# Recent measurements of jet imbalance and suppression in heavy-ion collisions with the ATLAS

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ATLAS

IN LVMINE TVO VIDEBIMVS LVMEN

# Jets in HI collisions

- **Recent results of jet quenching are becoming more precise and are taking advantage of higher statistics**
- **Allow more differential studies of jet kinematics that look at flavor dependence, path dependence, what happens at high $p_T$, etc.**

➡ **ATLAS unfolded dijet asymmetry measurement**

➡ **New ATLAS jet suppression measurement in run 2**

# Performance

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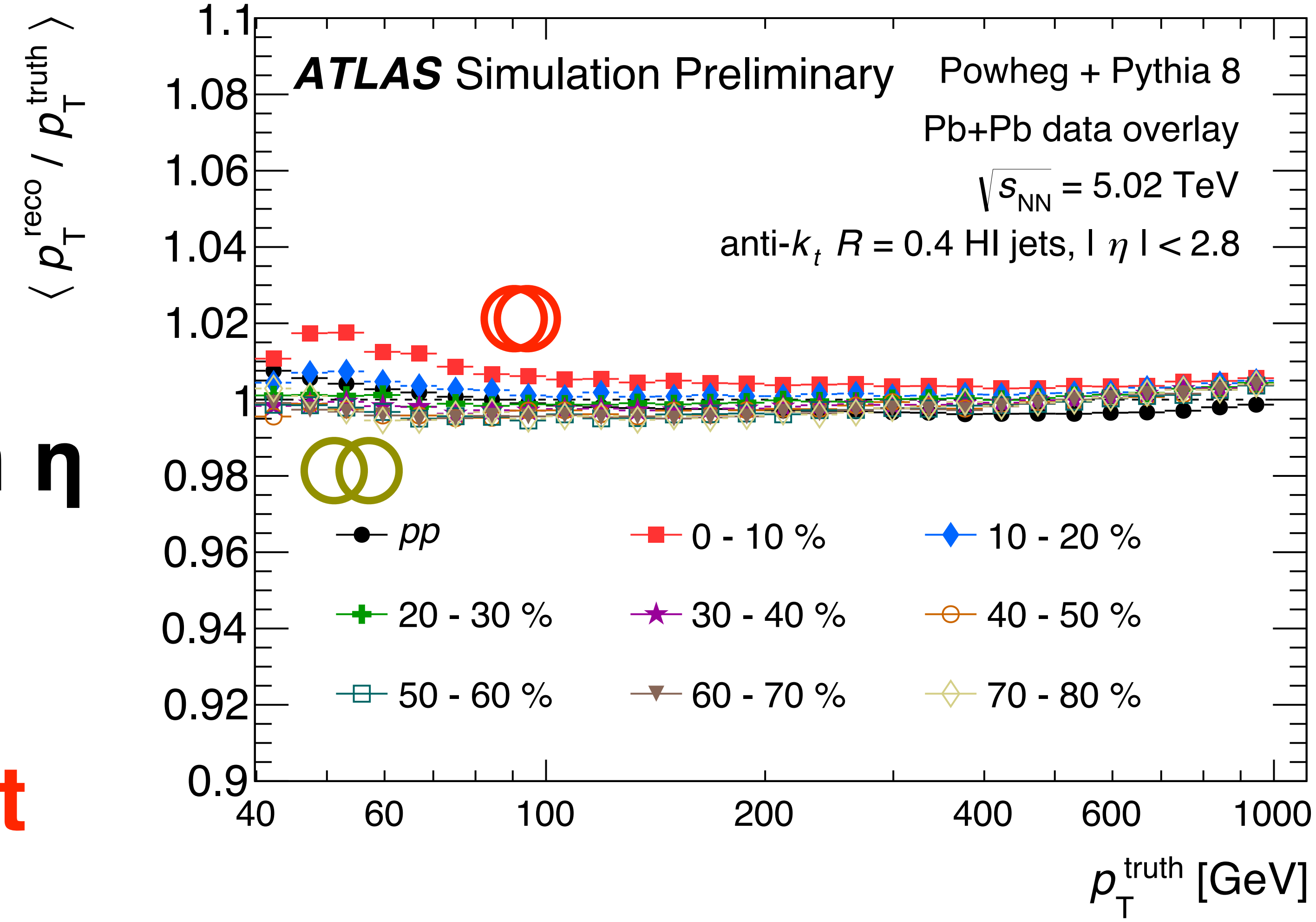

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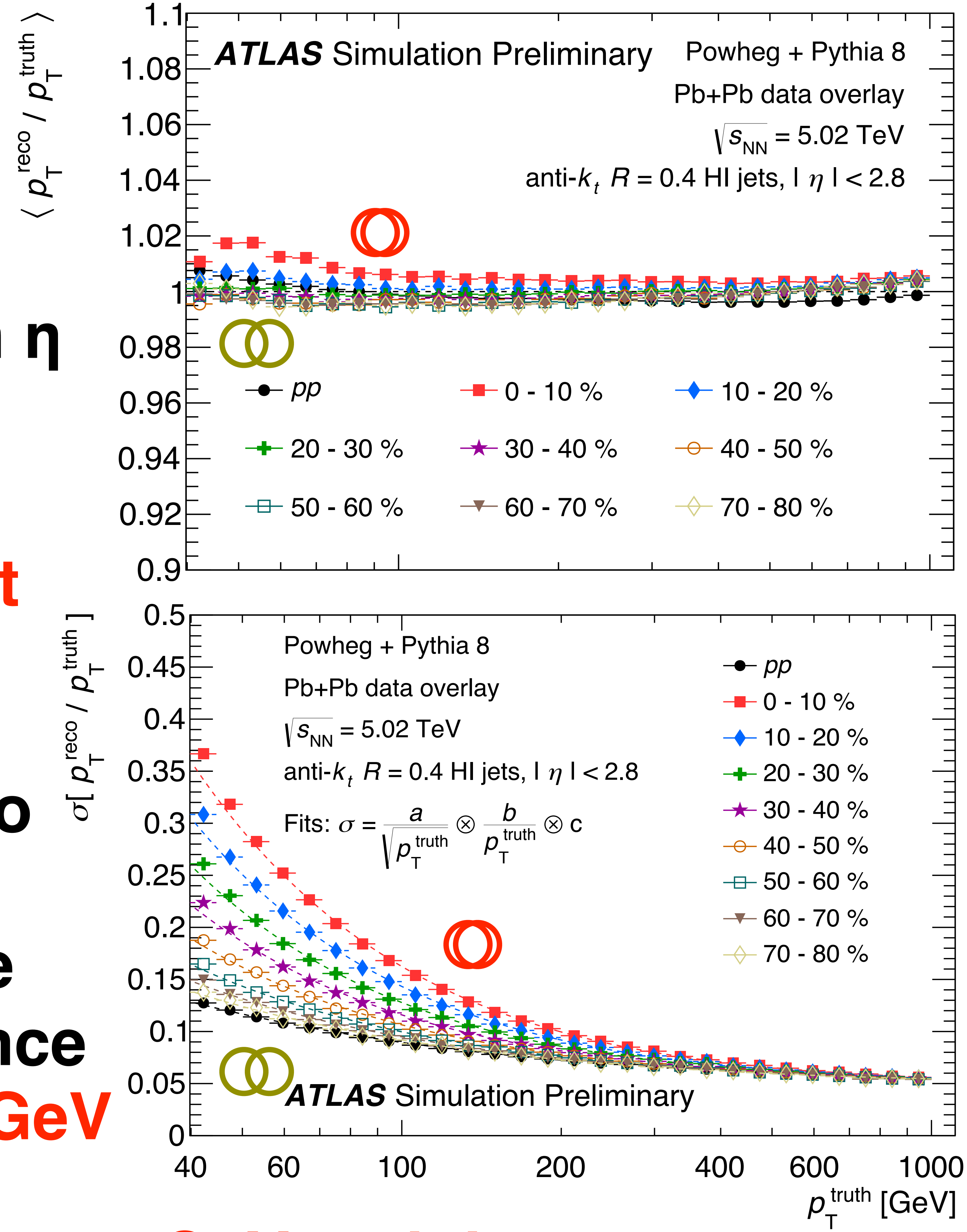

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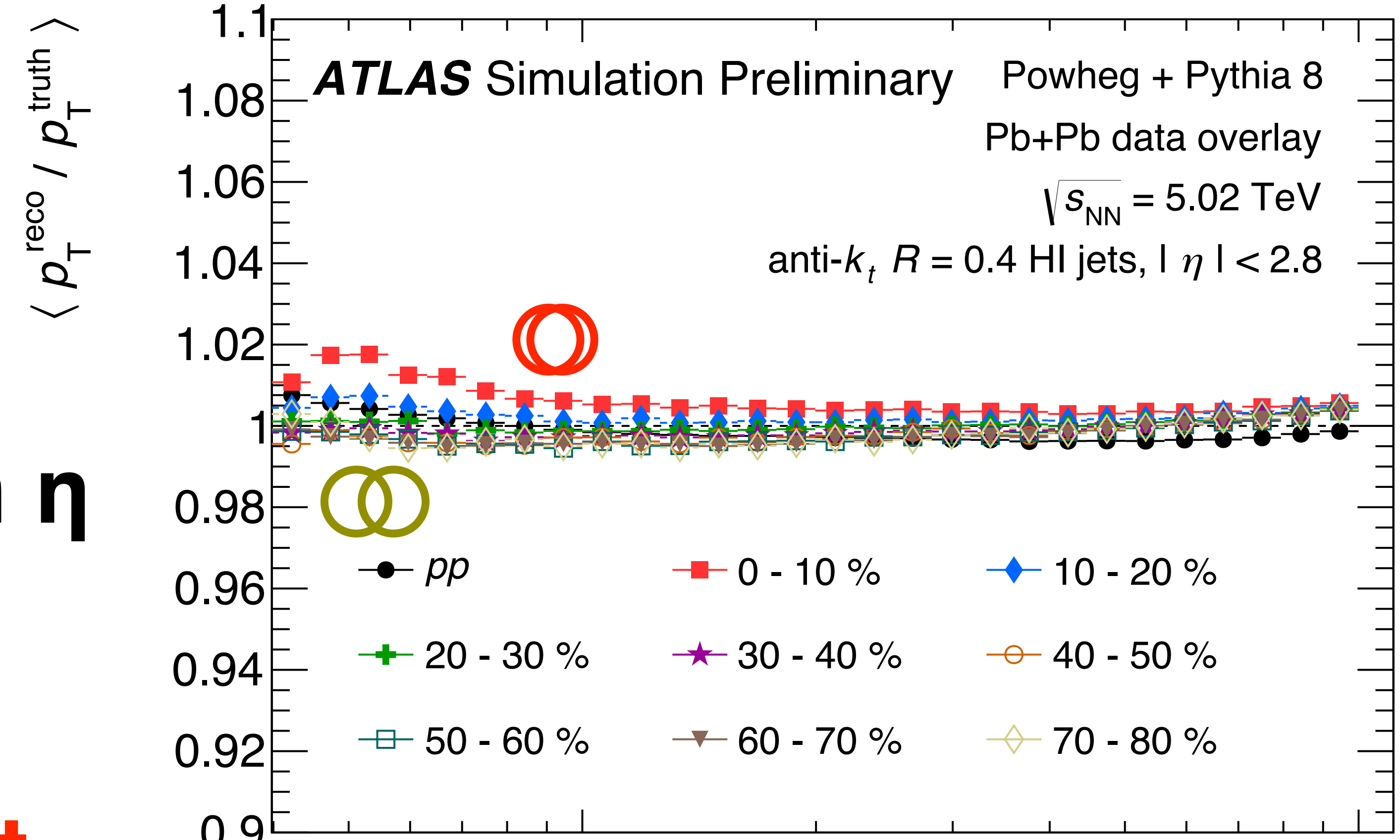
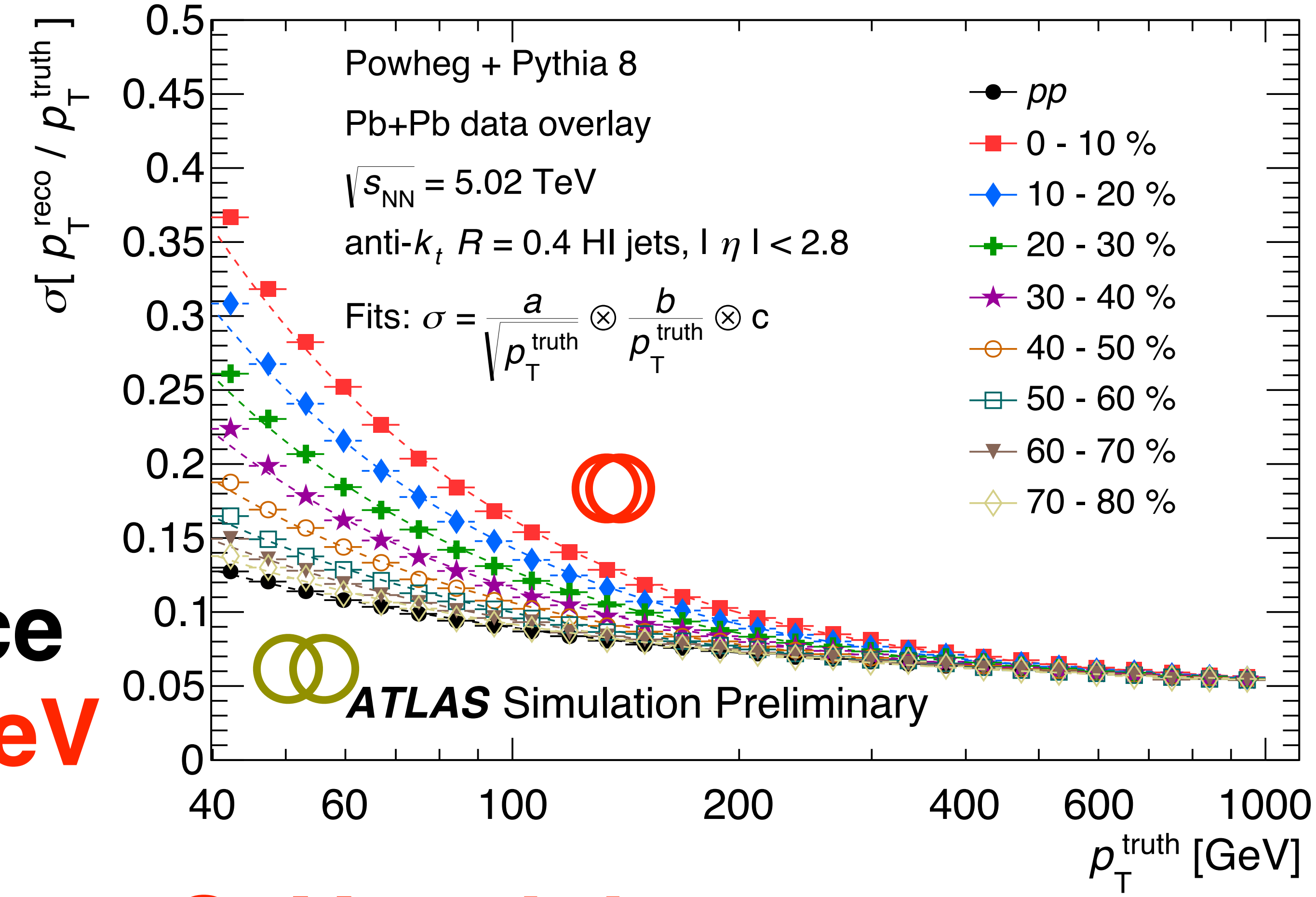
▸ ***Unfolding removes remaining JES/JER***



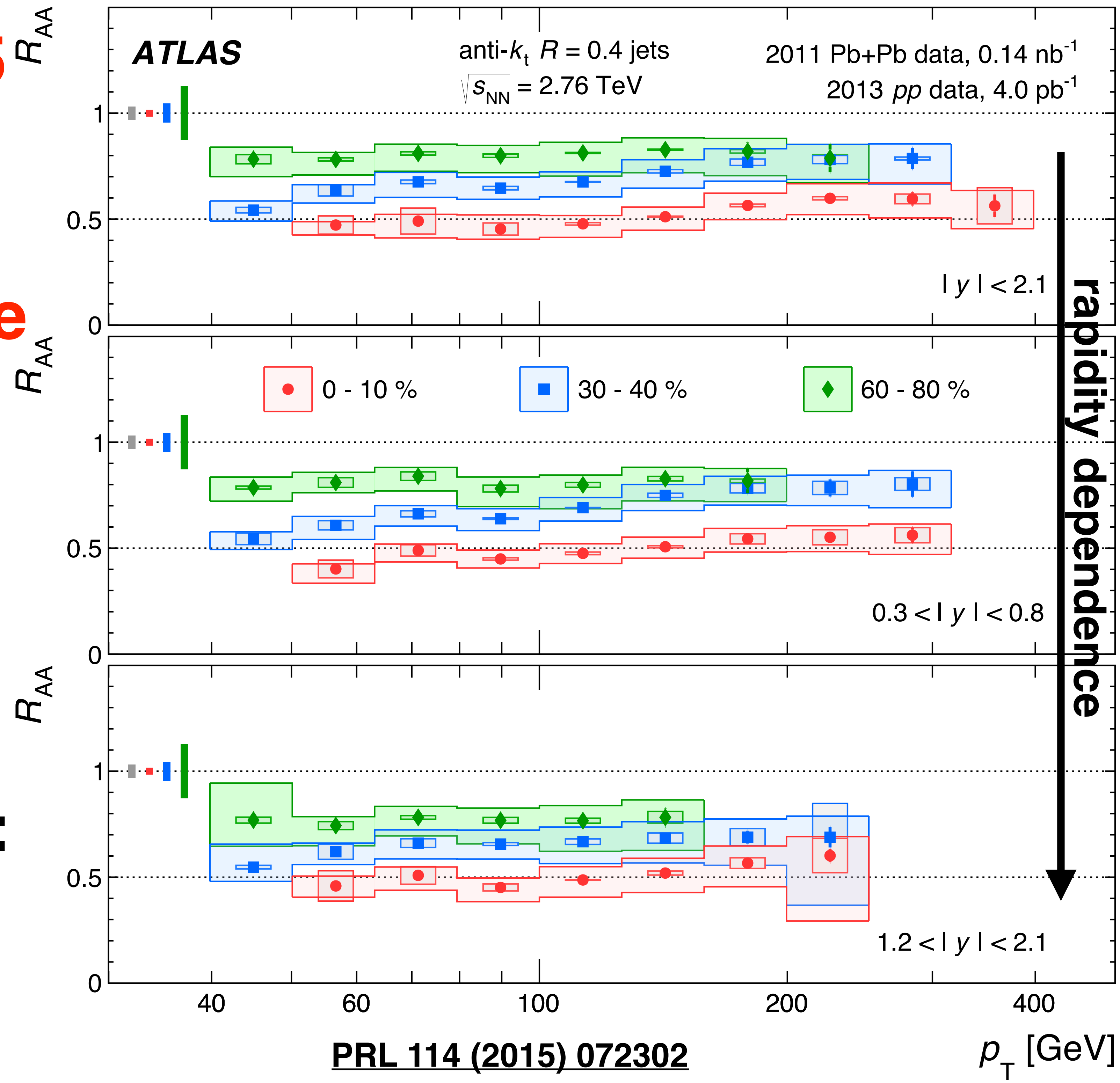



# Jet suppression

- **Previous ATLAS measurement in run 1 ($\sqrt{s_{NN}}$ =2.76 TeV):**
  - **Suppression is ~0.5 in central collisions**
  - ***No* significant rapidity dependence**

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

- **New measurement in run 2 ($\sqrt{s_{NN}}$ = 5.02 TeV):**
  - **better statistics at higher $p_T$ and forward rapidity**

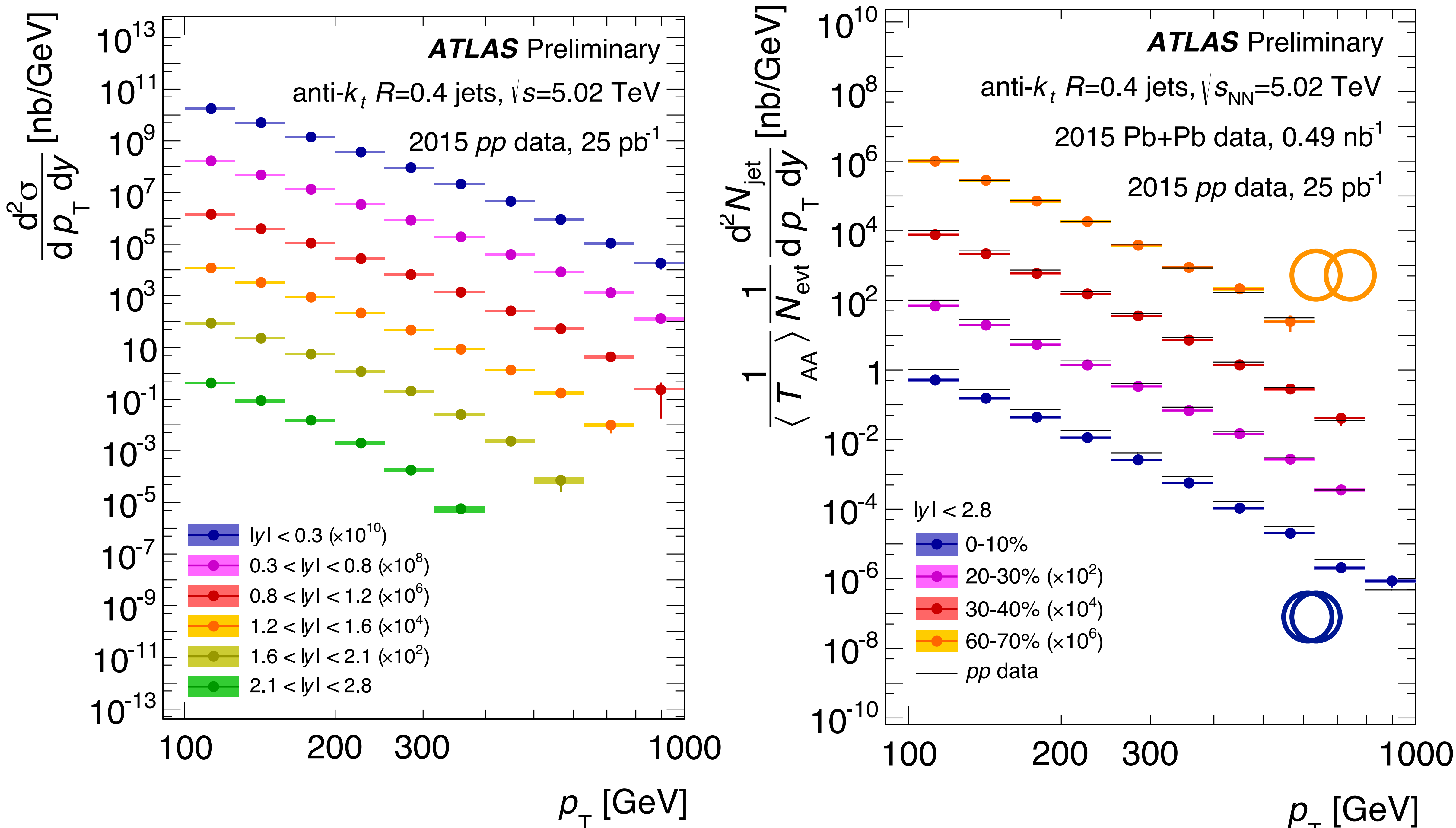



PRL 114 (2015) 072302

# Jet spectra

ATLAS-CONF-2017-009

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

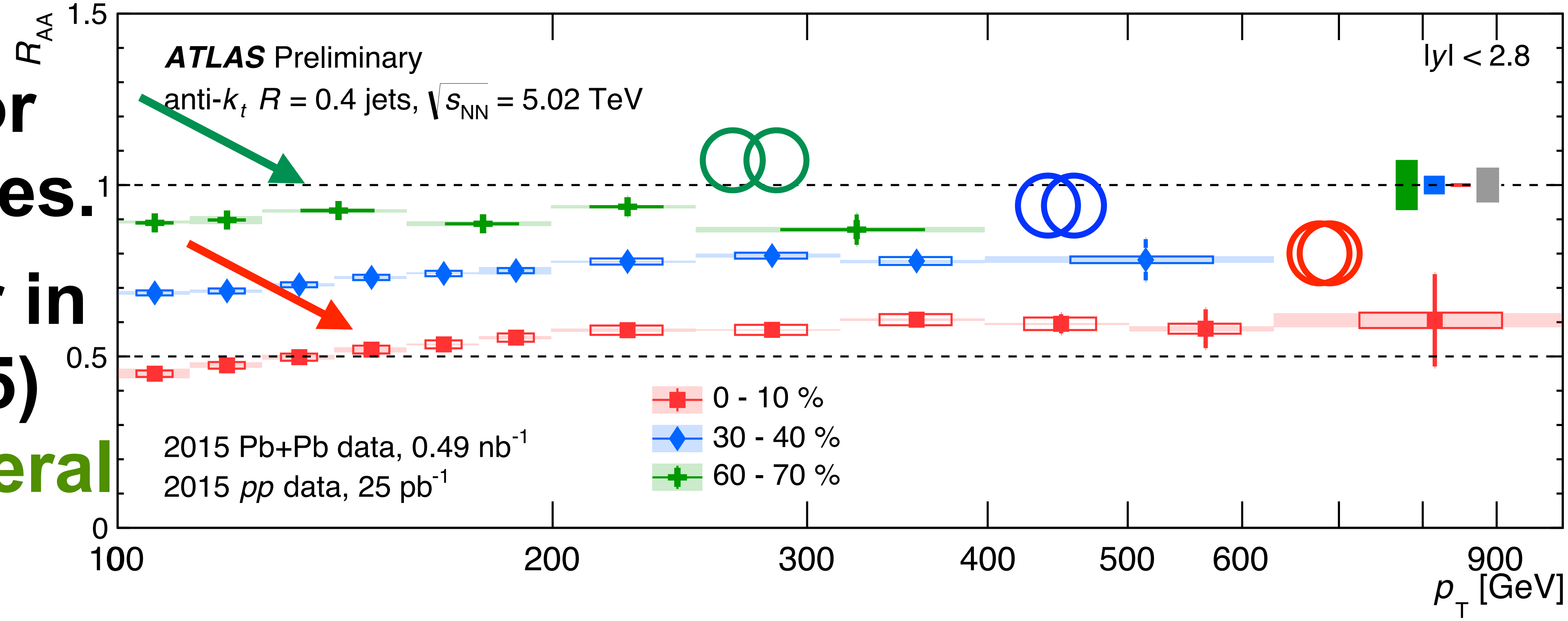



- **Spectra is unfolded using 1D Bayesian unfolding.**

# $R_{AA}$ vs. $p_T$

ATLAS-CONF-2017-009

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



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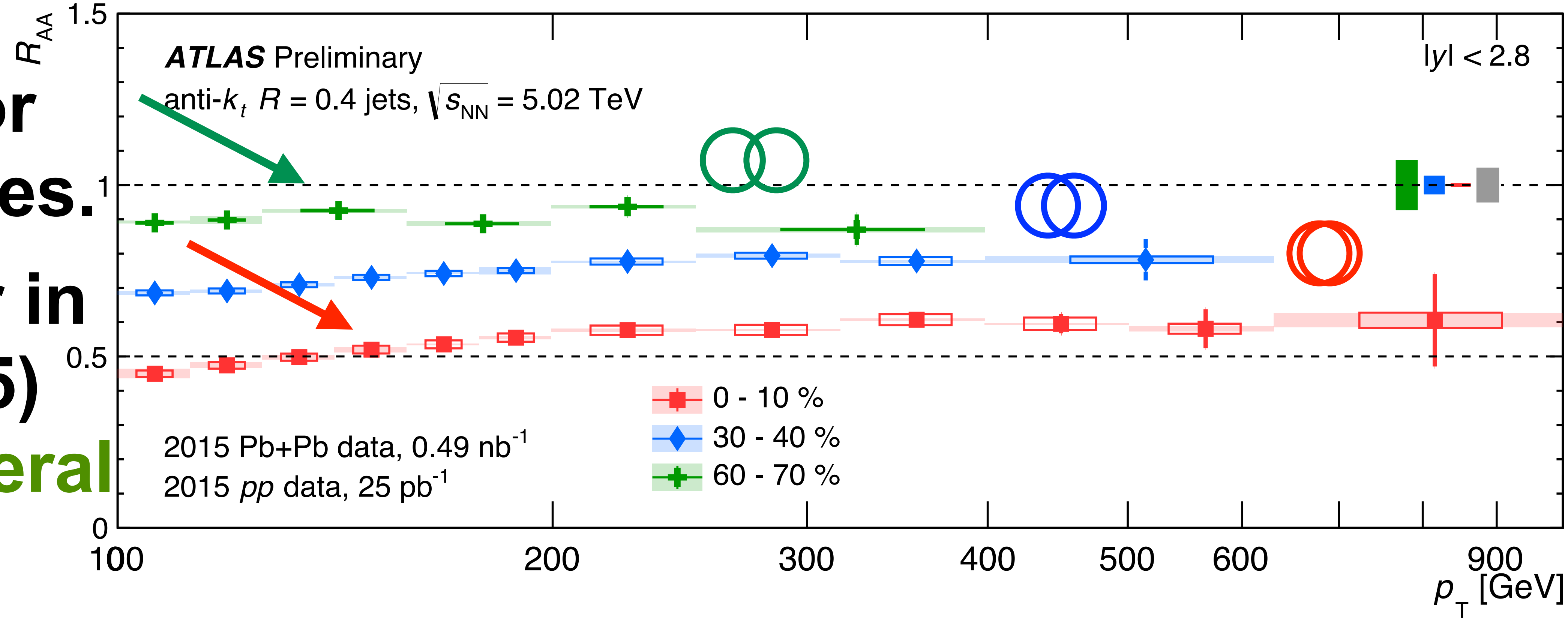


- $R_{AA}$ rises with jet $p_T$ until ~300 GeV where it begins to flatten.

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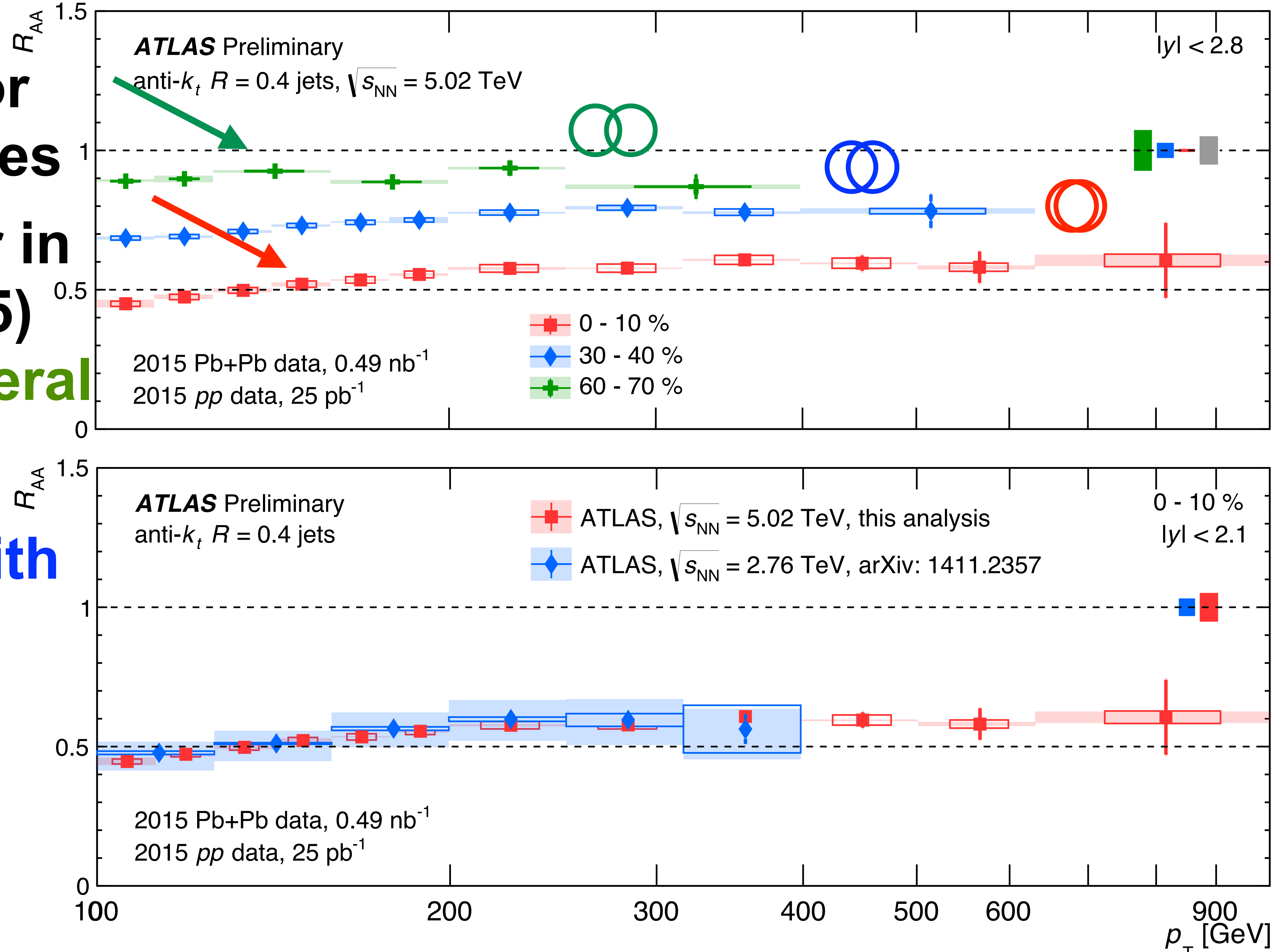
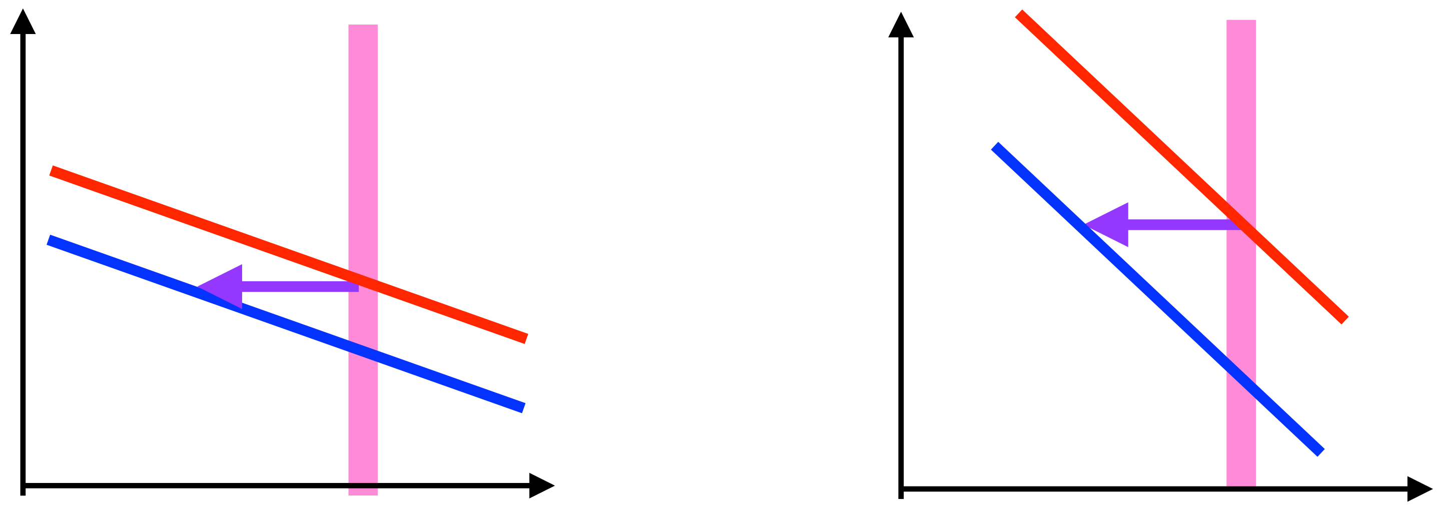



- $R_{AA}$ is independent of $\sqrt{s_{NN}}$ (over a narrow range)
- Systematics greater reduced

# $R_{AA}$ vs. rapidity

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

➡ **lower $R_{AA}$**



**mid-rapidity** **foward-rapidity**

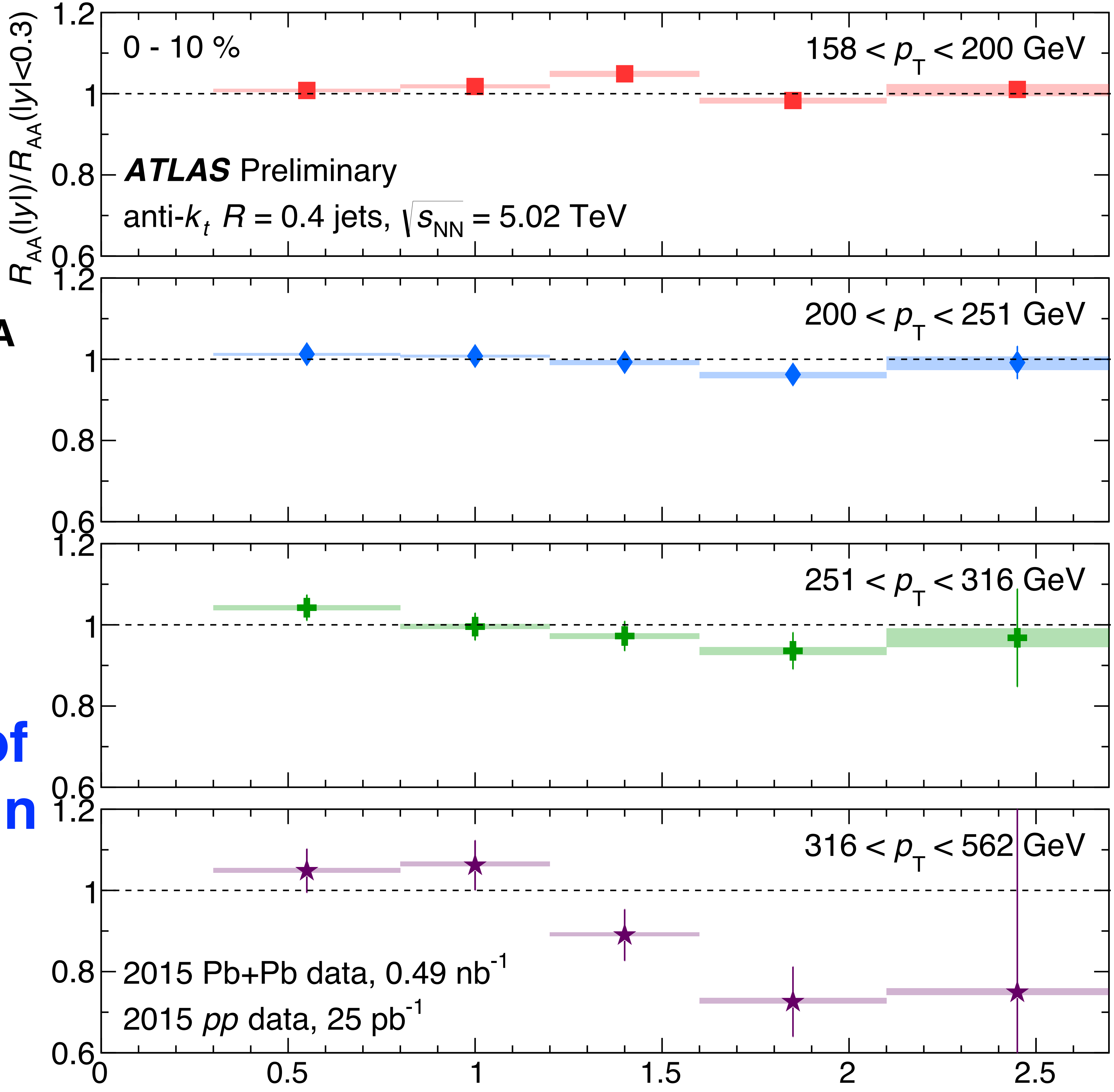
- **Guark and gluon fraction changes with rapidity and $p_T$ with more quarks at forward rapidity which should be quenched less.**

➡ **higher $R_{AA}$**

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

# $R_{AA}$ vs. rapidity

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

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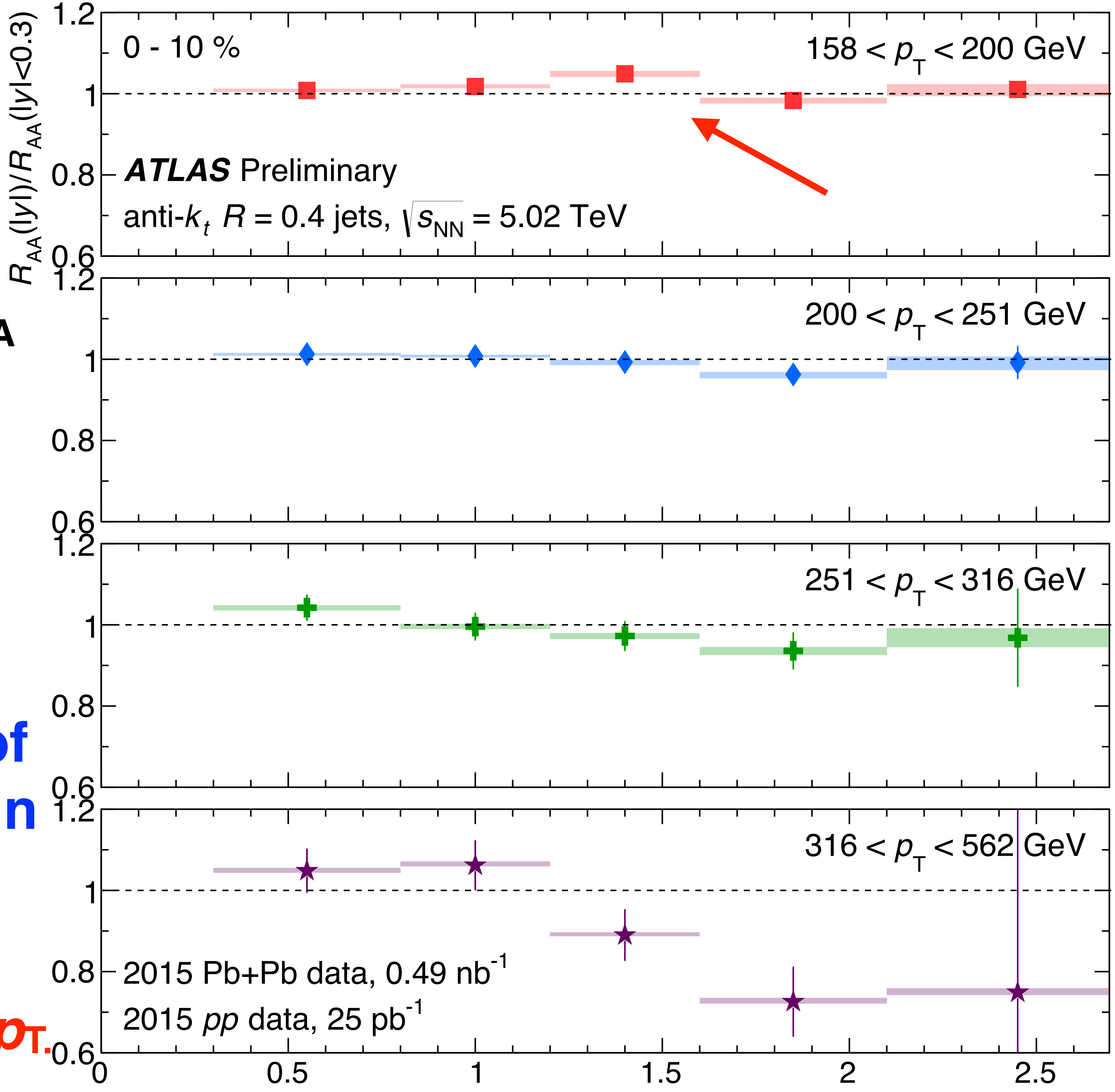


**ATLAS-CONF-2017-009**

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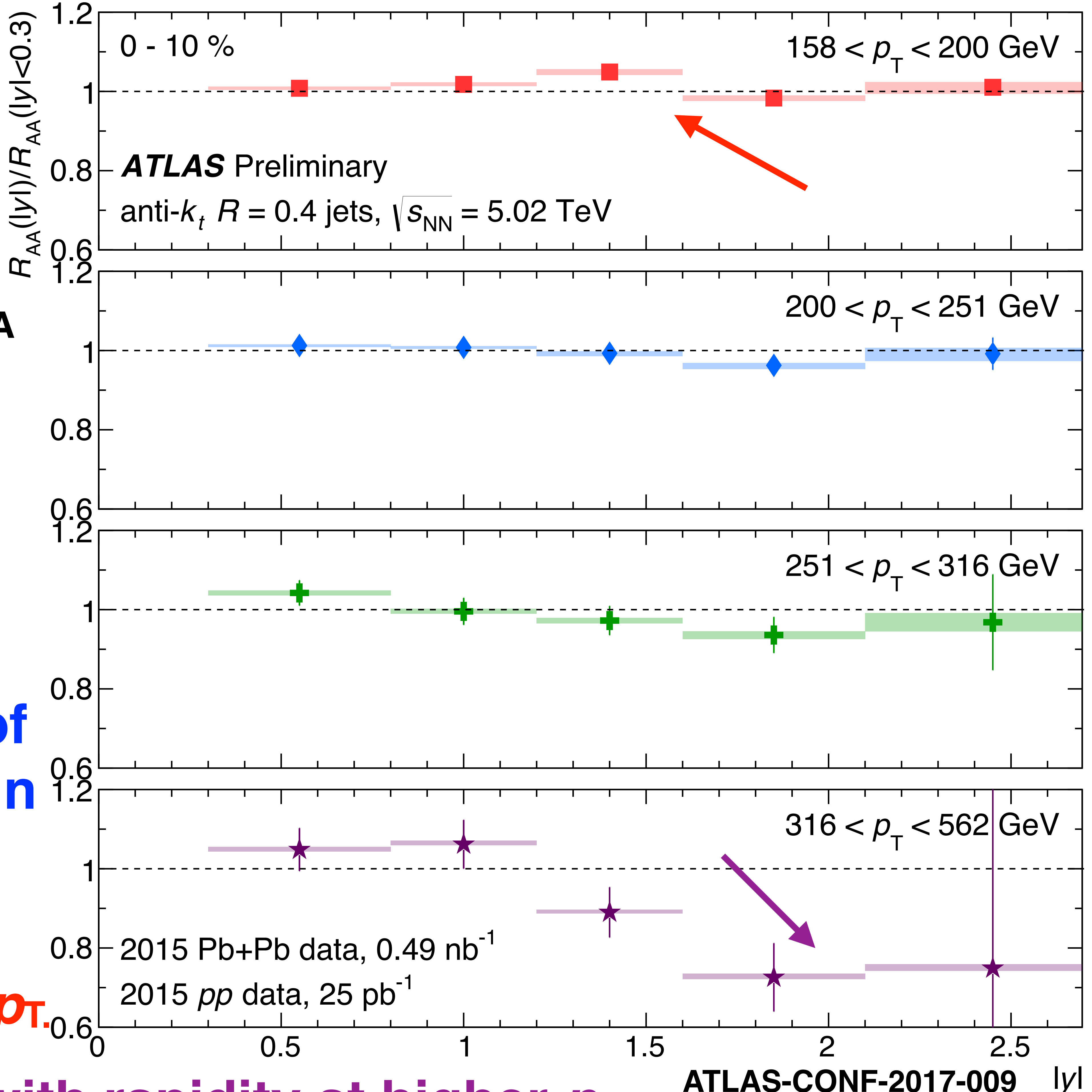


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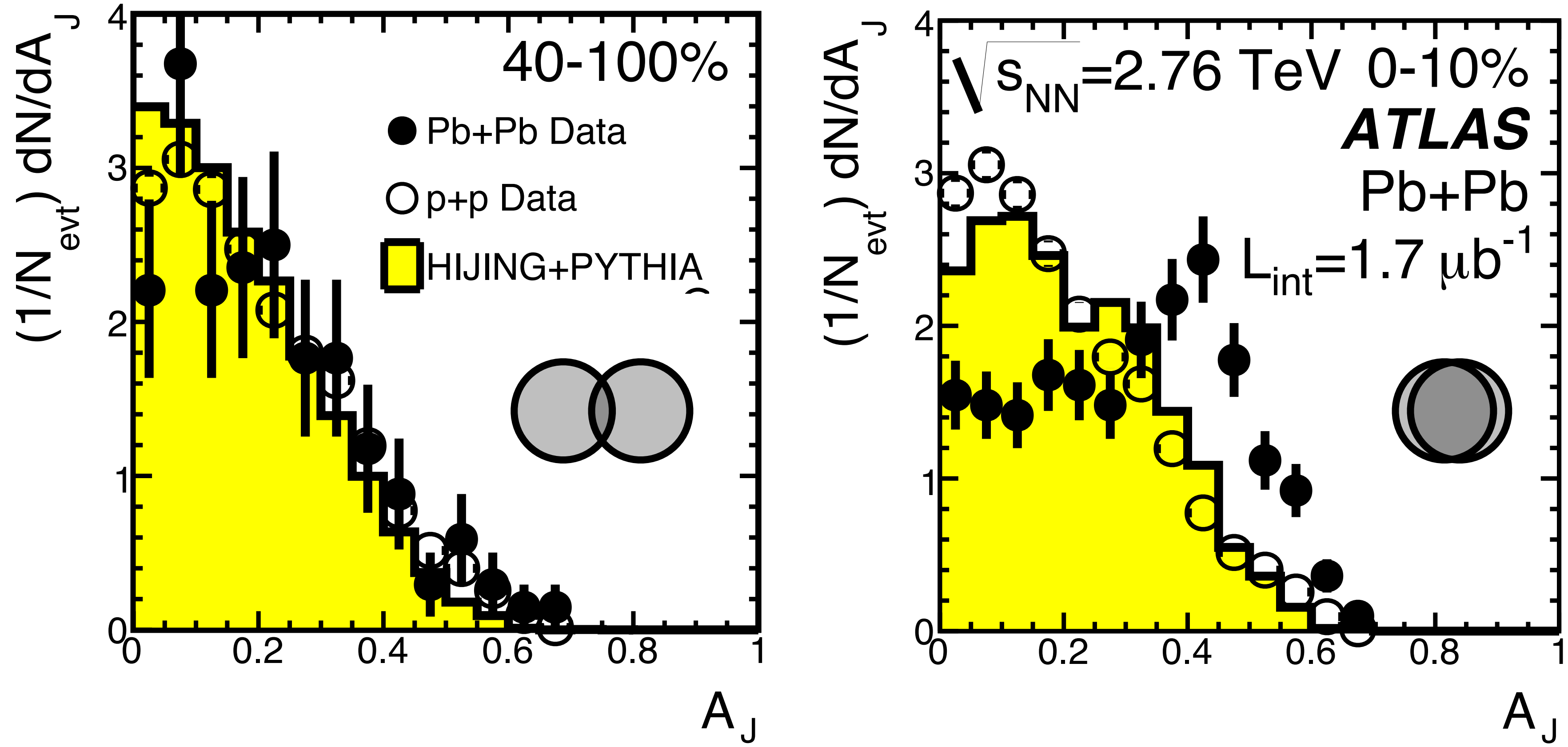
  - **Large cancelation of systematics in ratio.**
- **$R_{AA}$ is flat with rapidity at low $p_T$.**
- **$R_{AA}$ decreases with rapidity at higher $p_T$.**

**ATLAS-CONF-2017-009**

# Dijet asymmetry

- **ATLAS observed an asymmetry in dijets ($\sqrt{s_{NN}}$ =2.76 TeV)**
  - ➡ **Dijets are more asymmetric in Pb+Pb collisions when compared to MC and *pp***




**PRL 105 (2010) 252303**

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

$E_{T1} > 100$ GeV

$E_{T2} > 25$ GeV

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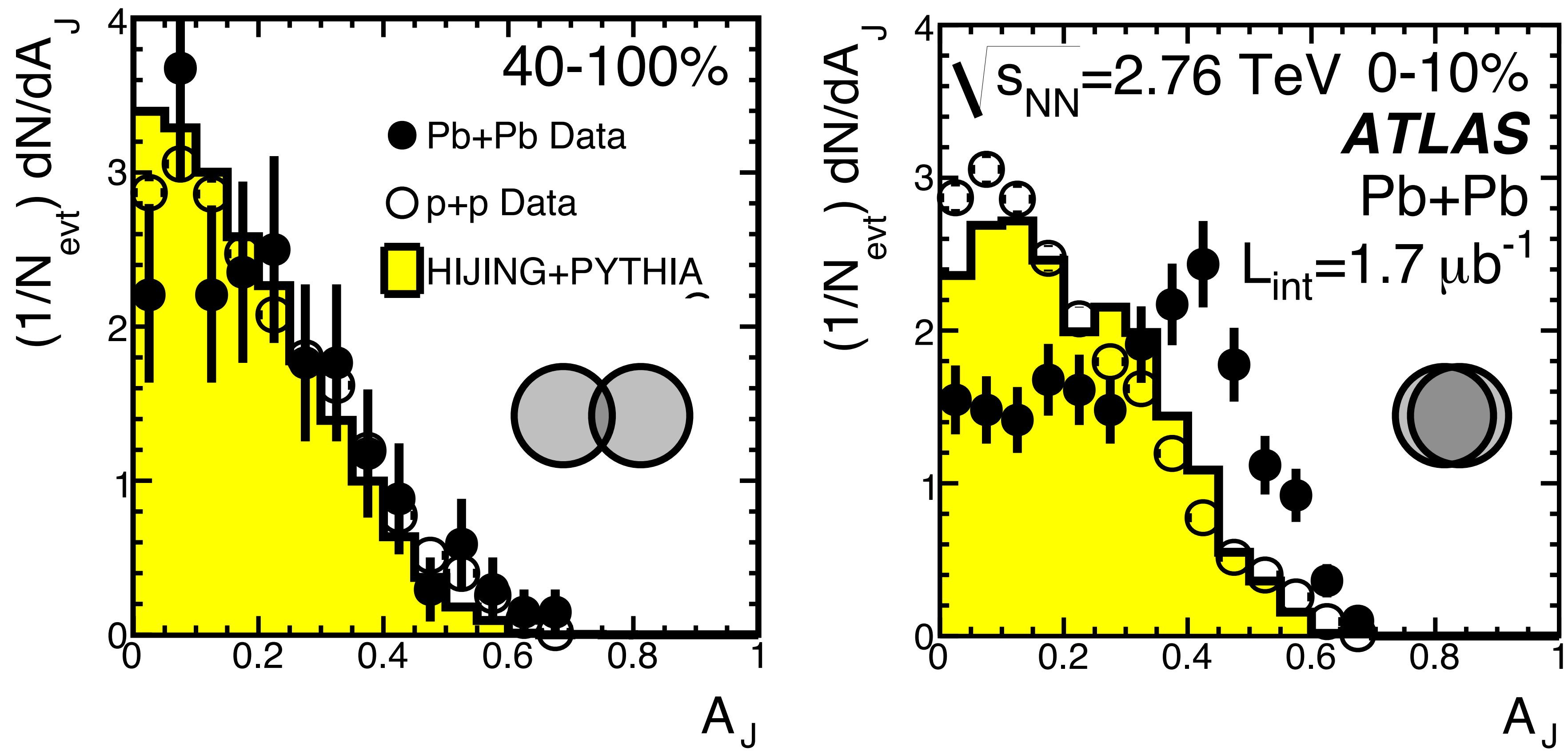


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$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

$$E_{T1} > 100 \text{ GeV}$$

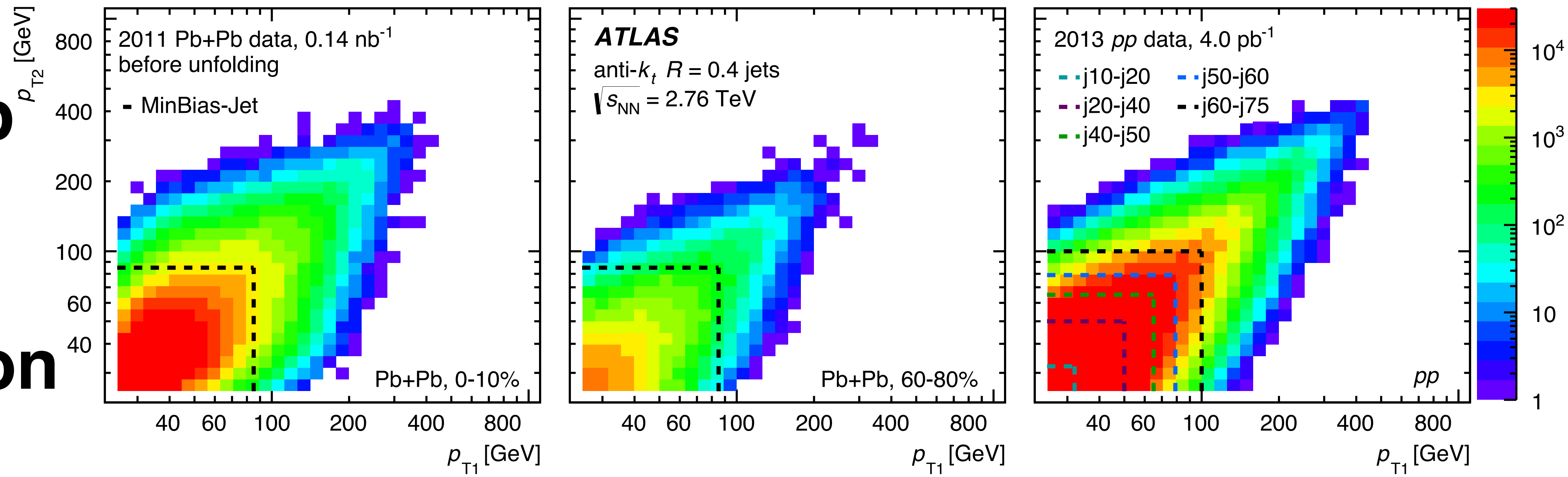
$$E_{T2} > 25 \text{ GeV}$$

► ***Includes smearing effects from the detector resolution***

- ***New* measurement is unfolded and has better statistics that allows for a leading jet $p_T$ dependence.**

# Dijet pair selection

- **Two highest jets with $p_T$ > 25 GeV with $\Delta\phi > 7\pi/8$**
  - ➡ **After unfolding $p_{T1}$ > 100 GeV**
- **Fill Pb+Pb and *pp* 2D $p_{T1}/p_{T2}$ distribution**



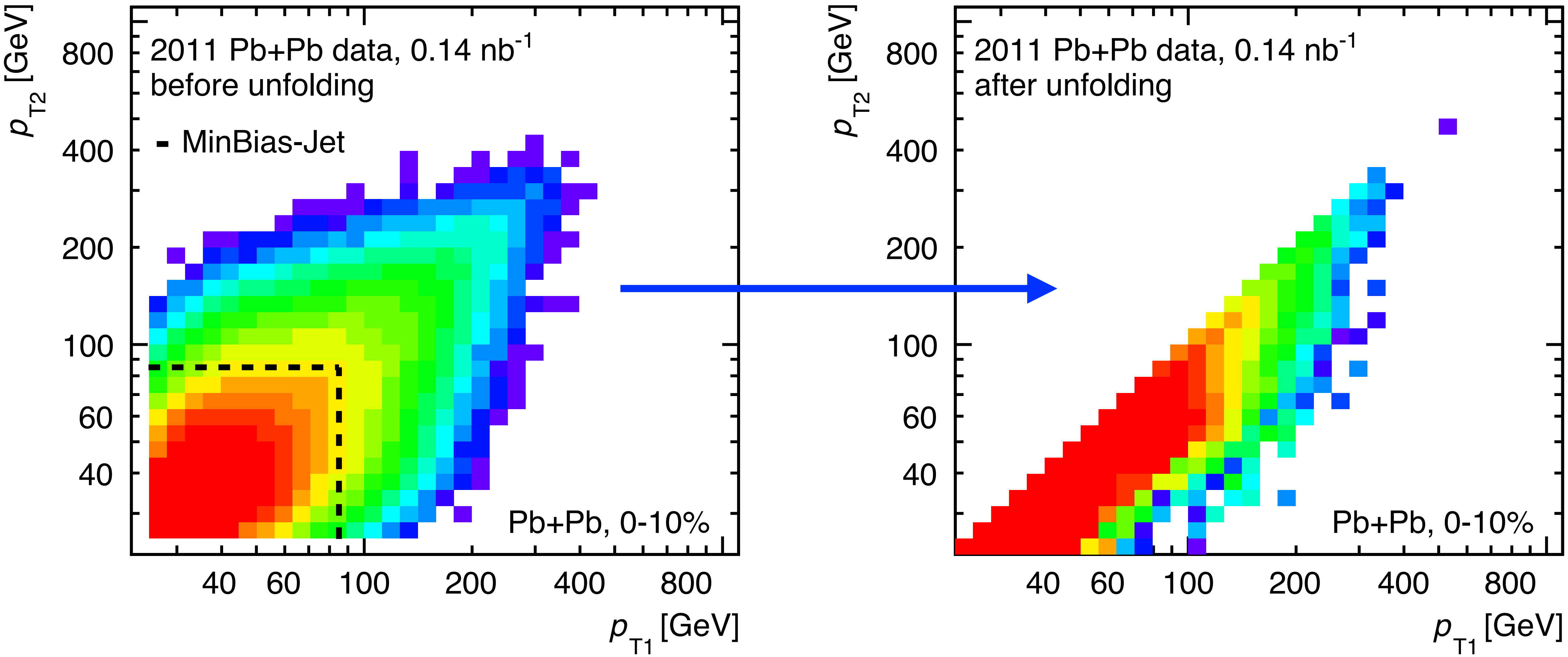

  - ➡ **Symmetrized to account for bin migration across the diagonal when unfolding**
- **Remove combinatoric background from uncorrelated dijets**
  - ➡ **Estimated with uncorrelated jets ($\Delta\Phi < \pi/2$) where the shape is influenced by residual harmonic flow**

# Effect of unfolding

- **Unfolded using 2D Bayesian unfolding to account for bin migration simultaneously in $p_{T1}$ and $p_{T2}$.**

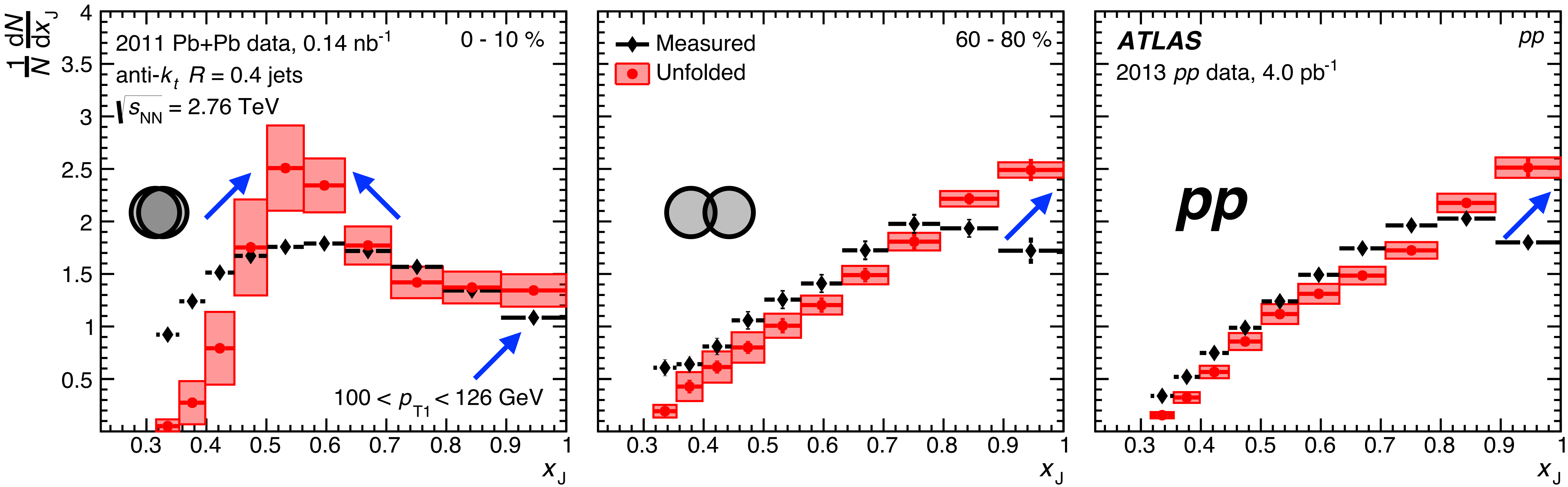
➡ **Filled response symmetrically from MC with same UE as the data in $p_{T1}^{true}$, $p_{T2}^{true}$, $p_{T1}^{reco}$, and $p_{T2}^{reco}$**

**2D distribution *before* unfolding** | **2D distribution *after* unfolding**



# Effect of unfolding

- **Project 2D distribution into $x_J$ distribution**

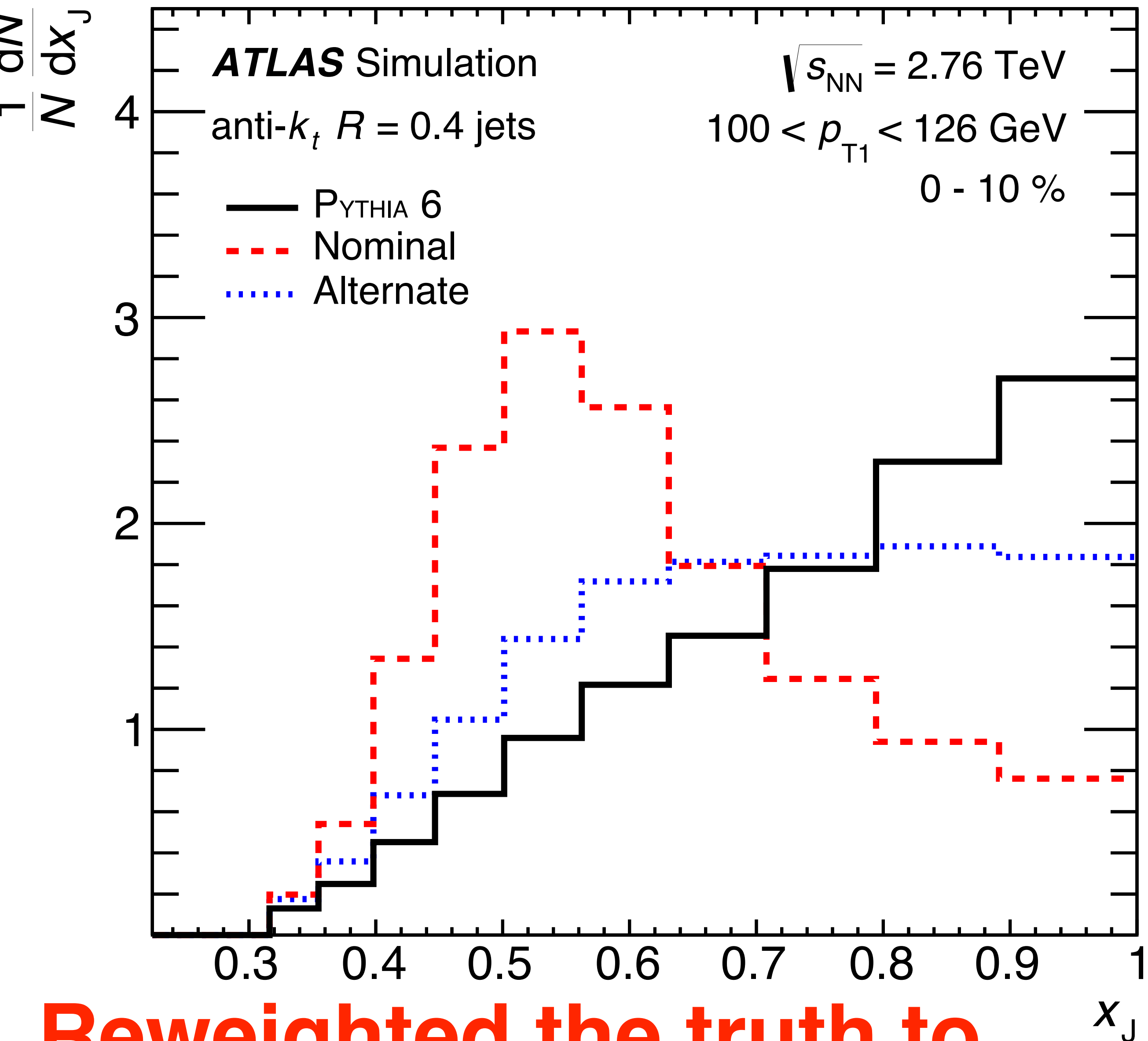


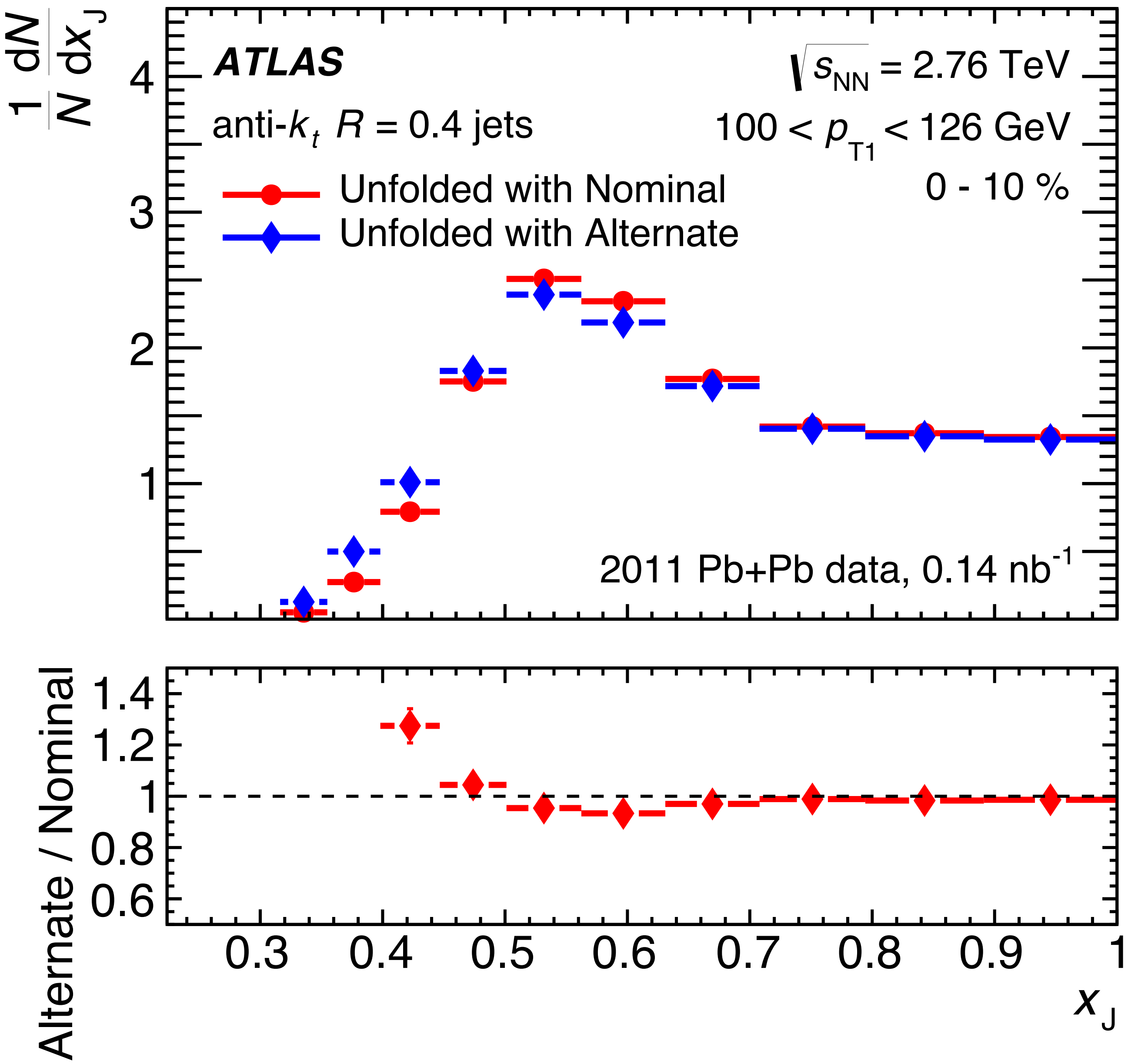

- **Moves jets in pp and peripheral to more balanced configurations and jets in central to both more balanced and asymmetric configurations at $x_J$ ~0.5**

► ***Unfolded result can be compared directly to theory***

# Re-weighting Truth (prior)

**MC truth is from pythia**




**Reweighted the truth to look more like the data for the nominal response**

**Different reweighting for systematic**

# Re-weighting Truth (prior)

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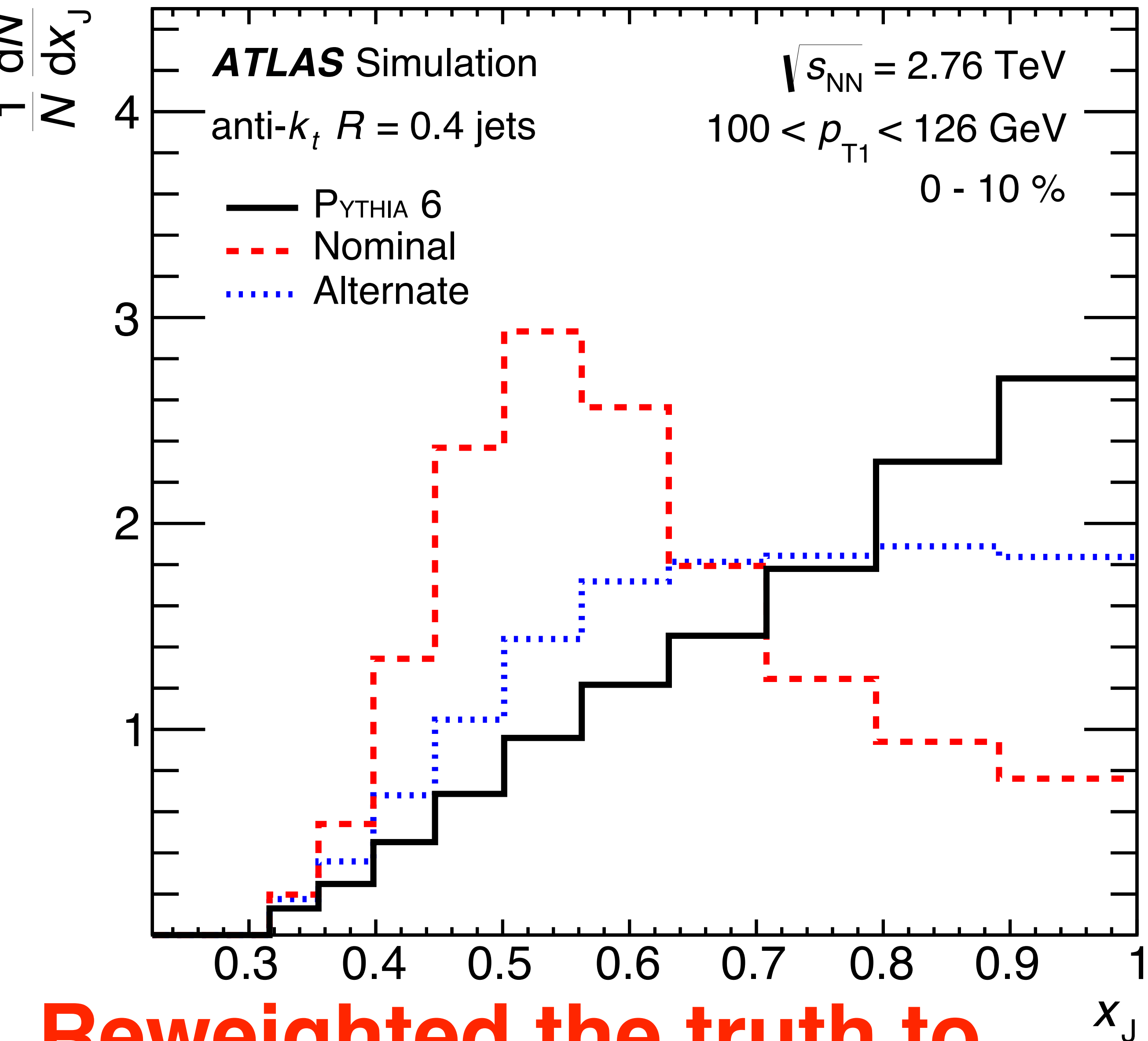
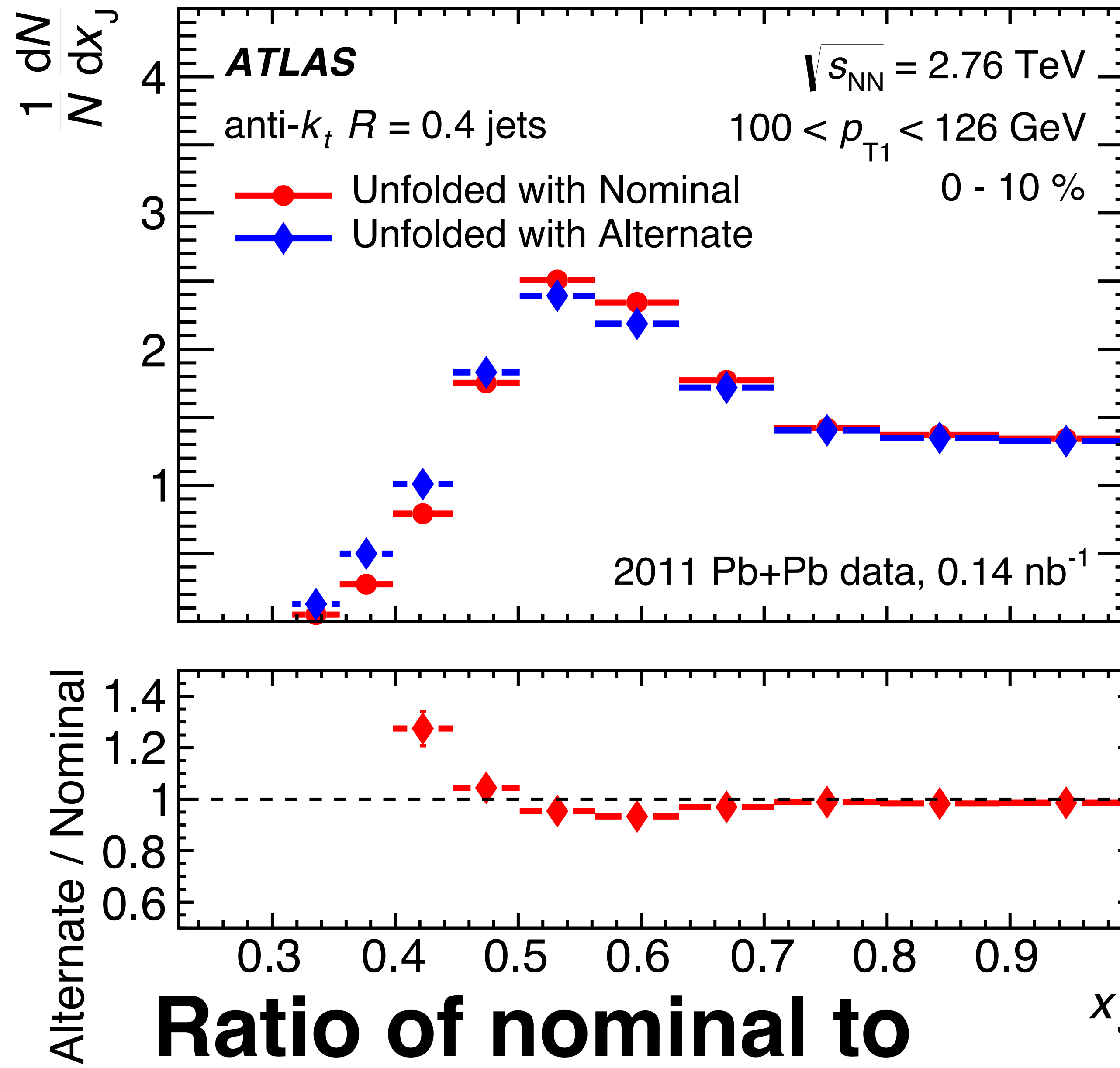
**Unfolded data with nominal and systematic response**




**Reweighted the truth to look more like the data for the nominal response**

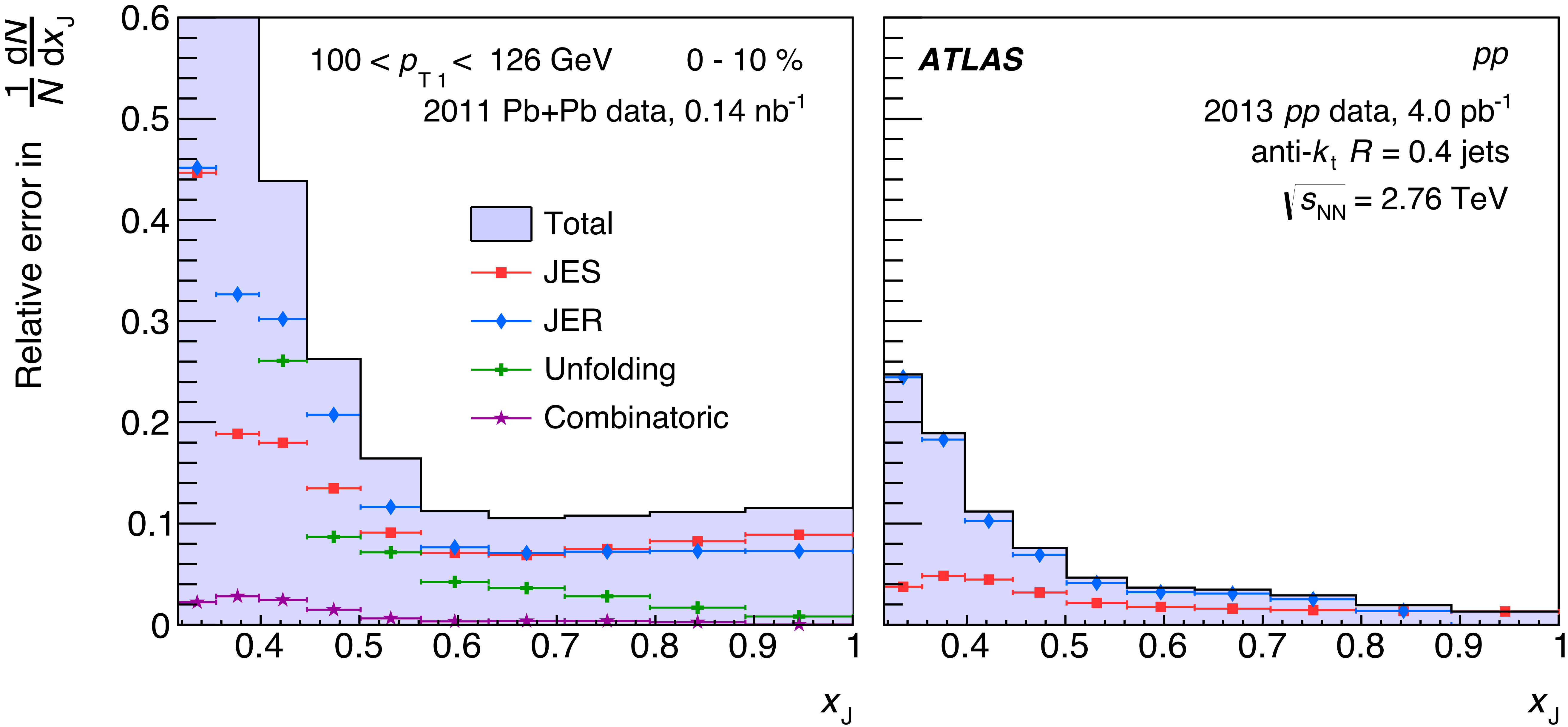
**Different reweighting for systematic**

**Ratio of nominal to systematic unfolded result is reweighting systematic**

# $x_J$ systematics uncertainties

- **Uncertainties on JES, JER, combinatoric, and unfolding**

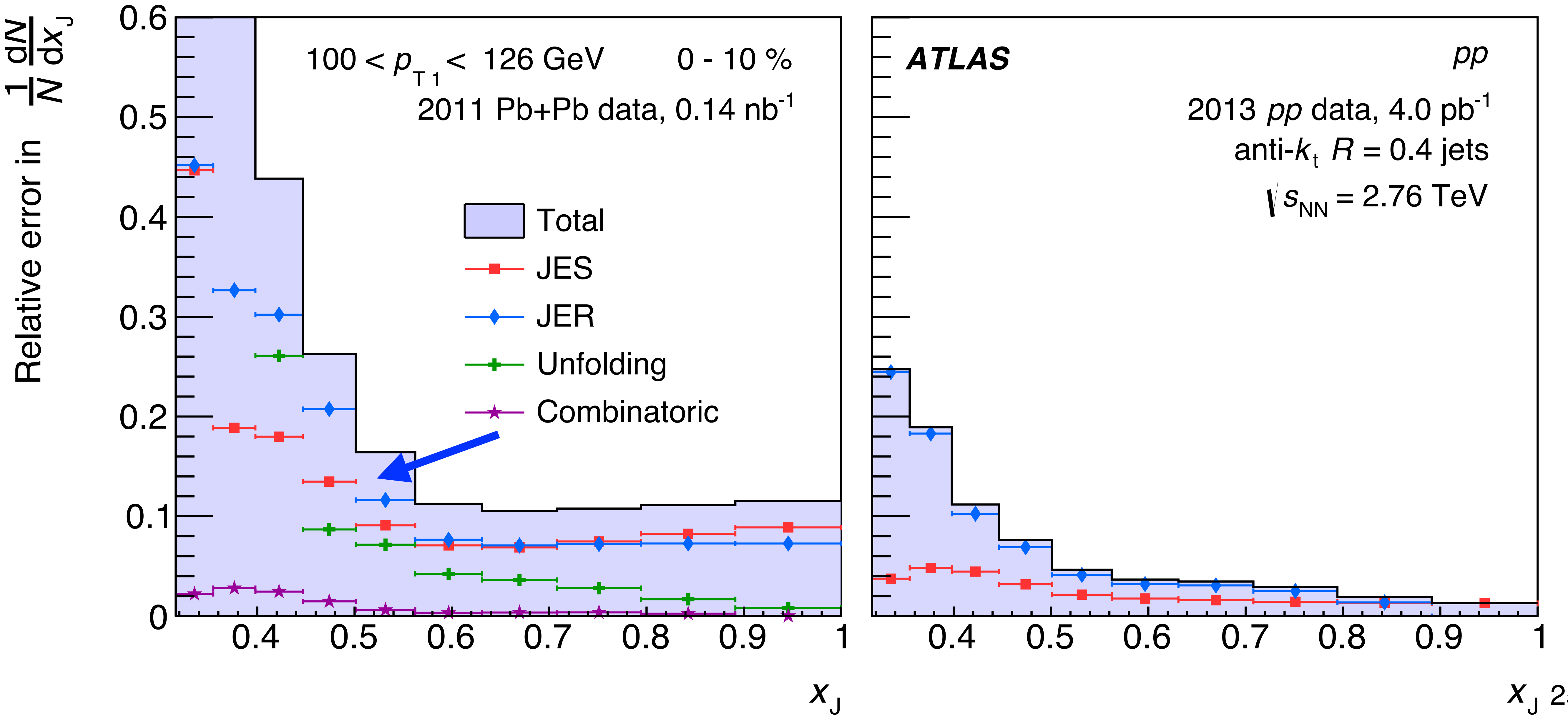
➡ **Rebuild response with a systematically varied relationship between true and reconstructed jet kinematics**



# $x_J$ systematics uncertainties

- **Uncertainties on JES, JER, combinatoric, and unfolding**
- **JER is largest: 10% ($x_J$ ~1) and 15% ($x_J$ ~0.5) in central**

➡ **Dominant contribution from the UE which is described well in the MC sample (data overlay)**



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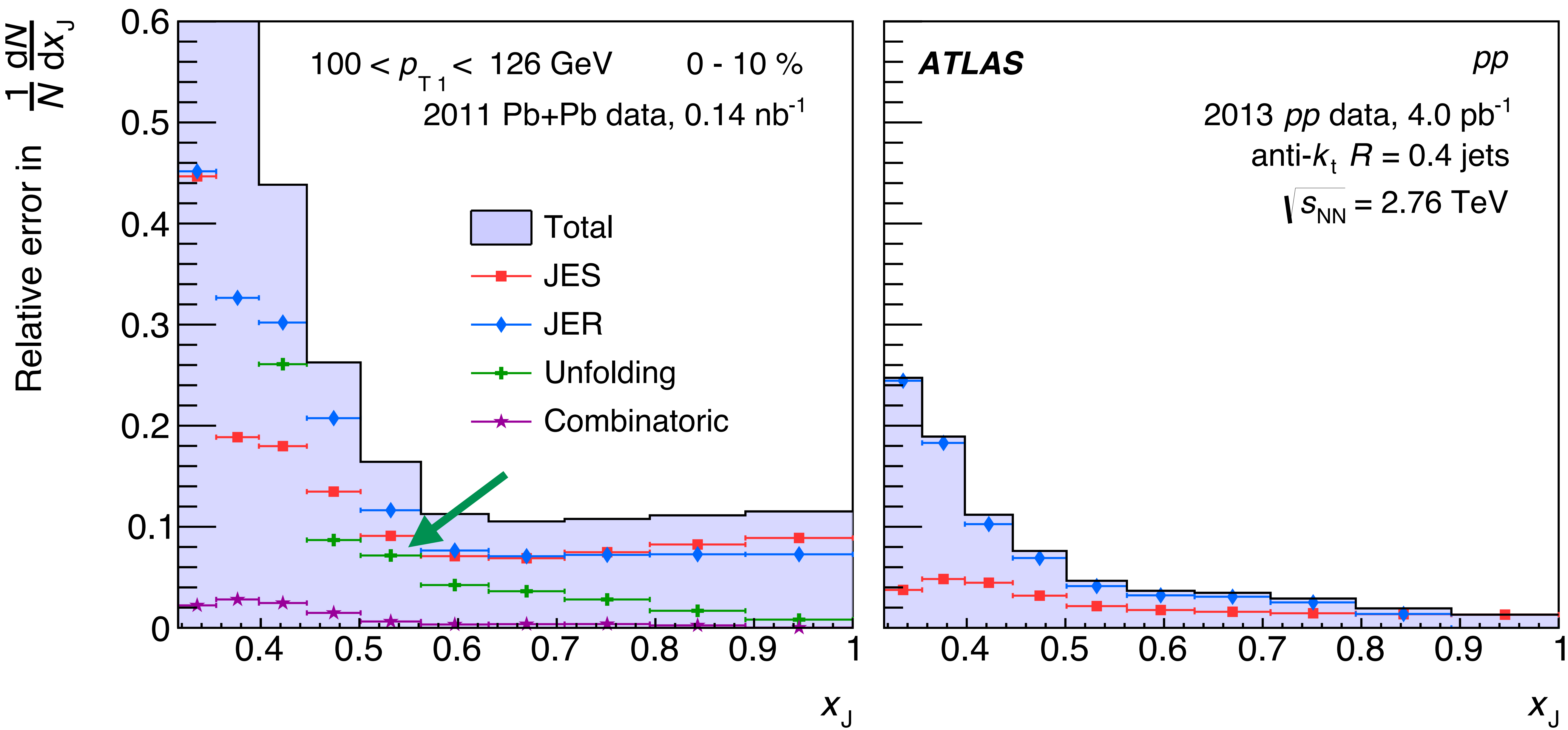
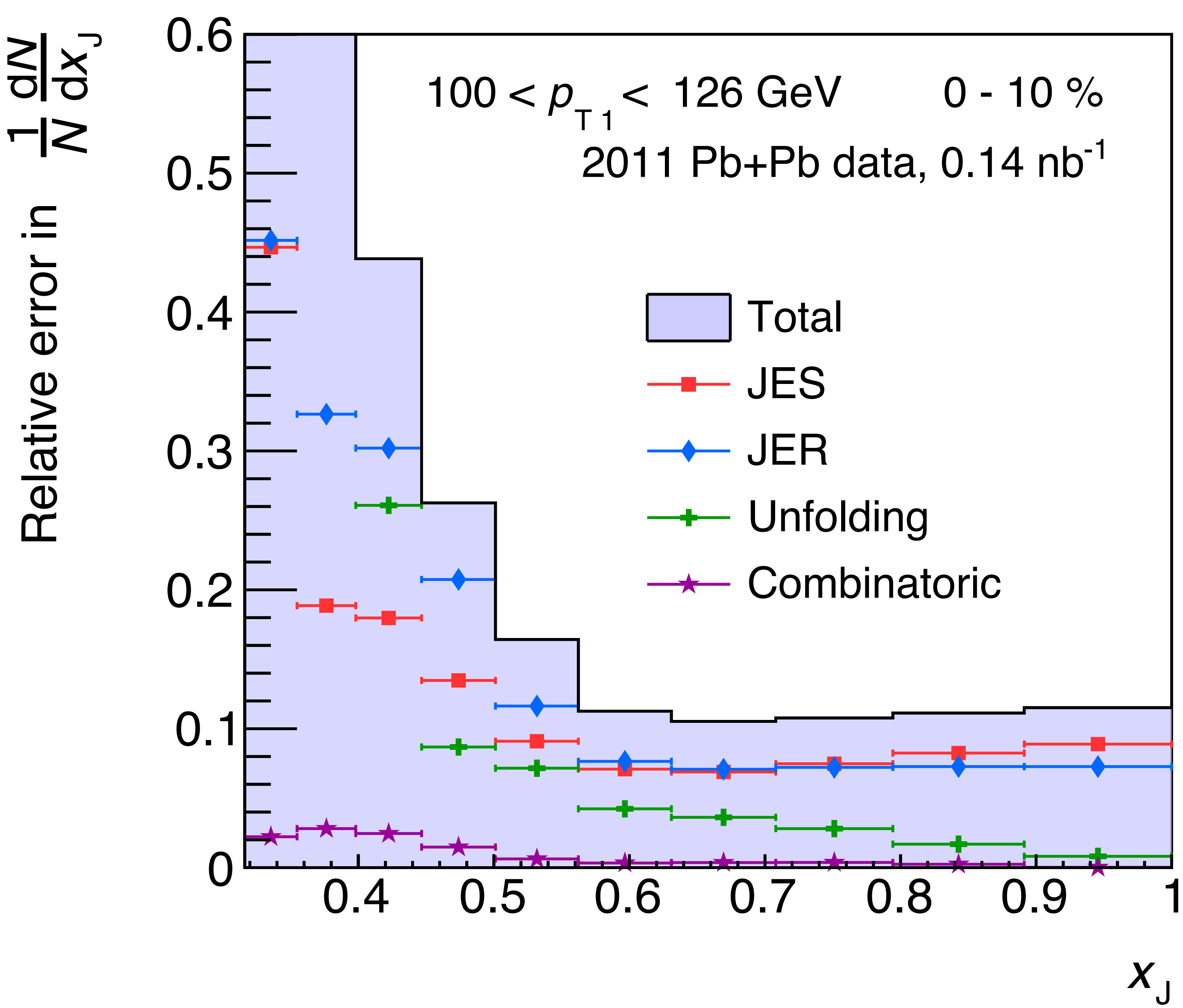
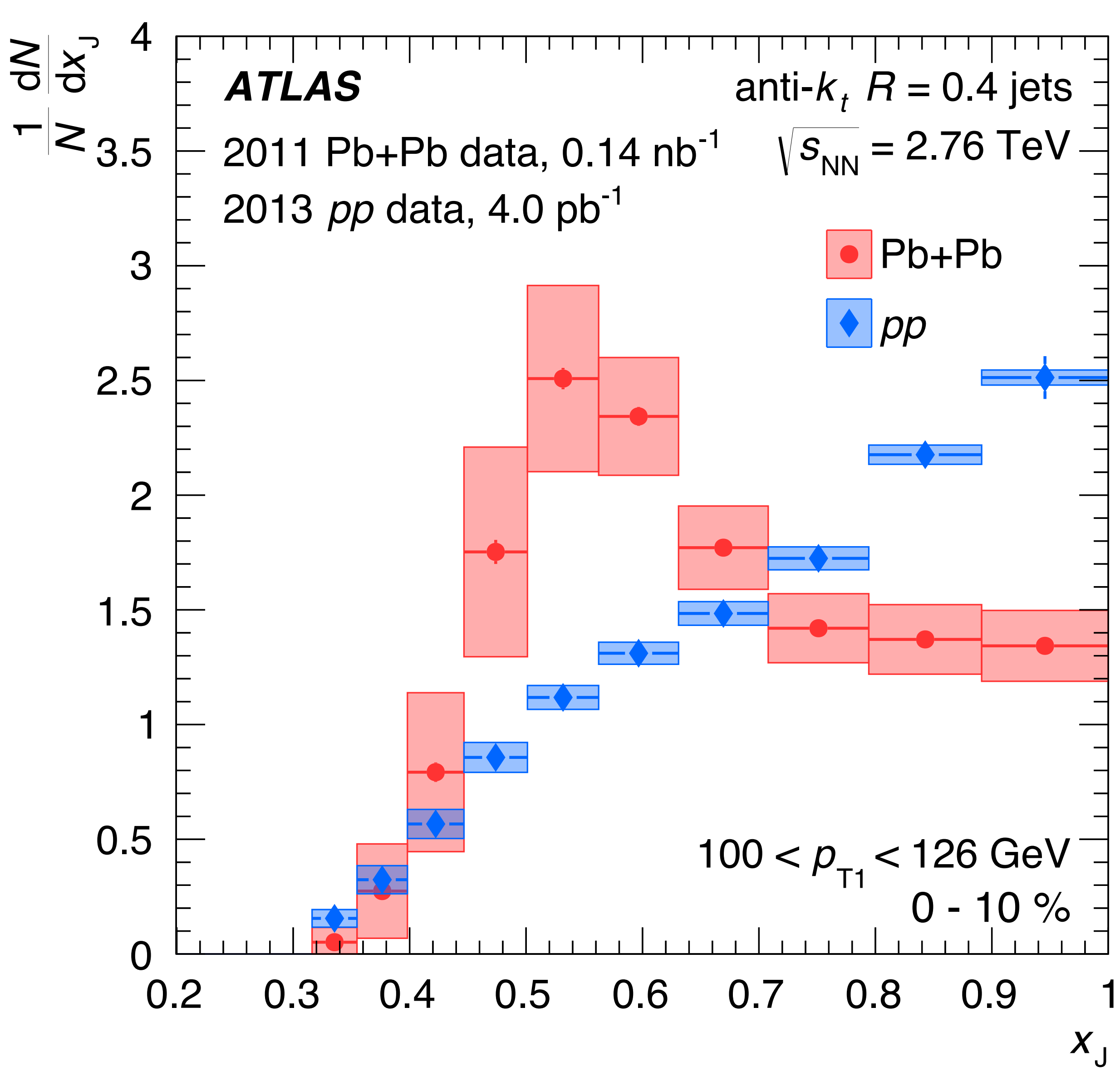
- **Unfolding as large as JER in central at lower $x_J$**



# $x_J$ systematics uncertainties

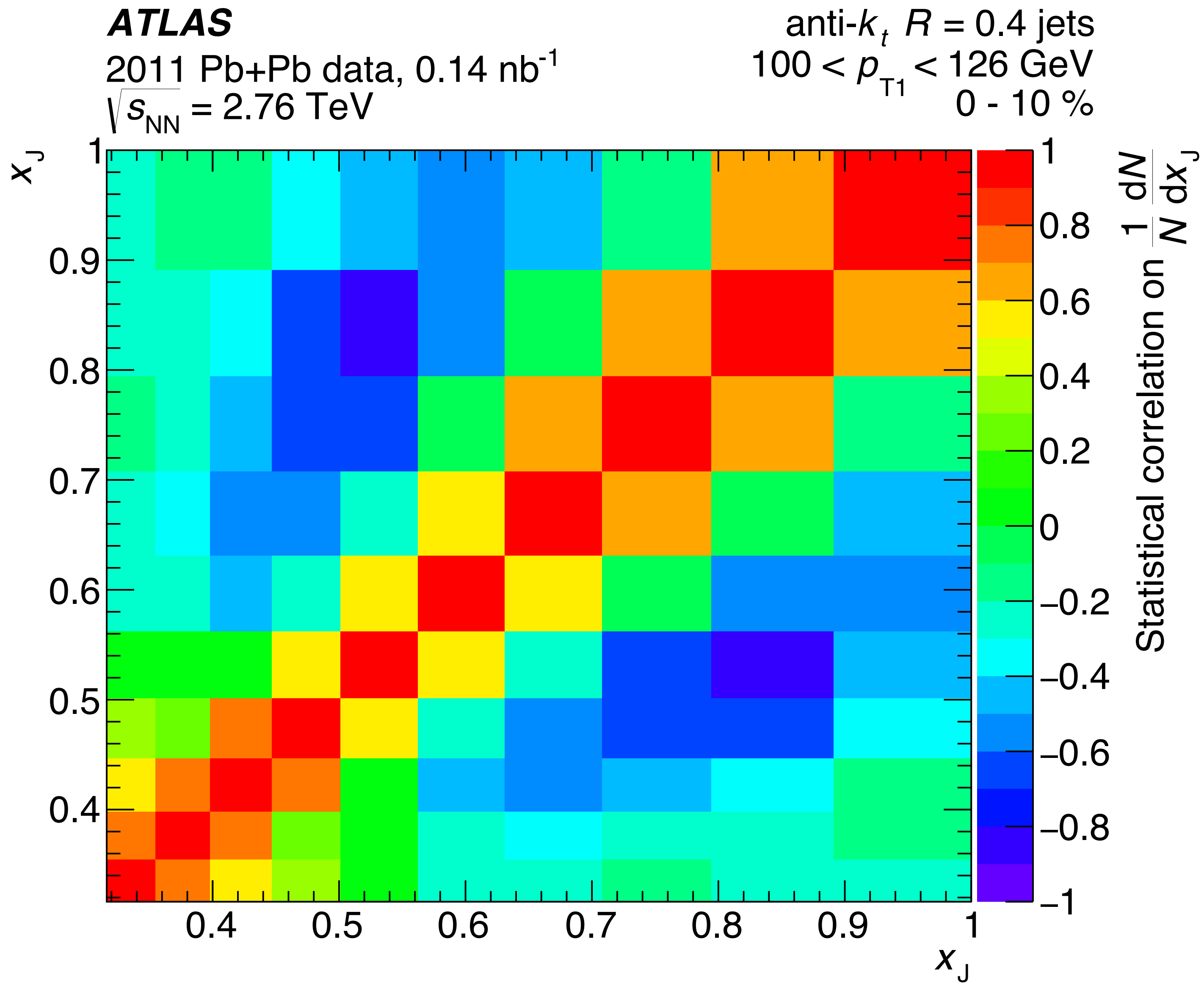
- **Uncertainties on the JES, JER, combinatoric, unfolding**
- **Systematics are correlated but because of the normalization the correlation is non-trivial and not always positive**

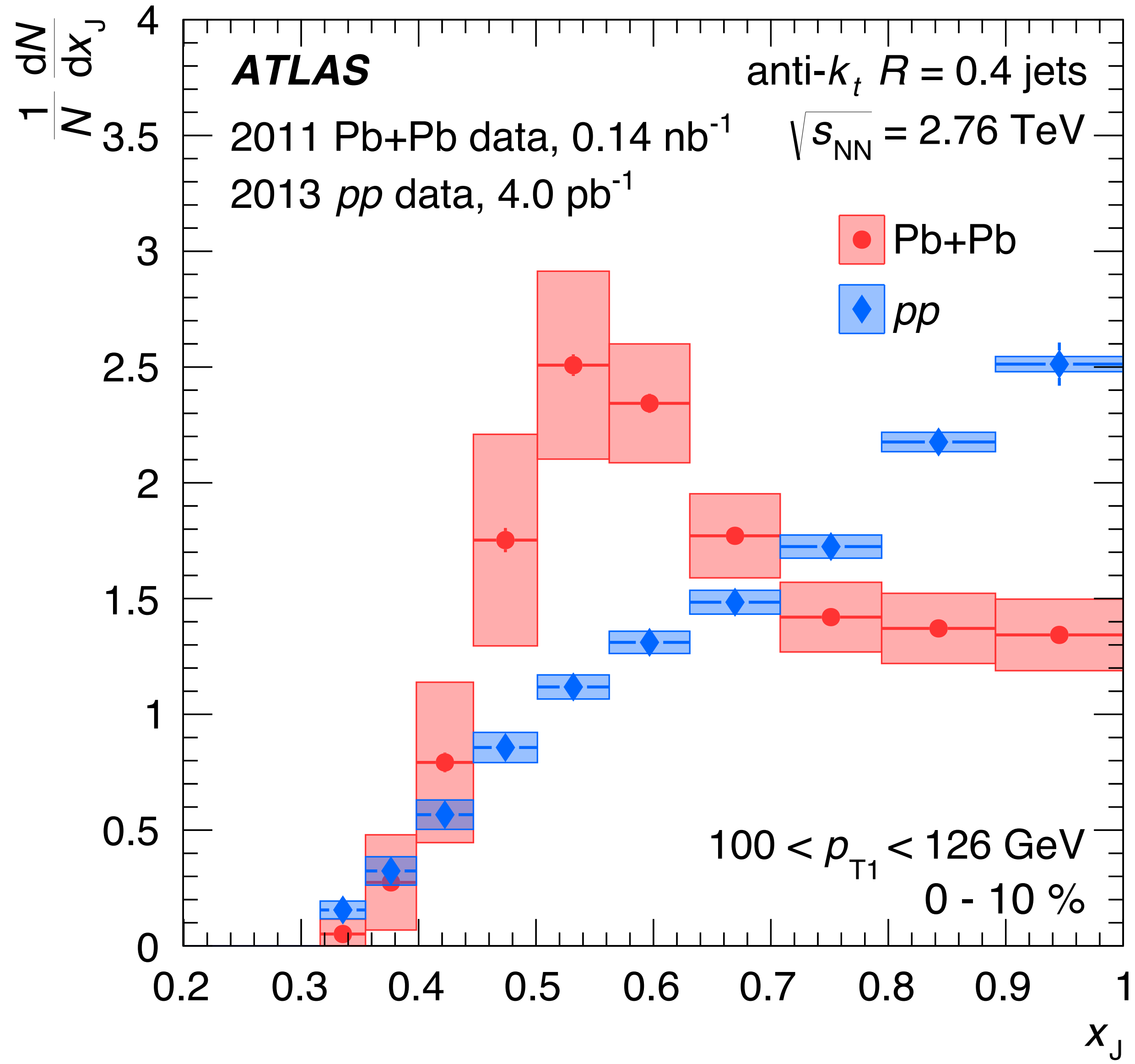


# $x_J$ statistical uncertainties

- **The statistical correlations were evaluated and included on the statistical error in the result**
- **Positive correlation along the diagonal but also some negative, anti-correlation in areas off the diagonal**

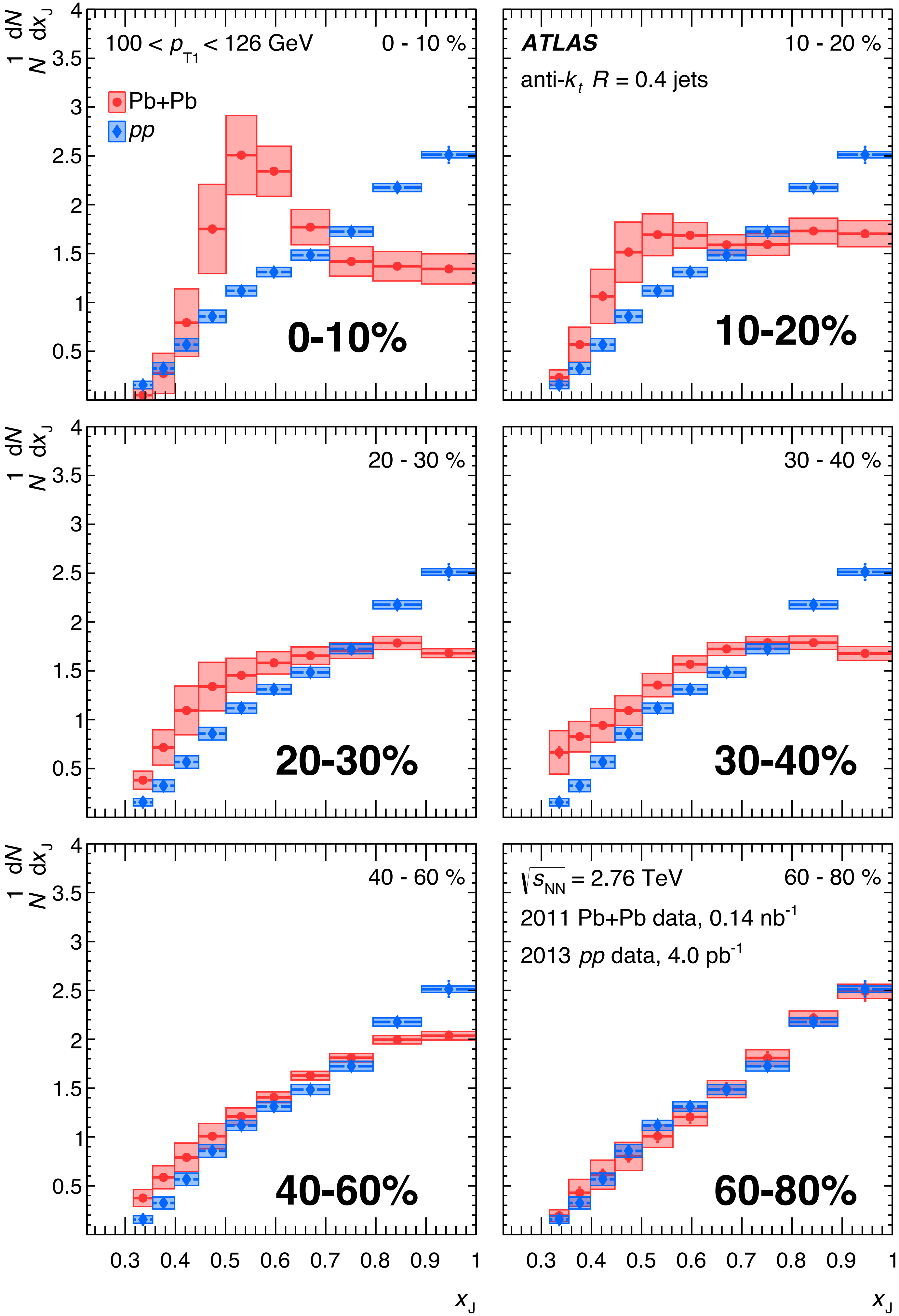


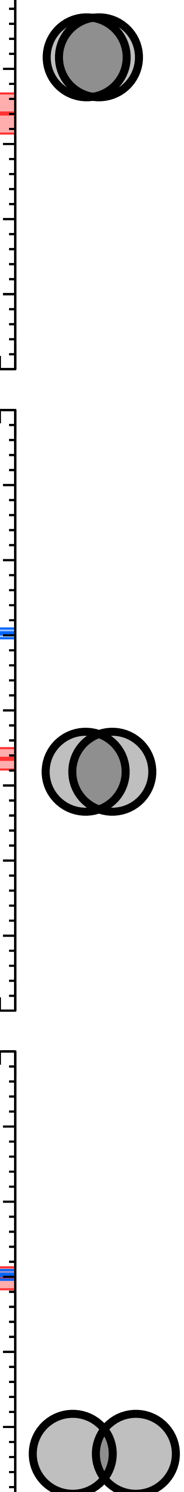



# $x_J$ distribution

**centrality dependence**

**$100 < p_{T1} < 126$ GeV**



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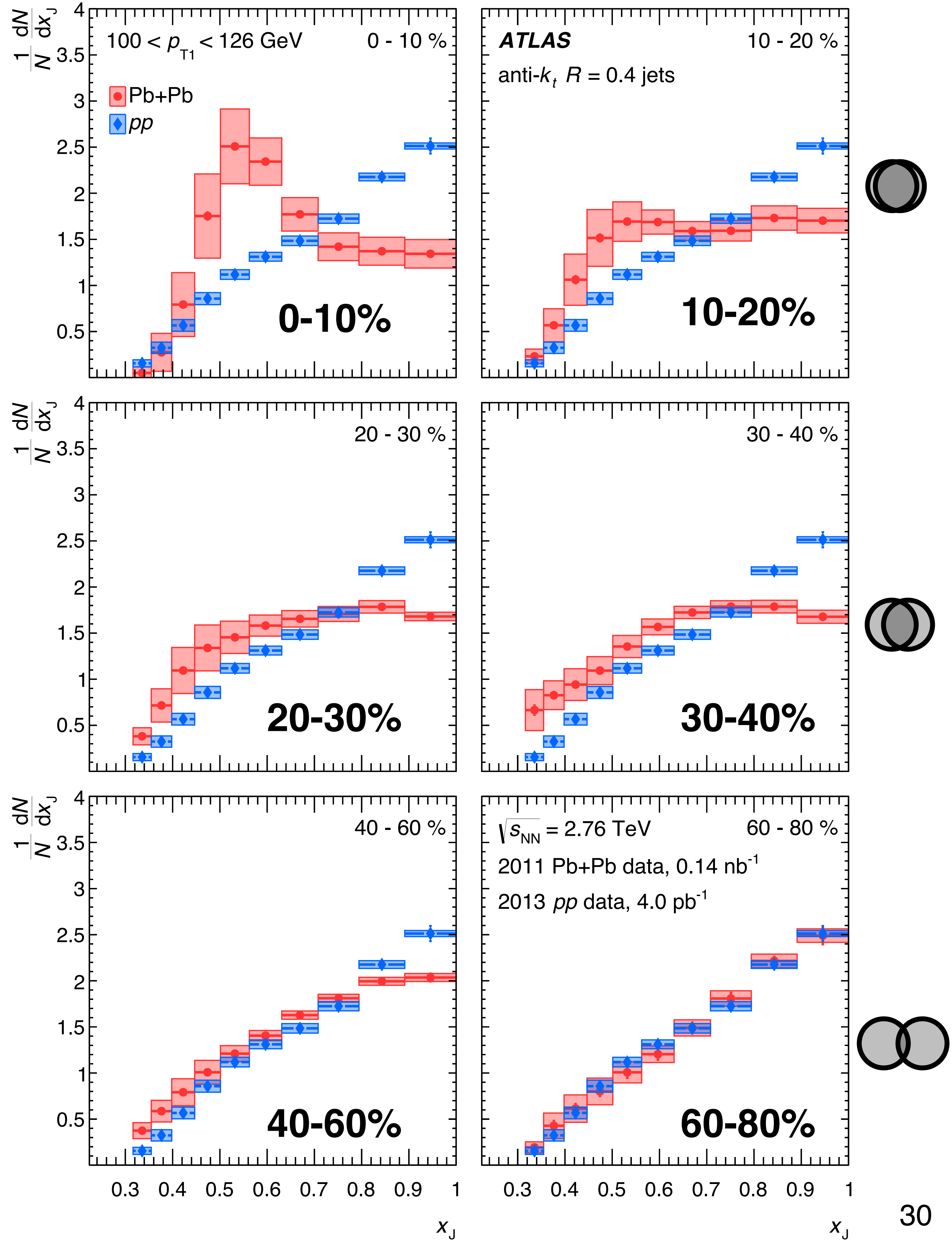
- **Pb+Pb more asymmetric in more central collisions**



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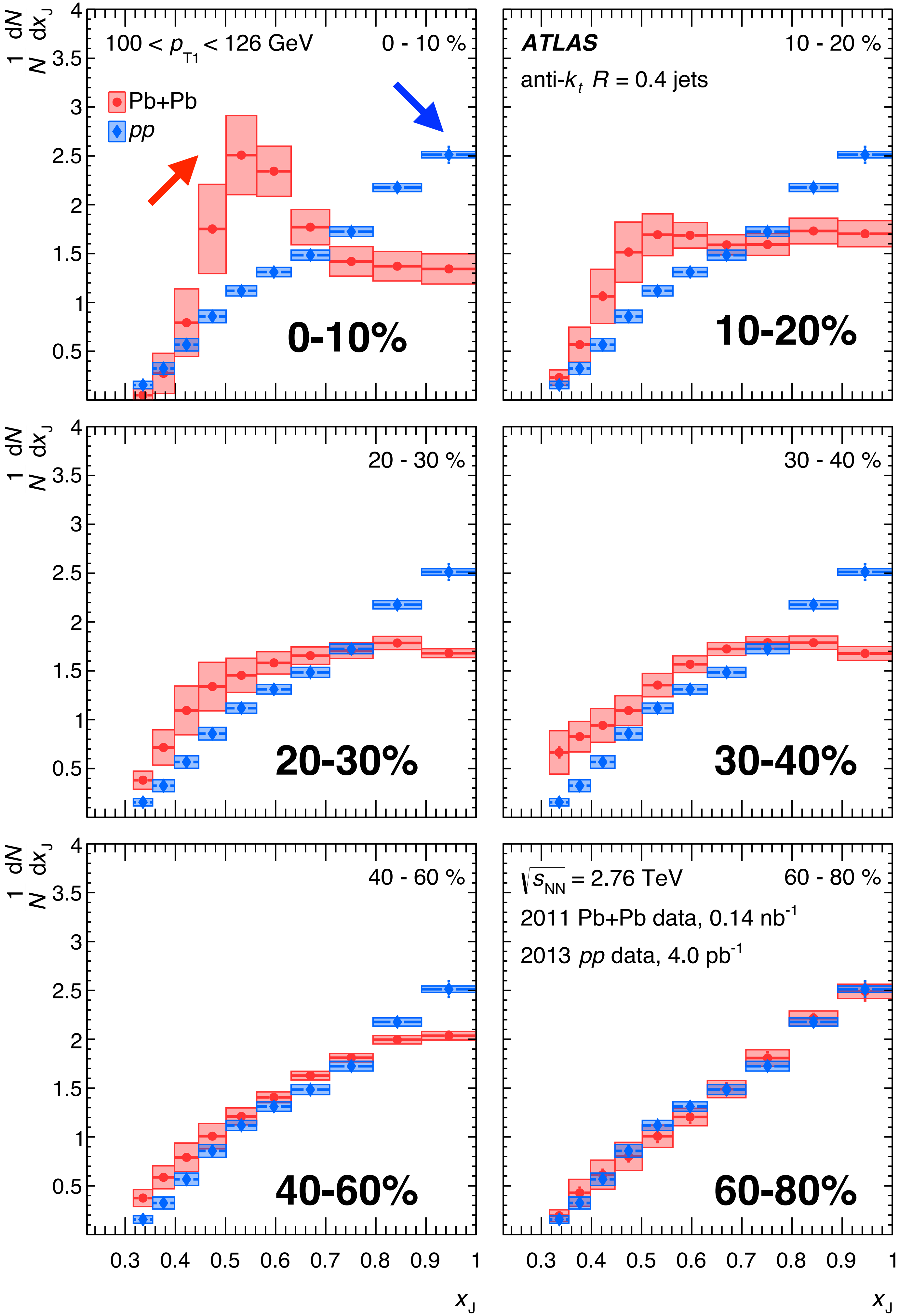
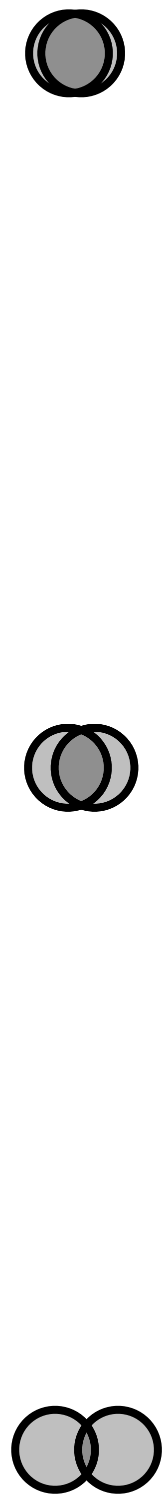
## centrality dependence

**$100 < p_{T1} < 126$ GeV**

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



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## centrality dependence

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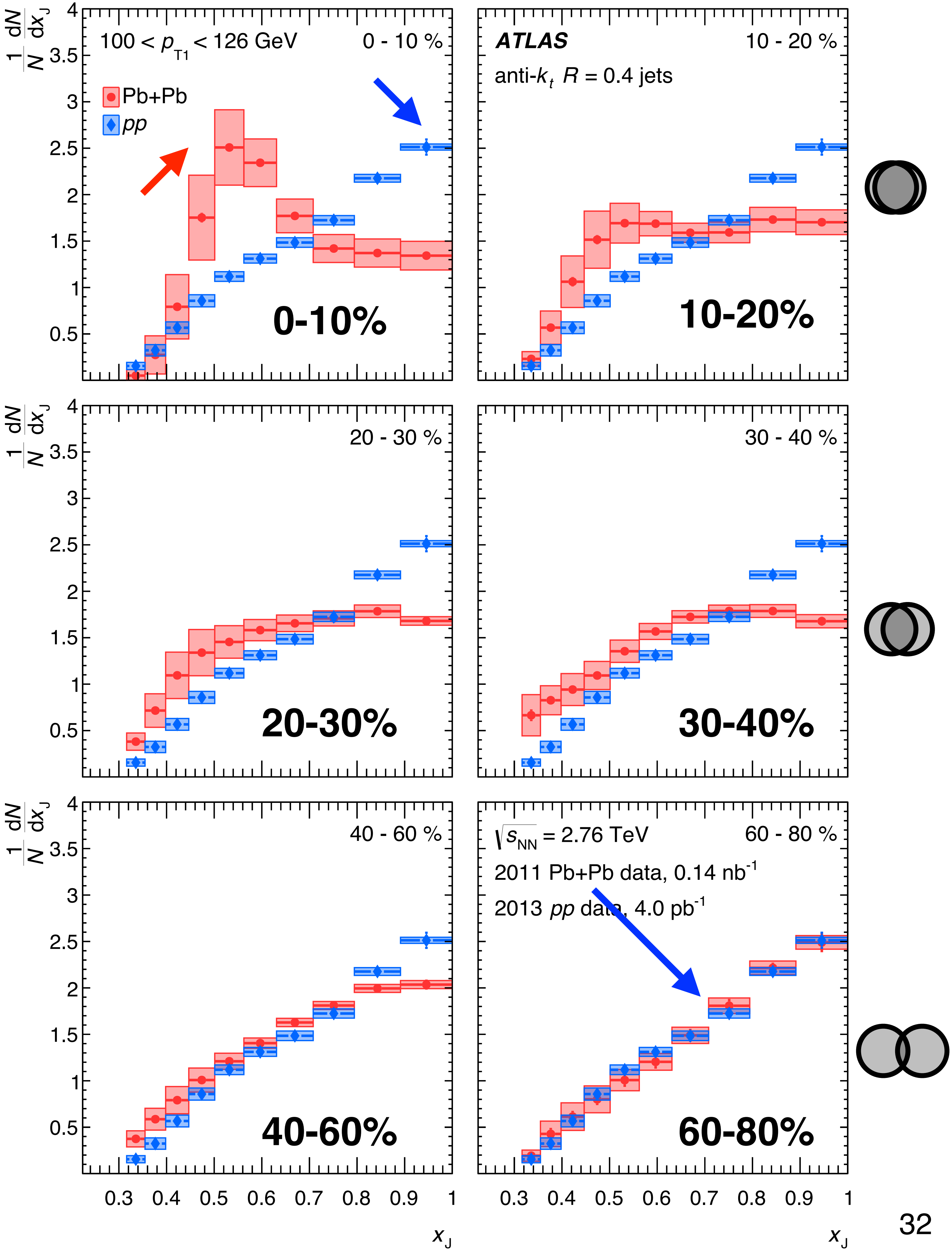
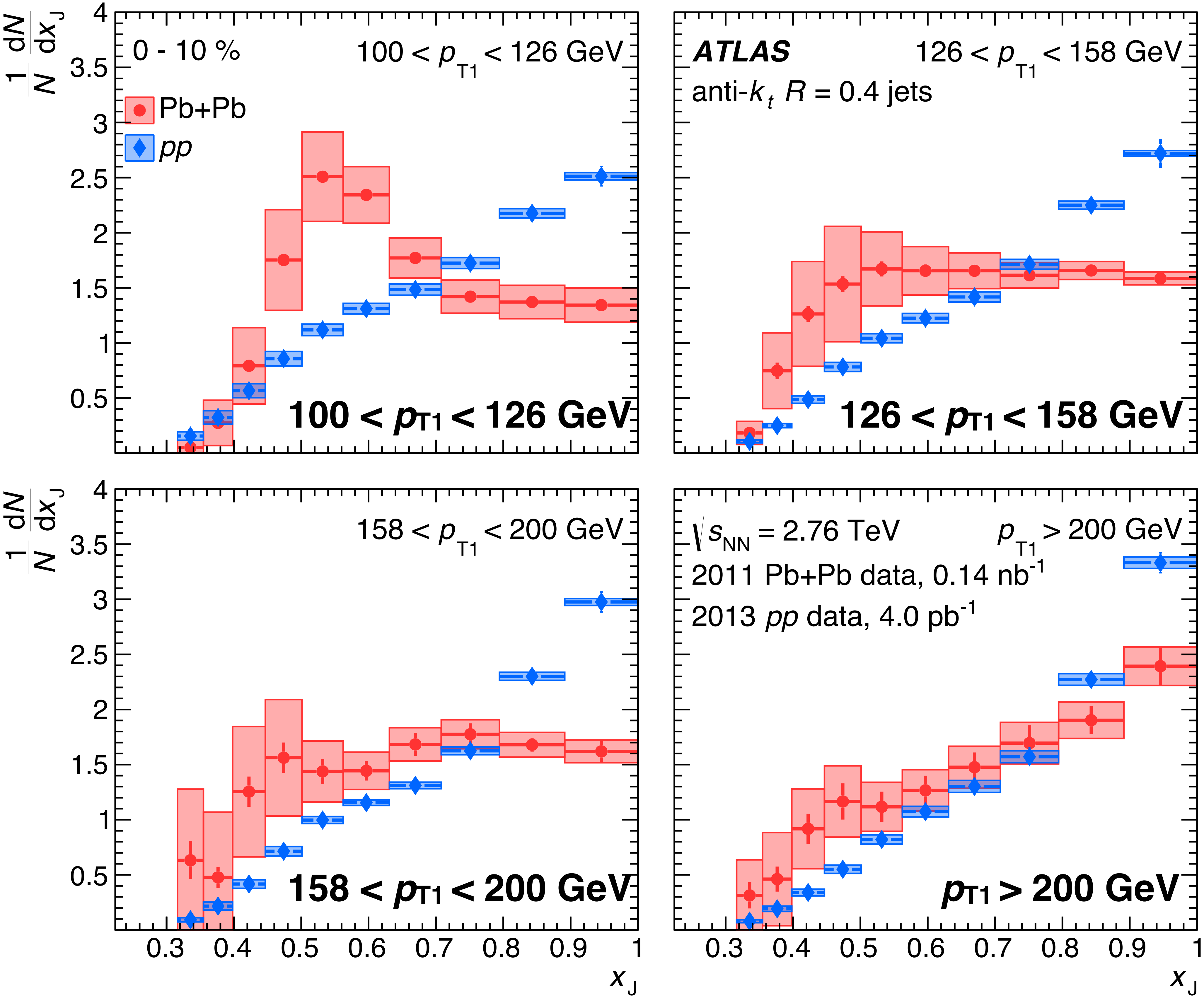
- Pb+Pb more asymmetric in more central collisions
- Most probable configuration for *pp* collisions is $x_J \sim 1$
- For central Pb+Pb collisions it is $x_J \sim 0.5$
- As Pb+Pb becomes more peripheral the distribution is like *pp*



# $x_J$ distribution

**$p_{T1}$ dependence**
**0-10%**



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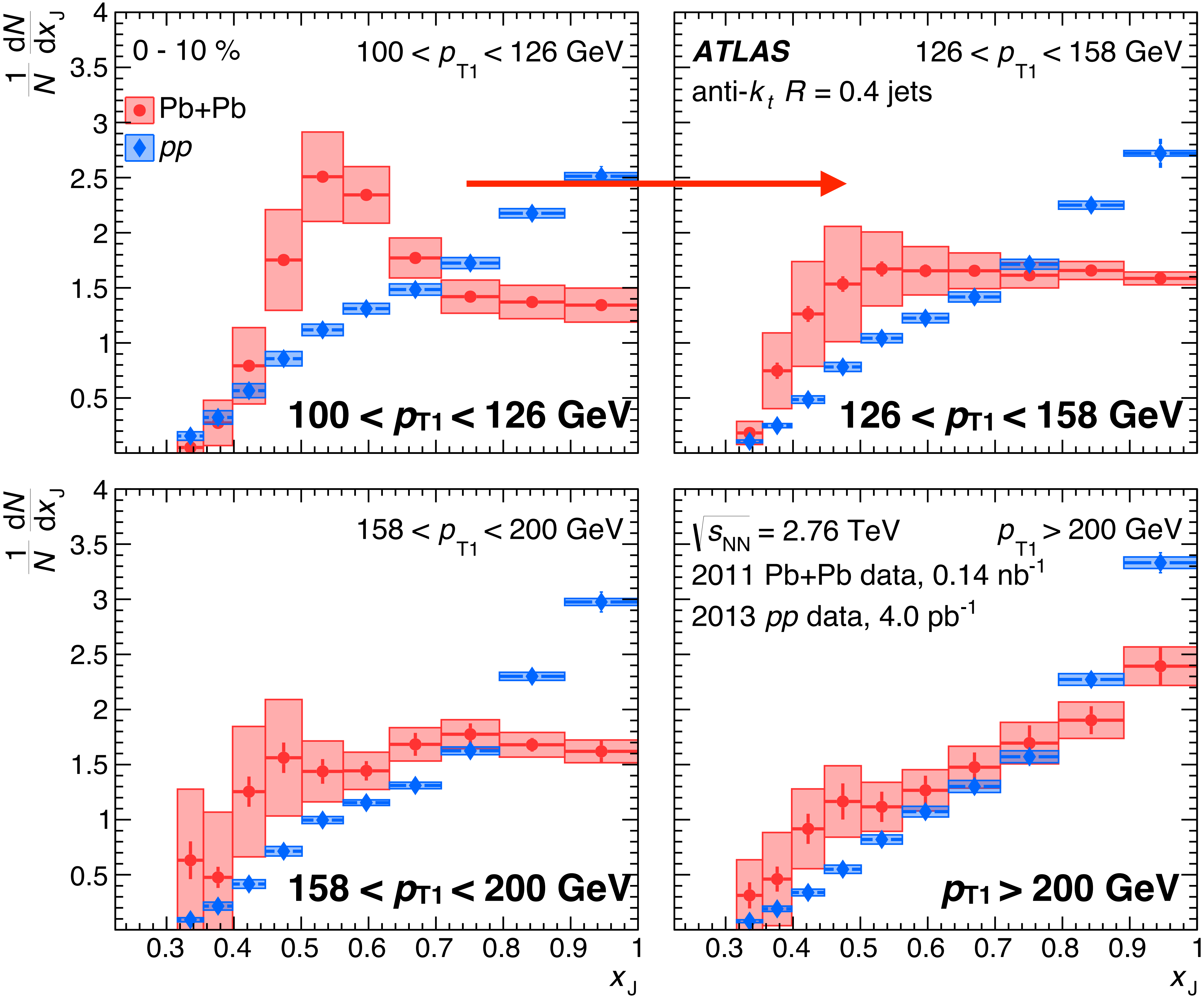


- **Drastic $p_{T1}$ dependence**

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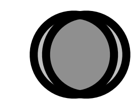

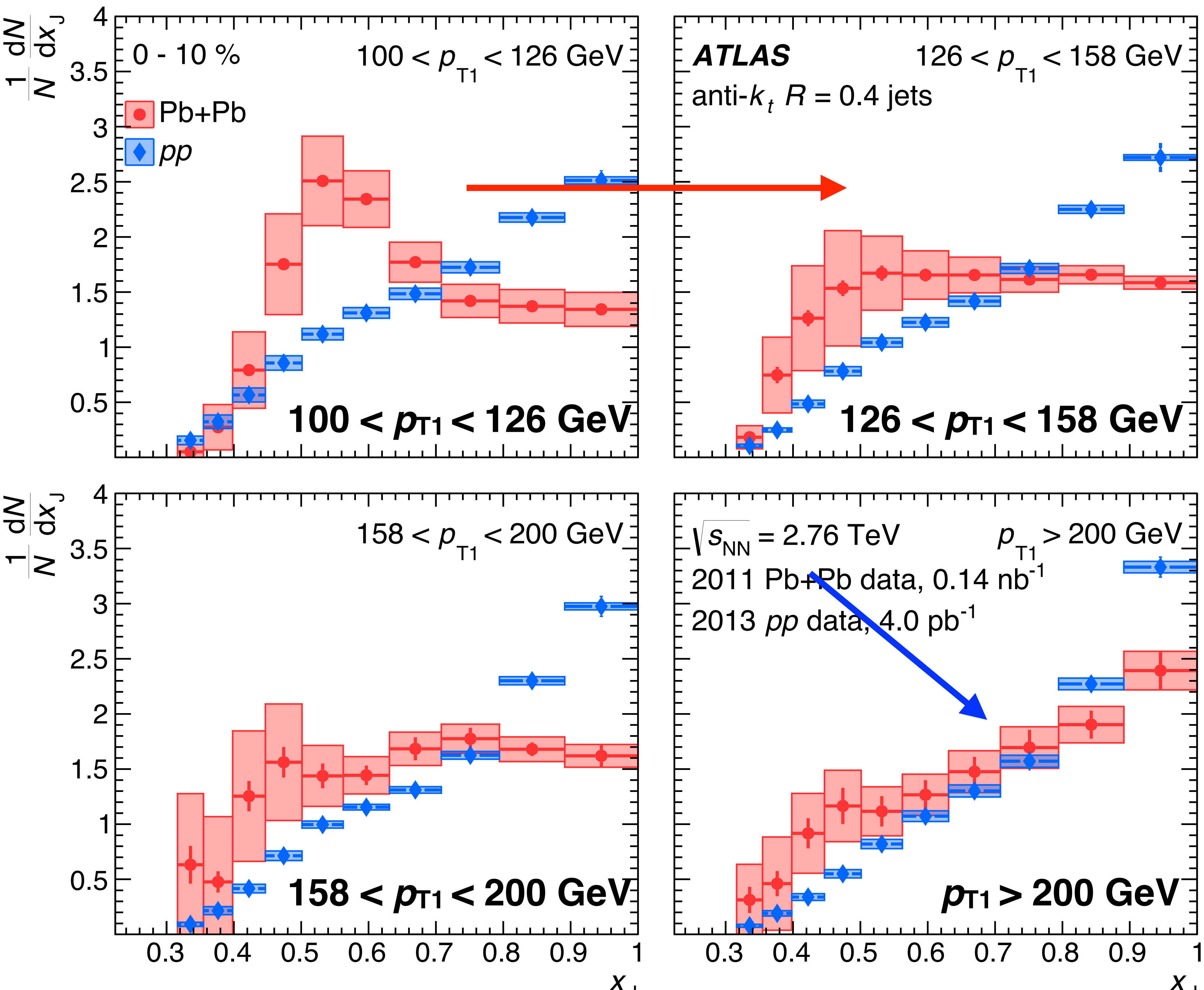


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**$p_{T1}$ dependence**

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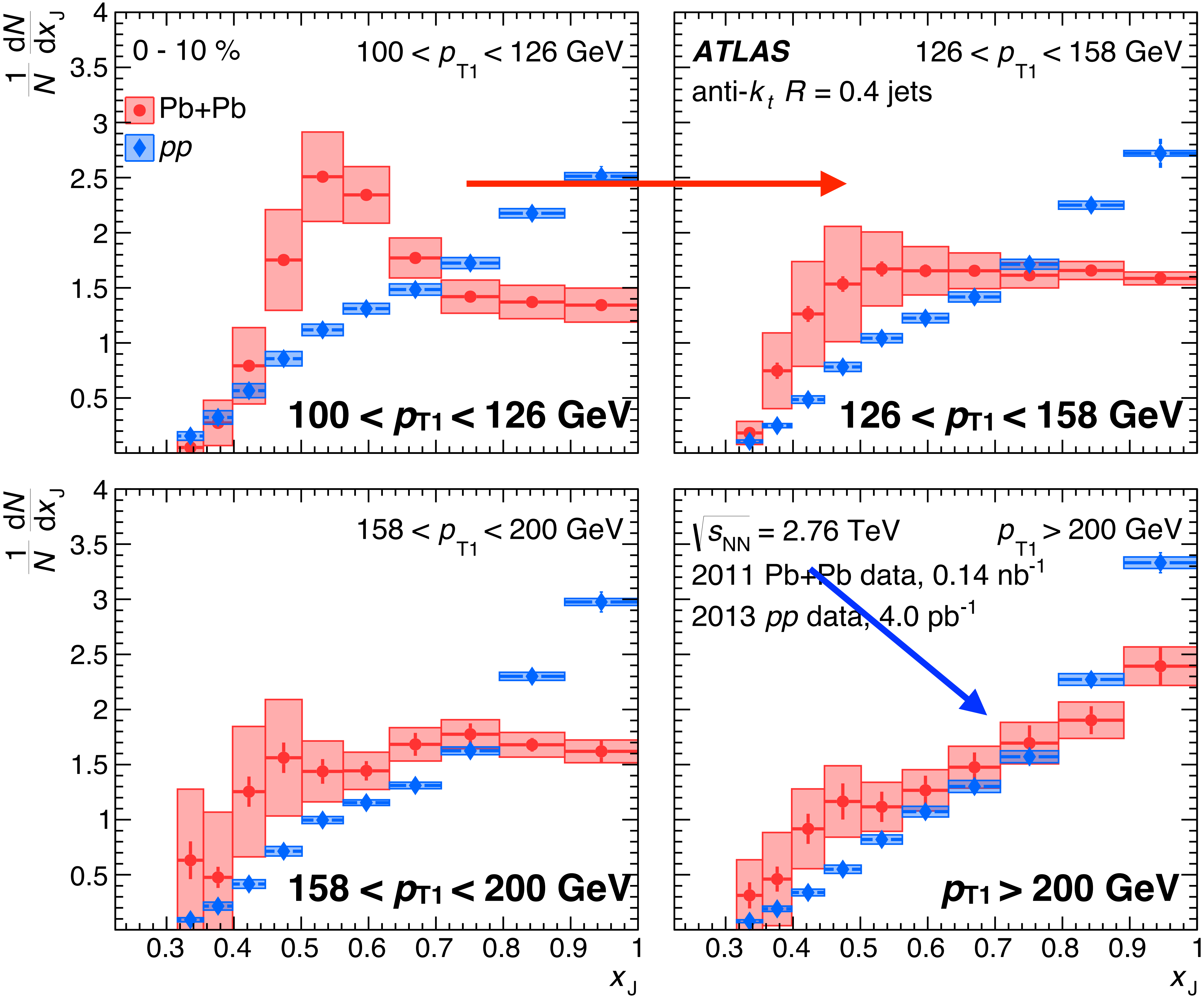


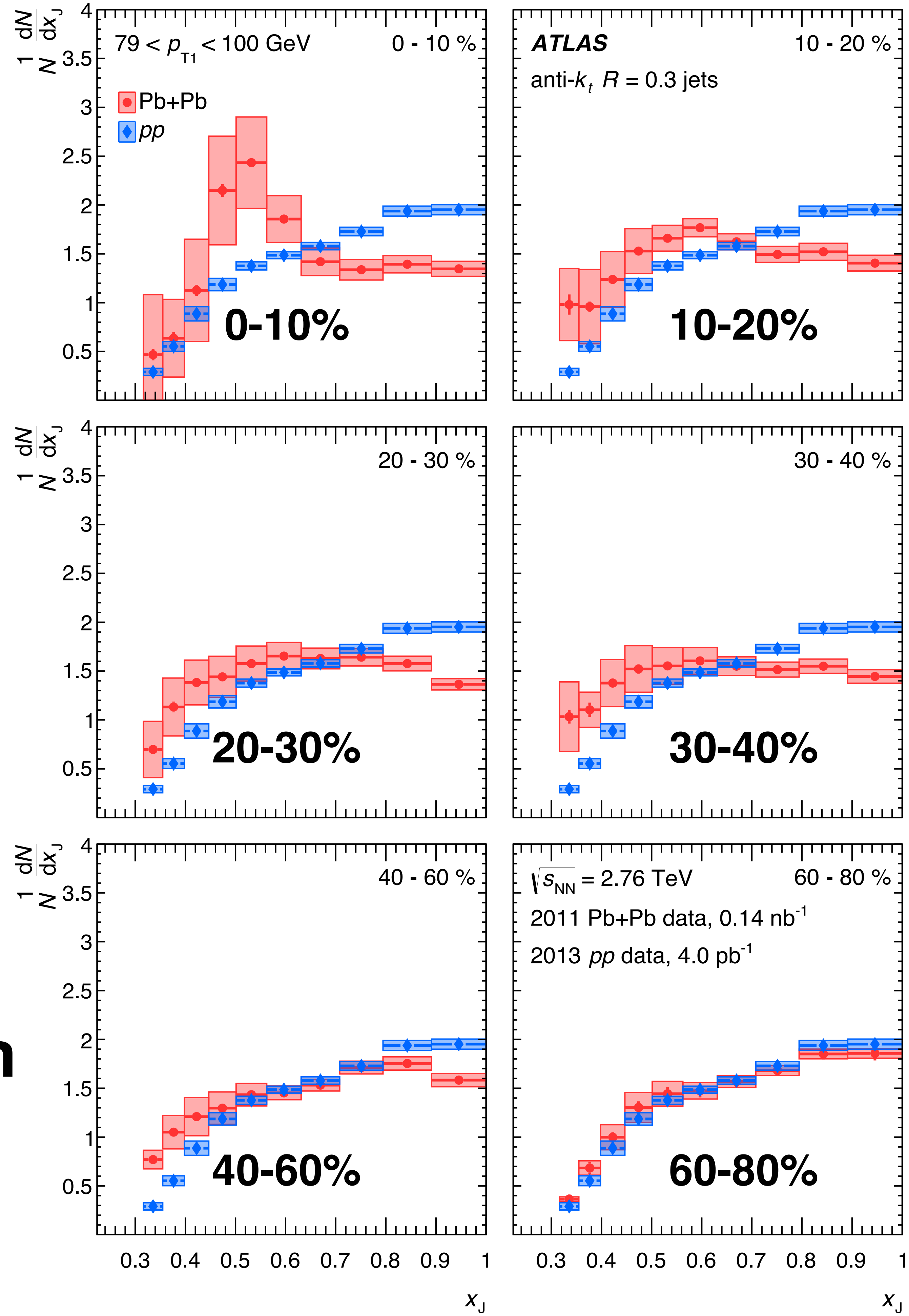

- **Drastic $p_{T1}$ dependence**
- **Pb+Pb becomes like *pp* at high $p_{T1}$**
- ***Flavor dependence probe since quark/gluon fractions change with $p_T$?***

# $x_J$ R=0.3

## centrality dependence

### $79 < p_{T1} < 100$ 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 $p_T$.
- See similar results!



# Summary

- **New measurements with ATLAS are more precise and differential than previous results**
  - ➡ **$p_T$ dependence to the jet imbalance**
  - ➡ **Single jets are suppressed up to high (TeV scale) $p_T$**
  - ➡ **Rapidity dependence for jet suppression**
- **Era of precision measurements with higher statistics and careful underlying event subtraction and unfolding for resolution (along with systematic uncertainties)**
  - ➡ **Allow for direct comparisons to theoretical calculations**
  - ➡ **Very relevant to JETSCAPE where we want more quantitative data and calculations**

# Backup

# Jet reconstruction

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

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

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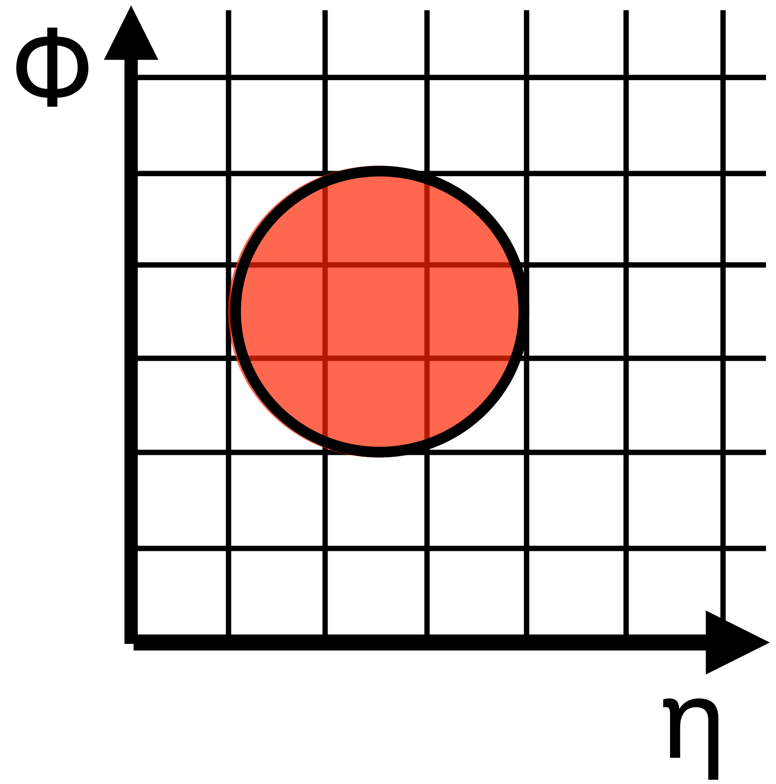


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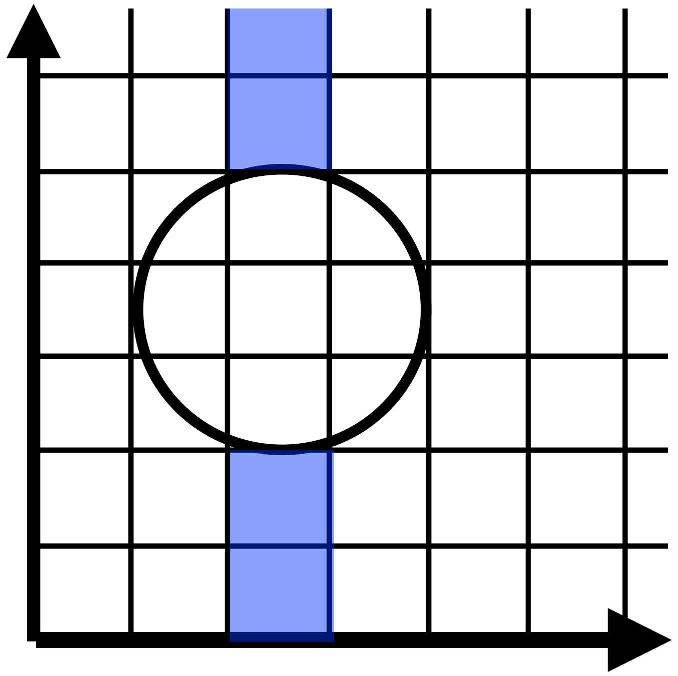
➡ **Find the jets**

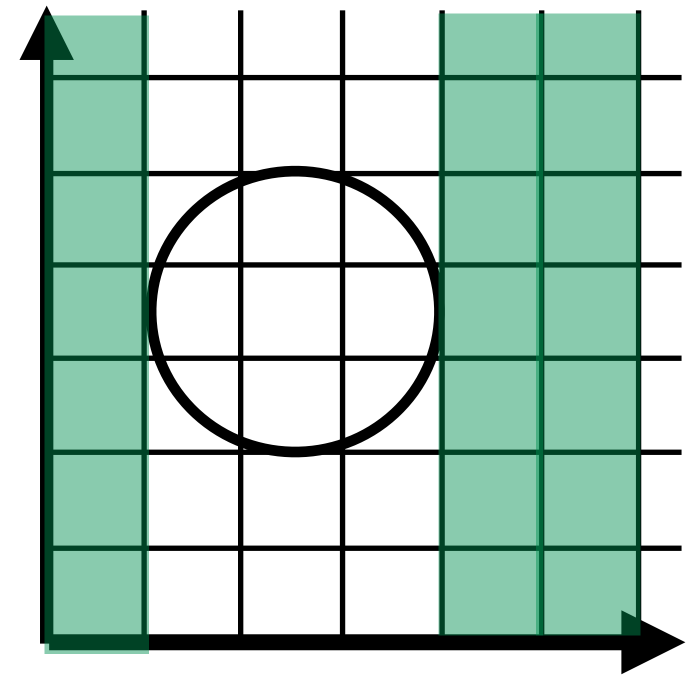
➡ **Remove the jet "seeds" and estimate the transverse energy density ρ (η-dependent)**



# Jet reconstruction

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

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



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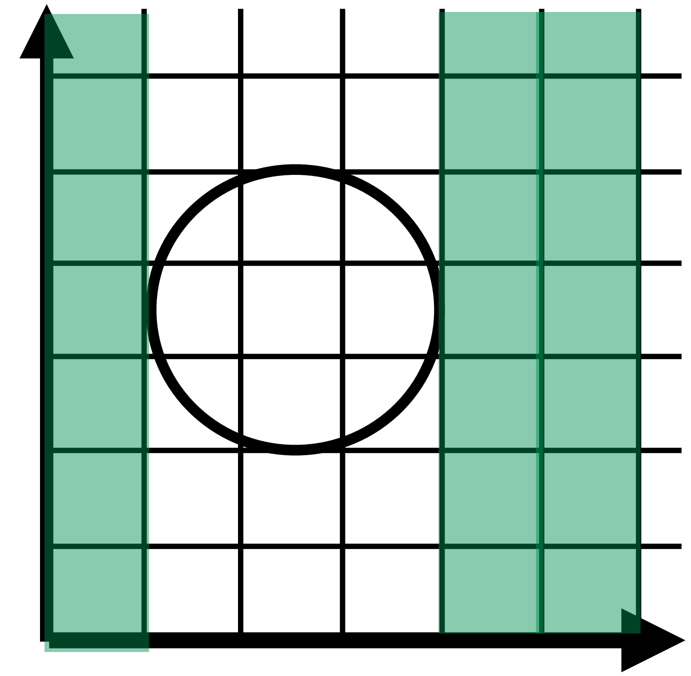

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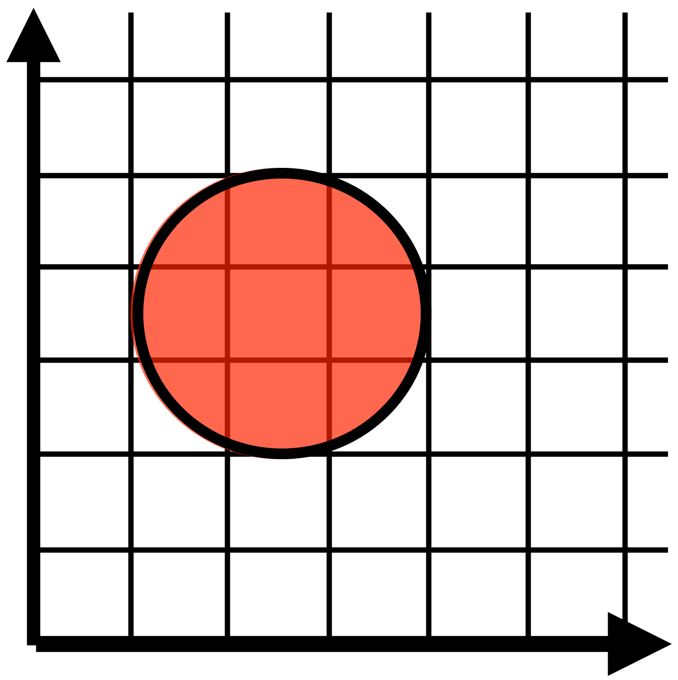

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➡ **Remove the jet "seeds" and estimate the transverse energy density ρ (η-dependent)**

➡ **Find $v_n$ and $\Psi_n$ 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**

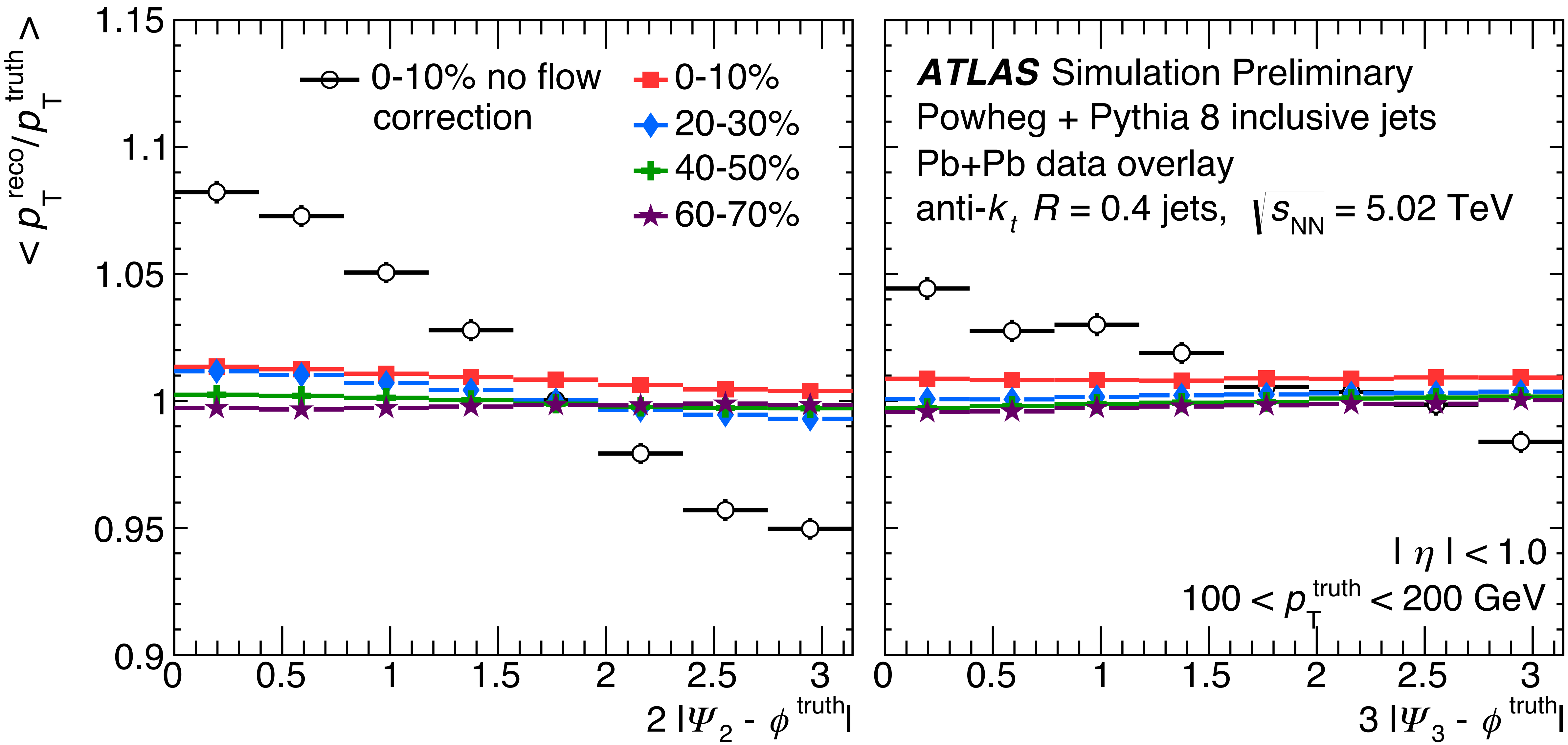
➡ **Re-run jet finding to find jets with background removed!**

# JES $\Delta\phi_n$ dependence

- **Careful measures taken to subtract the UE background for harmonic flow**

  ➡ **In run 2 this is done for n = 2, 3, and 4**

- **JES reduced significantly vs. $\Delta\phi_2$ and also for $\Delta\phi_3$**




▸ ***This also reduces the JER***

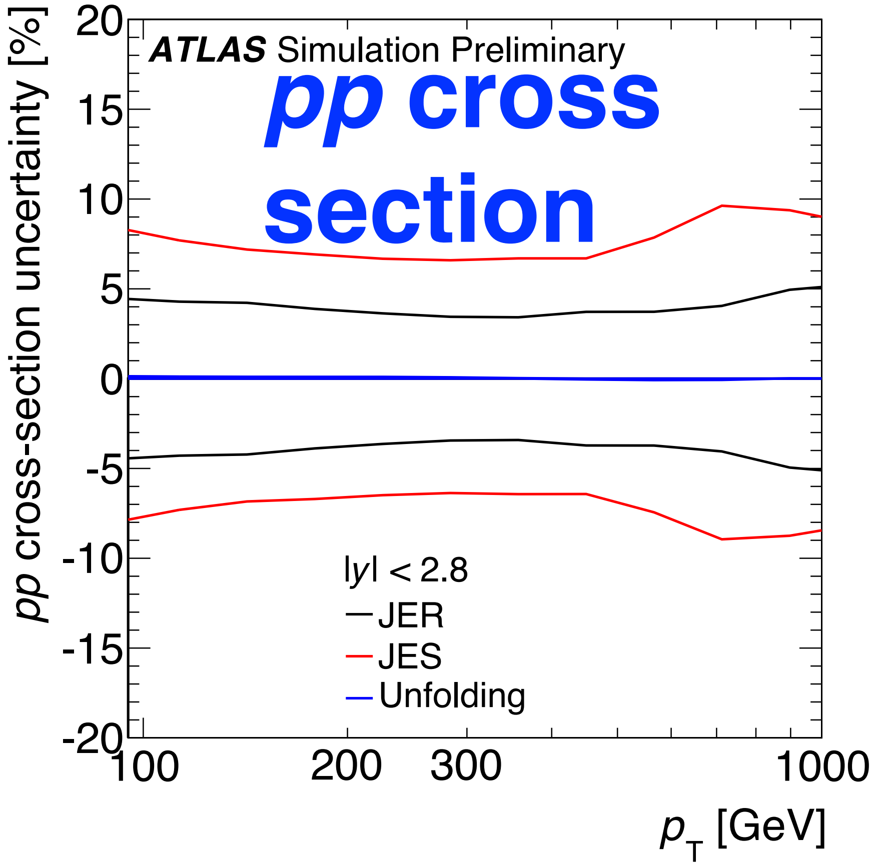
# $R_{AA}$ systematic uncertainties

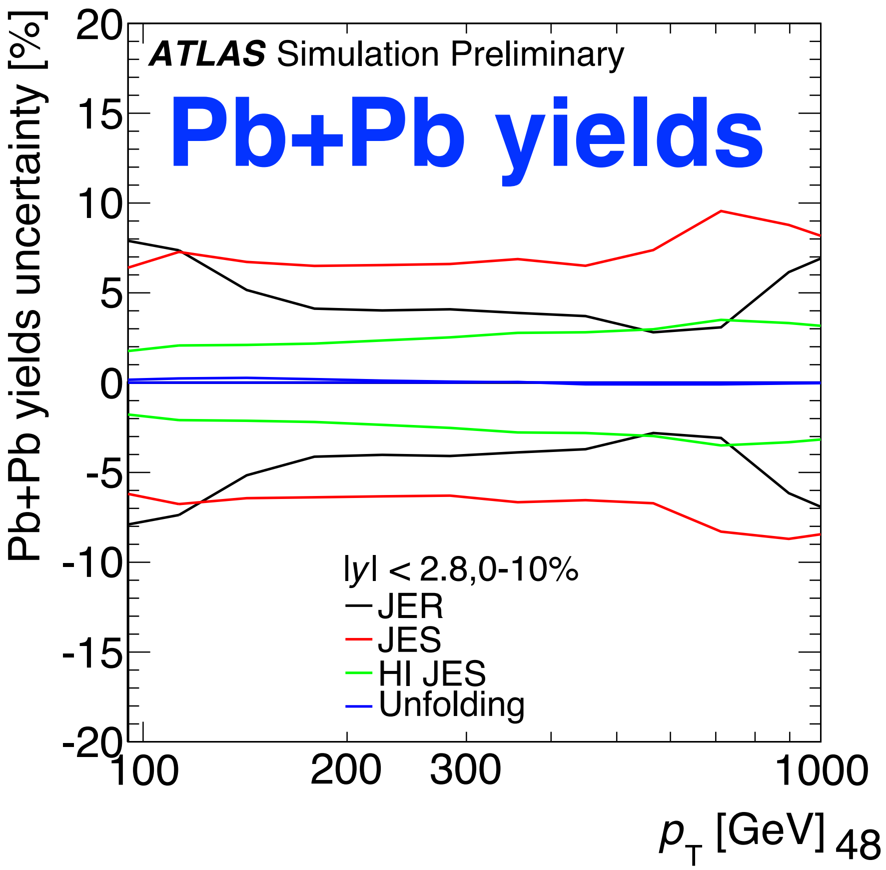
- **Jet energy scale**
  - ➡ **Standard *pp* JES components + 5 TeV flavor and HI cross-calibration (following ATL-CONF-2015-016)**
  - ➡ **HI specific uncertainty due to jet quenching (estimated using studies of the ratio of calo-jet to track-jet $p_T$)**
- **Jet energy resolution**
  - ➡ **Standard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

- **Uncertainties on the JES, JER, unfolding, luminosity, and $T_{AA}$**
- **Regenerate a response for each systematic and determine systematics separately in *pp* and Pb+Pb**

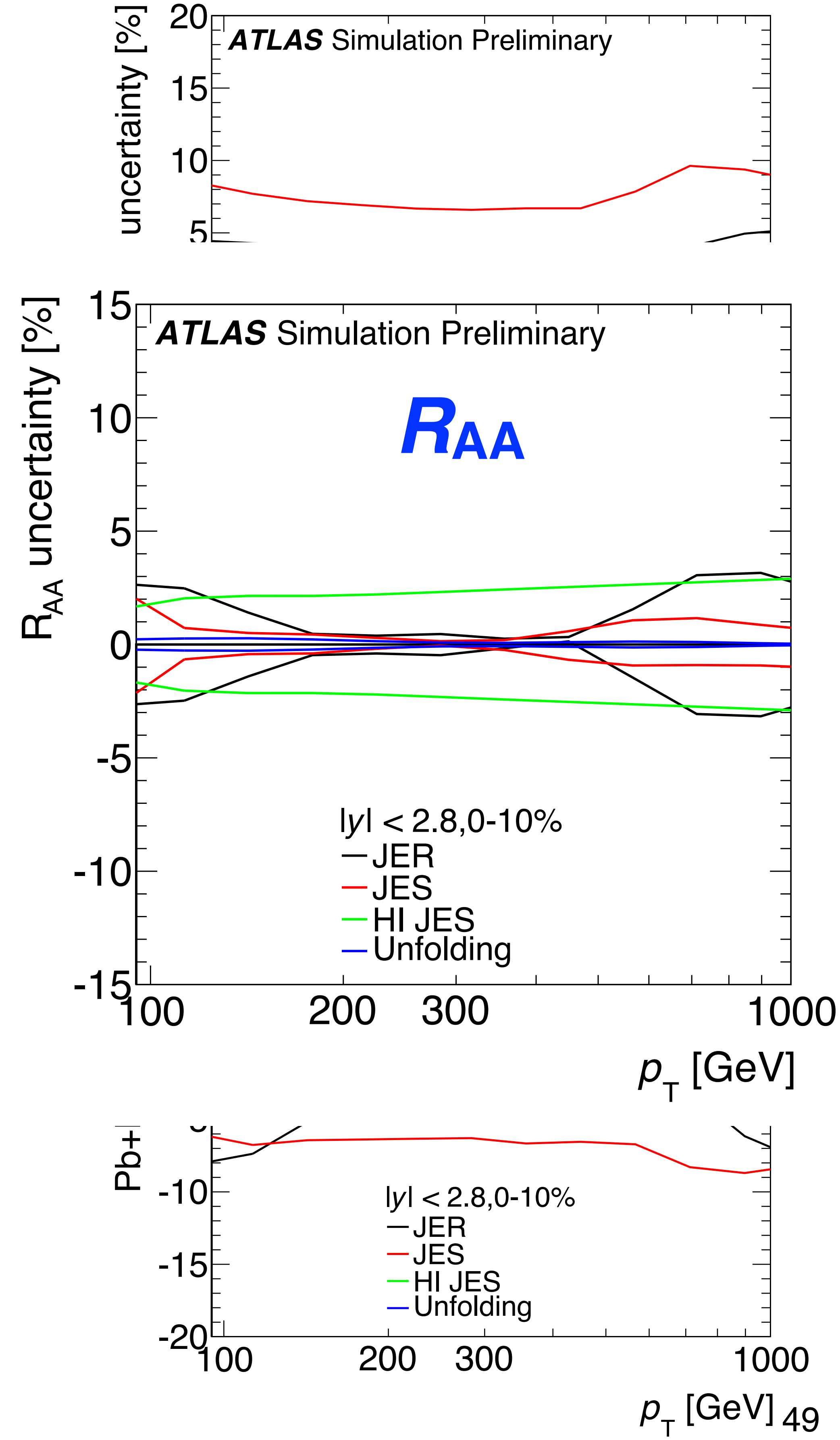
➡ **re-unfold with each new response and take the difference from the original as the systematic**



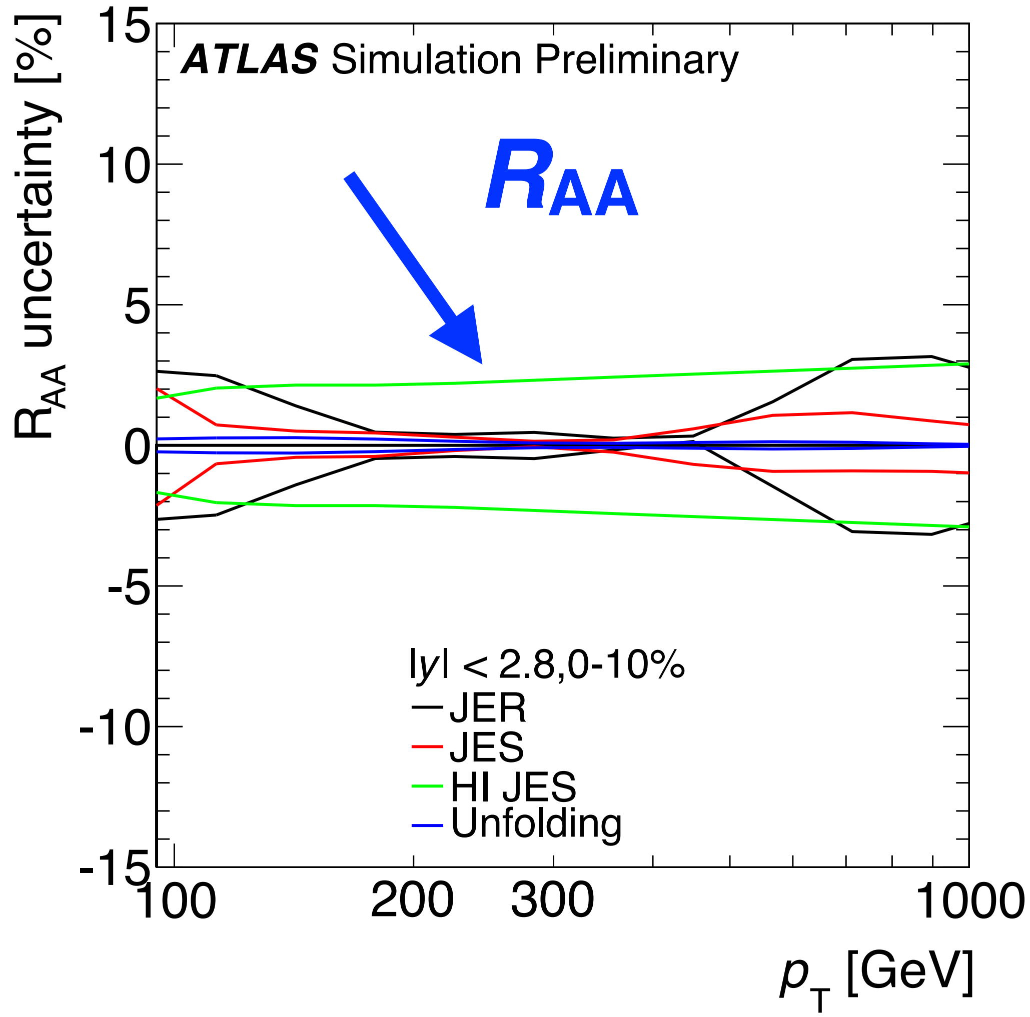
# $R_{AA}$ systematics uncertainties

- **Uncertainties on the JES, JER, unfolding, luminosity, and $T_{AA}$**
- **Regenerate a response for each systematic and determine systematics separately in *pp* and Pb+Pb**
- **Propagate them to the ratio:**
  - ➡ **Same in Pb+Pb and pp were taken to be correlated uncertainties so cancel a lot in the ratios**
  - ➡ **Different taken to be uncorrelated and added in quadrature**



# $R_{AA}$ systematics uncertainties

- **Uncertainties on the JES, JER, unfolding, luminosity, and $T_{AA}$**
- **Regenerate a response for each systematic and determine systematics separately in pp and Pb+Pb**
- **Propagate them to the ratio:**
  - ➡ **Correlated uncertainties cancel a lot in the ratios**
  - ➡ **Uncorrelated added in quadrature**
- **Largest uncertainty on $R_{AA}$ is the JES component due to jet quenching which is 4%**



# $R_{AA}$ systematics uncertainties

- **Uncertainties on the JES, JER, unfolding, luminosity, and $T_{AA}$**
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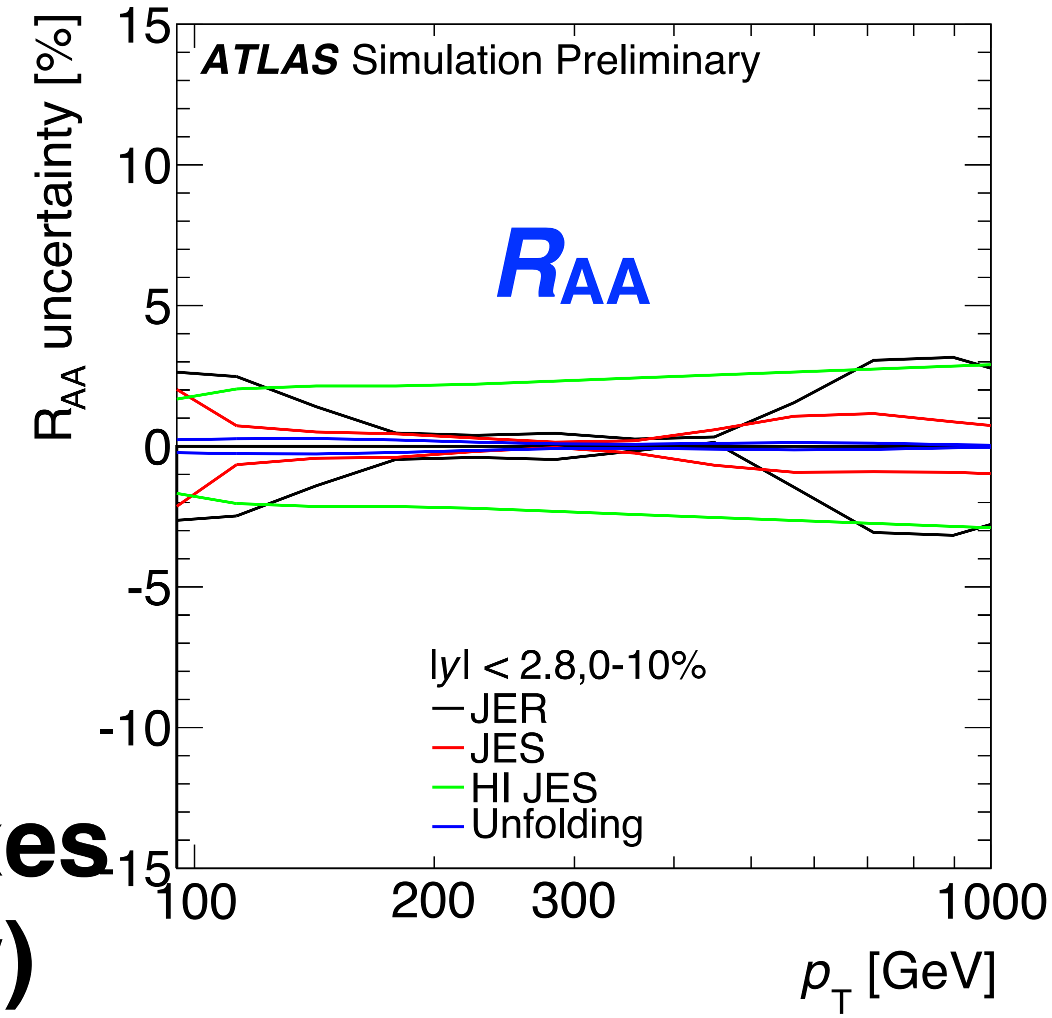


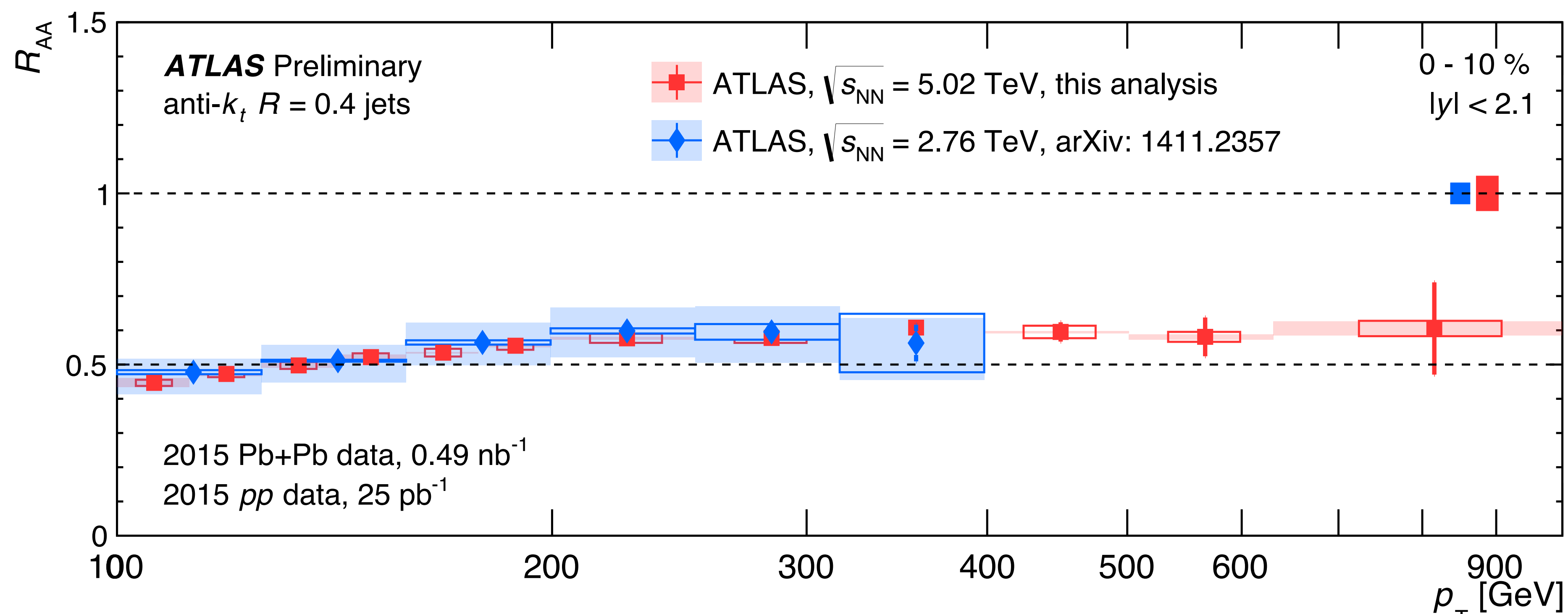

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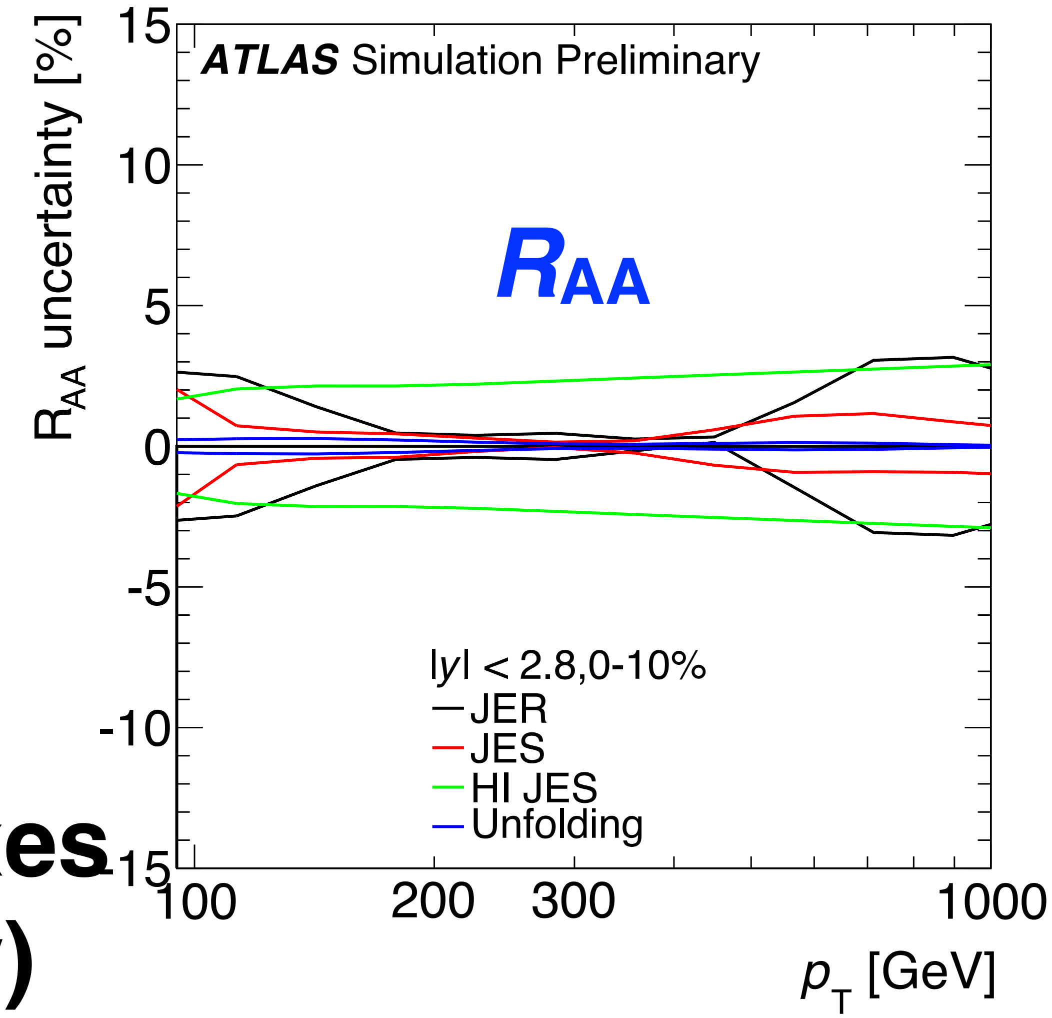
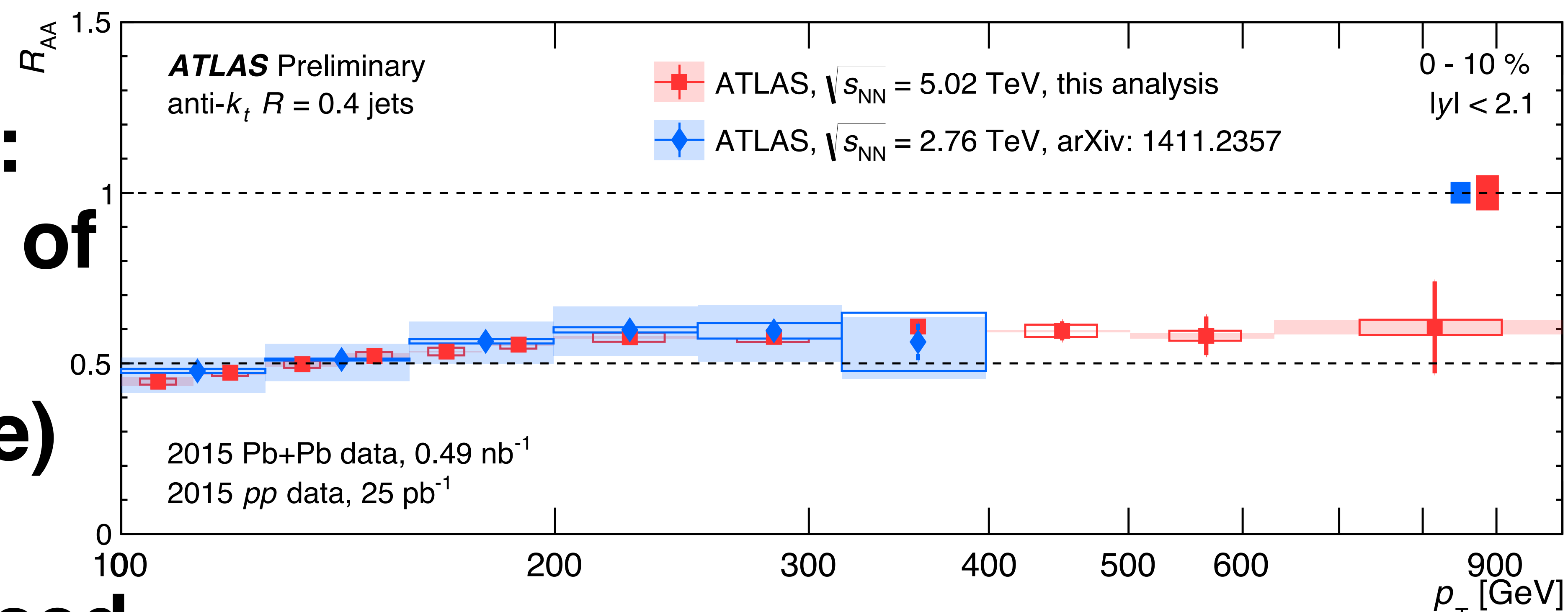
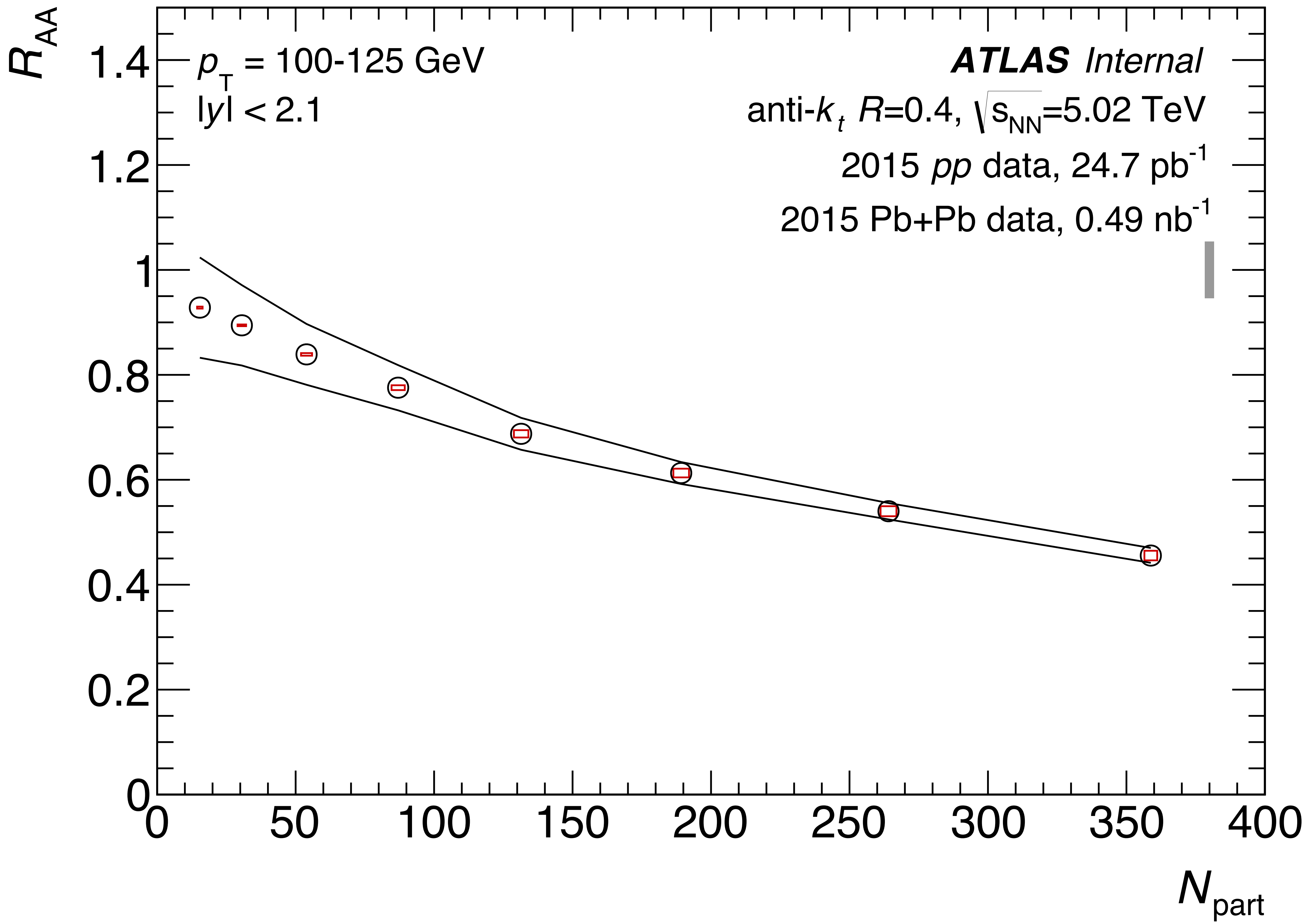



- **Run 1 vs. Run 2:**
  - ➡ **Independent of $\sqrt{s_{NN}}$ (over a narrow range)**
  - ➡ **Systematics greater reduced**



# $R_{AA}$ vs. $N_{part}$

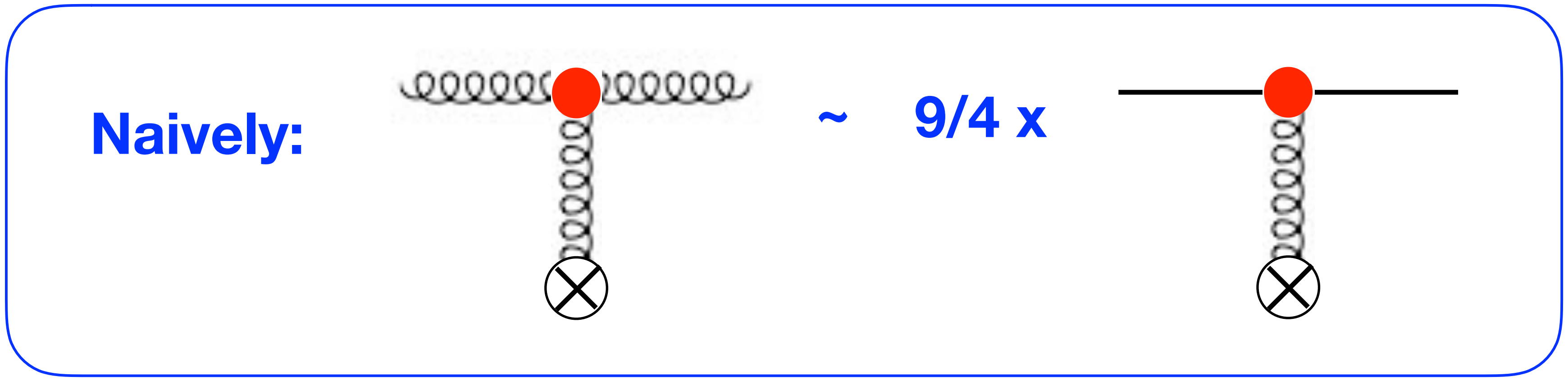



- $R_{AA}$ **decreases with** $N_{part}$

# Energy loss: flavor dependence

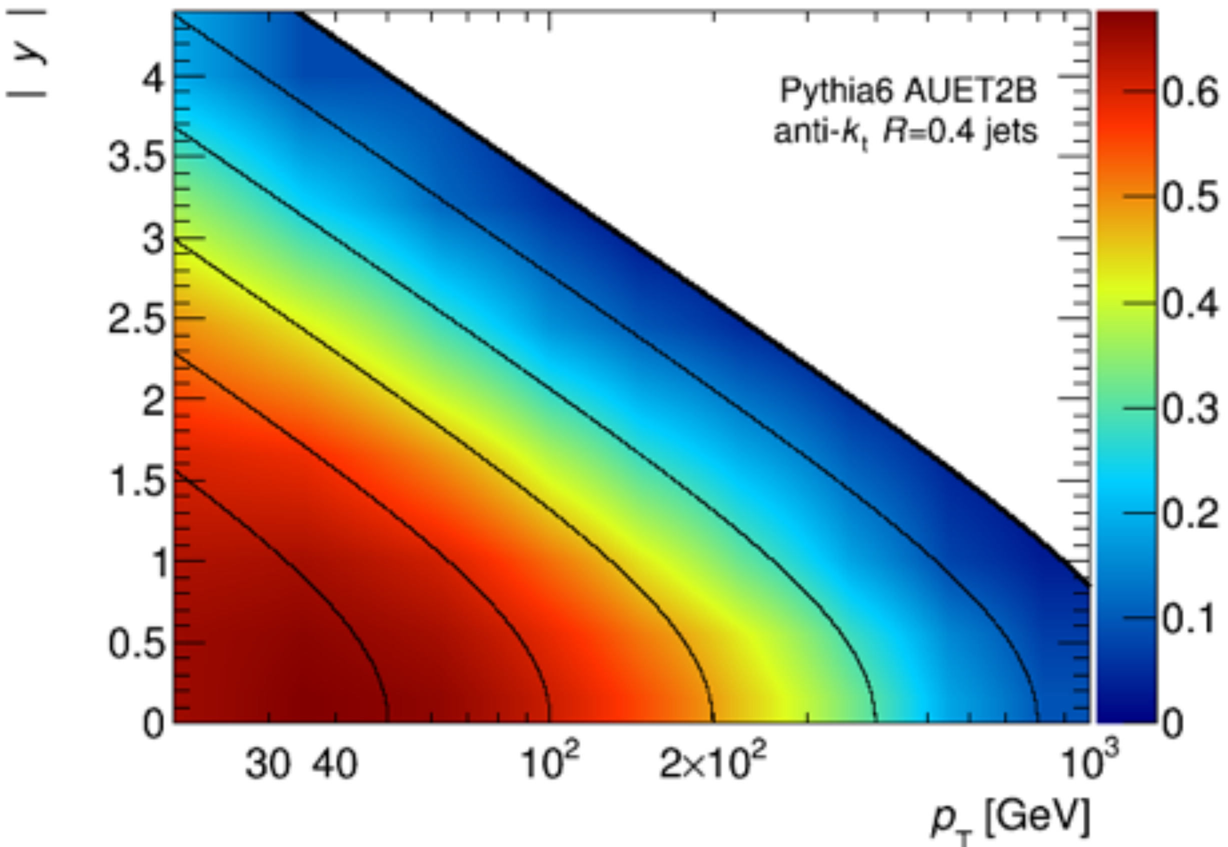
- **How does energy loss depend on the details of the parton show?**

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



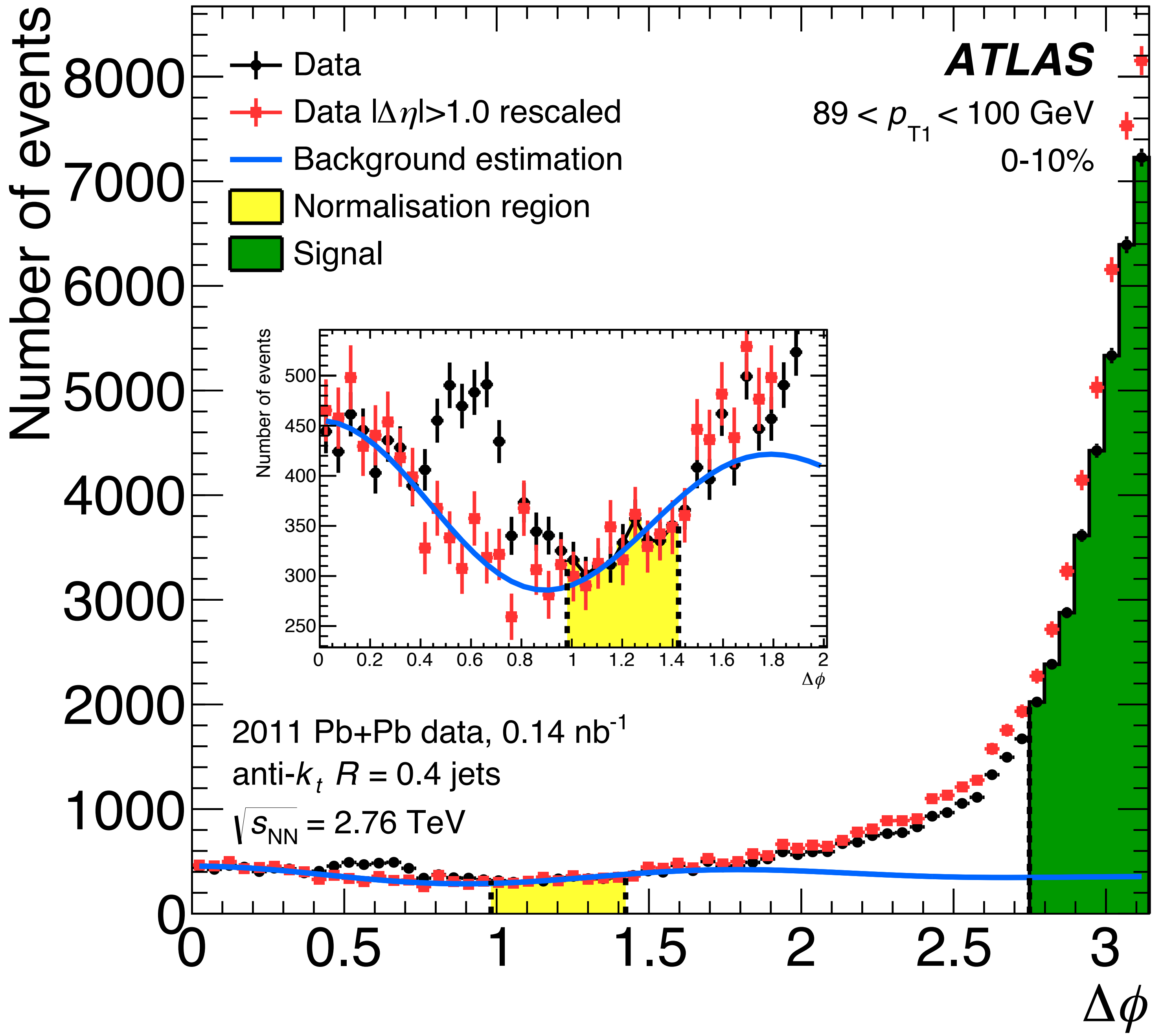

- **Measure suppression as a function of rapidity or jet $p_T$ since gluon fraction decreases with rapidity and jet $p_T$.**

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



# ΔΦ Combinatoric Subtraction

- significant contribution of pairs arise from jets not originating from the same hard scattering
  - ➡ uncorrelated hard scatterings in same event
  - ➡ correlated hard scattering that comes from a “fake” jet (upward UE fluctuation)
- combinatoric pairs expected to be uncorrelated in ΔΦ except for small harmonic modulation arising from imperfect removal of flow effects in the reconstruction
  - ➡ background estimated in uncorrelated region (ΔΦ<π/2)
  - ➡ flow effects estimated by fitting the distribution where ΔΦ distribution when Δη>1.0

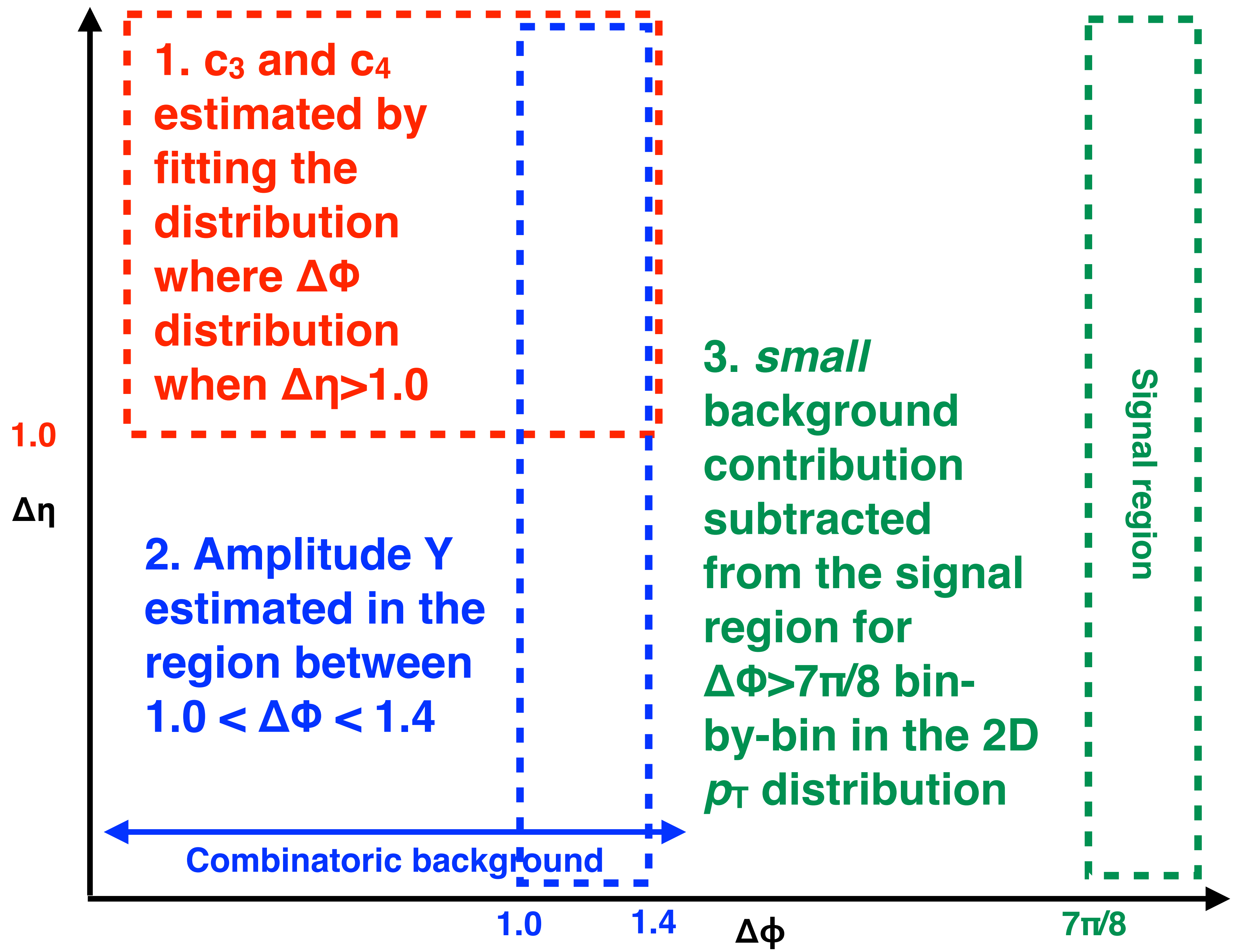



$$C(\Delta\Phi) = Y(1 + 2c_3 \cos 3\Delta\Phi + 2c_4 \cos 4\Delta\Phi)$$

➡ *small* background contribution subtracted from the signal region for ΔΦ>7π/8 bin-by-bin in the 2D $p_T$ distribution

# ΔΦ combinatoric subtraction

- **Significant contribution of pairs arise from jets not originating from the same hard scattering**
- **combinatoric pairs expected to be uncorrelated in ΔΦ < π/2**
  - ➡ **except for small harmonic modulation from imperfect removal of flow effects in the reconstruction**
  - ➡ **$v_2$ contribution to the ΔΦ distribution was observed to be fully removed by the UE subtraction**

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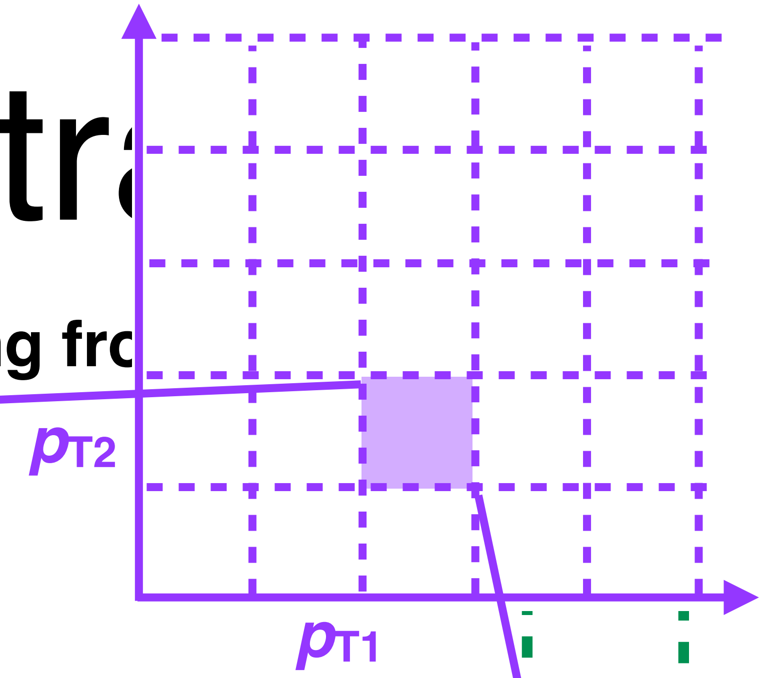


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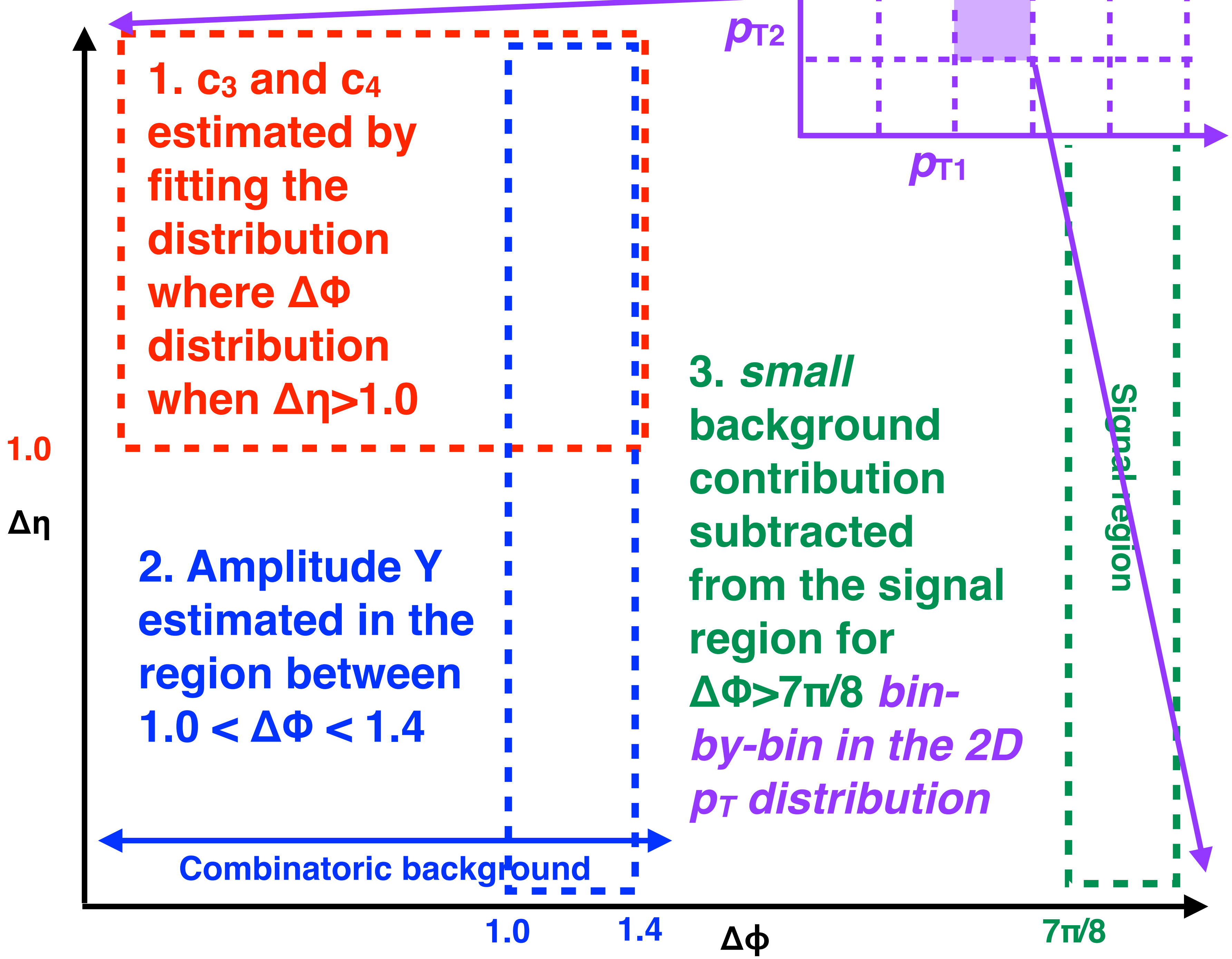
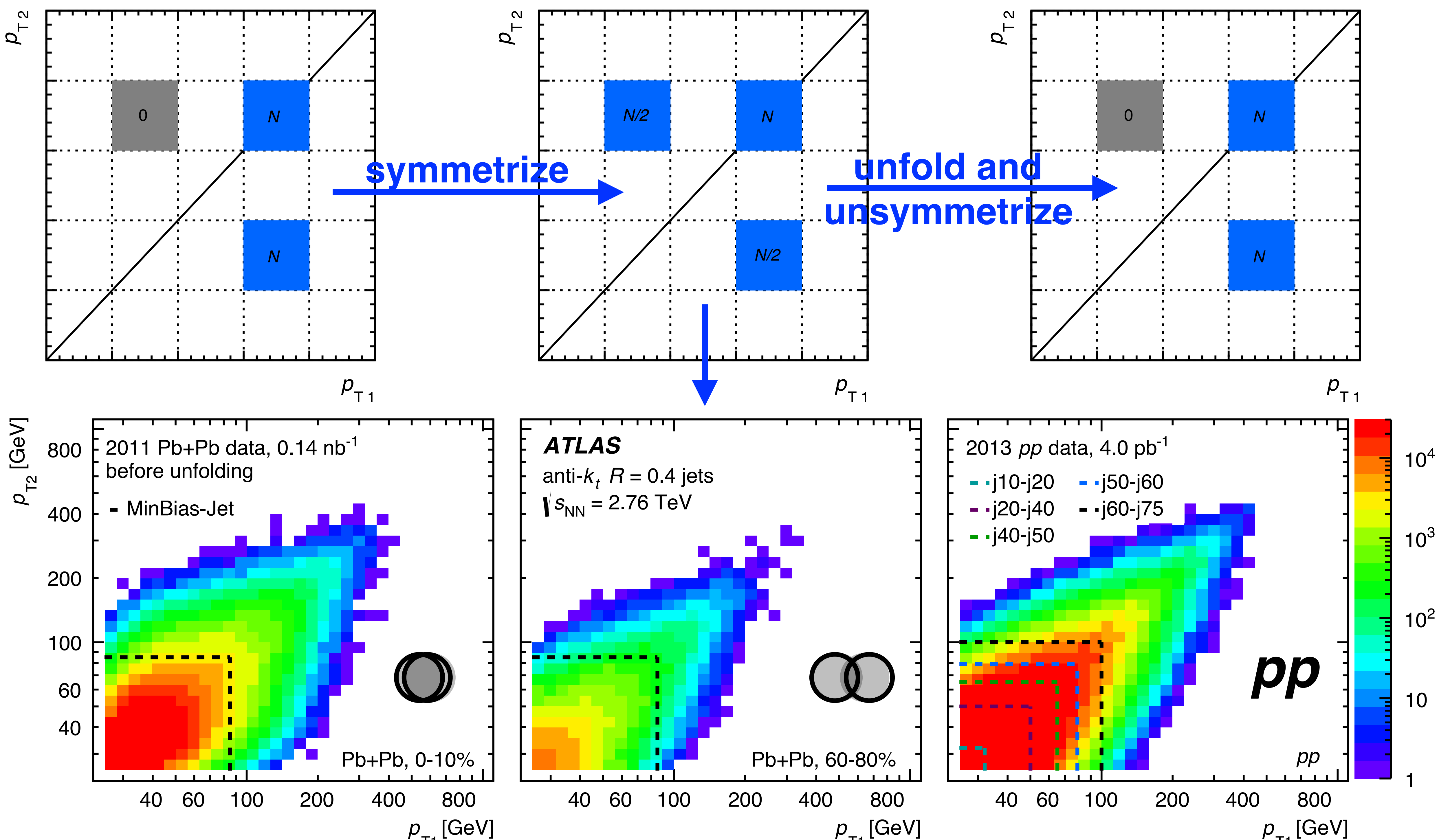



$$C(\Delta\phi) = Y(1+2c_3\cos 3\Delta\phi+2c_4\cos 4\Delta\phi)$$

# Symmetrize 2D distribution

- **Before unfolding the distribution has to be symmetrized because the role of the leading jet can switch due to bin migration across the diagonal**

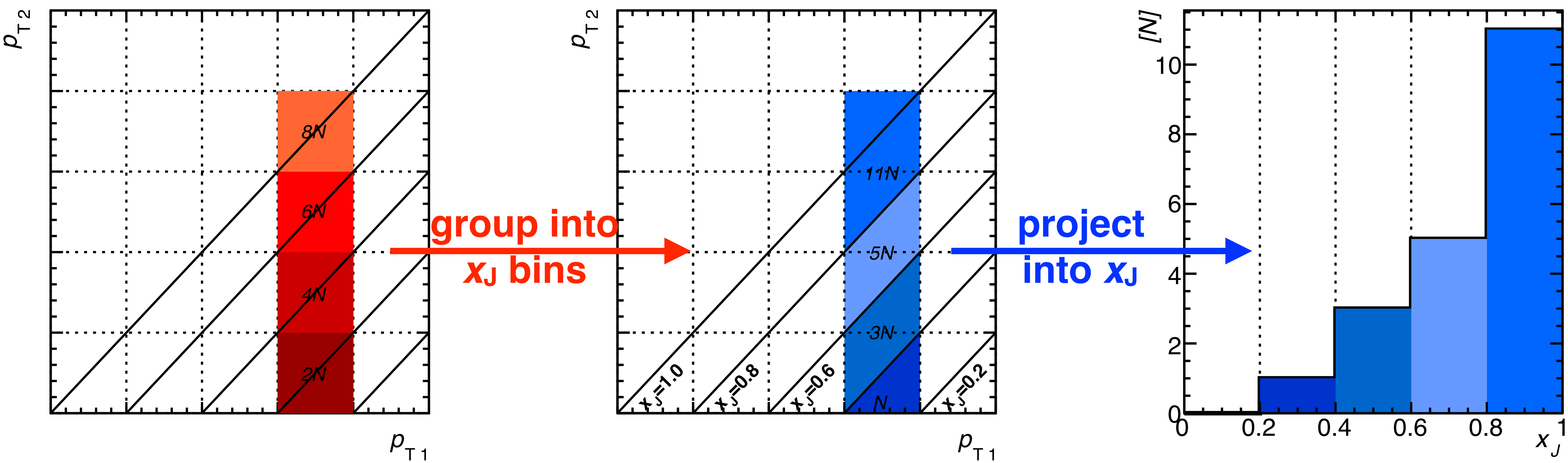



- ***Final symmetrized 2D distributions before unfolding including the combinatoric subtraction***

# Projection into $x_J$

- **The measurement is in the area normalized quantity (1/*N*)d*N*/d$x_J$ which is obtained by projection the 2D $p_{T1}$-$p_{T2}$ distribution into $x_J$ bins.**

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




- **Start with 2D distribution**
- **Fix the $x_J$ bins along the diagonals and divide the counts into the $x_J$ bins**
- **Project into the 1D $x_J$ distribution**

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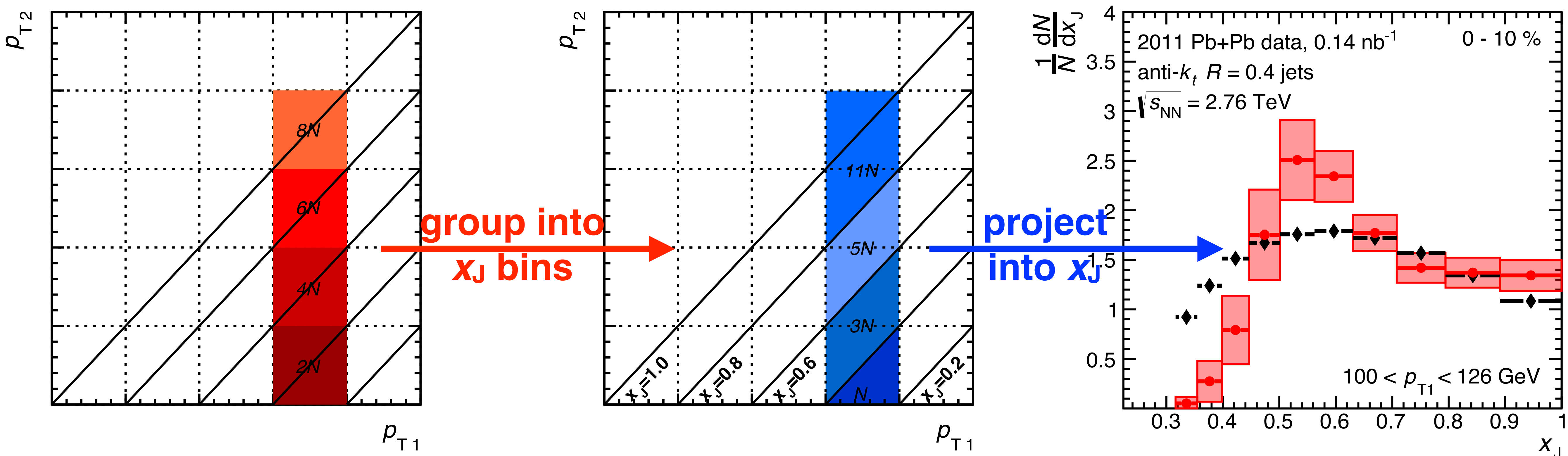


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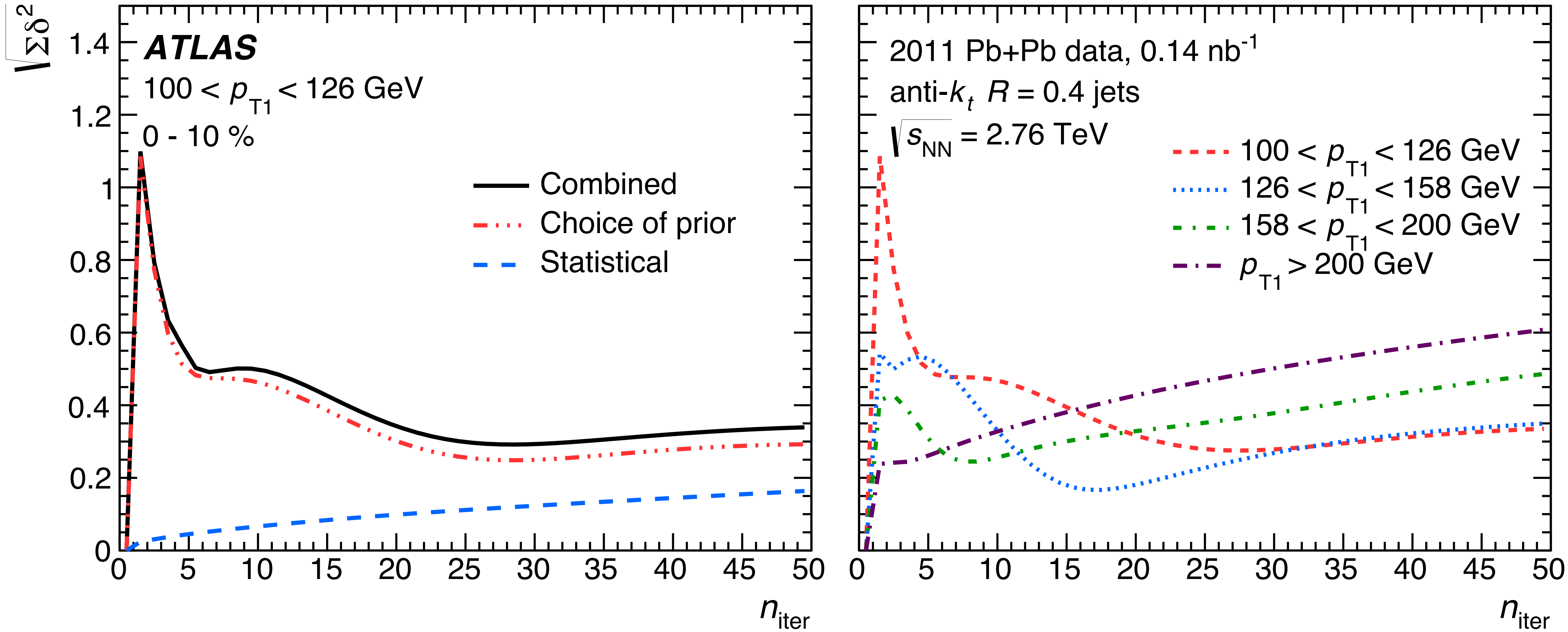
# Systematics Uncertainties

- **Jet energy scale (JES)**
  - ➡ Baseline 8 nuisance parameters from *in situ* calibration with additional parameters due to flavor response and composition and cross calibration
  - ➡ Additional uncertainty for the R=0.3 jet
  - ➡ Two addition in Pb+Pb due to the difference in the data taking period and detector response to quenched jets
- **Jet energy scale (JER)**
  - ➡ standard centrality-independent JER uncertainties
  - ➡ Additional uncertainty for the R=0.3 jets
  - ➡ additional centrality dependent uncertainty for possible disagreement between fluctuation terms in JER in the MC and independent analysis of fluctuations in data
- **Combinatoric background subtraction:** unfold using a different ΔΦ range (1.1-1.5)
- **Unfolding:**
  - ➡ **sensitivity to bayesian prior:** use a different re-weighting to the truth distribution in the response
  - ➡ **sensitivity to sparsely populated response:** conservative systematic that fills sparsely populated bins in the response matrix with a factorized response which is where there is no correlation between jet 1 and jet 2 so $R(p_{T1}^{true}, p_{T2}^{true}, p_{T1}^{reco}, p_{T2}^{reco}) \rightarrow R(p_{T1}^{true}, p_{T1}^{reco})R(p_{T2}^{true}, p_{T2}^{reco})$

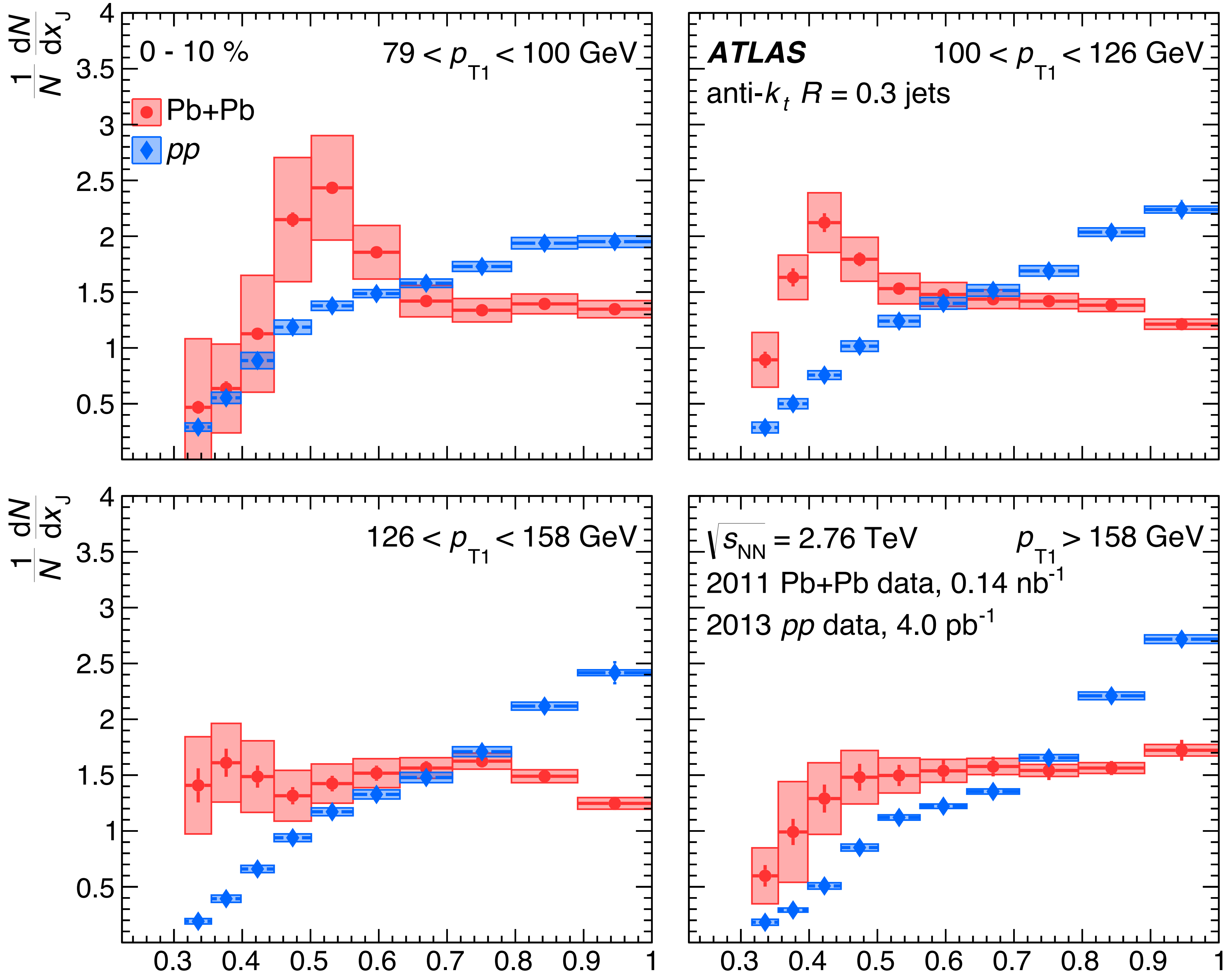



# Iterations Summary

| Jet Radii | Centrality [%] | Iterations |
|---|---|---|
| 0.4 | 0 - 10 | 20 |
| 0.4 | 10 - 20 | 18 |
| 0.4 | 20 - 30 | 15 |
| 0.4 | 30 - 40 | 15 |
| 0.4 | 40 - 60 | 10 |
| 0.4 | 60 - 80 | 7 |
| 0.4 | *pp* | 12 |
| 0.3 | 0 - 10 | 21 |
| 0.3 | 10 - 20 | 15 |
| 0.3 | 20 - 30 | 12 |
| 0.3 | 30 - 40 | 10 |
| 0.3 | 40 - 60 | 8 |
| 0.3 | 60 - 80 | 6 |

# R=0.3 $x_J$ $p_{T1}$ dependence

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



# $x_J$ 3rd jet

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

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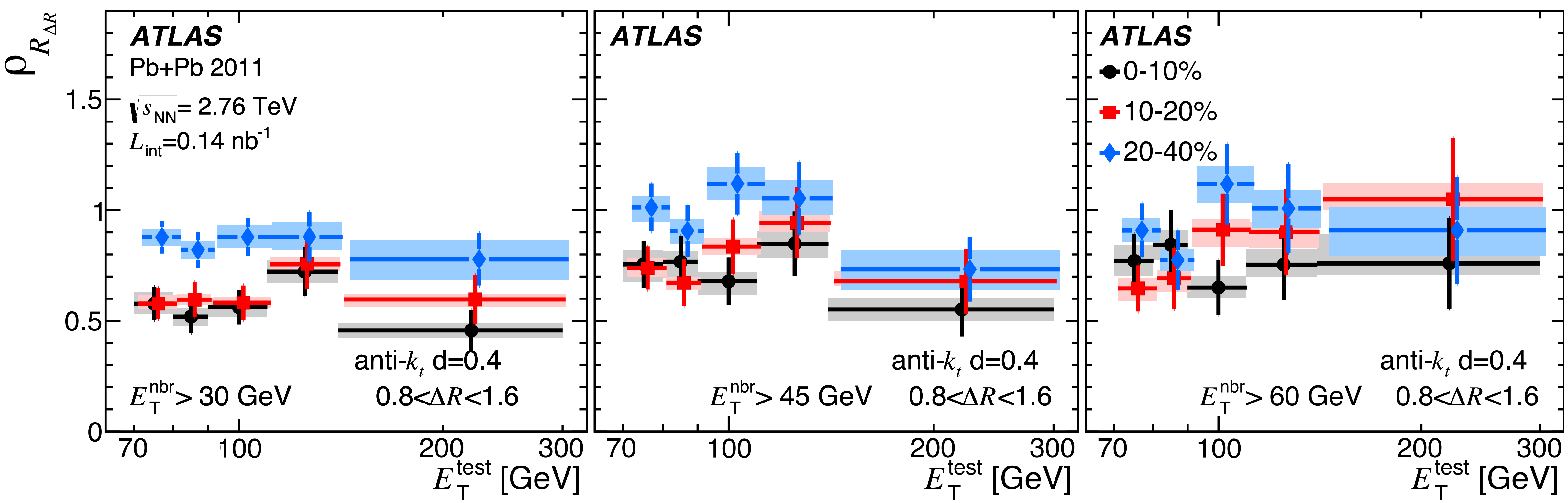


- **Tested this by unfolding with a new response that takes into account the contribution to the 3rd jet with a weighting applied to match the 3rd jet distribution in data**

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

# $x_J$ *pp* data to MC comparison