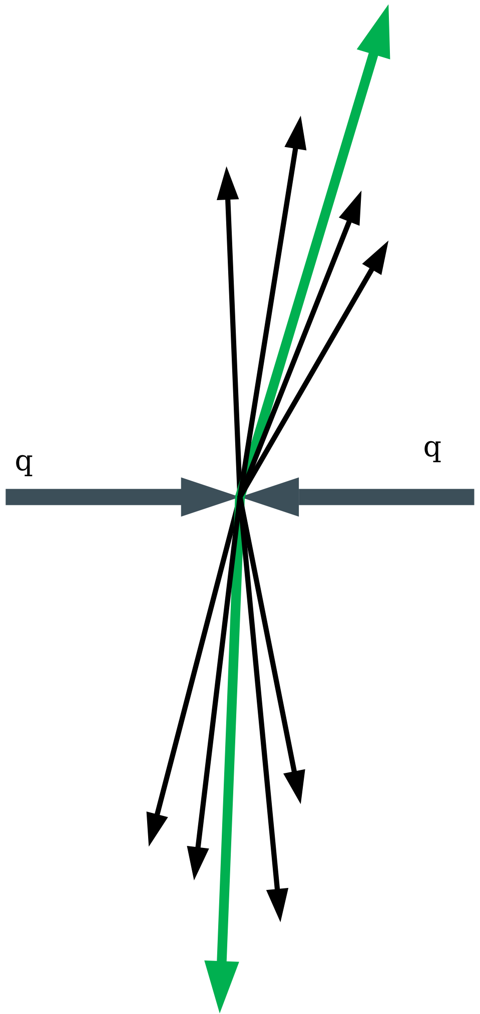
Latest results on jet measurements with the ATLAS detector

Laura Havener, Columbia University

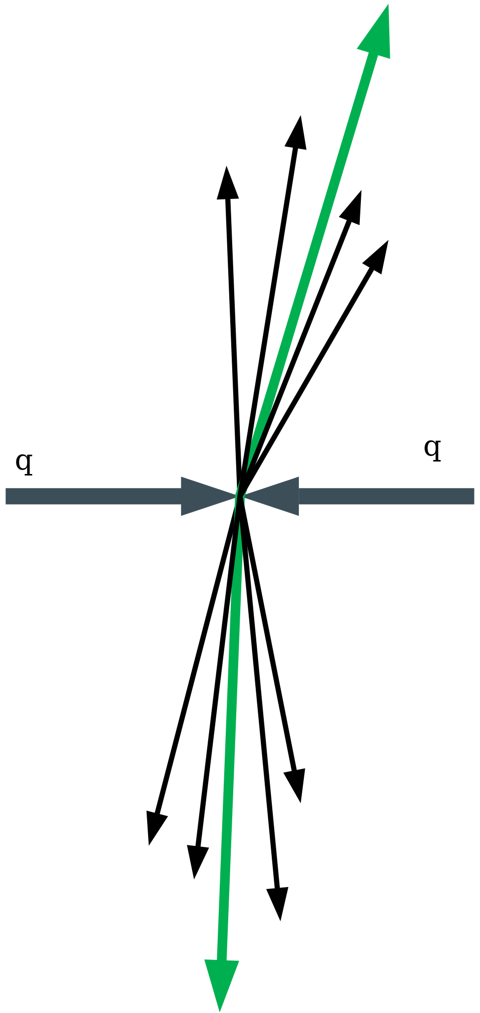
WWND 2019, Beaver Creek, Colorado
Monday, January 7th, 2019

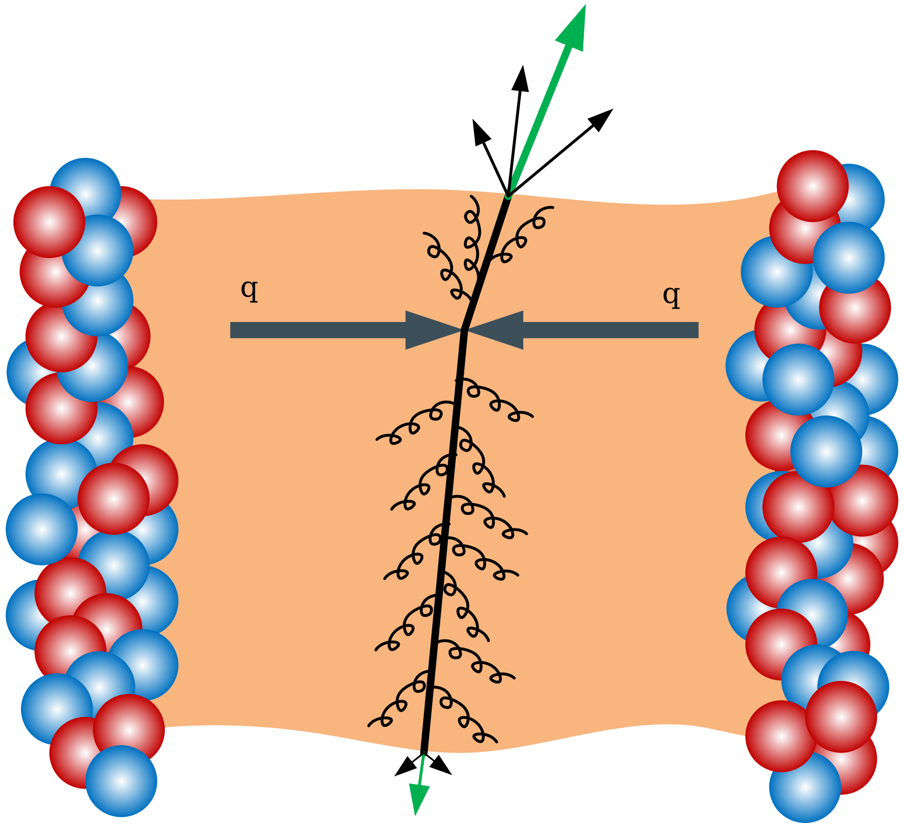
Jets in HI collisions?



- **Jets in *pp* collisions**

Jets in HI collisions?





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

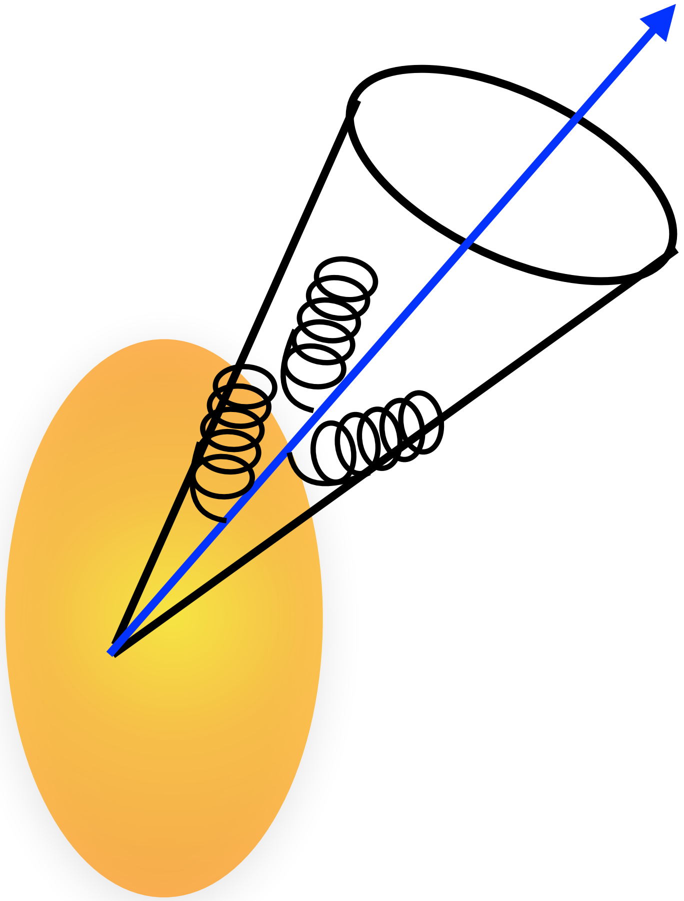
▶ ***Jet quenching:*** **phenomena where partons are expected to lose energy in interactions with the hot dense medium produced in HI collisions**

➡ **jets are sensitive to the microscopic structure of the medium and are a useful probe of the medium**

Measuring jet quenching

- **Measuring jet quenching includes:**

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



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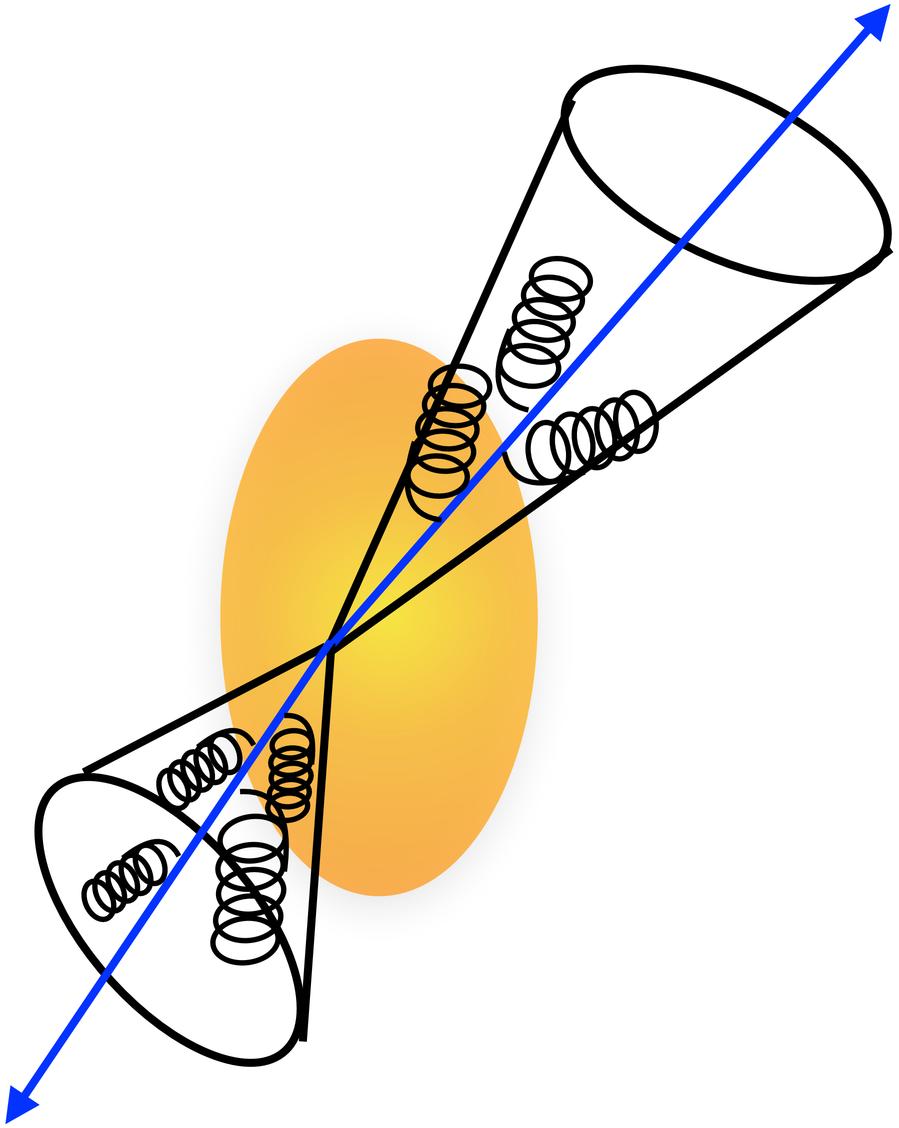
  - ➡ **Differential energy loss through jet correlations to study the path length dependence of energy loss**



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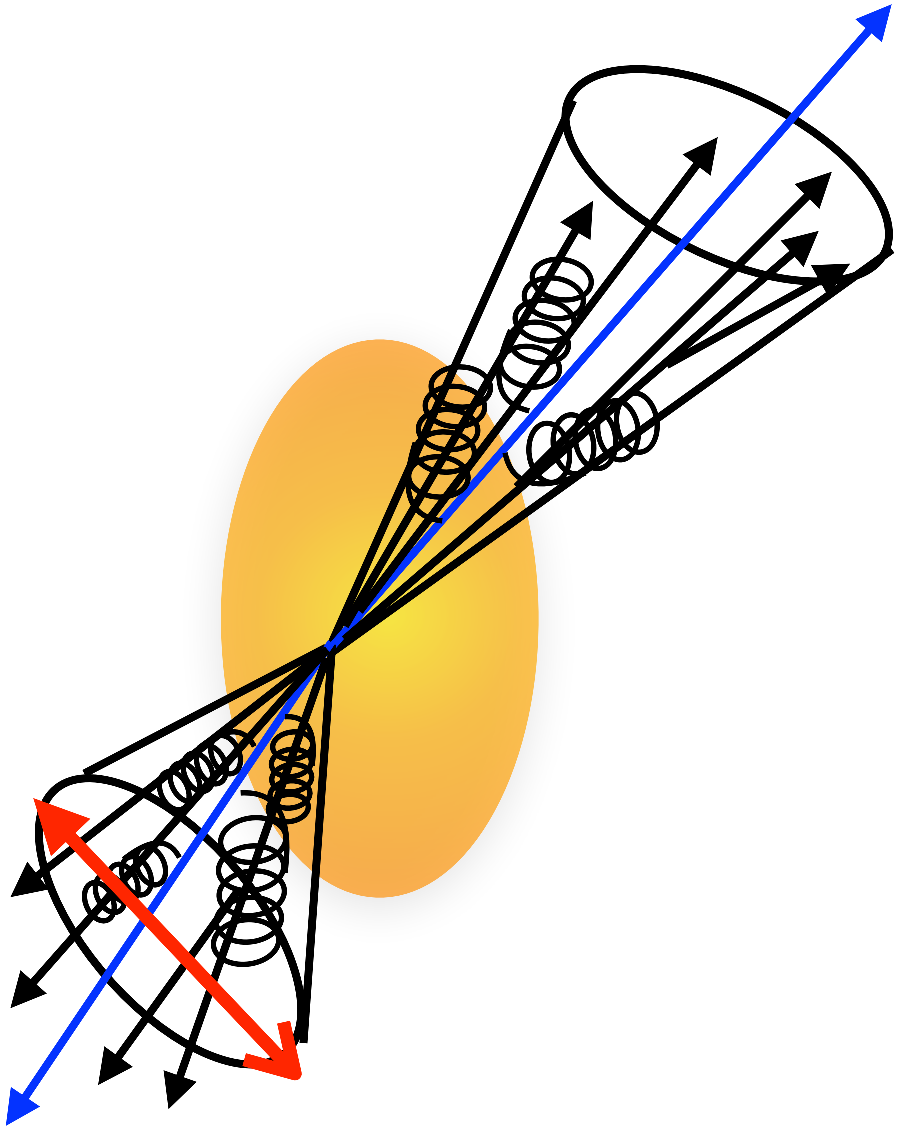

  - ➡ **Jet structure modification by measuring charged particles in jets and jet mass since jets have a complicated internal structure that is modified in the medium**

Jets in HI collisions

- **New results from ATLAS at 5.02 TeV 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**

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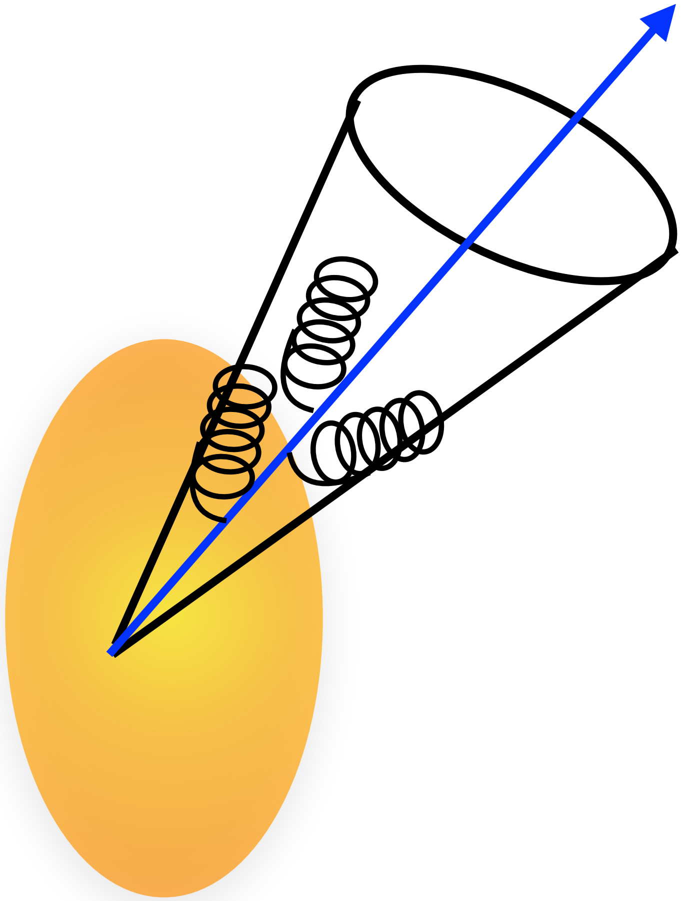

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Jet suppression

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}**

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

Jet yield in heavy ion collisions

Nuclear thickness function

Jet cross-section in *pp* collisions

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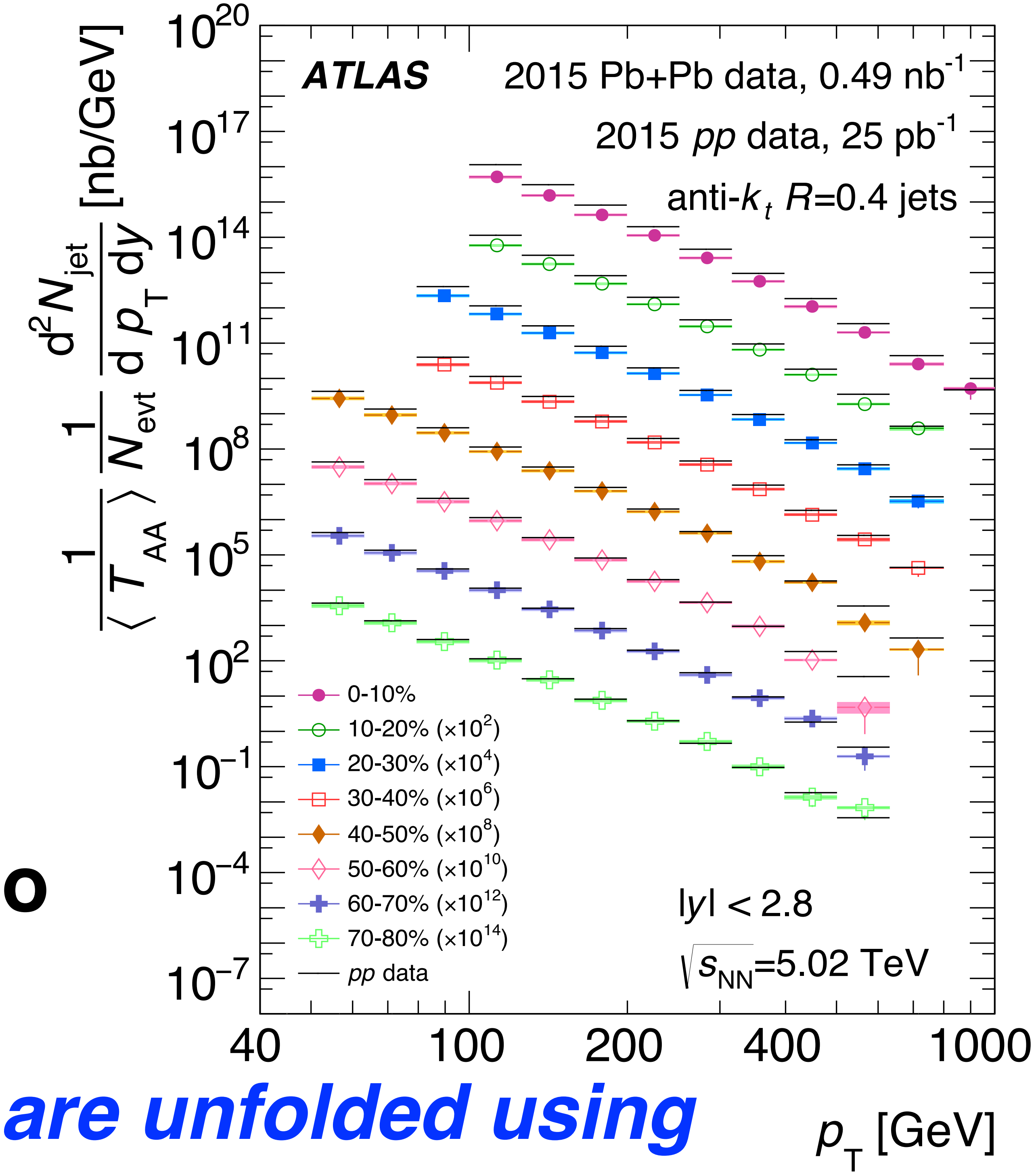
Jet cross-section in *pp* collisions

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

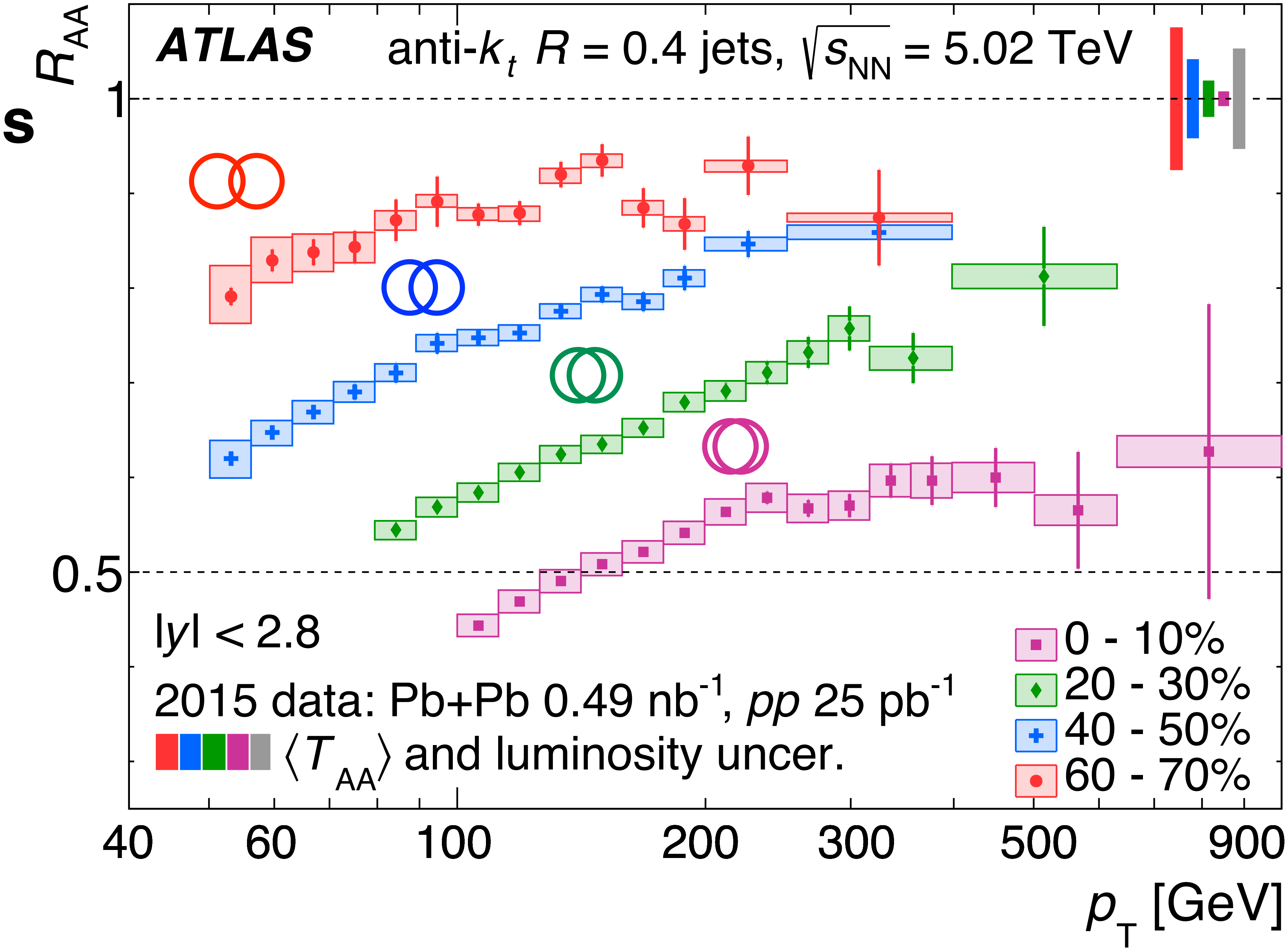


► ***Jet spectra in Pb+Pb and pp are unfolded using 1D Bayesian unfolding.***

R_{AA}: p_T dependence

arXiv:1805.05635

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



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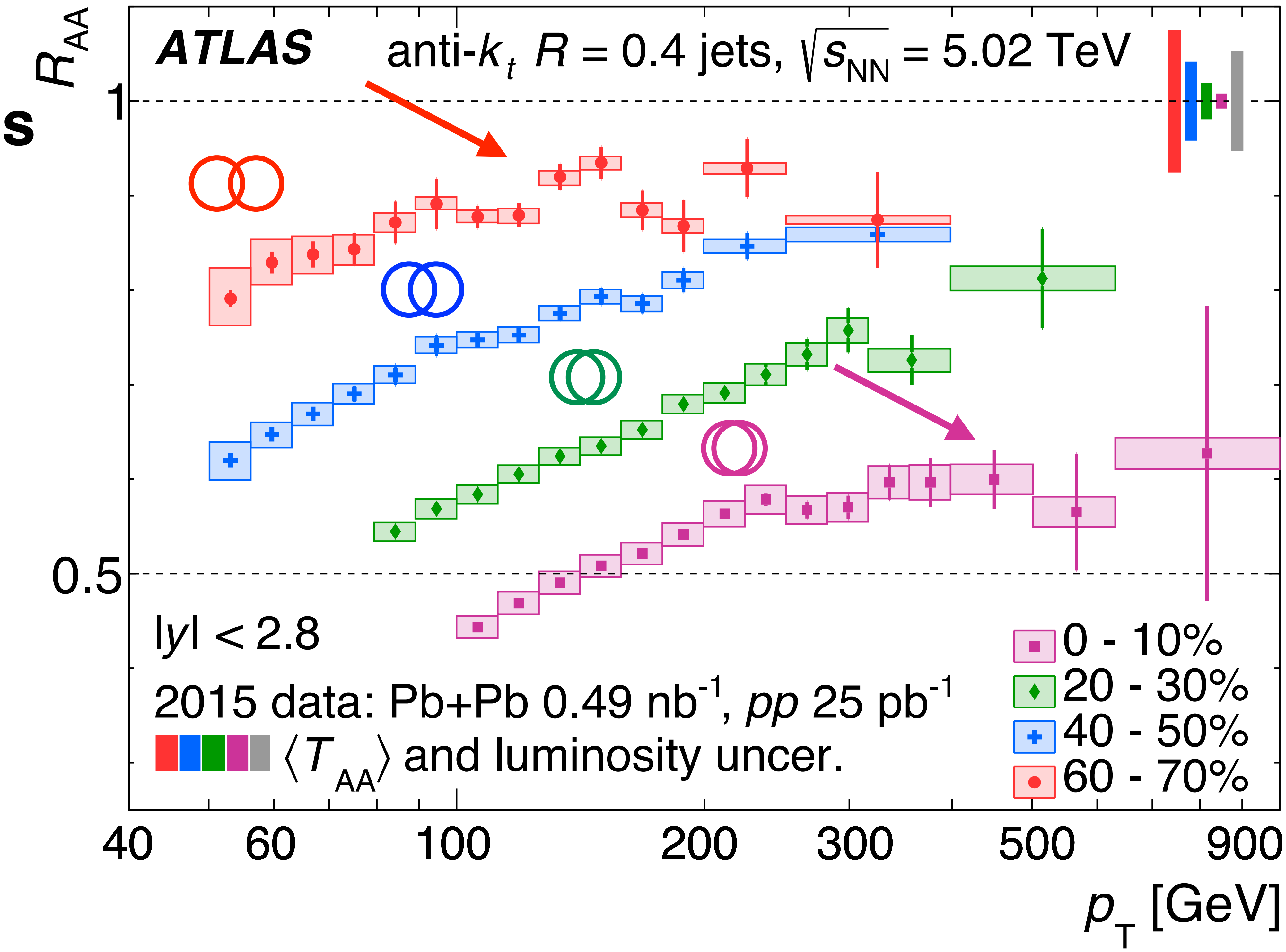
- ***R_{AA}* is lower in central (~0.5) than peripheral (~0.9)**



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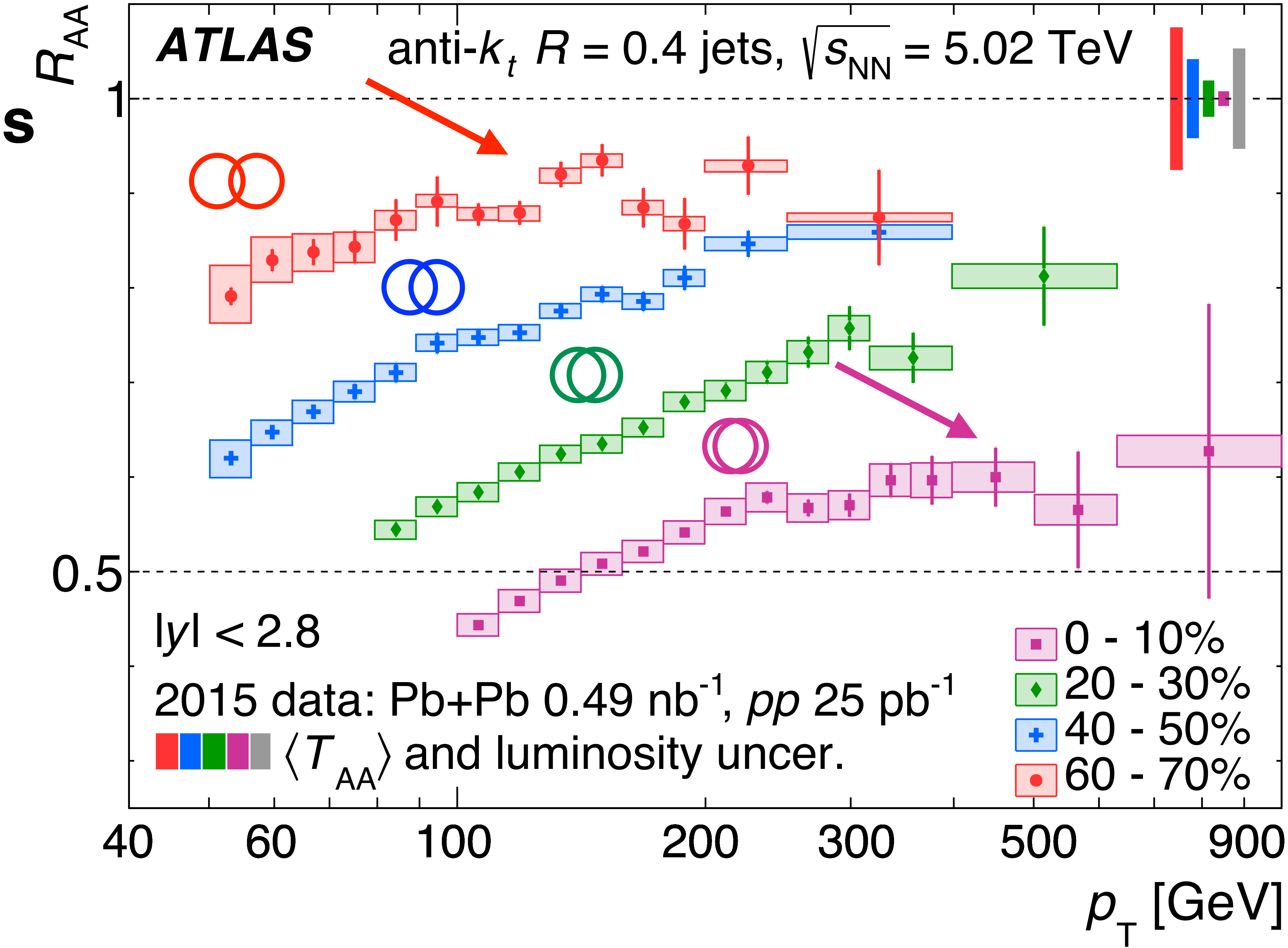

- ***R_{AA}* show slight *p_T* dependence where it increases and then begins to flatten at high *p_T***

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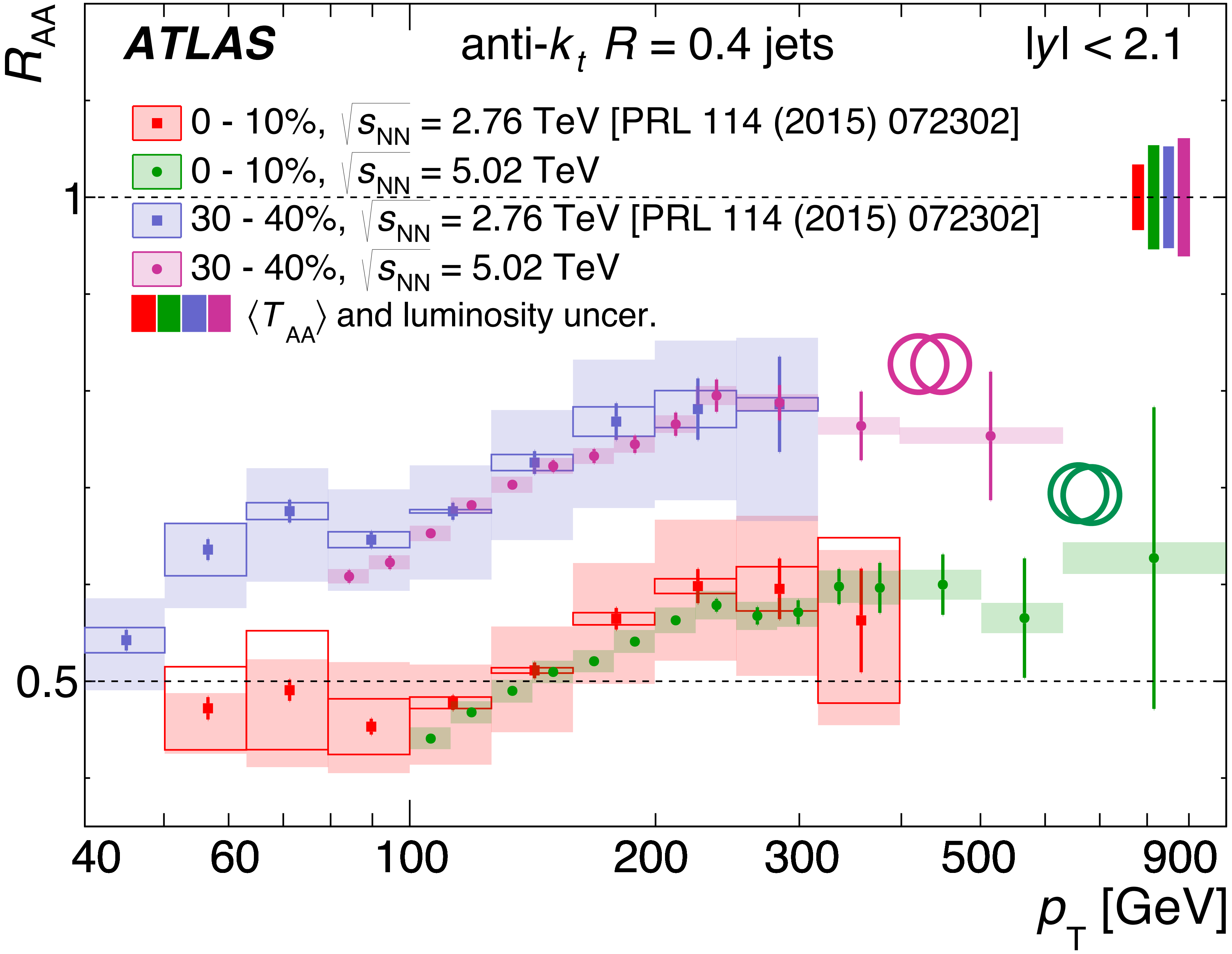

- **R_{AA} is independent of $\sqrt{s_{NN}}$ (over a narrow range) when comparing 2.76 and 5.02 TeV results**
- ***Significant reduction in systematic uncertainties***

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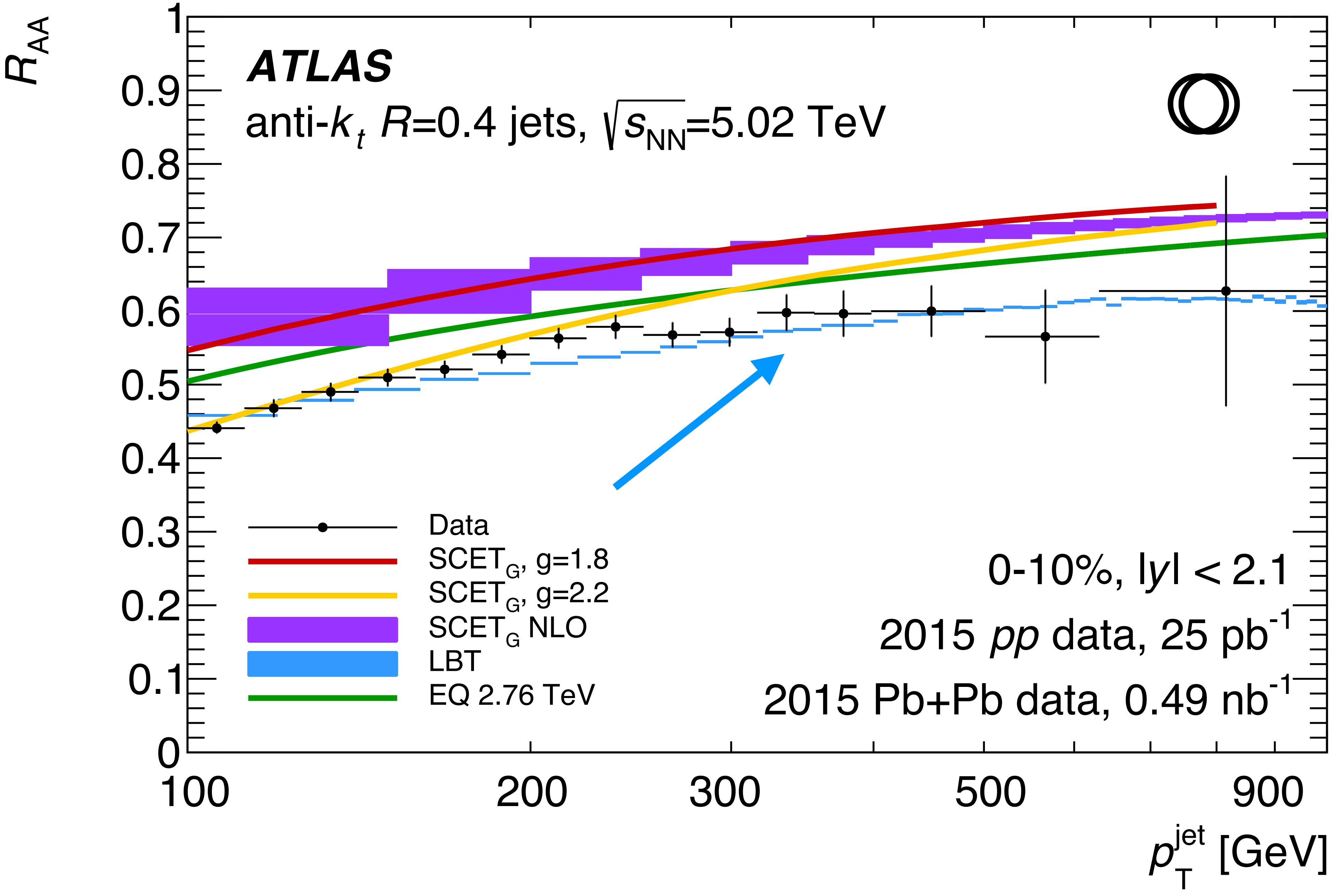
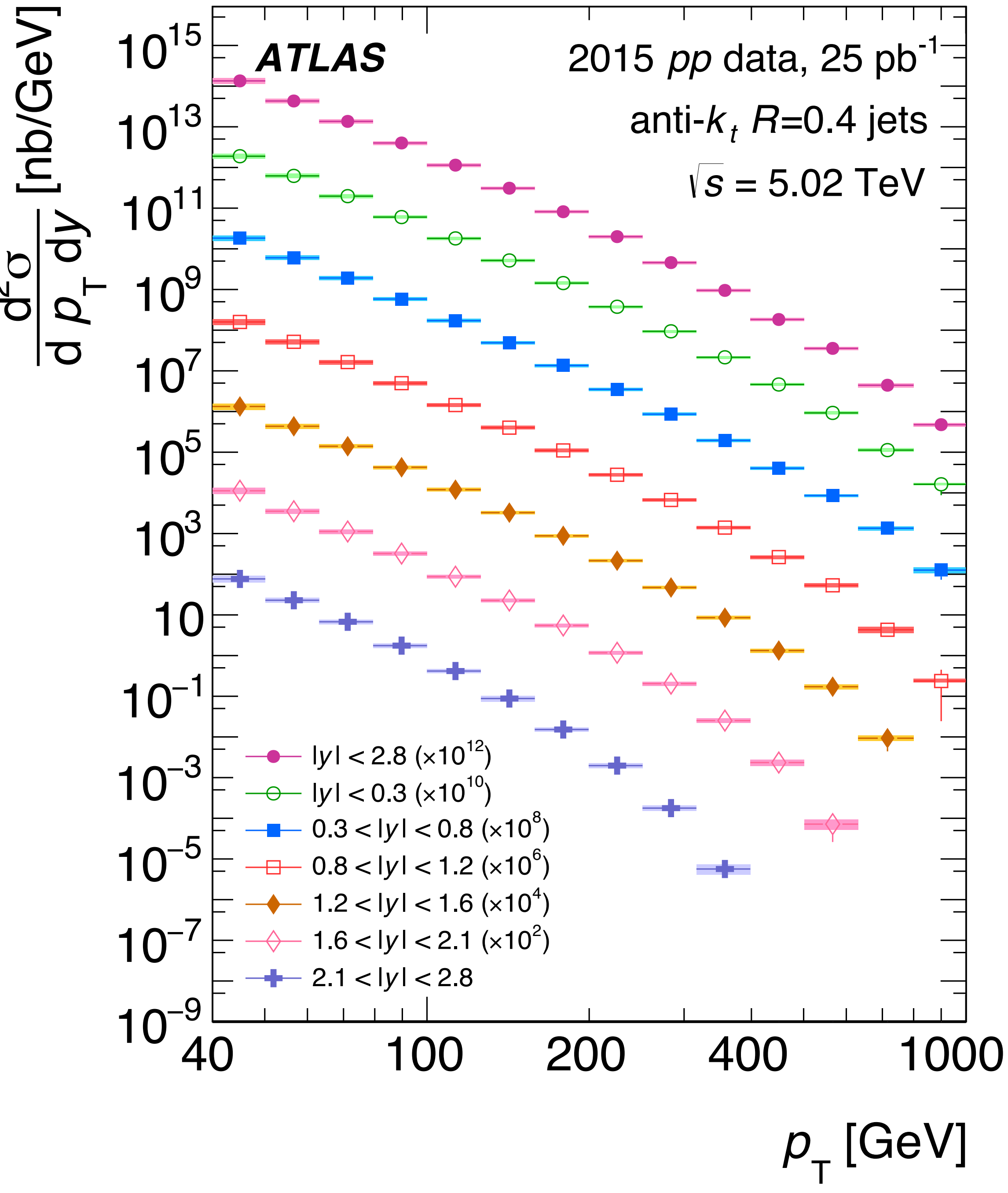
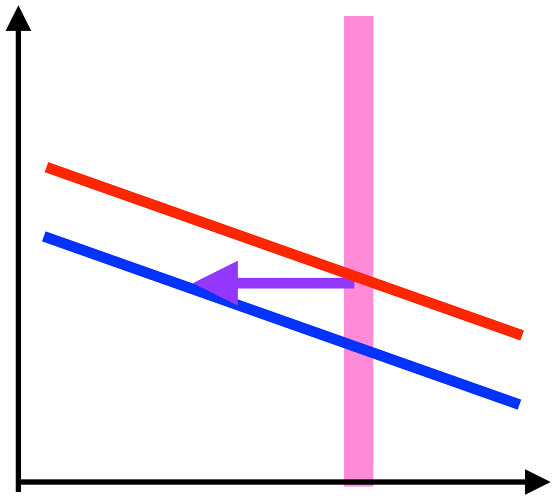


- **Comparison to theory: LBT describes it well at higher p_T and SCETg describes it better at lower p_T**

R_{AA}: rapidity dependence

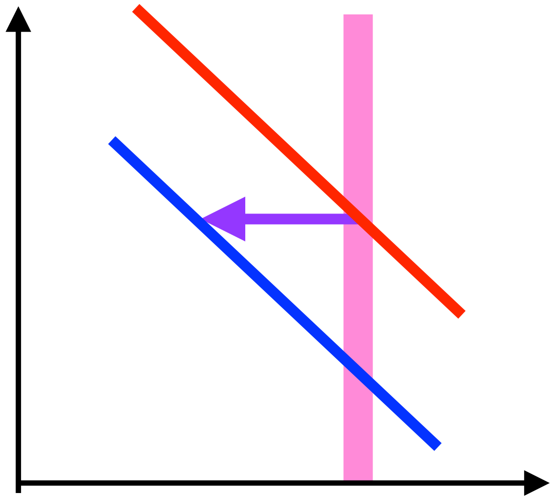
Spectra is steeper with increasing rapidity at fixed p_T for the same amount of energy loss and since R_{AA} ~ red/blue.





mid-rapidity

➡ **lower R_{AA}**



foward-rapidity

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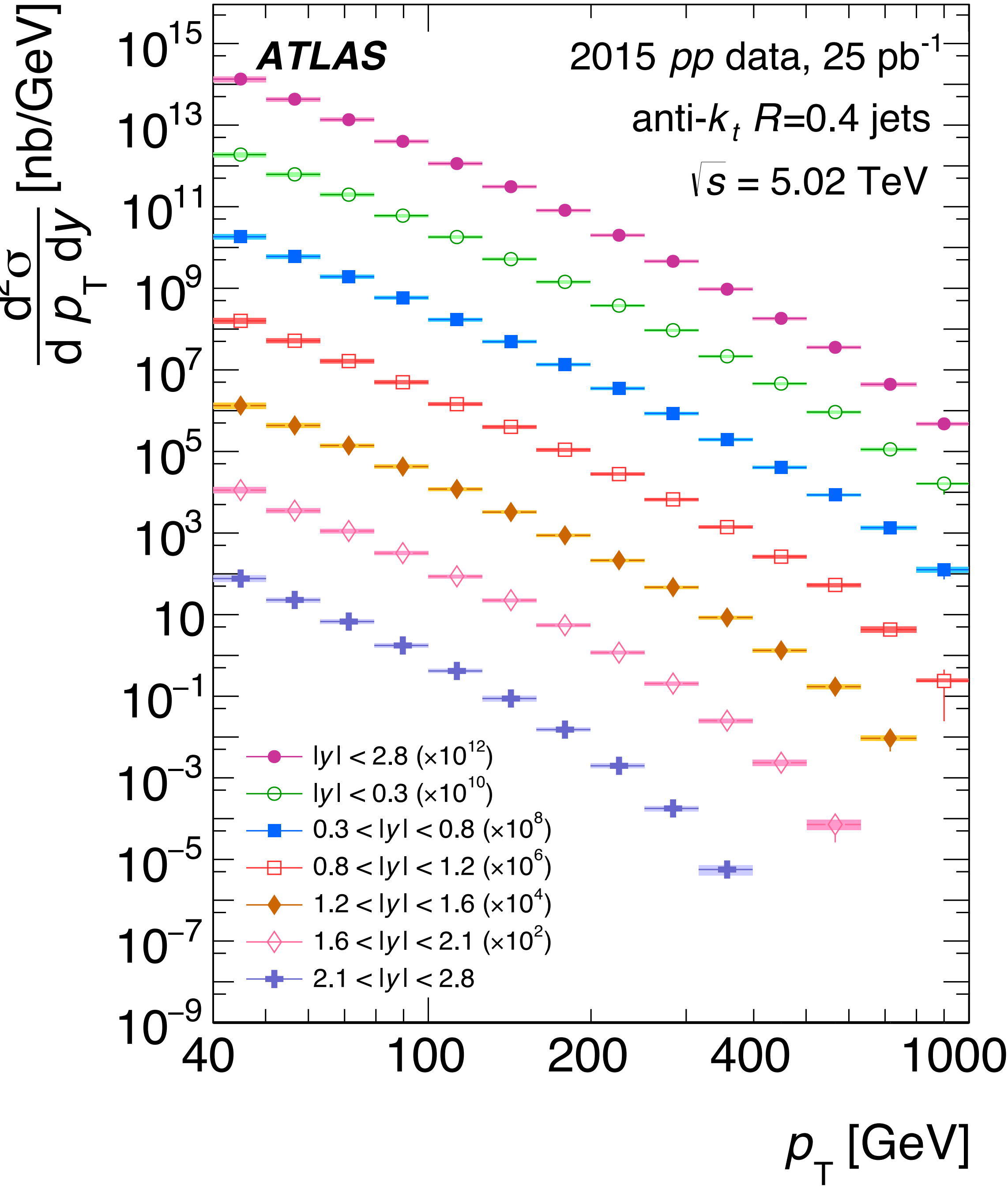

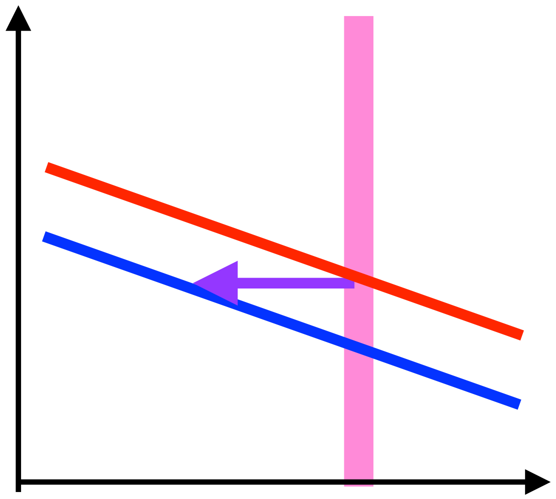

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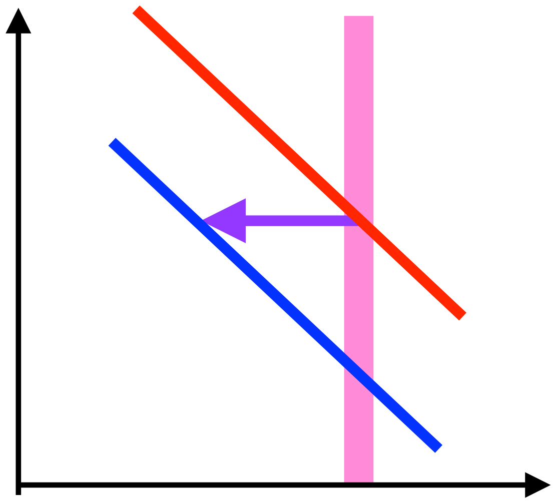


foward-rapidity

➡ **lower R_{AA}**

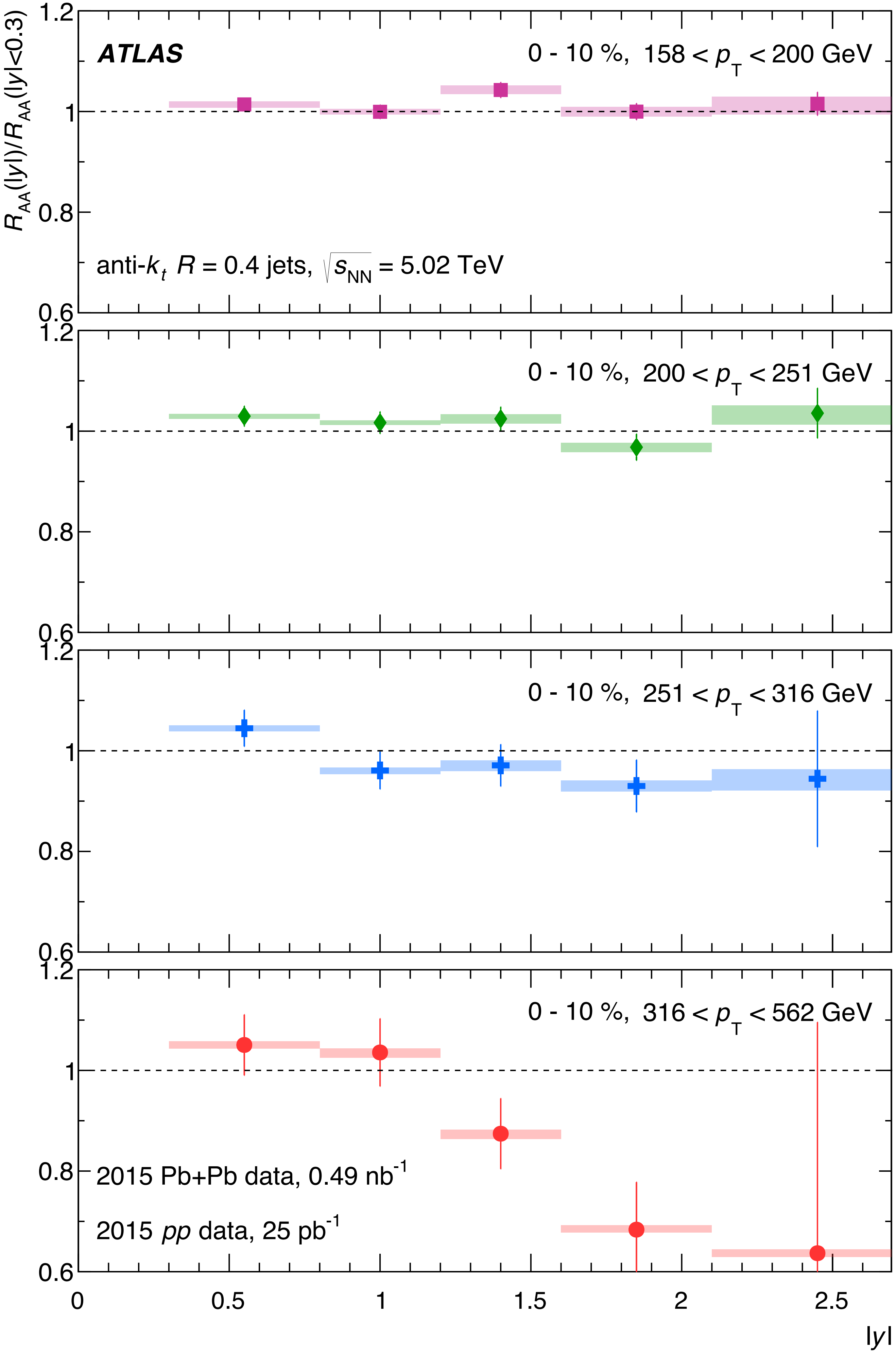
Quark and gluon fraction changes with rapidity and p_T with more quarks at forward rapidity which should be quenched less.

➡ **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 |y| < 0.3 in different p_T ranges**
  - ▸ **Large cancelation of systematics in ratio**



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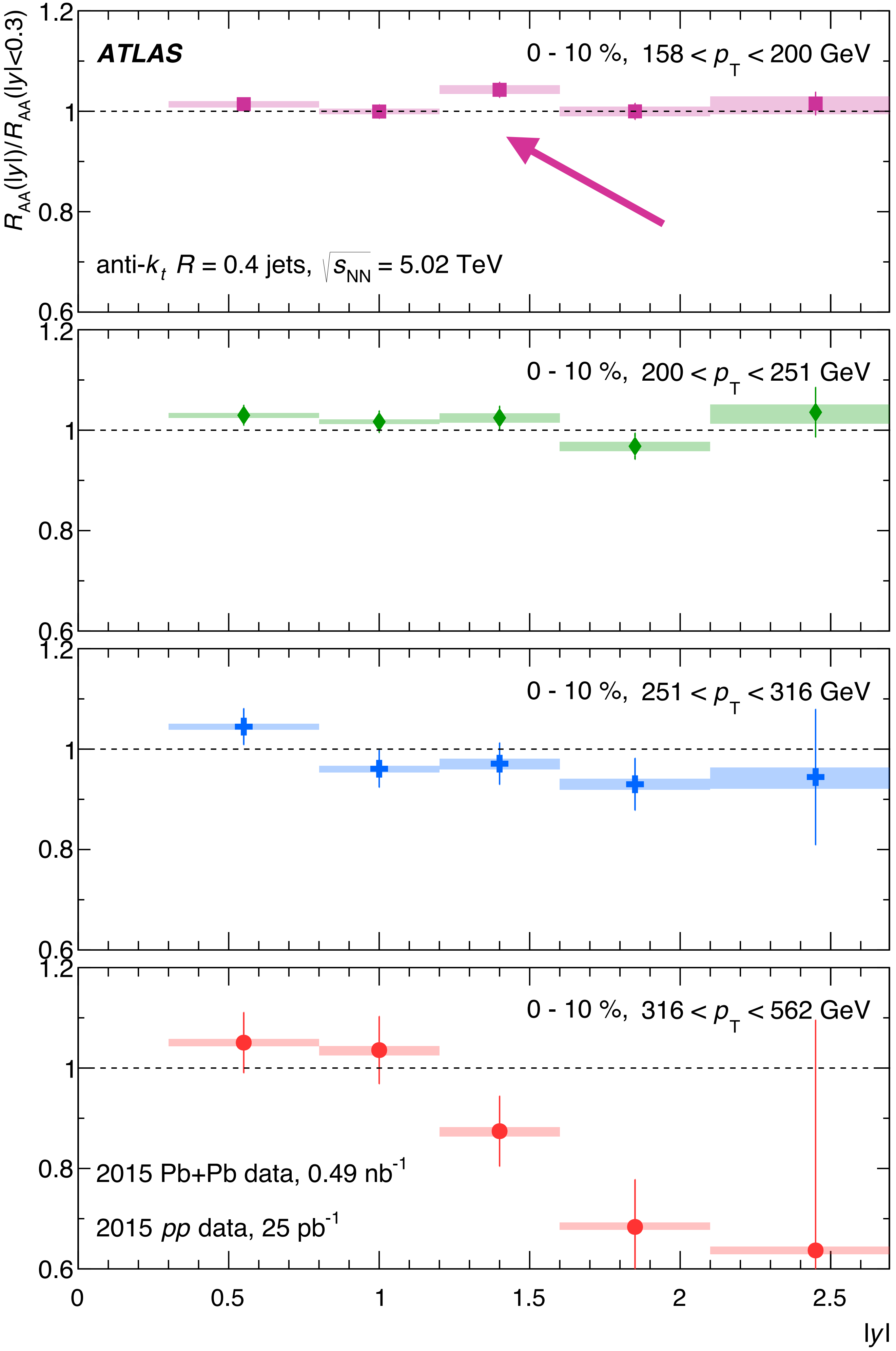

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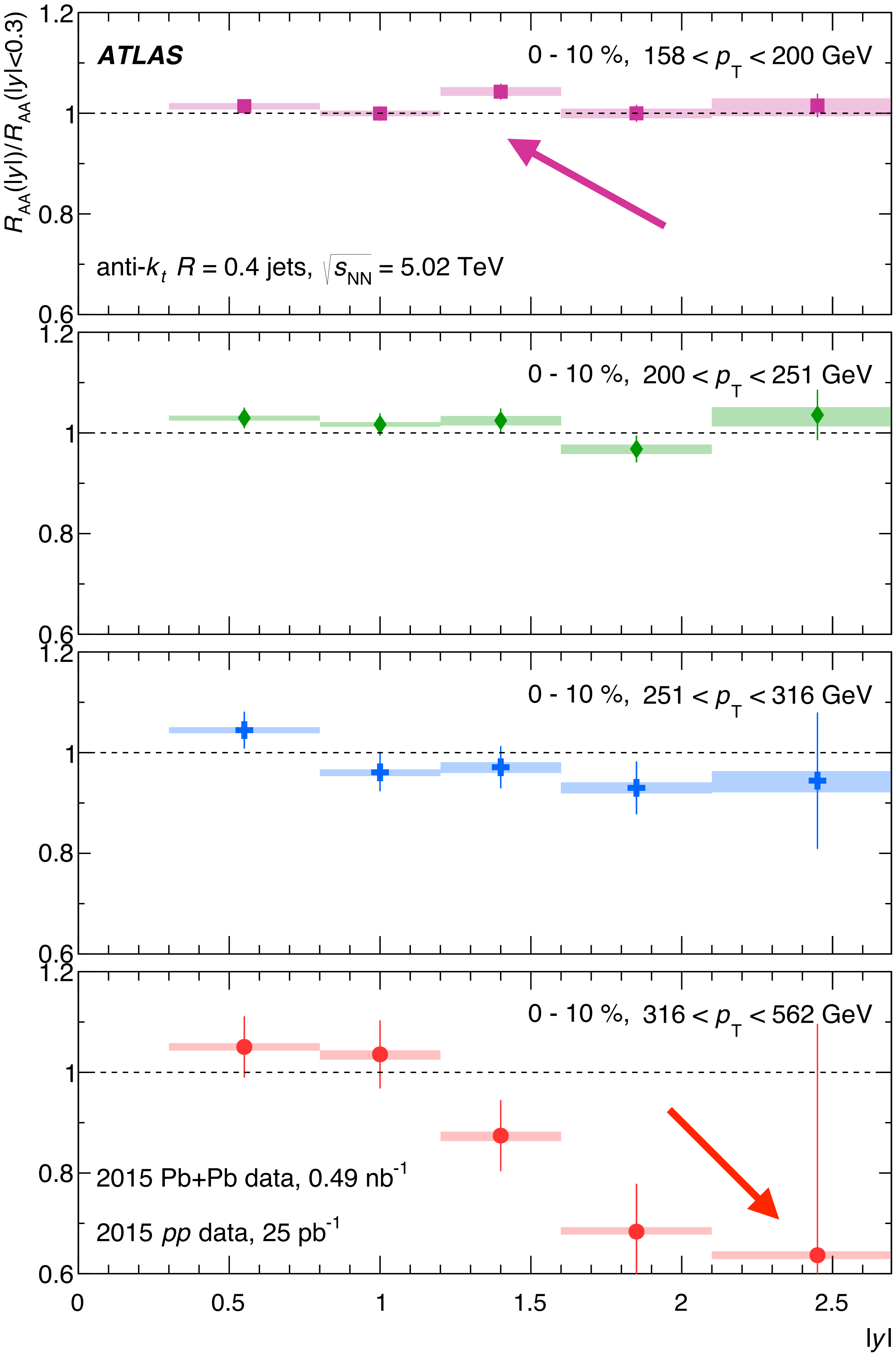
- **R_{AA} decreases with rapidity at higher p_T**



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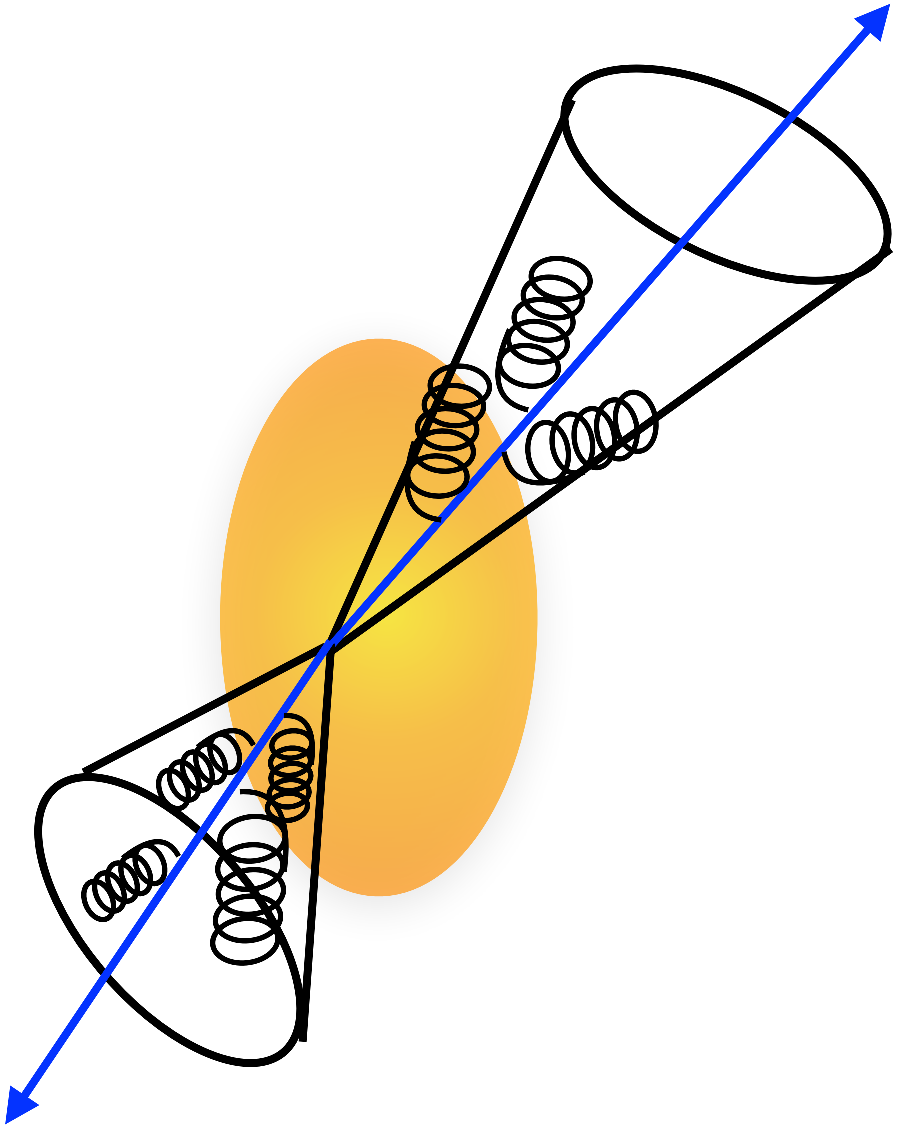

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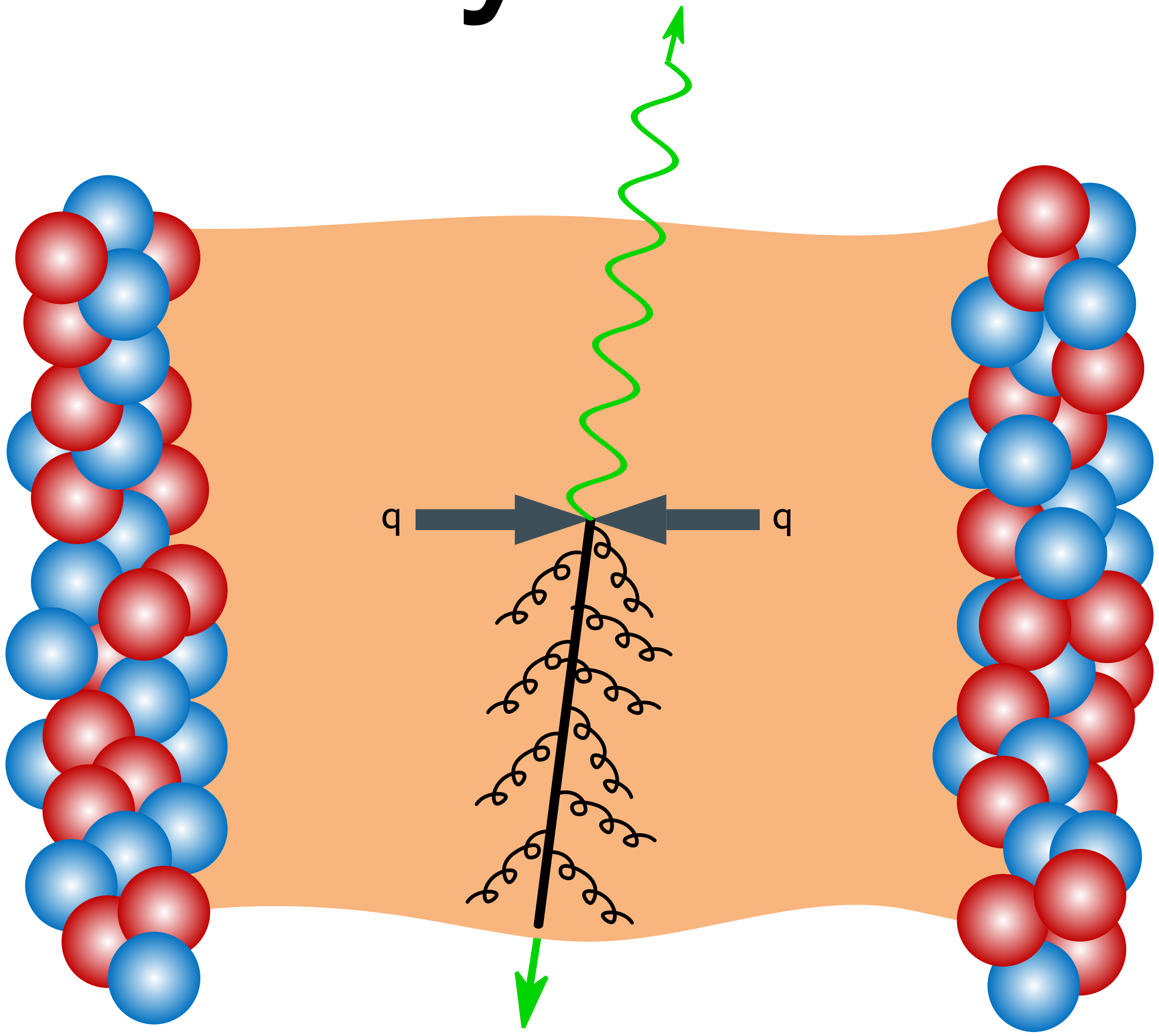
jets have a complicated internal structure that is modified in the medium

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**



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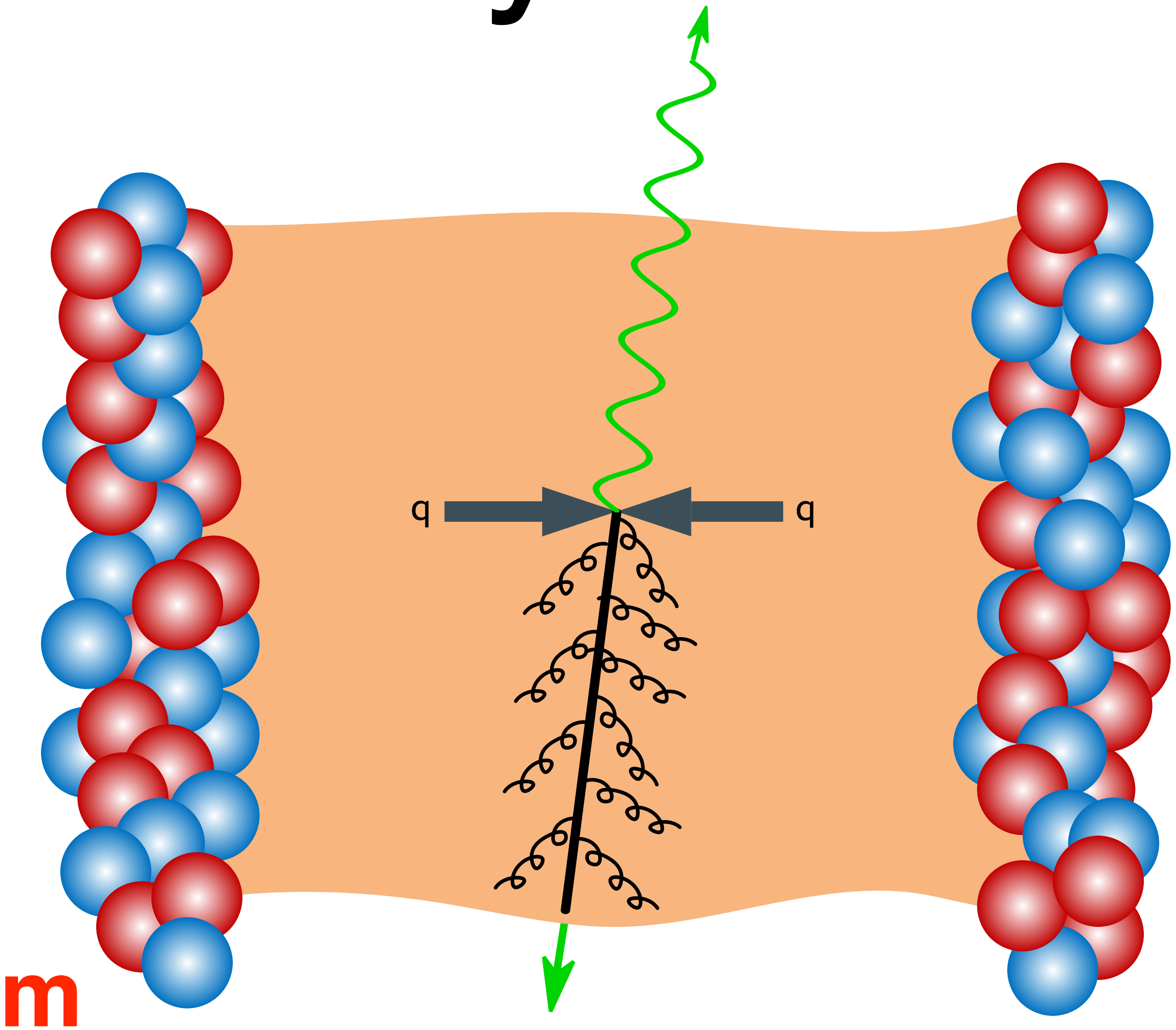

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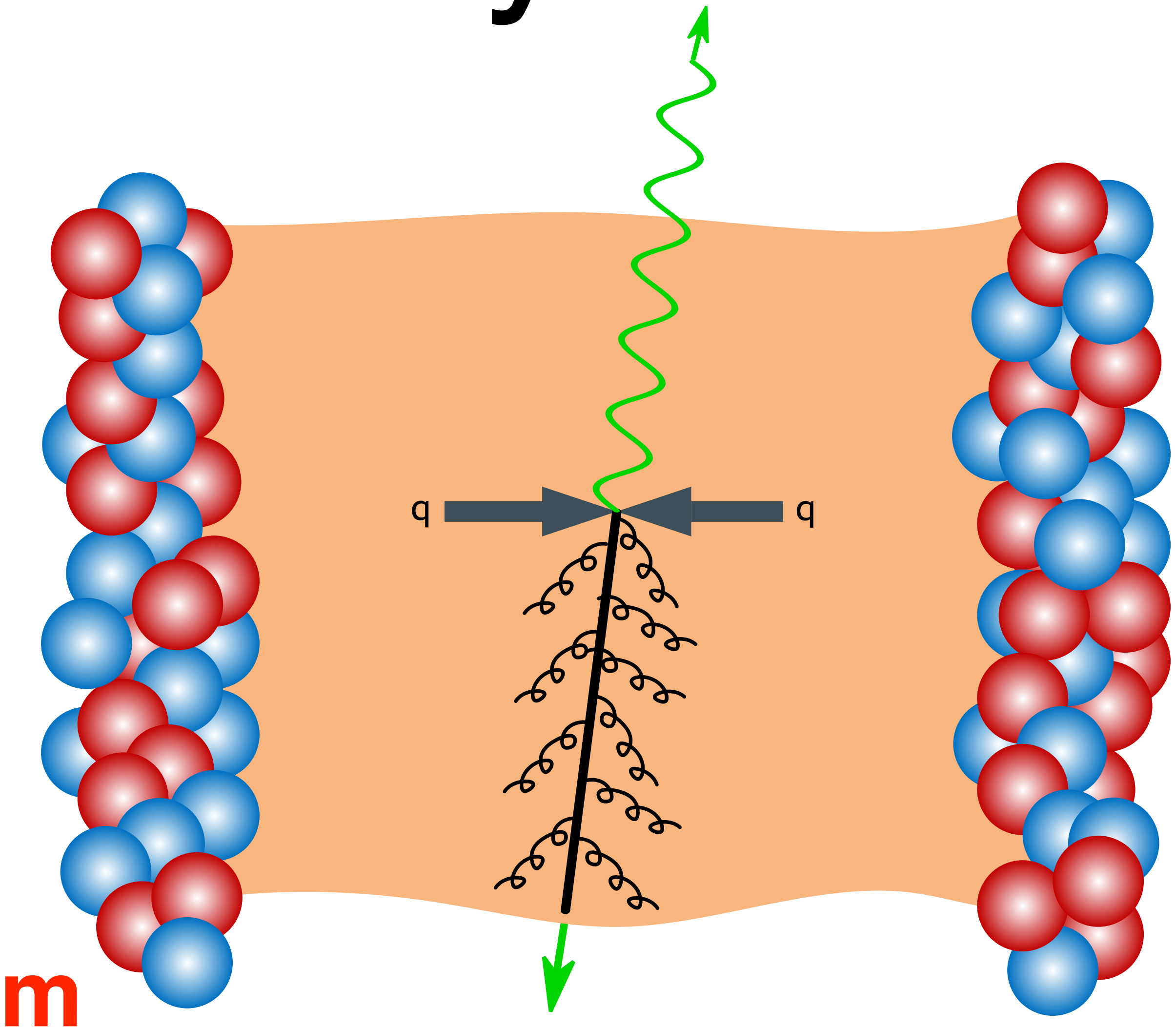


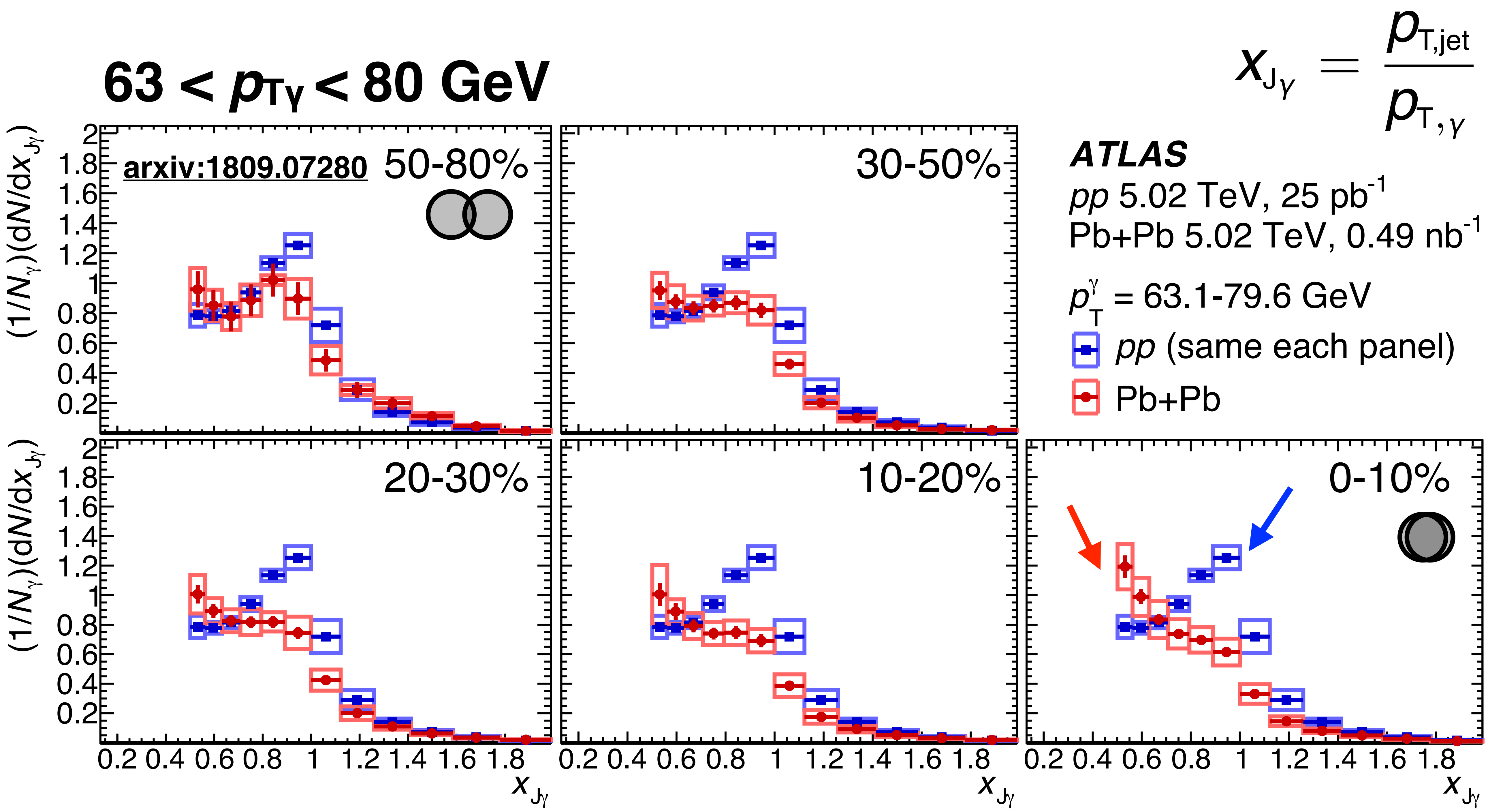
$$x_{J\gamma} = \frac{p_{T,\mathrm{jet}}}{p_{T,\gamma}}$$

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

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

γ-jet asymmetry: centrality

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

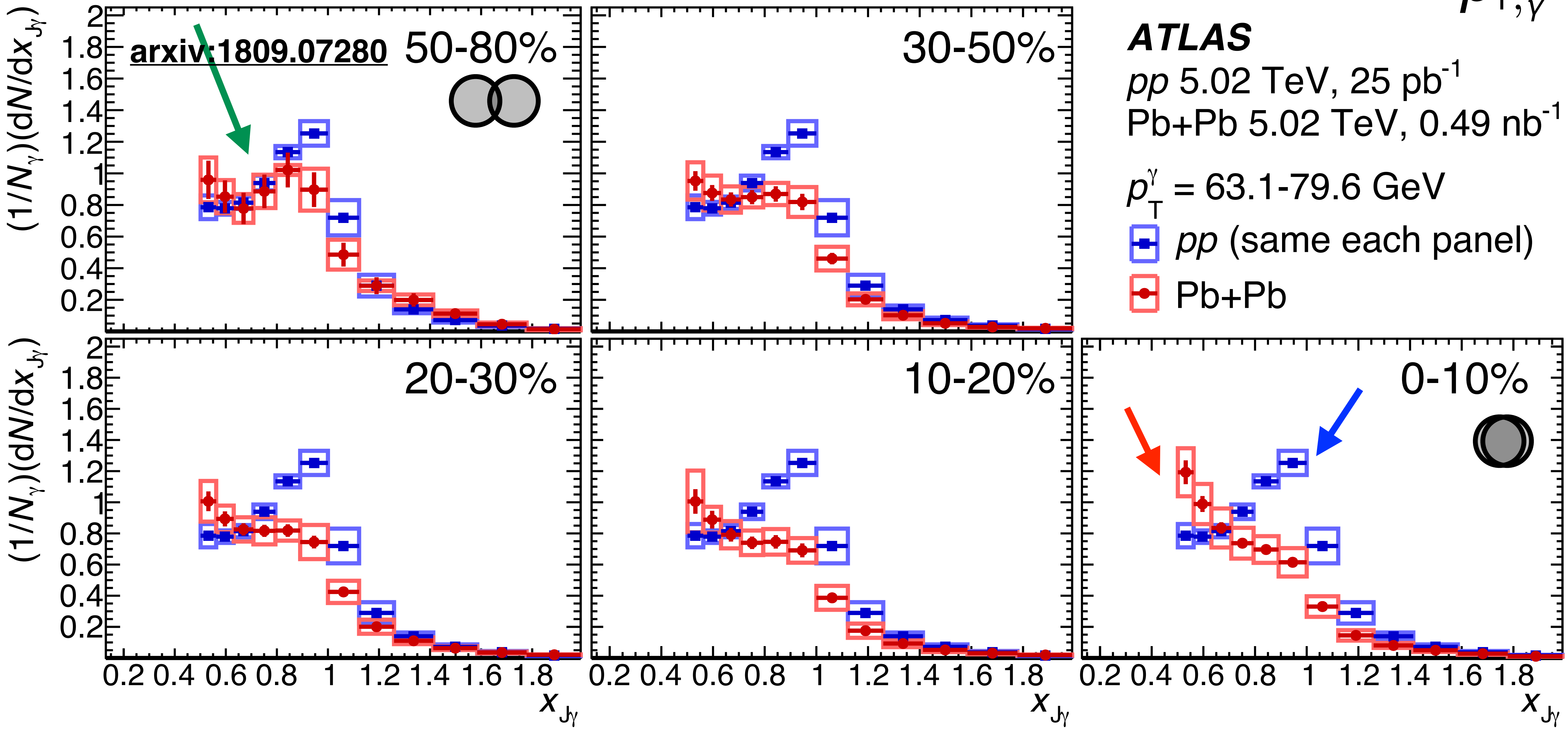


γ-jet asymmetry: centrality

- **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**

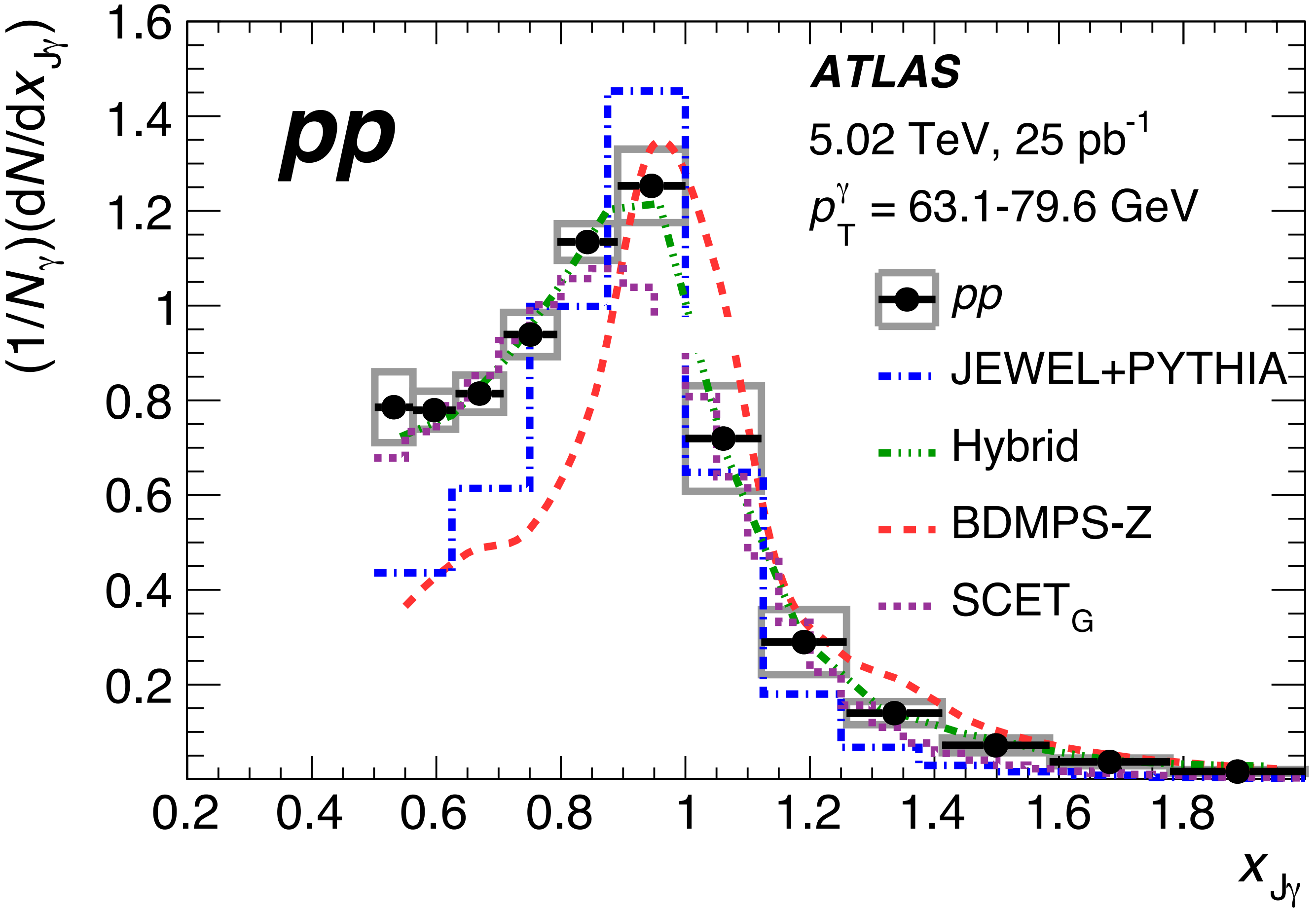
$63 < p_{T\gamma} < 80$ GeV

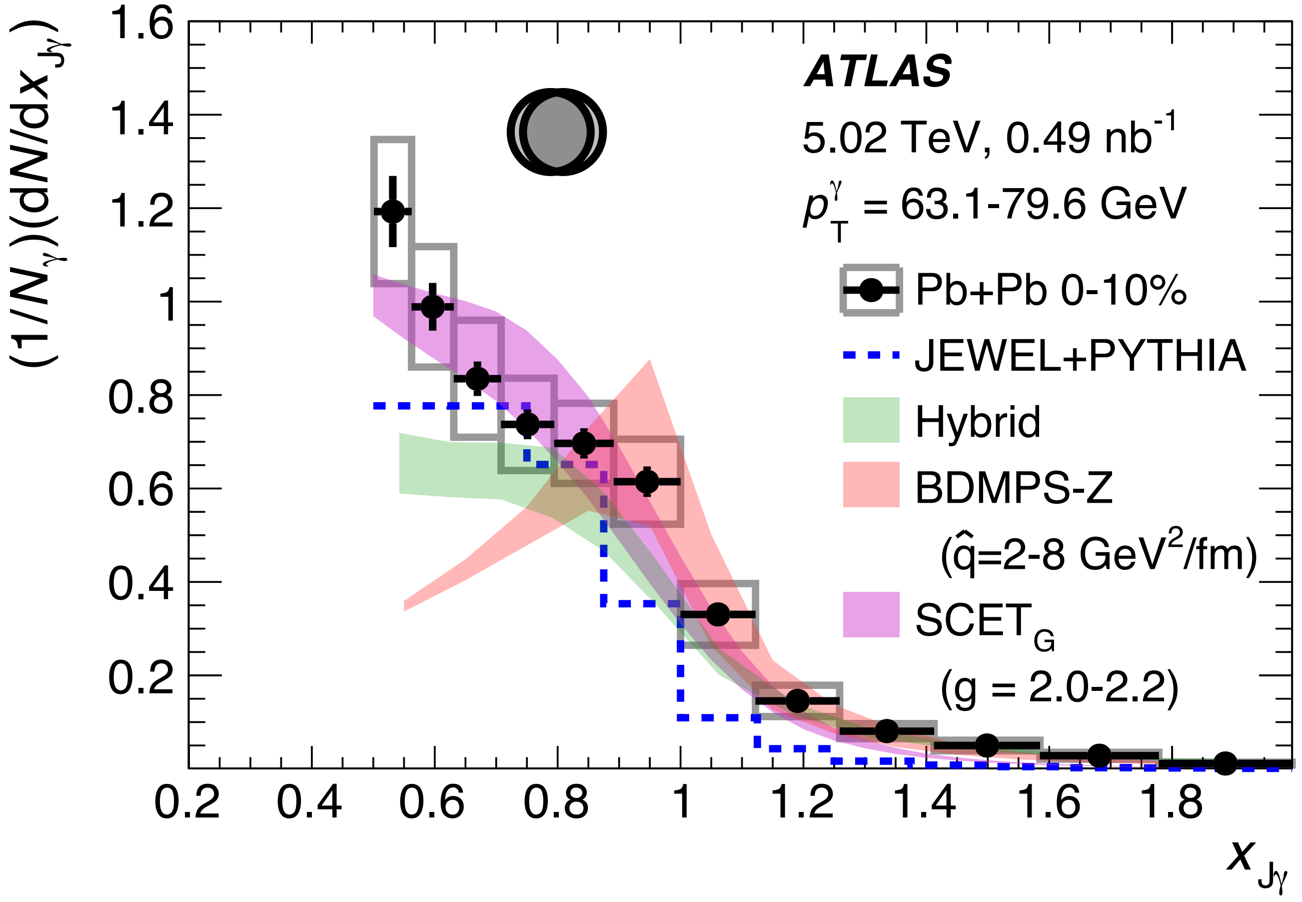
$$x_{J\gamma} = \frac{p_{T,\mathrm{jet}}}{p_{T,\gamma}}$$



γ-jet asymmetry: models

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





- **SCET$_g$ describes the central Pb+Pb well but misses the peak at 1 in *pp***

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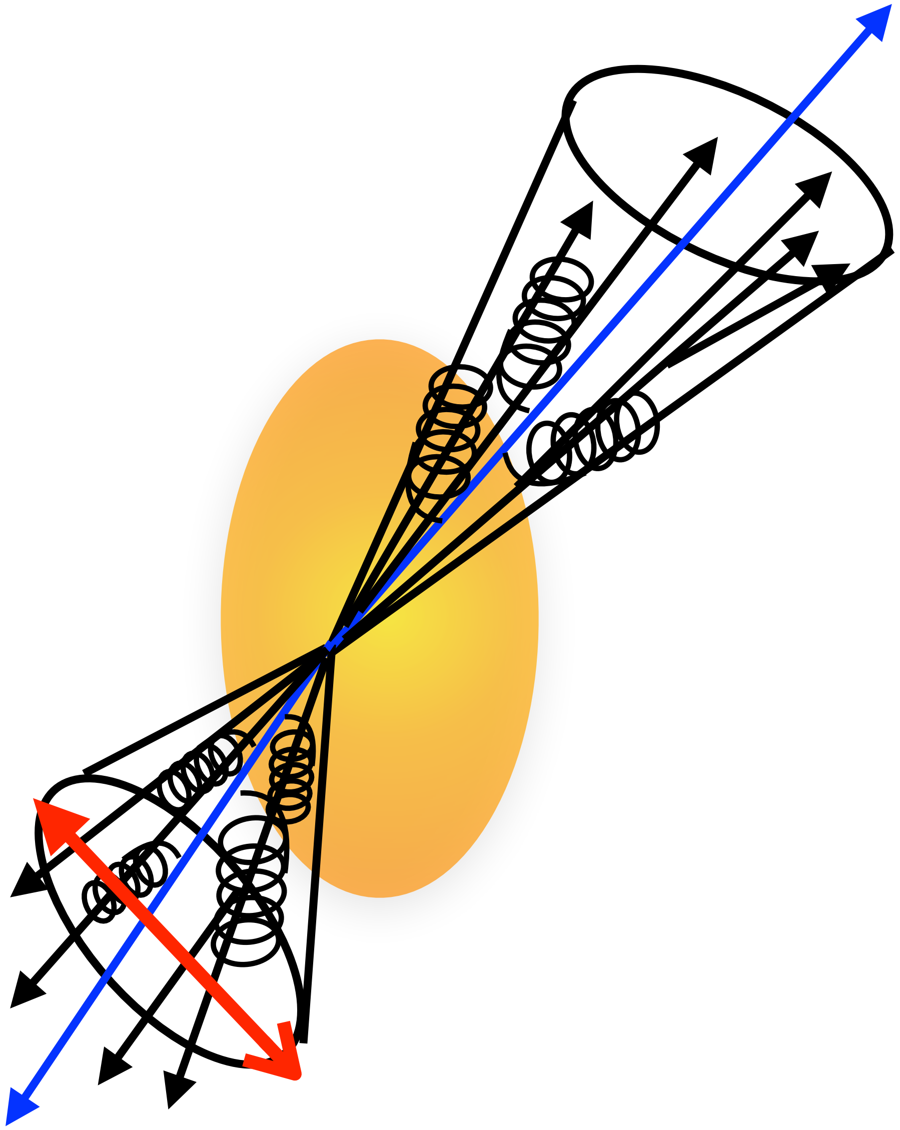
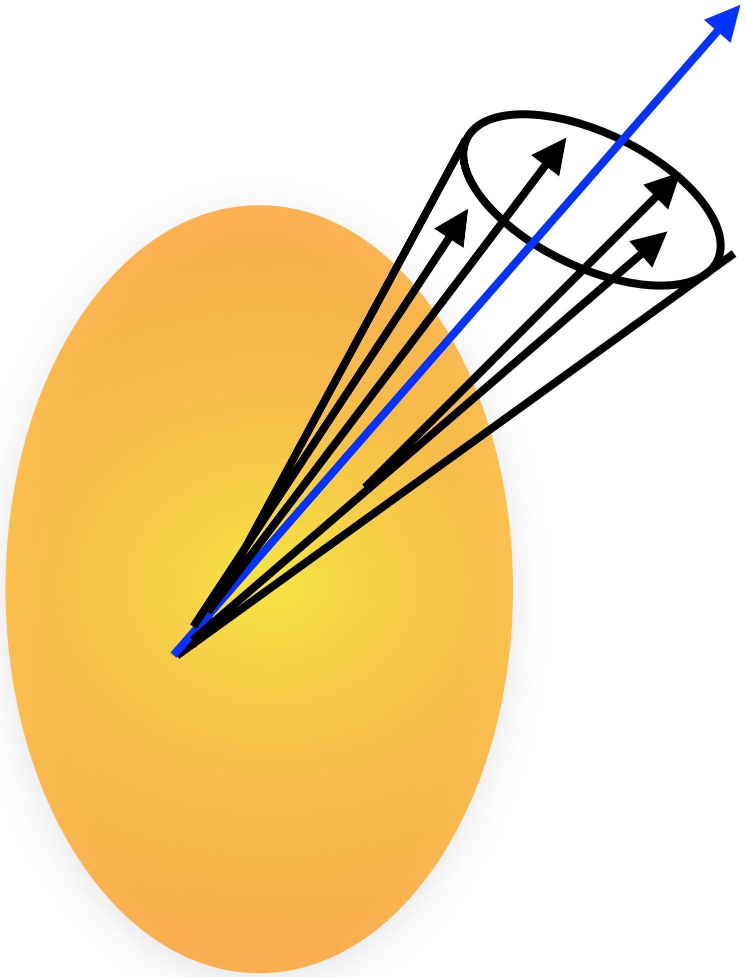


Jet-medium interactions



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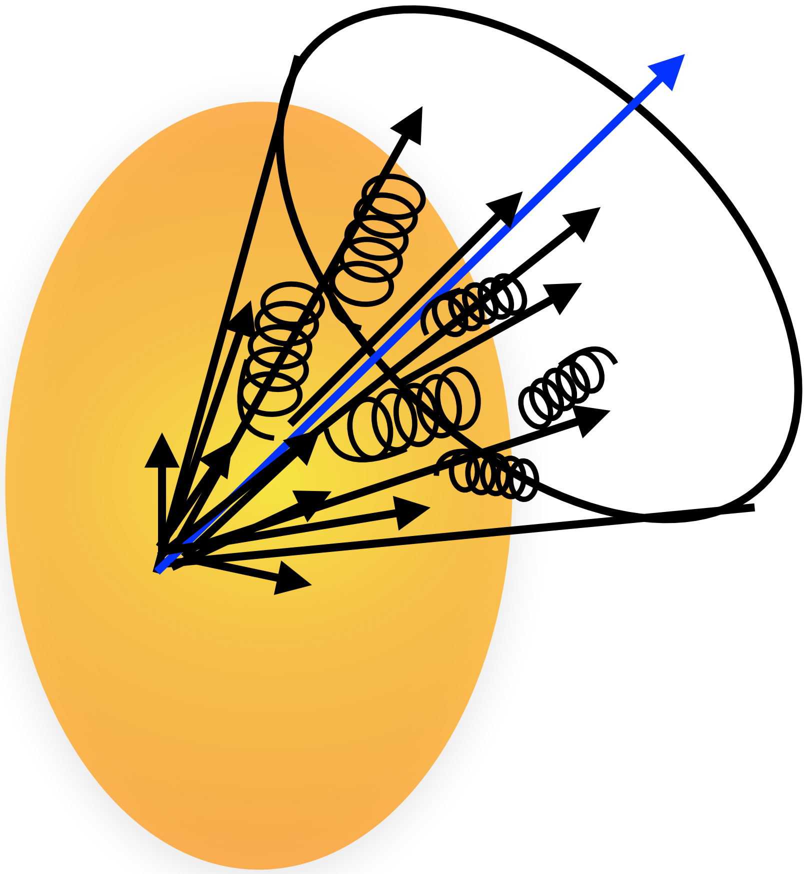

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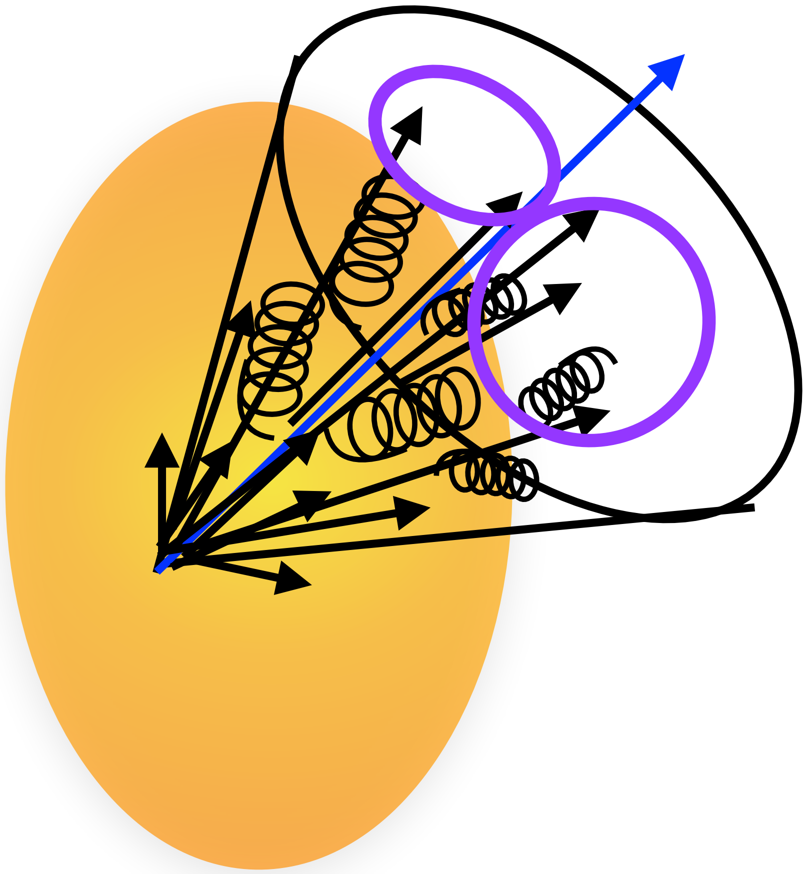

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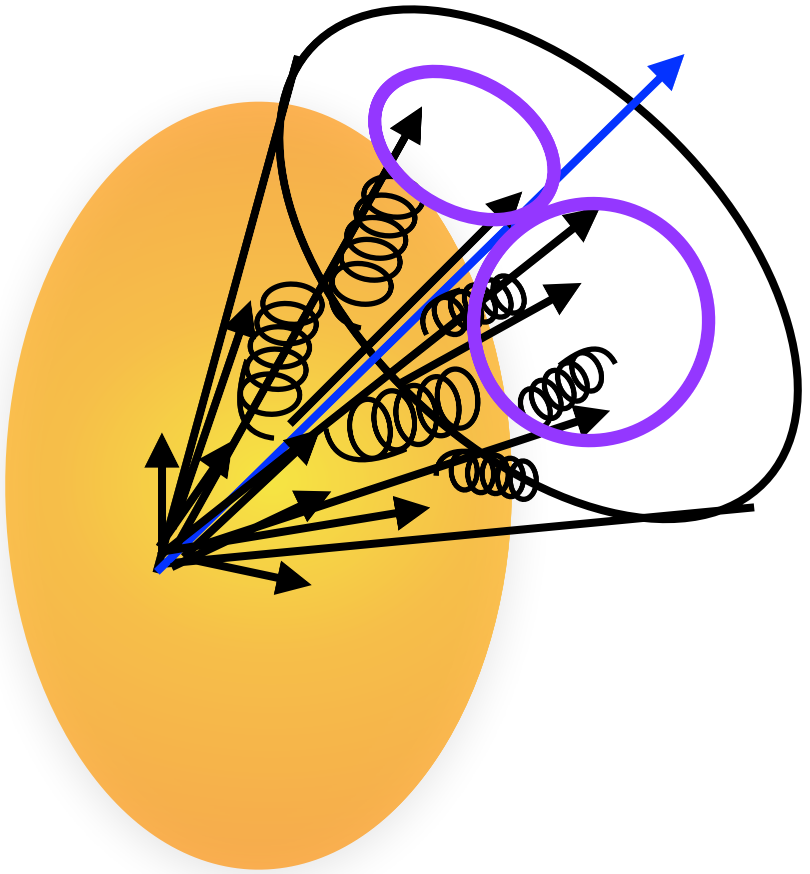
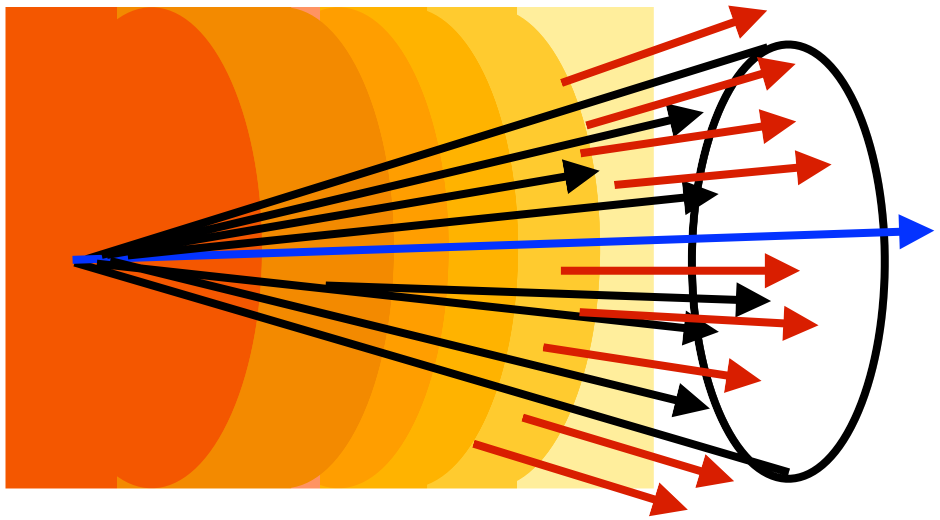


- **Decoherence: medium resolves subjets and modifies them as separate jets**

- **Medium responds to jet and recoils, causing a wake that pushes soft particles back inside the jet**



Jet mass

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

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

- **Ratio m/p_T (like the opening angle θ) which is easier to unfold and has a weak dependence on p_T**

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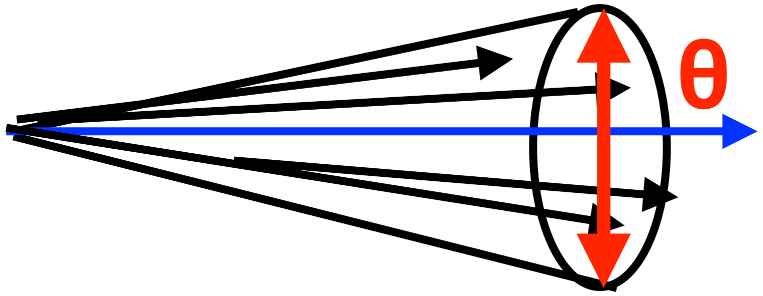
narrow jets:

lower mass and m/p_T



wide jets:

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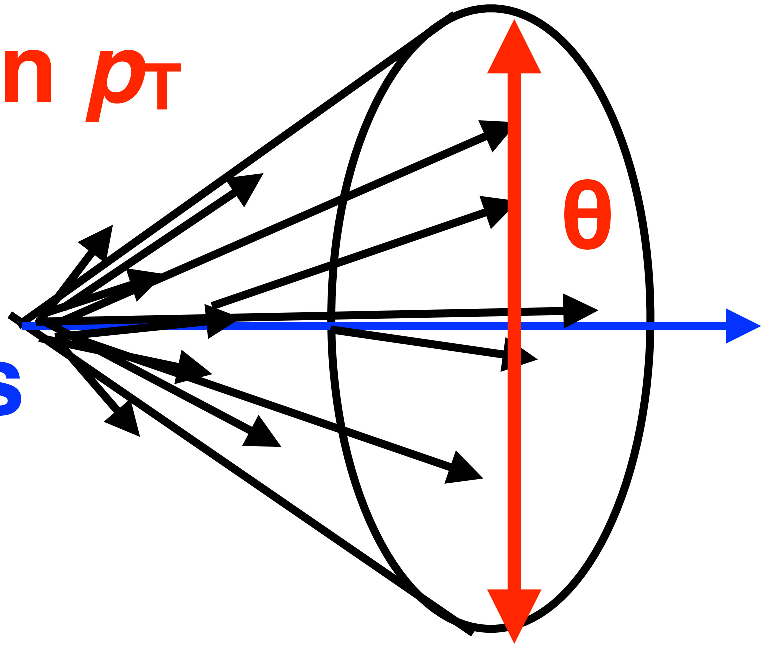

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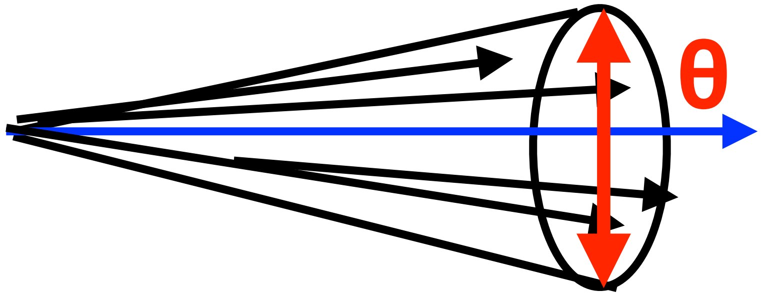

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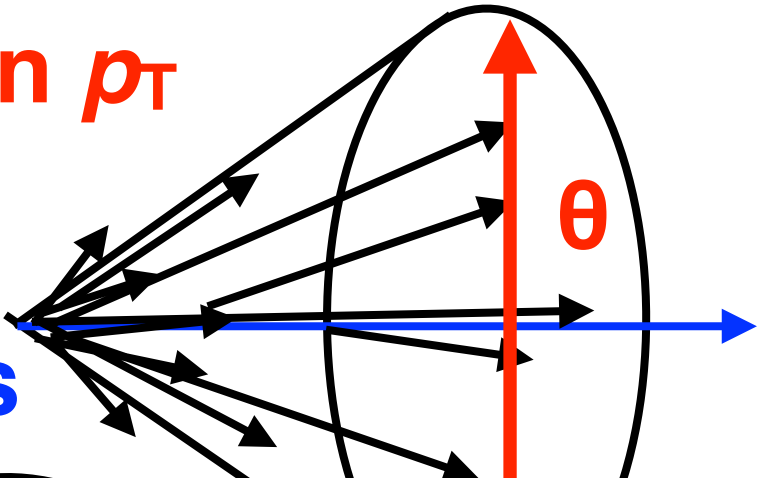

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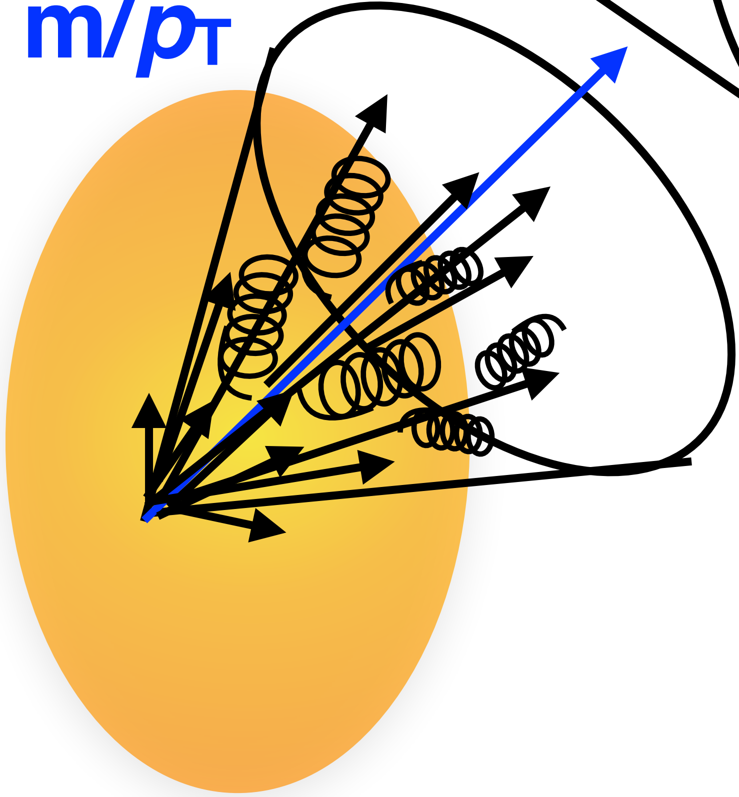
  - **Jet widens -> larger mass**



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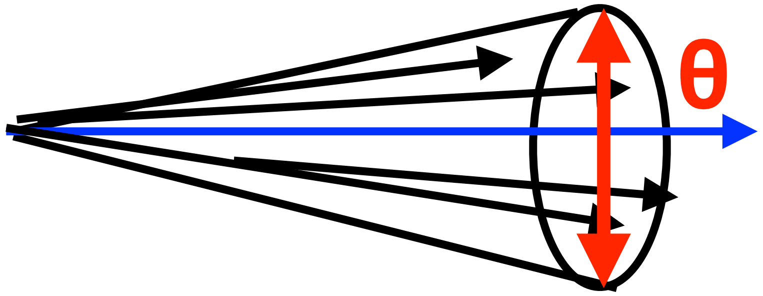

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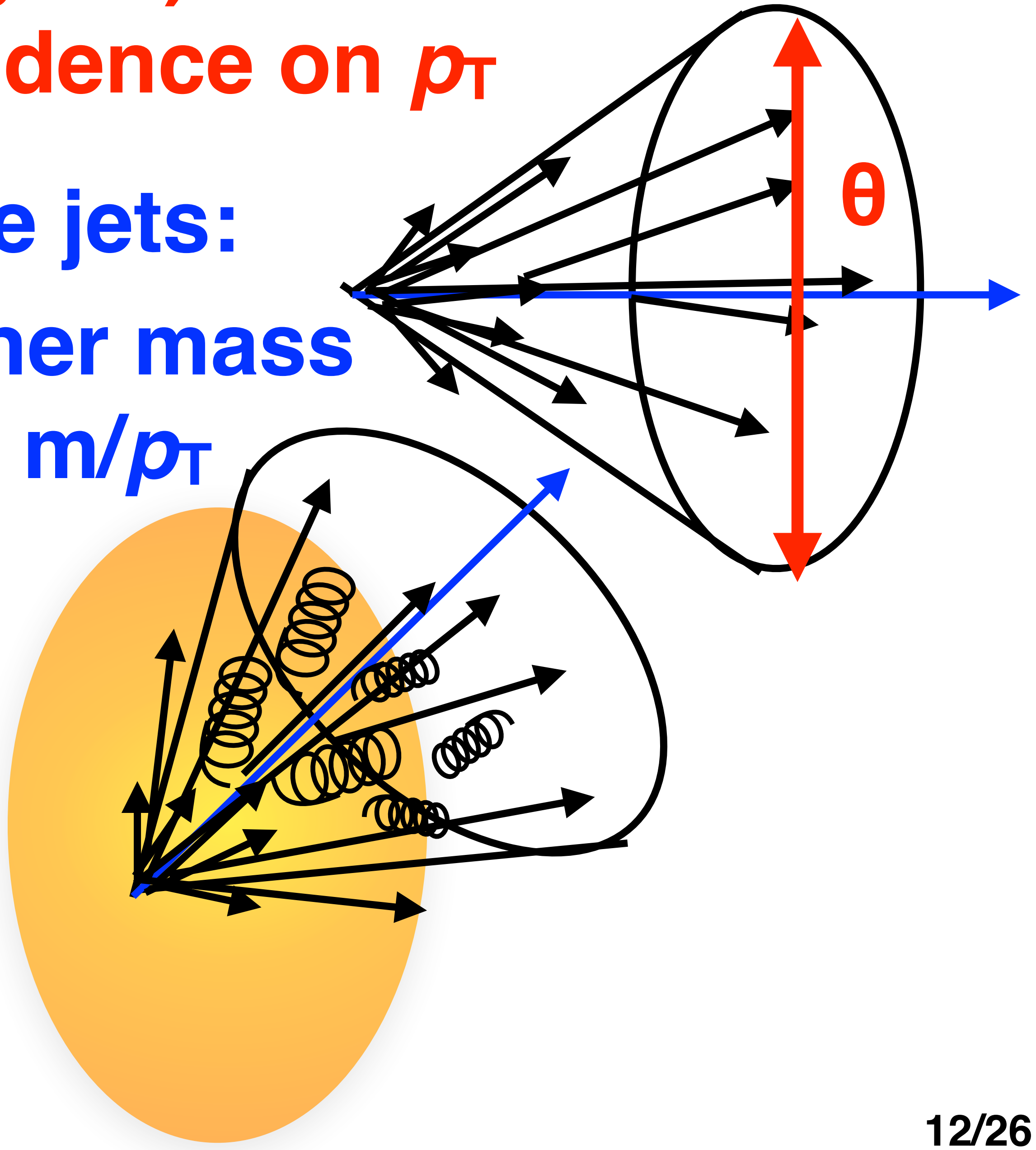
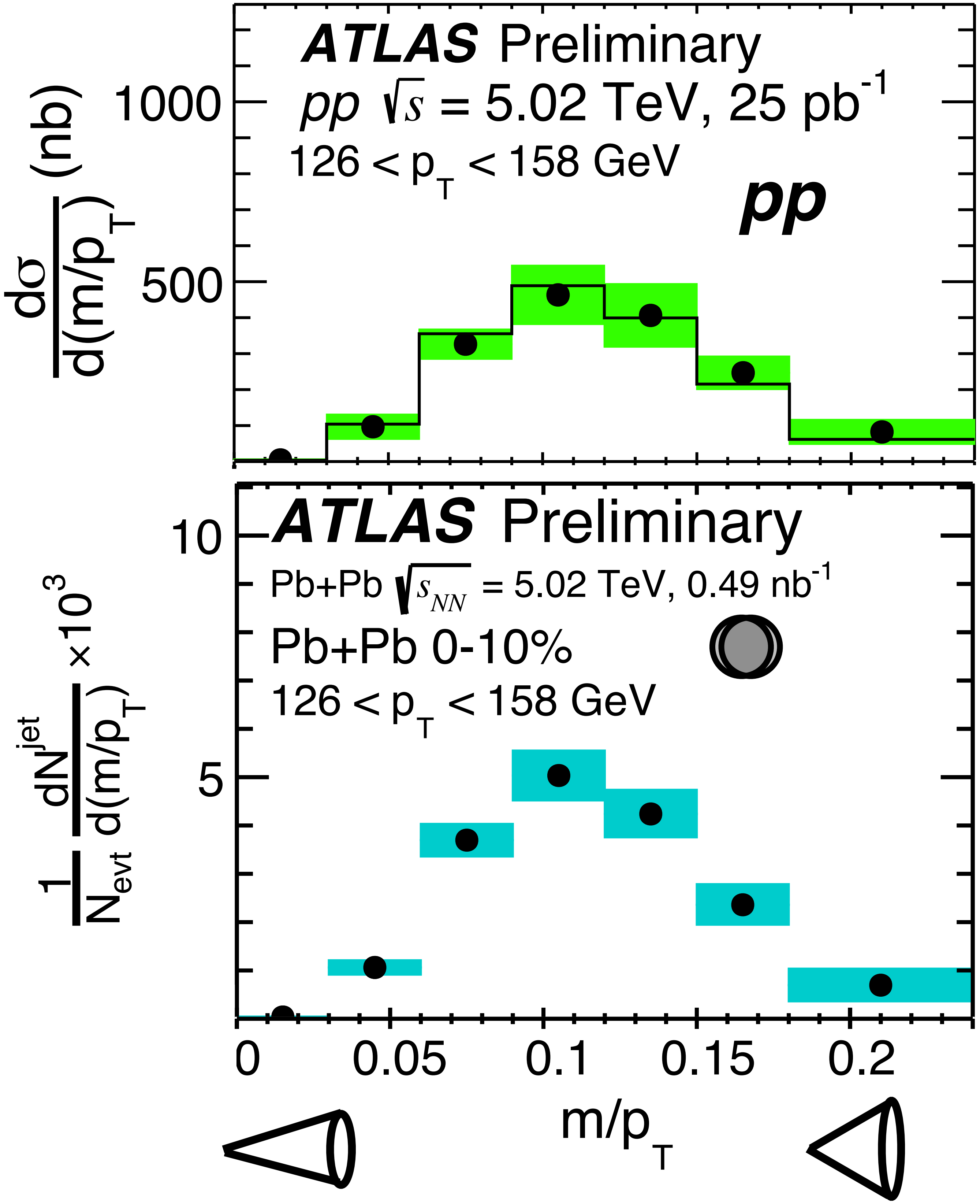


- **In medium:**
  - **Jet widens -> larger mass**
  - **Jet widens too much and energy moves outside of jet cone-> smaller mass**

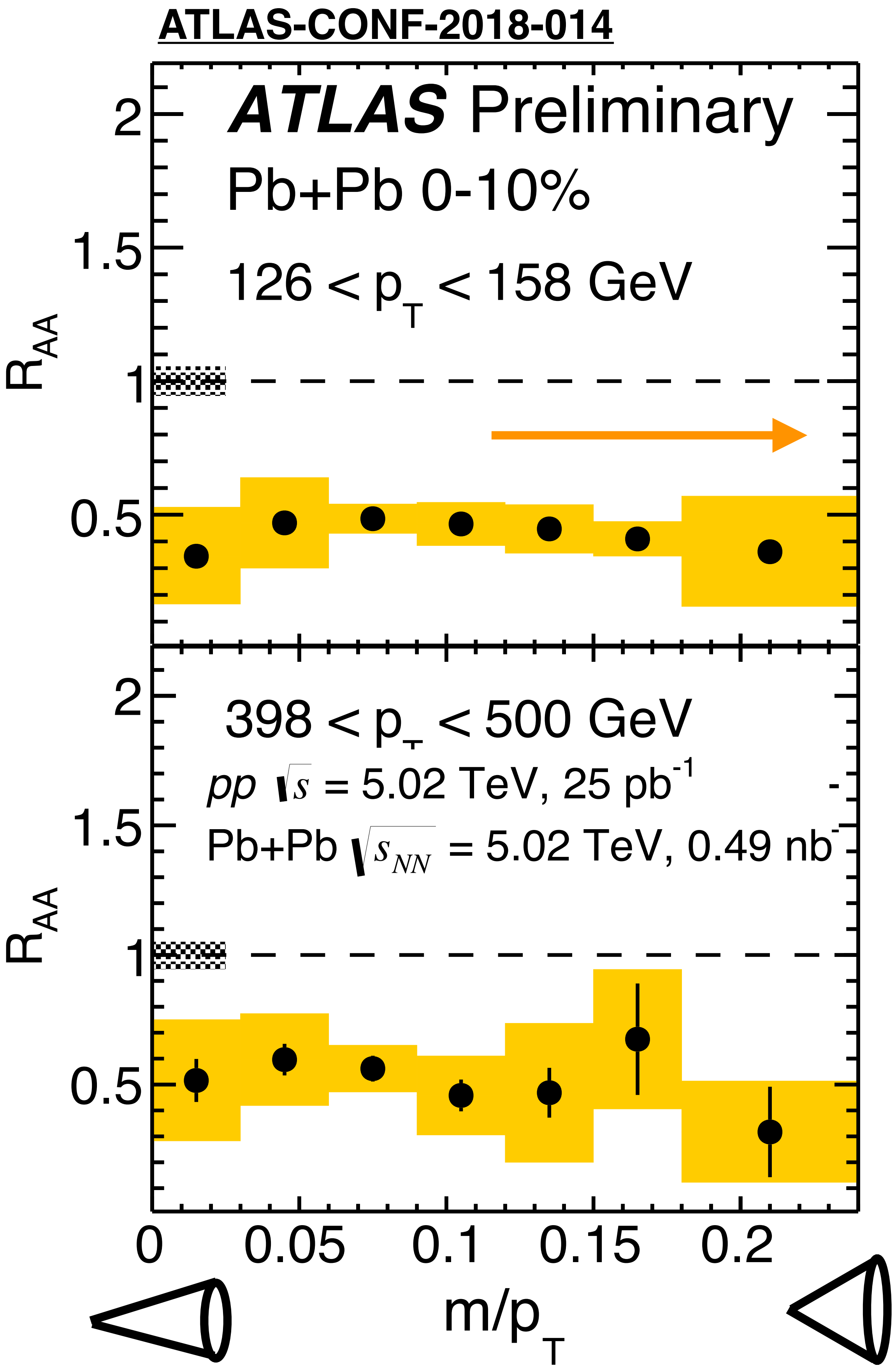
Jet mass



ATLAS-CONF-2018-014

- **ATLAS m/p_T in Pb+Pb and *pp***

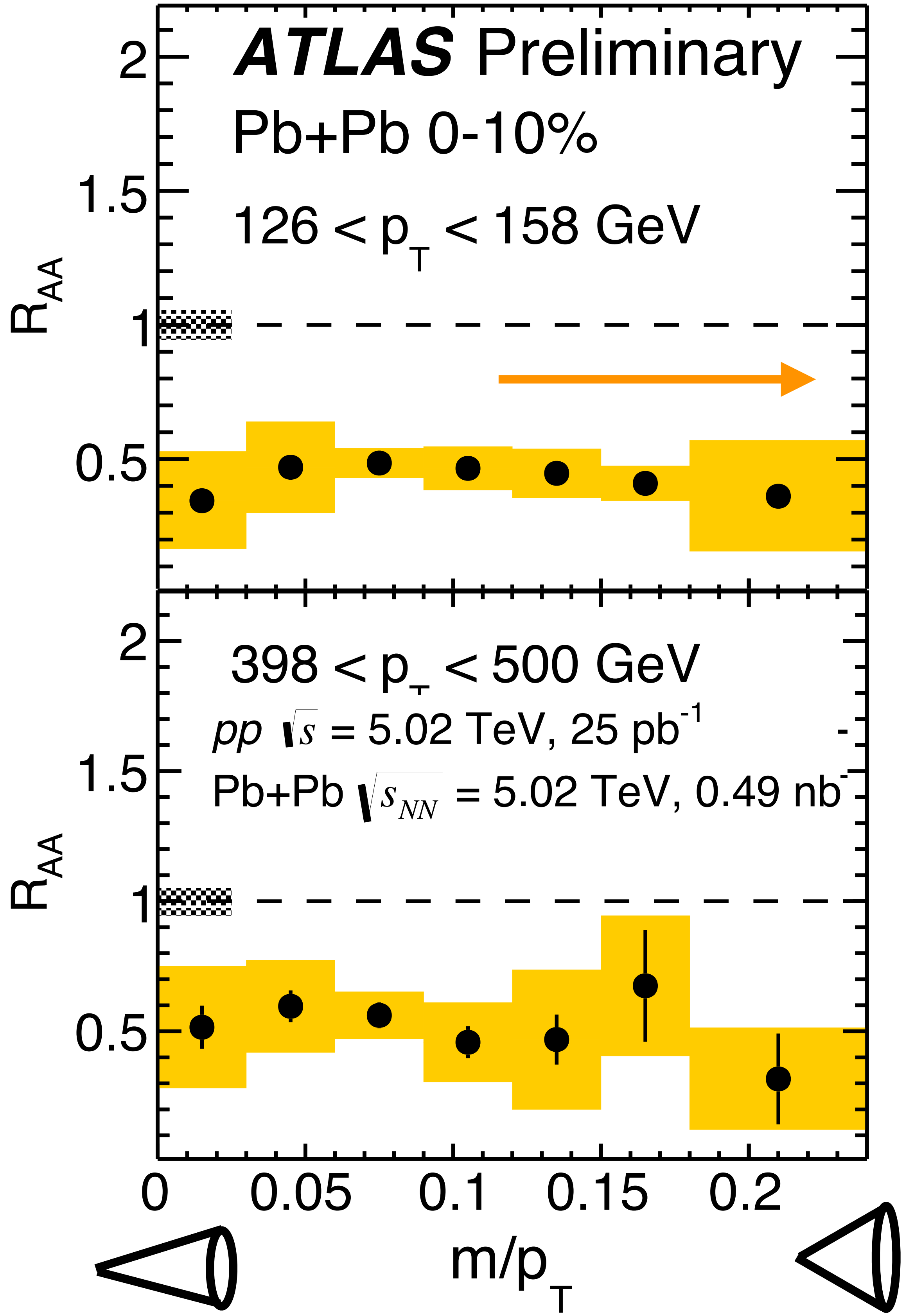
Jet mass: ratio



- **ATLAS R_{AA} vs. m/pT: no significant modification**

Jet mass: ratio

ATLAS-CONF-2018-014

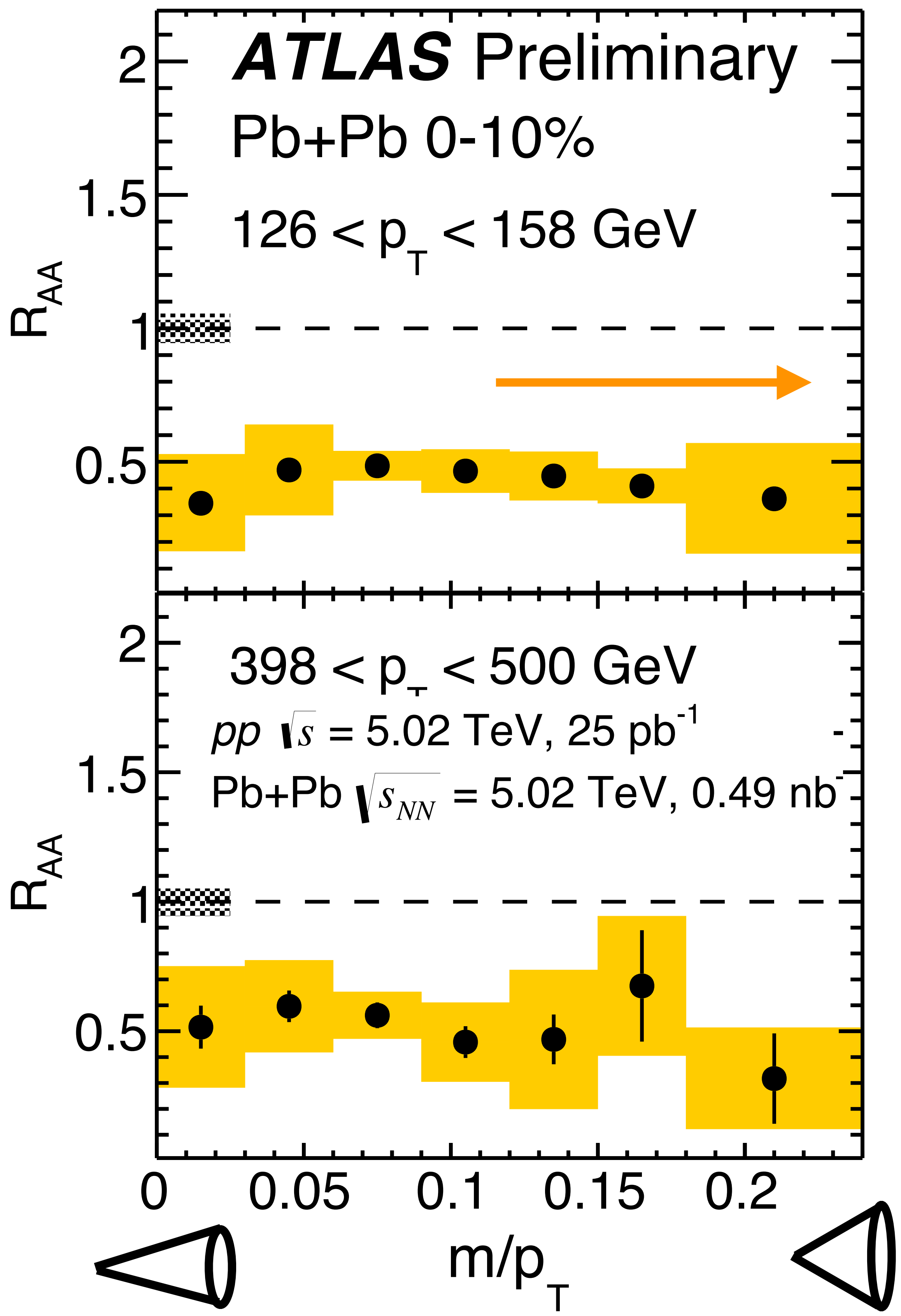


- **ATLAS R_{AA} vs. m/pT: no significant modification**

- **Suggests coherence?**

Jet mass: ratio

ATLAS-CONF-2018-014



- **ATLAS R_{AA} vs. m/pT: no significant modification**

- **Suggests coherence?**

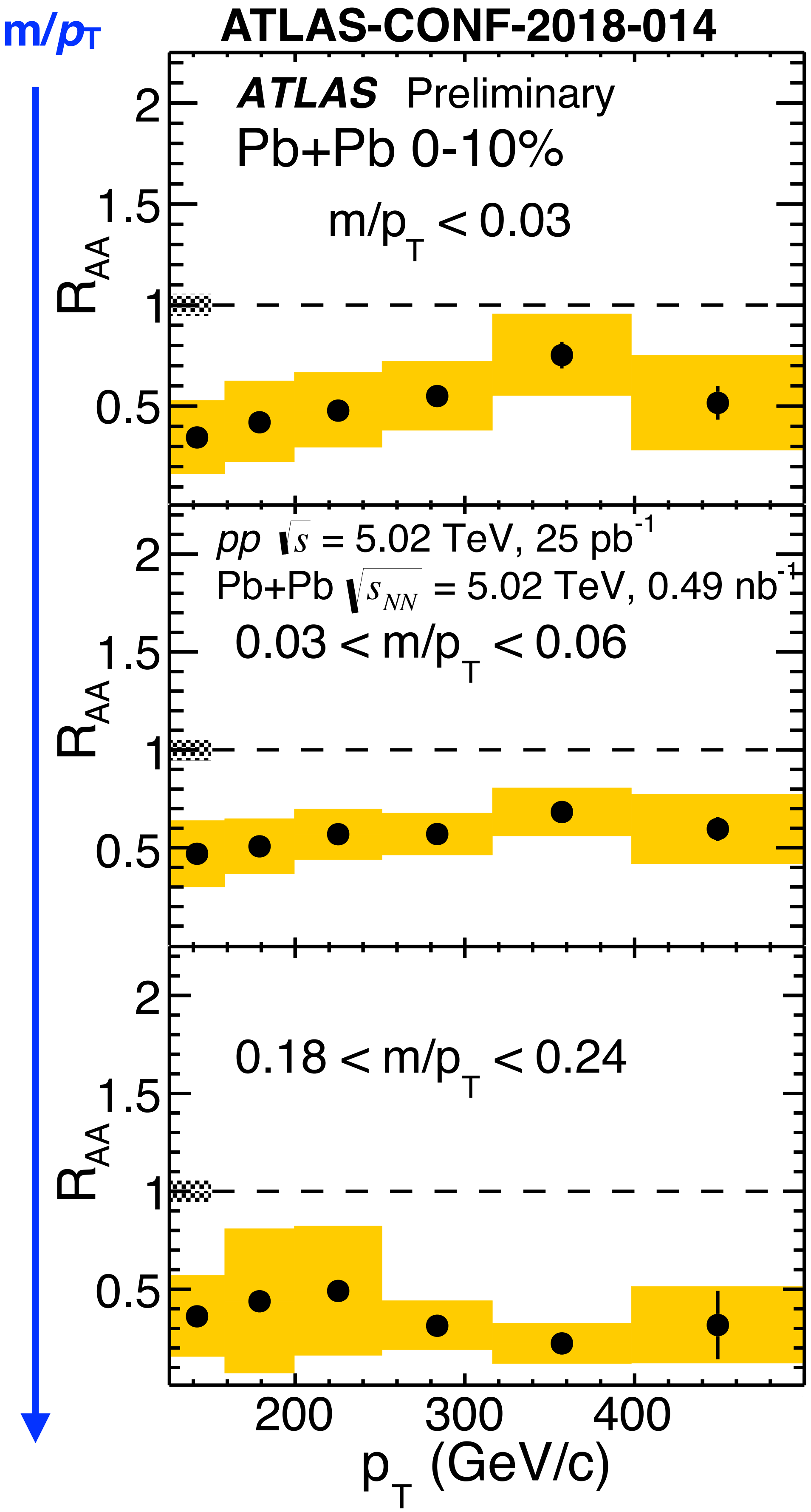
- **The medium recoil increases the jet mass**

- **k_T broadening outside jet cone decreases mass**

Canceling effects?

Jet mass: ratio

- **ATLAS R_{AA} vs. p_T: no significant modification**
- **R_{AA} is consistent with inclusive R_{AA} for all m/p_T**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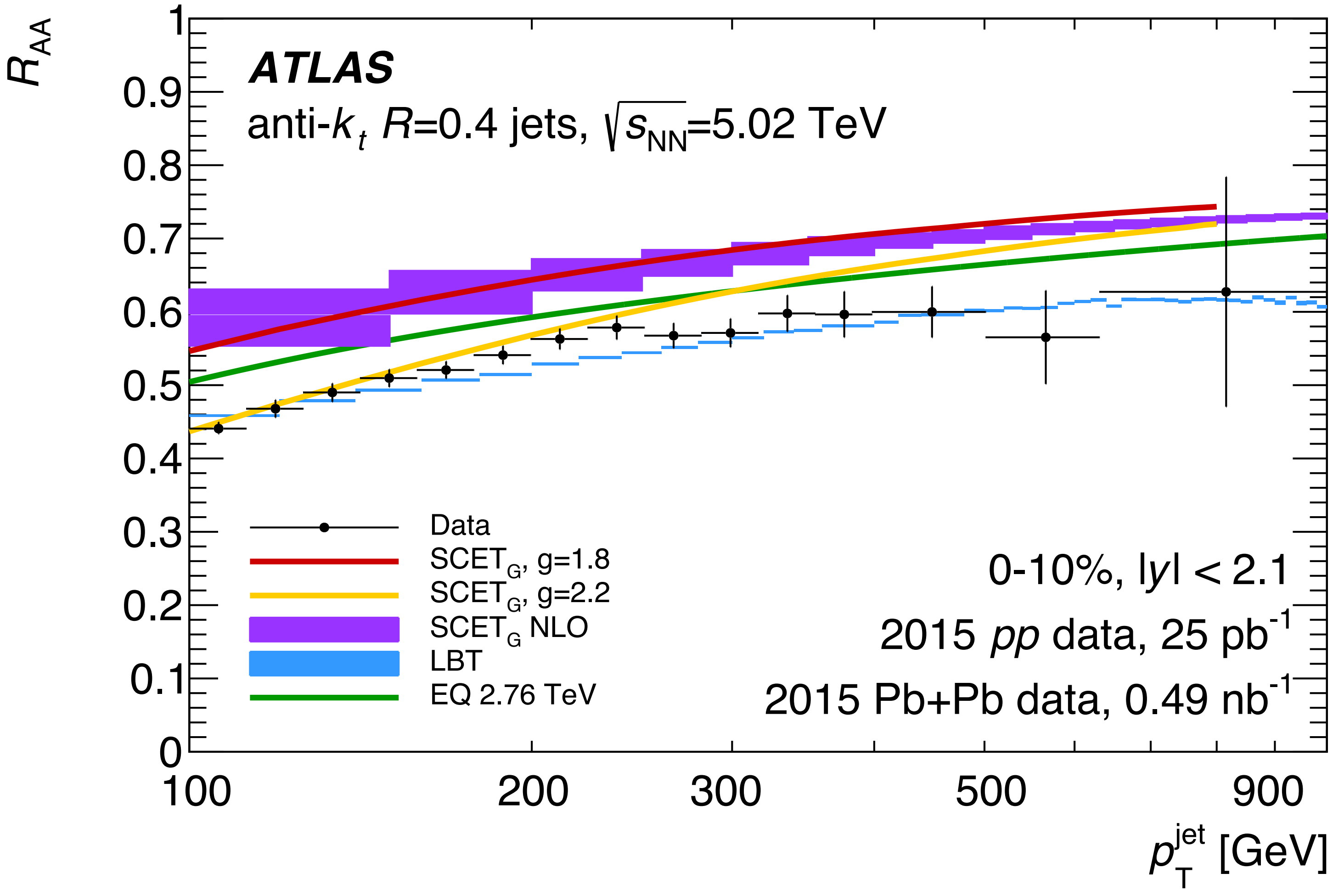


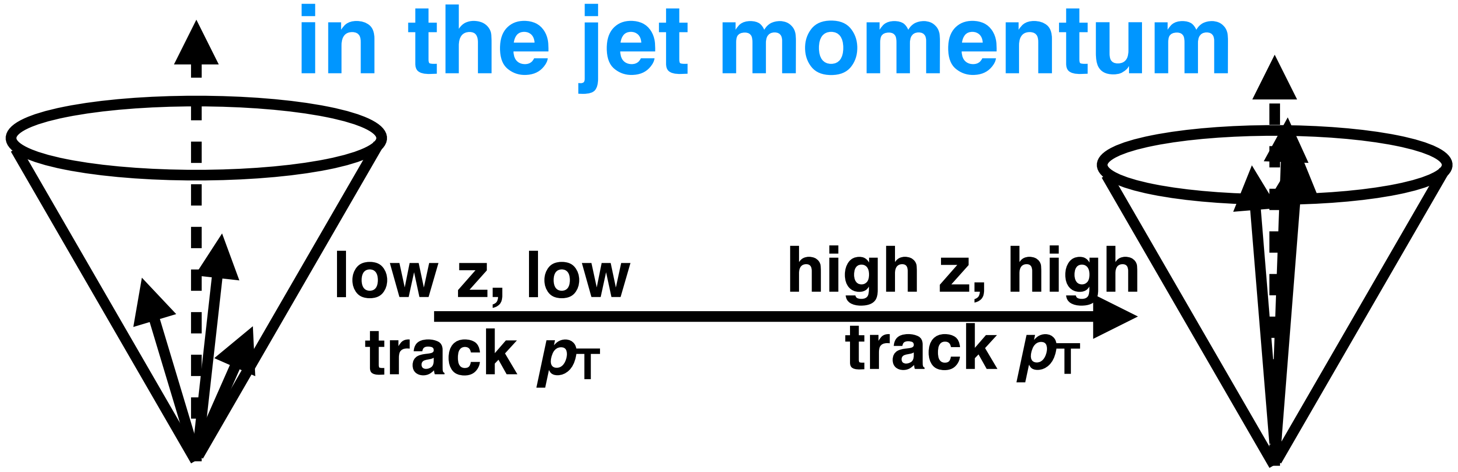
Jet fragmentation functions

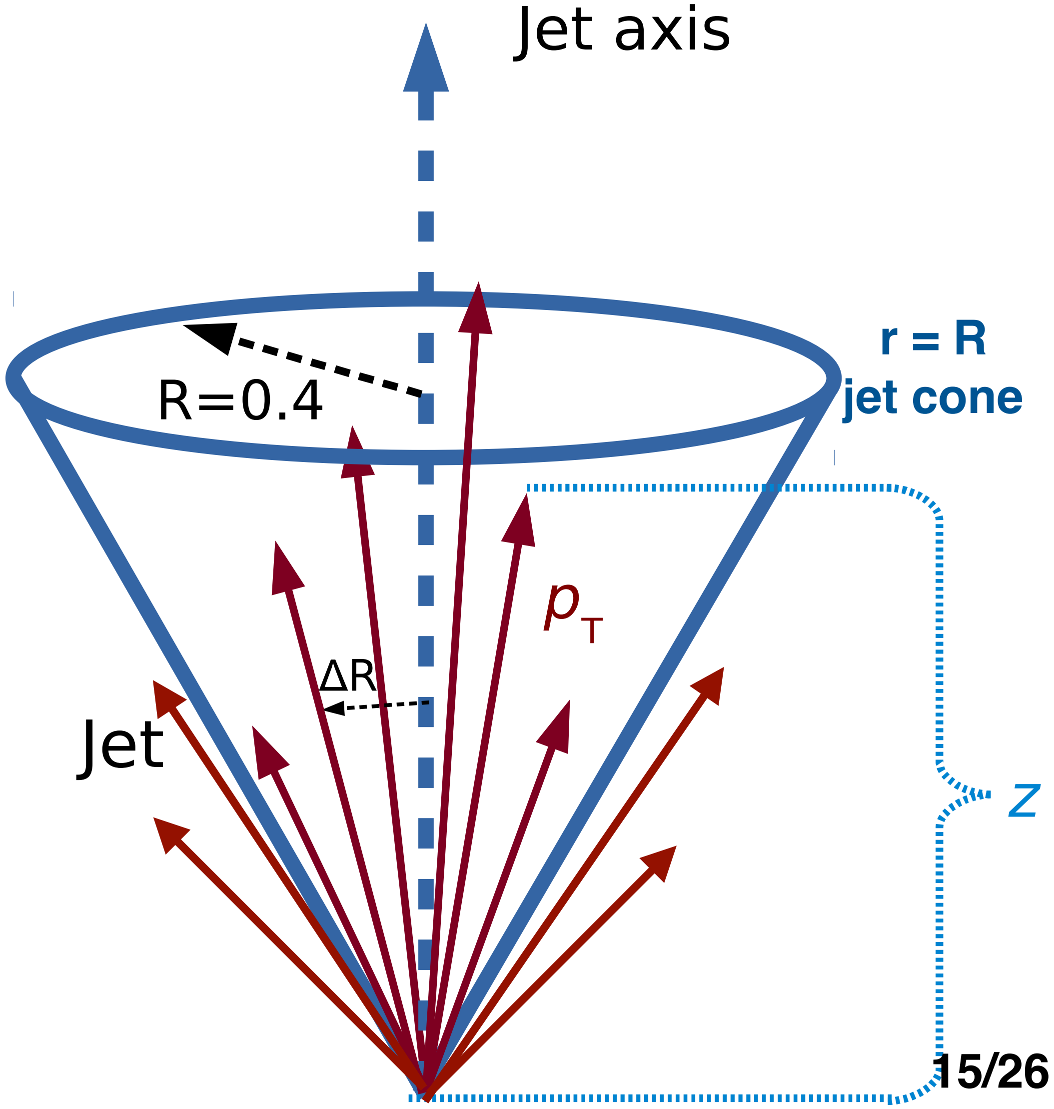
- **Measures how charged particles are distributed within a jet by looking at number of charged particles in jets ($N_{\rm ch}$)**

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

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

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

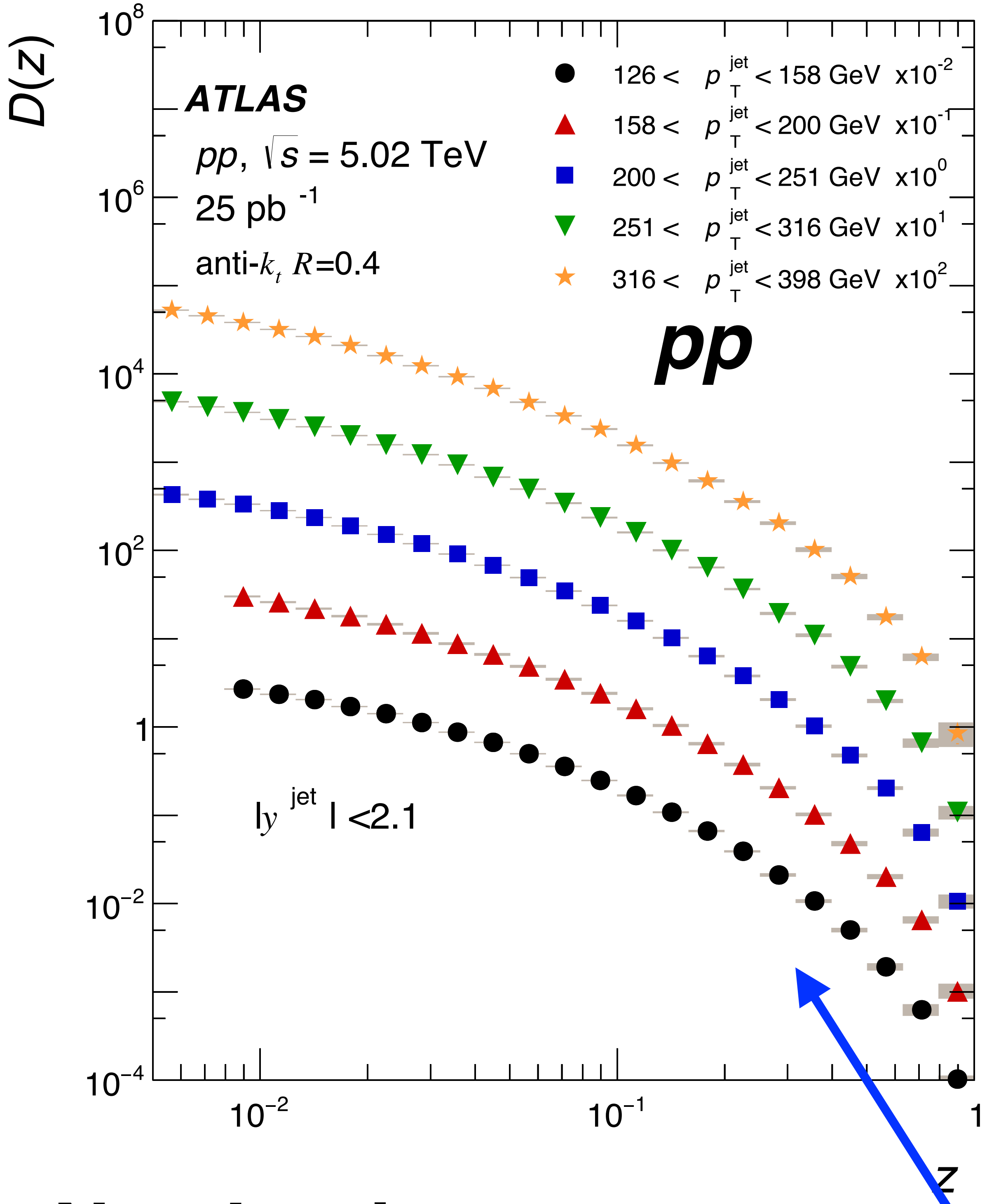


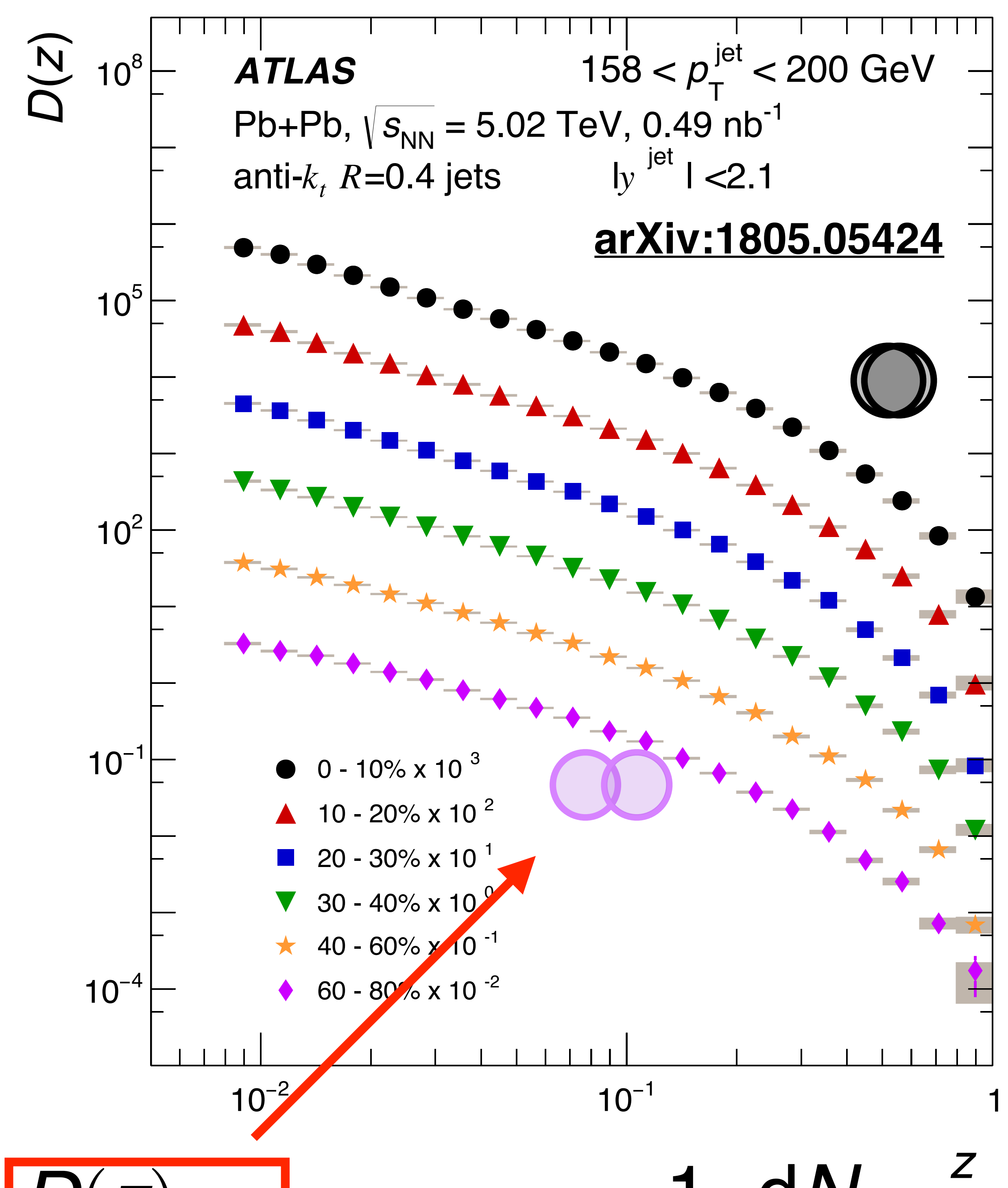


- **R=0.4 jets with charged tracks > 1 GeV**

Jet fragmentation functions

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





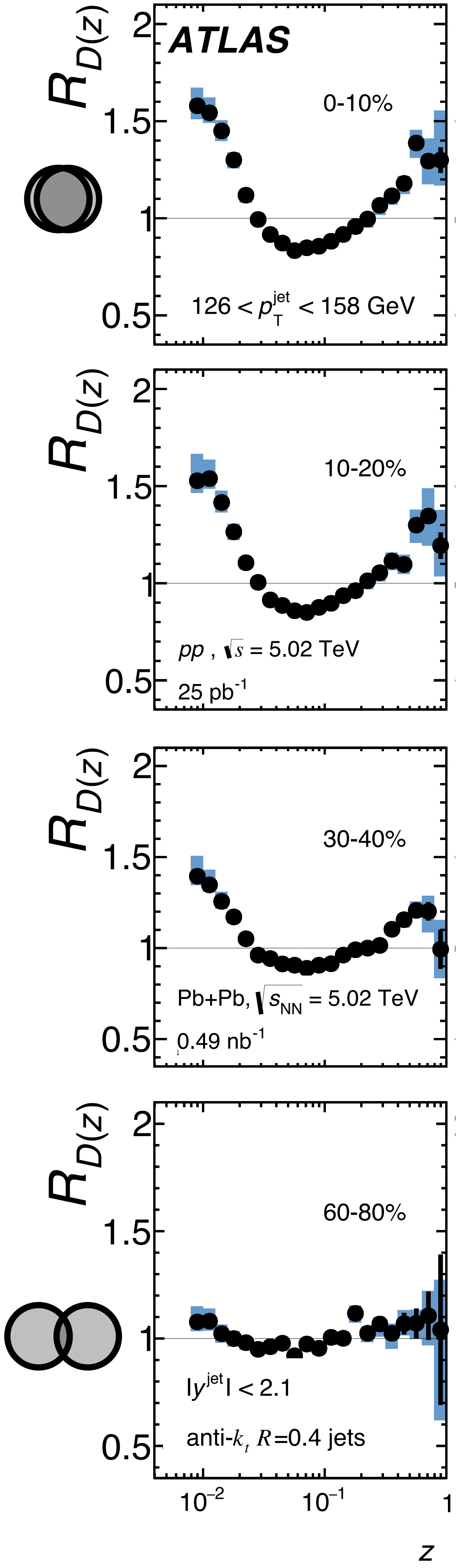
- **Need ratio to see modification.**

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

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

Internal structure

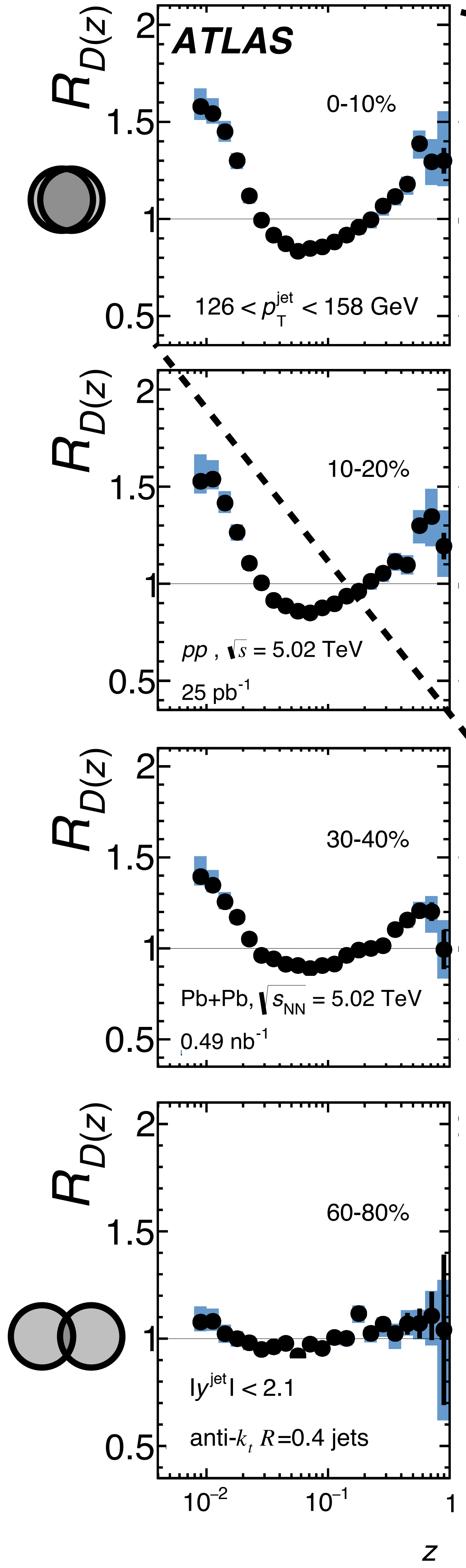
$$R_{\mathrm{D(z)}} = \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}}$$

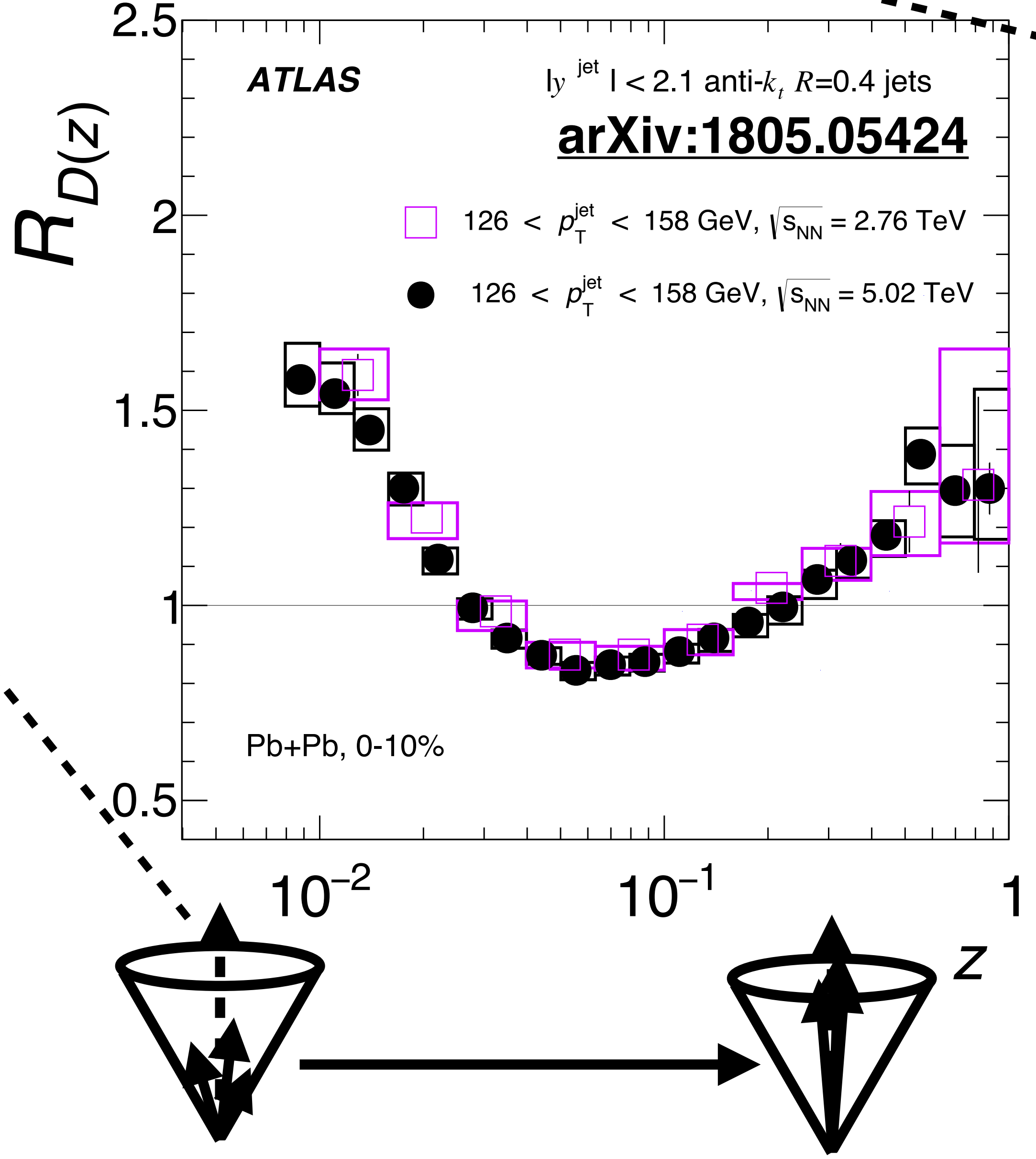


- **Jets are more modified in central collisions**

Internal structure

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

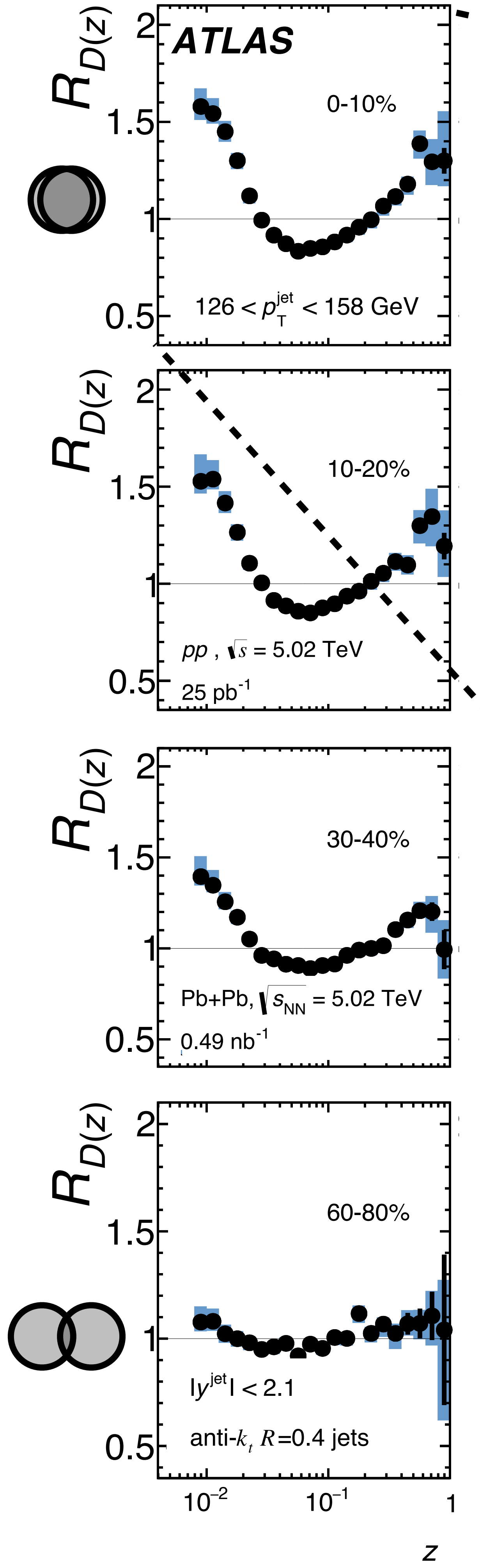


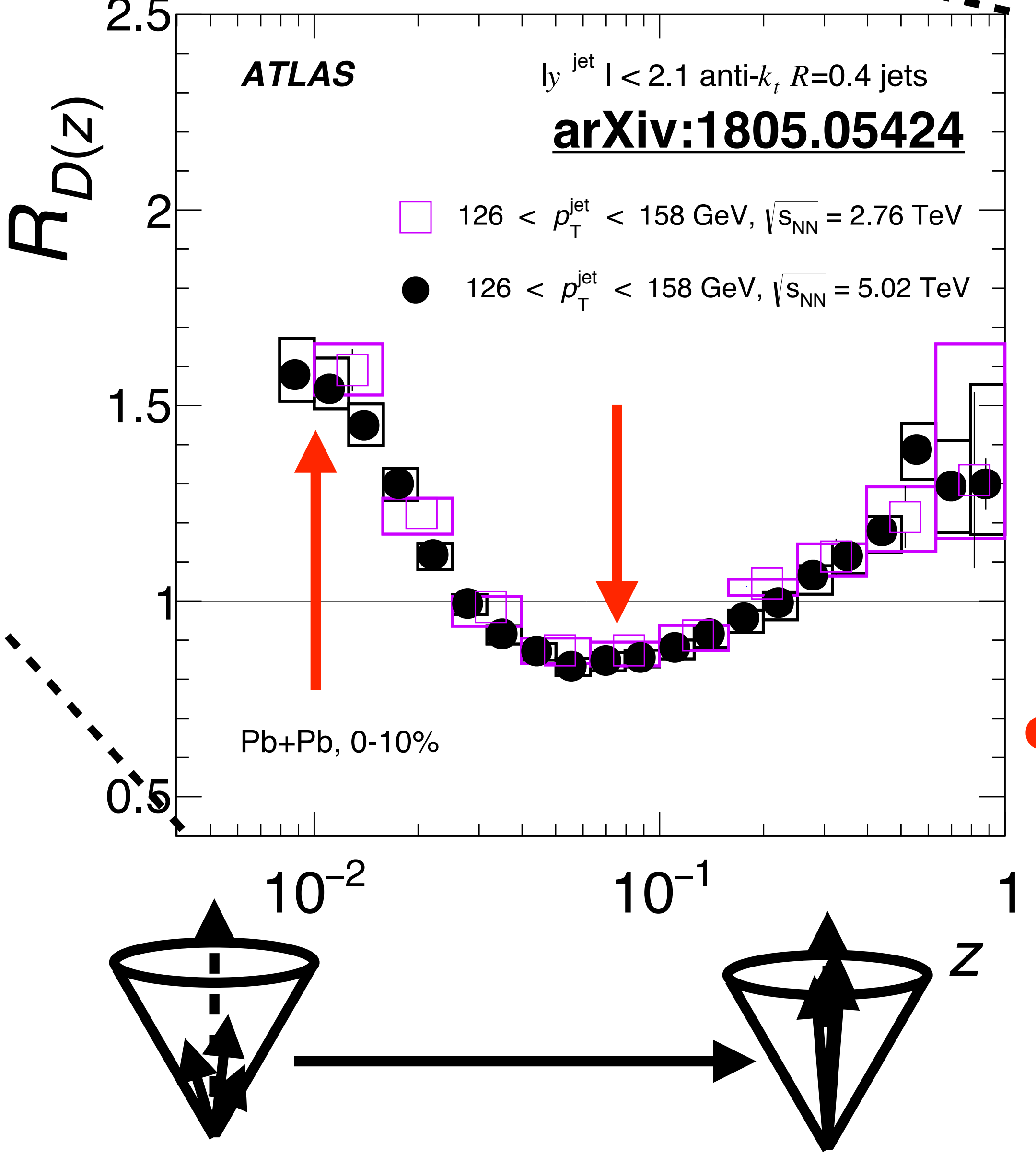


- **Jets are more modified in central collisions**
- **Consistent between 2.76 and 5.02 TeV**

Internal structure

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



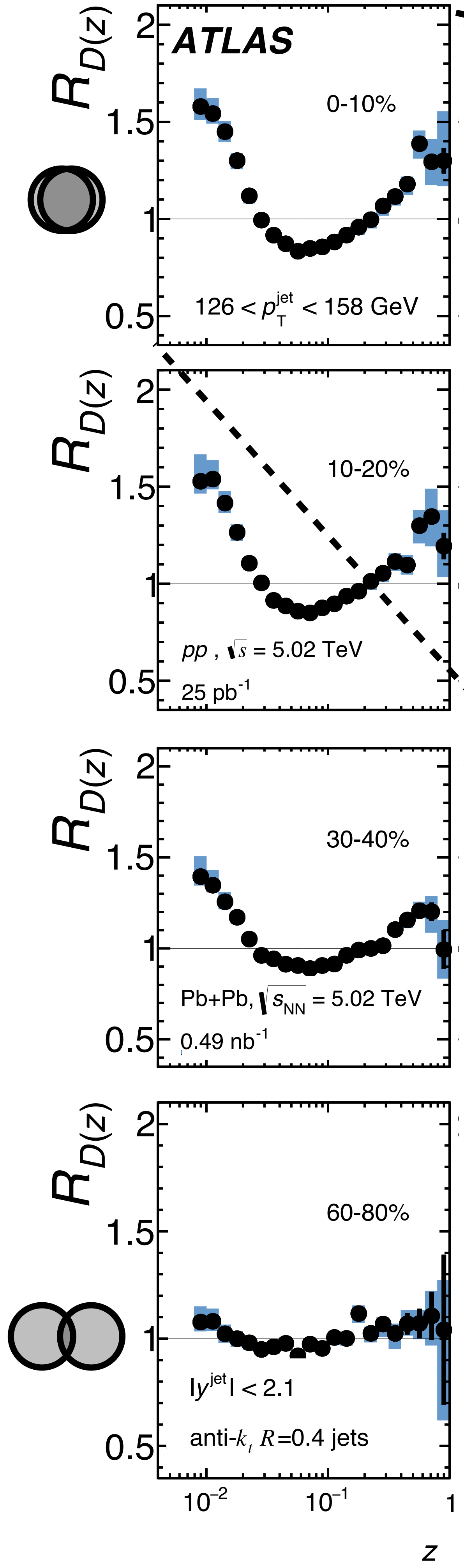


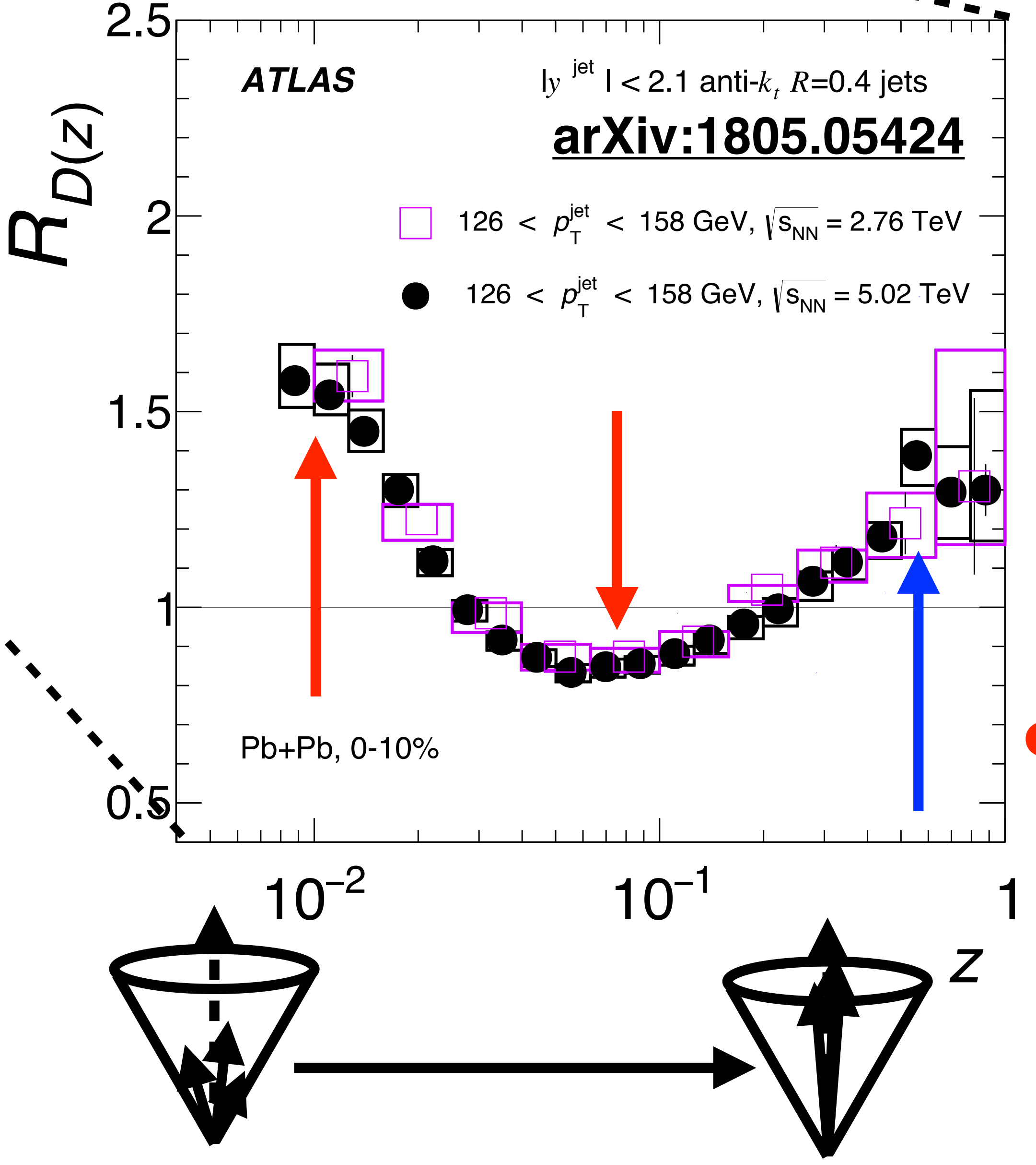
- **Jets are more modified in central collisions**
- **Consistent between 2.76 and 5.02 TeV**
- **Enhancement at low z and suppression at intermediate z**

➡ Energy transferred to soft particles in and around the jet

Internal structure

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





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

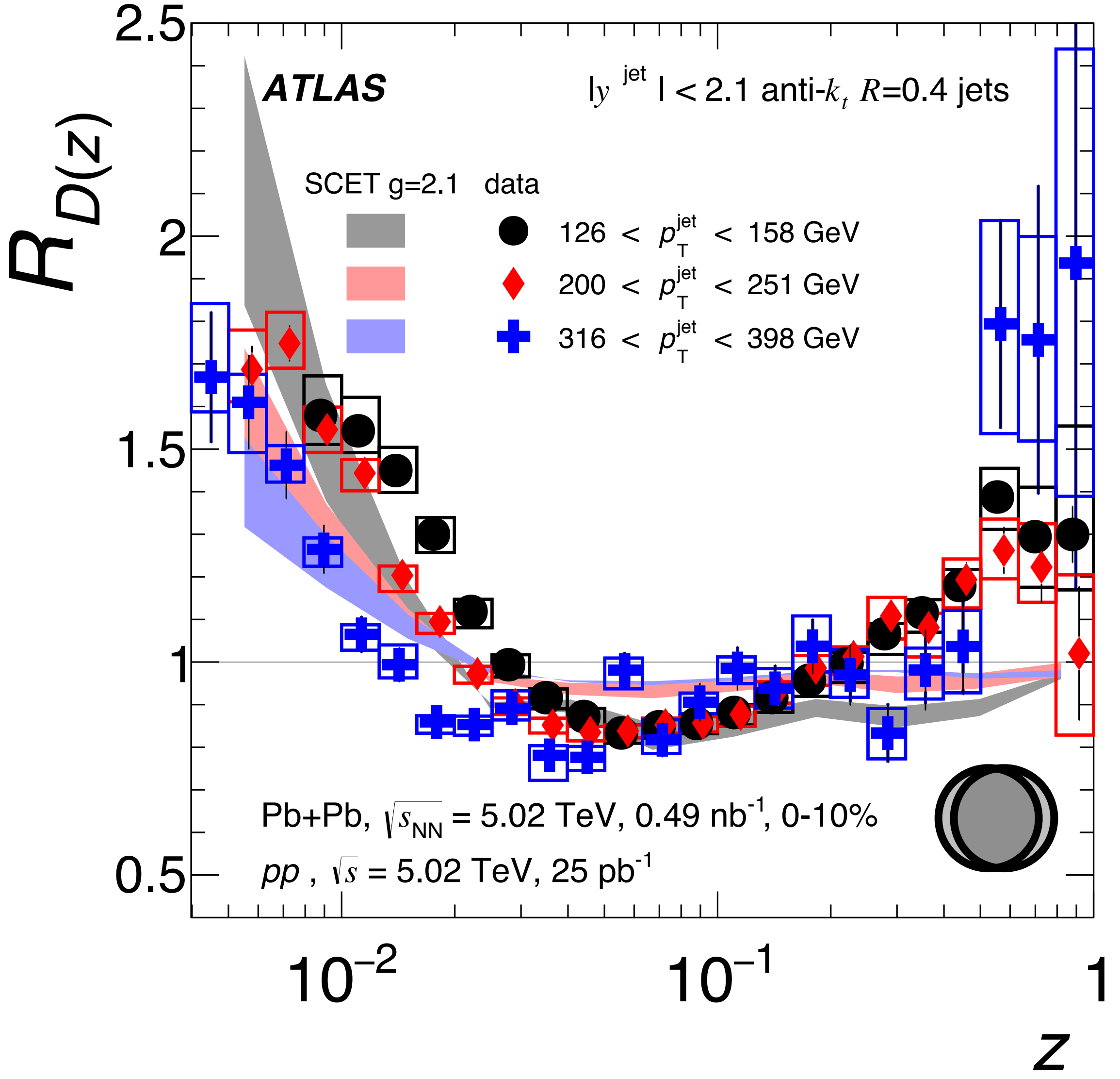
➡ Energy transferred to soft particles in and around the jet

- **Enhancement at high z**

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

Internal structure: p_T dep.

arXiv:1805.05424

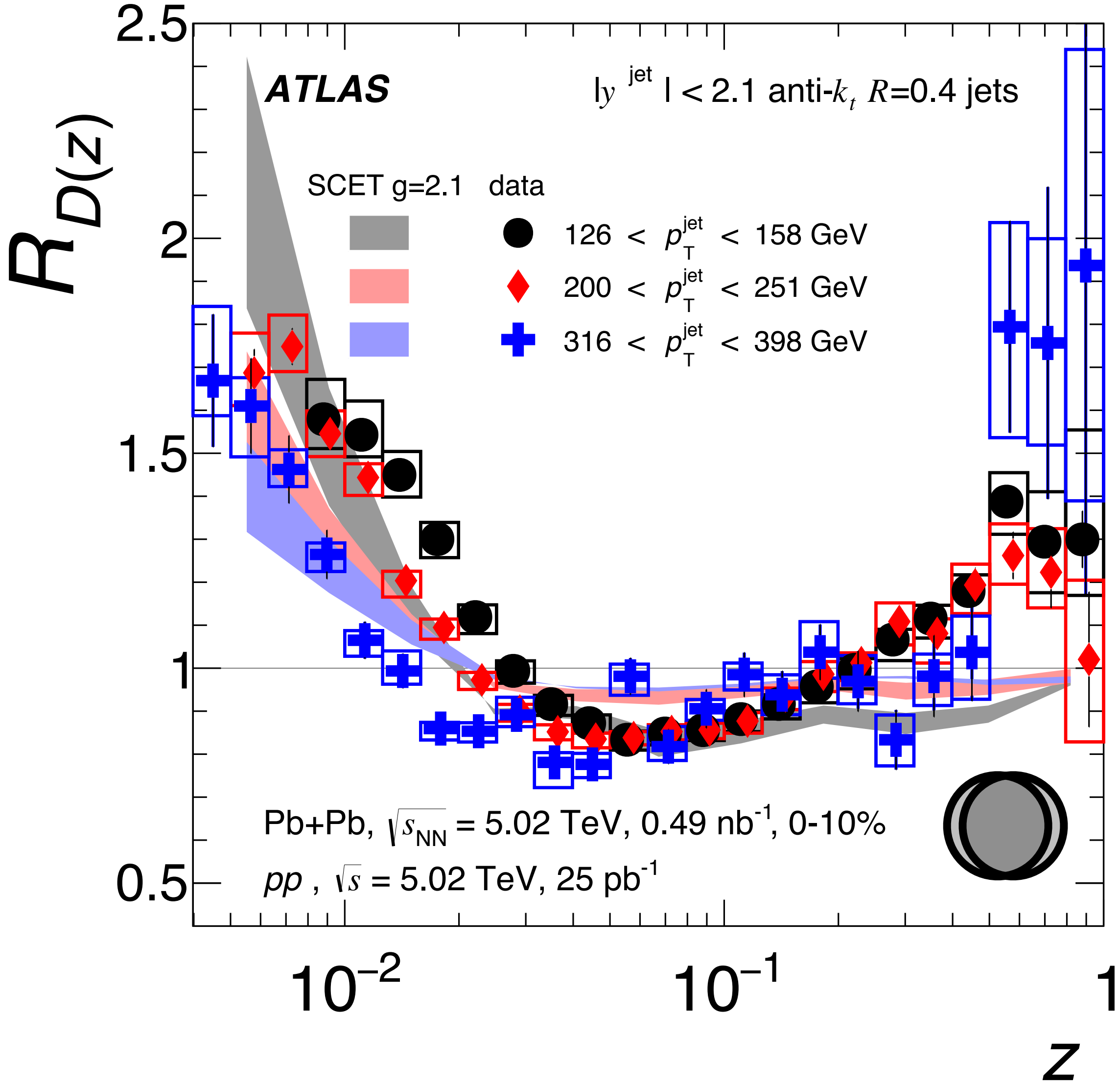


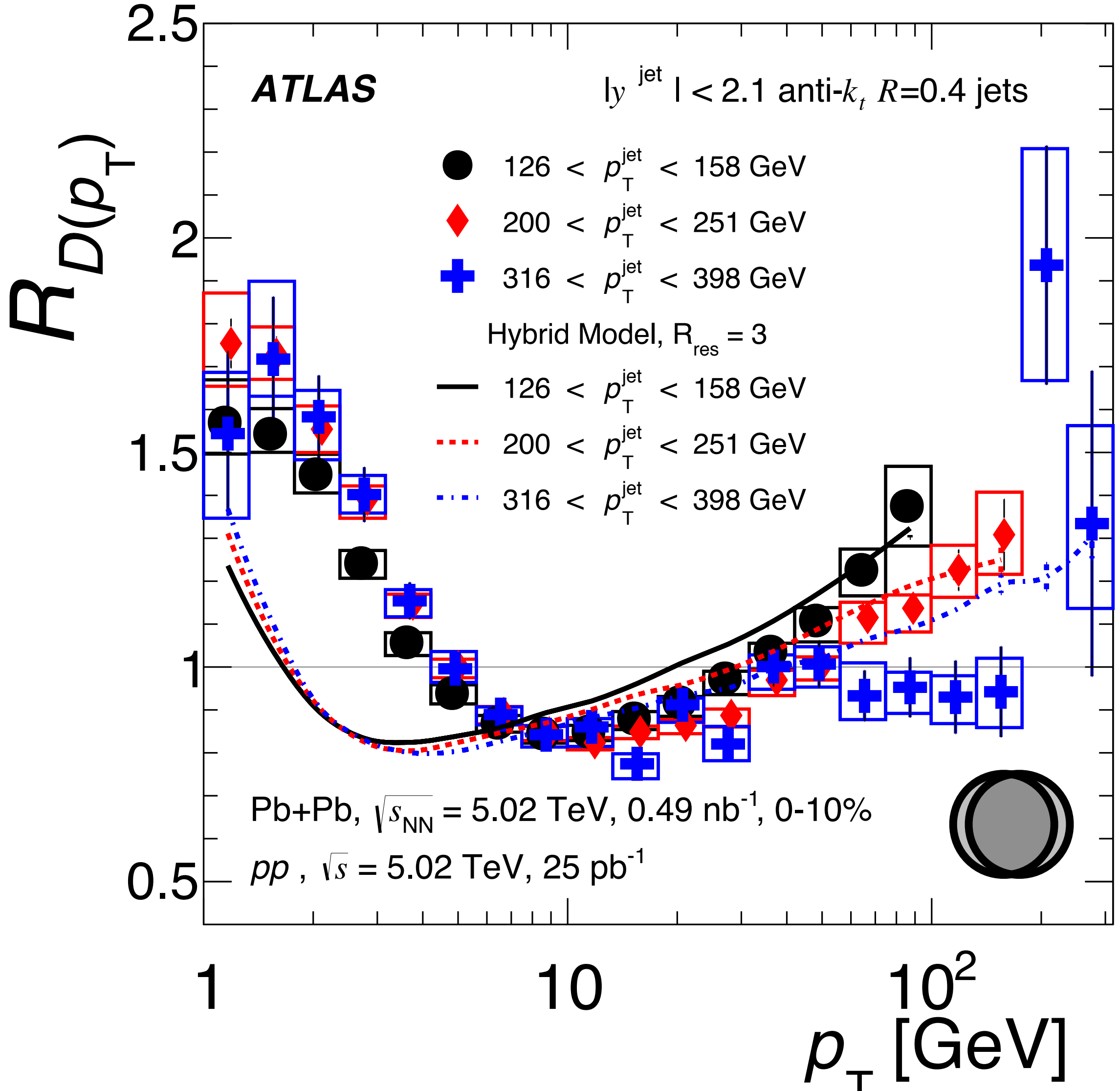
- **No jet p_T dependence at high z**
- **Less enhancement for higher p_T at low z**

  ➡**Described by model**

Internal structure: p_T dep.

arXiv:1805.05424





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

  ➡Described by model

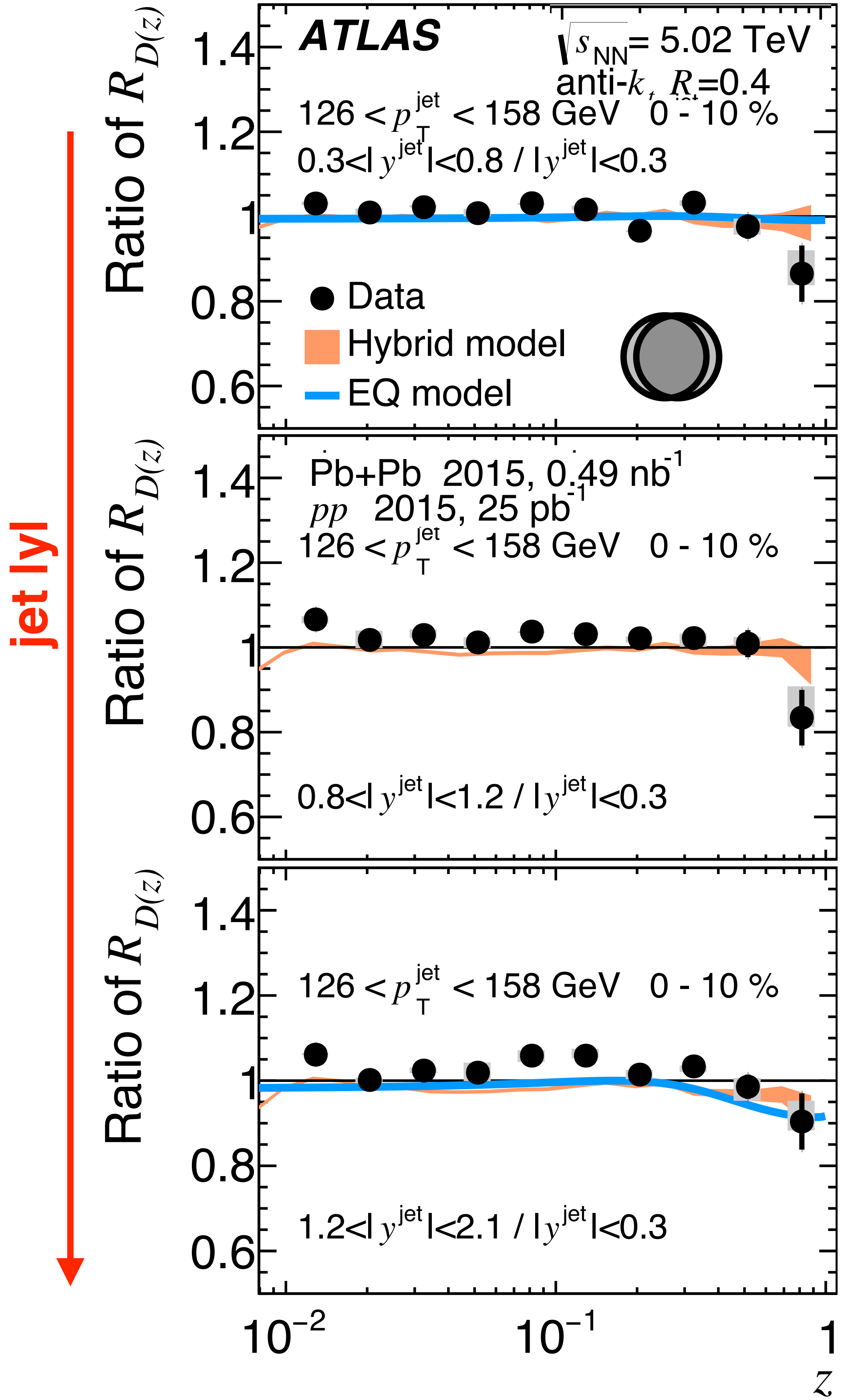
- **Jet p_T dependence shows more low p_T tracks at high p_T**

  ➡response of medium to jets?

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

Internal structure: rapidity dep.

arXiv:1805.05424



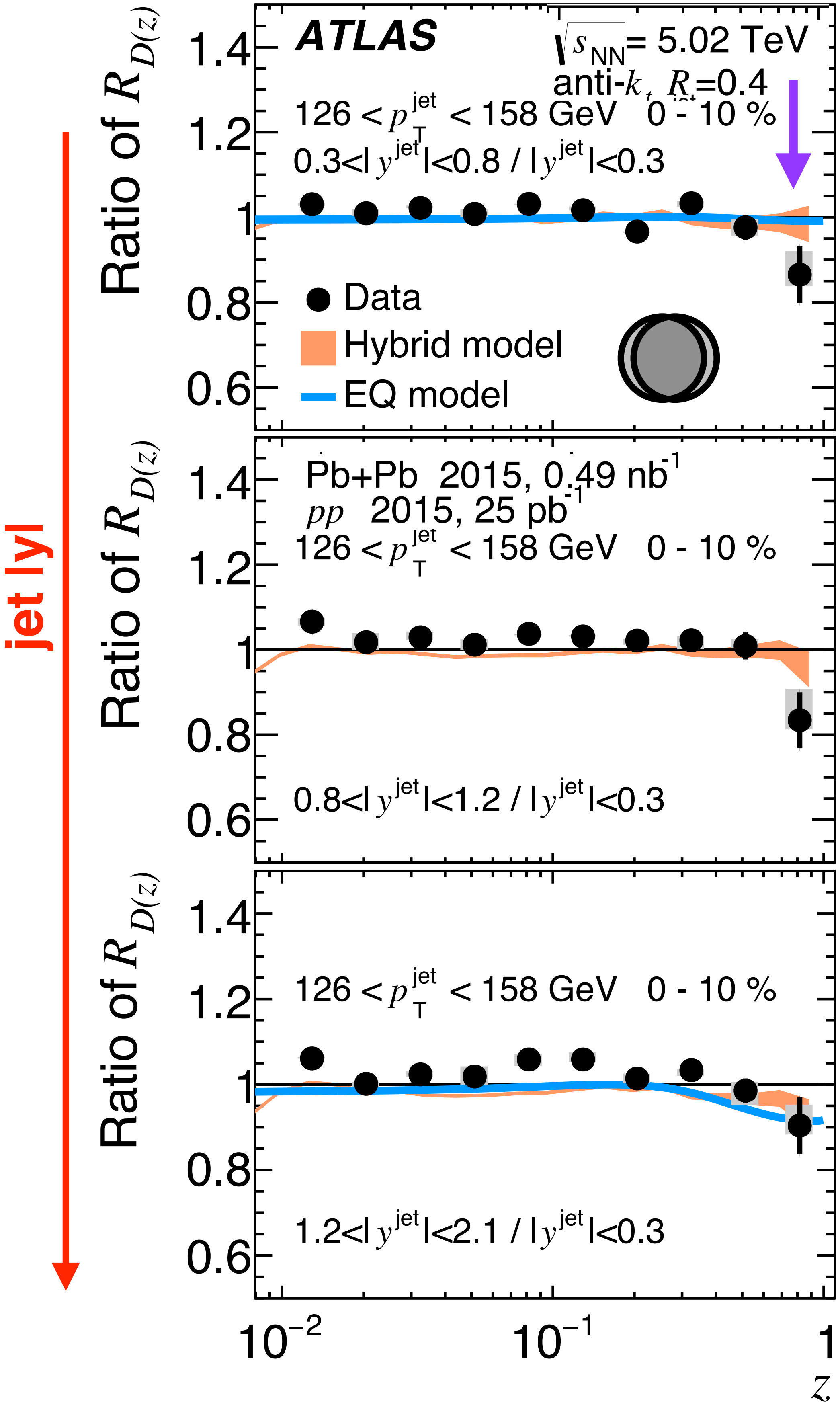
- **Ratio of $R_{D(z)}$ at fixed |y| intervals to |y| < 0.3**

  ➡ **No significant rapidity dependence**

  ➡ **Consistent with models**

Internal structure: rapidity dep.

arXiv:1805.05424



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

➡ **No significant rapidity dependence**

➡ **Consistent with models**

➡ **Slight hint of an enhancement at high z**

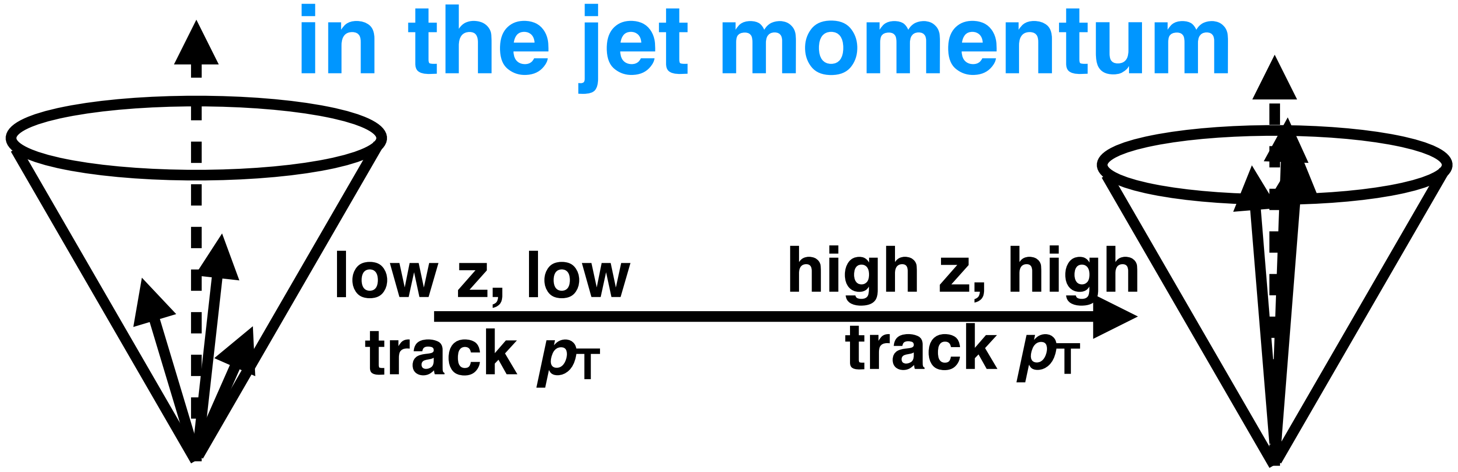
Jet fragmentation functions

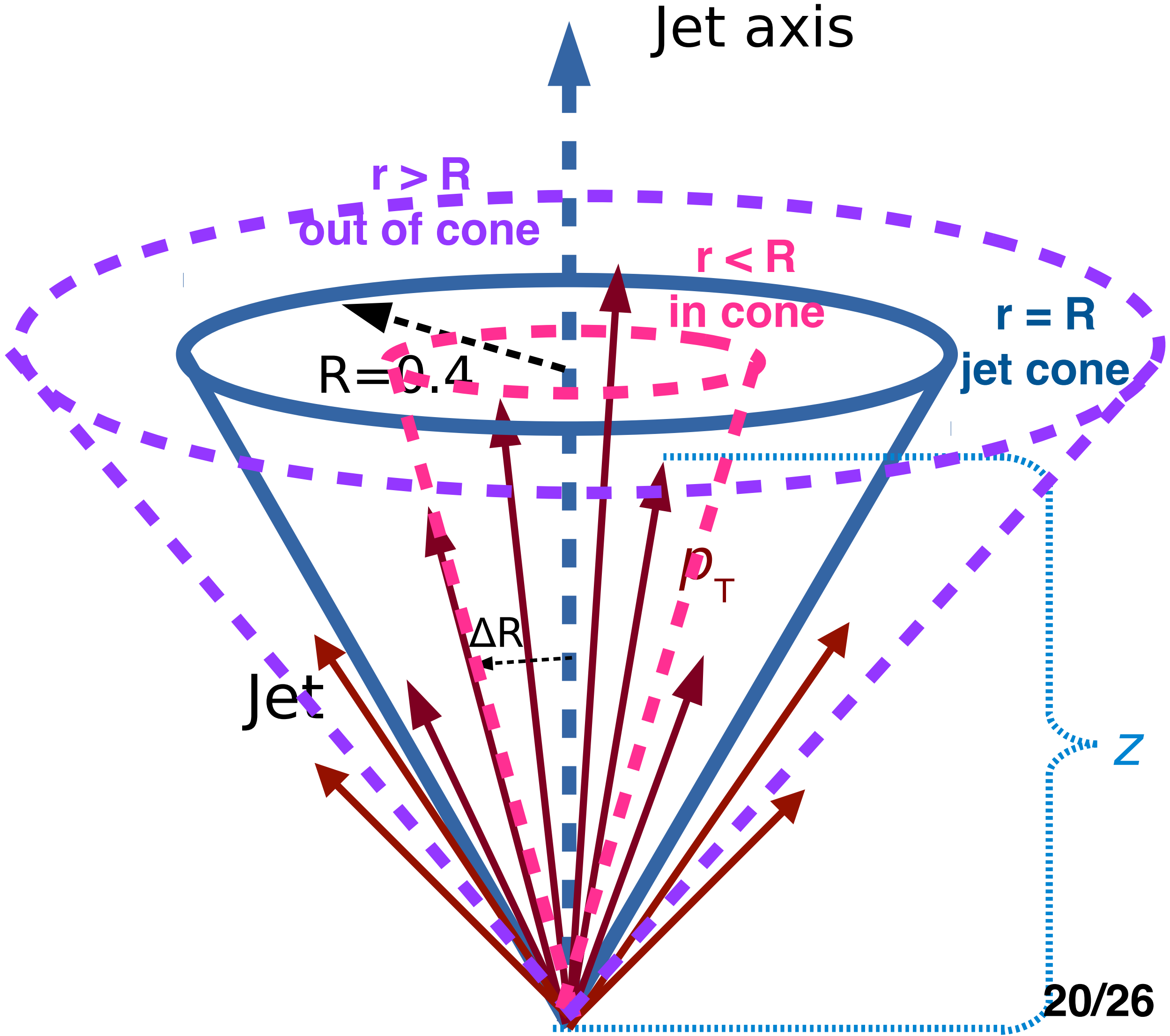
- **Measures how charged particles are distributed within a jet by looking at number of charged particles in jets (N_{ch})**

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

➡ **r measures the shape of the jet**

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





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

Radial profile

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

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

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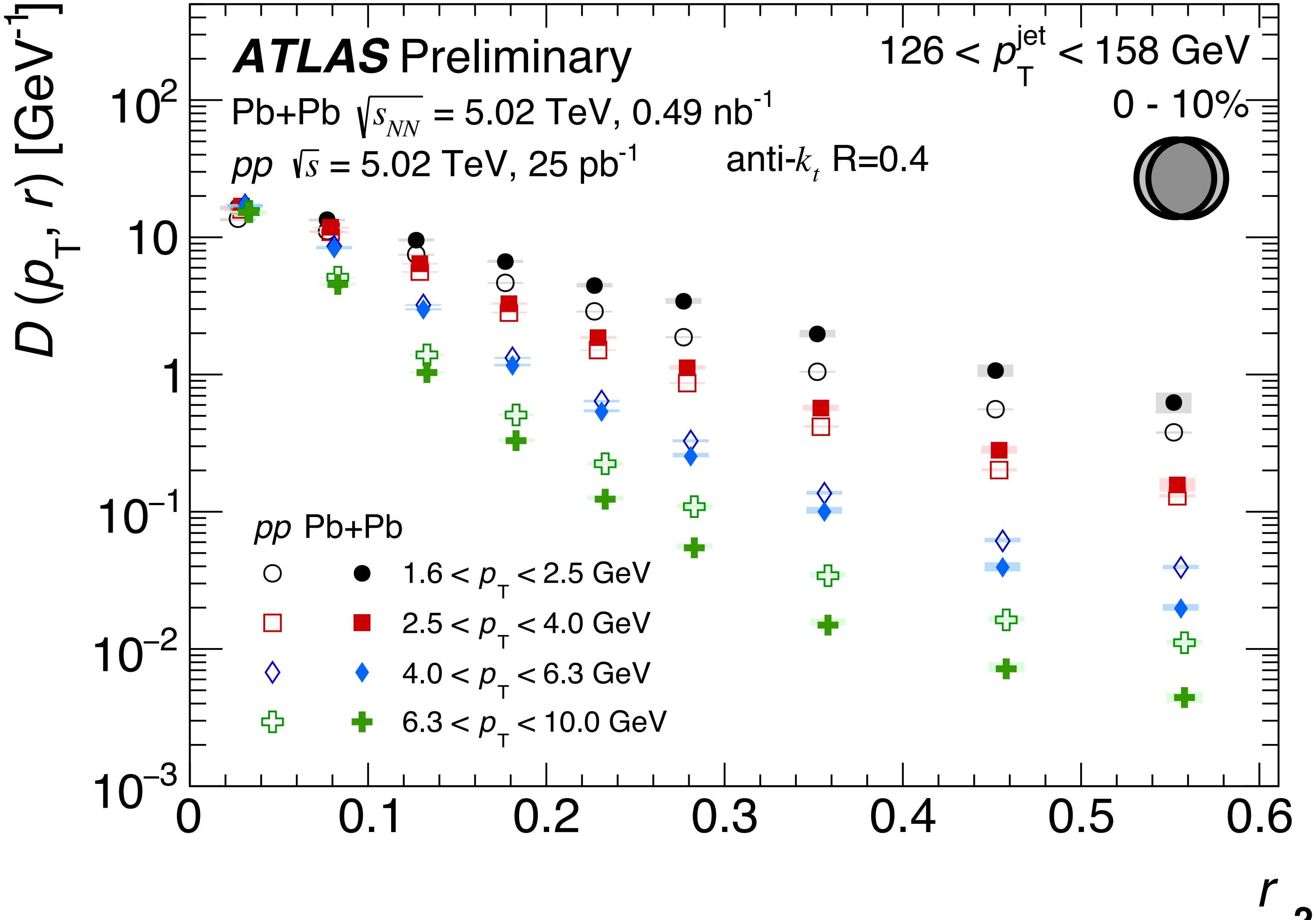

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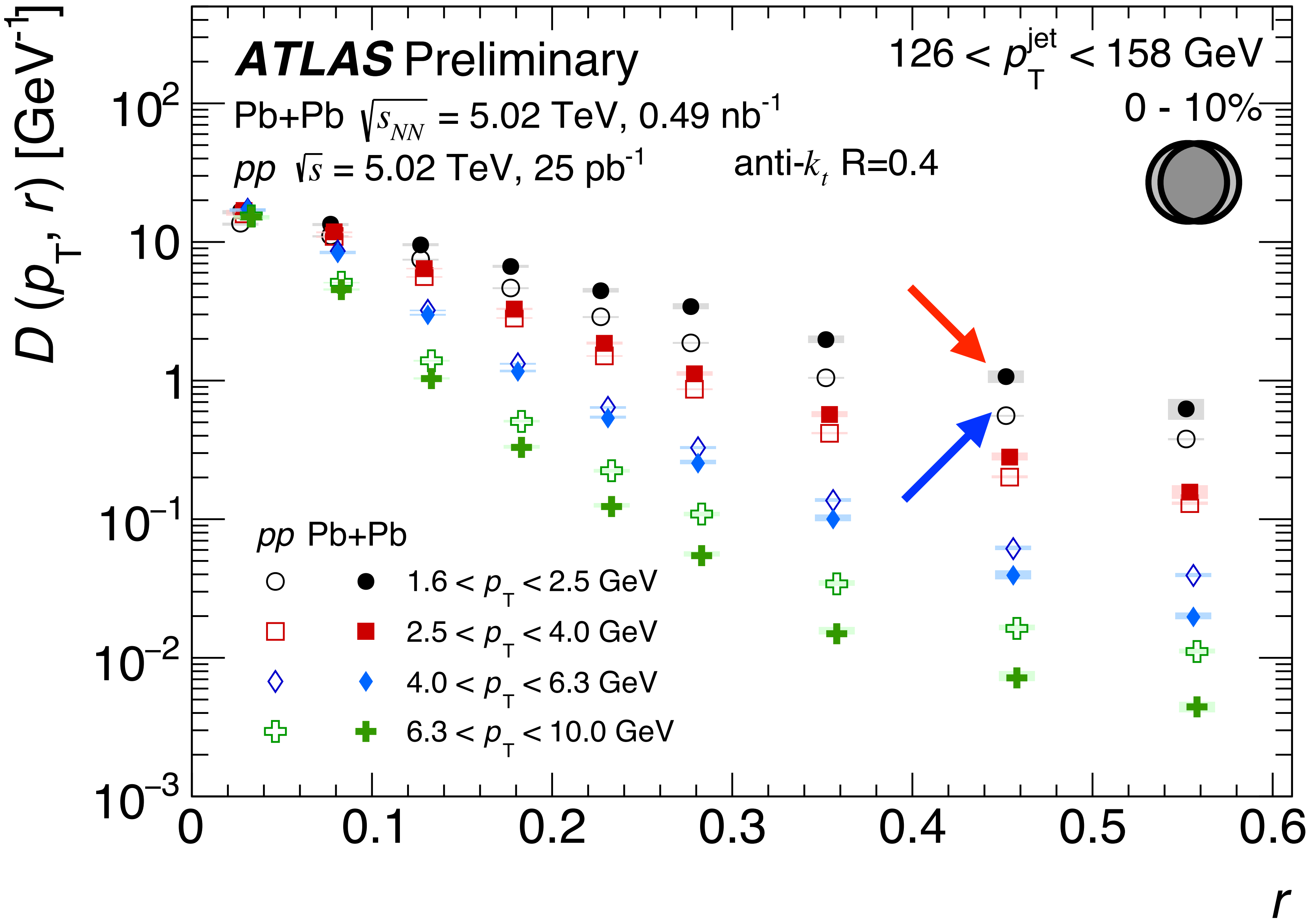
ATLAS-CONF-2018-010



- **Take the ratio of D(p_{T}, r) in Pb+Pb and *pp* to evaluate difference**

Internal structure: radial dep.

- **Ratio of D(p_T, r) in Pb+Pb to *pp* as a function of radius shows**

$$R_{D(p_{\mathrm{T}},r)} = \frac{D(p_{\mathrm{T}},r)_{\mathrm{PbPb}}}{D(p_{\mathrm{T}},r)_{\mathrm{pp}}}$$

- **Less modification with decreasing radius**

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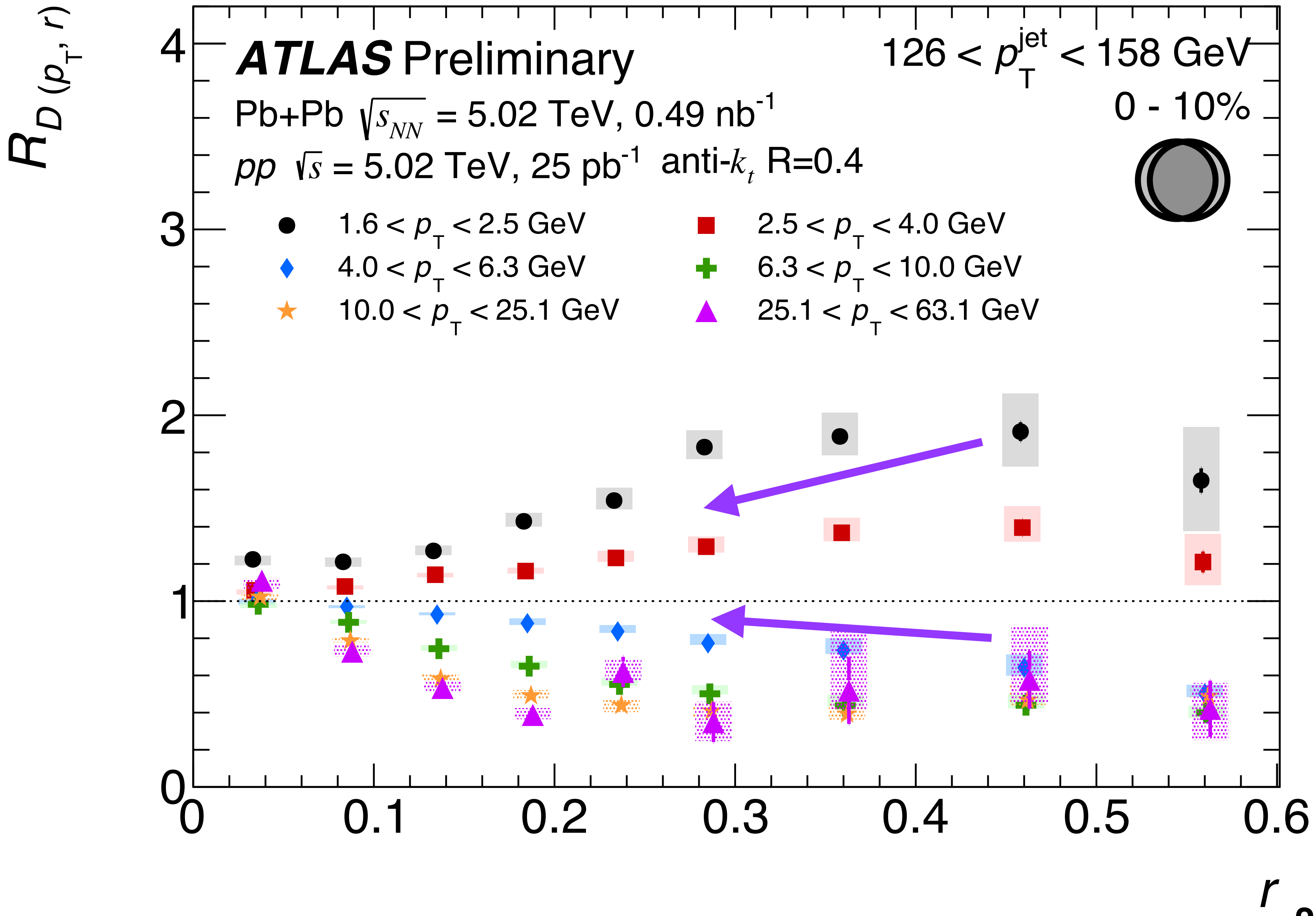

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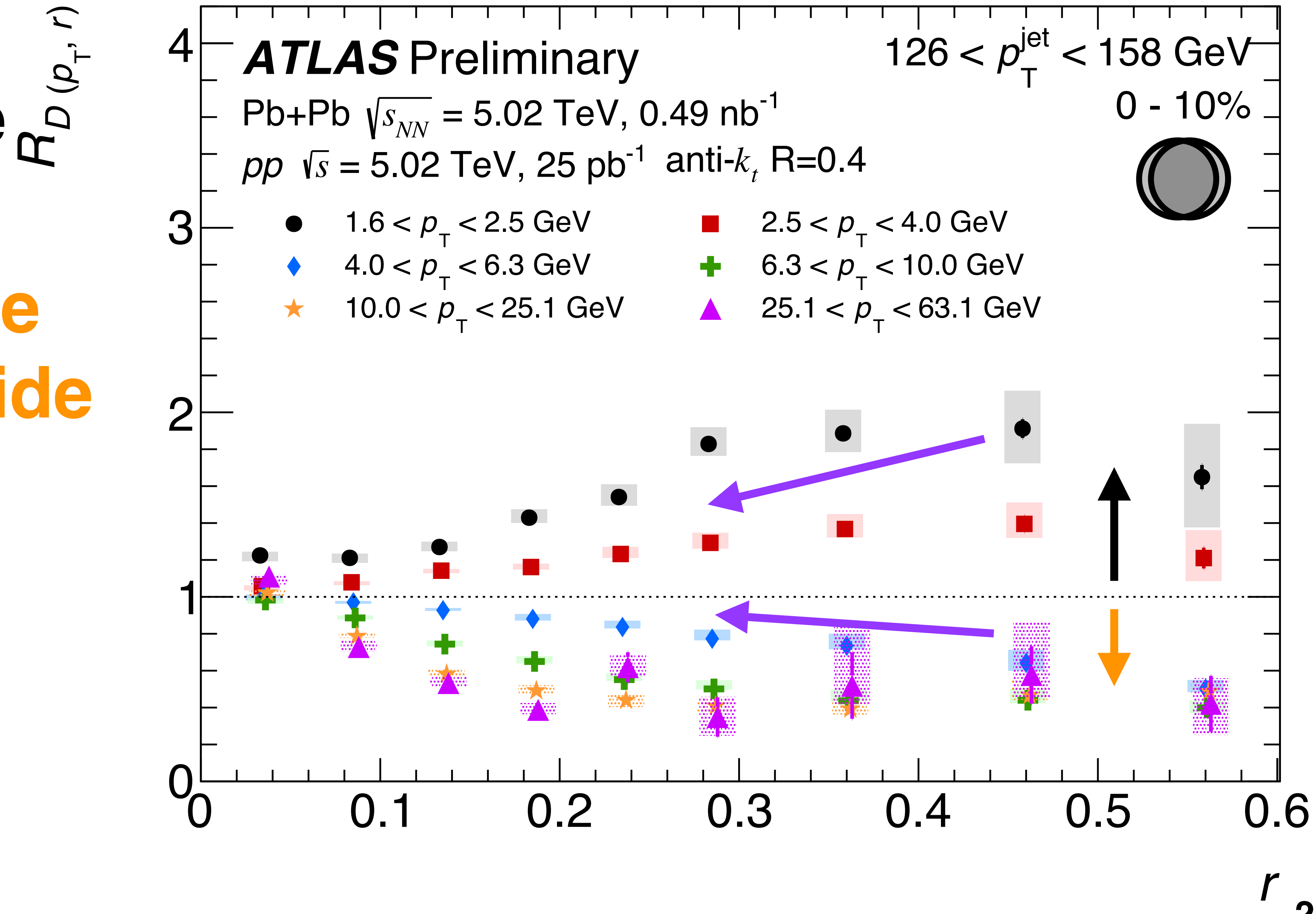
- **More soft particles outside the jet cone**
- **Less intermediate p_T particles outside the cone**



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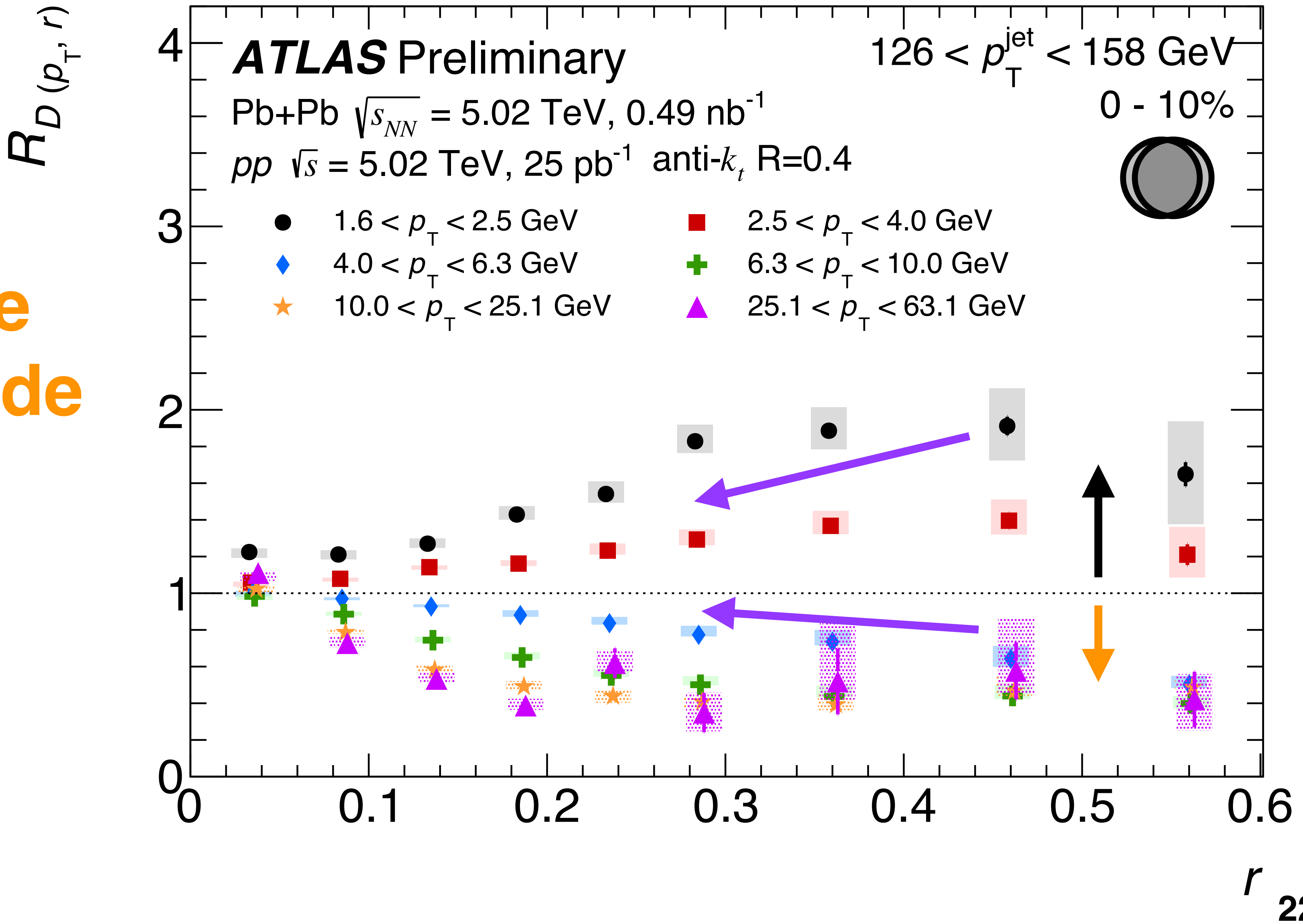
- **More soft particles outside the jet cone**
- **Less intermediate p_T particles outside the cone**

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



Jets in Xe+Xe collisions?

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

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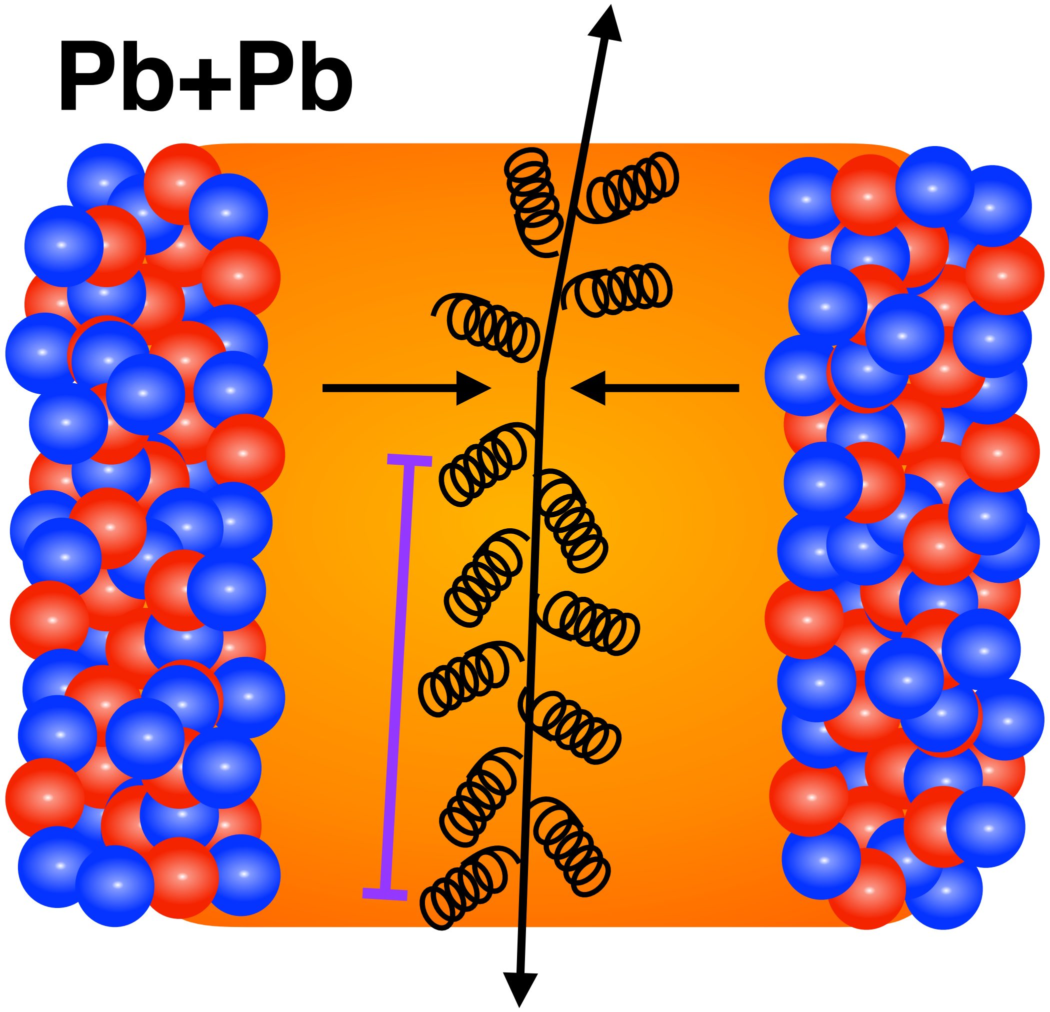
➡**Jet quenching expected to be less for lighter nuclei (Xe^{129} vs. Pb^{208}) due to the reduced medium density and smaller path lengths**



$$Z_{Pb} > Z_{Xe}$$

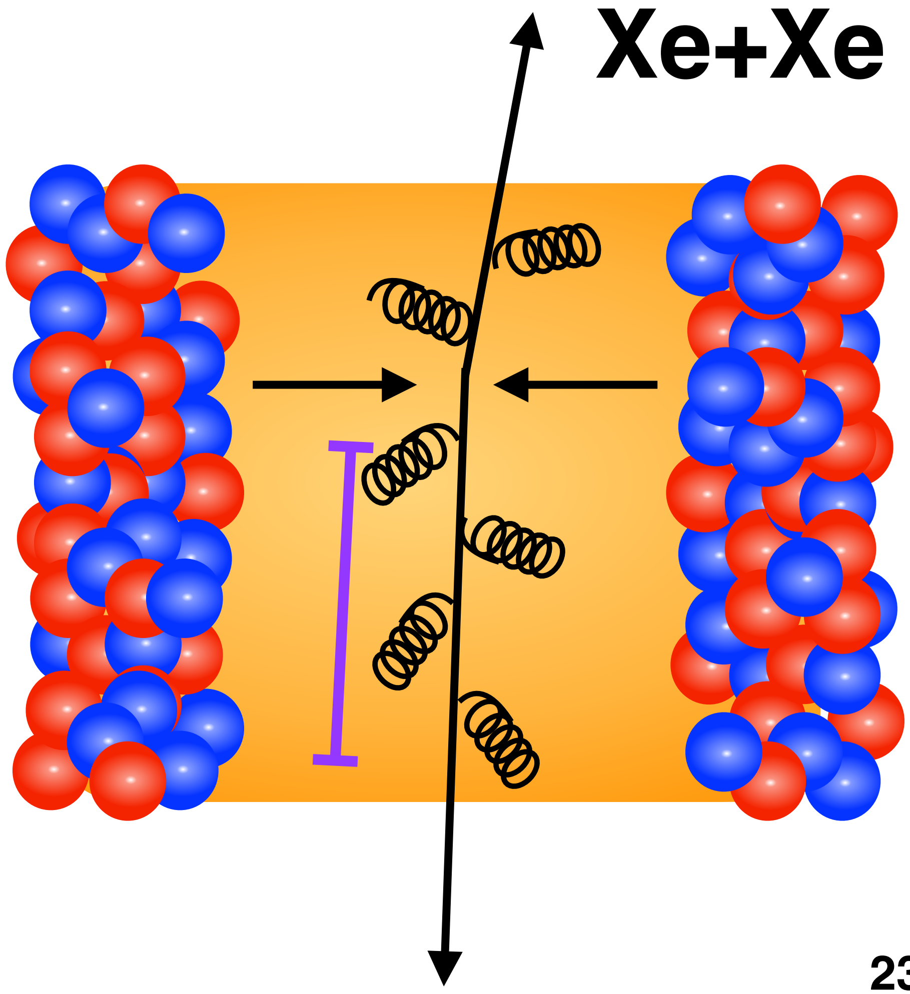
$$\downarrow$$

$$\rho_{Pb} > \rho_{Xe}$$

$$L_{Pb} > L_{Xe}$$

$$\downarrow$$

$$\Delta E_{Pb} > \Delta E_{Xe}$$



Jets in Xe+Xe collisions?

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➡**Jet quenching expected to be less for lighter nuclei (Xe^{129} vs. Pb^{208}) due to the reduced medium density and smaller path lengths**

➡**Lighter nuclei should have a smaller underlying event in central collisions**

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

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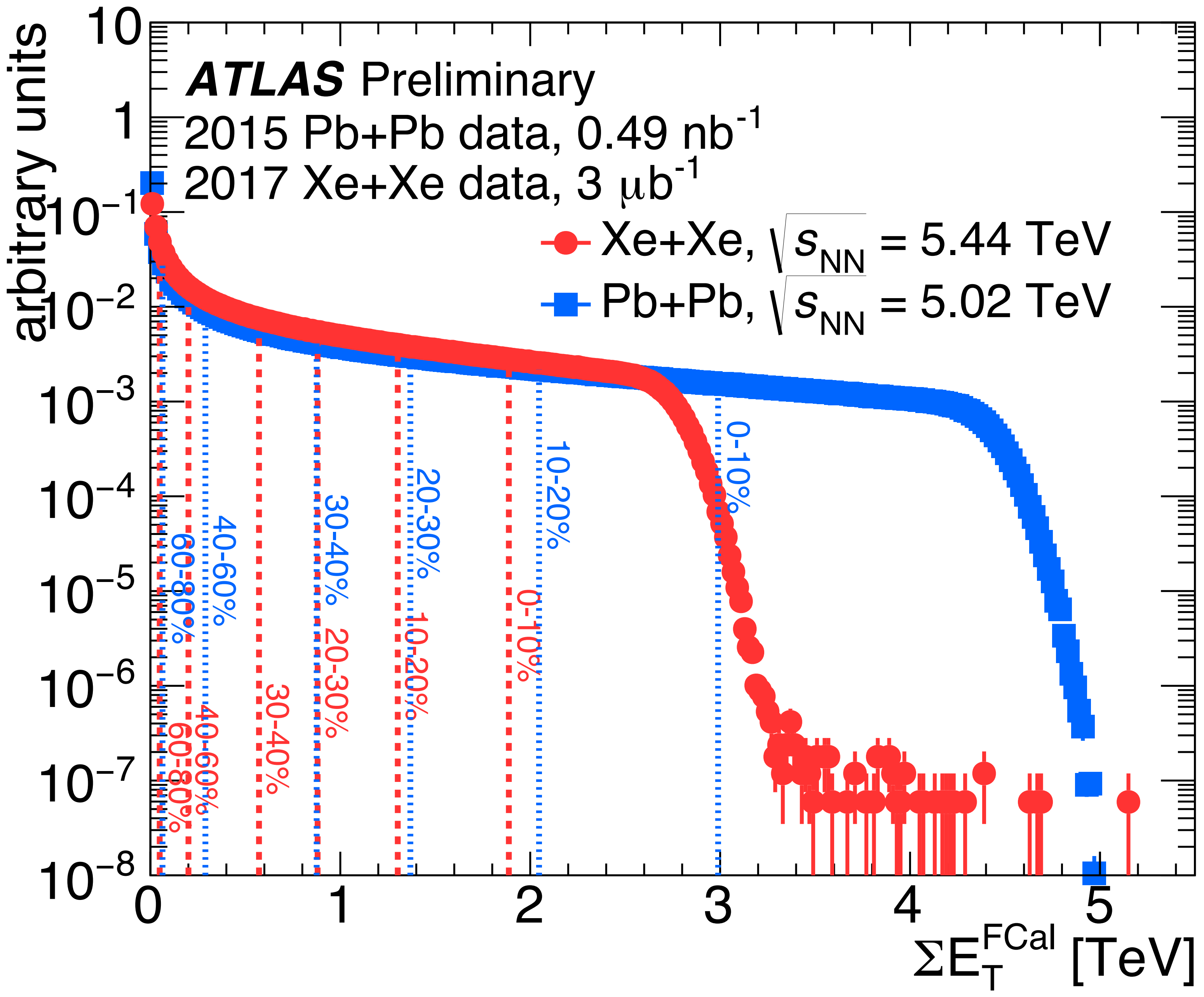
➡ **Lighter nuclei should have a smaller underlying event in central collisions**

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

► **Replicate the dijet asymmetry analysis in Xe+Xe and compare to *pp* and 2015 Pb+Pb (without unfolding)**

ΣE_T^{FCal} Pb vs. Xe

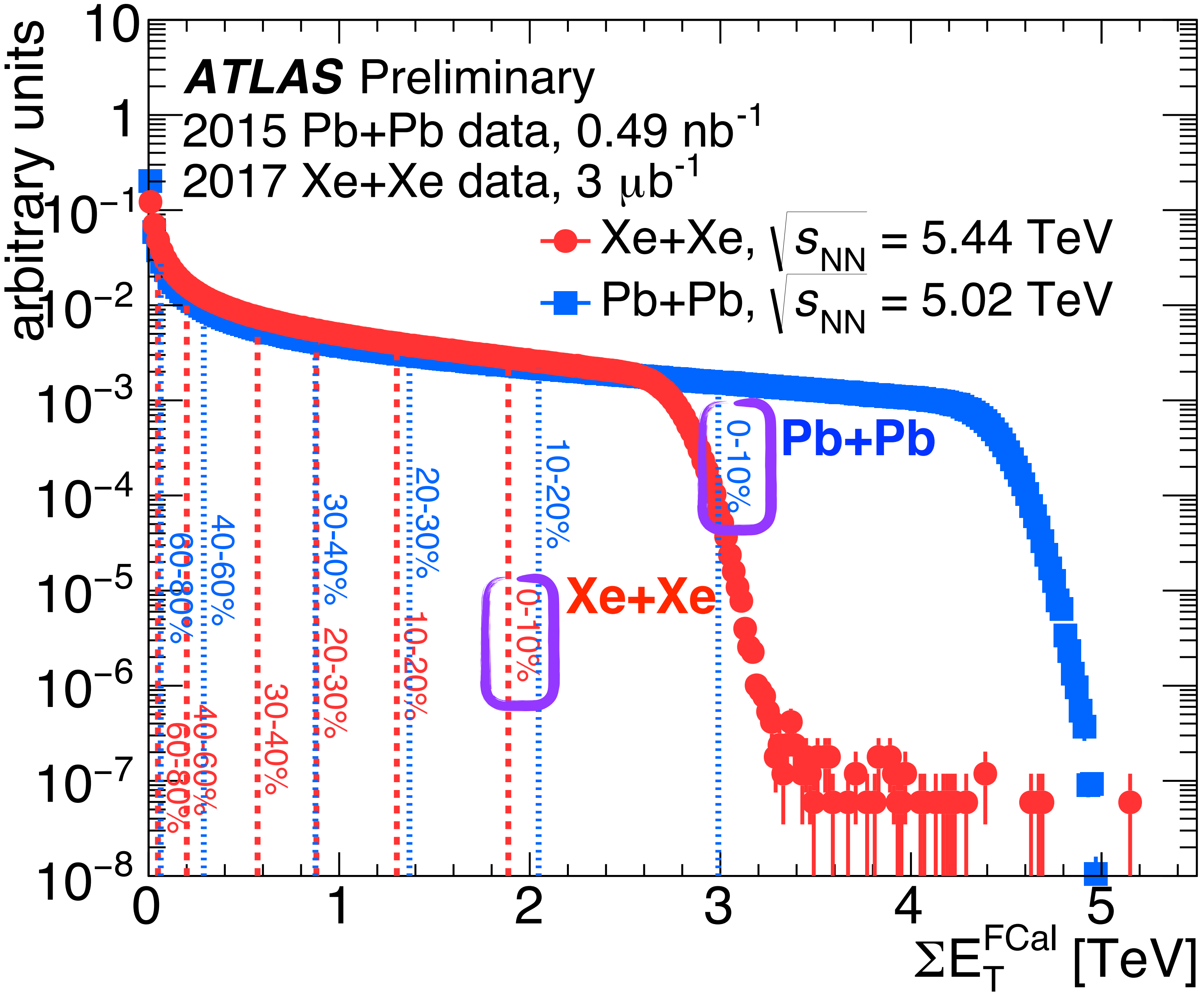
- **The ΣE_T^{FCal} distributions are partitioned in centrality bins separately in Pb+Pb and Xe+Xe**



$\Sigma E_T^{\mathrm{FCal}}$ Pb vs. Xe

- **The $\Sigma E_T^{\mathrm{FCal}}$ distributions are partitioned in centrality bins separately in Pb+Pb and Xe+Xe**

Compare with the same degree of overlap (centrality):

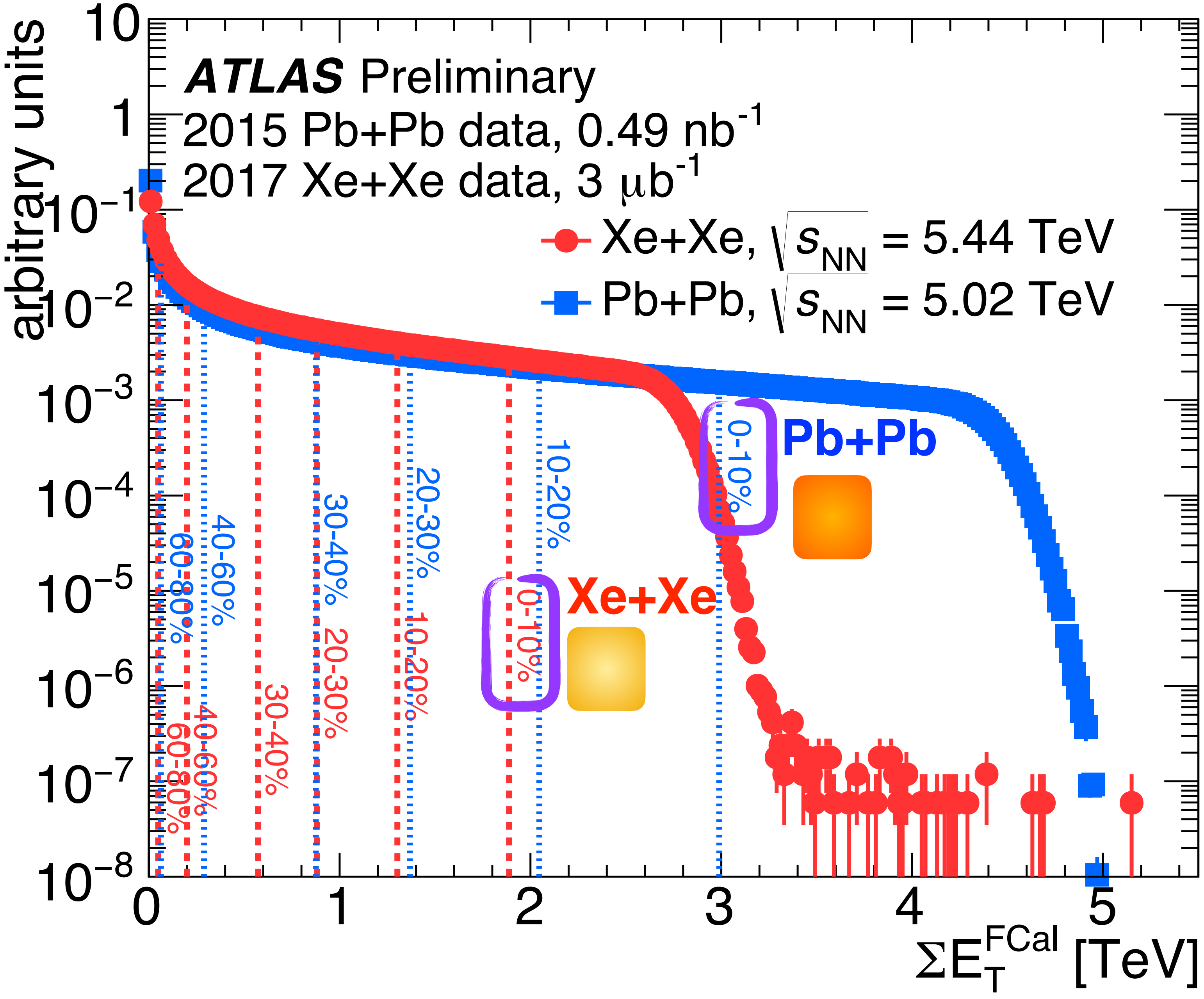


ΣE_T^{FCal} Pb vs. Xe

- **The ΣE_T^{FCal} distributions are partitioned in centrality bins separately in Pb+Pb and Xe+Xe**

➡ **Compare with the same degree of overlap (centrality):**

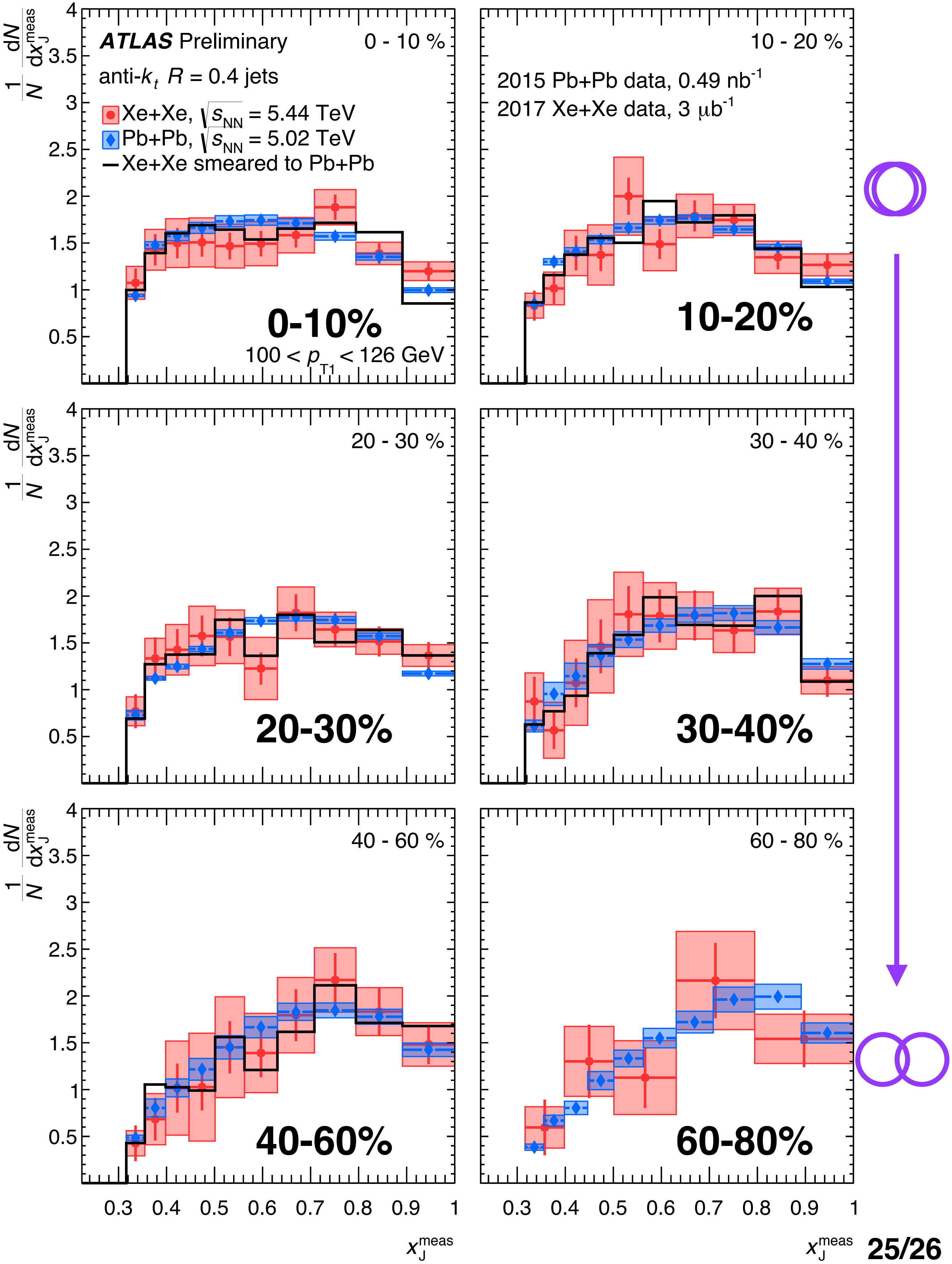
➡ **Pb+Pb should be denser and larger (larger path length) than Xe+Xe**



x_J: centrality dependence

Similar geometry

- **Compare 2017 Xe+Xe to 2015 Pb+Pb**
- ***x_J* consistent between Pb+Pb and Xe+Xe for all centralities**
- **Xe+Xe smeared to Pb+Pb to account for differences in UE fluctuations**



ATLAS-CONF-2018-007

Conclusion

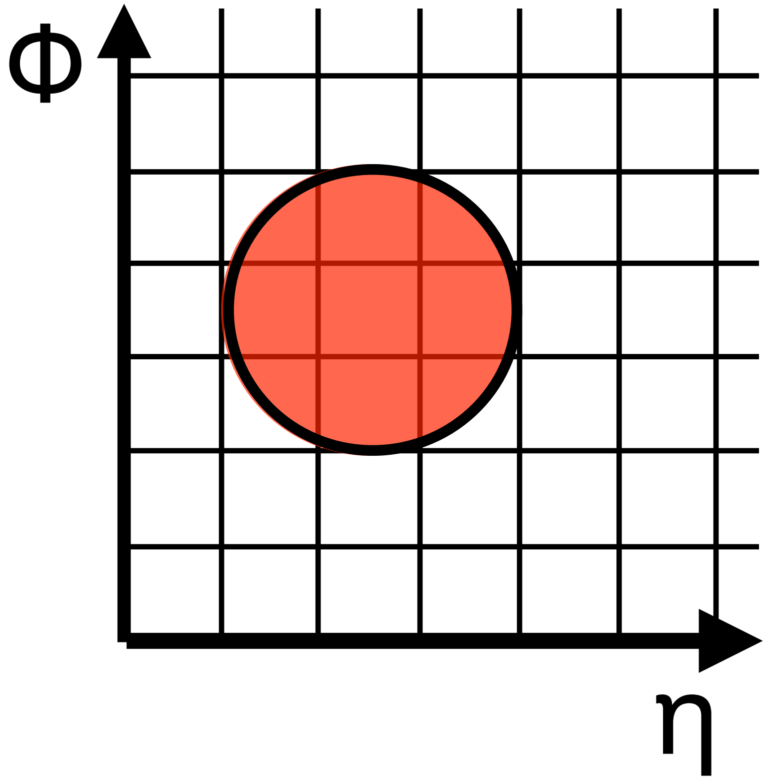
- **Wide variety of new results from ATLAS at 5.02 TeV allow for precision measurements of jet quenching**
  - ➡ **An asymmetry was found in γ+jet systems**
  - ➡ **Inclusive jets saw suppression out to a TeV and observed a rapidity dependence to the suppression**
    - ▸ **Measured differentially in jet mass**
  - ➡ **FFs measured jet internal structure modification**
    - ▸ **Differentially in jet momentum, rapidity, and shape**
  - ➡ **New Xe+Xe results**
- **These precise measurements have careful underlying event subtraction, reduced systematic uncertainties, and unfolding for detector effects**
  - ➡ **Many measurements compared to theoretical calculations which can help constrain models**
- ▸ **~4x more Pb+Pb data at 5.02 TeV from 2018 to analyze!**

Backup

Jet reconstruction

- **Background is subtracted using an iterative procedure that is modulated by harmonic flow with amplitude v_n and phase Ψ_n**

$$E_{Tj}^{sub} = E_{Tj} - A_j\boxed{\rho_i(\eta_j)}(1 + 2\boxed{v_{ni}}\cos 2(\phi_j - \boxed{\psi_n}))$$



➡ **Find the jets**

➡ **Remove the jet “seeds” and estimate the transverse energy density ρ (η-dependent)**

➡ **Find v_n and Ψ_n integrated over η but excluding regions with jets**

➡ **Subtract this energy from the towers inside the jet**

➡ **Re-find new jet “seeds” and repeat procedure**

➡ **Re-run jet finding to find jets with background removed!**

Performance

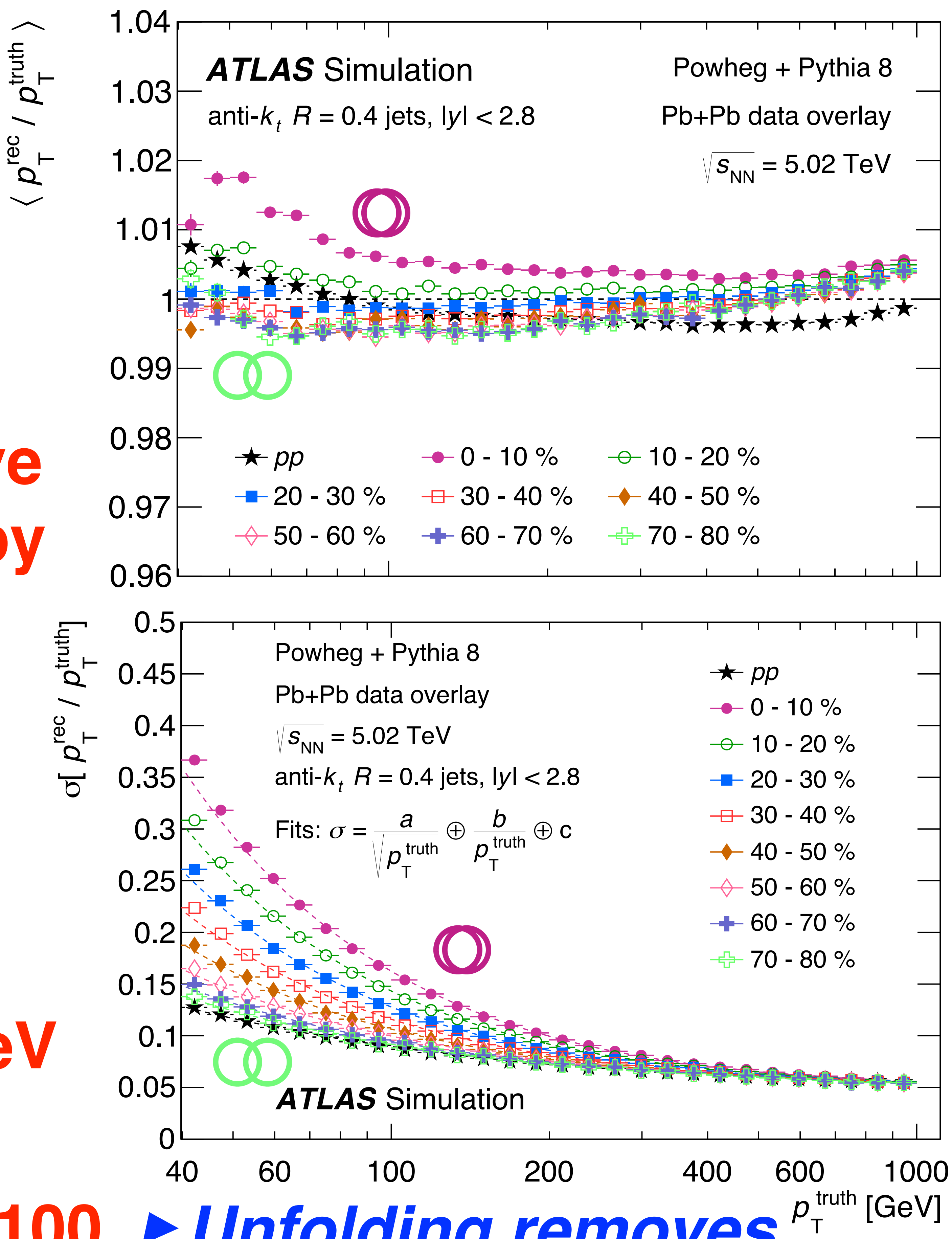
- **Large uncorrelated underlying event (UE) that varies with η, Φ and event**

➡ 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**

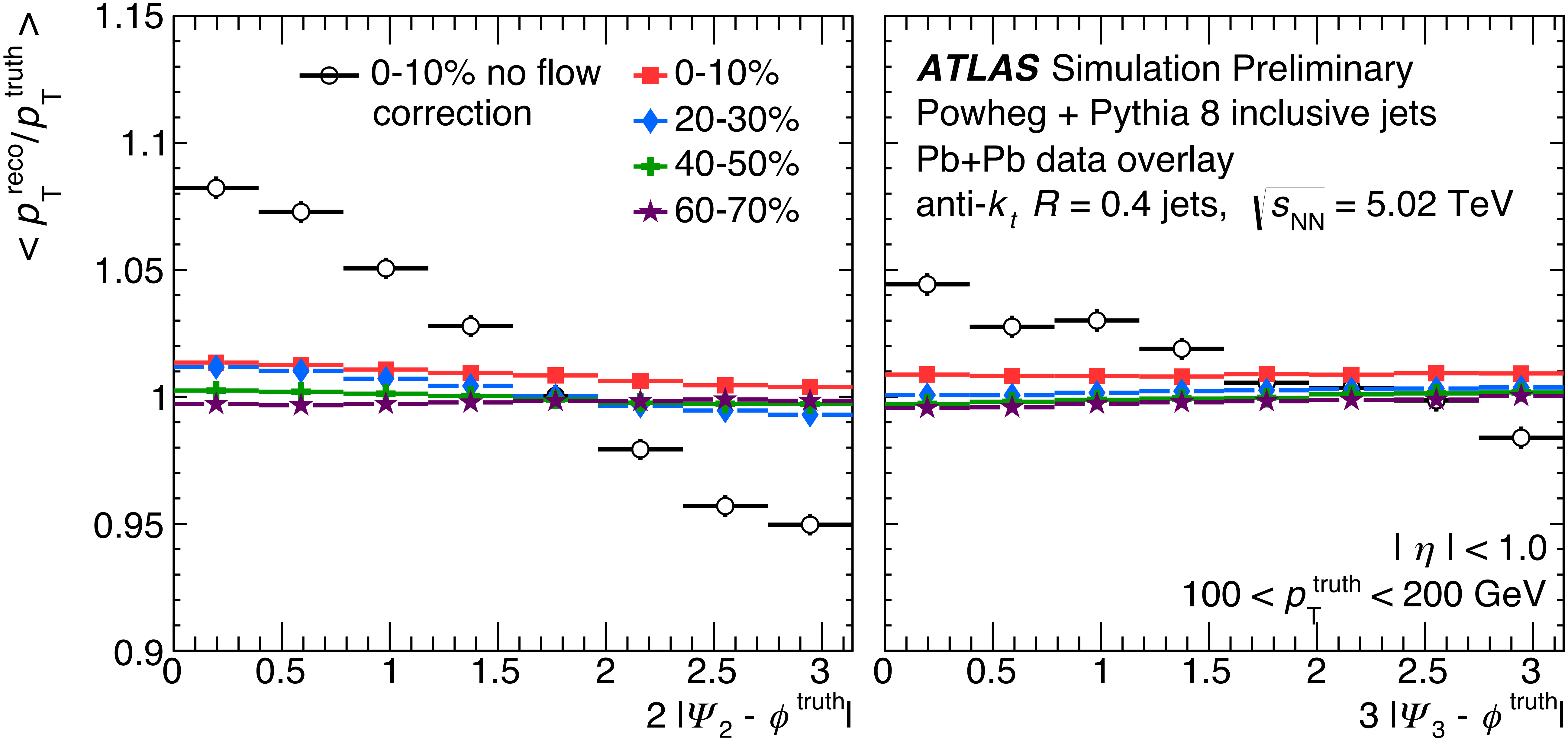
➡ JES is ~1% above 100 GeV for 0-10%

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

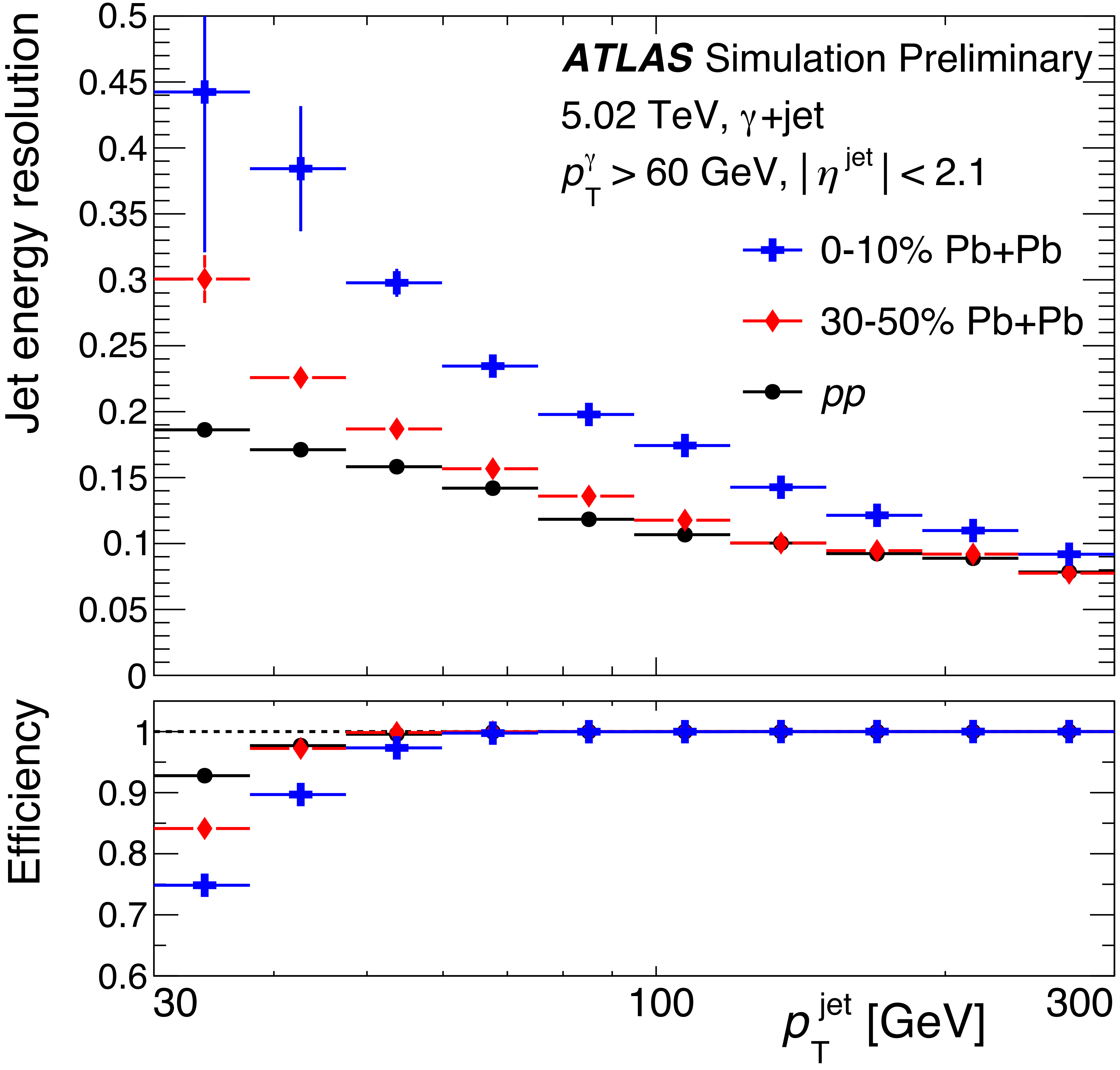


► Unfolding removes remaining JES/JER

Jet performance: JES

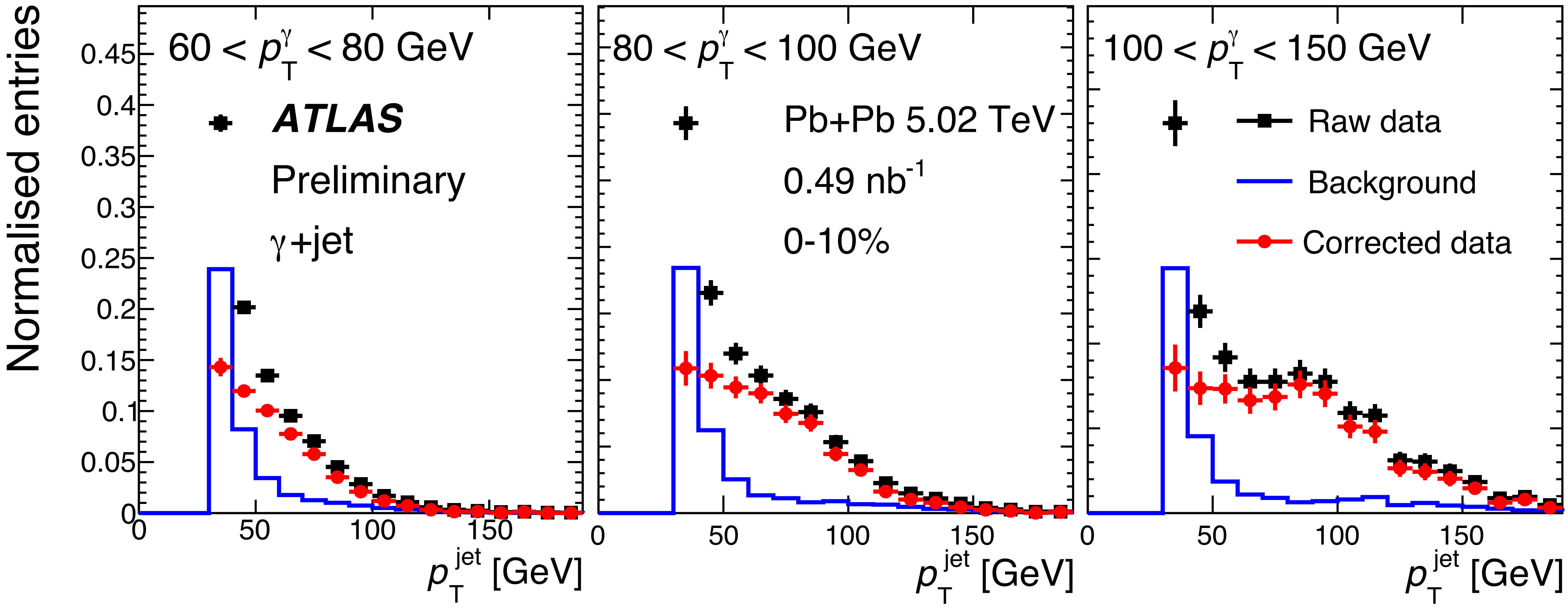


γ-jet JER


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
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Efficiency
1
0.9
0.8
0.7
0.6
30
100
300
p_T^{jet} [GeV]

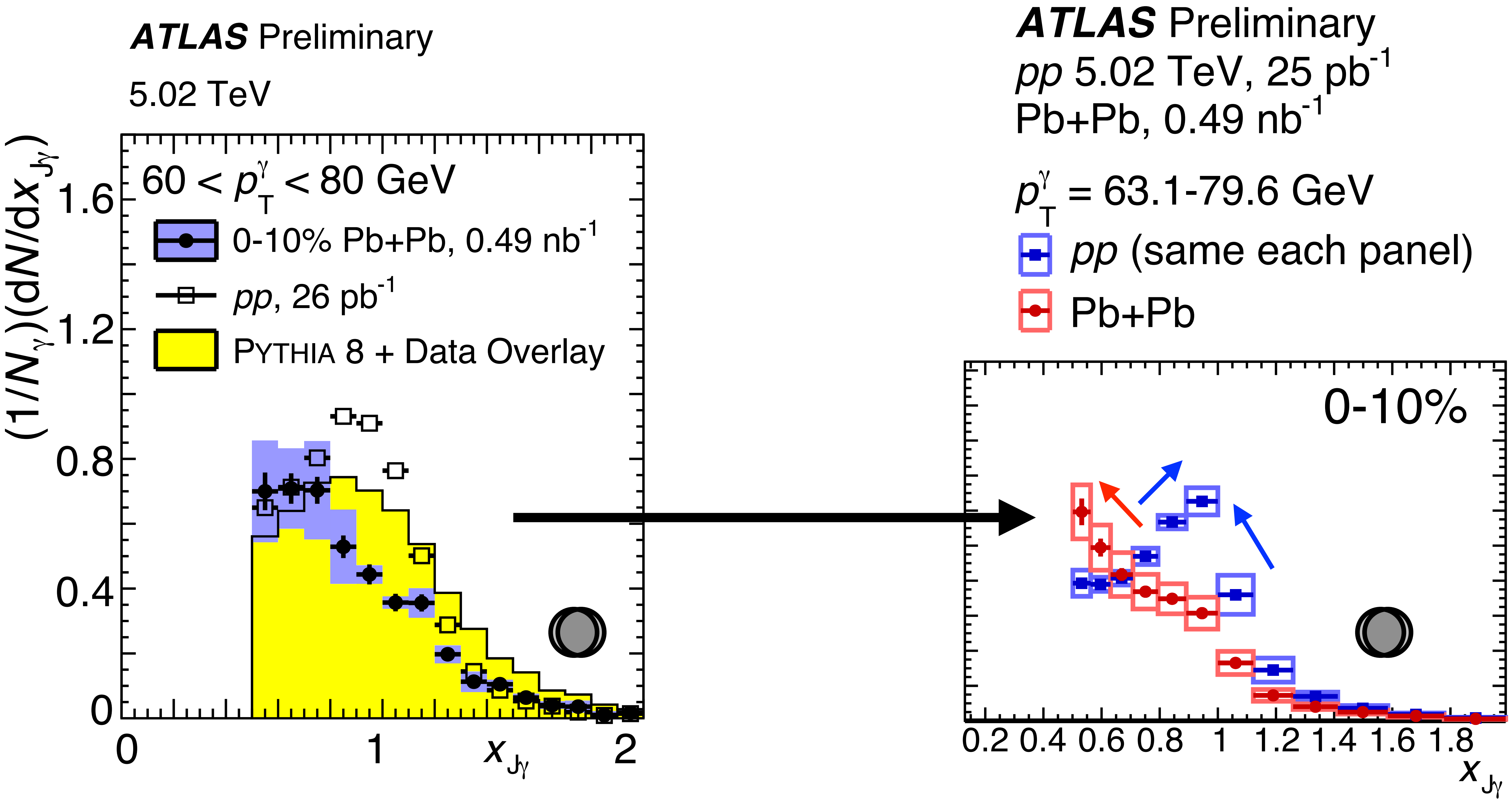
γ-jet background subtraction

- **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**

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 $x_{J\gamma} \sim 0.5$**

γ-jet systematic uncertainties

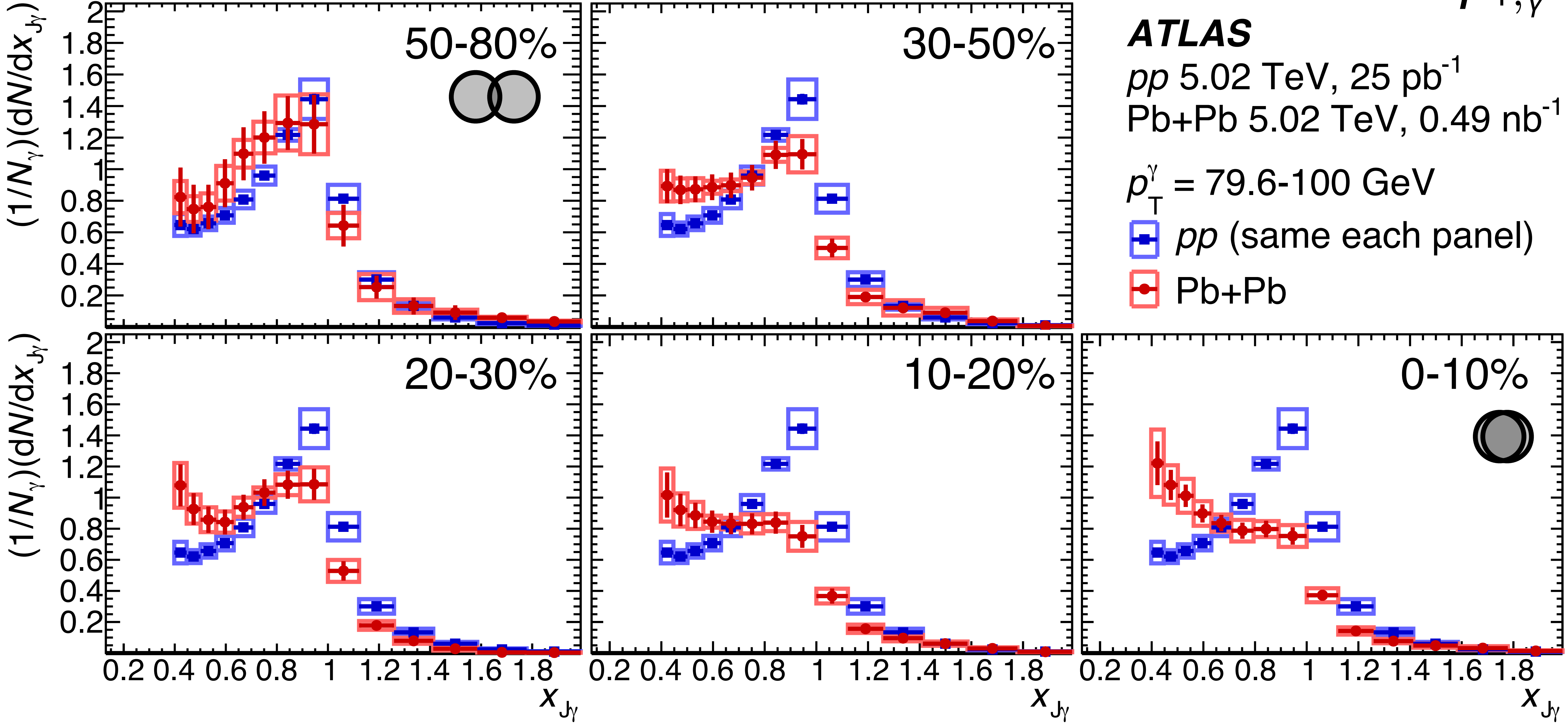
- **Jets:**
  - **JES is 5% at low p_T and decreases with p_T**
  - **Cross calibration: 1% addition JES uncertainty**
  - **JER is evaluated by increasing the resolutions measured in *pp* by a few percent**
  - **Uncertainty on flavor composition and different in flavor response is 2% at low p_T and 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 asymmetry: p_T dep.

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

$80 < p_{T\gamma} < 100$ GeV

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

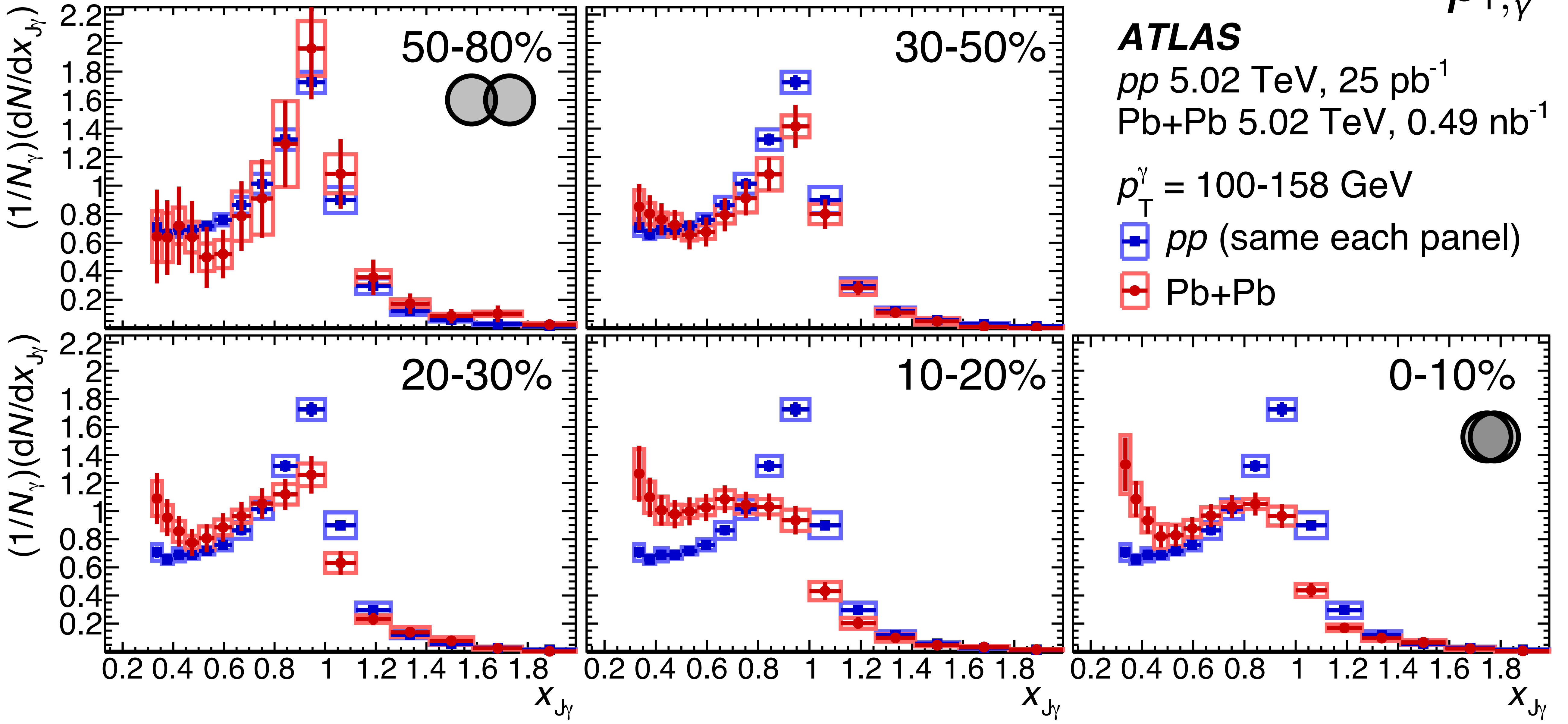


γ-jet asymmetry: p_T dep.

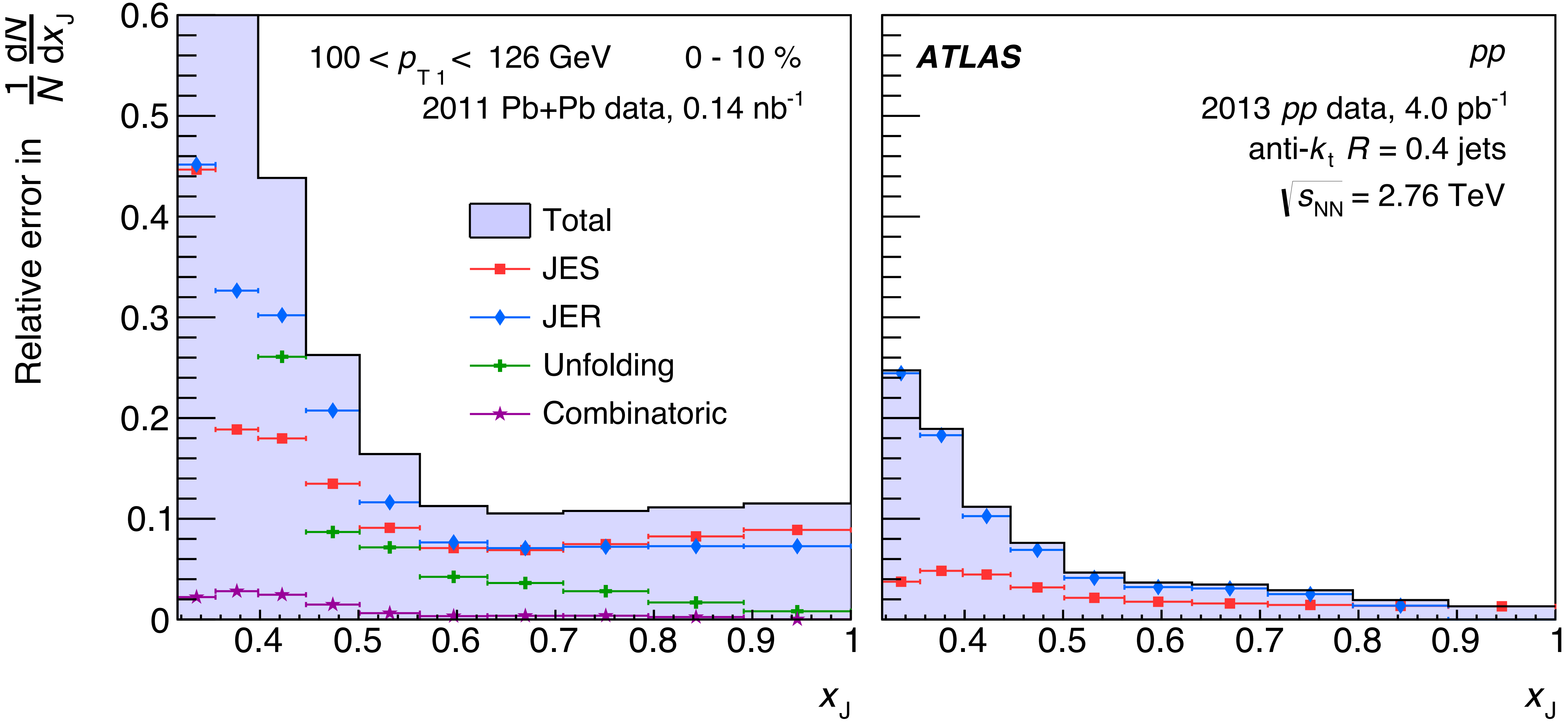
- **central Pb+Pb peaks $x_{J\gamma} \sim 0.5$ compared to *pp* at $x_{J\gamma} \sim 1$**
- **Pb+Pb becomes similar to *pp* in peripheral collisions**
- **Slight $p_{T\gamma}$ dependence observed**

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

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



x_J systematics summary

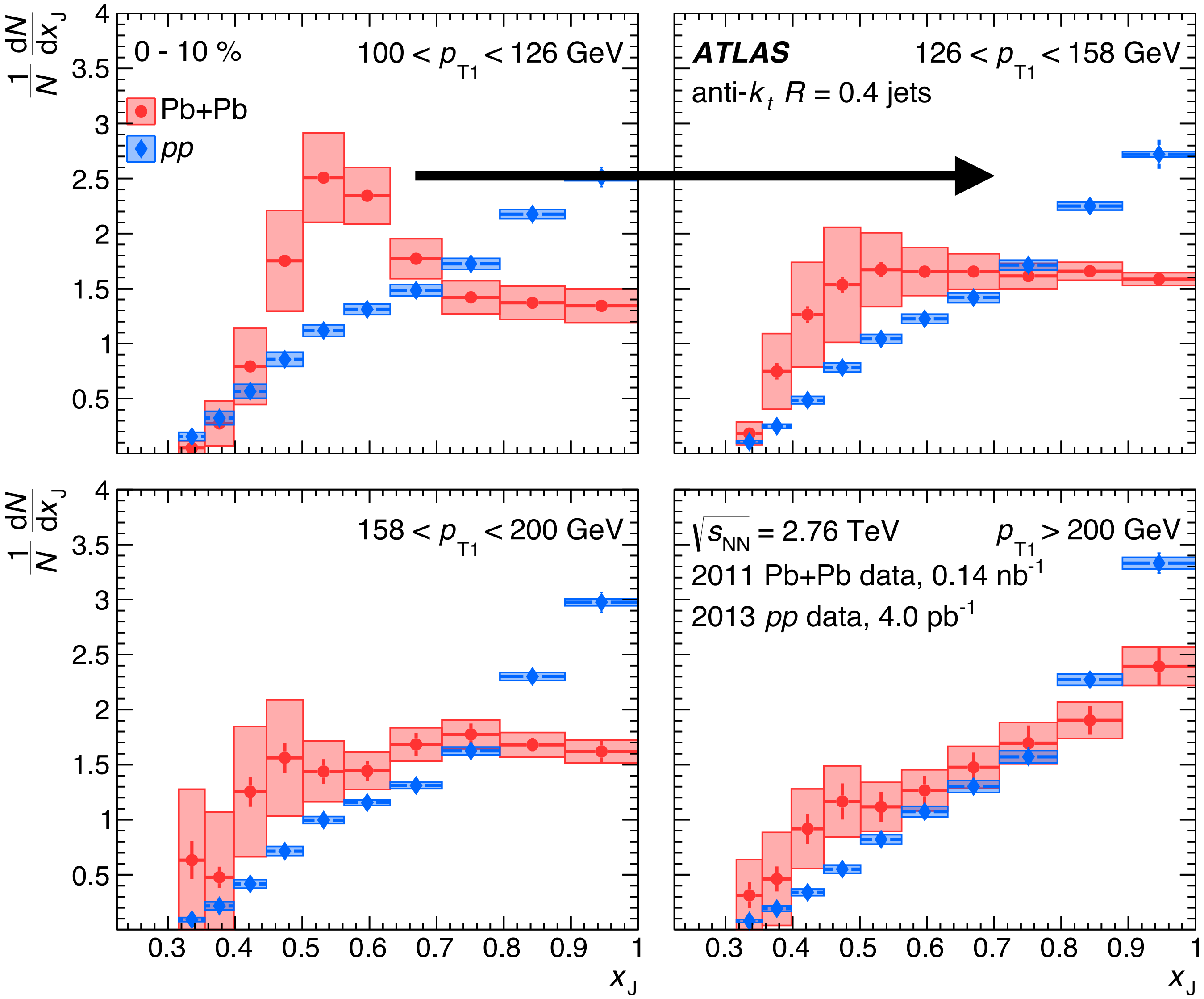


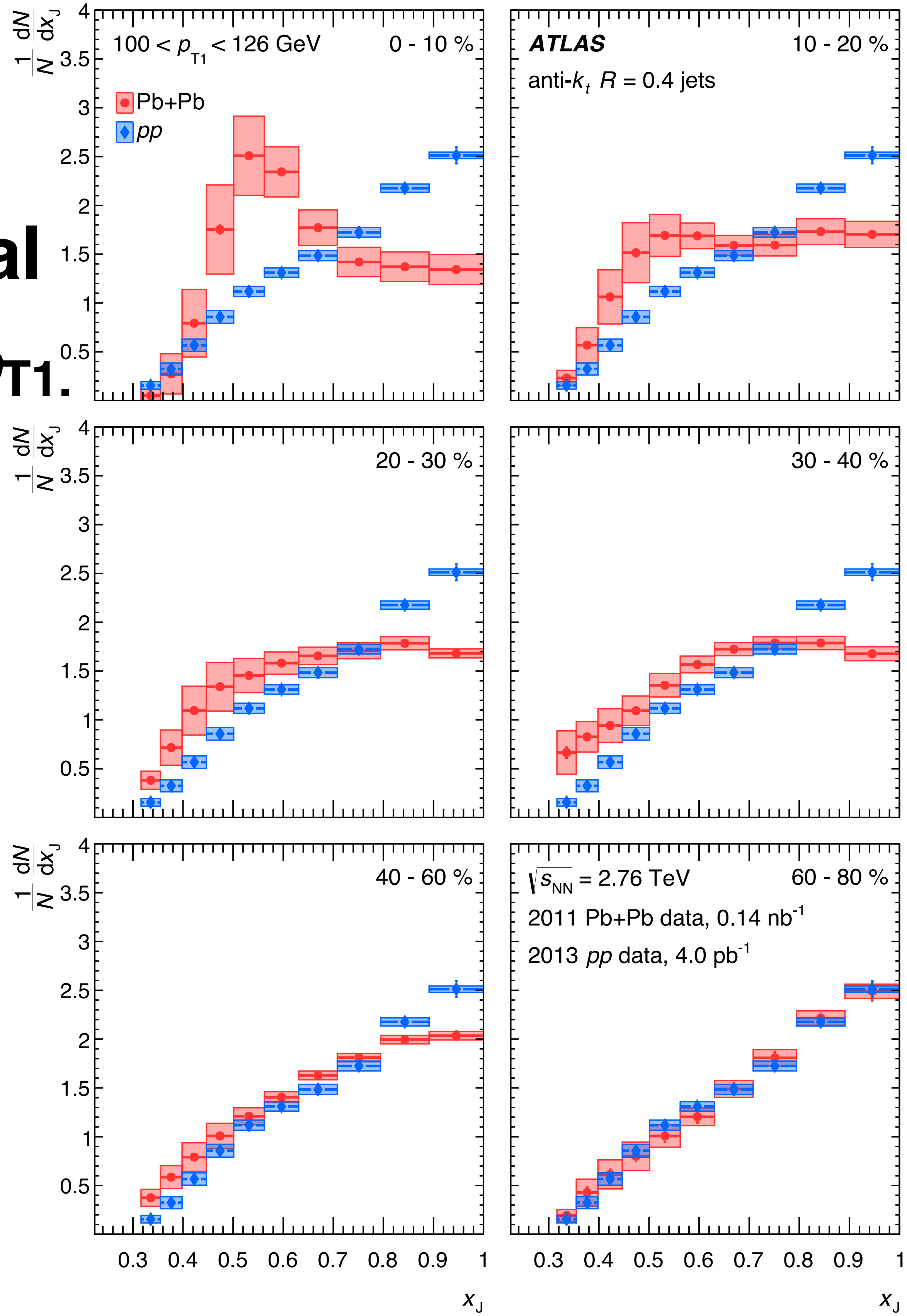
2011 Pb+Pb
2013 pp

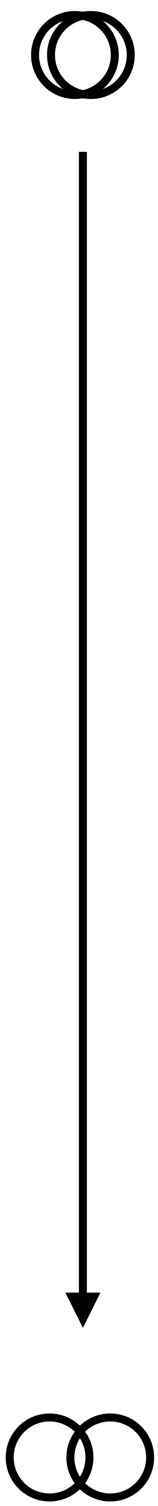
x_J distribution

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

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





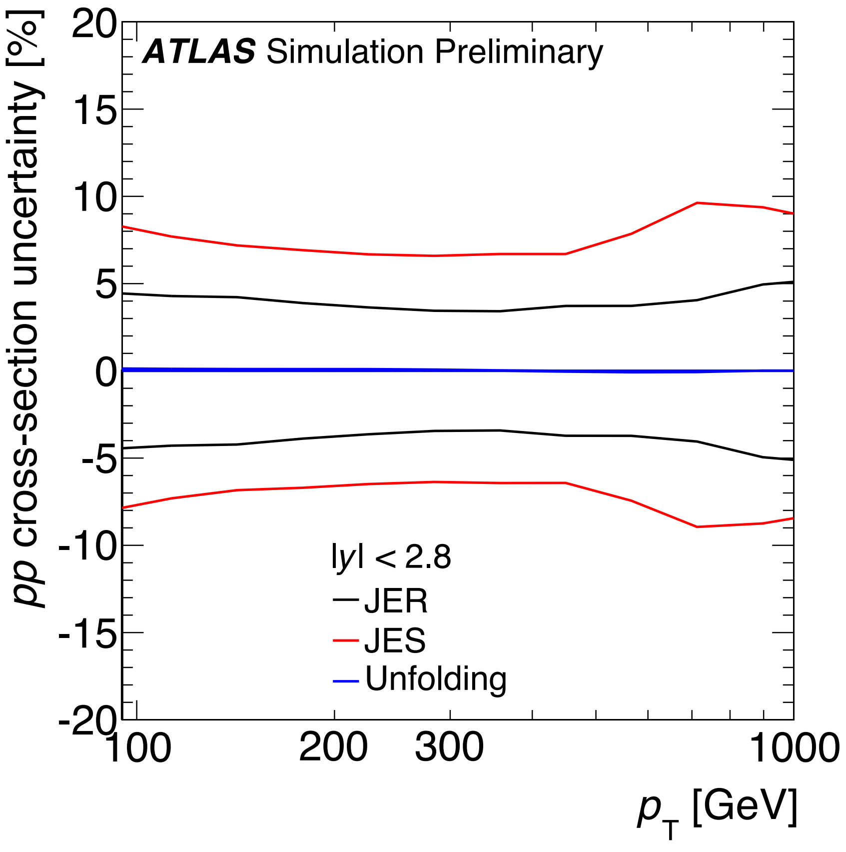


R_{AA} systematic uncertainties

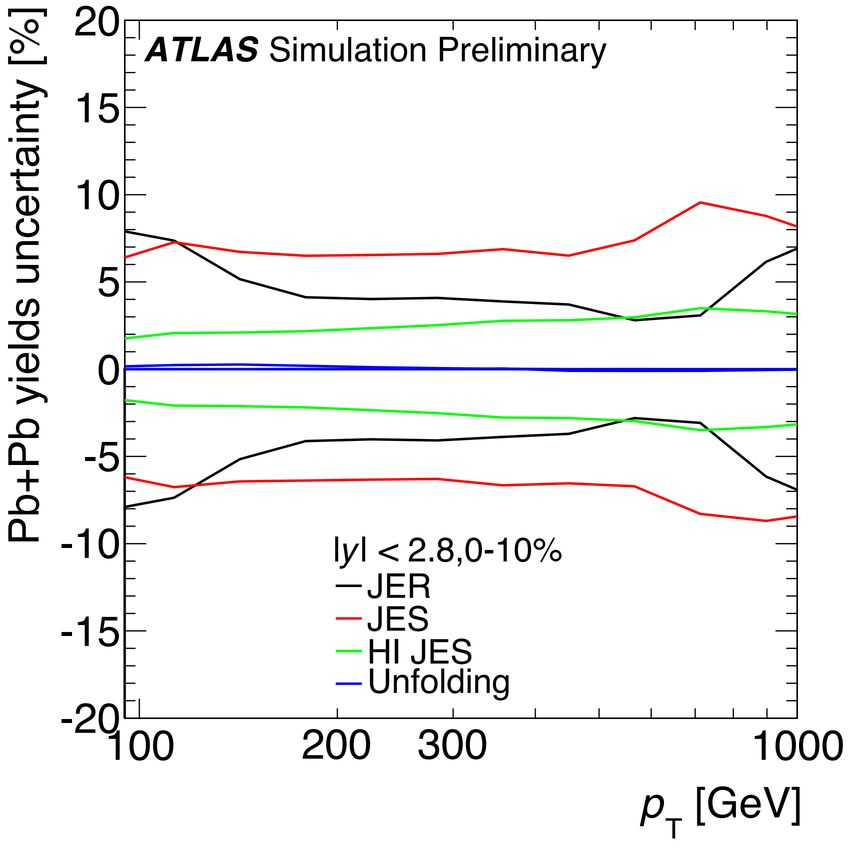
- Jet energy scale
  - ➡ Standard *pp* JES components + 5 TeV flavor and HI cross-calibration (following ATL-CONF-2015-016)
  - ➡ HI specific uncertainty due to jet quenching (estimated using studies of the ratio of calo-jet to track-jet p_T)
- Jet energy resolution
  - ➡ Standard *pp* component
  -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

R_{AA} systematics summary

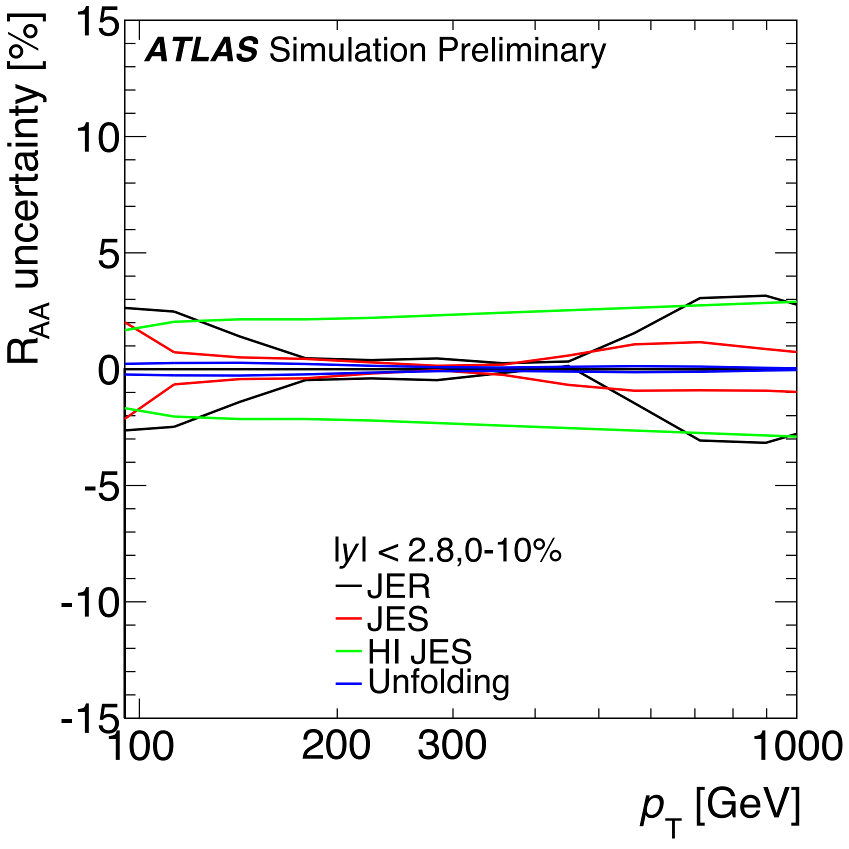
- **uncertainties on the *pp* cross section**



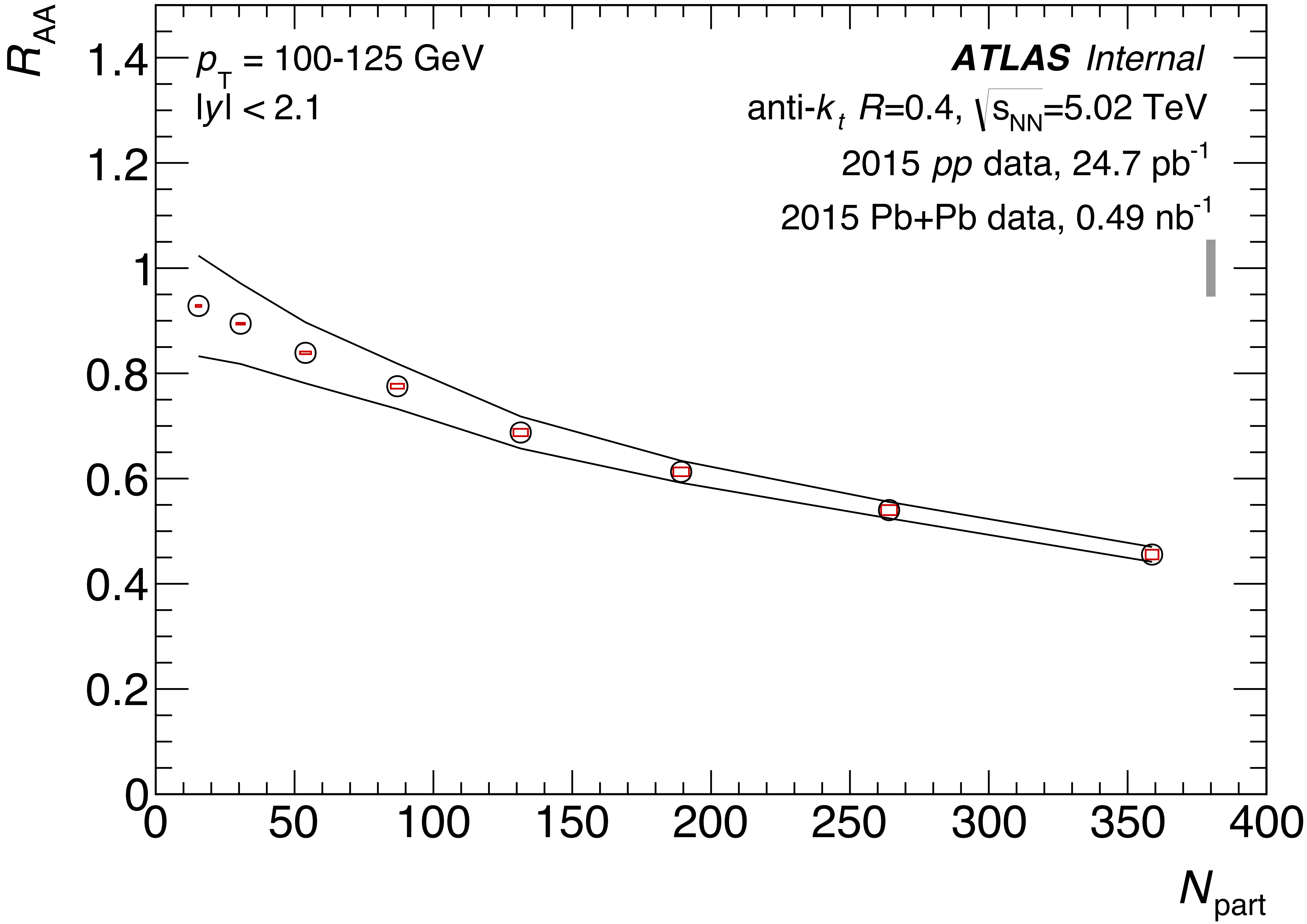
- **uncertainties on Pb+Pb yields**



- **uncertainties on R_{AA}**



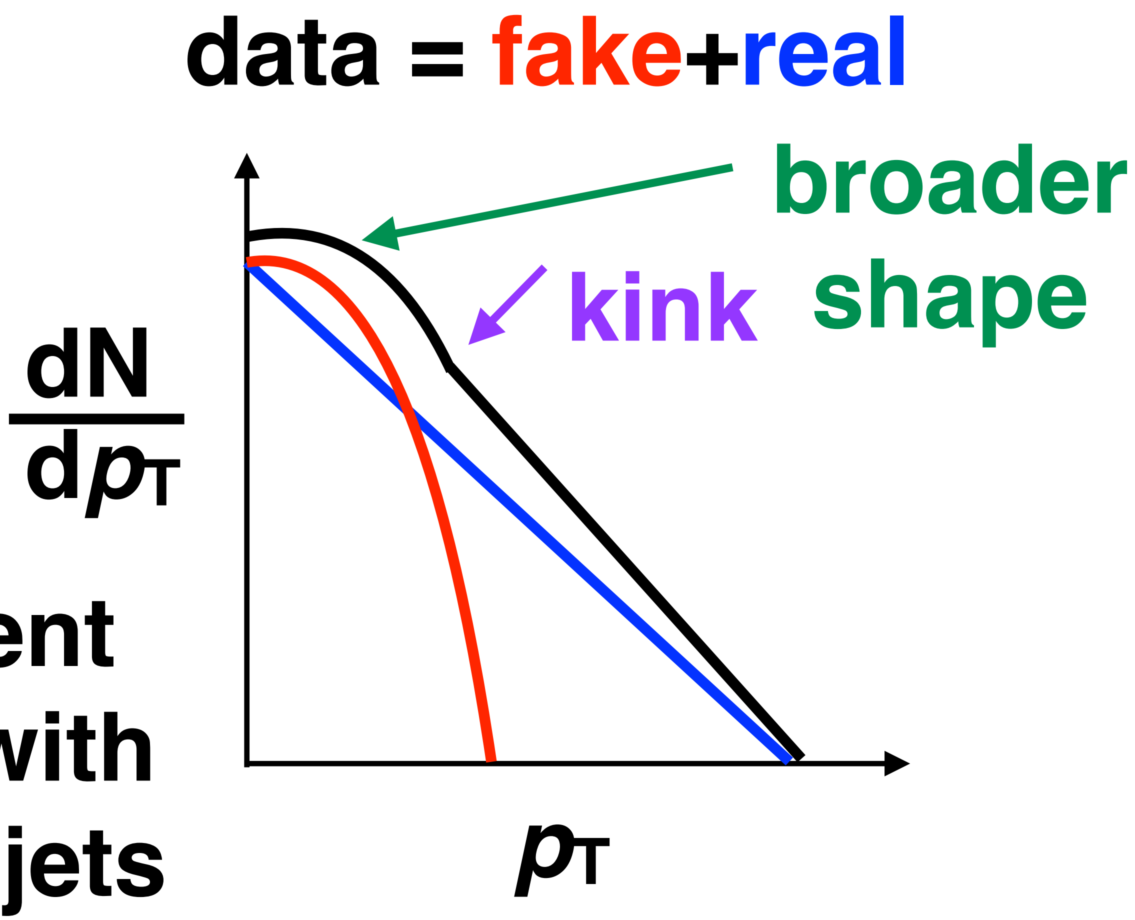
R_{AA} vs. N_{part}



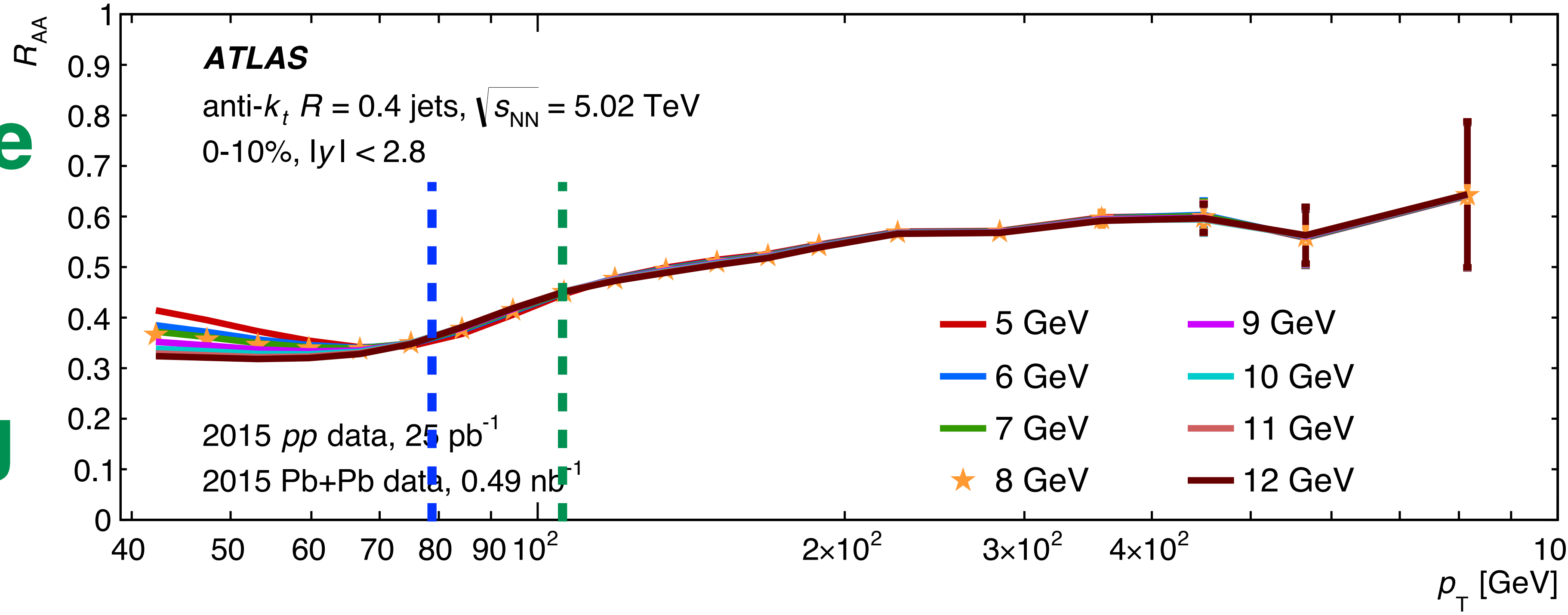
- **R_{AA} decreases with N_{part}**

Fakes

- Fake, or “UE jets”, are jets that are reconstructed from upward fluctuations due the UE
- Removed before unfolding
- R_{AA} fake rejection: look at different Σp_T^{trk} cuts for charged tracks with $p_T^{trk} > 4$ GeV within $\Delta R < 0.4$ of jets



- Fakes mostly contribute below ~75 GeV in 0-10%
- Above this see little change so use $\Sigma p_T^{trk} > 8$ GeV as the rejection
- Determines the measurement kinematic cut after unfolding to be 100 GeV



Model comparisons

- Lorentz Boltzmann Transport (LBT) model:
  - ➡ MC model of parton propagation
  - ➡ Elastic and inelastic e-loss
  - ➡ UE estimate from hydrodynamics with medium recoil and recoil propagation

Y. He, T. Luo, X.-N. Wang and Y. Zhu

- Soft Collinear Effective Field Theory (SCETg):
  - ➡ EFT for soft and collinear particles
  - ➡ Jets and their interactions with the medium are mediated by a Glauber gluon exchange
  - ➡ Modifications are made to the splitting functions
  - ➡ No medium recoil

Y.-T. Chien, A. Emerman, Z.-B. Kang, G. Ovanesyan and I. Vitev

- Effective Quenching (EQ) model:
  - ➡ two downward shifts in p_T, larger for gluons than quarks

B. Cole and M. Spousta

B. Cole and M. Spousta

Model comparisons

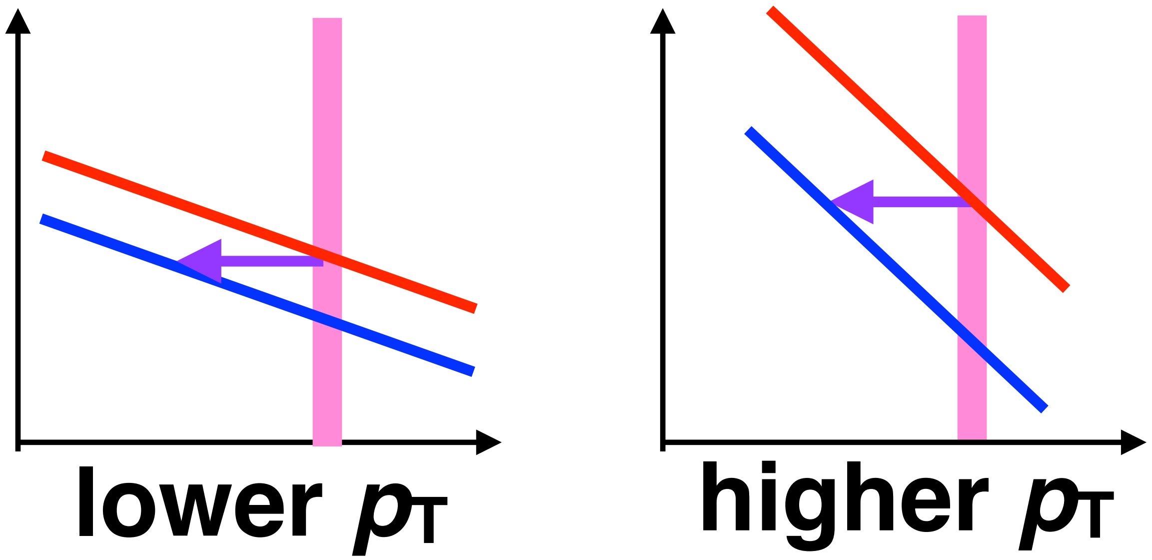
- **Effective Quenching (EQ) model:**
  - ➡ **fractional energy loss decreases with p_T**
  - ➡ **p_T dependence to the power-law distribution**

$$S = \Delta p_T^{\rm jet} = s'\left(\frac{p_T^{\rm jet}}{p_{T0}}\right)^{\boxed{\alpha}}$$

$$\alpha < 1$$

$$\frac{dN}{dp_T^{\rm jet}} \propto \left(p_T^{\rm jet}\right)^{-\boxed{n}} \qquad n \propto \ln p_T^{\rm jet}$$

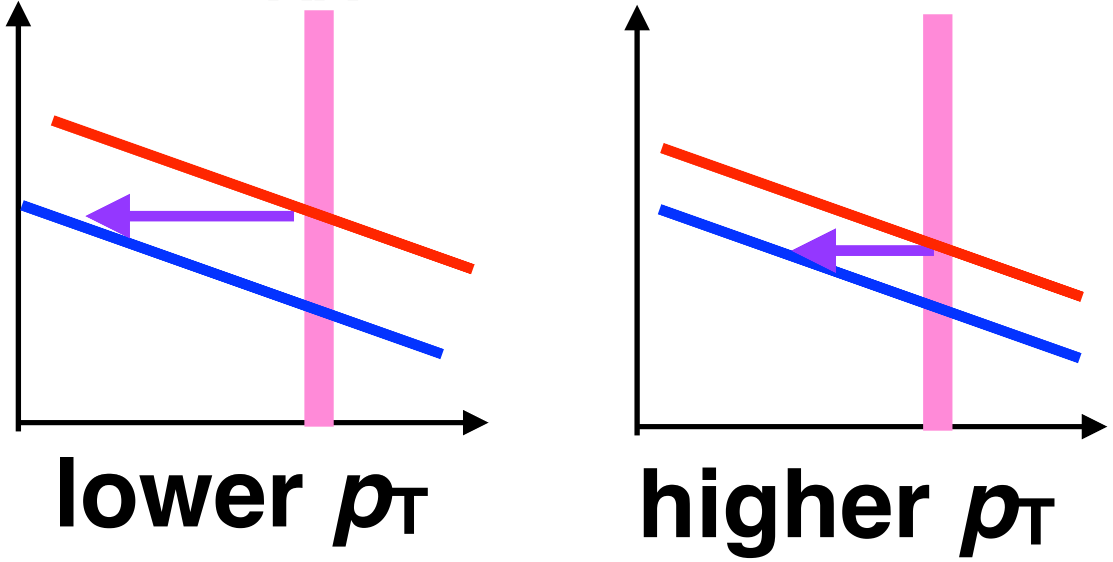
Spectra steeper with increasing p_T for the same amount of energy loss



➡ **lower R_{AA} at high p_T**

Amount of energy loss smaller at high p_T

R_{AA} ~ red/blue



➡ **higher R_{AA} at high p_T**

Internal structure

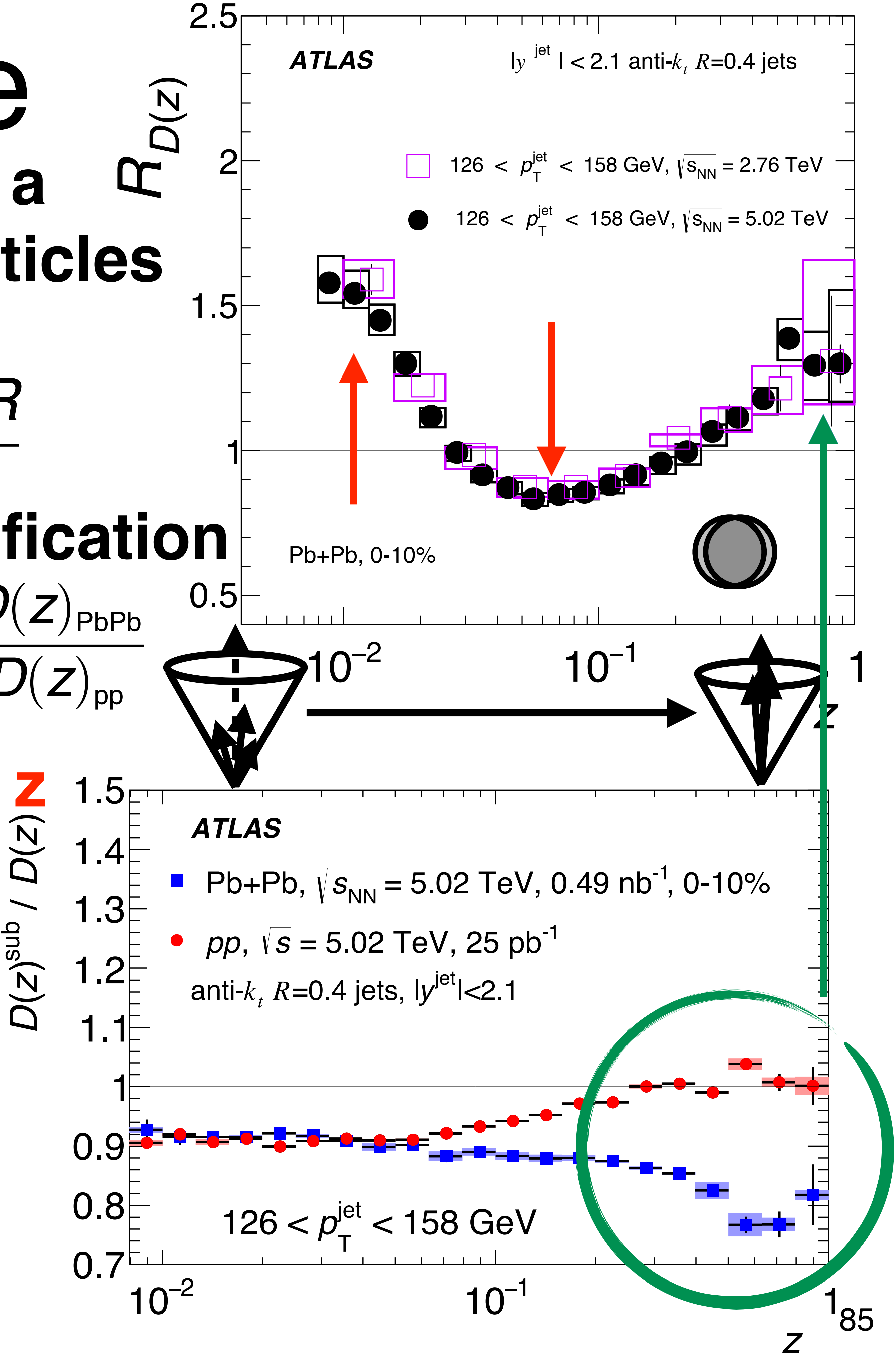
- **Fragmentation functions are a measure of how charged particles are distributed inside a jet**

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

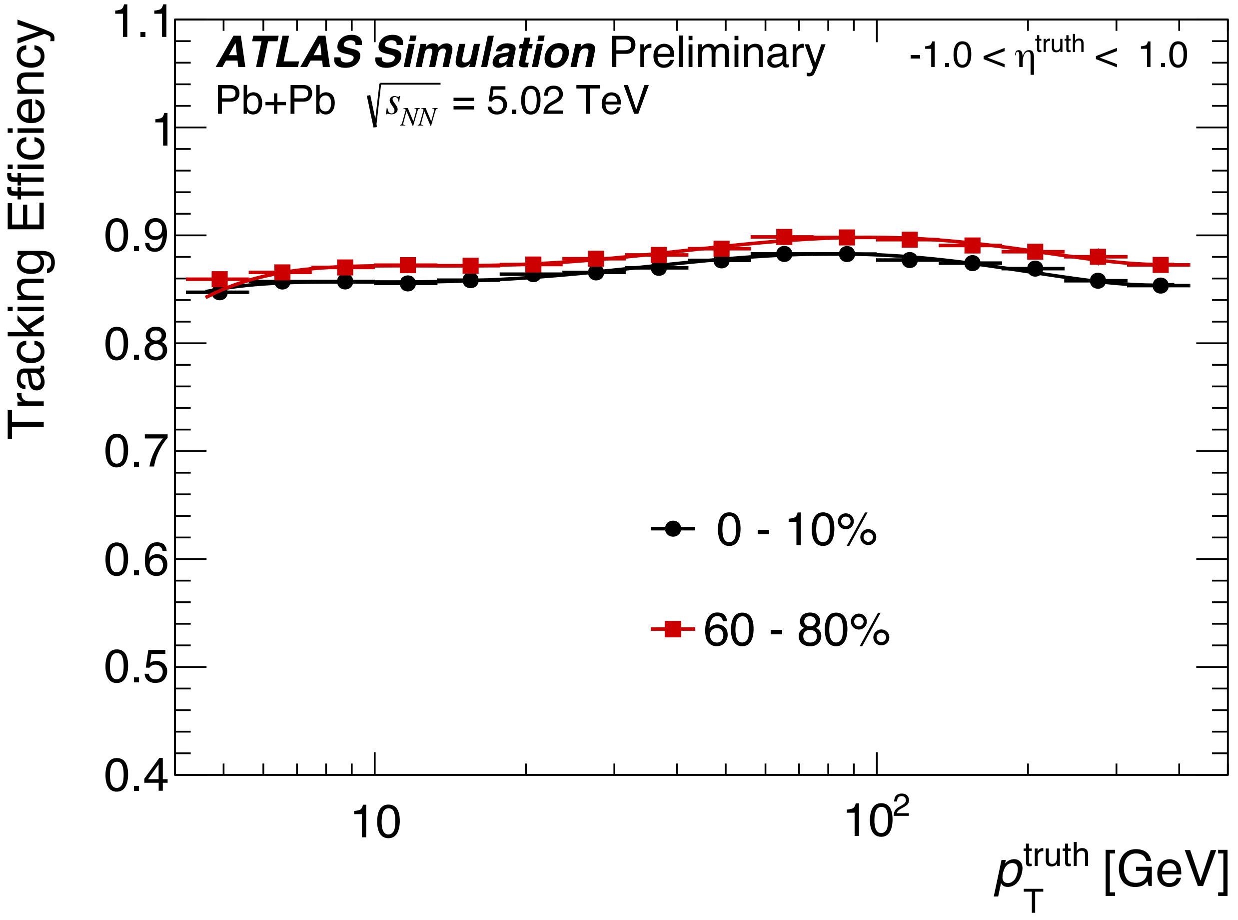
- **Ratio of FF used to see modification of jet structure**

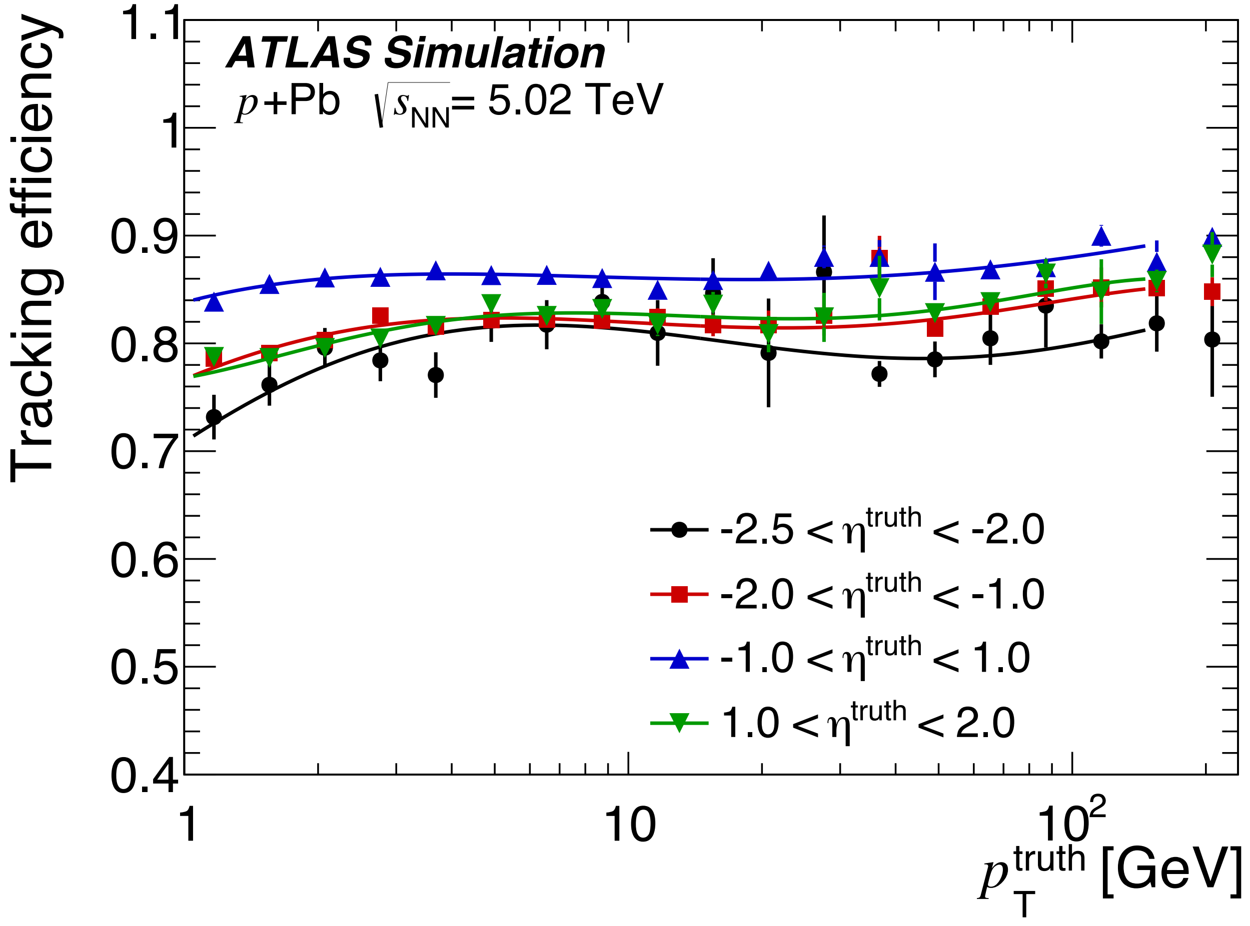
$$R_{\mathrm{D(z)}} = \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}}$$

- **Enhancement at low z and suppression at intermediate z**
- **Enhancement at high z**
- **2D unfolding in z and jet p_{T}**
- **Unfolding increases Pb+Pb FF and decreases pp FF at high z, resulting in the enhancement at high z**



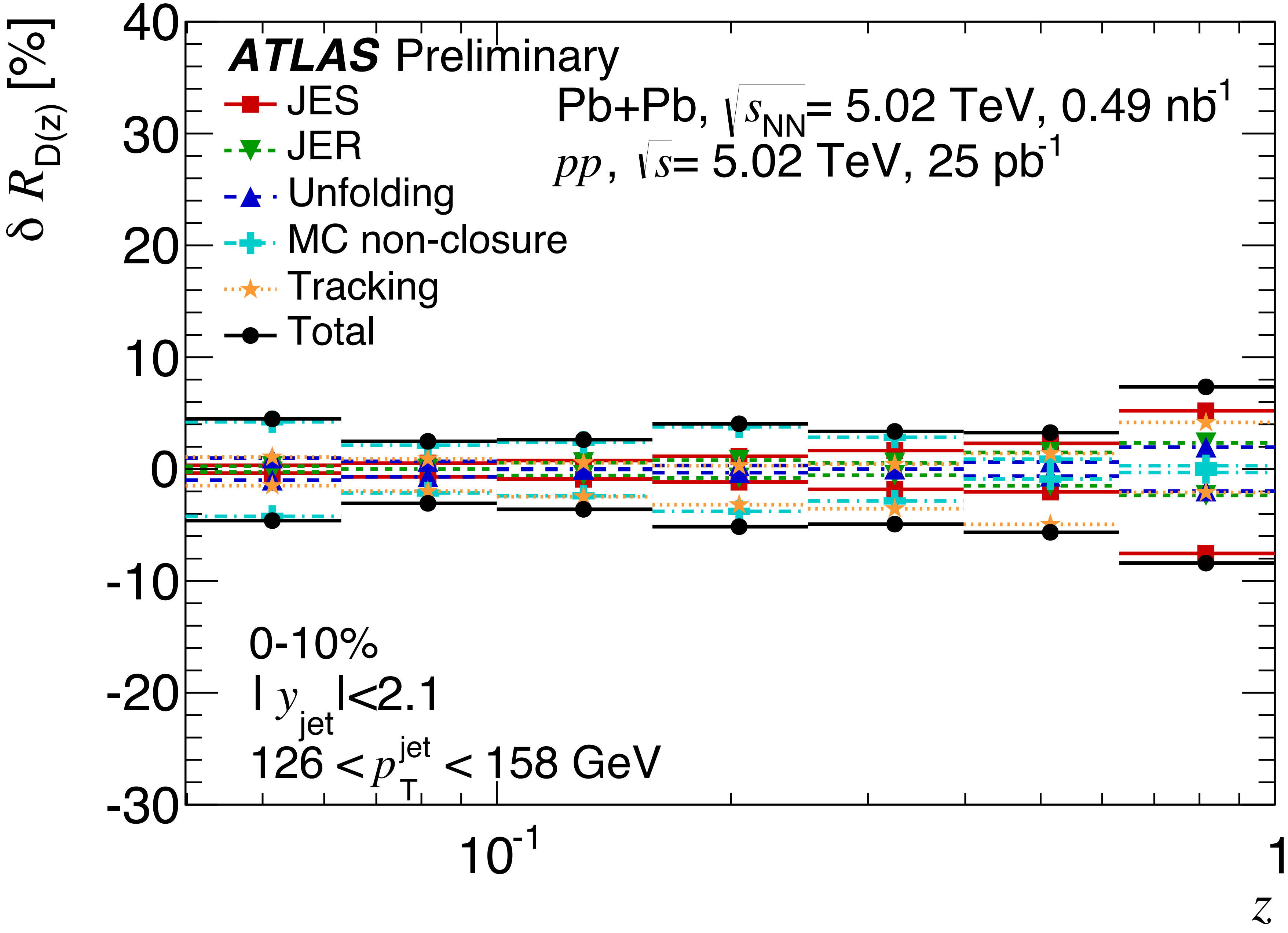
Tracking efficiencies





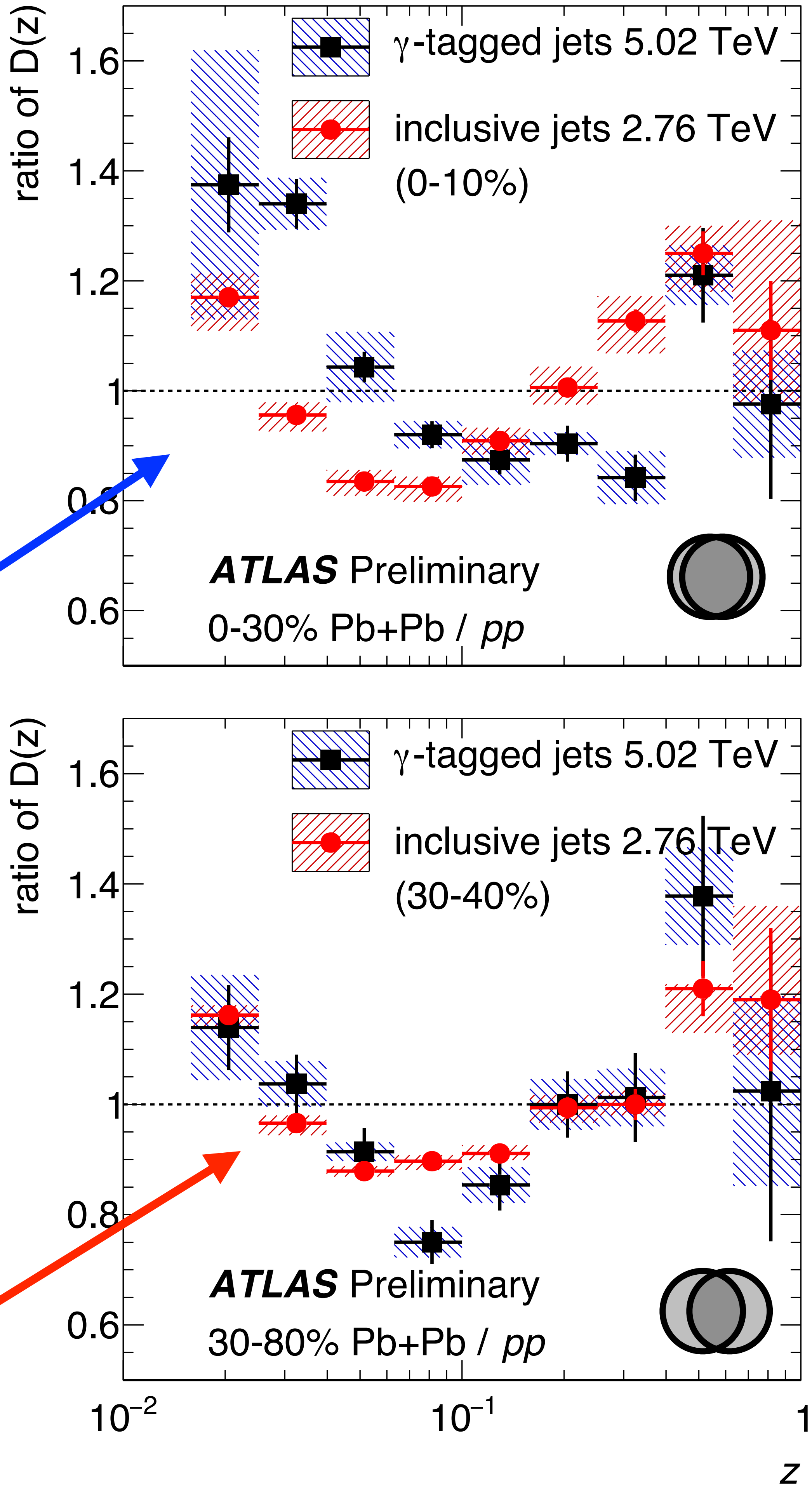
Systematic uncertainties on Pb+Pb $R_{D(z)}$

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



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%**



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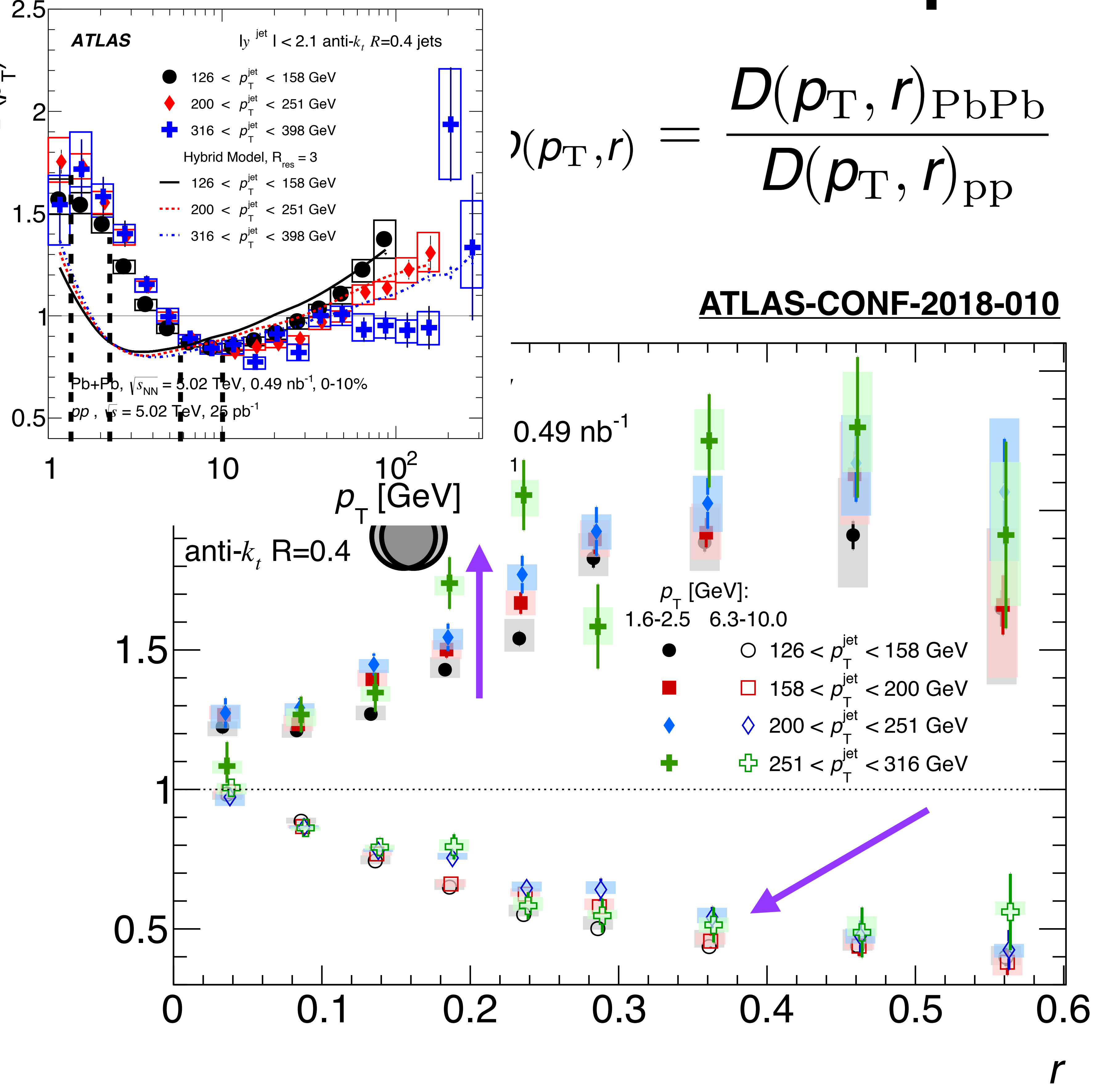
Internal structure: radial dep.

- **Jet p_{T} depende**
  jet shape mod

$$(p_{\mathrm{T}}, r) = \frac{D(p_{\mathrm{T}}, r)_{\mathrm{PbPb}}}{D(p_{\mathrm{T}}, r)_{\mathrm{pp}}}$$



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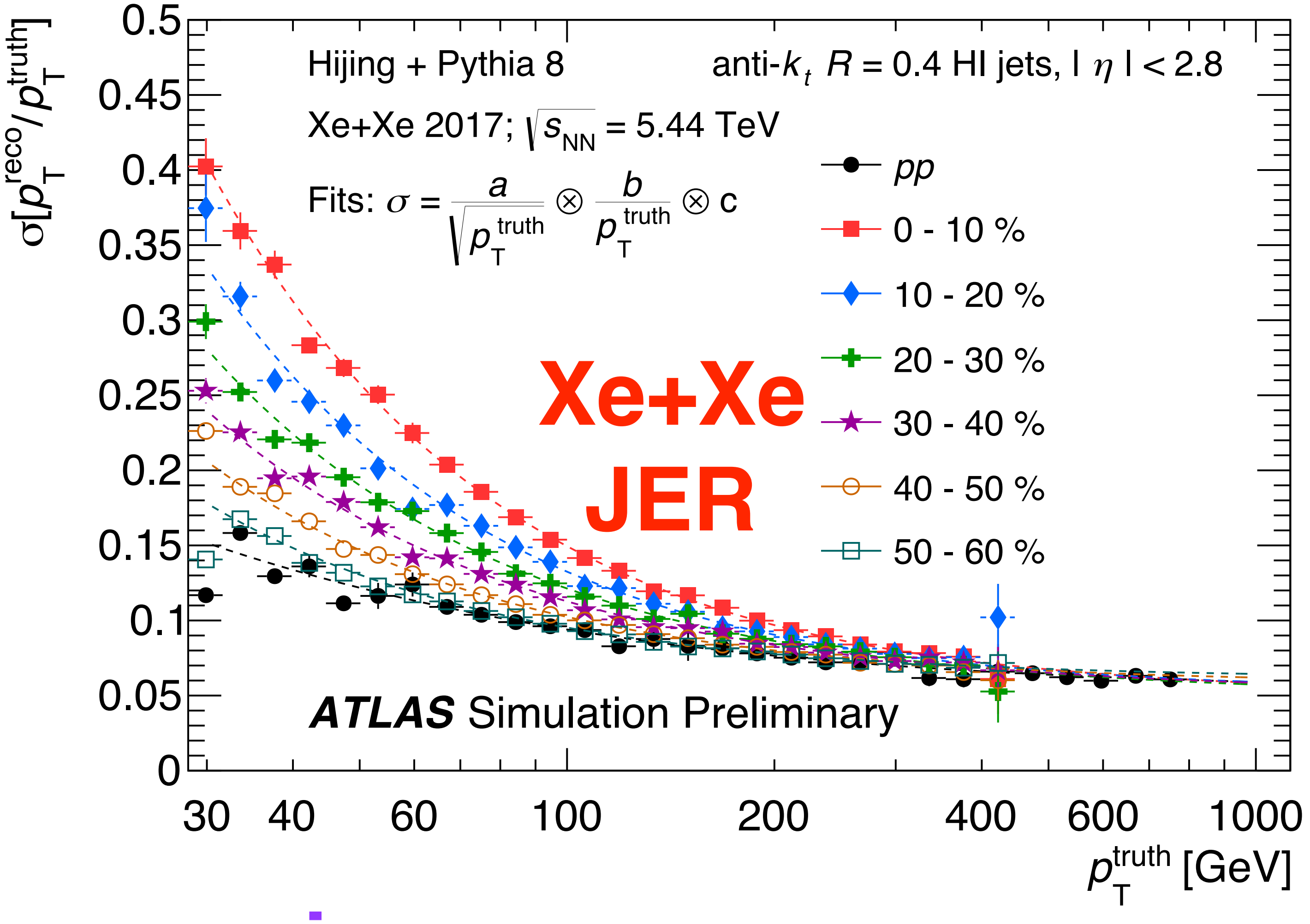
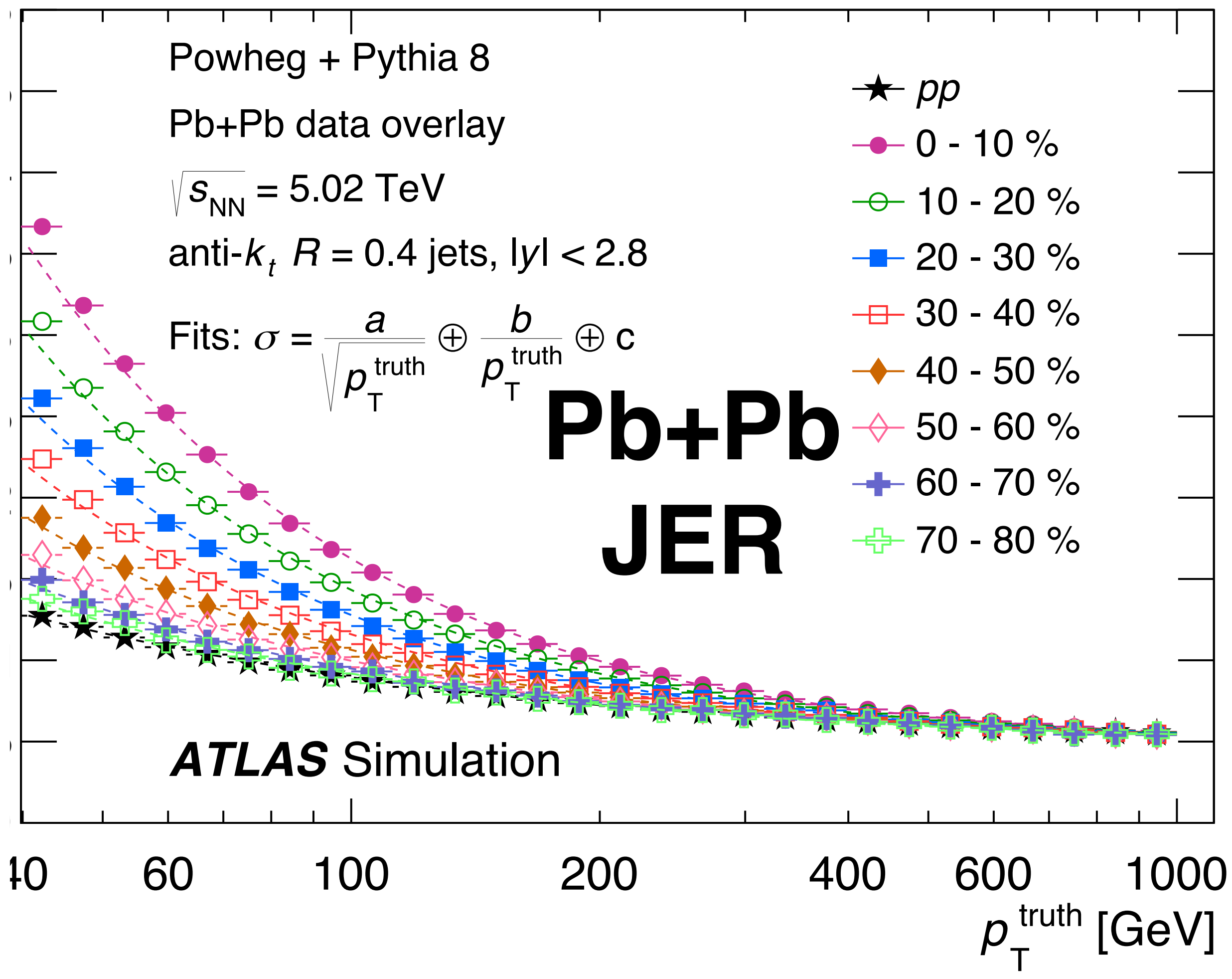
- **More soft particles at high jet p_{T}**
- **No significant dependence on jet p_{T} at intermediate p_{T}**

► ***Consistent with inclusive FF measurement***

UE fluctuations

- **Due to the difference in the UE in Pb+Pb and Xe+Xe, a study of the fluctuations of the UE was performed**



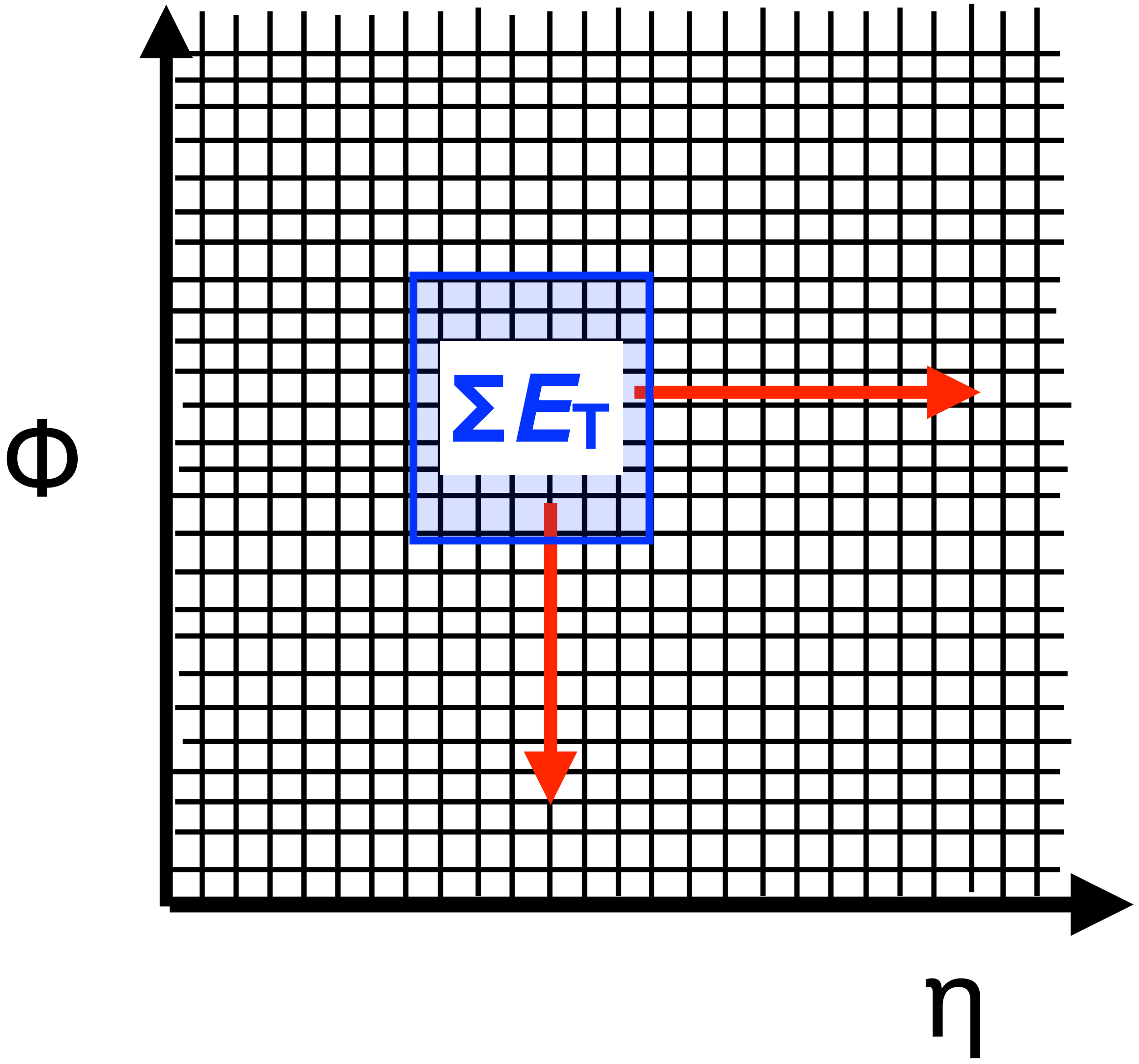


UE fluctuations

- **Due to the difference in the UE in Pb+Pb and Xe+Xe, a study of the fluctuations of the UE was performed**

  ➡**Sum the E_T in 7x7 windows of towers in η-ϕ**

  ➡**Slide through each window in the event and get the average $\langle E_T \rangle$ and standard deviation $\sigma(E_T)$**



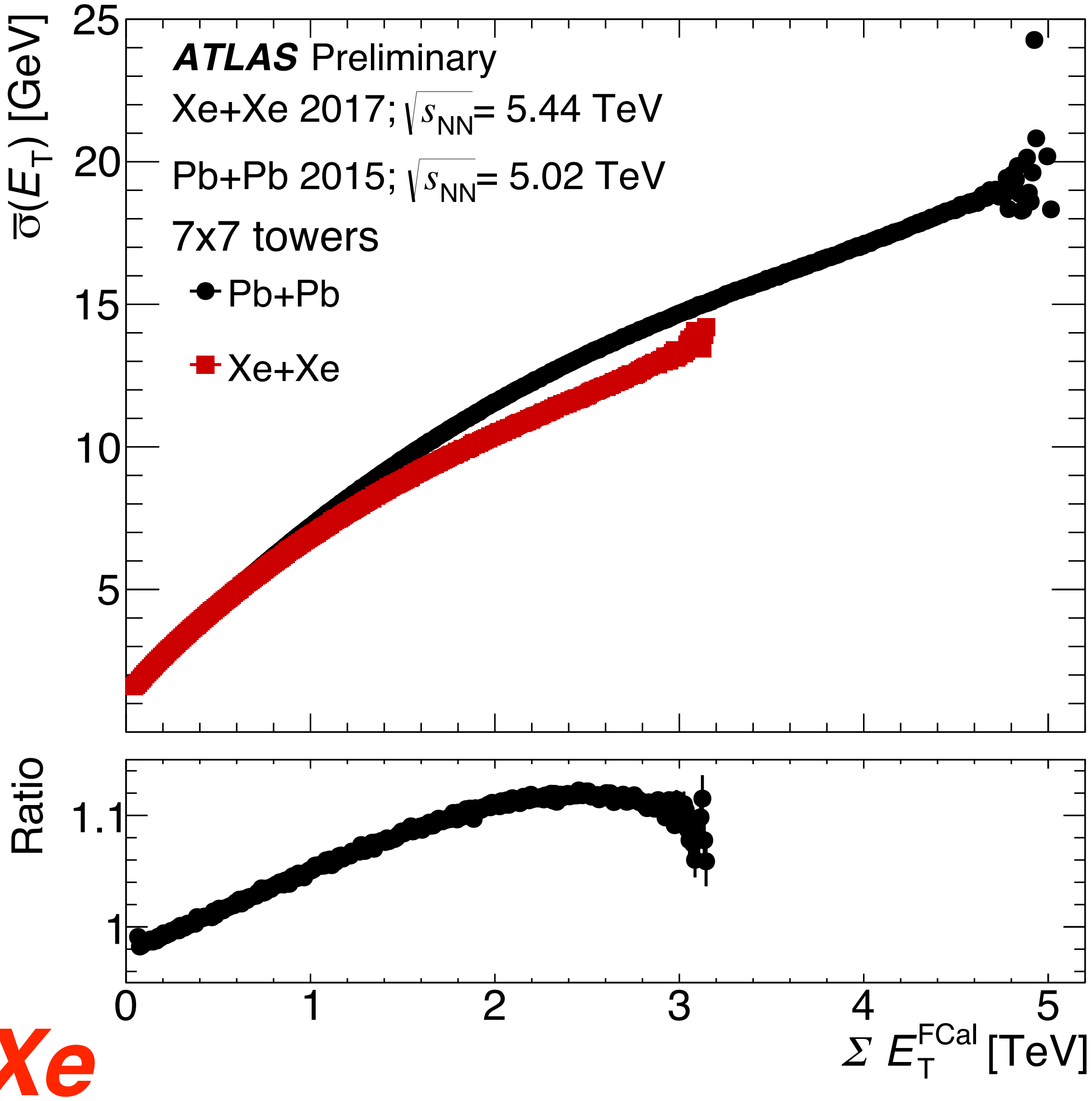
UE fluctuations

- **Due to the difference in the UE in Pb+Pb and Xe+Xe, a study of the fluctuations of the UE was performed**

  ➡**Sum the E_T in 7x7 windows of towers in η-ϕ**

  ➡**Slide through each window in the event and get the average $\langle E_T \rangle$ and standard deviation $\sigma(E_T)$**

  ➡**Take the average $\bar{\sigma}(E_T)$ of the $\sigma(E_T)$ of all the events in a particular ΣE_T^{FCal} bin**



- ***Pb+Pb* slightly larger than *Xe+Xe***

► ***Difference represents the difference between the UE contributions to the JER and is used as an "uncertainty" in the measurement***

Xe systematics uncertainties

- **Jet energy scale (JES)**
  - ➡ Baseline 11 nuisance parameters from *in situ* calibration (stand pp calibration) with additional parameters due to flavor response and composition and cross calibration)
  - ➡ Additional one in Xe+Xe and P+Pb due to the detector response to quenched jets that is by comparing the ratio of the sum of p_T of the tracks associated with a reconstructed jet to the reconstructed jet p_T between data and MC
  - ➡ Uncertainty due the the residual non-closure in the JES in the MC
  - ➡ Evaluated on the reconstructed pT so that pTreco' = pTreco(1+/-uncertainty)
- **Jet energy resolution (JER)**
  - ➡ standard baseline JER from pp and cross calibration
  - ➡ HI specific for the difference in fluctuations in data and MC

Summary of systematic uncertainties

Pb+Pb and pp are only used for a comparison to Xe+Xe so only the uncertainties that are different between them and Xe+Xe are needed

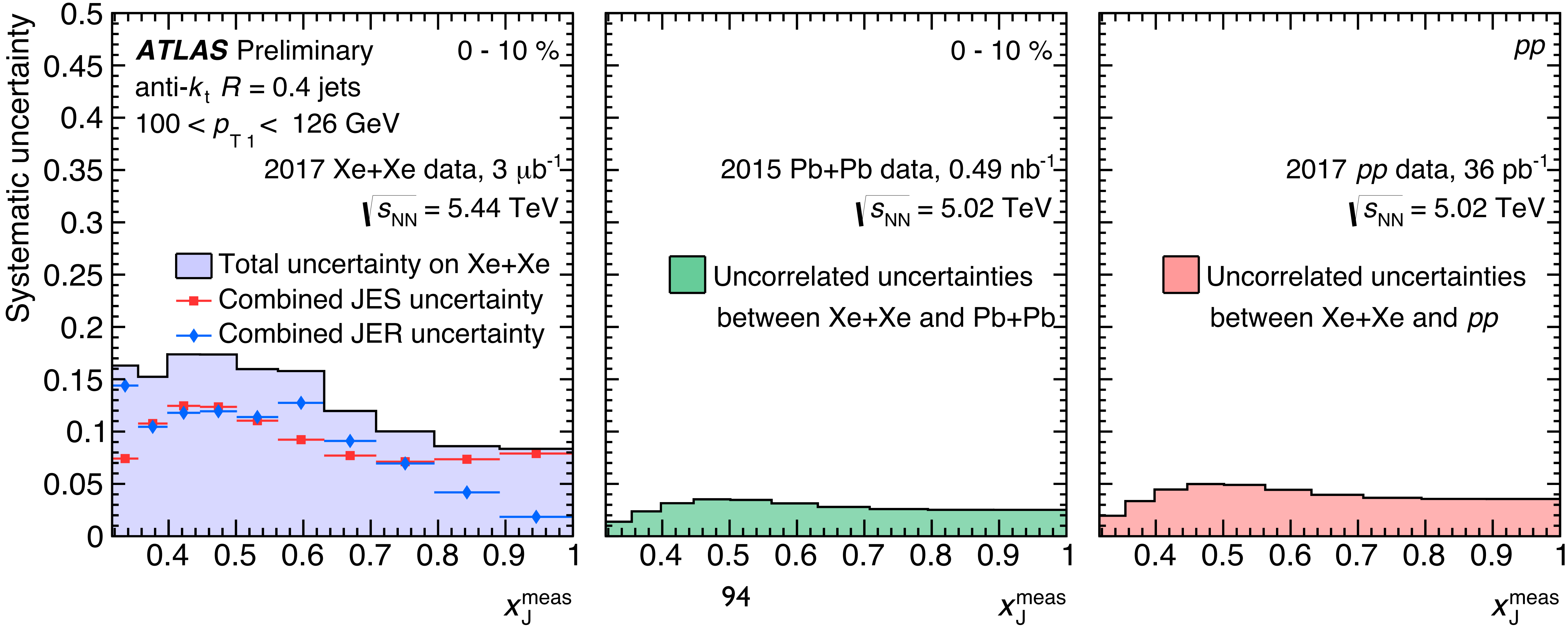
Uncertainty on Xe+Xe:
all of the combined systematic uncertainties on the JES as described in the previous slide

Uncertainty on Pb+Pb:
Only the uncertainties that are uncorrelated between Pb+Pb and Xe+Xe are included on the Pb+Pb result

- centrality dependence JES in Pb+Pb
- difference between the MC non-closure uncertainty in Xe+Xe and Pb+Pb

Uncertainty on pp:
Only the uncertainties that are uncorrelated between pp and Xe+Xe are included on the pp result

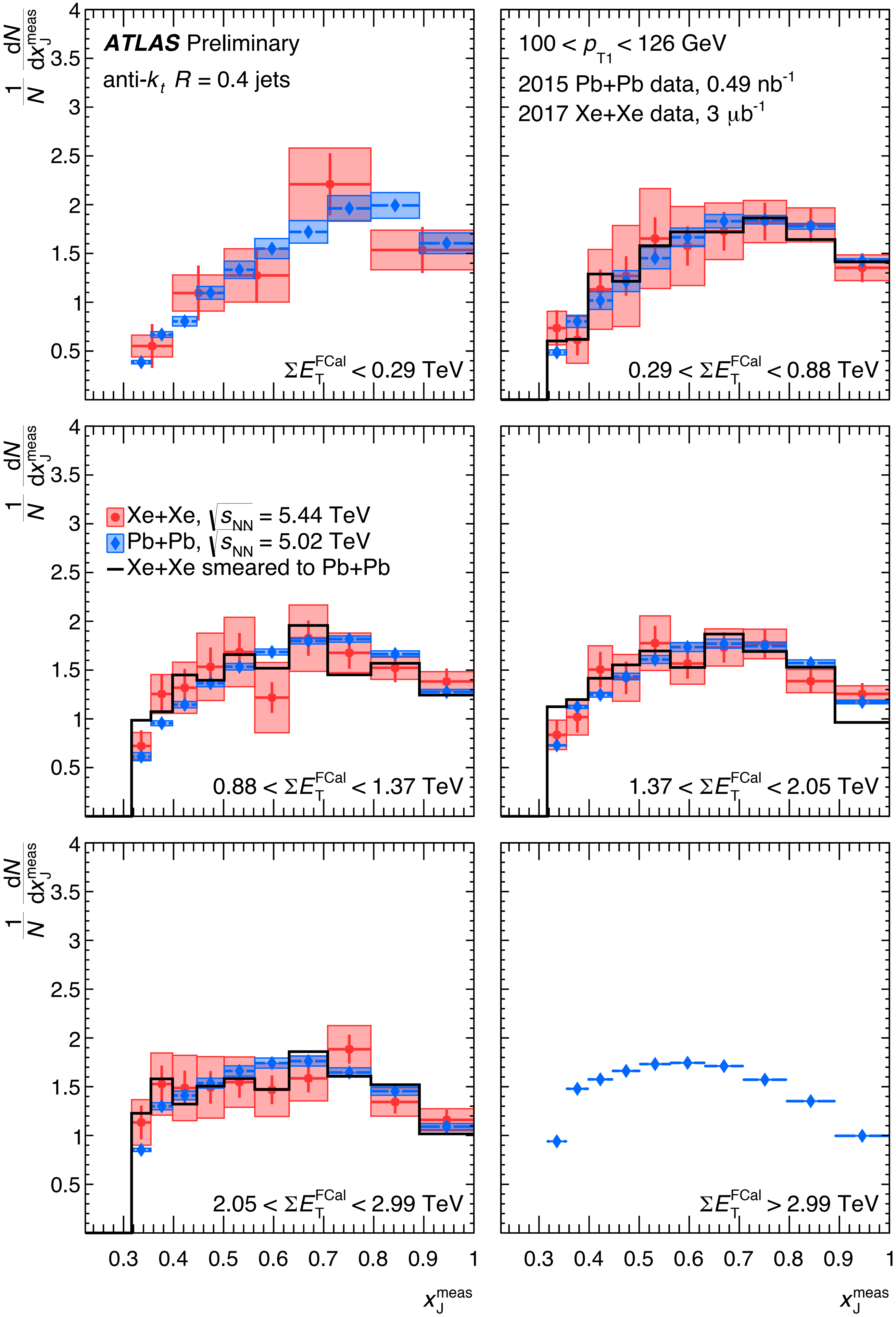
- centrality dependence JES in Xe+Xe
- difference between the MC non-closure uncertainty in Xe+Xe and pp



x_J: ΣE_T^{FCal} dependence

Similar density

- **Compare 2017 Xe+Xe to 2015 Pb+Pb**
- ***x_J* consistent between Pb+Pb and Xe+Xe for all ΣE_T^{FCal}**
- **Xe+Xe smeared to Pb+Pb to account for differences in UE fluctuations**



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