Inclusive jets and jet substructure in 2.76 TeV and 5.02 TeV *pp* and Pb+Pb collisions with the ATLAS detector

Martin Spousta
for the ATLAS Collaboration

Charles University
Prague

26th international conference on ultrarelativistic heavy-ion collisions,
February 5-11, 2017, Chicago

Introduction

- Measurements of inclusive jet suppression:
  - Phys. Lett. B 719 (2013) 220
  - Phys. Rev. Lett. 114 (2015) 072302
  - ATLAS-CONF-2017-009 **… new for QM**
- Measurements of internal structure of jets:
  - Phys. Lett. B739 (2014) 320
  - arXiv:1702.00674 **… new for QM**
  - ATLAS-CONF-2017-005 **… new for QM**
- Used data:
  - Run 1: Pb+Pb: $\sqrt{s_{NN}} = 2.76$ TeV, $L_{int} = 0.14$ nb^{-1}
    pp: $\sqrt{s} = 2.76$ TeV, $L_{int} = 4.2$ pb^{-1}
  - Run 2: Pb+Pb: $\sqrt{s_{NN}} = 5.02$ TeV, $L_{int} = 0.49$ nb^{-1}
    pp: $\sqrt{s} = 5.02$ TeV, $L_{int} = 25$ pb^{-1}

Inclusive jet suppression

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

Jet yield in heavy ion collisions

Nuclear tickness fuction

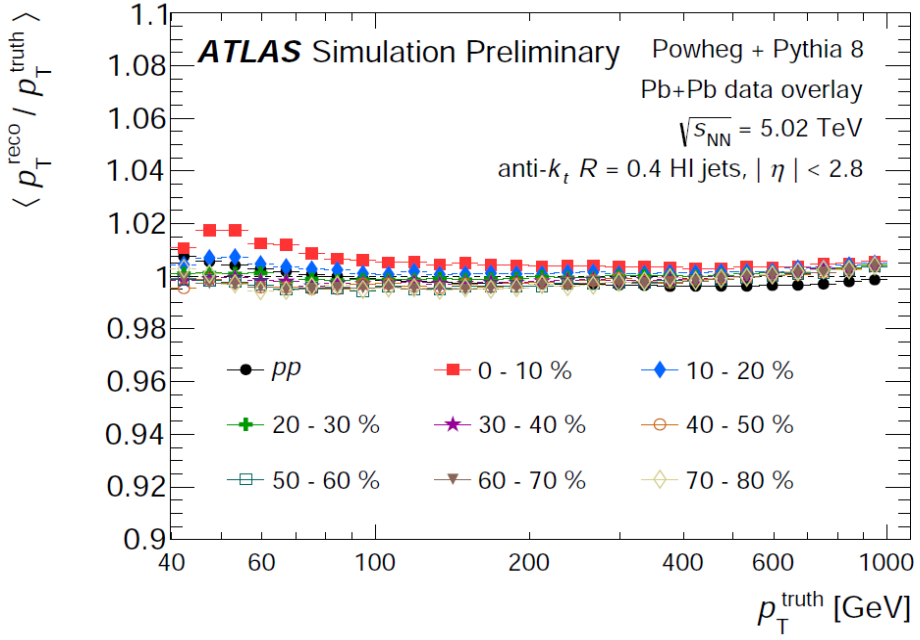
Jet cross-section in *pp* collisions

Number of expected jets per event of a given centrality

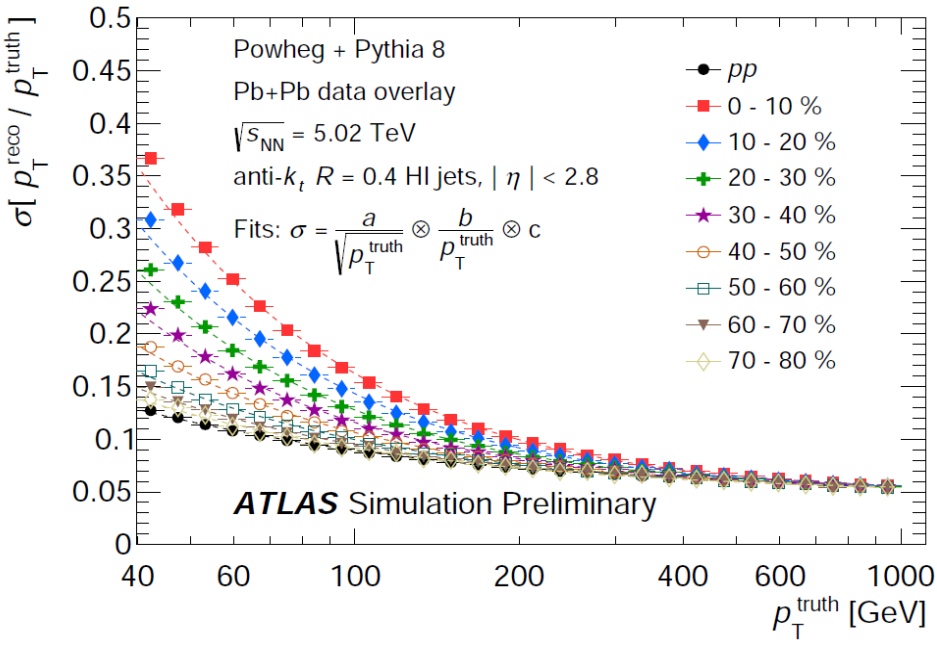
Nuclear modification factor quantifies the magnitude of the jet suppression which is dominantly due to final state interactions with constituents of the medium

Jet reconstruction performance in run 2

Jet energy scale

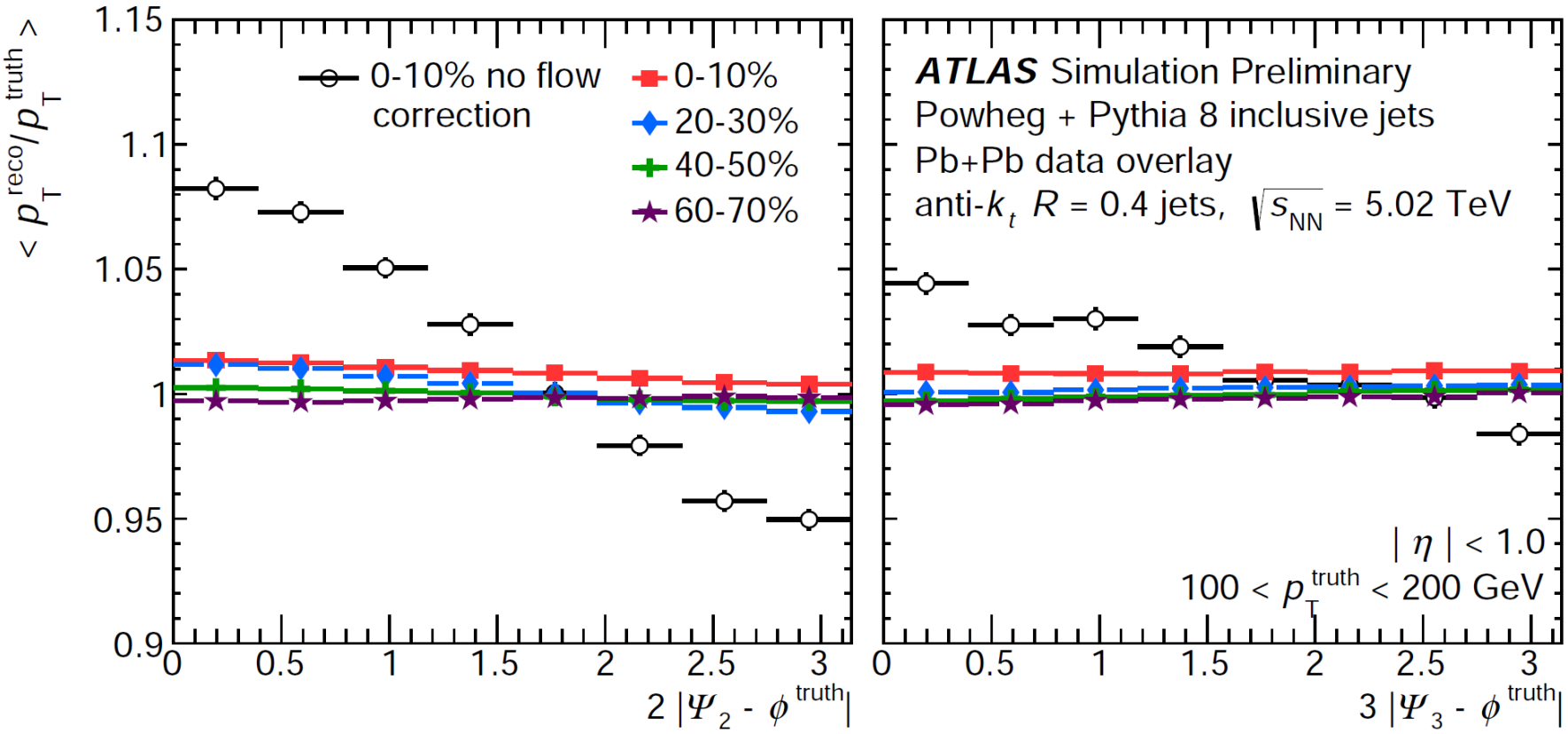


Jet energy resolution



- Realistic jet simulations: NLO POWHEG+PYTHIA8 MC + minimum bias Pb+Pb data overlay.
- Good understanding of jet energy scale.
- Expected behavior of jet energy resolution.

Jet reconstruction performance in run 2



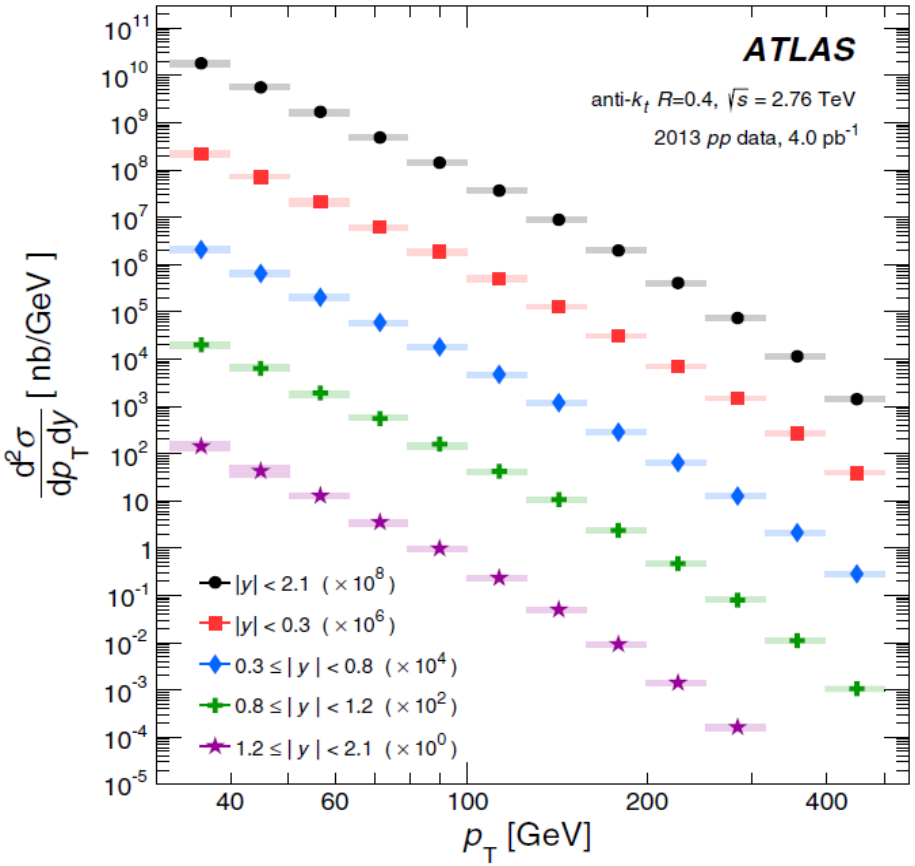
… Example of the improvement in the jet energy scale: implementing the higher order flow corrections.

=> Jet energy scale does not dependent on the orientation with respect to the reaction plane.

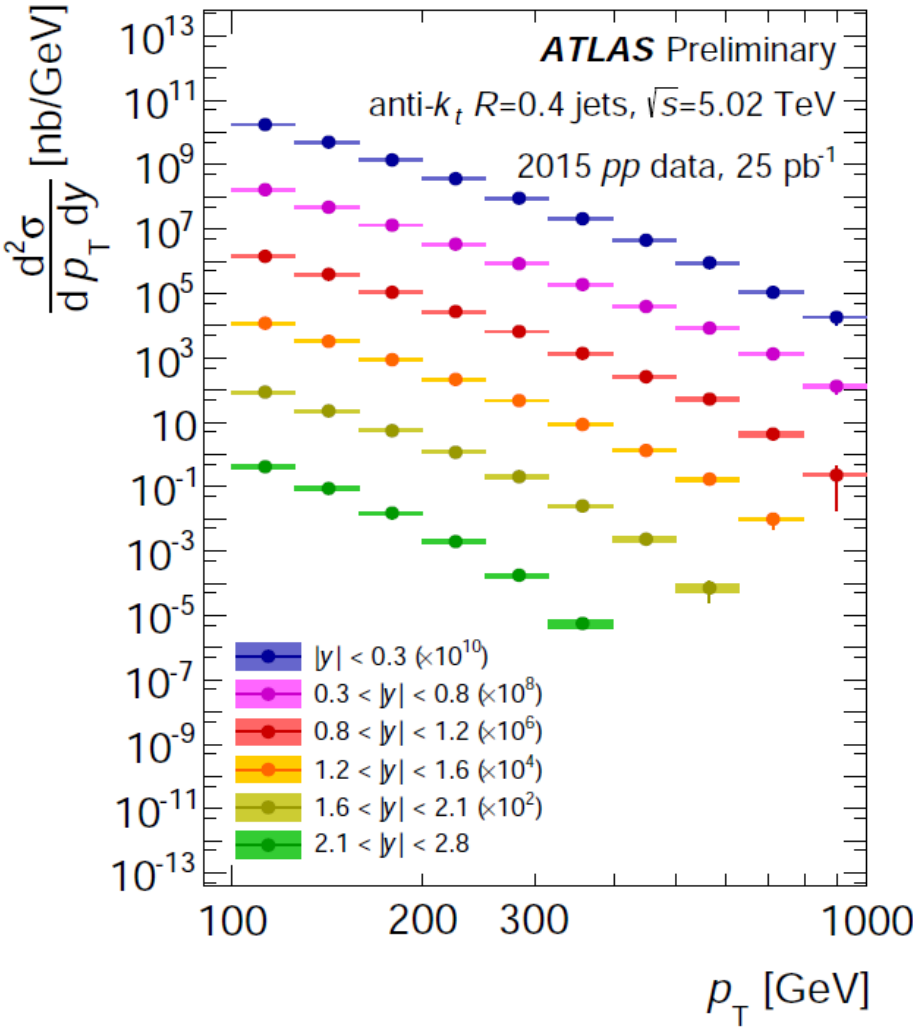
See also poster by Akshat Puri

Jet cross-section in pp collisions

2.76 TeV

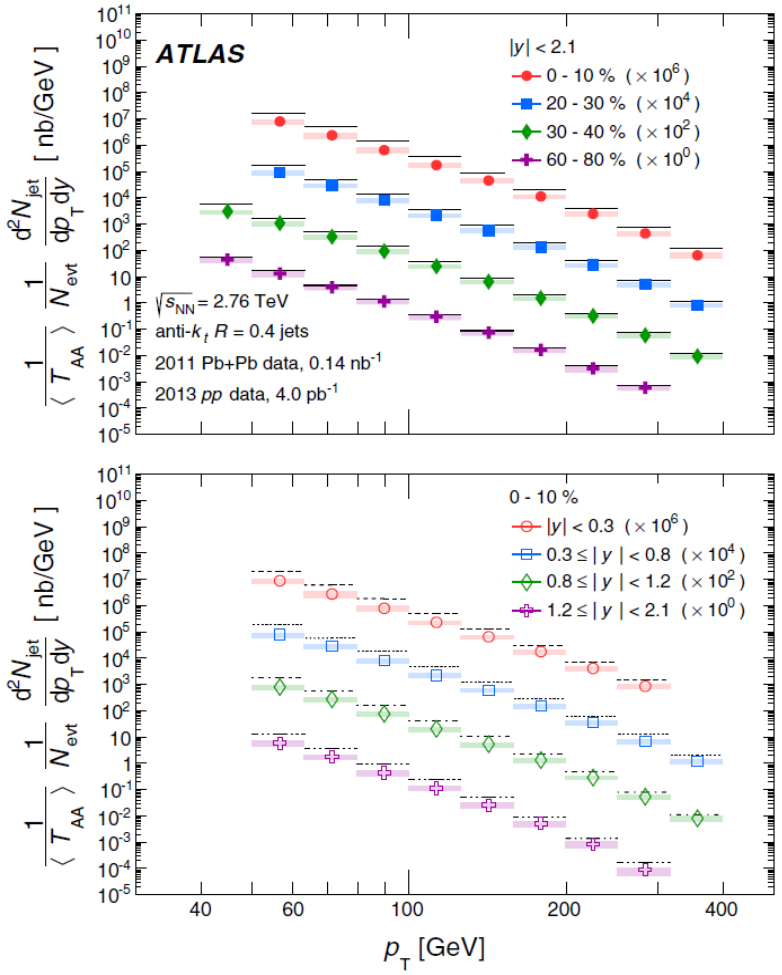


5.02 TeV

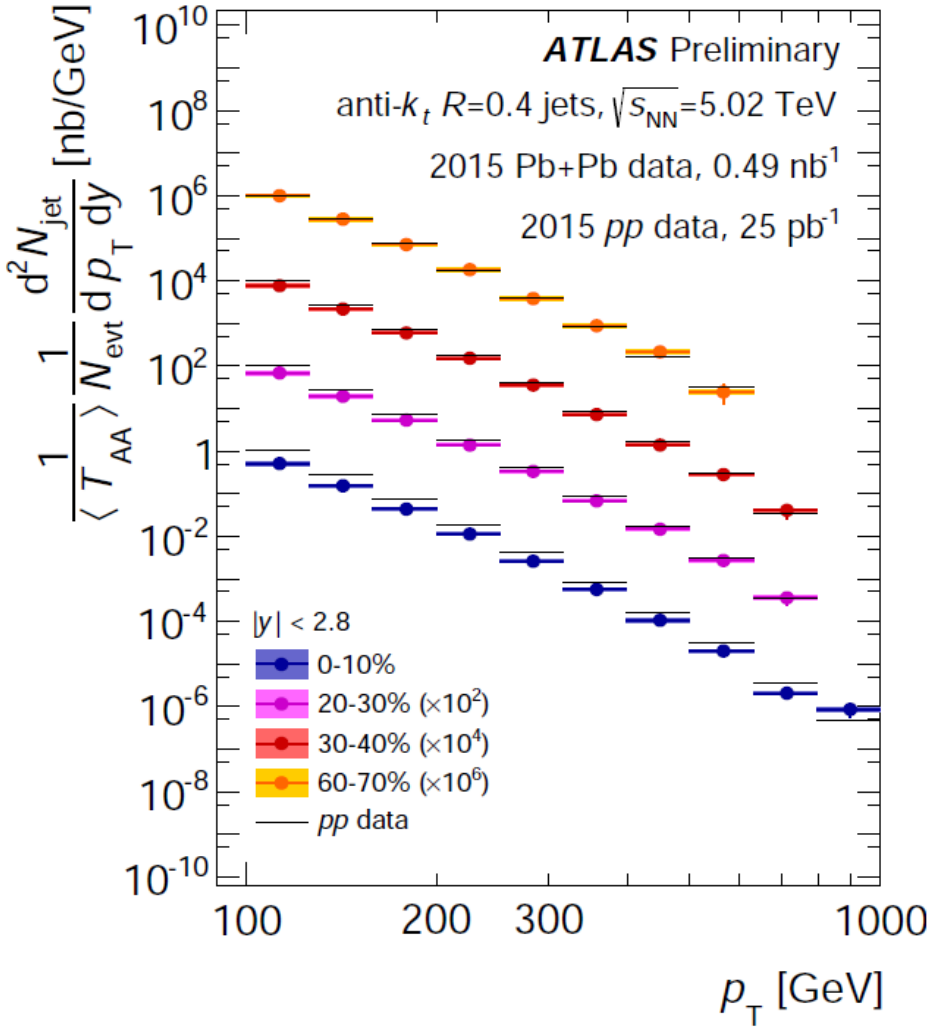


Jet yeilds in Pb+Pb collisions

2.76 TeV

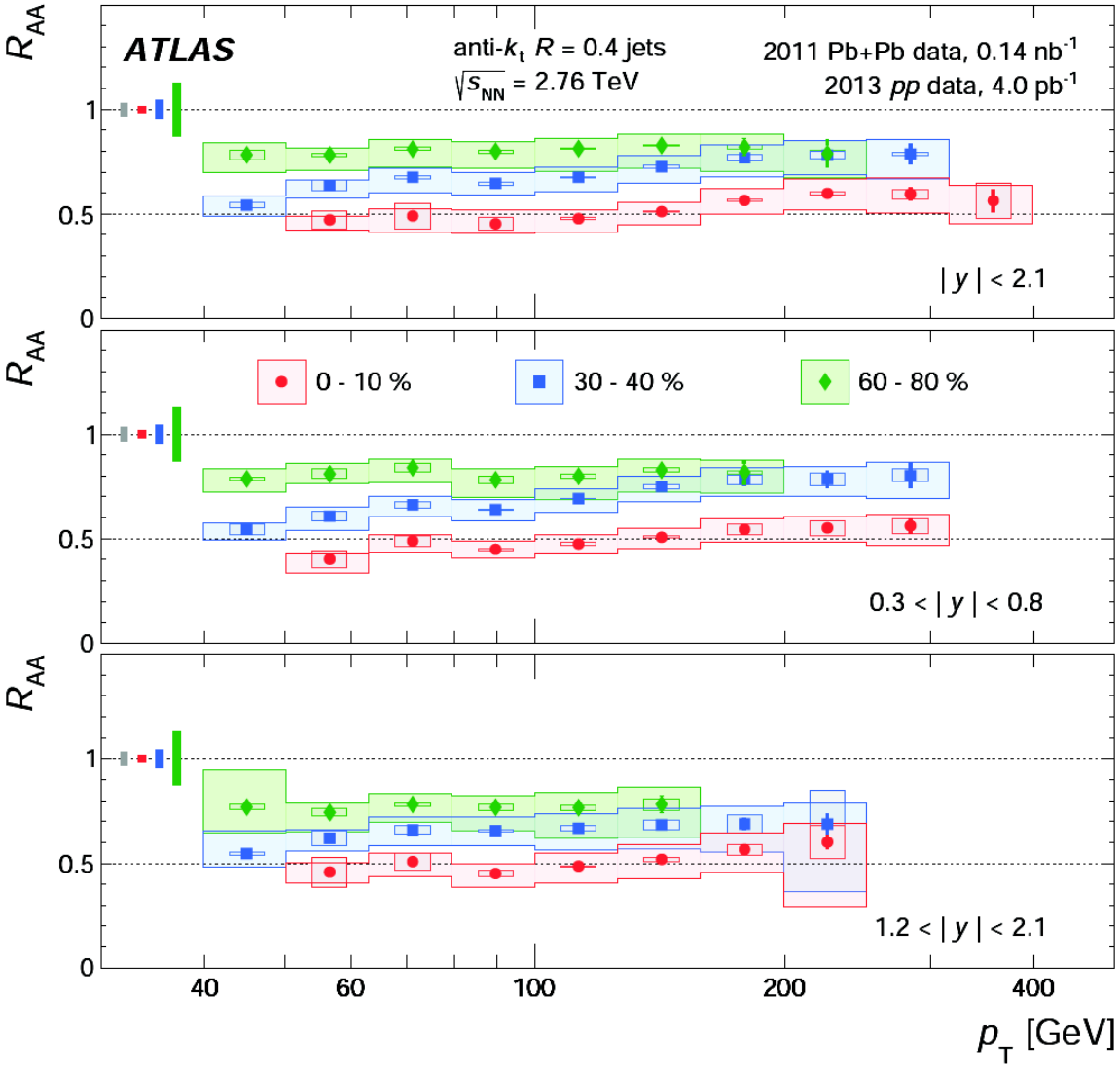


5.02 TeV



Jet R_{AA}: p_T-dependence, $\sqrt{s_{NN}}$ = 2.76 TeV

PRL 114 (2015) 072302

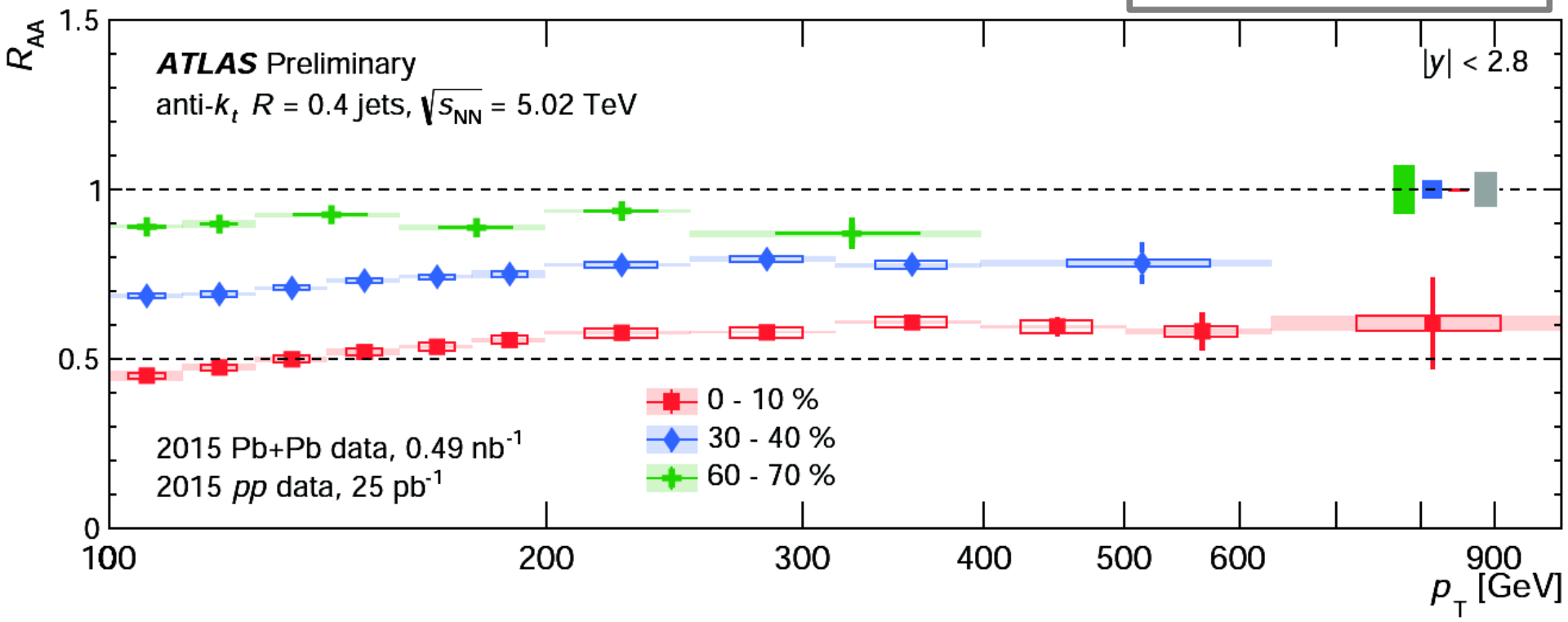


$$R_{\mathrm{AA}} = \frac{\frac{1}{N_{\mathrm{evnt}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}} \rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2 \sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

- A **modest grow** of jet R_{AA} with increasing jet p_T.
- Still significant **suppression even for 60-80%** centrality bin.

Jet R_{AA}: p_T-dependence, $\sqrt{s_{NN}}$ = 5.02 TeV

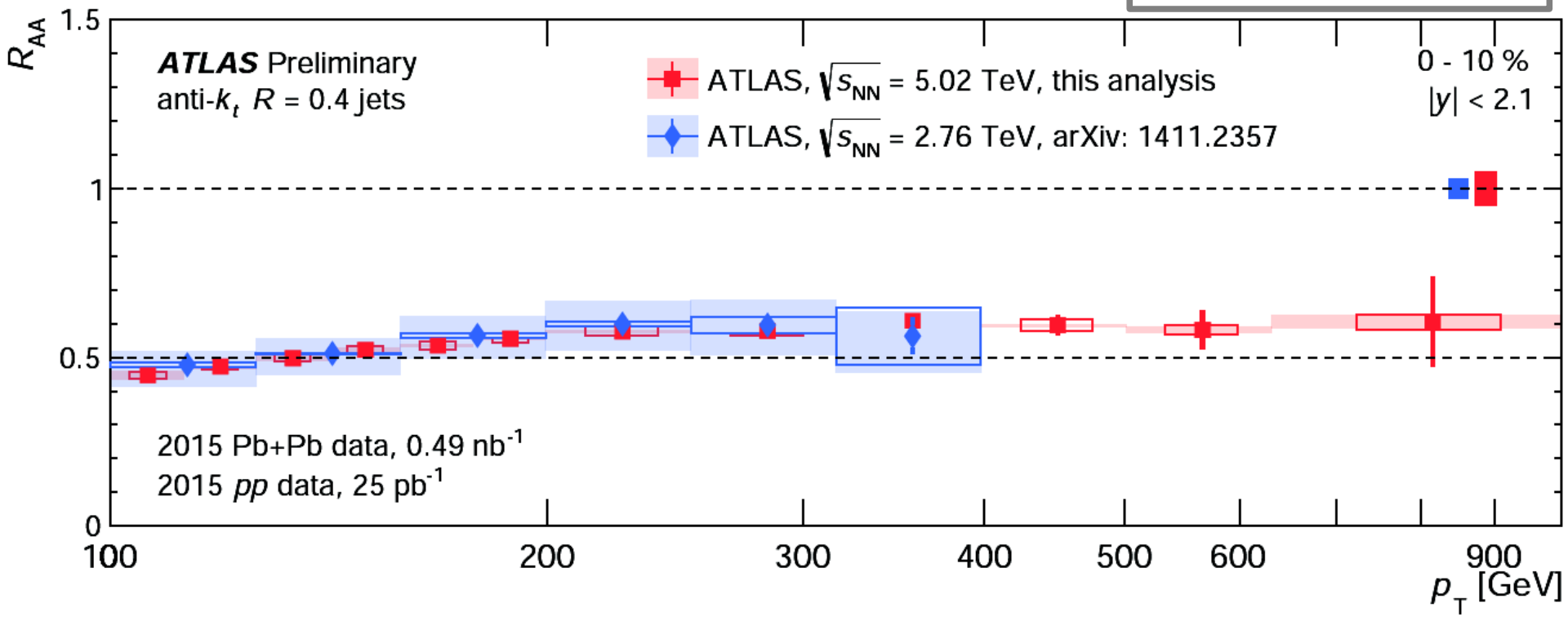
ATLAS-CONF-2017-009



- Quantifying jet R_{AA} in the p_T range of **100 GeV to 1 TeV** and for $|y|<2.8$.
- Allows for **detailed comparison** with predictions e.g.: X-N Wang et al. (arXiv:1611.07211), Chien and Vitev (arXiv:1509.07257), Casalderrey-Solana et al. (arXiv:1508.00815).

Jet R_{AA}: p_T-dependence, 2.76 TeV versus 5.02 TeV

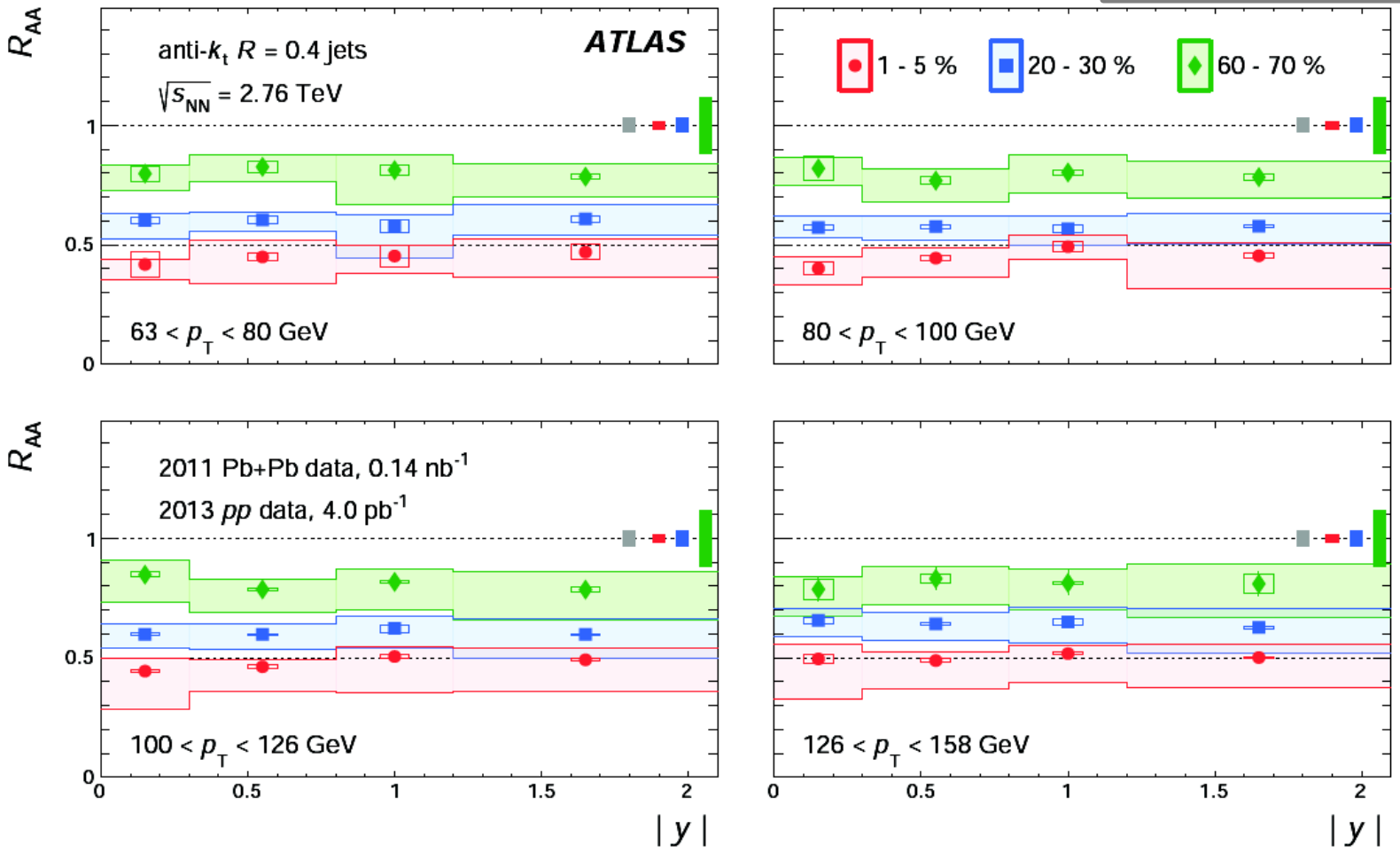
ATLAS-CONF-2017-009



- **Same magnitude** of R_{AA} within systematic uncertainties seen at the two different center-of-mass energies.
- Significant **reduction of** (experimental) **systematic uncertainties** in the new measurement mainly due to taking the data in the same running period.

Jet R_{AA}: y-dependence, $\sqrt{s_{NN}}$ = 2.76 TeV

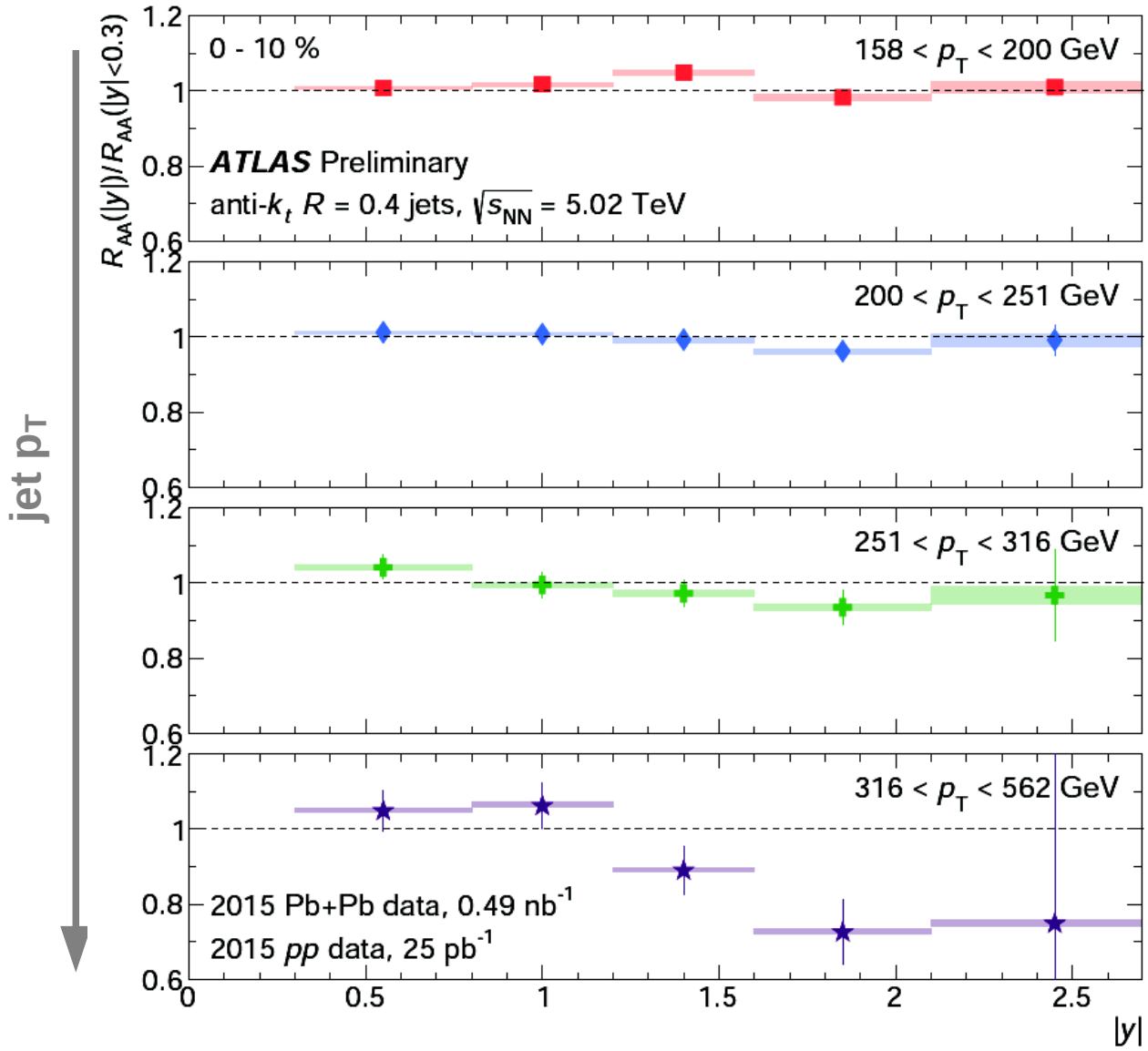
PRL 114 (2015) 072302



… no rapidity dependence seen

Jet R_{AA}: y-dependence, $\sqrt{s_{NN}}$ = 5.02 TeV

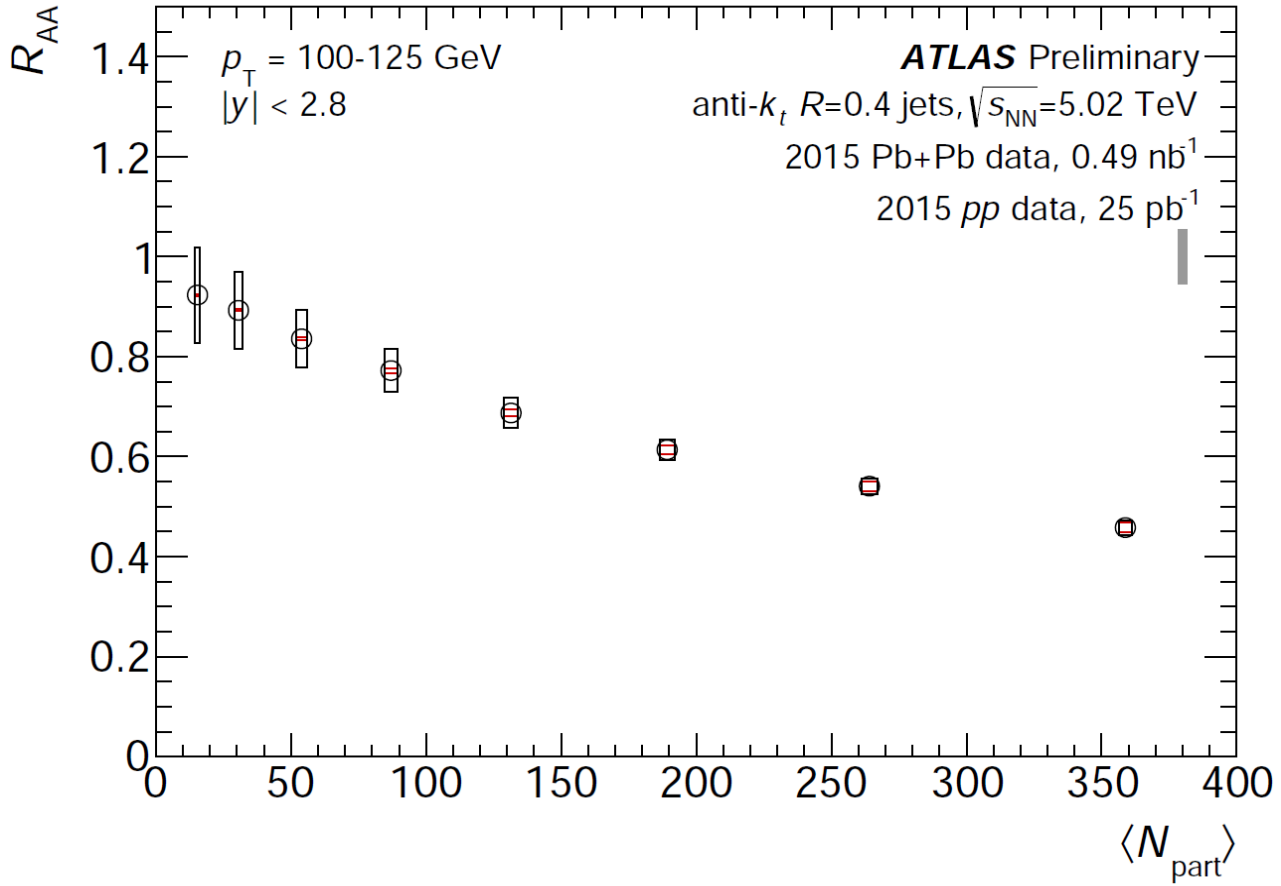
ATLAS-CONF-2017-009



- Vertical-axis: ratio of R_{AA} in a given rapidity to the R_{AA} for jets with $|y|<0.3$.
- With increasing jet p_T R_{AA} getting **smaller in the forward region** as compared to the mid-rapidity region (predicted in arXiv:1504.05169).

Jet R_{AA}: N_{part}-dependence $\sqrt{s_{NN}}$ = 5.02 TeV

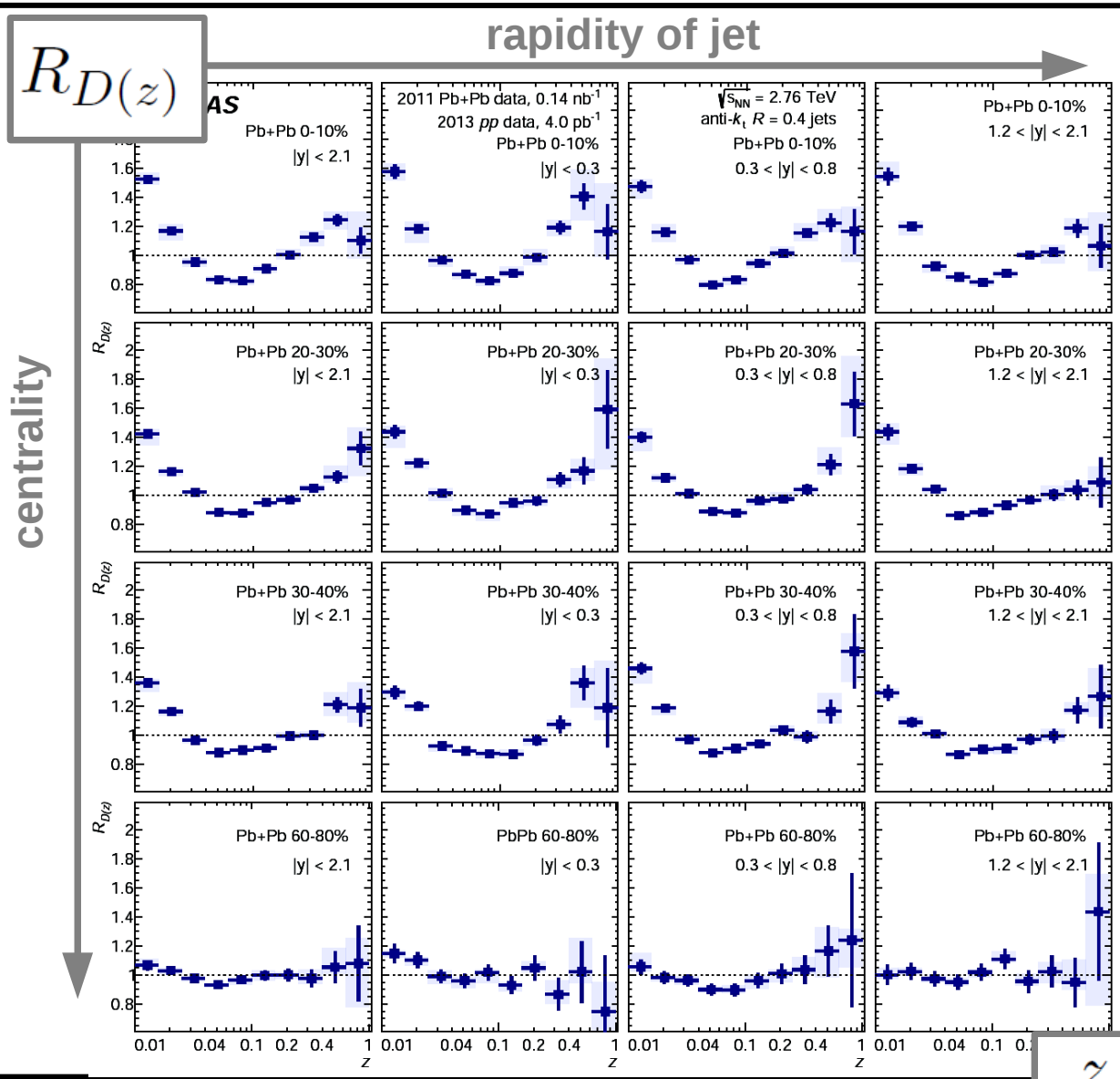
ATLAS-CONF-2017-009



… **smooth decrease** of R_{AA}
with increasing centrality

Internal structure of jets at 2.76 TeV

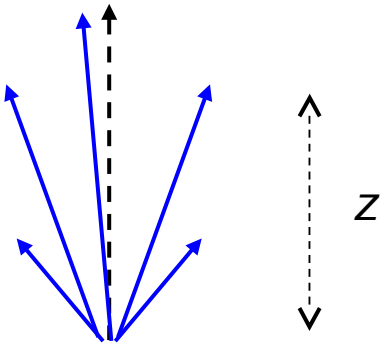
arXiv:1702.00674



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

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

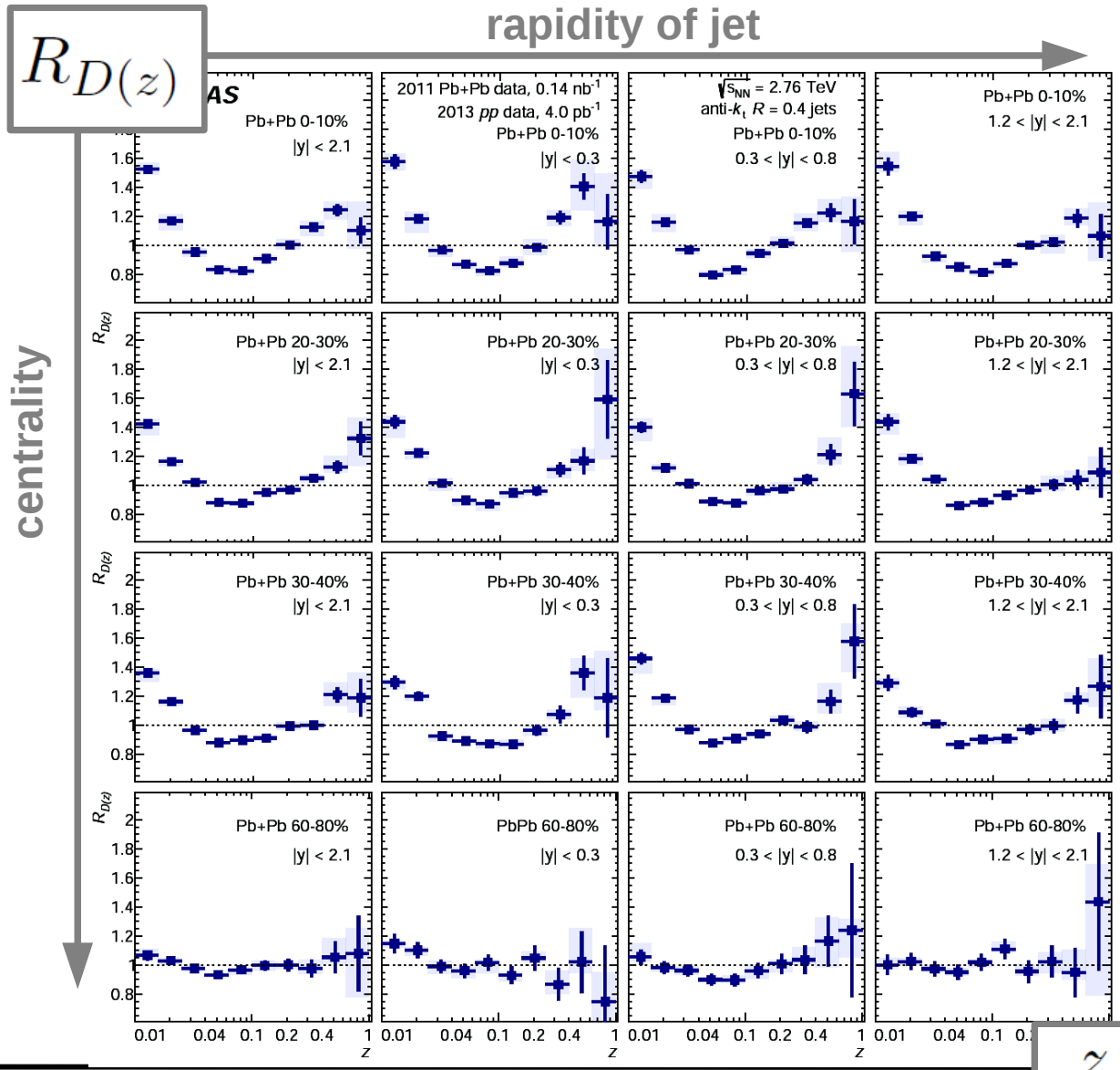
$$z = \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{jet}} \cos \Delta R$$



See also talk by Radim Slovák Tue 11:40

Internal structure of jets at 2.76 TeV

arXiv:1702.00674



Centrality dependence

- Enhancement at low z and at high z
- Suppression at intermediate z

Jet pt dependence

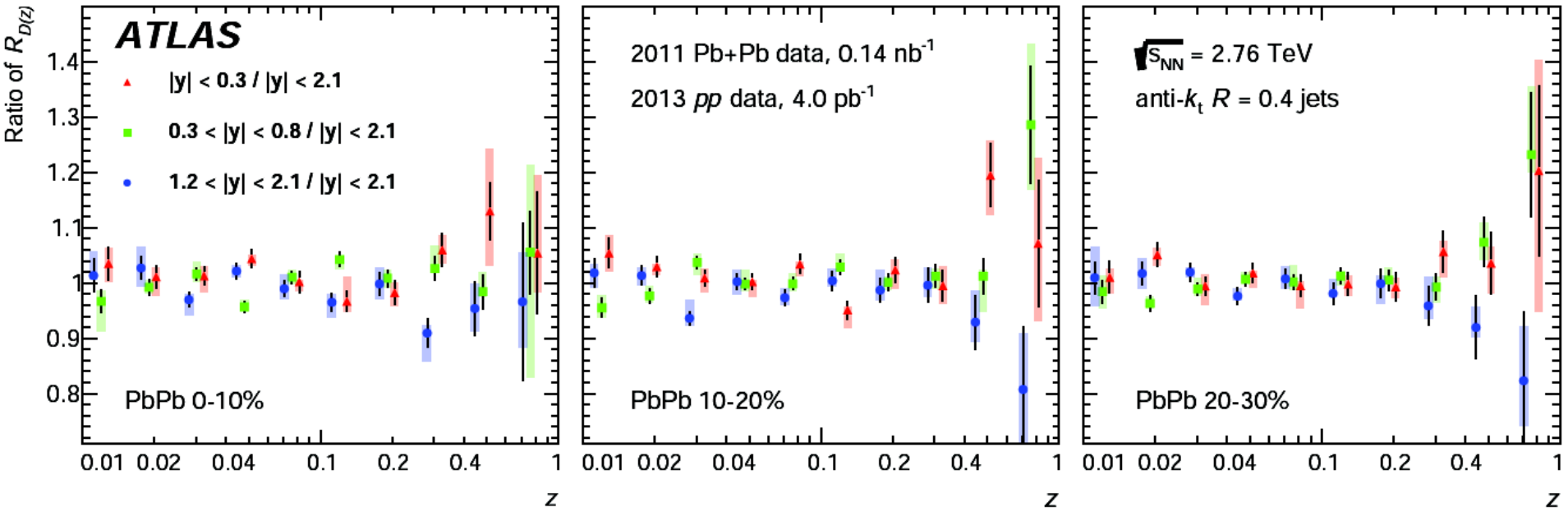
- No significant dependence on jet p_T (not shown here)

Rapidity dependence

… next slide

Internal structure of jets at 2.76 TeV

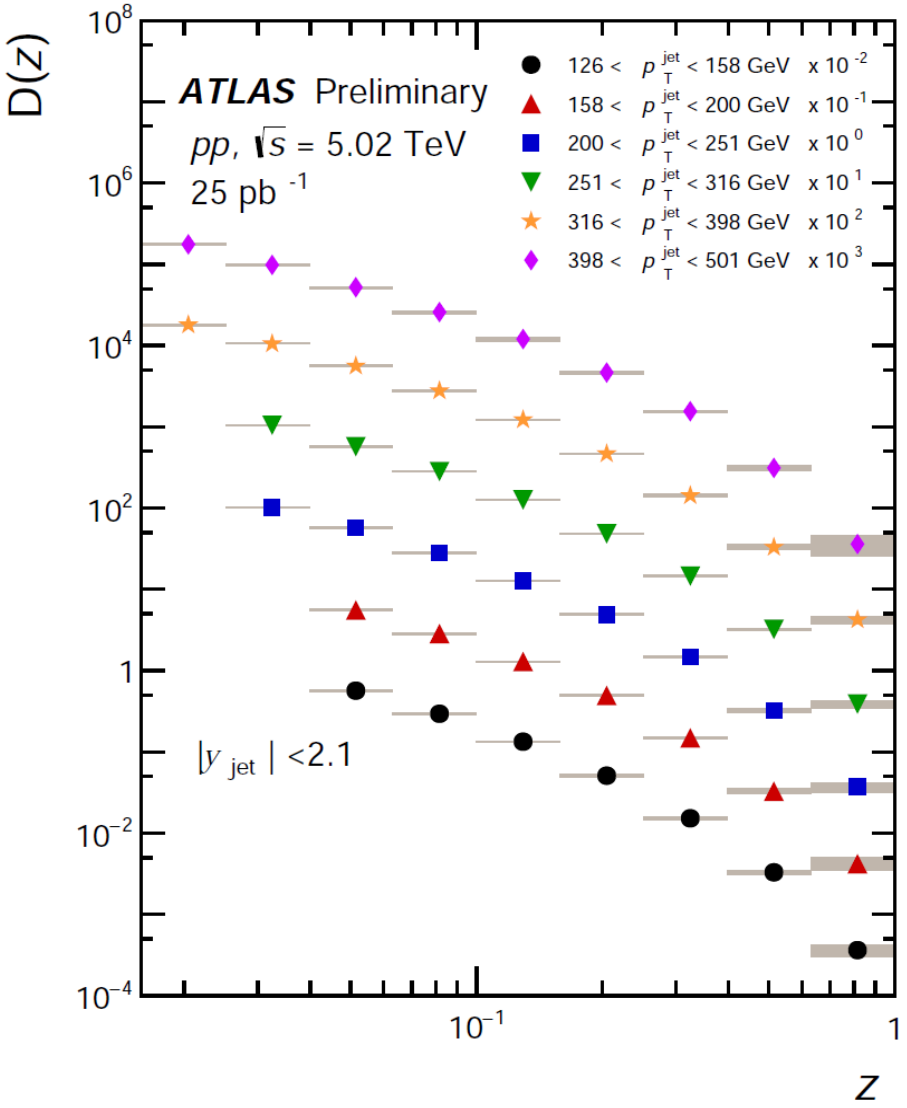
arXiv:1702.00674



Sign of a larger enhancement at high z in the mid-rapidity region as compared to the forward rapidity region (explanation for this proposed in arXiv:1504.05169).

Internal structure of jets in *pp*

ATLAS-CONF-2017-005

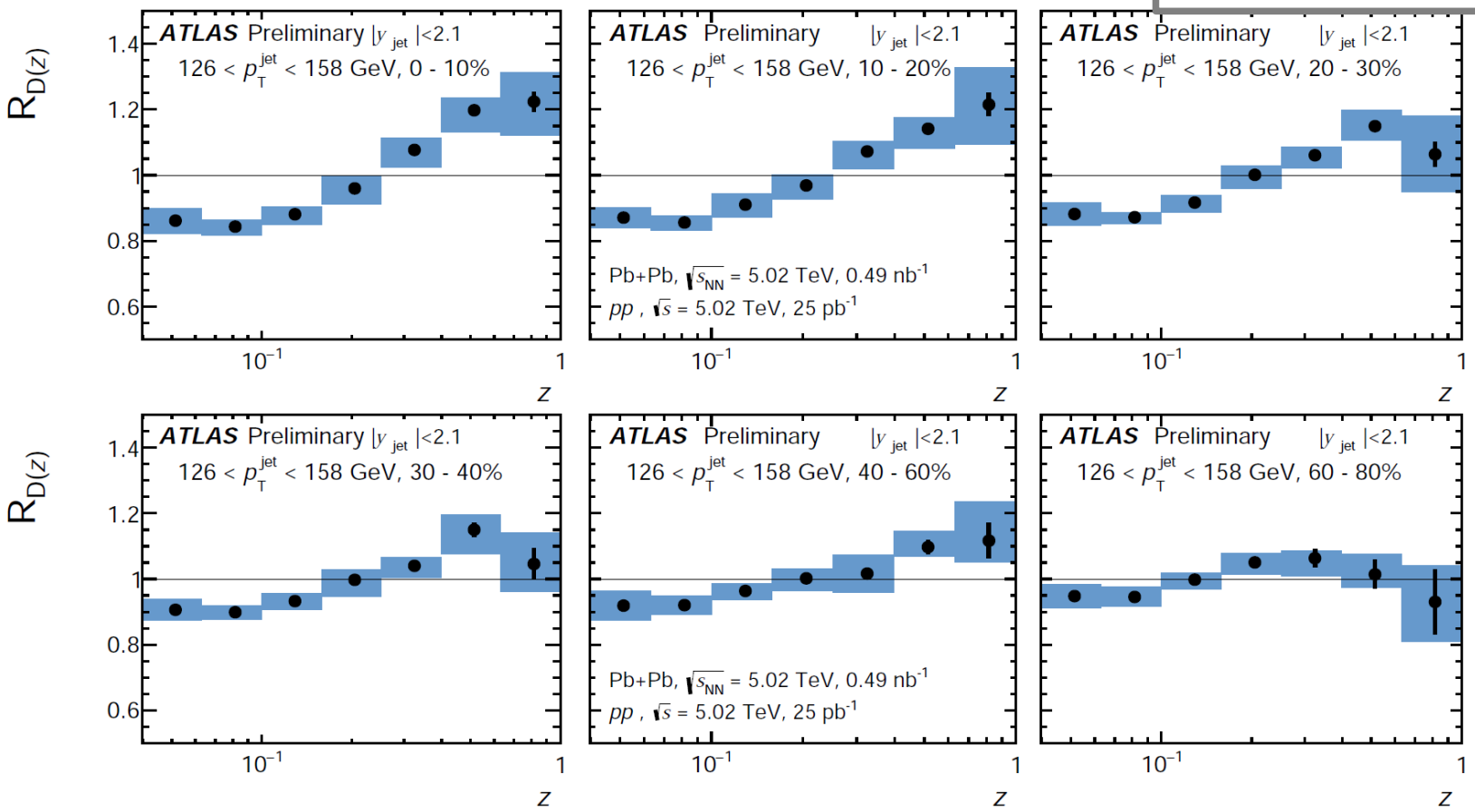


Fragmentation functions and distributions of charge particle momentum inside jet **measured in *pp* collisions** both at 2.76 TeV and 5.02 TeV.

=> Can be used as a **realistic *pp* reference** for jet quenching studies and to tune the MC generators.

Internal structure of jets at 5.02 TeV

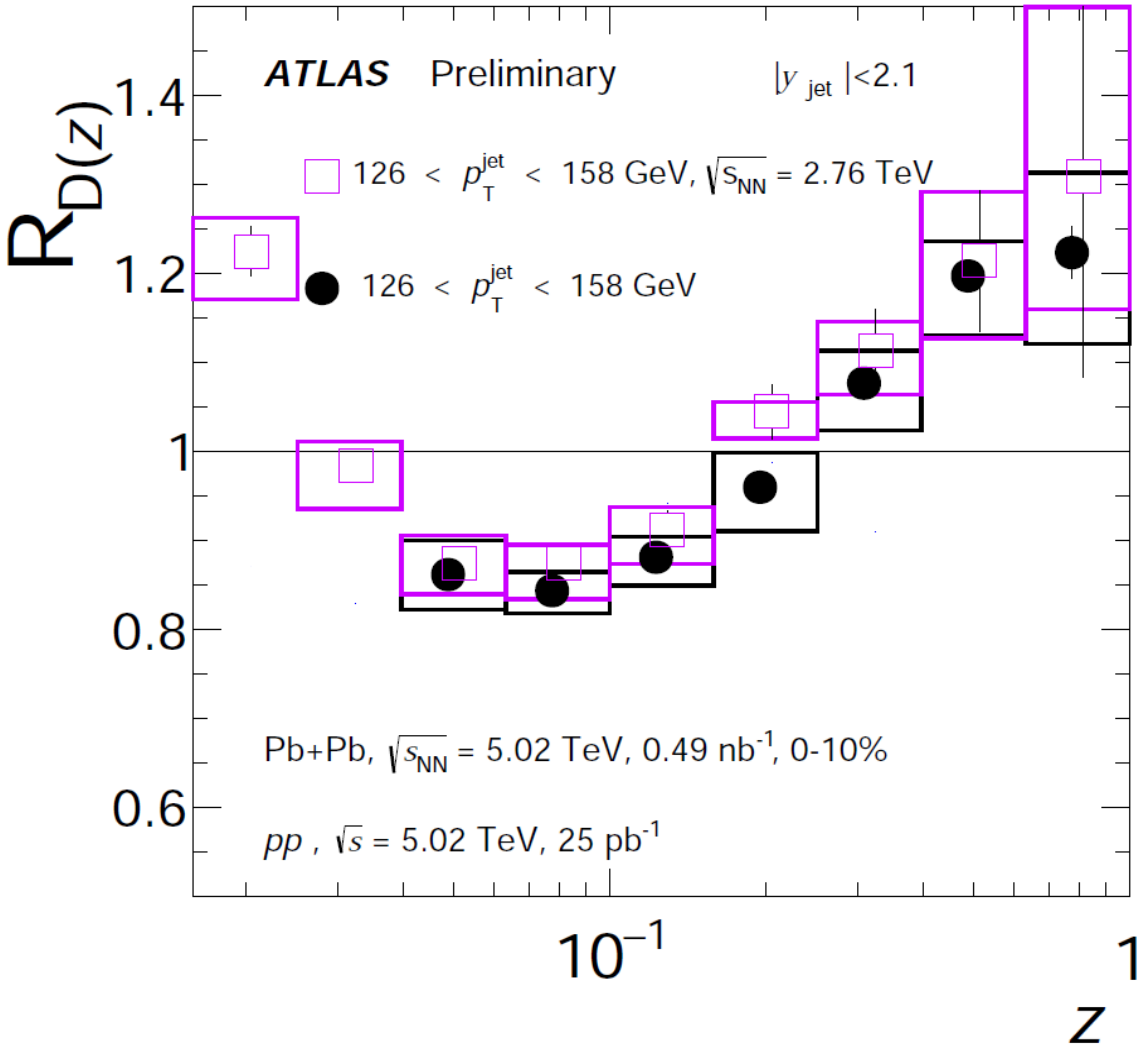
ATLAS-CONF-2017-005



- Ratios of $D(z)$ distributions for tracks with p_T>4 GeV.
- Same features seen in 5.02 TeV as in 2.76 TeV (the enhancement at high z and depletion at intermediate z).

Internal structure of jets at 5.02 TeV

ATLAS-CONF-2017-005

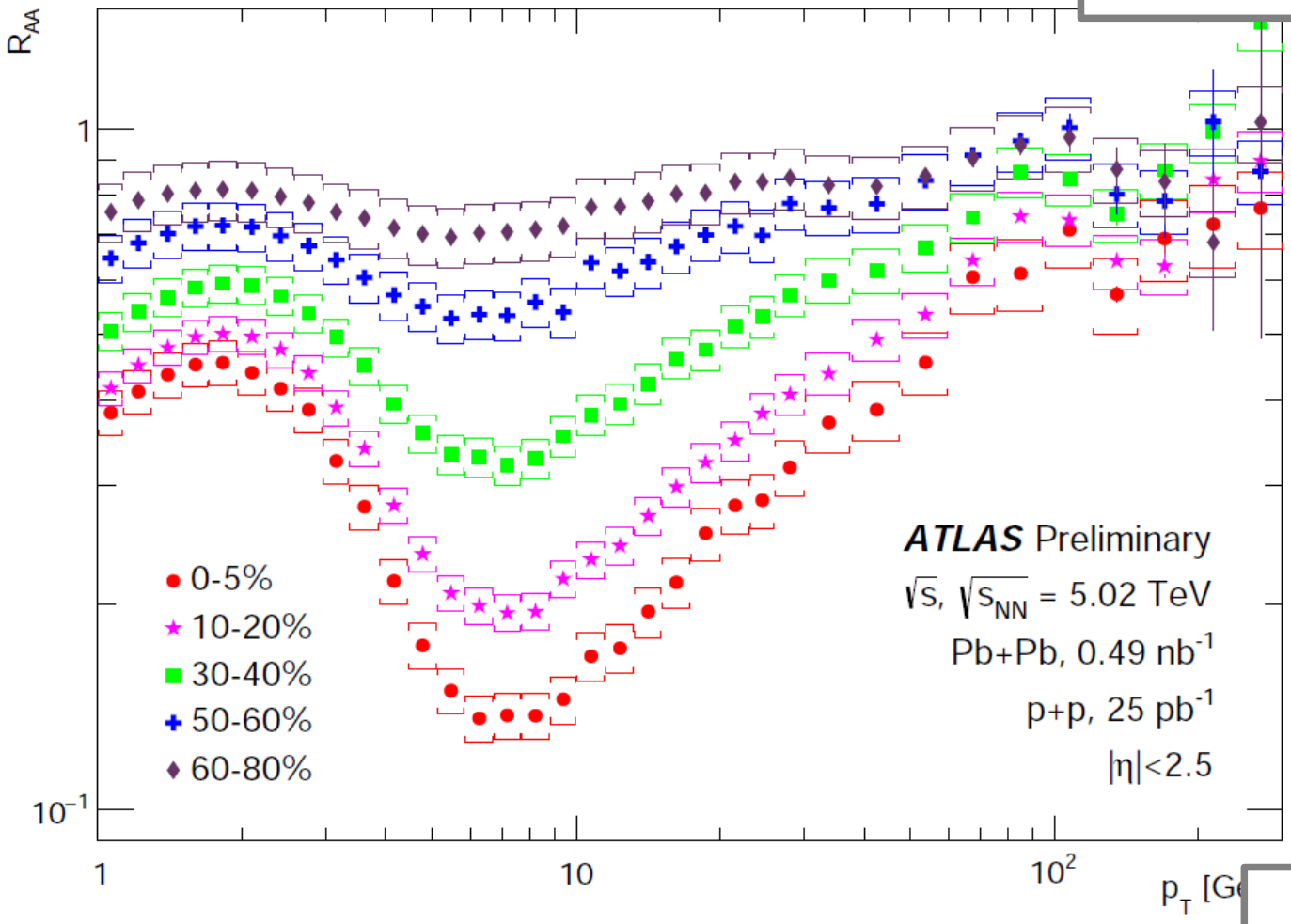


… 5.02 TeV measurement agrees with 2.76 TeV measurement at the comparable *z* domain

See also talk by Radim Slovák Tue 11:40

Charged hadron R_{AA}

ATLAS-CONF-2017-012

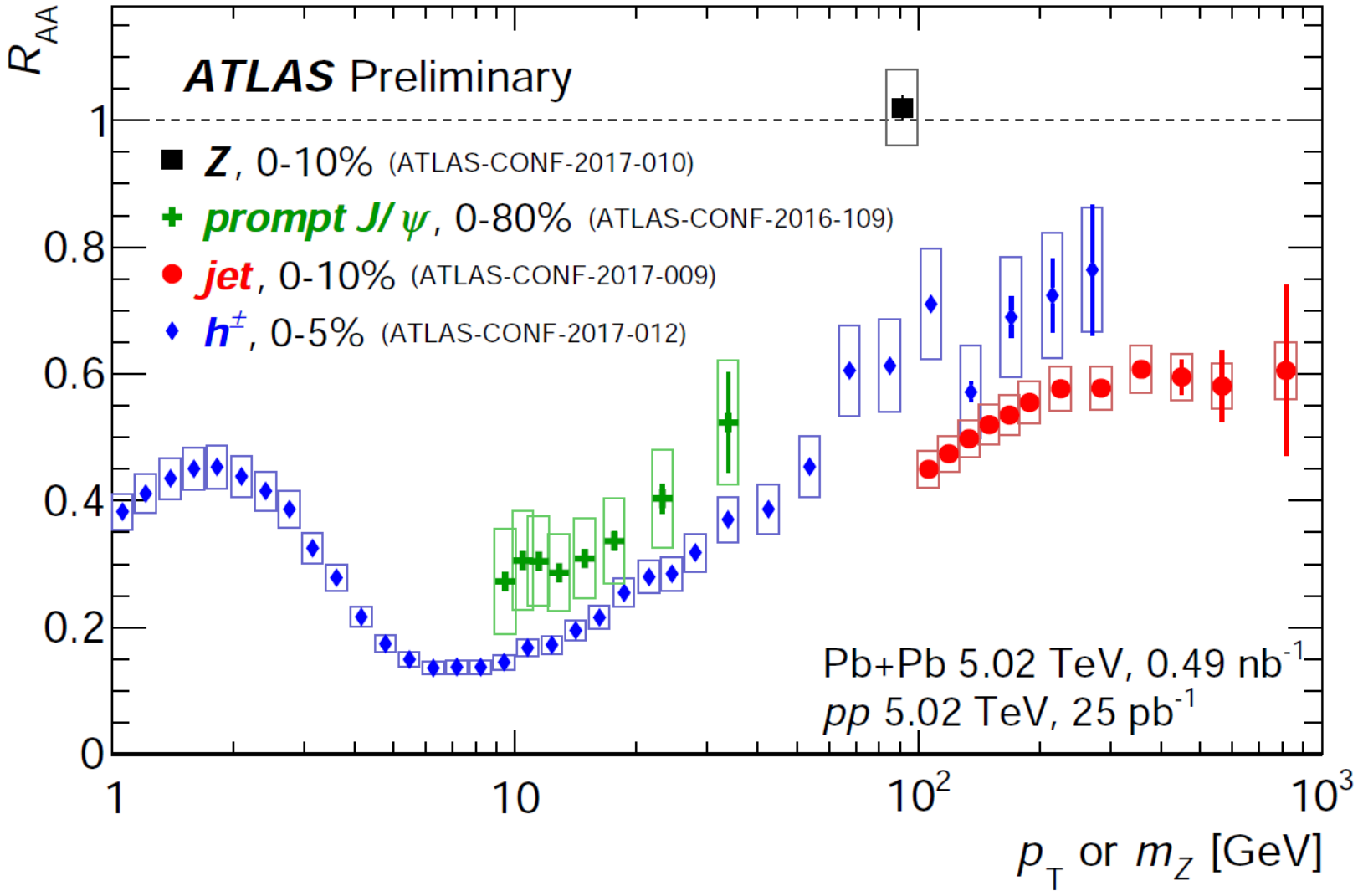


Charged hadron R_{AA} measured for p_T=1-300 GeV

–> a trend of flattening at high p_T

See also poster by Alexander Milov

Charged hadron R_{AA} versus jet R_{AA}

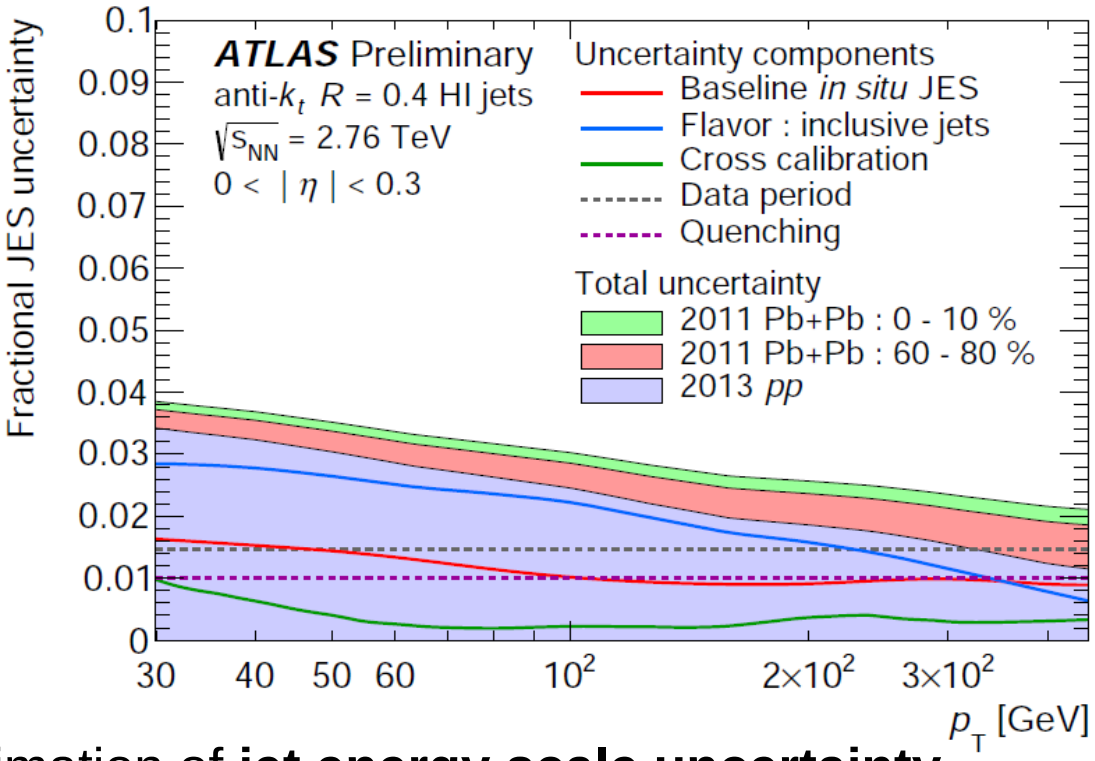


Summary

- Inclusive jet suppression:
  - Significant suppression seen up to ~1 TeV.
  - Rapidity dependence of R_{AA} observed for high-p_T jets.
  - Quantitatively consistent R_{AA} between 2.76 TeV and 5.02 TeV.
- Internal structure of jets:
  - Measured differentially in jet p_T and rapidity.
  - Enhancement at low z, suppression at intermediate z, and enhancement at high z precisely quantified.
  - Different size of high-z enhancement seen for forward and mid-rapidity jets.
  - Qualitatively same modifications of jet fragmentation seen at 2.76 TeV and 5.02 TeV.

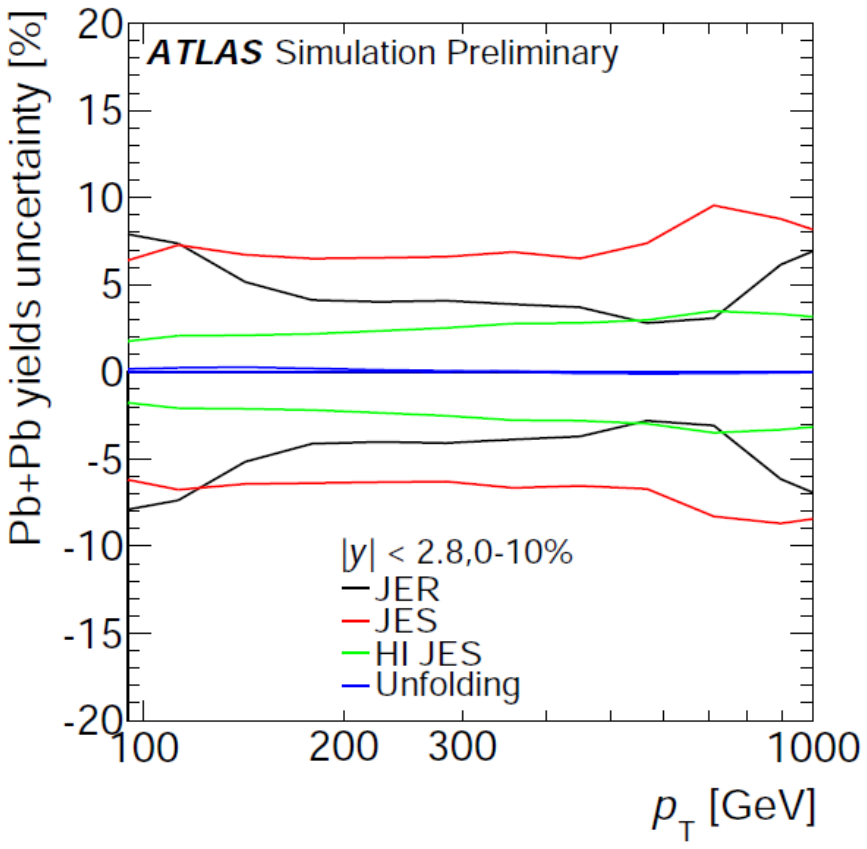
Backup slides

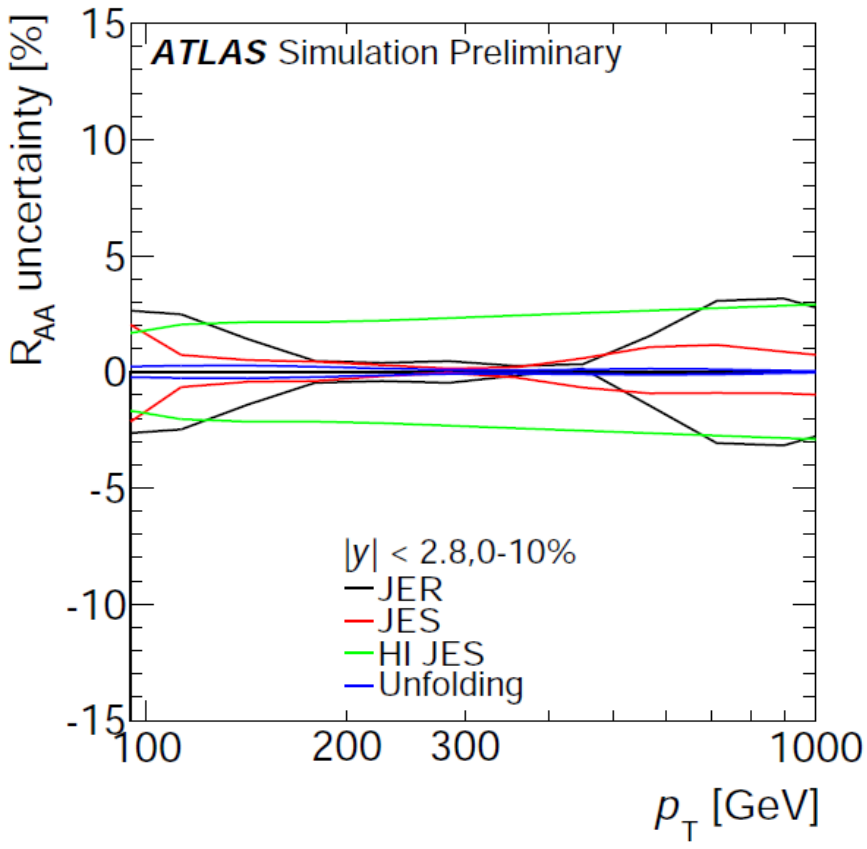
Jet energy scale uncertainties



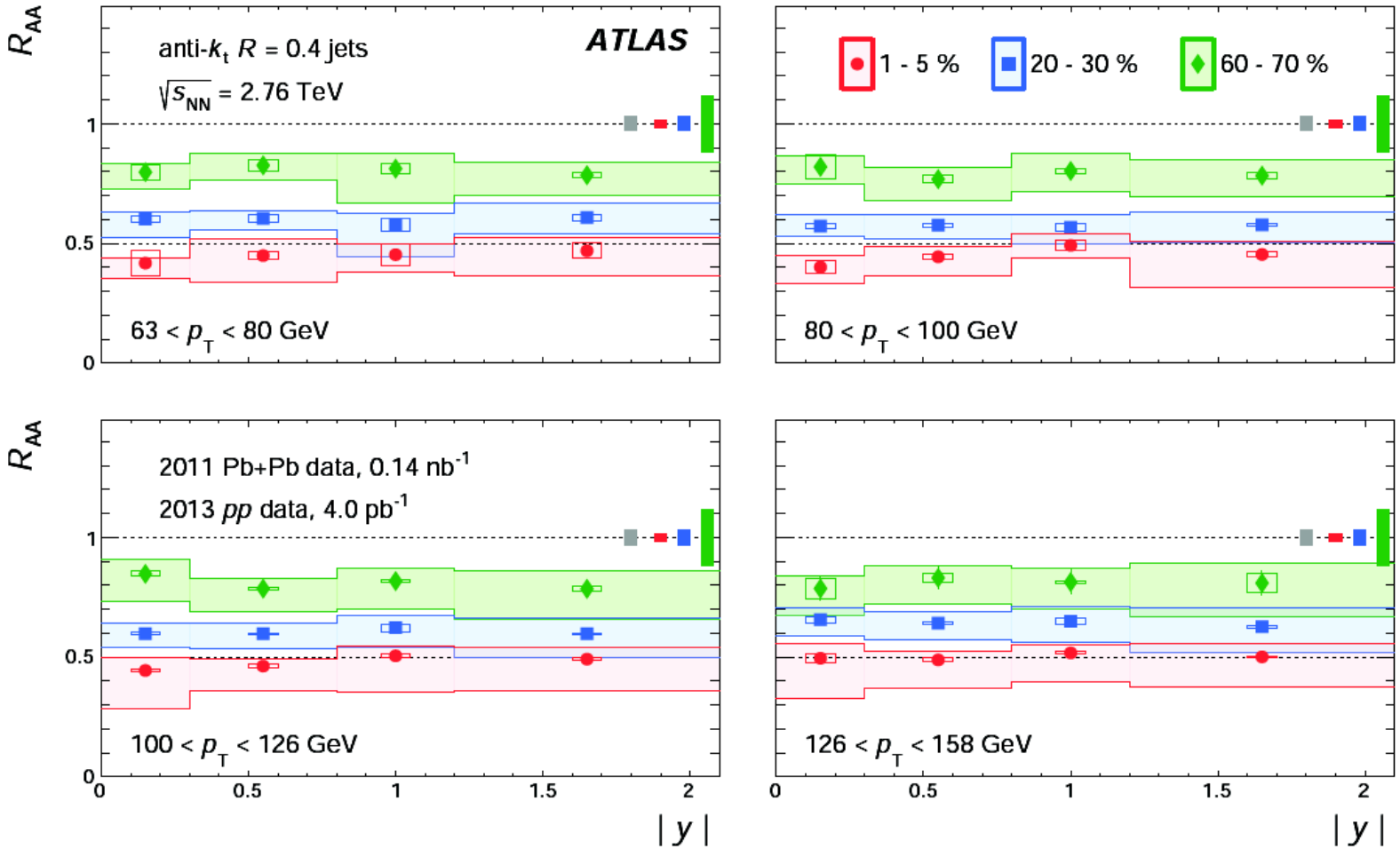
- Detailed estimation of **jet energy scale uncertainty**.
- Using ***in situ*** techniques (γ+jet and Z+jet) and limits on the impact of modified fragmentation on jet energy scale.
- Same level of **rigor as in precision pQCD** measurement should be a standard for precision HI measurements in the run II.

Run 2 jet yields and Raa uncertainties

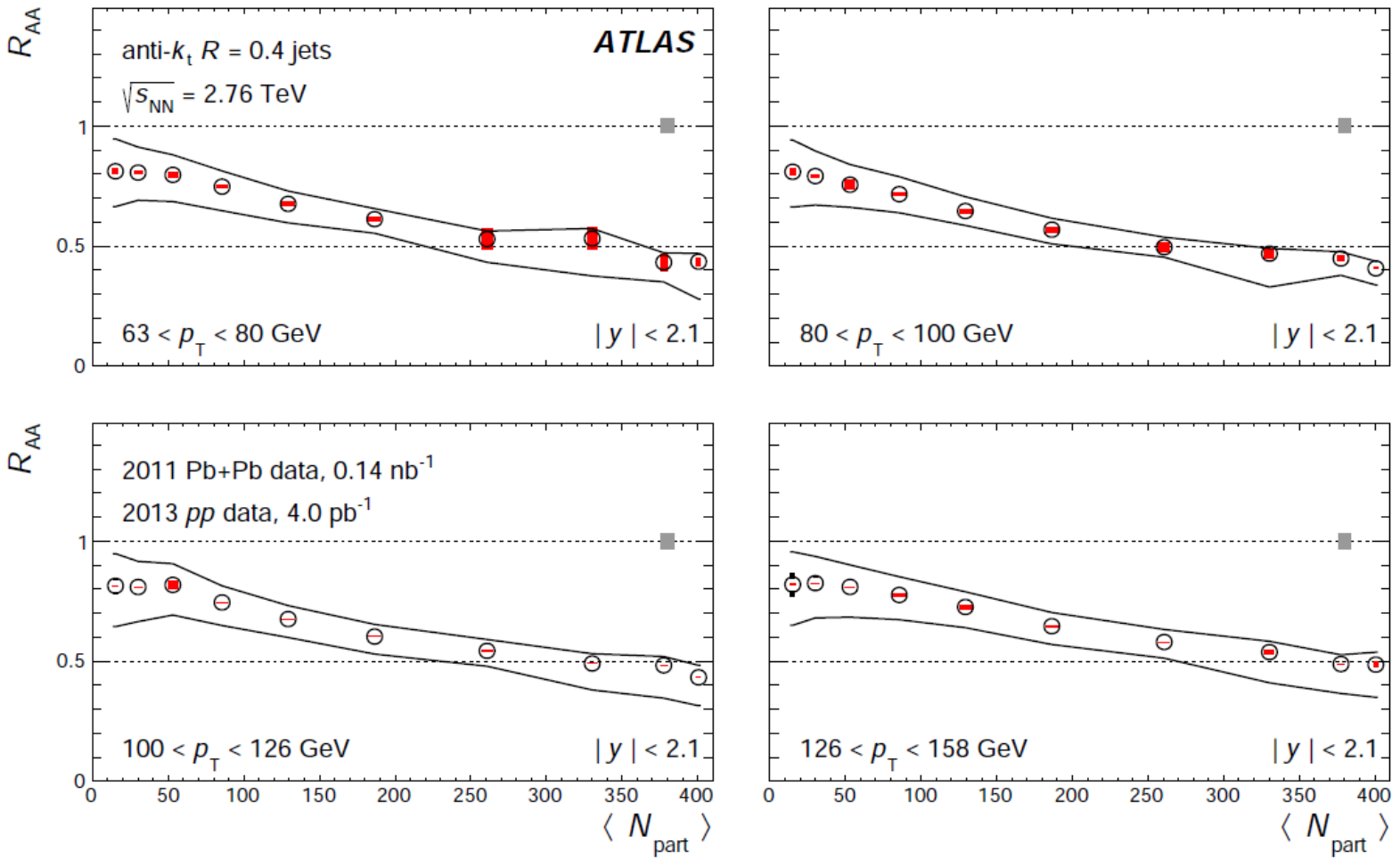




Jet R_{AA}

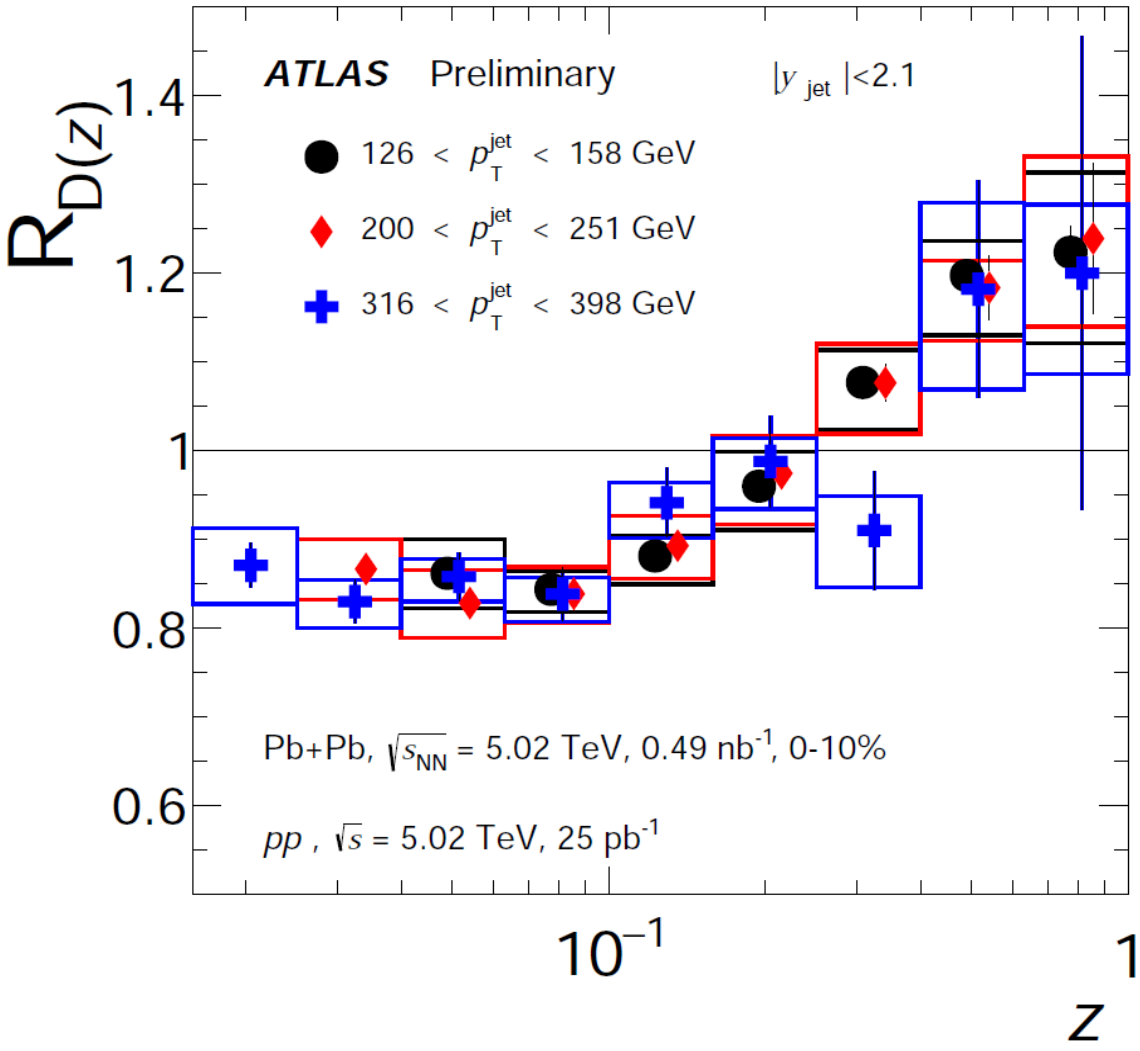

R_{AA}
anti-k_t R = 0.4 jets
$\sqrt{s_{NN}}$ = 2.76 TeV
ATLAS
1 - 5 %
20 - 30 %
60 - 70 %
63 < p_T < 80 GeV
80 < p_T < 100 GeV
2011 Pb+Pb data, 0.14 nb^{-1}
2013 pp data, 4.0 pb^{-1}
100 < p_T < 126 GeV
126 < p_T < 158 GeV
| y |

Jet R_{AA}


R_{AA}
anti-k_t R = 0.4 jets
$\sqrt{s_{NN}}$ = 2.76 TeV
ATLAS
63 < p_T < 80 GeV
| y | < 2.1
80 < p_T < 100 GeV
| y | < 2.1
2011 Pb+Pb data, 0.14 nb^{-1}
2013 pp data, 4.0 pb^{-1}
100 < p_T < 126 GeV
| y | < 2.1
126 < p_T < 158 GeV
| y | < 2.1
0
0.5
1
0
50
100
150
200
250
300
350
400
⟨ N_{part} ⟩

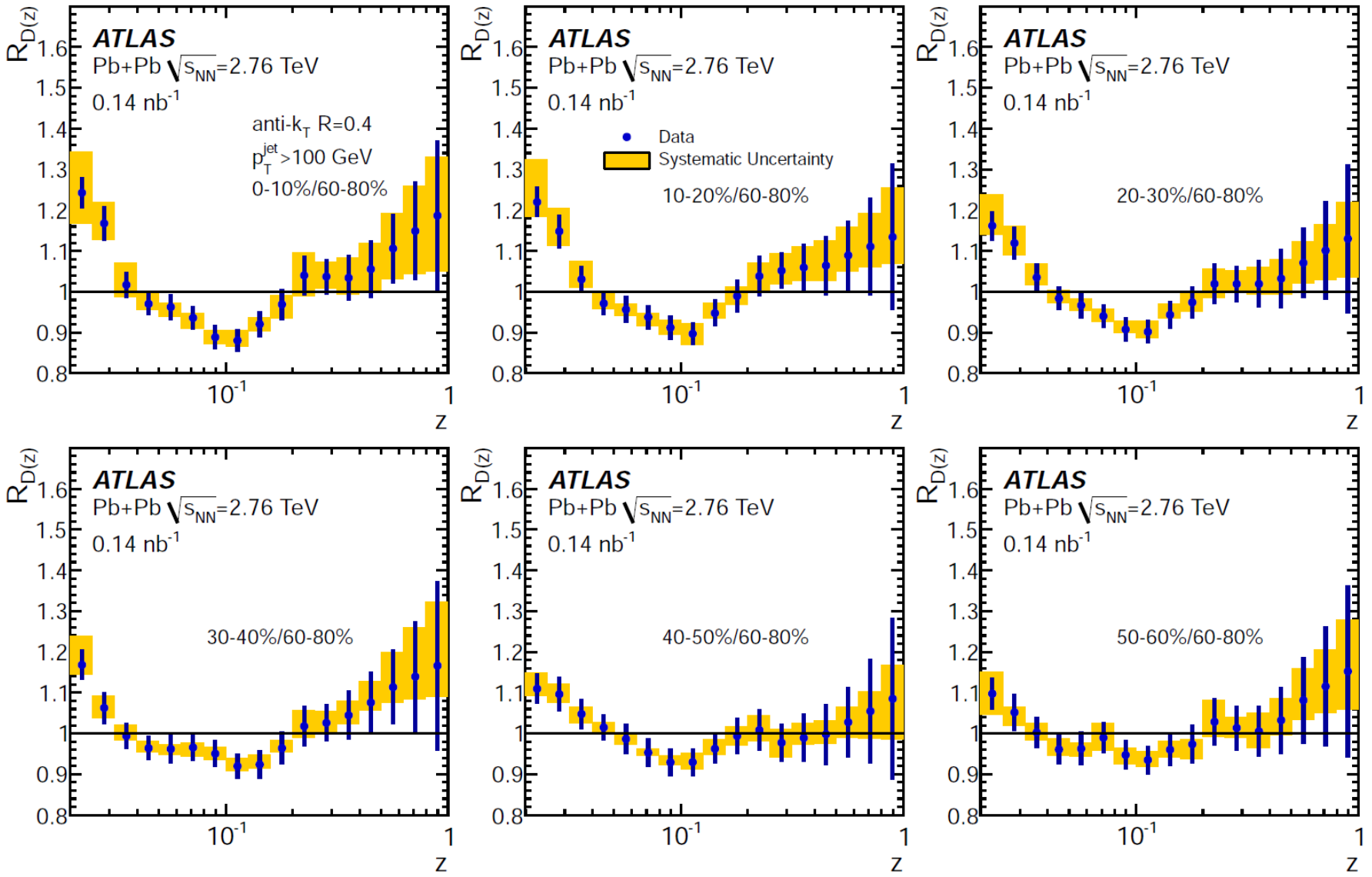
Internal structure of jets at 5.02 TeV

ATLAS-CONF-2017-005

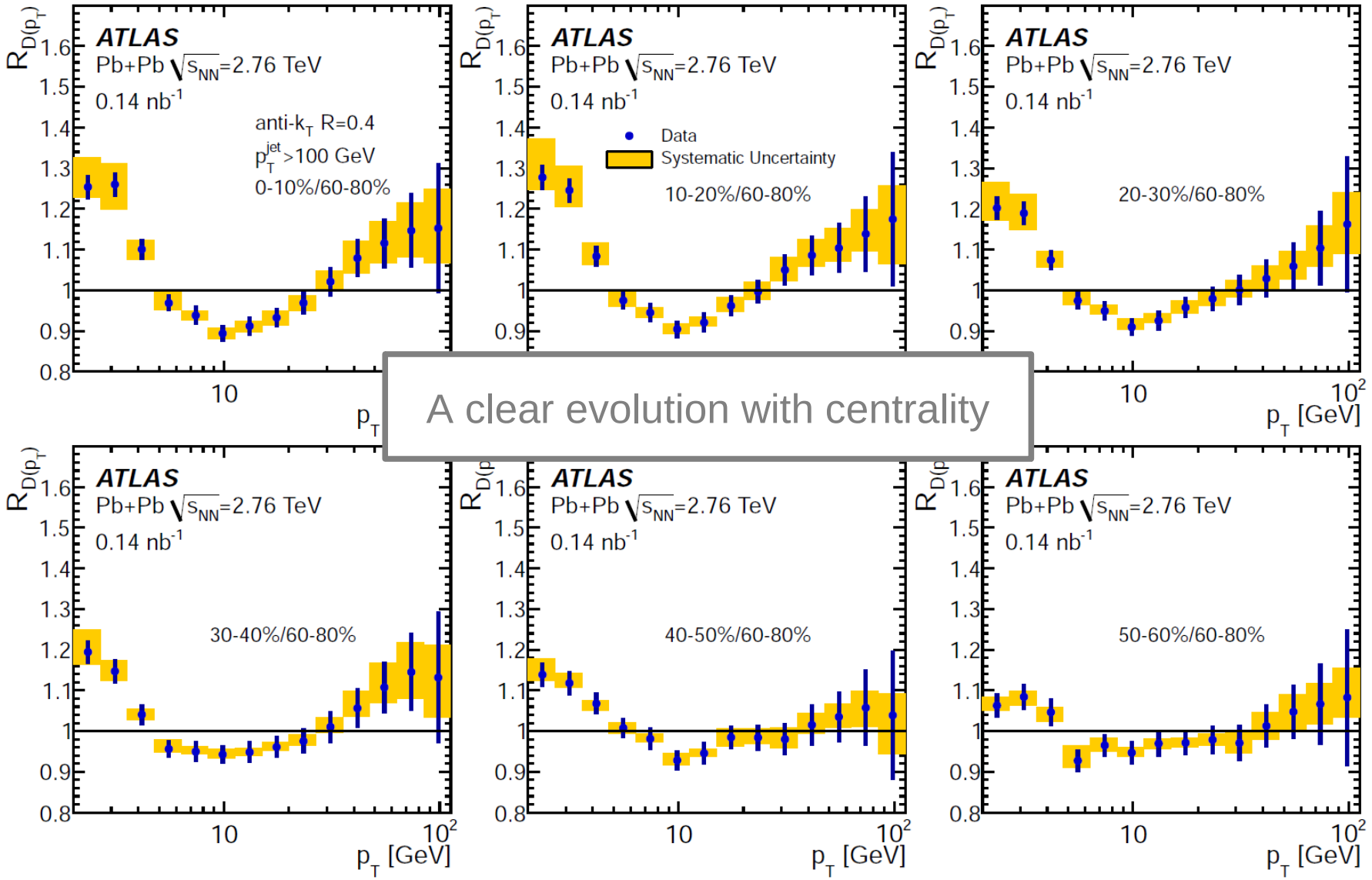


… no jet p_T dependence observed

$R_{D(z)}$ in Pb+Pb for R=0.4 jets



$R_{D(pt)}$ in Pb+Pb for R=0.4 jets



A clear evolution with centrality