Recent results on jets and high p_T hadrons from ATLAS

Laura Havener, Columbia University

2018 RHIC & AGS Annual Users' Meeting, BNL

Tuesday, June 12th, 2018

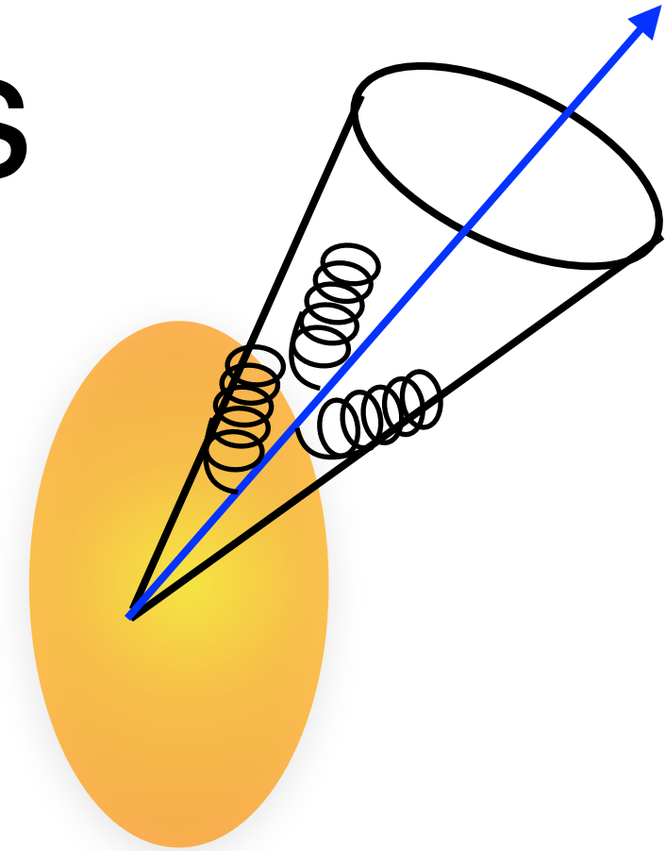
Jets in HI collisions

- **New results from ATLAS are improvements over previous measurements:**
  - ➡ **More precise measurements with better control over the background subtraction and systematics**
  - ➡ **Unfolding for detector effects allow direct comparisons to theoretical models of jet quenching**
  - ➡ **Better statistics allow for differential studies of jet kinematics that look at flavor and path dependence of energy loss, what happens at high p_T, etc.**
  - ➡ **boson+jet systems probe the flavor dependence and absolute energy loss**
  - ➡ **Xe+Xe collisions look at density and path dependence of energy loss**

Measuring jets

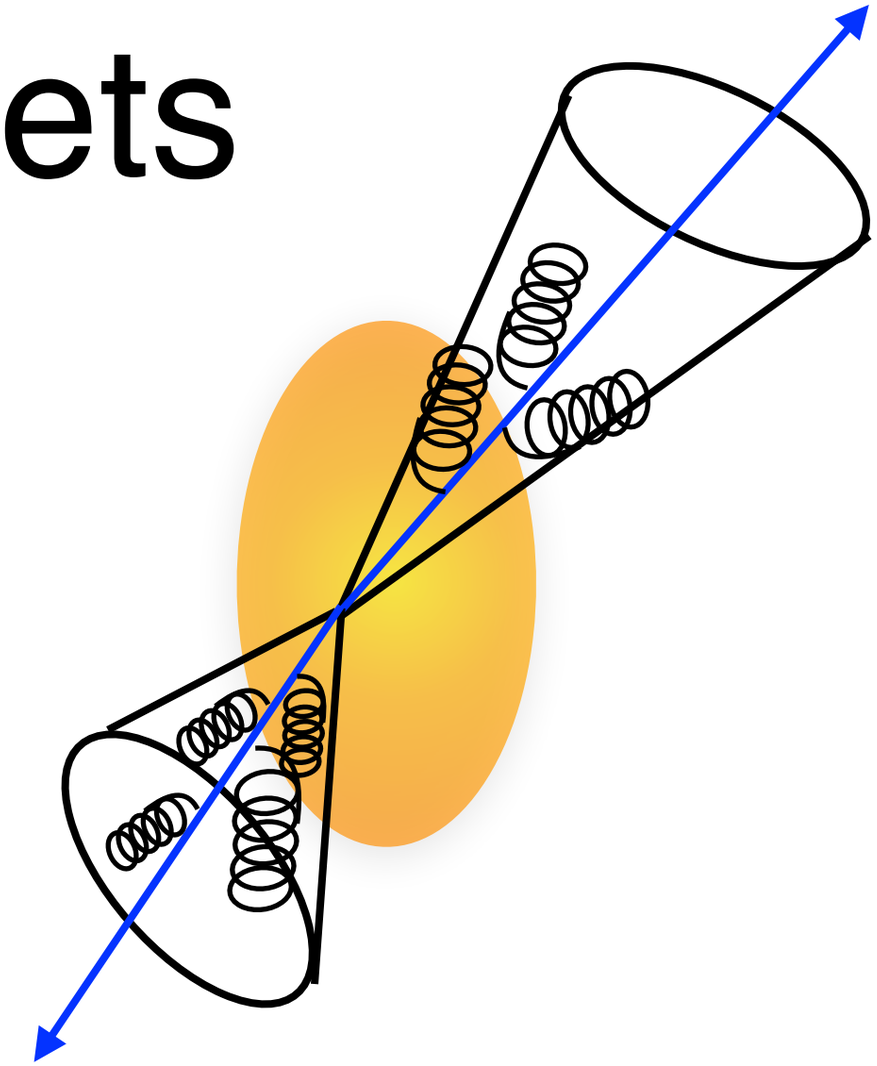
- **Measuring jet quenching includes:**

  ➡ **Inclusive energy loss through the suppression of hard scattering rates of single jets**



Measuring jets

- **Measuring jet quenching includes:**
  - ➡ **Inclusive energy loss through the suppression of hard scattering rates of single jets**
  - ➡ **Differential energy loss through jet correlations**



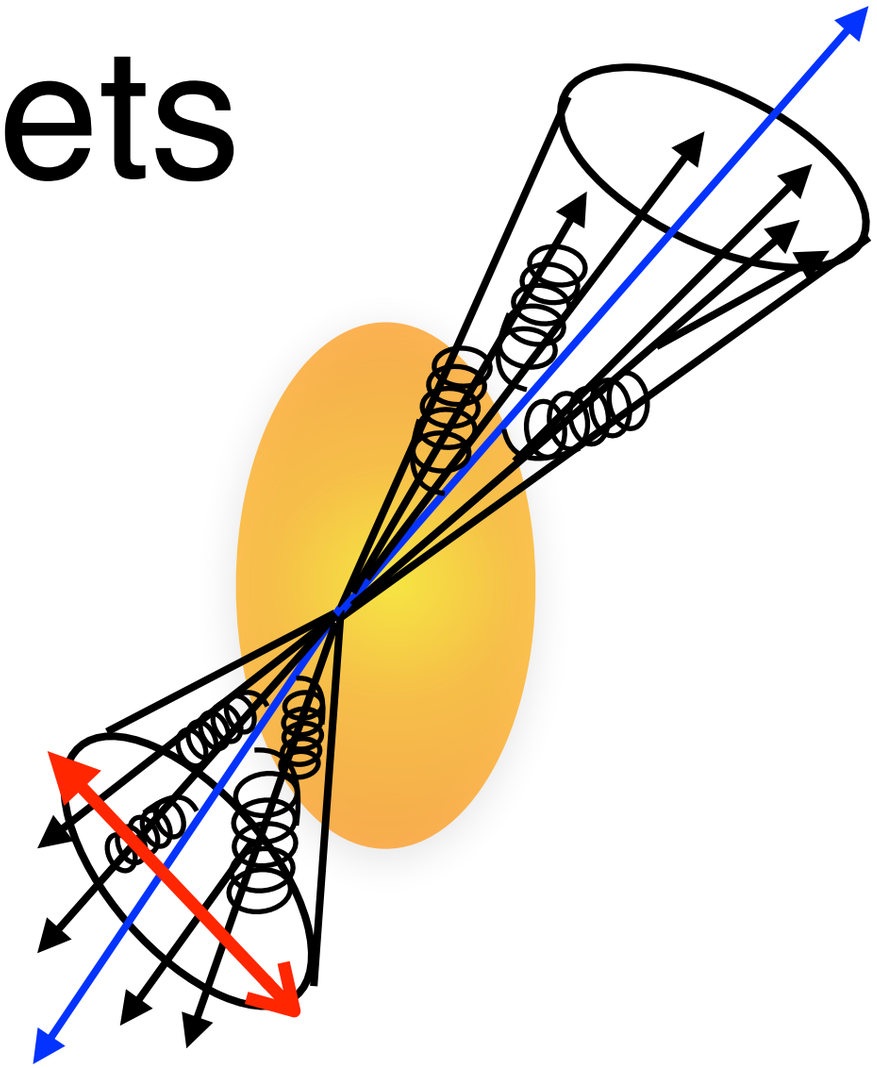
Energy loss depends on path length and on flavor with gluons experiencing more quenching than quarks

Measuring jets

- **Measuring jet quenching includes:**
  - ➡ **Inclusive energy loss through the suppression of hard scattering rates of single jets**
  - ➡ **Differential energy loss through jet correlations**

Energy loss depends on path length and on flavor with gluons experiencing more quenching than quarks

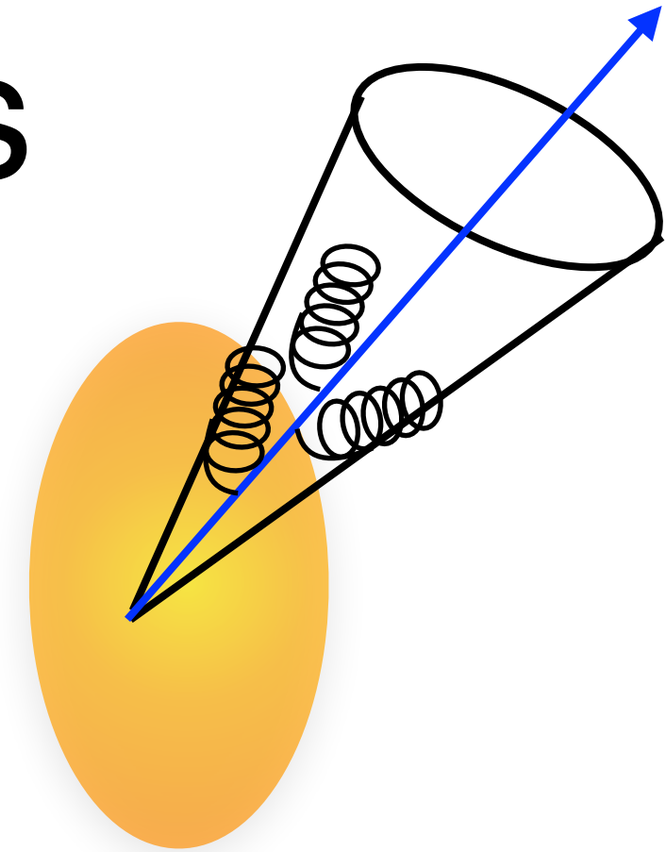
  - ➡ **Jet structure modification by measuring charged particles in jets and jet mass**



Momentum broadening from soft gluon radiation in-medium interactions

Medium response to the jet adds soft particles along jet direction

Measuring jets



- Measuring jet quenching includes:

➡ **Inclusive energy loss through the suppression of hard scattering rates of single jets**

➡ Differential energy loss through jet correlations

Energy loss depends on path length and on flavor with gluons experiencing more quenching than quarks

➡ Jet structure modification by measuring
particles in jets
mass

Momentum broadening from soft gluon radiation in-medium interactions

Medium response to the jet adds soft particles along jet direction

Jet suppression

arXiv:1805.05635

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

➡ **Compare number of jets in Pb+Pb to *pp* using the R_{AA}**

$$R_{\mathrm{AA}} = \frac{\frac{1}{N_{\mathrm{evnt}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}} \rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2 \sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

Jet yield in heavy ion collisions

Jet cross-section in *pp* collisions

Nuclear thickness function

Jet suppression

arXiv:1805.05635

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

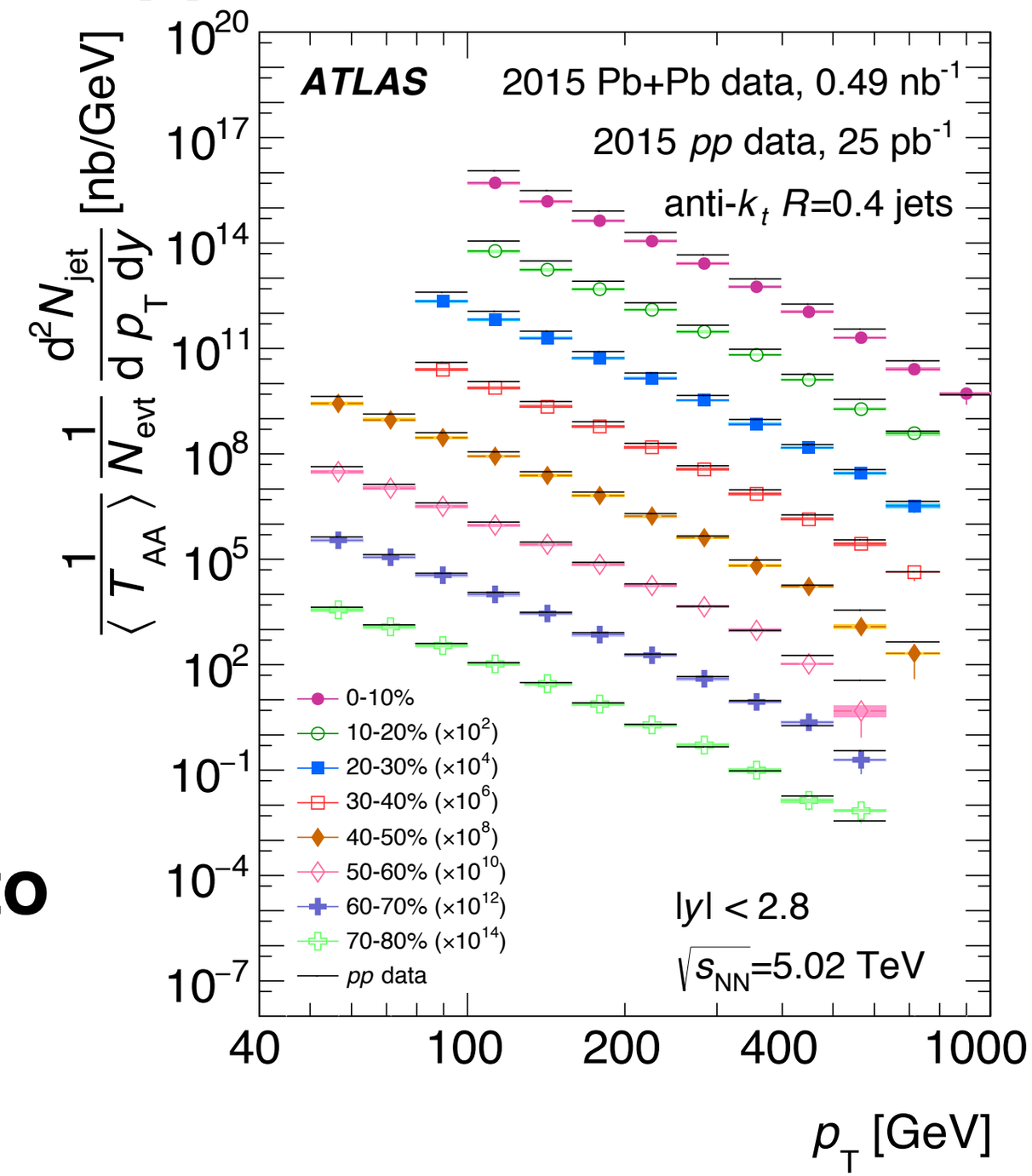
➡ **Compare number of jets in Pb+Pb to *pp* using the R_{AA}**

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

Jet yield in heavy ion collisions

Jet cross-section in *pp* collisions

Nuclear thickness function



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

Jet suppression

arXiv:1805.05635

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

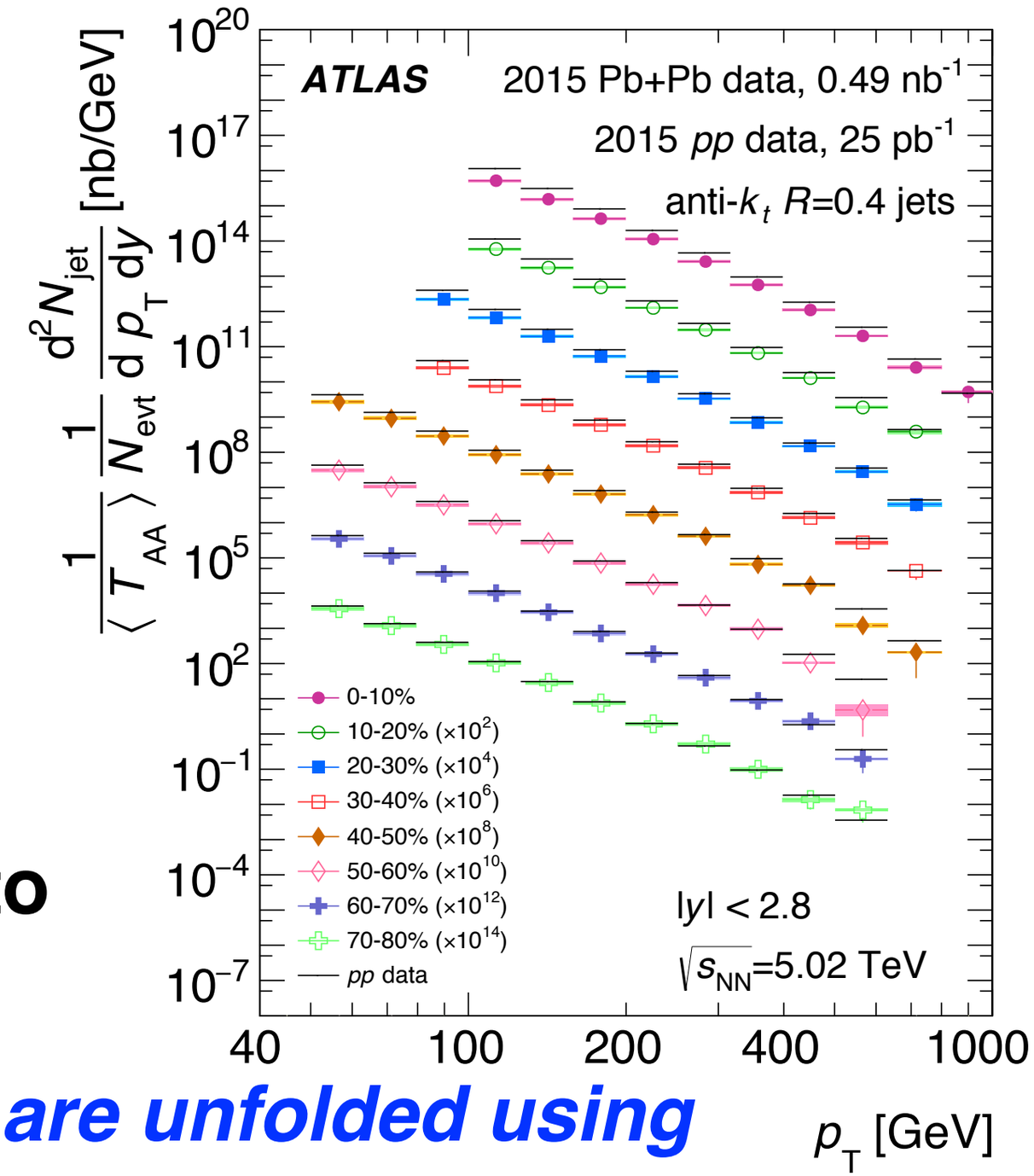
➡ **Compare number of jets in Pb+Pb to *pp* using the R_{AA}**

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

Jet yield in heavy ion collisions

Jet cross-section in *pp* collisions

Nuclear thickness function



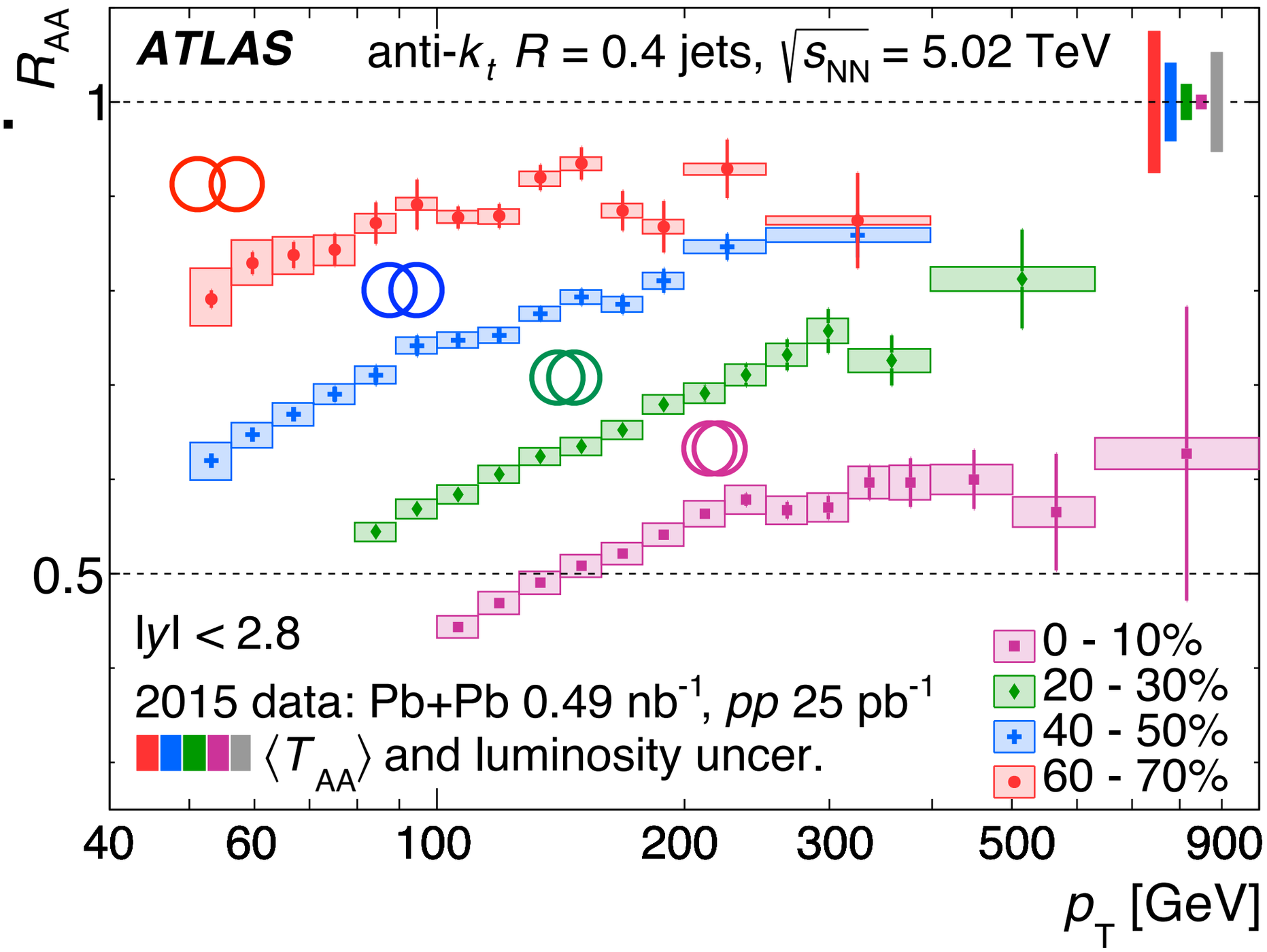
- **Jets measured in six bins of rapidity (out to 2.8) and up to ~ 1 TeV in jet p_T.**

▸ ***Jet spectra in Pb+Pb and pp are unfolded using 1D Bayesian unfolding.***

R_{AA}: p_T dependence

arXiv:1805.05635

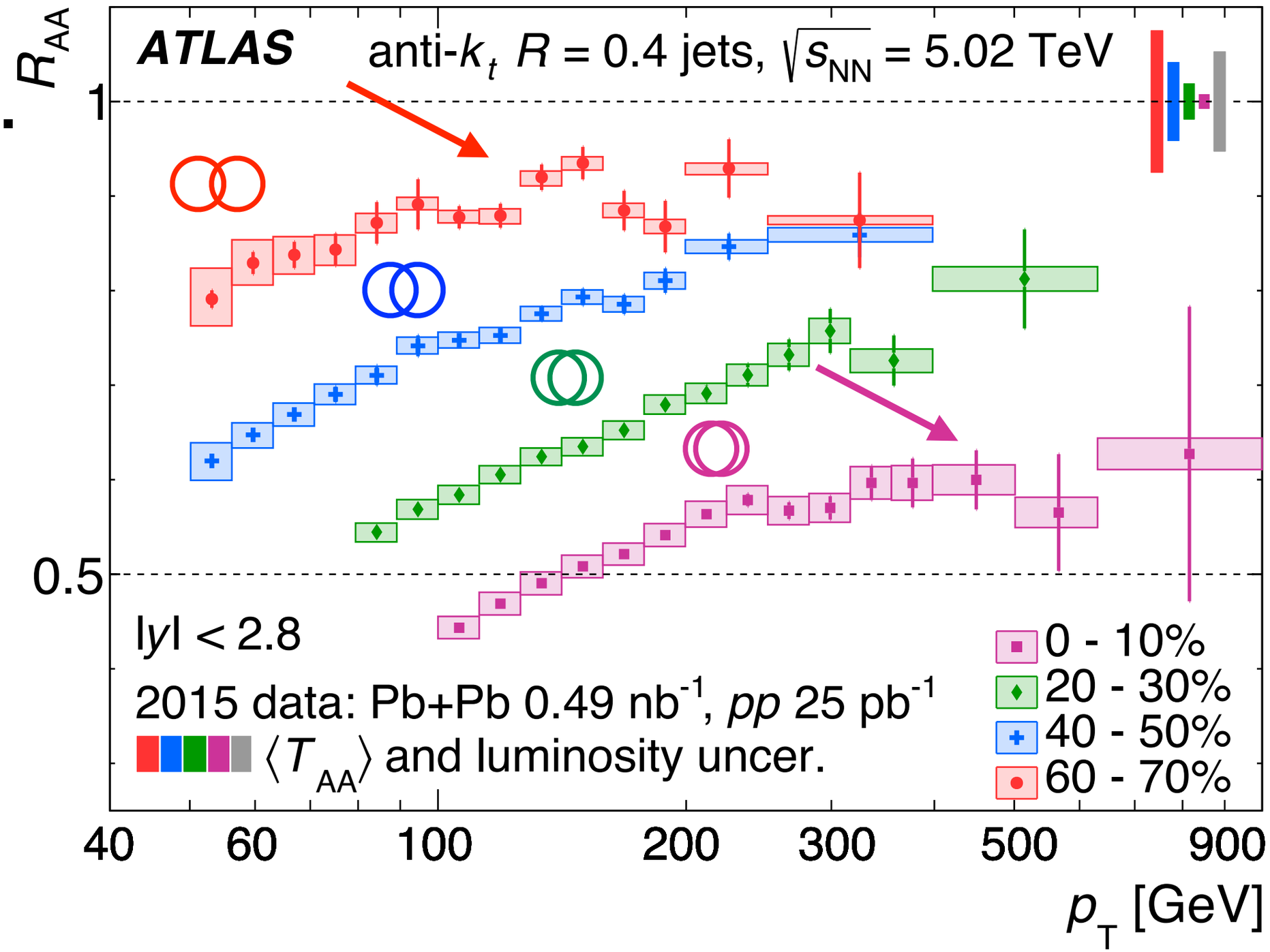
- **R_{AA} is < 1 for all centralities.**



R_{AA}: p_T dependence

arXiv:1805.05635

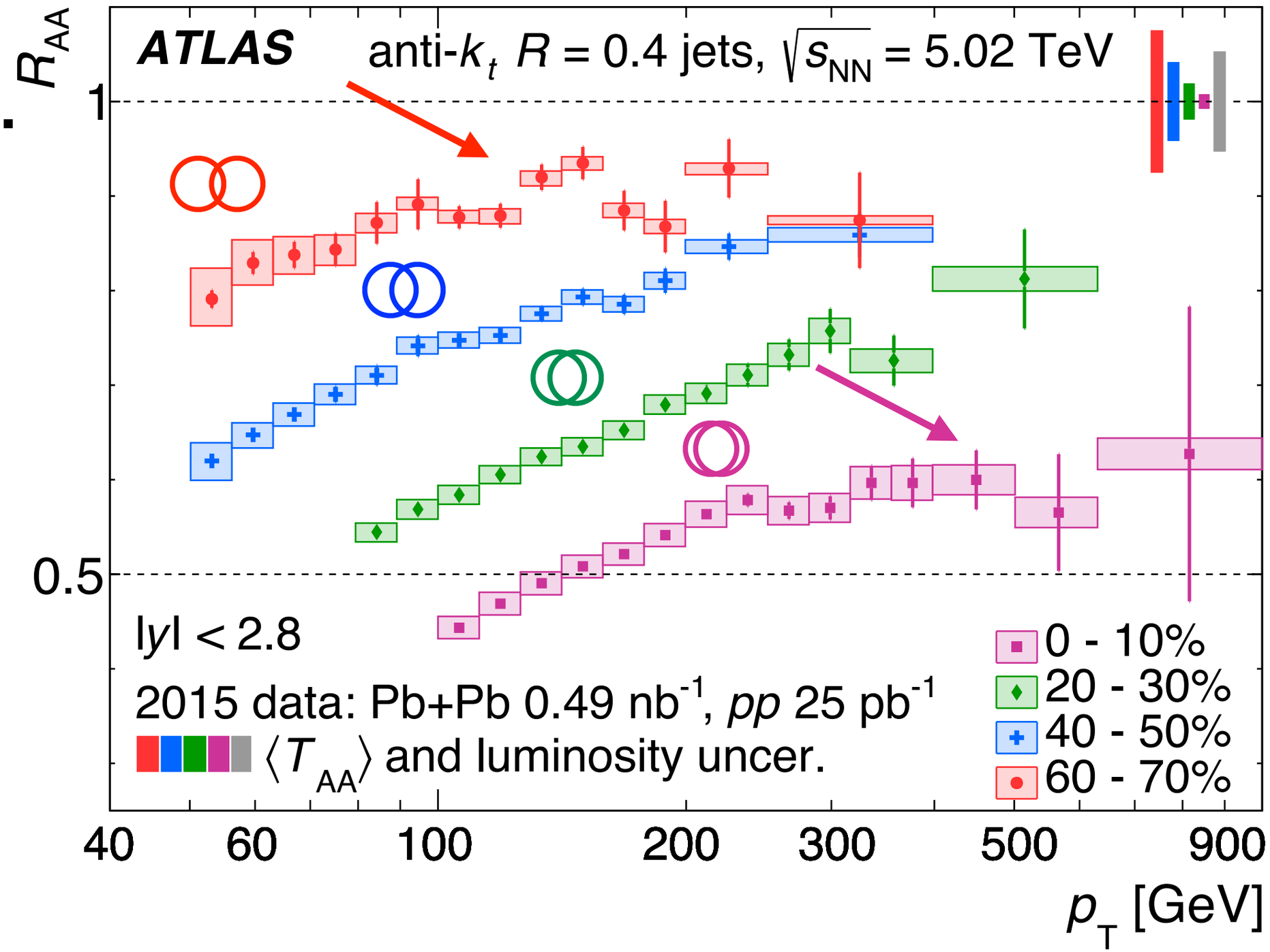
- **R_{AA} is < 1 for all centralities.**
- **R_{AA} is lower in central (~0.5) than peripheral (~0.9).**



R_{AA}: p_T dependence

arXiv:1805.05635

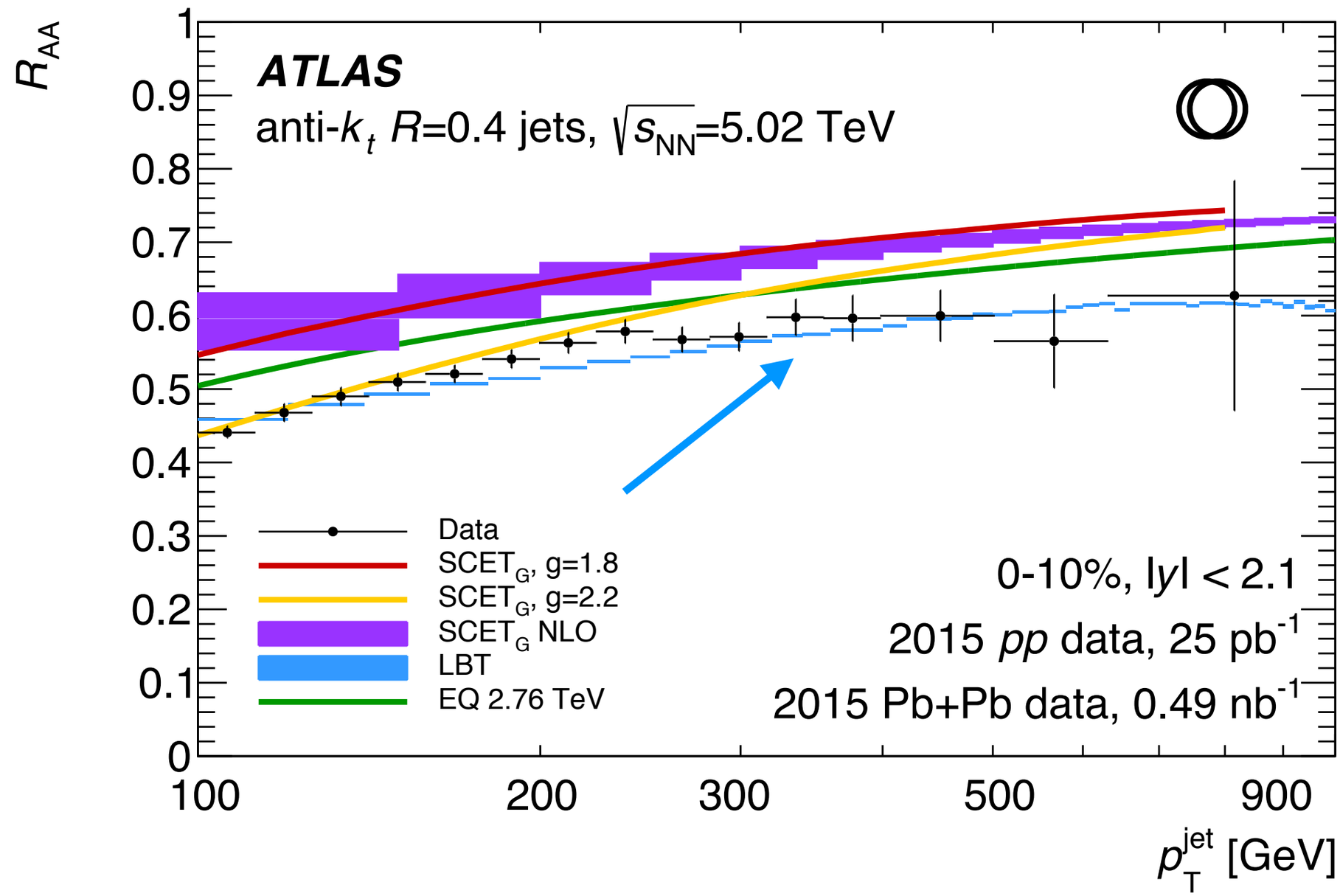
- **R_{AA} is < 1 for all centralities.**
- **R_{AA} is lower in central (~0.5) than peripheral (~0.9).**
- **R_{AA} shows suppression up to a TeV!**



R_{AA}: p_T dependence

arXiv:1805.05635

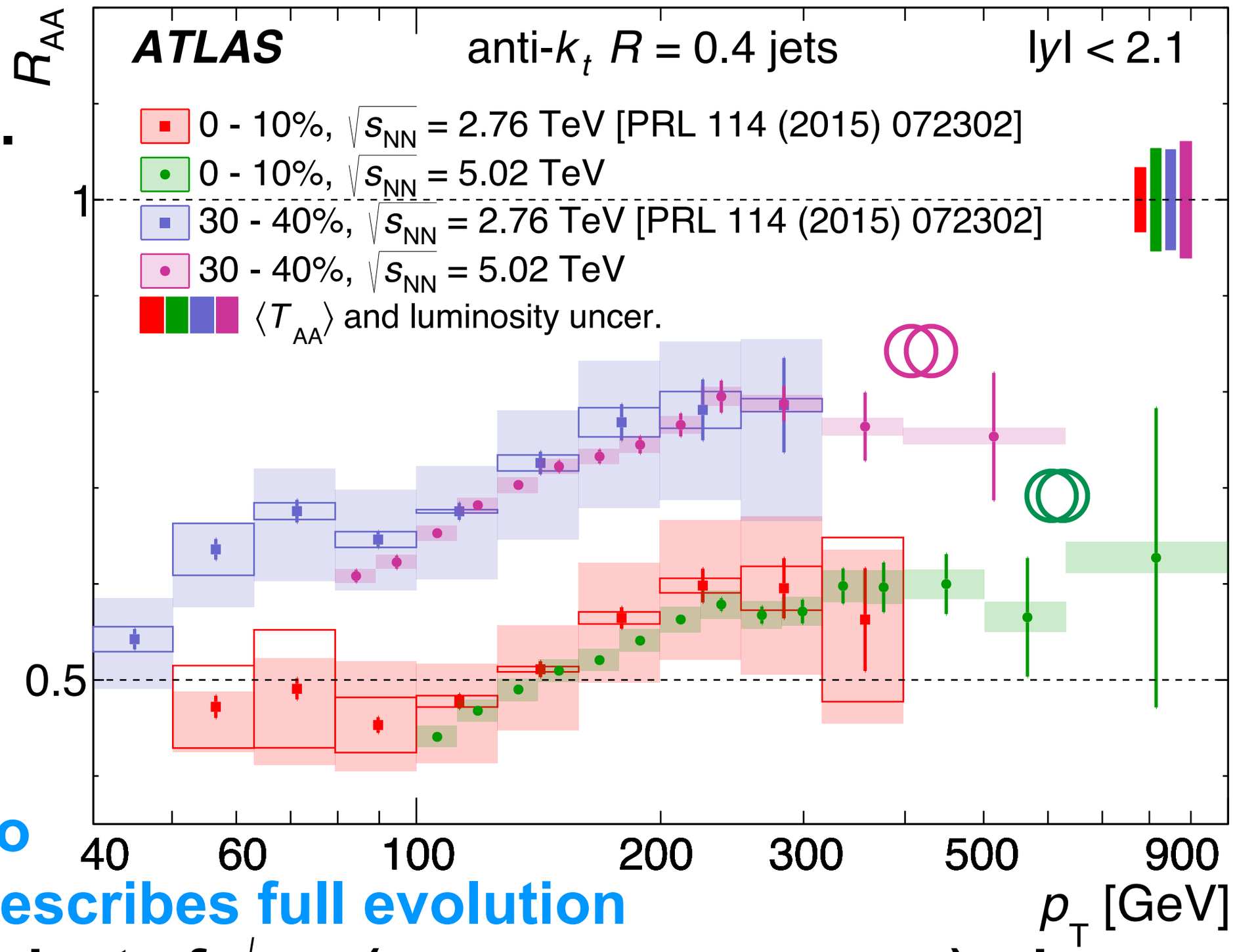
- **R_{AA} is < 1 for all centralities.**
- **R_{AA} is lower in central (~0.5) than peripheral (~0.9).**
- **R_{AA} shows suppression up to a TeV!**
- **Comparison to theory: LBT describes full evolution**



R_{AA}: p_T dependence

arXiv:1805.05635

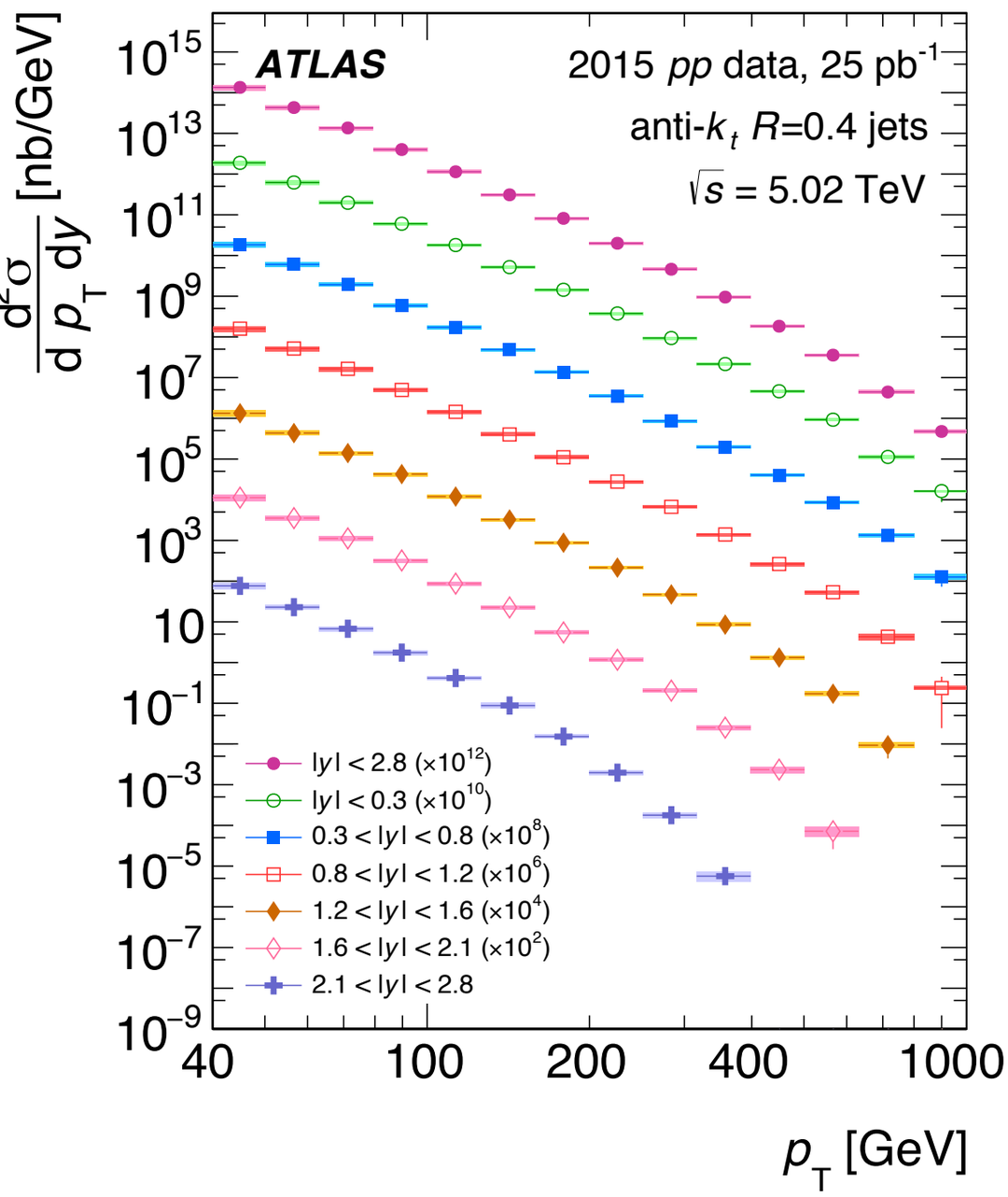
- **R_{AA} is < 1 for all centralities.**
- **R_{AA} is lower in central (~0.5) than peripheral (~0.9).**
- **R_{AA} shows suppression up to a TeV!**
- **Comparison to theory: LBT describes full evolution**

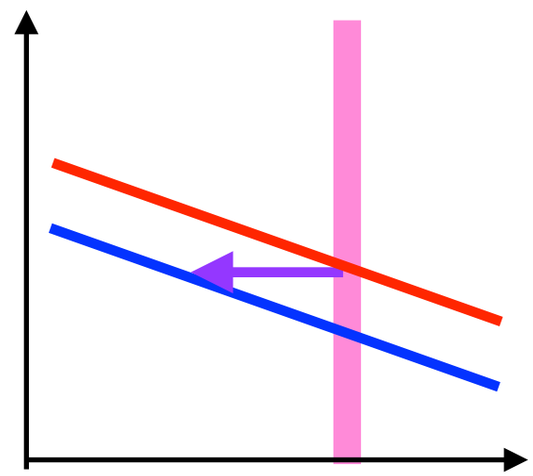


- **R_{AA} is independent of $\sqrt{s_{NN}}$ (over a narrow range) when comparing 2.76 and 5.02 TeV results.**

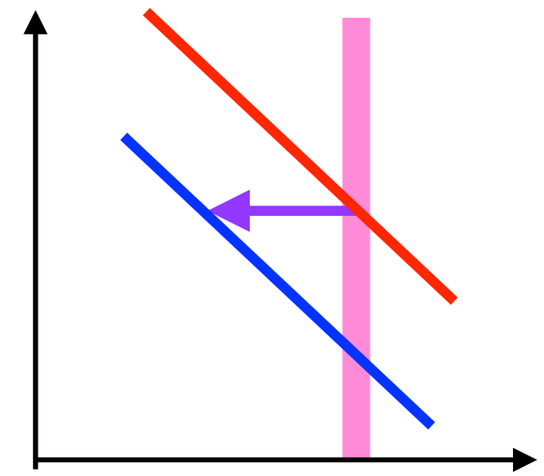
R_{AA}: rapidity dependence

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





mid-rapidity

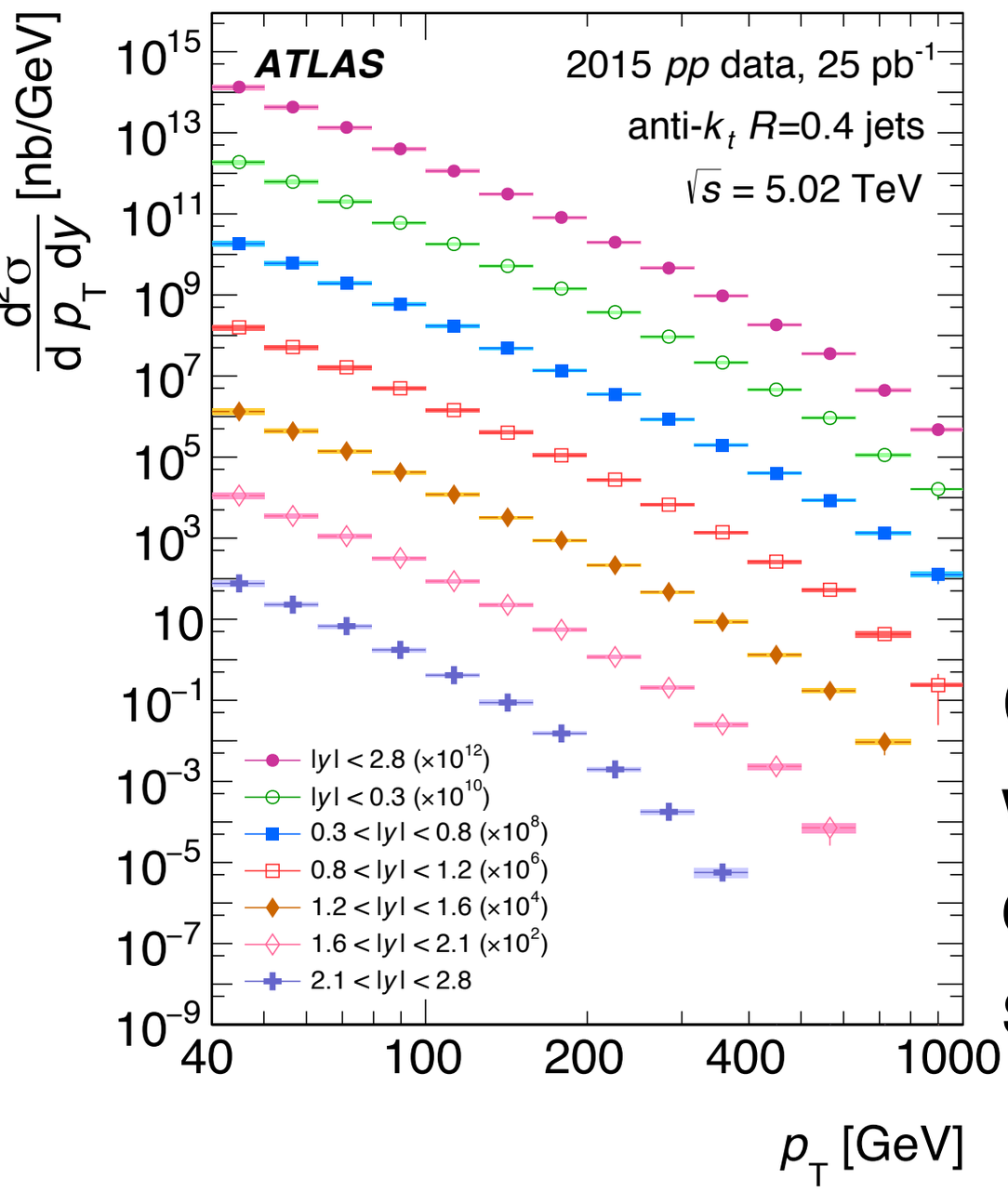


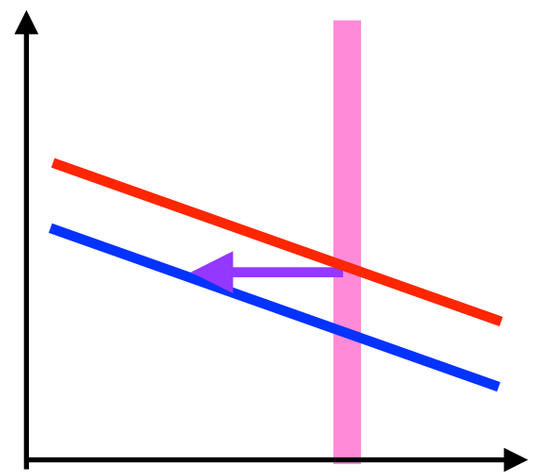
foward-rapidity

➡ **lower R_{AA}**

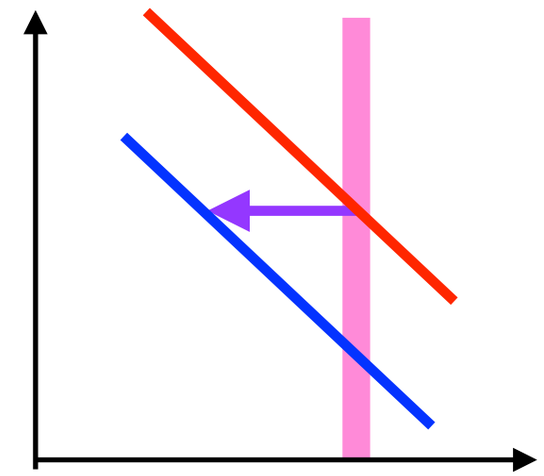
R_{AA}: rapidity dependence

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





mid-rapidity



foward-rapidity

➡ **lower R_{AA}**

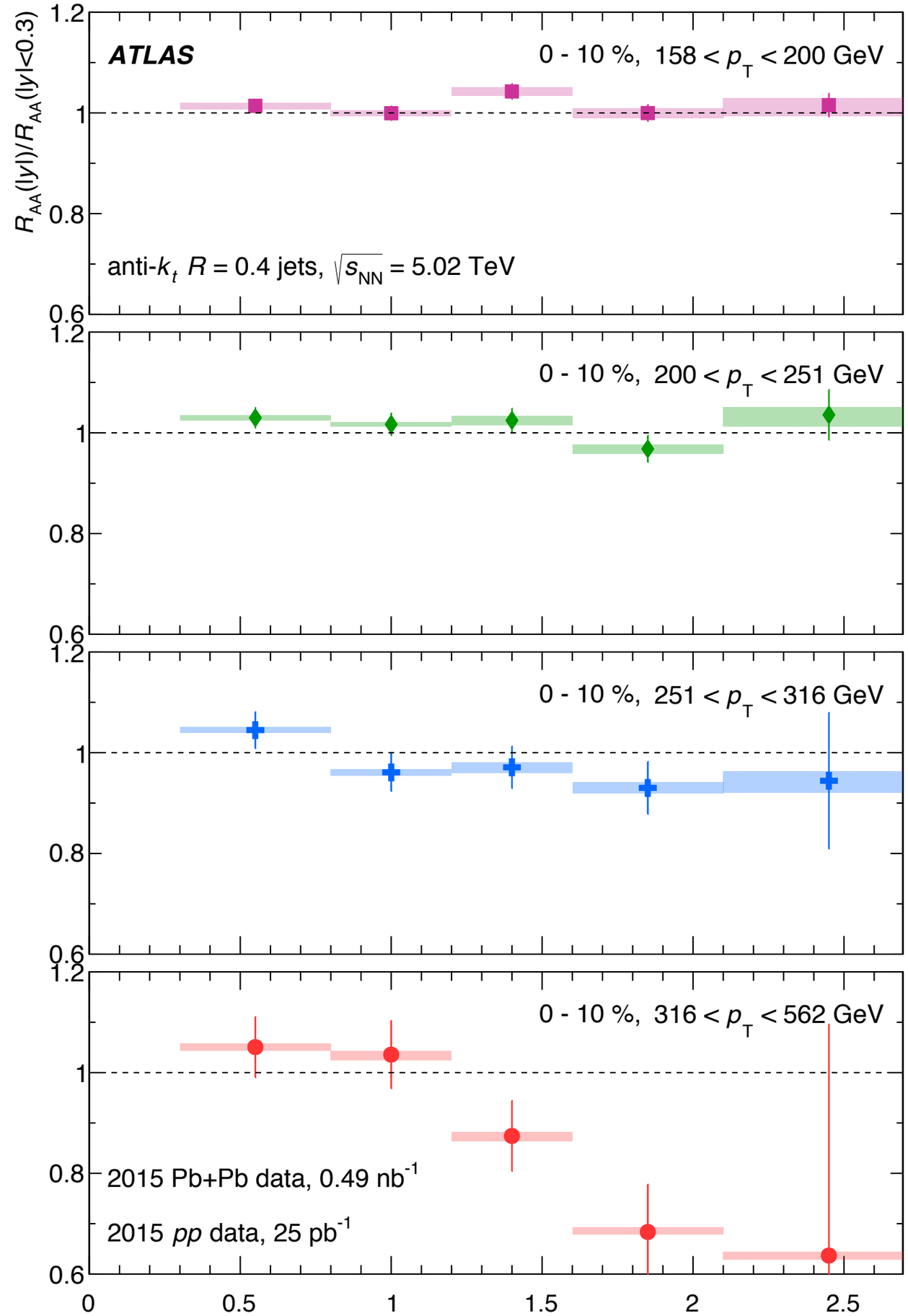
Quark and gluon fraction changes with rapidity and p_T with more quarks at forward rapidity which should be quenched less.

➡ **higher R_{AA}**

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

R_{AA}: rapidity dependence

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

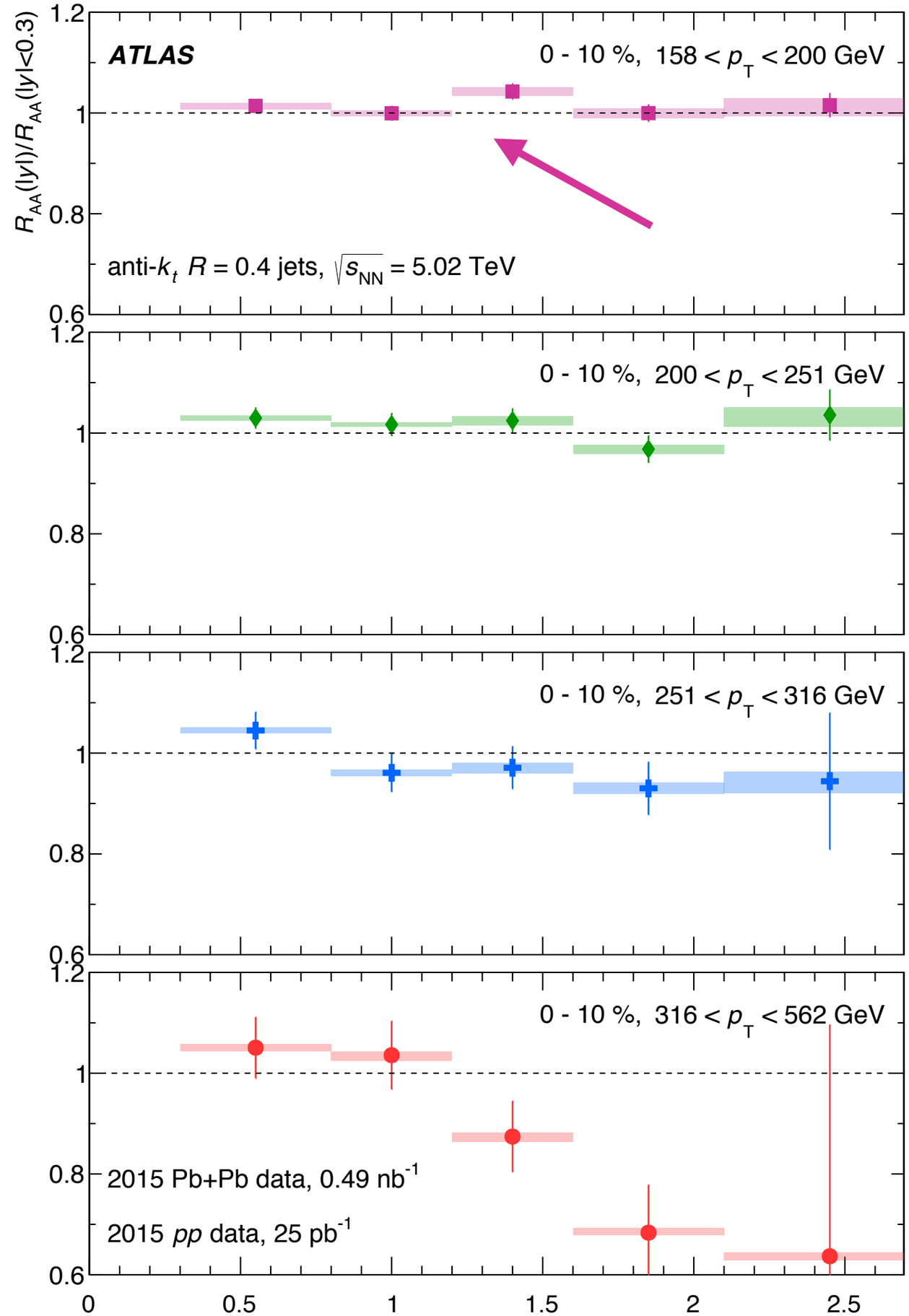


arXiv:1805.05635

R_{AA}: rapidity dependence

- **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**

- **R_{AA} is flat with rapidity at low p_T**



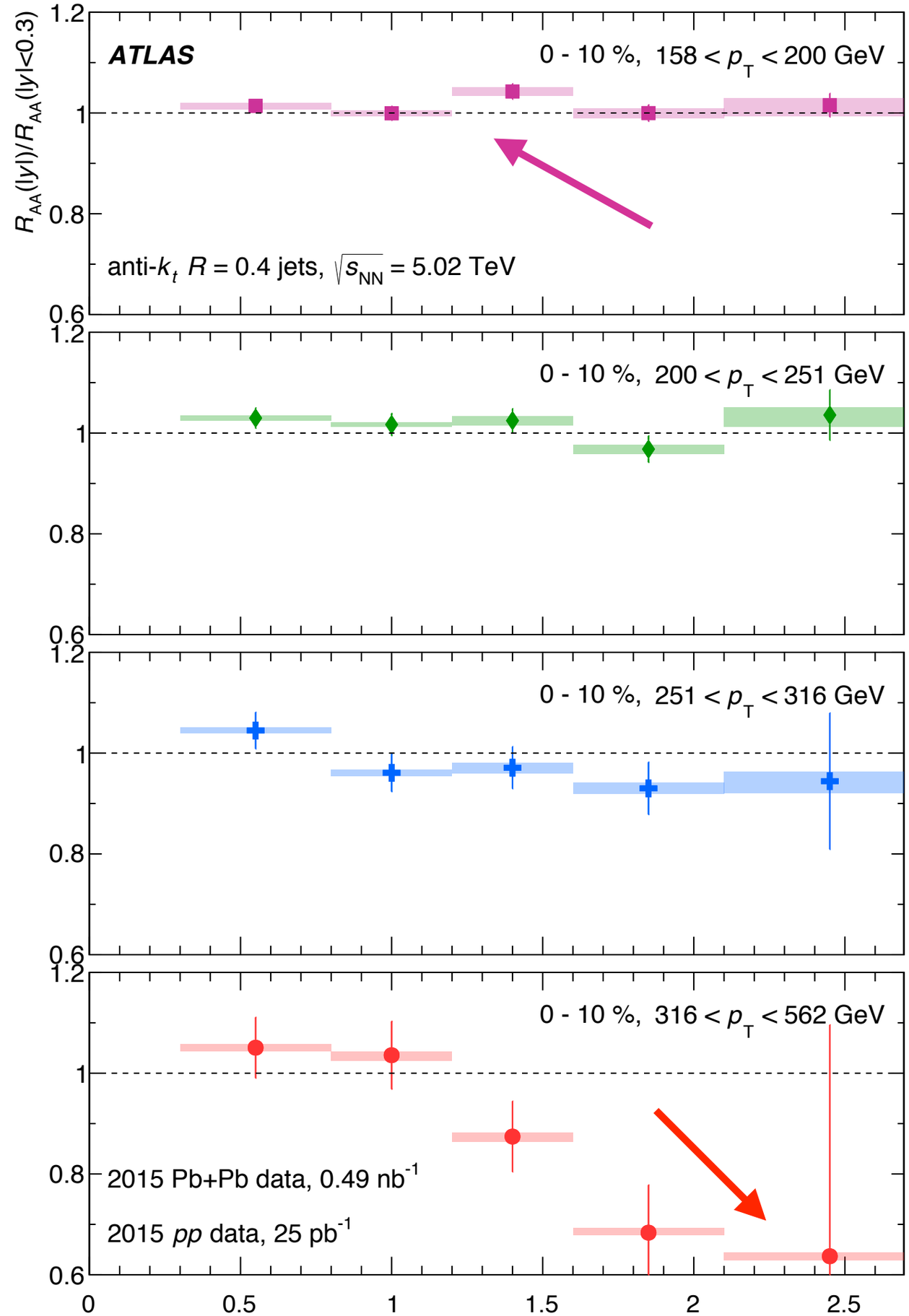
arXiv:1805.05635

R_{AA}: rapidity dependence

- **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**

- **R_{AA} is flat with rapidity at low p_T**

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



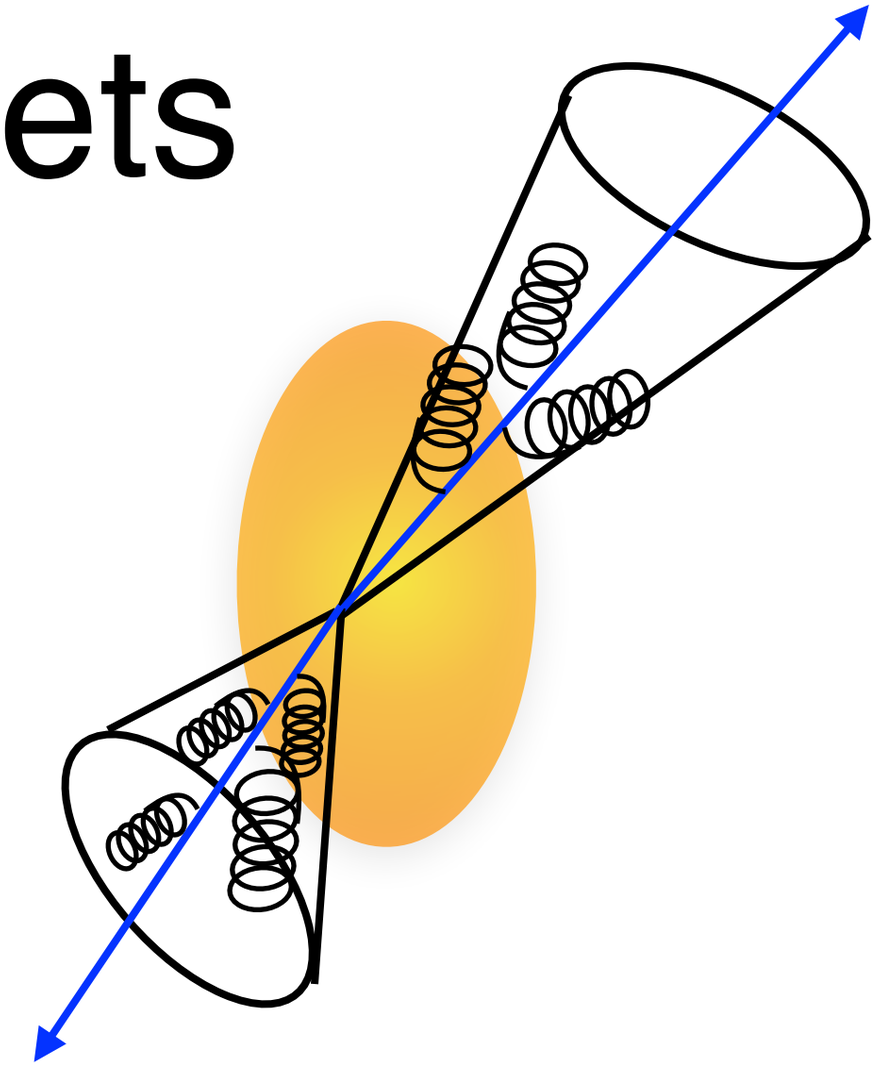
arXiv:1805.05635

Measuring jets

- Measuring jet quenching includes:
  - ➡ Inclusive energy loss through the suppression of hard scattering rates of single jets
  - ➡ **Differential energy loss through jet correlations**

Energy loss depends on path length and on flavor with gluons experiencing more quenching than quarks

  - ➡ Jet structure modification by measuring
    - particles in jets
    - mass

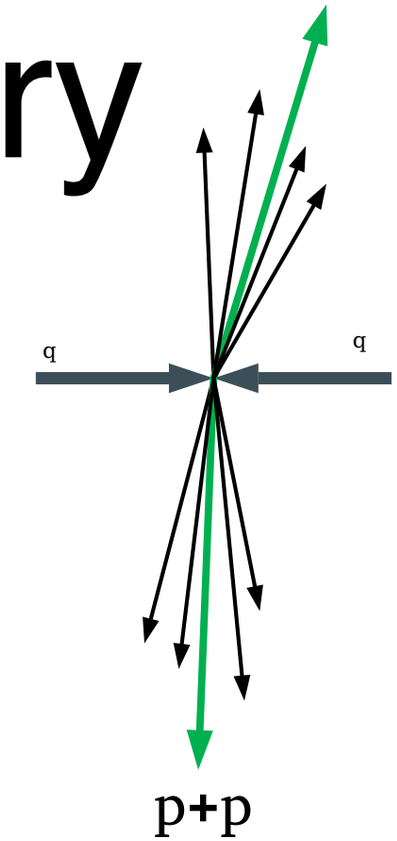


Momentum broadening from soft gluon radiation in-medium interactions

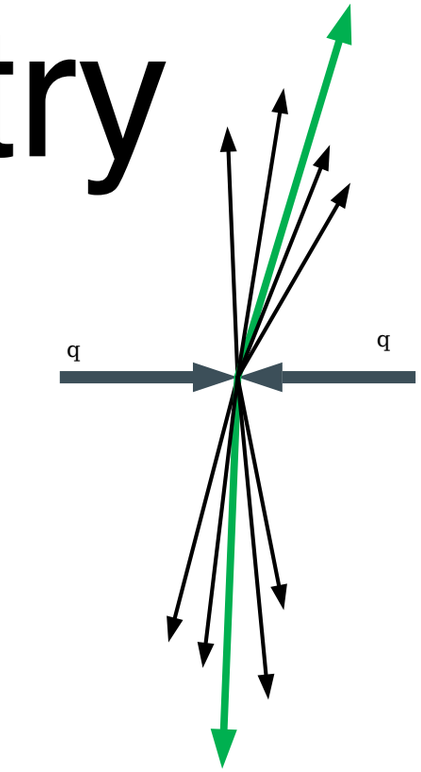
Medium response to the jet adds soft particles along jet direction

Dijet asymmetry

- **Dijets in *pp* collisions are approximately balanced in energy**

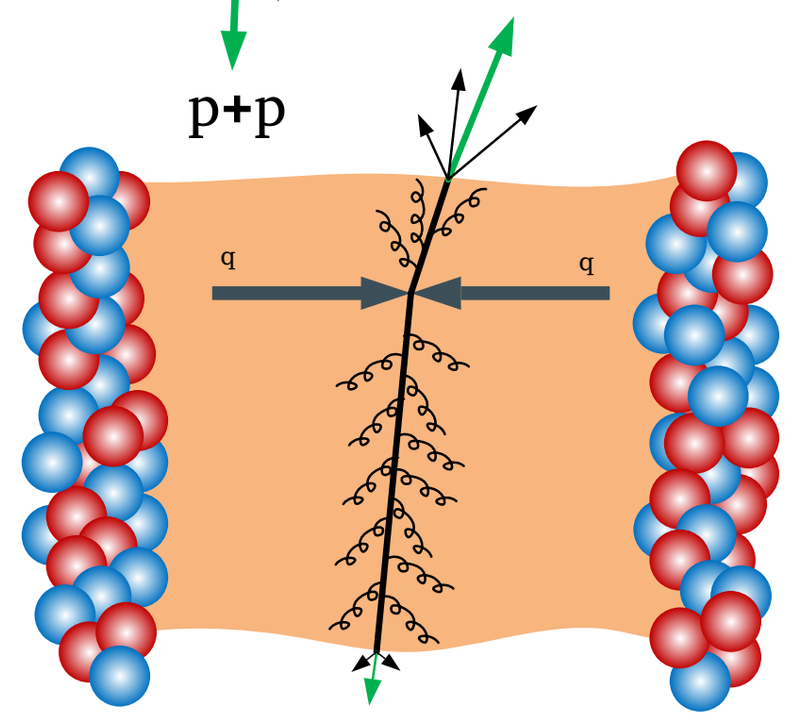


Dijet asymmetry



- **Dijets in *pp* collisions are approximately balanced in energy**
- **In Pb+Pb the two jets lose different amounts of energy because they travel different paths in the plasma or jet-by-jet fluctuations in the energy loss**

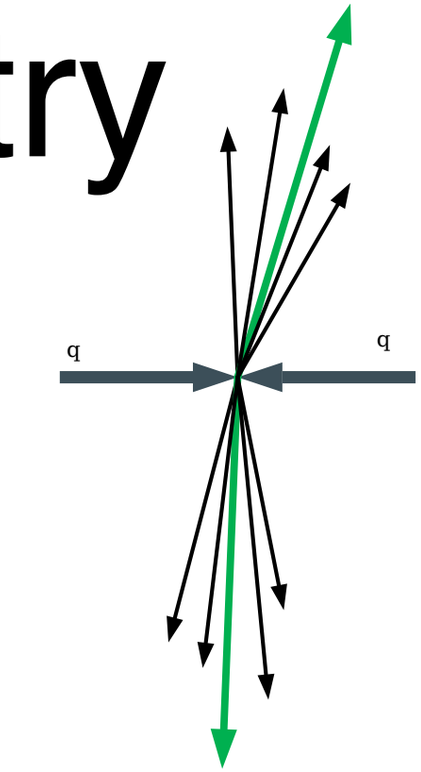
➡ **Use ratio of the lower jet p_T (sub-leading jet) to the higher jet p_T (leading jet)**



- **Compare A+A to pp dijets where we expect the $x_J \sim 1$**

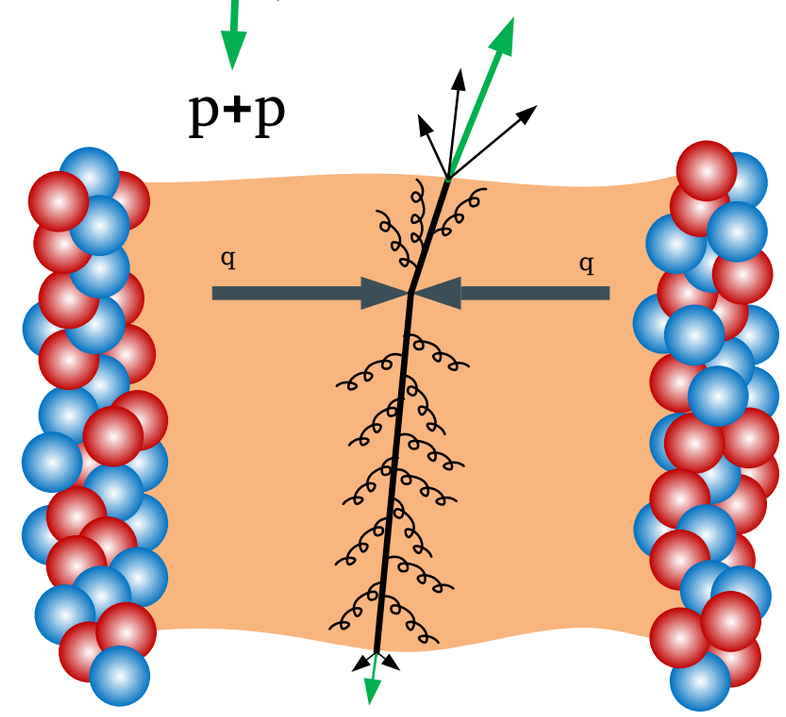
$$x_J = \frac{p_{T2}}{p_{T1}} \quad \text{A+A}$$

Dijet asymmetry



- **Dijets in *pp* collisions are approximately balanced in energy**
- **In Pb+Pb the two jets lose different amounts of energy because they travel different paths in the plasma or jet-by-jet fluctuations in the energy loss**

➡ **Use ratio of the lower jet p_T (sub-leading jet) to the higher jet p_T (leading jet)**



- **Compare A+A to pp dijets where we expect the $x_J \sim 1$**

$$x_J = \frac{p_{T2}}{p_{T1}} \quad \text{A+A}$$

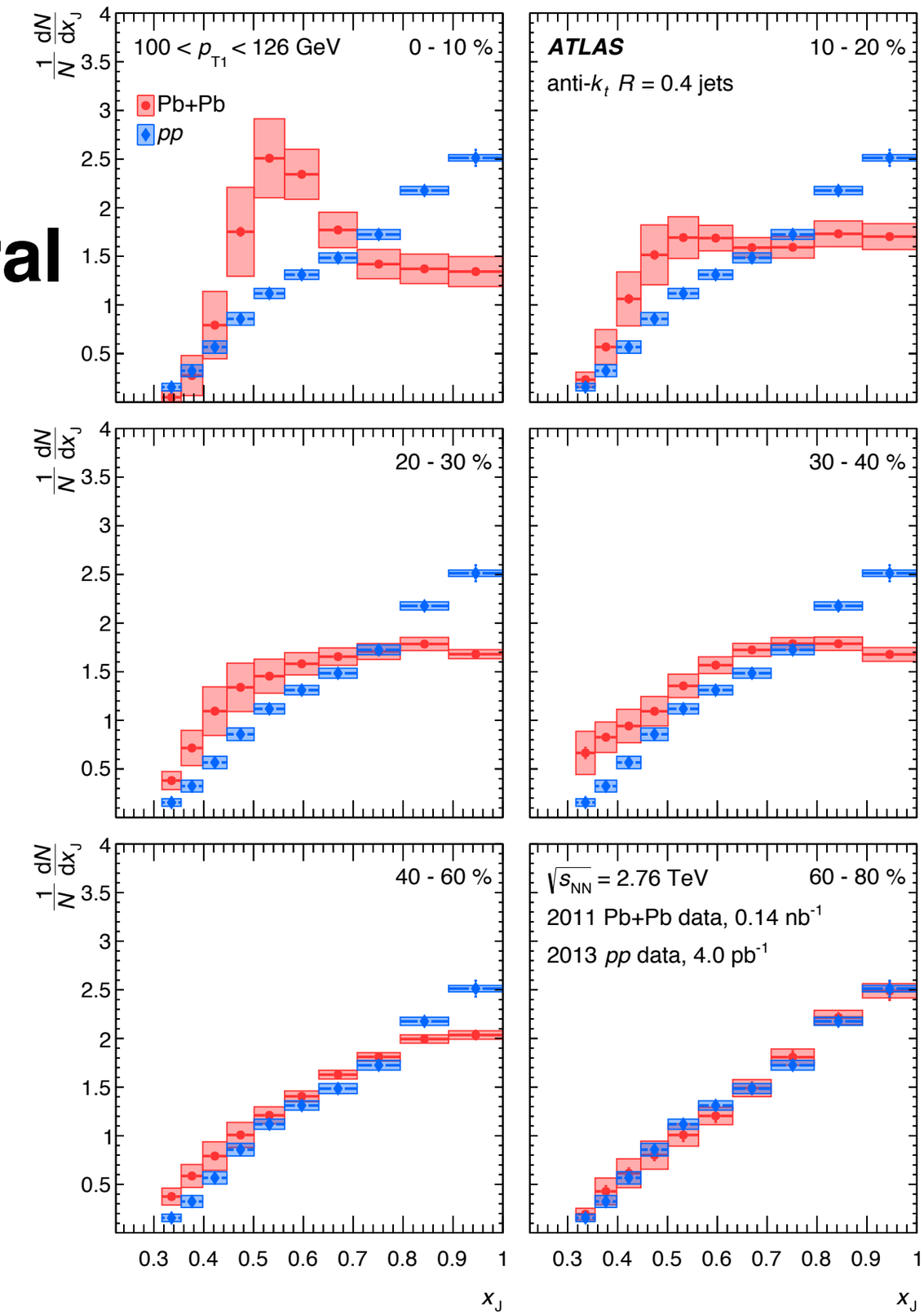
▸ **Unfolded using 2D Bayesian unfolding in p_{T1} and p_{T2}.**

2011 Pb+Pb
2013 *pp*

x_J distribution

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

- **More asymmetry jets in central Pb+Pb than in *pp***
- **Becomes like *pp* in peripheral**

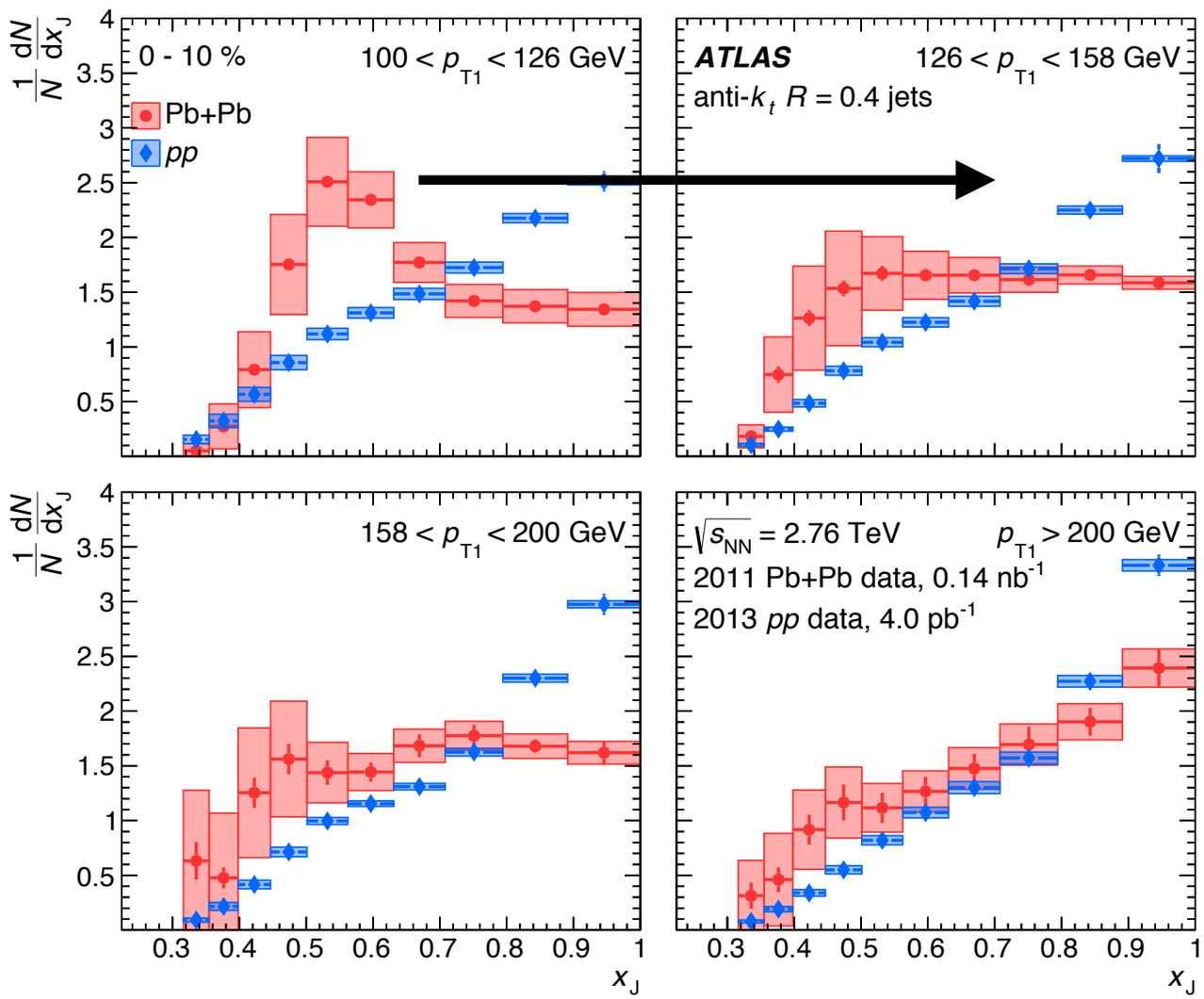


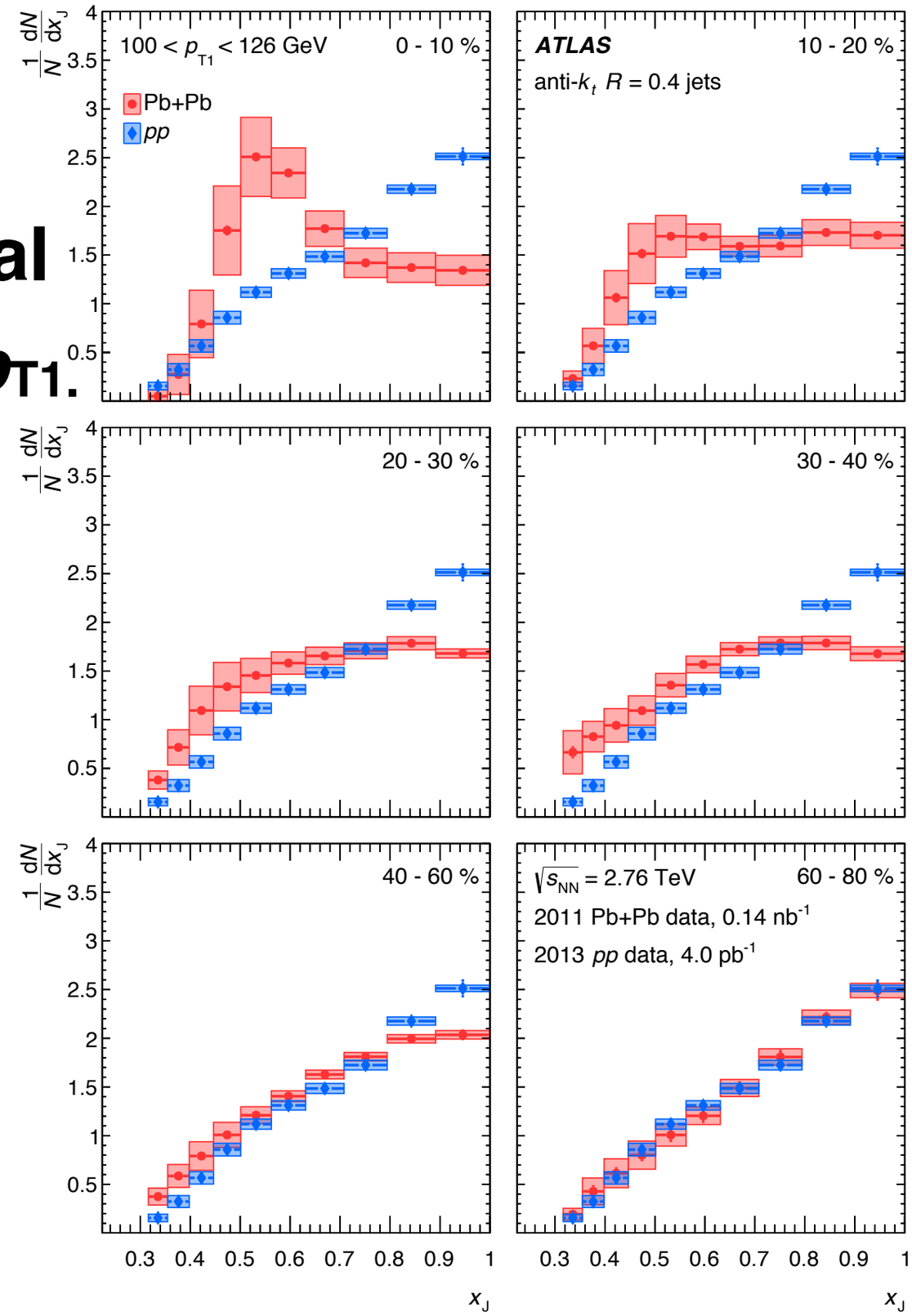
2011 Pb+Pb
2013 *pp*

x_J distribution

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

- **More asymmetry jets in central Pb+Pb than in *pp***
- **Becomes like *pp* in peripheral**
- **Significant dependence on p_{T1}.**



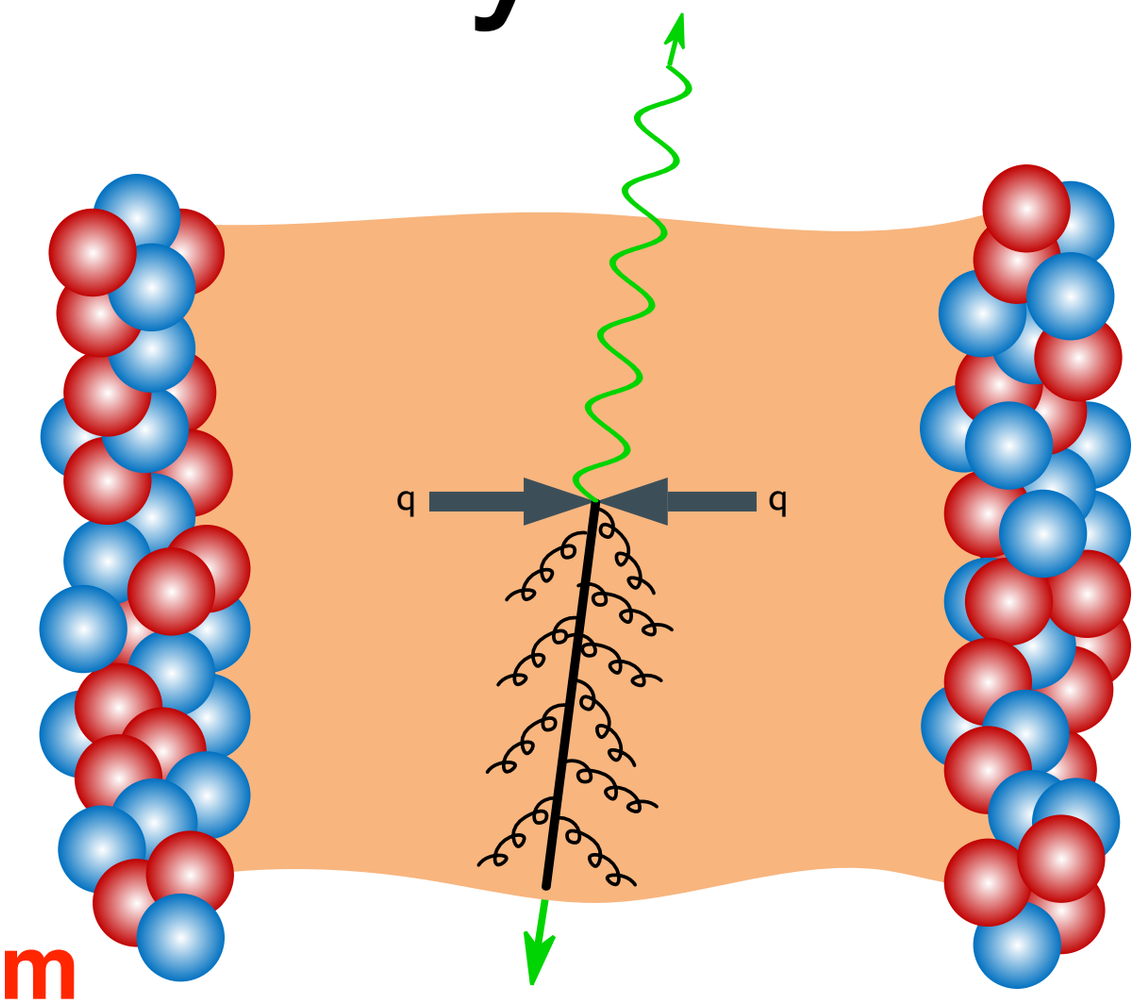


γ-jet asymmetry

- **γ+jet used to look at energy loss of the recoiling jet since photons aren't expected to interact strongly with the medium**

➡ **The initial production distributions are different**

➡ **More likely to originate from quark jets than inclusive/ dijets so it's a probe of the flavor dependence**



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

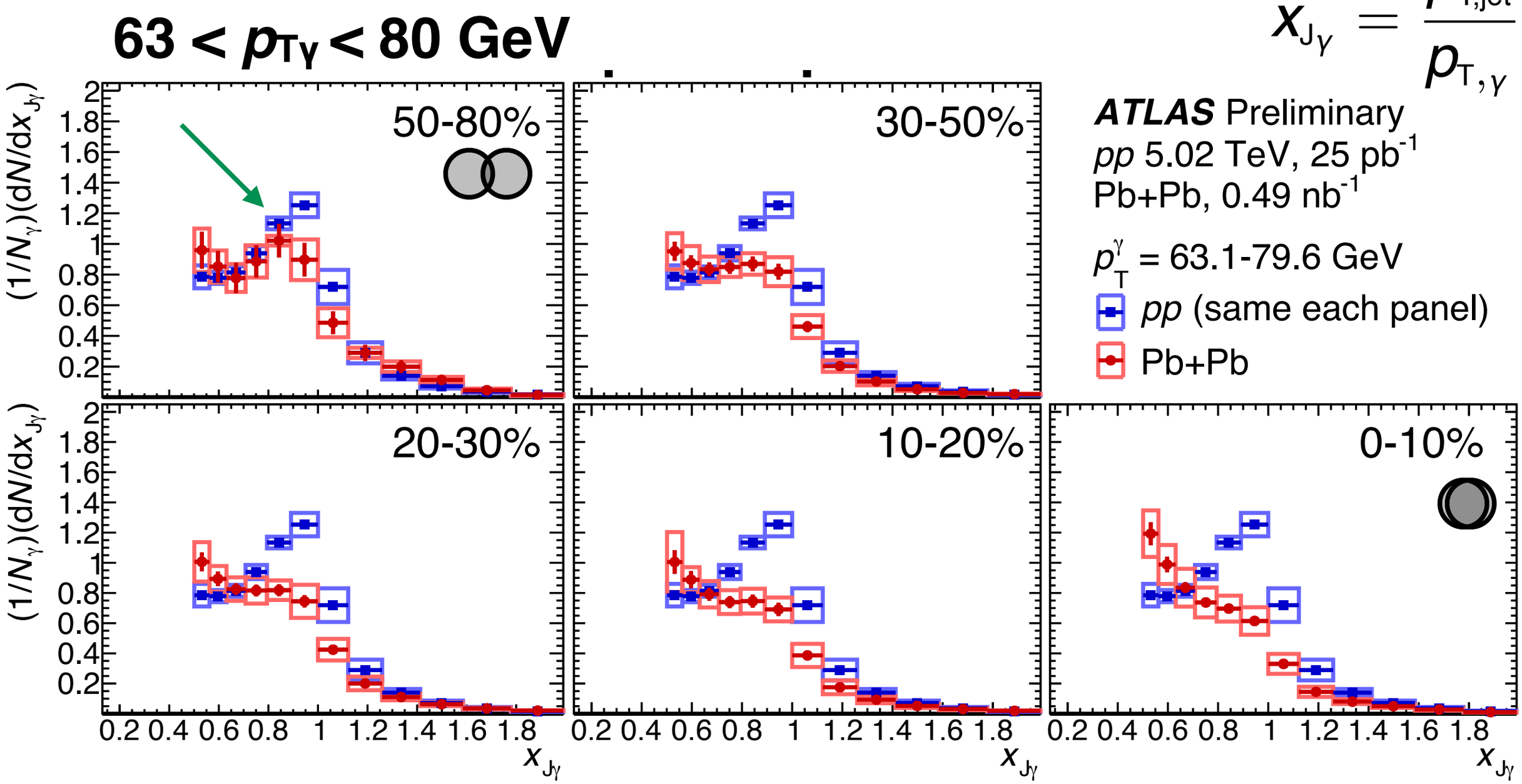
- **Measured $x_{J\gamma}$ for $p_{T\gamma} > 60$ GeV, $p_{T,jet} > 30$ GeV, $\Delta\phi > 7\pi/8$**

▸ **Unfolded using 2D Bayesian unfolding in $p_{T,jet}$ and $p_{T,\gamma}$**

γ-jet asymmetry: centrality

- **central Pb+Pb peaks $x_{J\gamma} \sim 0.5$ compared to *pp* at $x_{J\gamma} \sim 1$**
- **Pb+Pb becomes similar to *pp* in peripheral collisions**

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

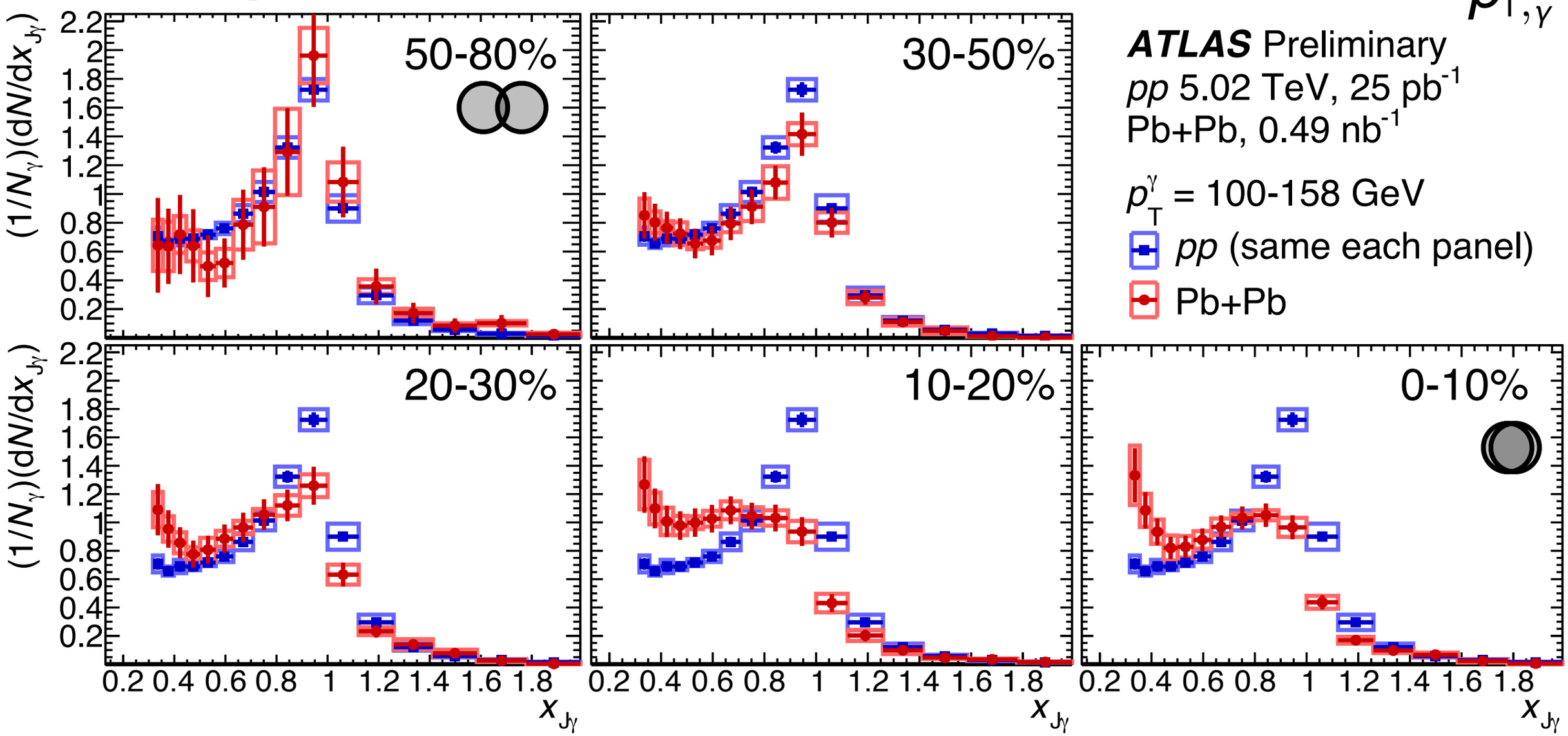


γ-jet asymmetry: p_T dep.

- **central Pb+Pb peaks $x_{J\gamma} \sim 0.5$ compared to *pp* at $x_{J\gamma} \sim 1$**
- **Pb+Pb becomes similar to *pp* in peripheral collisions**
- **Slight $p_{T\gamma}$ dependence observed**

$100 < p_{T\gamma} < 158$ GeV

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

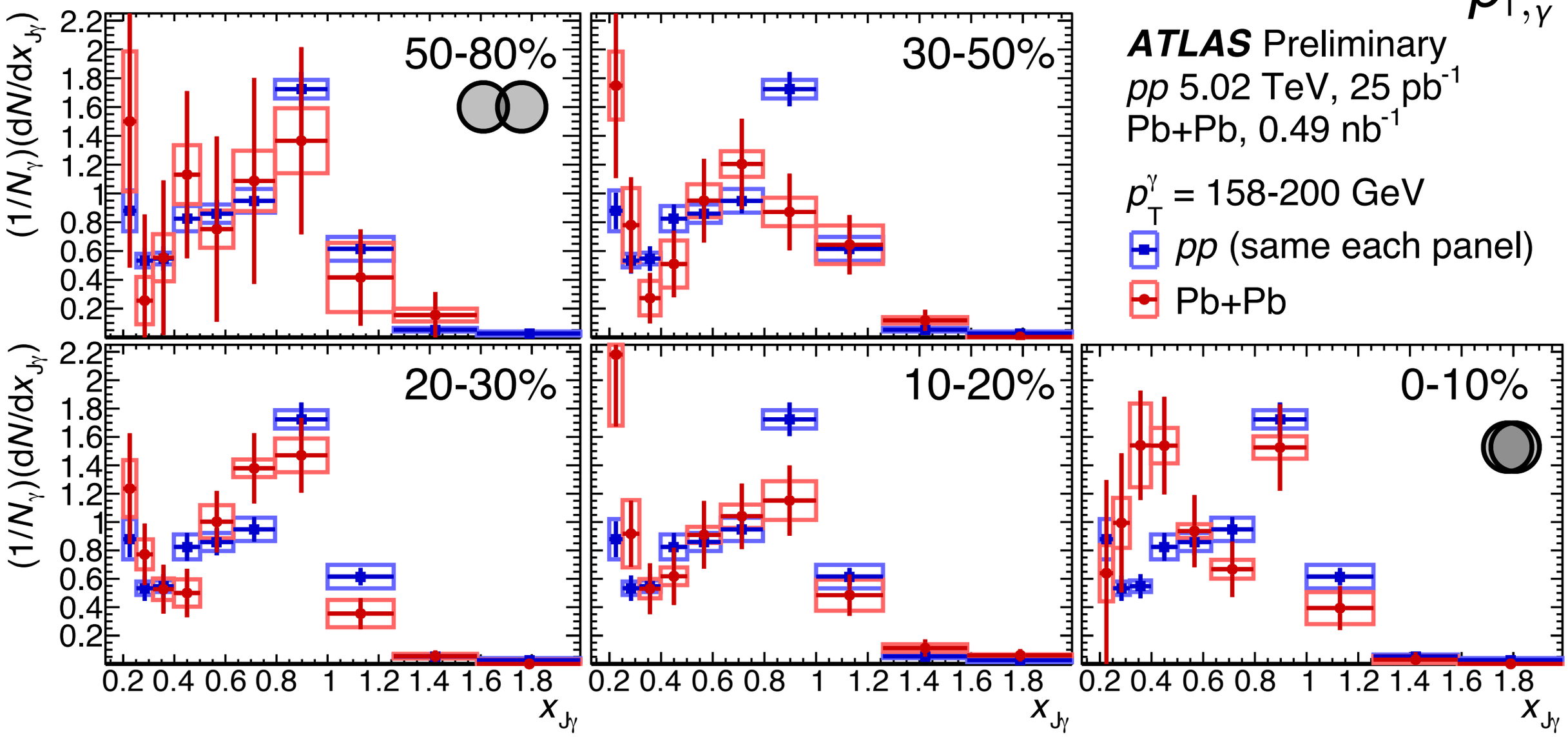


γ-jet asymmetry: p_T dep.

- **central Pb+Pb peaks $x_{J\gamma} \sim 0.5$ compared to *pp* at $x_{J\gamma} \sim 1$**
- **Pb+Pb becomes similar to *pp* in peripheral collisions**
- **Slight $p_{T\gamma}$ dependence observed**

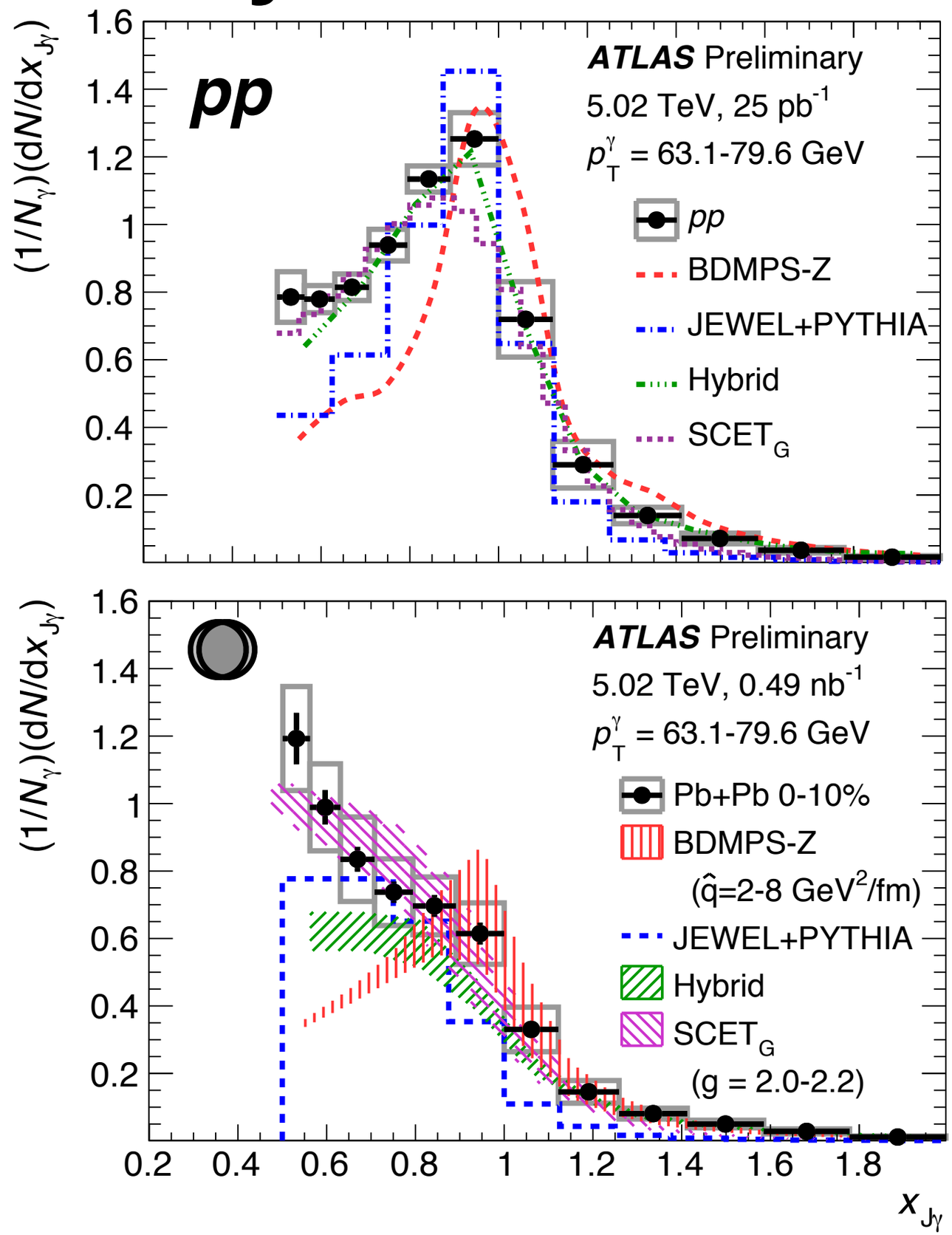
$158 < p_{T\gamma} < 200$ GeV

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



γ-jet asymmetry: models

- **Direct comparison of unfolded result to theory in *pp* and central Pb+Pb**

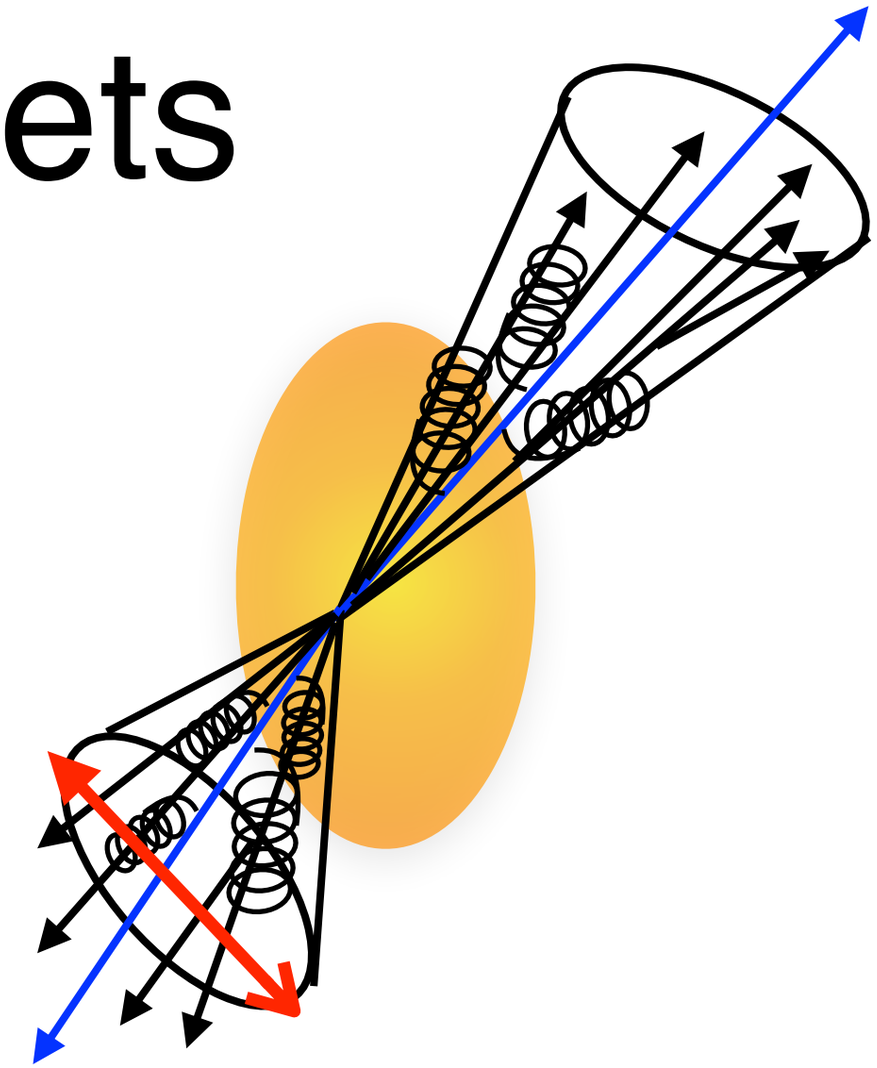


Measuring jets

- Measuring jet quenching includes:
  - ➡ Inclusive energy loss through the suppression of hard scattering rates of single jets
  - ➡ Differential energy loss through jet correlations

Energy loss depends on path length and on flavor with gluons experiencing more quenching than quarks

  - ➡ **Jet structure modification by measuring charged particles in jets and jet mass**



Momentum broadening from soft gluon radiation in-medium interactions

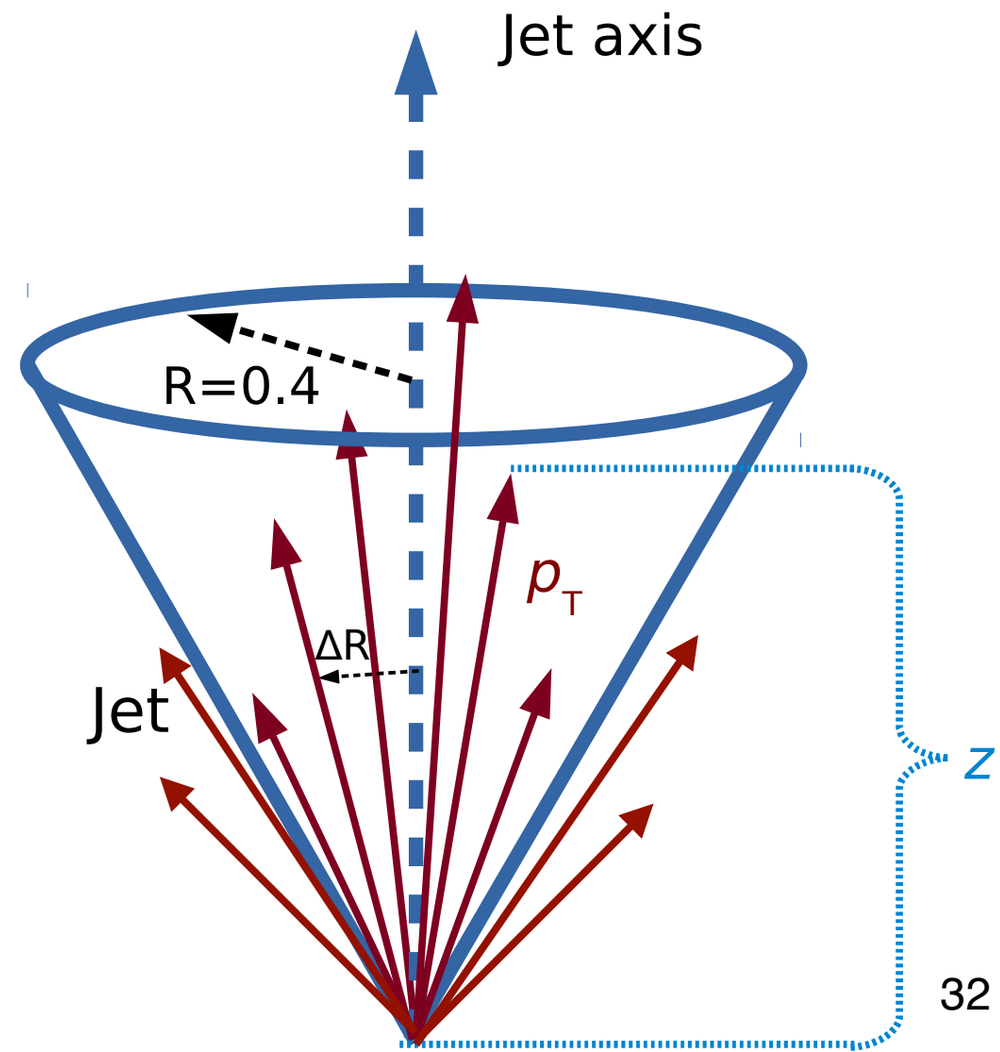
Medium response to the jet adds soft particles along jet direction

Jet fragmentation functions

- **Measures how charged particles are distributed within a jet by looking at number of charged particles in jets (N_{ch})**

$$D(z) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

$$D(p_{\mathrm{T}}) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}p_{\mathrm{T}}} \qquad z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\text{jet}}}$$



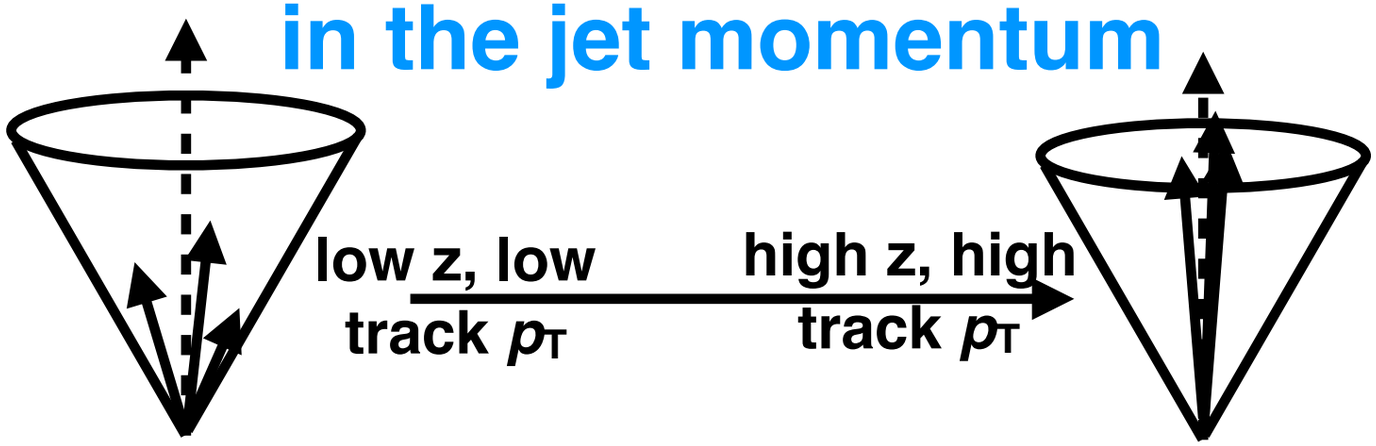
Jet fragmentation functions

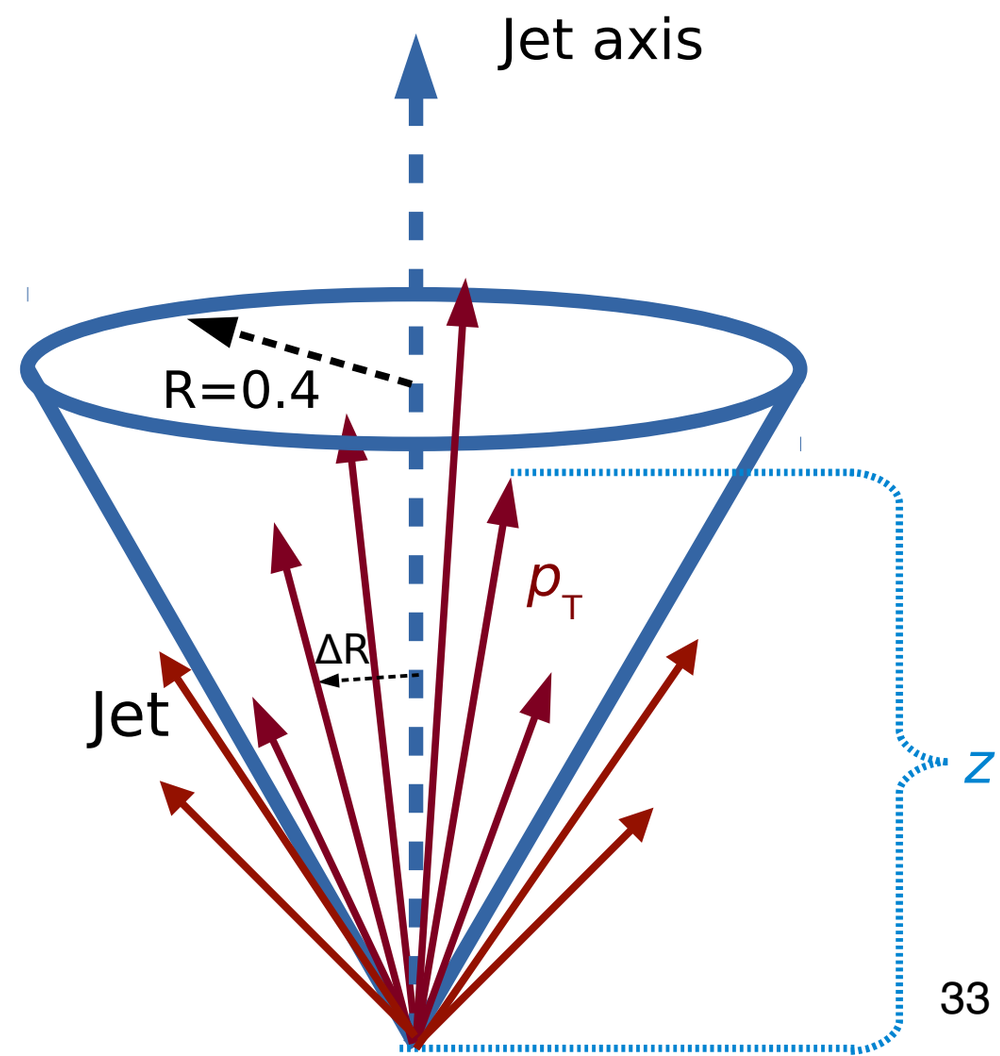
- **Measures how charged particles are distributed within a jet by looking at number of charged particles in jets (N_{ch})**

$$D(z) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

$$D(p_{\mathrm{T}}) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}p_{\mathrm{T}}} \qquad z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\text{jet}}}$$

➡ **z measures the fraction of the track momentum in the jet momentum**





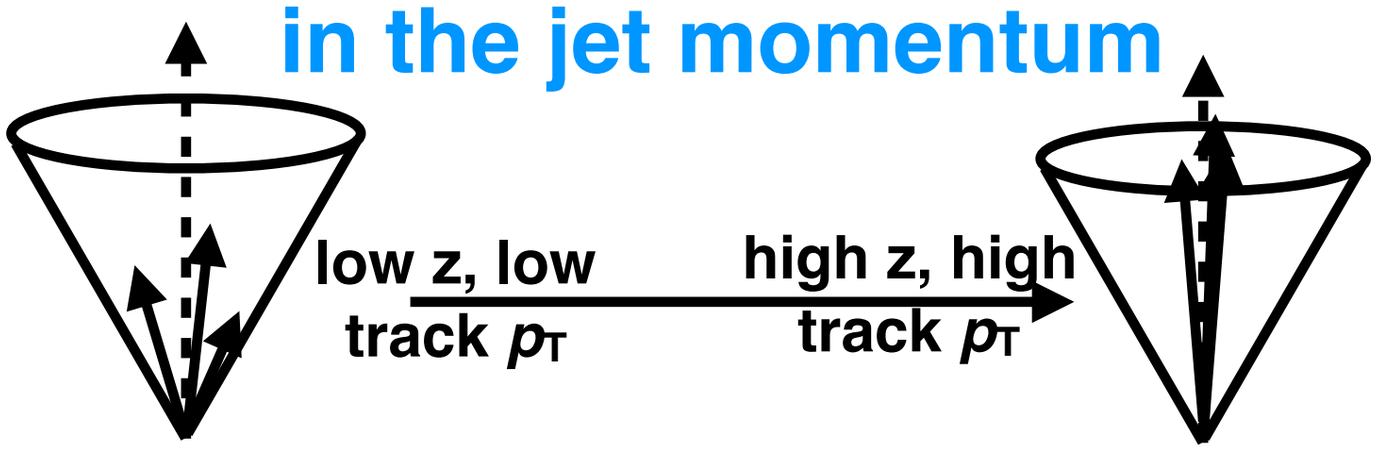
Jet fragmentation functions

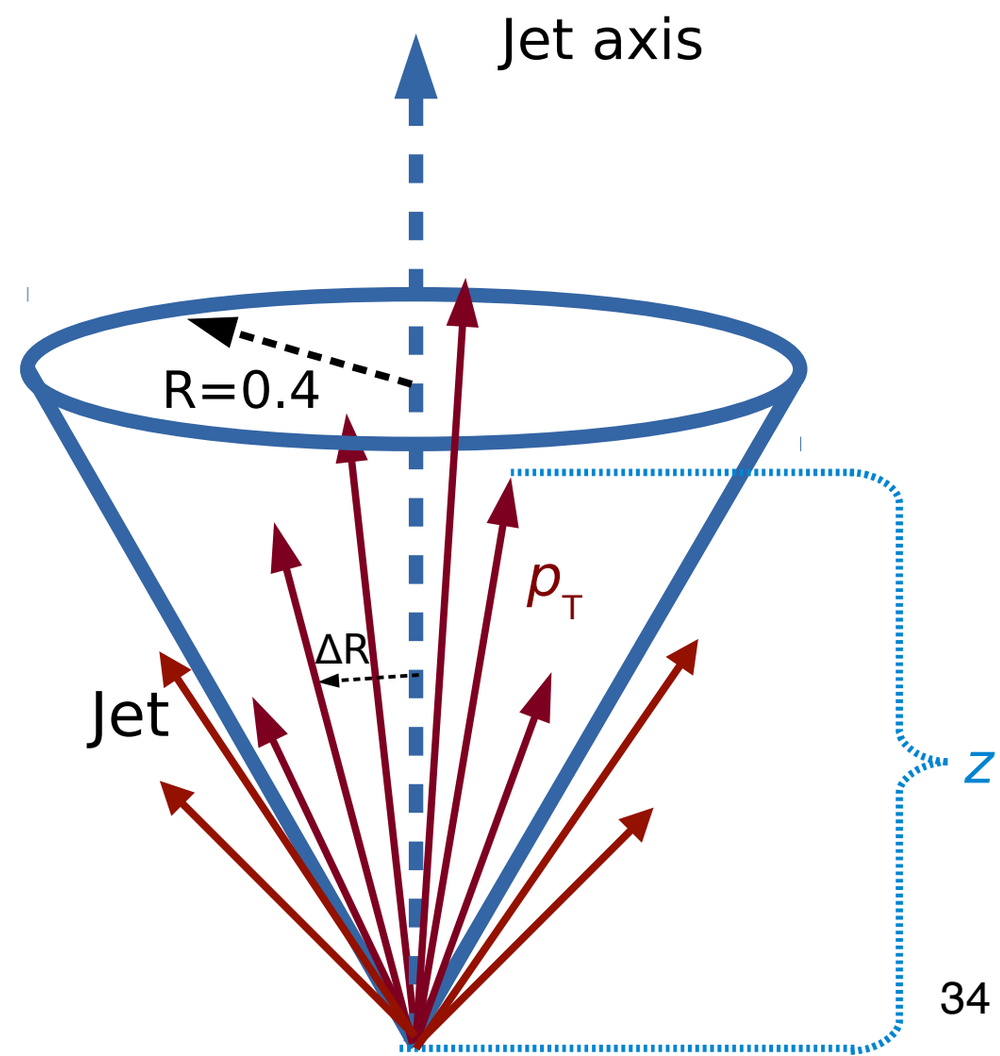
$$D(z) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

- **Measures how charged particles are distributed within a jet by looking at number of charged particles in jets (N_{ch})**

$$D(p_{\text{T}}) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}p_{\text{T}}} \qquad z = \frac{p_{\text{T}} \cos \Delta R}{p_{\text{T}}^{\text{jet}}}$$

➡ **z measures the fraction of the track momentum in the jet momentum**





- **R=0.4 jets with charged tracks > 1 GeV**

Jet fragmentation functions

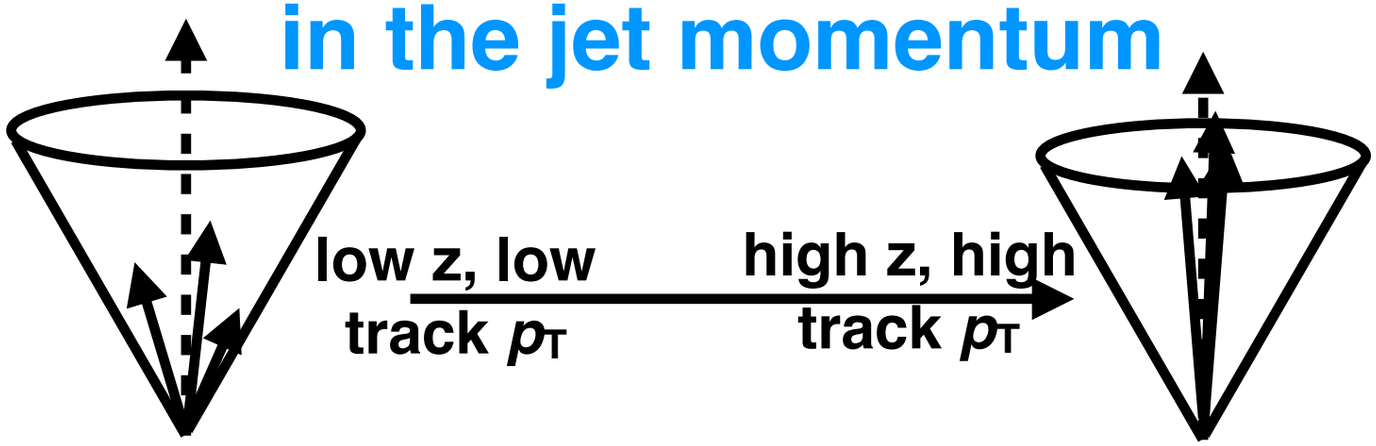
- **Measures how charged particles are distributed within a jet by looking at number of charged particles in jets (N_{ch})**

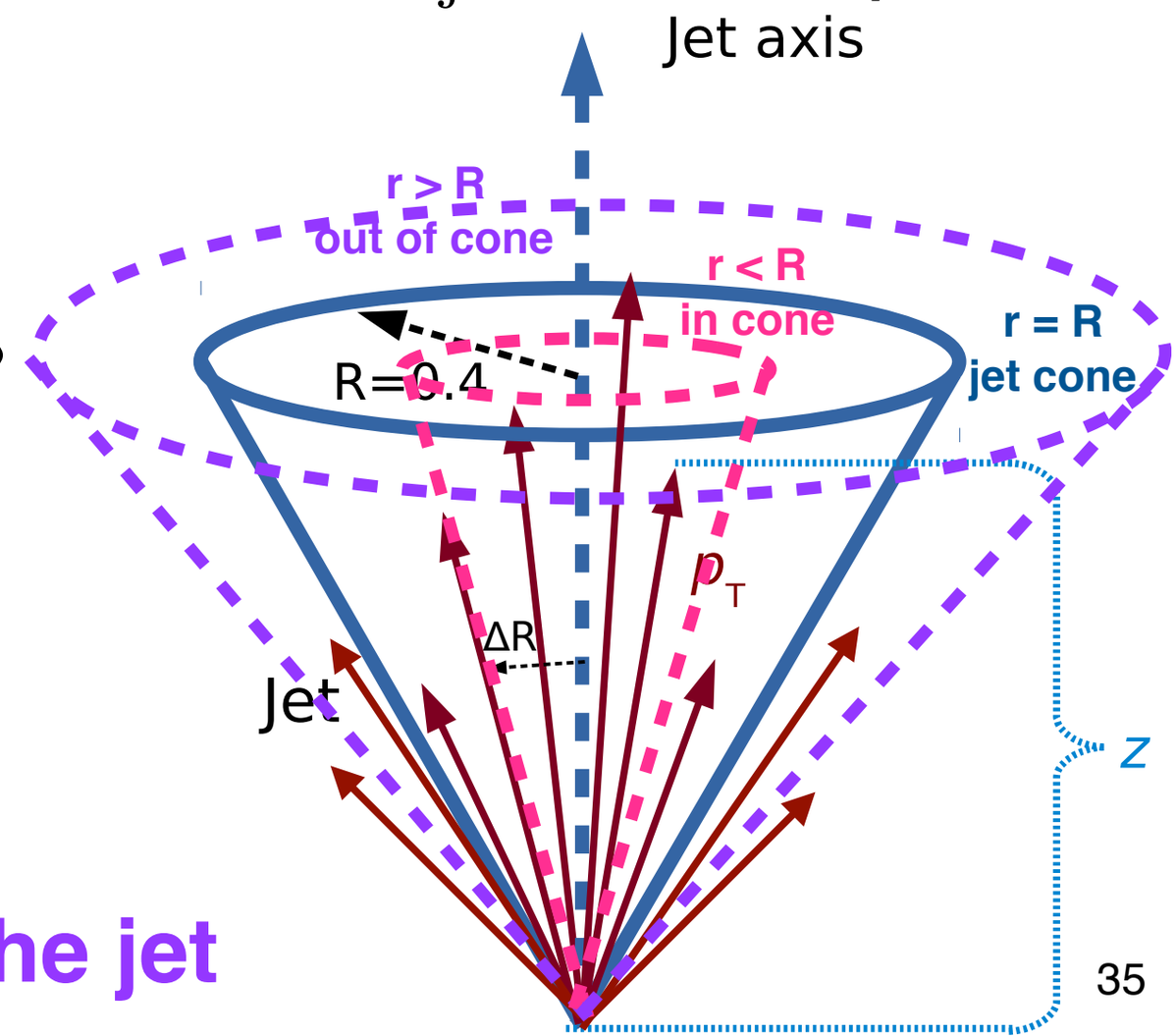
$$D(z) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

$$D(p_{\mathrm{T}}) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}p_{\mathrm{T}}} \qquad z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\text{jet}}}$$

$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r \mathrm{d}p_{\mathrm{T}}}$$

➡ **z measures the fraction of the track momentum in the jet momentum**



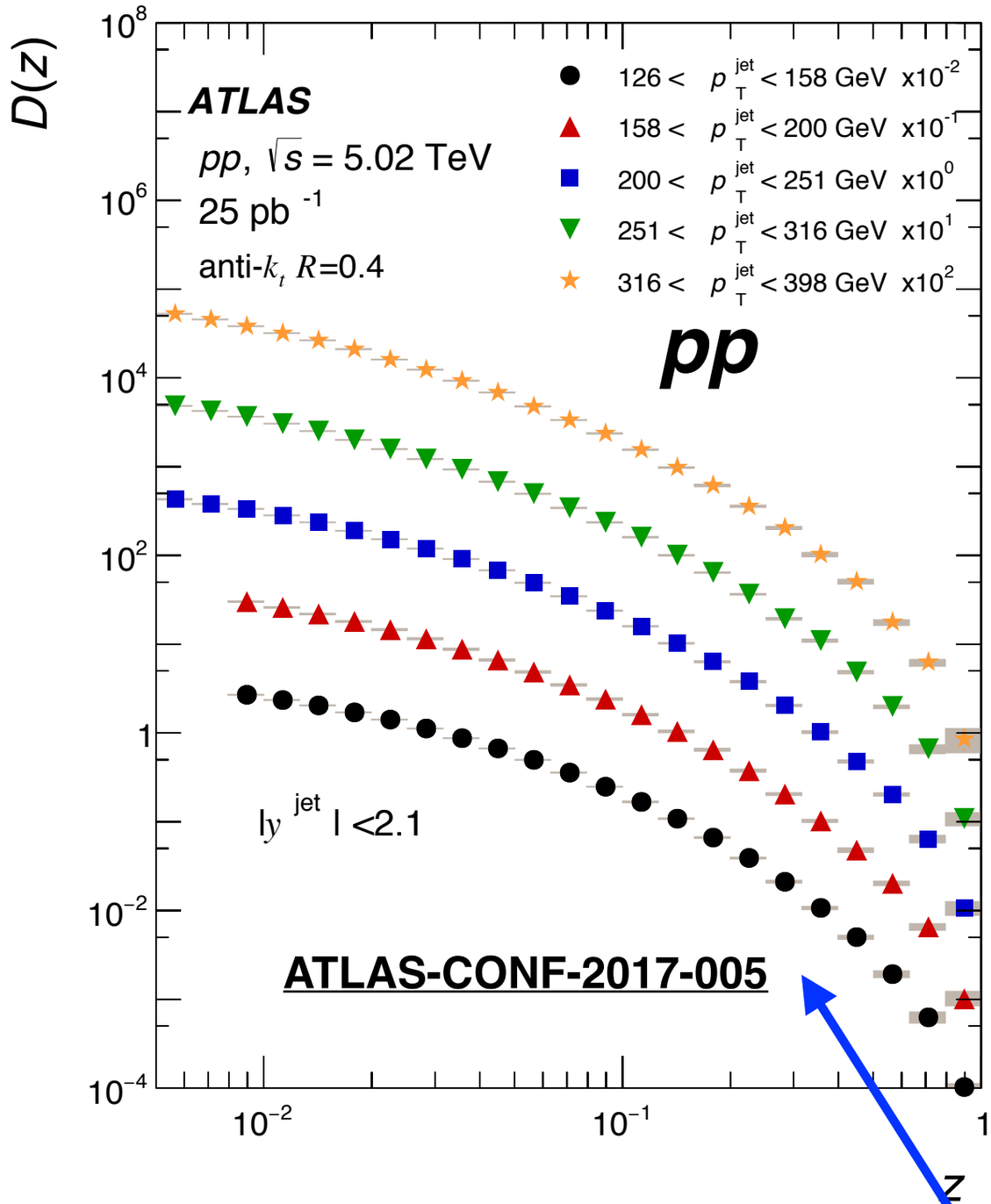


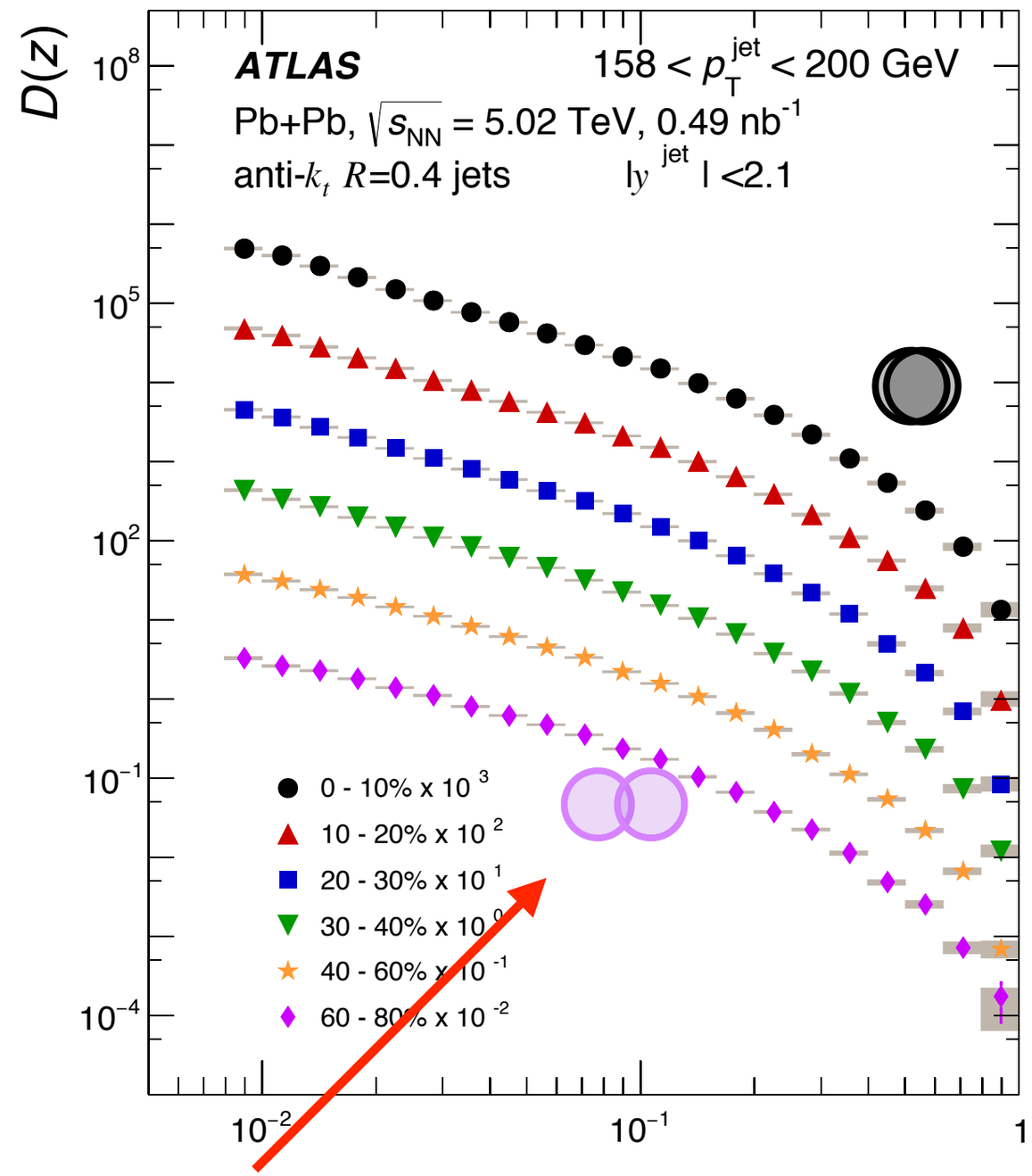
- **R=0.4 jets with charged tracks > 1 GeV**

➡ **r measures the shape of the jet**

Jet fragmentation: Pb+Pb

- **FF are fully 2D unfolded in jet p_T and z (or p_T^{trk})**



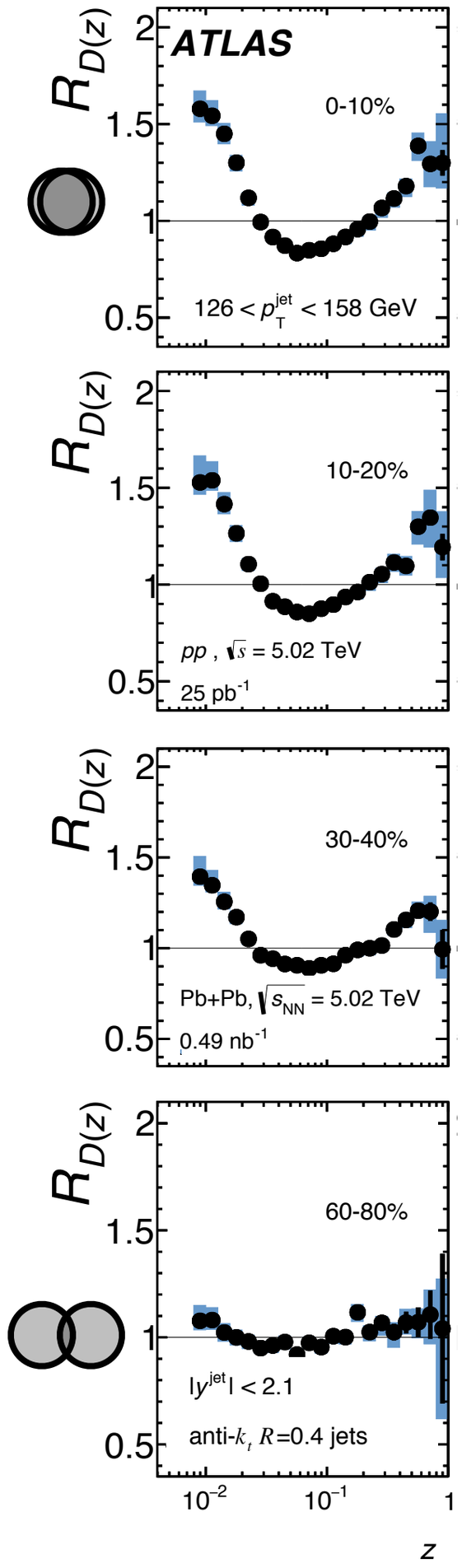


- **Need ratio to see modification.**

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

Internal structure

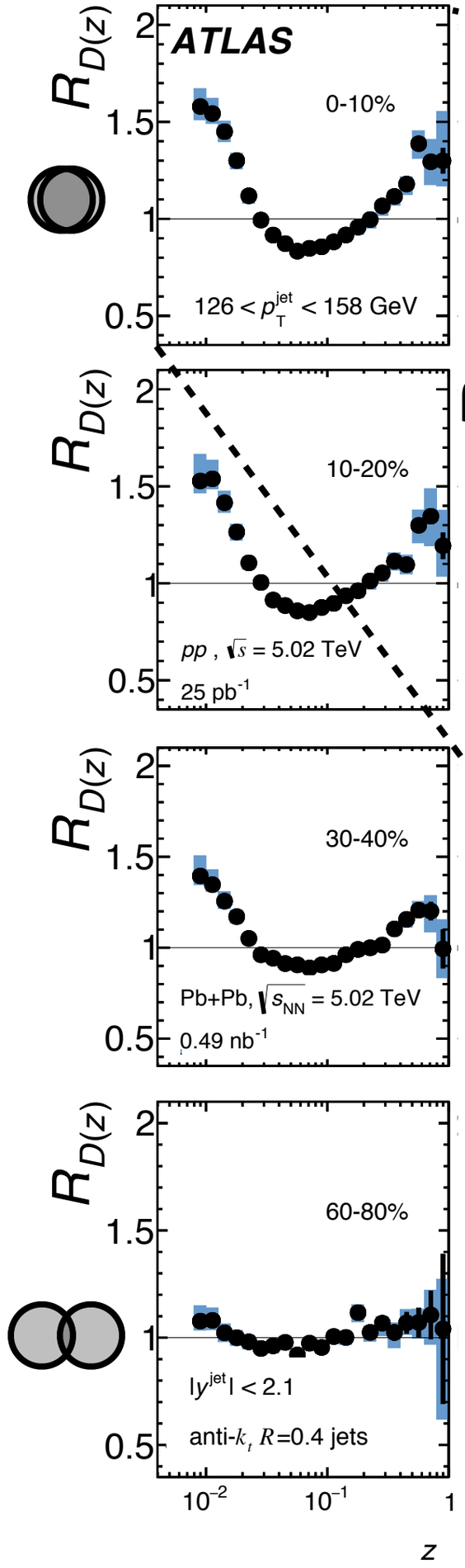
$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

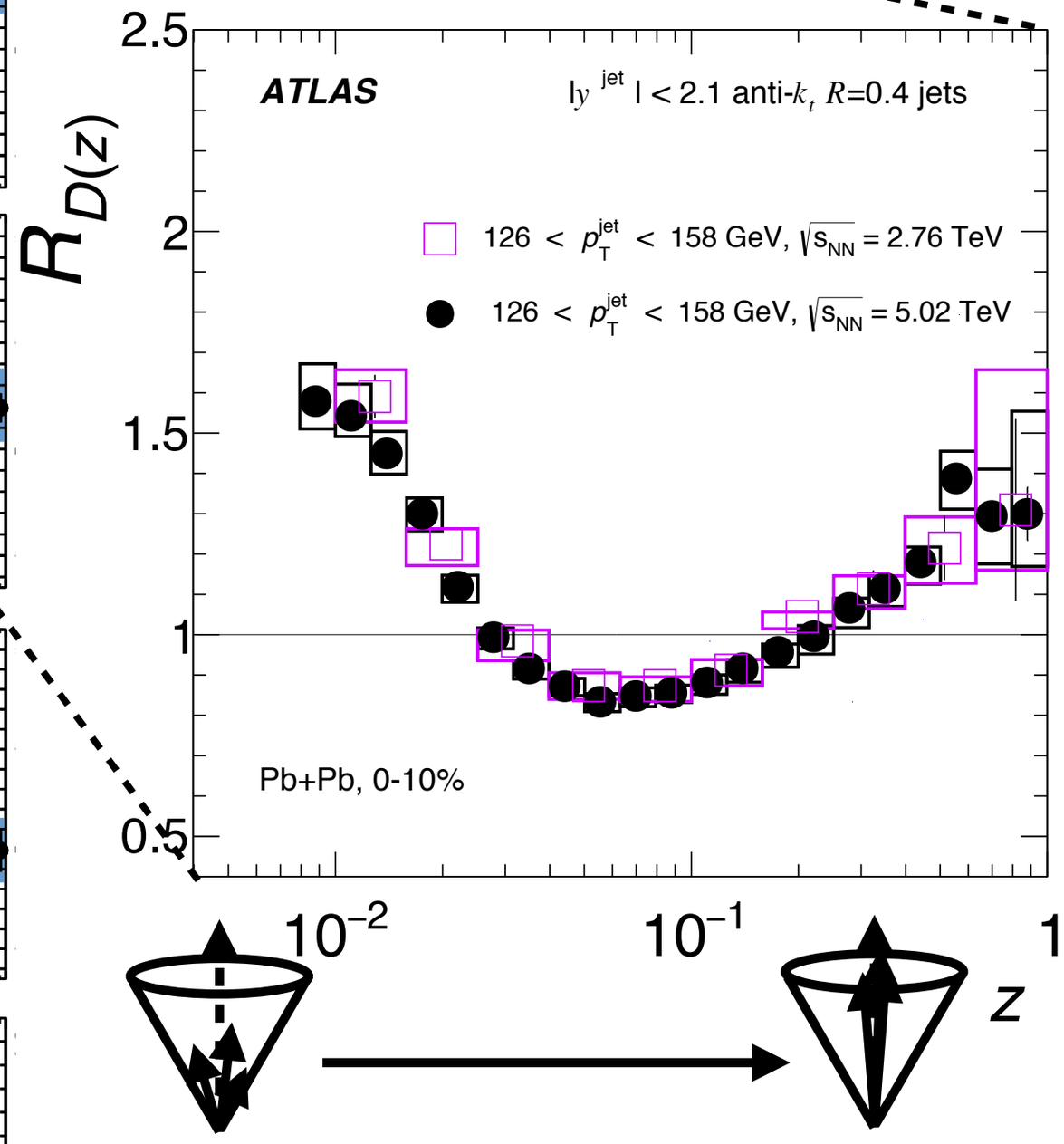


- **Jets are more modified in central collisions**

Internal structure

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

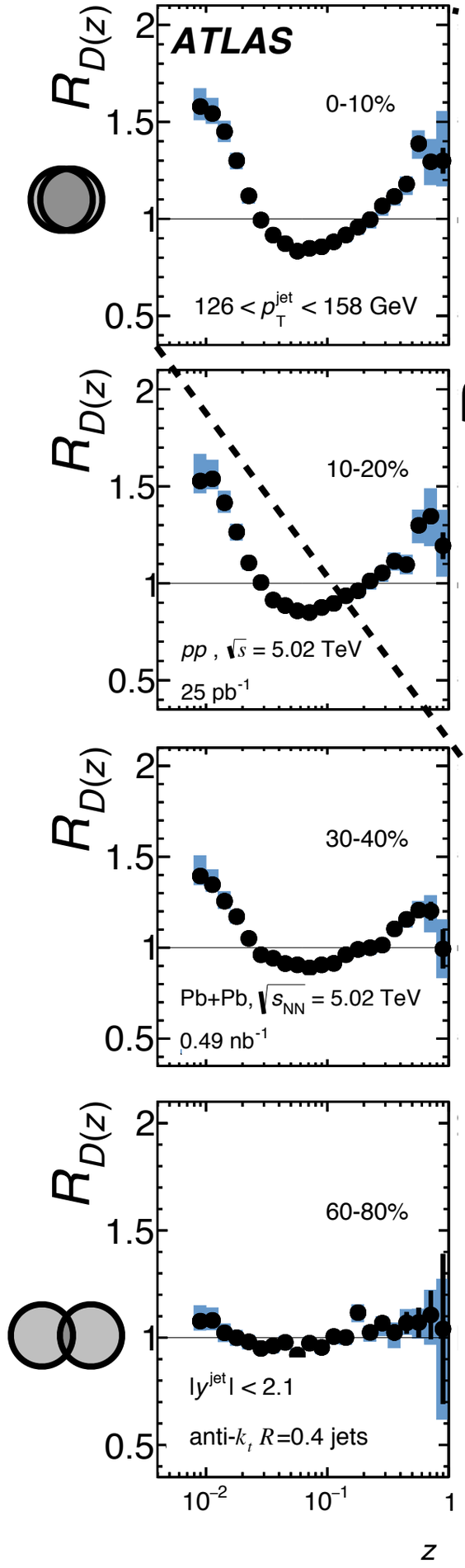


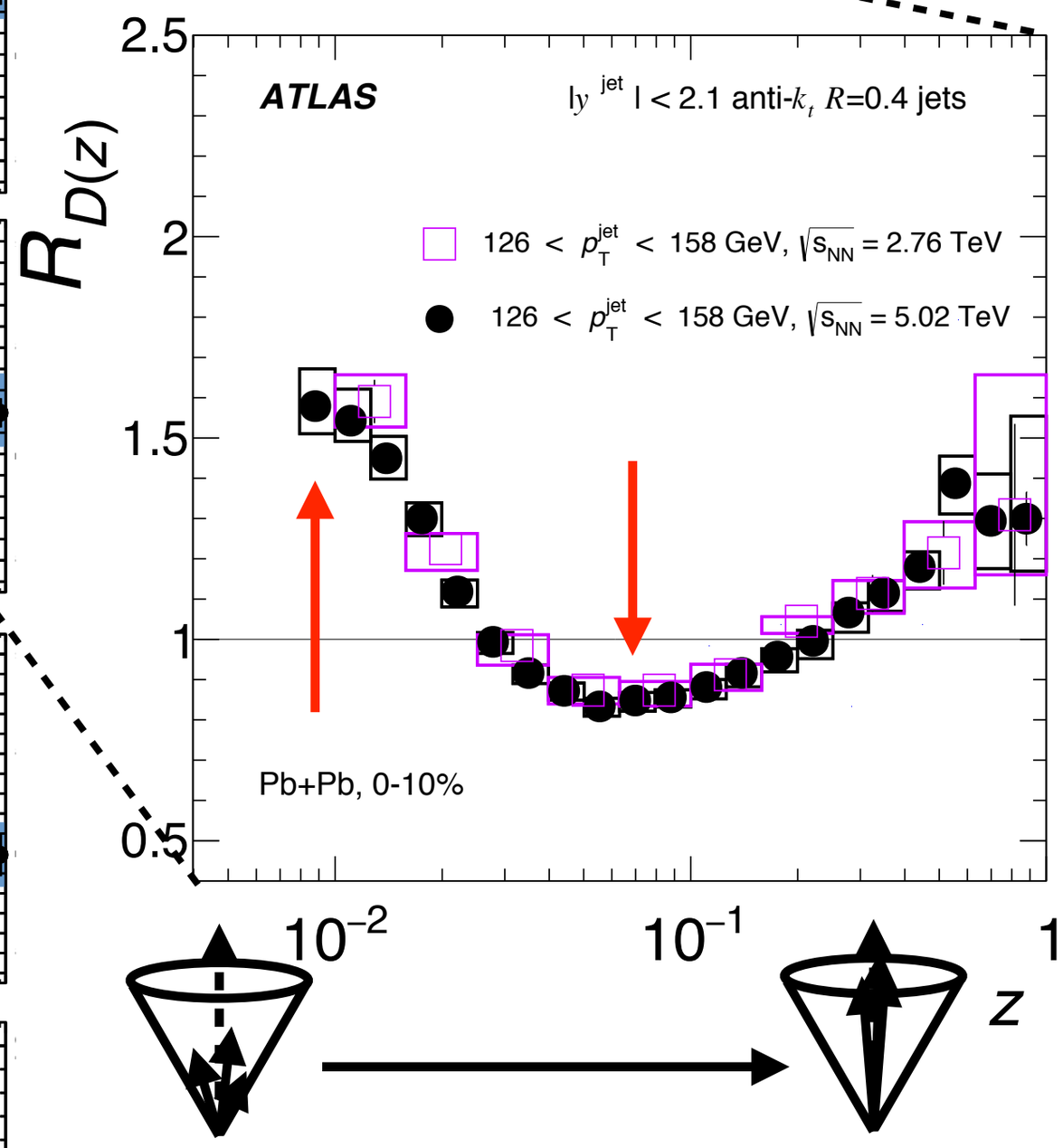


- **Jets are more modified in central collisions**
- **Consistent between 2.76 and 5.02 TeV**

Internal structure

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



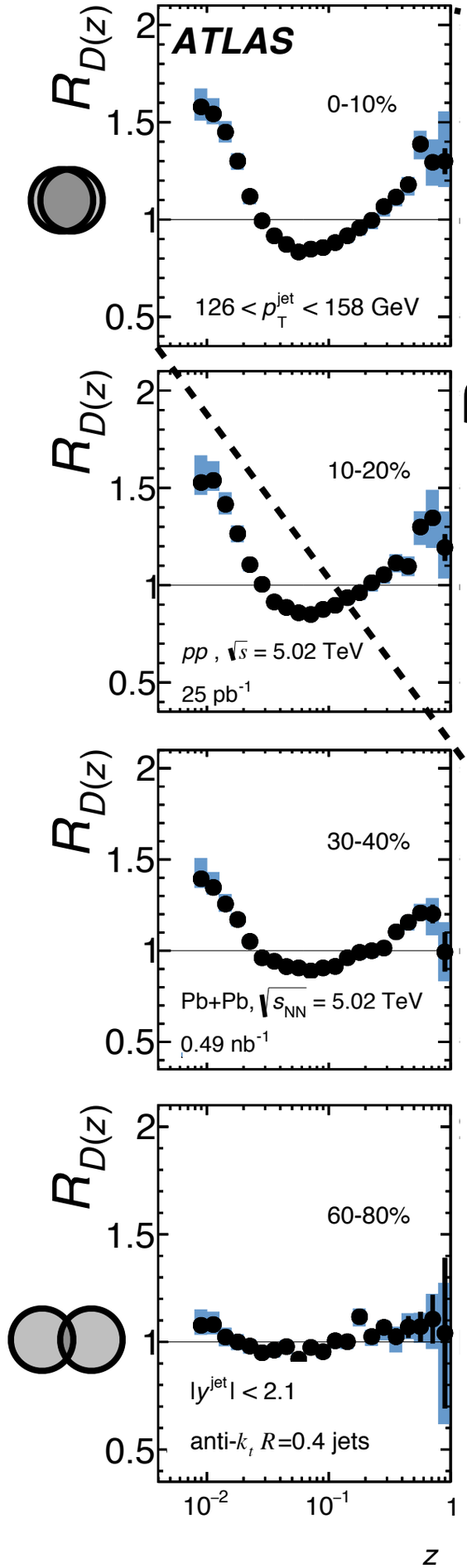


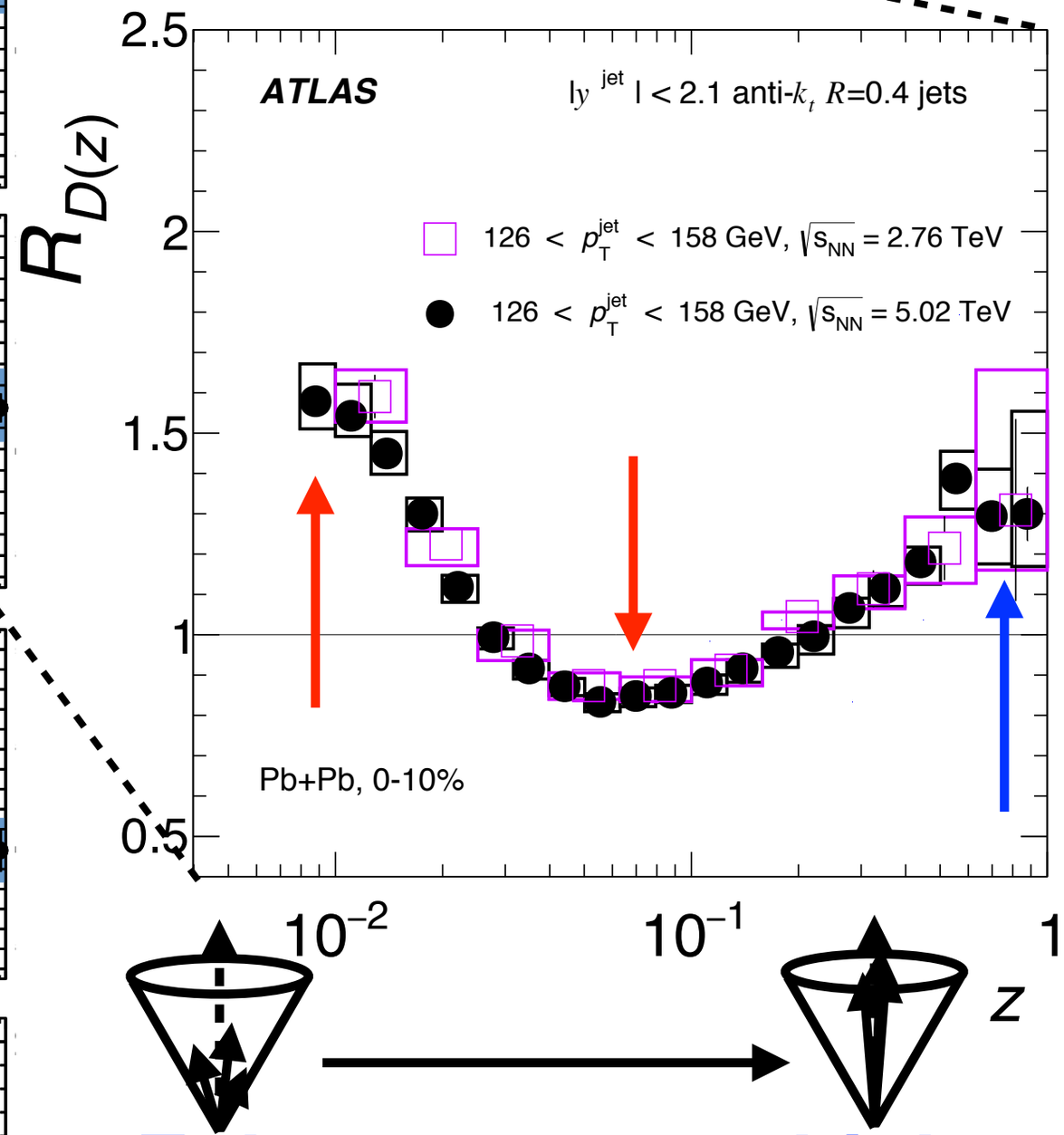
- **Jets are more modified in central collisions**
- **Consistent between 2.76 and 5.02 TeV**
- **Enhancement at low z and suppression at intermediate z**

➡ **Energy is transferred to soft particles in and around the jet**

Internal structure

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





- **Jets are more modified in central collisions**
- **Consistent between 2.76 and 5.02 TeV**
- **Enhancement at low z and suppression at intermediate z**

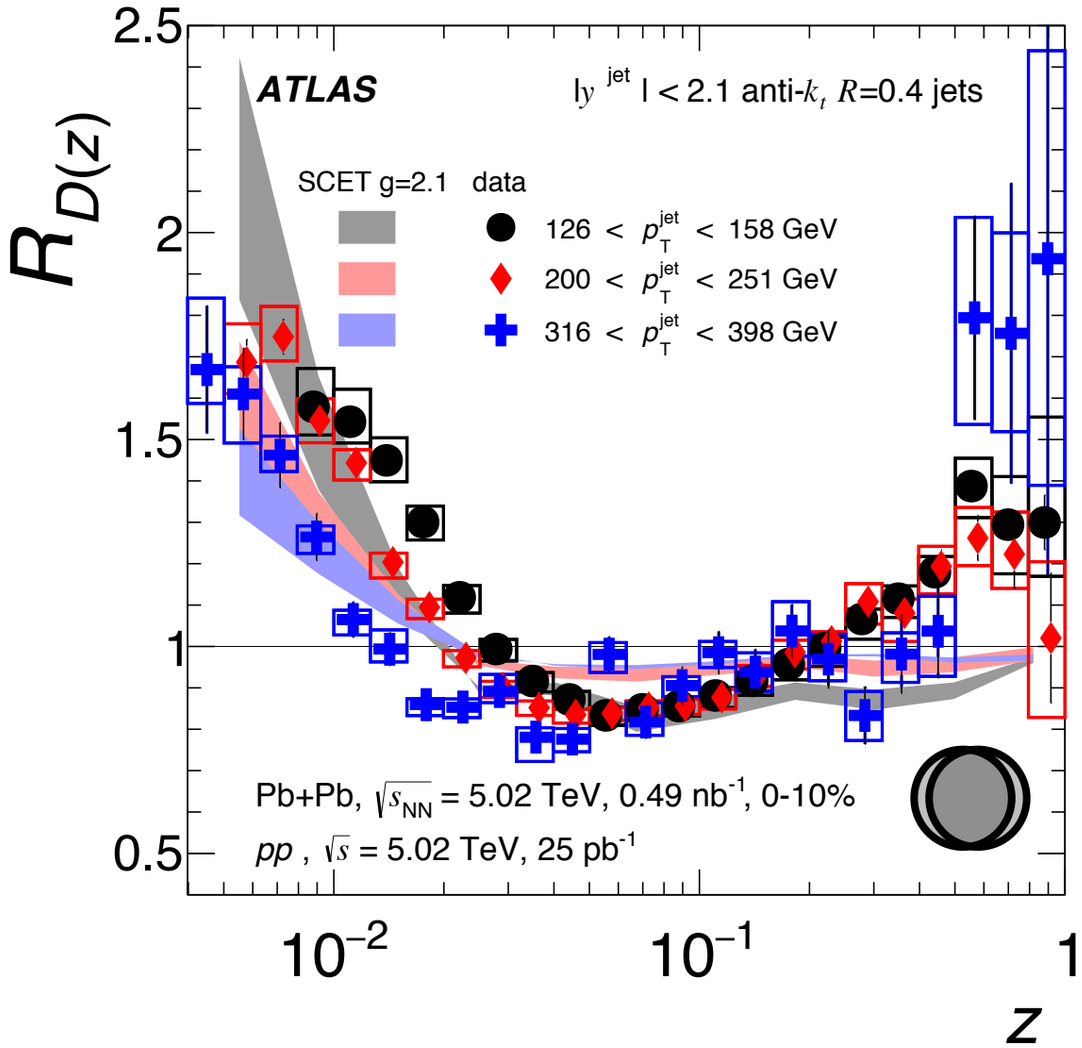
➡ **Energy is transferred to soft particles in and around the jet**

- **Enhancement at high z**

➡ **More quark jets at high z that could be modified differently than gluon jets**

Internal structure: p_T dep.

ATLAS-CONF-2017-005

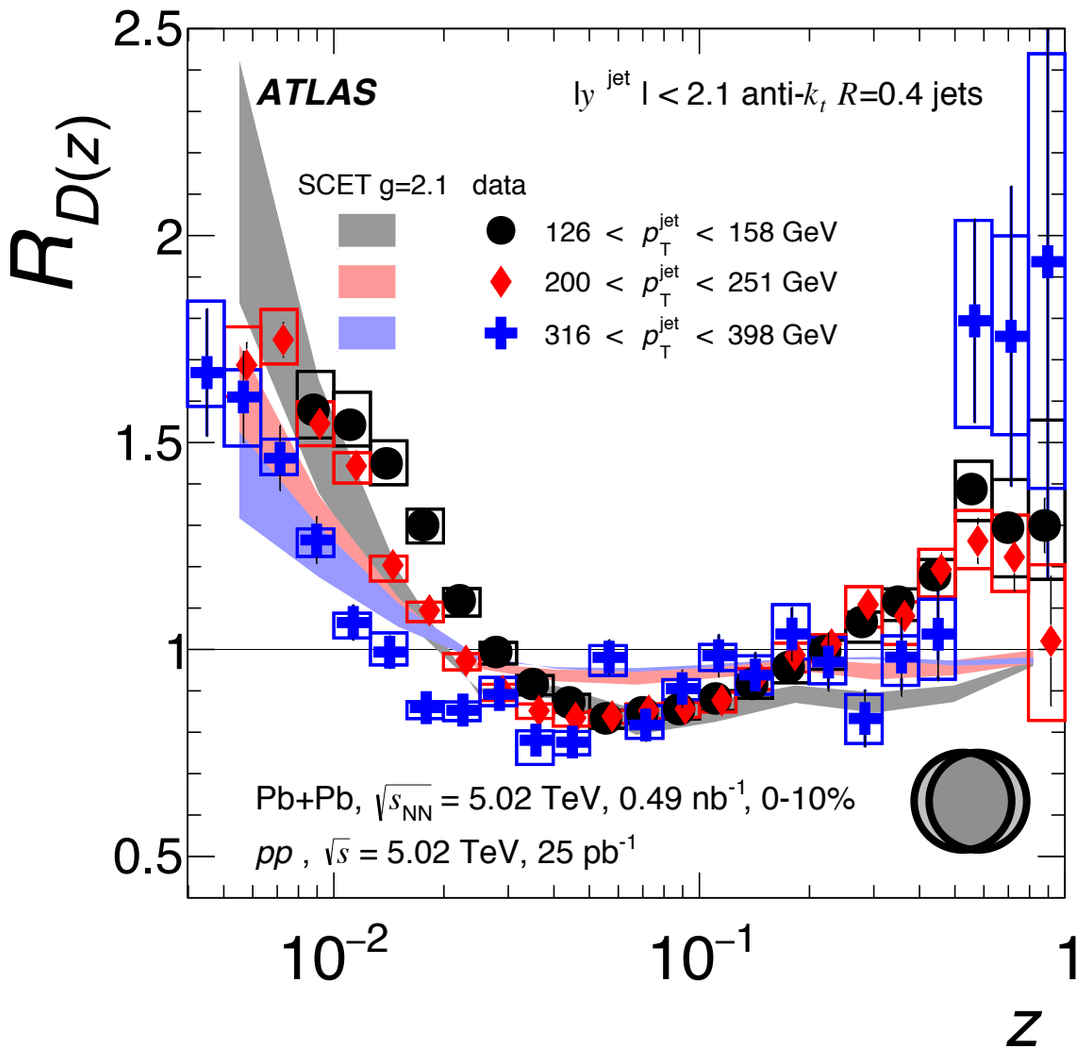


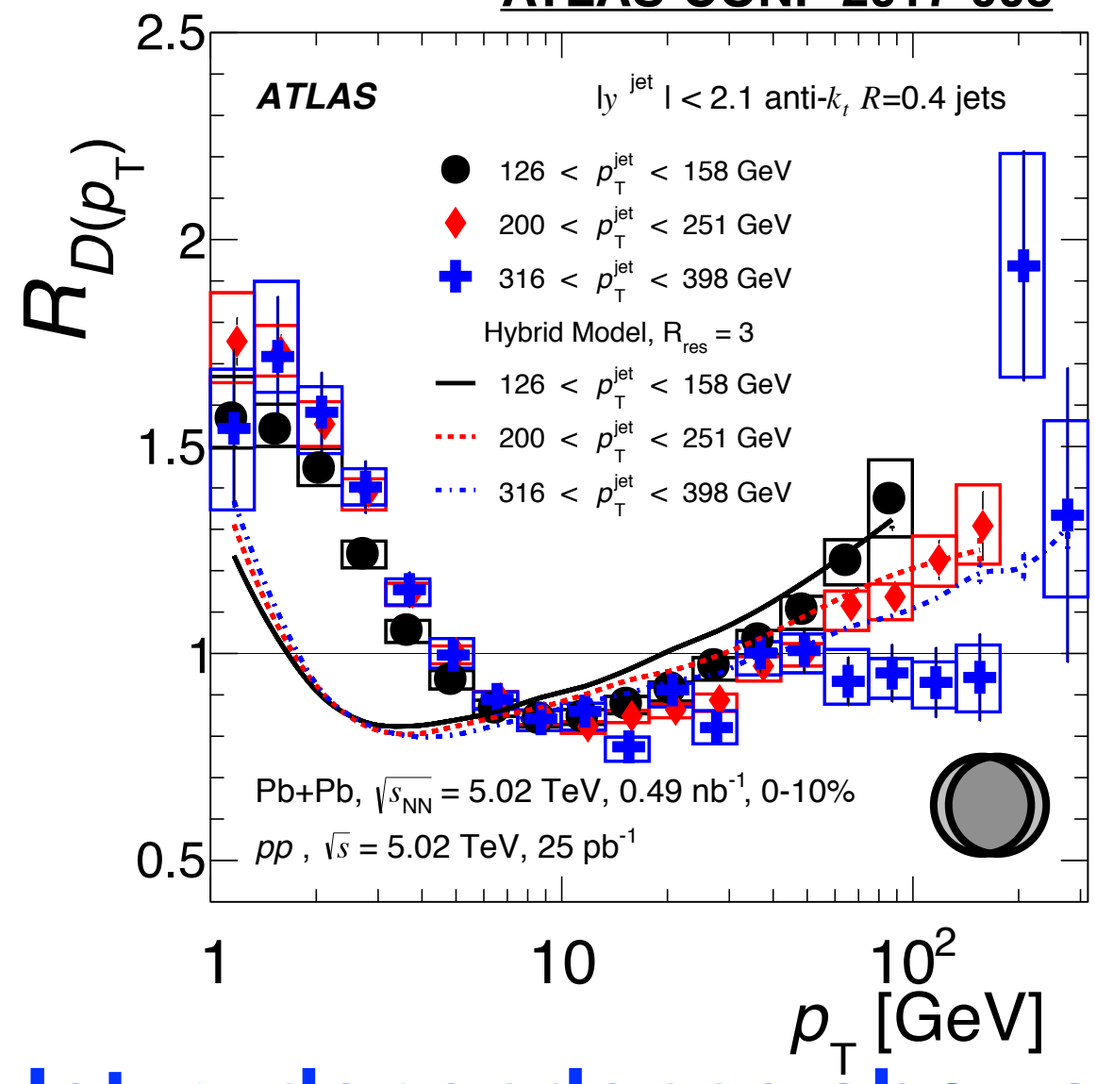
- **No jet p_T dependence at high z**
- **Less enhancement for higher p_T at low z**

➡**Described by model**

Internal structure: p_T dep.

ATLAS-CONF-2017-005





- **No jet p_T dependence at high z**
- **Less enhancement for higher p_T at low z**

➡Described by model

- **Jet p_T dependence shows more low p_T tracks at high p_T**

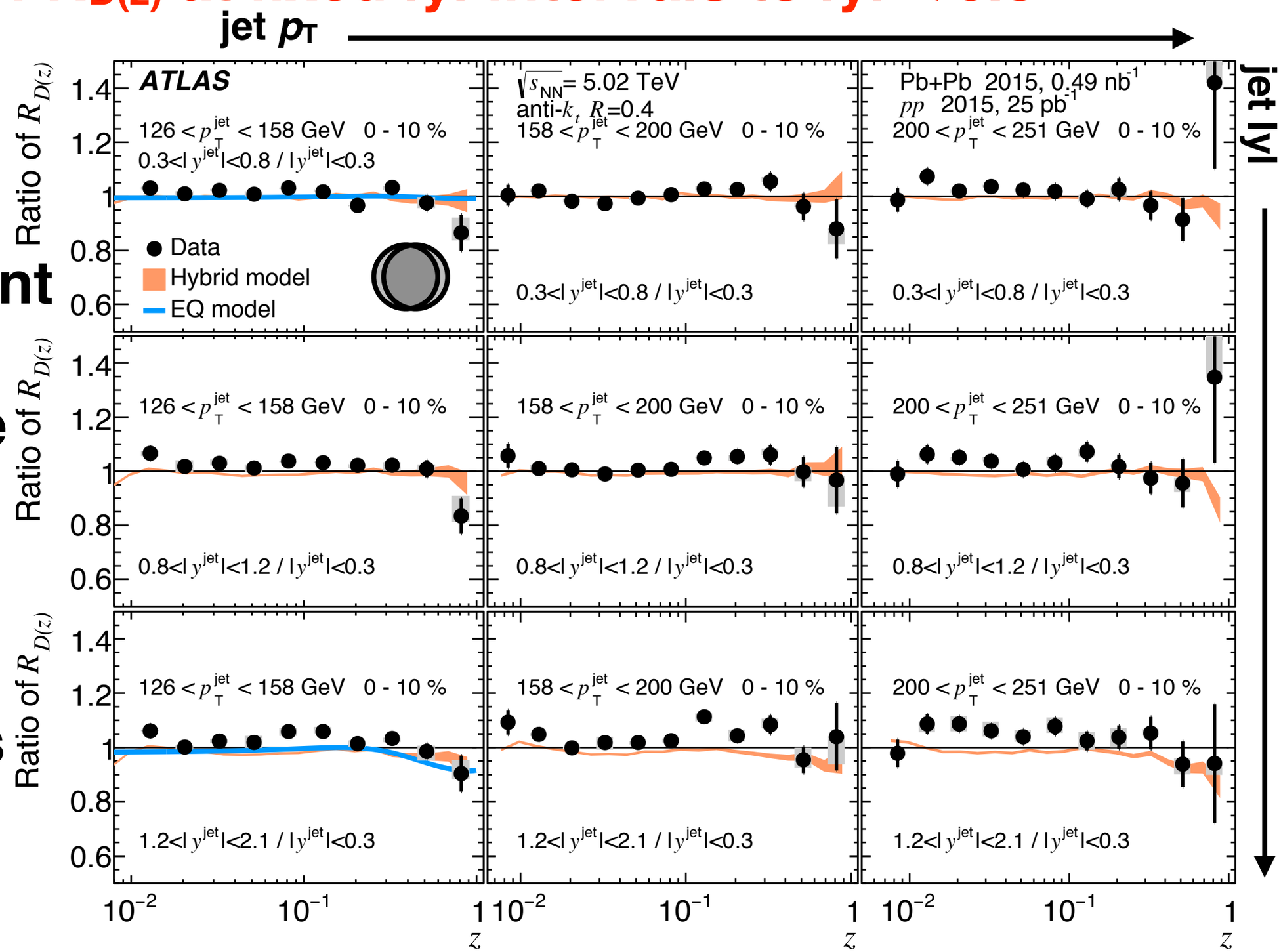
➡response of medium to jets?

- **Model describes jet p_T dependence at high track p_T**

Internal structure: rapidity dep.

- **Ratio of $R_{D(z)}$ at fixed |y| intervals to |y| < 0.3**

ATLAS-CONF-2017-005

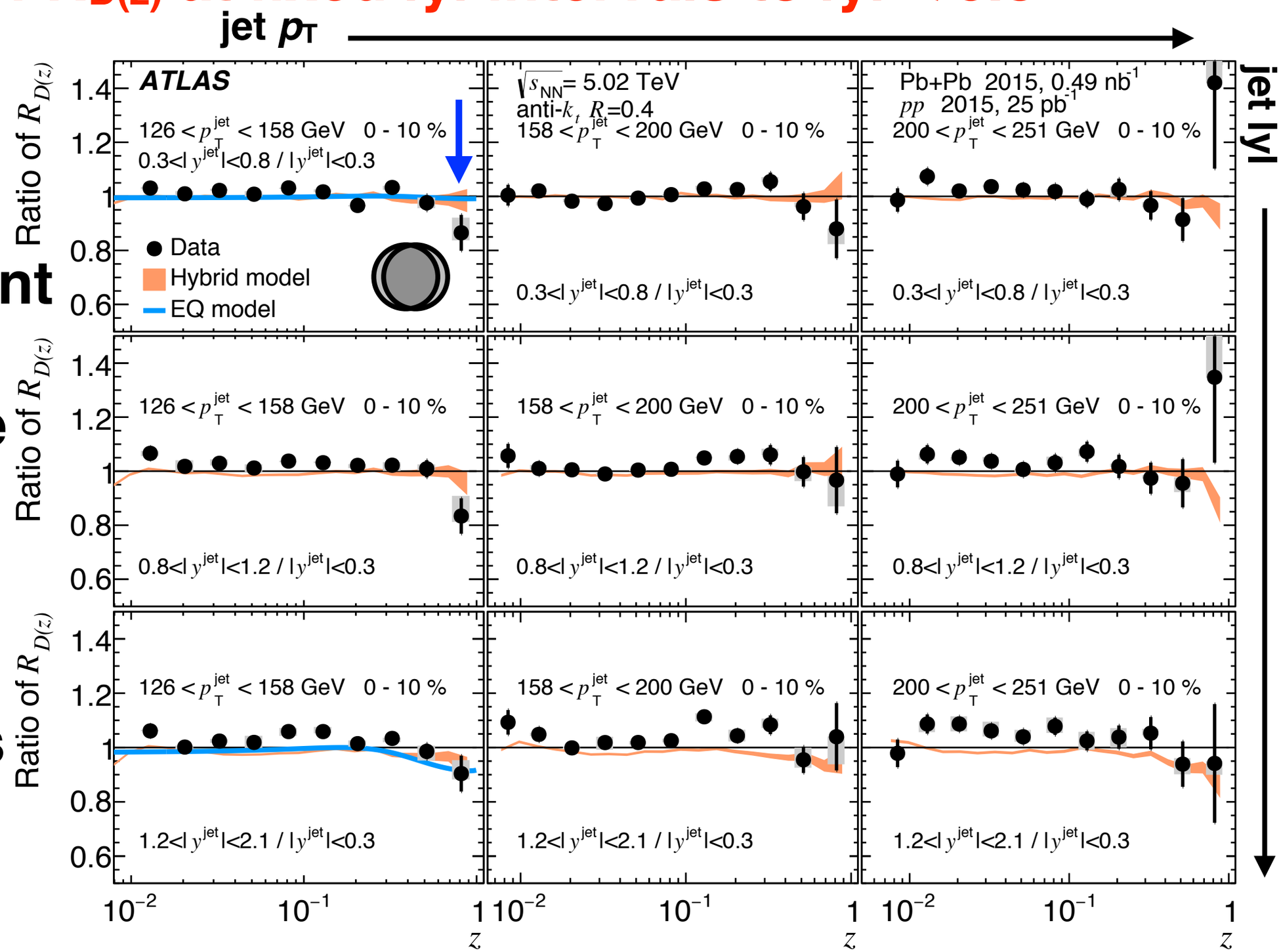


- **No significant rapidity dependence**
- **Consistent with models**

Internal structure: rapidity dep.

- **Ratio of $R_{D(z)}$ at fixed |y| intervals to |y| < 0.3**

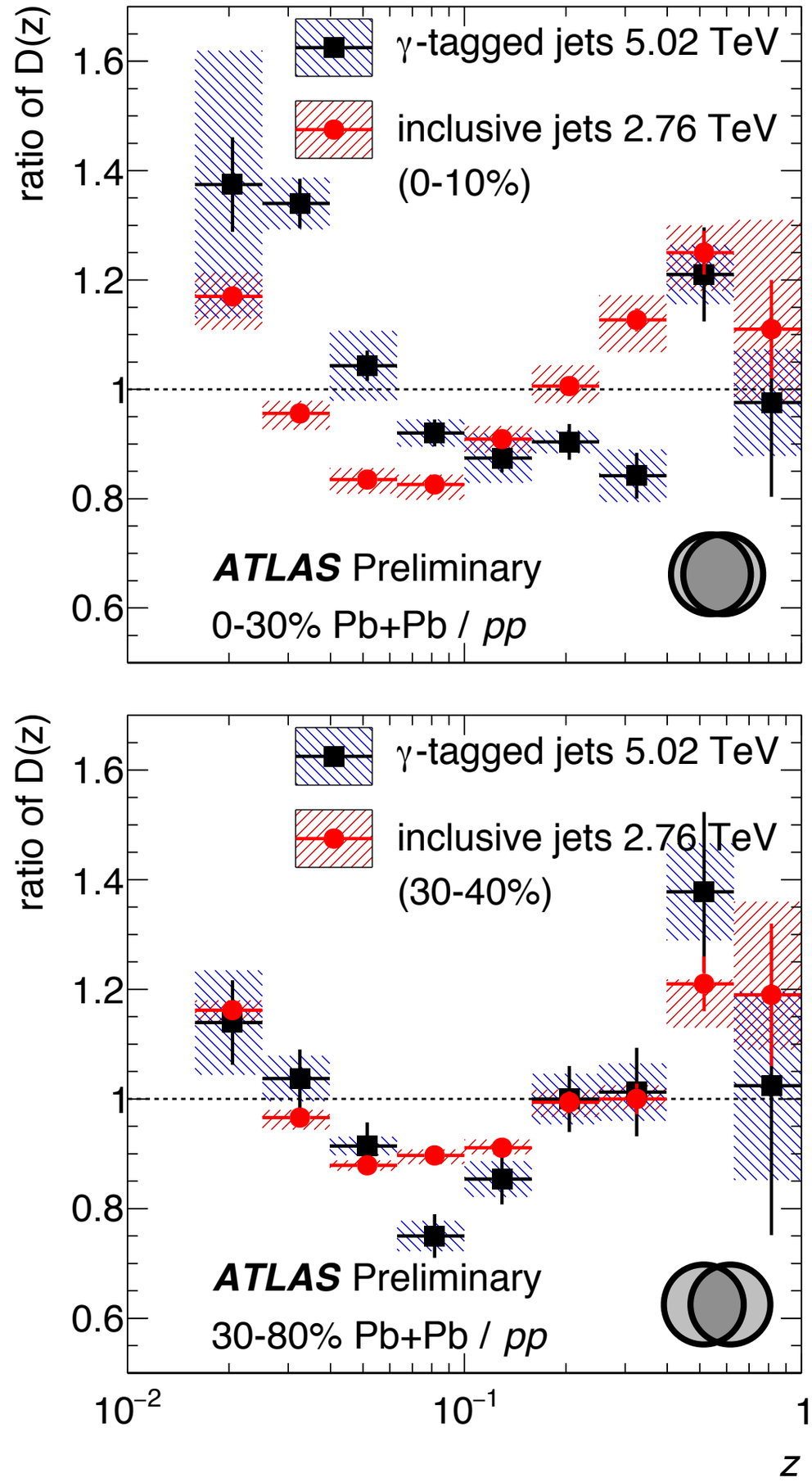
ATLAS-CONF-2017-005



- **No significant rapidity dependence**
- **Consistent with models**
- **Slight hint of enhancement decrease with |y| at high z**

Internal structure: photon tagged

- **FF in γ-tagged jets compared to inclusive jets**



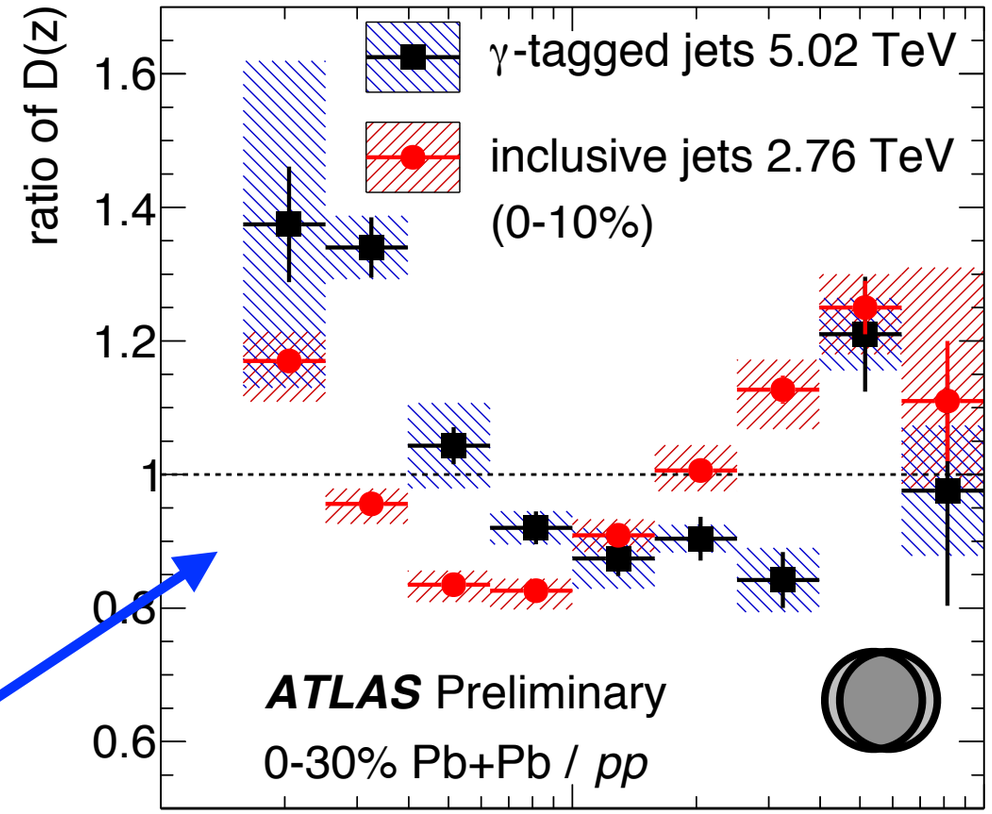
ATLAS-CONF-2017-074

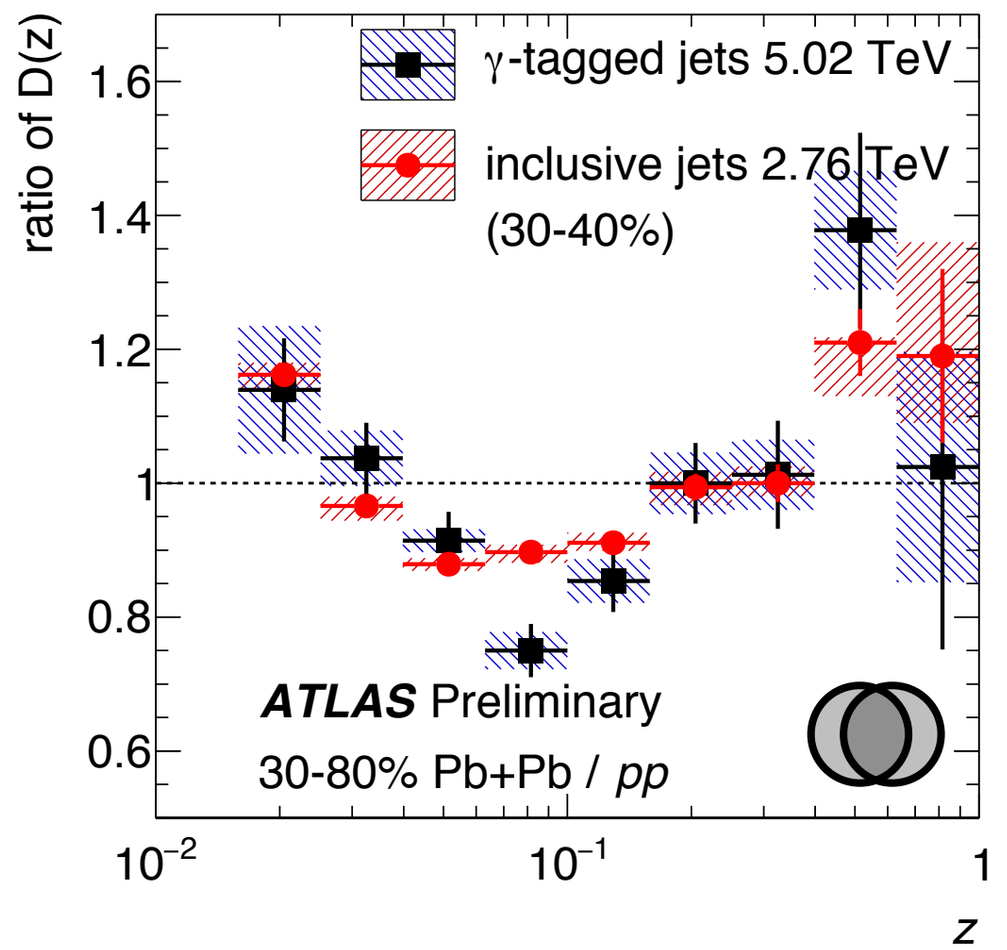
Internal structure: photon tagged

- **FF in γ-tagged jets compared to inclusive jets**
- **γ-tagged jets have stronger modification in central**

➡ **This could be do to different jet p_T selections in the two analyses**

➡ **Inclusive FF is also preferentially selecting jets that have lost less energy**





ATLAS-CONF-2017-074

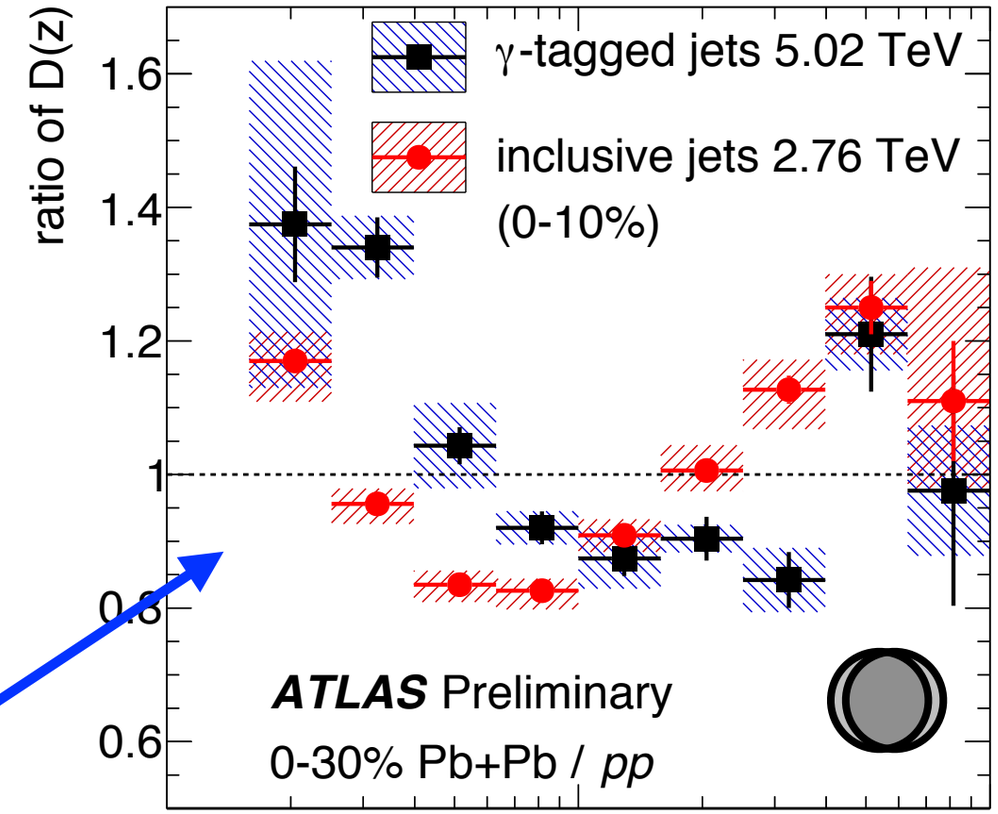
Internal structure: photon tagged

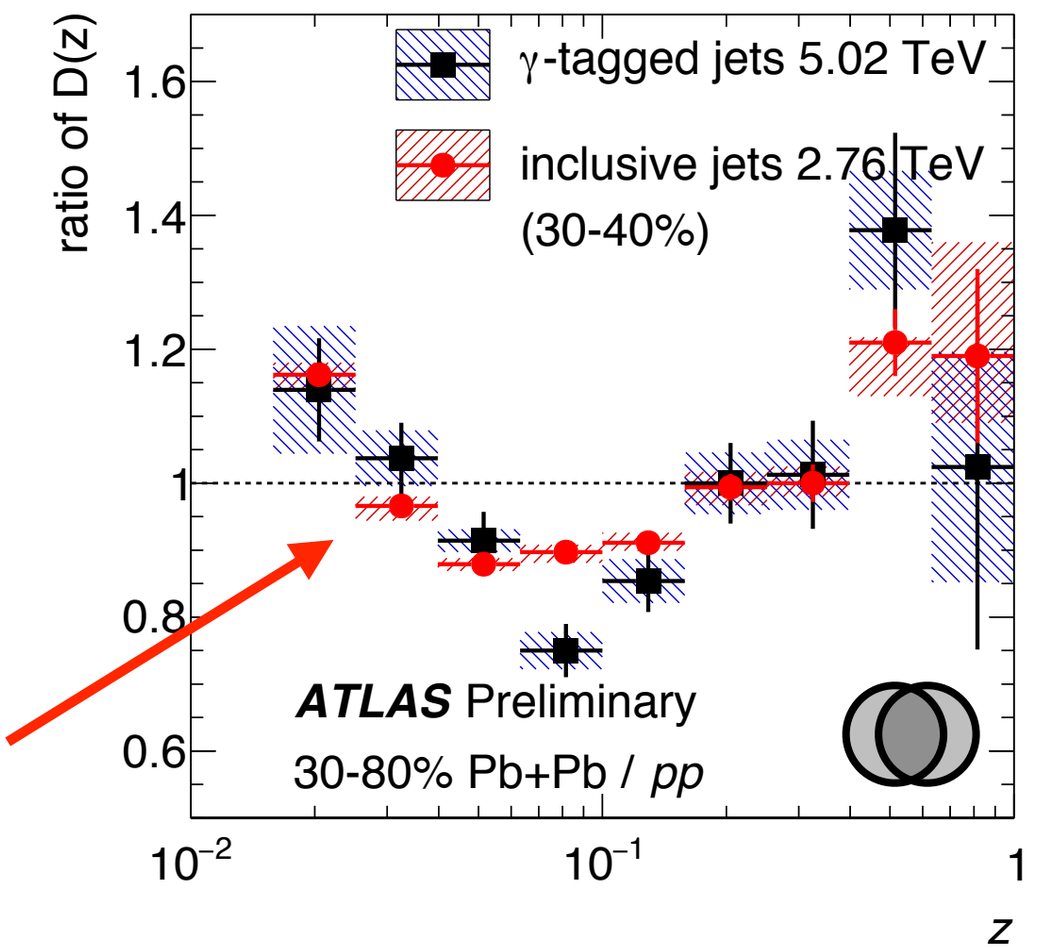
- **FF in γ-tagged jets compared to inclusive jets**
- **γ-tagged jets have stronger modification in central**

➡ **This could be do to different jet p_T selections in the two analyses**

➡ **Inclusive FF is also preferentially selecting jets that have lost less energy**

- **Better agreement in 30-40%**





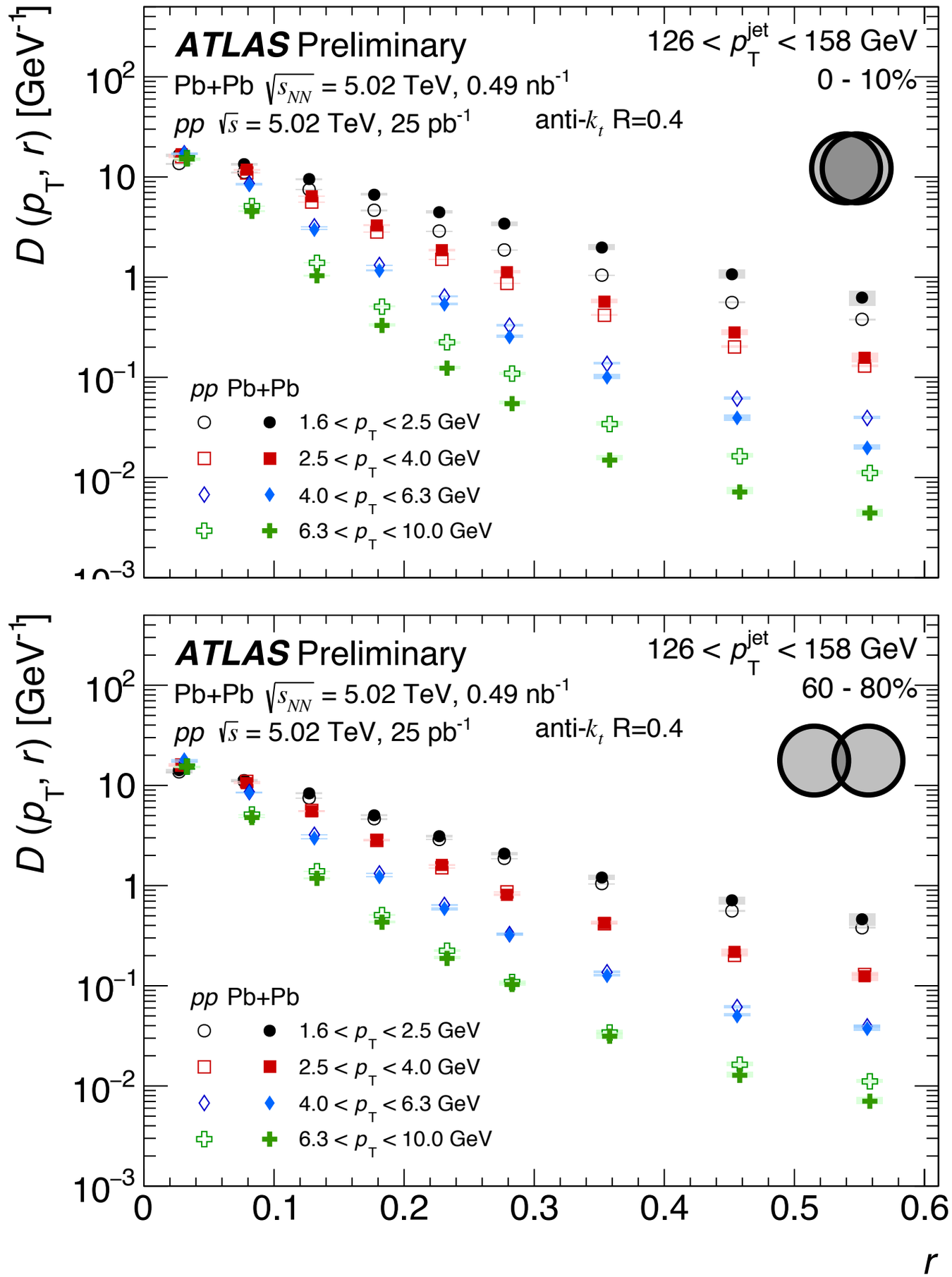
ATLAS-CONF-2017-074

Radial profile

$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\mathrm{d}p_{\mathrm{T}}}$$

- **FF as a function of the radius to measure the jet shape in and out of the jet cone in *pp* compared to central and peripheral Pb+Pb**

ATLAS-CONF-2018-010

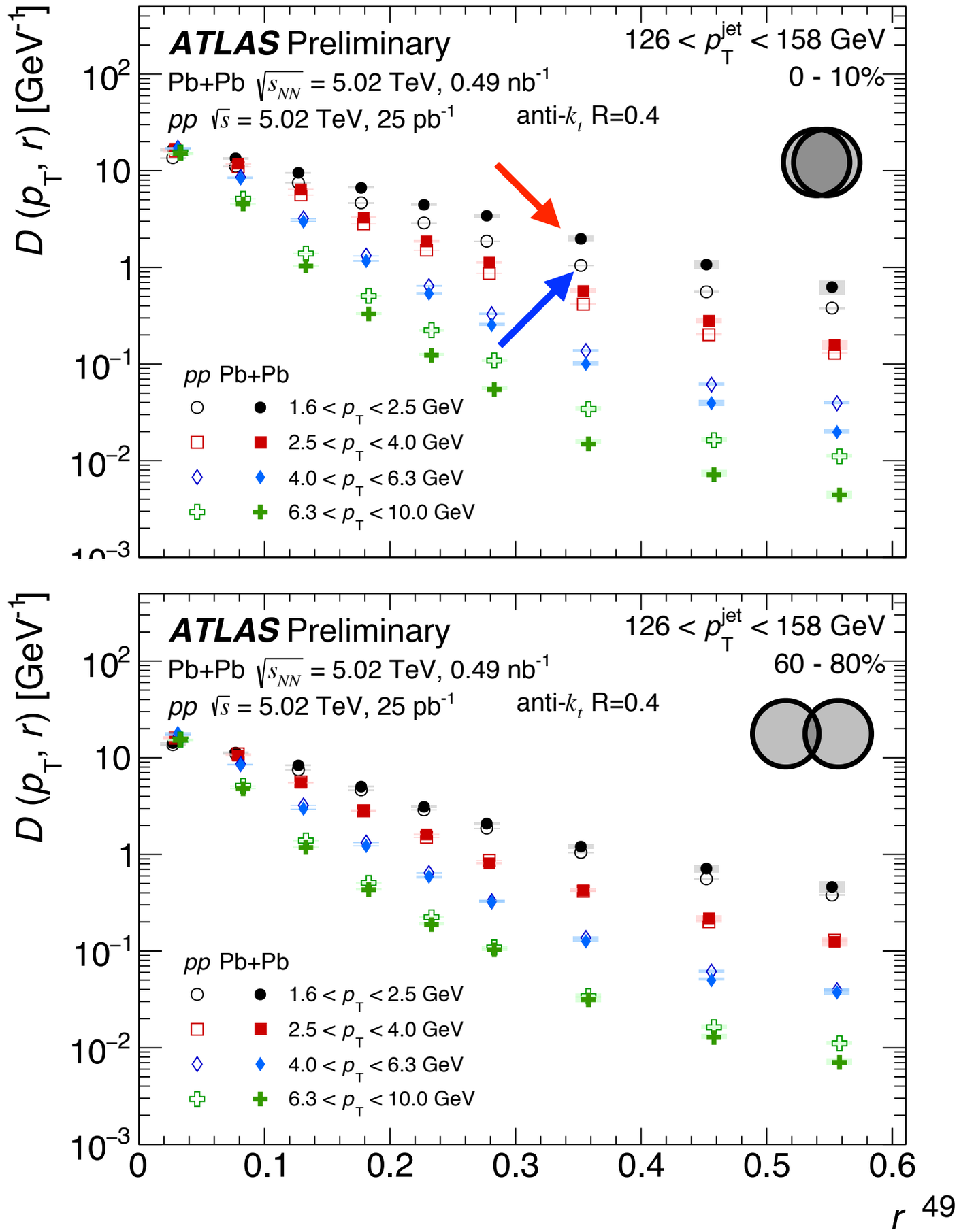


Radial profile

$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\mathrm{d}p_{\mathrm{T}}}$$

- **FF as a function of the radius to measure the jet shape in and out of the jet cone in *pp* compared to central and peripheral Pb+Pb**
- **See a difference in central Pb+Pb and *pp***
  - **Take ratio of D(p_T, r) in Pb+Pb and *pp* to evaluate difference**

ATLAS-CONF-2018-010



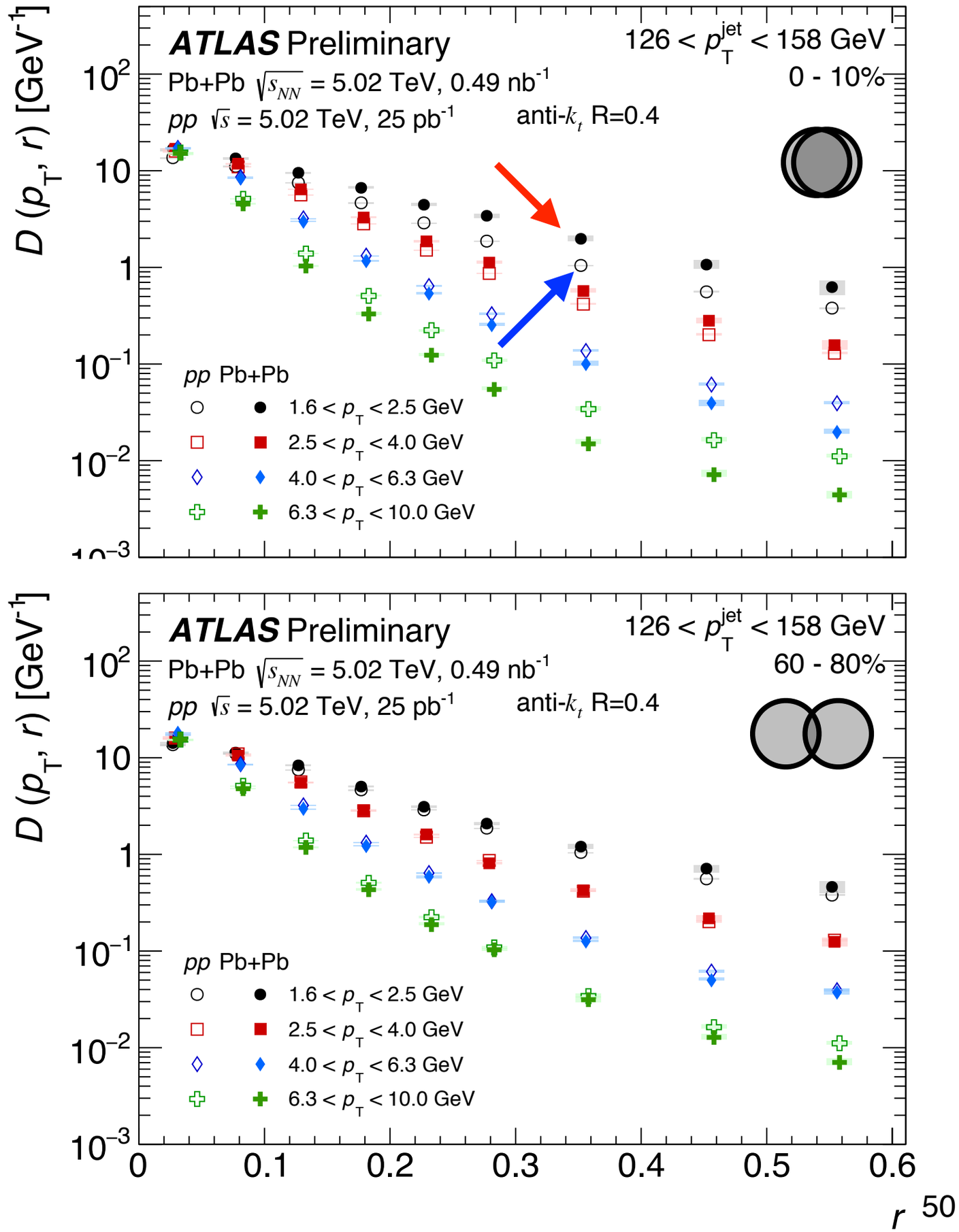
Radial profile

$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\mathrm{d}p_{\mathrm{T}}}$$

- **FF as a function of the radius to measure the jet shape in and out of the jet cone in *pp* compared to central and peripheral Pb+Pb**
- **See a difference in central Pb+Pb and *pp***
  - **Take ratio of D(p_T, r) in Pb+Pb and *pp* to evaluate difference**

► ***Unfolded for position resolution***

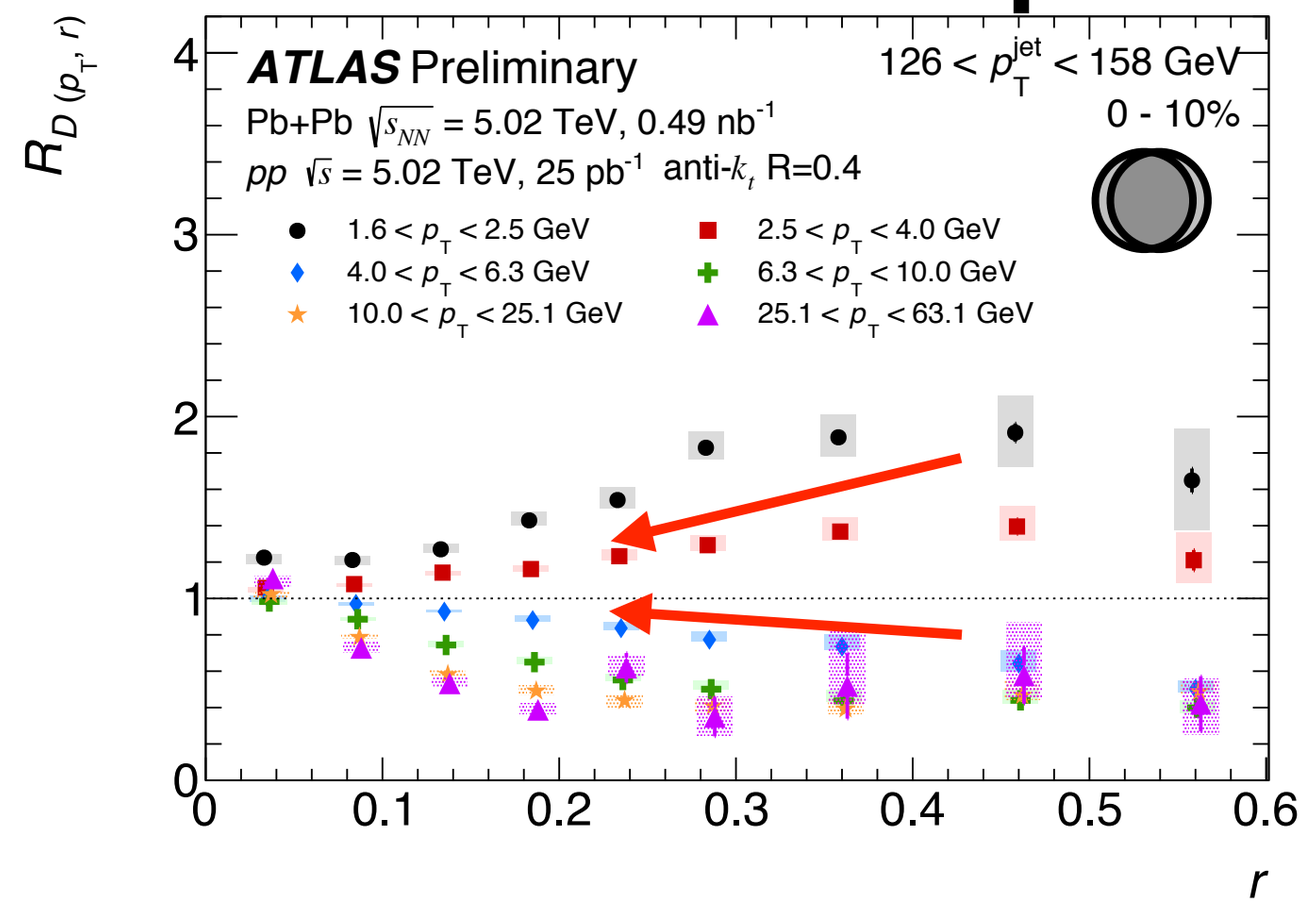
ATLAS-CONF-2018-010



Internal structure: radial dep.

ATLAS-CONF-2018-010

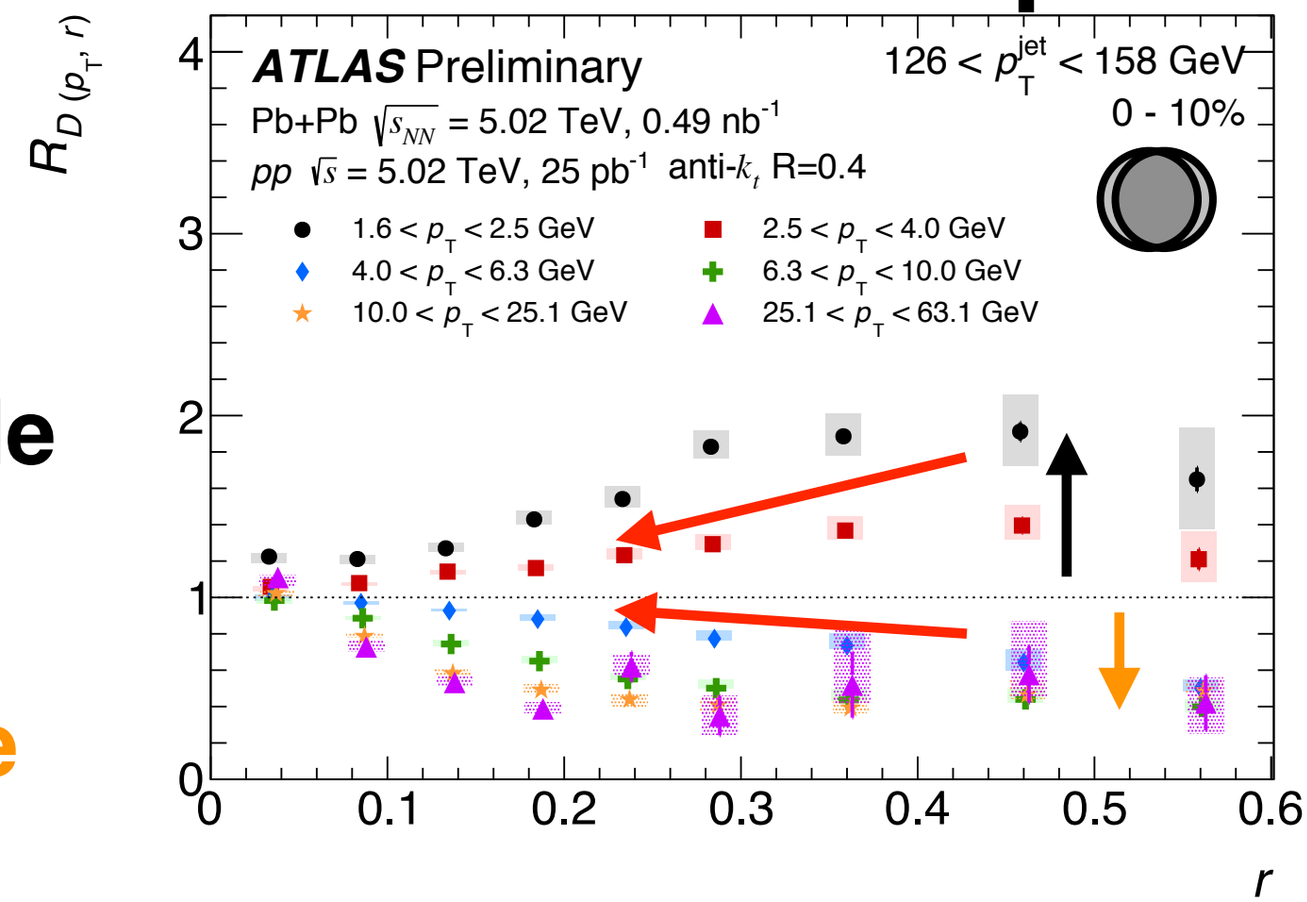
- **Less modification with decreasing radius**



Internal structure: radial dep.

ATLAS-CONF-2018-010

- **Less modification with decreasing radius**
- **More soft particles outside the jet cone**
- **Less intermediate p_T particles outside the cone**

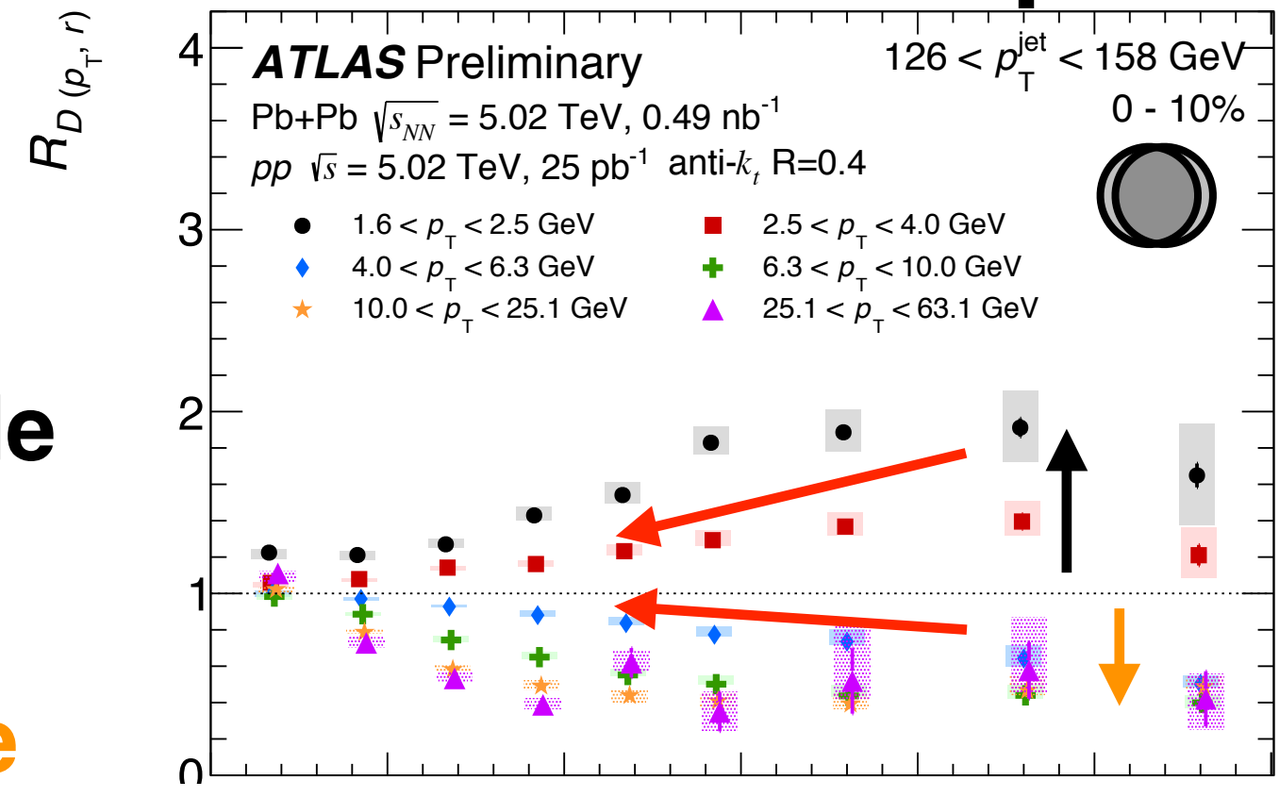


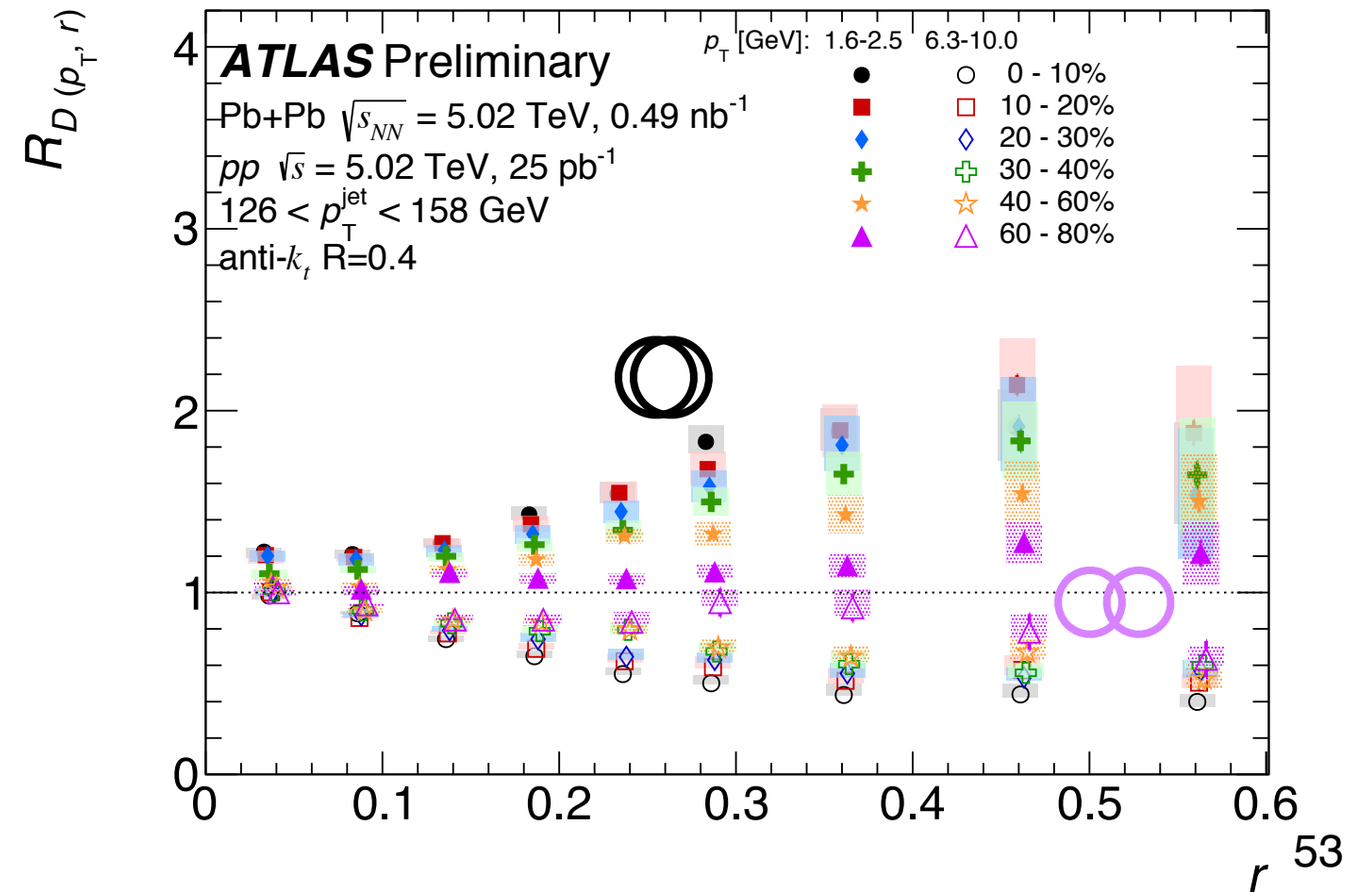
Internal structure: radial dep.

ATLAS-CONF-2018-010

- **Less modification with decreasing radius**
- **More soft particles outside the jet cone**
- **Less intermediate p_T particles outside the cone**

- **Central has more soft and less intermediate p_T particles while peripheral has more intermediate p_T and less soft particles**





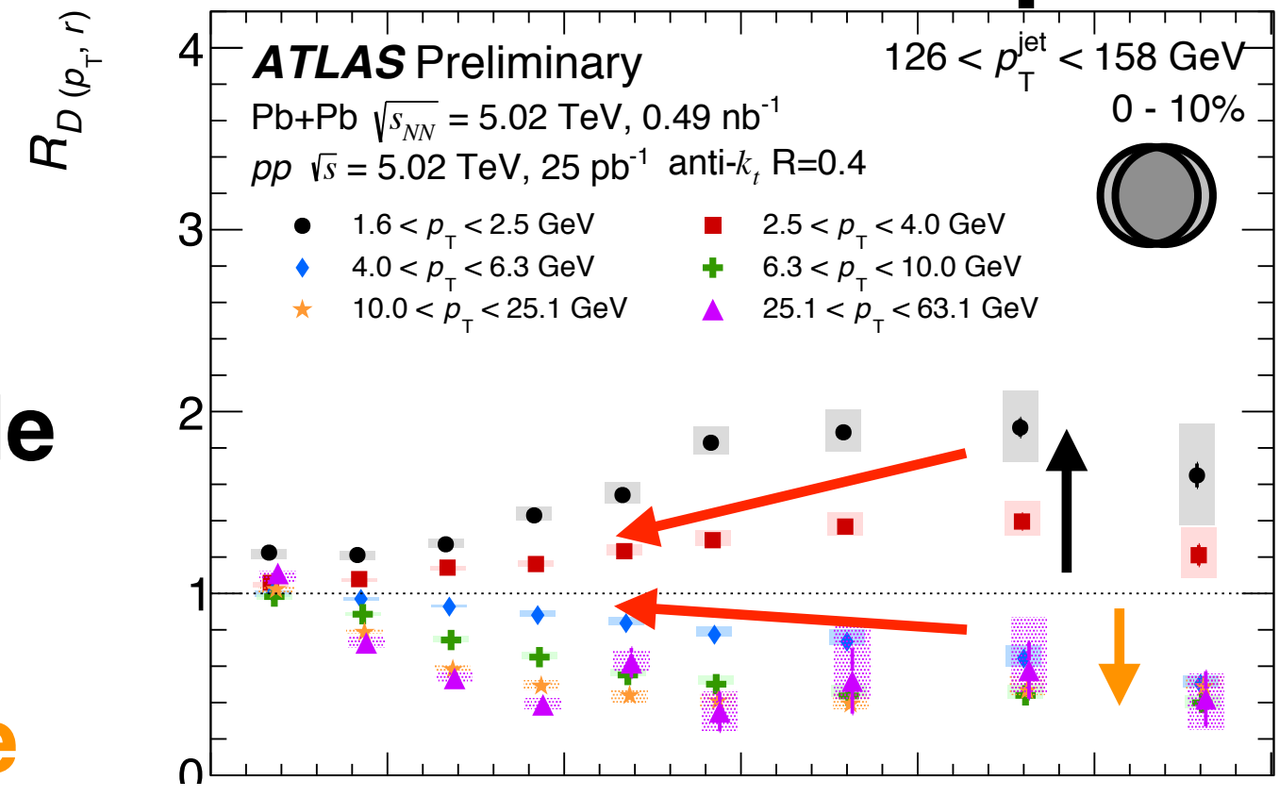
Internal structure: radial dep.

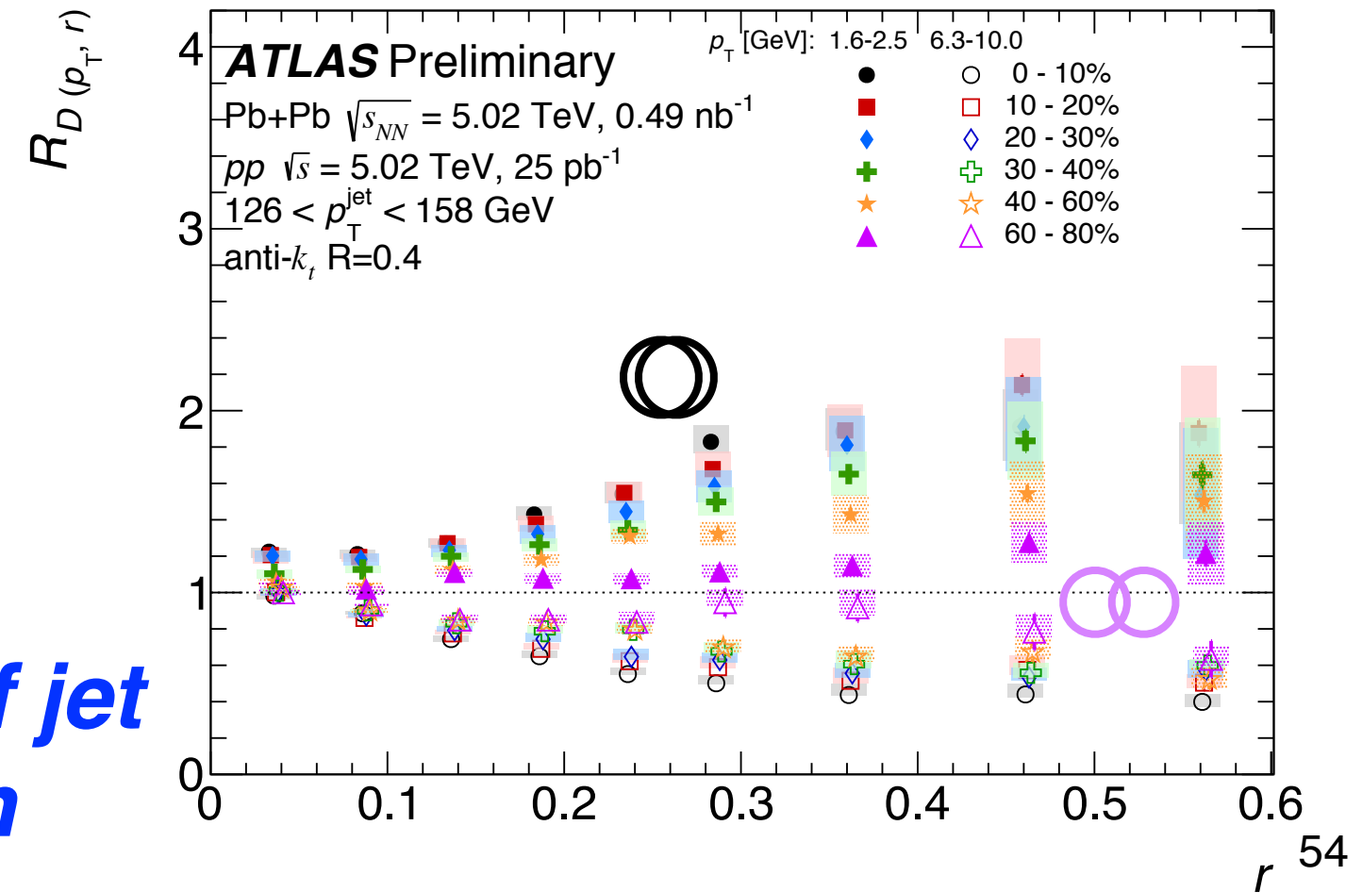
ATLAS-CONF-2018-010

- **Less modification with decreasing radius**
- **More soft particles outside the jet cone**
- **Less intermediate p_T particles outside the cone**

- **Central has more soft and less intermediate p_T particles while peripheral has more intermediate p_T and less soft particles**

▸ ***Consistent with picture of jet broadening in the medium***

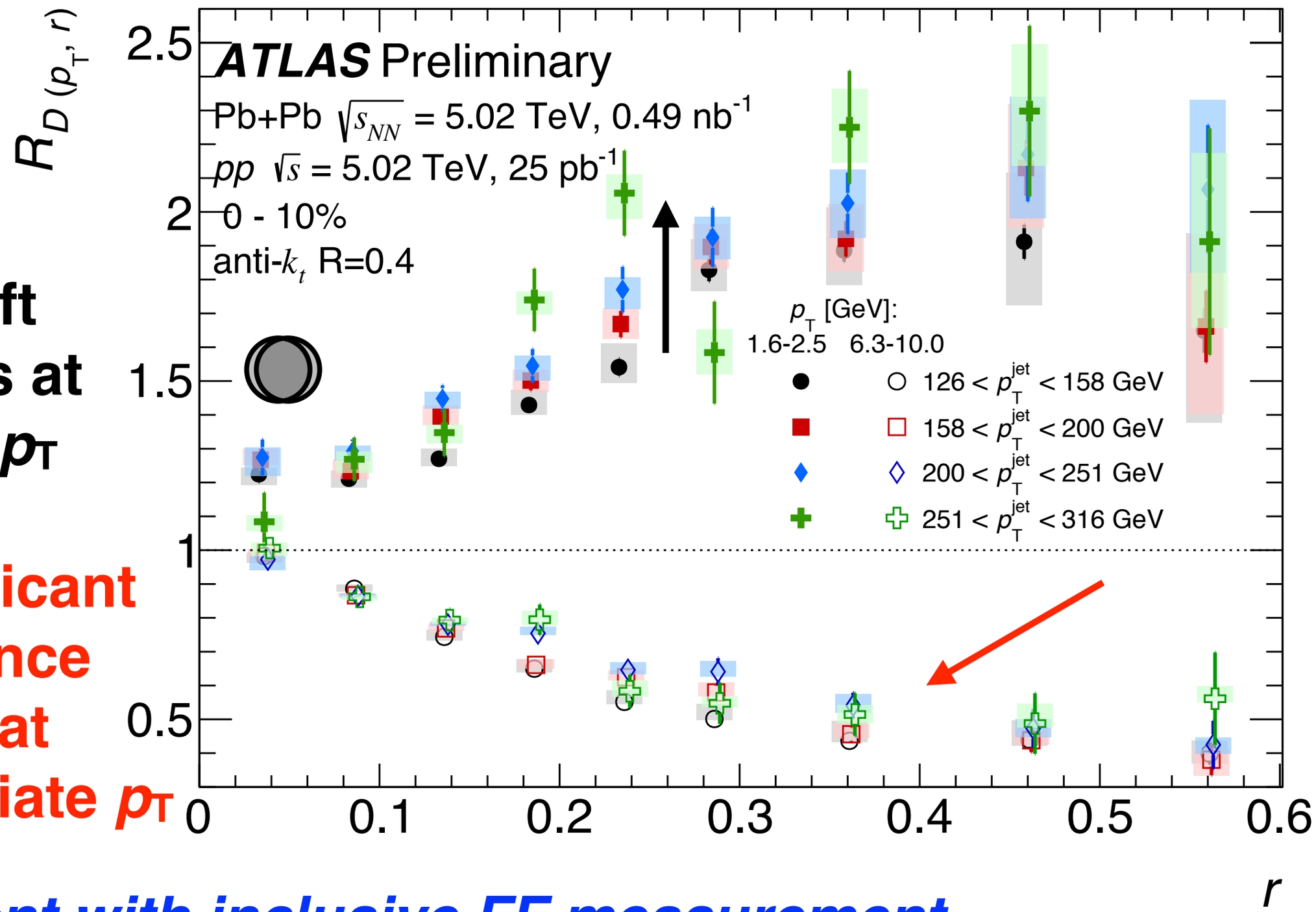




Internal structure: radial dep.

- **Jet p_T dependence of the jet shape modification**

ATLAS-CONF-2018-010



- **More soft particles at high jet p_T**

- **No significant dependence on jet p_T at intermediate p_T**

▸ ***Consistent with inclusive FF measurement***

ATLAS-CONF-2018-014

Jet mass

$$m = \sqrt{(\sum_{i \in J} E_i)^2 - (\sum_{i \in J} \vec{p_i})^2)}$$

- **Jet mass is reconstructed from summing the energy and p_T of calorimeter towers inside of jets**

➡ **Wider jets=higher mass, narrower=lower mass**

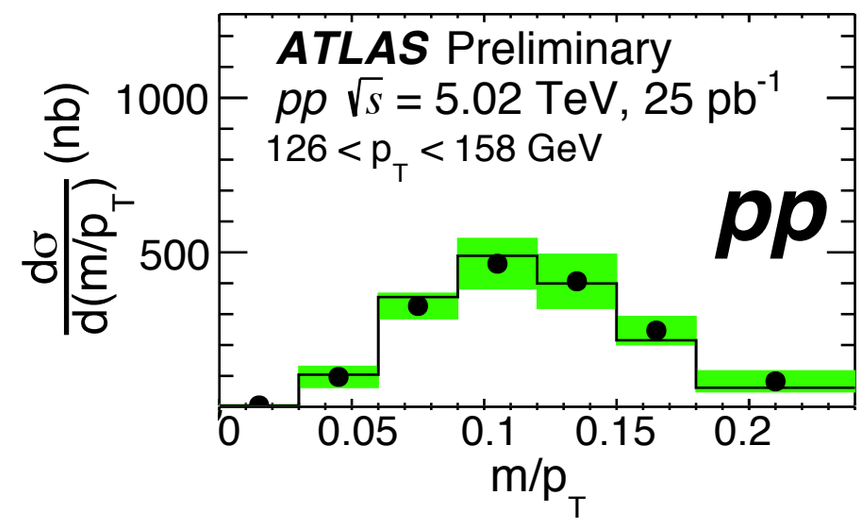
ATLAS-CONF-2018-014

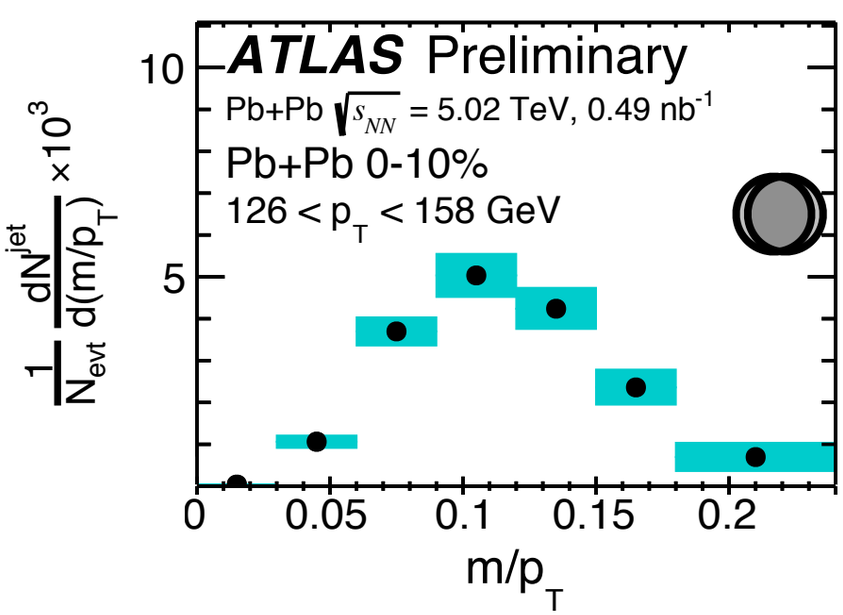
Jet mass

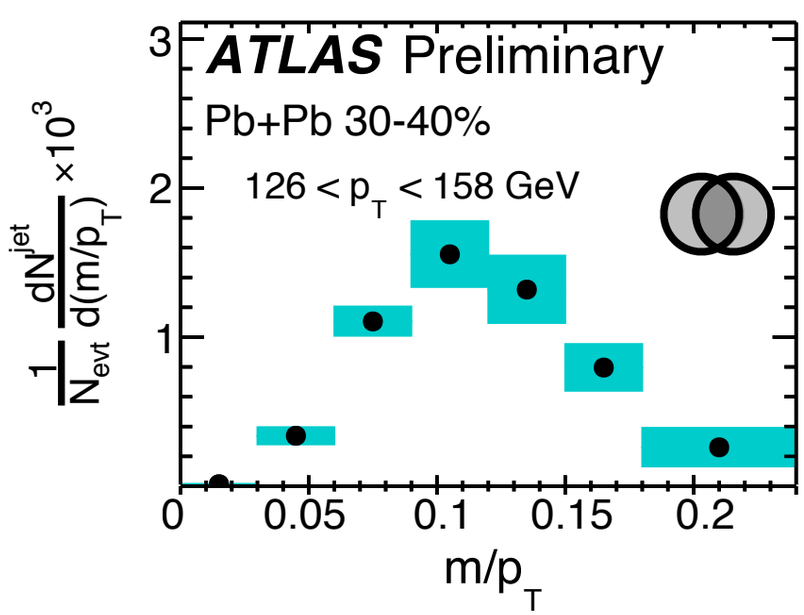
$$m = \sqrt{(\sum_{i \in J} E_i)^2 - (\sum_{i \in J} \vec{p_i})^2)}$$

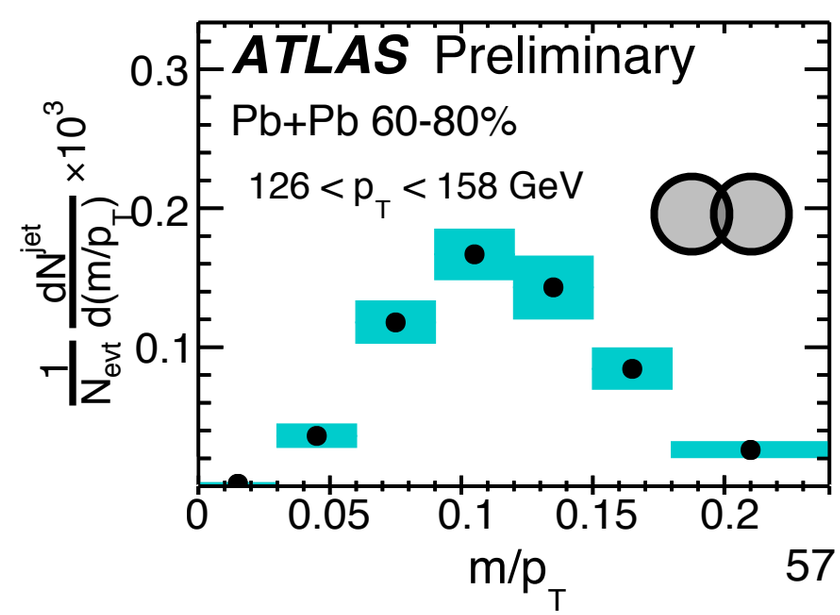
- **Jet mass is reconstructed from summing the energy and p_T of calorimeter towers inside of jets**

  ➡ **Wider jets=higher mass, narrower=lower mass**
- **Ratio m/p_T which is easier to unfold and has a weak dependence on p_T: it is like the opening angle of the jet**
- **Compare Pb+Pb and *pp* by evaluating the ratio, or the R_{AA}**









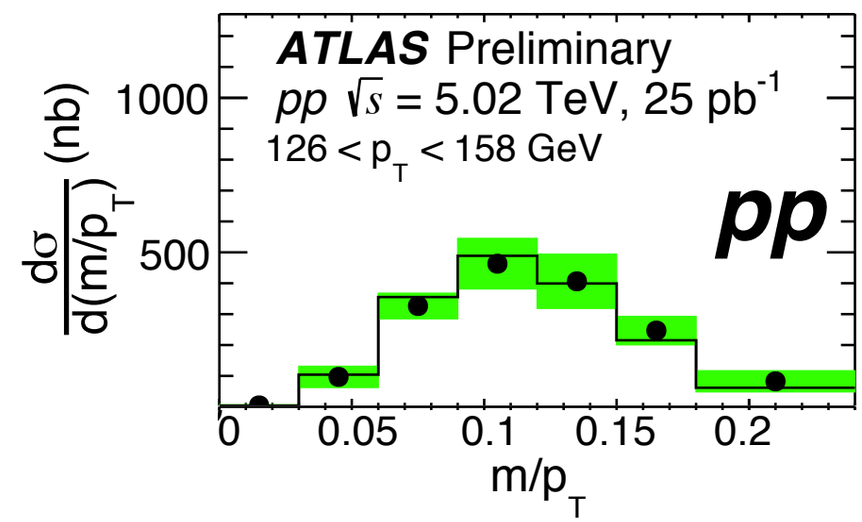
ATLAS-CONF-2018-014

Jet mass

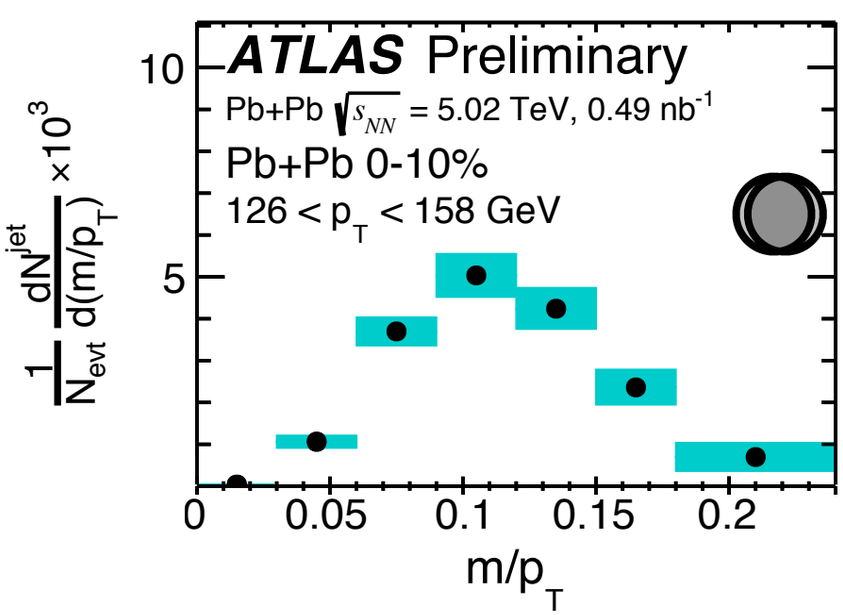
$$m = \sqrt{(\sum_{i \in J} E_i)^2 - (\sum_{i \in J} \vec{p_i})^2)}$$

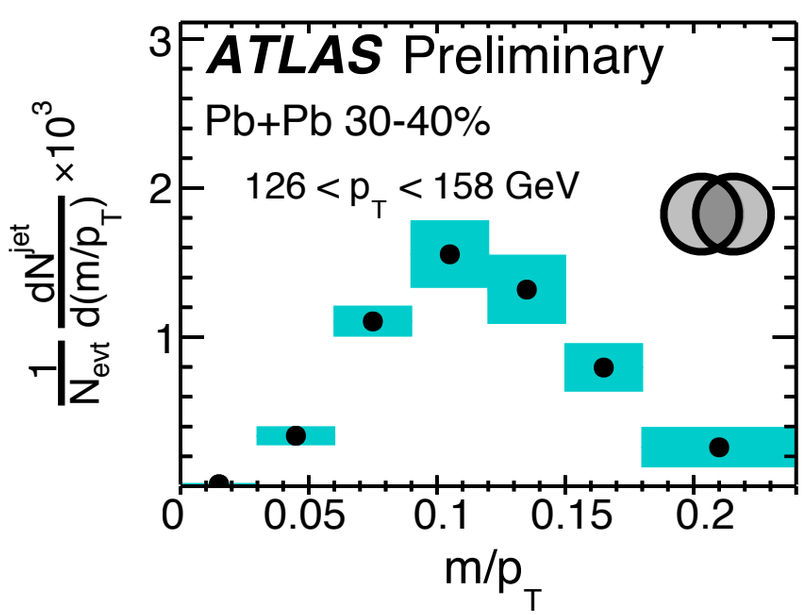
- **Jet mass is reconstructed from summing the energy and p_T of calorimeter towers inside of jets**

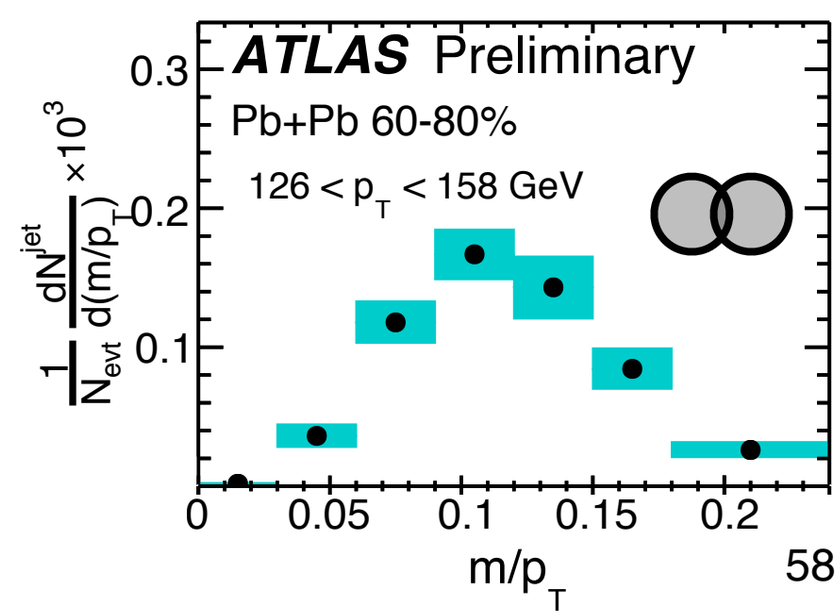
  ➡ **Wider jets=higher mass, narrower=lower mass**
- **Ratio m/p_T which is easier to unfold and has a weak dependence on p_T: it is like the opening angle of the jet**
- **Compare Pb+Pb and *pp* by evaluating the ratio, or the R_{AA}**



▸ ***2D unfolding m/p_T and p_T***



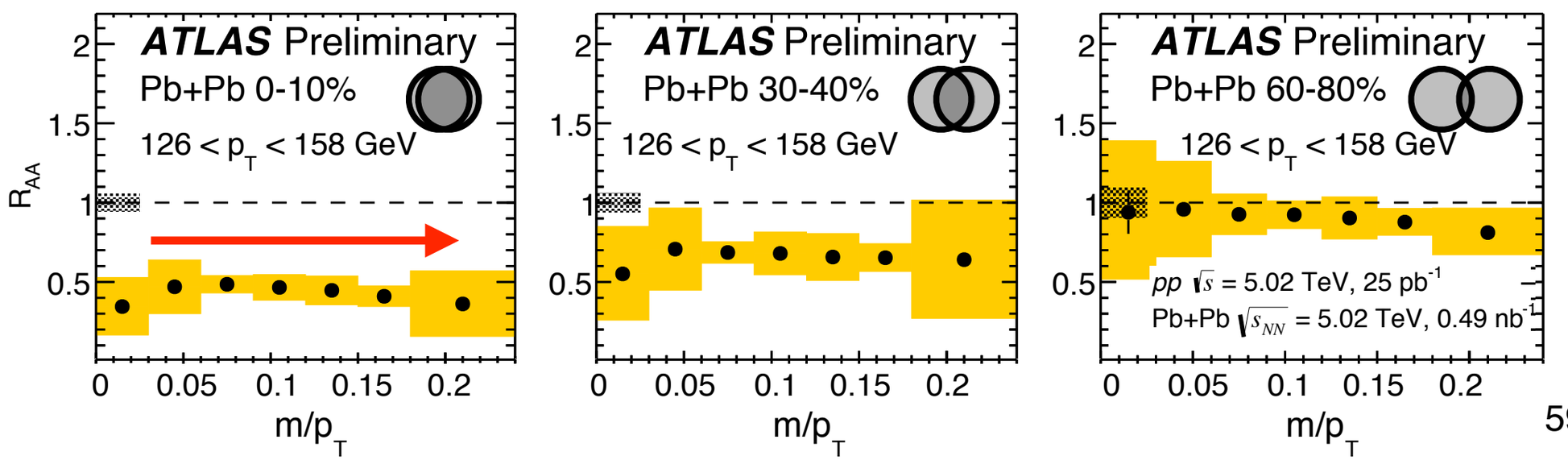




$R_{AA}(m/p_T)$

ATLAS-CONF-2018-014

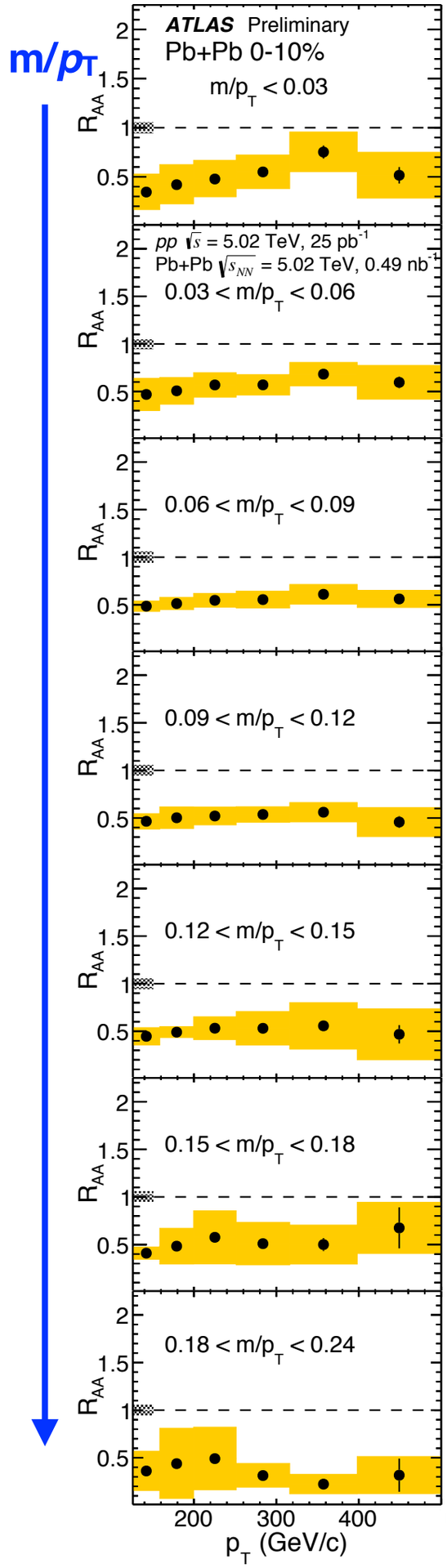
- **No significant dependence on m/p_T**

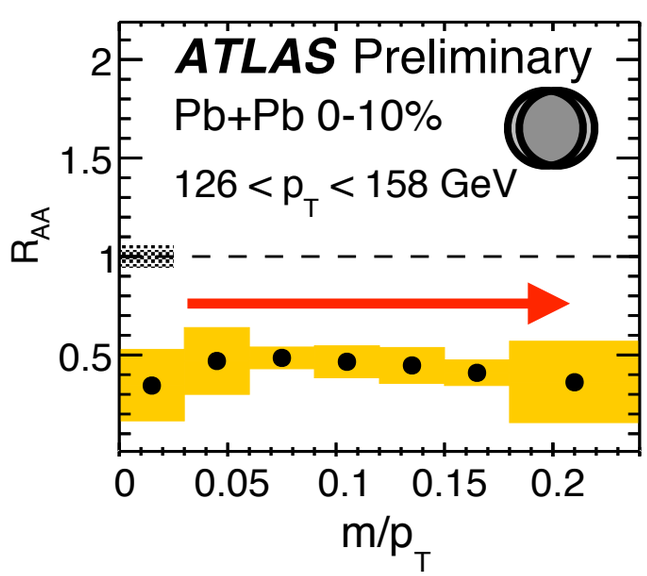


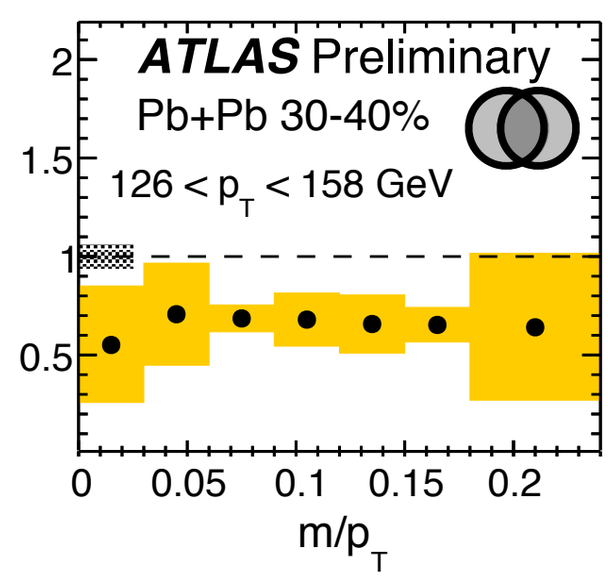
$R_{AA}(m/p_T)$

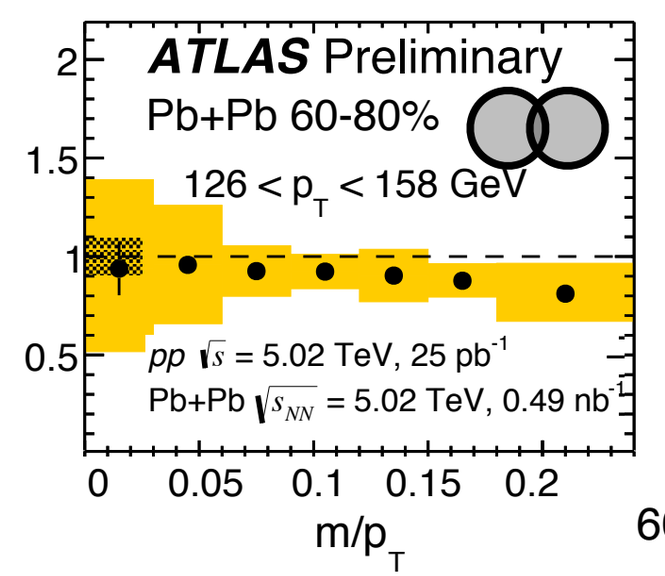
ATLAS-CONF-2018-014

- **No significant dependence on m/p_T**
- **No significant dependence on p_T and R_{AA} is consistent with inclusive R_{AA}**



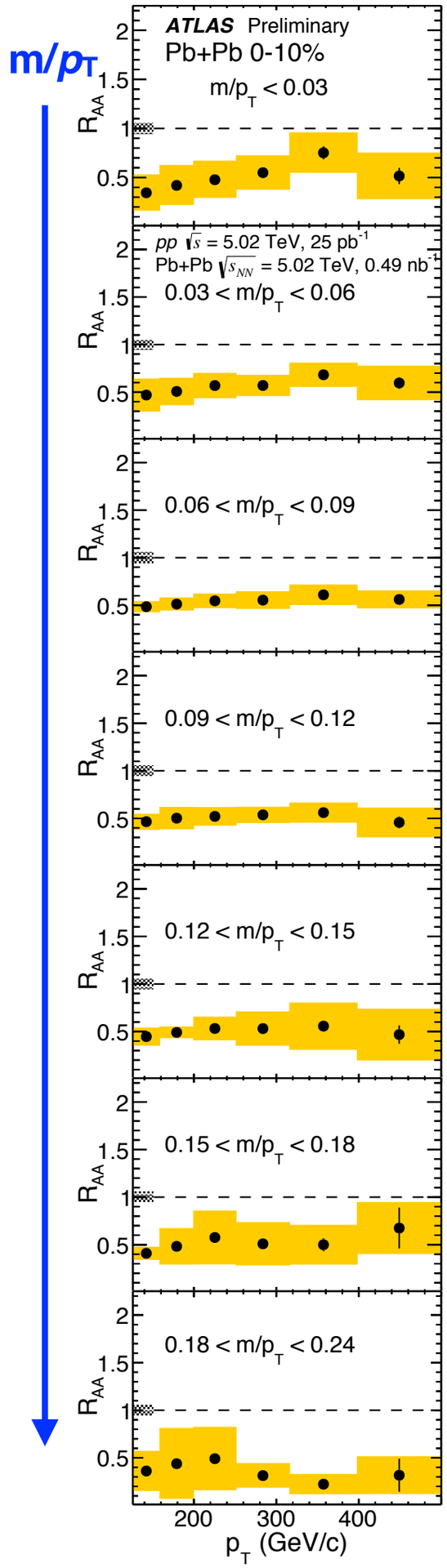




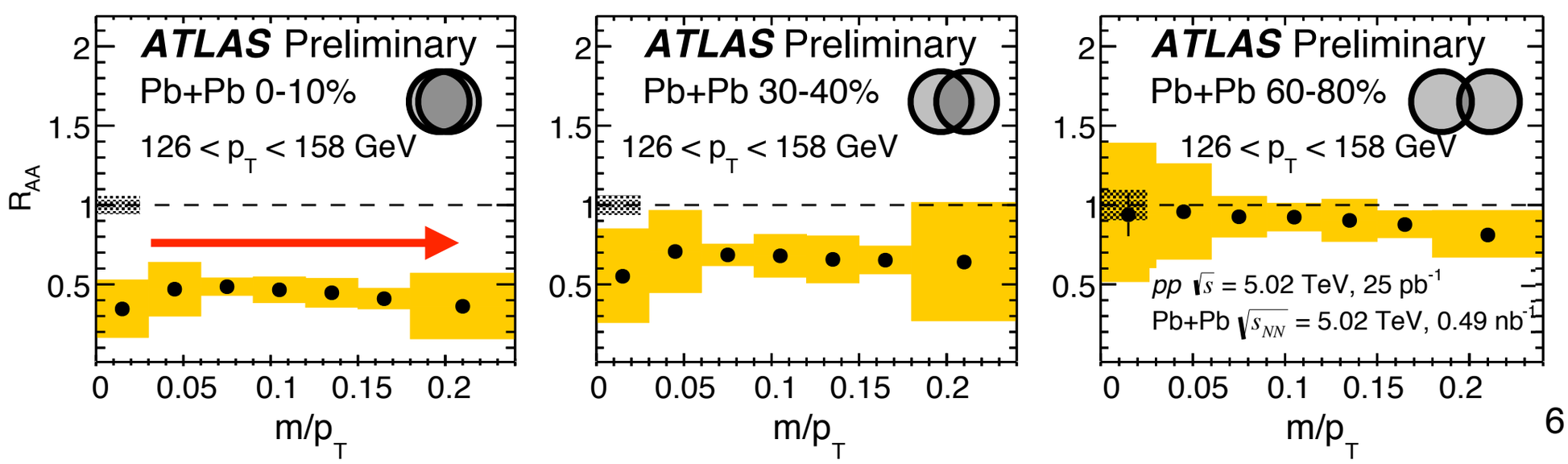


$R_{AA}(m/p_T)$

ATLAS-CONF-2018-014



- **No significant dependence on m/p_T**
- **No significant dependence on p_T and R_{AA} is consistent with inclusive R_{AA}**
- **If the medium resolves the jet constituents medium then energy is incoherent, if not energy loss is coherent and no structure modification is expected**
- **Decrease in pT from jet quenching combined with increase from recoil of medium -> canceling effects?**



Jets and charged hadrons in Xe+Xe collisions?

- **Short, low statistics Xe+Xe run in 2017 at the LHC**
- **Motivation:**

➡ **Lighter nuclei (Xe^{129} vs. Pb^{208}) should have a smaller underlying event in central collisions**

➡ **Jet quenching expected to be less due to the reduced medium density and smaller path lengths in the lower atomic number Xe+Xe collisions**

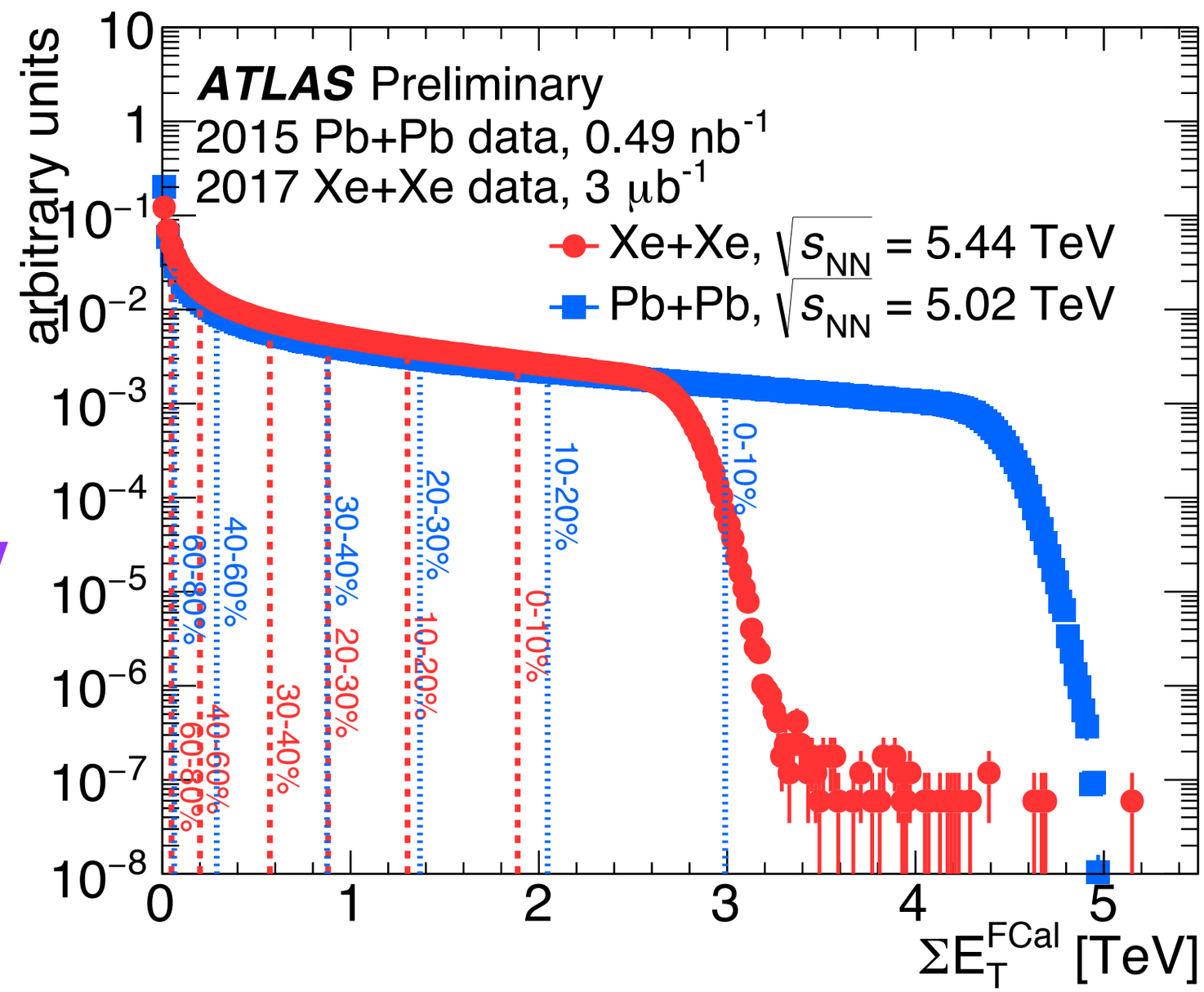
➡ **Showing that there is something interesting in the low statistics Xe+Xe motivates future runs at different collisions systems**

ΣE_T^{FCal} Pb vs. Xe

- **The FCalEt distributions are partitioned in centrality bins separately in Pb+Pb and Xe+Xe**
- **Two different comparisons in analysis:**

➡ **Same overlap (centrality): probes geometry dependence**

➡ **Same forward transverse energy (ΣE_T^{FCal}) or N_{part}: probes density dependence, similar UE**

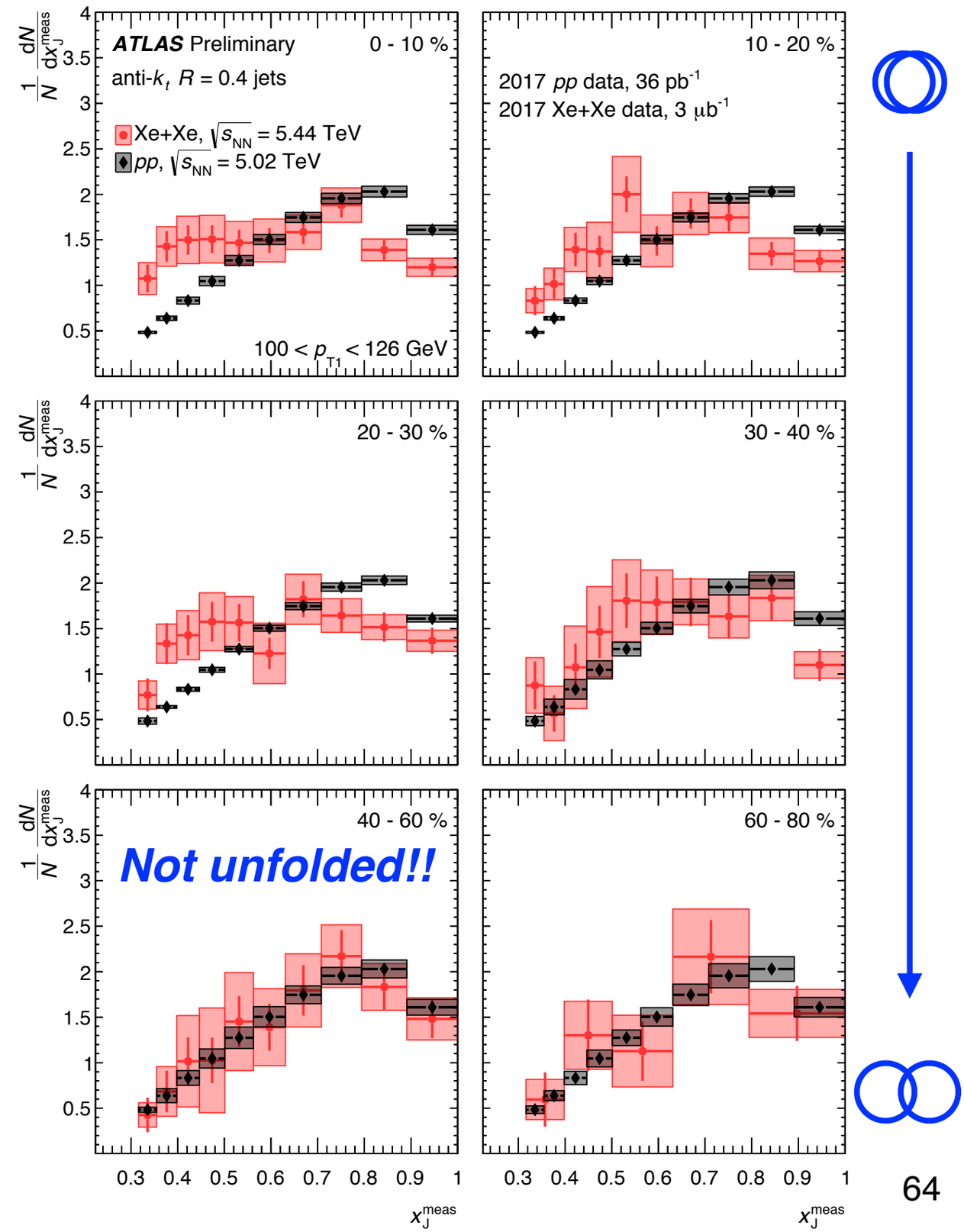


2017 Xe+Xe
2017 *pp*

x_J distribution

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

- **Centrality dependence shows similar evolution as previous Pb+Pb results**

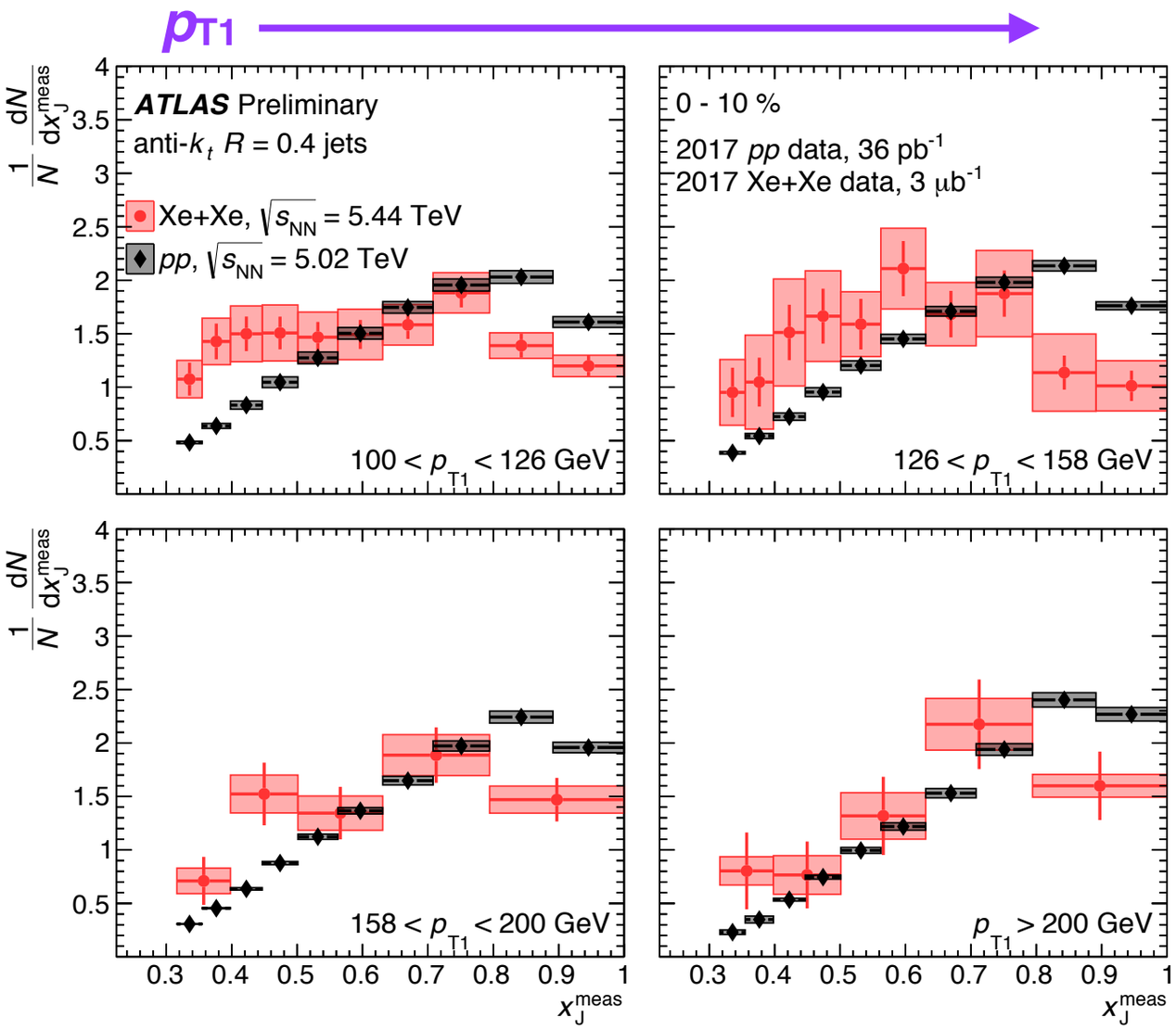


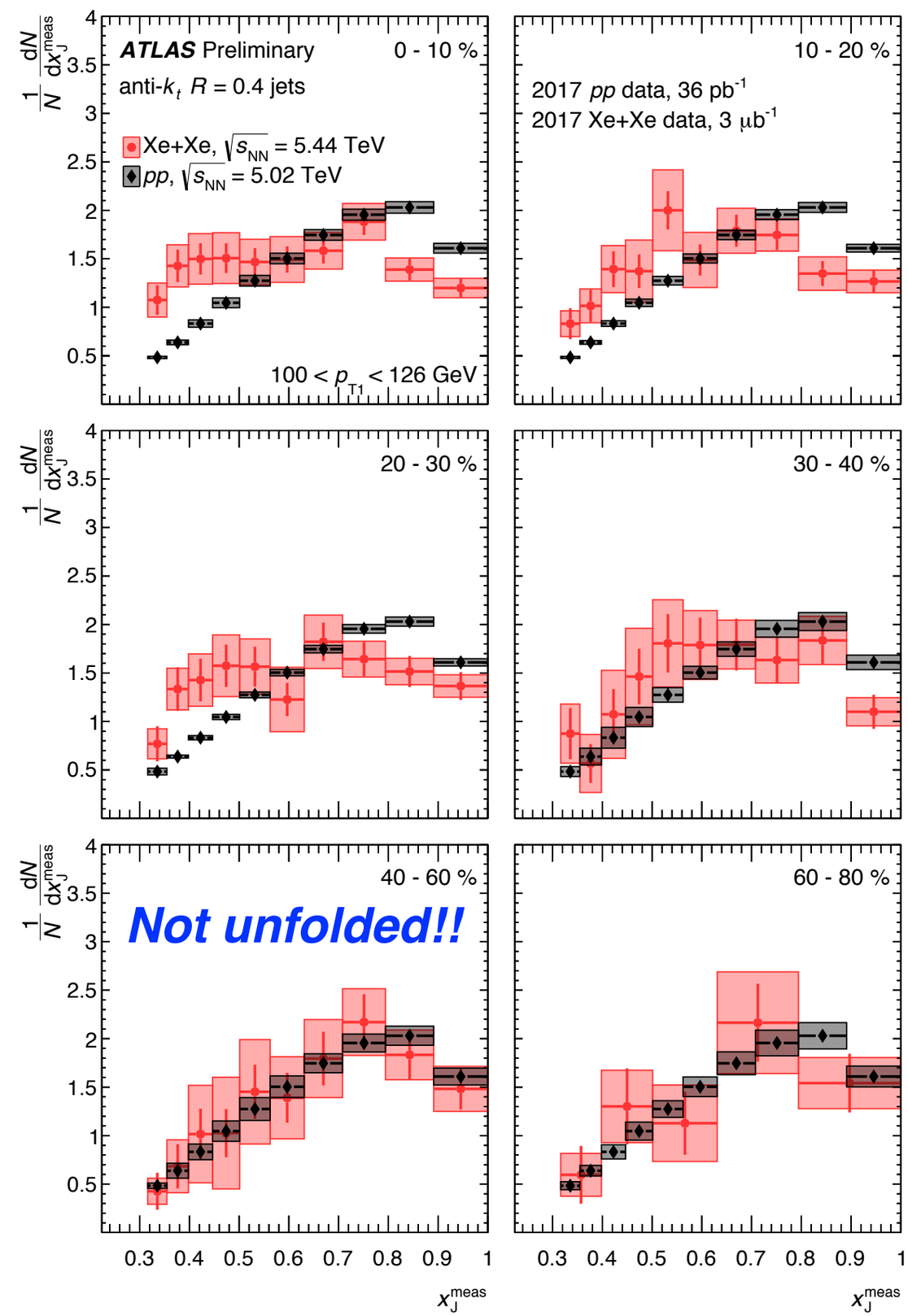
2017 Xe+Xe
2017 *pp*

x_J distribution

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

- **Centrality dependence shows similar evolution as previous Pb+Pb results**
- **p_{T1} dependence also shows similar features**





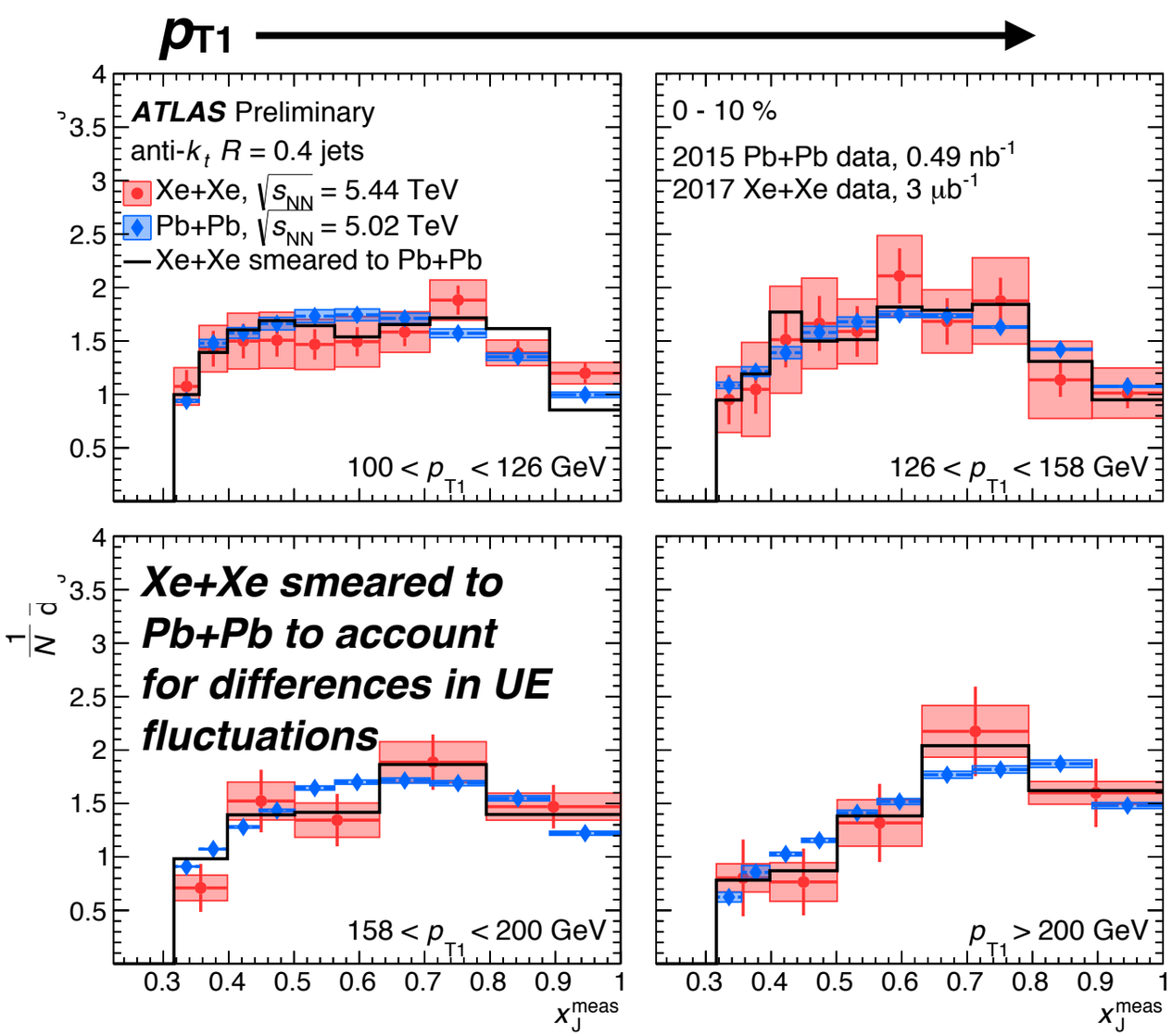
2017 Xe+Xe
2015 Pb+Pb

x_J distribution

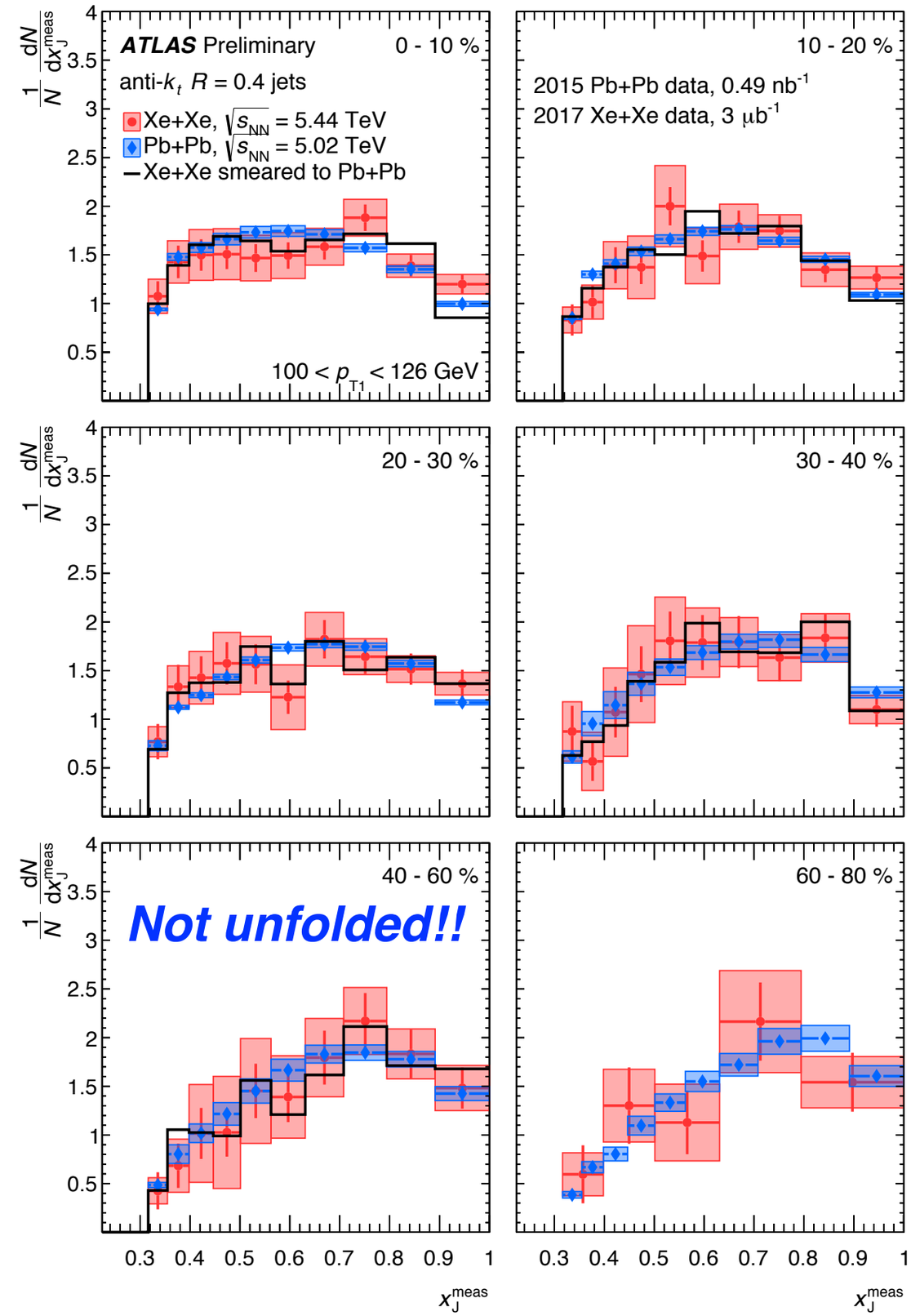
$$x_J = \frac{p_{T2}}{p_{T1}}$$

Similar geometry

- **x_J consistent between Pb+Pb and Xe+Xe for all centralities and p_{T1}**



Xe+Xe smeared to Pb+Pb to account for differences in UE fluctuations



Not unfolded!!

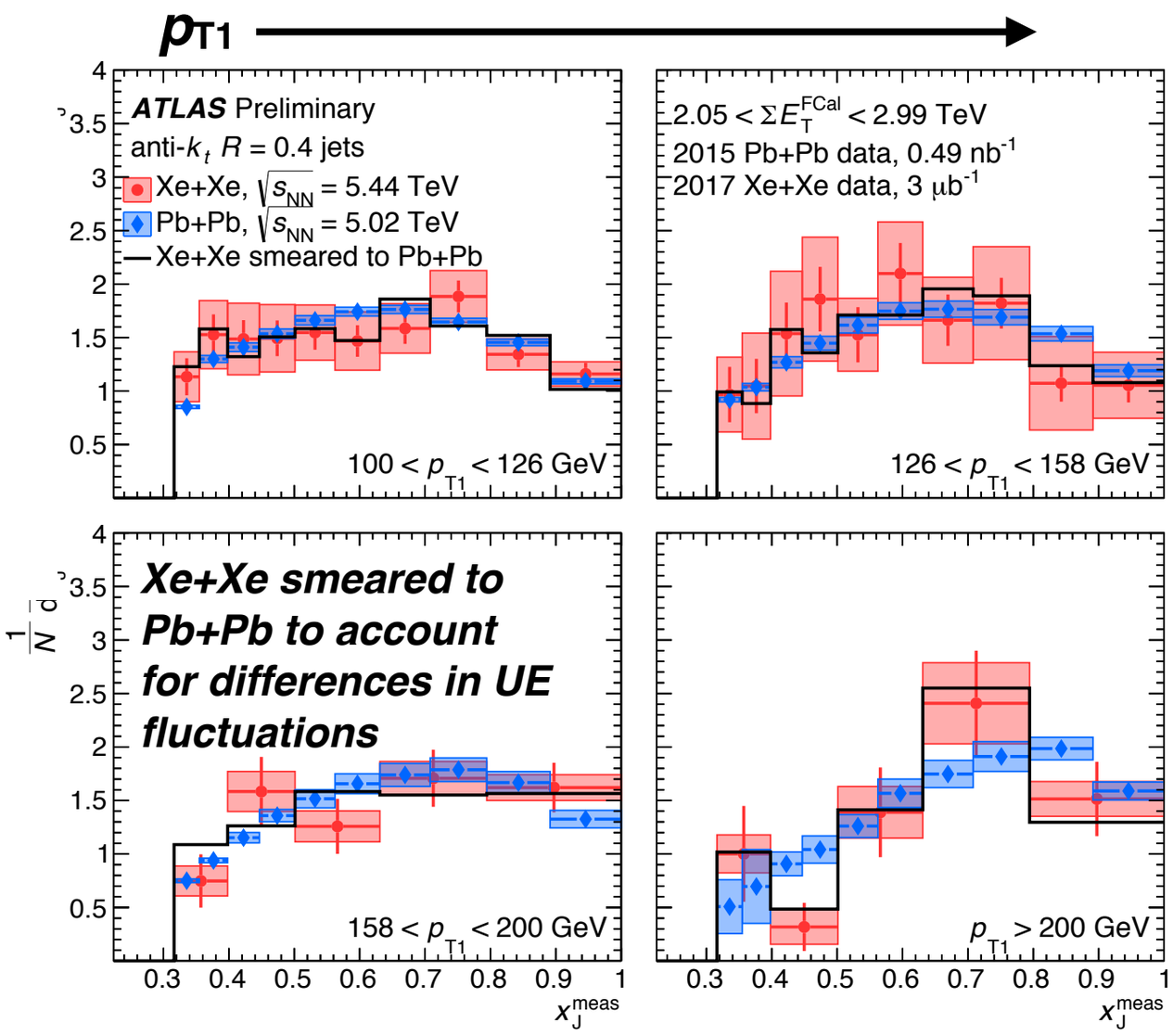
2017 Xe+Xe
2015 Pb+Pb

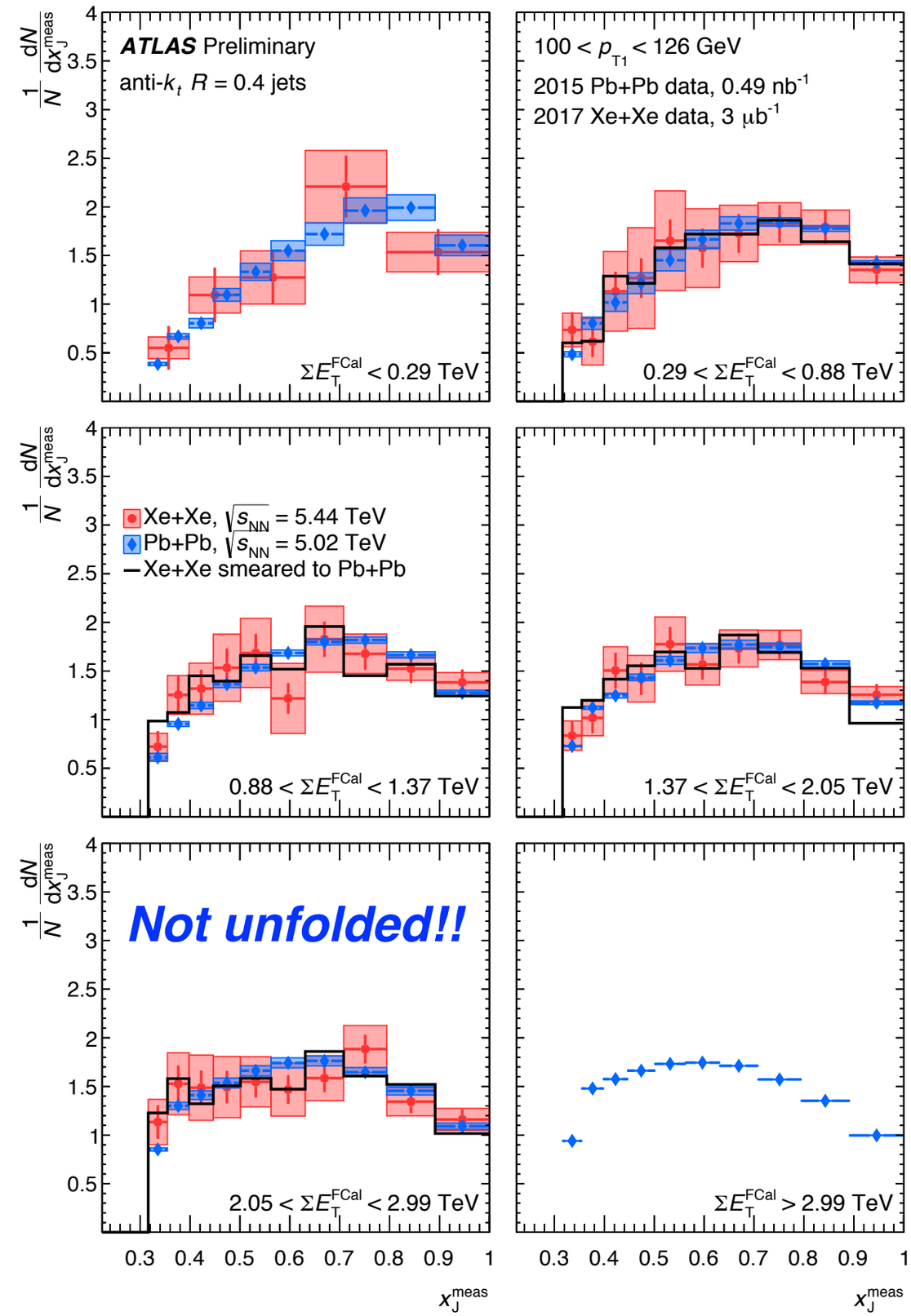
x_J distribution

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

Similar density

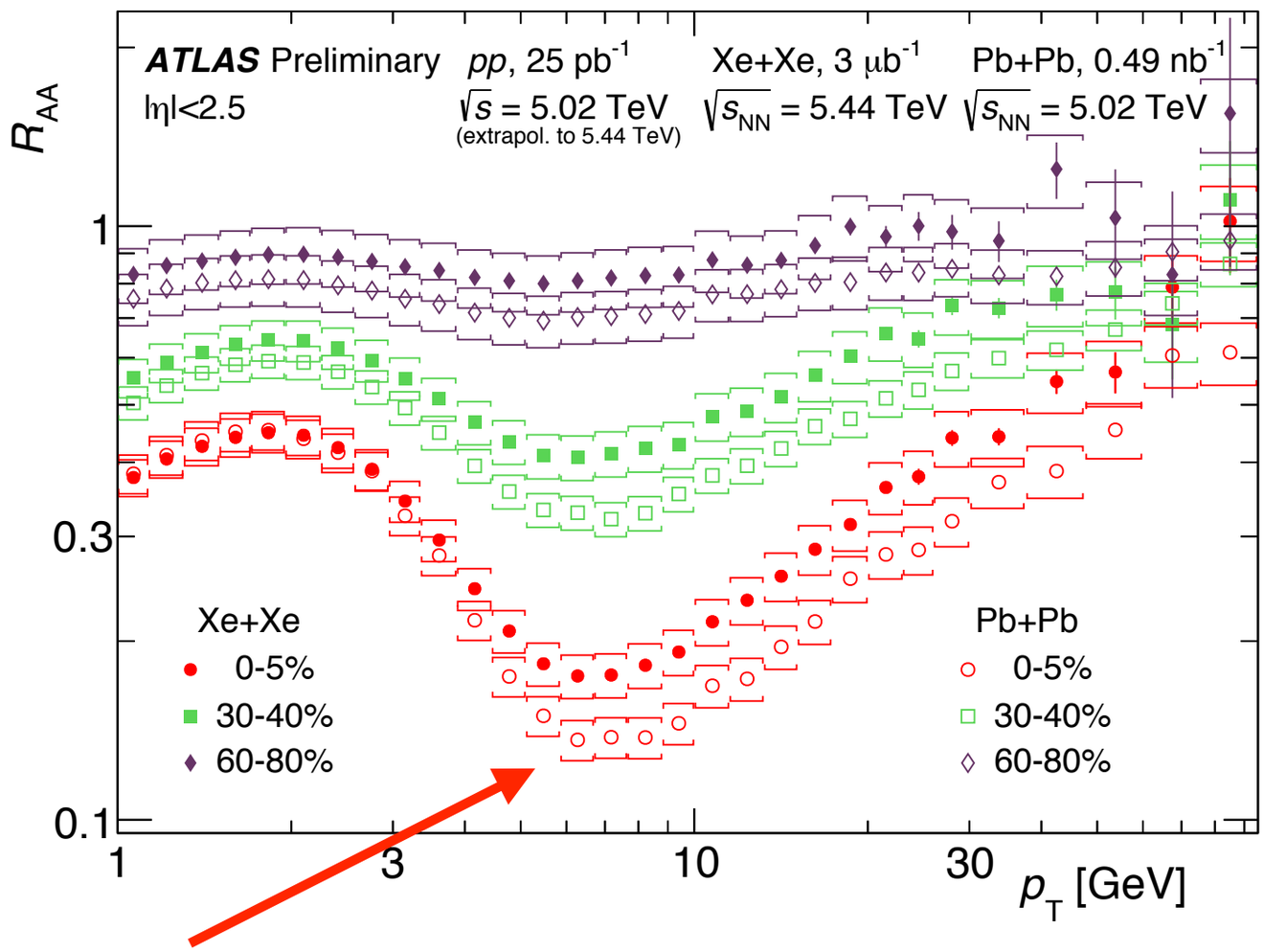
- **x_J consistent between Pb+Pb and Xe+Xe for all ΣE_T^{FCal} and p_{T1}**





Charged hadron R_{AA}

- **Compare Xe+Xe and Pb+Pb at the same centrality**

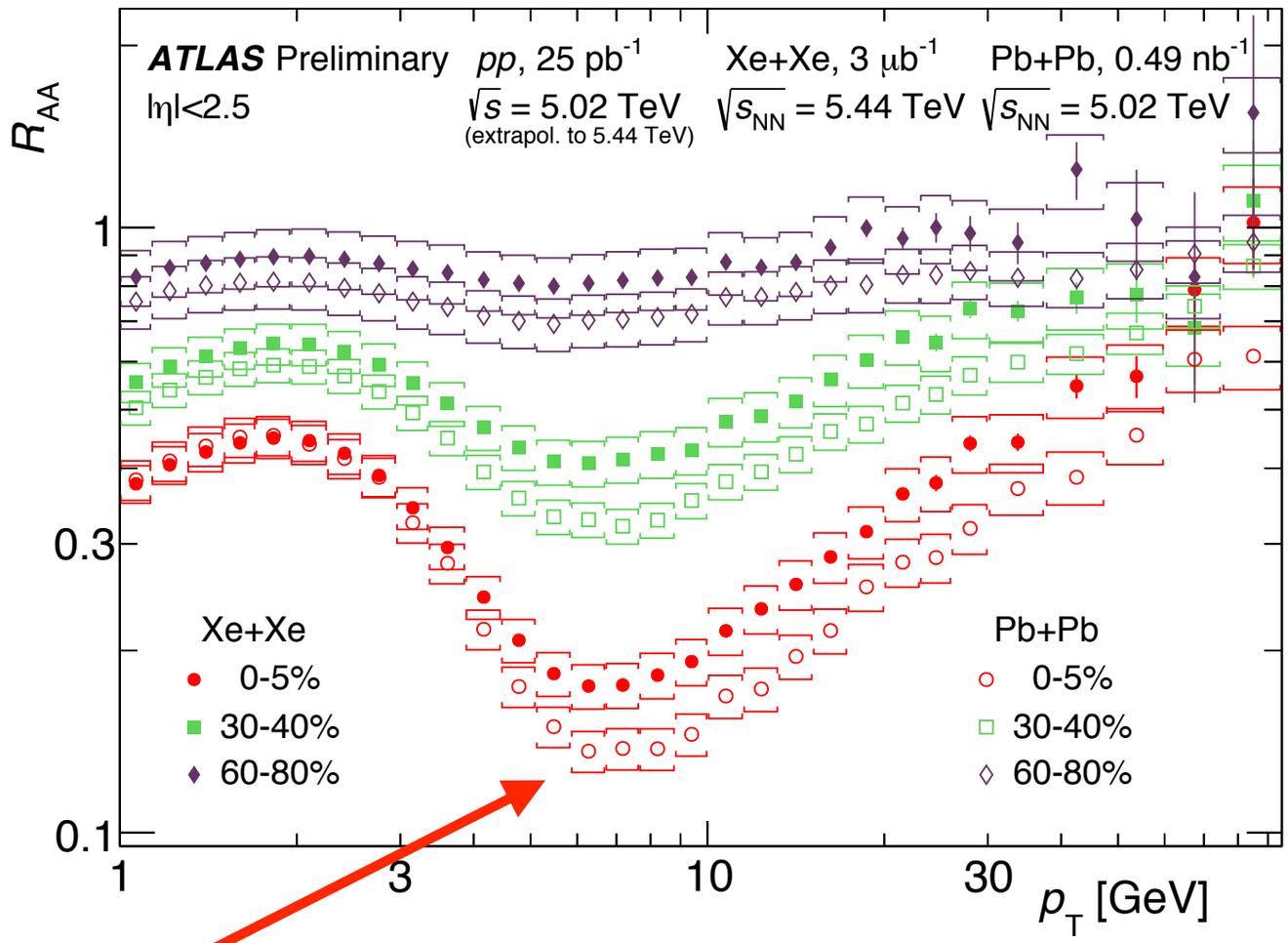


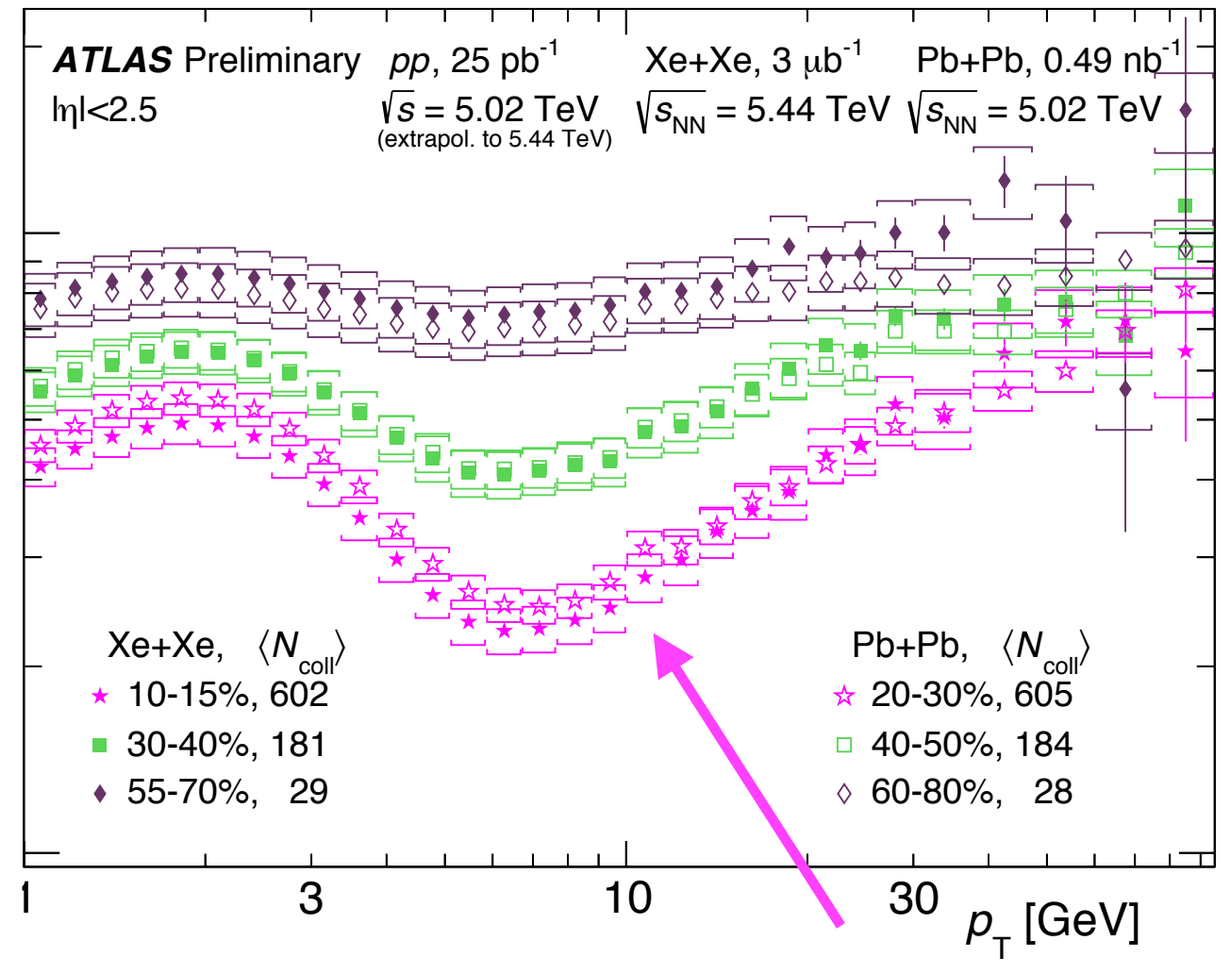
- **Xe shows less suppression than Pb**

- **Consistent p_T dependence between the two systems**

Charged hadron R_{AA}

- **Compare Xe+Xe and Pb+Pb at the same centrality**
- **Compare Xe+Xe and Pb+Pb at the same ΣE_T^{FCal}**

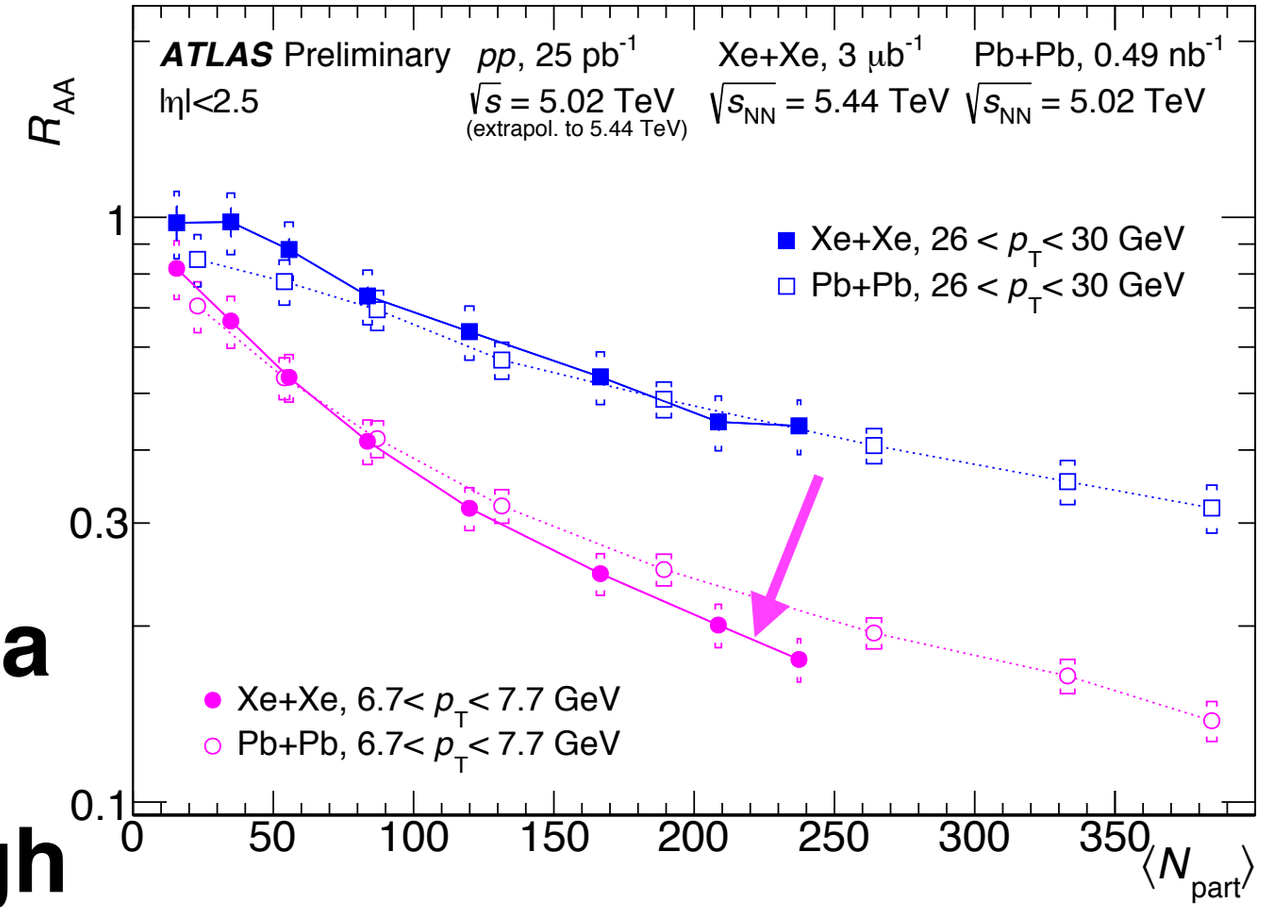




- **Xe shows less suppression than Pb**
- **Consistent results between Xe and Pb for same N_{coll}**
- **Consistent p_T dependence between the two systems**

Charged hadron R_{AA}

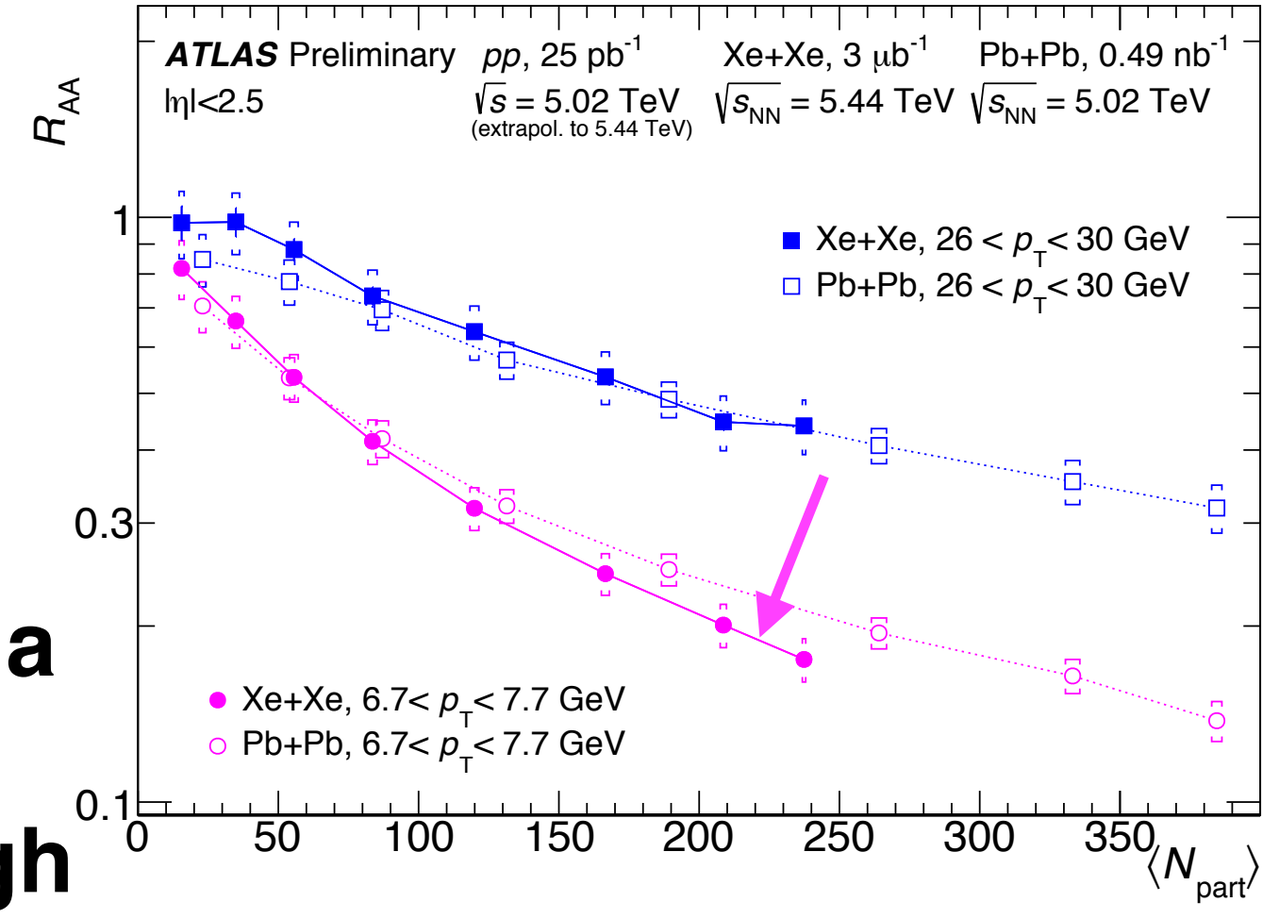
- **Compare Xe+Xe and Pb+Pb as a function of N_{part} shows a similar decrease with more suppression in Xe+Xe at high N_{part} and low hadron p_T**

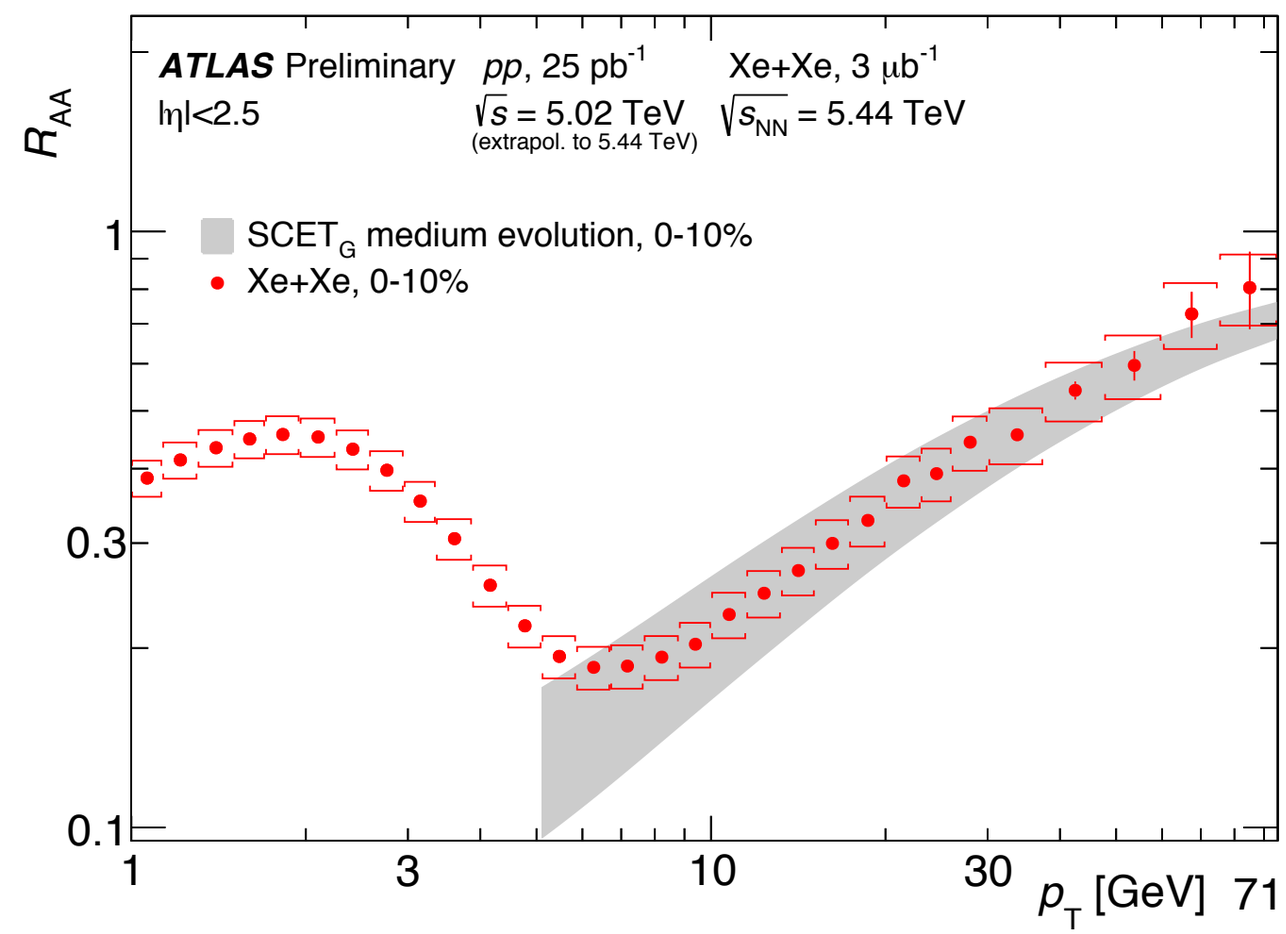


Charged hadron R_{AA}

- **Compare Xe+Xe and Pb+Pb as a function of N_{part} shows a similar decrease with more suppression in Xe+Xe at high N_{part} and low hadron p_T**

- **Xe+Xe is consistent with theoretical calculations**





Conclusion

- **Wide variety of new results from ATLAS with new datasets at 5.02 TeV**
  - ➡ **Precision results on jet quenching see suppression up to a TeV, dijet and γ+jet asymmetry, and modification of jet structure in jet and γ+jet systems**
  - ➡ **Jet mass and shape measurements**
  - ➡ **New Xe+Xe results**
- **Era of precision measurements with careful underlying event subtraction, reduced systematic uncertainties, and unfolding for detector effects.**
  - ➡ **Many measurements compared to theoretical calculations which can help constrain models**

▸ **Looking forward to Pb+Pb data at 5.02 TeV in 2018!**

Backup

Performance

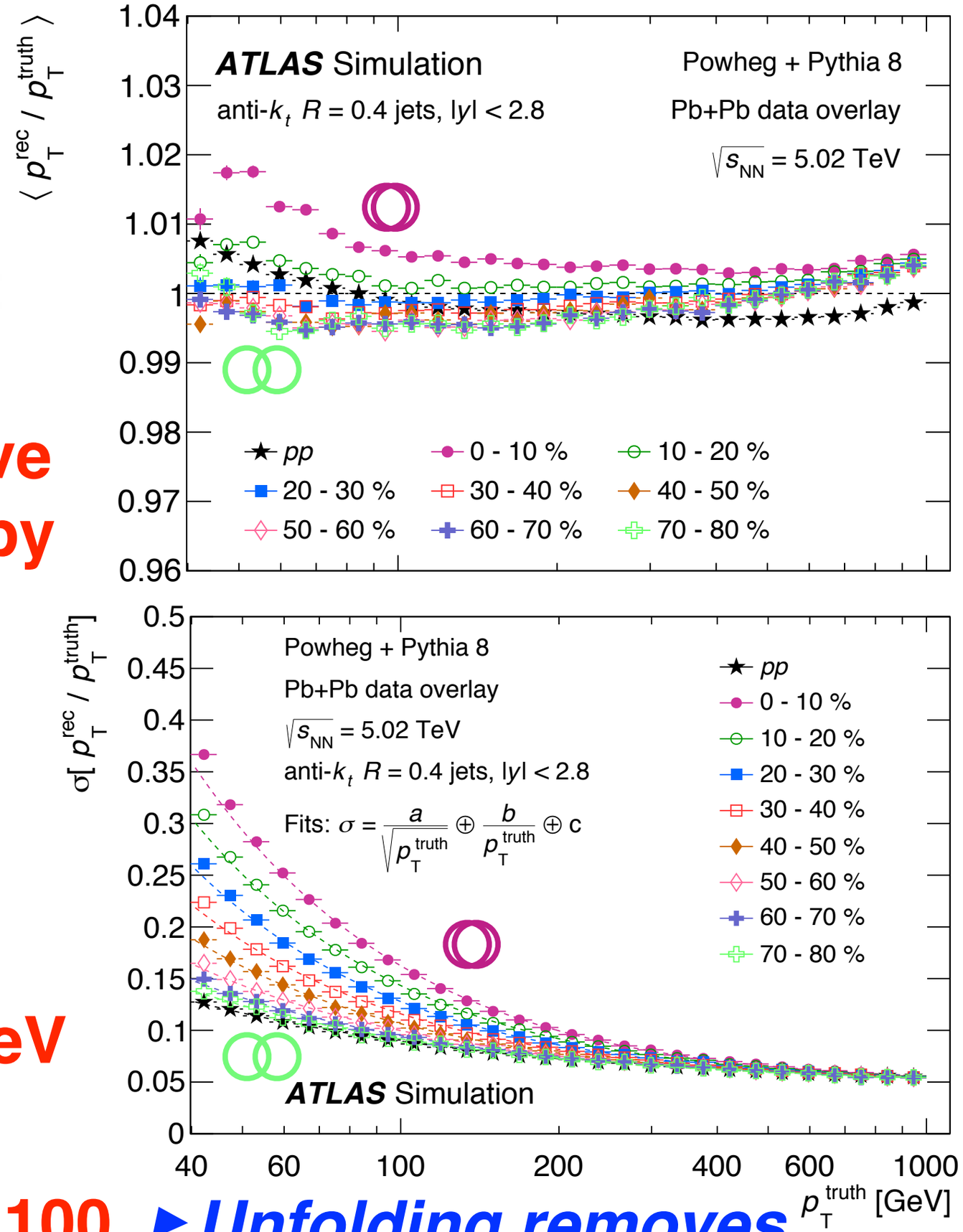
- **Large uncorrelated underlying event (UE) that varies with η, Φ and event**

➡ **Subtracted with iterative procedure modulated by harmonic flow**

- **MC jets are embedded into real Pb+Pb data and reconstructed in the same way as data**

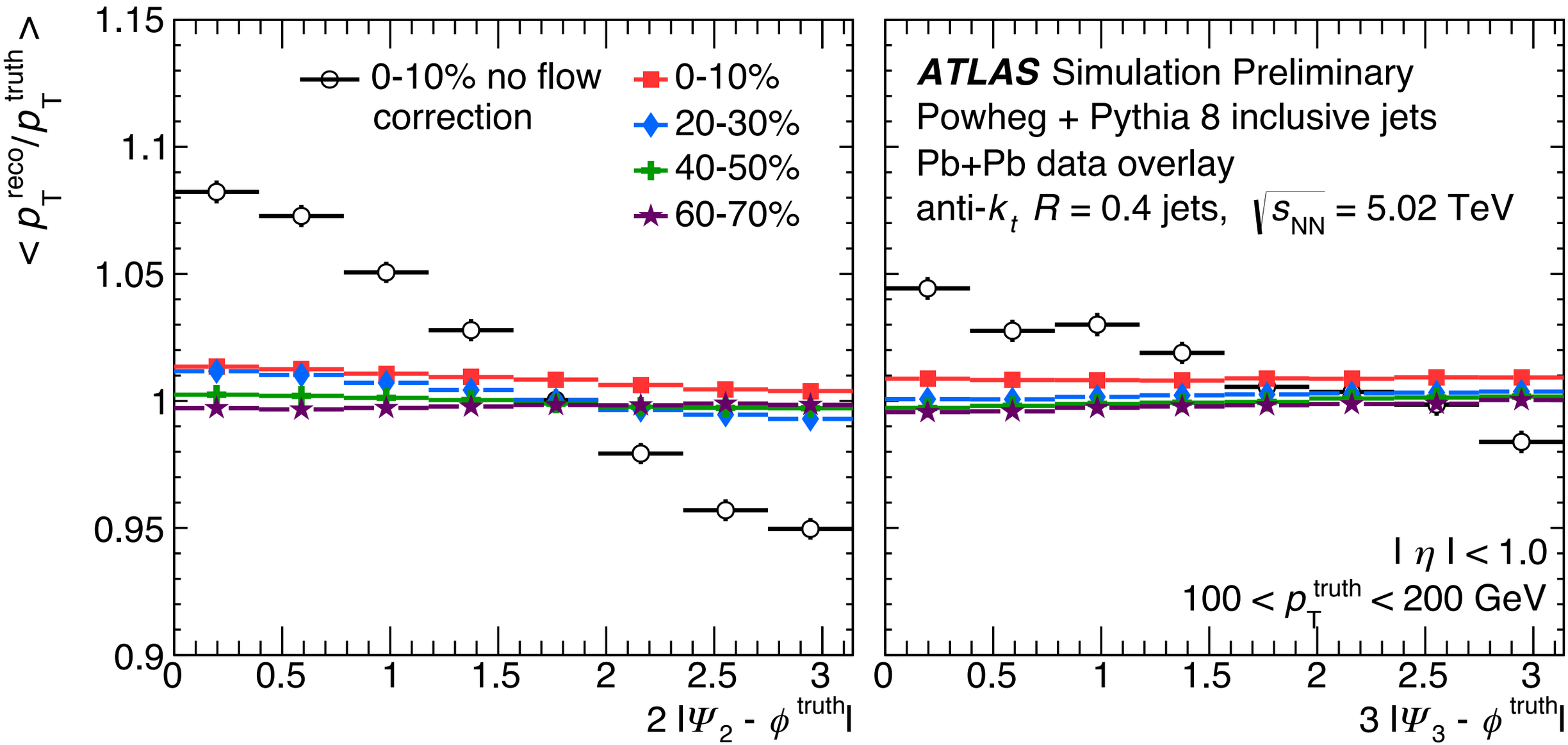
➡ **JES is ~1% above 100 GeV for 0-10%**

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

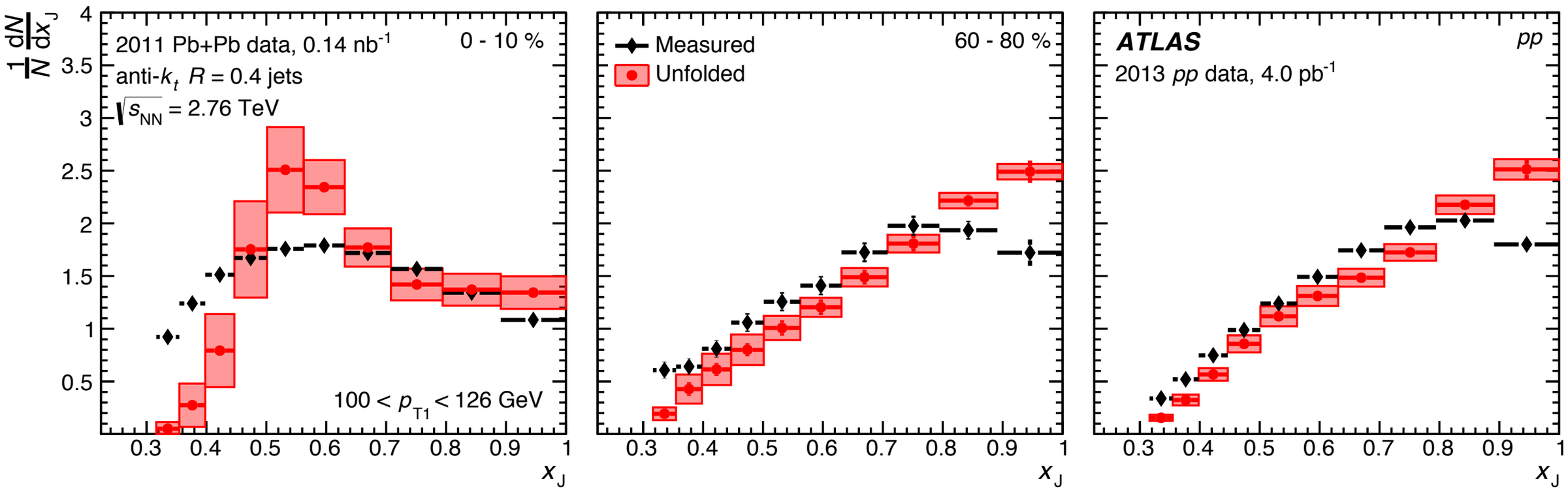


▶ ***Unfolding removes remaining JES/JER***

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***

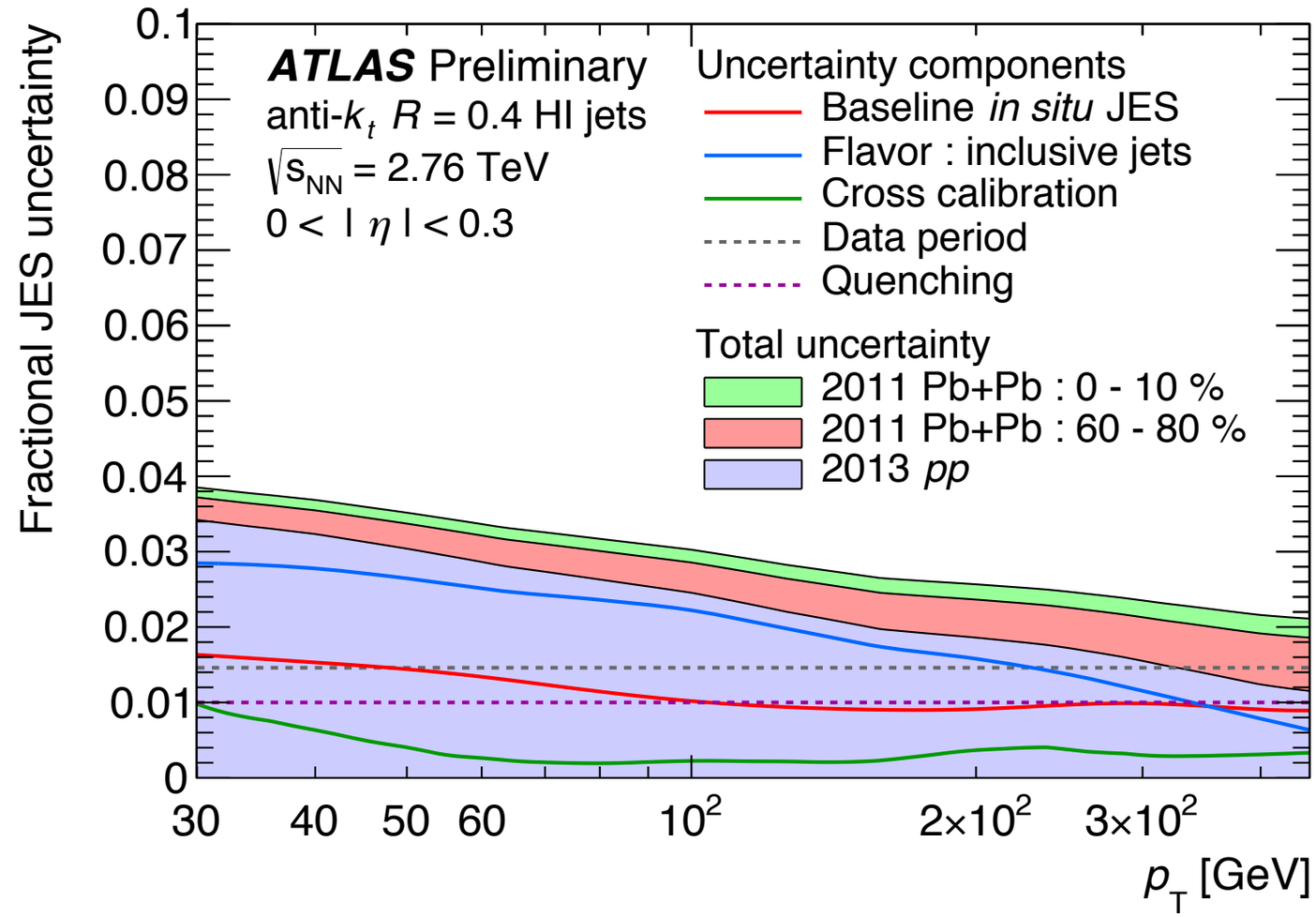
x_J systematics

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)**



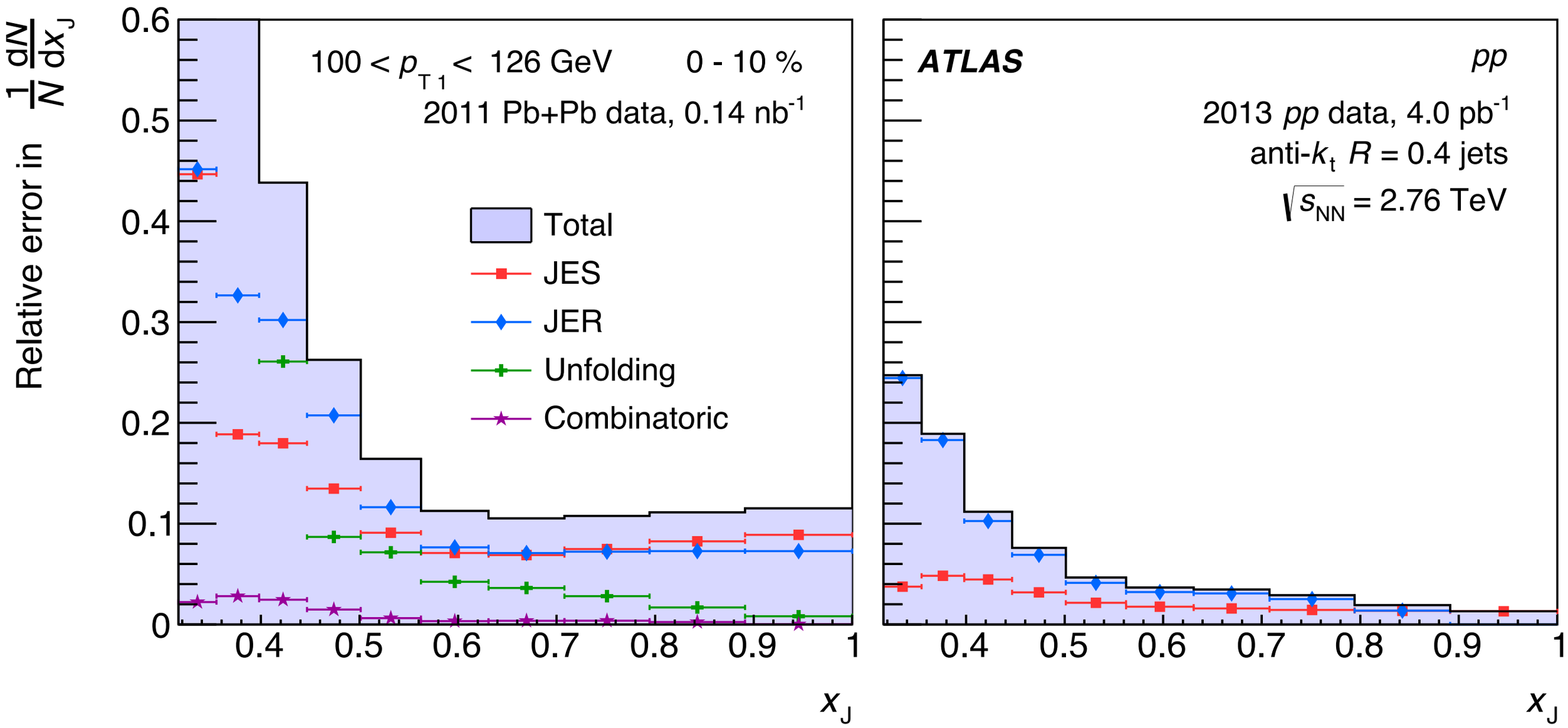
➡ **Evaluated by rebuilding the response matrix with a systematically varied relationship between the true and reconstructed jet kinematics**

► ***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

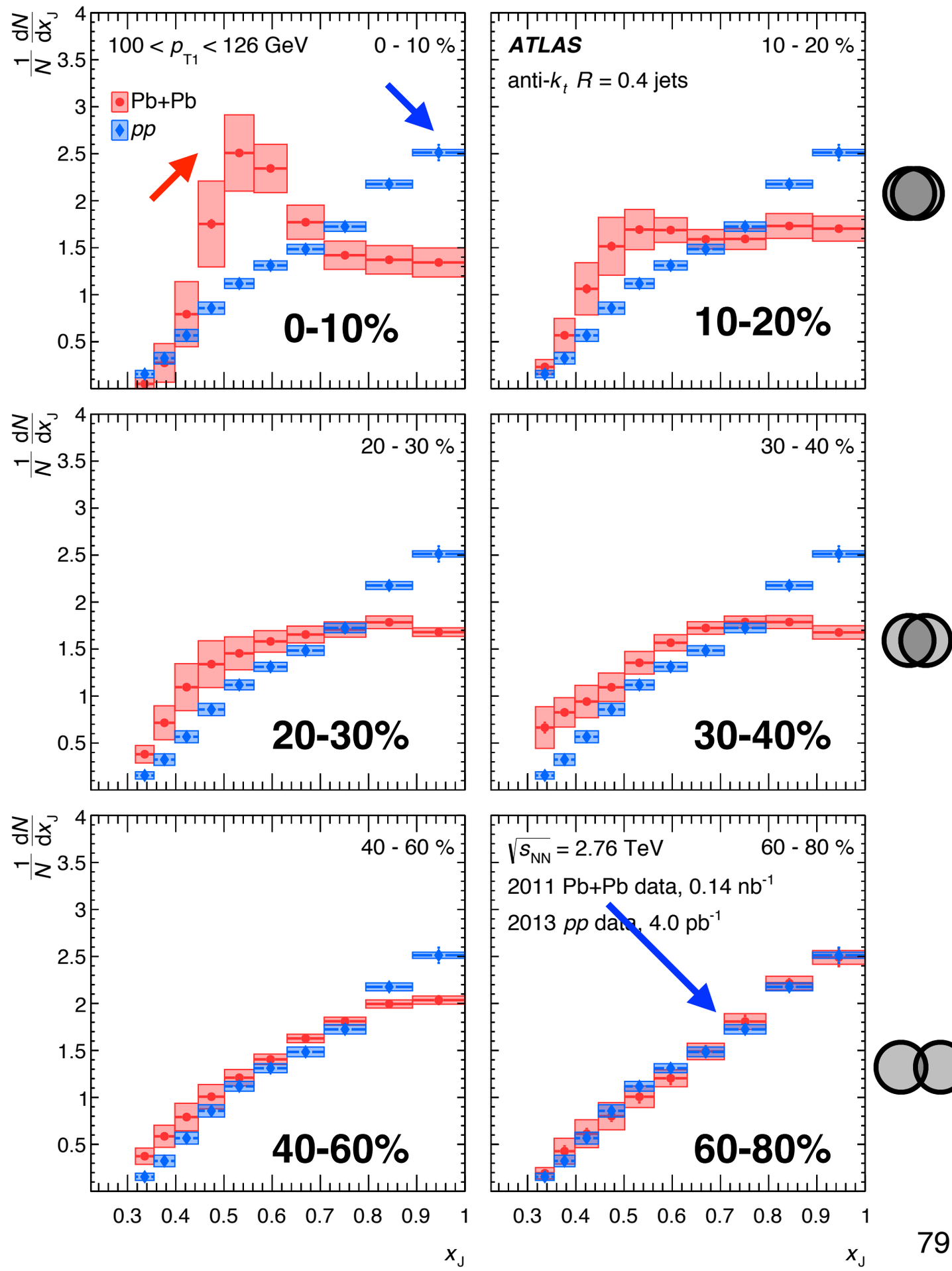


x_J distribution

centrality dependence

$100 < p_{T1} < 126$ GeV

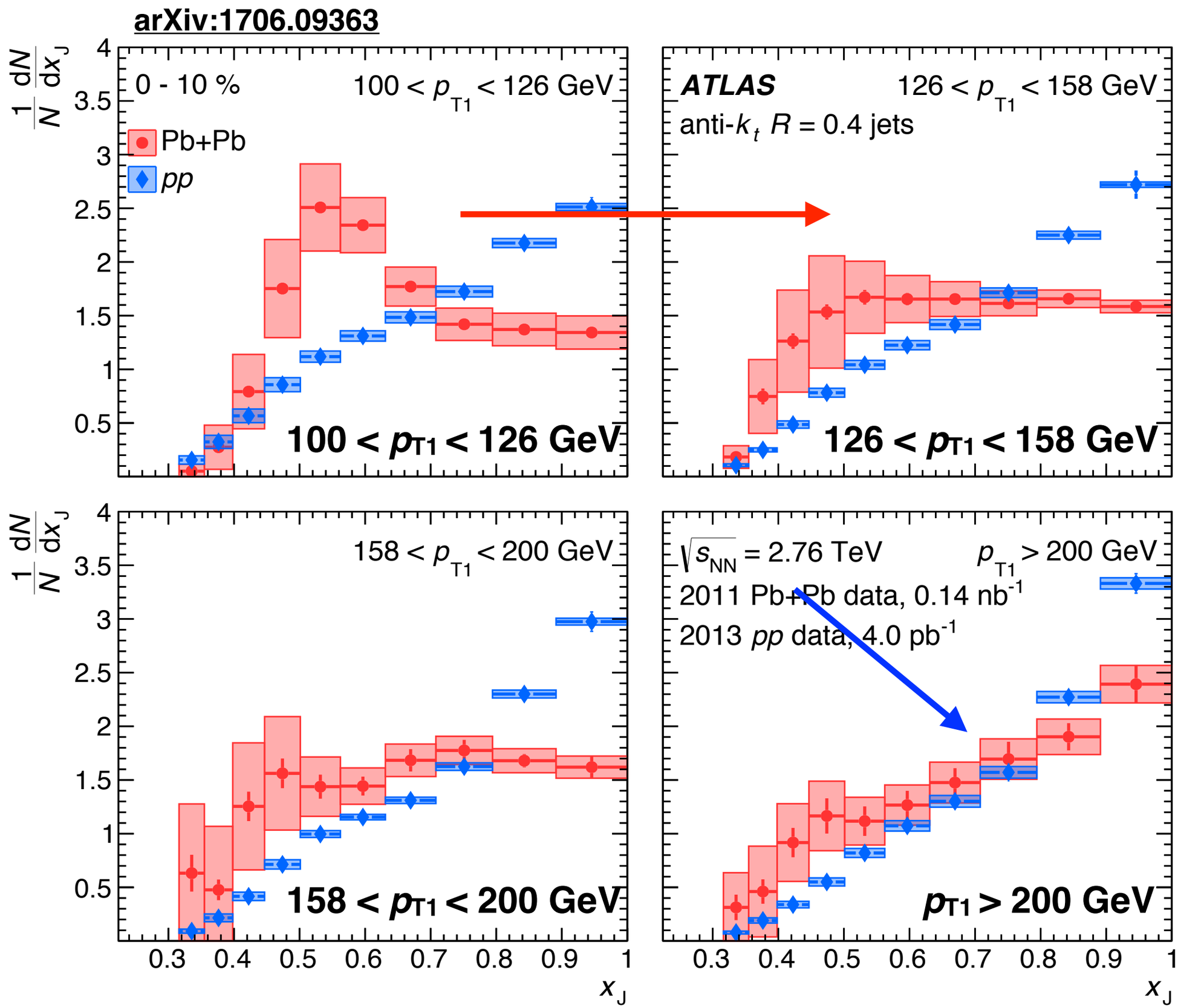
- **x_J in Pb+Pb is more asymmetric in more central collisions.**
- **The most probable configuration for *pp* collisions is $x_J \sim 1$.**
- **For central Pb+Pb collisions it is $x_J \sim 0.5$.**
- **As Pb+Pb becomes more peripheral the x_J is like in *pp*.**



arXiv:1706.09363

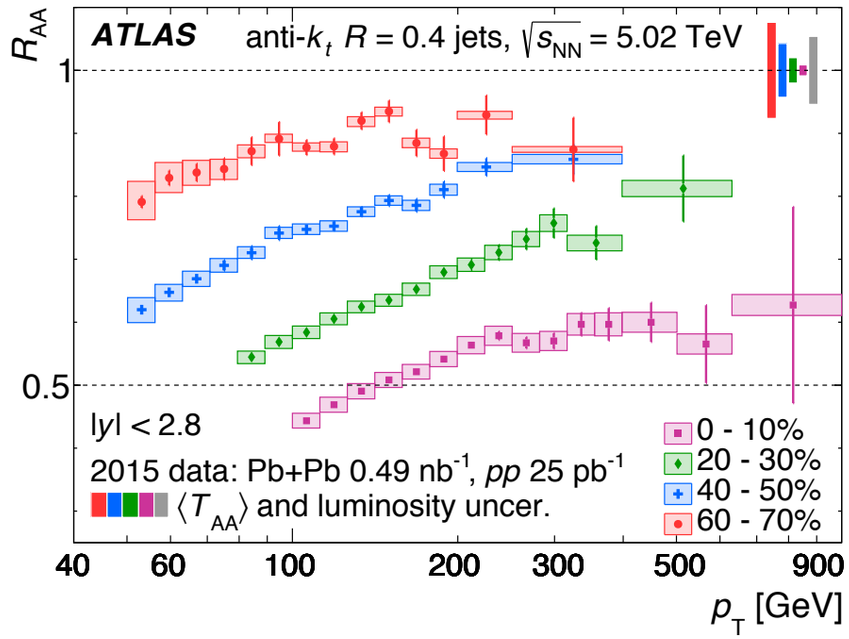
x_J distribution

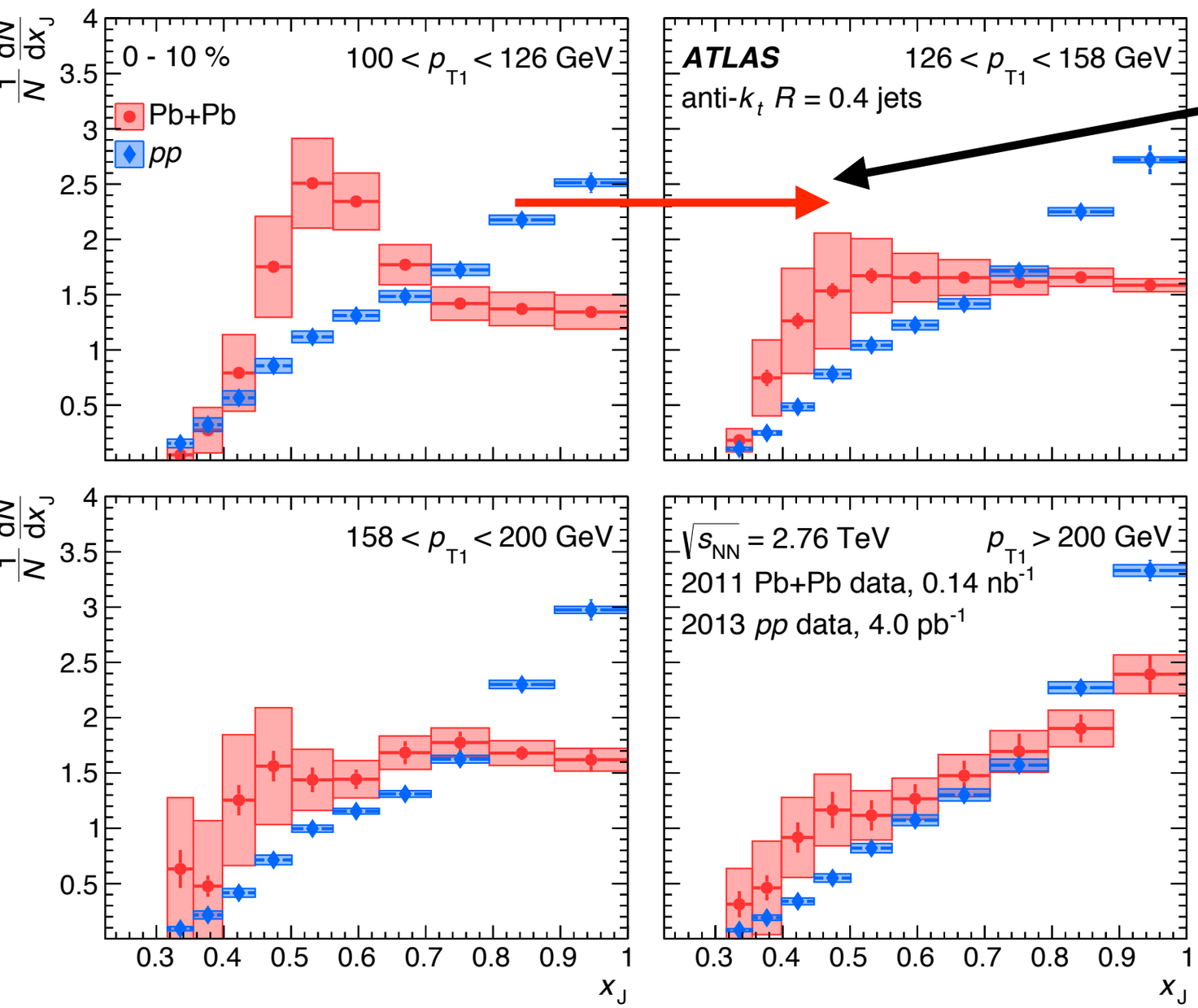
p_{T1} dependence
0-10%



- **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!***

p_{T1} dependence 0-10%





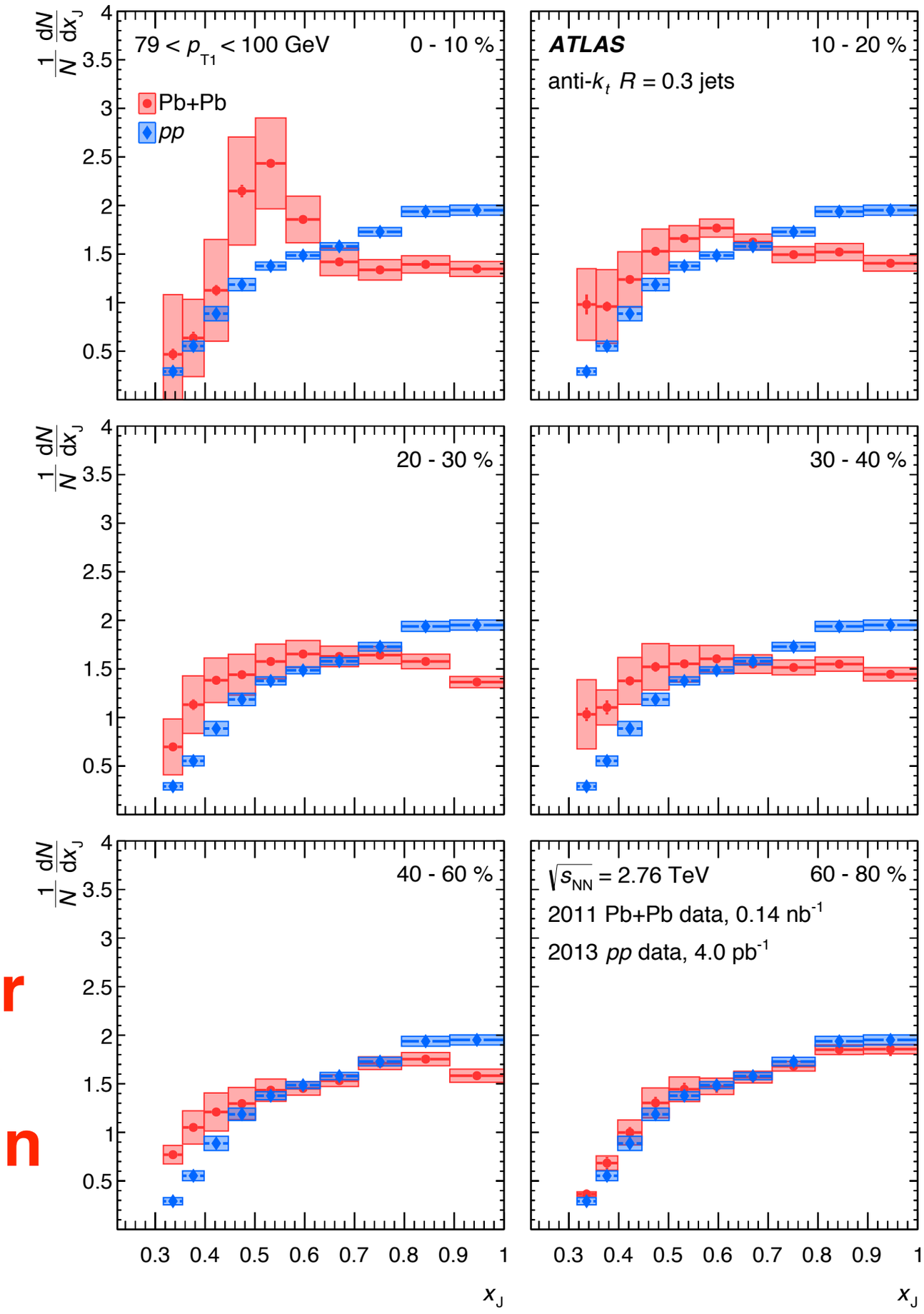
- **Is the strong p_T dependence of the differential jet measurement x_J is in contrast with the weak dependence in the inclusive jet measurement R_{AA}?**

➡ **Dijets measure relative jet energy loss**

R=0.3 x_J

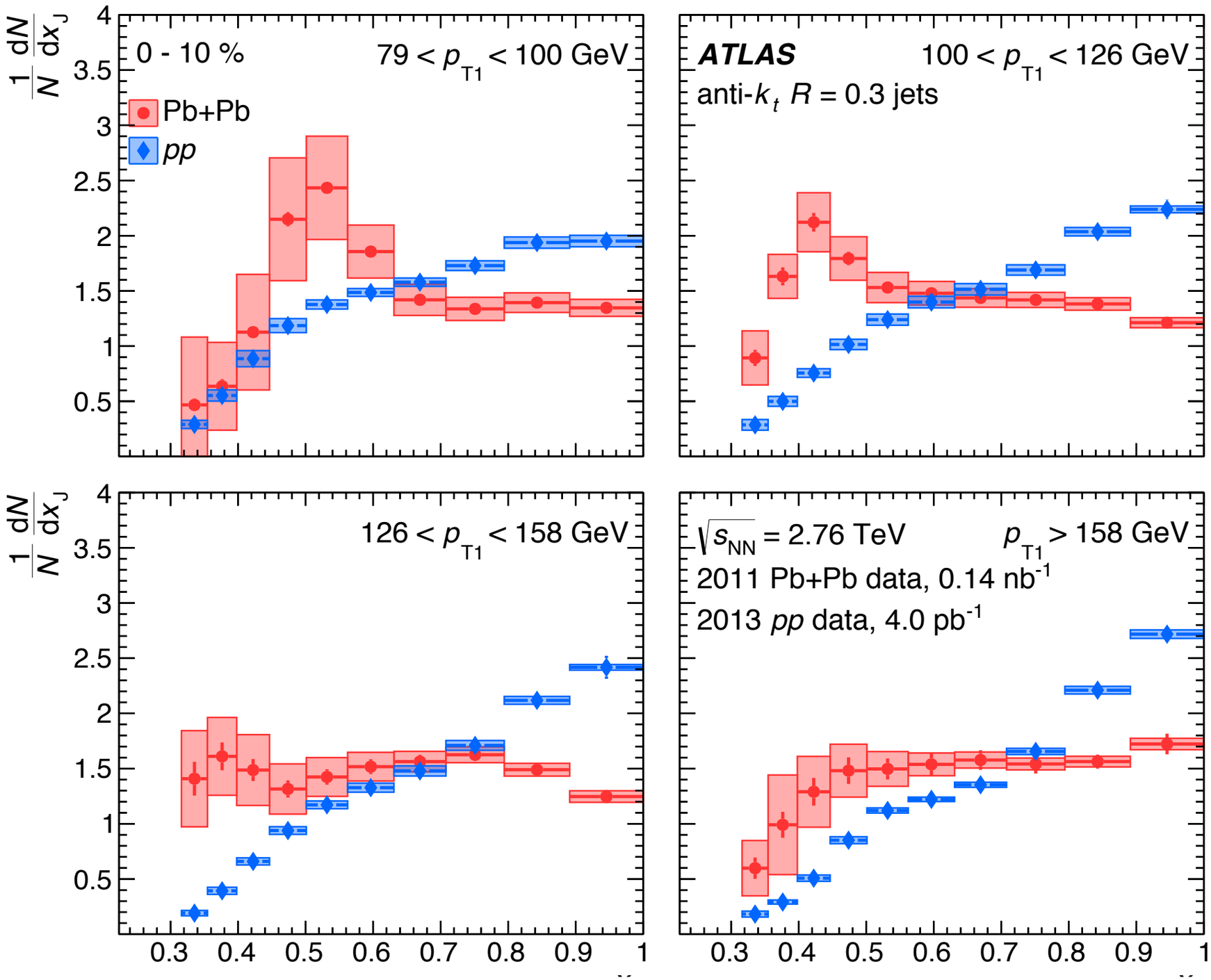
Centrality dependence of Pb+Pb compared to *pp* dijets for 79<p_{T1}<100 GeV.

- **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.**

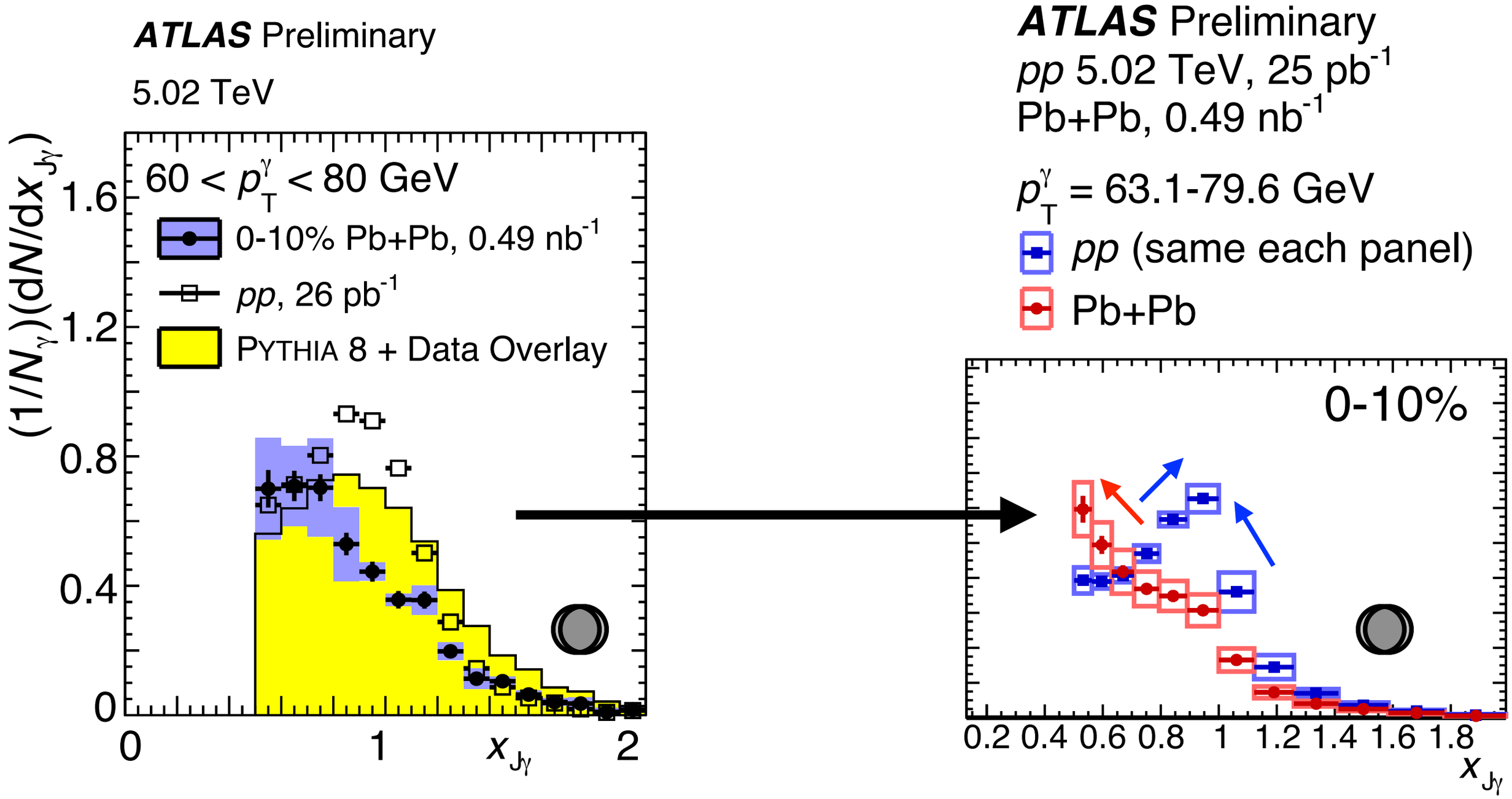


R=0.3 x_J p_{T1} dependence

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

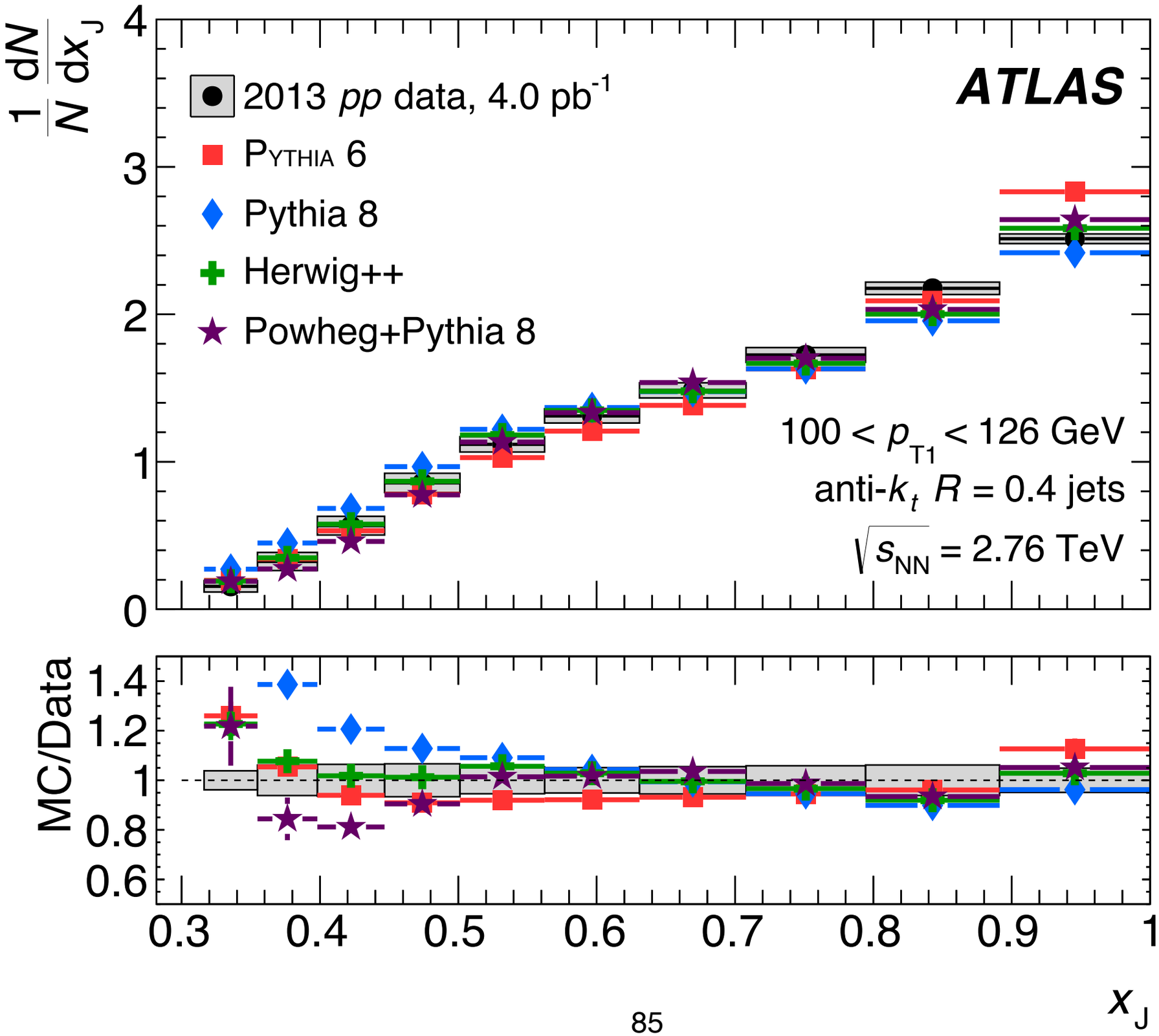


Effect of unfolding



- ***pp* moves jets the sharp peak at $x_{J\gamma} \sim 1$**
- **Central Pb+Pb depletes peak at 1 and moves jets to a rise around $x_{J\gamma} \sim 0.5$**

x_J *pp* data to MC comparison

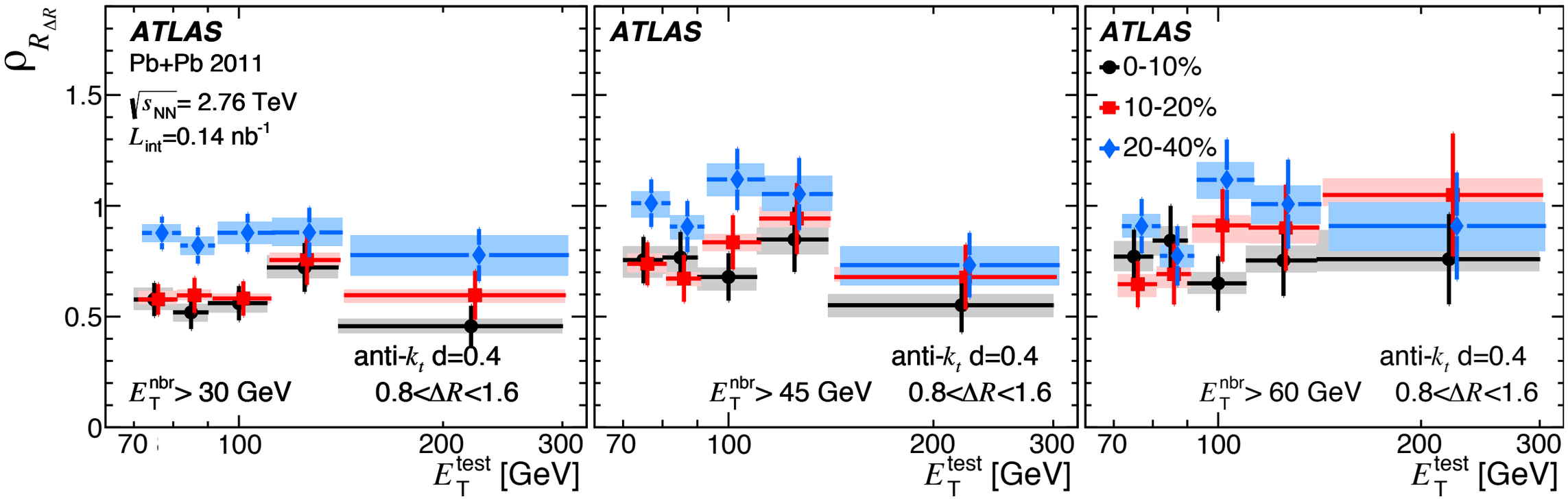


85

x_J 3rd jet

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

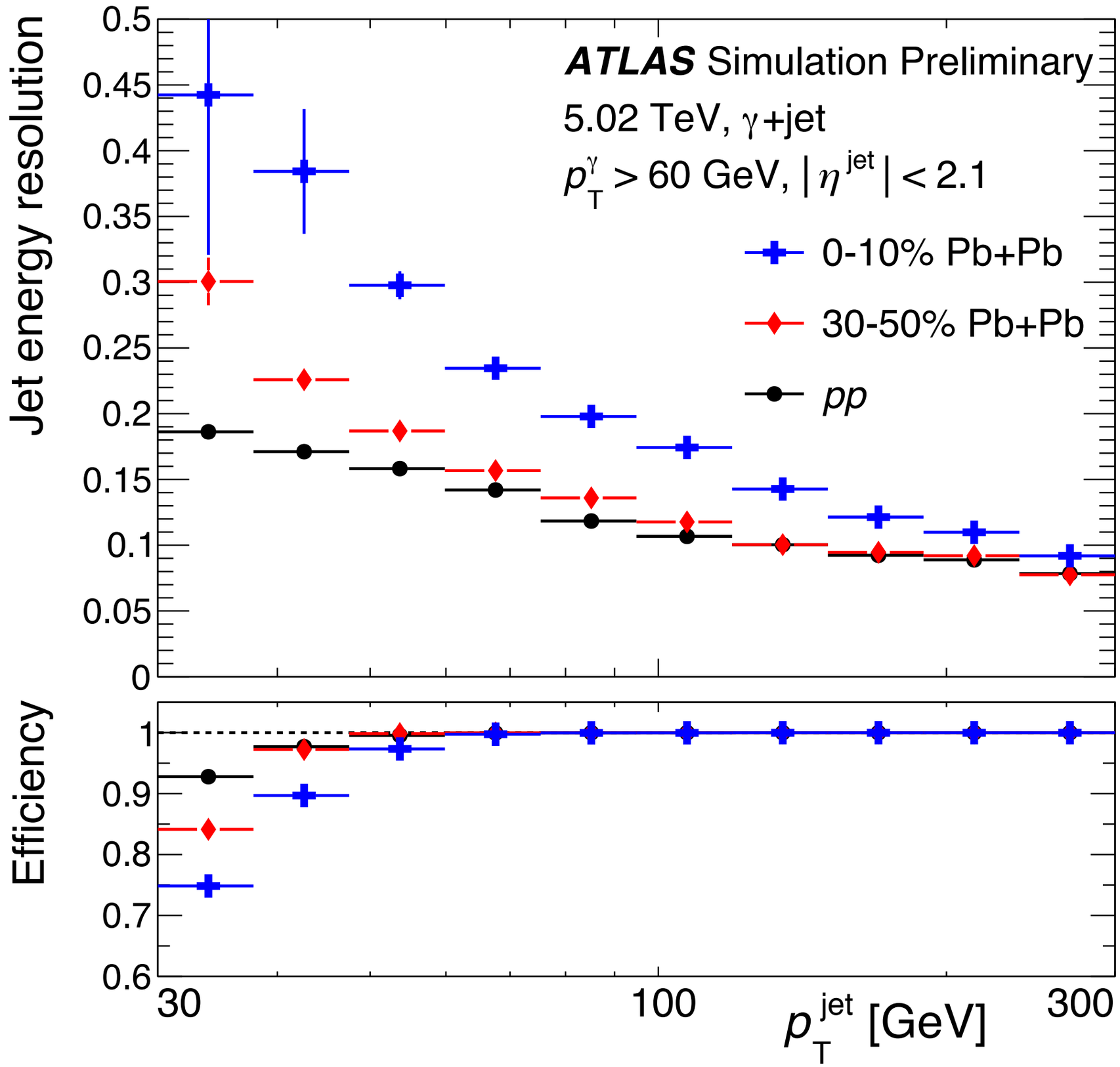
PLB 751 (2015) 376



- **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**

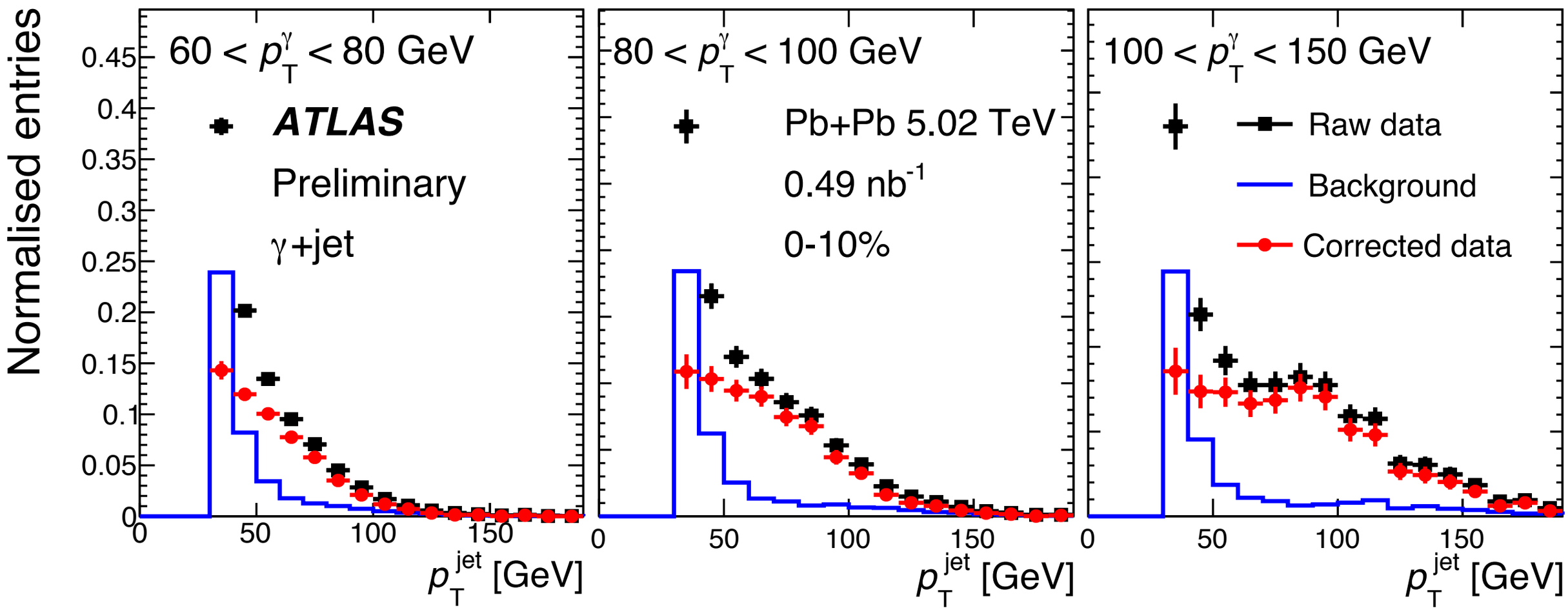
➡ **Deviations from the result was well within the systematics of the measurement**

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 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**



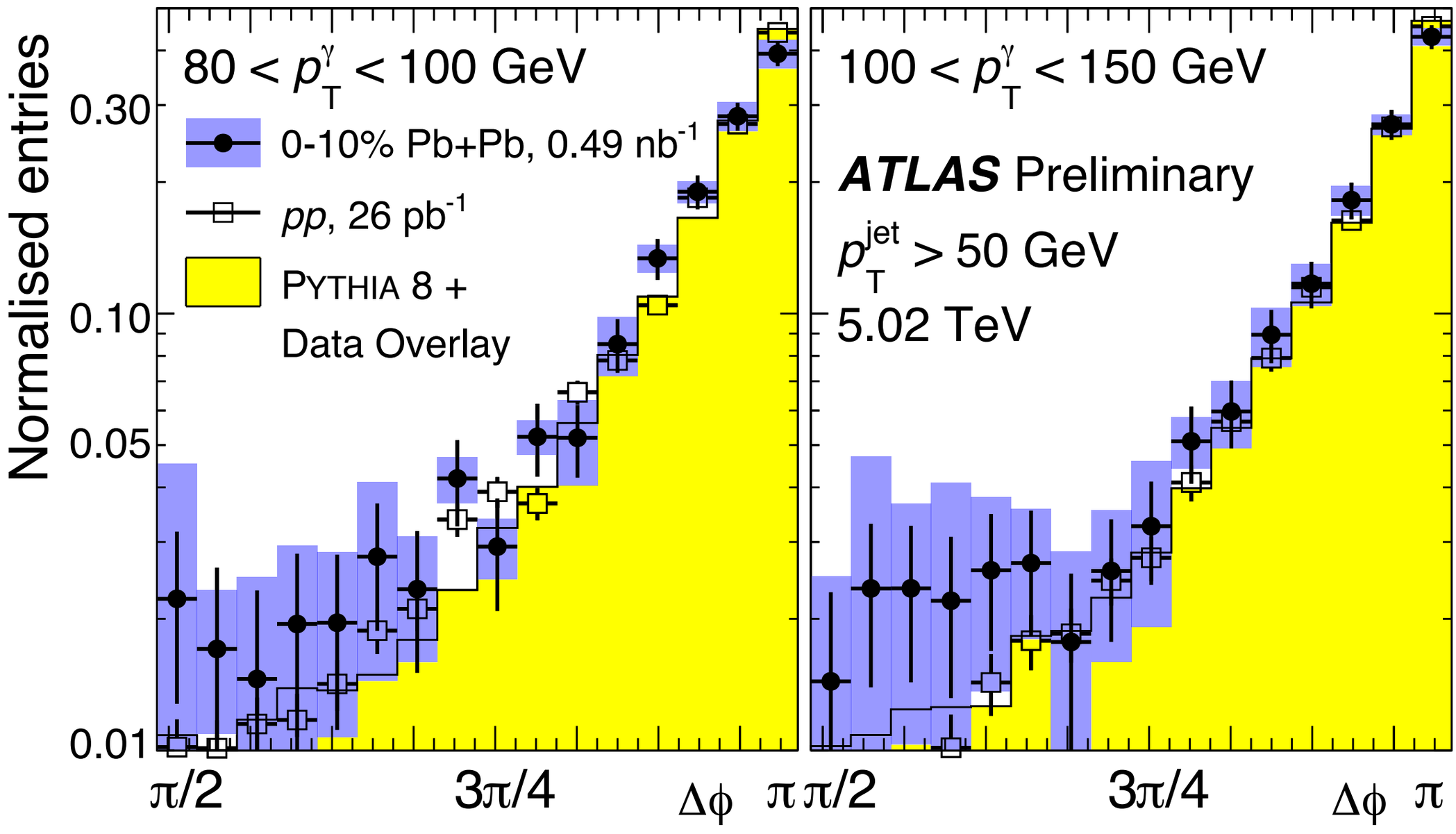
▶ **Combinatoric important at low p_T, dijet at high p_T**

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 angular correlations

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

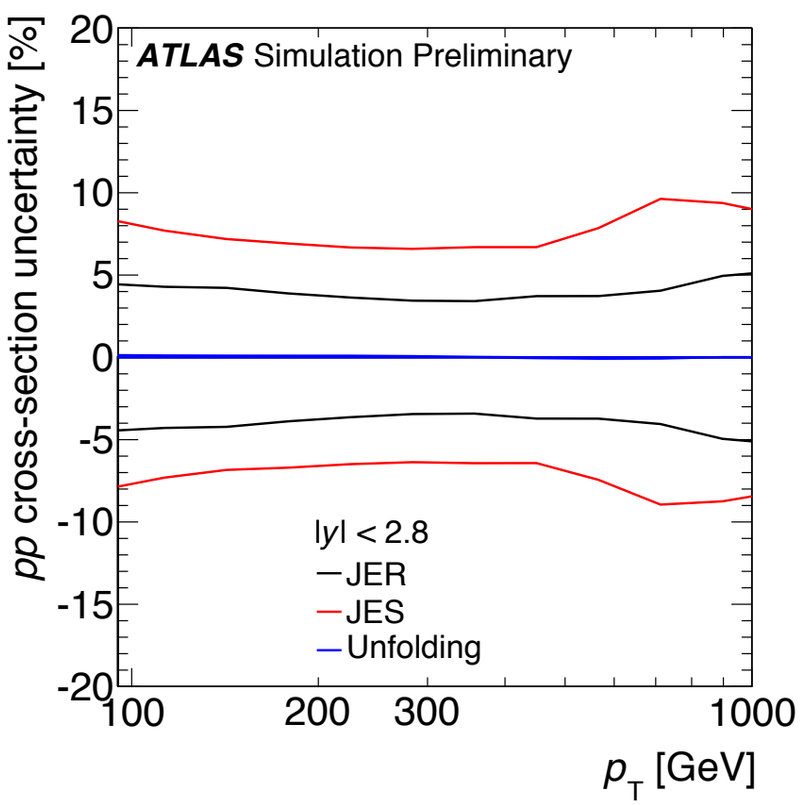


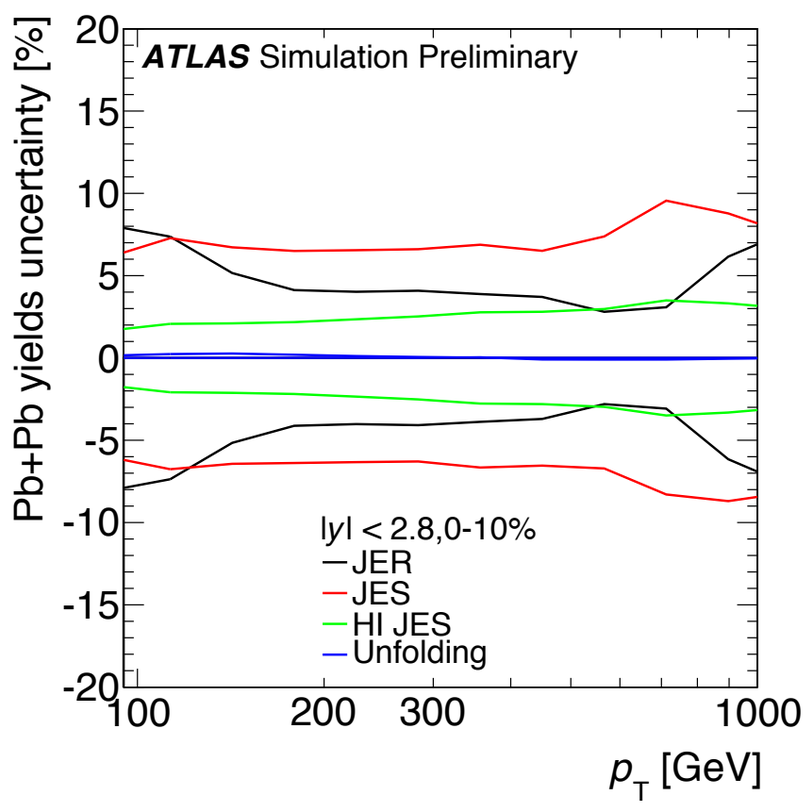
R_{AA} systematic uncertainties

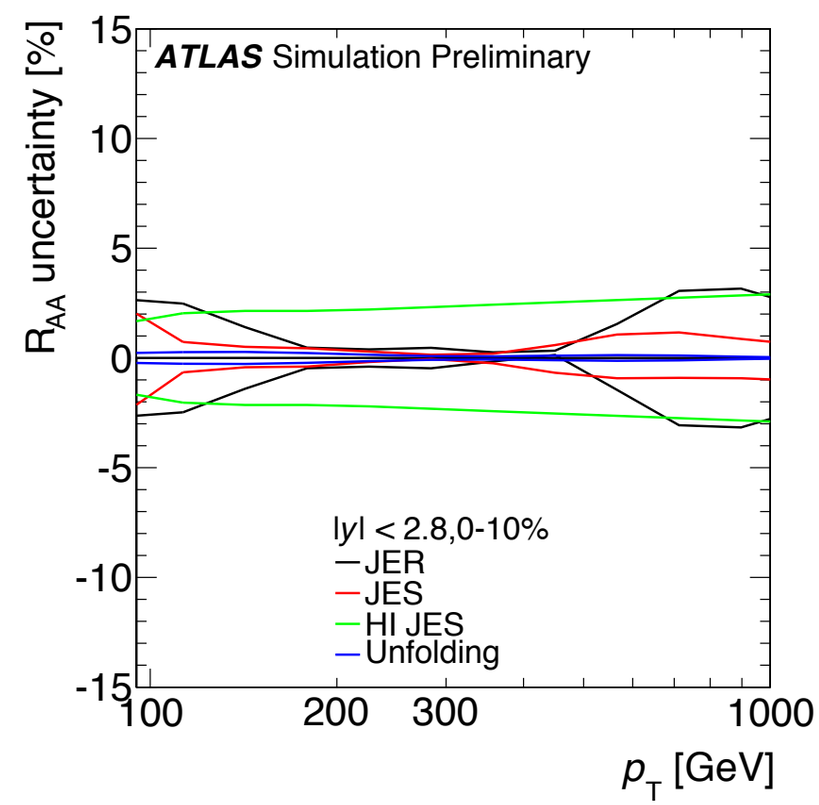
- **Jet energy scale**
  - ➡ **Standard *pp* JES components + 5 TeV flavor and HI cross-calibration (following ATL-CONF-2015-016)**
  - ➡ **HI specific uncertainty due to jet quenching (estimated using studies of the ratio of calo-jet to track-jet p_T)**
- **Jet energy resolution**
  - ➡ **Standard *pp* 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

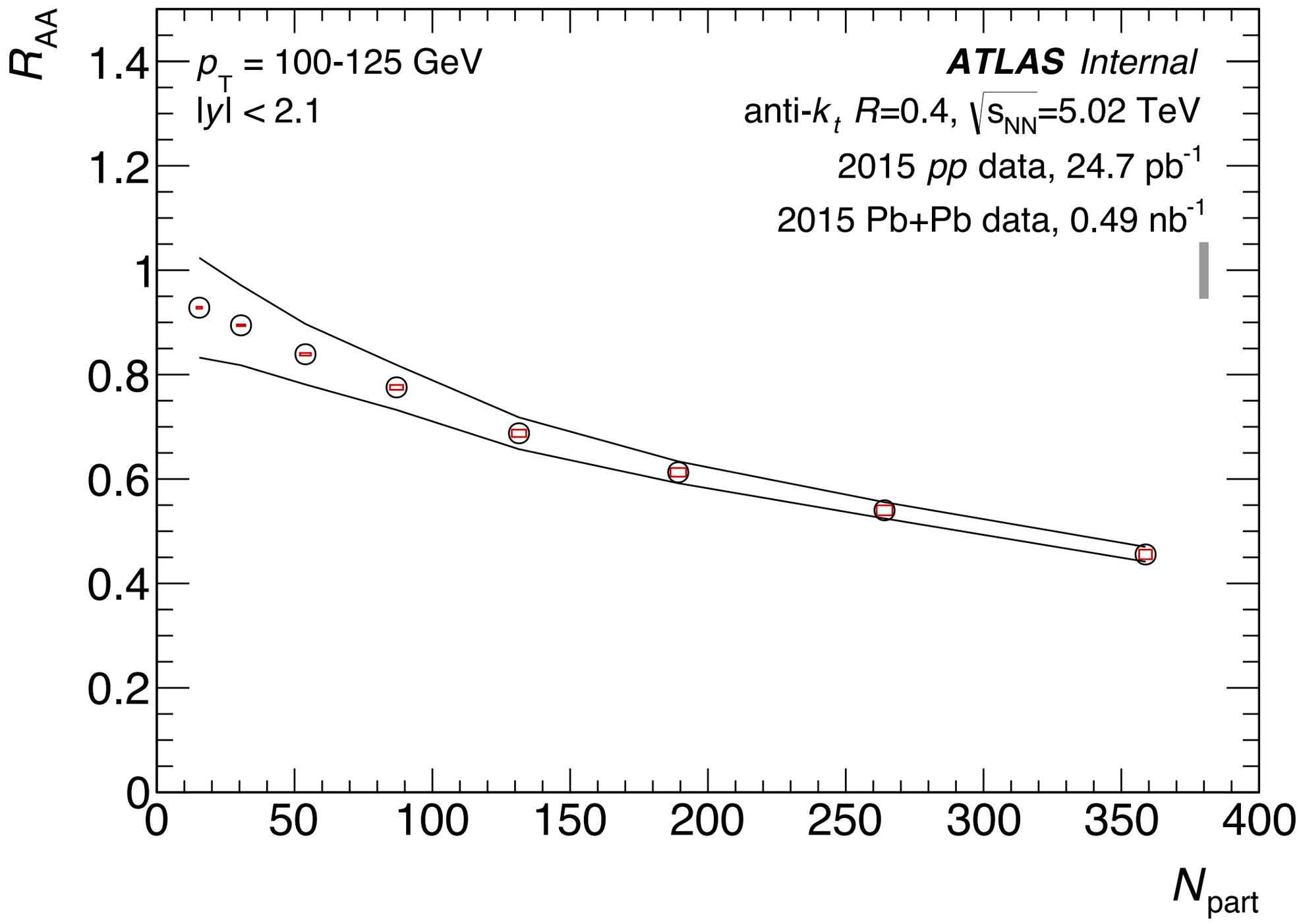
- **uncertainties on the *pp* cross section**
- **uncertainties on Pb+Pb yields**
- **uncertainties on R_{AA}**





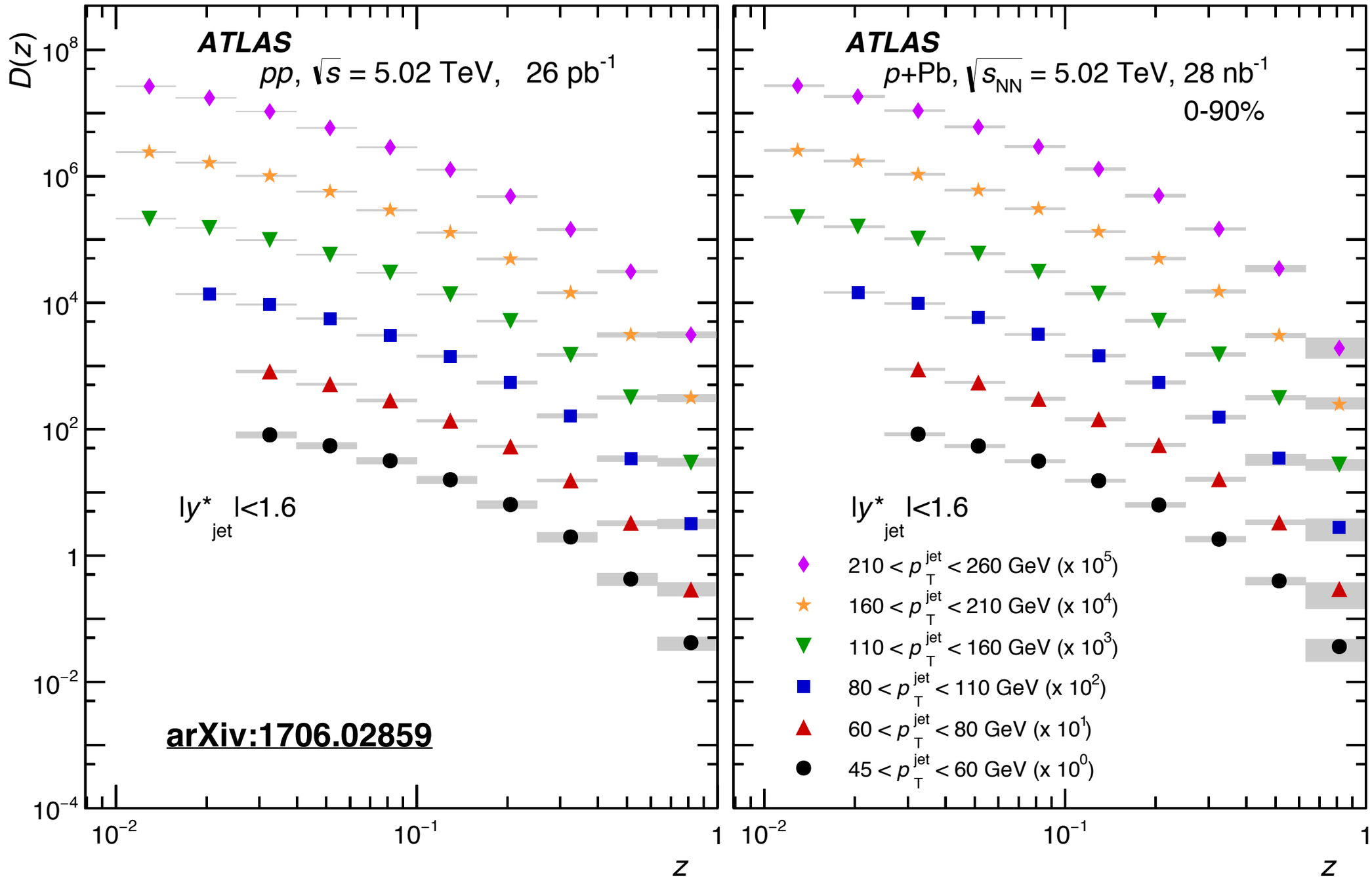


R_{AA} vs. N_{part}



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

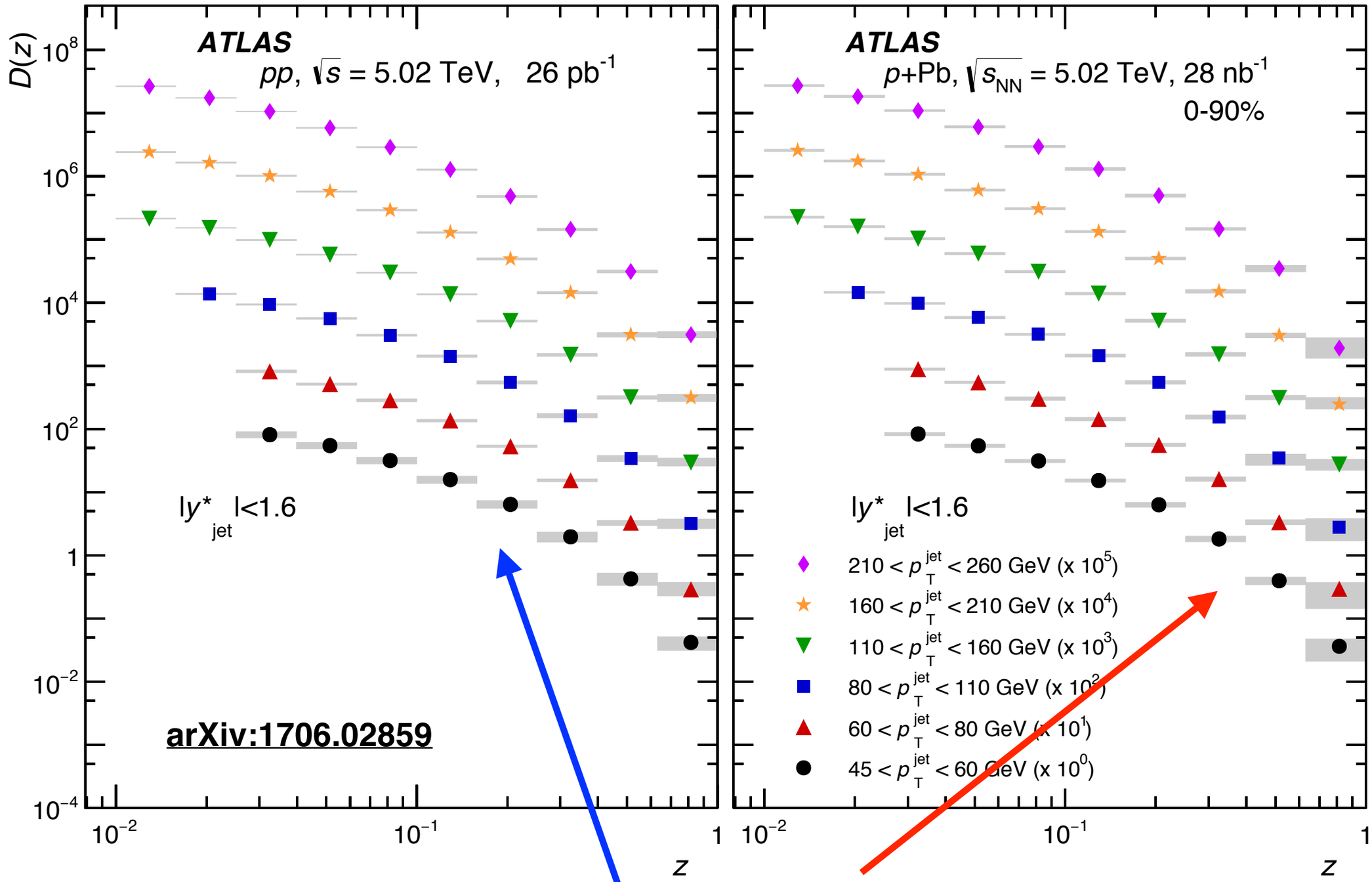
Jet fragmentation: *pp* and *p*+Pb



- **Ratio needed to see modification.**

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

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



- **Ratio needed to see modification.**

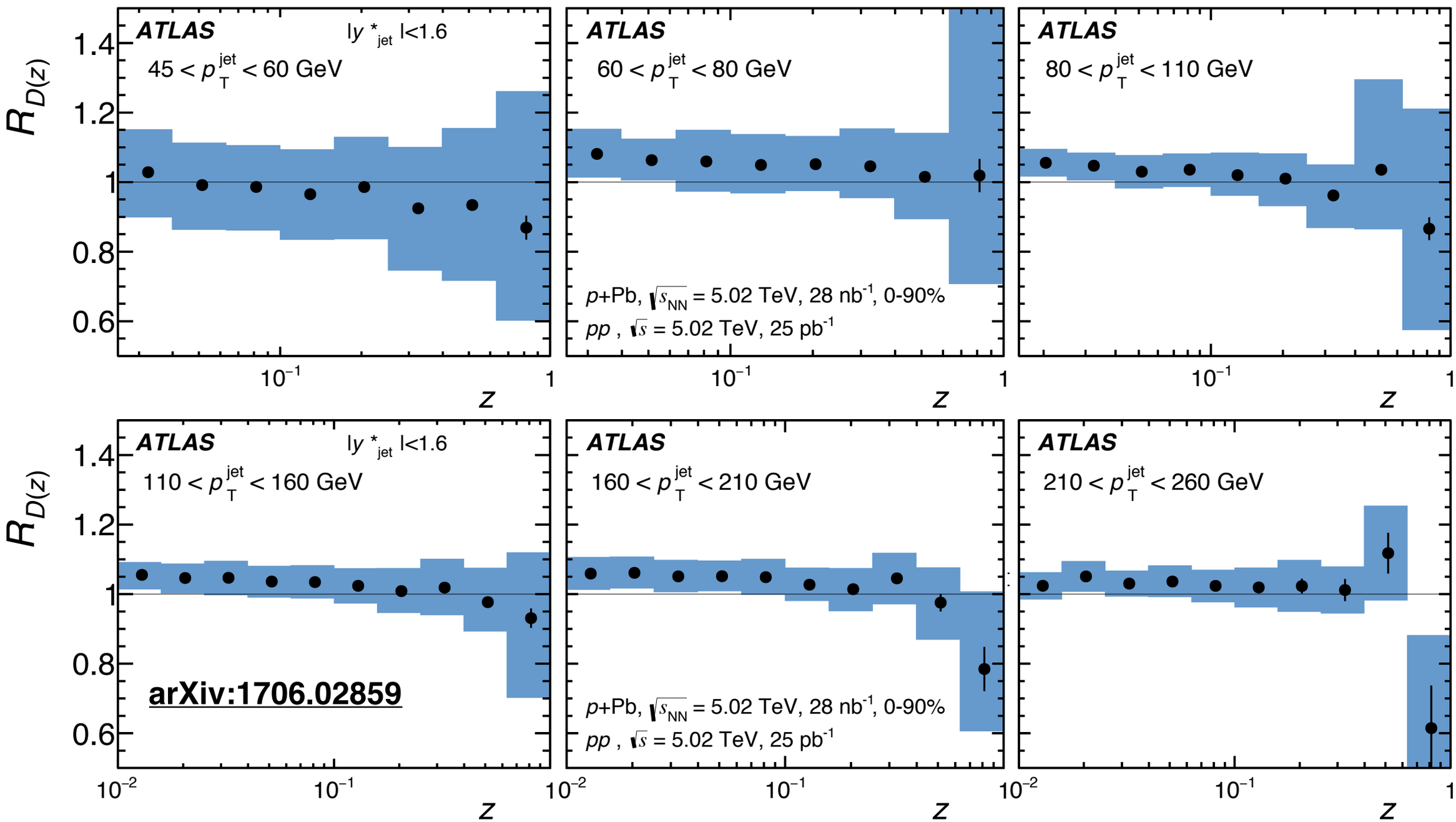
$$R_{D(z)} = \frac{D(z)_{pPb}}{D(z)_{pp}}$$

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

Internal structure: *p*+Pb

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

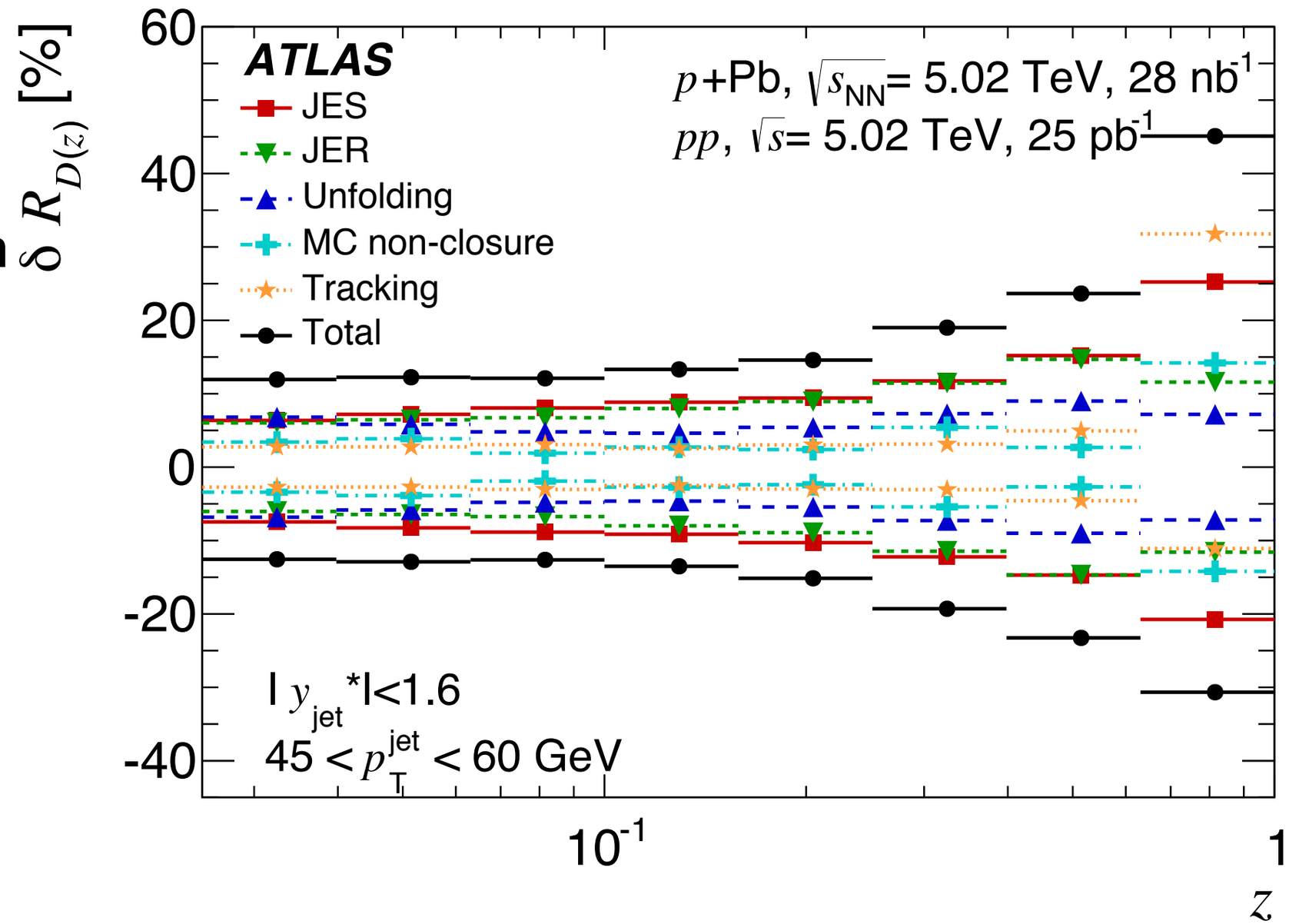
p+Pb $R_{D(z)}$ in jet p_T bins



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

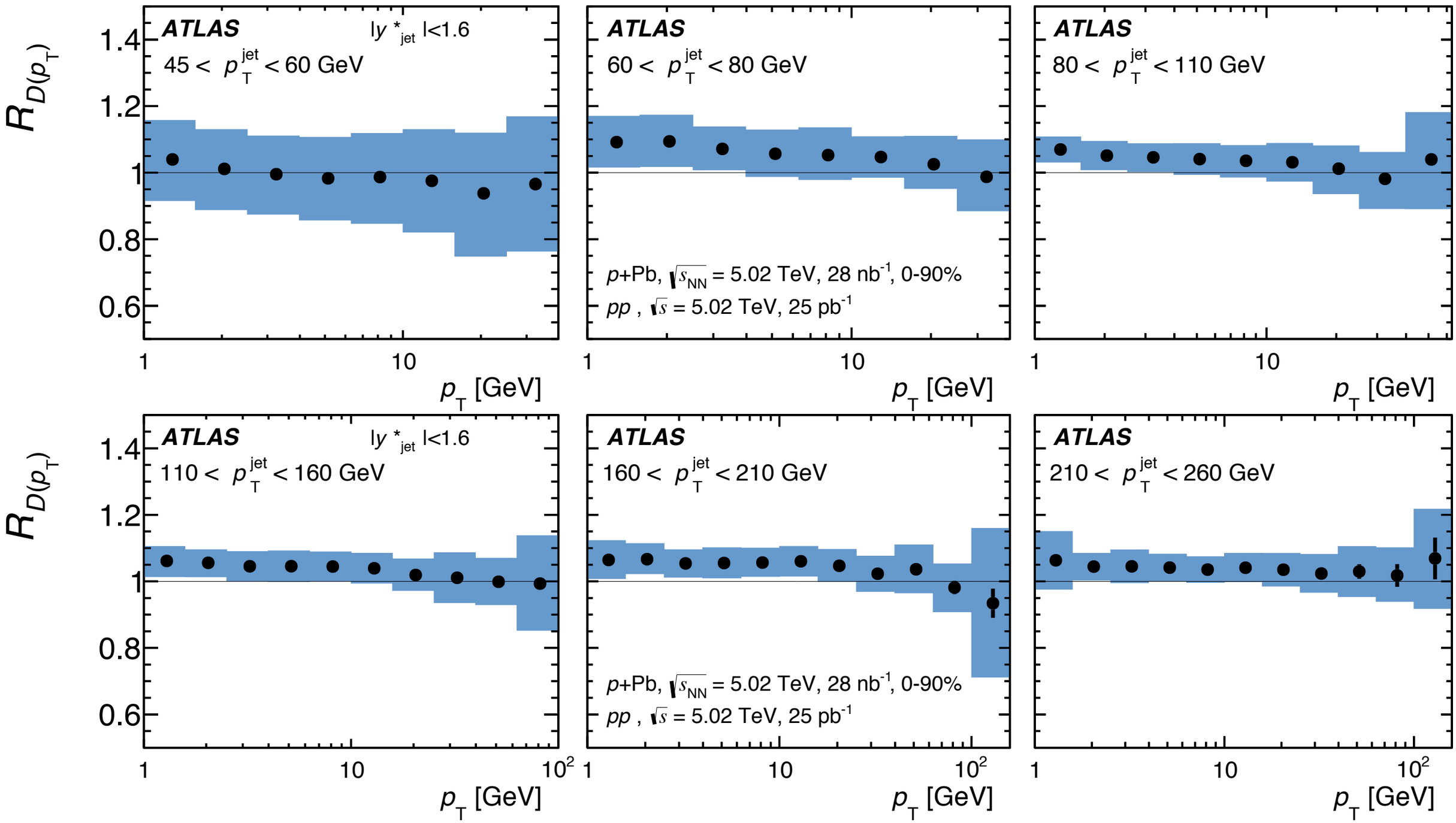
Systematic uncertainties on p+Pb $R_{D(z)}$

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



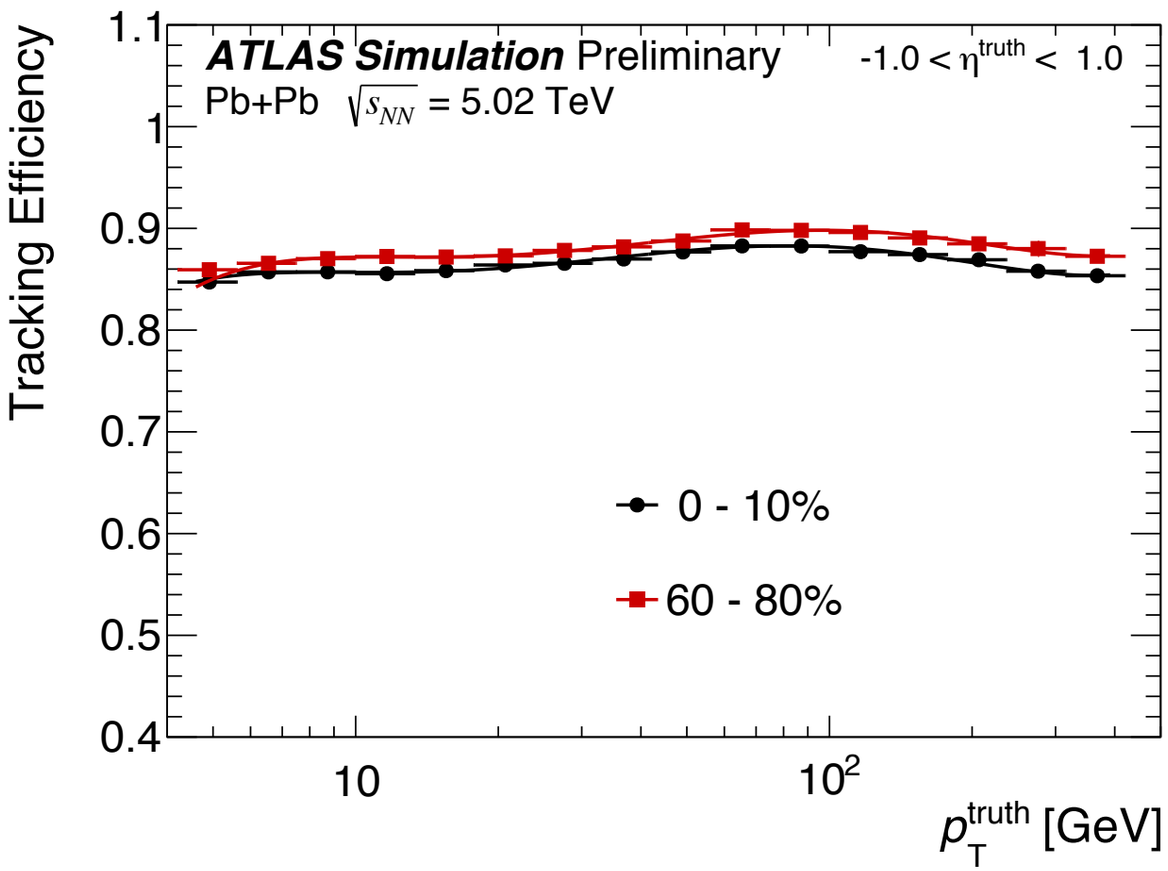
p+Pb $R_{D(p_T)}$ in jet p_T bins

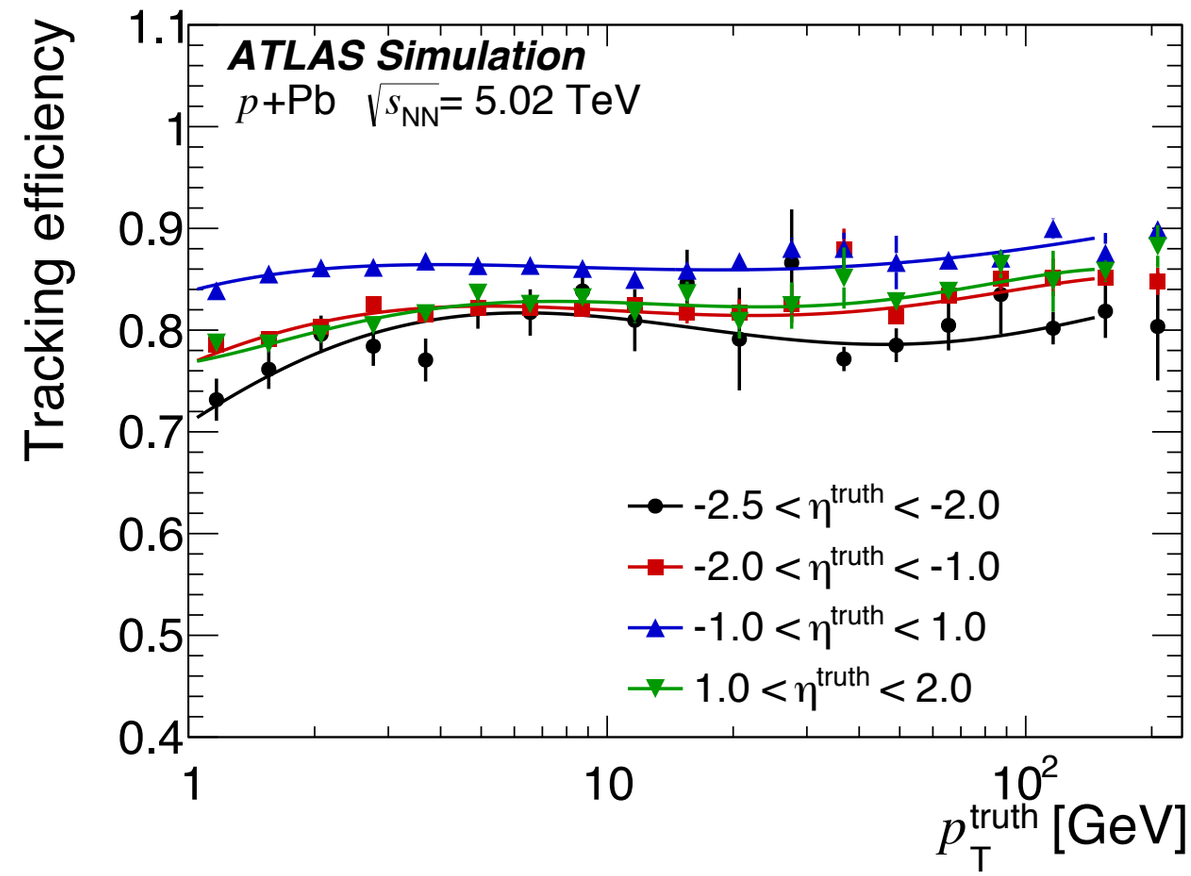
- **New *pp* reference at same center of mass energy**

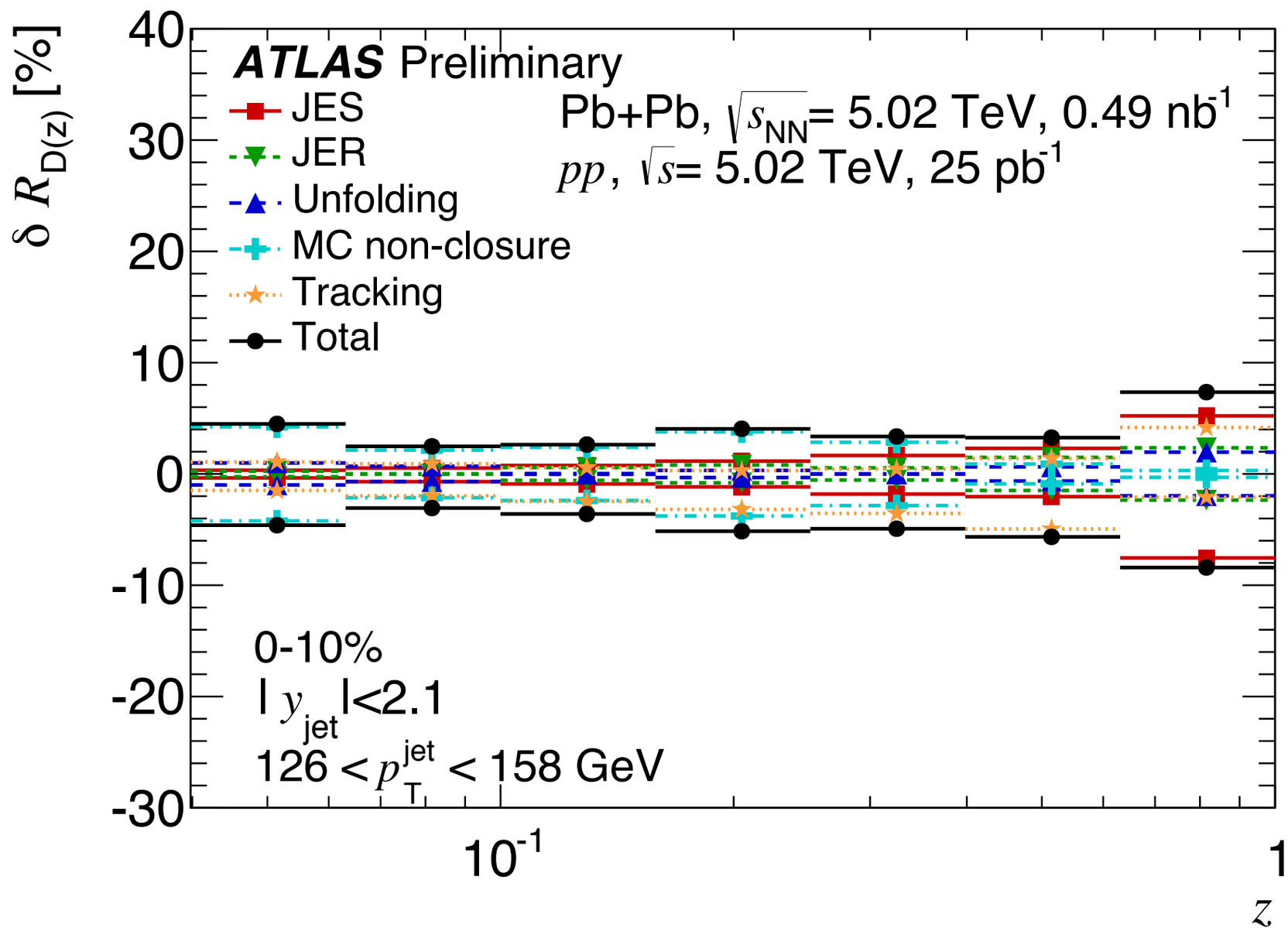


➡ **No modification of jet structure in *p*+Pb.**

Tracking efficiencies





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

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