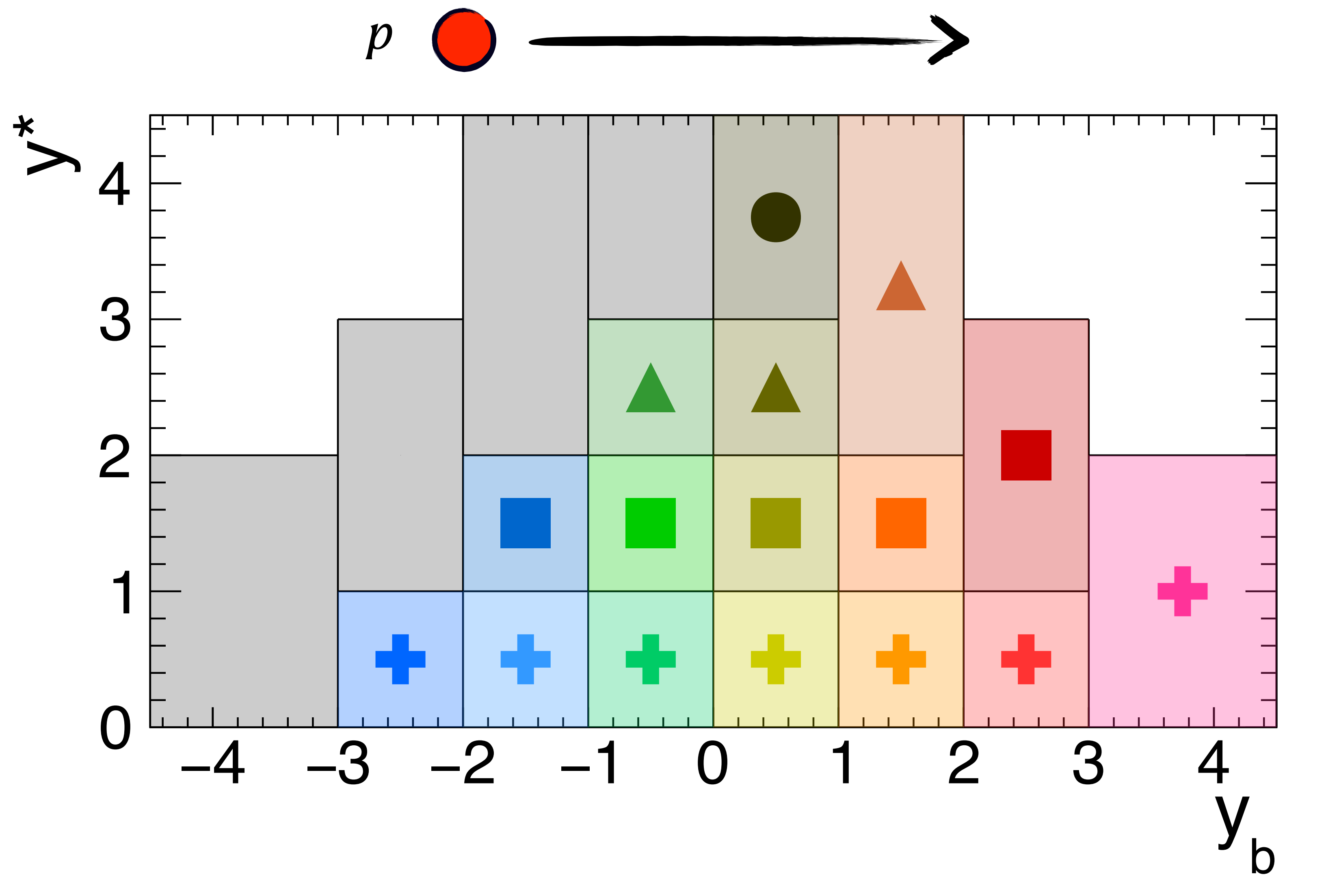




- Different panels (markers) represent different y^* ranges
- General trend: increasing suppression with $p_{T,Avg}$, and y_b (R_{CP} of dijets with a more forward boost is more suppressed)

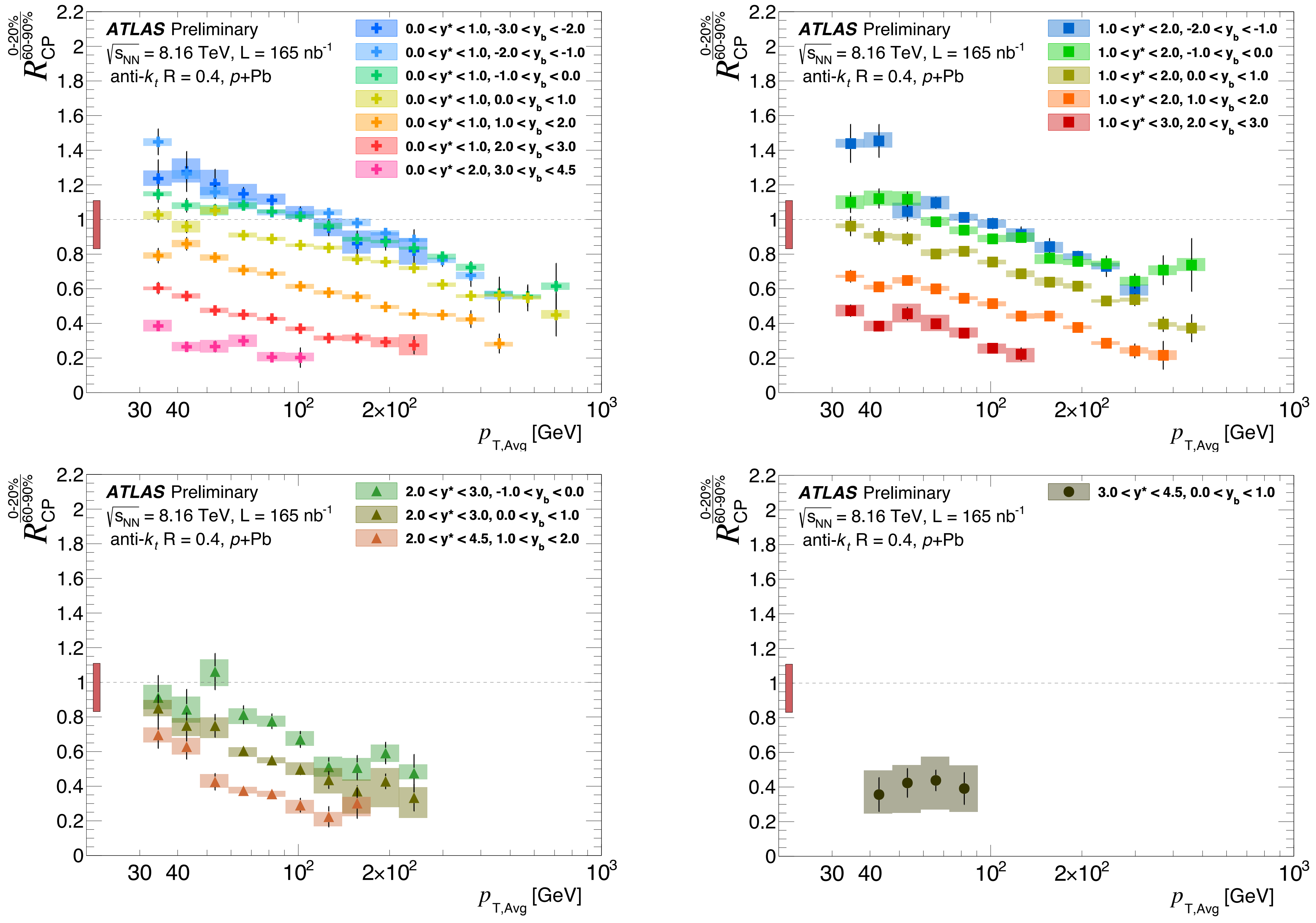
MAPPING RESULTS ON PARTON-LEVEL KINEMATICS

Approximated parton-level kinematics in each bin

- The parton-level kinematics in each bin can be approximated by using the average value of y_b and y^* in each kinematic bin
- For $p_{T,Avg}$, the center of the bin is used

$$x_p \simeq \frac{2p_{T,Avg}}{\sqrt{s}} e^{\langle y_b \rangle} \cosh\langle y^* \rangle, \quad x_{Pb} \simeq \frac{2p_{T,Avg}}{\sqrt{s}} e^{-\langle y_b \rangle} \cosh\langle y^* \rangle$$

$$m_{1,2} = \sqrt{x_p x_{Pb} s} \simeq 2p_{T,Avg} \cosh\langle y^* \rangle$$



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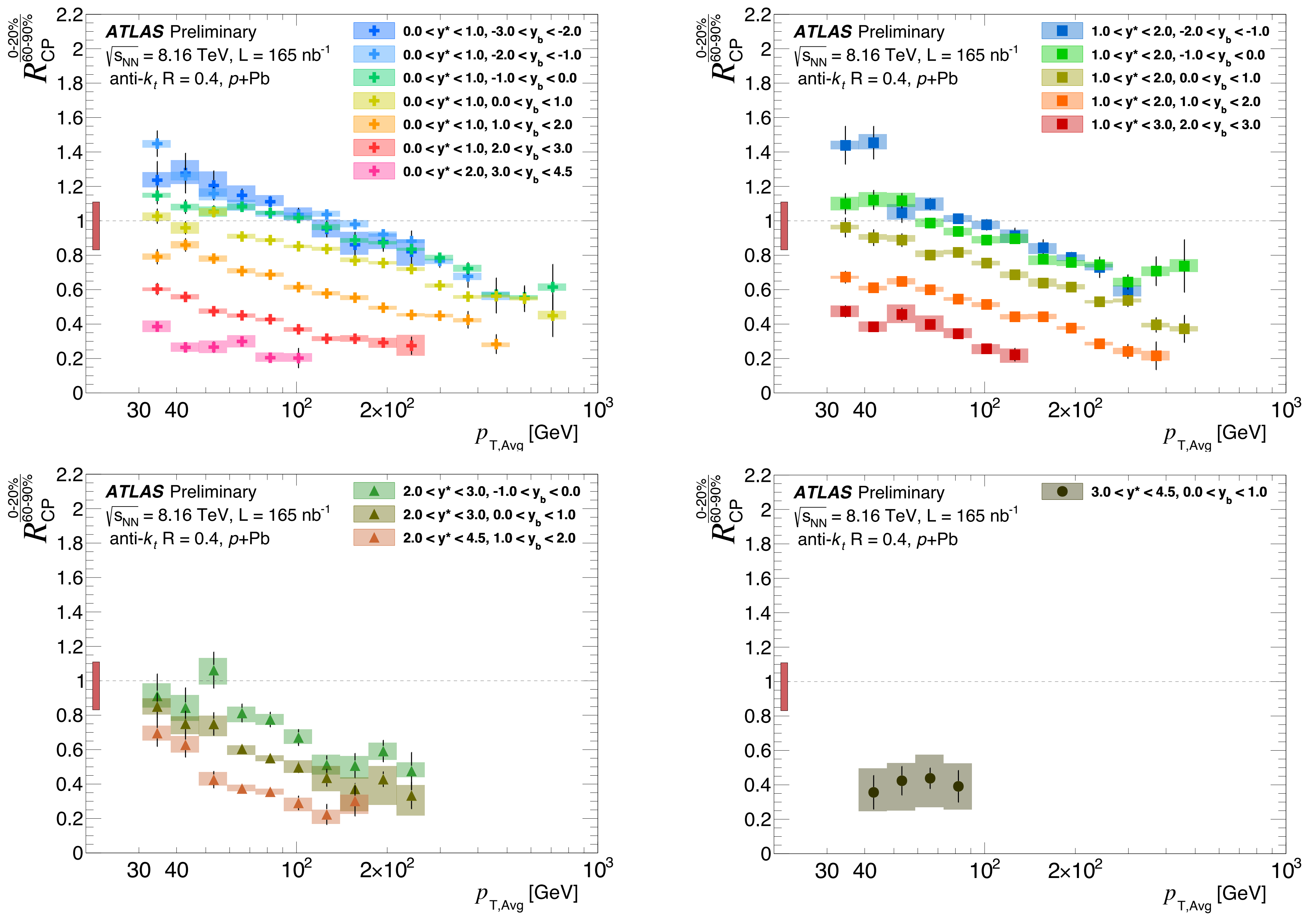
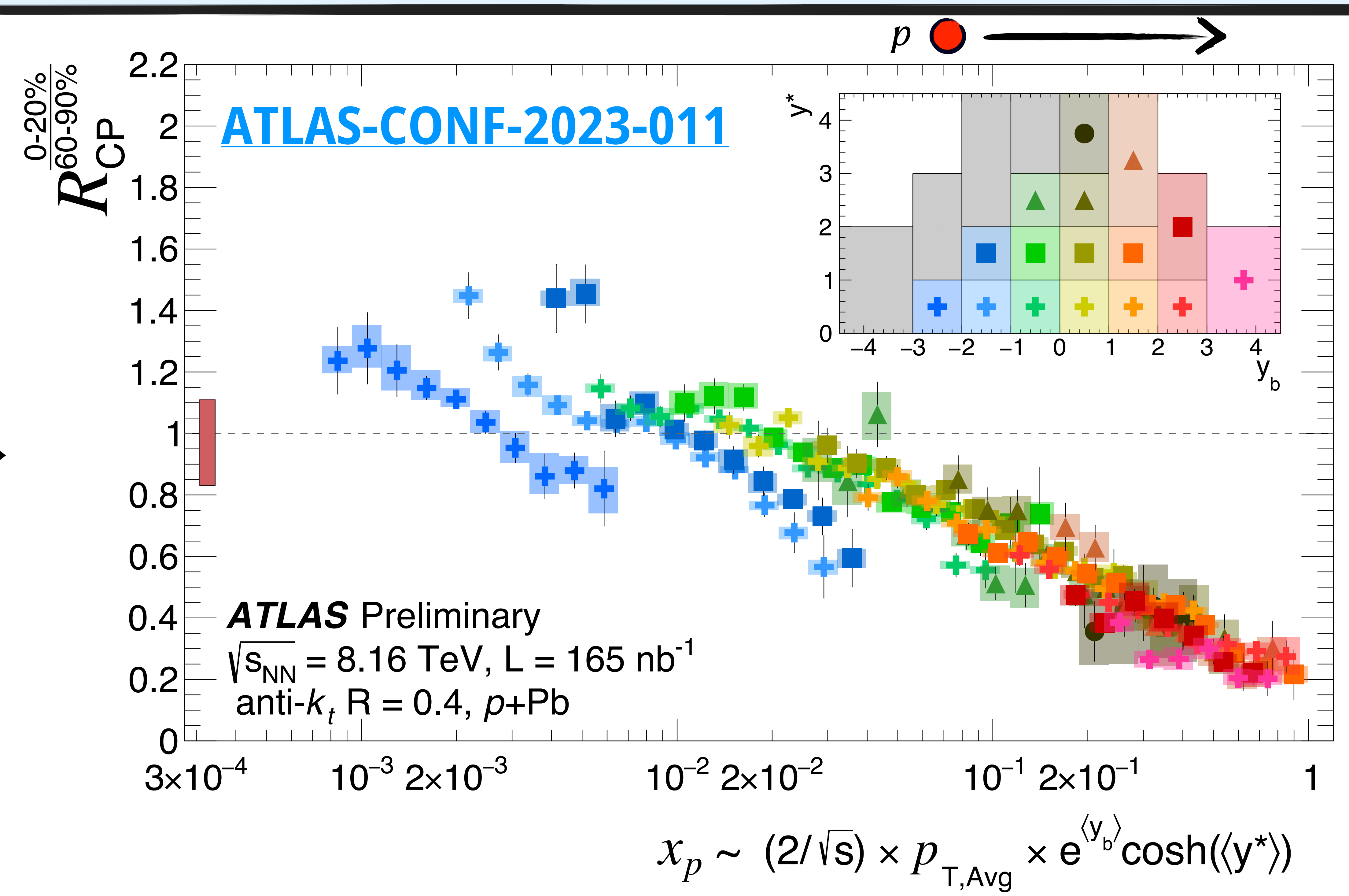
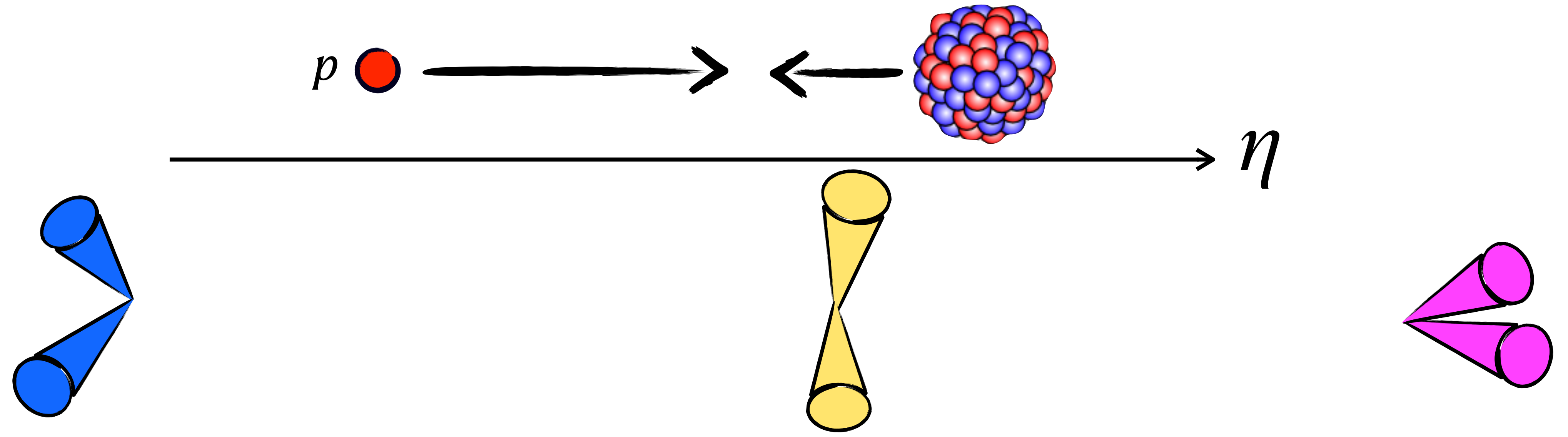
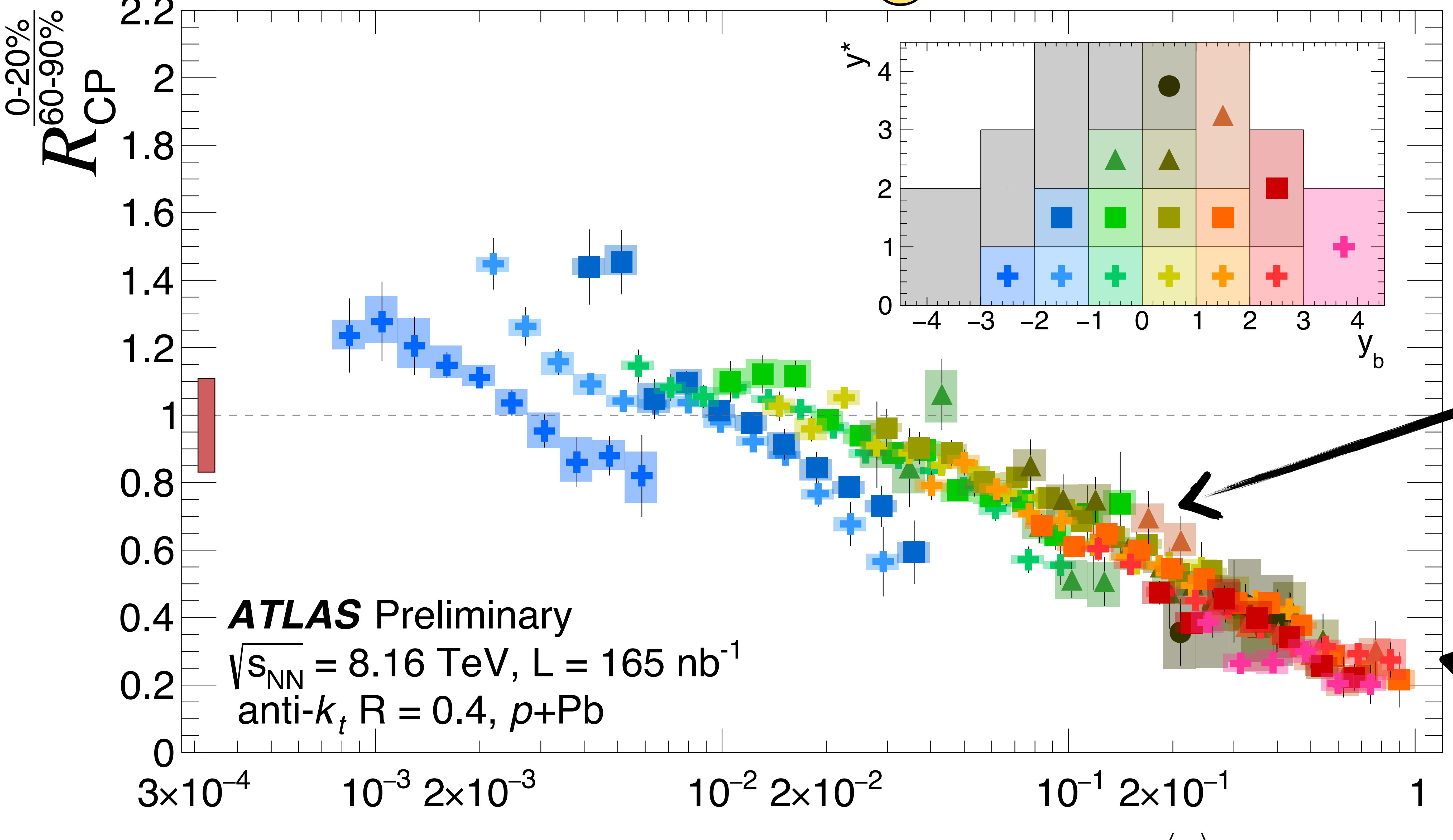




DIJET R_{CP} (x_p)





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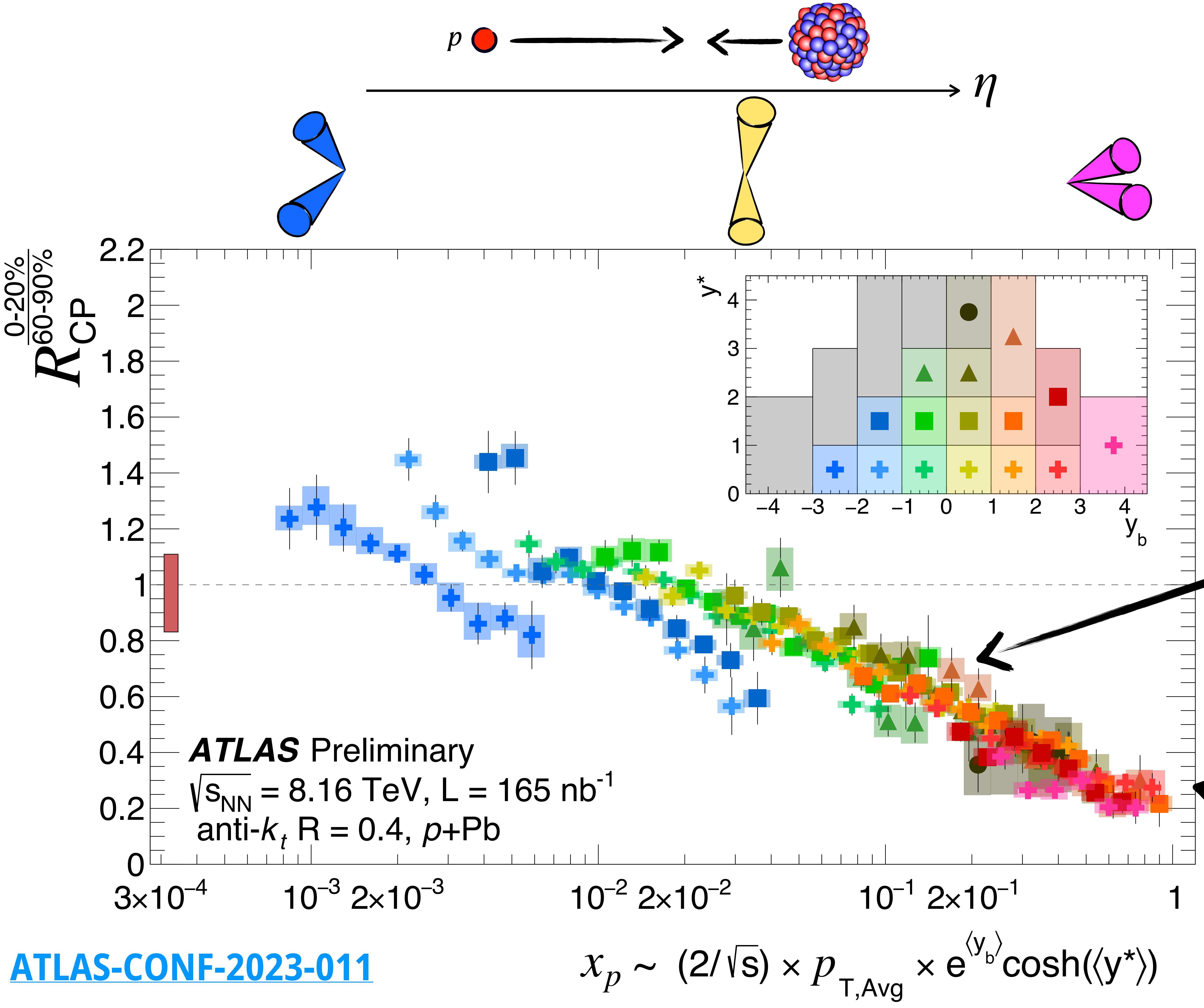
Log-linear decrease observed as a function of x_p in the valence region

The strongest R_{CP} suppression is observed at the highest values of x_p probed

DIJET R_{CP} (x_p)



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These results are qualitatively **compatible with** an interpretation in terms of **color transparency effects**

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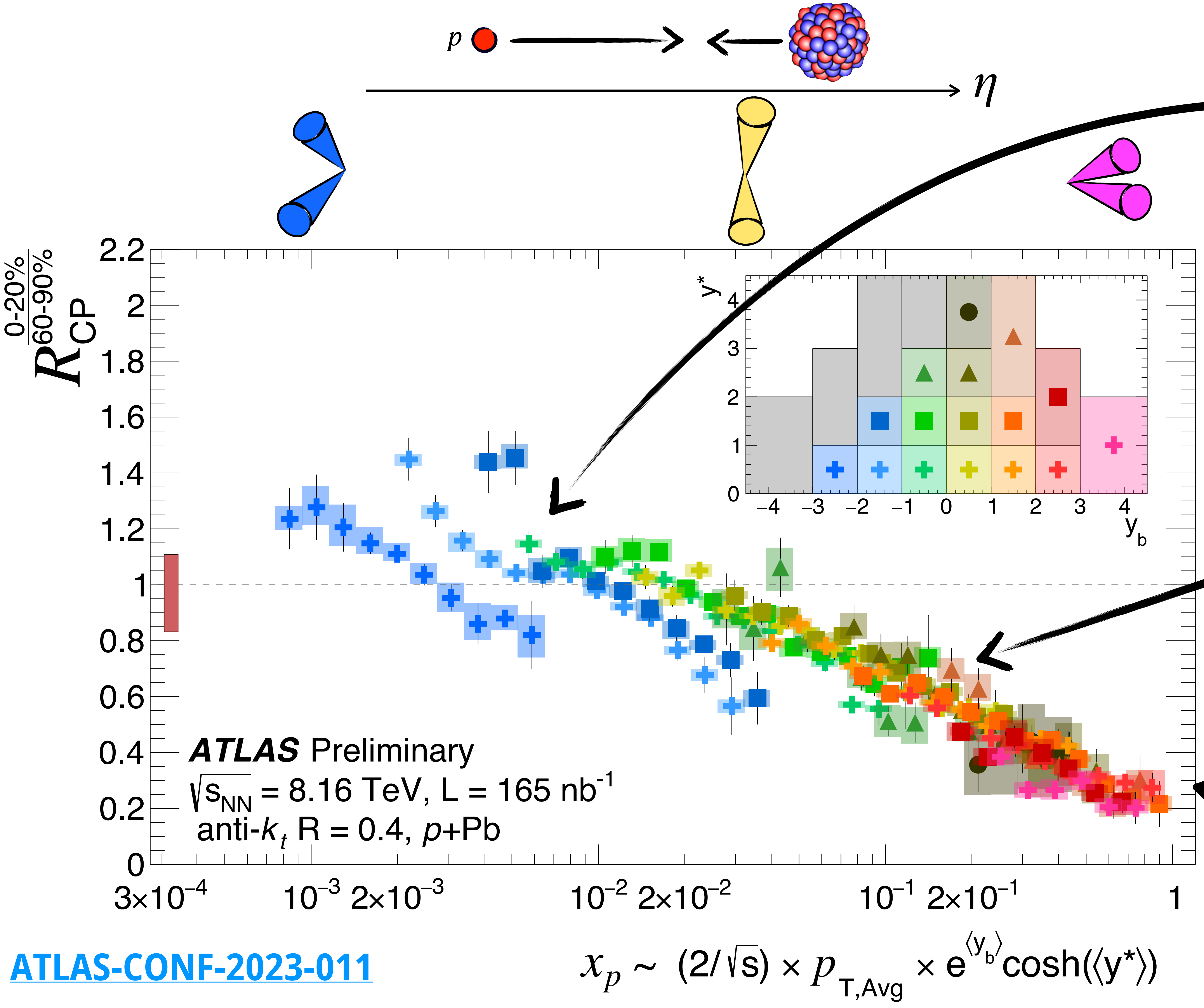

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Log-linear trend disappears when approaching low-x_p (high-x_{Pb}) region

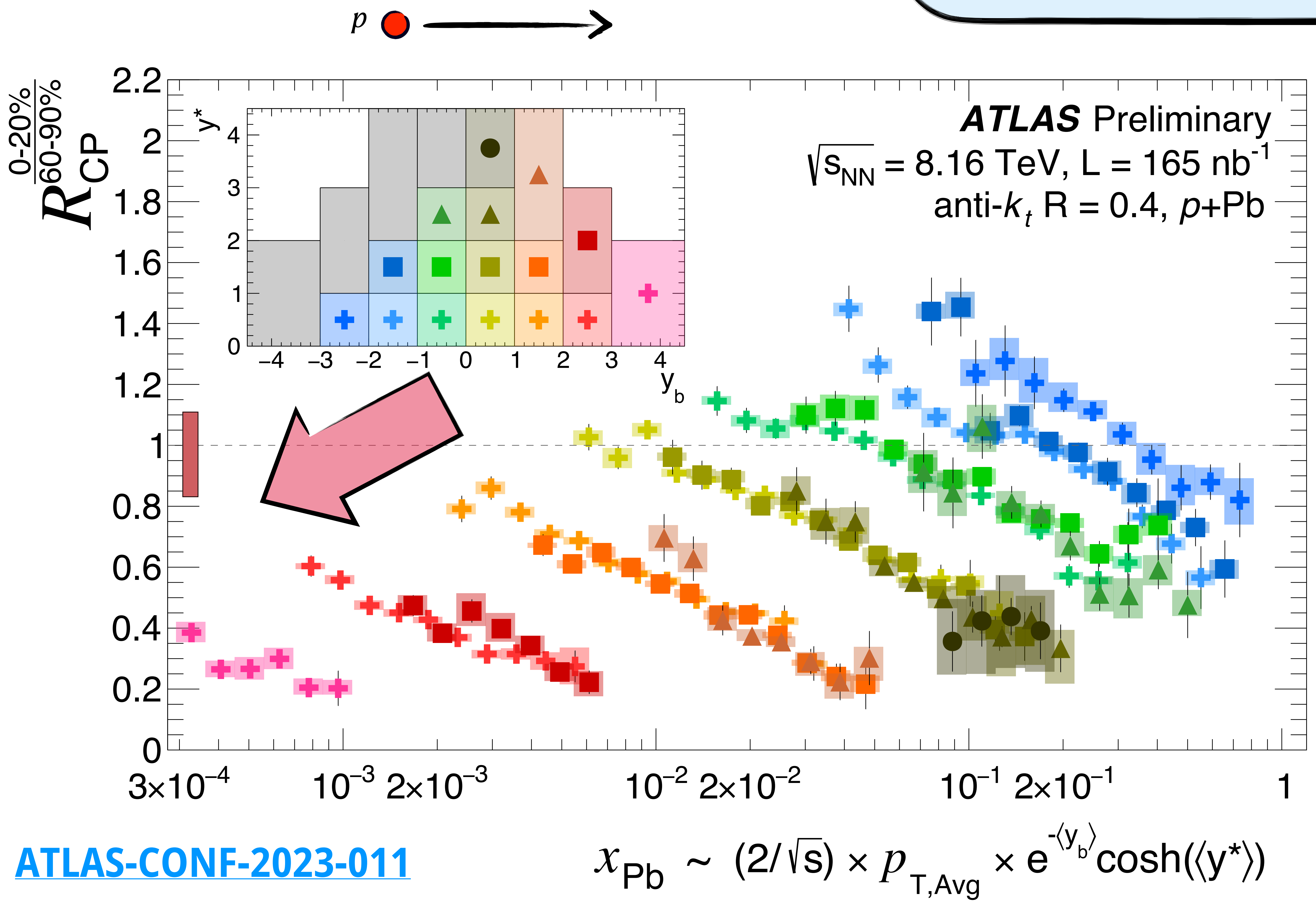
These results are qualitatively **compatible with** an interpretation in terms of **color transparency effects**

Log-linear decrease observed as a function of x_p in the valence region

The strongest R_{CP} suppression is observed at the highest values of x_p probed

DIJET R_{CP} (x_{Pb})

Overall, an increasing R_{CP} suppression while moving towards low-x_{Pb} is observed



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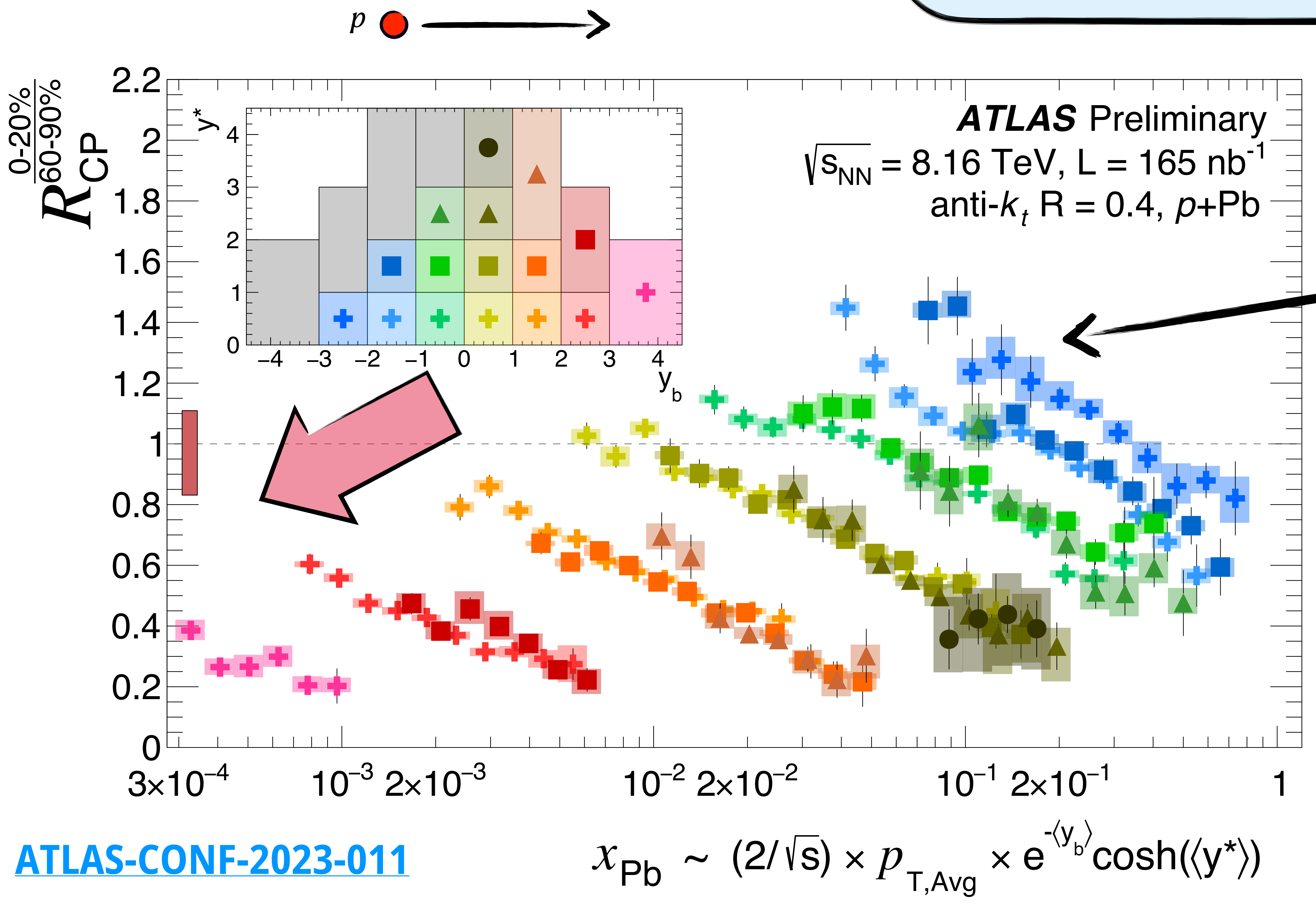

Values of $R_{CP} > 1$ found to be localized in the range $\sim 10^{-2} < x_{Pb} < \sim 2 \cdot 10^{-1}$, where anti-shadowing effects in the nucleus are expected.

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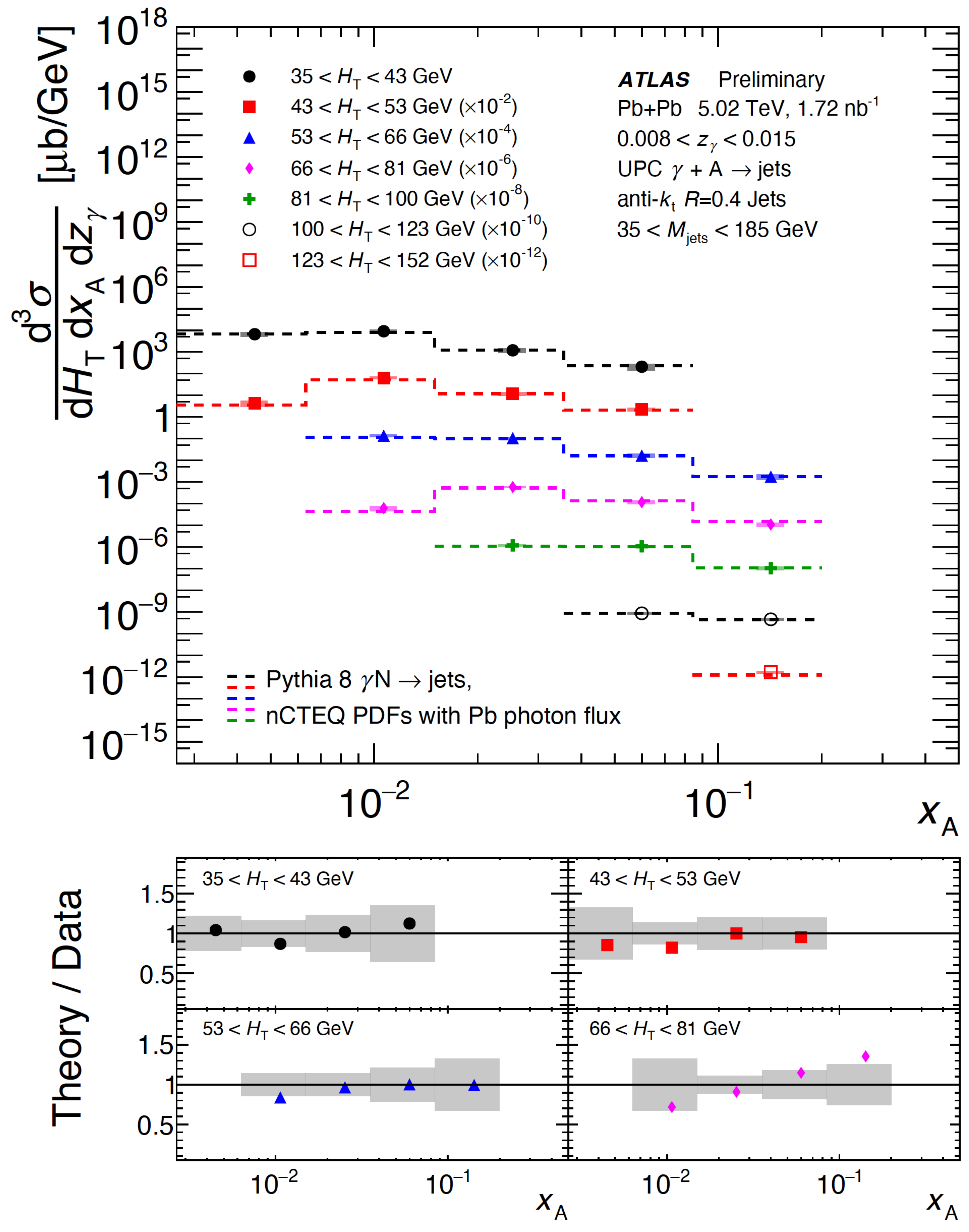
SUMMARY

- ATLAS can measure dijet events over a wide kinematic range to investigate the nuclear structure and the QCD nature in nuclear collisions.
  - **Measurement of triple differential cross-section of photonuclear jet production in 2018 5.02 TeV Pb+Pb collisions using particle flow jets**
    - Preliminary results are sensitive to **nPDF effects**
      - Ongoing effort to substantially reduce systematic uncertainty due to low-μ jet response and enhance the sensitivity of the results



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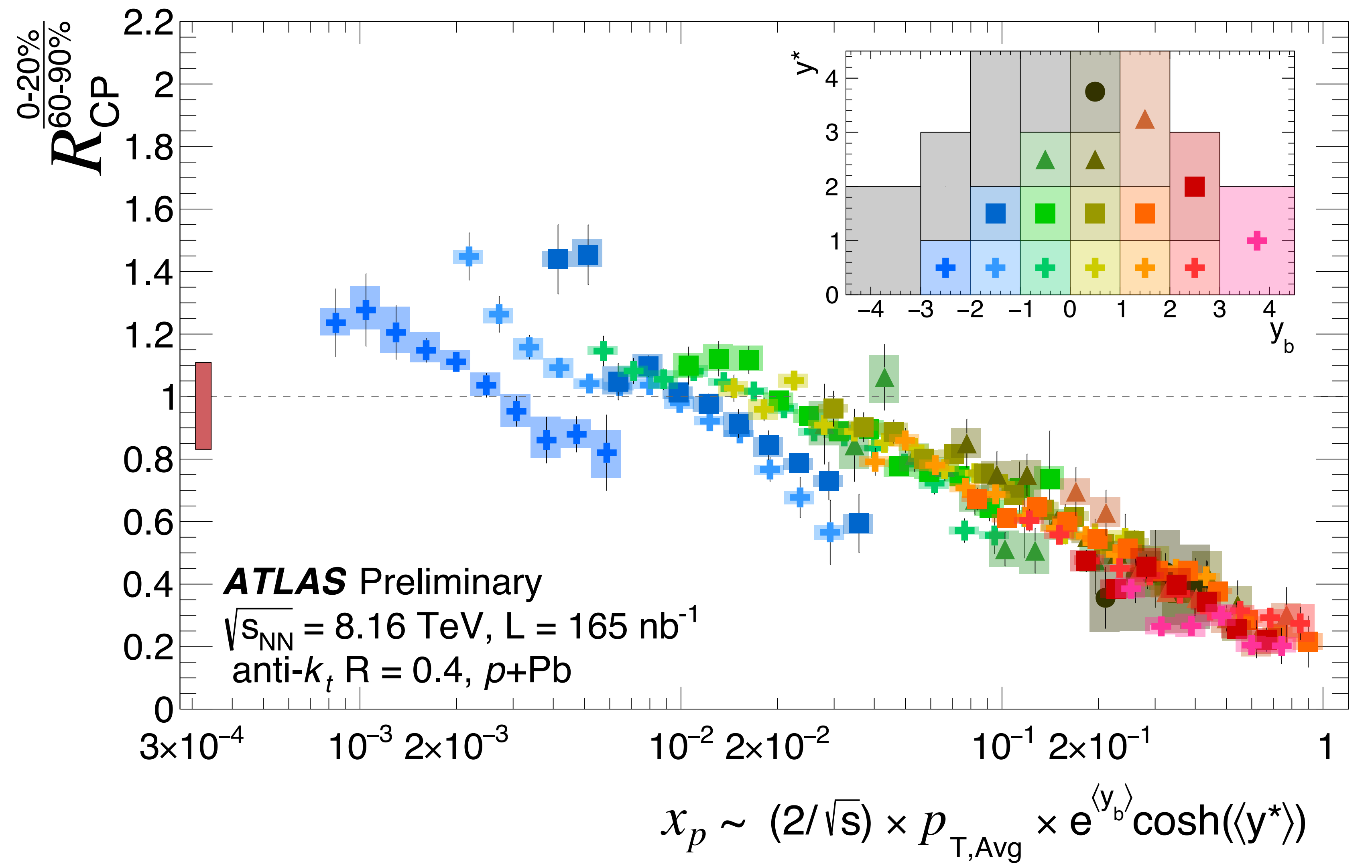
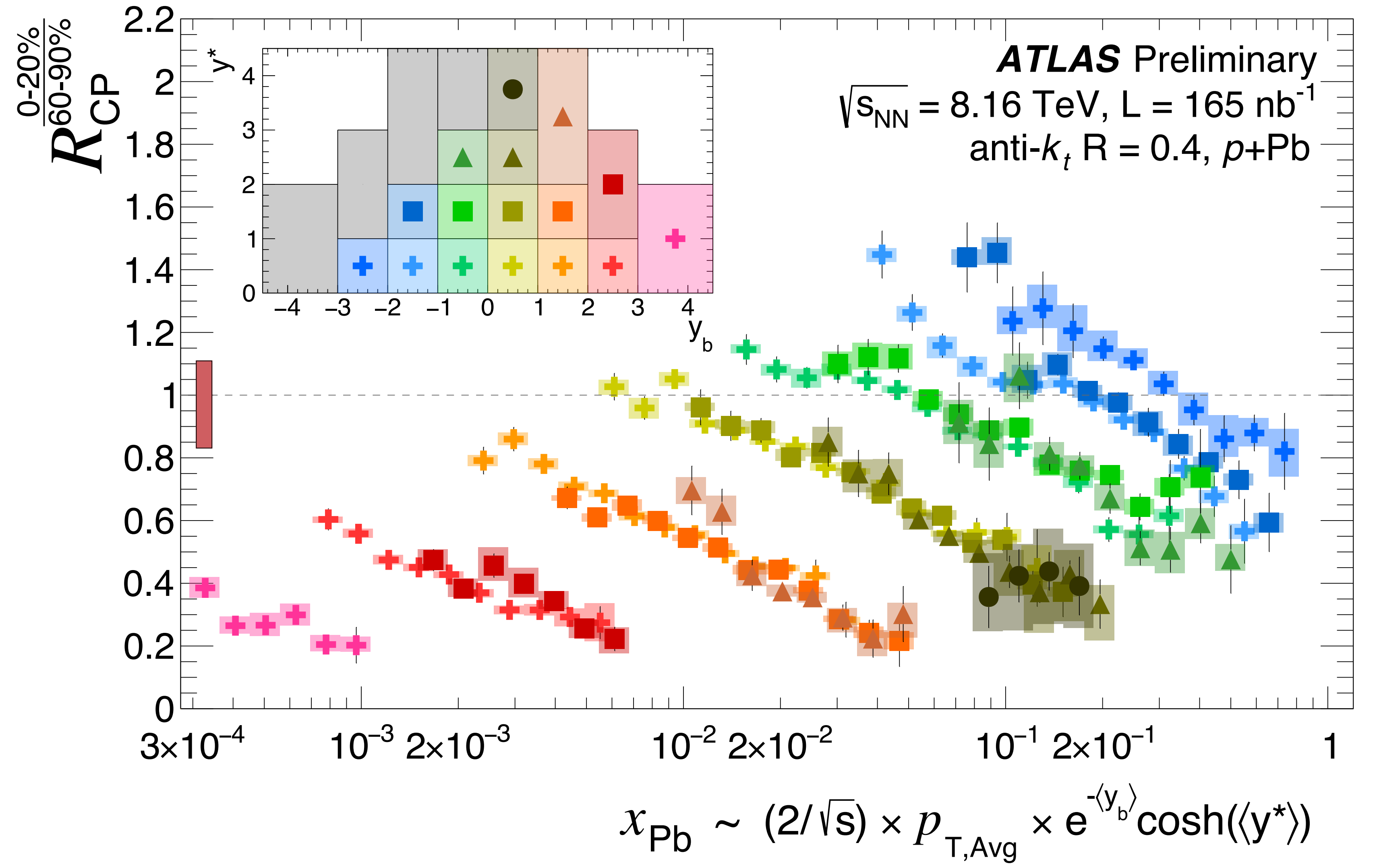
    - The results suggest that the observed trend is governed by physics effects similar to those probed in the inclusive production of jets in *p*+Pb collisions at 5.02 TeV, **related to color transparency manifestation!**





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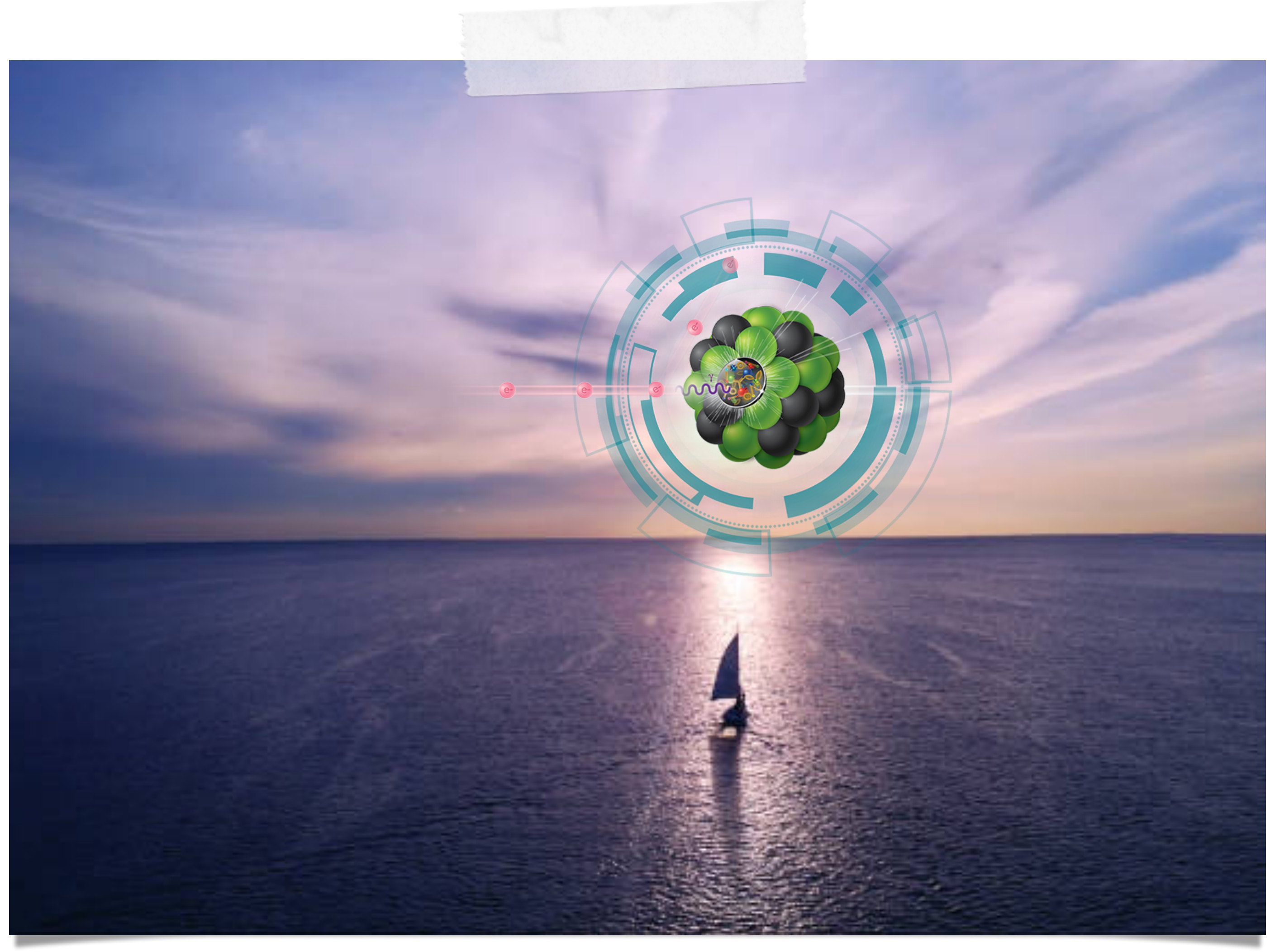
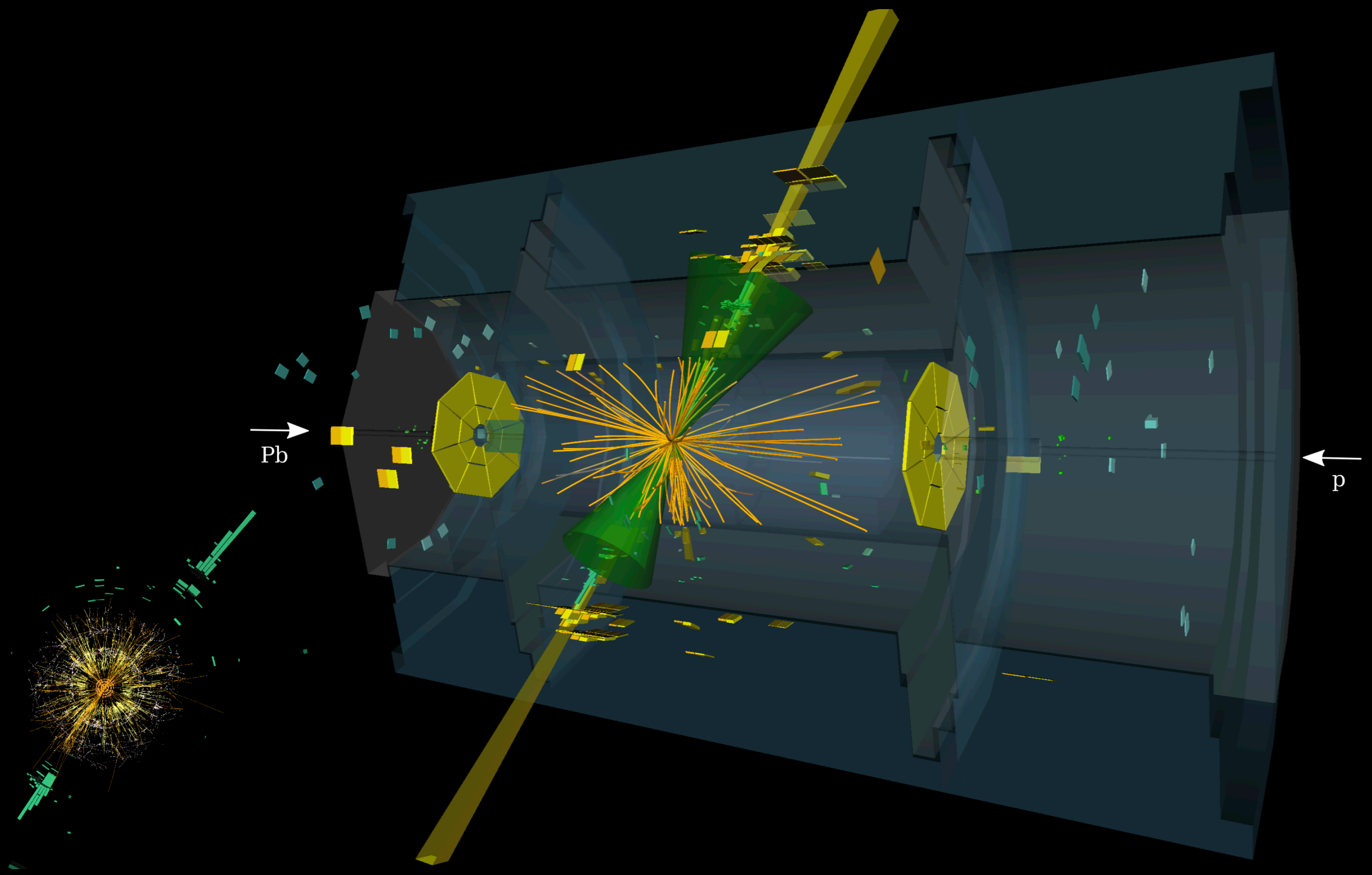
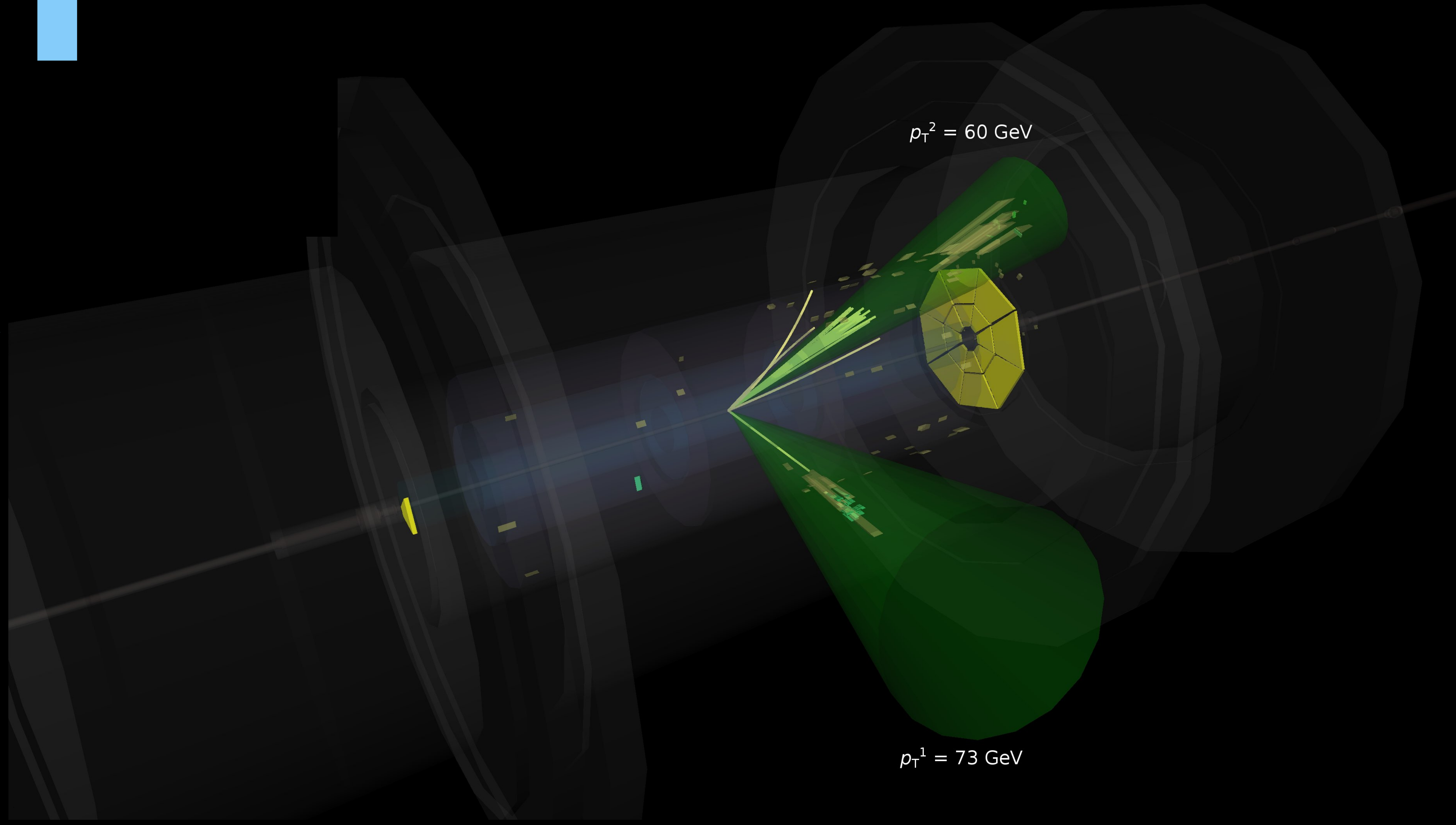


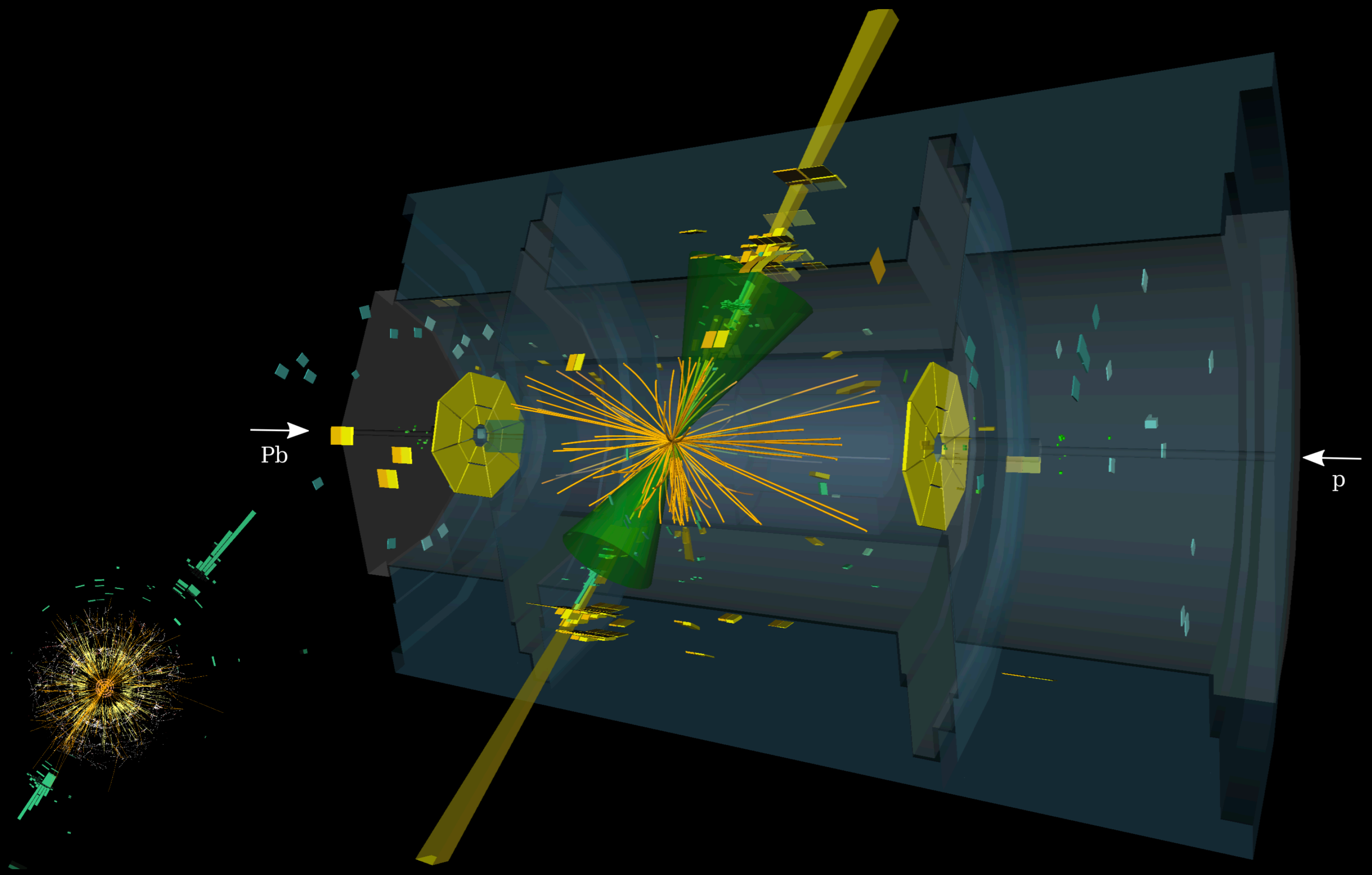
Results closely related to early physics goals of the EIC!

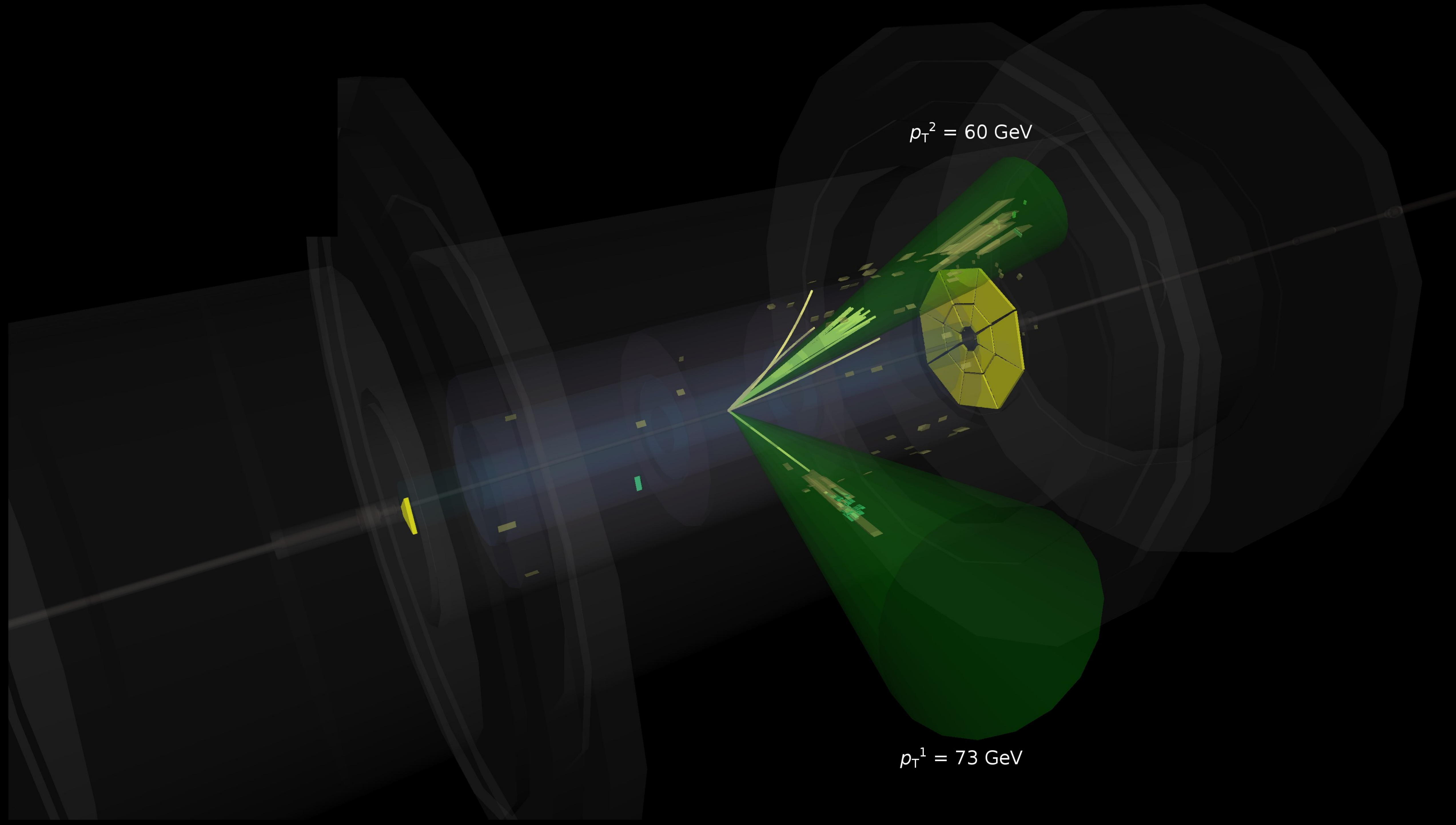
THANKS A LOT FOR YOUR ATTENTION!



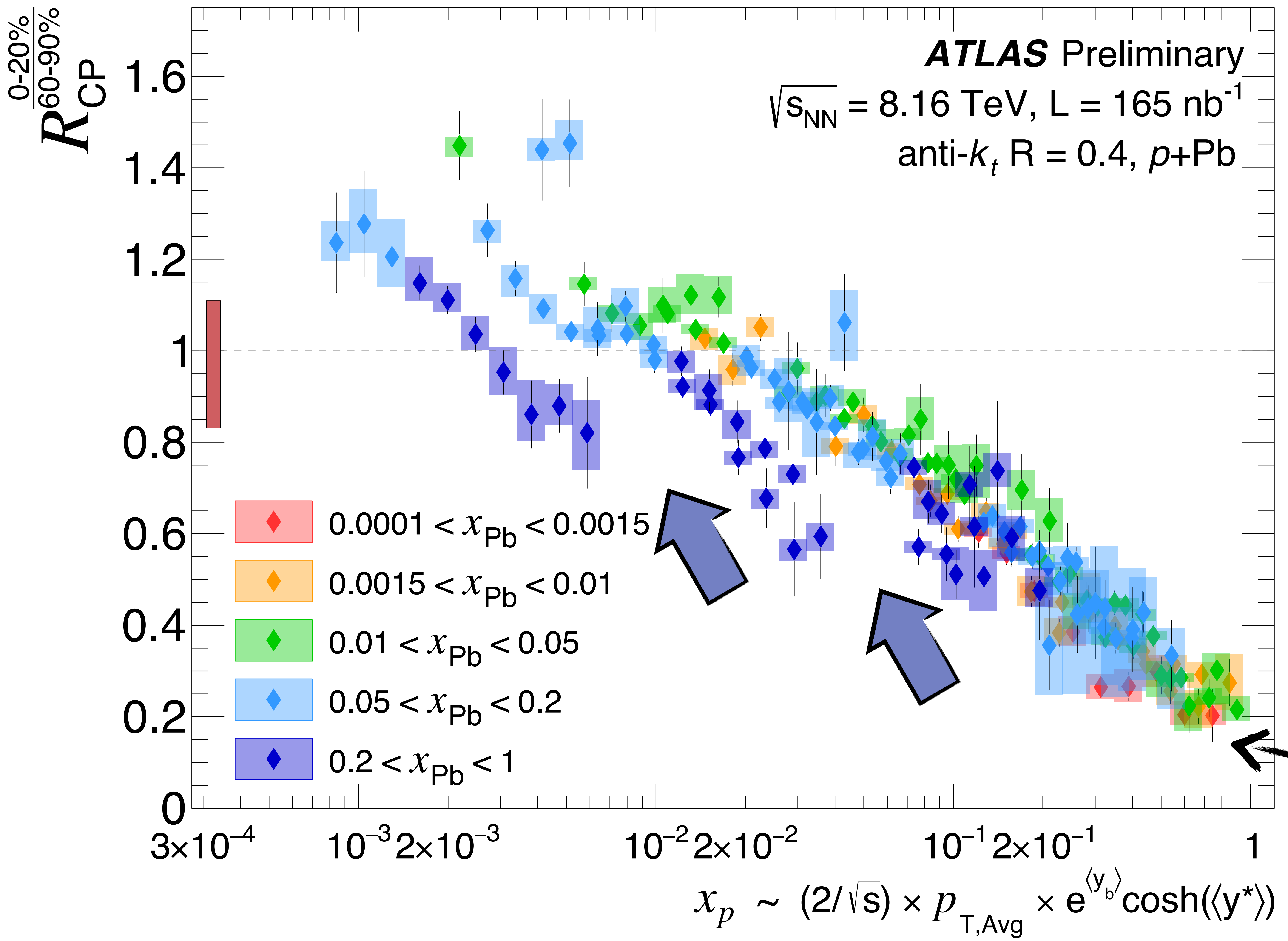


BACKUP SLIDES





DIJET R_{CP} (x_p) IN BINS OF x_{Pb}



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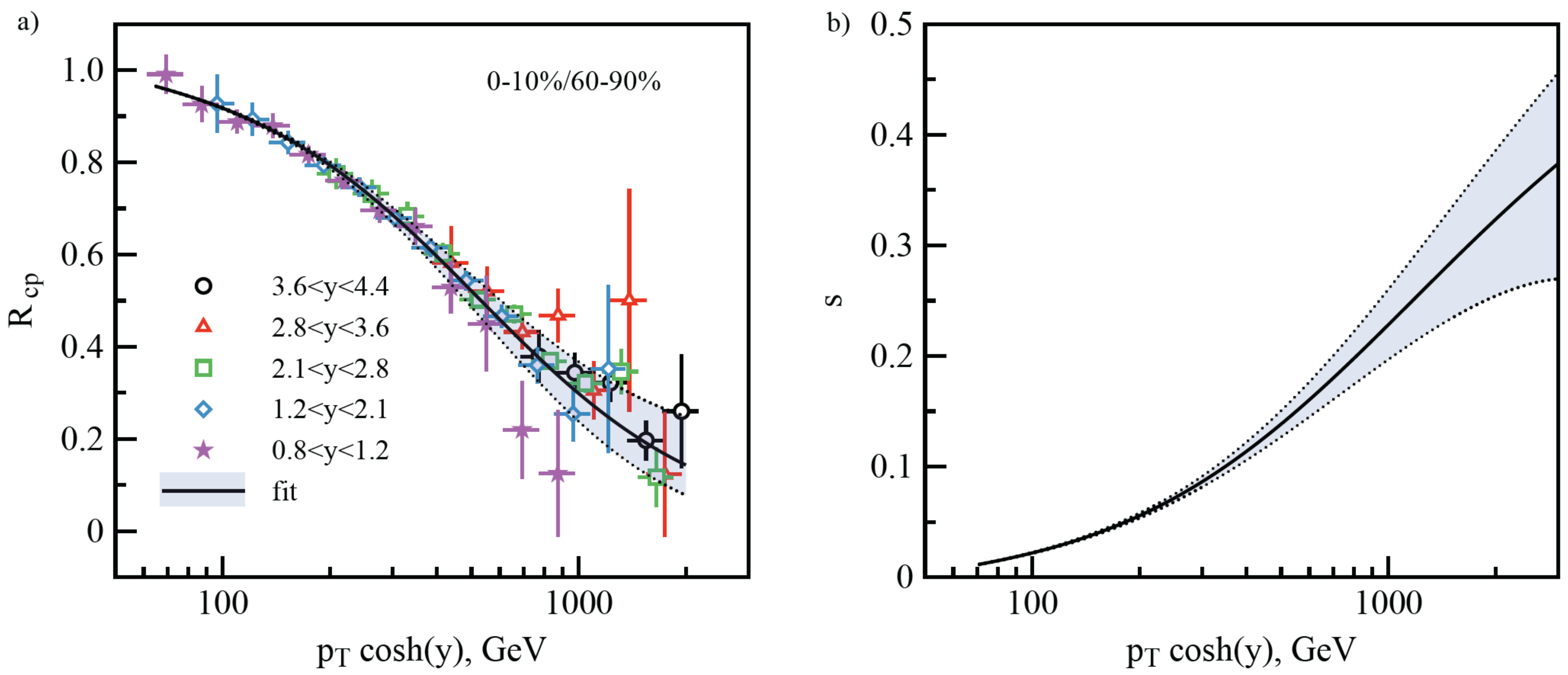
Results now displayed as a function of approximated x_p, in different intervals of approximated x_{Pb}

Intriguing break-down of the log-linear structure observed for results in the Pb **valence region**

Highest suppression observed corresponds to the **lowest x_{Pb} class of results**

JETS IN p+Pb: FURTHER INTERPRETATIONS (& DATA)

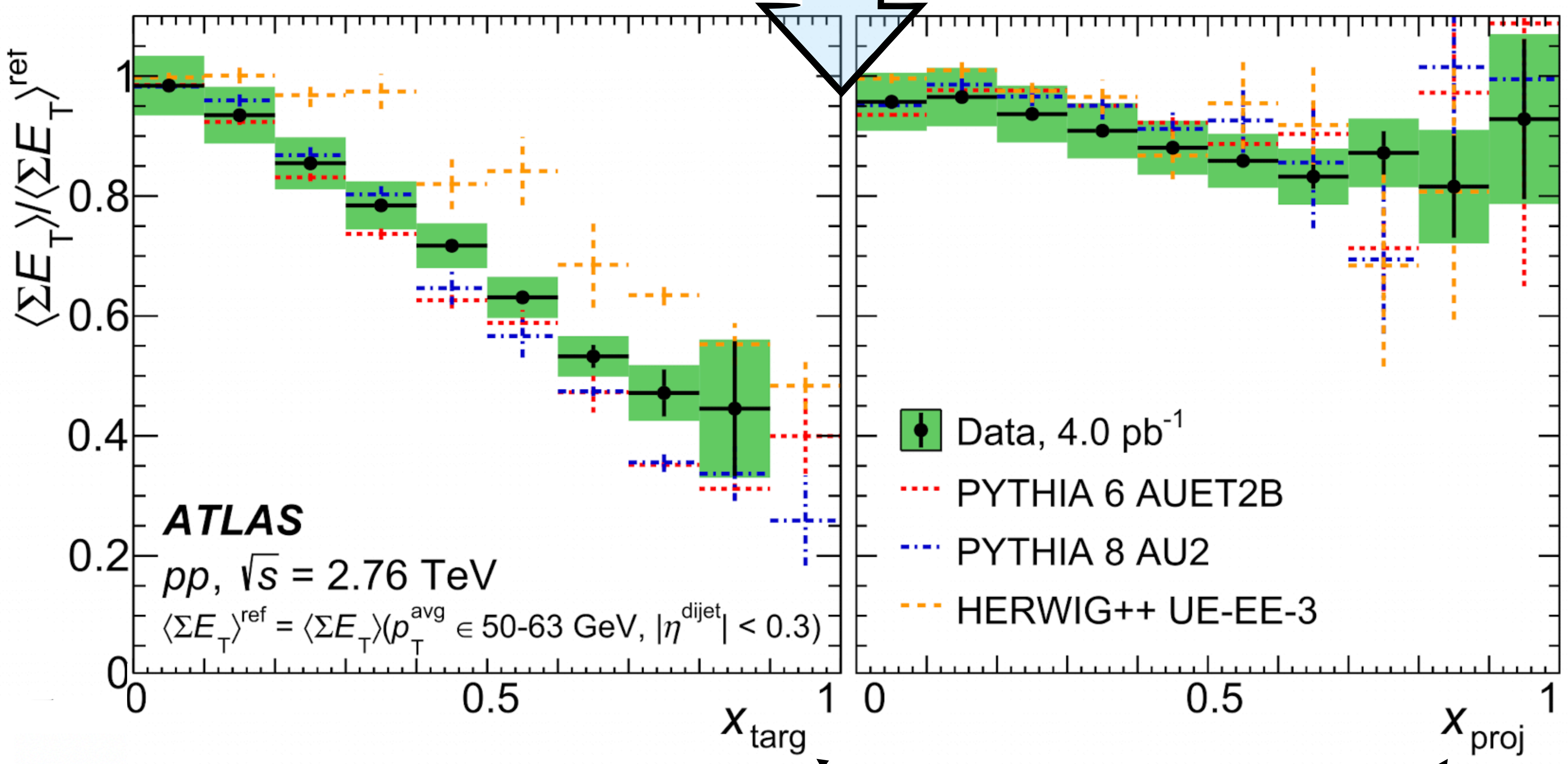
- Suppression of soft particle production dependent on the amount of energy removed from the projectile proton
  PRC 93 (2016) 044901

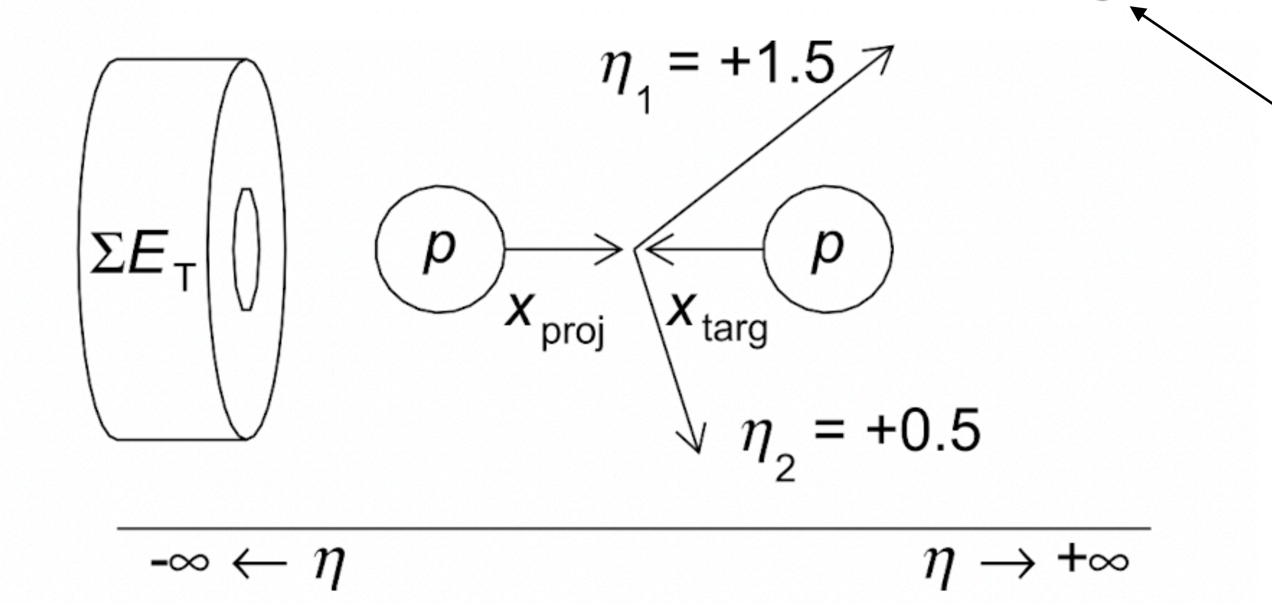


- Kinematic bias introduced by energy momentum conservation between the hard process and the production of soft particles **PLB 747 (2015) 441**

- Suppression of soft particle production away from the jet, caused by the depletion of energy available in the proton after the production of a hard jet
  PRC 97 (2018) 5, 054904

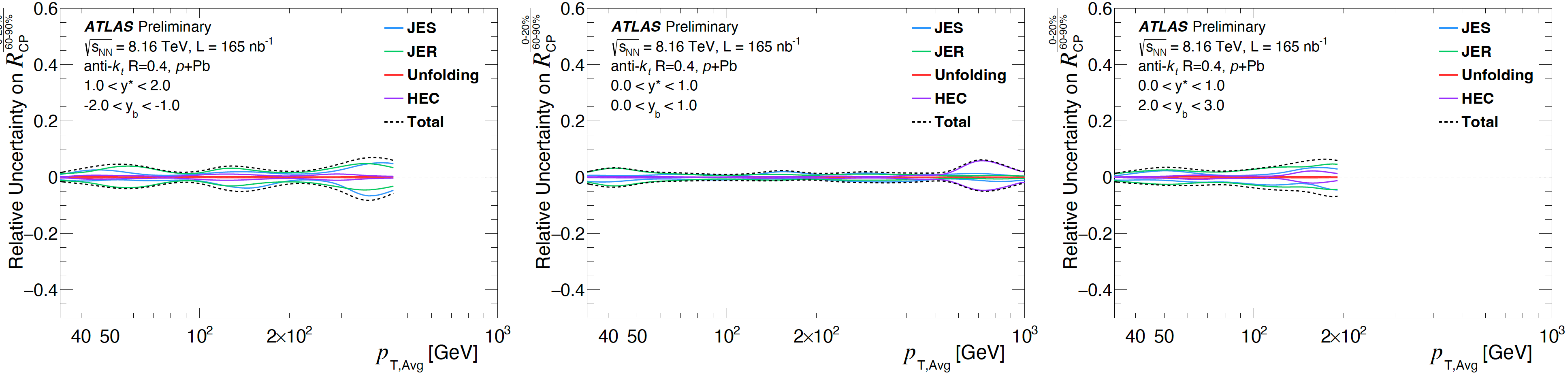
Measurement of the dependence of transverse energy production at large pseudorapidity on the hard-scattering kinematics of *pp* collisions at $\sqrt{s} = 2.76$ TeV with ATLAS
PLB 756 (2016) 10–28





Fractional momentum of the initial state partons extracted from target and projectile

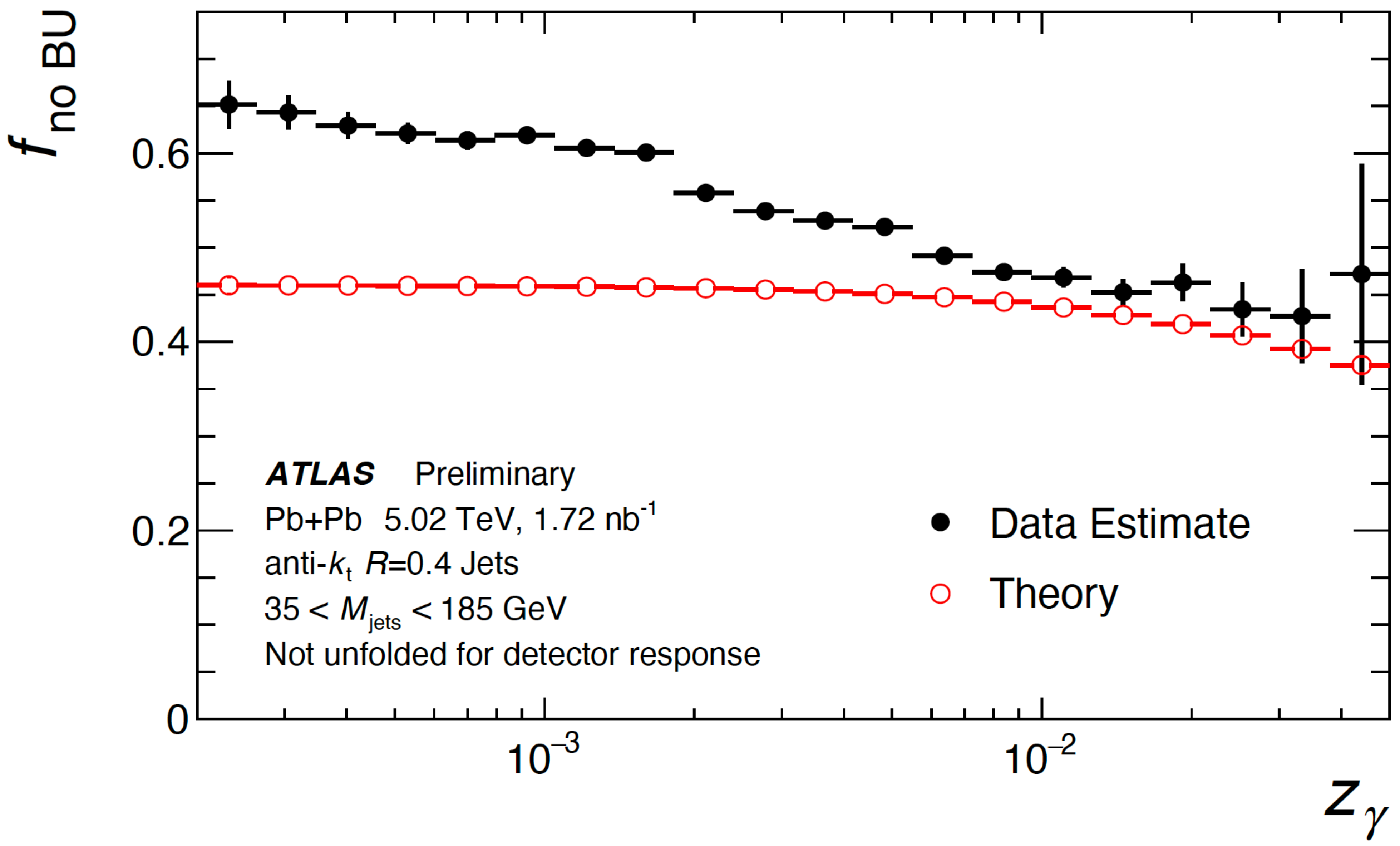
R_{CP}: SYSTEMATIC UNCERTAINTY



- Dominant source of systematic uncertainty on the R_{CP} is associated to the Jet Energy Resolution (JER)
- Other uncertainties assigned are associated to the Jet Energy Scale (JES), the unfolding procedure, the exclusion of a portion of the Hadronic Endcap Calorimeter (HEC) that was disabled during the 2016 run and the evaluation of the nuclear overlap function T_{AB}
- All of the systematic uncertainties, except for the one related to the unfolding, are treated as correlated in the R_{CP}

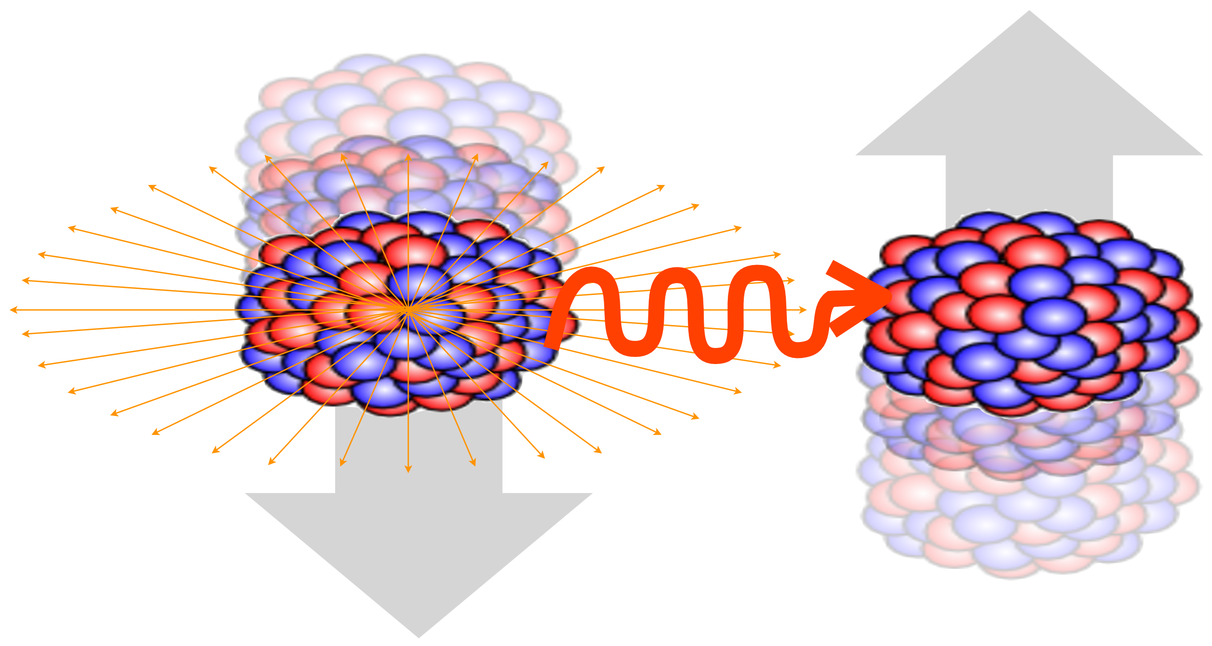
XnXn EVENTS

- Photo-nuclear jet events requirements select events with high-energy photons
  - $E_\gamma \propto 1/b$ ➡ Bias toward lower impact parameter of the collisions

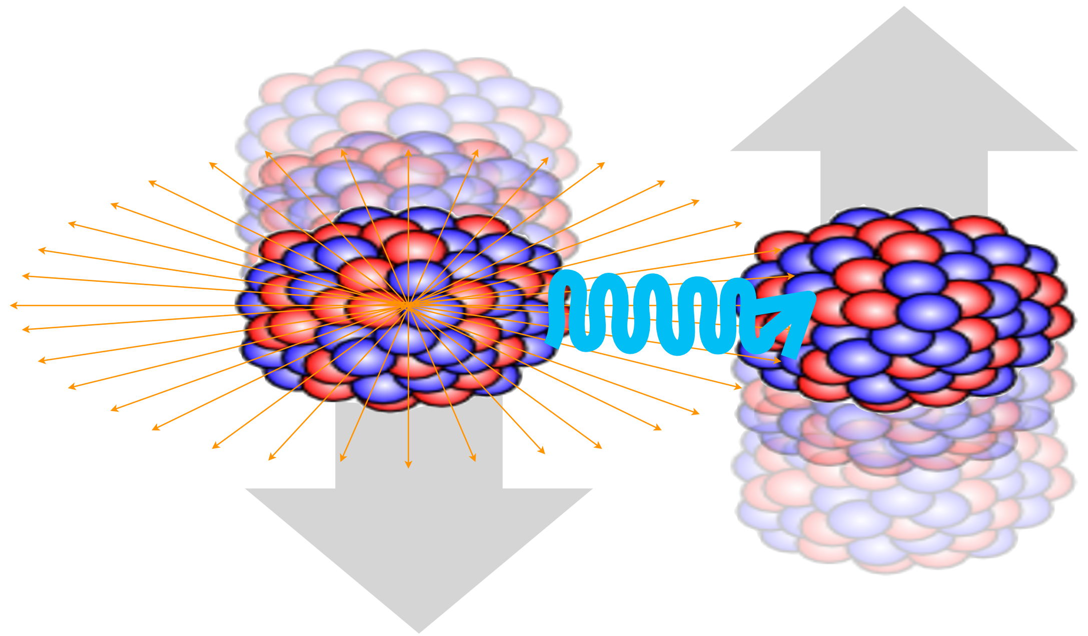


$$f_{\text{no BU}} \equiv \frac{d\sigma/dz_\gamma|_{0nXn}}{d\sigma/dz_\gamma|_{XnXn} + d\sigma/dz_\gamma|_{0nXn}}$$

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

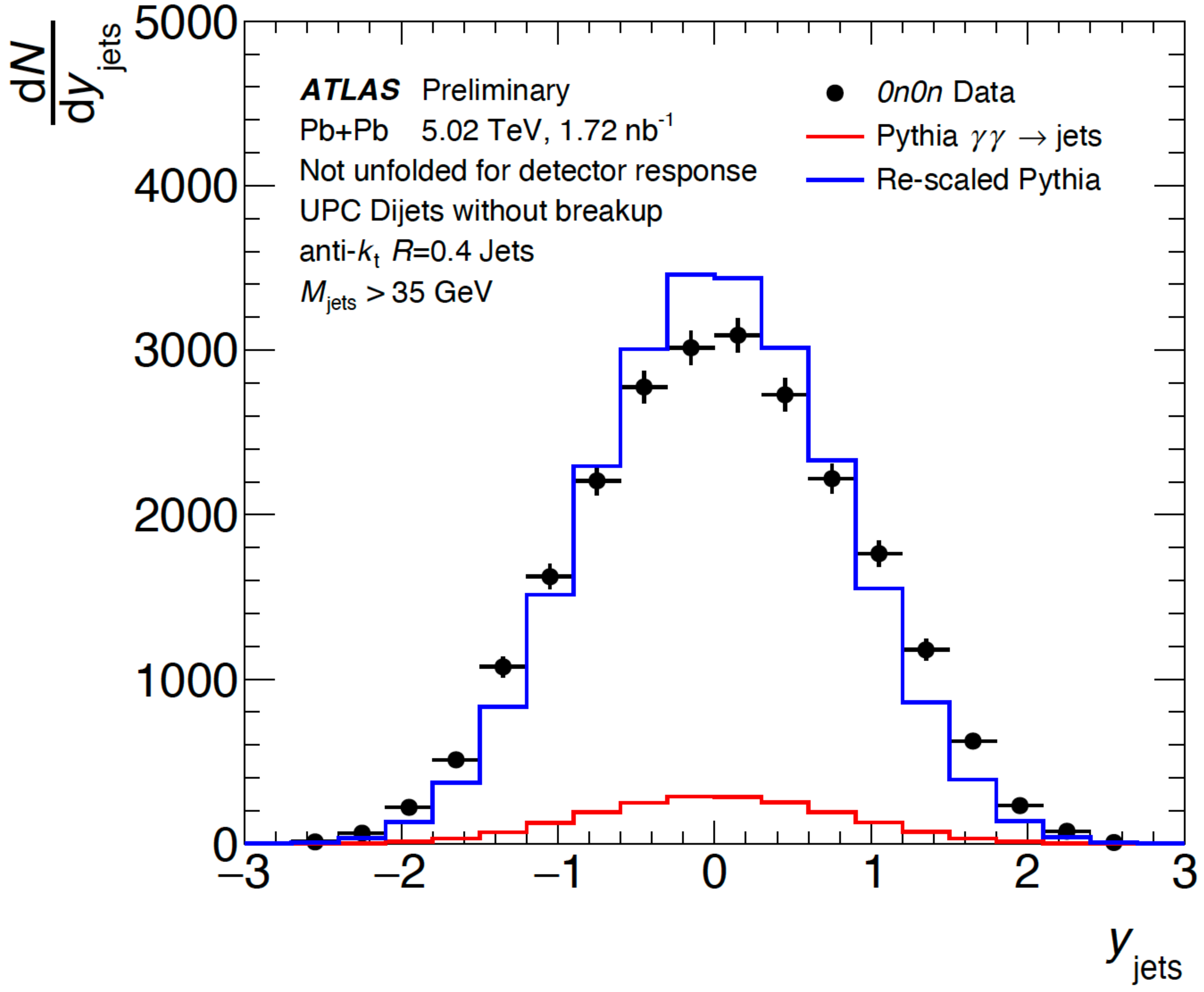


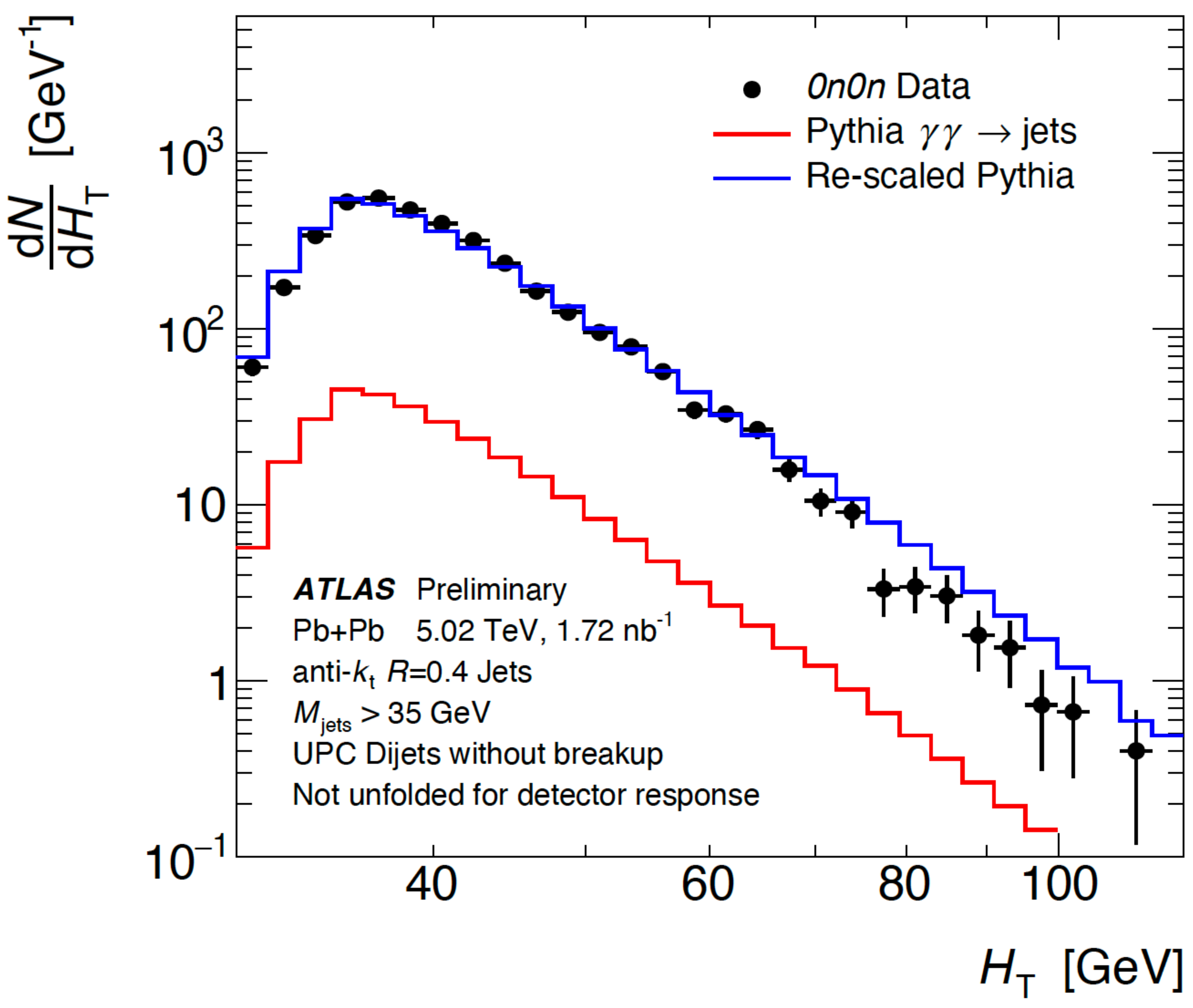
Basic theoretical modeling predicts an even higher rate

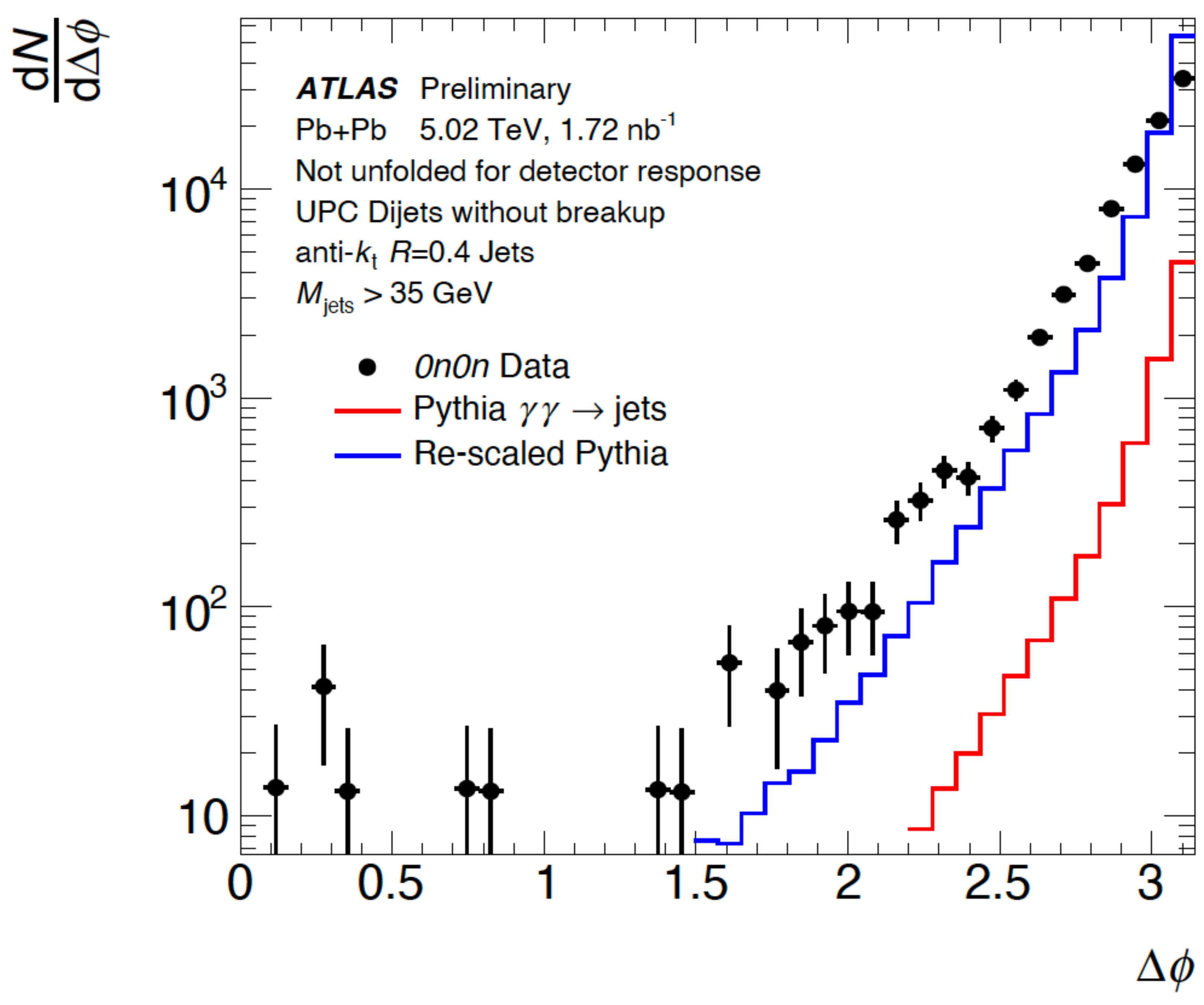


DIJET PRODUCTION W/O NUCLEAR BREAKUP

- Tagged requiring 0n0n pattern in the ATLAS ZDC and gaps on both side of the detector
- Originated by $\gamma\,\gamma$ scattering or diffractive photo-production
- A factor of 10 more events are observed in data than are predicted from $\gamma\,\gamma \rightarrow$jets, estimated by Pythia







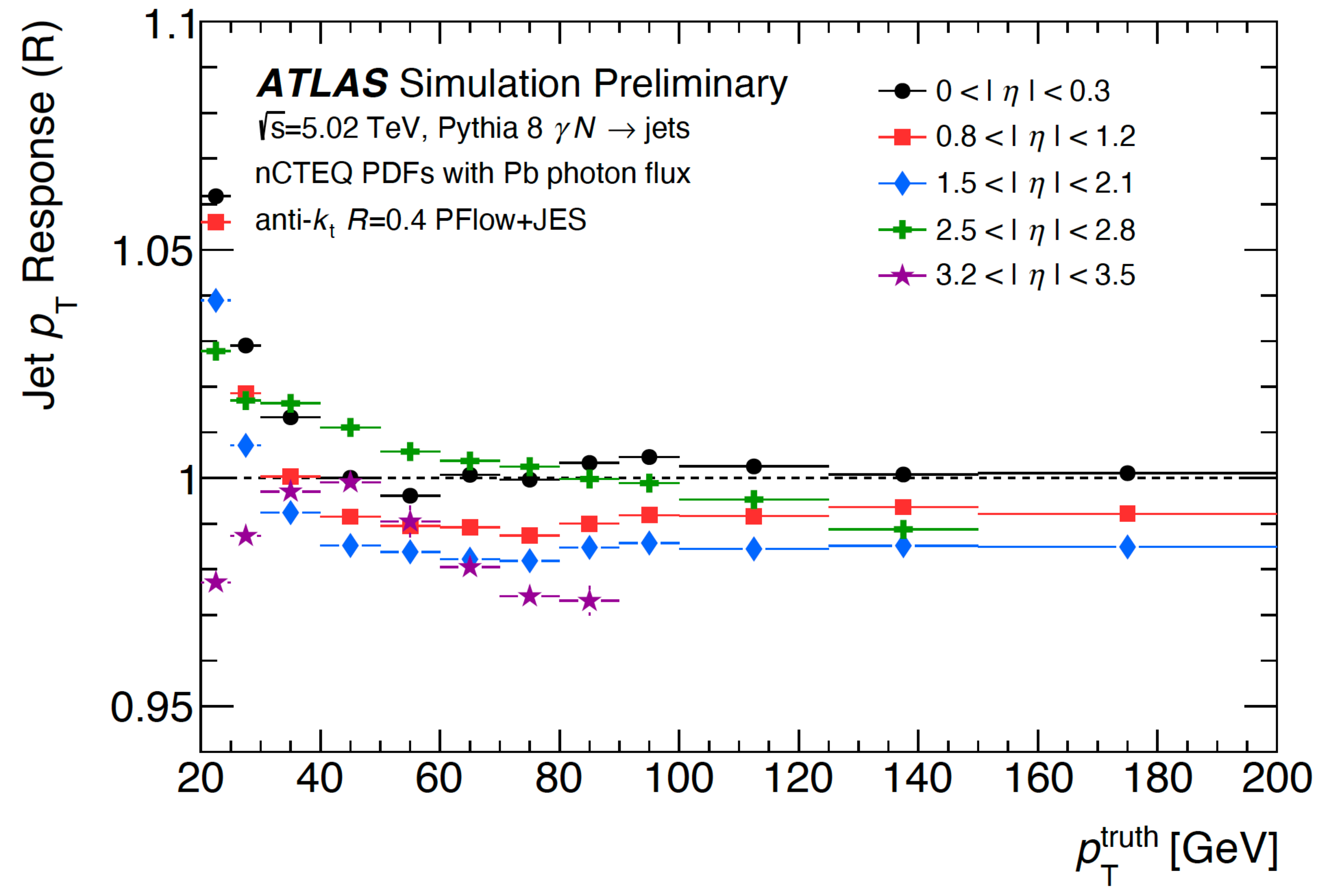
THEORETICAL MODEL OF NUCLEAR BREAKUP

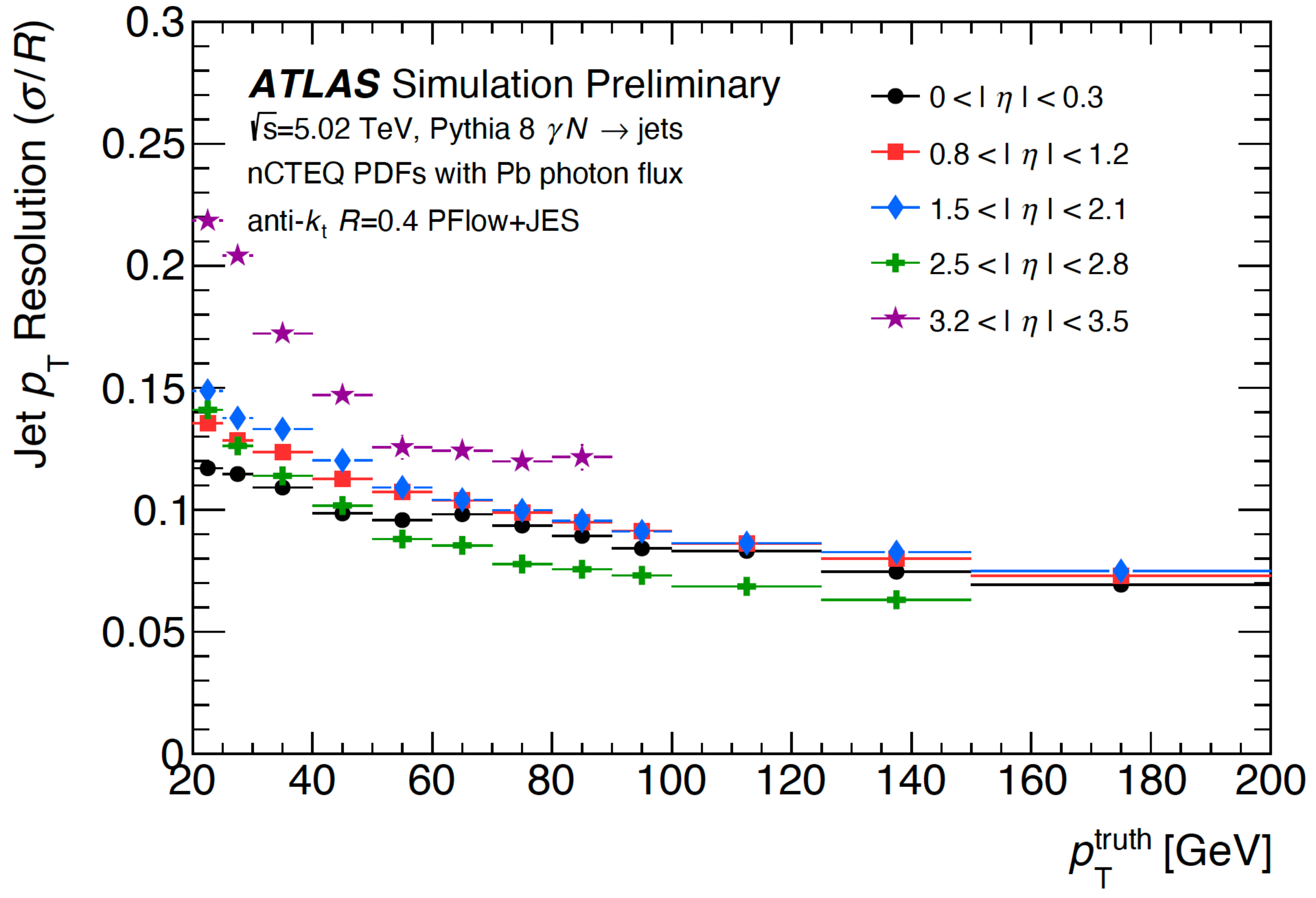
- Pythia8 allows for generation of γ+A collisions
  - The photons is taken from the equivalent flux of a lepton or a nucleon beam
  - Photon energy distribution treated as an attribute of one of the incident beams and not a feature of the full collision system → can't fully describe UPC

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

- New integrated flux factor introduced to improve comparison with data. It includes:
  - **Integration over** A-A impact parameter (***b***) and impact parameter relative to the photon emitting nucleus (**s_A**)
  - Correction for the probability of no **hadronic** or **electromagnetic breakup** occurs (from STARlight)
  - Correction to Pythia8 point source treatment to turn it into **coherent nuclear emission.**
  - **Nuclear thickness function**

JET RECONSTRUCTION PERFORMANCE IN Pb+Pb





- Small deviations in the jet energy scale arise due to differences between the sample in which the calibration was derived (inclusive jets in $\sqrt{s}$ = 13 TeV *pp* collisions) and this one due to the fact that the calibration is derived and applied as a function of E and not p_T.

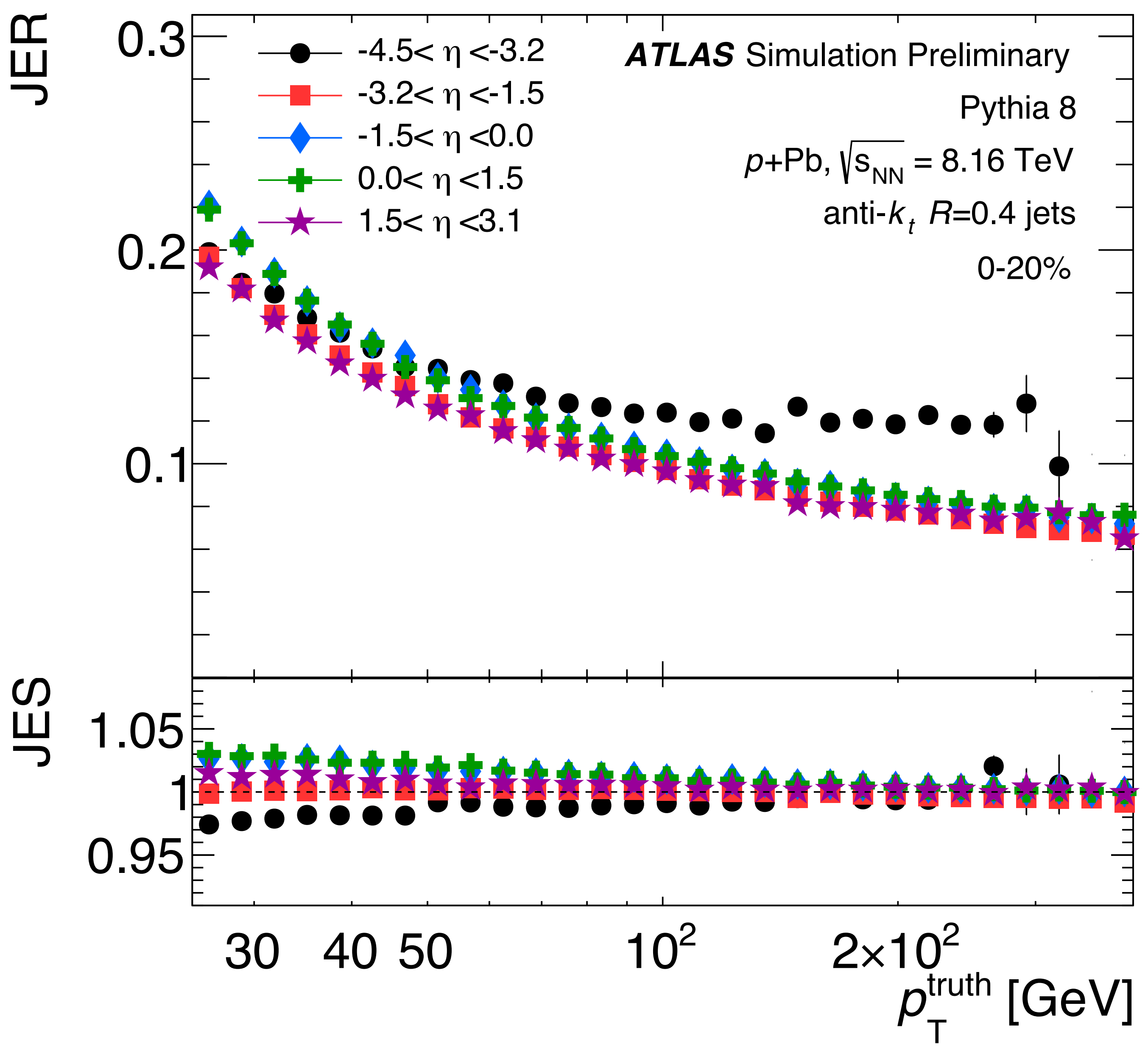
- Better resolution at low p_T compared to *pp* thanks to lower pile-up level in Pb+Pb

- All the JES and JER effects corrected for at level of unfolding of the detector effects

JET RECONSTRUCTION PERFORMANCE IN p+Pb

- Jet Energy Resolution (JER) and Jet Energy Scale (JES) compatible between the two beam orientations
- JES and JER corrected for at level of unfolding
- Jet reconstruction efficiency > 99% in all the η regions of the calorimeter for $p_{\mathrm{T}}^{\mathrm{truth}} = 25\,\mathrm{GeV}$
- No significant dependence on the centrality of the collision

Central collisions (0-20%)



Peripheral collisions (0-20%)