Jet measurements in heavy-ion collisions with the ATLAS detector

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on behalf of the ATLAS Collaboration
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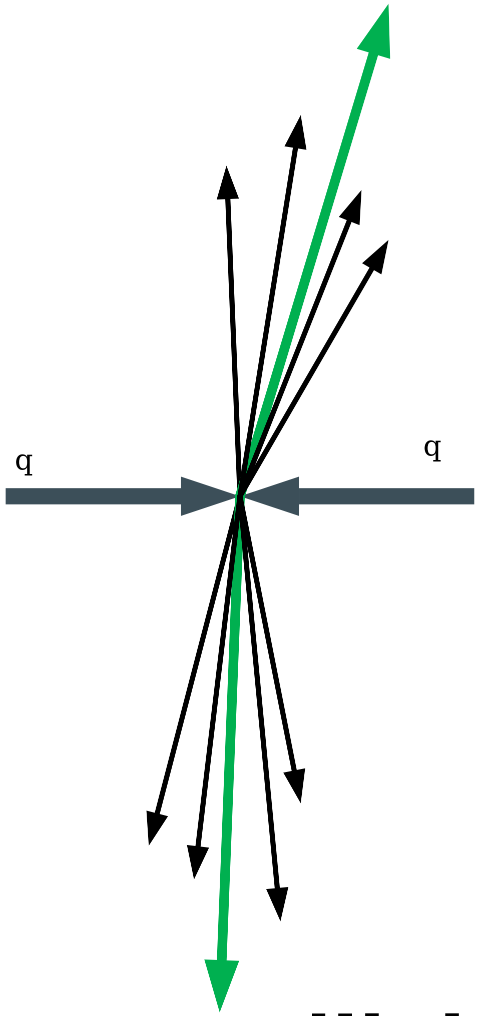
Thursday, September 14th, 2017

Jets in HI collisions?



- **Jets in *pp* collisions**

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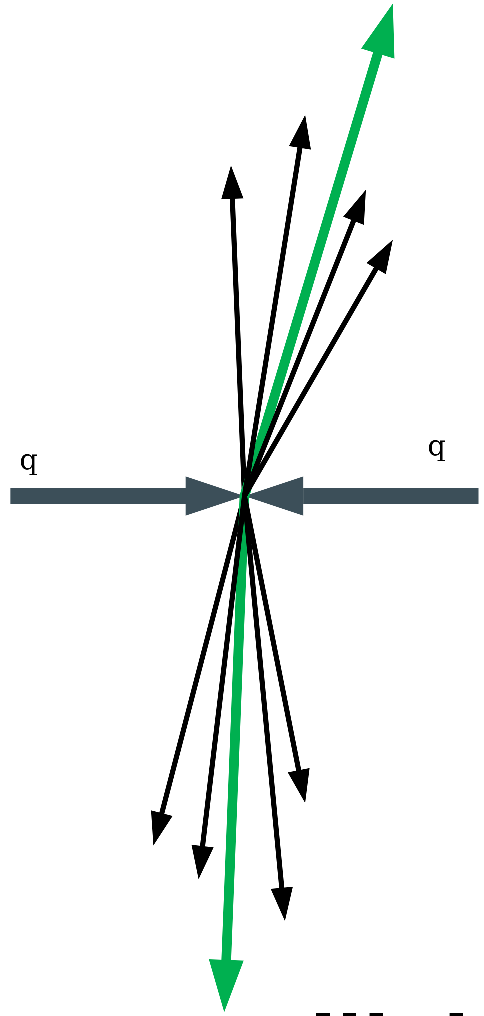
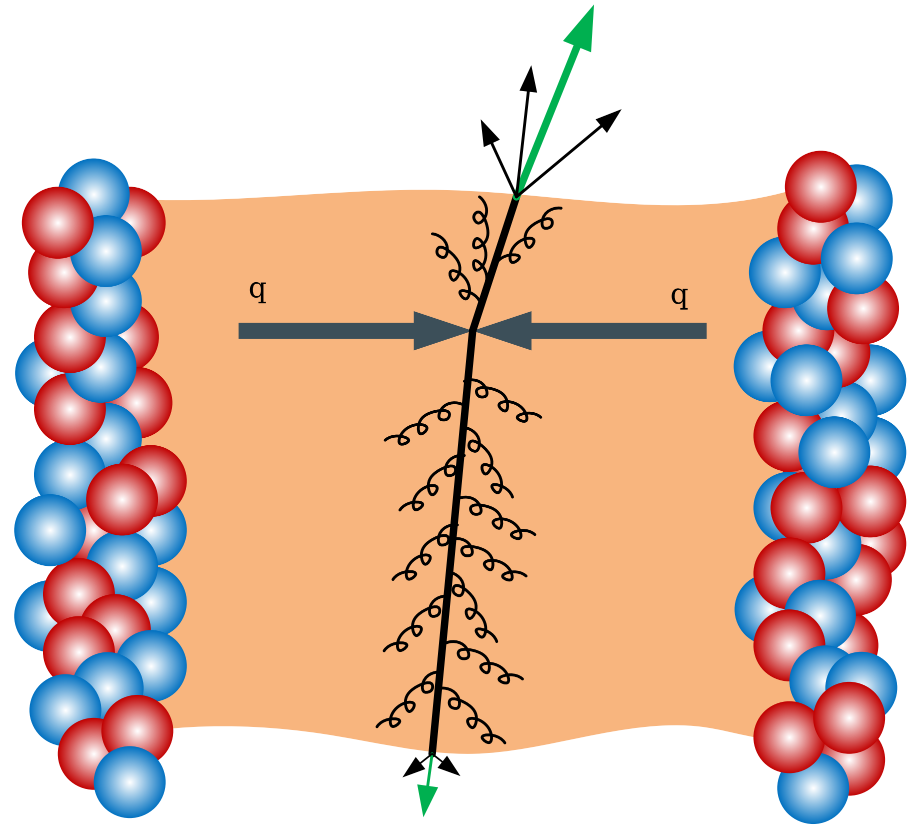




- **Jets in *pp* collisions**
- **Jets in Pb+Pb collisions**

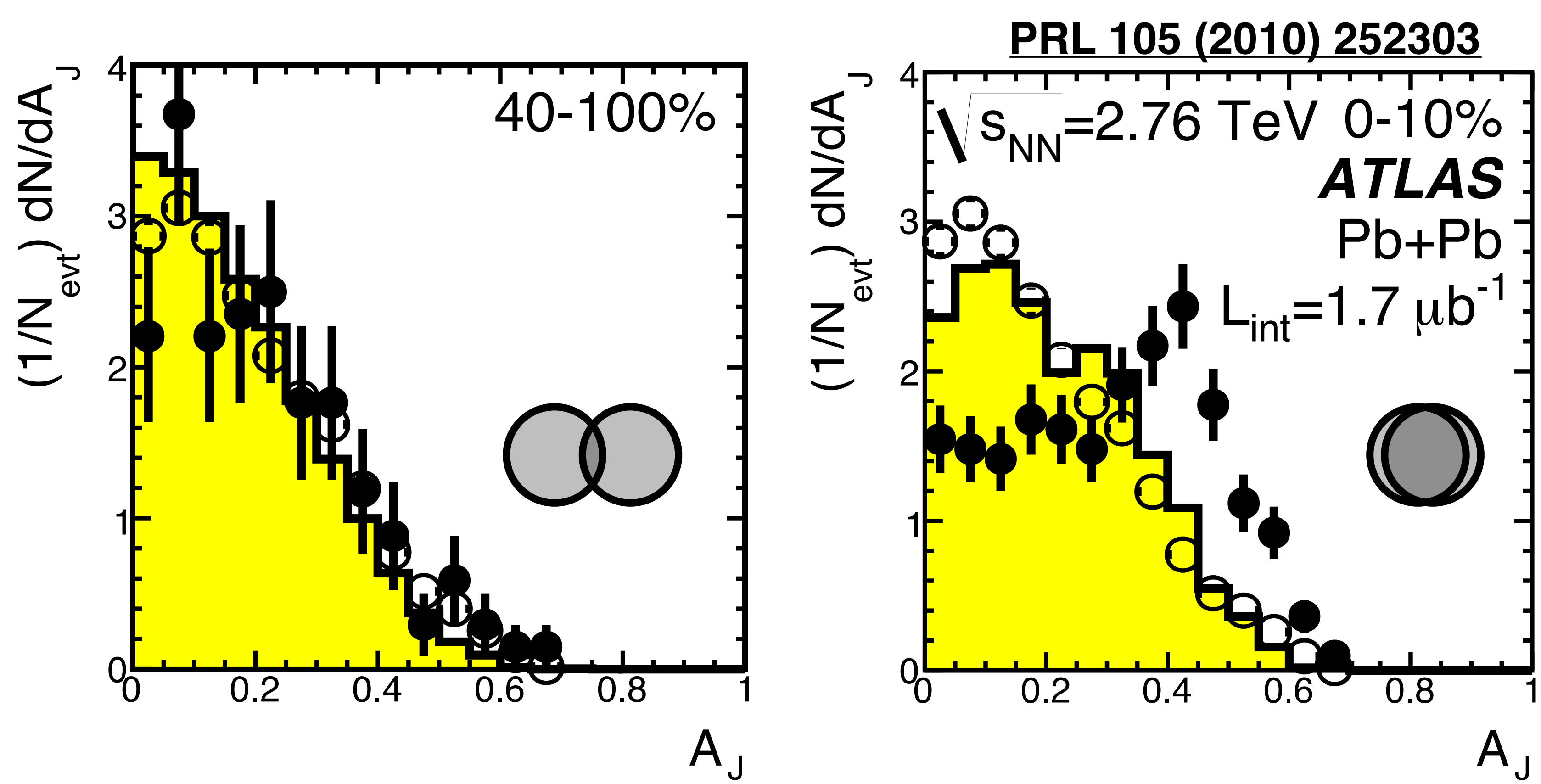
► ***Jet quenching:*** **phenomena where partons are expected to lose energy in interactions with the hot dense medium produced in HI collisions.**

➡ **jets are thus sensitive to the microscopic structure of the medium.**

Jets in HI collisions

- **Many measurements of jet quenching done in HI collisions at the LHC and RHIC.**
- **Jet measurements with ATLAS in run 1 ($\sqrt{s_{NN}}$ =2.76 TeV):**

➡ **Dijet asymmetry: dijets are more asymmetric in Pb+Pb compared to MC**



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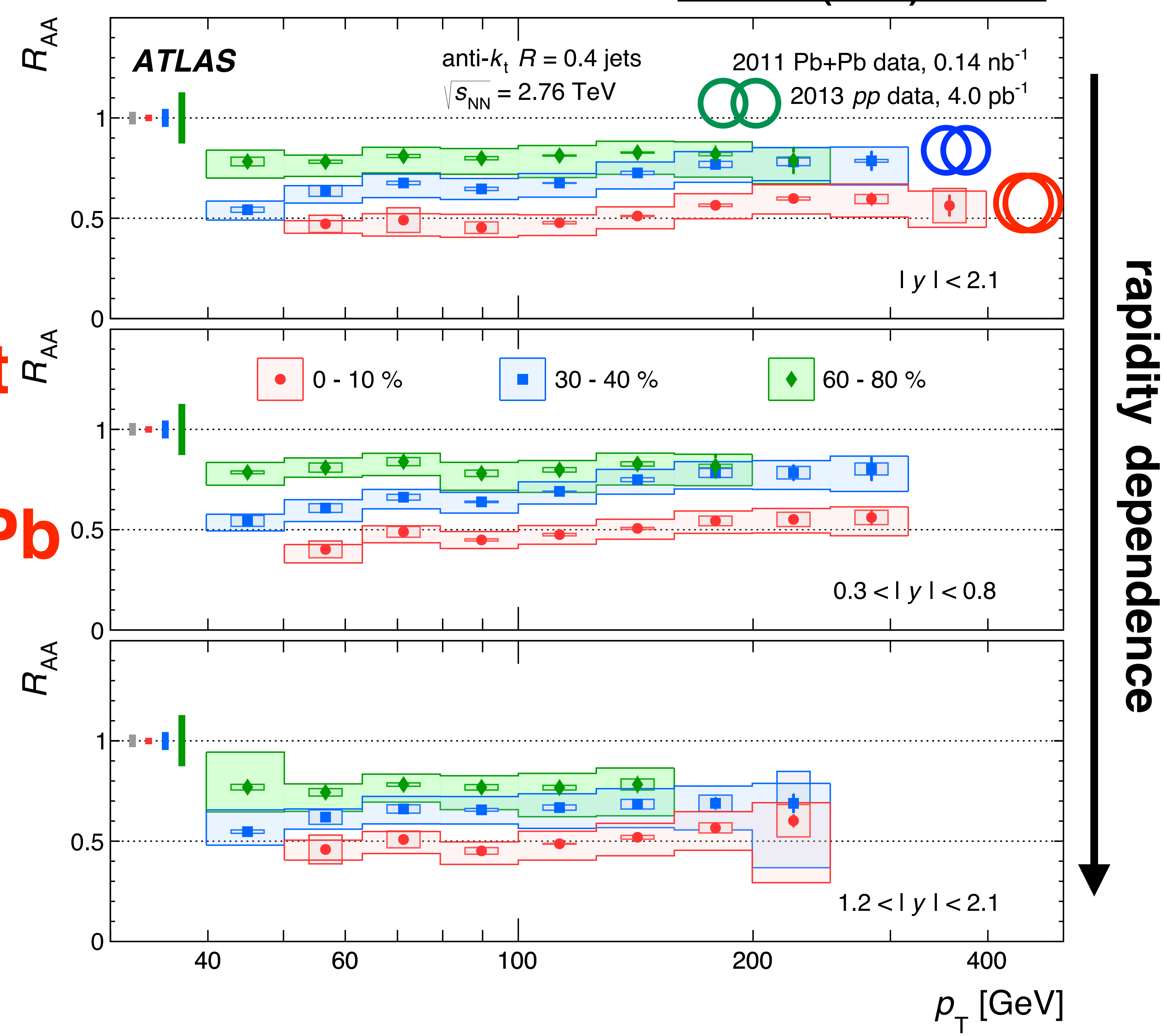
  - ➡ **Jet suppression: jet yields are suppressed in Pb+Pb compared to pp**

PRL 114 (2015) 072302



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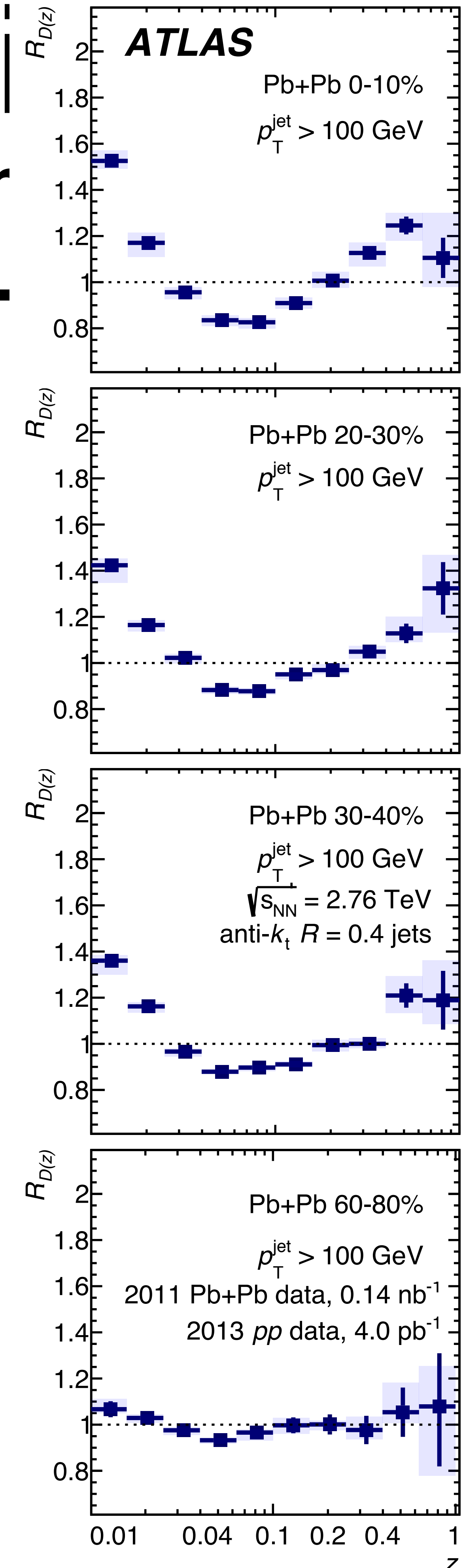
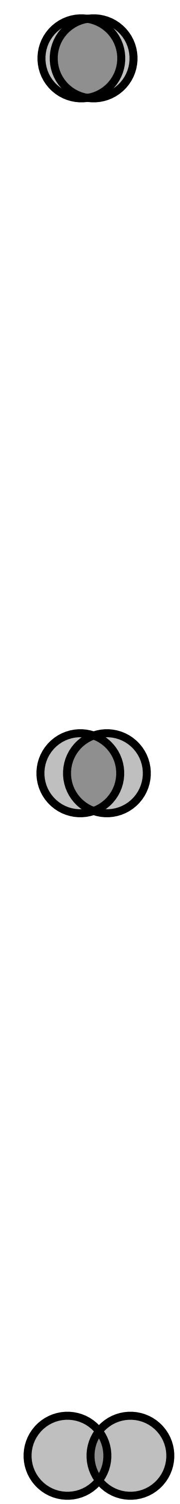
➡ **Jet suppression**

➡ **Jet fragmentation: the internal structure of jets is modified in Pb+Pb**



EPJC (2017) 77: 379



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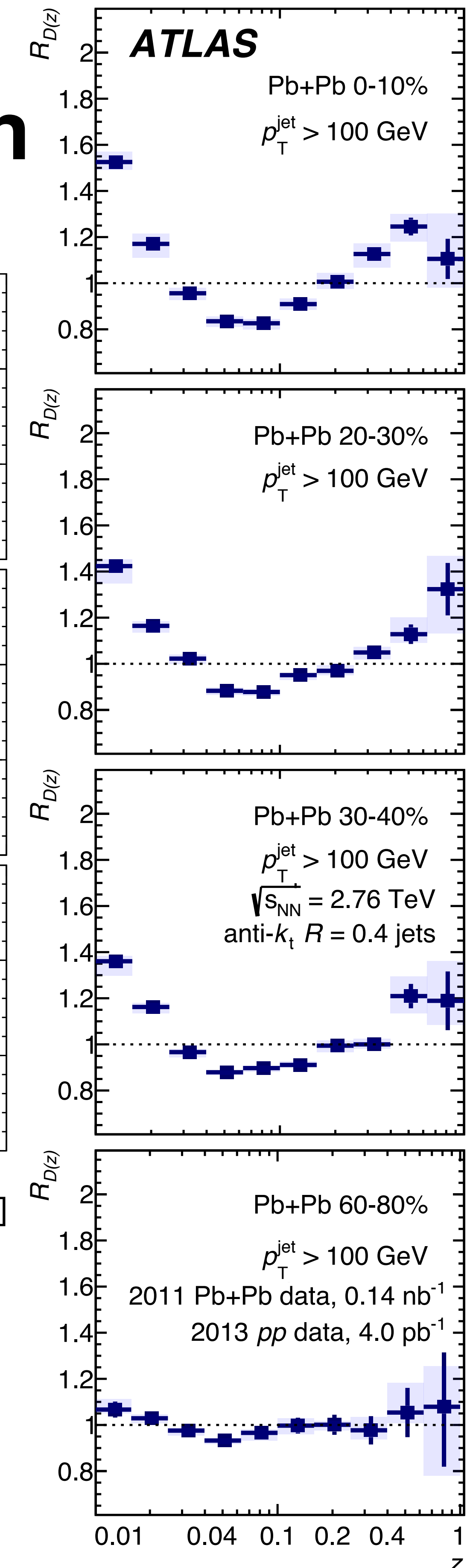
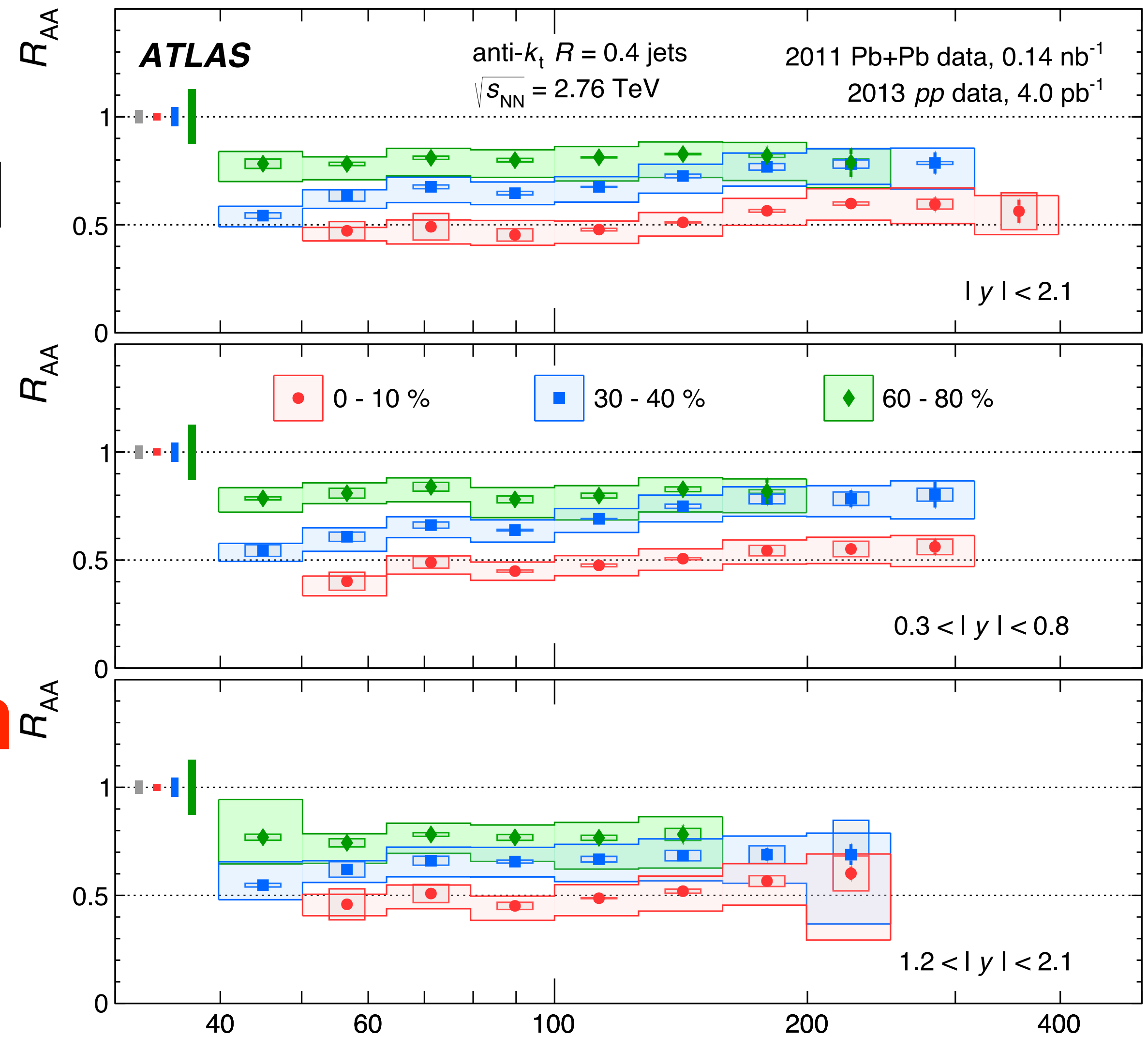
  - ➡ **Jet fragmentation**
  - ➡ **etc.**

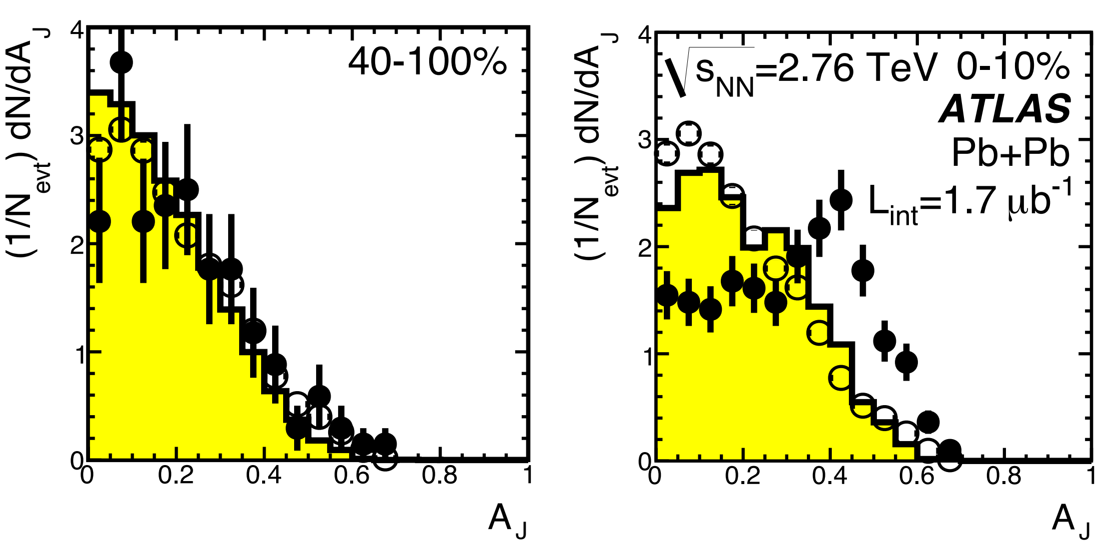
EPJC (2017) 77: 379





PRL 114 (2015) 072302 p_T [GeV]

PRL 105 (2010) 252303



- **There is something here but we need to dig deeper….**

Jets in HI collisions

- **New results dig deeper to better understand jet quenching:**
  - ➡ **More precise measurements with better control over the background subtraction and systematics and unfolded so they can be directly compared to theory.**
  - ➡ **Better statistics allows for measurements at high jet p_T and differentially in jet p_T and rapidity that address specific questions such as what is the flavor dependence of jet quenching and what happens to jet suppression at high jet p_T.**
  - ➡ **Measurements at different center-of-mass energies.**
  - ➡ **What happens in boson+jet systems, etc.**

Jet reconstruction: procedure

- **Jets are reconstructed using the anti-k_t algorithm for R=0.4 in *pp*, *p*+Pb, and Pb+Pb collisions.**

- **Uncorrelated underlying event (UE) contributes background energy inside that jet cone that varies with η and Φ and hugely event-by-event.**

➡ **Background is subtracted using an iterative procedure that is modulated by harmonic flow.**

$$\frac{dE_T}{d\eta d\phi} \approx \frac{dE_T}{d\eta}\left(1 + \sum_n v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

- **Measured quantities are influenced by both the effect of the UE and the detector.**

➡ **Removed through an unfolding procedure that is under better control if UE is subtracted jet-by-jet.**

Jet reconstruction: performance

- **Measure of how well you can do any jet measurement.**
- **MC jets (with a simulated detector response) are embedded into real Pb+Pb data and reconstructed in the same way as data.**
- **Jet energy scale (JES) and jet energy resolution (JER) are the mean and the width of the p_T^{reco}/p_T^{true} distribution.**

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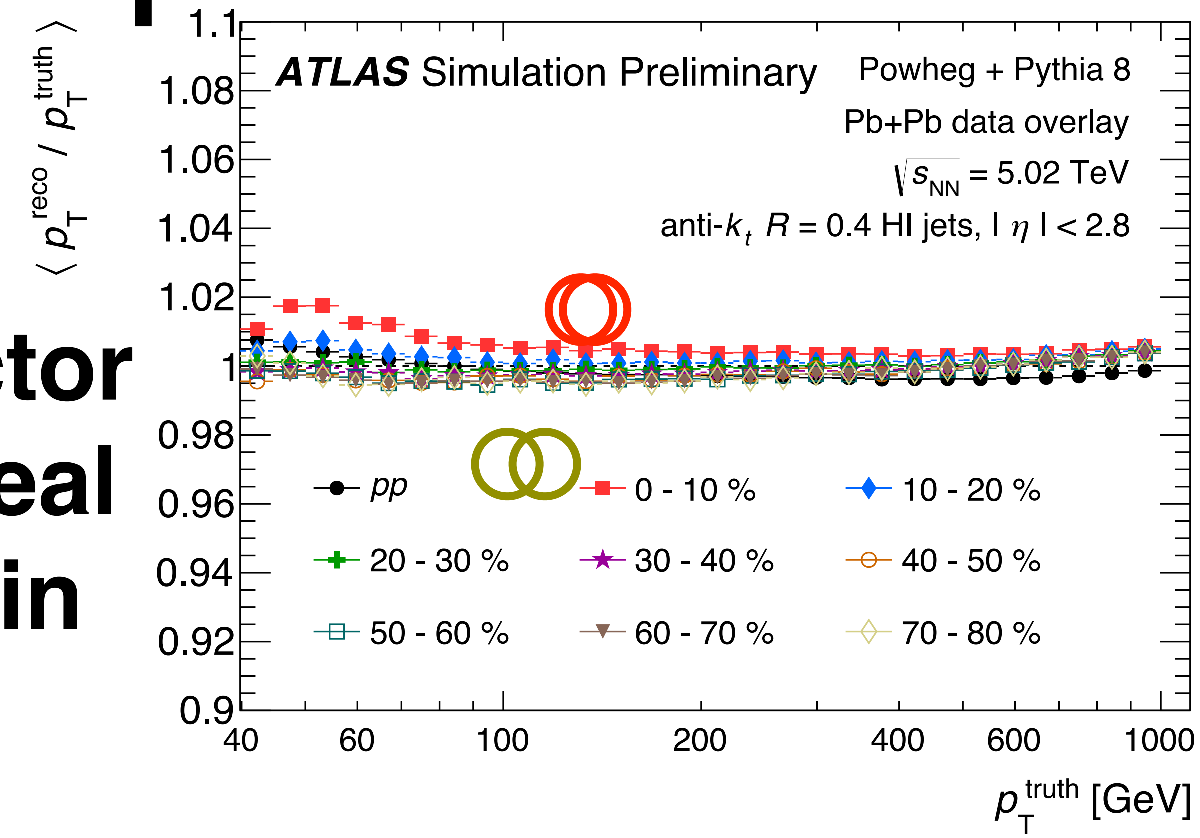
➡ **JES is ~1% above 100 GeV for 0-10% meaning the additive UE background was removed to within 1% of the jet energy.**



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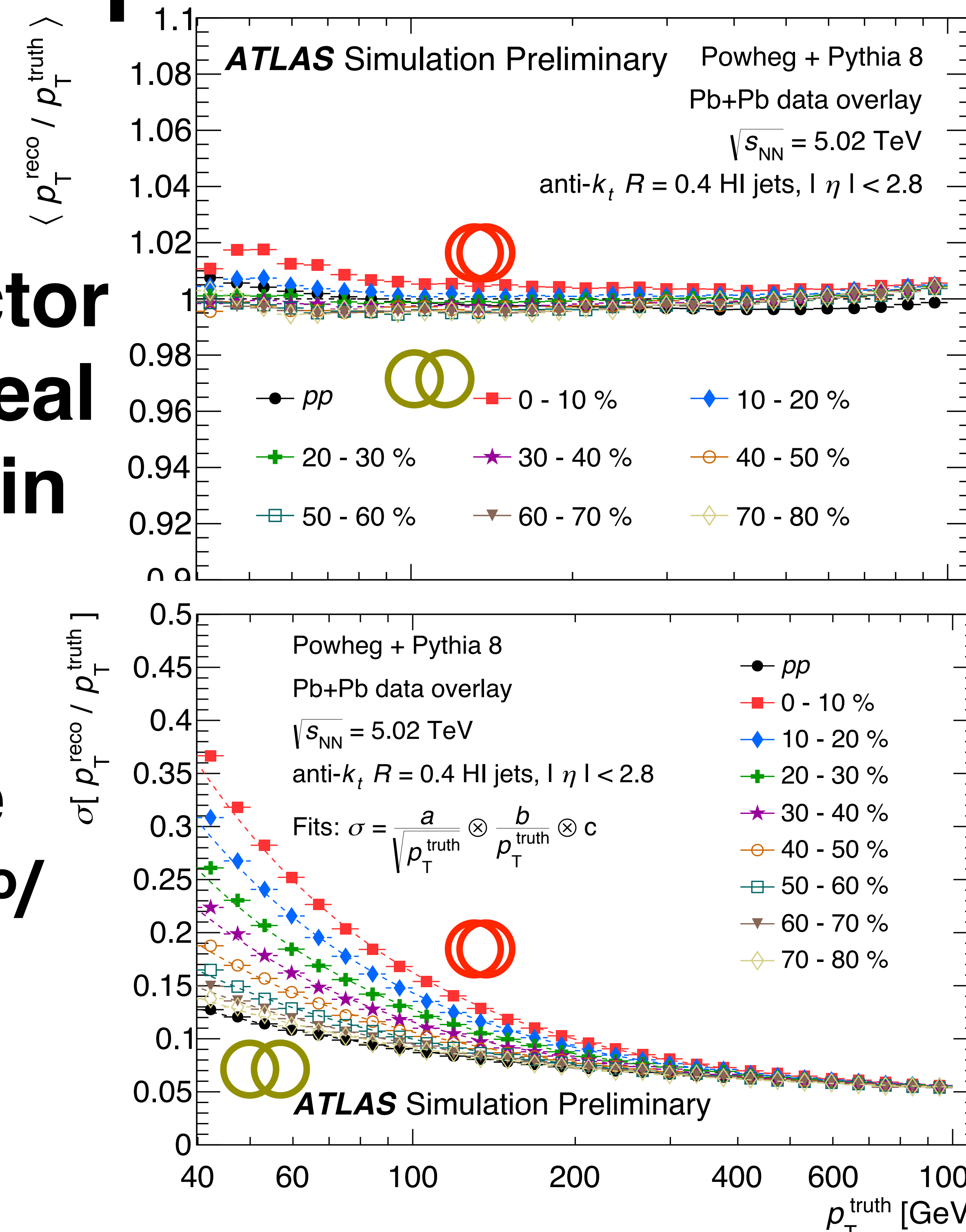
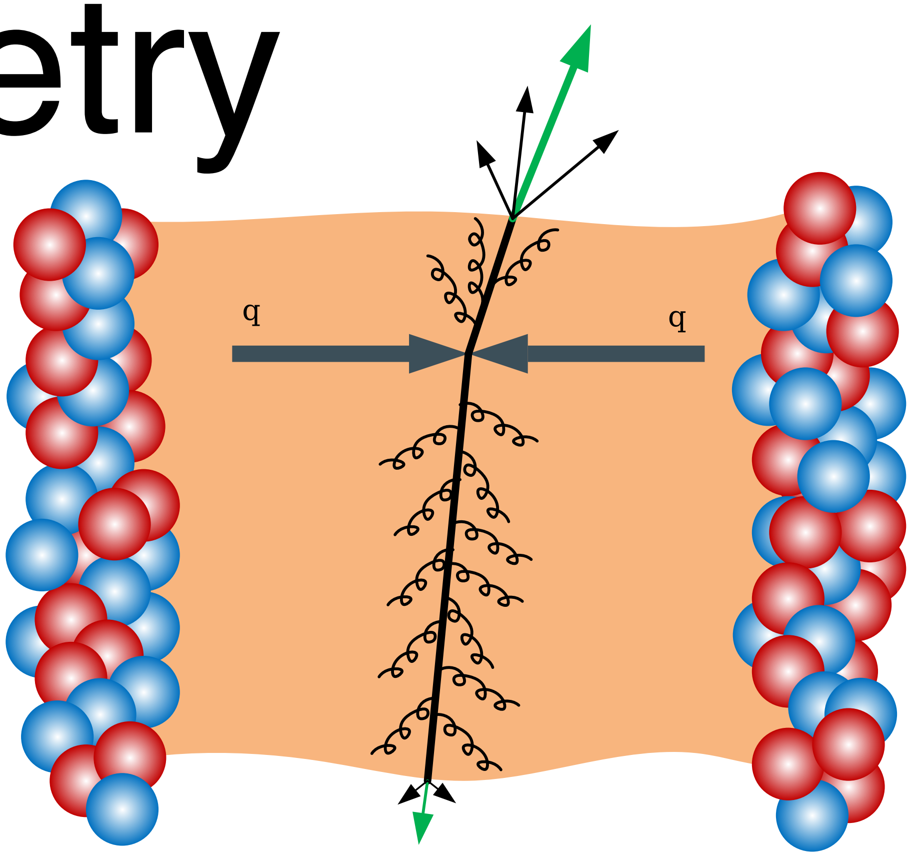


➡ **JER in 0-10% is ~16% at 100 GeV and decreases to a constant value at ~6%.**

Dijet asymmetry

arXiv:1706.09363



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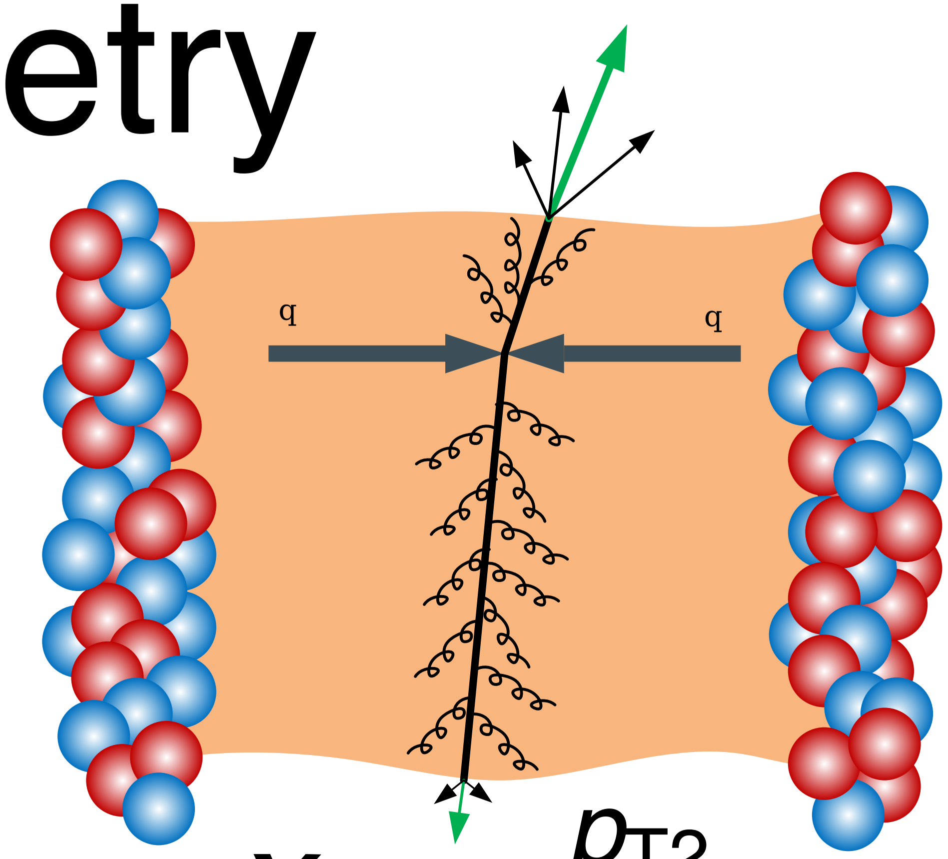

$$x_J = \frac{p_{T2}}{p_{T1}}$$

➡ **Use ratio of sub-leading jet p_T to the leading jet p_T.**

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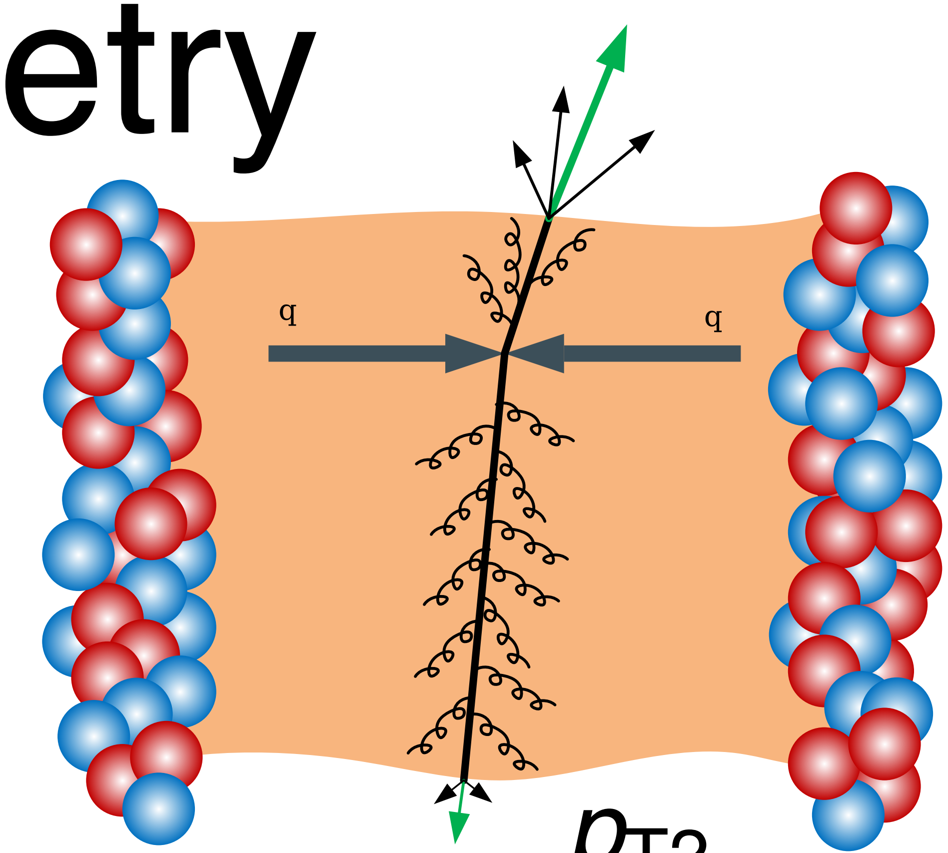

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➡ **Use ratio of sub-leading jet p_T to the leading jet p_T.**

- **Measure x_J as a function of leading jet p_T and centrality.**

➡ **Compare to *pp* dijets.**

➡ **Kinematic selections: two highest jets in each event with $p_{T1} > 100$ GeV and $p_{T2} > 25$ GeV and $\Delta\phi > 7\pi/8$.**

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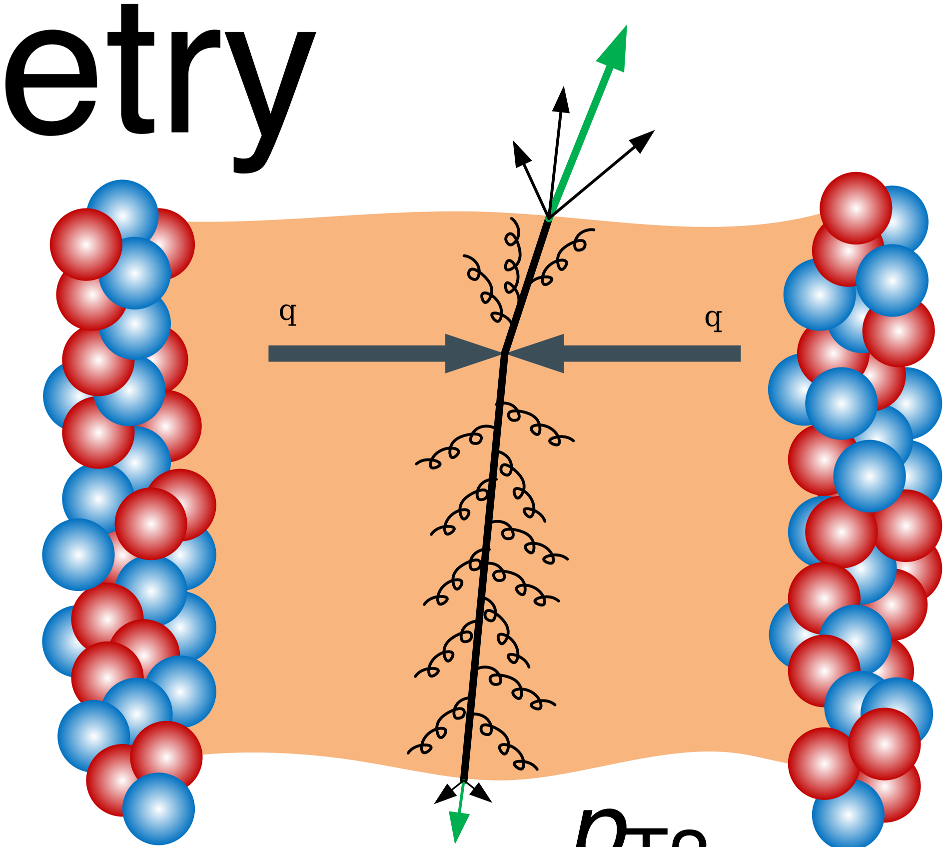

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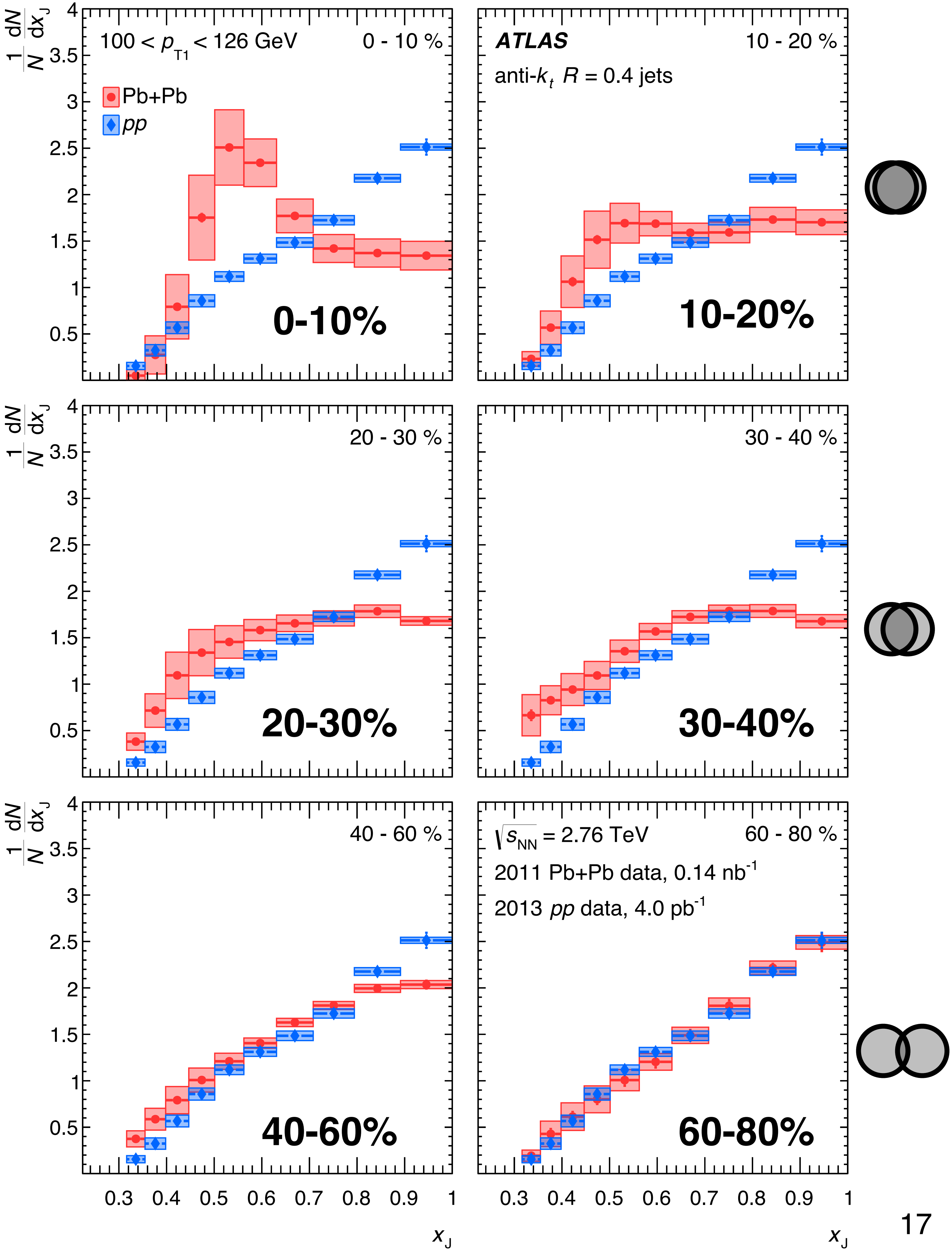
▸ **Unfolded using 2D Bayesian unfolding in p_{T1} and p_{T2}.**

x_J distribution

centrality dependence

100 < p_{T1} < 126 GeV



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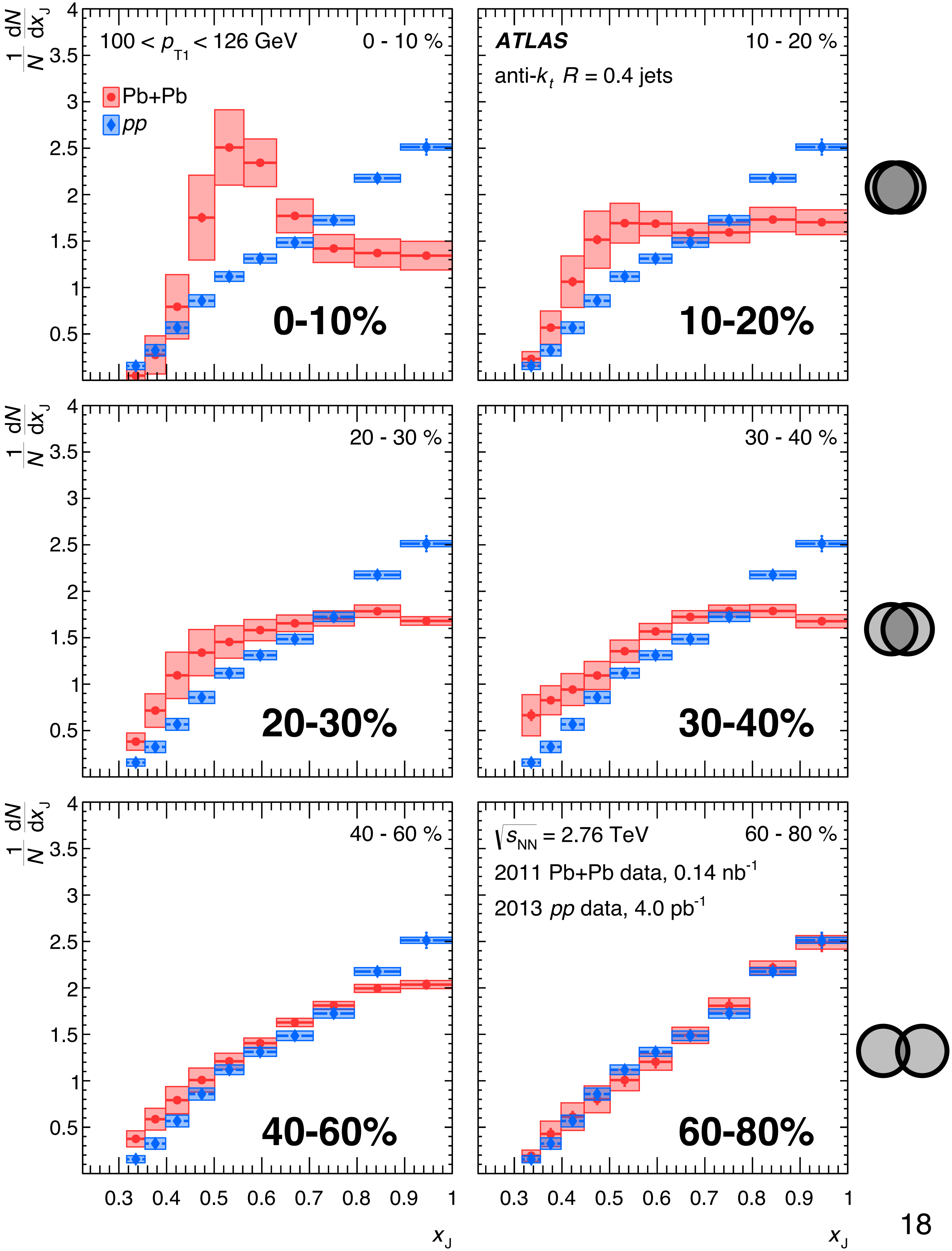
- **x_J in Pb+Pb is more asymmetric in more central collisions.**



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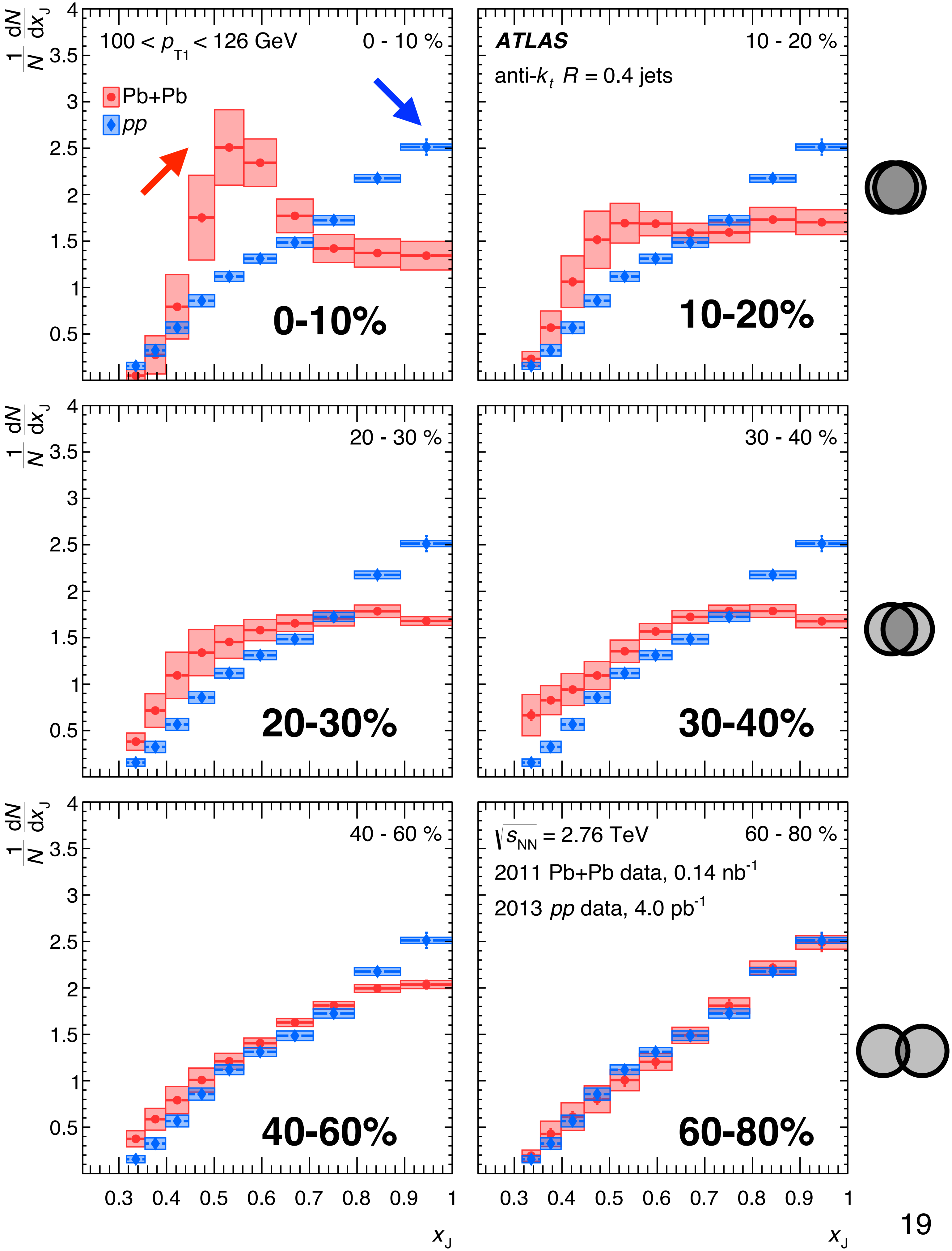
- **x_J in Pb+Pb is more asymmetric in more central collisions.**
- **The most probable configuration for *pp* collisions is $x_J \sim 1$.**
- **For central Pb+Pb collisions it is $x_J \sim 0.5$.**



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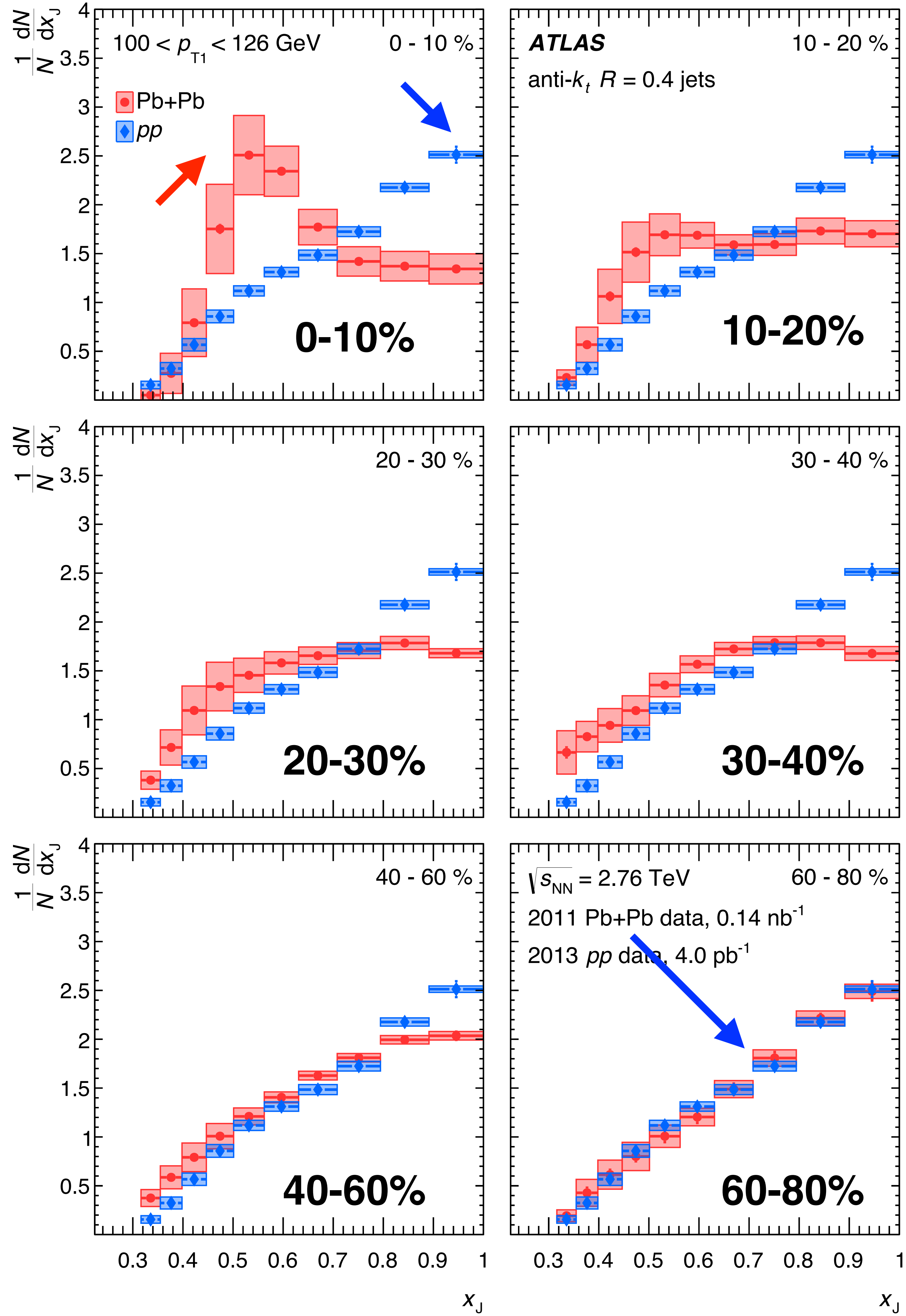
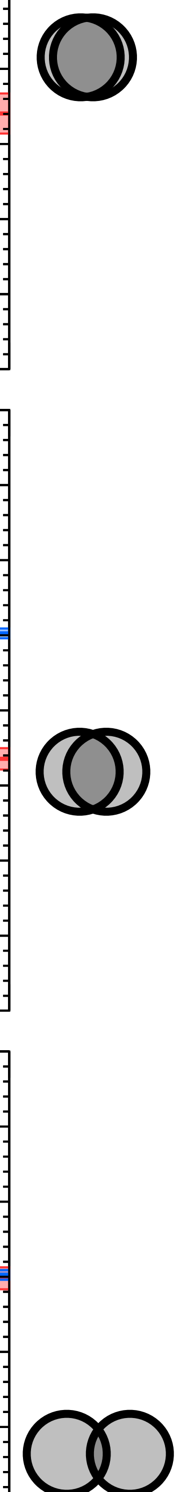
- **As Pb+Pb becomes more peripheral the x_J is like in *pp*.**





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x_J distribution

p_{T1} dependence
0-10%

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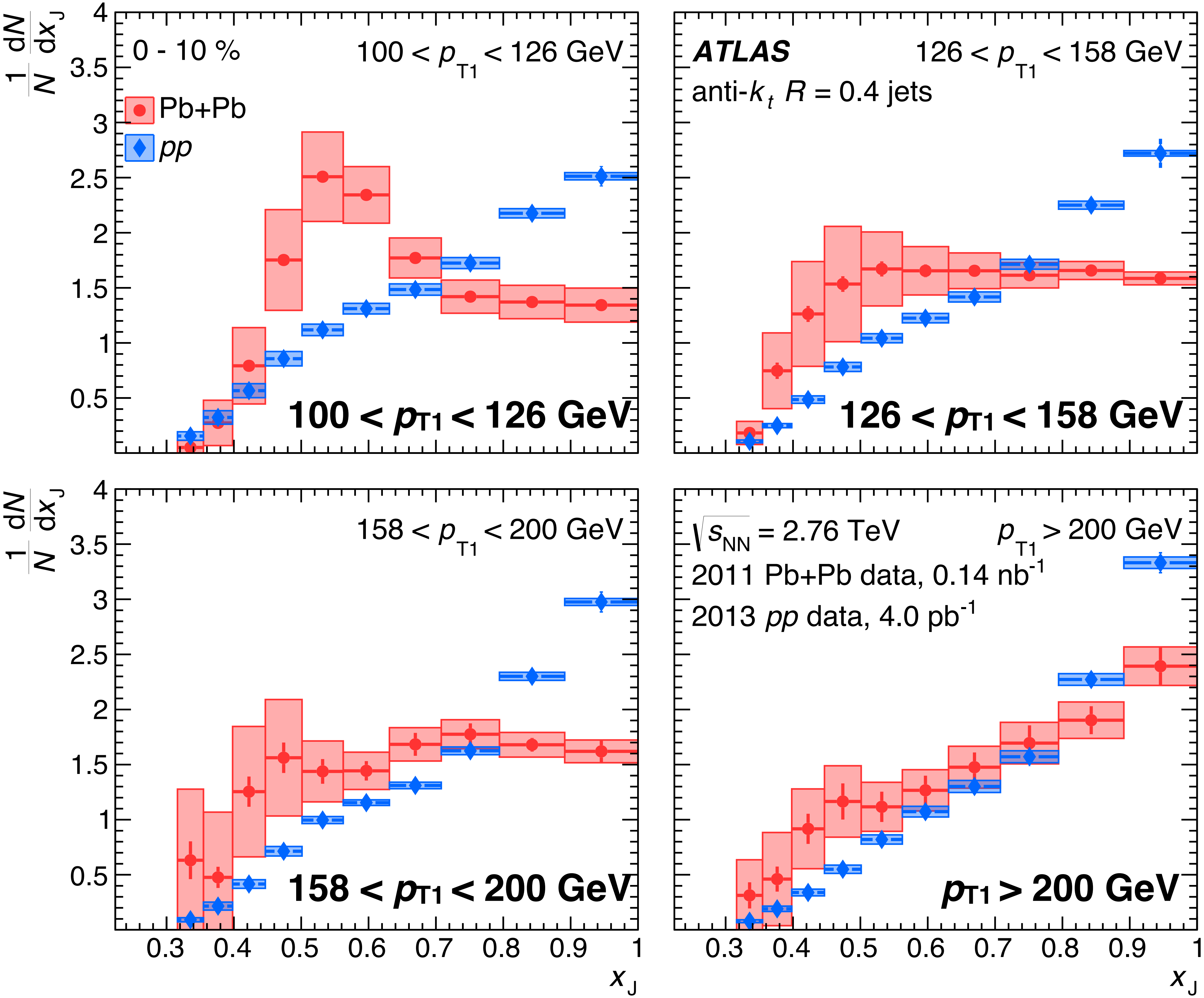

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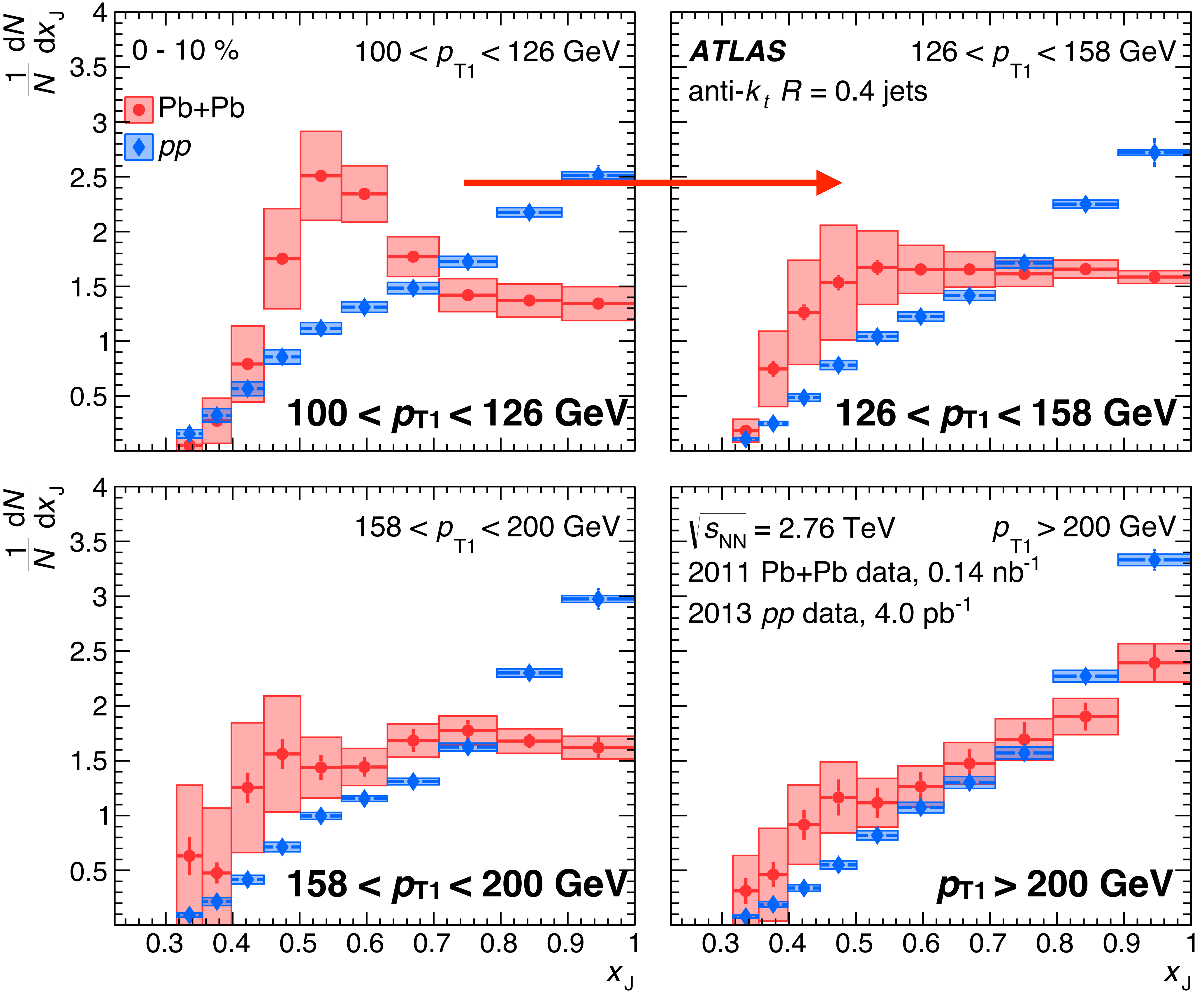
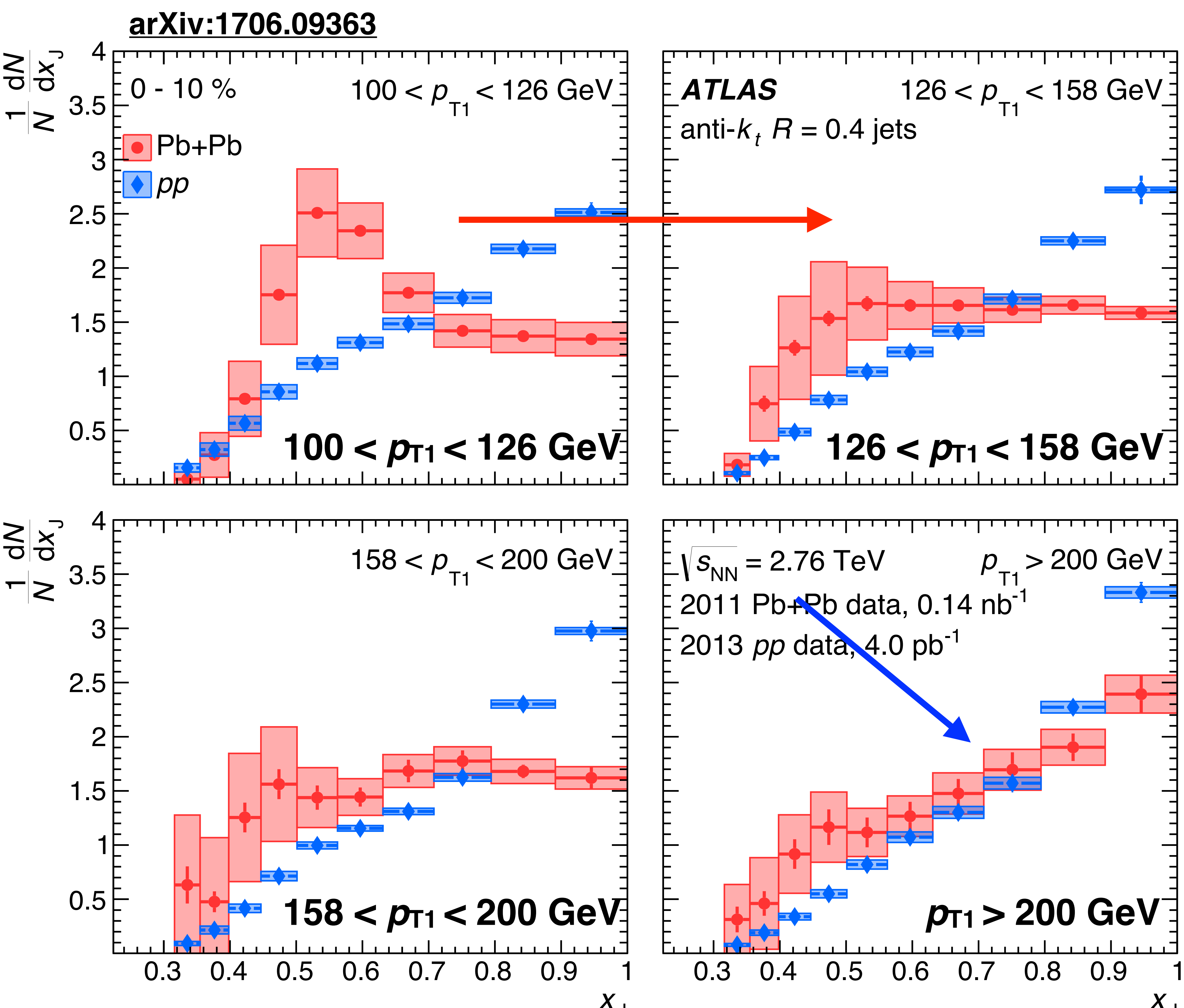


- **Significant dependence on p_{T1}.**

x_J distribution

p_{T1} dependence
0-10%



- **Significant dependence on p_{T1}.**
- **Pb+Pb becomes like *pp* at high p_{T1}.**

x_J distribution

p_{T1} dependence
0-10%

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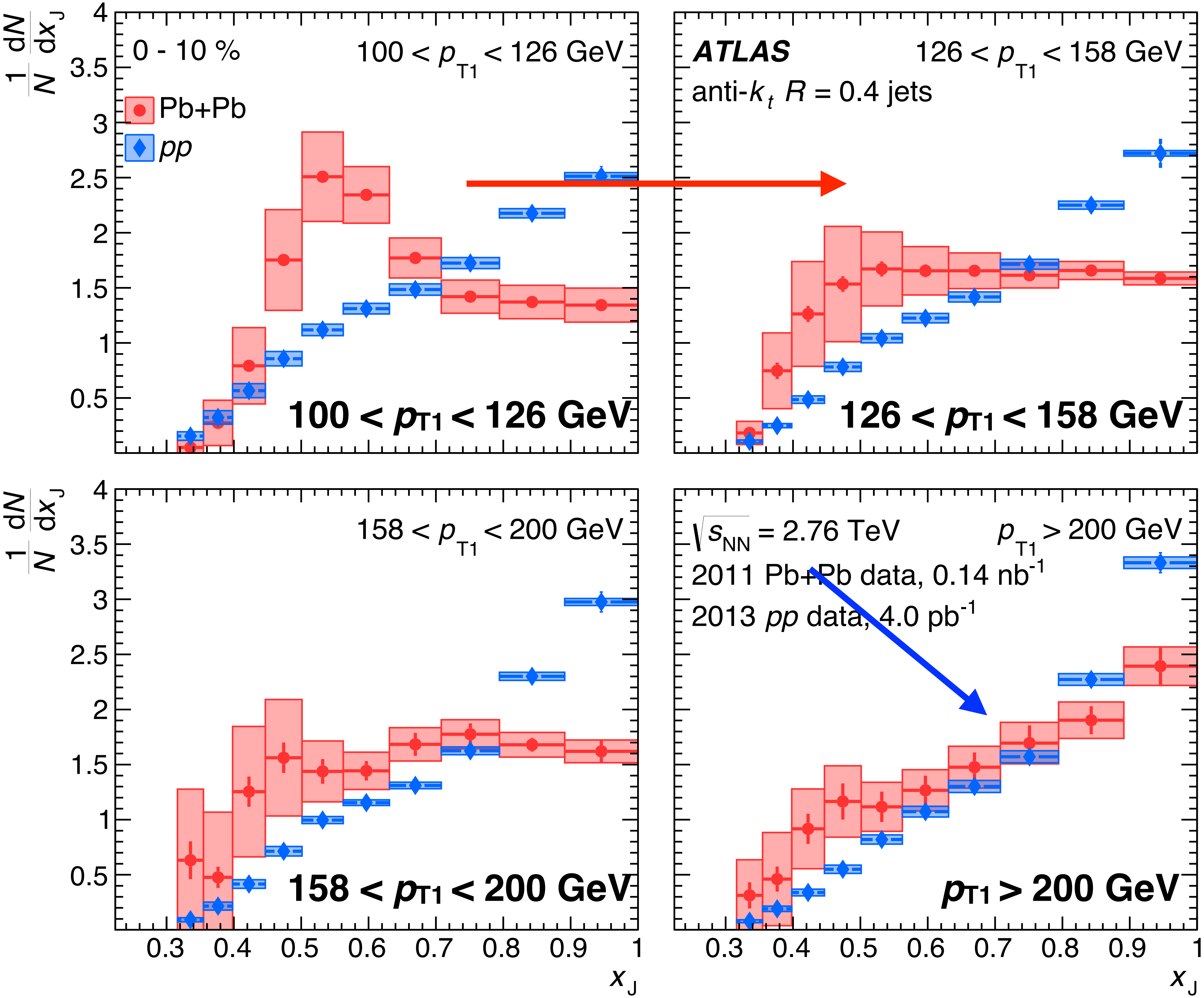

- **Significant dependence on p_{T1}.**
- **Pb+Pb becomes like *pp* at high p_{T1}.**
- ***Probe of the flavor dependence because quark/gluon fractions change with p_T!***

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$$x_{J_\gamma} = \frac{p_{T,jet}}{p_{T,\gamma}}$$

γ-jet asymmetry

- **The photon does not interact with the plasma so the energy loss of the recoiling jet can be probed.**
- **Measured $x_{J\gamma}$ for $p_{T\gamma} > 60$ GeV, $p_{T,jet} > 30$ GeV, $\Delta\phi > 7\pi/8$**

ATLAS-CONF-2016-110

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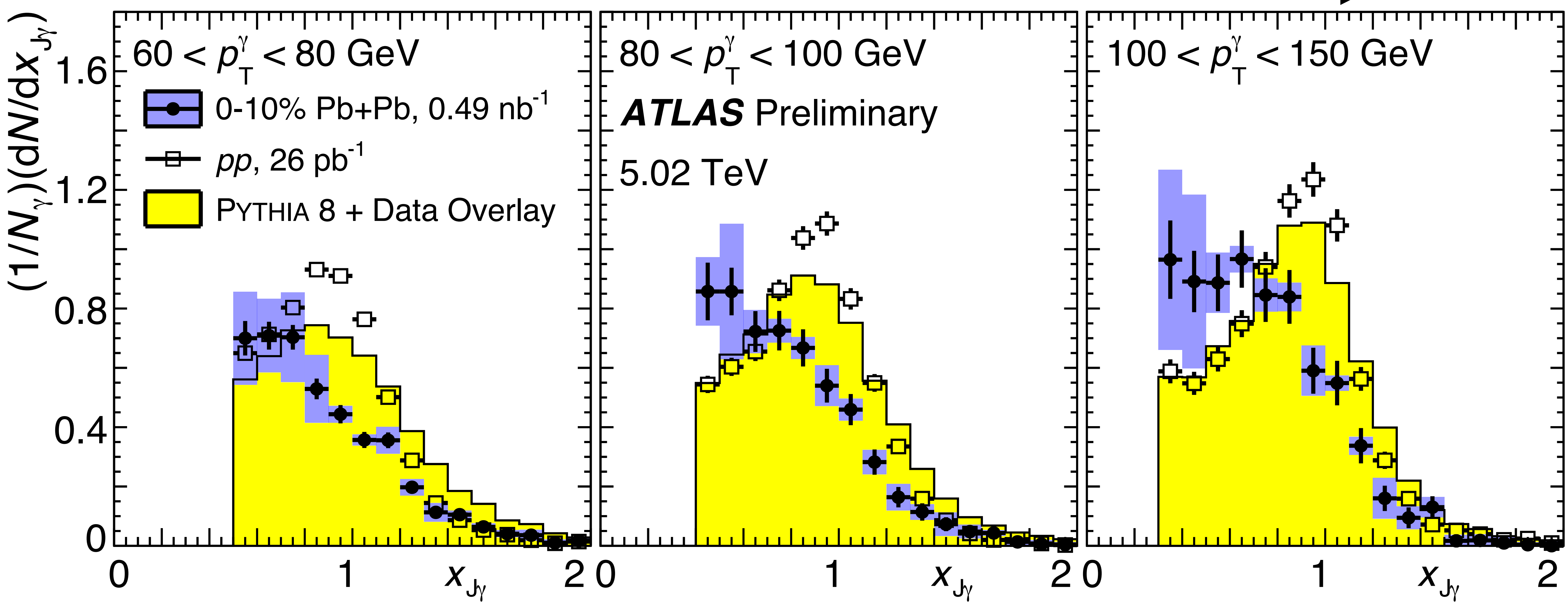
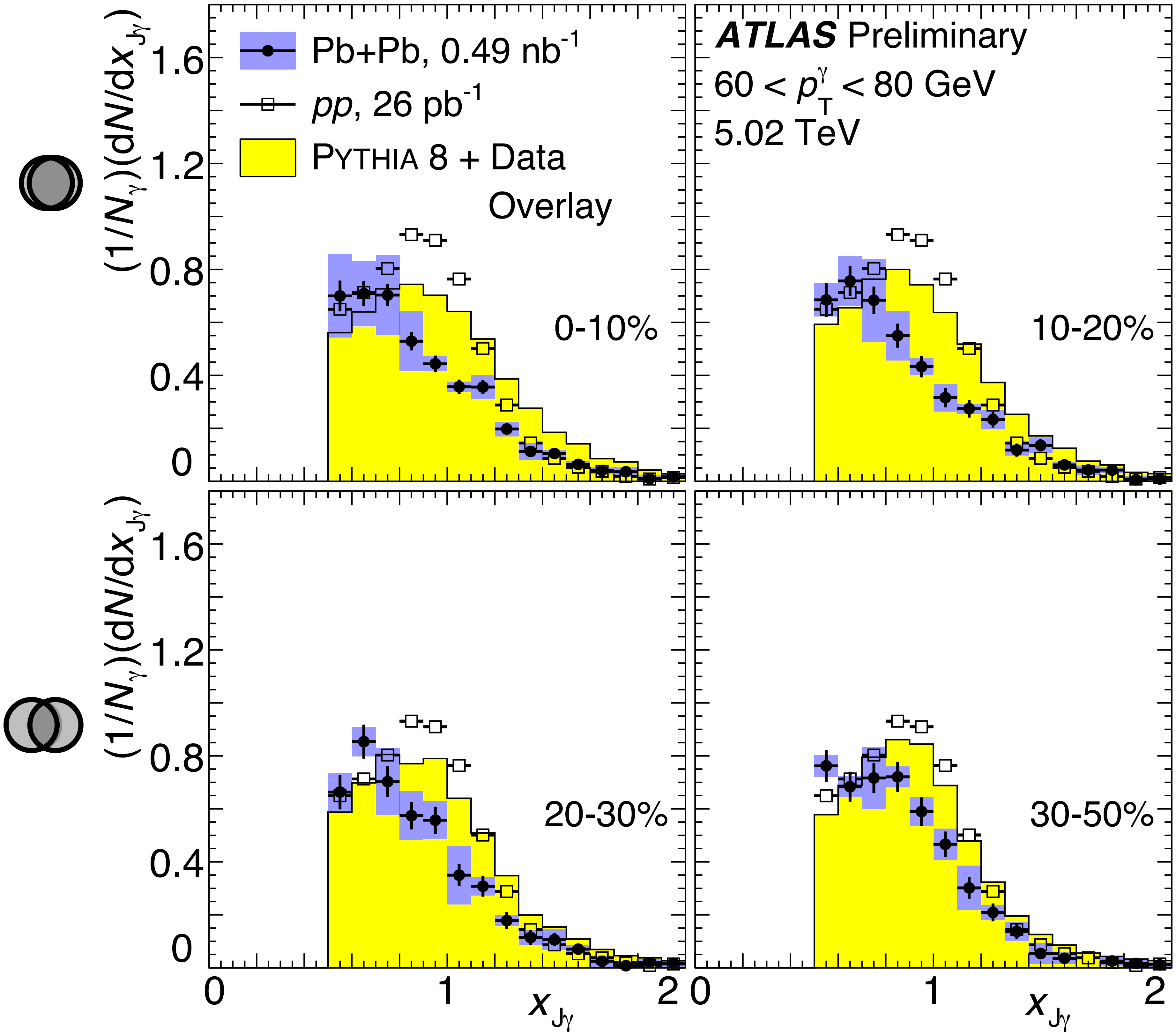
➡ **Pb+Pb has more asymmetric pairs than *pp* and MC.**

increasing $p_{T\gamma}$



- **Corrected for background and JES but not unfolded.**

γ-jet asymmetry



centrality dependence

$60 < p_{T\gamma} < 80$ GeV

- **The distributions become less asymmetric with increasing centrality.**

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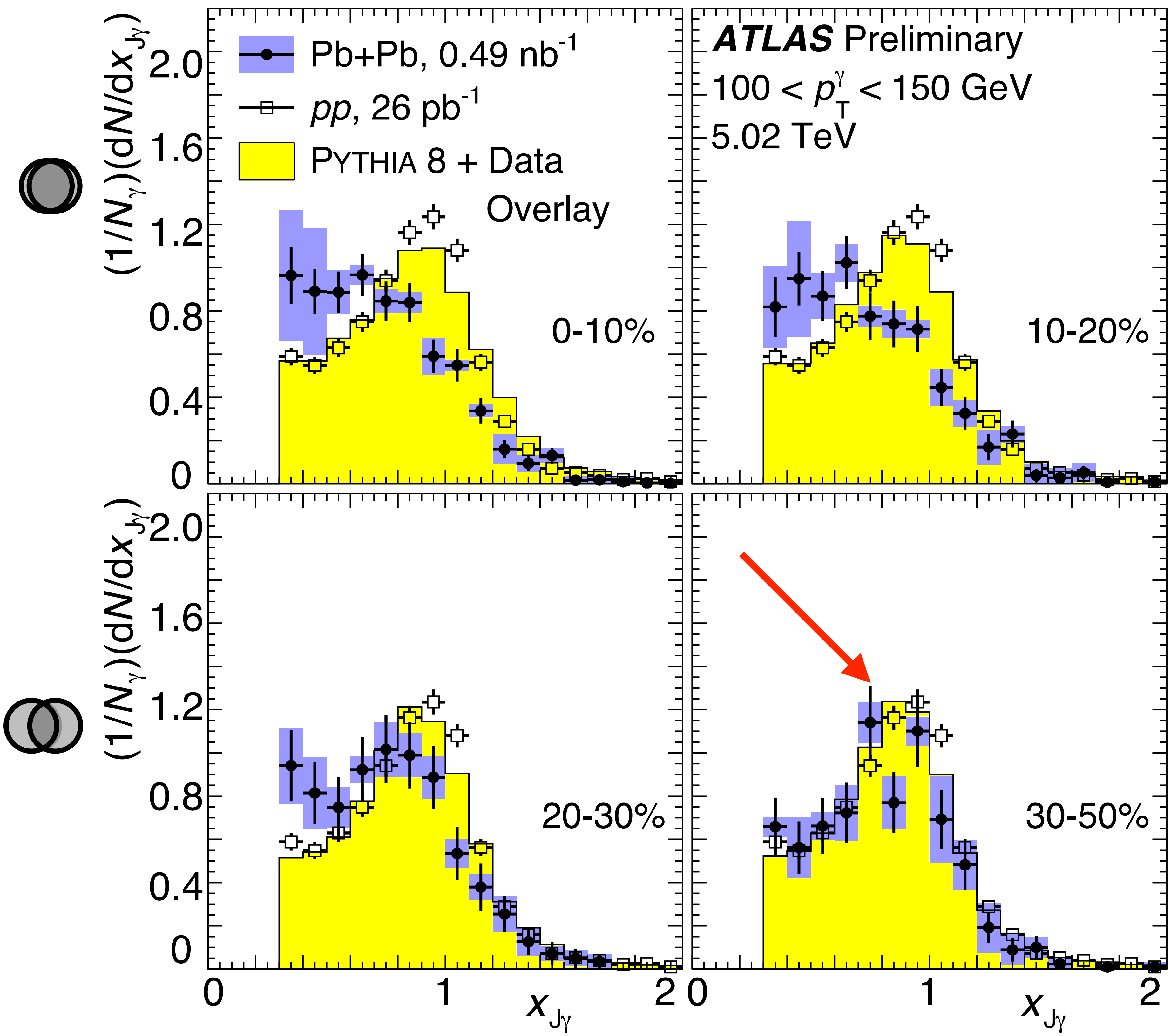
γ-jet asymmetry



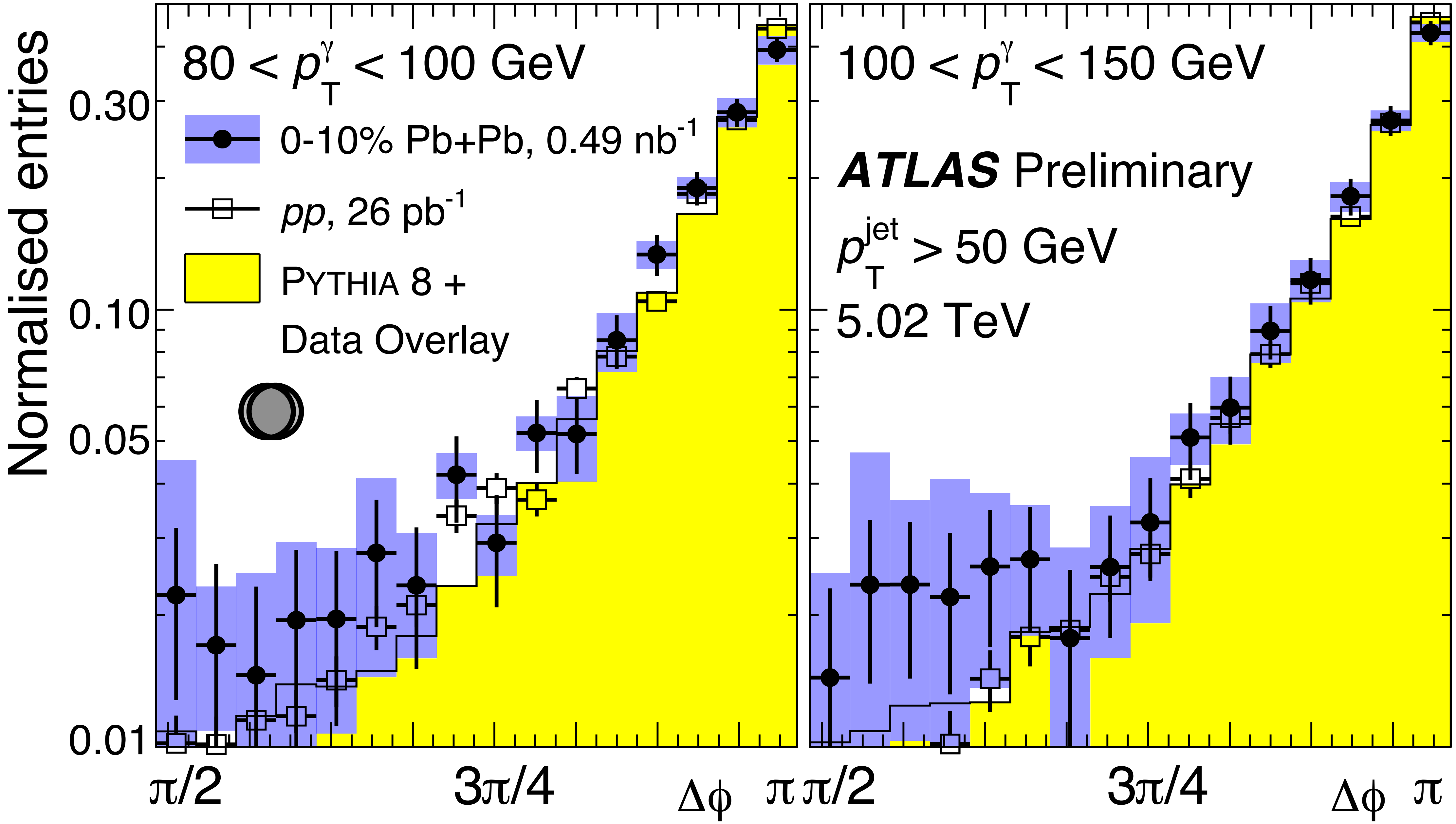
centrality dependence

$100 < p_{T\gamma} < 150$ GeV

- **The distribution becomes like simulation for 30-50% suggesting that the fraction of energy loss decreases with parton p_T.**

γ-jet angular correlations

- **No evidence for large modifications of angular distributions in Pb+Pb compared to *pp* collisions for photon+jet.**



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Jet suppression

- **Jet quenching implies jet yields in Pb+Pb are expected to be suppressed at a fixed p_T compared to *pp* collisions.**

➡ **Compare the number of jets in *pp* to Pb+Pb vs. p_T.**

$$R_{AA} = \frac{\frac{1}{N_{evnt}} \frac{d^2 N^{PbPb}_{jet}}{dp_T dy}\Big|_{cent}}{\langle T_{AA} \rangle_{cent} \times \frac{d^2 \sigma^{pp}_{jet}}{dp_T dy}}$$

Jet yield measured in heavy ion collisions

Nuclear thickness function

Jet cross-section measured in *pp* collisions

- **The nuclear thickness function (<T_{AA}>) contains the effects of nuclear geometry and accounts for the fact that per Pb+Pb collision there are multiple chances for hard scatterings.**

Jet spectra

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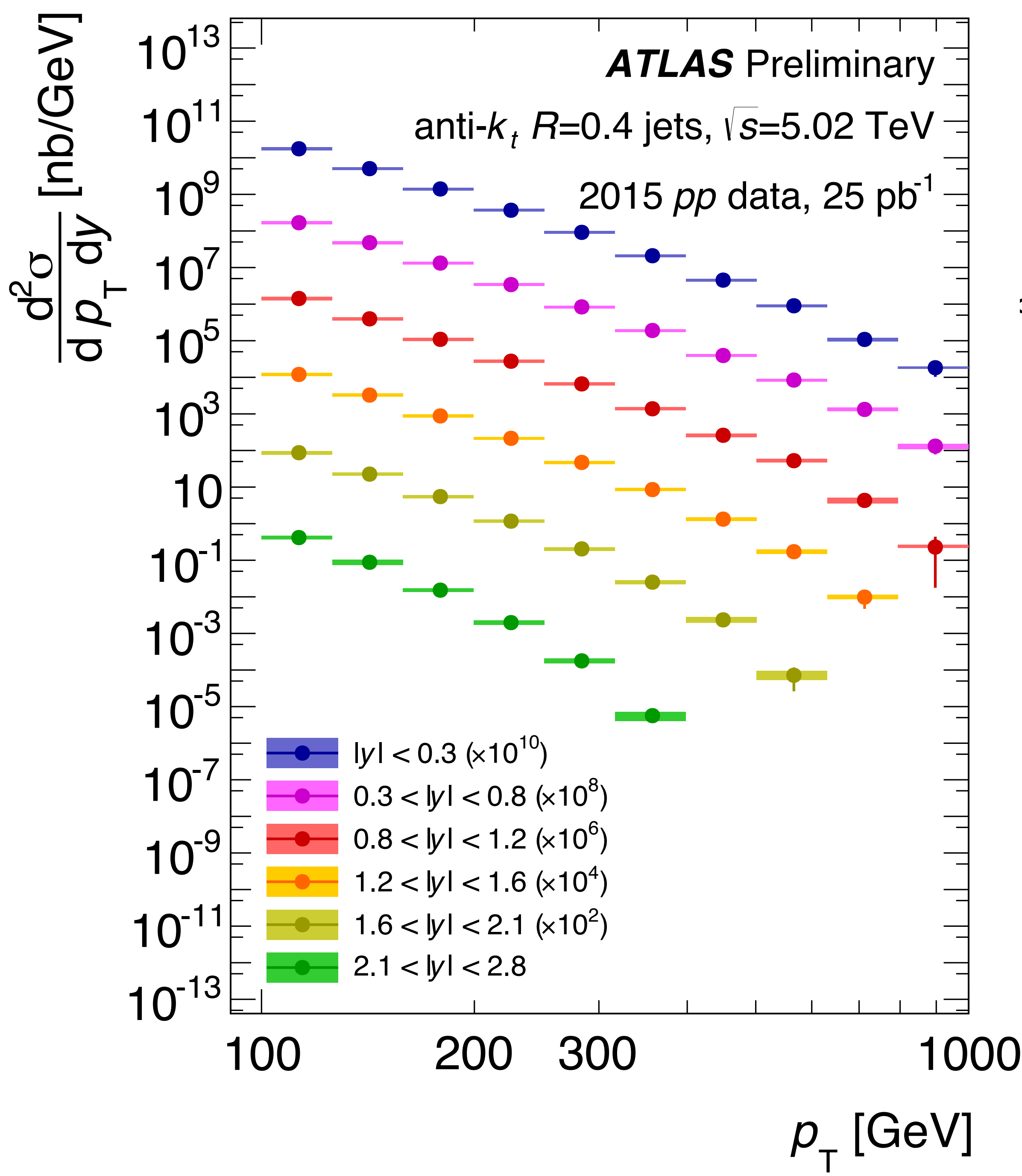
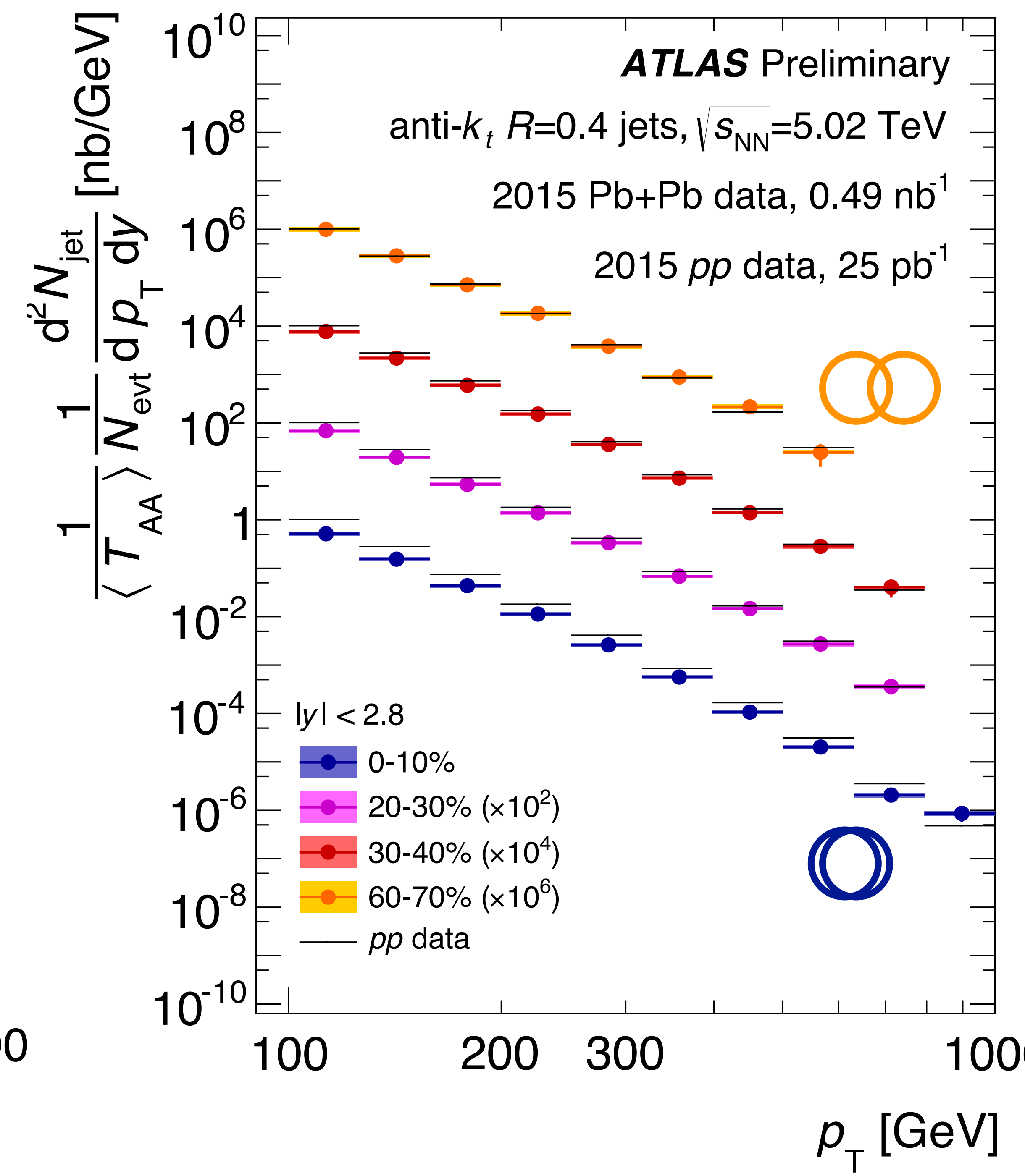
- **Jets are measured in six bins of rapidity (out to 2.8) and up to a ~ 1 TeV in jet p_T.**





- **Spectra is unfolded using 1D Bayesian unfolding.**

R_{AA} vs. p_T

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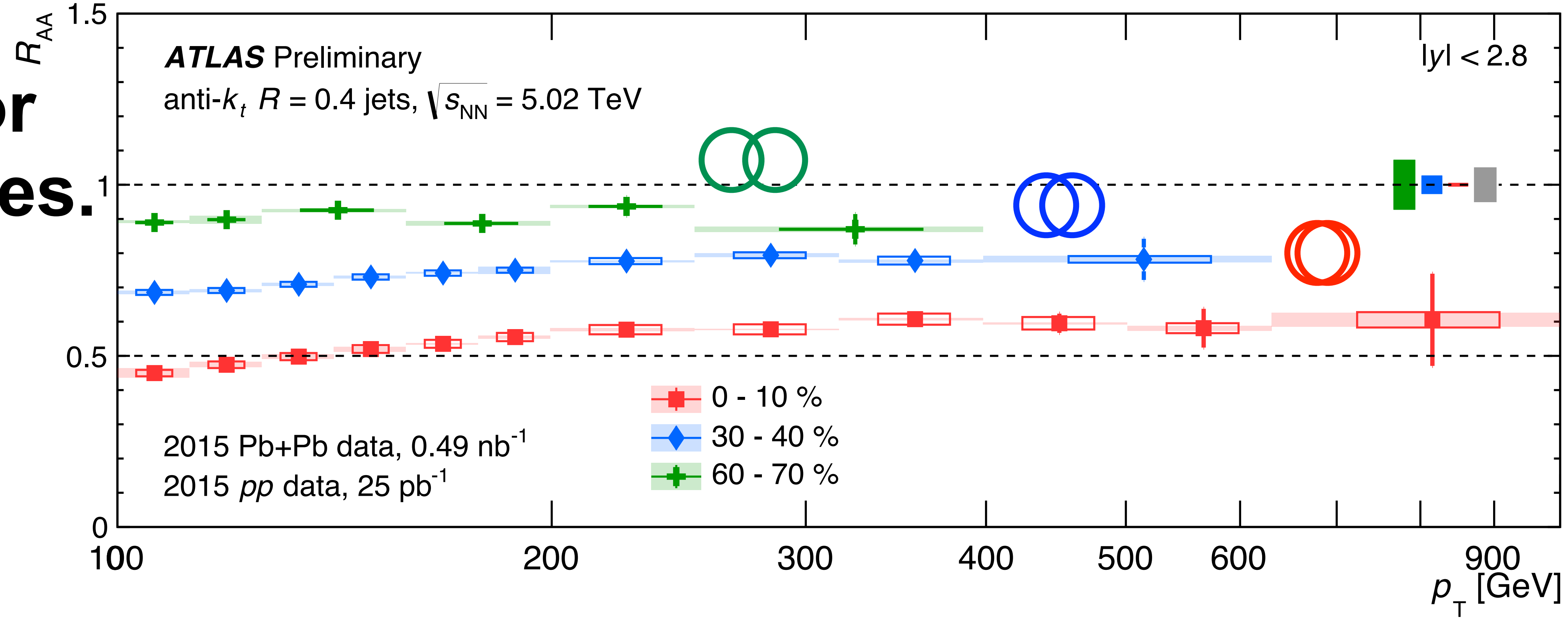
- R_{AA} is < 1 for all centralities.



R_{AA} vs. p_T

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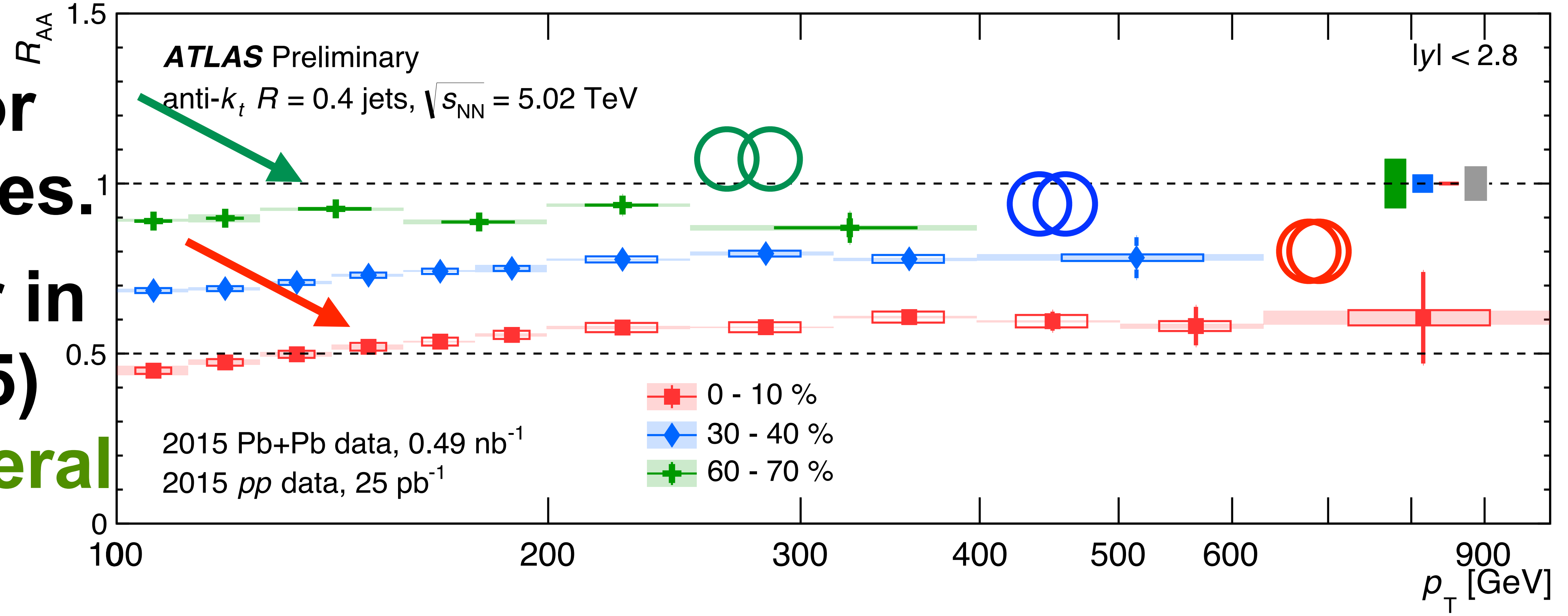
- R_{AA} is < 1 for all centralities.
- R_{AA} is lower in central (~0.5) than peripheral (~0.9)



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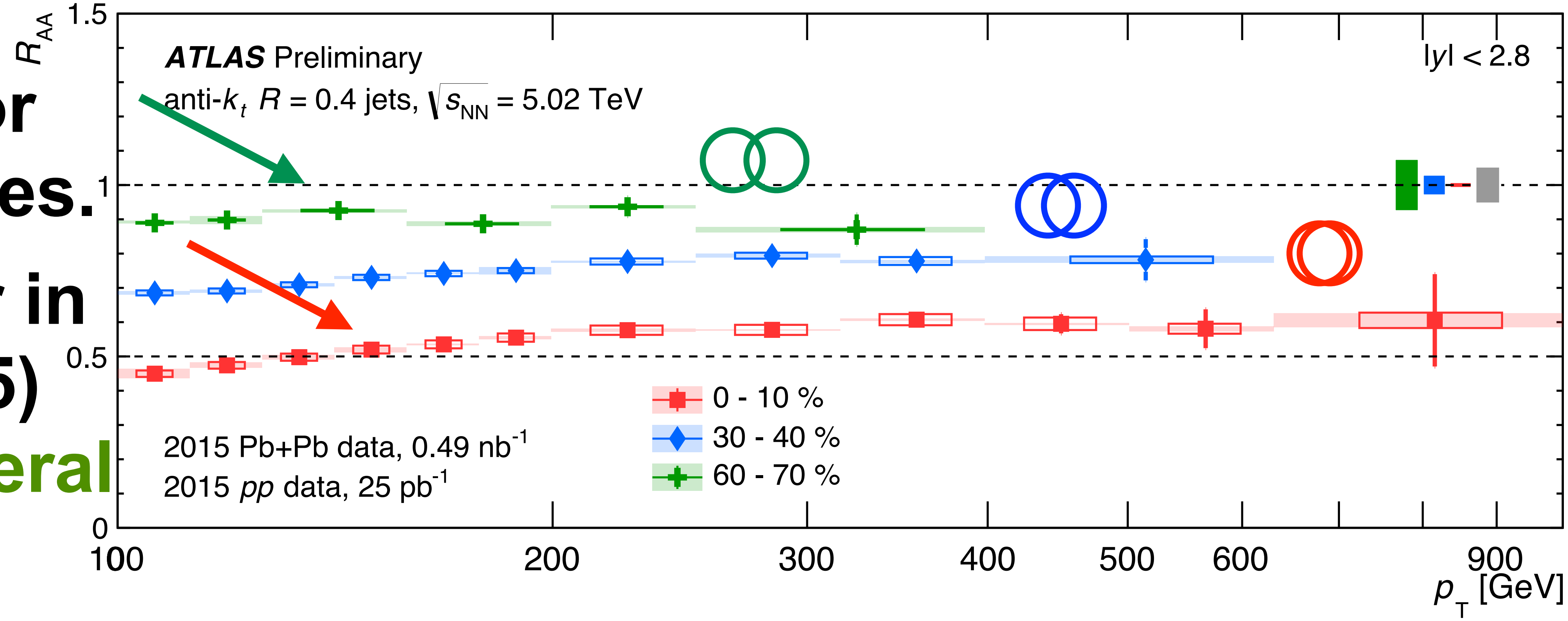

- R_{AA} rises with jet p_T until ~300 GeV where it begins to flatten.

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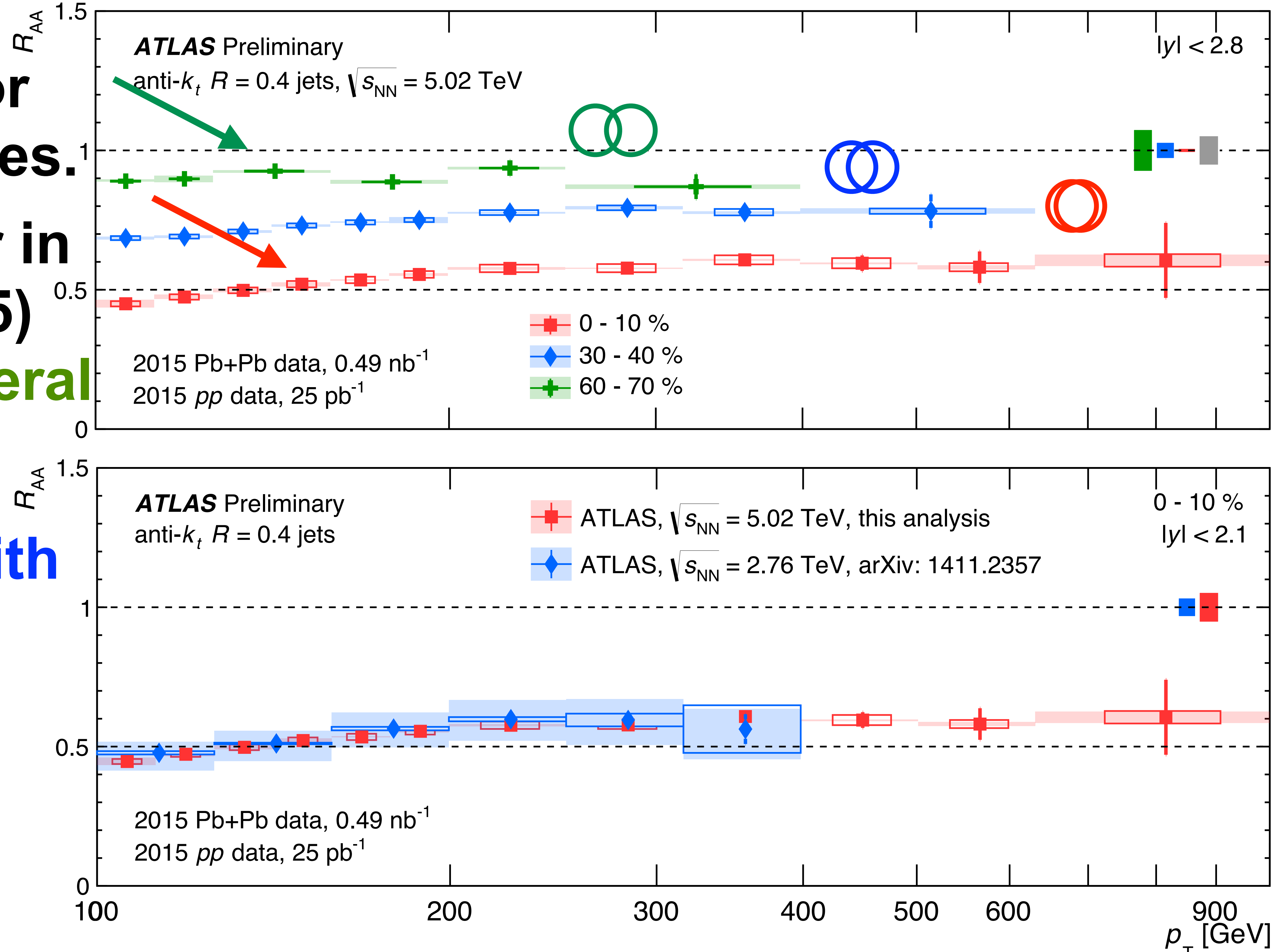
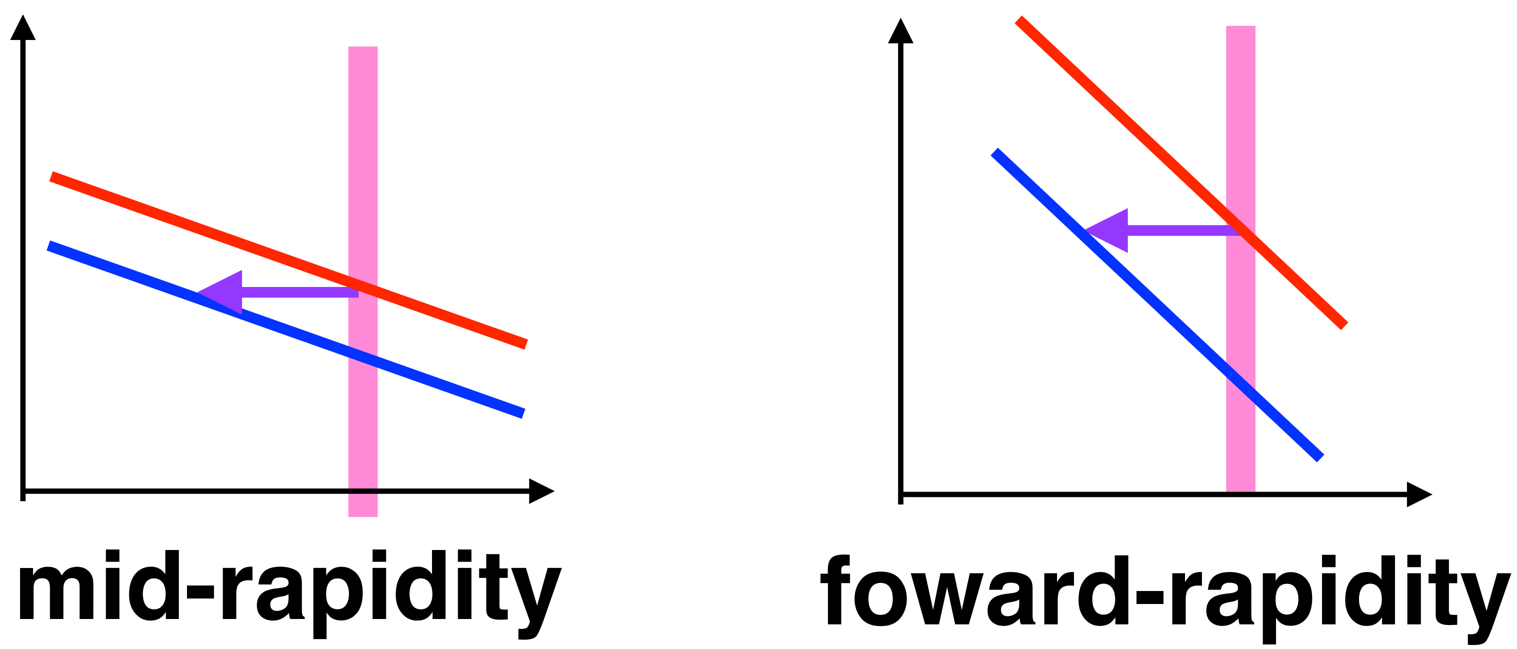


- **R_{AA} is independent of $\sqrt{s_{NN}}$ (over a narrow range) when comparing run 1 and run 2 results.**

R_{AA} vs. rapidity

- **Spectra is steeper with increasing rapidity at fixed p_T for the same amount of energy loss and since R_{AA} ~ red/blue.**

➡ **lower R_{AA}**



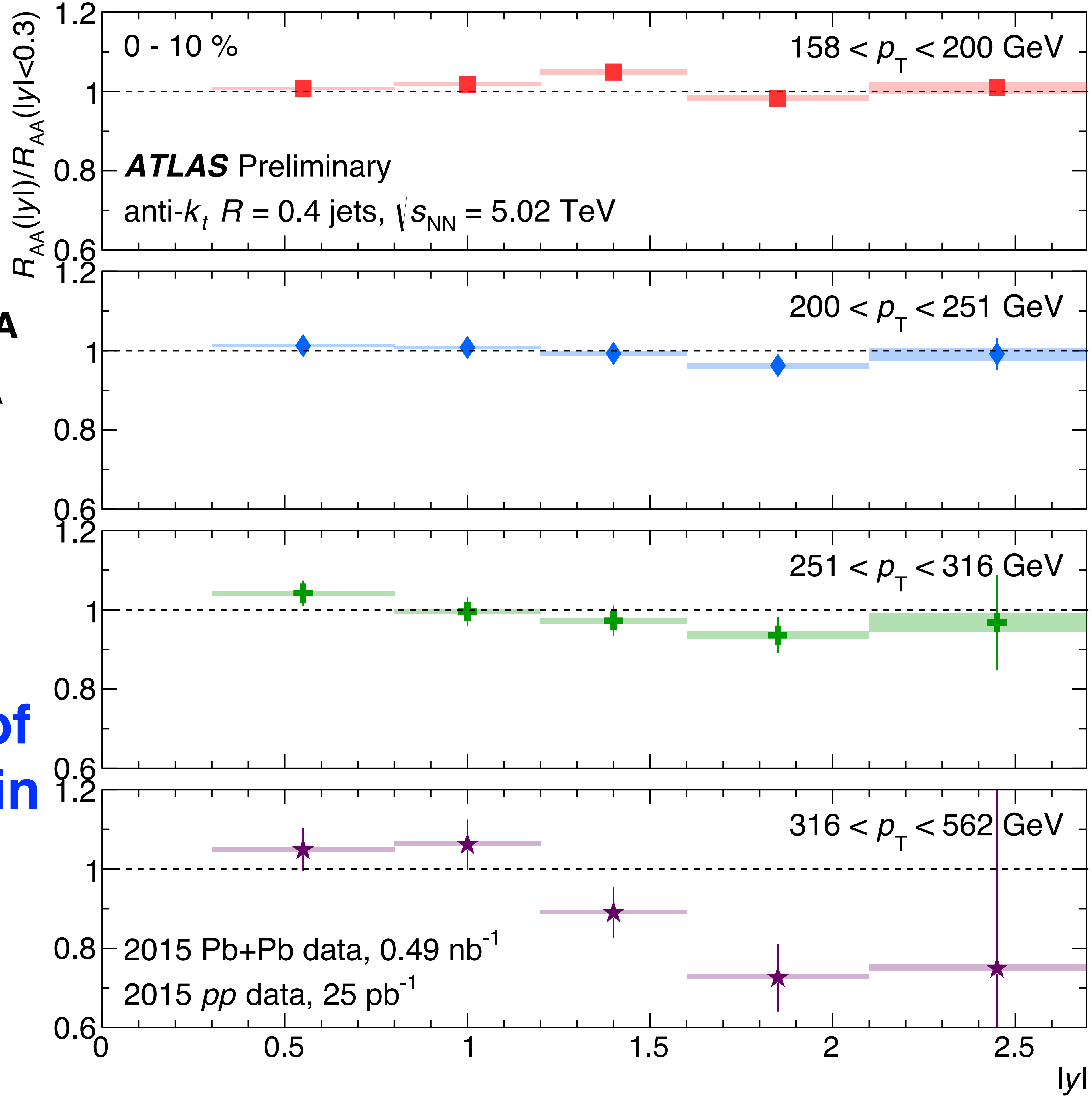
- **Guark and gluon fraction changes with rapidity and p_T with more quarks at forward rapidity which should be quenched less.**

➡ **higher R_{AA}**

▸ ***Competing effects: which one wins or do they cancel?***

R_{AA} vs. rapidity

- **Ratio of the R_{AA} vs. y to the R_{AA} for |y| < 0.3 in different p_T ranges.**
  - **Large cancelation of systematics in ratio.**



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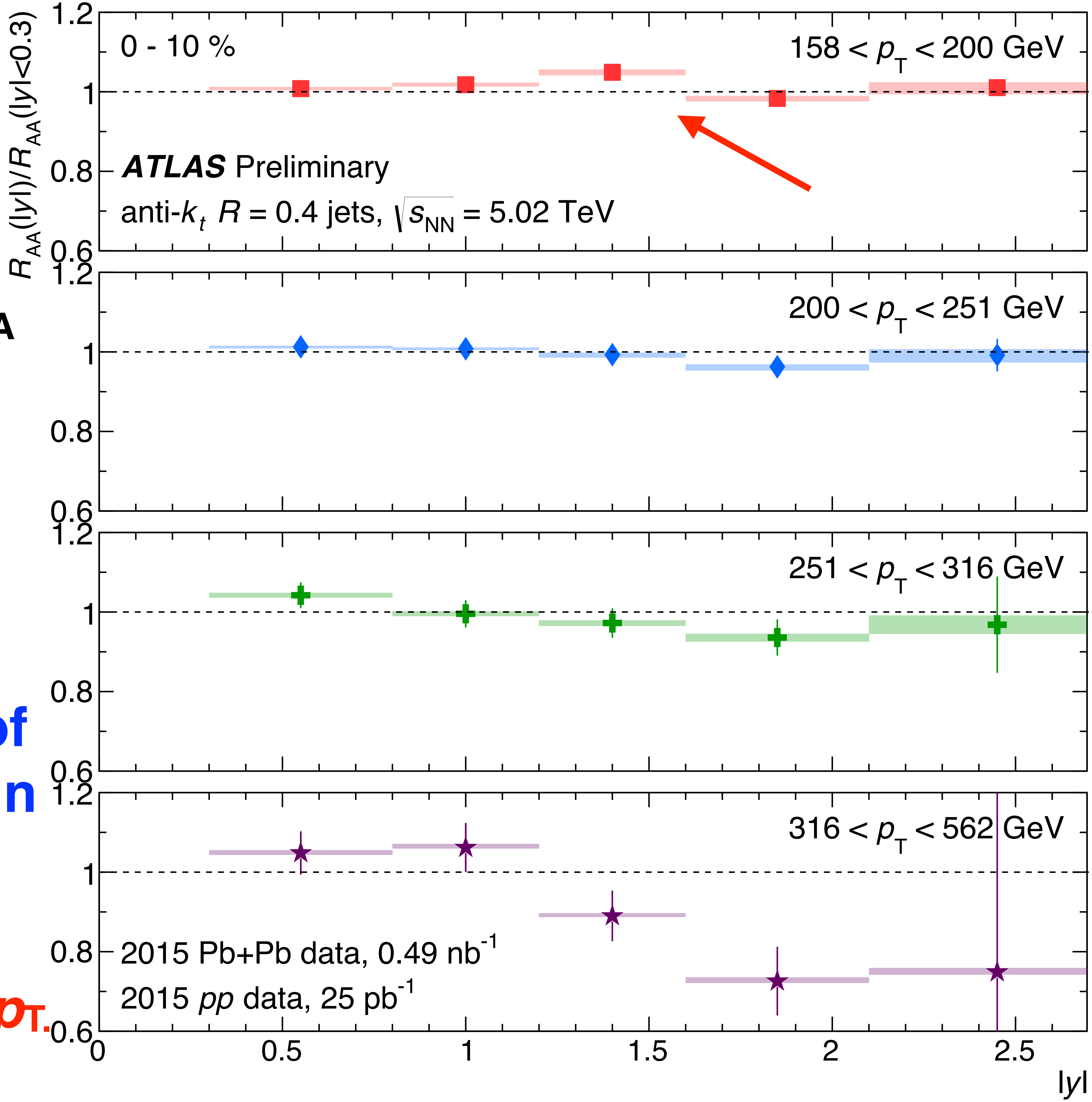

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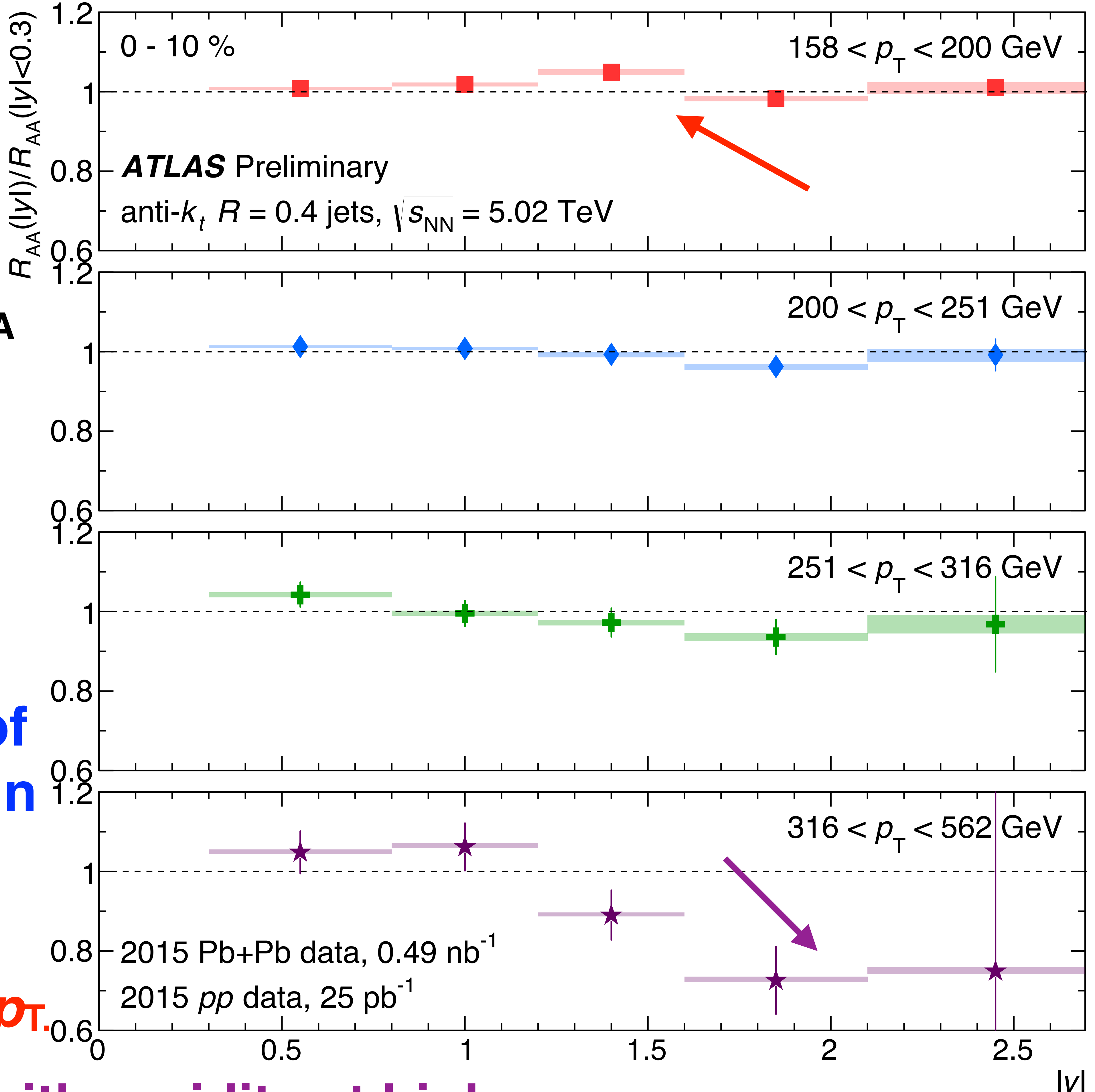
- **R_{AA} decreases with rapidity at higher p_T.**



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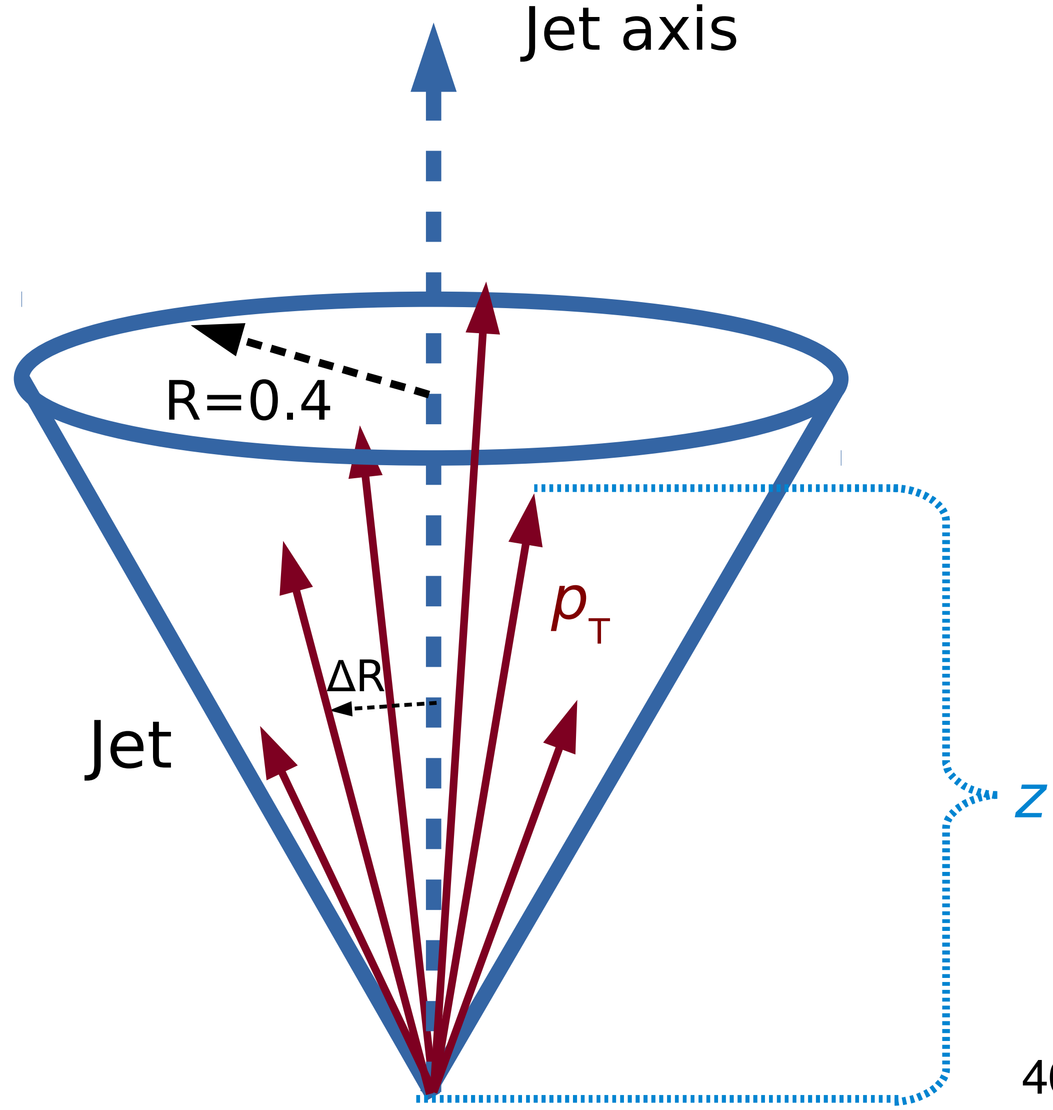
Jet fragmentation functions (FF)

$$D(z) = \frac{1}{N_{\mathrm{jet}}} \frac{dN_{ch}}{dz}$$

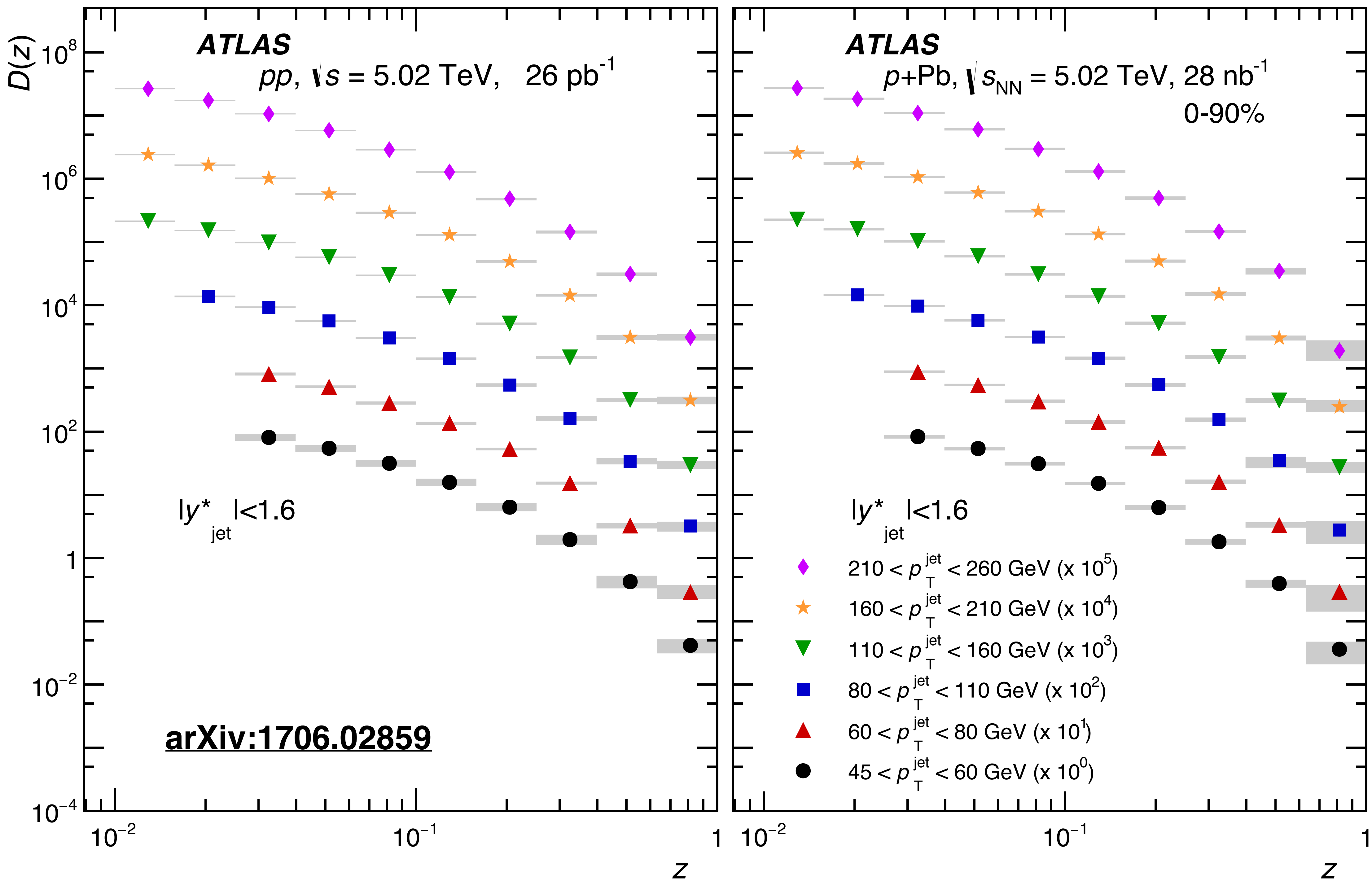
$$z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

$$D(p_{\mathrm{T}}) = \frac{1}{N_{\mathrm{jet}}} \frac{dN_{ch}}{dp_{\mathrm{T}}}$$

- **Measures how the particles within the jet are distributed.**
  - ➡ **N_{ch} is the number of charged particles associated with the jet.**
- **R=0.4 jets with charged tracks starting at 4 GeV for Pb+Pb and 1 GeV *p*+Pb.**
- **FF are background subtracted, corrected for tracking efficiency, and fully 2D unfolded in jet p_{T} and z.**



Jet fragmentation: *pp* and *p*+Pb

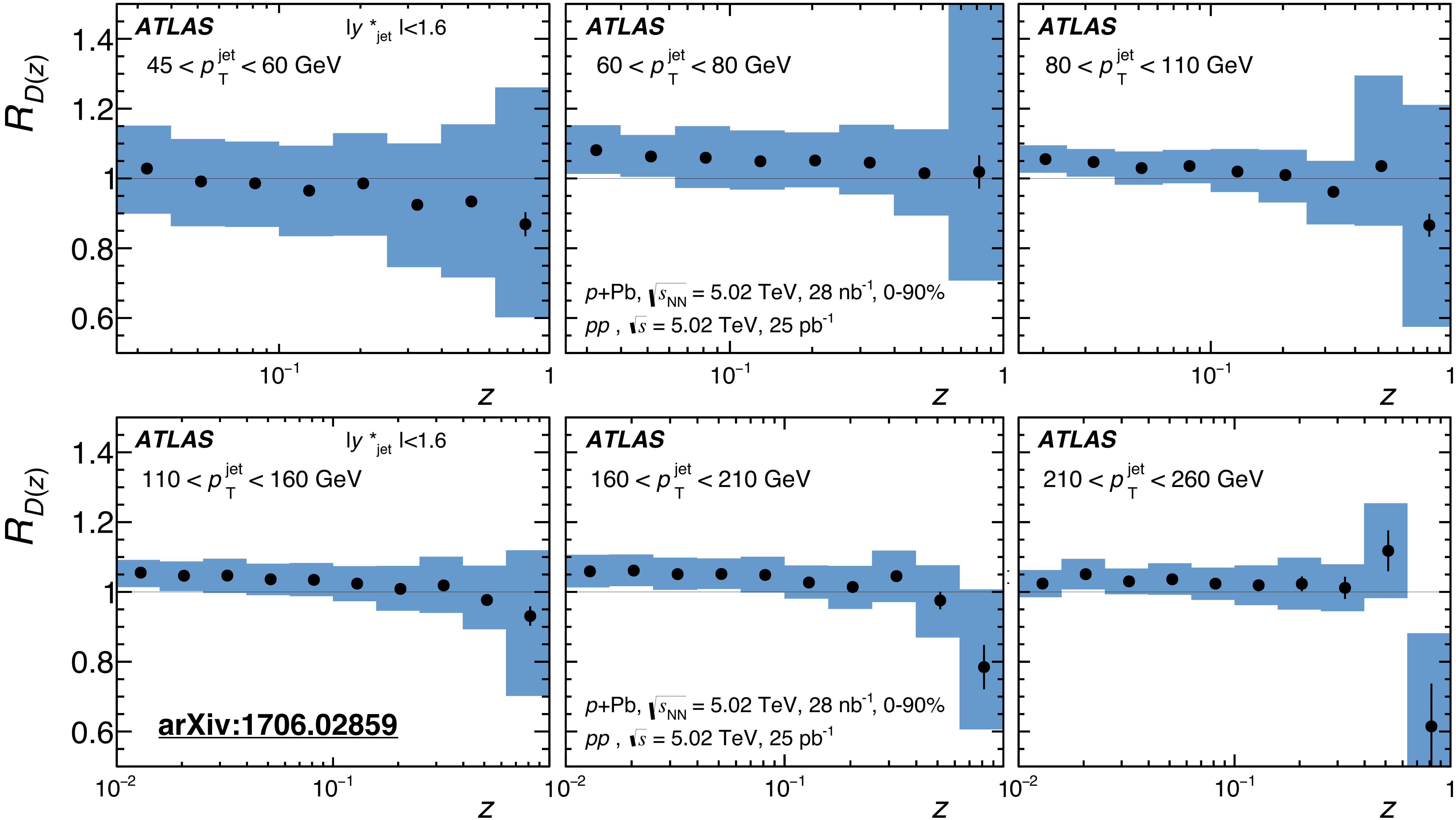


- **Ratio needed to see modification.**

$$R_{D(z)} = \frac{D(z)_{pPb}}{D(z)_{pp}} \qquad D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

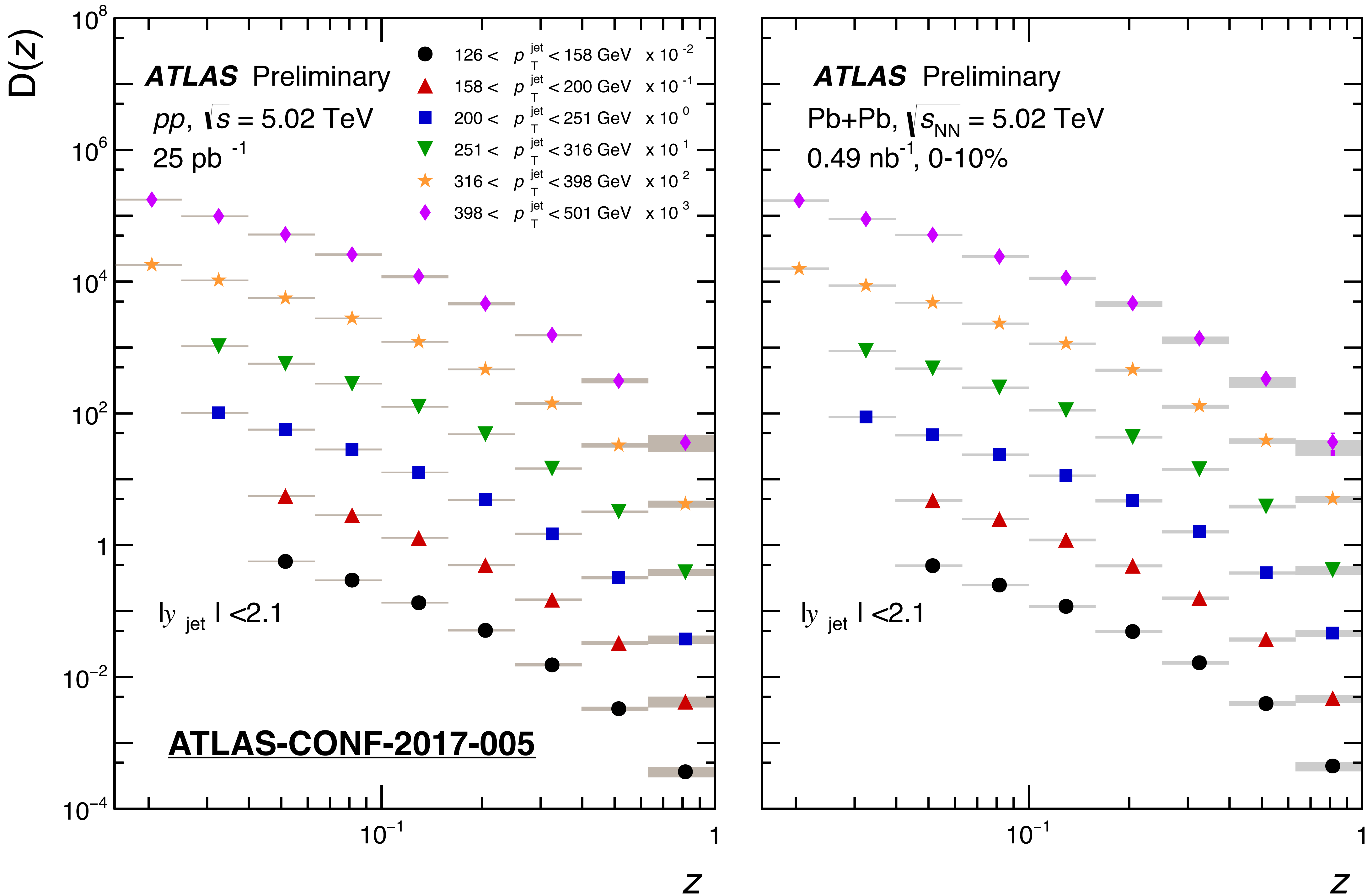
p+Pb $R_{D(z)}$ in jet p_T bins

$$R_{D(z)} = \frac{D(z)_{pPb}}{D(z)_{pp}}$$



➡ **No modification of jet structure in p+Pb.**

Jet fragmentation: Pb+Pb



- **Need ratio to see modification.**

$$R_{D(z)} = \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}} \qquad D(z) = \frac{1}{N_{\mathrm{jet}}}\frac{dN_{ch}}{dz}$$

Pb+Pb $R_{D(z)}$

$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

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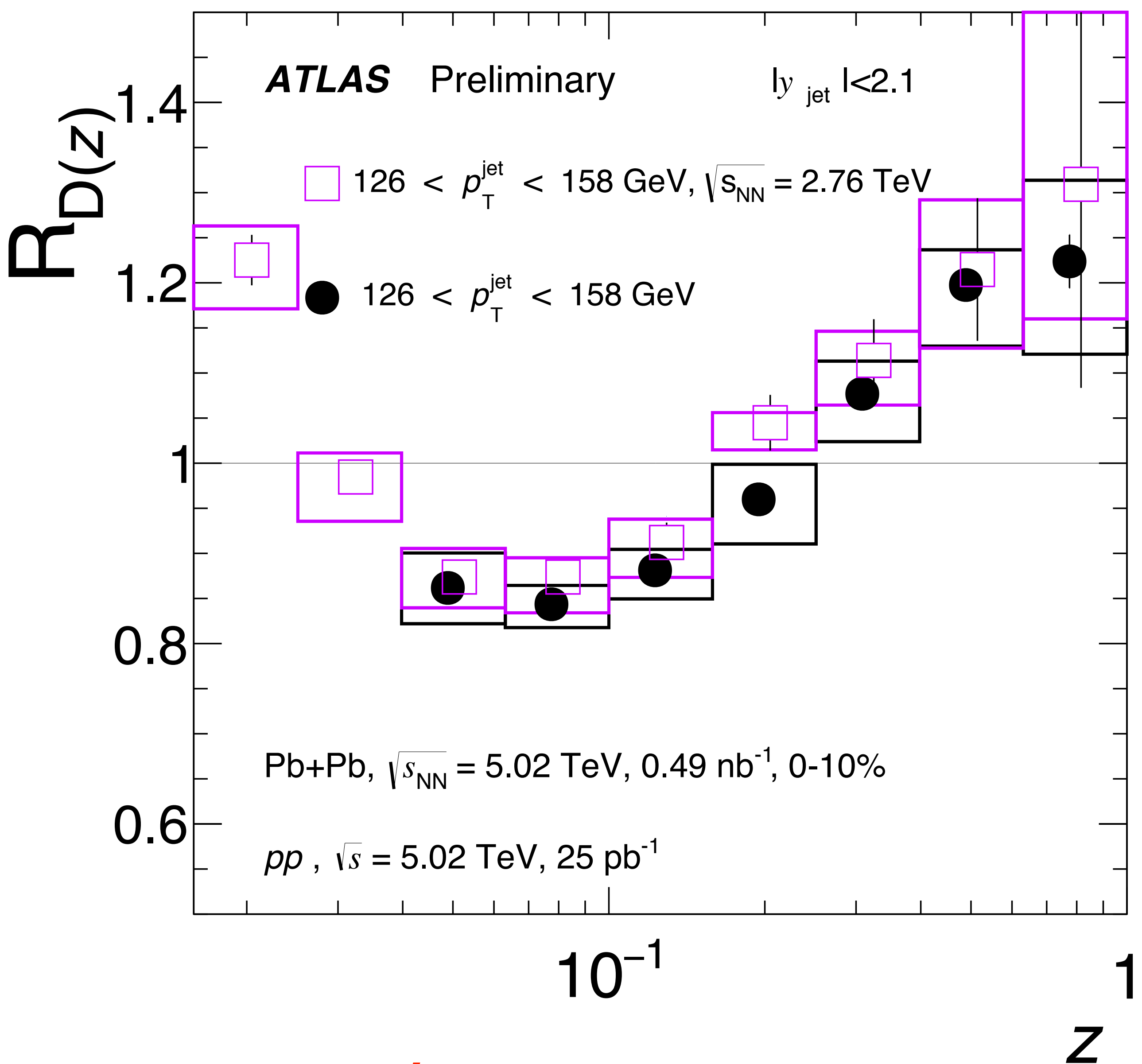
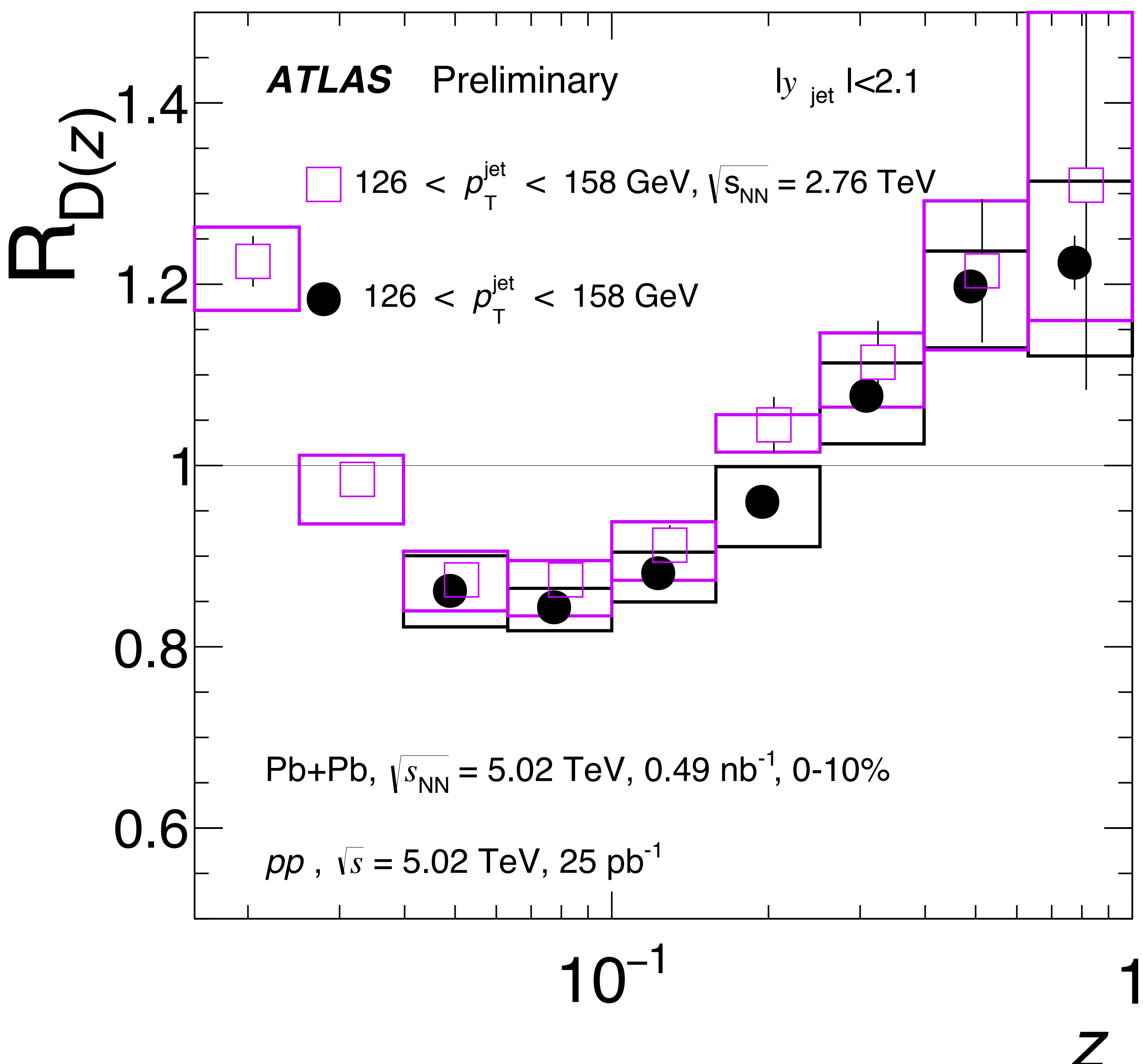


➡ **No $\sqrt{s_{NN}}$ dependence.**

Pb+Pb $R_{D(z)}$

$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

ATLAS-CONF-2017-005

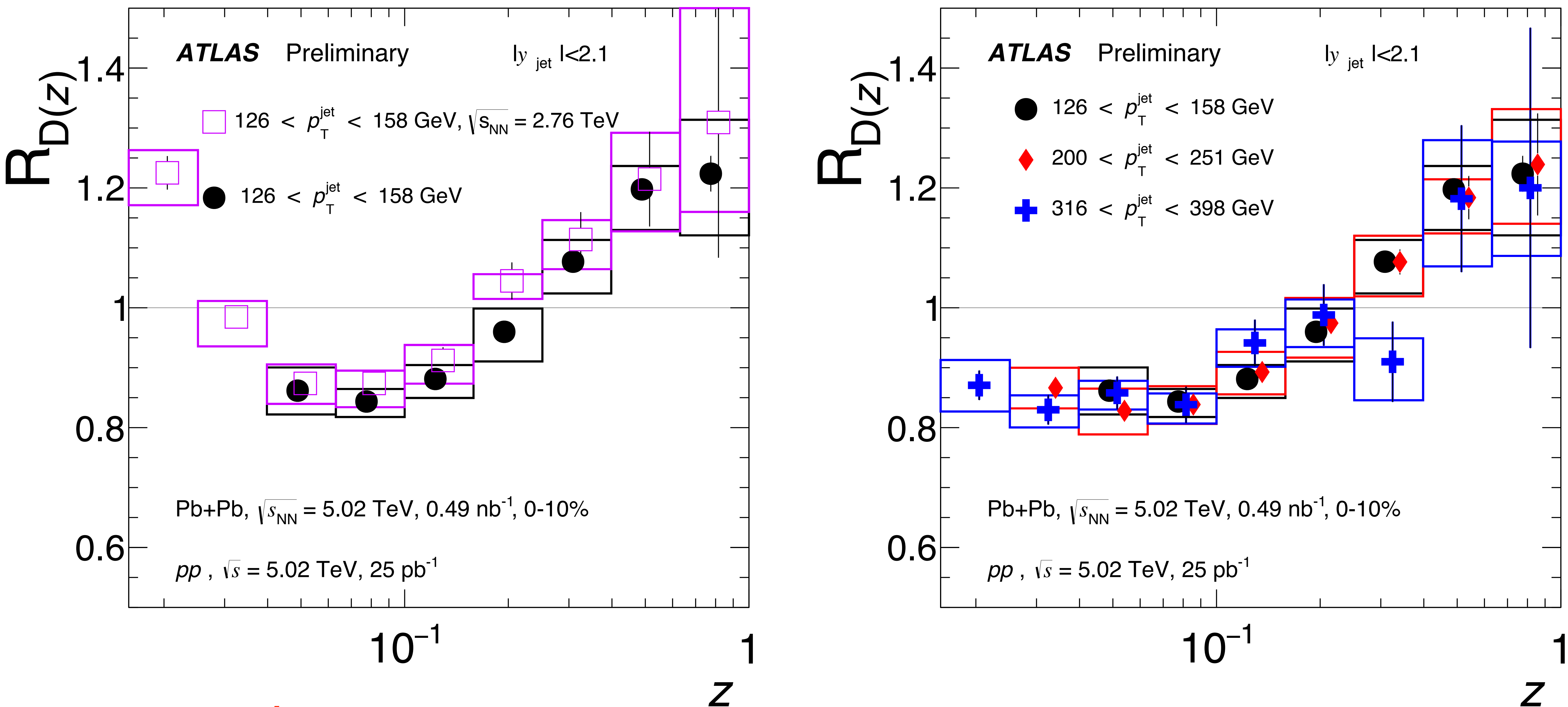


- No $\sqrt{s_{NN}}$ dependence.
- Enhancement at low z, suppression at intermediate z, enhancement at high z: low z missing from 5.02 TeV because p_T^{trk} cut at 4 GeV.

Pb+Pb $R_{D(z)}$

$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

ATLAS-CONF-2017-005



➡ **No $\sqrt{s_{NN}}$ dependence**

➡ **No jet p_T dependence.**

➡ **Enhancement at low z, suppression at intermediate z, enhancement at high z: low z missing from 5.02 TeV because p_T^{trk} cut at 4 GeV.**

Summary

- **Wide variety of jet measurements from ATLAS:**
  - **dijet and γ+jet balance, inclusive jet suppression, and jet substructure in Pb+Pb and p+Pb**
- **Era of precision measurements with careful underlying event subtraction, reduced systematic uncertainties, and unfolding for detector effects.**
- **Increased statistics in run 2 allowed for differential and high jet p_T studies:**

➡ **Single jets are suppressed up to high (TeV scale) p_T.**

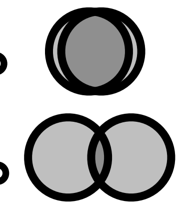
➡ **No jet p_T dependence in jet internal structure modification.**

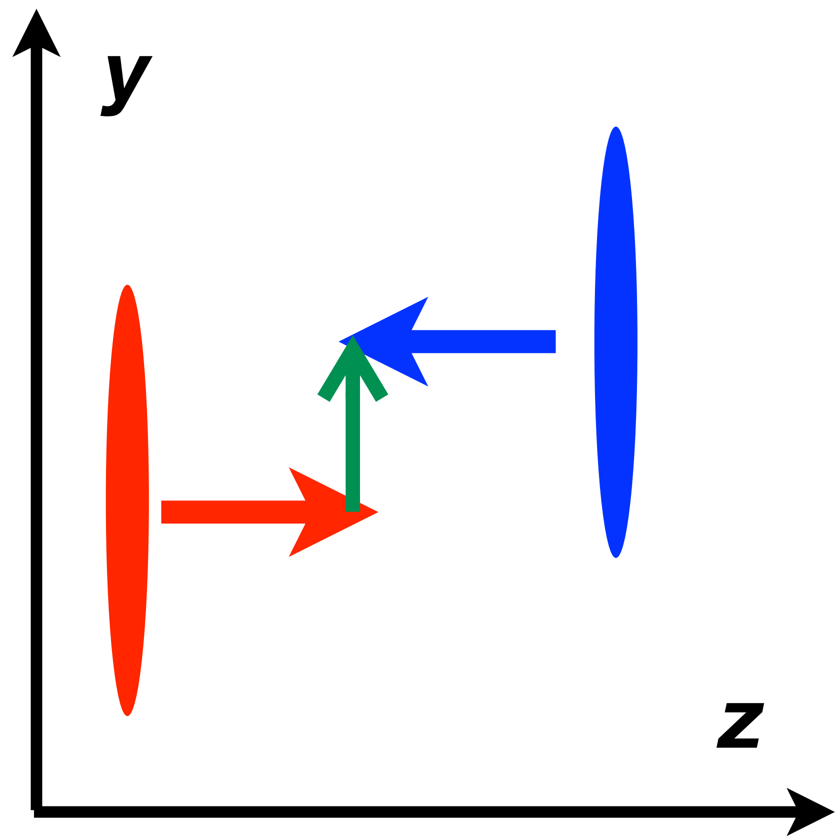
➡ **Jets are more balanced at higher values of jet p_T.**

Backup

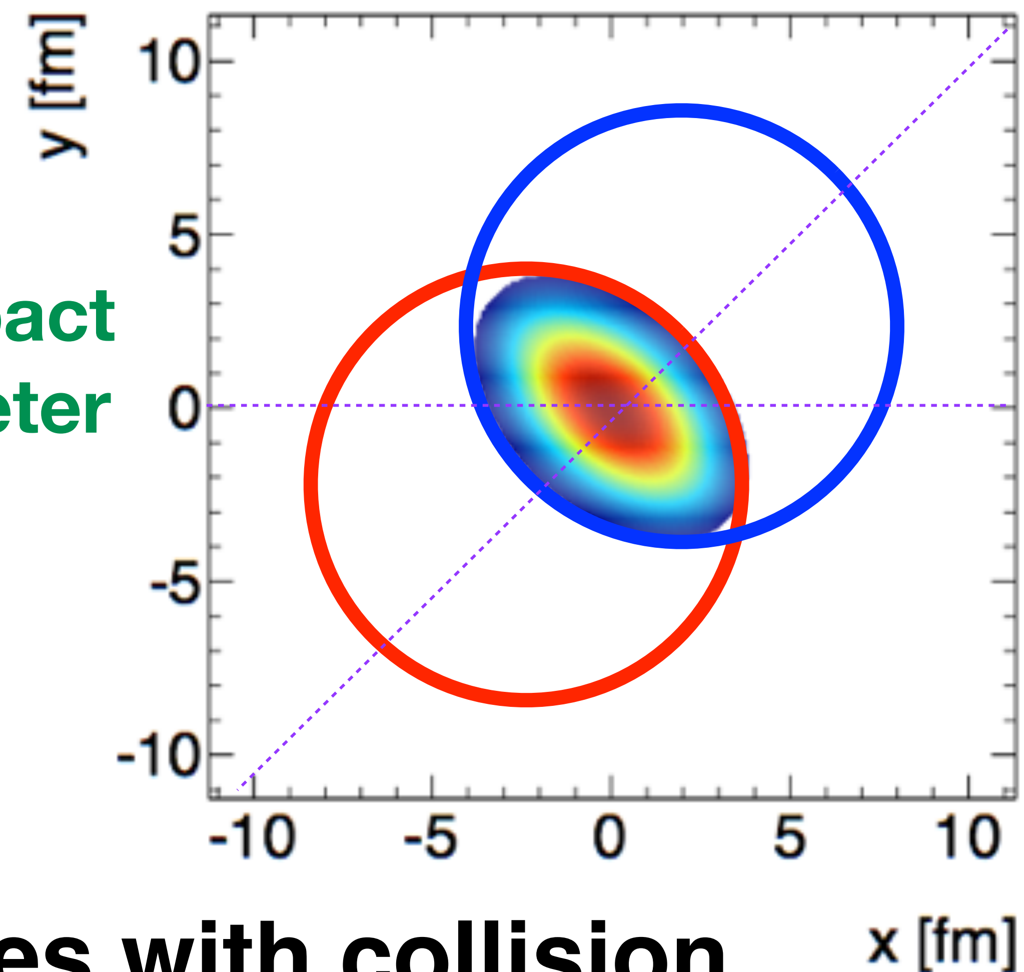
Centrality

most central: 0-10%
most peripheral: 70-80%





b = impact parameter

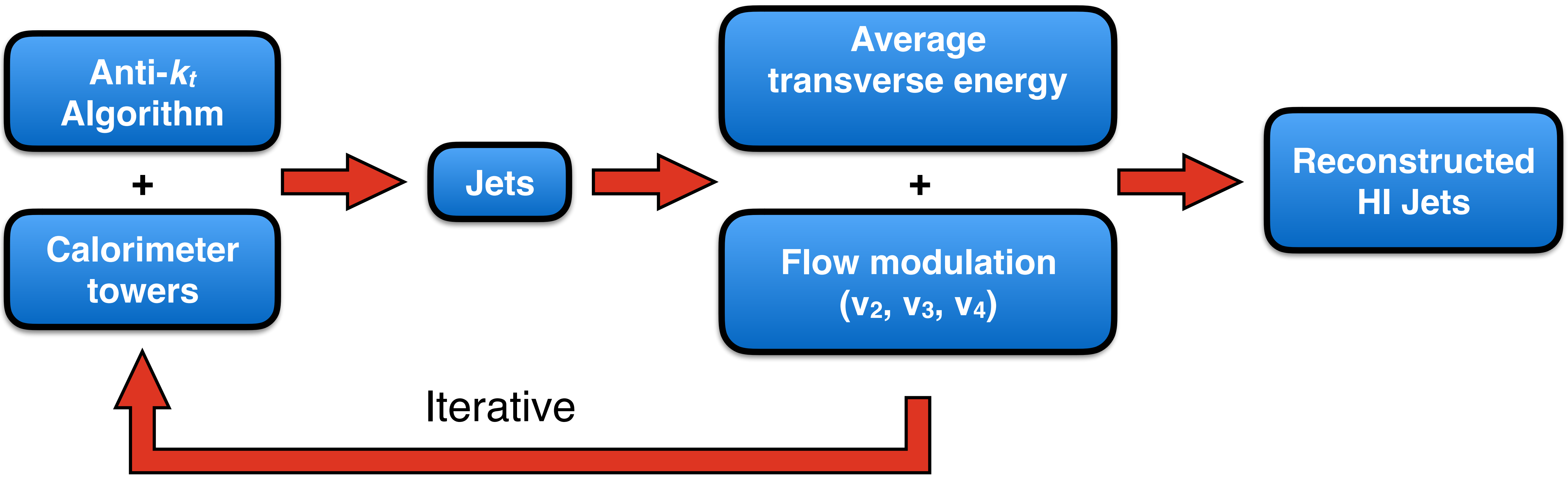


- **Flux of nucleons increases with collision “centrality”.**
- **Define “centrality classes”:**

➡ Events with similar degree of overlap.

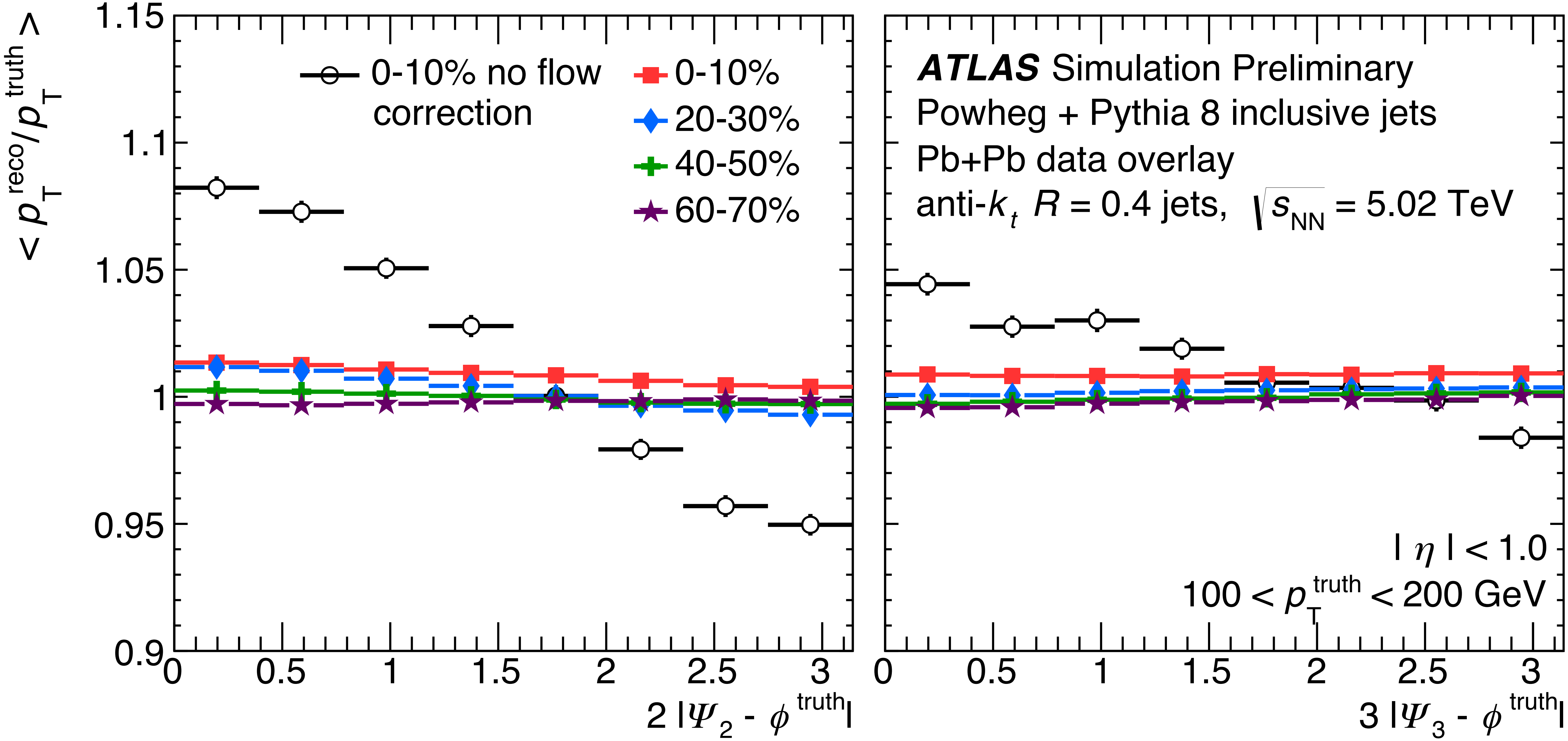
- **In experiment the total particle production is used as a proxy for b.**

Jet reconstruction: procedure

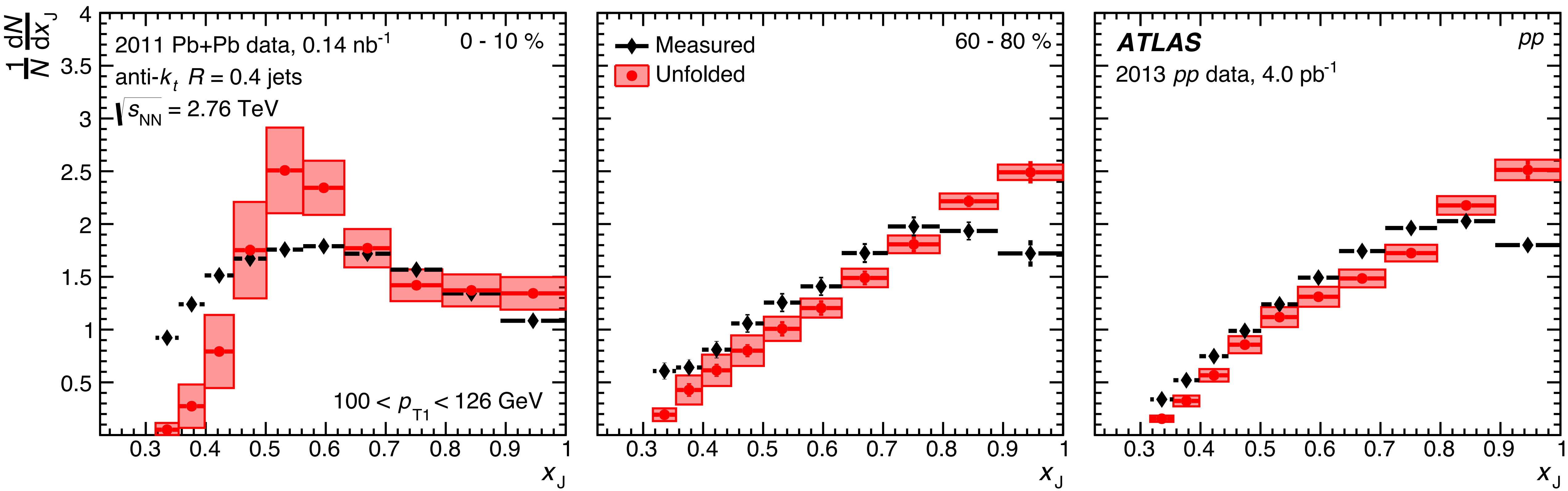


$$\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}\eta\mathrm{d}\phi} \approx \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}\eta}\left(1 + \sum_n v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

Jet performance: JES



Effect of unfolding on x_J

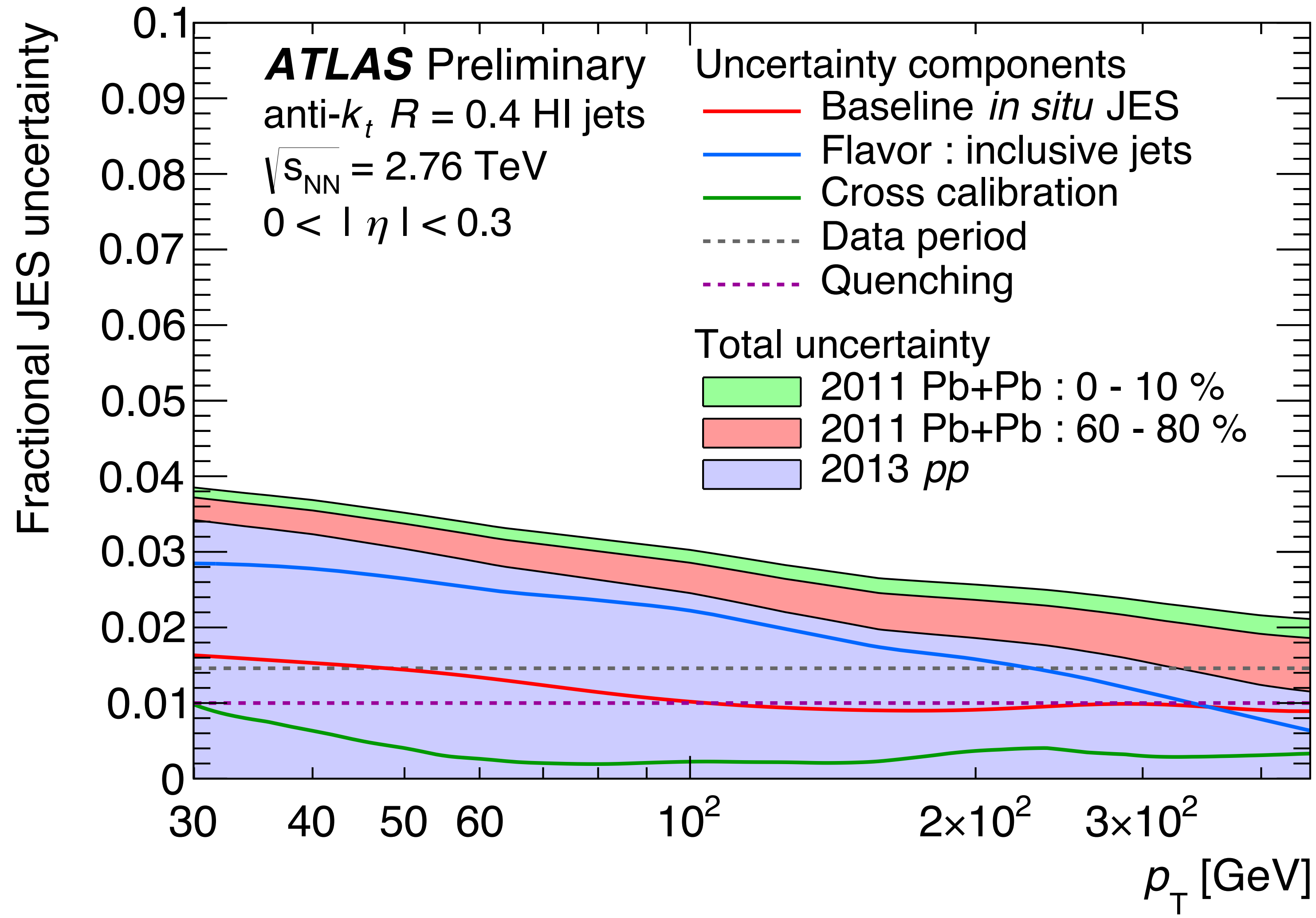


- ***Moves jets in pp and peripheral to more balanced configurations and jets in central to both more balanced and asymmetric configurations at x_J~0.5***

x_J systematics

ATLAS-CONF-2015-016

- **JES/JER systematics**
  - ➡ **JES: rigorous uncertainty broken down by source that is p_T, η, and centrality dependent**
  - ➡ **JER: dominant contribution comes from the UE which is described well in the MC sample (data overlay)**

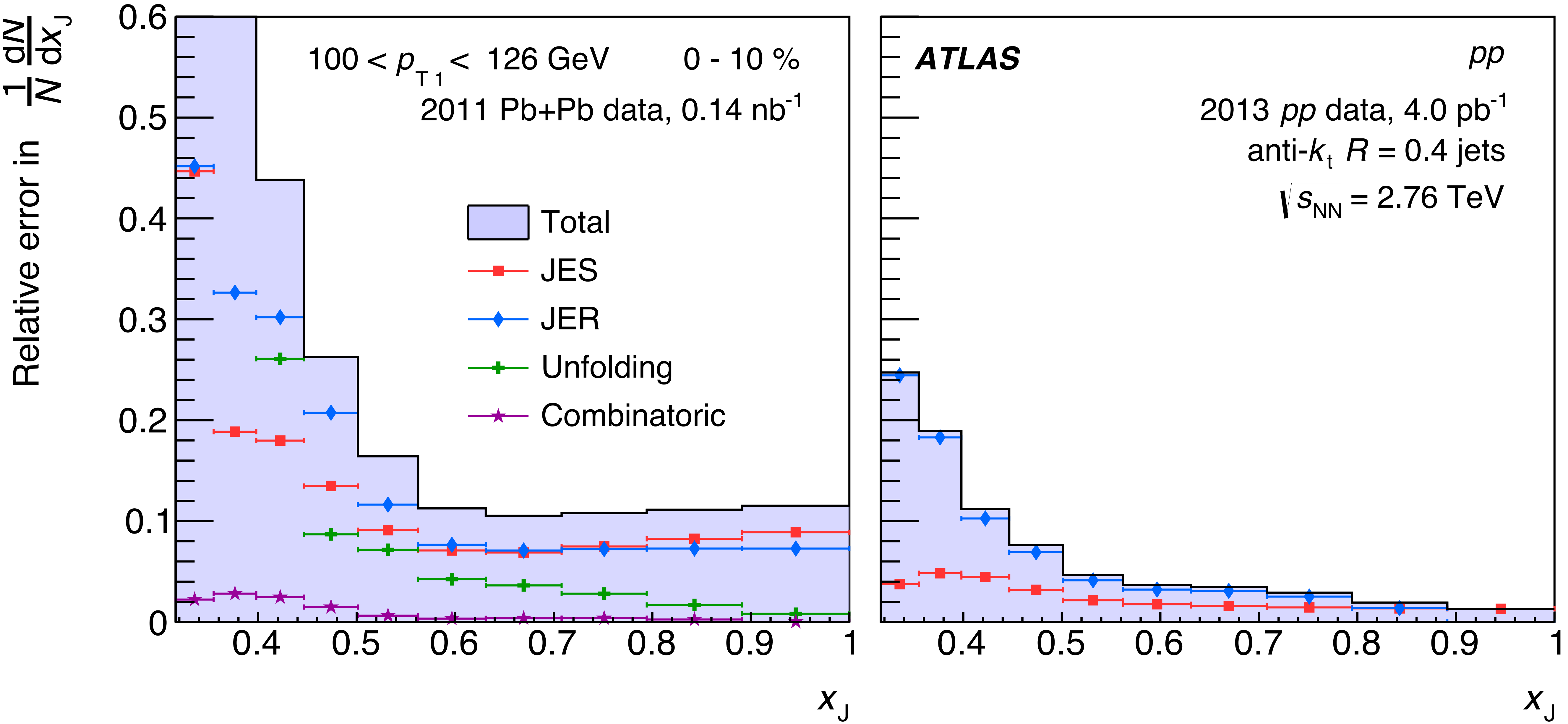


  - ➡ **Evaluated by rebuilding the response matrix with a systematically varied relationship between the true and reconstructed jet kinematics**

► ***JES is the largest uncertainty in this measurement: 10% at x_J~1 and 15% at x_J ~0.5 in central collisions***

- **Analysis specific systematics for the combinatoric background and unfolding**
  - ➡ **Unfolding systematic can be as large as JES in central at lower x_J**

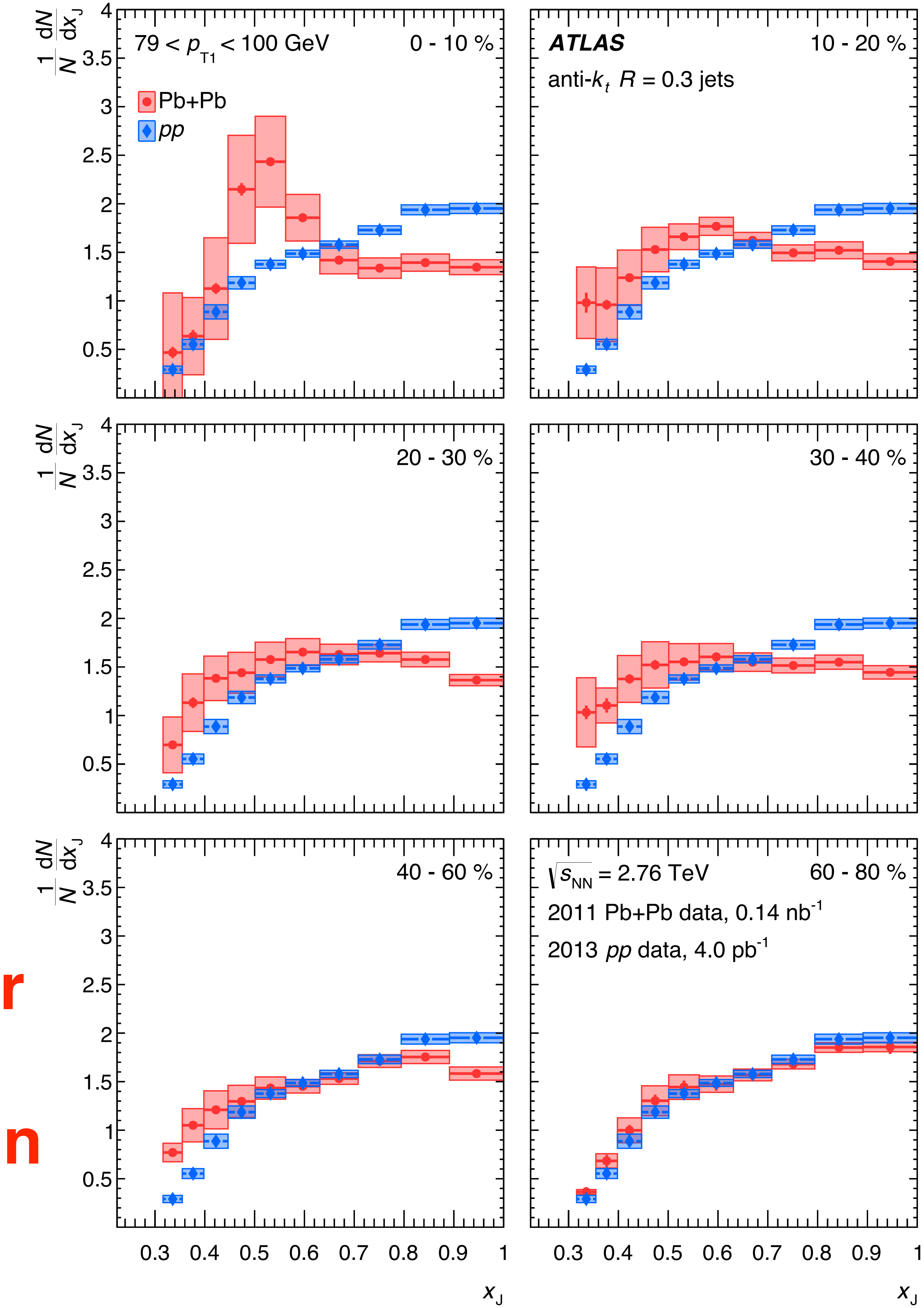
x_J systematics summary



R=0.3 x_J

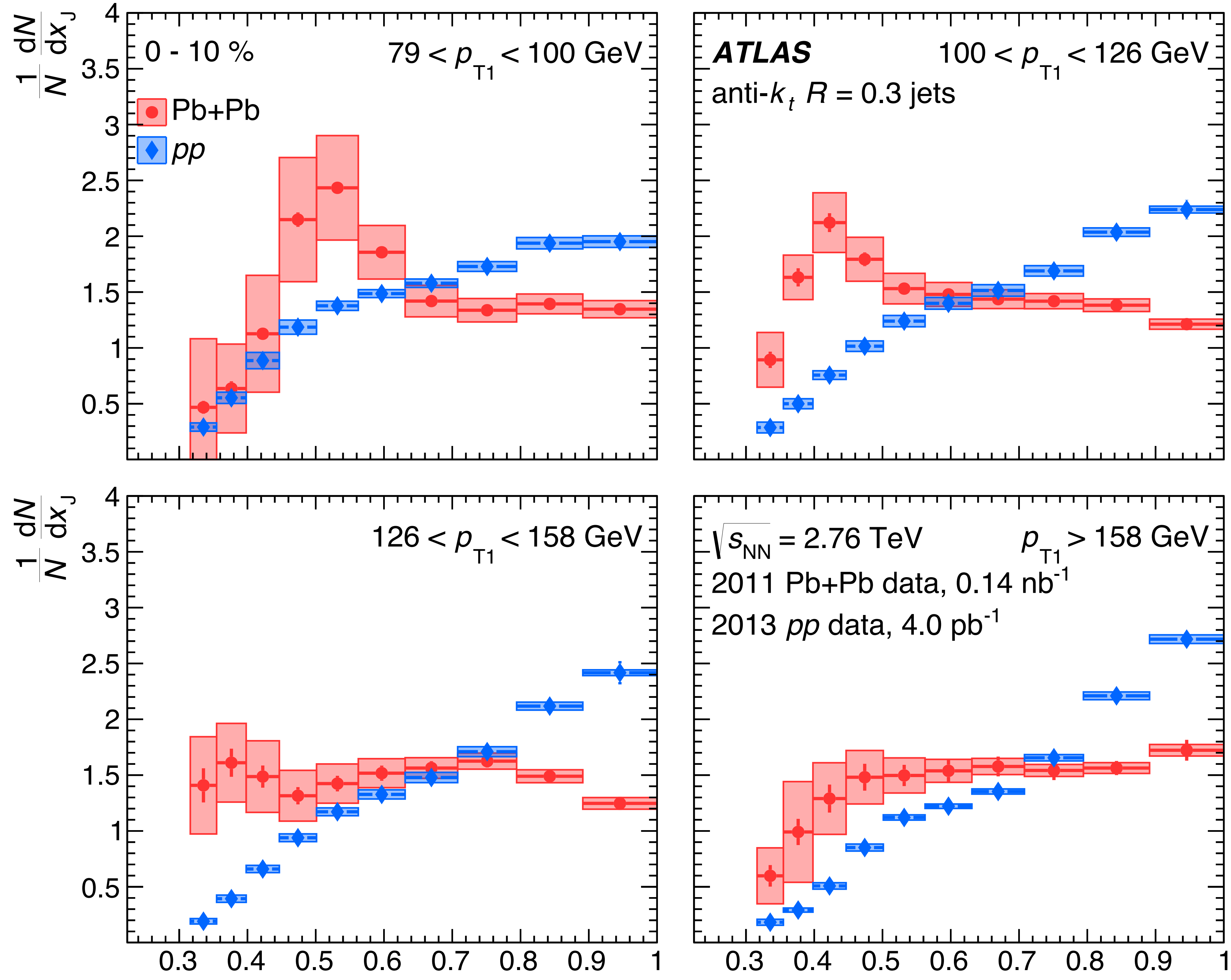
Centrality dependence of Pb+Pb compared to *pp* dijets for 79<p_{T1}<100 GeV.

- **Same analysis for R=0.3 jets since effects of the JER and the background are much less**
- **R=0.3 jets correspond to R=0.4 jets at a larger energy due to the smaller jet cone so the R=0.3 are shifted to one bin lower in leading jet p_T.**

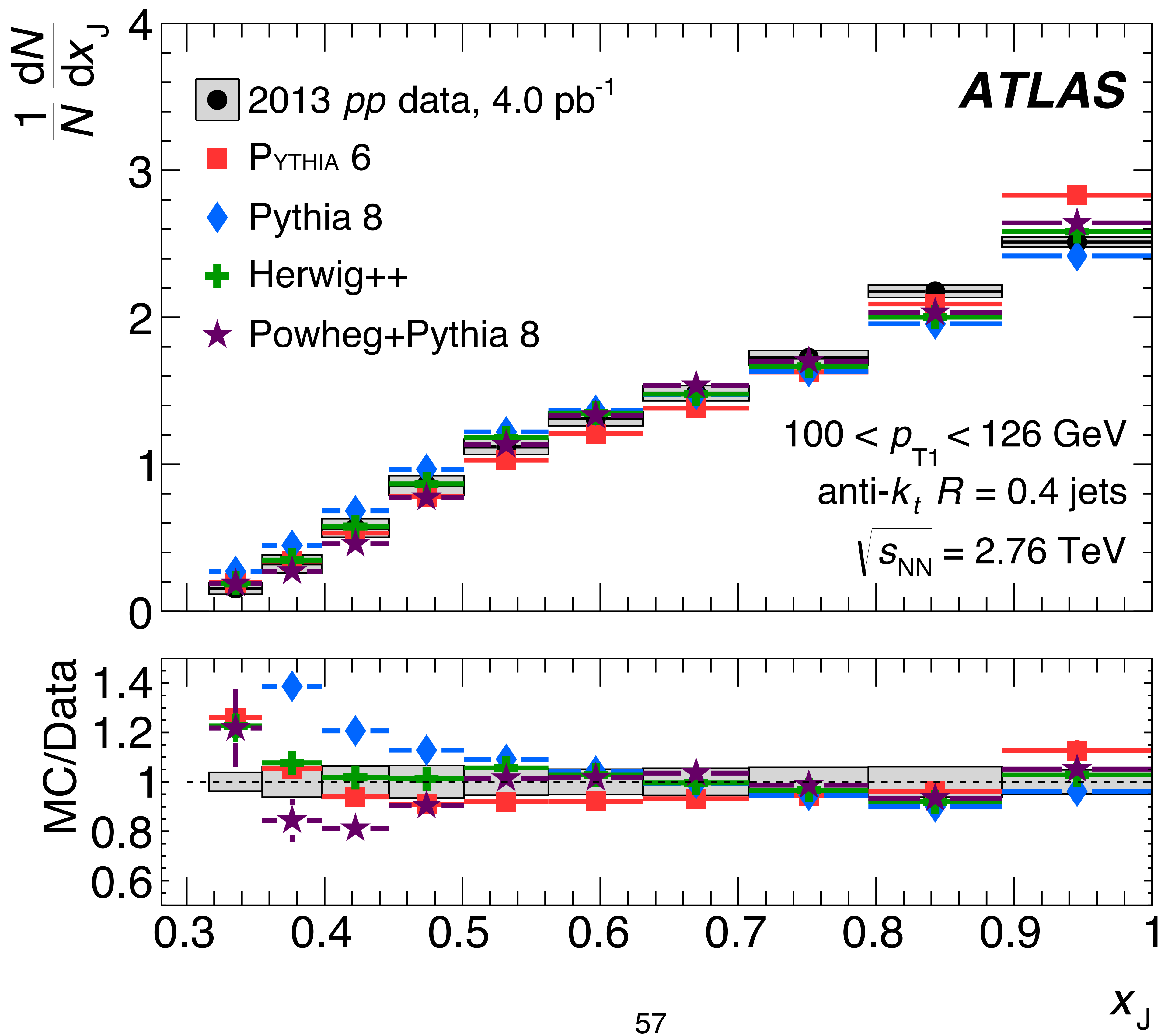


R=0.3 x_J p_{T1} dependence

Pb+Pb 0-10% centrality compared to *pp* dijets.



x_J *pp* data to MC comparison



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x_J 3rd jet

- **See less nearby jets in more central collisions.**

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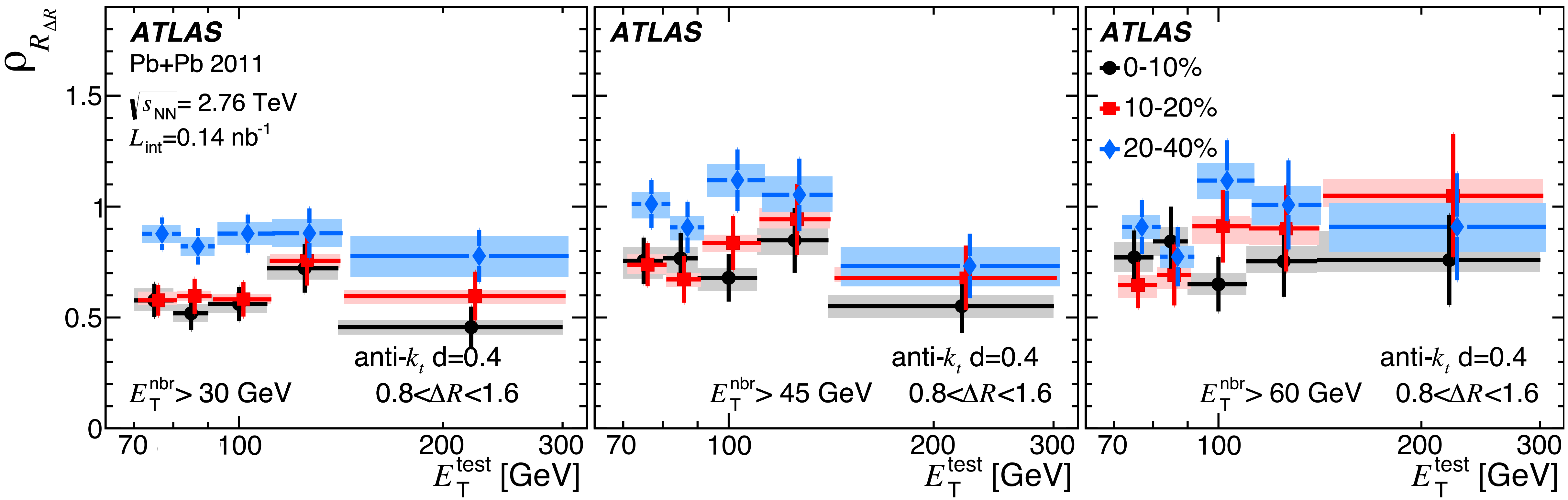
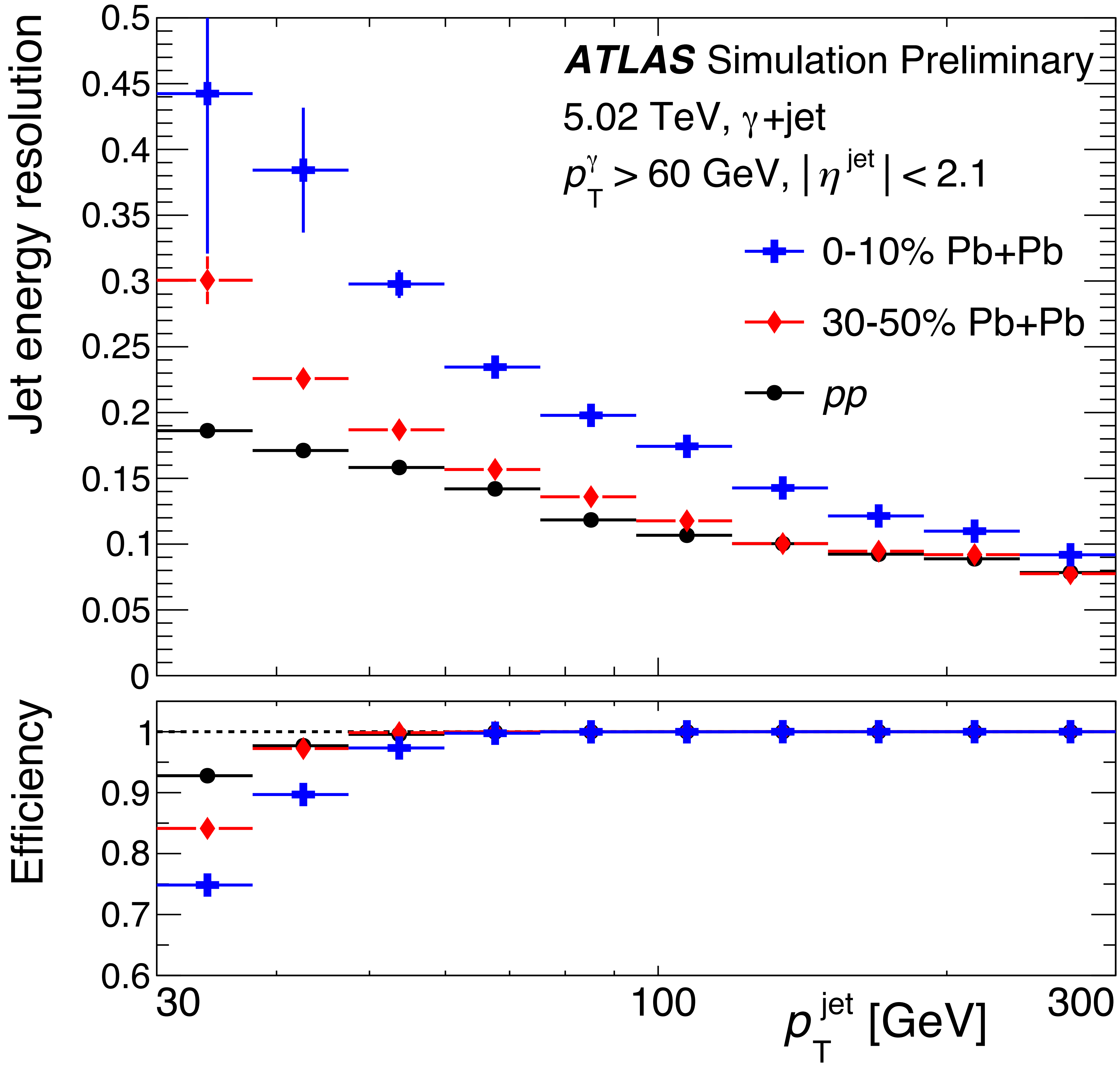


- **Tested this by unfolding with a new response that takes into account the contribution to the 3rd jet with a weighting applied to match the 3rd jet distribution in data**

➡ **Deviations from the result was well within the systematics of the measurement**

γ-jet JER

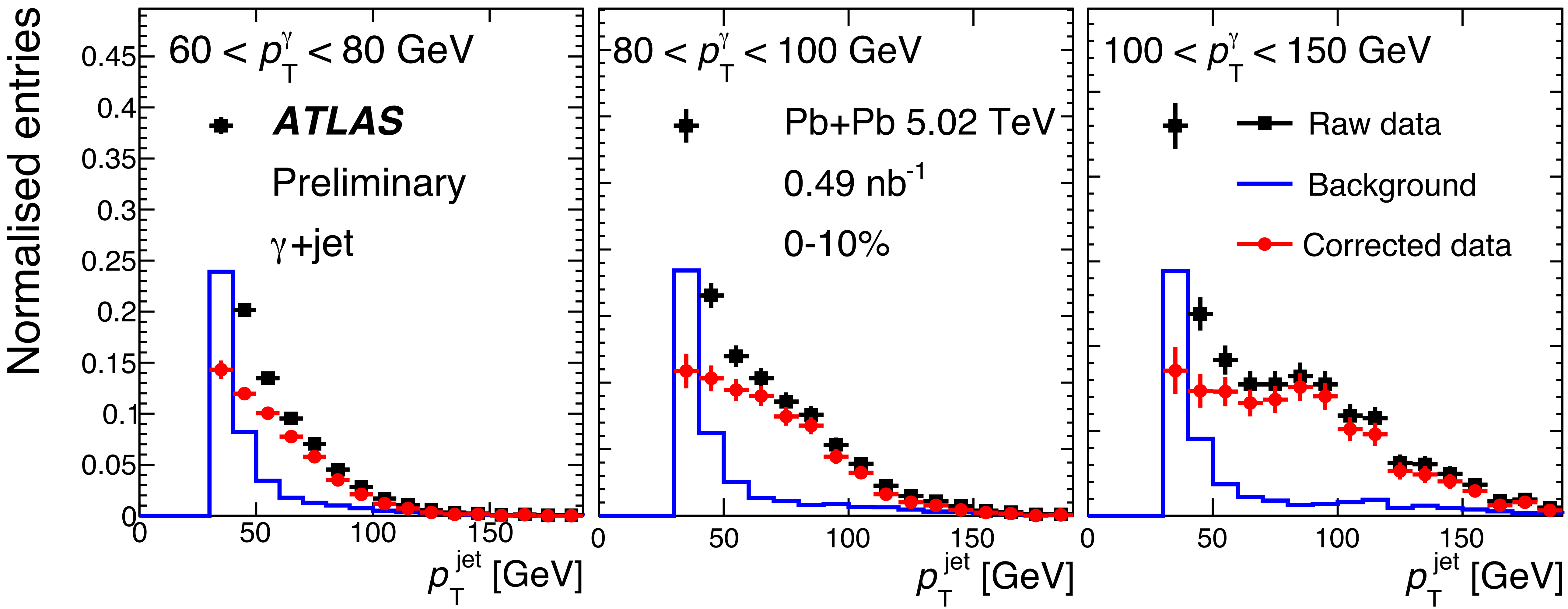

ATLAS Simulation Preliminary
5.02 TeV, γ+jet
$p_T^{\gamma} > 60$ GeV, $|\eta^{jet}| < 2.1$
0-10% Pb+Pb
30-50% Pb+Pb
pp
Jet energy resolution
Efficiency
p_T^{jet} [GeV]
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
0.9
0.8
0.7
0.6
30
100
300

γ-jet systematic uncertainties

- **Jets:**
  - **JES is 5% at low p_T and decreases with p_T**
  - **Cross calibration: 1% addition JES uncertainty**
  - **JER is evaluated by increasing the resolutions measured in *pp* by a few percent**
  - **Uncertainty on flavor composition and different in flavor response is 2% at low p_T and decreases with p_T**
  - **Addition JES uncertainty in Pb+Pb that is 1% for $p_T > 50$ GeV and up to 5-10% above 50 GeV from comparing charged-particle jets to calorimeter jets, studying the response of simulated quenched jets, and residual non-closure of simulated jets at low p_T**
- **Photons:**
  - **Photon purities adjusted by their statistical uncertainties**
  - **Photon isolation cut increased by 2 GeV in both *pp* and Pb+Pb, which increases efficiency and lowers purity**
  - **Non-tight selection varied**
  - **Photon energy uncertainties evaluated in *pp* which are less than 1%**
  - **Assumption that the distribution of background photons factorizes**

γ-jet background subtraction

- **Two contributions to the background:**
  - **Combinatoric: estimated by embedding PYTHIA8 photo+jet events into real Pb+Pb data**
  - **Dijet: per-photon distributions subtracted using non-tight photons, after scaling by the photon purity**



► **Combinatoric important at low p_T, dijet at high p_T**

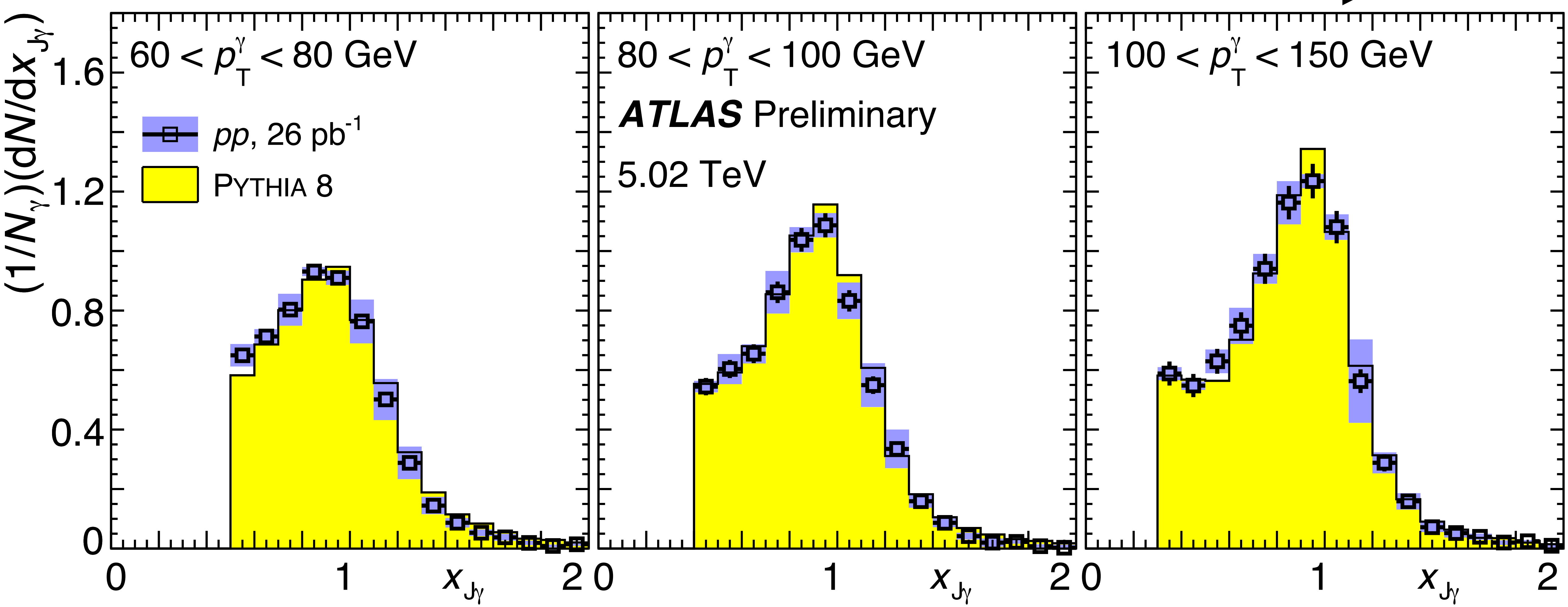
$$x_{J\gamma} = \frac{p_{T,jet}}{p_{T,\gamma}}$$

γ-jet asymmetry

pp

➡ ***pp* jets compared to MC generator**

increasing $p_{T\gamma}$

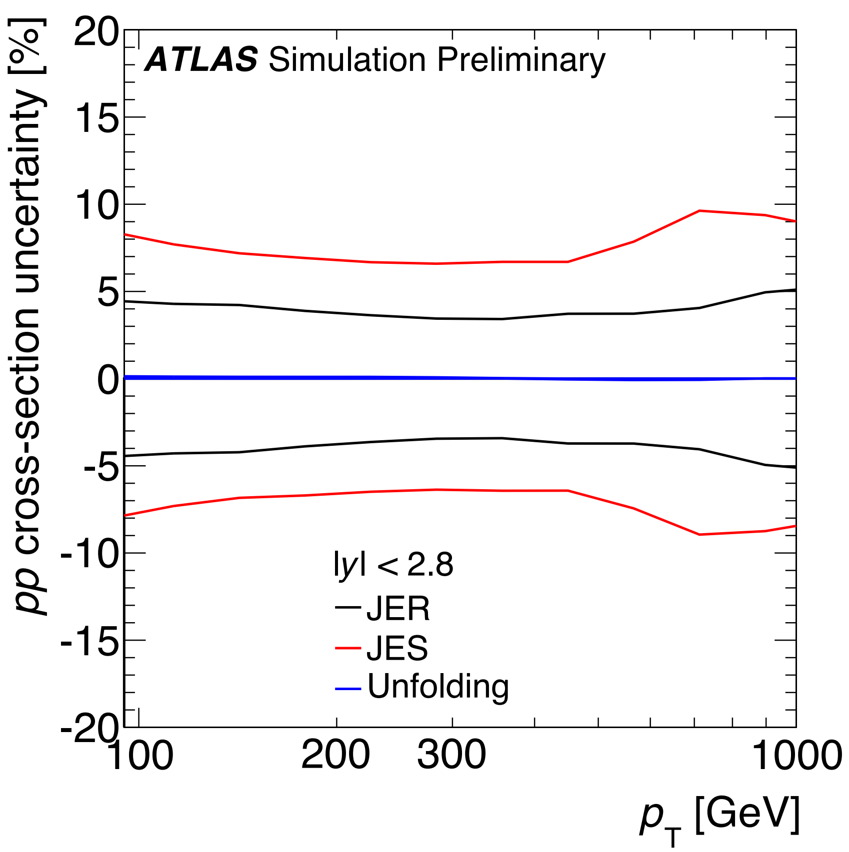


R_{AA} systematic uncertainties

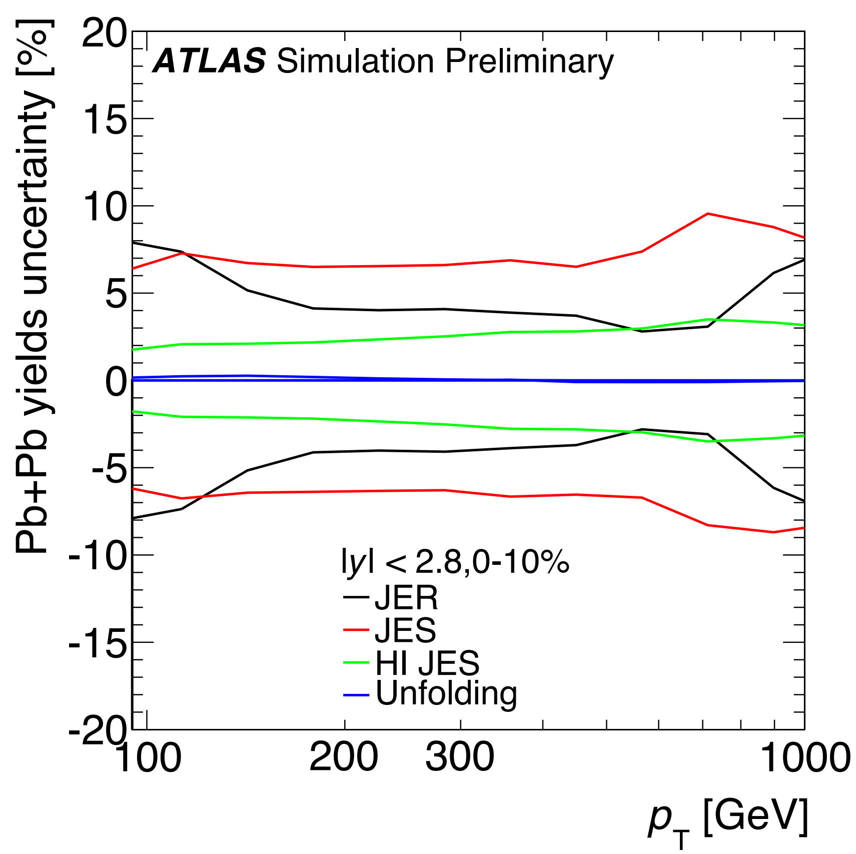
- **Jet energy scale**
  - ➡ **Standard *pp* JES components + 5 TeV flavor and HI cross-calibration (following ATL-CONF-2015-016)**
  - ➡ **HI specific uncertainty due to jet quenching (estimated using studies of the ratio of calo-jet to track-jet p_T)**
- **Jet energy resolution**
  - ➡ **Standard *pp* component**
  - ➡ **Established HI component**
- **Luminosity**
- **Nuclear thickness function**
- **Unfolding**
  - ➡ **By comparing to results unfolded using the response matrix without the reweighting**

R_{AA} systematics summary

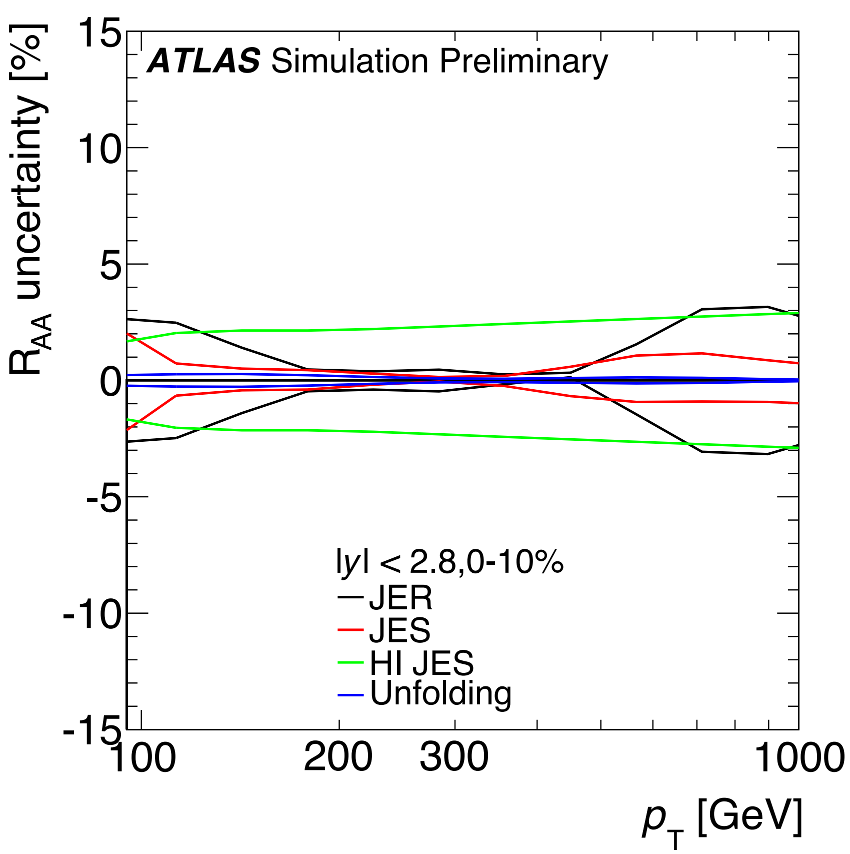
- **uncertainties on the *pp* cross section**



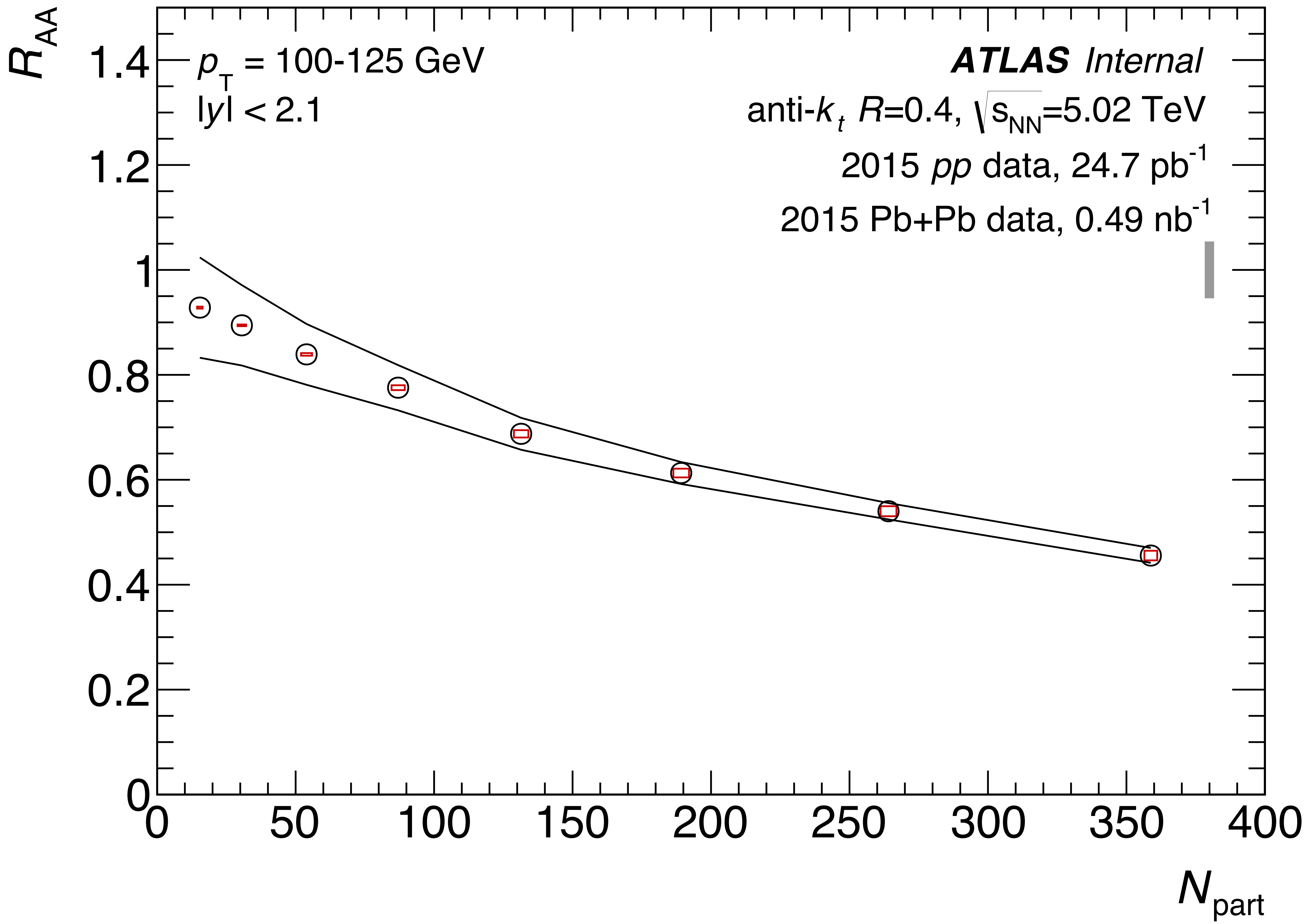
- **uncertainties on Pb+Pb yields**



- **uncertainties on R_{AA}**



R_{AA} vs. N_{part}

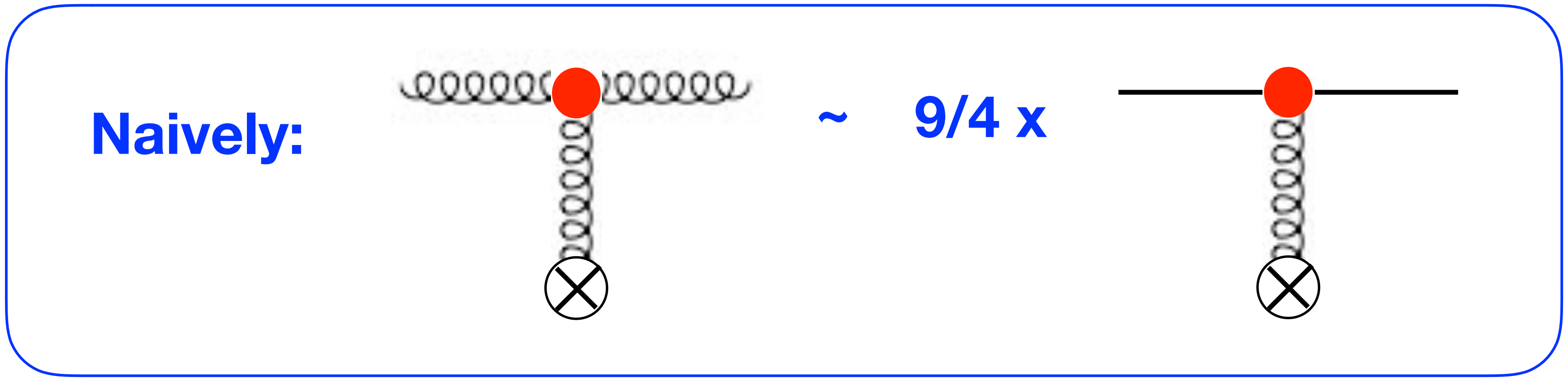


- **R_{AA} decreases with N_{part}**

Energy loss: flavor dependence

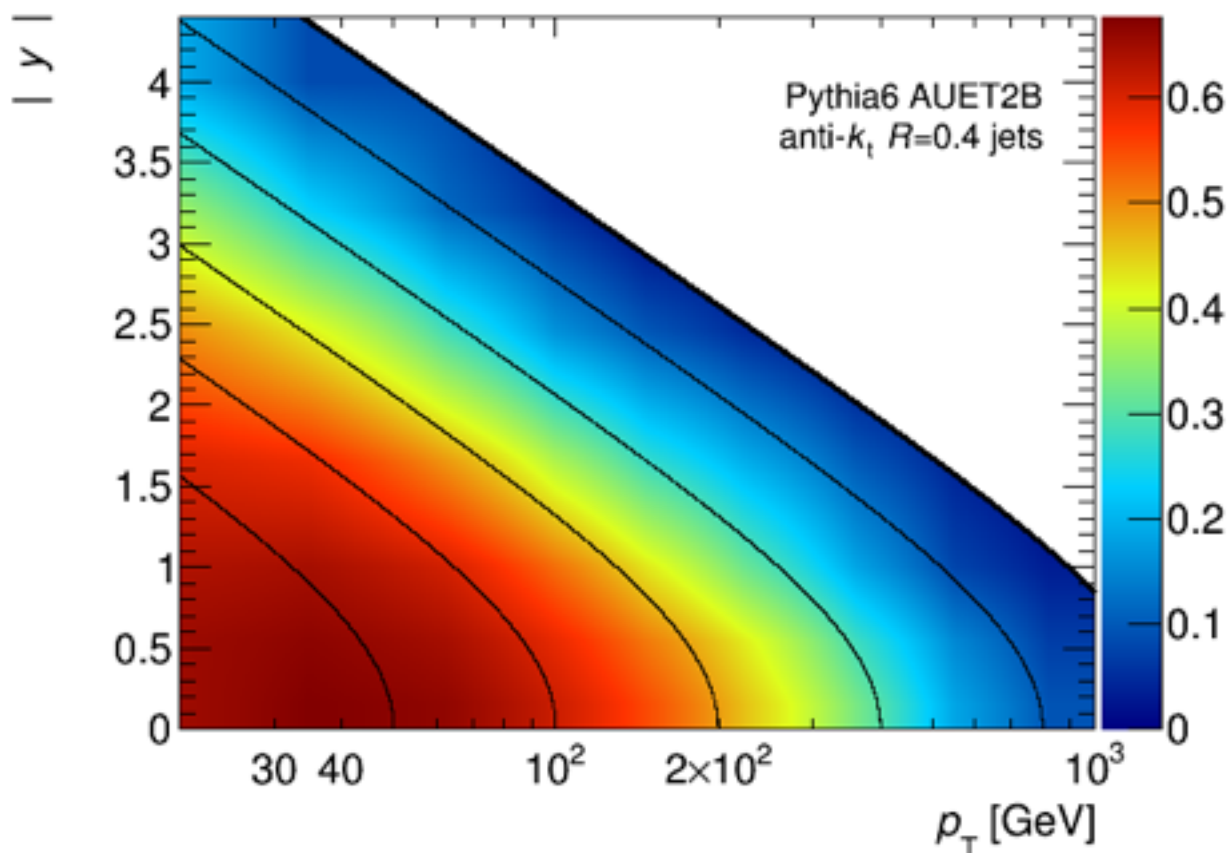
- **How does energy loss depend on the details of the parton show?**

  ➡ **Vary the quark and gluon contribution of the jets since gluons are quenched more than quarks.**

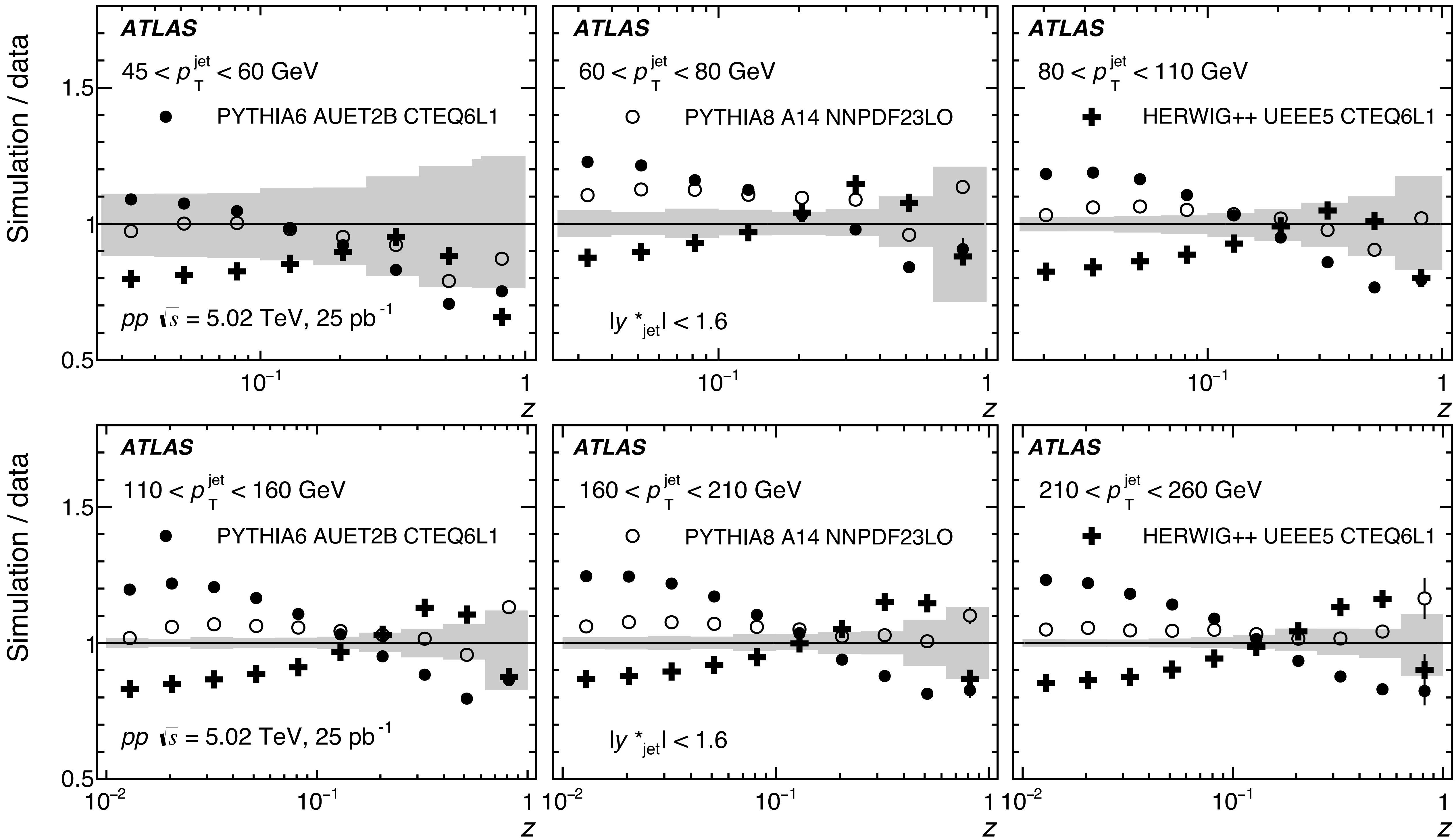


- **Measure suppression as a function of rapidity or jet p_T since gluon fraction decreases with rapidity and jet p_T.**

  ➡ **Higher R_{AA} at forward rapidity and high p_T.**

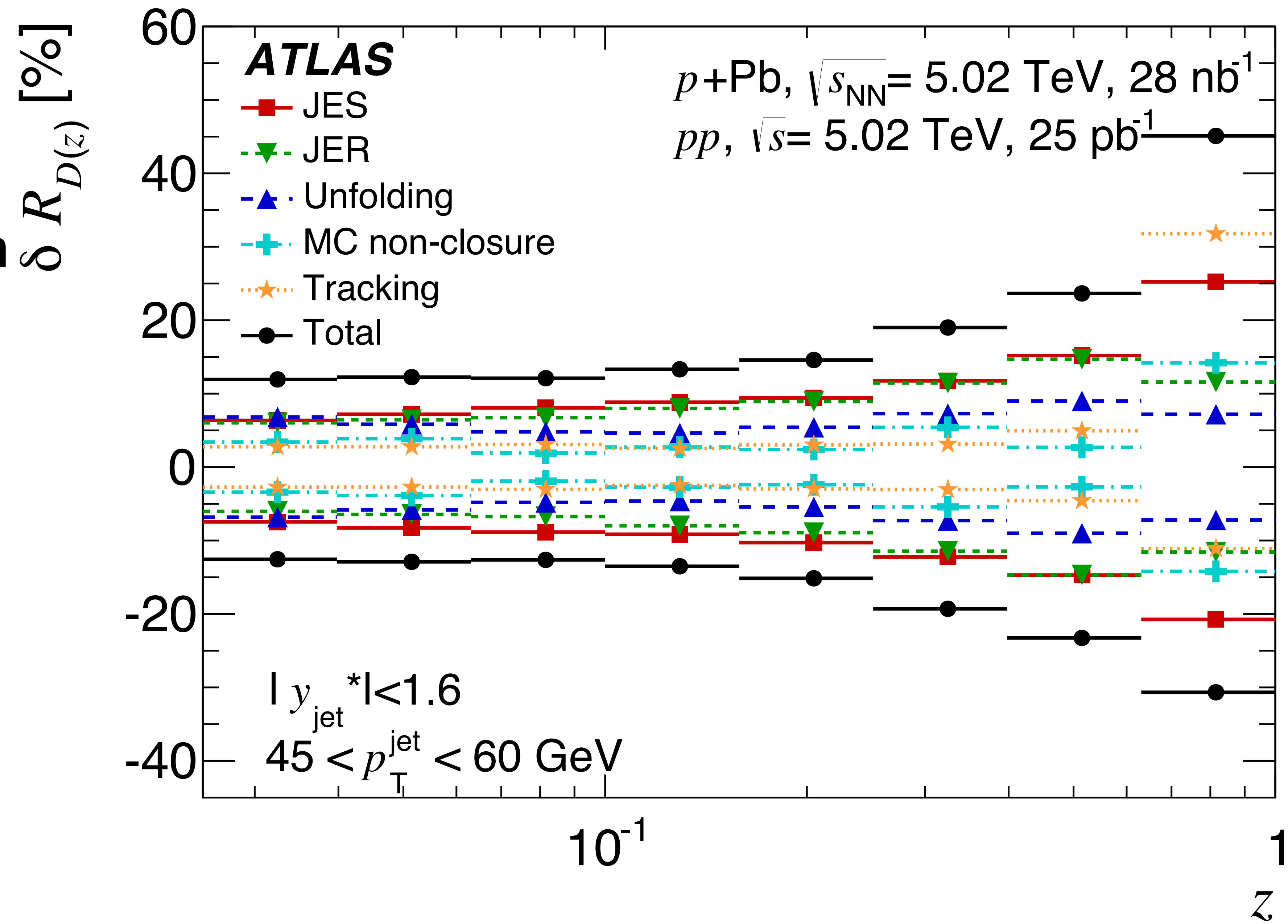


D(z)$_{pp}$ MC to data



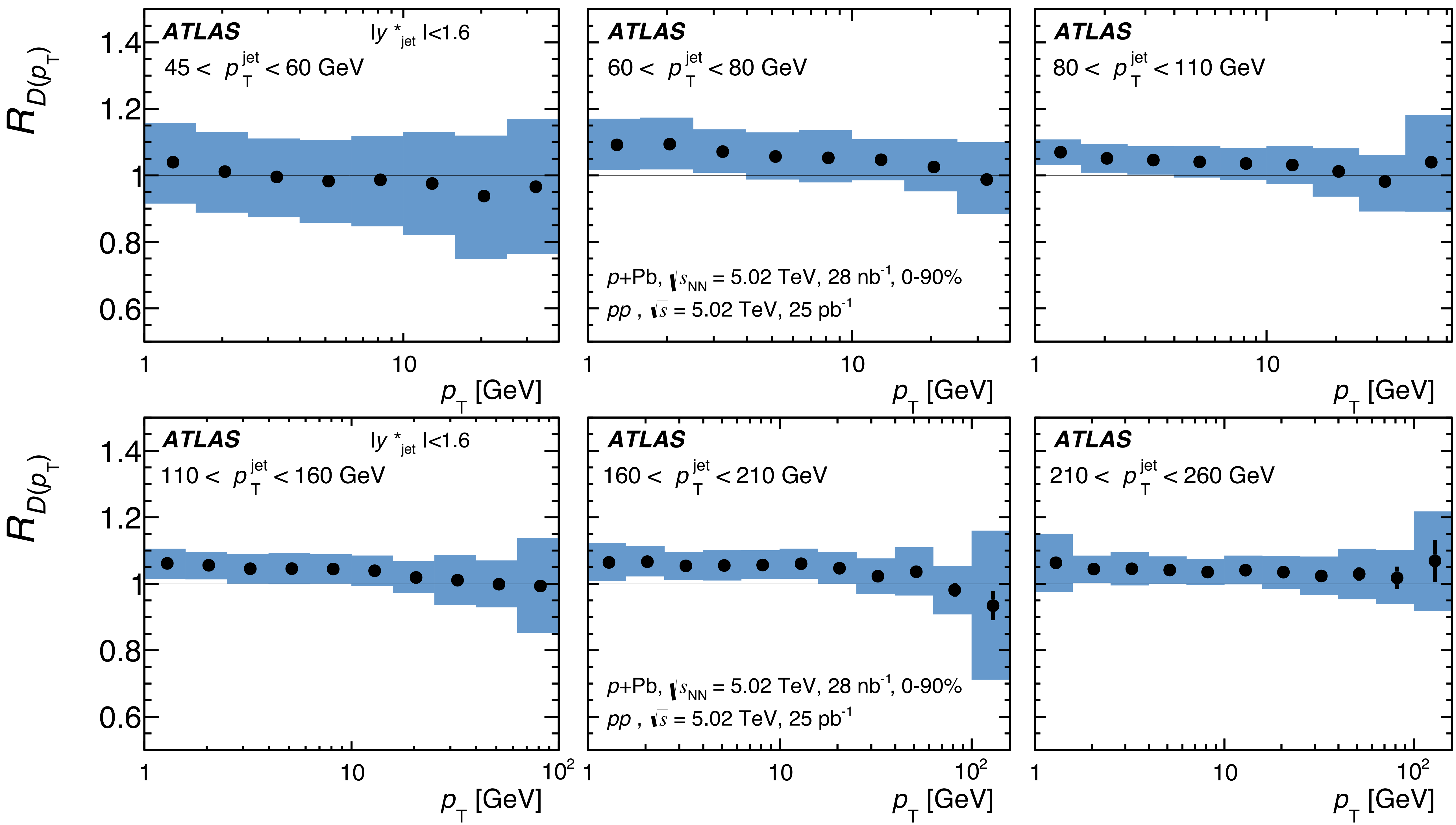
Systematic uncertainties on p+Pb $R_{D(z)}$

- **Jet energy scale**
- **Jet energy resolution**
- **Unfolding**
- **Track reconstruction**
- **MC non-closure**



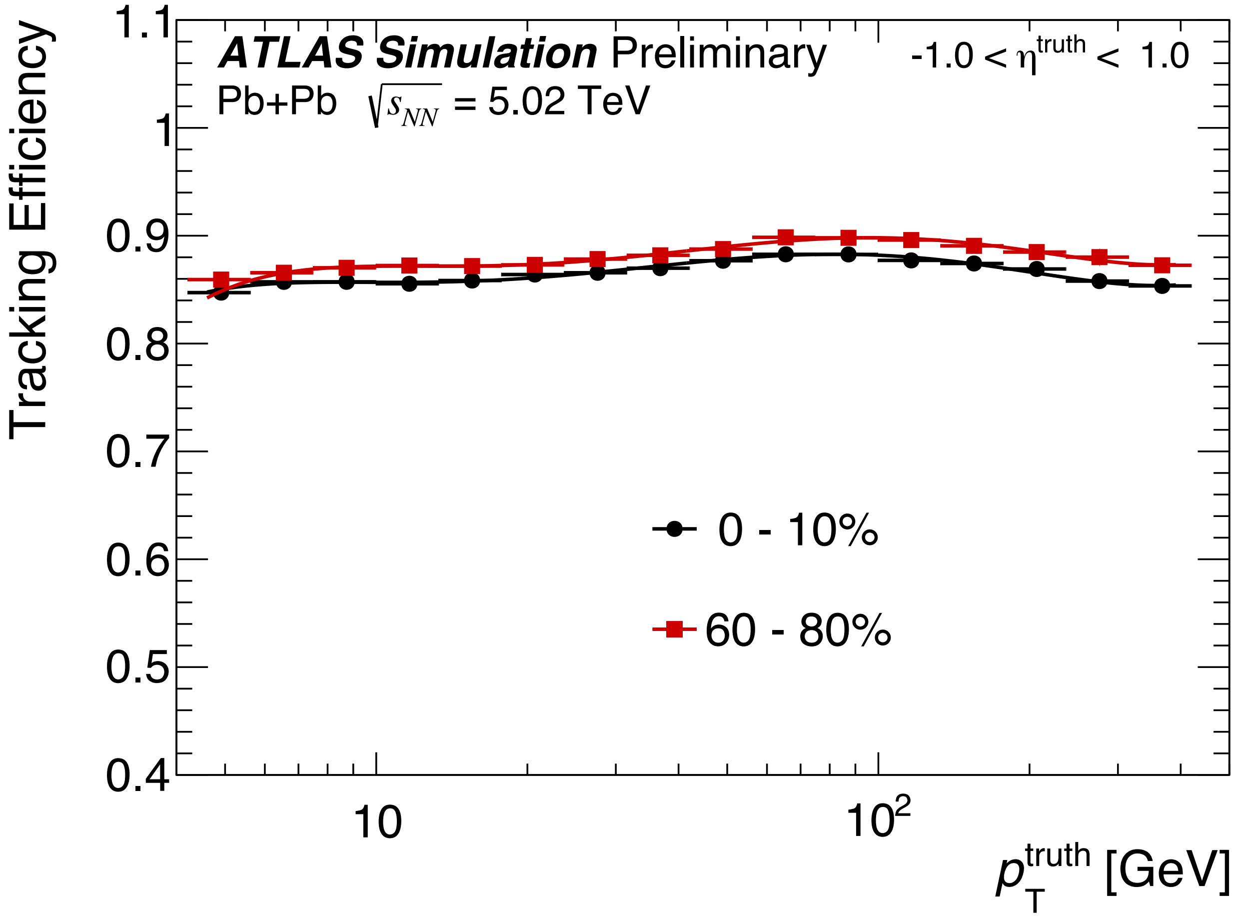
p+Pb $R_{D(p_T)}$ in jet p_T bins

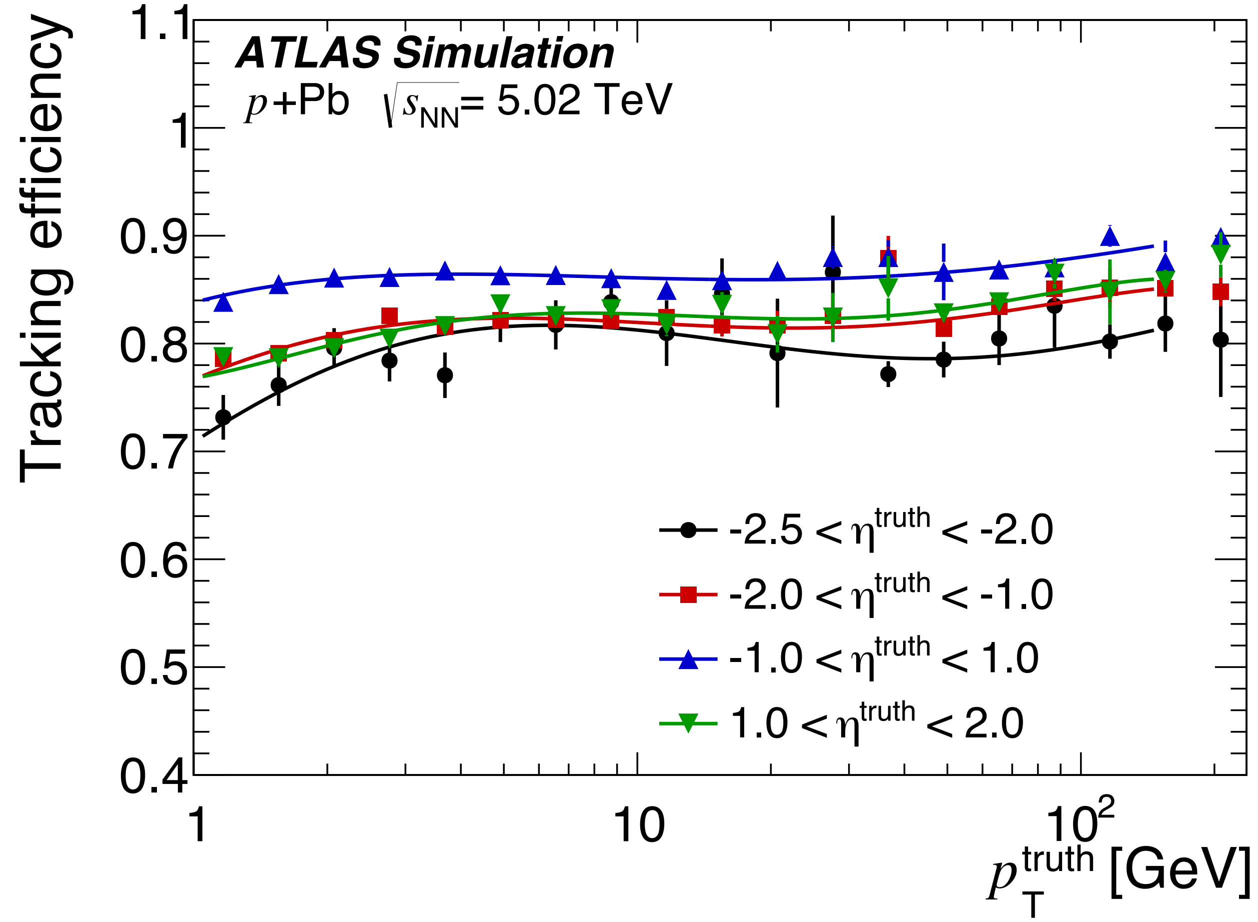
- **New *pp* reference at same center of mass energy**



➡ No modification of jet structure in *p*+Pb.

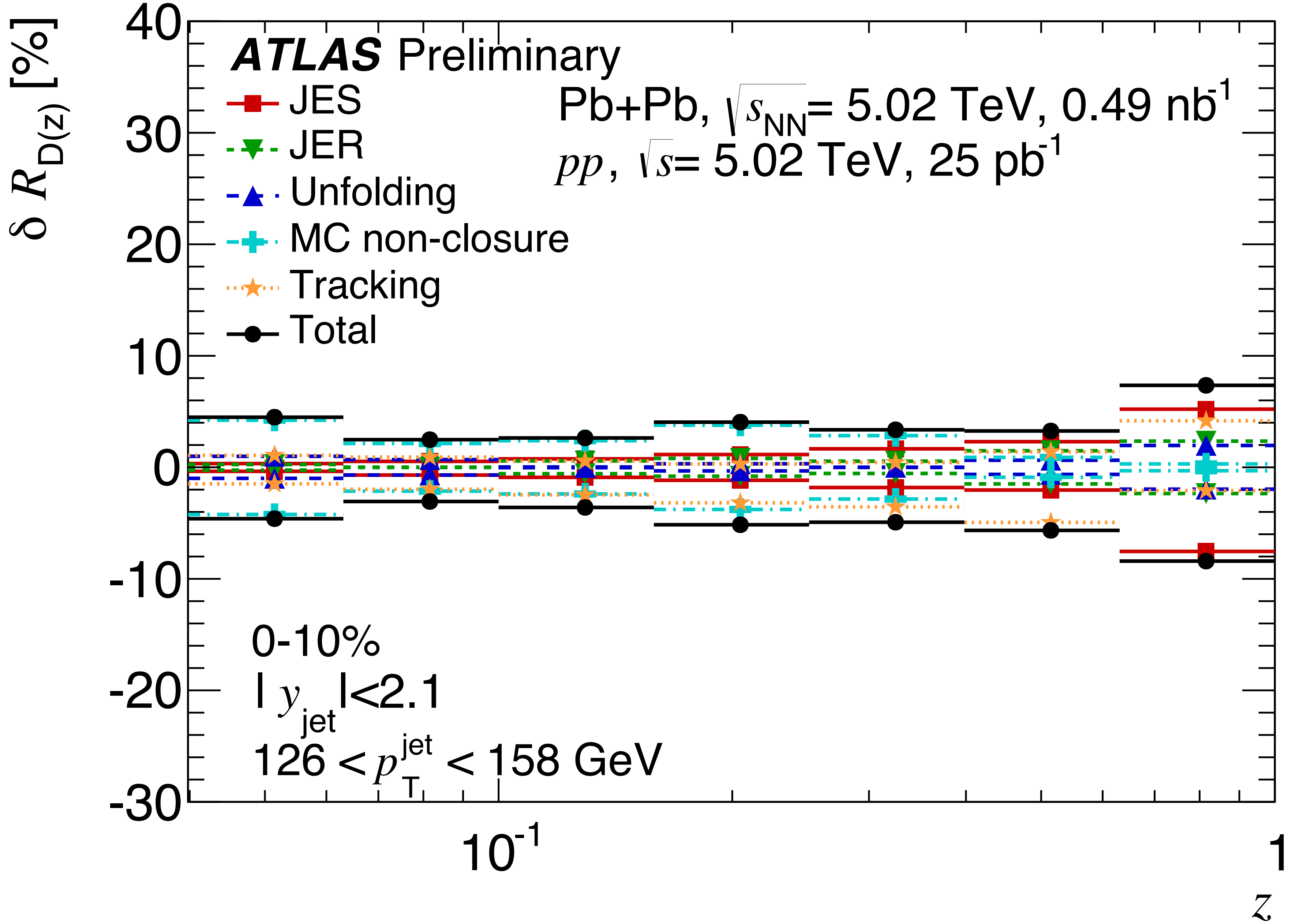
Tracking efficiencies





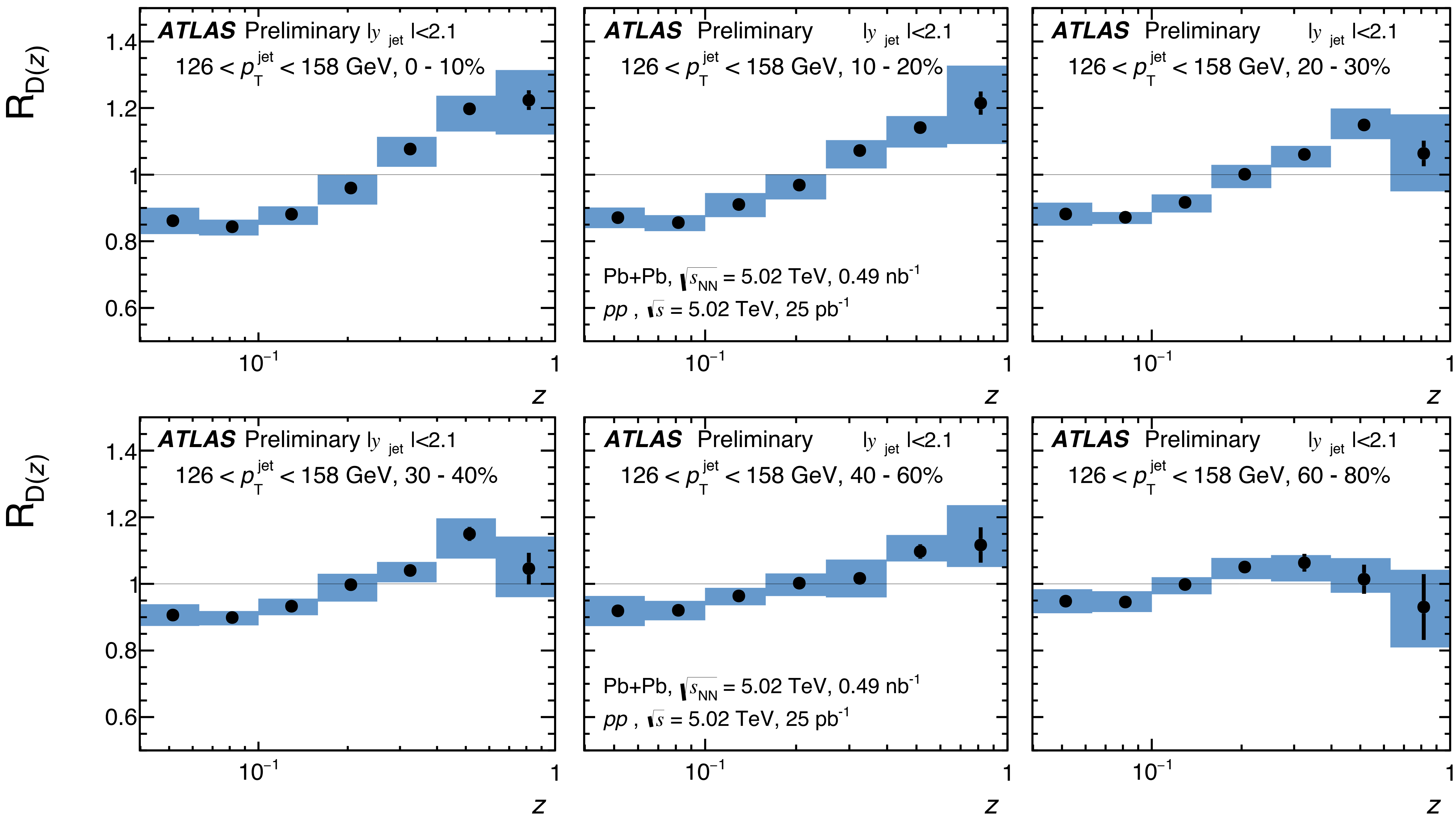
Systematic uncertainties on Pb+Pb $R_{D(z)}$

- **Jet energy scale**
- **Jet energy resolution**
- **Unfolding**
- **Track reconstruction**
- **MC non-closure**



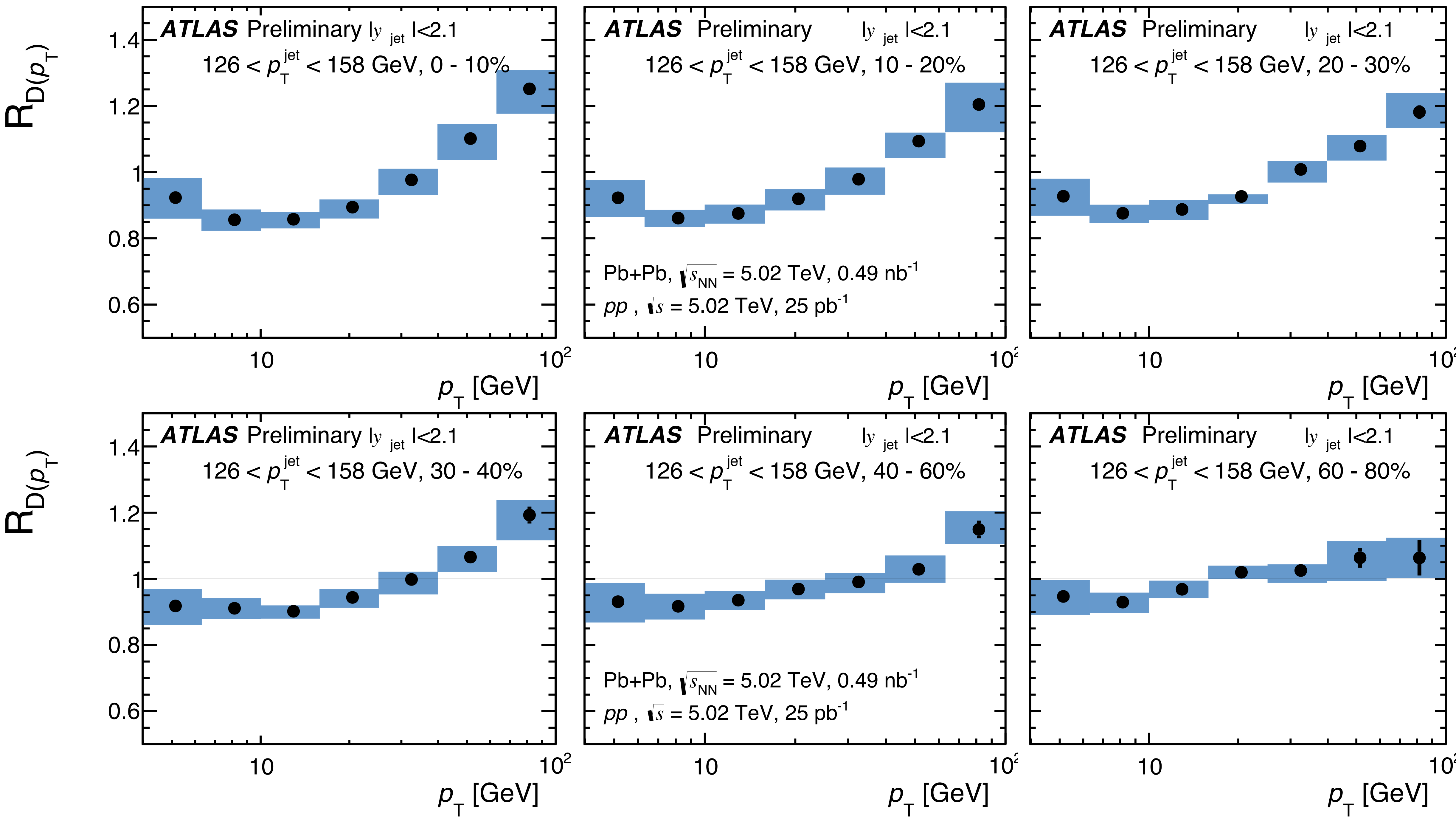
Systematic uncertainties on Pb+Pb $R_{D(z)}$

Pb+Pb $R_{D(z)}$ in jet p_T bins



➡ Jets are more modified in central collisions

Pb+Pb $R_{D(p_T)}$ in centrality bins



➡ **Jets are more modified in more central collisions**

Pb+Pb $R_{D(p_T)}$ jet p_T in bins