Measurement of internal jet structure in Pb+Pb and *pp* collisions at 2.76 TeV

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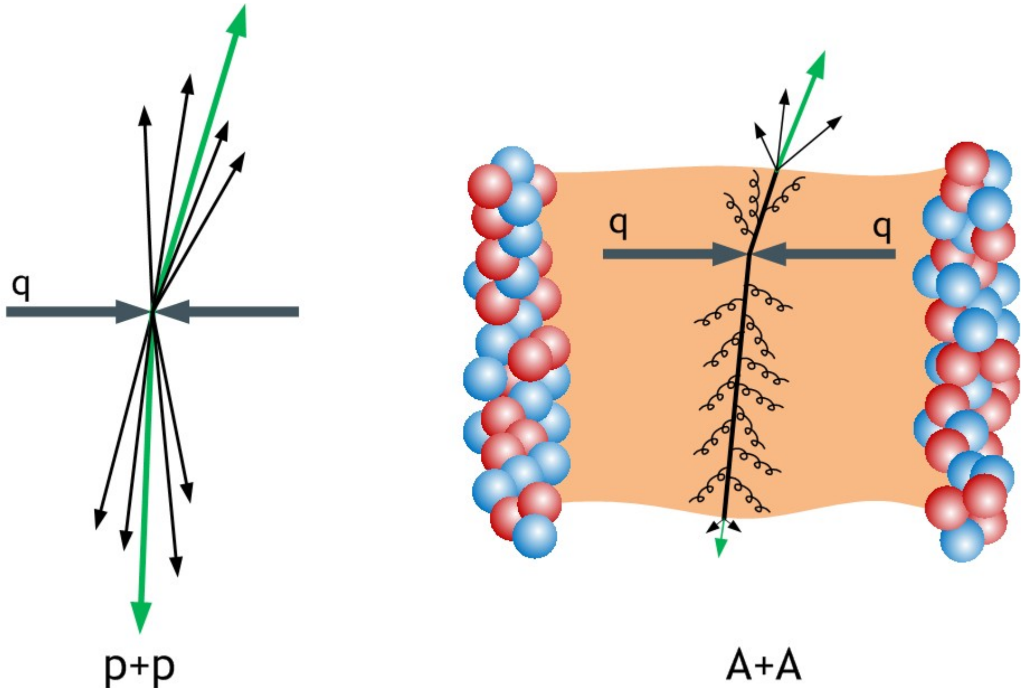
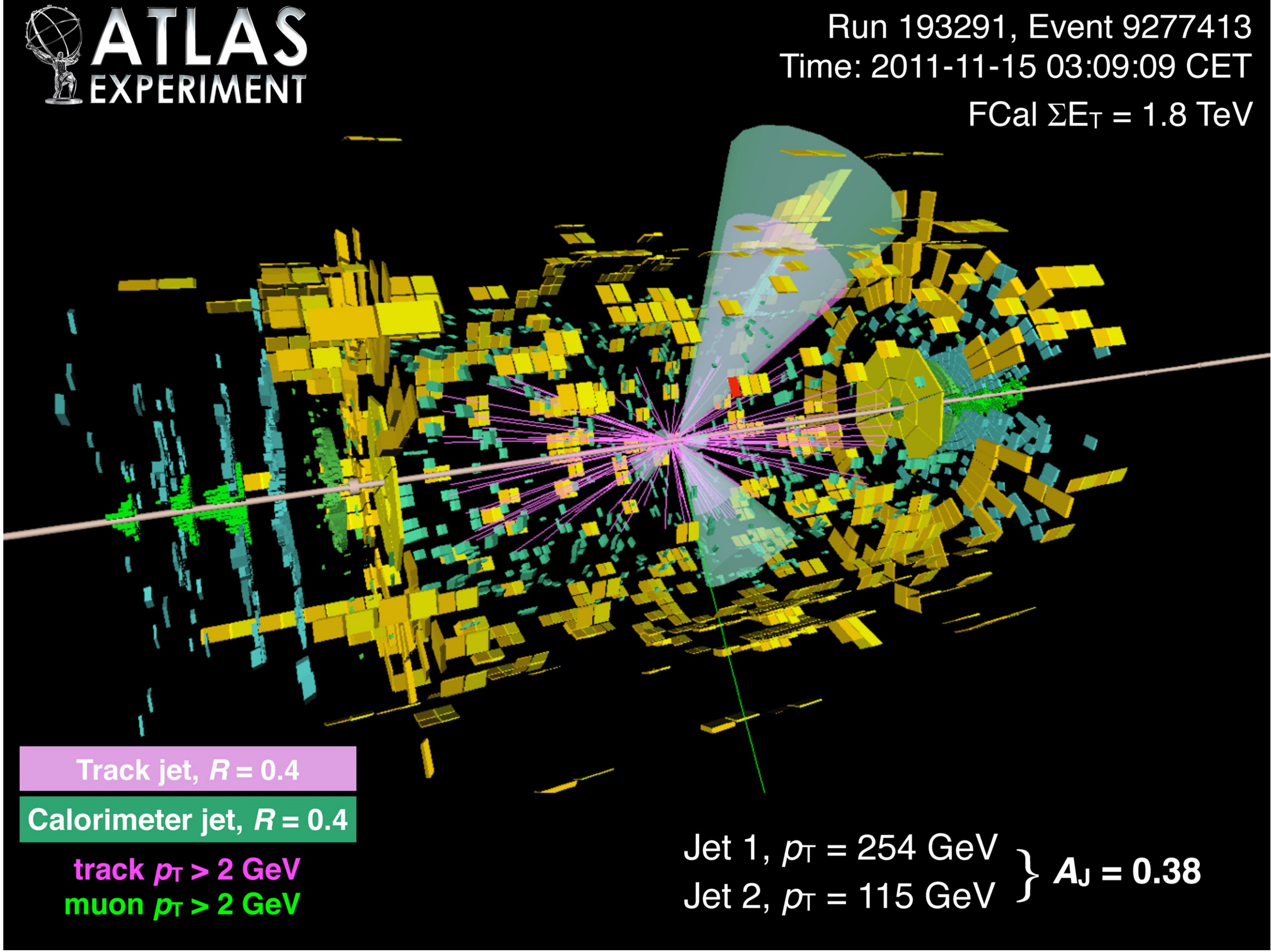
Motivation

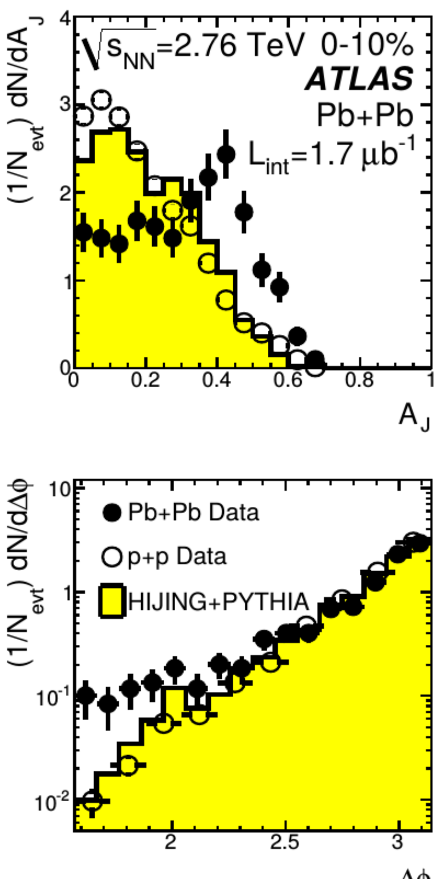
- HI collisions at Ultra-Rel. energies produce medium of strongly interacting matter commonly called Quark-Gluon Plasma (QGP)
- Hard-scattering processes in these collisions produce high-p_T partons that propagate through the medium and lose energy – this phenomenon is called “jet quenching”
- Jet quenching results in the suppression of jet production and the modification of jet internal structure

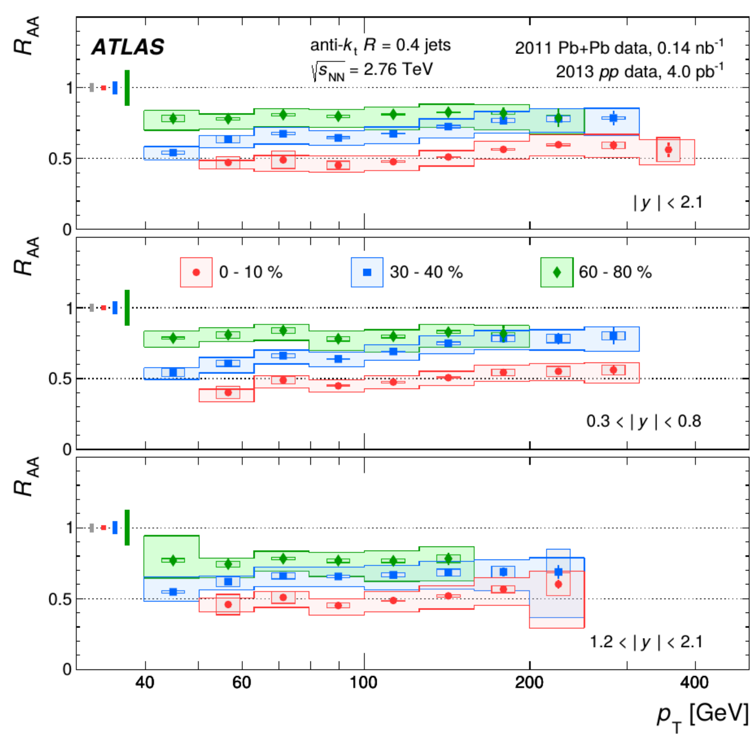


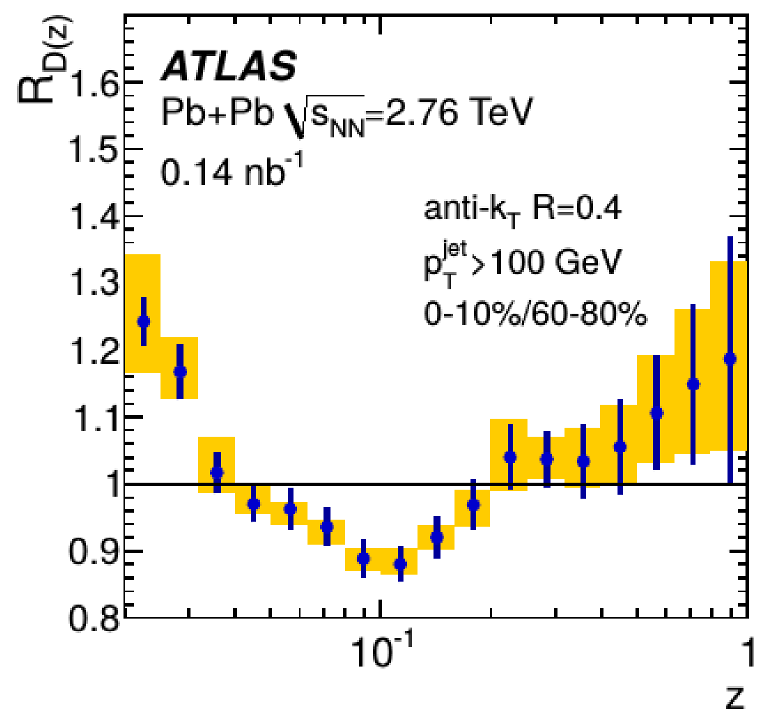

ATLAS EXPERIMENT
Run 193291, Event 9277413
Time: 2011-11-15 03:09:09 CET
FCal ΣE_T = 1.8 TeV
Track jet, R = 0.4
Calorimeter jet, R = 0.4
track p_T > 2 GeV
muon p_T > 2 GeV
Jet 1, p_T = 254 GeV
Jet 2, p_T = 115 GeV
A_J = 0.38

Illustrations of jet quenching

- Some older measurements showing effects of jet quenching on:
  - Dijet asymmetry (left)
  - Jet R_{AA} (middle)
  - Jet Fragmentation (right)







Motivation for this analysis

- Extend and improve our first measurement of FF:
  - Use 2013 pp data as a reference
  - Go lower with track p_T down to 1 GeV
  - Measure D(z) and D(p_T) distributions

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}z}, \qquad z \equiv \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{\mathrm{jet}}} \cos \Delta R = \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{\mathrm{jet}}} \cos \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}$$

    1) In 4 bins in |y|: inclusive, 0.0-0.3, 0.3-0.8, 1.2-2.1
    2) In 4 bins in jet p_T that match the jet R_{AA} measurement: >100, 100-126, 126-159, >159 GeV
  - Reduce systematic uncertainties on distributions using 2D Bayesian unfolding

Data, MC, tracks and jets

- Data:
  - 2011 Pb+Pb data at 2.76 TeV, int. luminosity $L^{PbPb} = 0.14\ nb^{-1}$
  - 2013 pp data at 2.76 TeV, int. luminosity $L^{pp} = 4\ pb^{-1}$
- MC:
  - Pb+Pb: Pythia samples embedded into MinBias Pb+Pb data
  - pp: plain Pythia
- Tracks: reconstructed using pp and HI reconstruction algorithms which are different due to different environment, tracks matched to jets by $\Delta R<0.4$ criterion
- Jets: anti-k_t clustering, R=0.4, p_T > 100 GeV, UE contribution subtracted, bad & fake & non-isolated jets removed,

Analysis flowchart

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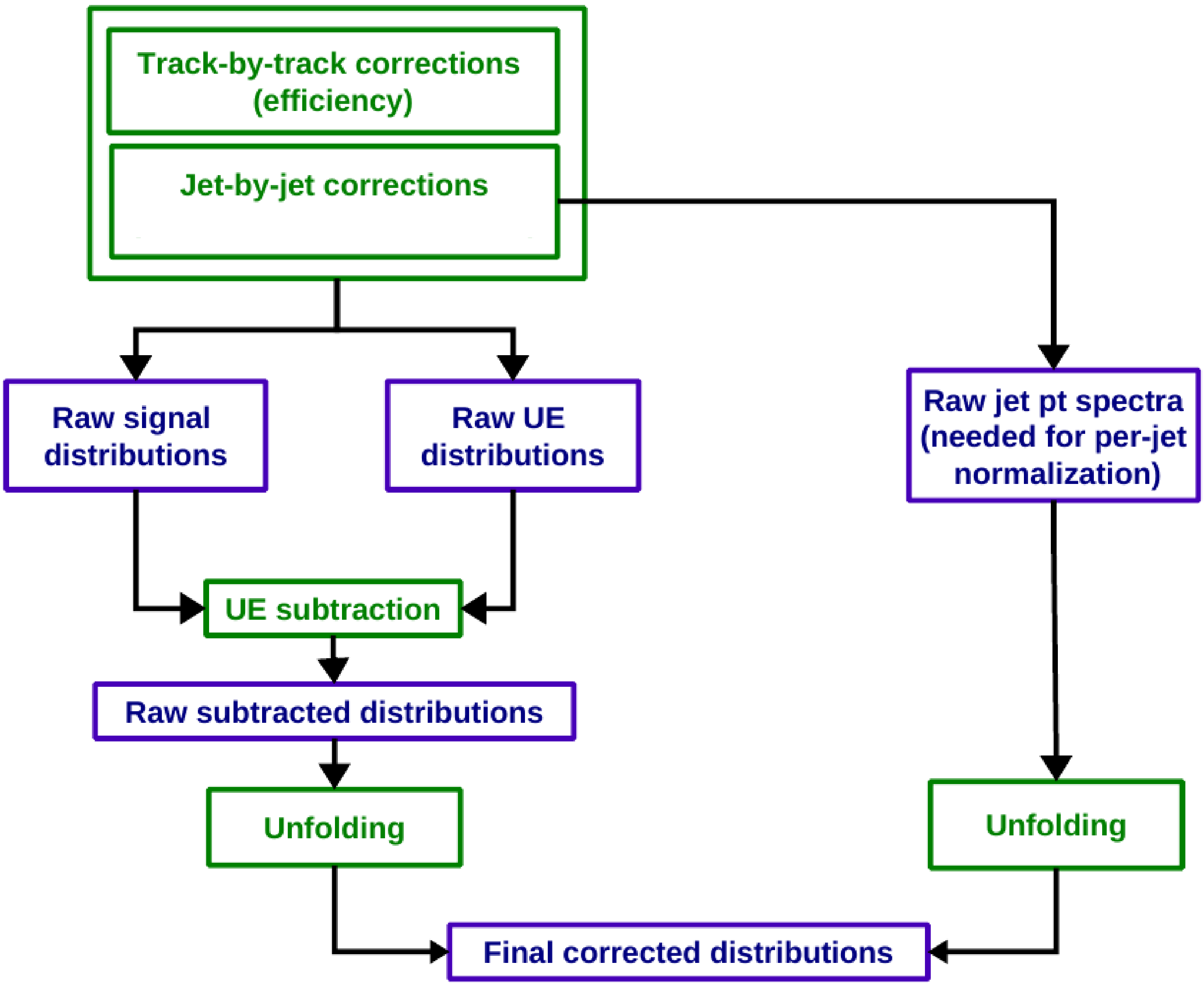

Corrections

- Correction for track reconstruction efficiency (next slide)
- Standard HI jet reconstruction corrections: UE subtraction, SEB, Numerical Inversion, ...
- FF UE subtraction – based on the event-by-event basis (slide 10)
- Resolution effects corrected by unfolding: 2D Bayesian unfolding in jet p_T and track p_T or z
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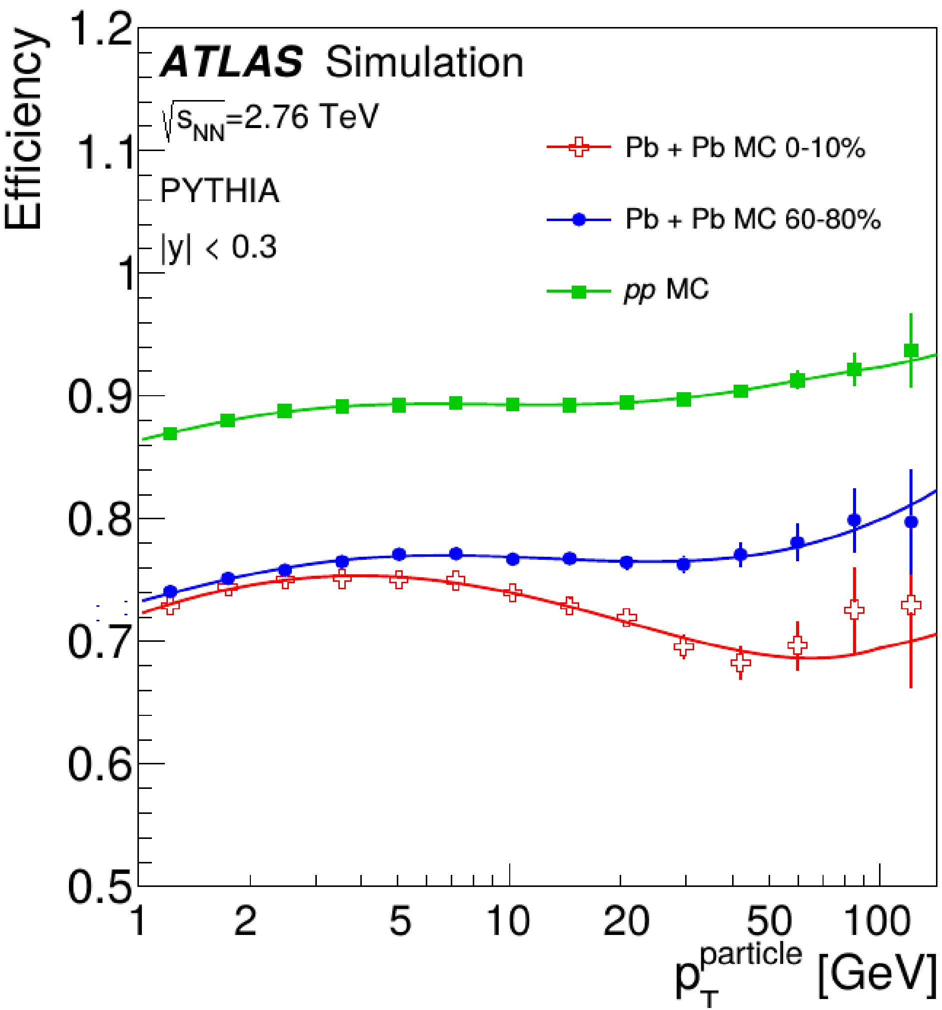
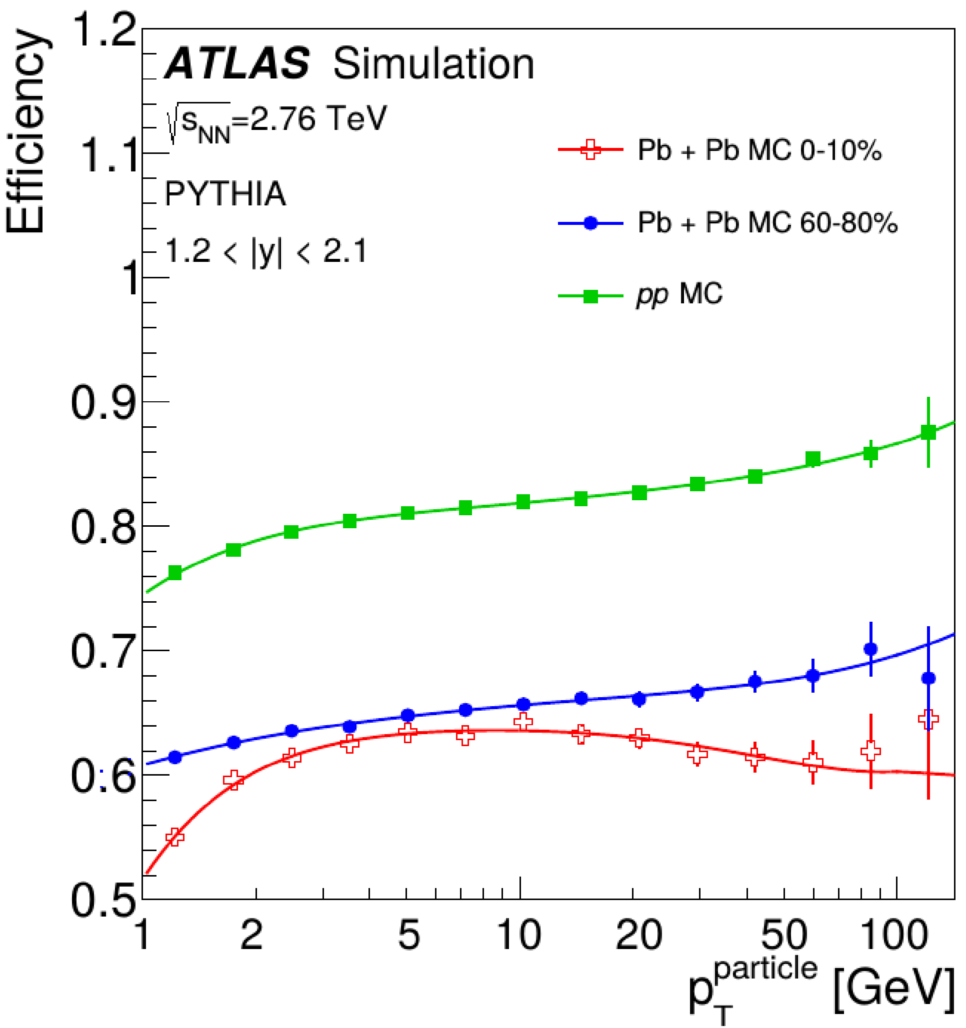
Efficiency correction

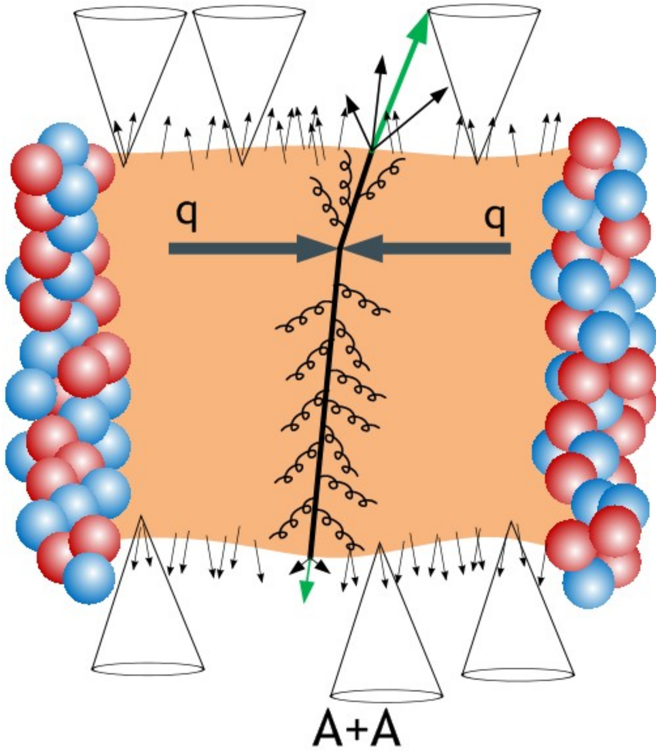
- Track reconstruction efficiency correction – derived from MC
- Done separately for pp and HI (for each centrality), binned in y (4 bins)





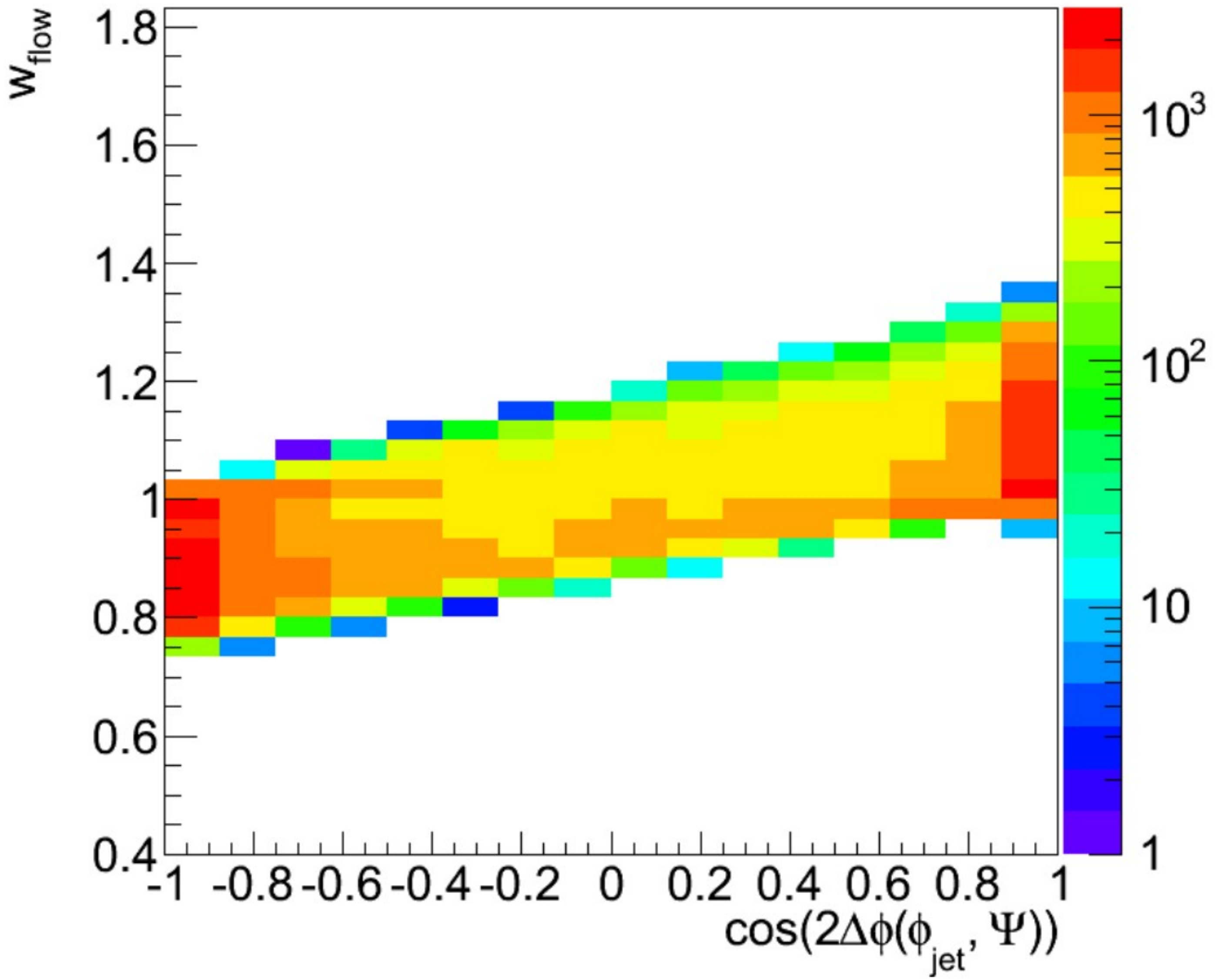
UE Subtraction

- At low track p_T, there is a large contribution from underlying event that needs to be subtracted (can be dominant in certain parts of phase space)
- Based on event-by-event basis – inner detector is spanned by the grid of cones, the UE contribution is then estimated
- Not to bias the size of UE contribution, cones that are likely coming from real jets were excluded



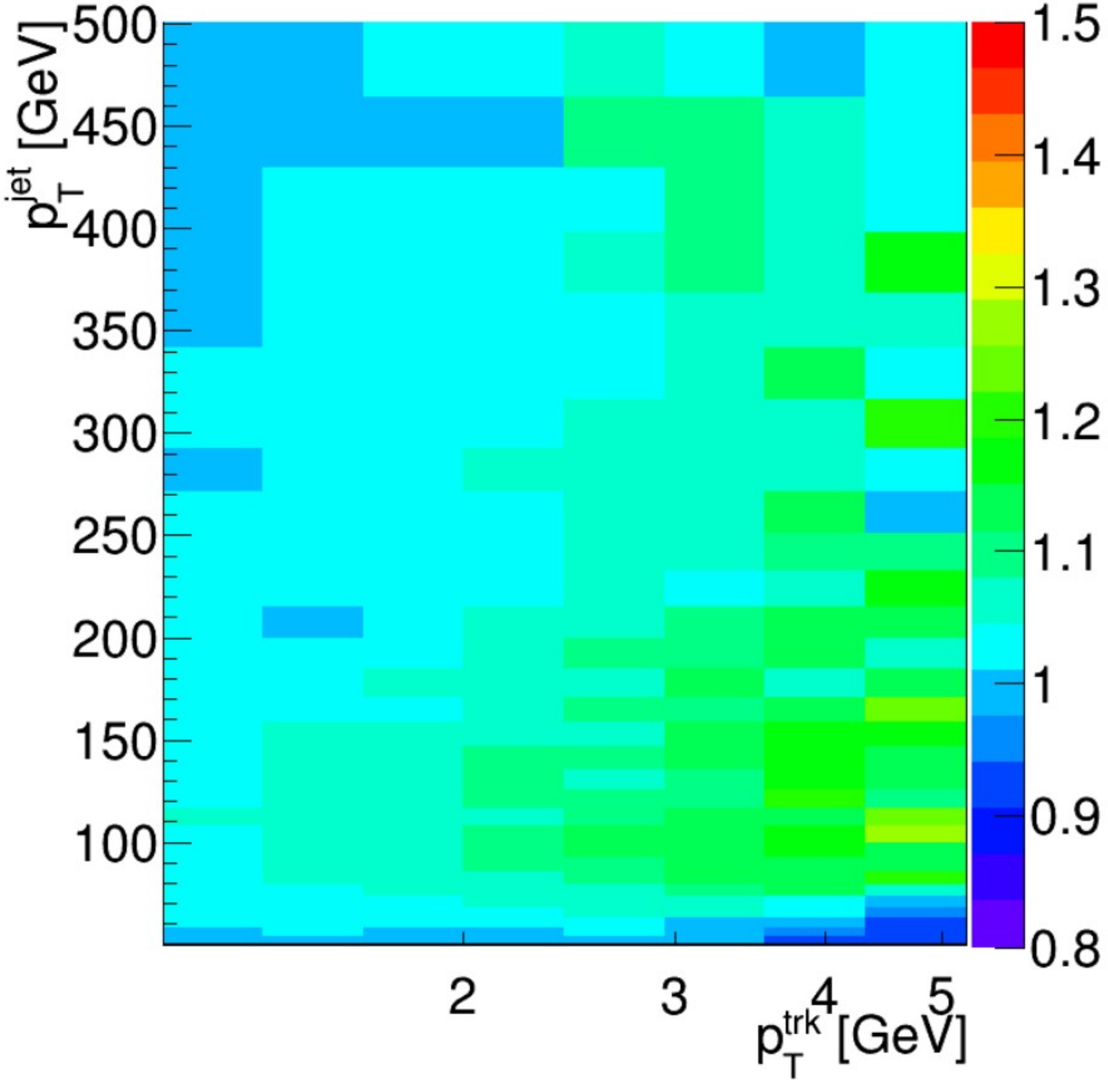
UE Subtraction (2)

- Correction for the elliptic flow as a function of angle between the jet axis and reaction plane



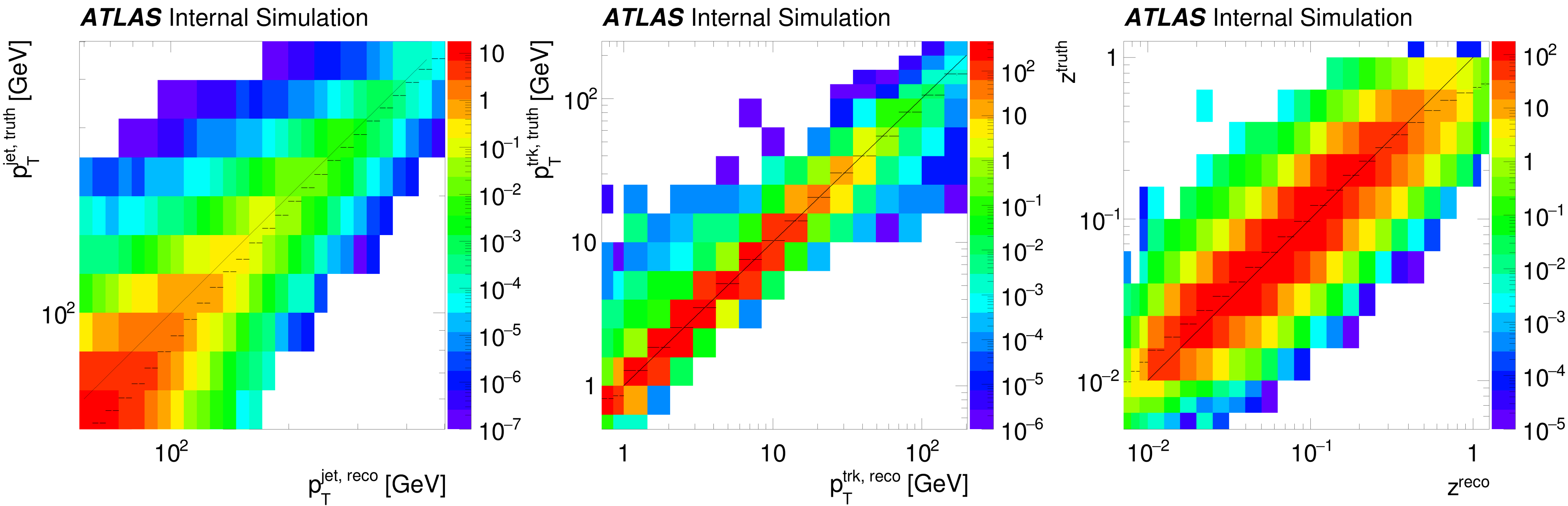
UE Subtraction (3)

- Correction for the correlation between UE and jet resolution
- Gives significant contribution only at relatively large track p_T (>3.5 GeV)



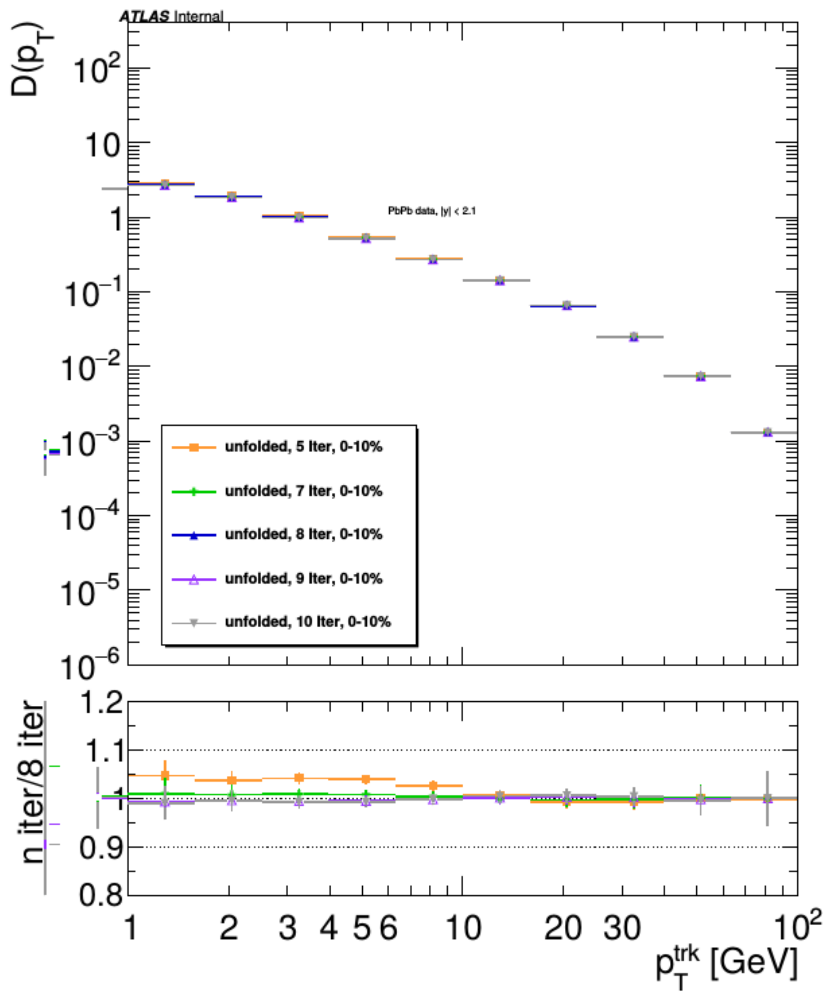
Unfolding

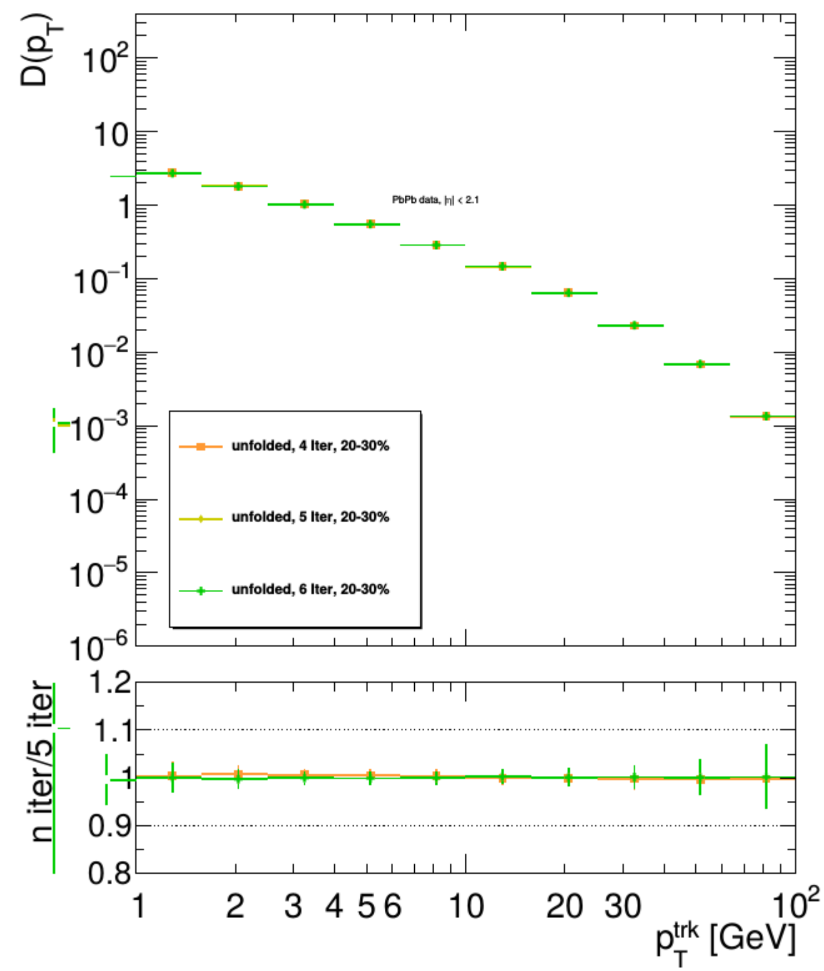
- 2D Bayesian unfolding in track p_T (z) and jet p_T was used to correct for resolution effects (jet energy resolution)
- 1D Bayesian unfolding used to unfold jet spectra for correct number of jets in pp and Pb+Pb



Unfolding – Stability

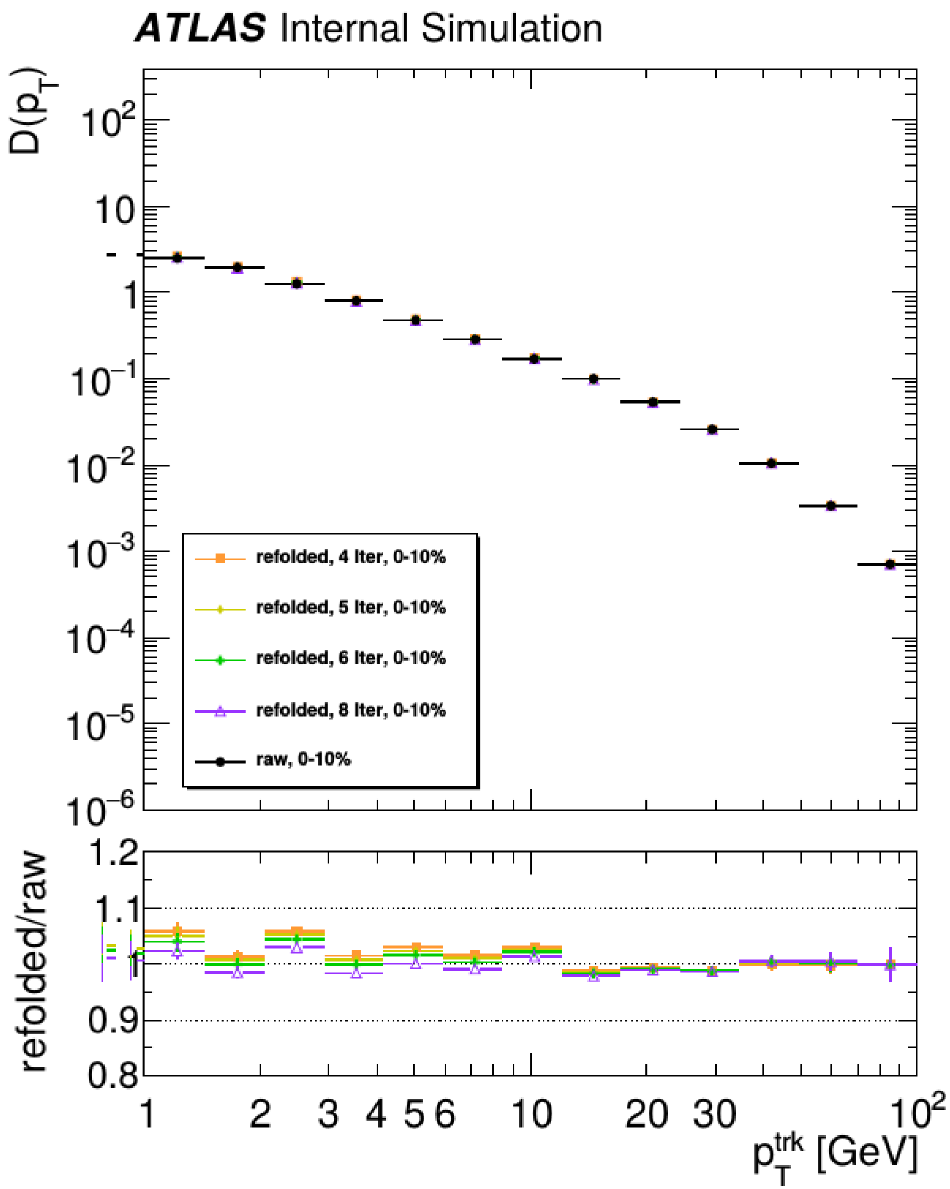
- Stability of unfolding in data: different number of iterations compared. Central HI collisions starts to be stable at 7 iterations, 8 iterations chosen to be default choice. In all other bins 5 iterations is sufficient (right)

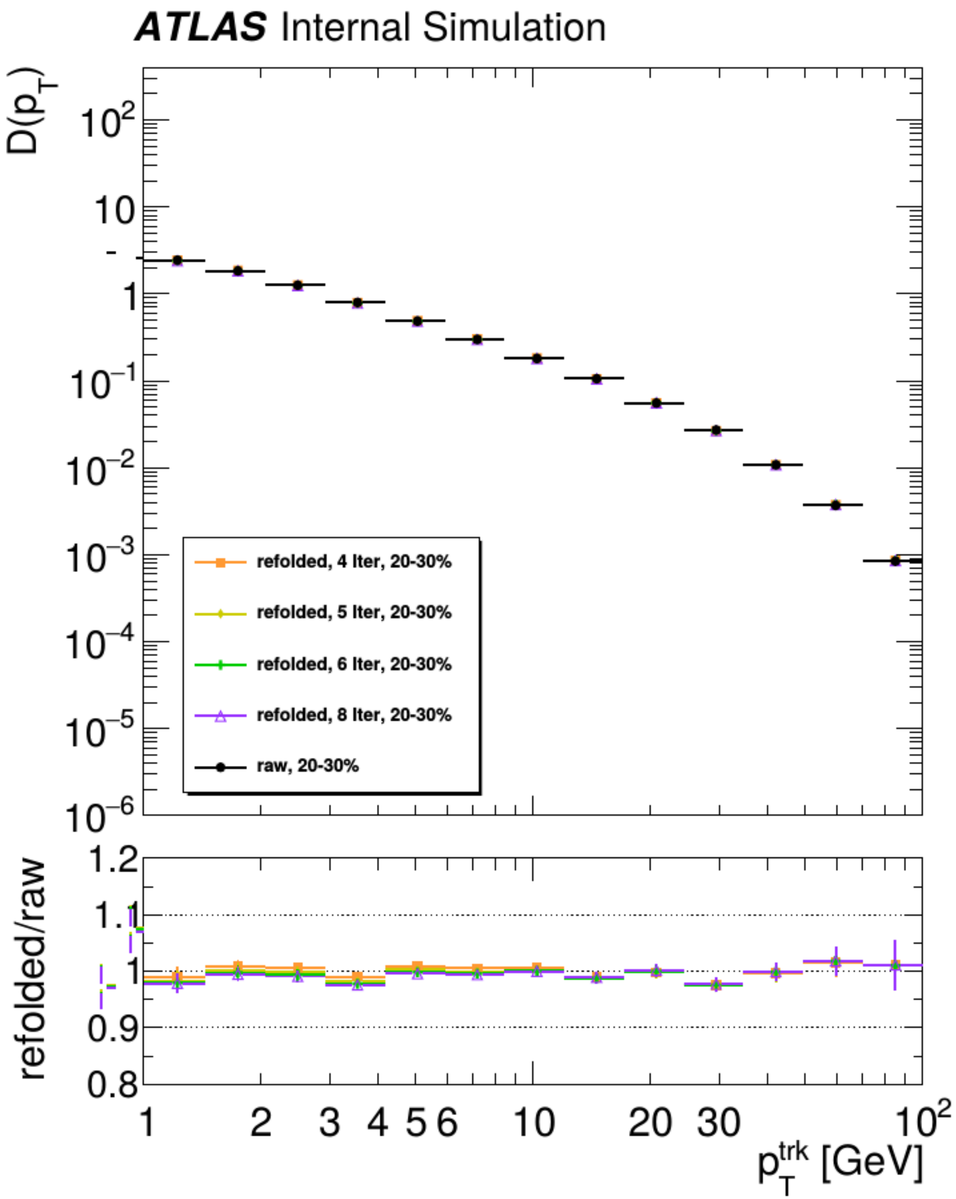




Refolding

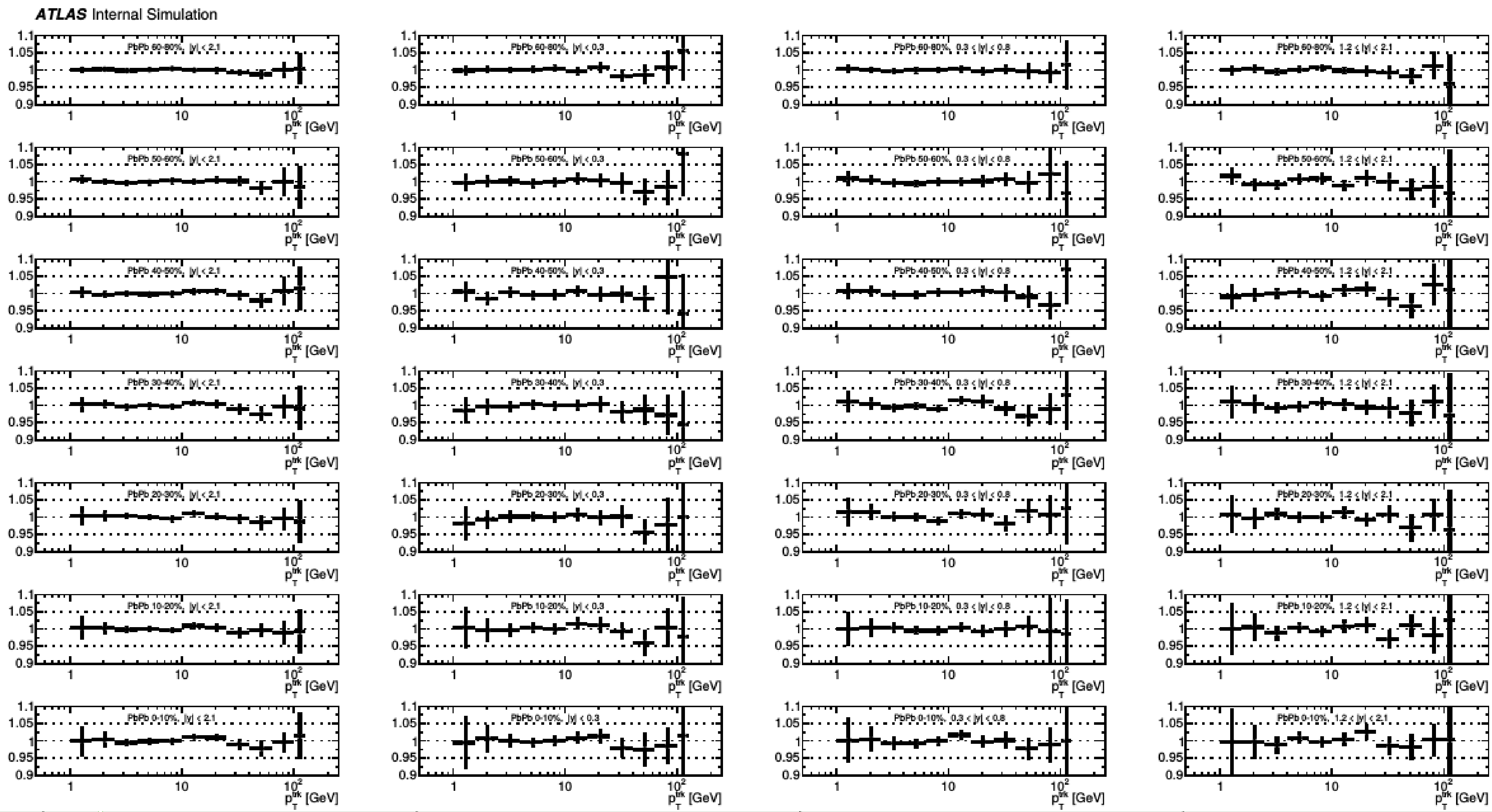
- Comparison of refolded distributions with raw distribution, $D(p_T)$, PbPb data





Closure tests

- Closure test: ratios of truth and unfolded FF in HI MC, $D(p_T)$ distributions, all centrality and rapidity bins

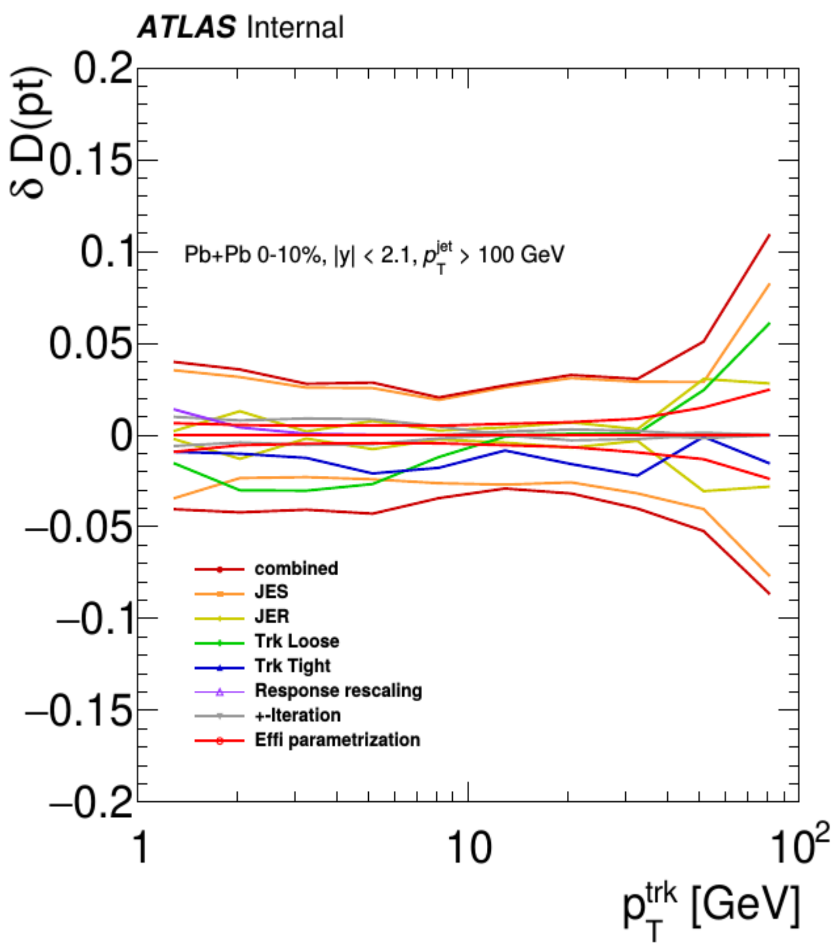


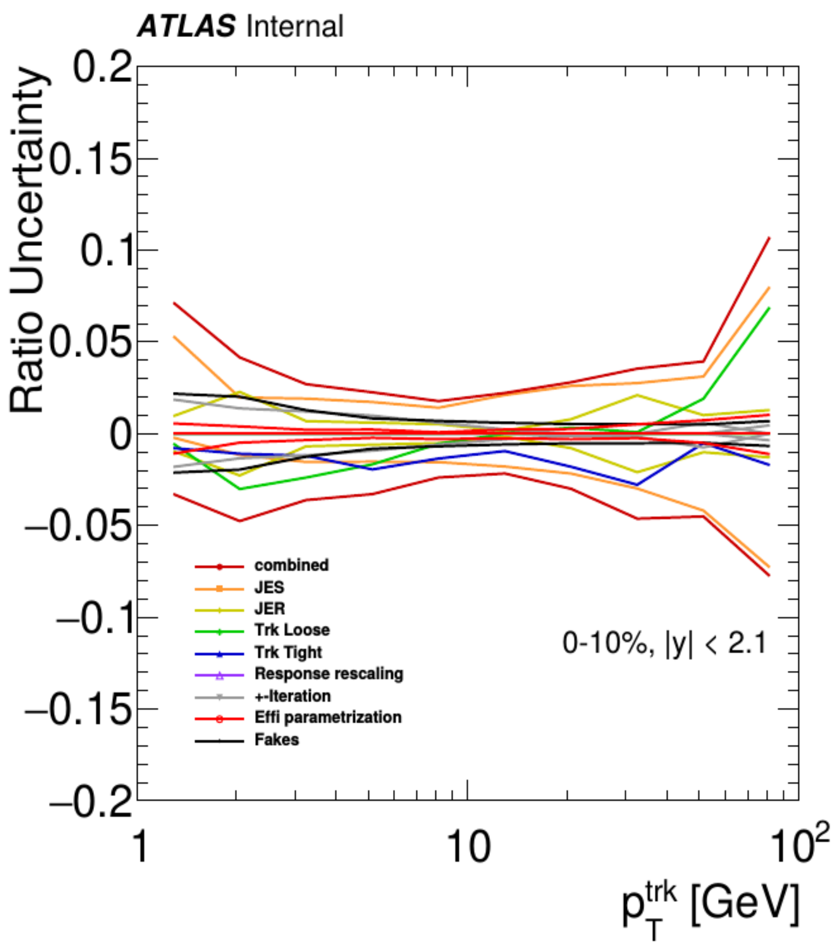
Systematic Uncertainties

- Jet energy scale: standard HI Jet systematic uncertainty, gives largest contribution
- Jet energy resolution: data unfolded with modified response matrix
- Track reconstruction – comparing distributions derived with efficiency derived with loose/tight cuts, gives significant contribution mainly at high track p_T
- Unfolding: Two components
  - Number of iterations: difference between results with given number of iterations N and N±1 iterations
  - Change of prior: PbPb distributions were unfolded with response rescaled by $1/R_{D(pT)}$
- Track reconstruction efficiency parametrization: Efficiency parametrization changed by ± uncertainty of the fitted efficiency

Systematic Uncertainties (2)

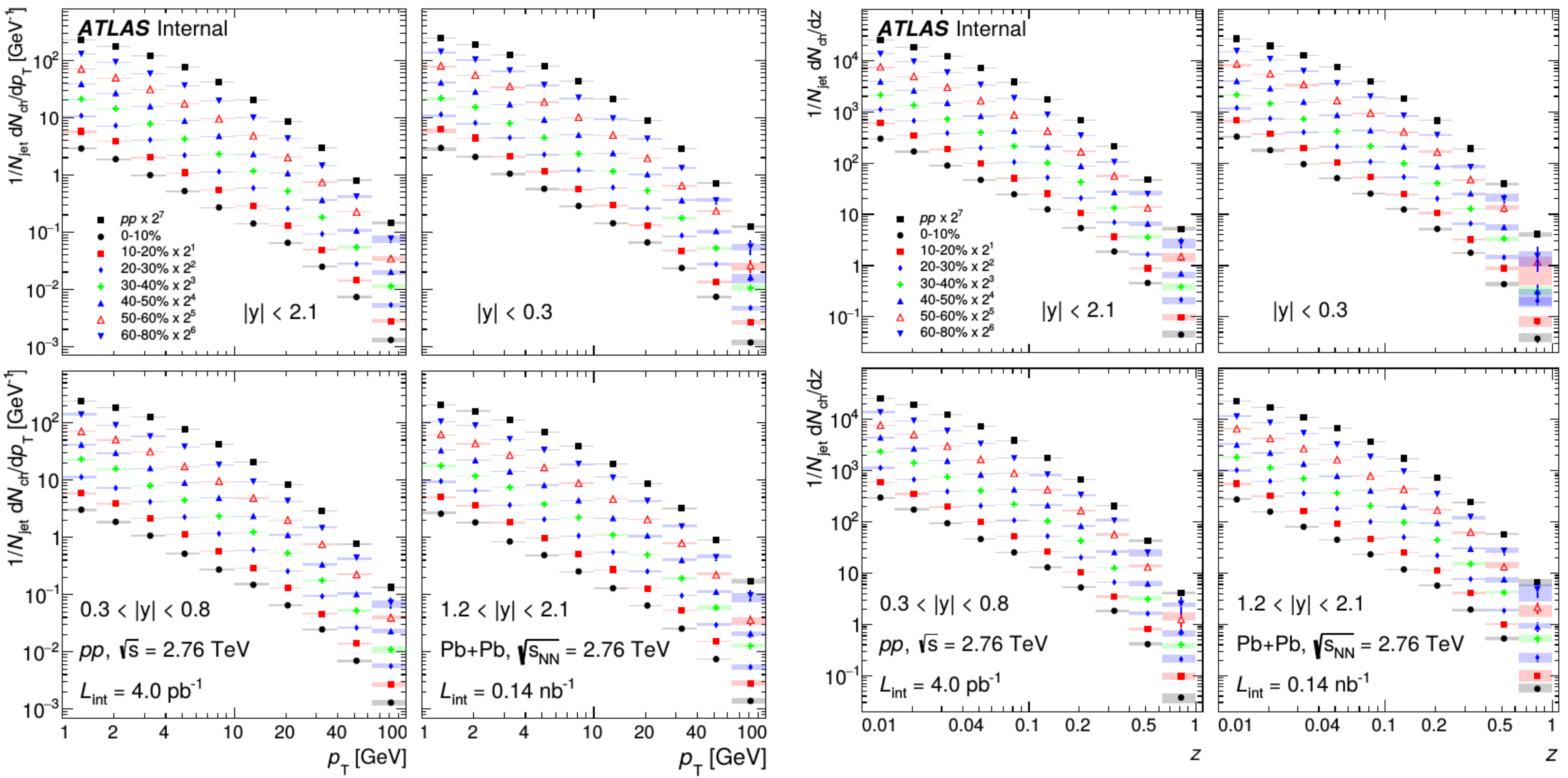
- Relative size of systematic uncertainty and it's sources for $D(p_T)$ in central PbPb collisions (left)
- Size of systematic uncertainty and it's sources for $R_{D(pT)}$ in central collisions (right)





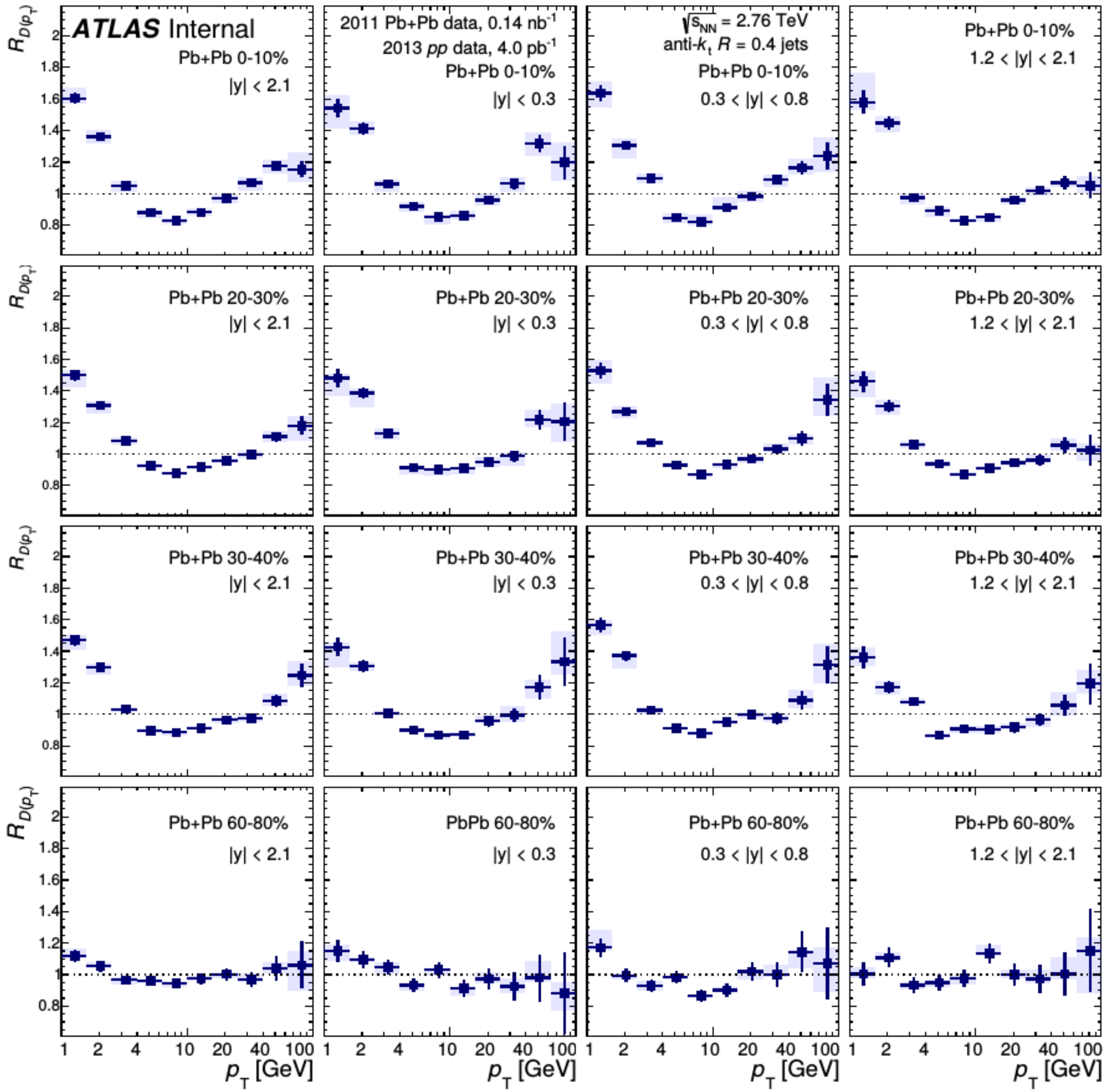
Final Distributions

- D(p_T) and D(z) in PbPb and pp in 4 rapidity bins



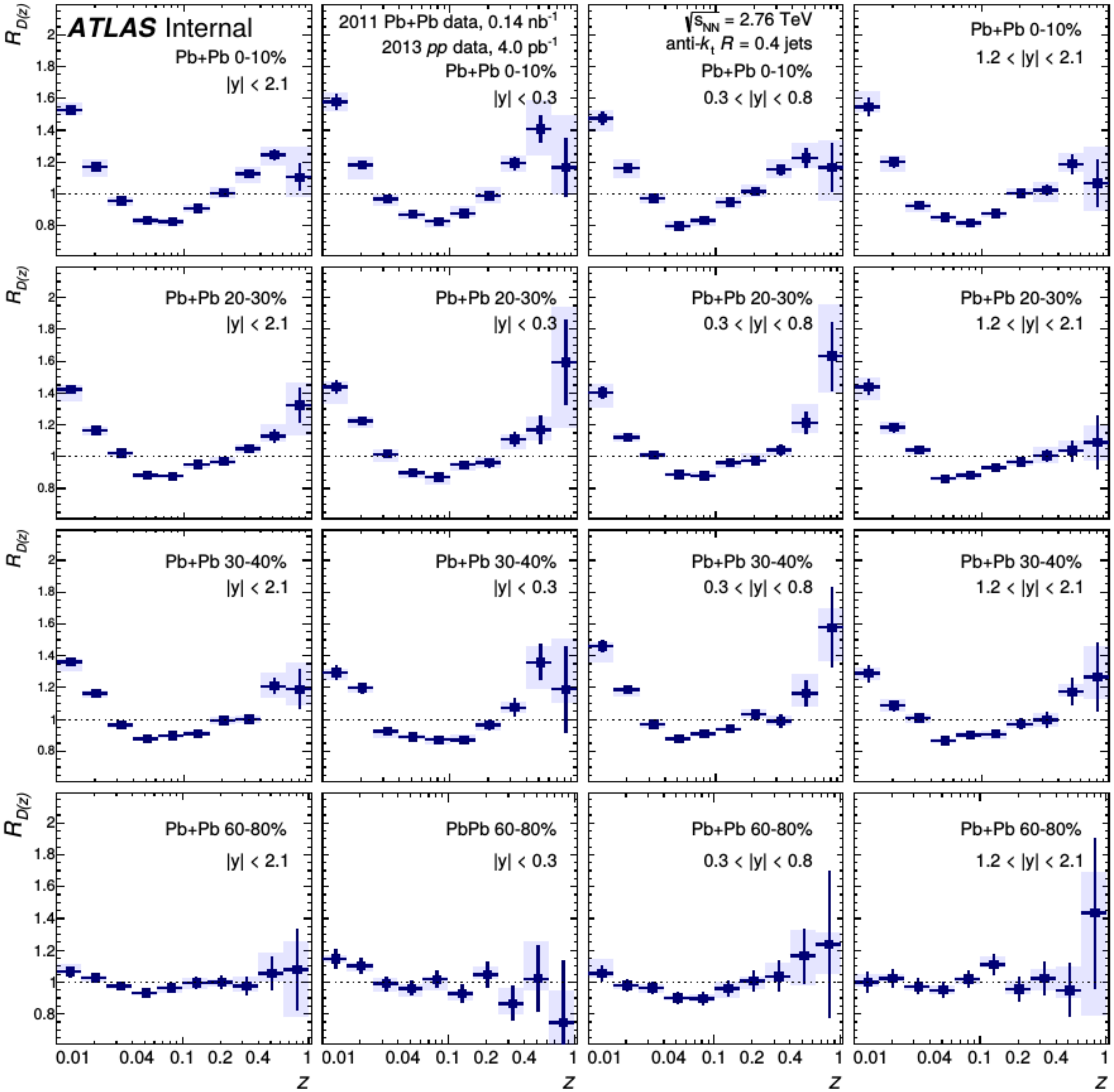
Ratios (1)

- $R_{D(pT)}$ for four different centrality bins shown for different rapidity bins



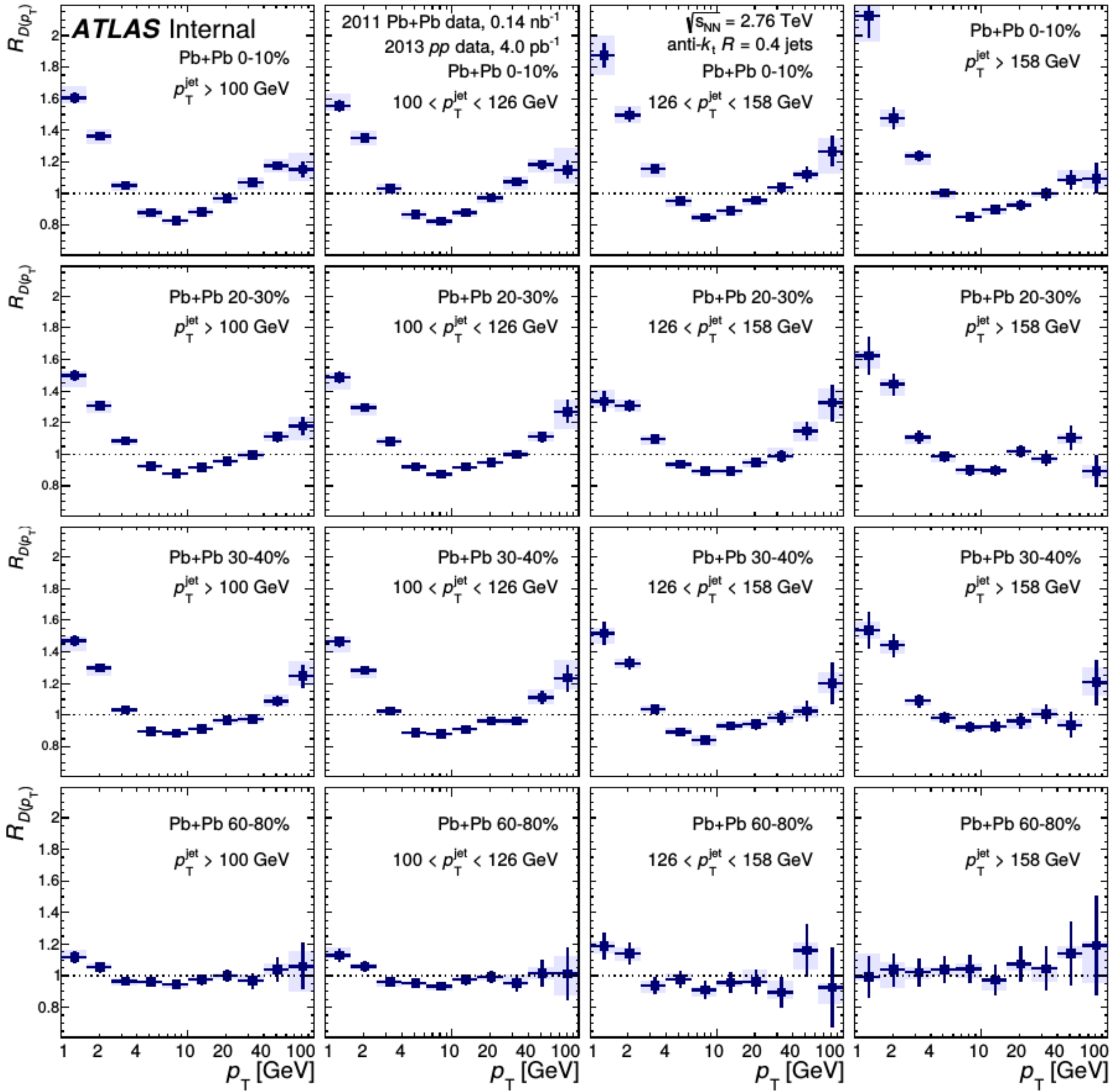
Ratios (2)

- $R_{D(z)}$ for four different centrality bins shown for different rapidity bins



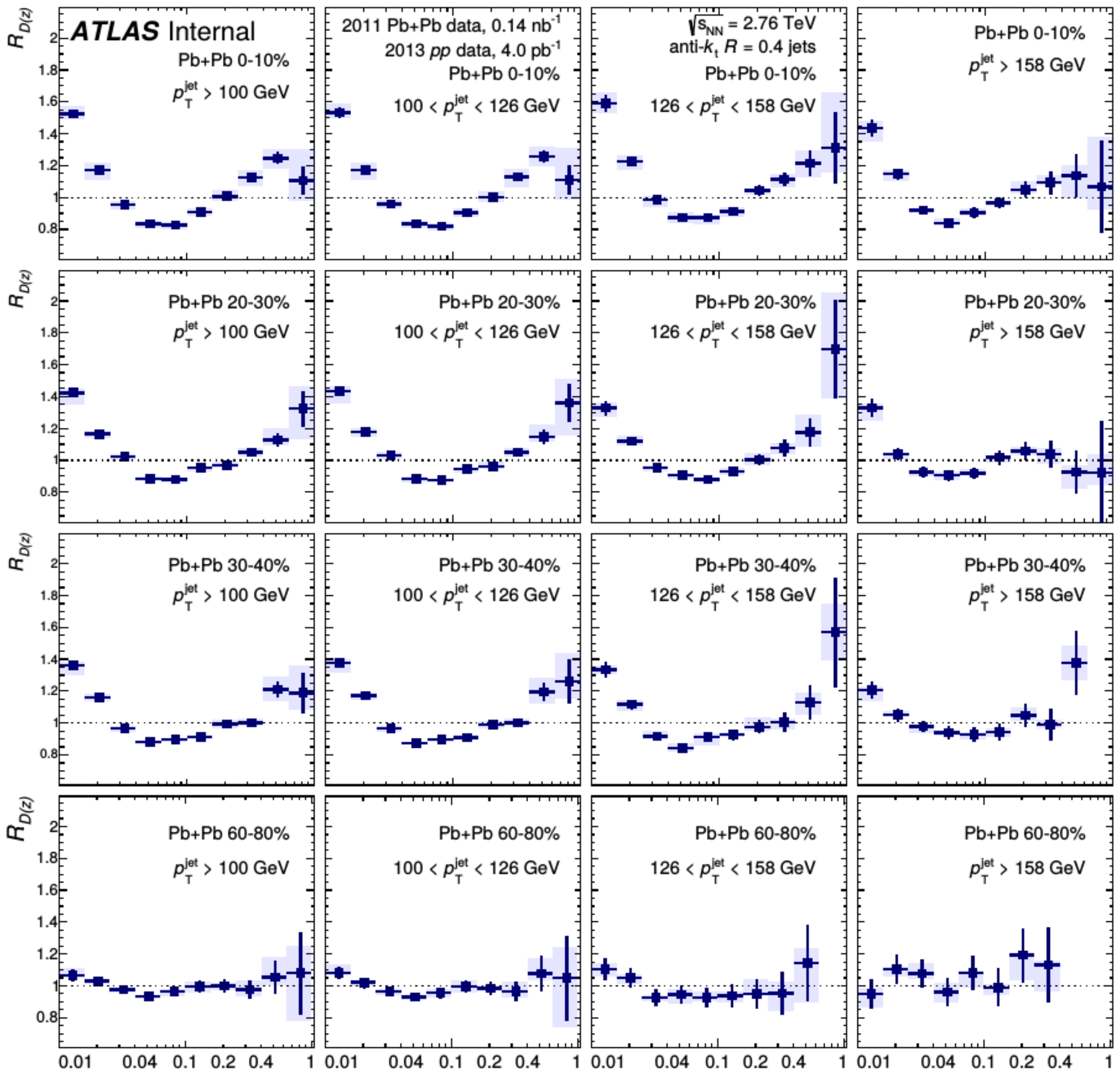
Results (3)

- $R_{D(pT)}$ for four different centrality bins shown for different jet p_T bins



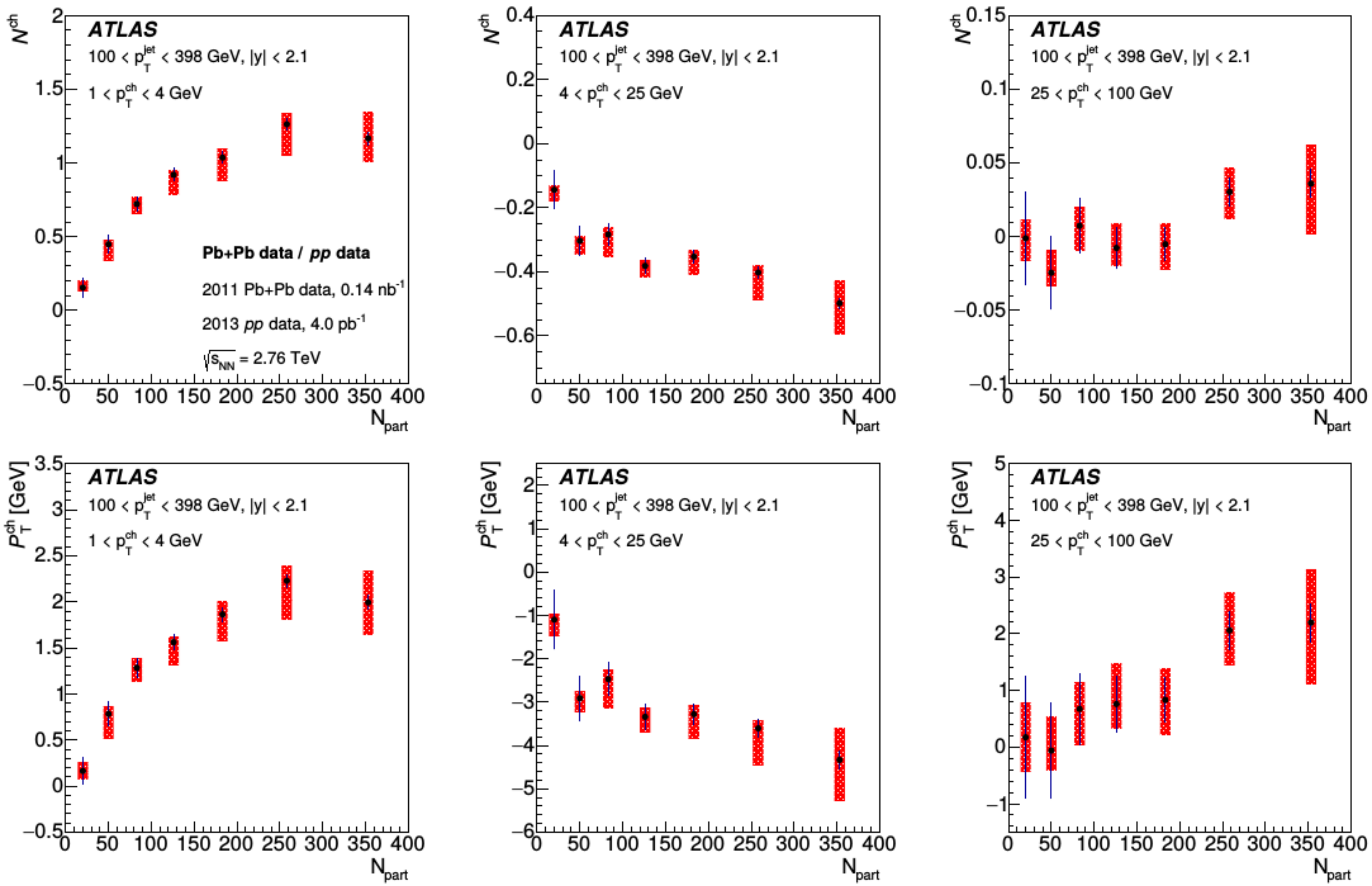
Ratios (4)

- $R_{D(z)}$ for four different centrality bins shown for different jet p_T bins



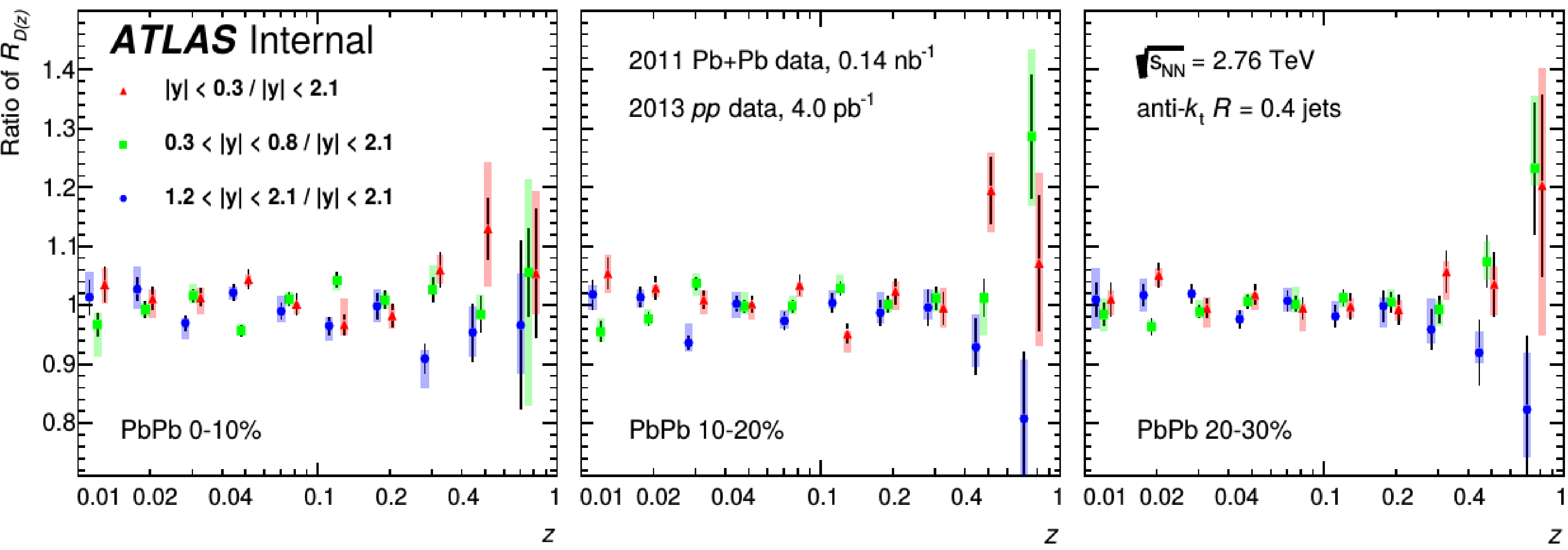
Integrals

- Upper panels: difference in total yields of particles in given track p_T bin as a function of N_{part} $N^{ch} \equiv \int_{p_{T,min}}^{p_{T,max}} \left(D(p_T)|_{cent} - D(p_T)|_{pp} \right) dp_T$
- Lower panels: difference in transverse momentum carried by track in given p_T bin as a function of N_{part} $P_T^{ch} \equiv \int_{p_{T,min}}^{p_{T,max}} \left(D(p_T)|_{cent} - D(p_T)|_{pp} \right) p_T \, dp_T$



Double Ratios

- To quantify the rapidity dependence of the behavior at large z we evaluated double ratios of $R_{D(z)}$



Conclusions

- Significant modification of jet fragmentation is observed, mainly the enhancement at low and high track p_T (z) and suppression at low track p_T (z)
- No significant dependence of the modifications on the jet p_T is measured, however a trend of a decrease of fragment yields at large p_T (z) is observed
- No significant evolution in modifications of the jet internal structure as a function of rapidity is seen except the change in the trends at high z which is quantified in the $R_{D(z)}$ double ratios

Backup

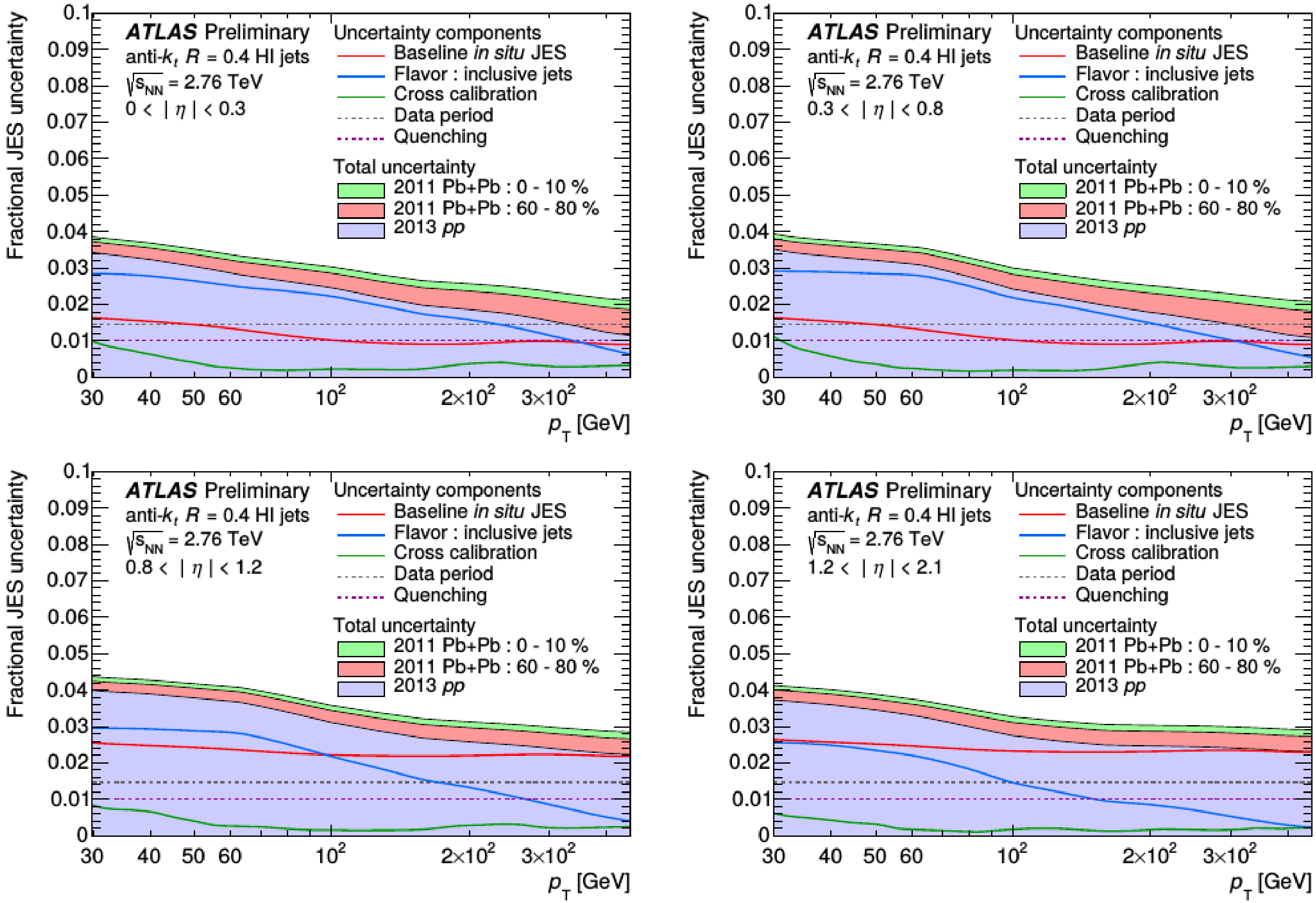
Results: P_T^{ch} and N^{ch}

- The difference in the total momentum and the total change in the yield of charged particles evaluated over the full range of charged particle p_T

Centrality	0 – 10%	10 – 20%	20 – 30%	30 – 40%	40 – 50%	50 – 60%	60 – 80%
P_T^{ch} [GeV]	$0.9^{+0.9}_{-1.7}$	$1.0^{+0.8}_{-1.3}$	$-0.0^{+0.7}_{-1.1}$	$-0.6^{+0.8}_{-0.8}$	$-0.5^{+1.0}_{-1.2}$	$-1.4^{+1.0}_{-1.2}$	$-0.8^{+1.3}_{-1.4}$
N^{ch}	$0.7^{+0.1}_{-0.2}$	$0.9^{+0.1}_{-0.1}$	$0.7^{+0.1}_{-0.1}$	$0.5^{+0.1}_{-0.2}$	$0.4^{+0.1}_{-0.1}$	$0.2^{+0.1}_{-0.2}$	$0.0^{+0.1}_{-0.1}$

JES – pp and Pb+Pb, 2.76 TeV

- Fractional JES uncertainty in pp and Pb+Pb at 2.76 TeV, p_T dependence for different |η| selections for pp, Pb+Pb central and peripheral collisions



Event selection and MC

- PbPb Data: 2011 Pb+Pb data at 2.76 TeV, Hard Probe stream, primary vertex required, combination of Level 1 MB and HLT j20 trigger, centrality range 0-80%, luminosity $L^{PbPb} = 0.14\ nb^{-1}$
- pp data: 2013 pp run triggered L1 MBTS and HLT j75 trigger, integrated luminosity $L^{pp} = 4\ pb^{-1}$
- PbPb MC: Pythia MC J2-J5 samples embedded into MinBias Pb+Pb data
- pp MC: plain Pythia
- MC distributions were reweighted to match the data

Track cuts and selections

- PbPb track-quality selections:
  - at least two hits in the Pixel ID
  - at least seven hits in the Semiconductor Tracker (SCT)
  - at least one hit in the first layer of the Pixel ID (BLayer) if expected
  - $\sigma_{d_0} \equiv \frac{d_0}{\sqrt{d_0^{cov}}} < 3$
  - $\sigma_{z_0} \equiv \frac{z_0 \sin\theta}{\sqrt{z_0^{cov} \sin^2\theta + \sin\theta^{cov} (z_0 \cos\theta)^2}} < 3$
- pp track-quality selections:
  - at least one hits in the Pixel ID
  - at least six hits in the Semiconductor Tracker (SCT)
  - at least one hit in the first layer of the Pixel ID (BLayer) if expected
  - $|d_0|$ impact parameter was parametrized in the region of $p_{\mathrm{T}}^{\mathrm{trk}}$ 1 - 100 GeV using

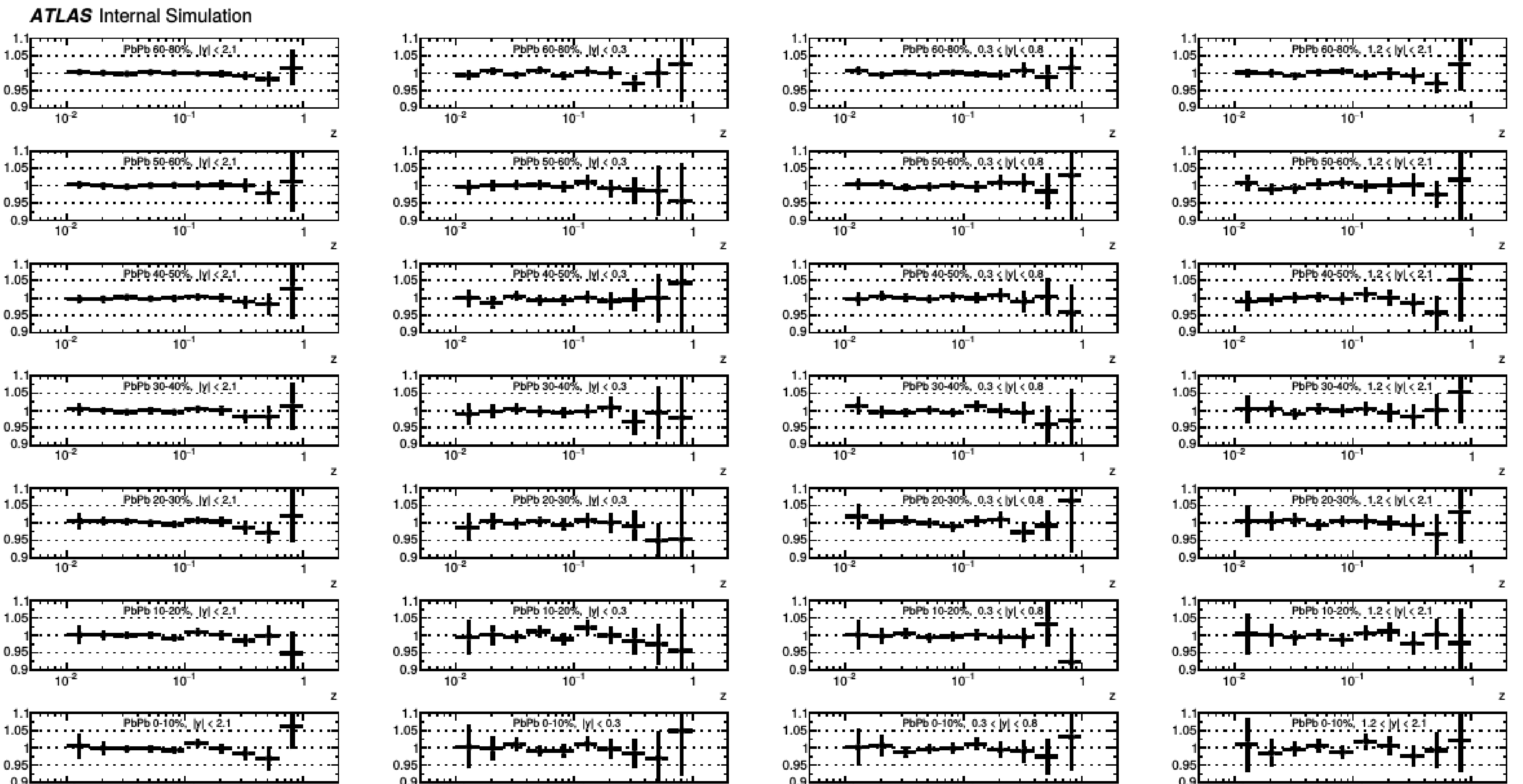
    $$d_0(p_{\mathrm{T}}^{\mathrm{trk}}) = a_0 e^{a_1 p_{\mathrm{T}}} + a_3 e^{a_4 p_{\mathrm{T}}} \tag{13}$$

    where a_i represent free parameters of the fit. Recommendation values are $|d_0| < 1.5$ mm for tracks with $p_{\mathrm{T}} < 10$ GeV and $|d_0| < 0.2$ mm for tracks with $p_{\mathrm{T}} > 10$ GeV.

    This was chosen to guarantee a smooth behaviour of the d_0 parameter as a function of track momentum.
  - $|z_0 \sin(\theta)| < 1.5$ mm

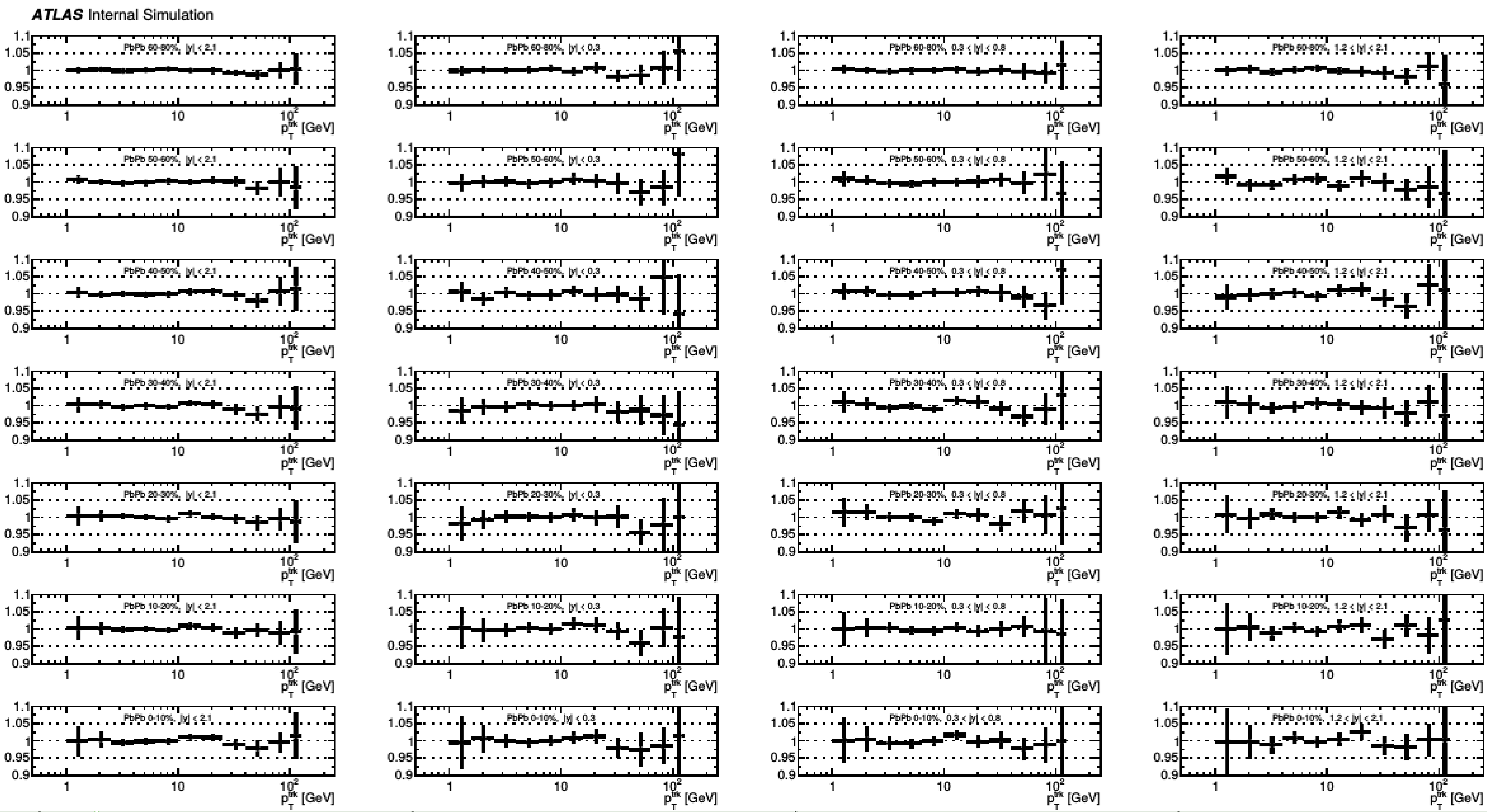
Closure tests – all (1)

- Closure test D(z) – PbPb, all centralities and rapidity bins



Closure tests – all (2)

- Closure test $D(p_T)$ – PbPb, all centralities and rapidity bins



Closure tests – all (3)

- Closure test D(z) and D(p_T) – pp, all rapidity bins