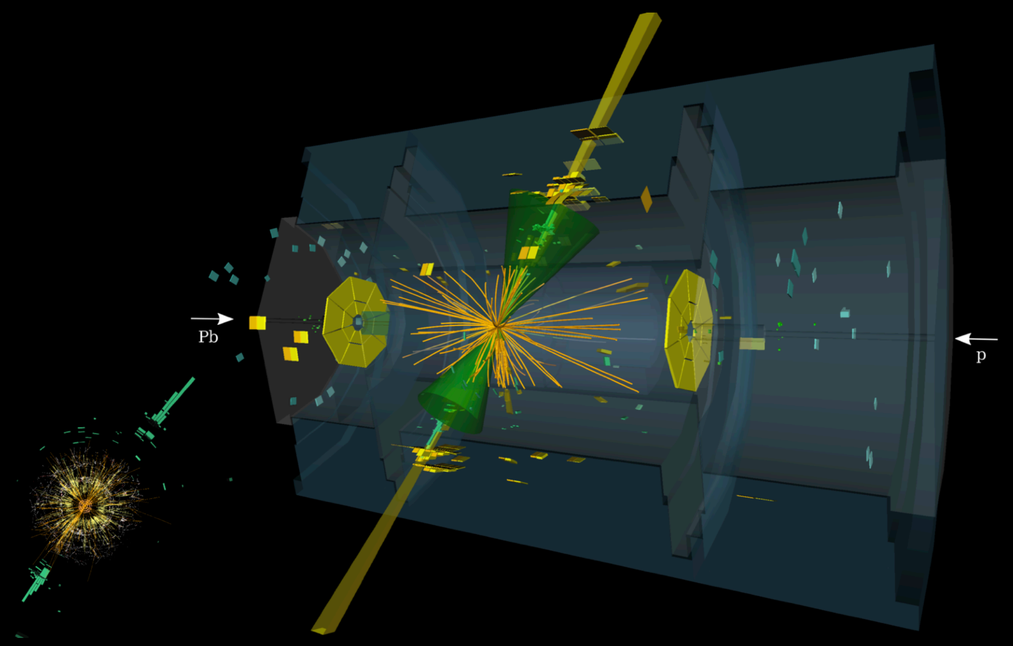


Investigation of initial state effects in p+Pb collisions at ATLAS via measurement of dijet production

Riccardo Longo
On behalf of the ATLAS Collaboration

29th March 2023
11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

ATLAS EXPERIMENT

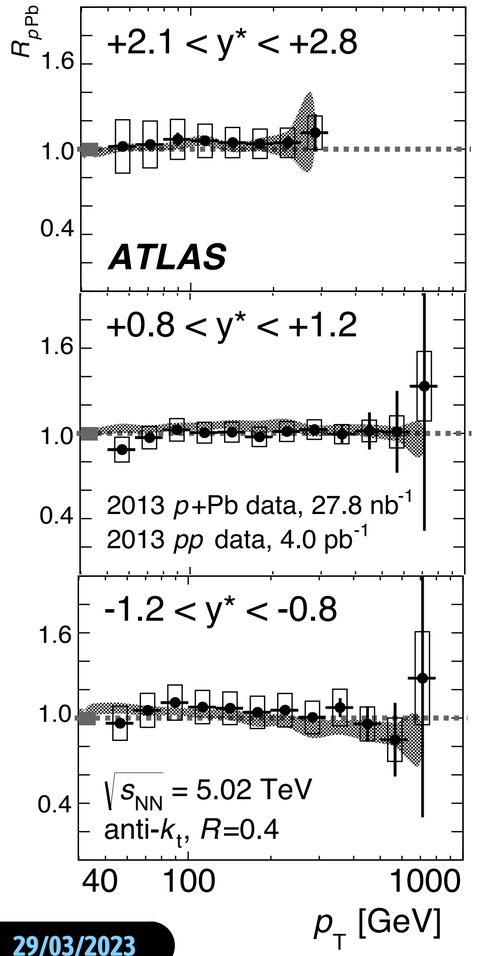
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

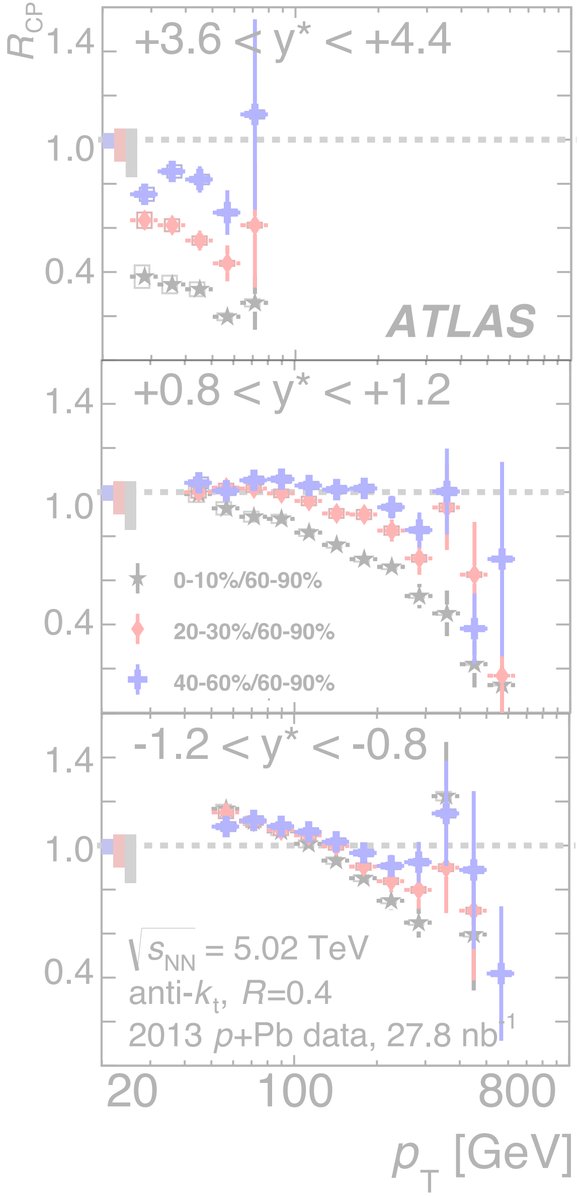
NSF

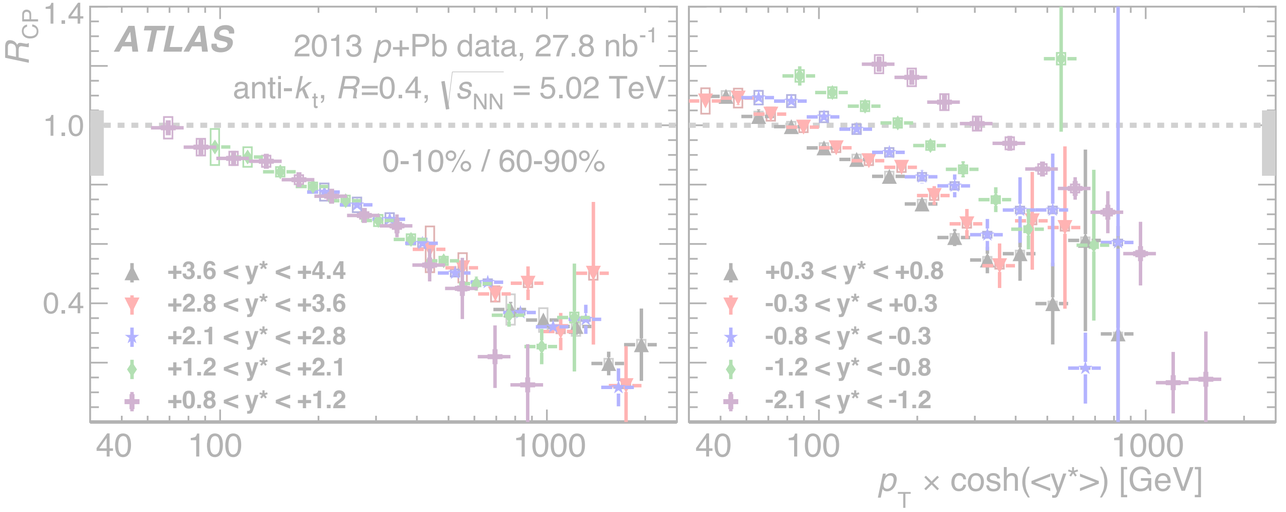
2023 HARD PROBES Aschaffenburg

JETS AS HARD PROBES IN p+Pb COLLISIONS

Centrality and rapidity dependence of **inclusive jet production** in $\sqrt{s_{NN}} = 5.02$ TeV p+Pb collisions with the ATLAS detector
PLB 748 (2015) 392–413







- Measurement of double-differential (p_T, y^*) per-collision jet yield in different centralities
- R_{pPb} results - no evidence for large modification of the total yield of jets relative to the geometric expectation observed
- 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
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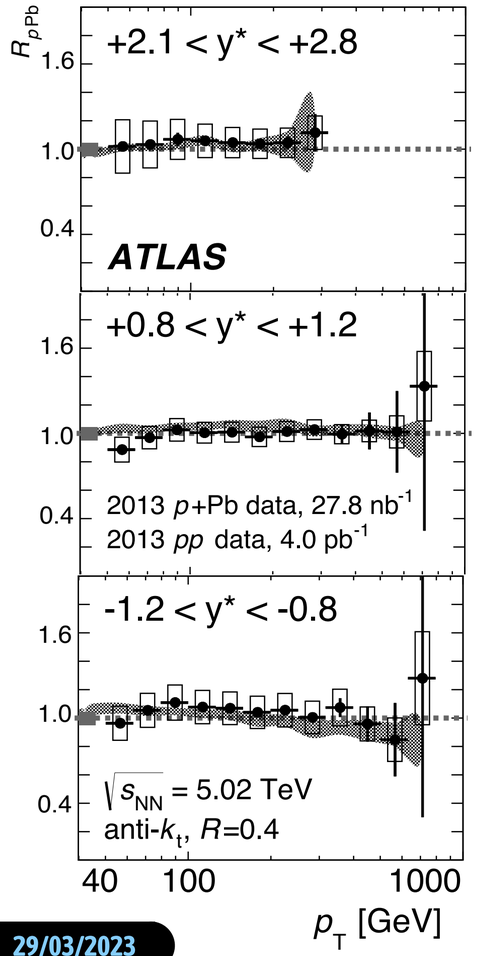

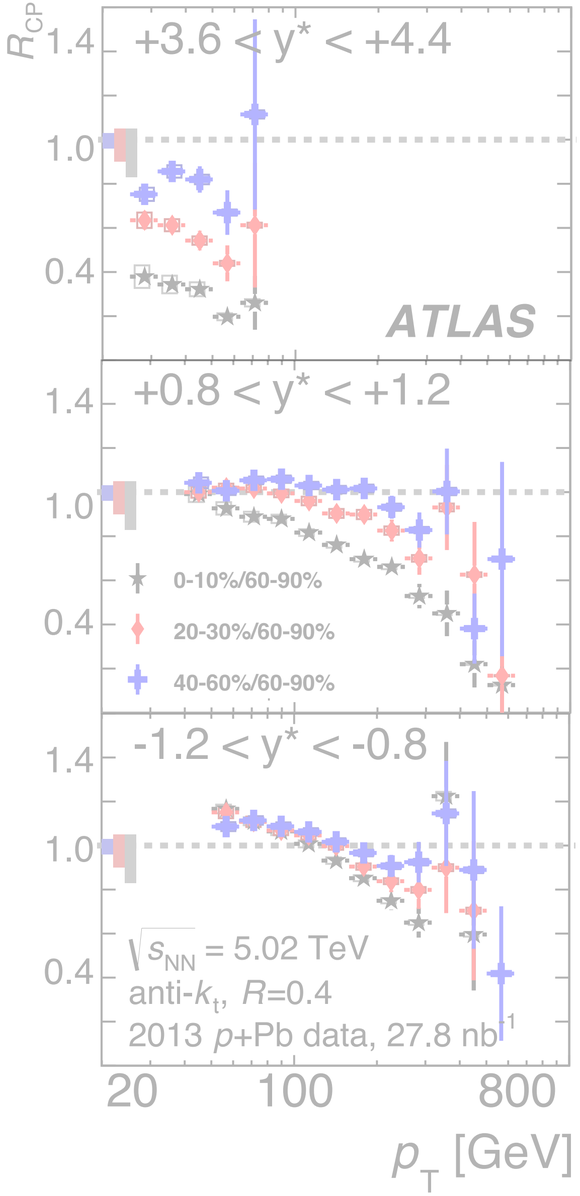

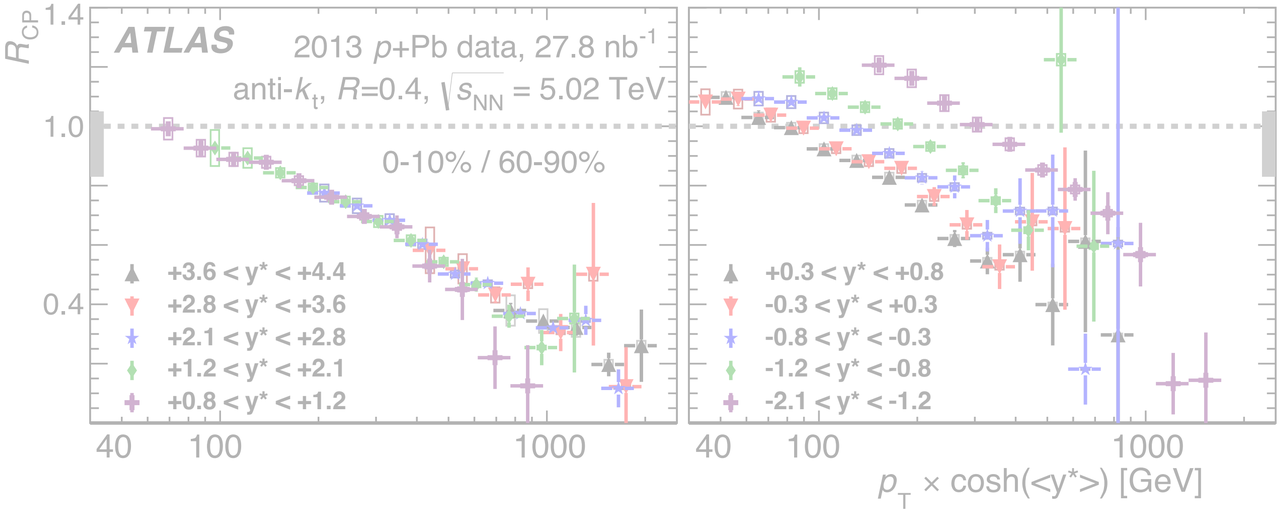

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Reminder: no evidence for jet quenching in p+Pb. See talk by J.Nagle on Thu 10:20, "Strong constraints on jet quenching in centrality-dependent p+Pb collisions at 5.02 TeV from ATLAS

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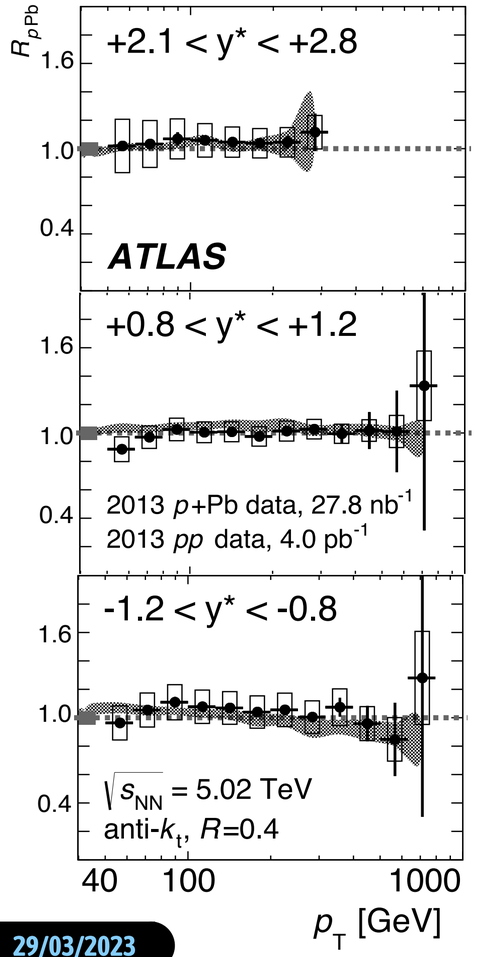

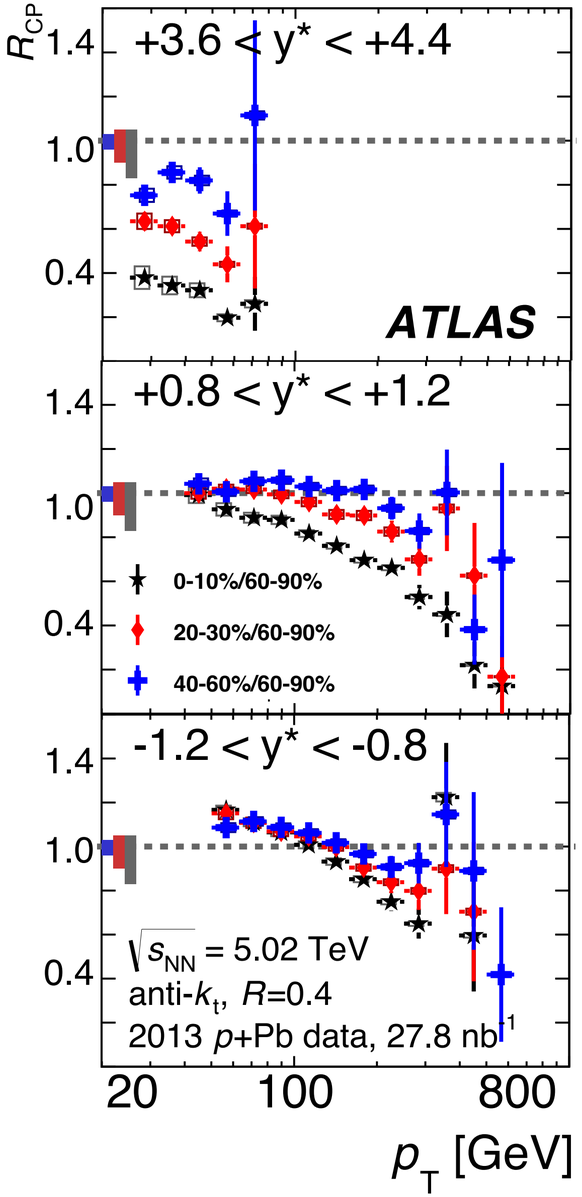

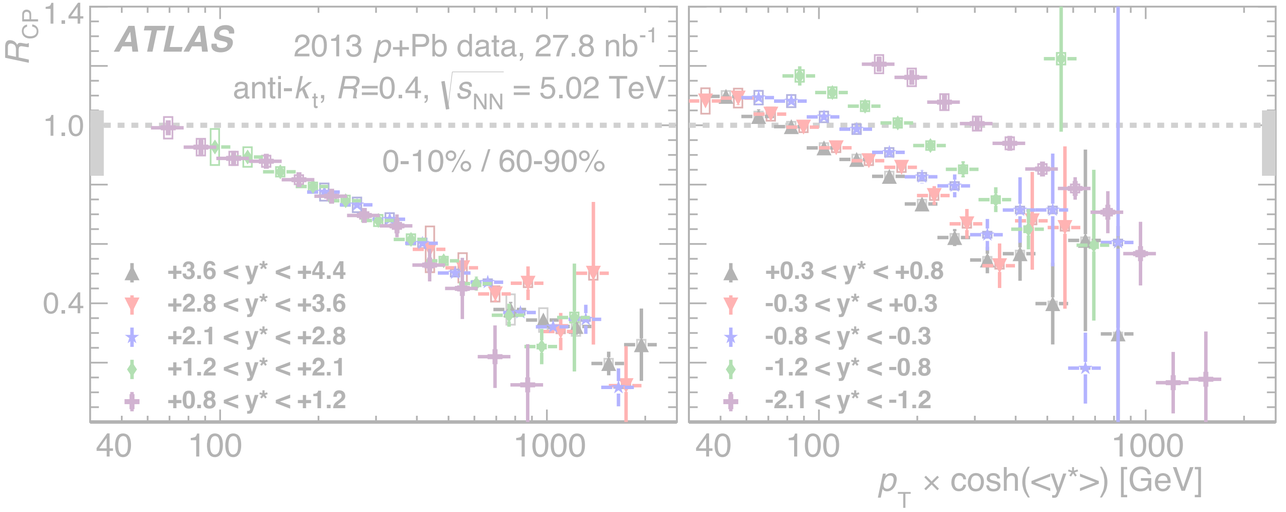

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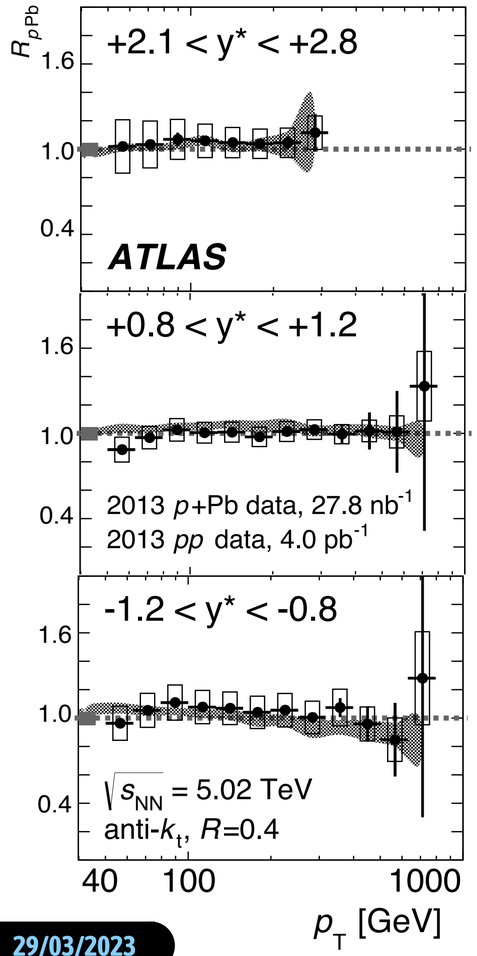

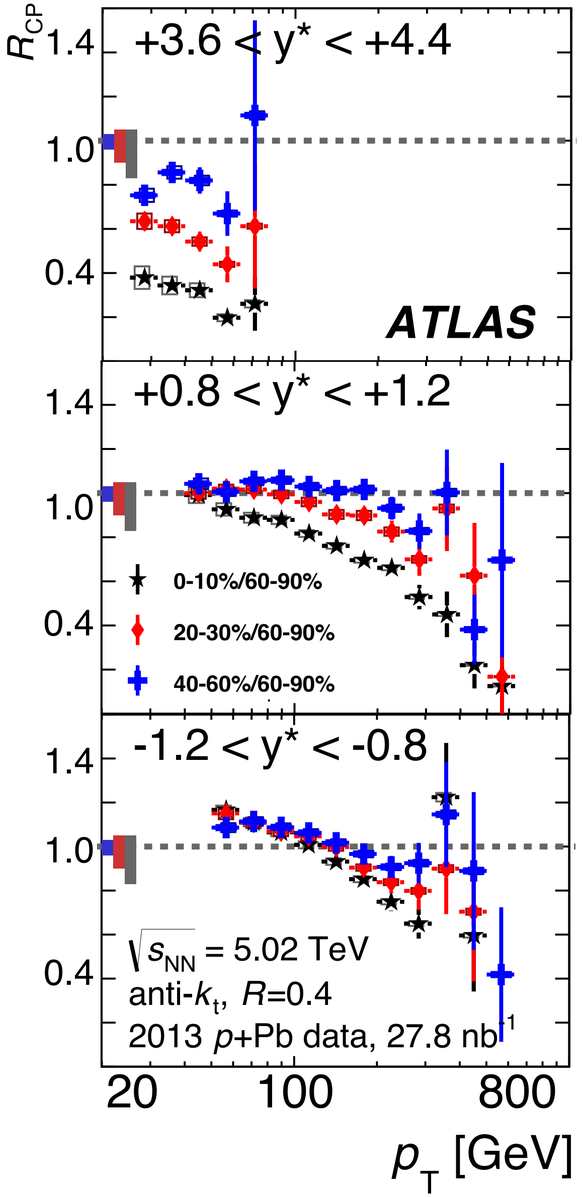

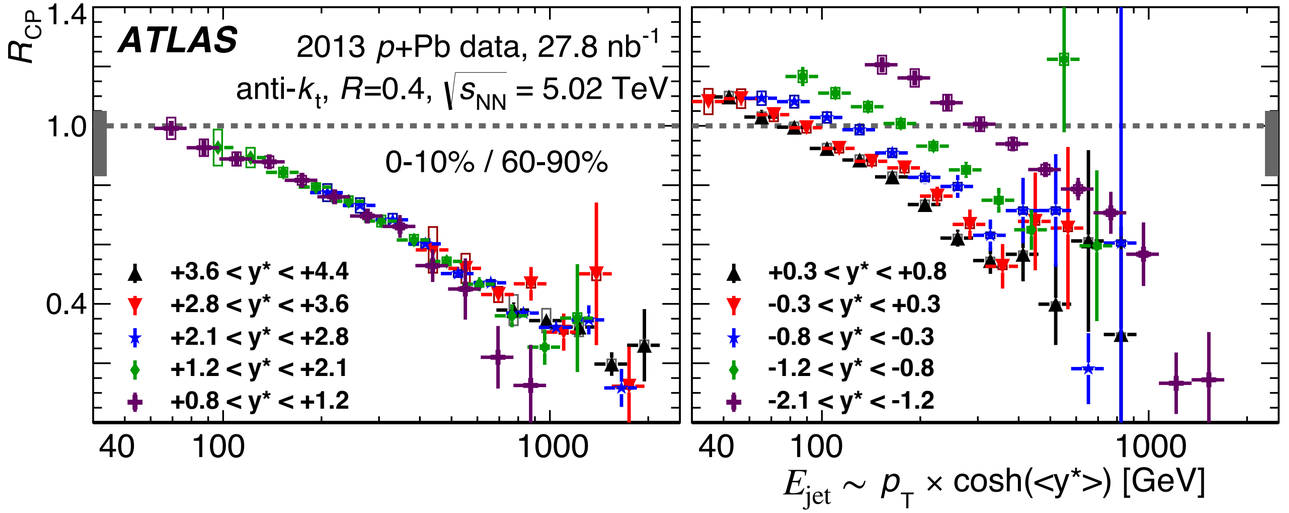

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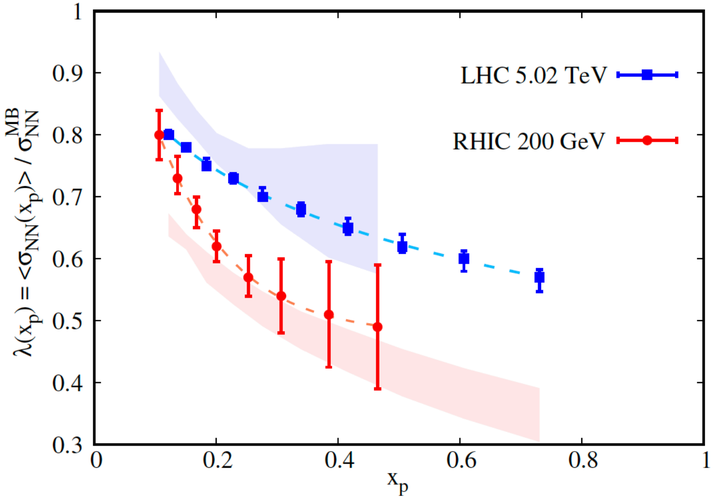
JETS AS HARD PROBES IN p+Pb COLLISIONS

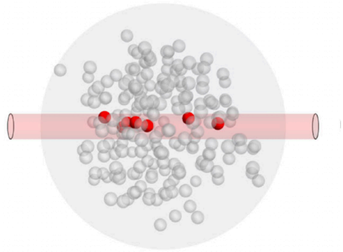
PRD 98 (2018) 071502

- *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*)

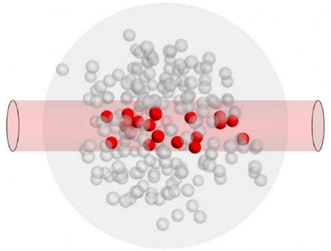


- x_p-dependent shrinking of the average interaction strength at a given collision energy:
$\lambda(x_p) = \langle\sigma_{NN}^{MB}\rangle(x_p)/\sigma_{NN}^{MB}$

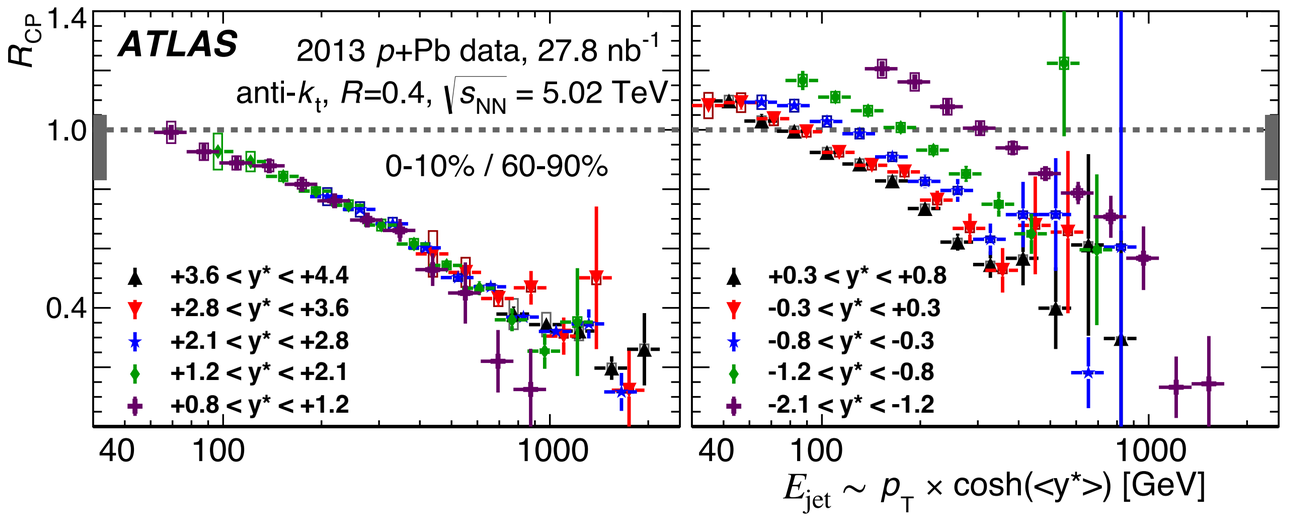
***p* w/ high-x parton**

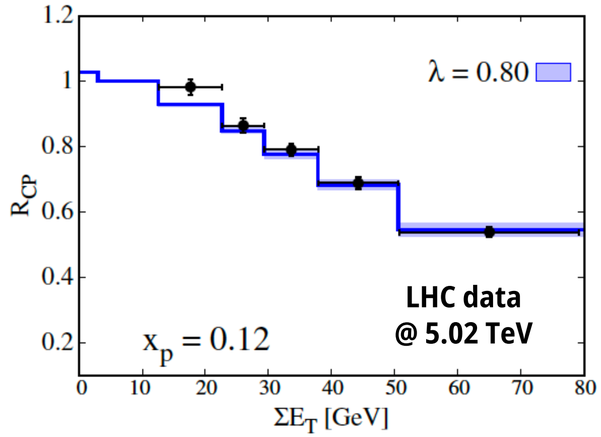


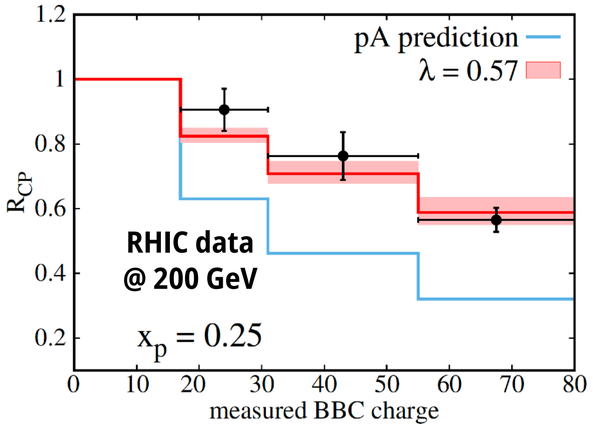
***p* w/ average configuration**



PLB 748 (2015) 392–413





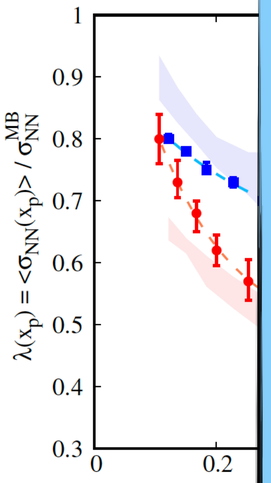


- Model capable of describing both LHC (*p*+Pb - ↑) and RHIC data (PHENIX, *d*+Au @ 200 GeV - **PRL 116, 122301 (2016)**)

DIJETS HARD PROBES IN p+Pb COLLISIONS

PRD 98 (2018) 071502

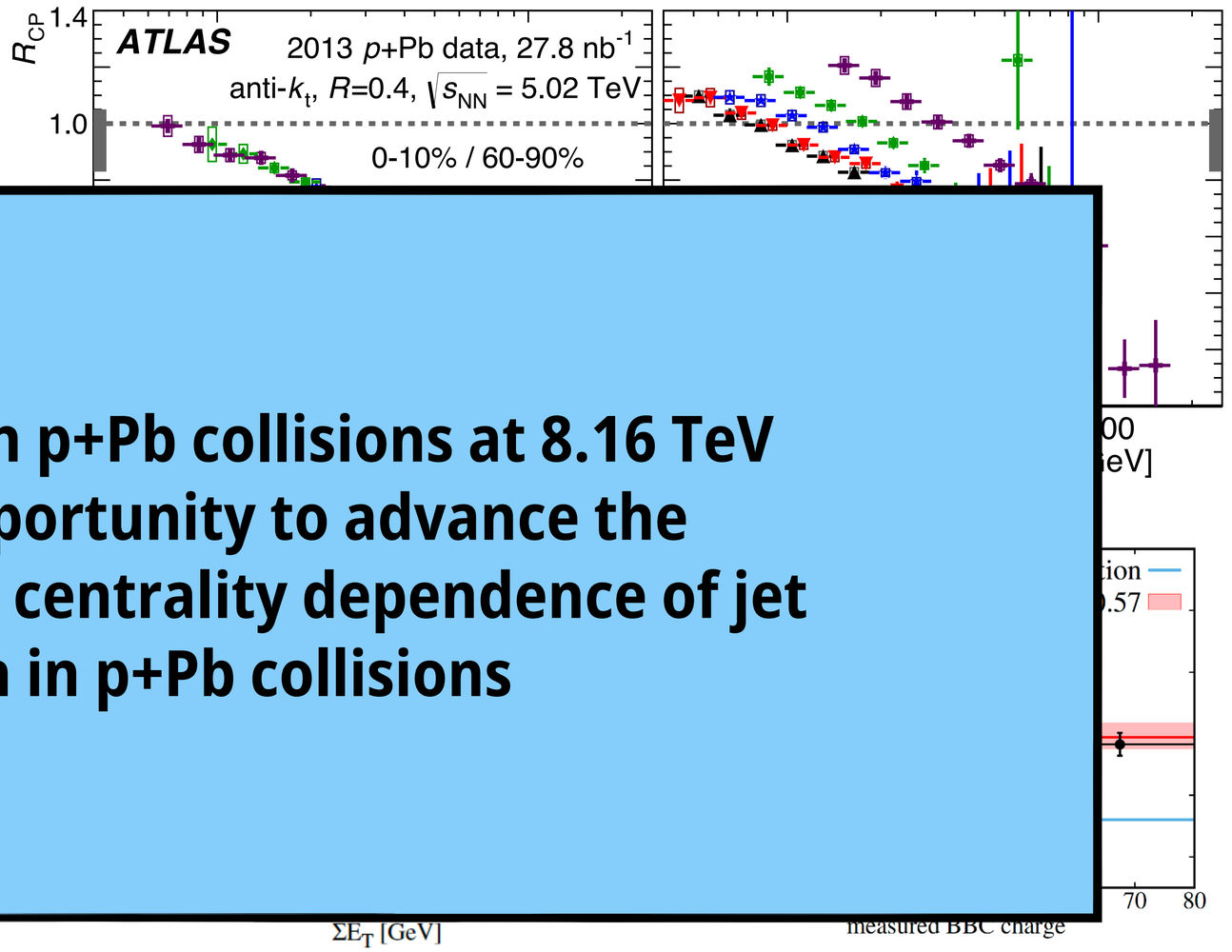
- *p* containing a parton with large x interacts with a nuclear target with smaller than average cross-section
  of color



- x_p-deper
  average interaction strength at a given collision energy:
  $\lambda(x_p) = \langle\sigma_{NN}^{MB}\rangle(x_p)/\sigma_{NN}^{MB}$

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

PLB 748 (2015) 392–413



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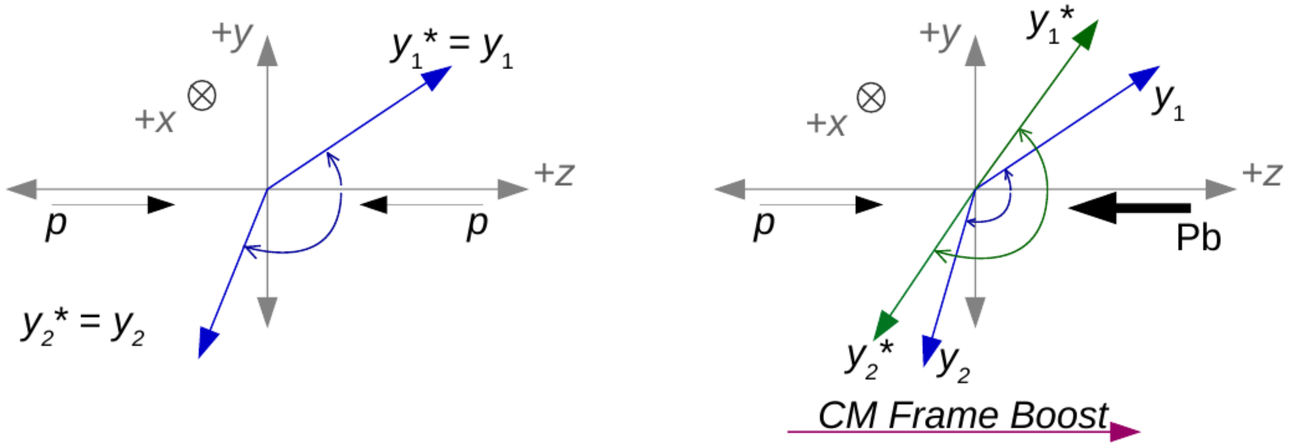
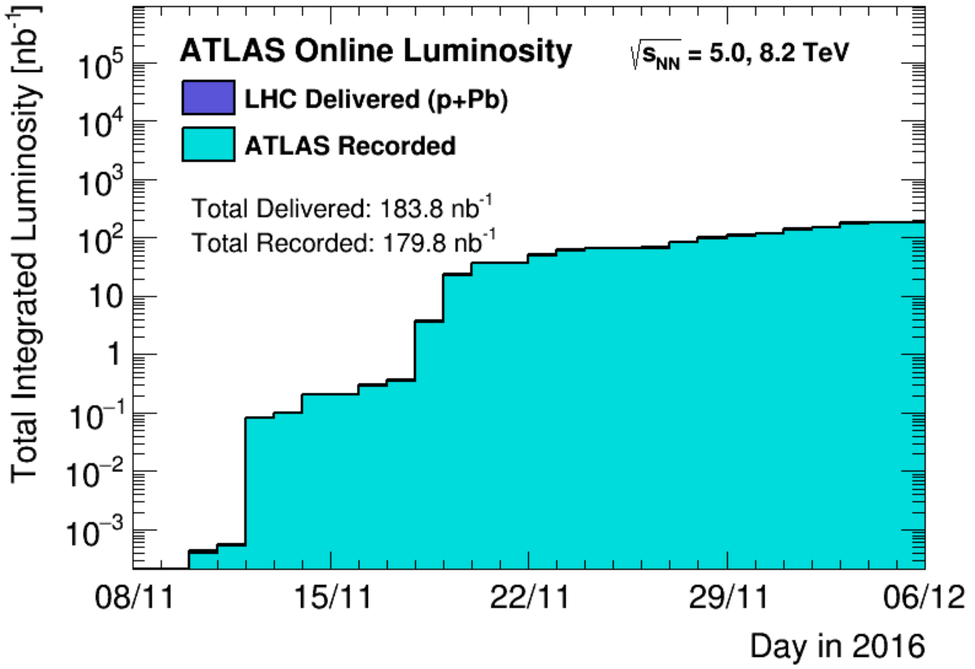
ATLAS 2016 p+Pb DATA @ 8.16 TeV



- 165 nb^{-1} collected with two beam orientations
  - p+Pb: p going from positive to negative η ($\Delta y^{\mathrm{CM}} = -0.465$)
  - Pb+p: p going from negative to positive η ($\Delta y^{\mathrm{CM}} = +0.465$)
- Largest p+Pb dataset collected to date by ATLAS
- Enough statistics for triple differential analysis in different centrality intervals
- $\langle\mu\rangle$ ranging from 0.15 to 0.3 across the run

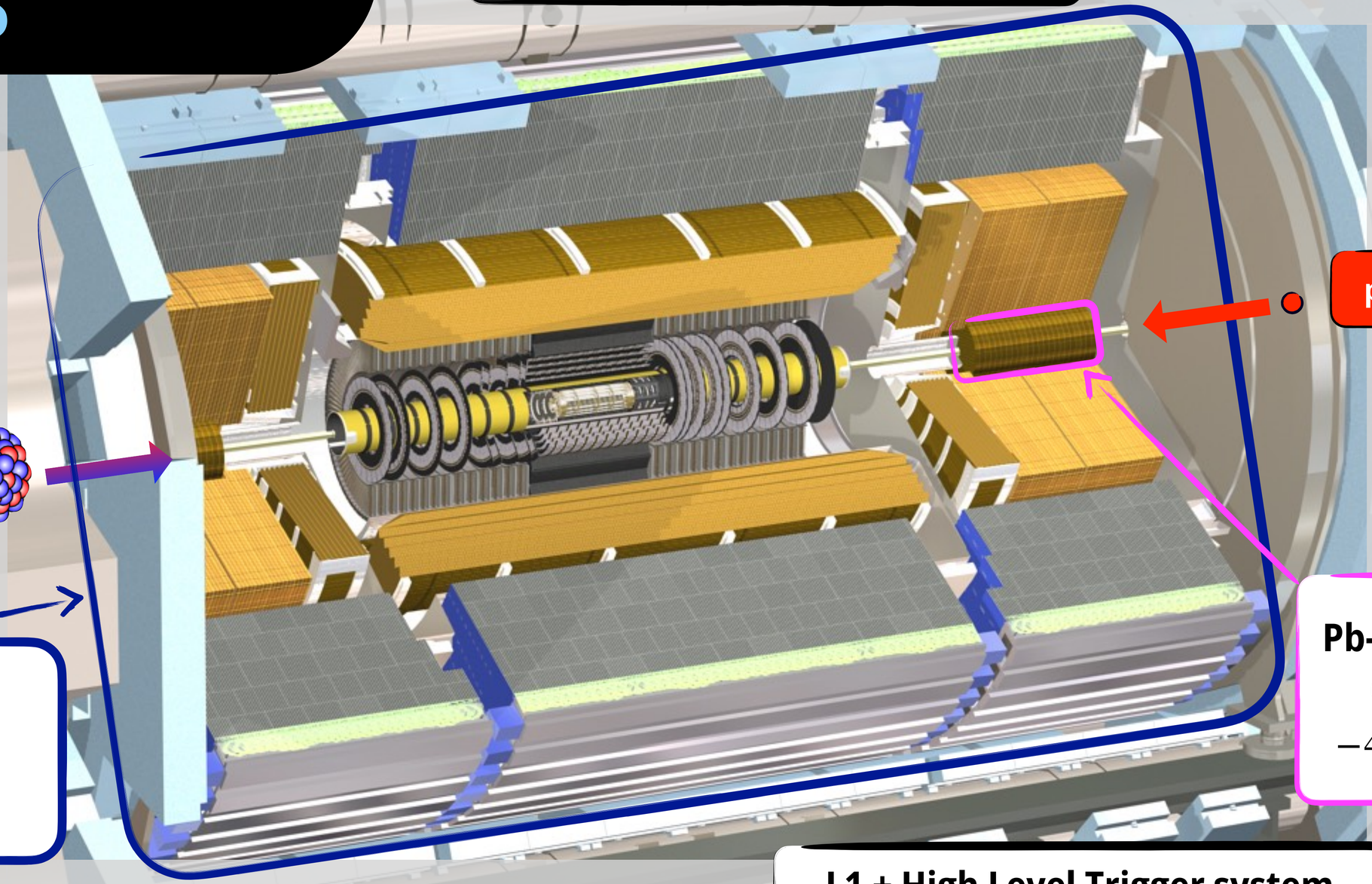
Public ATLAS Luminosity Results for Run 2



92% of 2016 p+Pb recorded luminosity at 8.16 TeV

p+Pb COLLISIONS IN ATLAS

Convention: $y_b > 0$ corresponds to the proton-going direction



Pb ion

p

EMCal+HCal system
$|\eta| < 4.9$

Pb-going Forward Calorimeter
$-4.9 < \eta < -3.2$

L1 + High Level Trigger system

MEASUREMENT OF PER-EVENT DIJET YIELD

- Anti-k_t R = 0.4 calorimeter jets

- Measurement of the centrality-dependence of the **triple differential** per-event dijet yield

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

  - Average transverse momentum: $p_{\mathrm{T,Avg}} = \dfrac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2}$
  - Boost of Dijet System: $y_{\mathrm{b}} = \dfrac{1}{2}(y_1^{\mathrm{CM}} + y_2^{\mathrm{CM}})$
  - Dijet Half Rapidity Separation: $y^* = \dfrac{1}{2}|y_1^{\mathrm{CM}} - y_2^{\mathrm{CM}}|$

- 3D measurement provides **access to partonic system kinematics**

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

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

KINEMATIC DOMAIN

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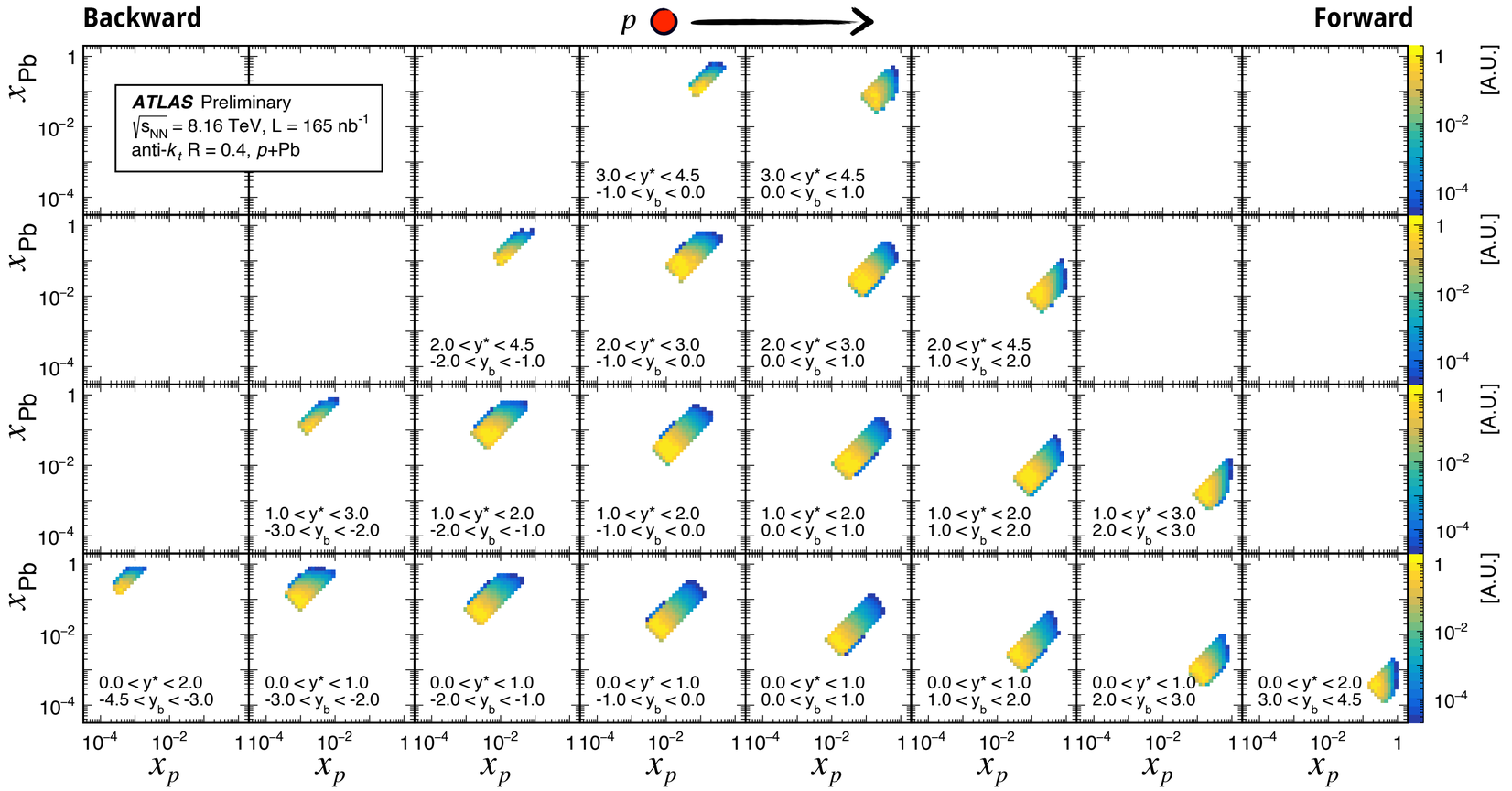
$$30\,\text{GeV} < p_{\text{T,Avg}} < 10^3\,\text{GeV}$$
$$-4.5 < y_{\text{b}} < 4.5$$
$$0 < y^* < 4.5$$



- Measurement that probes 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^* (also corrected for during unfolding)

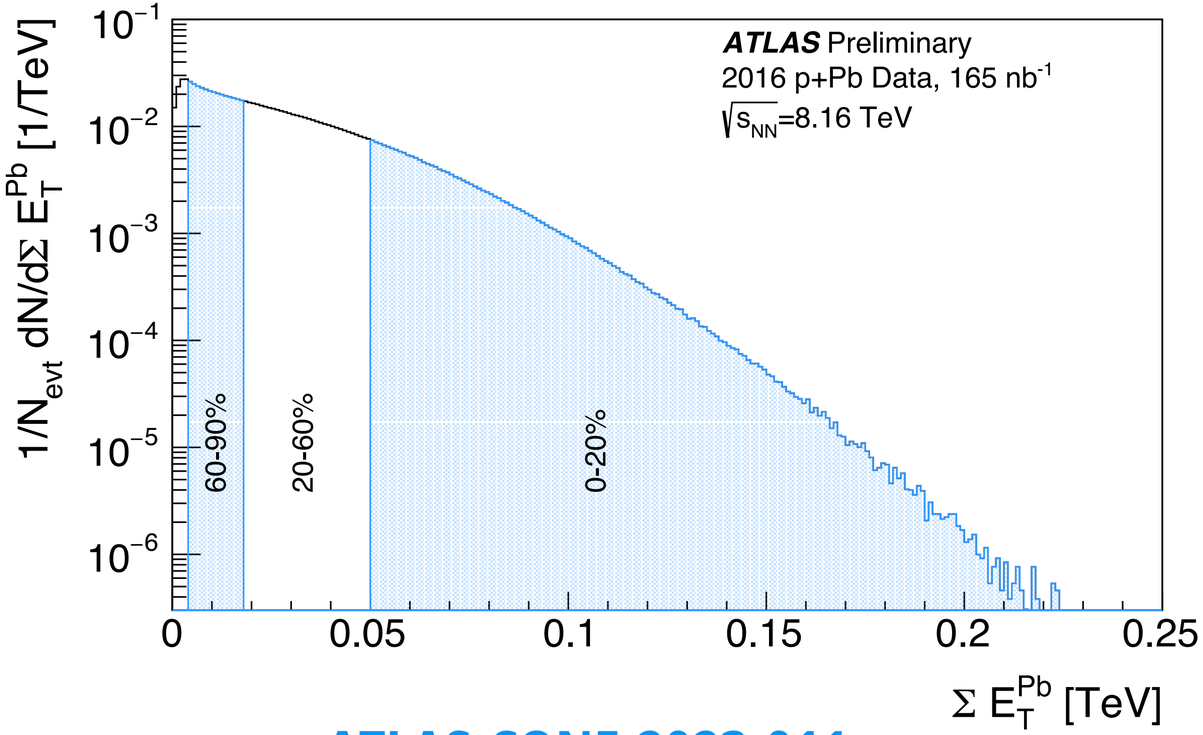
- The measurement is **not directly carried out in parton system kinematic variables**

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

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

CENTRALITY DETERMINATION

- 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**)



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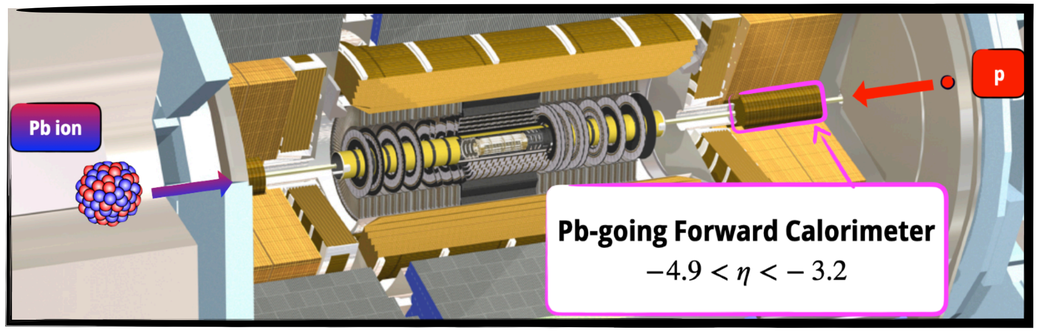
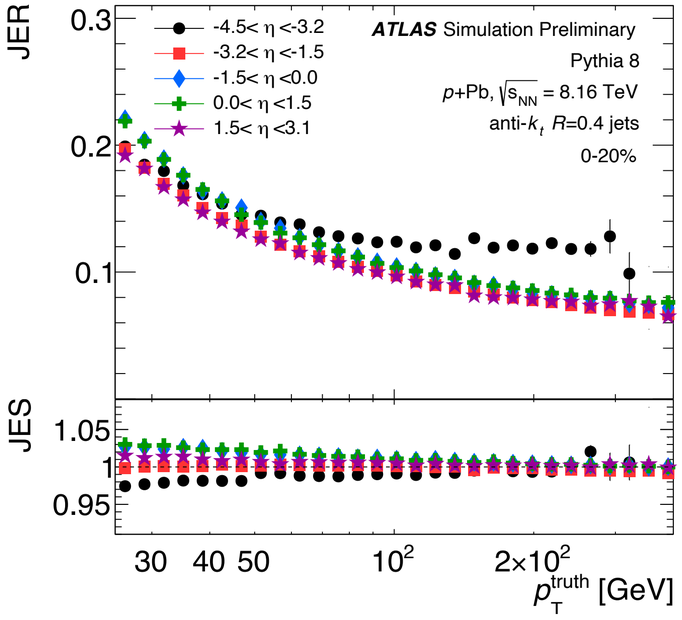


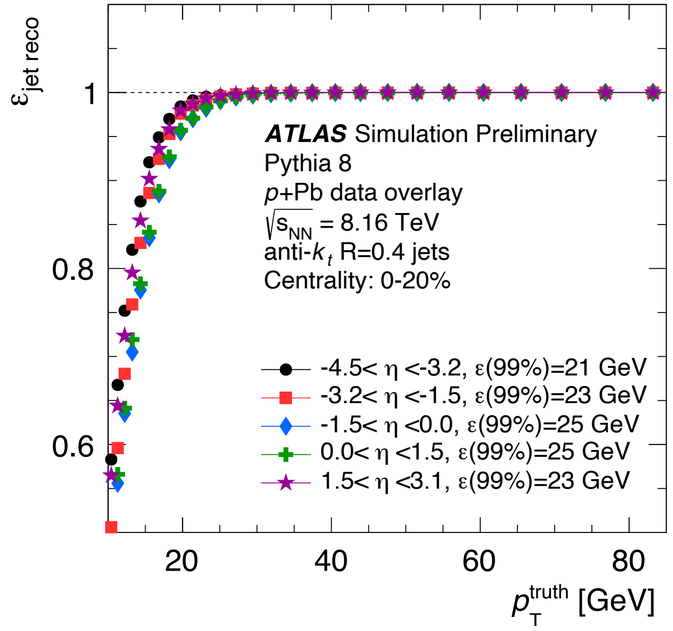
- Centrality determination fully separated from the analysis thanks to fiducial cut on η of leading and sub-leading jet
- Two centrality classes considered in the analysis:
  - 0-20% → **Central events**
  - 60-90% →**Peripheral events**

JET RECONSTRUCTION PERFORMANCE

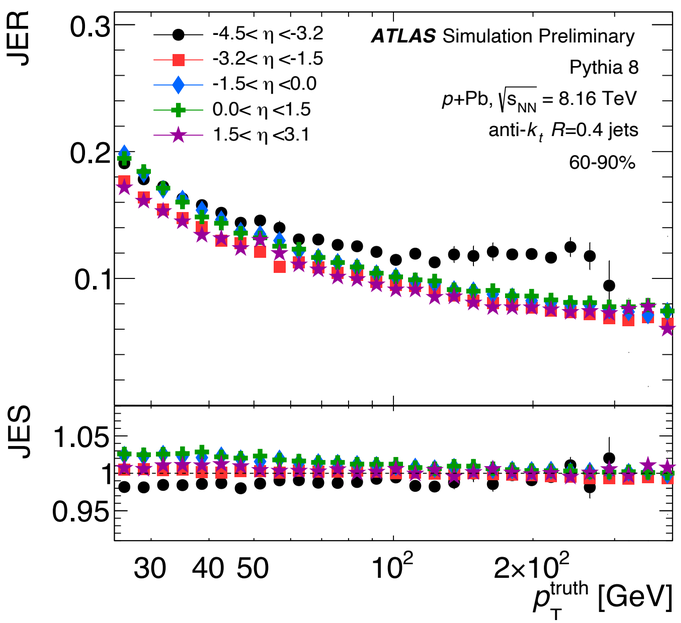
- Jet Energy Resolution (JER) and Jet Energy Scale (JES) compatible between the two beam orientations
- JES and JER corrected for at level of unfolding
- Jet reconstruction efficiency > 99% in all the η regions of the calorimeter for $p_{\mathrm{T}}^{\mathrm{truth}} = 25\,\mathrm{GeV}$
- No significant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

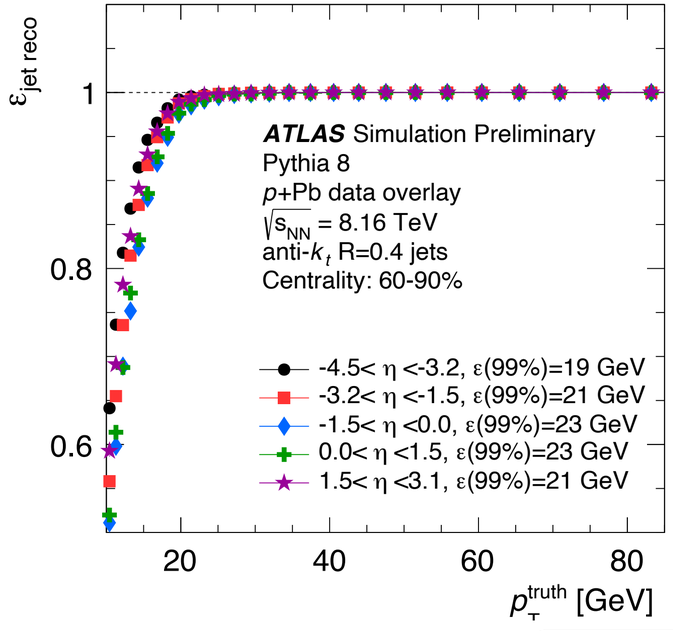
Central collisions (0-20%)





Peripheral collisions (60-90%)





ANALYSIS SUMMARY

Dijet Event Selection

- Stable detector conditions and at least one primary vertex reconstructed
- Events selected by level-1 + high-level jet triggers
- Fiducial cuts on η of the jets ($-2.8 < \eta < 4.5$)
- p_{T} requirement on leading ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$) and sub-leading ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$) jets
- In-time pile-up rejection via cut on number of tracks associated to secondary vertices
- UPC contribution effectively rejected by centrality selection (0-90%)

Monte Carlo Simulations

- Pythia8 *pp* dijet events boosted in *p*+Pb/Pb+*p* reference frame and overlaid onto real minimum bias *p*+Pb data

1D Bayesian unfolding in $p_{\mathrm{T,Avg}}$

Per-event dijet yield extracted separately for *p*+Pb and Pb+*p* orientations

p+Pb data flipped in y_{b} to unify reference frame - results combined using statistically weighted average

Centrality dependent per-event dijet yield in *p*+Pb collisions ($y_{\mathrm{b}} > 0$ for *p* going direction)

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

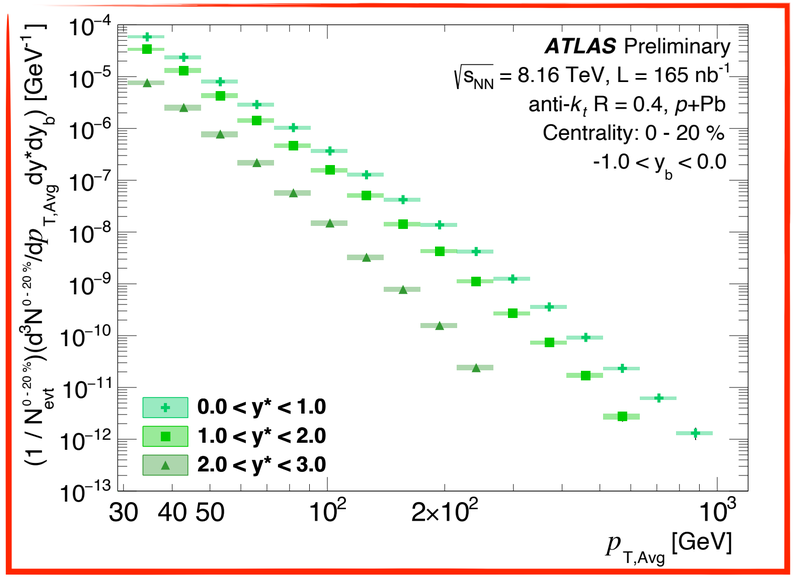
R_{CP} definition

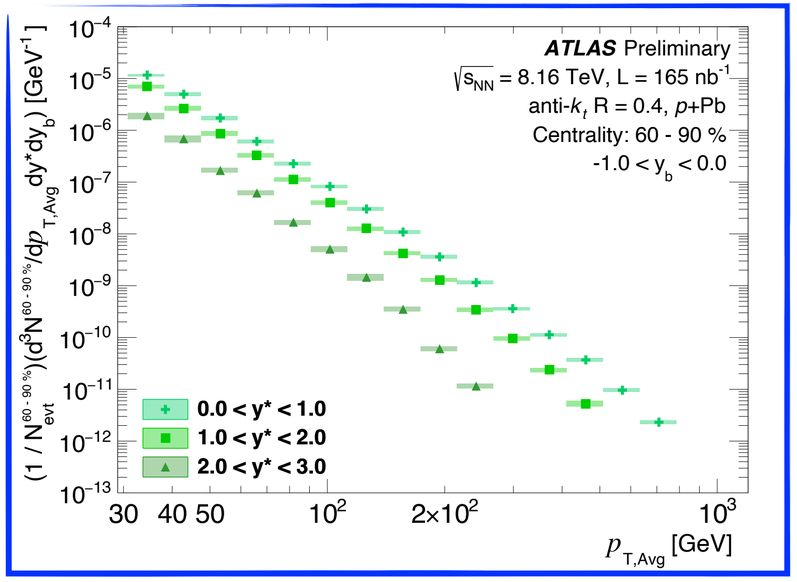
$$R_{\mathrm{CP}}^{\frac{0-20\,\%}{60-90\,\%}}(p_{\mathrm{T,Avg}}, y_{\mathrm{b}}, y^*) = \frac{\frac{1}{\langle T_{\mathrm{AB}}^{0-20\%}\rangle}\frac{1}{N_{\mathrm{evt}}^{0-20\%}}\frac{\mathrm{d}N_{\mathrm{dijet}}^{0-20\%}}{\mathrm{d}p_{\mathrm{T,Avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^*}}{\frac{1}{\langle T_{\mathrm{AB}}^{60-90\%}\rangle}\frac{1}{N_{\mathrm{evt}}^{60-90\%}}\frac{\mathrm{d}N_{\mathrm{dijet}}^{60-90\%}}{\mathrm{d}p_{\mathrm{T,Avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^*}}$$

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
- Mean number of participants used then to evaluate the nuclear thickness function, T_{AB}

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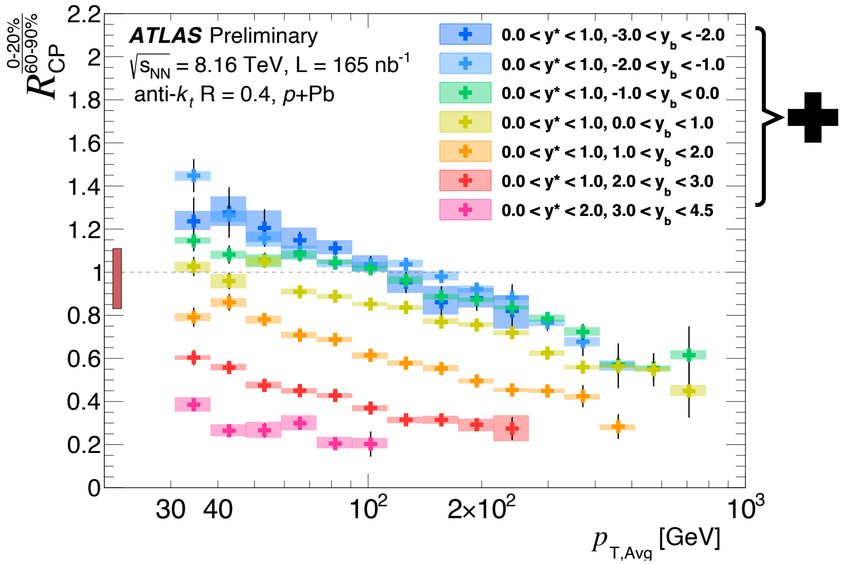
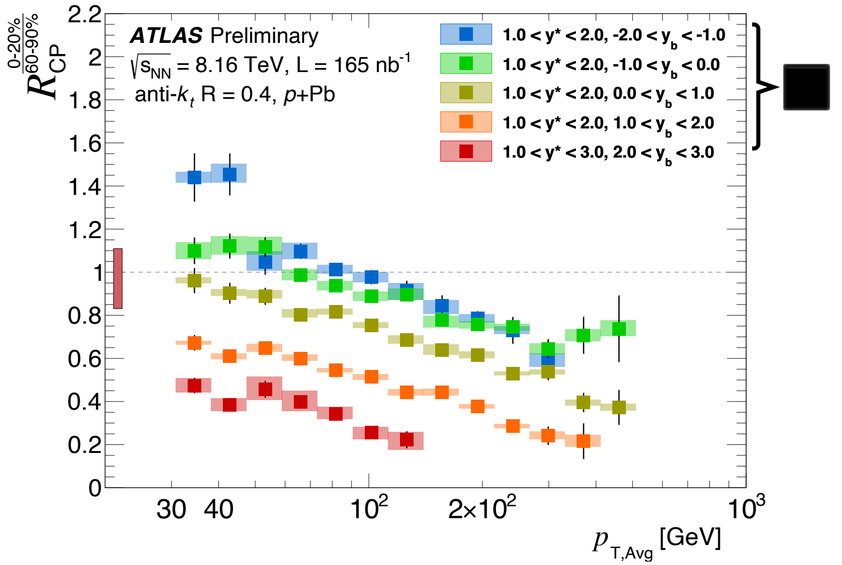
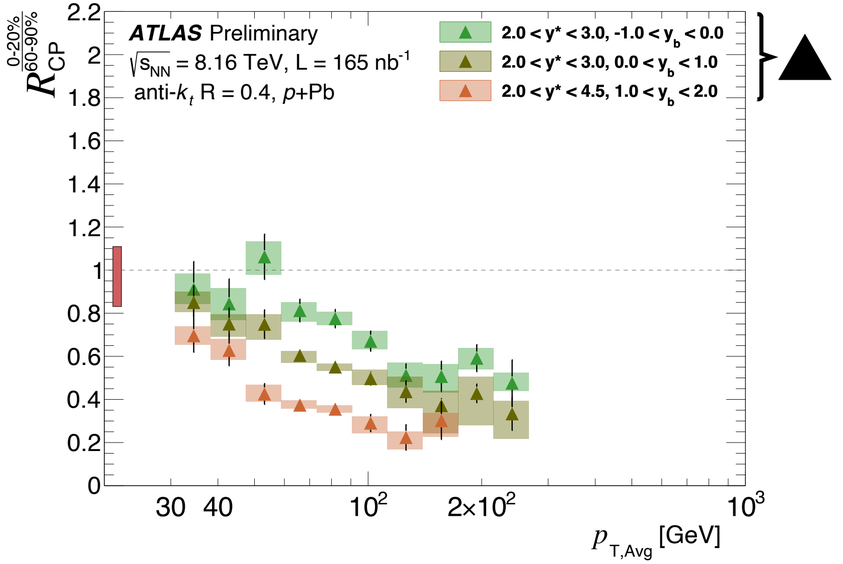
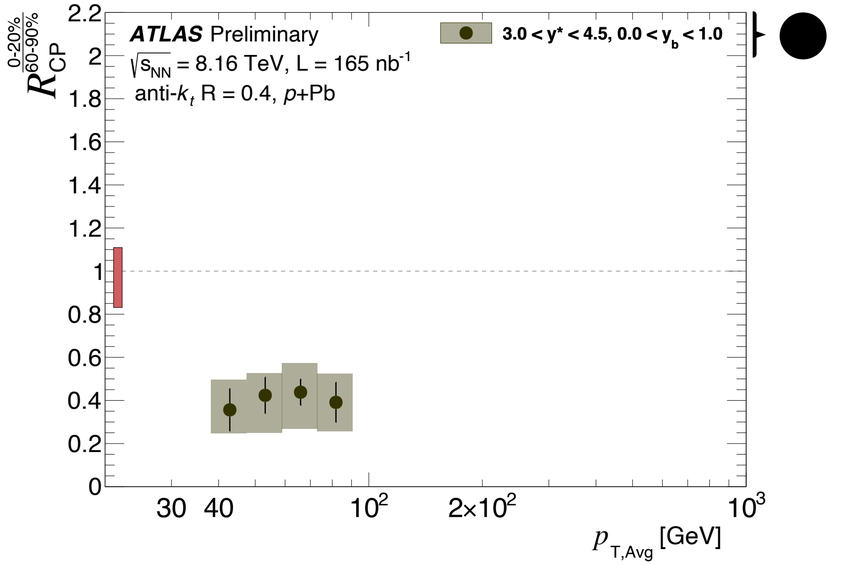
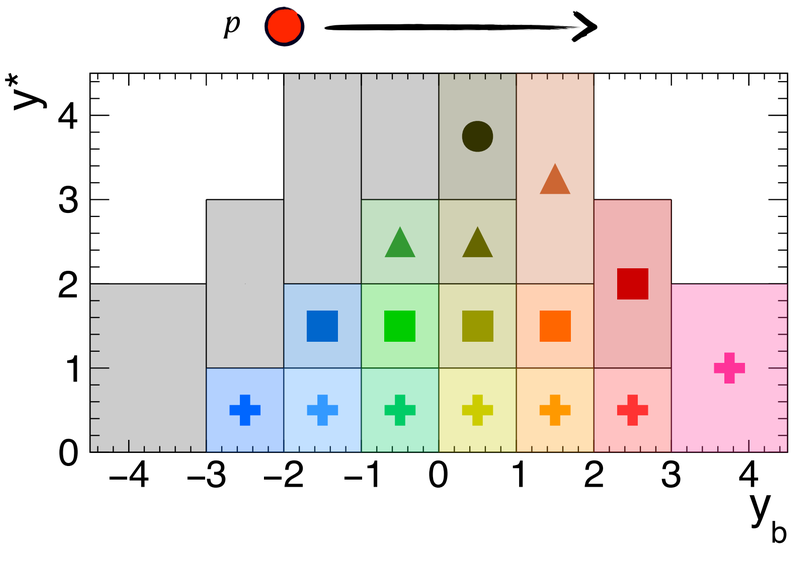
PER-EVENT DIJET YIELD $R_{CP}(p_{T,Avg})$











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

[ATLAS-CONF-2023-011]

MAPPING R_{CP} 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

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

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

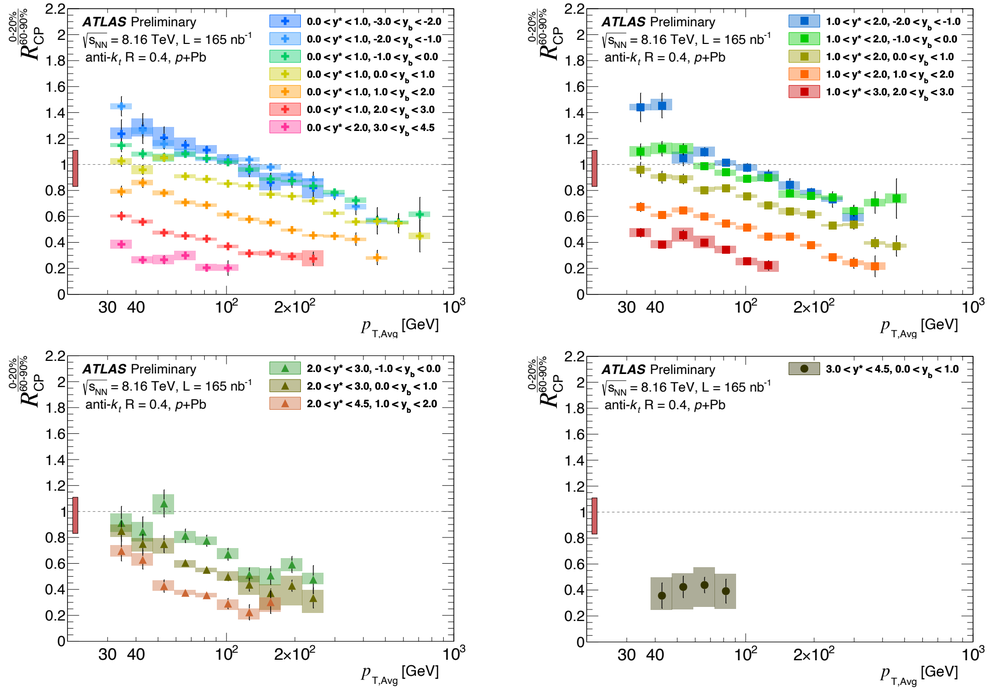
MAPPING R_{CP} RESULTS ON PARTON-LEVEL KINEMATICS

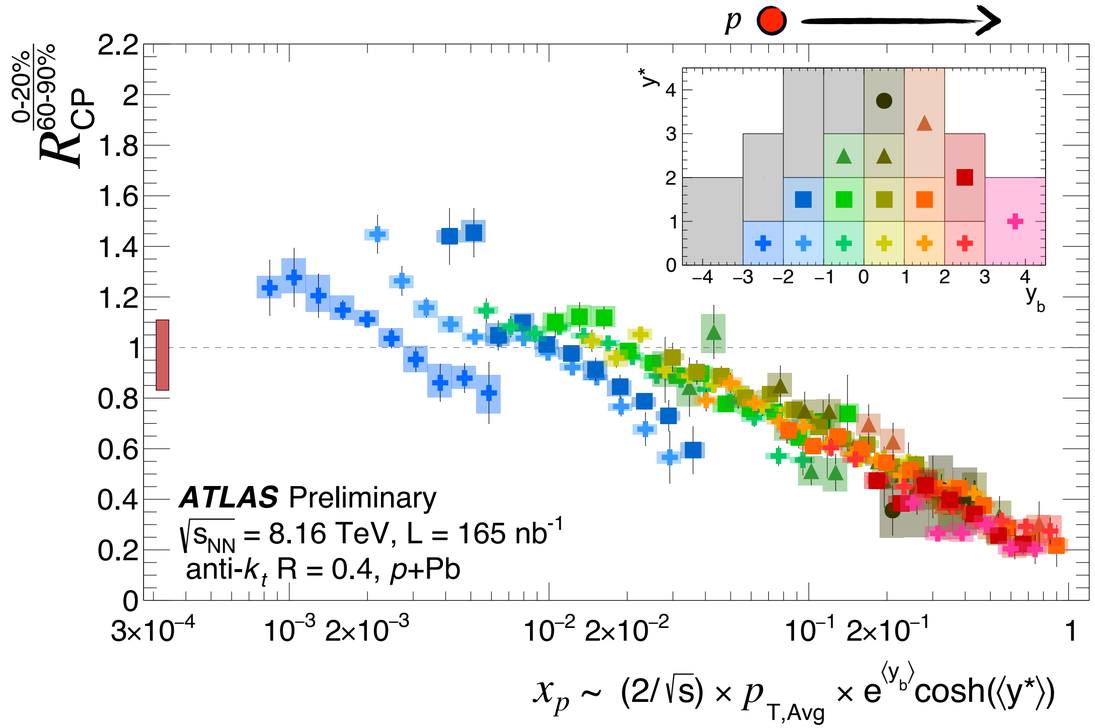
Approximated parton-level kinematics in each bin

- 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

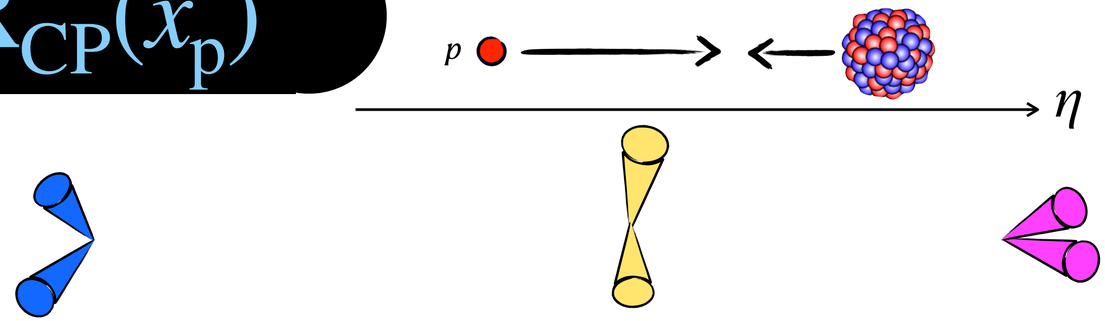
$$x_p \simeq \frac{2p_{T,Avg}}{\sqrt{s}} e^{\langle y_b \rangle} \cosh\langle y^* \rangle, \quad x_{Pb} \simeq \frac{2p_{T,Avg}}{\sqrt{s}} e^{-\langle y_b \rangle} \cosh\langle y^* \rangle$$

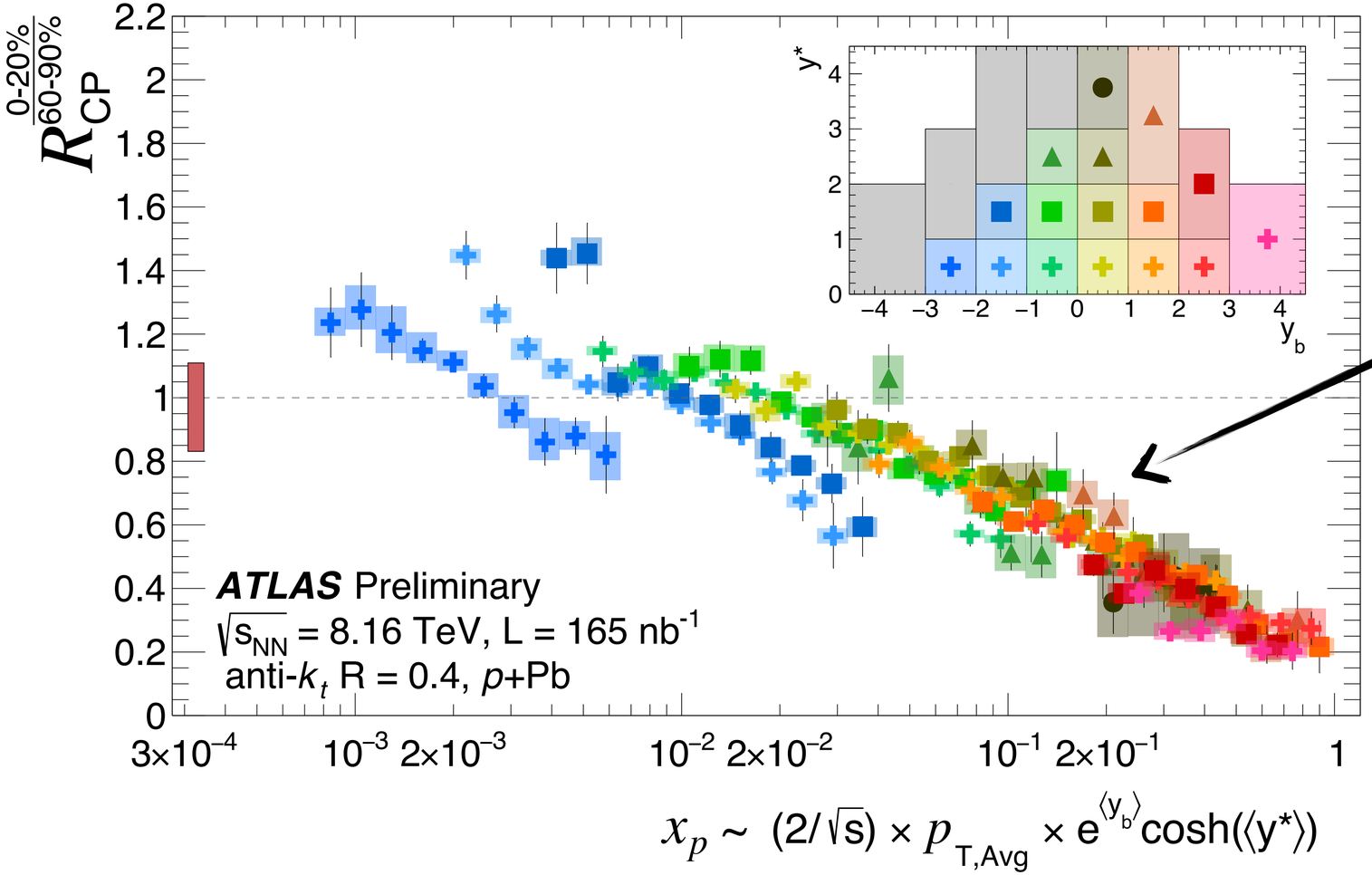
$$m_{1,2} = \sqrt{x_p x_{Pb} s} \simeq 2p_{T,Avg} \cosh\langle y^* \rangle$$





DIJET $R_{CP}(x_p)$

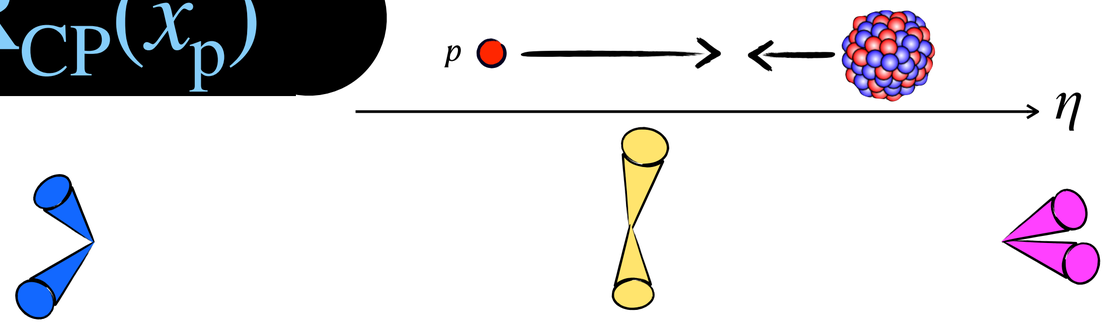


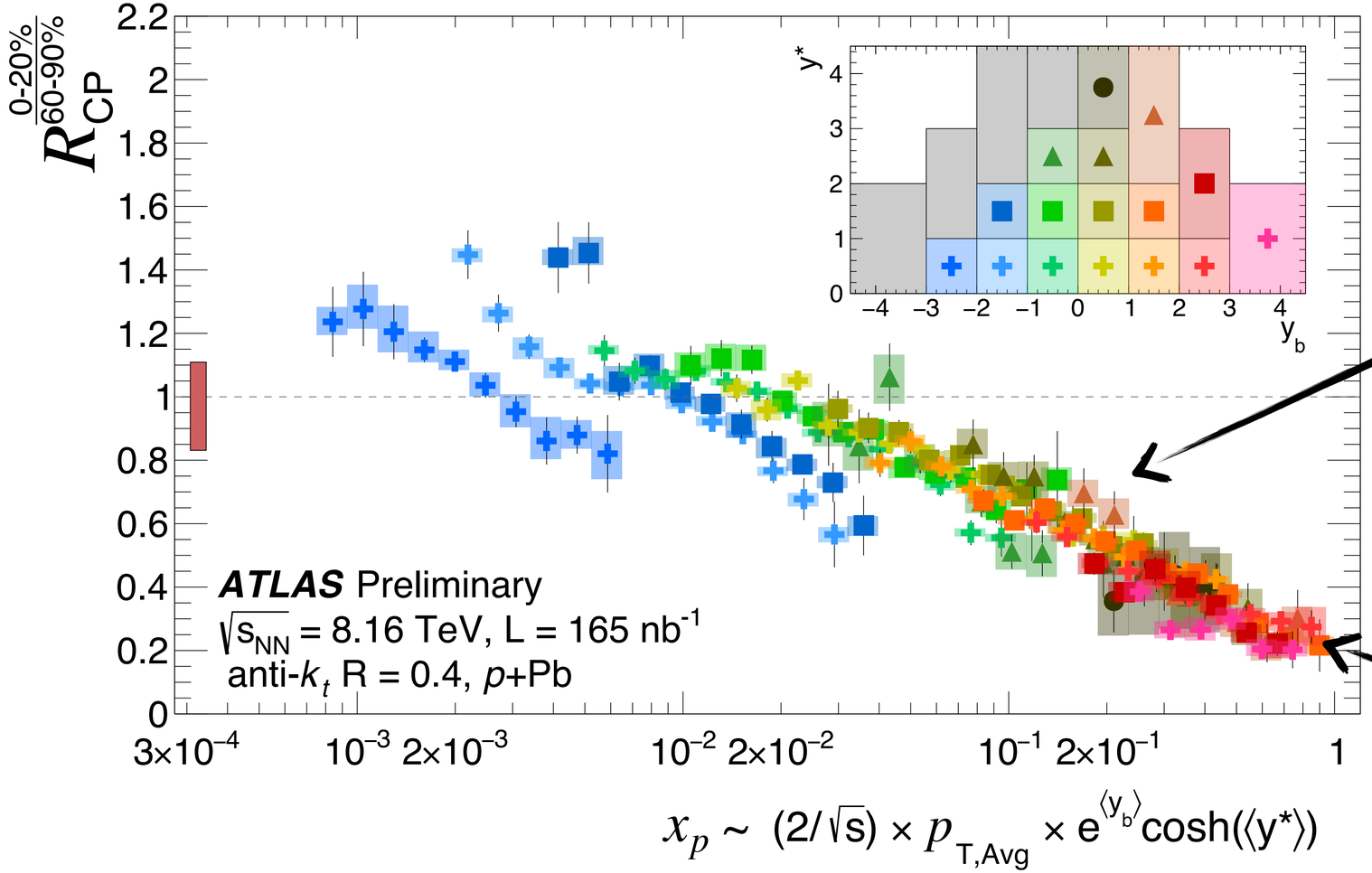


$$x_p \sim (2/\sqrt{s}) \times p_{T,Avg} \times e^{\langle y_b \rangle} \cosh(\langle y^* \rangle)$$

Log-linear decrease observed as a function of the fractional momenta of the parton extracted from the proton, x_p

DIJET $R_{CP}(x_p)$

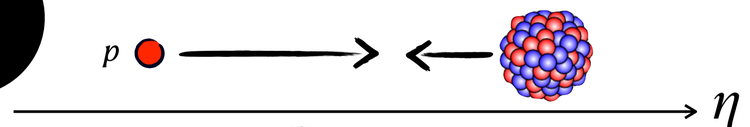




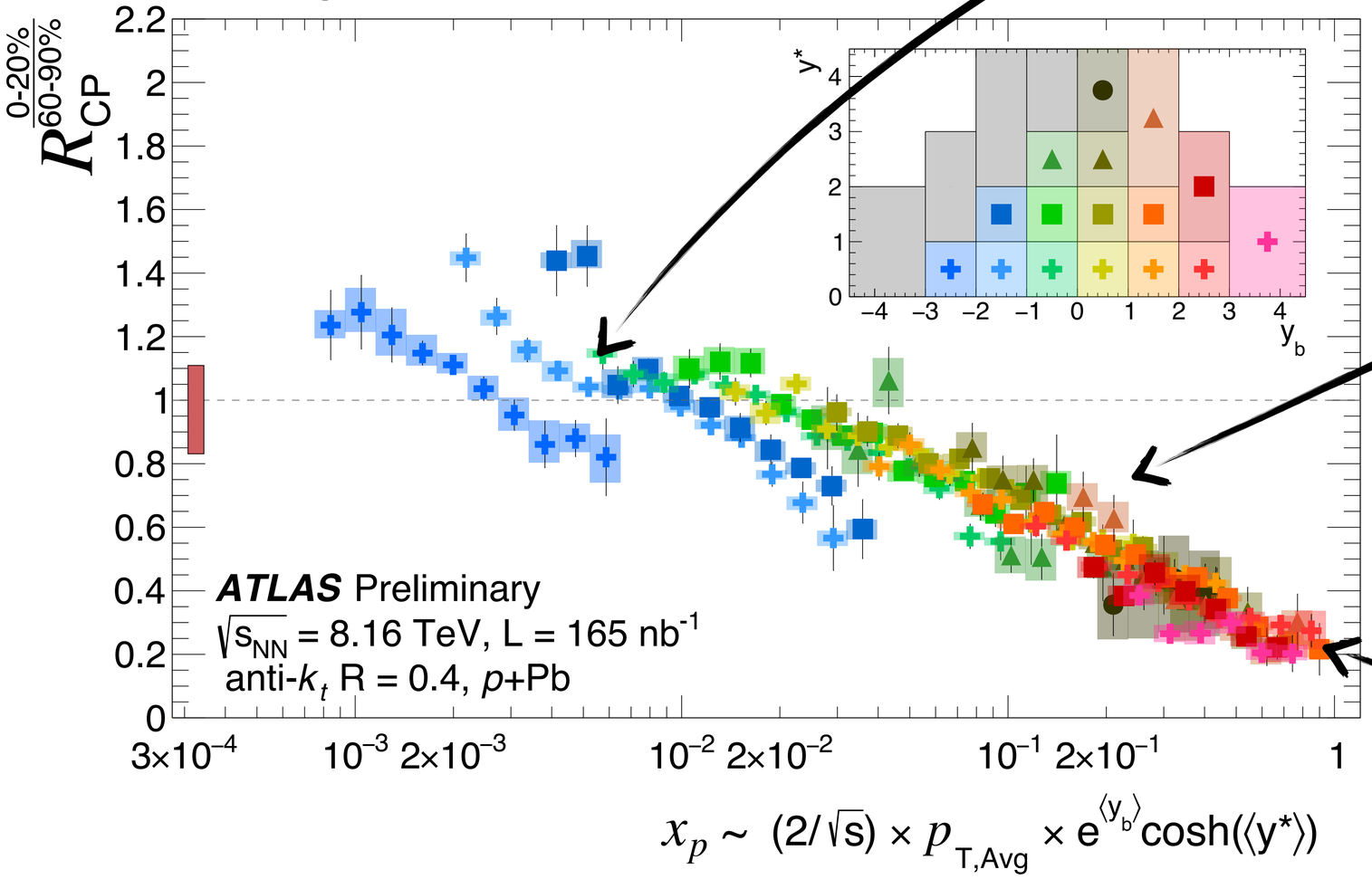
Log-linear decrease observed as a function of the fractional momenta of the parton extracted from the proton, x_p

The strongest R_{CP} suppression is observed in correspondence with the proton's valence region

DIJET $R_{CP}(x_p)$



Log-linear trend disappears when approaching low-x_p region, corresponding to backward dijets

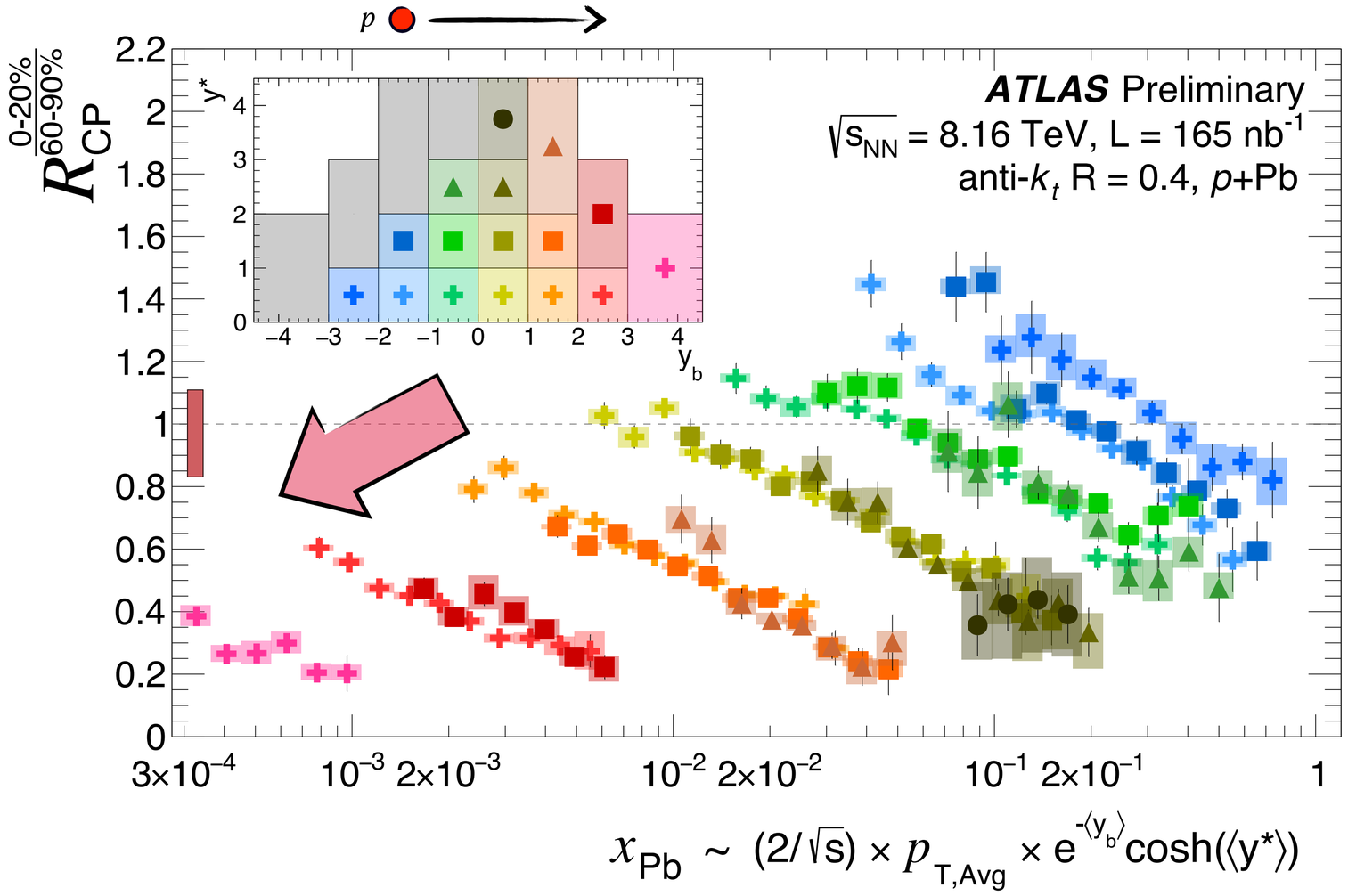


Log-linear decrease observed as a function of the fractional momenta of the parton extracted from the proton, x_p

The strongest R_{CP} suppression is observed in correspondence with the proton's valence region

DIJET $R_{CP}(x_{Pb})$

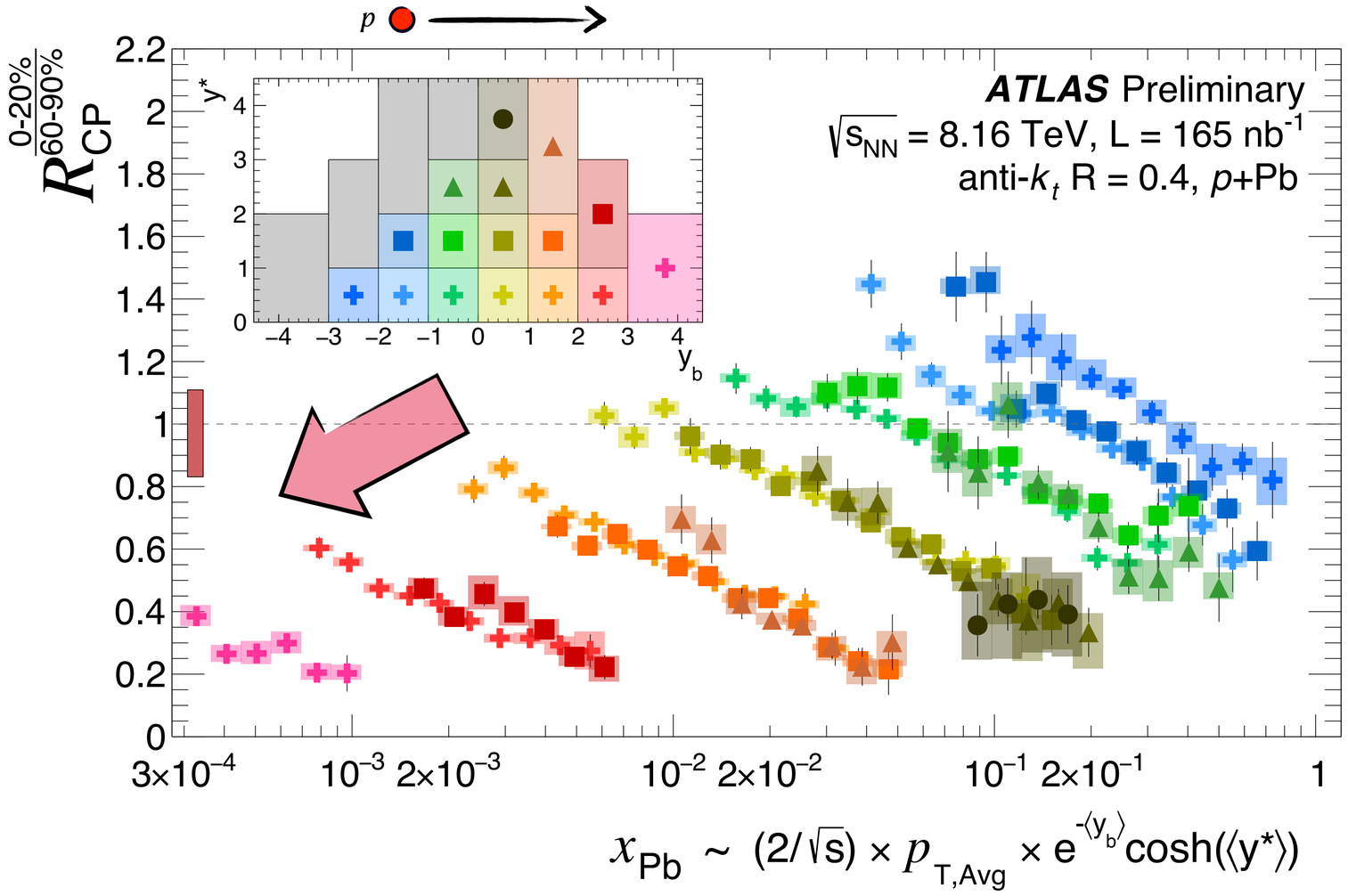
Overall, an increasing R_{CP} suppression while moving towards low-x_{Pb} is observed



ATLAS-CONF-2023-011

DIJET $R_{CP}(x_{Pb})$

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

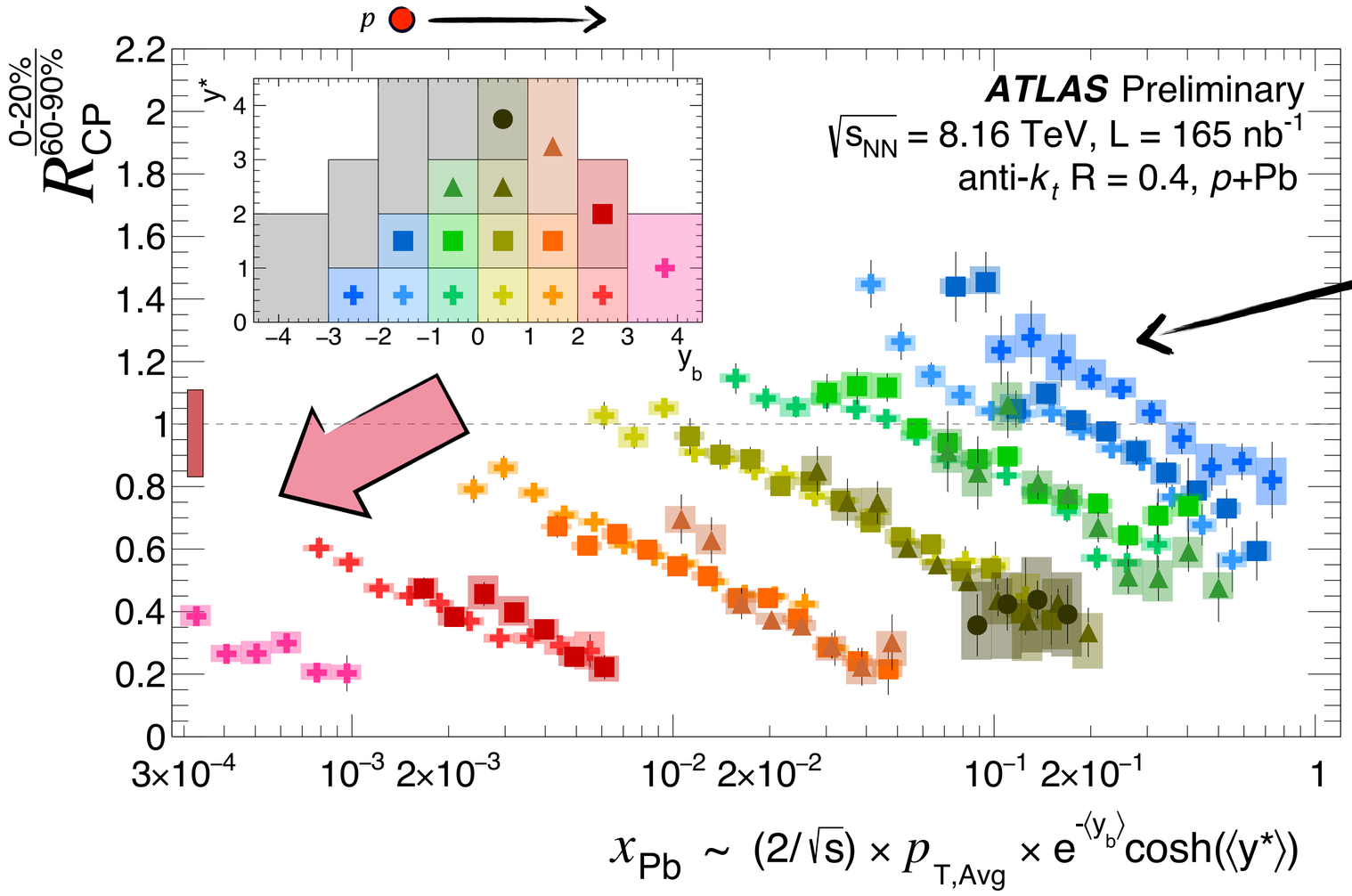


For each slice in y_b, a log-linear trend with increasing suppression moving toward higher x_{Pb} is observed

ATLAS-CONF-2023-011

DIJET $R_{CP}(x_{Pb})$

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



Values of $R_{CP} > 1$ found to be localized in the range $\sim 10^{-2} < x_{Pb} < \sim 2 \cdot 10^{-1}$

For each slice in y_b, a log-linear trend with increasing suppression moving toward higher x_{Pb} is observed

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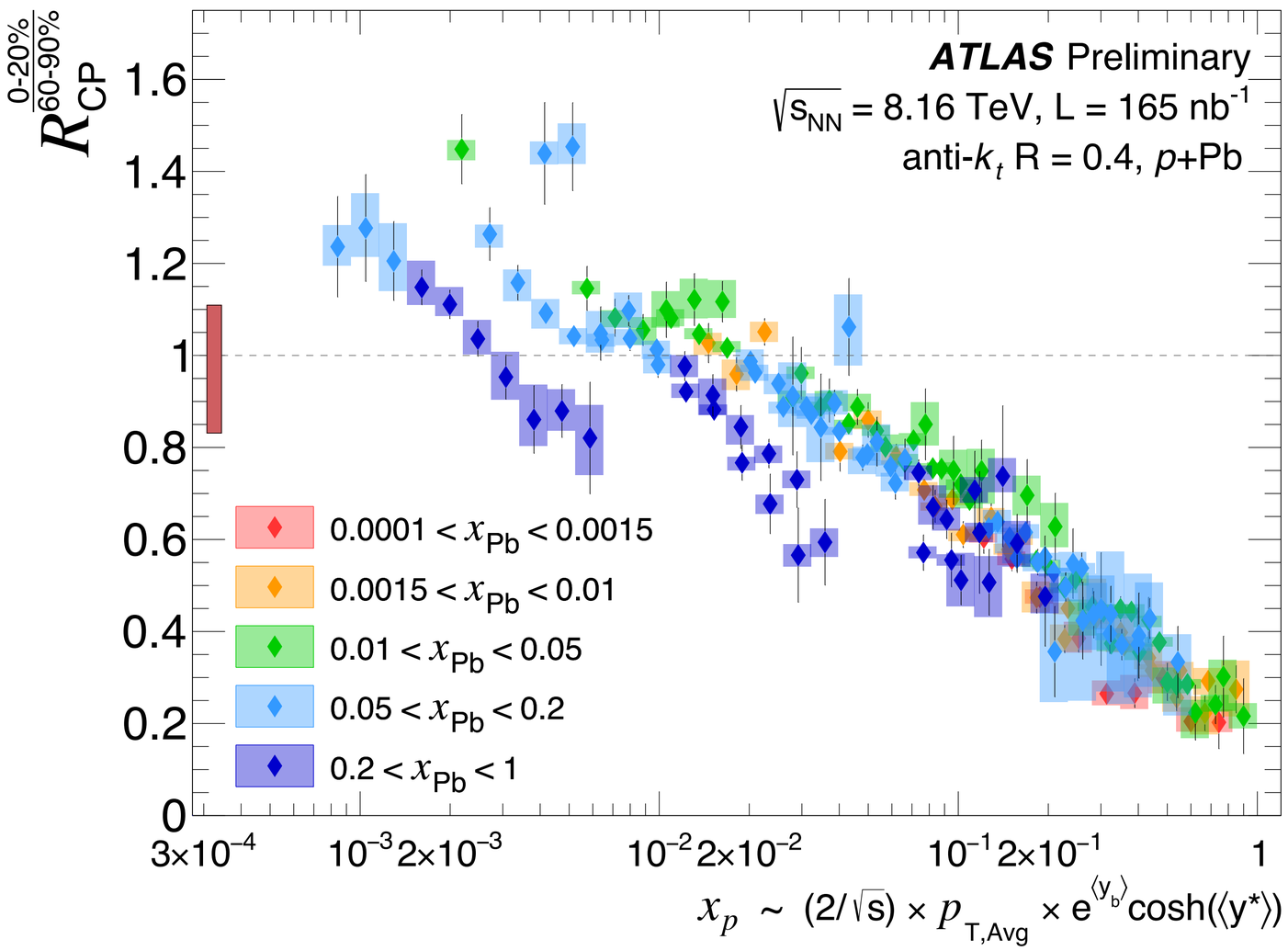
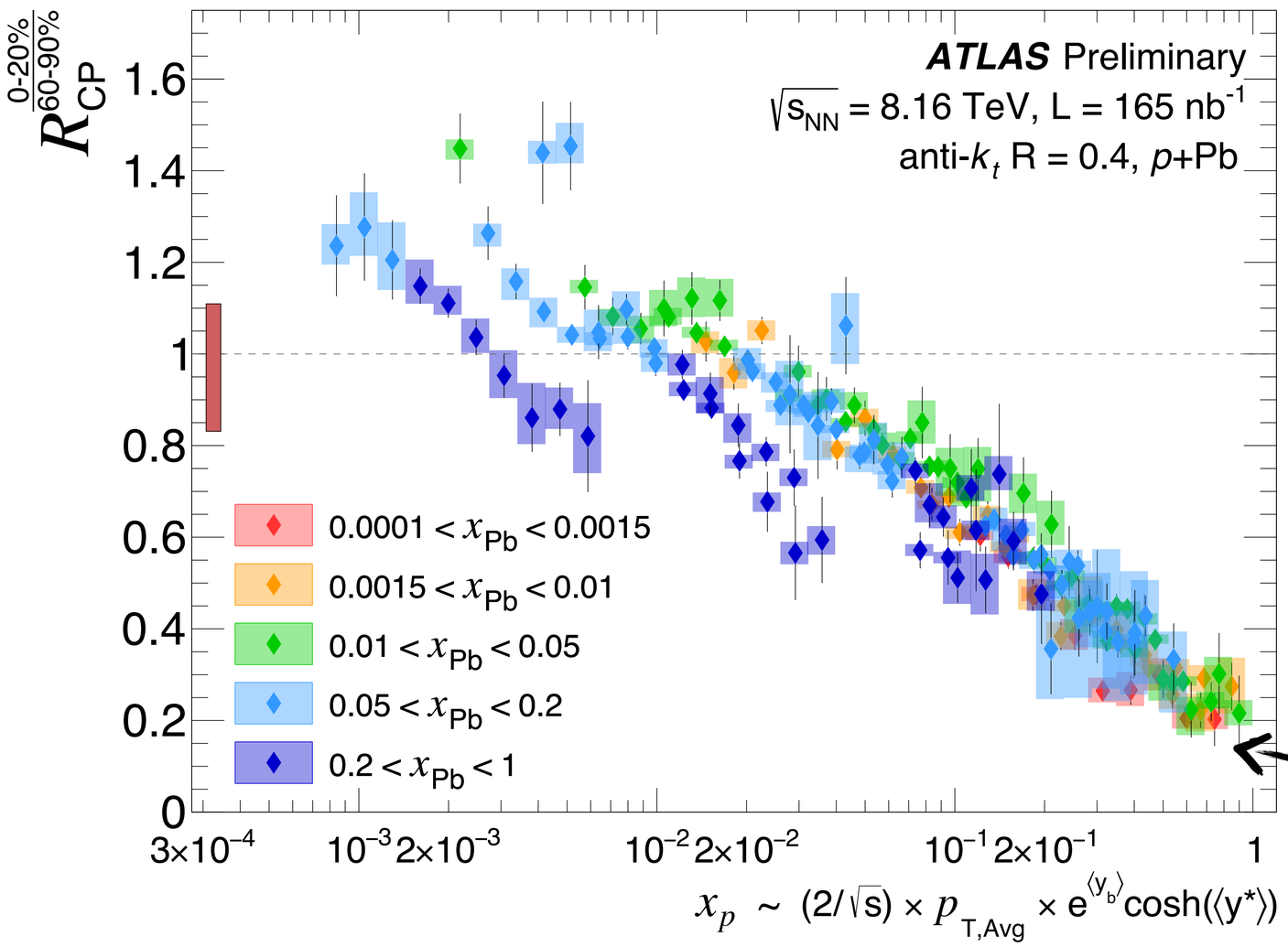
DIJET $R_{CP}(x_p)$ IN BINS OF x_{Pb}



ATLAS-CONF-2023-011

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

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

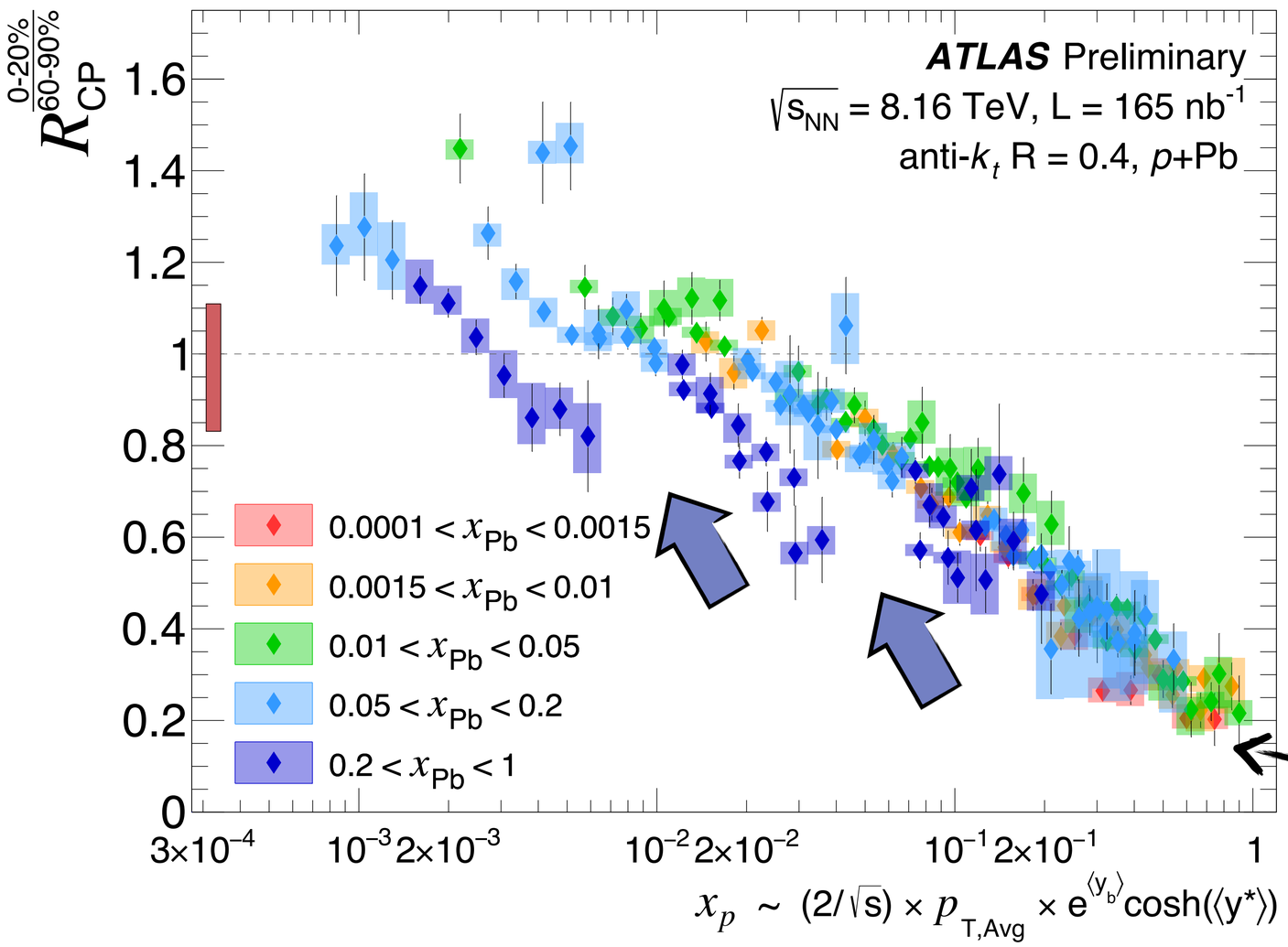


Results now displayed as a function of approximated x_p, in different intervals of approximated x_{Pb}

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

ATLAS-CONF-2023-011

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



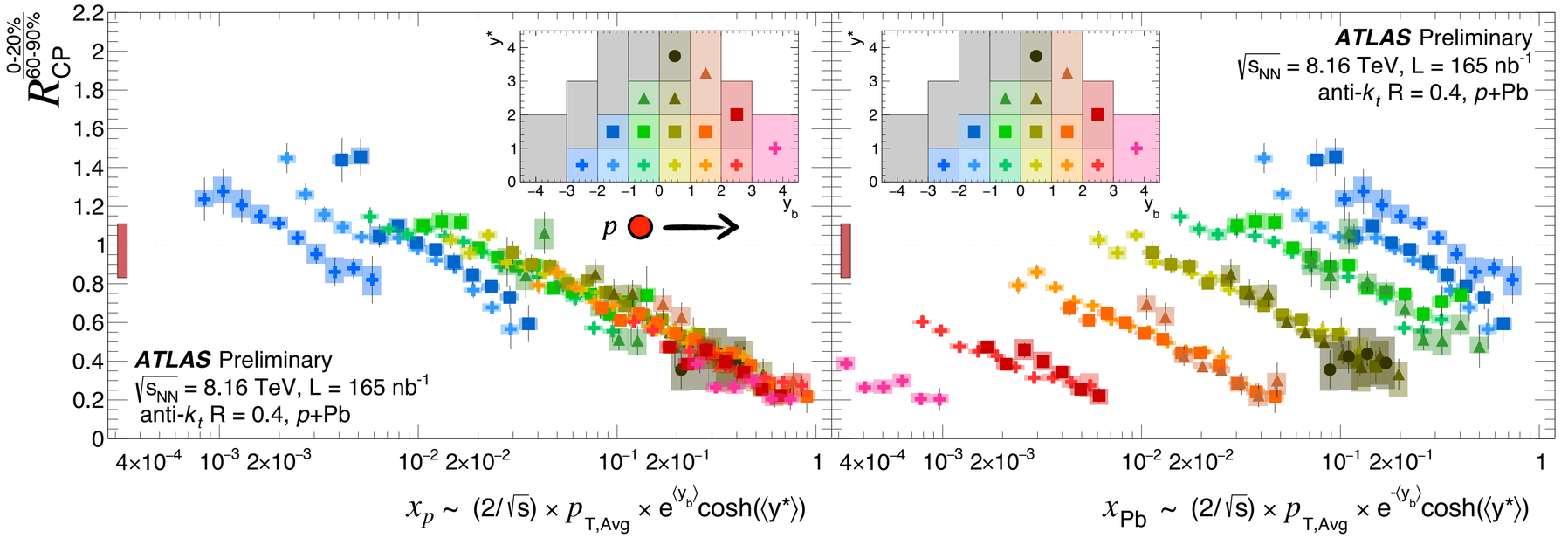
Results now displayed as a function of approximated x_p, in different intervals of approximated x_{Pb}

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

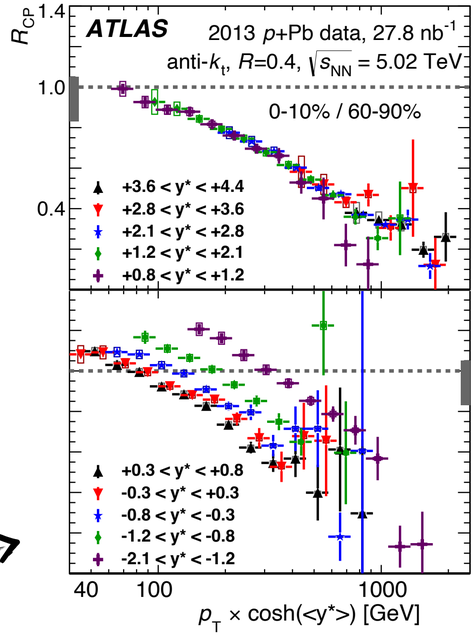
Highest suppression observed corresponds to the **lowest** x_{Pb} **class of results**

[ATLAS-CONF-2023-011]

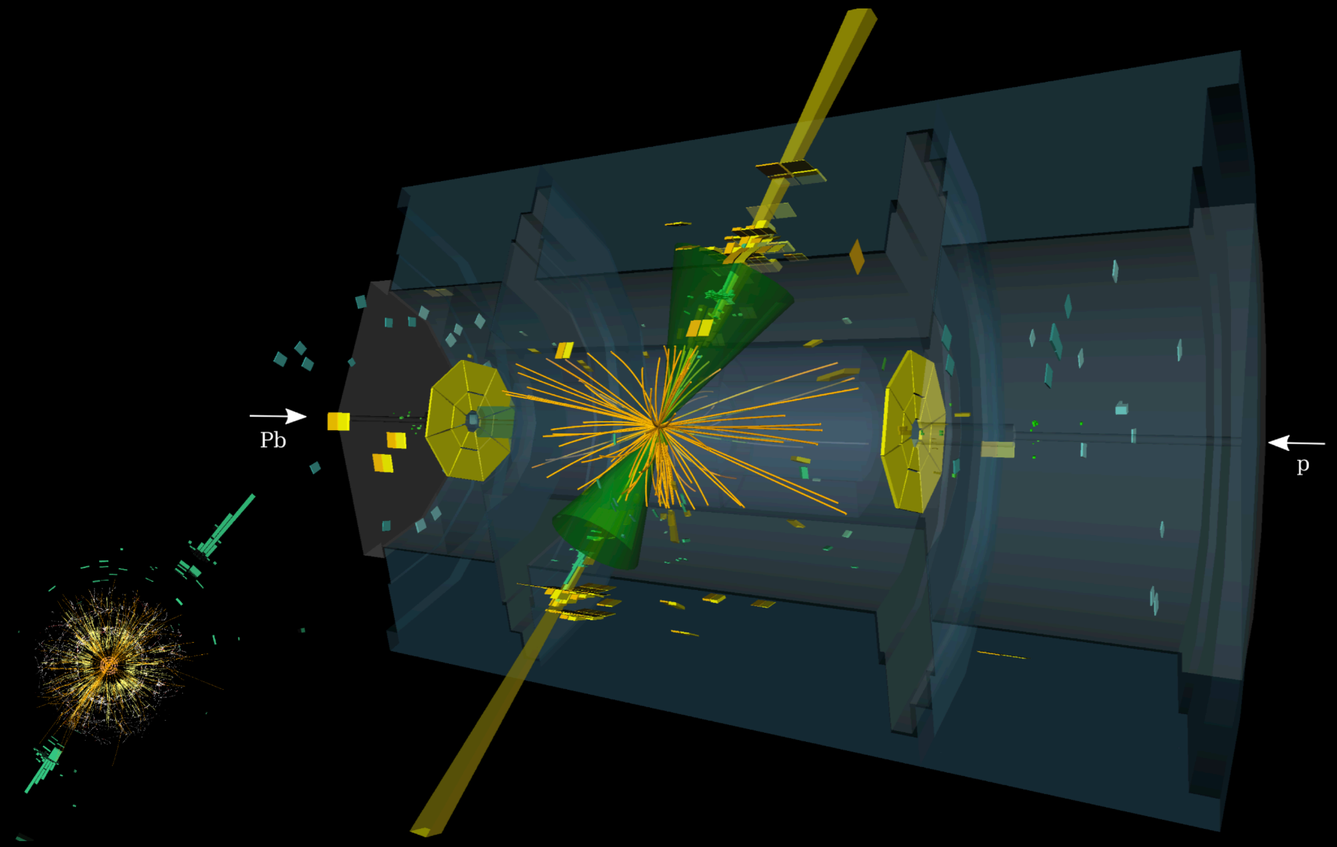
SUMMARY



- ATLAS has measured the centrality dependence of the dijet yield in p+Pb collisions at 8.16 TeV
  (**ATLAS-CONF-2023-011 - see also poster by A.Tate**).
  - Both per-event dijet yield and R_{CP} preliminary results are reported
- 3D analysis using dijets →detailed mapping of the results in terms of approximated parton system kinematics.
  - New input to understand the R_{CP} suppression in (di)jet production in p+A collisions
- 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

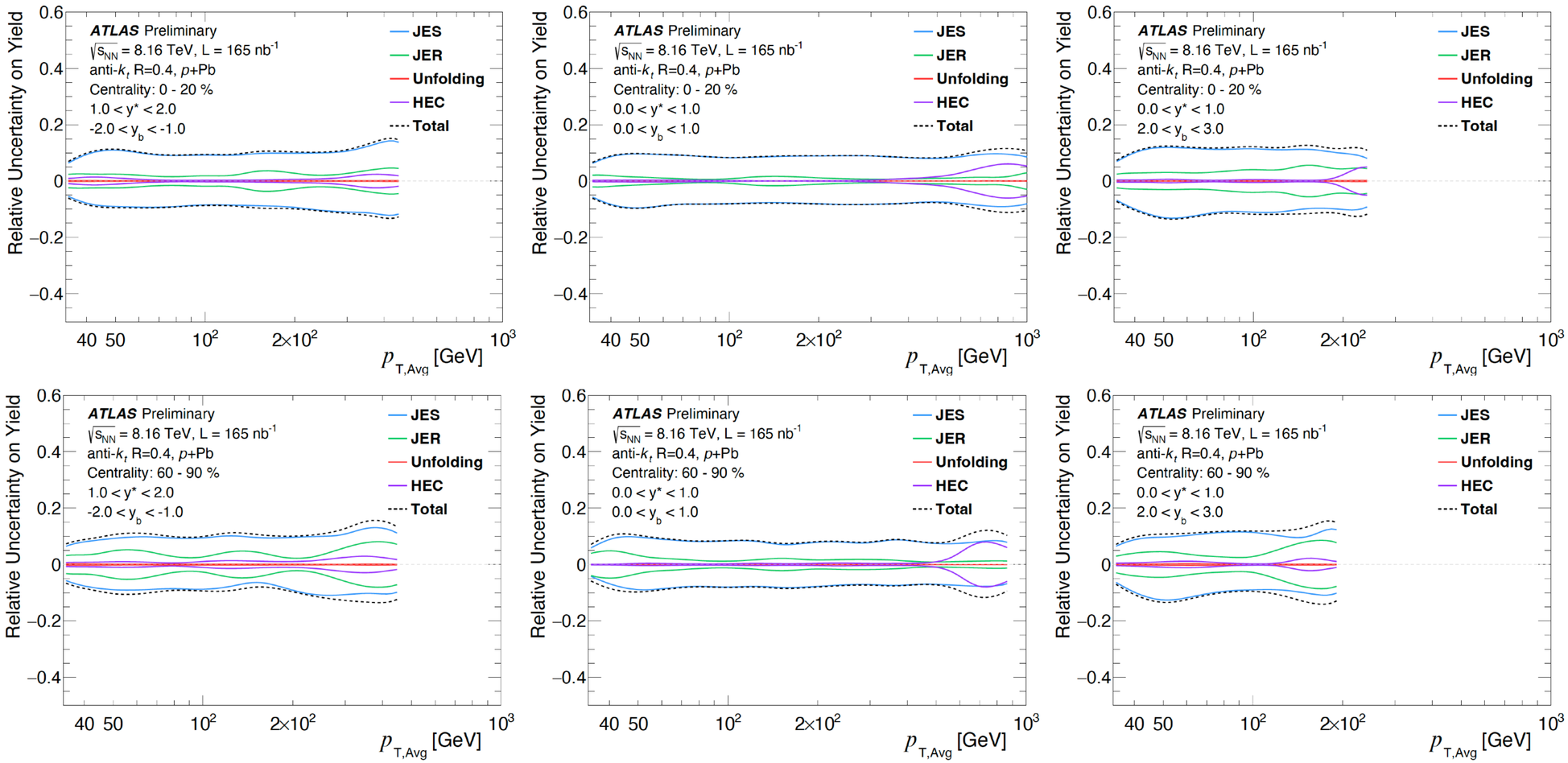


(**PLB 748 (2015) 392–413**)



BACKUP SLIDES

SYSTEMATICS: PER-EVENT DIJET YIELD



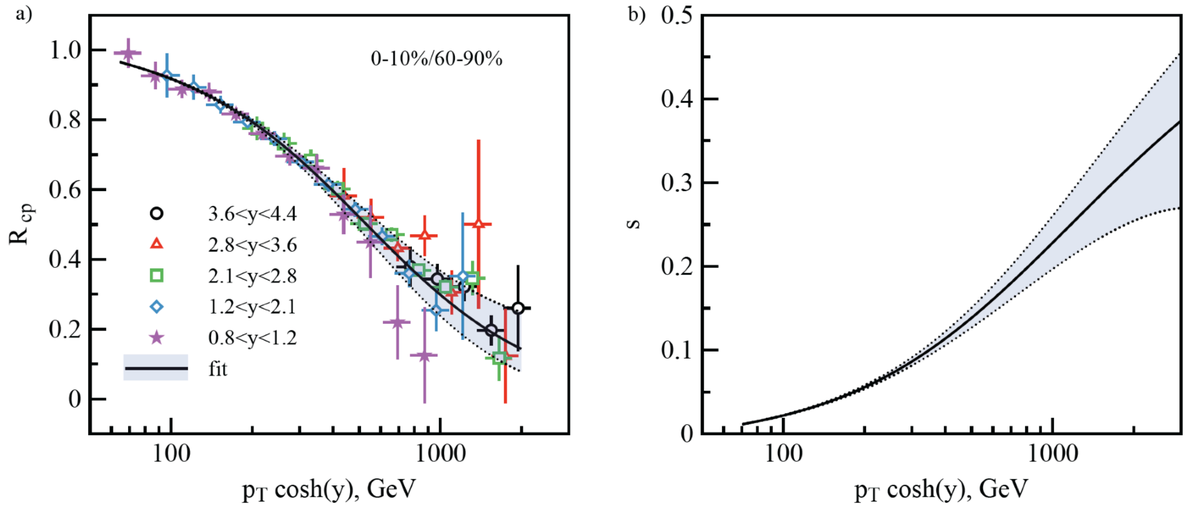
Central Dijet Yield

Peripheral Dijet Yield

- Dominant source of systematic uncertainty on the per-event dijet yields comes from the Jet Energy Scale (JES)
- Other uncertainties assigned are associated to the Jet Energy Resolution (JER), the unfolding procedure, and the exclusion of a portion of the Hadronic Endcap Calorimeter (HEC) that was disabled during the 2016 run

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

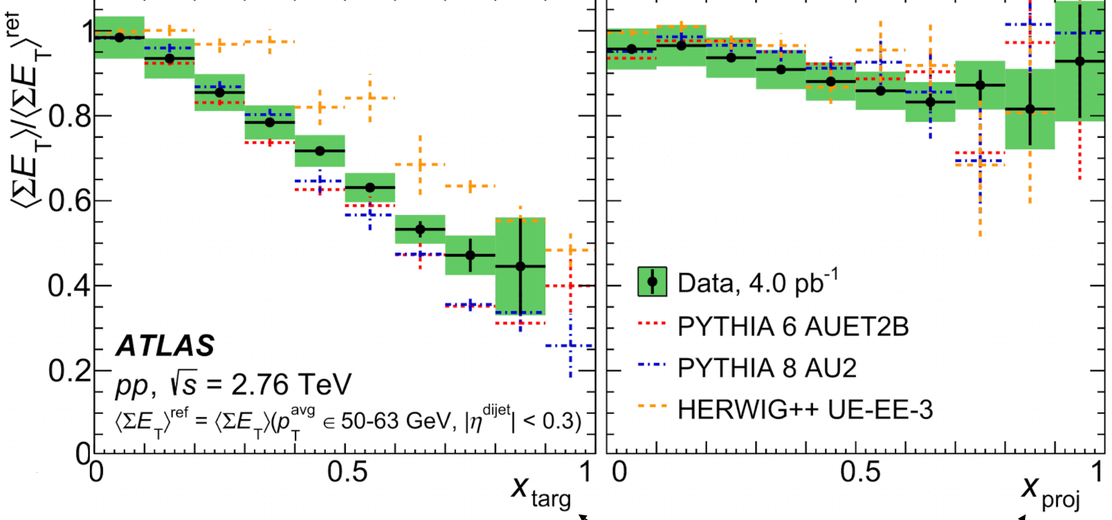
- Suppression of soft particle production dependent on the amount of energy removed from the projectile proton
  PRC 93 (2016) 044901

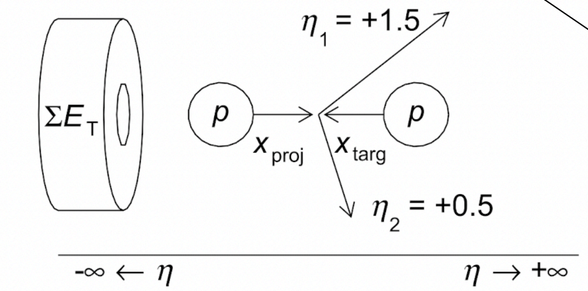


- Kinematic bias introduced by energy momentum conservation between the hard process and the production of soft particles
  PLB 747 (2015) 441

- 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

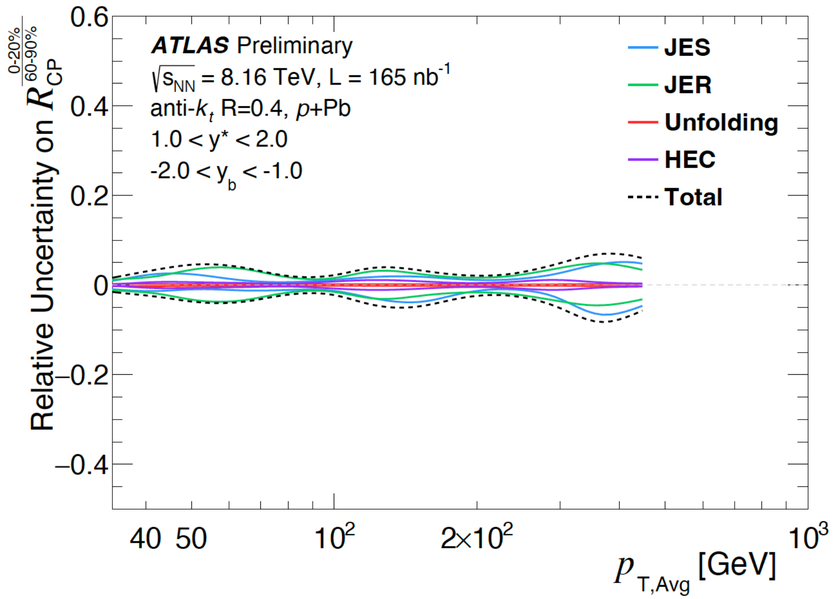
Measurement of the dependence of transverse energy production at large pseudorapidity on the hard-scattering kinematics of *pp* collisions at $\sqrt{s} = 2.76\,\text{TeV}$ with ATLAS
PLB 756 (2016) 10–28

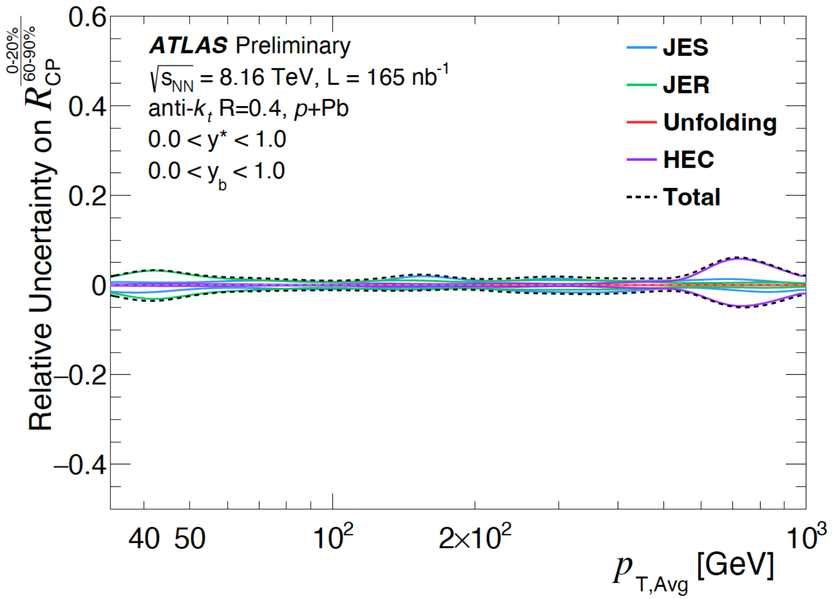


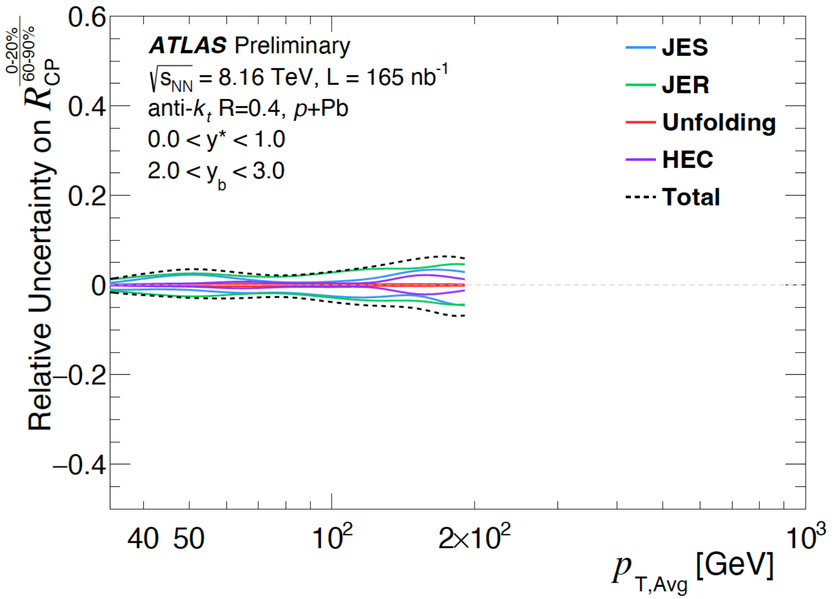


Fractional momentum of the initial state partons extracted from target and projectile

SYSTEMATICS: R_{CP}



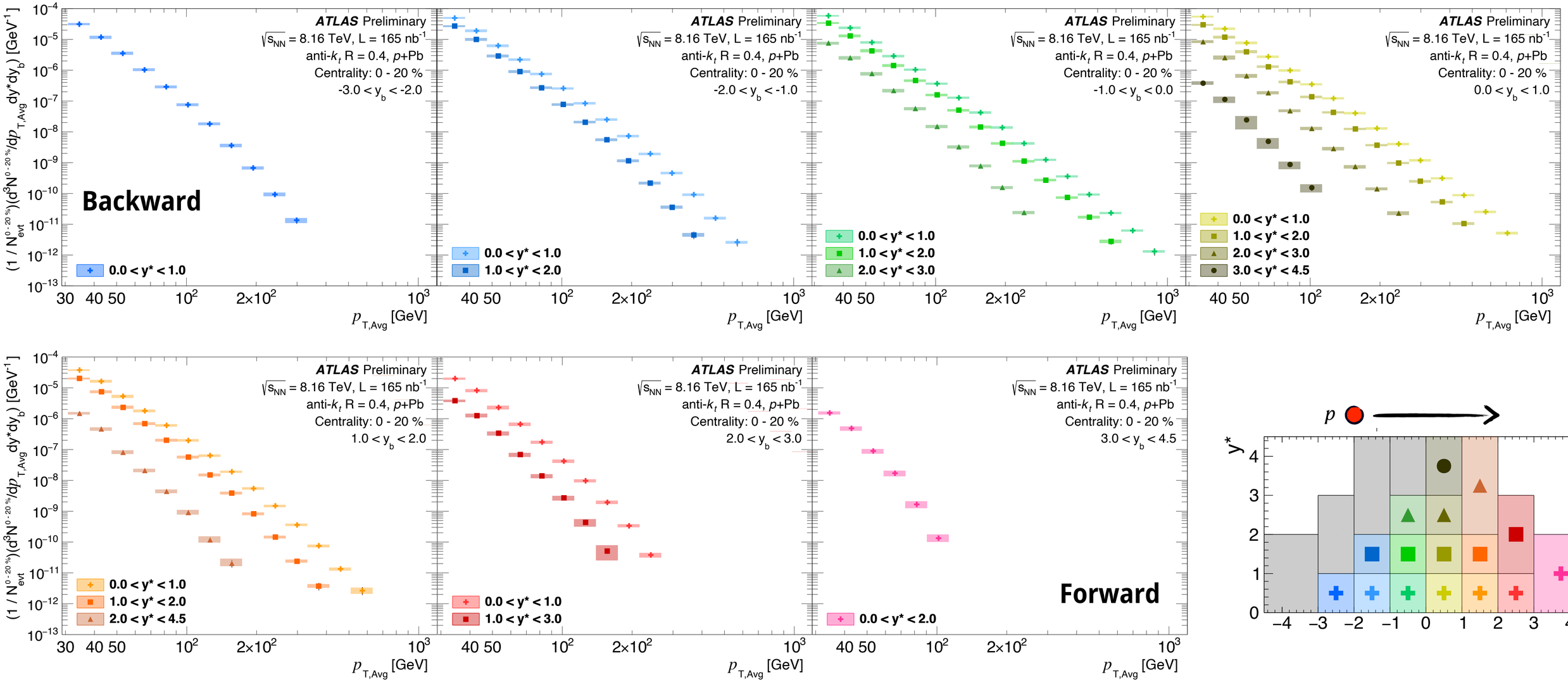




- Dominant source of systematic uncertainty on the R_{CP} is associated to the Jet Energy Resolution (JER)
- Other uncertainties assigned are associated to the Jet Energy Scale (JES), the unfolding procedure, the exclusion of a portion of the Hadronic Endcap Calorimeter (HEC) that was disabled during 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}

PER-EVENT DIJET YIELDS: 0-20%

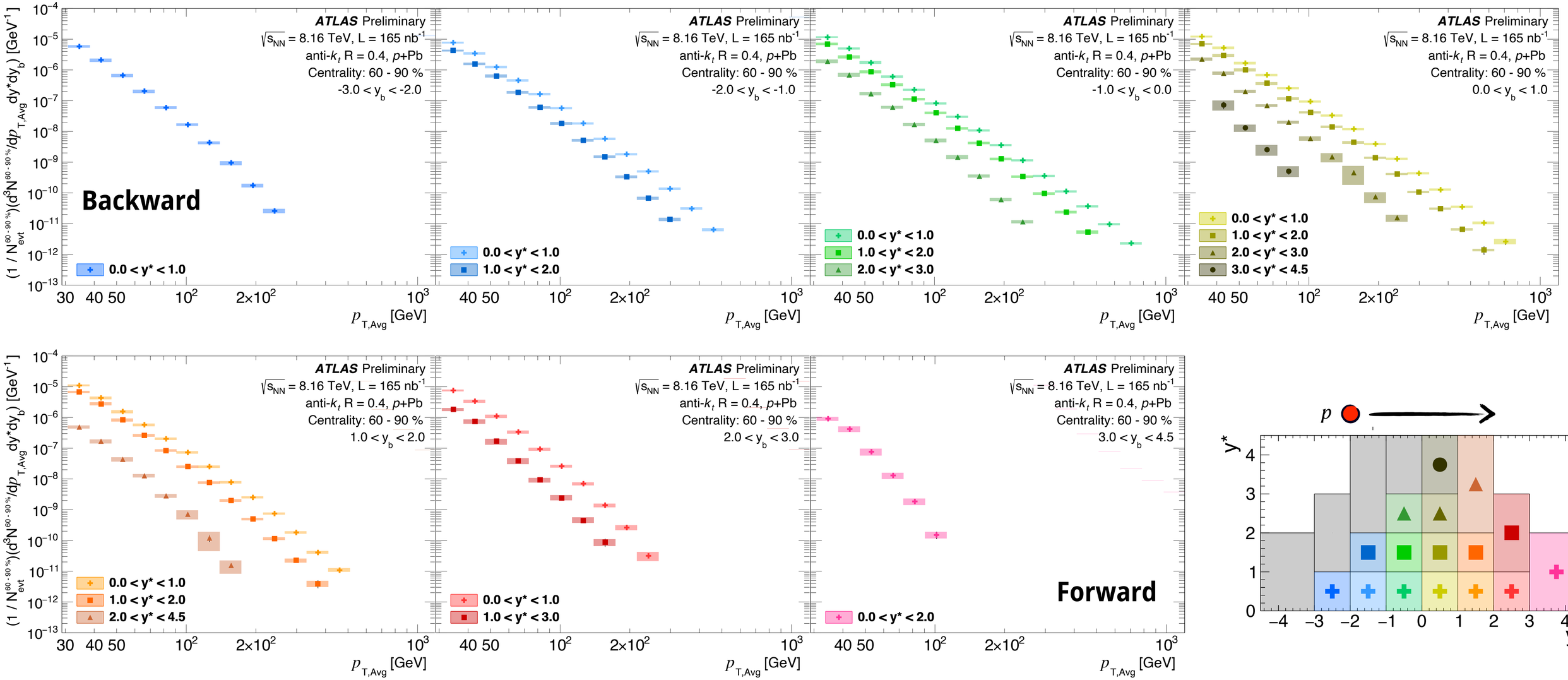
- Per-event dijet yield decreasing with $p_{\mathrm{T,Avg}}$ and with y^* in each y_{b} bin
- Same results for 60-90% available in backup



- Backward-most y_{b} bins excluded from the analysis given the sizable impact of the fiducial cut applied to ensure no contamination from jets in the Pb-going FCal

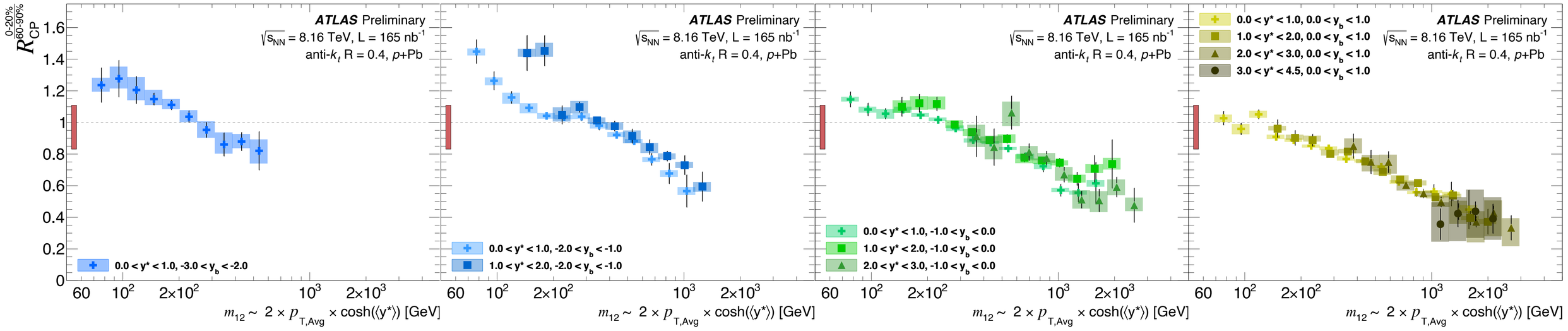
PER-EVENT DIJET YIELDS: 60-90%

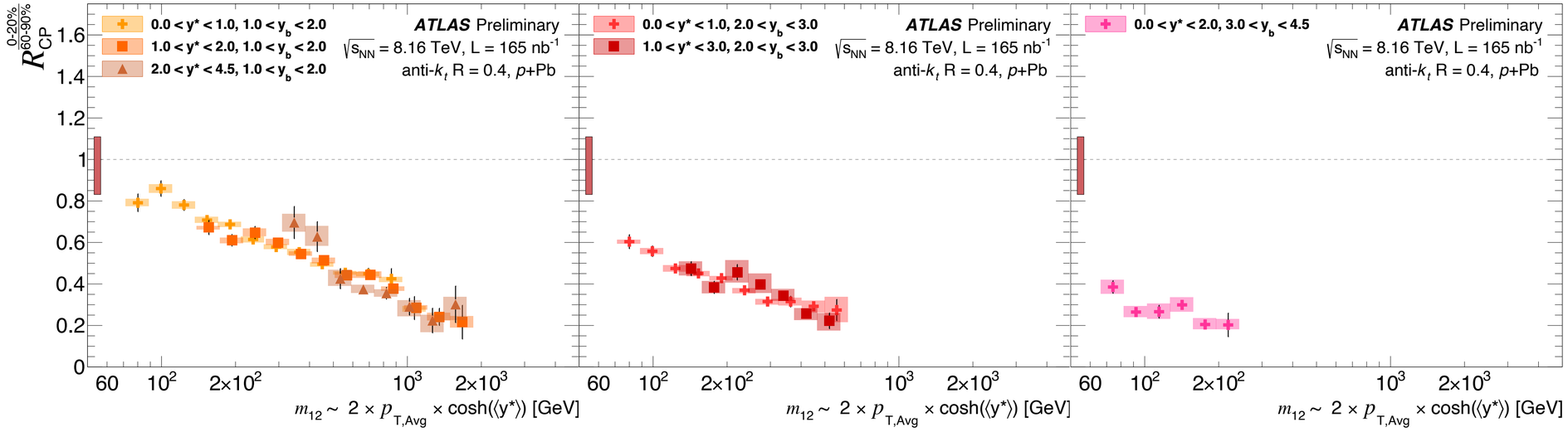
- Similar trends also observed in peripheral collisions
- Proper analysis of centrality dependence via R_{CP} construction



- Backward-most y_{b} bins excluded from the analysis given the sizable impact of the fiducial cut applied to ensure no contamination from jets in the Pb-going FCal

DIJET $R_{CP}(x_p)$ IN BINS OF $m_{1,2}$



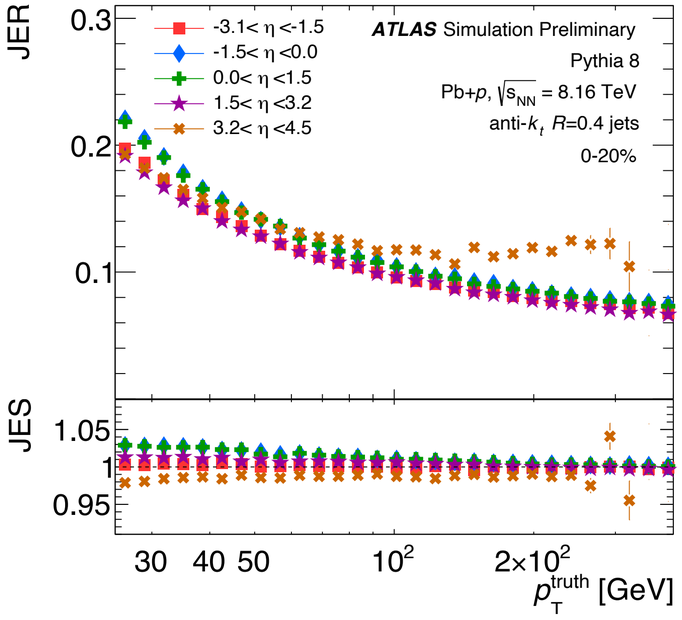


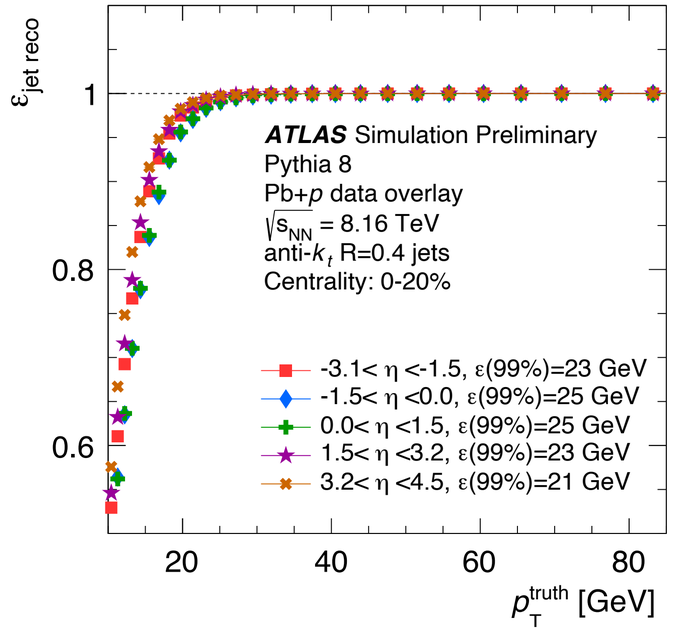
- Log-linear decrease with increasing dijet mass, $m_{1,2}$
-

JET RECONSTRUCTION PERFORMANCE

- Other beam orientation compared to the one shown in the main slides
- Compatible JES and JER picture
  - no significant detector effects related to the beam orientation are observed

Central collisions (0-20%)





Peripheral collisions (60-90%)