Jet studies in heavy ion collisions with the ATLAS detector

Radim Slovak

On behalf of the ATLAS Collaboration

Charles University in Prague

Hard Probes Wuhan 2016

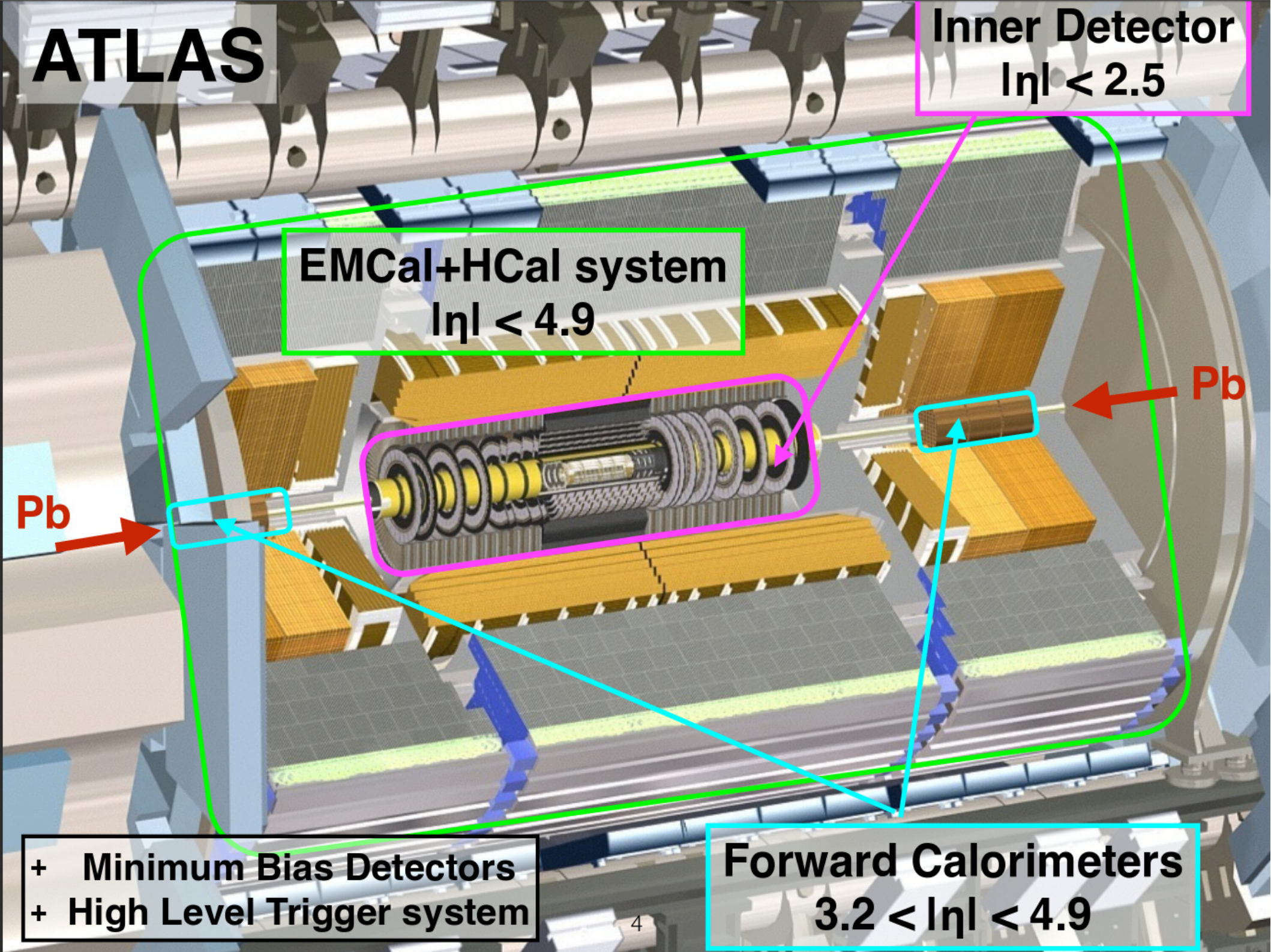
Introduction

- Broad program of jet suppression and modification measurements in Pb+Pb collisions by ATLAS
- Study of jets in Pb+Pb collisions should tell us about e.g.:
  - Properties of de-confined matter created in heavy ion collisions
  - Radiation of energetic color charges in the de-confined medium
- LHC heavy ion runs at ATLAS:
  - Run 1: Pb+Pb: $\sqrt{s_{NN}}$ = 2.76 TeV, L_{int} = 0.15 nb^{-1}

    pp: $\sqrt{s}$ = 2.76 TeV, L_{int} = 4.2 nb^{-1}

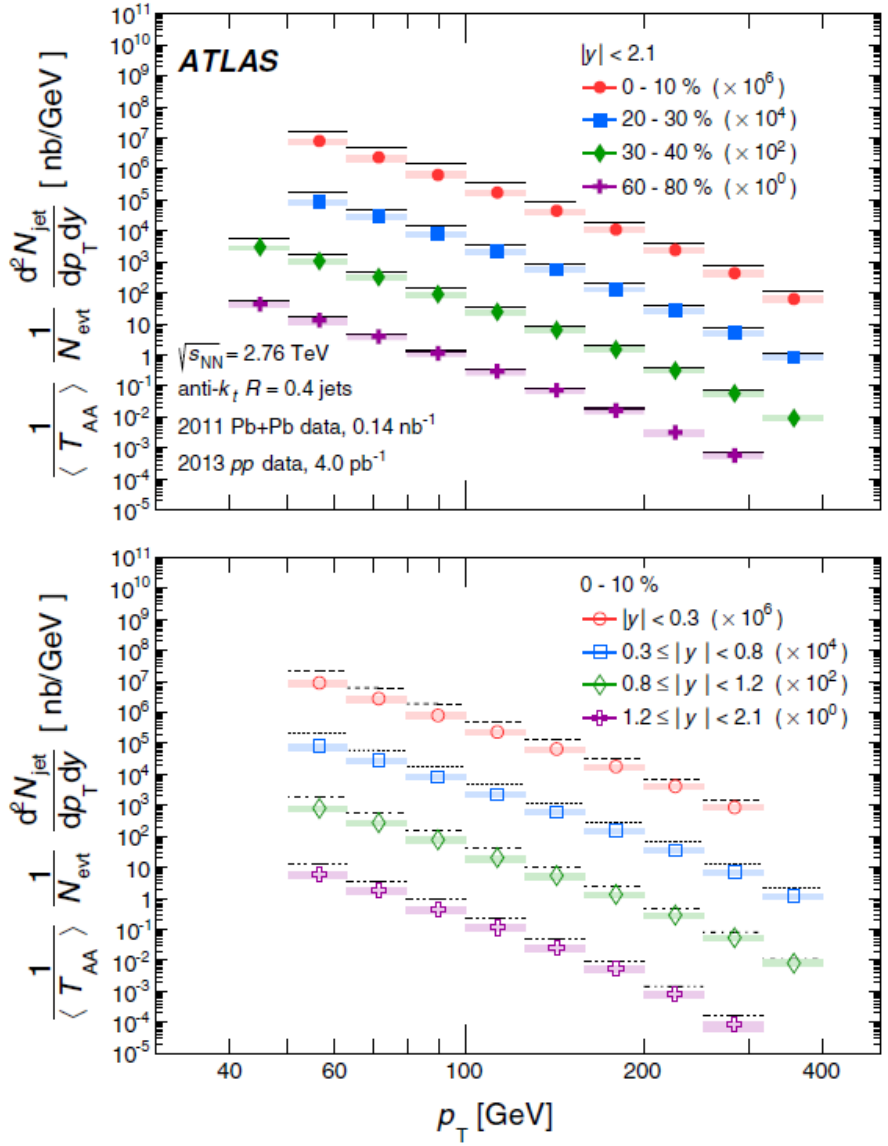
    p+Pb: $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 29 nb^{-1}
  - Run 2: Pb+Pb: $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 0.5 nb^{-1}

    pp: $\sqrt{s}$ = 5.02 TeV, L_{int} = 28 pb^{-1}


ATLAS
Inner Detector
|η| < 2.5
EMCal+HCal system
|η| < 4.9
Pb
Pb
+ Minimum Bias Detectors
+ High Level Trigger system
Forward Calorimeters
3.2 < |η| < 4.9

Jet production in Pb+Pb collisions

PRL114 (2015) 072302



- Centrality variation at fixed rapidity

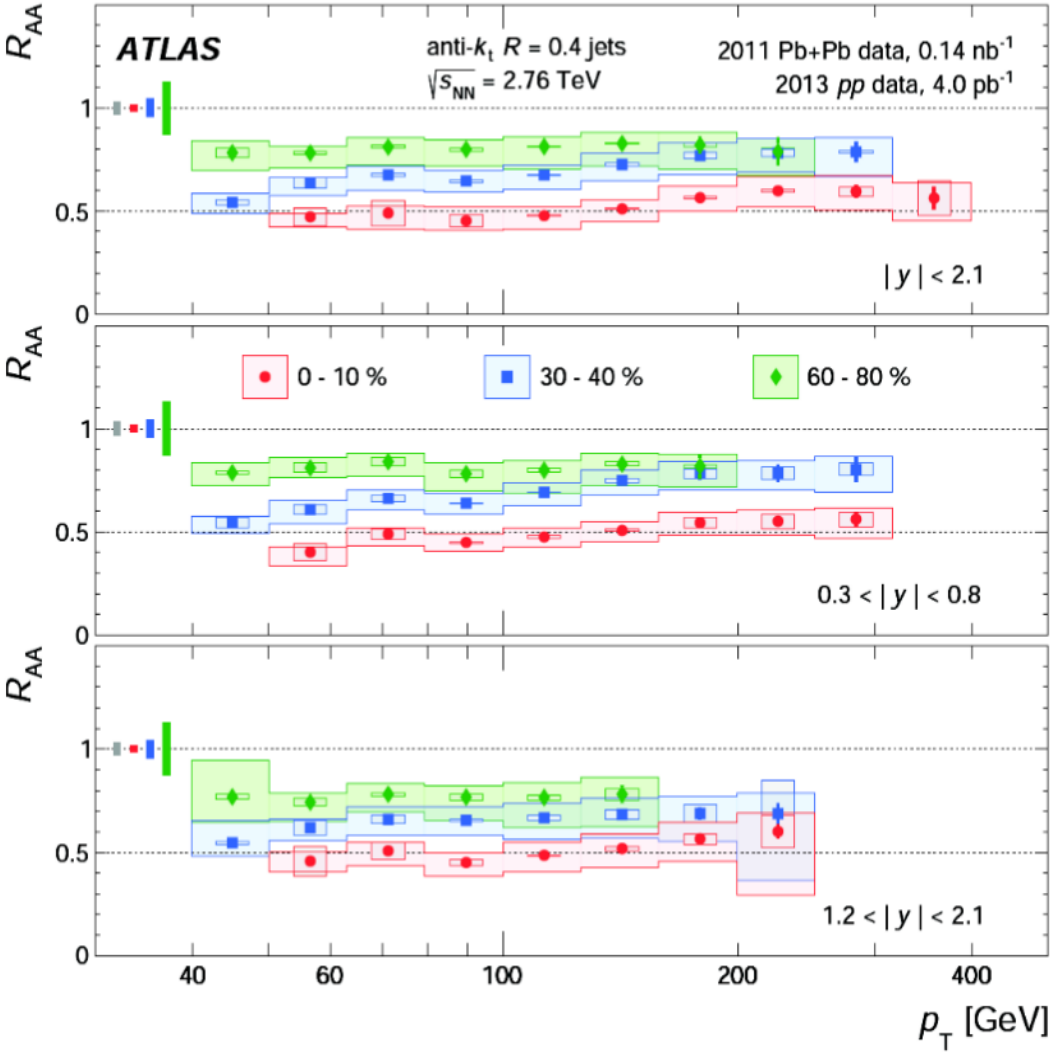
- Rapidity variation at fixed centrality

Dashed line are *pp* reference

Suppression evident from points falling below the reference

Inclusive jet suppression

PRL114 (2015) 072302

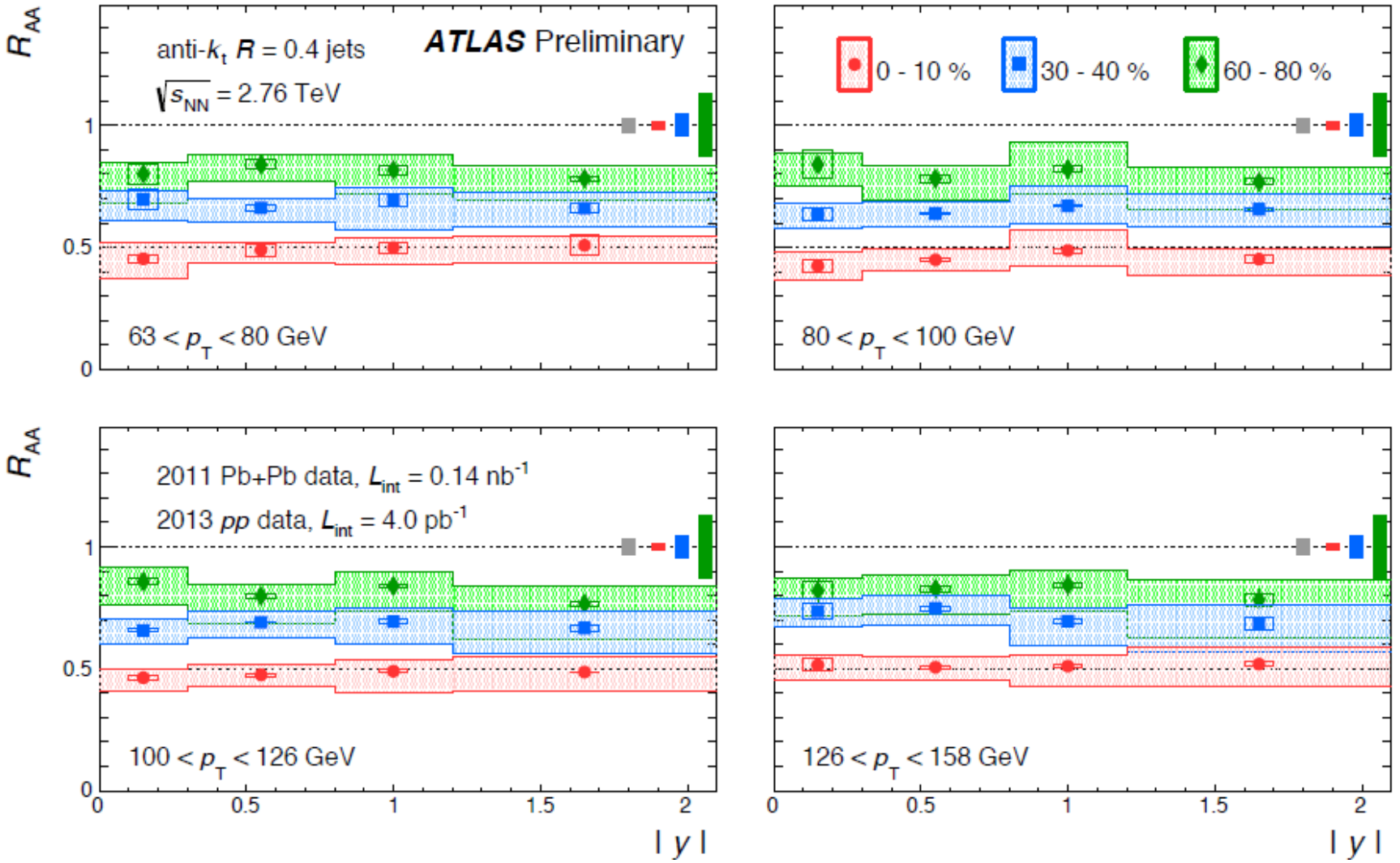


$$R_{\mathrm{AA}} = \frac{\frac{1}{N_{\mathrm{evnt}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}} \rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2 \sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

- A modest grow of jet R_{AA} with increasing jet p_T
- Still a significant suppression even for 60-80% centrality bin
- Practically no rapidity dependence

PRL114 (2015) 072302

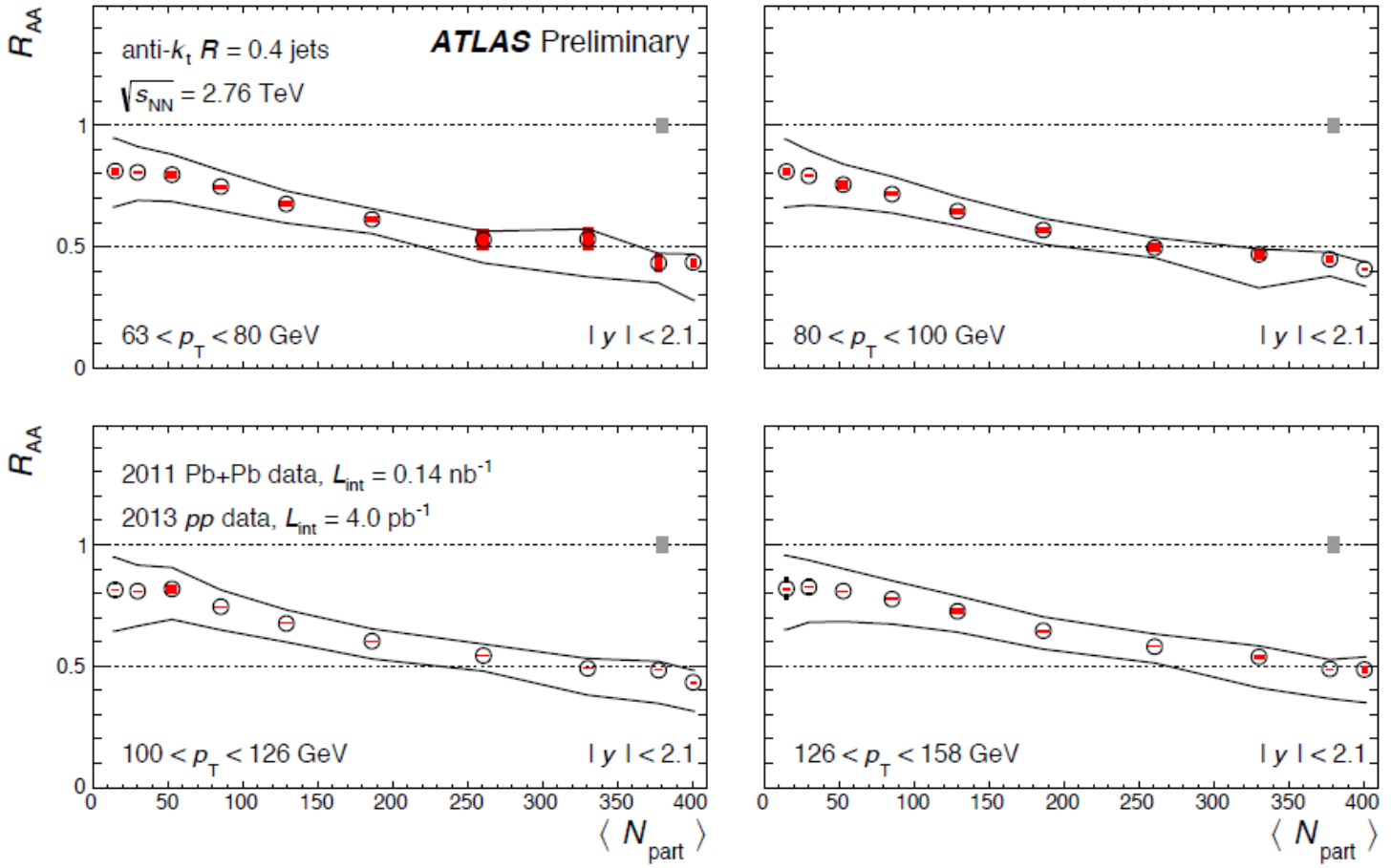
More on the rapidity dependece



- Not observed any variation with | y |

R_{AA} vs N_{part}

PRL114 (2015) 072302

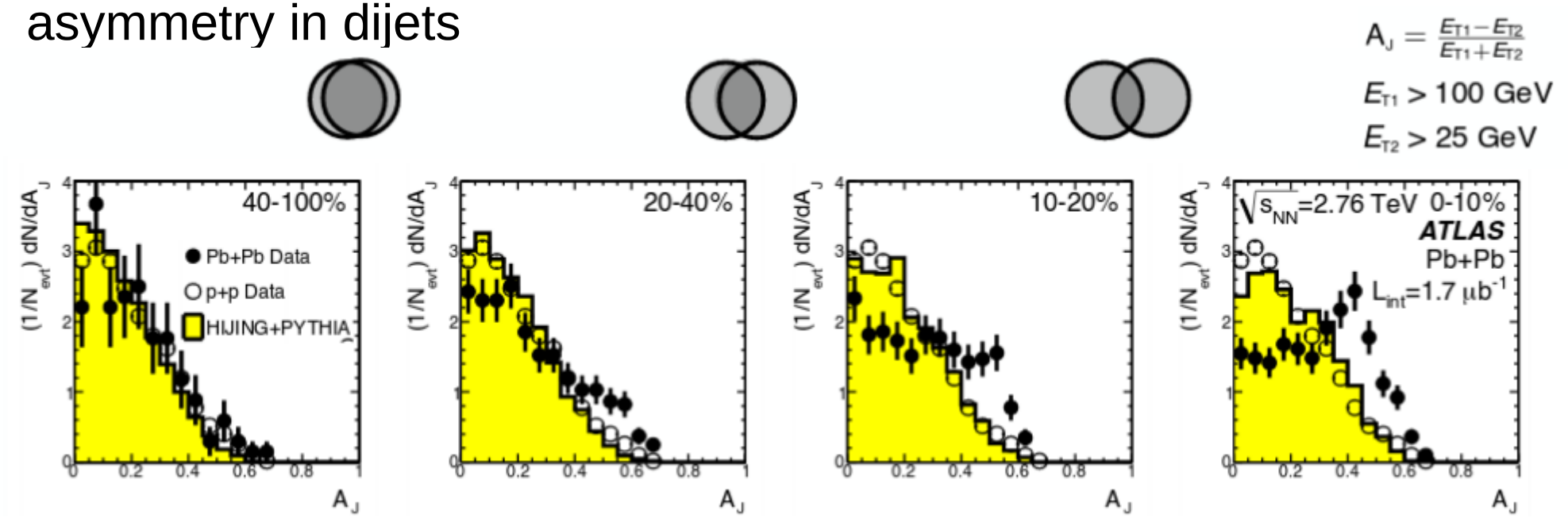


- Smooth behavior with N_{part}, maximal suppression in 0—1% is 0.4

Dijet asymmetry measurement

ATLAS-CONF-2011-075

- First HI paper published by ATLAS was an observation of the asymmetry in dijets



- Back to back jets see different path lengths, destroying the expected p_T-balance
- Enhancement of asymmetric dijets in Pb+Pb, relative to *pp* as the centrality increases

ATLAS-CONF-2015-052

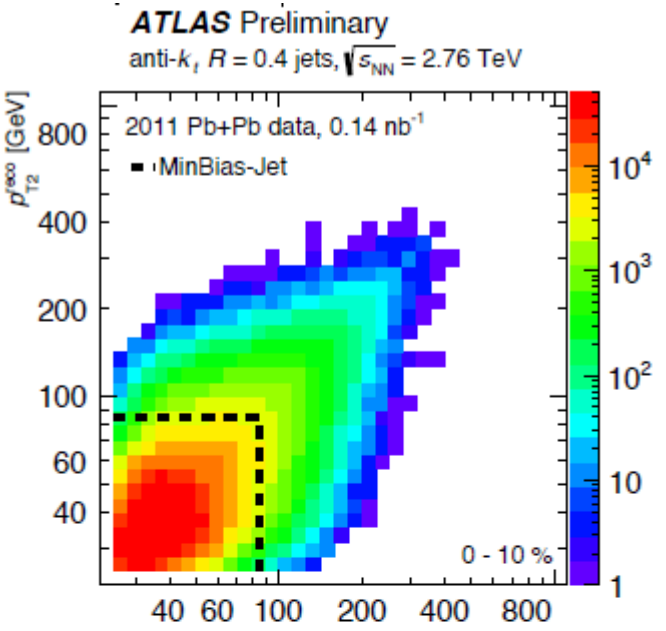
New dijet asymmetry measurement

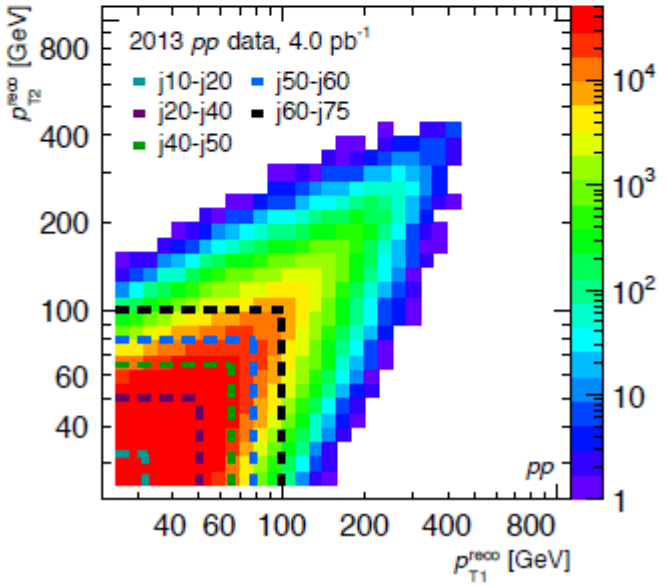
- Important to undestand quenching on a jet-by-jet basis
  - Previously observed but it needs to be understood *without* smearing effects from the detector resolution
- New measurement of the unfolded asymmetry in Pb+Pb collisions compared to *pp* at 2.76 TeV as a function of centrality for R=0.4 jets
- Improvements to previous measurement:
  - Increased statistics for Pb+Pb from 1-2 μb^{-1} to 140 μb^{-1}
  - Compare to 2013 *pp* reference at 2.76 TeV instead of 7 TeV
  - Improved jet calibration and reconstruction
  - Better control of the background due to the underlying event
  - Dijets were corrected for jet energy resolution by 2D Bayesian unfolding to account for bin migration in $p_{T,1}$ and $p_{T,2}$ silmultaneously
  - Leading jet p_T dependence

Dijet pair selection

ATLAS-CONF-2015-052

- Find the two highest jets in the event with p_T > 25 GeV and |η| < 2.1
  - ΔΦ > 7π/8, $p_{T1} > p_{T2}$
- Fill Pb+Pb 2D p_{T1} / p_{T2} distributions:
  - Minimum bias trigger for p_{T1} < 85 GeV
  - Jet trigger with a trigger efficiency correction for p_{T1} > 85 GeV
- Fill *pp* 2D p_{T1} / p_{T2} distributions:
  - 6 different trigger samples for ranges in p_{T1} where the trigger is efficient
  - Scaled by the inverse of its corresponding luminosity



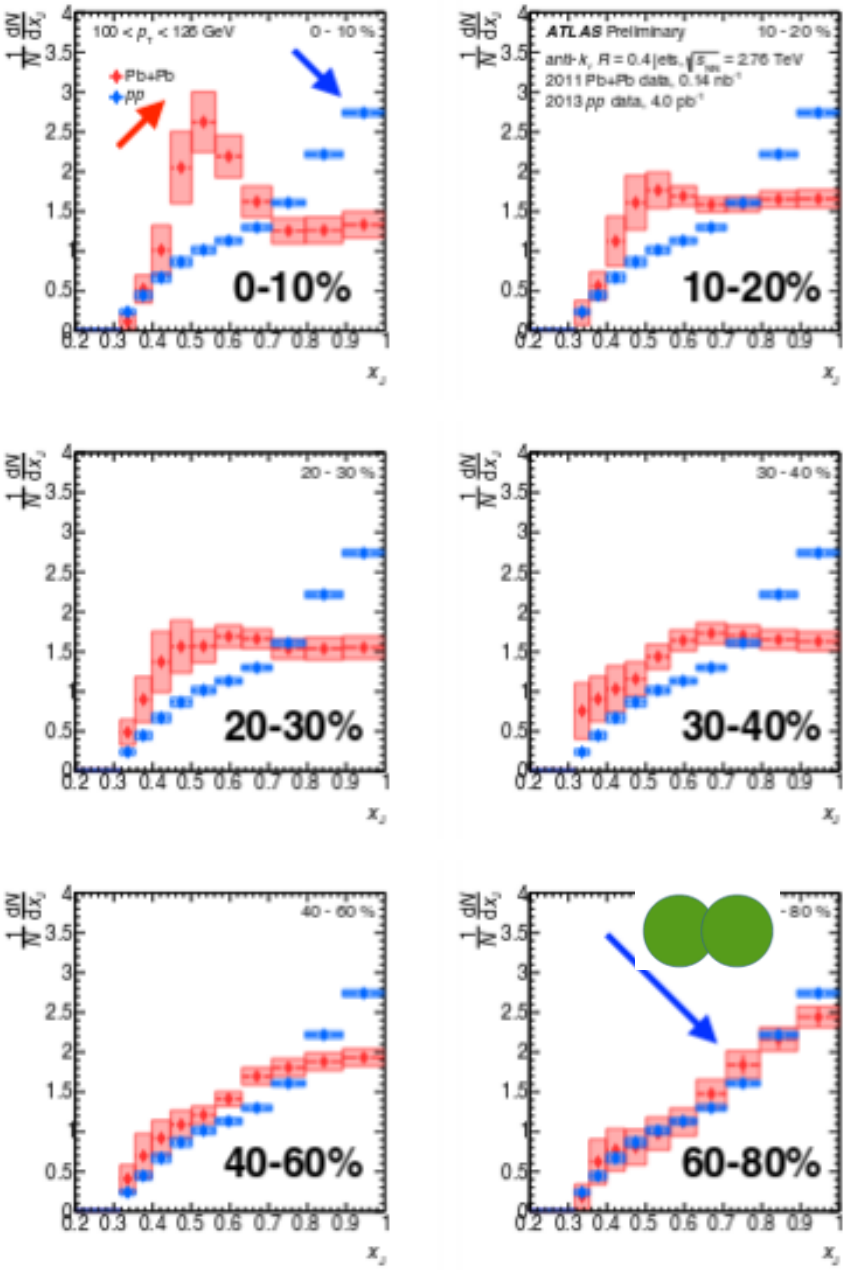


ATLAS-CONF-2015-052

Dijet asymmetry measurement

Centrality dependence

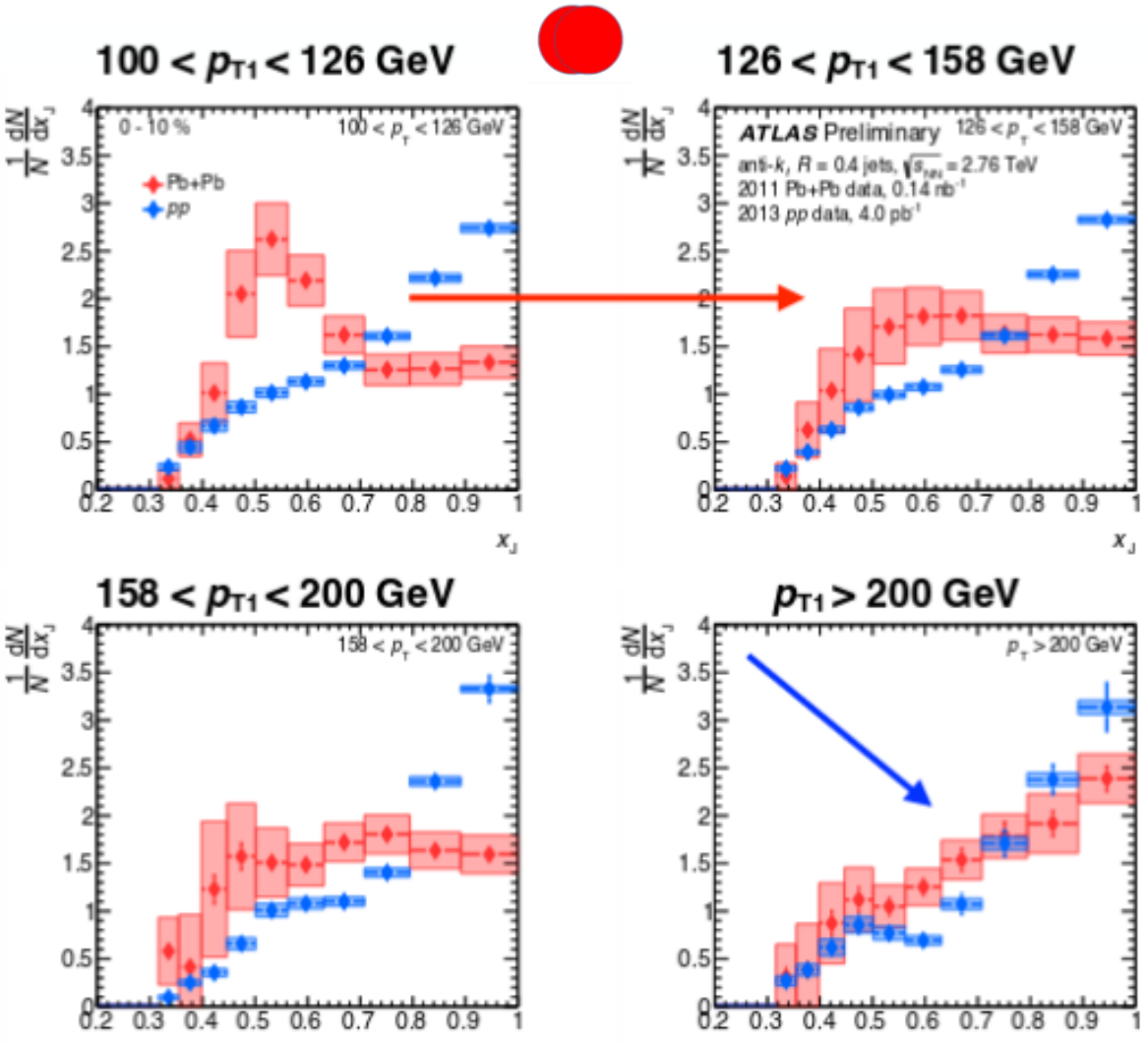
100 < p_{T1} < 126 GeV



- Pb+Pb becomes more asymmetric as more central collisions are probed
- Most probable configuration for *pp* is $x_J \sim 1$
- Most probable configuration for central Pb+Pb collisions is $x_J \sim 0.5$
- As Pb+Pb becomes more peripheral the distribution converges to *pp*

$$x_J = \frac{p_{\mathrm{T},1}}{p_{\mathrm{T},2}}$$

Dijet asymmetry measurement



p_{T1} dependence 0-10 %

- Central collisions show a significant p_{T1} dependence
- Pb+Pb collisions become similar to *pp* at high p_{T1}
- Significant difference in the path-length?
- Flavor efects?

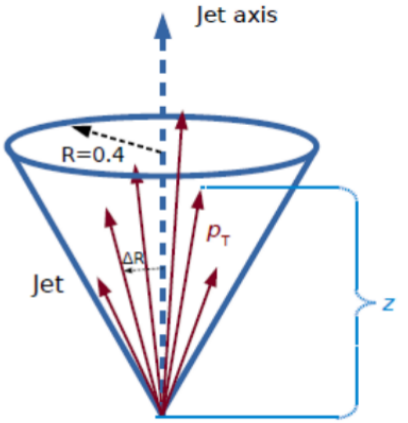
Jet fragmentation

See Martin Rybar talk, Sat 24th

ATLAS-CONF-2015-055

- How much is the jet structure modified?
- Jet fragmentation functions (FF) are defined as:

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

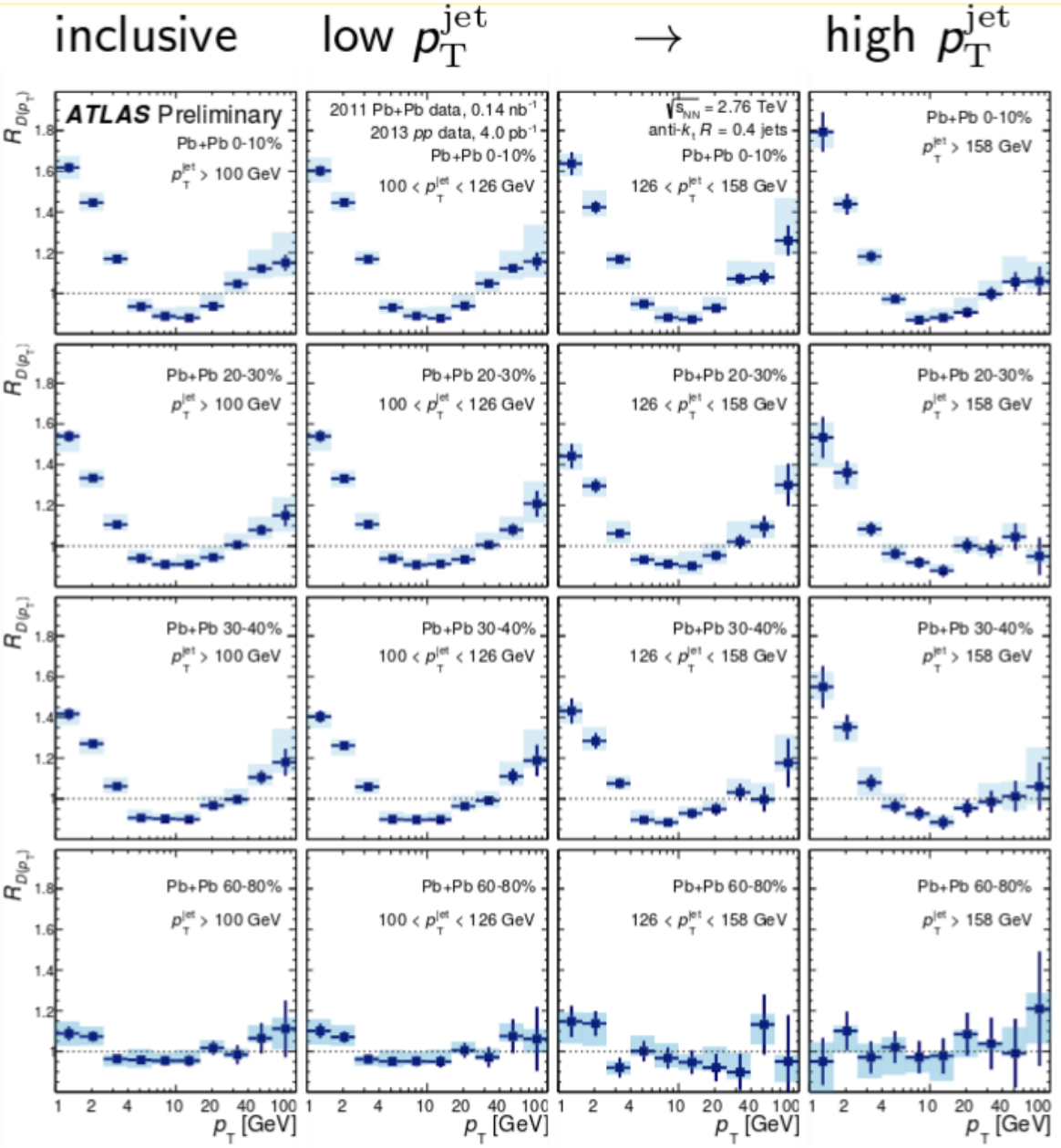


- N_{ch} is the number of charged particles associated to a jet
- Measurement was done for R = 0.4 jets differentially in η and p_T
- Jet substructure measured using charged tracks starting at p_T = 1 GeV
- FF are background subtracted, corrected for tracking efficiency and fully unfolded with 2D Bayesian unfolding

Jet fragmentation ratios

Ratios of $D(p_T)$ for 4 centralities in 4 p_T bins

See Martin Rybar talk, Sat 24th



ATLAS-CONF-2015-055

Centrality dependence

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

Jet p_T dependence

- No significant dependence on jet p_T

Rapidity dependence

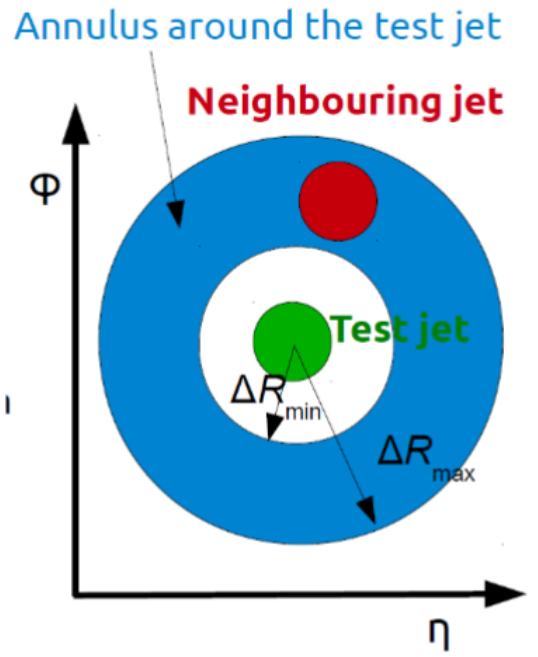
- Hint of rapidity dependence
- Consistent with prediction in arXiv: 1504.05169

Nearby jets

PLB 751 (2015) 376

- The rate of the neighbouring jets that accompany a test jet was measured:

$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}}, \Delta R)$$

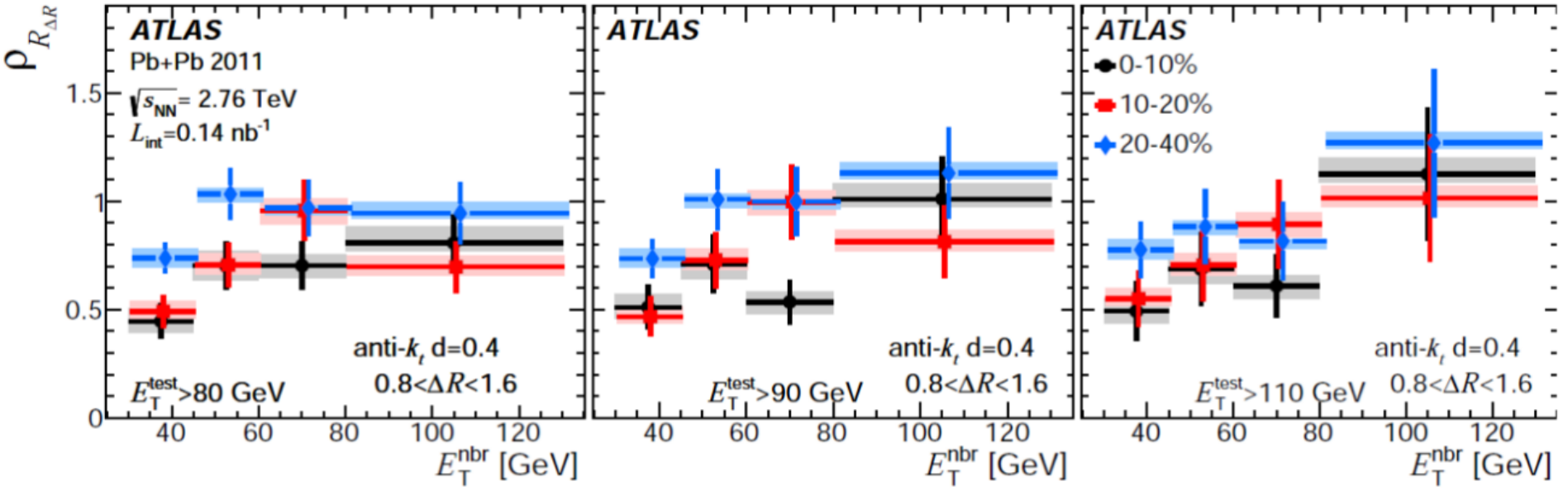


- Neighboring jet production quantified using this quantity previously measured at Tevatron

- To quantify the centrality dependence the central to peripheral ratios $\rho(R_{\Delta R})$ are evaluated

Nearby jets

PLB 751 (2015) 376



- Central to peripheral ratio of $R_{\Delta R}$ as a function of neighboring jet E_T
- Decrease of suppression (by a factor ≈ 2 in central collisions) with increasing neighbouring-jet E_T

Summary

- Broad program of jet-based imaging of the hot nuclear medium in ATLAS
- Inclusive jets in Pb+Pb are suppressed relatively to *pp* by up to a factor of 2, no dependence on rapidity
- First fully corrected dijet measurement provided
  - Enhancement in Pb+Pb, relatively to *pp* as the centrality increases
  - Clear dependence on the p_T of the leading jet in contrast to inclusive jets

Summary

- Jet internal structure measured differentially in jet p_T and rapidity, observed modest but significant modification of jet fragmentation functions
- Production of nearby jets quantified
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

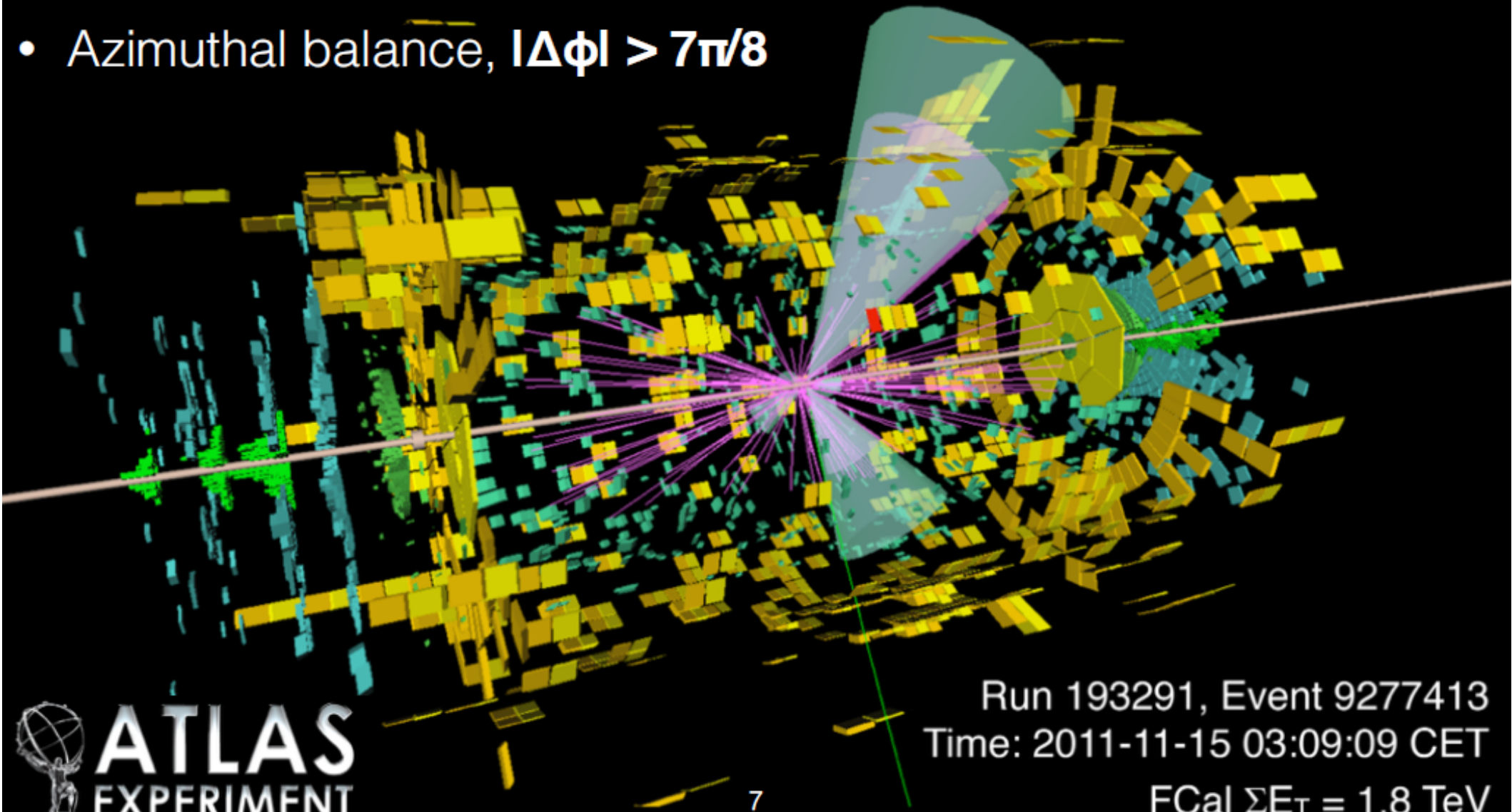
Back up

New Dijet Asymmetry

(ATLAS-CONF-2015-052)

- Jets within $|\eta| < 2.1$
- Leading $p_{T,1} > 100$ GeV
- Subleading $p_{T,2} > 25$ GeV
- Azimuthal balance, $|\Delta\phi| > 7\pi/8$

➡ $x_J = p_{T,2} / p_{T,1}$



ATLAS EXPERIMENT

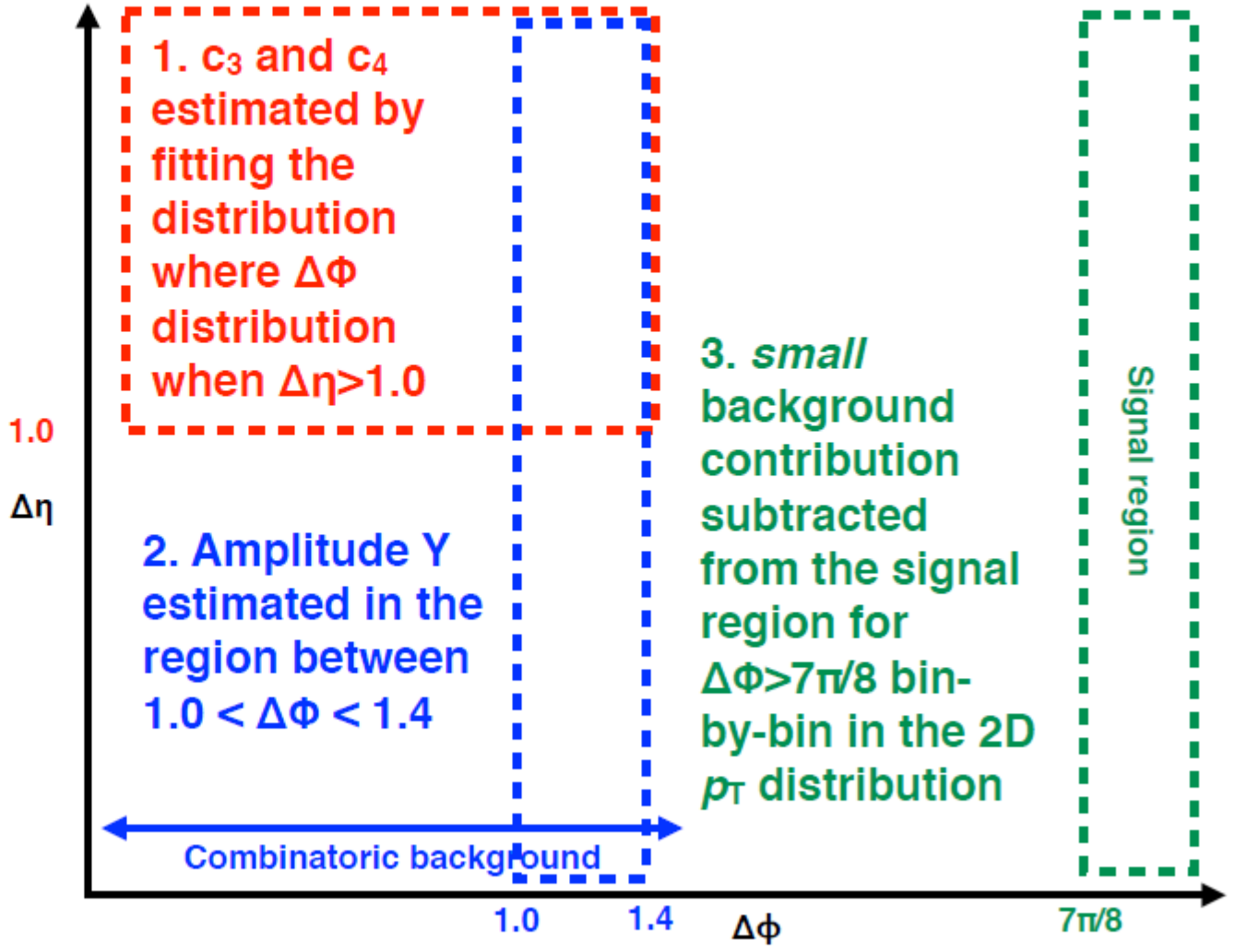
Run 193291, Event 9277413
Time: 2011-11-15 03:09:09 CET
FCal ΣE_T = 1.8 TeV

ΔΦ combinatoric subtraction

- Significant contribution of pairs arise from jets not originating from the same hard scattering
- combinatoric pairs expected to be uncorrelated in $\Delta\Phi < \pi/2$

  ➡ 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



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

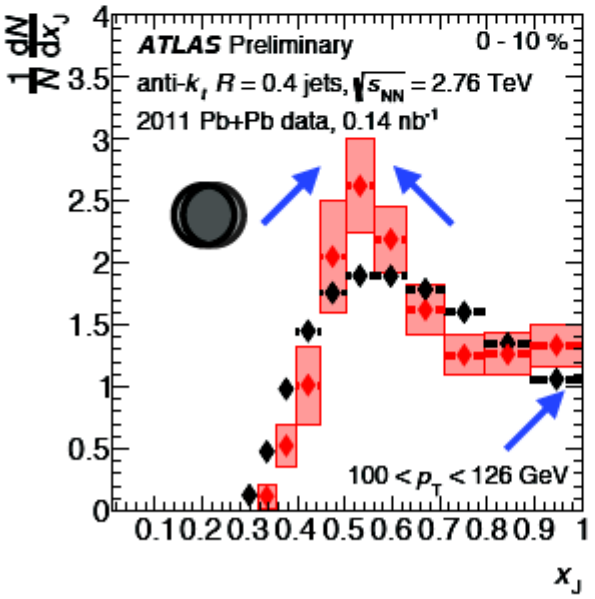
Unfolding

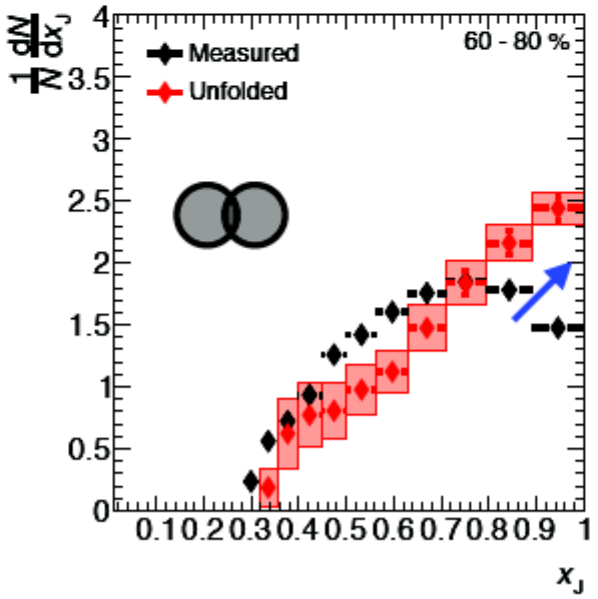
- **Unfolded to correct for the Jet Energy Scale (JES) and Resolution (JER) in the detector which is the mean (< 1%) and width (~40% in central low p_T) of the measured jet p_T distributions at a given value of p_T true**

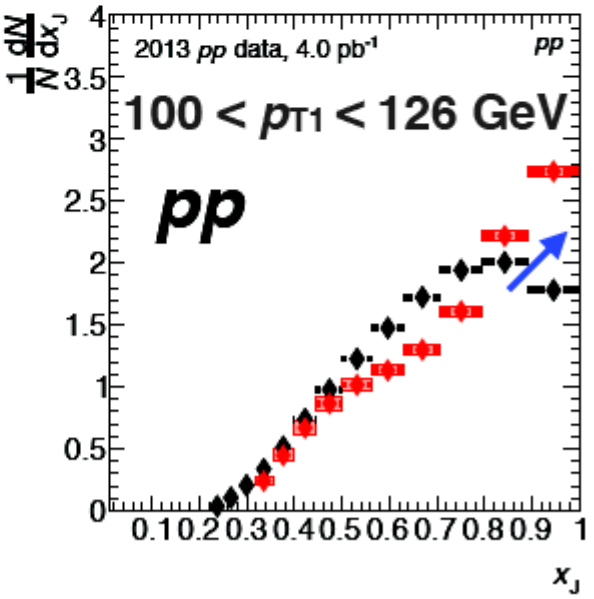
- **2D Bayesian unfolding to account for bin migration in p_{T1} and p_{T2} simultaneously**

➡ **Filled response symmetrically from MC in p_{T1}^{true}, p_{T2}^{true}, p_{T1}^{reco}, and p_{T2}^{reco}**

➡ **MC sample is pythia dijet events run through a GEANT simulation of ATLAS and then embedded into real minimum bias HI data**







► ***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***

Unfolding details

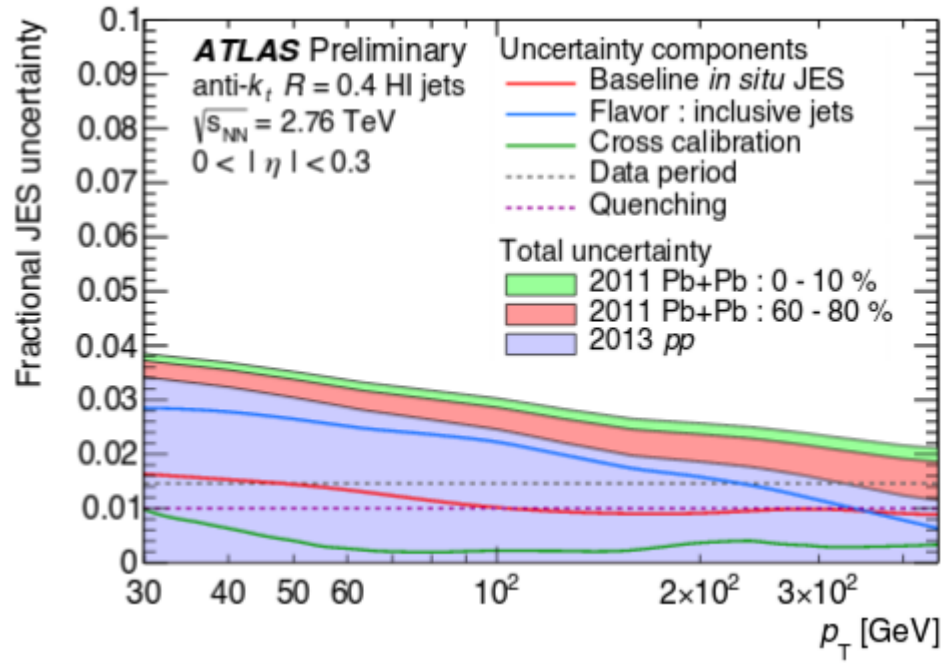
- Filled a response symmetrically in p_{T1}^{true}, p_{T2}^{true}, p_{T1}^{reco}, and p_{T2}^{reco}
- Response is generated from the MC in the Pb+Pb and the p+p separately
  - ➡ Truth pair with pT>25 GeV, |η|<2.1, and |Δϕ|>7π/8
  - ➡ Match each truth jet to a reconstructed jet for pT>25 GeV and |η|<2.1 with ΔR<0.3
  - ➡ Reconstructed pair must be within |Δϕ|>7π/8
- Decide the number of iterations in the unfolding based on 3 criteria:
  - ➡ stability against number of iterations
  - ➡ closure in refolding (putting the unfolded distribution back though the response)
  - ➡ Monitor the fluctuations in the statistical errors with unfolding

► *Number of iteration chosen to be 26 for Pb+Pb and 15 for p+p.*

JES/JER uncertainty

JES:

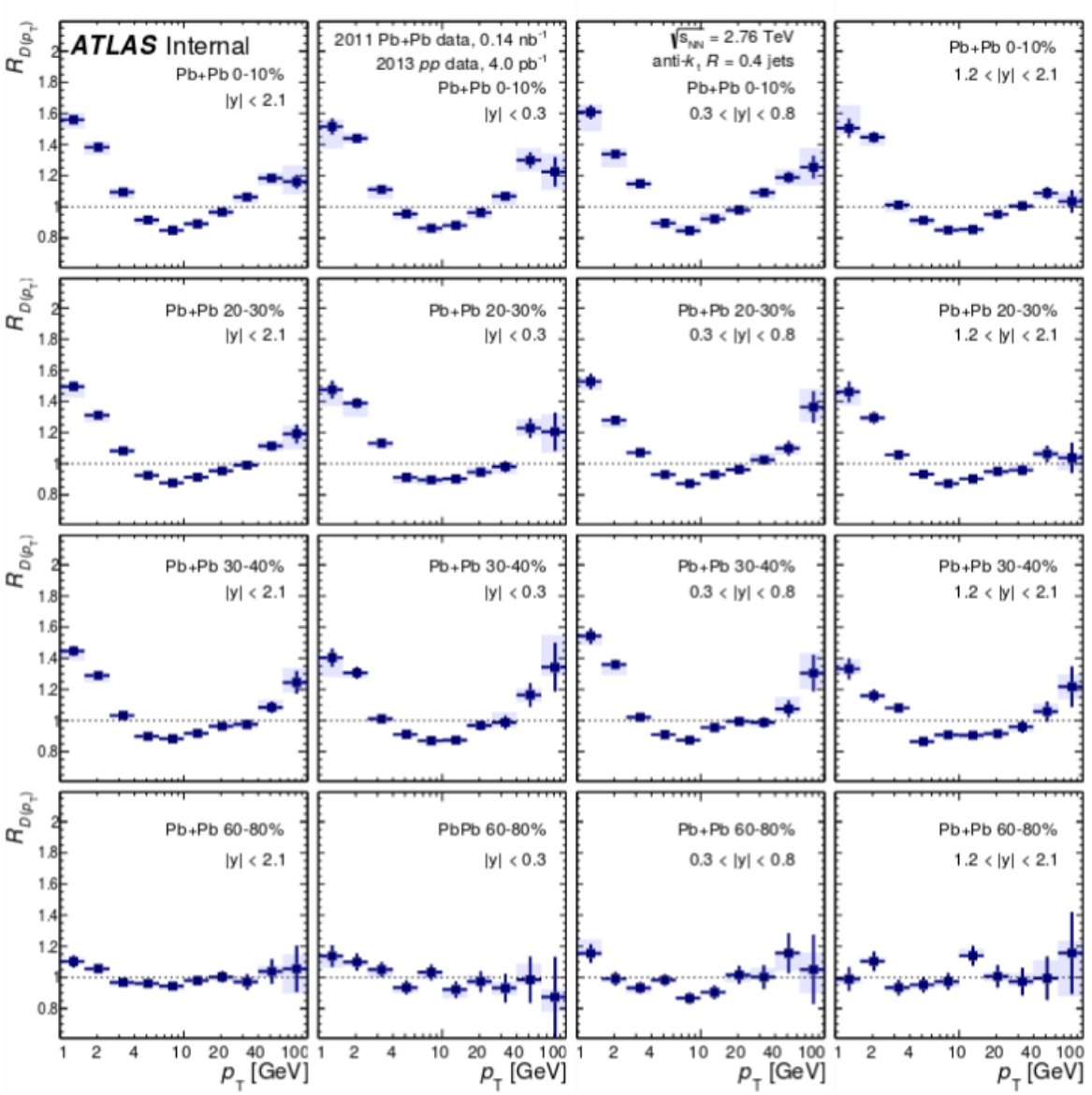
- Use the baseline 8 nuisance parameters from *in situ* calibration
- Additional parameters due to flavor responce and composition and cross calibration
- Two addition parameters for Pb+Pb due to the difference in the data taking period and detector responce to quenched jets



JER:

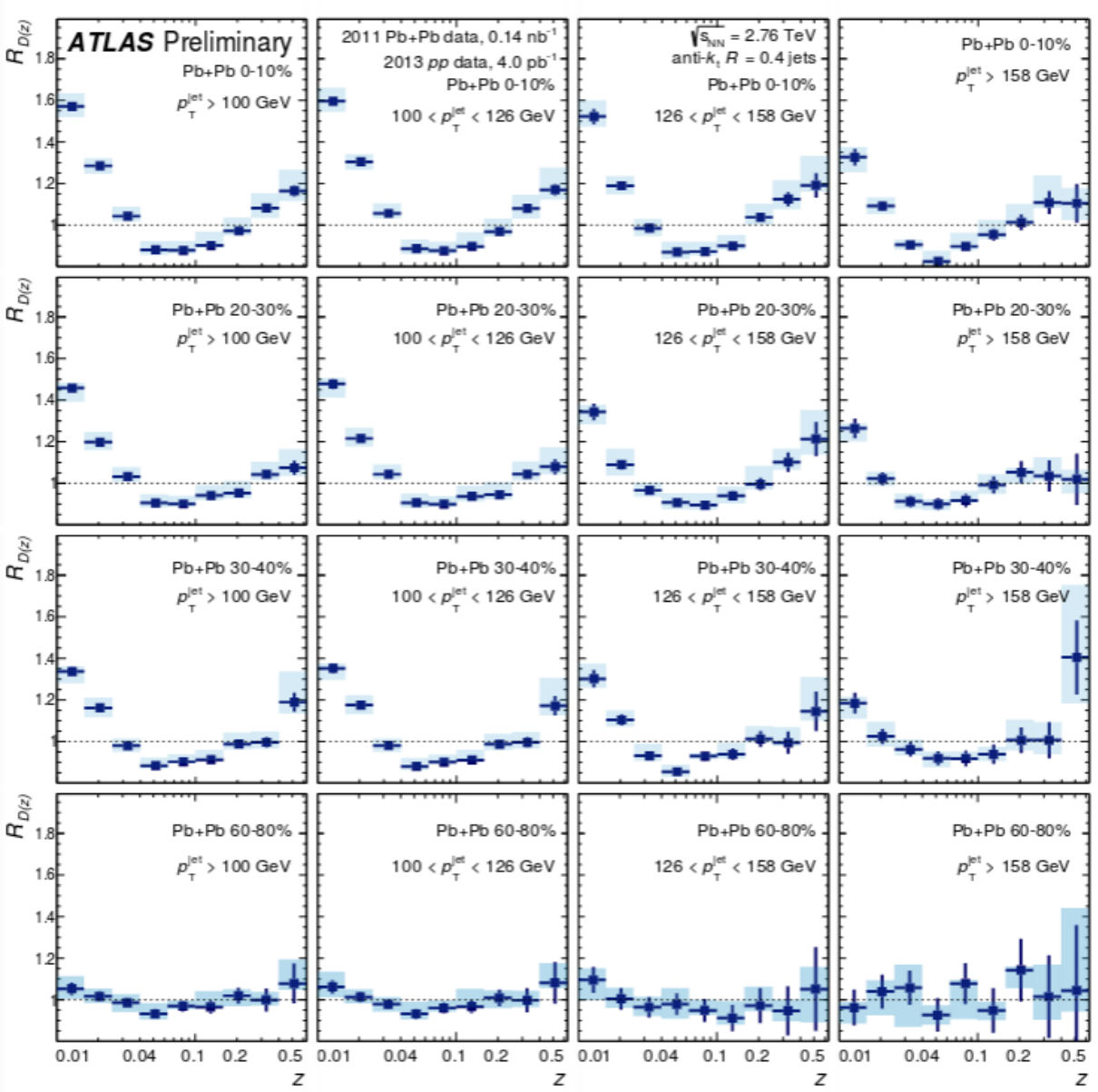
- Standart centrality-independent JER uncertainties
- Additional centrality dependent uncertaitny for possible disagreement between fluctuations term in JES in the MC independent analysis of fluctuations in data
- This is very small because MC sample is data everlay

Jet fragmentation



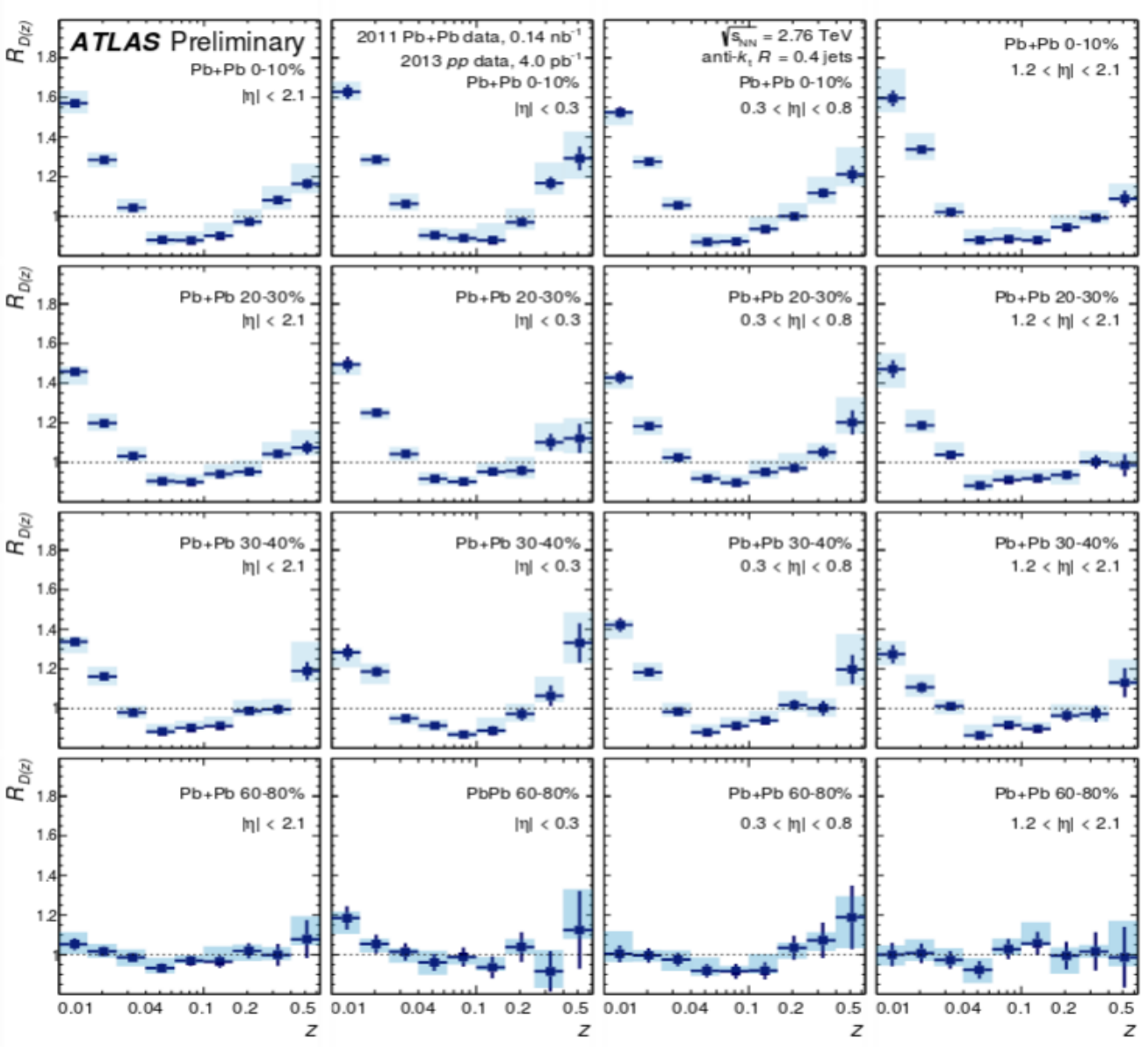
- Ratios of FF $D(p_T)$ for different centrality and rapidity bins

Jet fragmentation



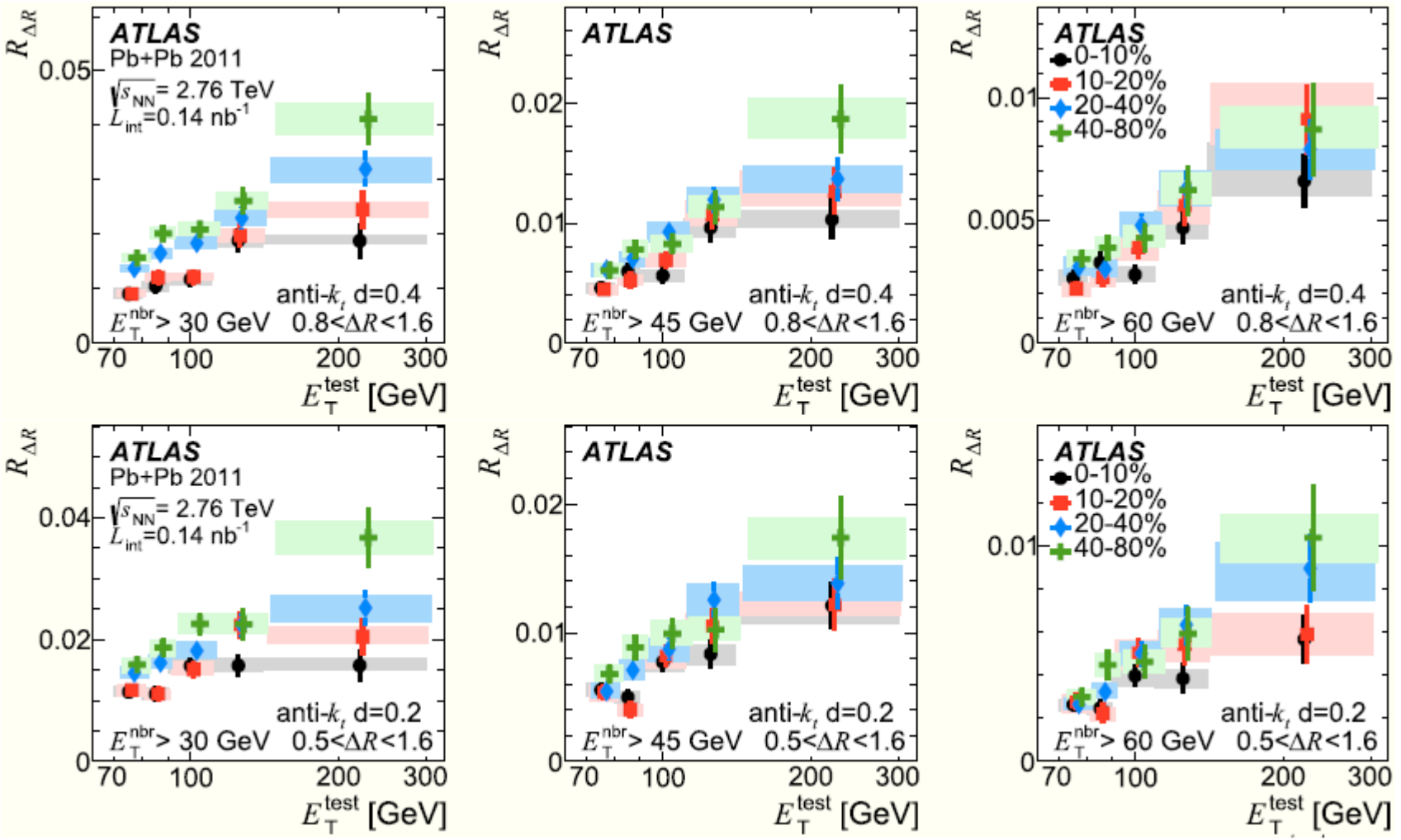
- Ratios of FF $D(z)$ for different centrality and jet p_T bins

Jet fragmentation

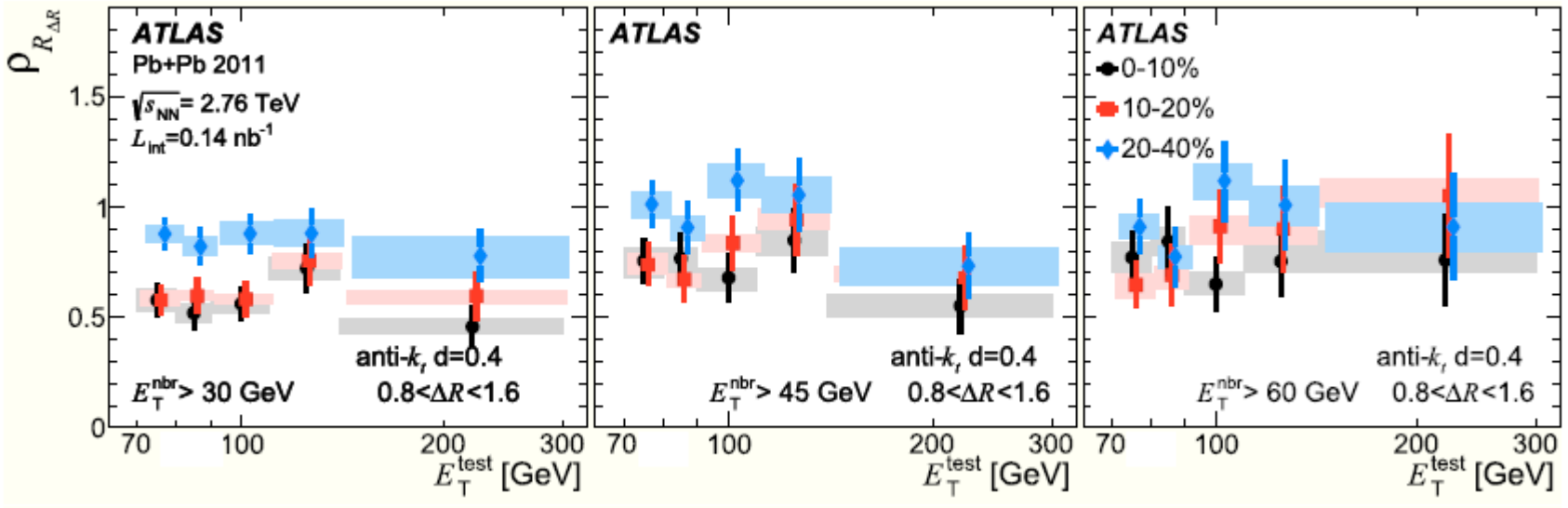


- Ratios of FF $D(z)$ for different centrality and rapidity bins

Nearby jets


ATLAS
Pb+Pb 2011
$\sqrt{s_{NN}}$= 2.76 TeV
L_{int}=0.14 nb^{-1}
anti-k_t d=0.4
E_T^{nbr}> 30 GeV 0.8<ΔR<1.6
E_T^{nbr}> 45 GeV 0.8<ΔR<1.6
E_T^{nbr}> 60 GeV 0.8<ΔR<1.6
anti-k_t d=0.2
E_T^{nbr}> 30 GeV 0.5<ΔR<1.6
E_T^{nbr}> 45 GeV 0.5<ΔR<1.6
E_T^{nbr}> 60 GeV 0.5<ΔR<1.6
0-10%
10-20%
20-40%
40-80%
$R_{\Delta R}$
E_T^{test} [GeV]

Nearby jets



- Central to peripheral ratio of $R_{\Delta R}$ as a function of neighboring jet E_T