Small Rock Seminar

Study of jet fragmentation and inclusive jet production in heavy-ion collisions with the ATLAS experiment

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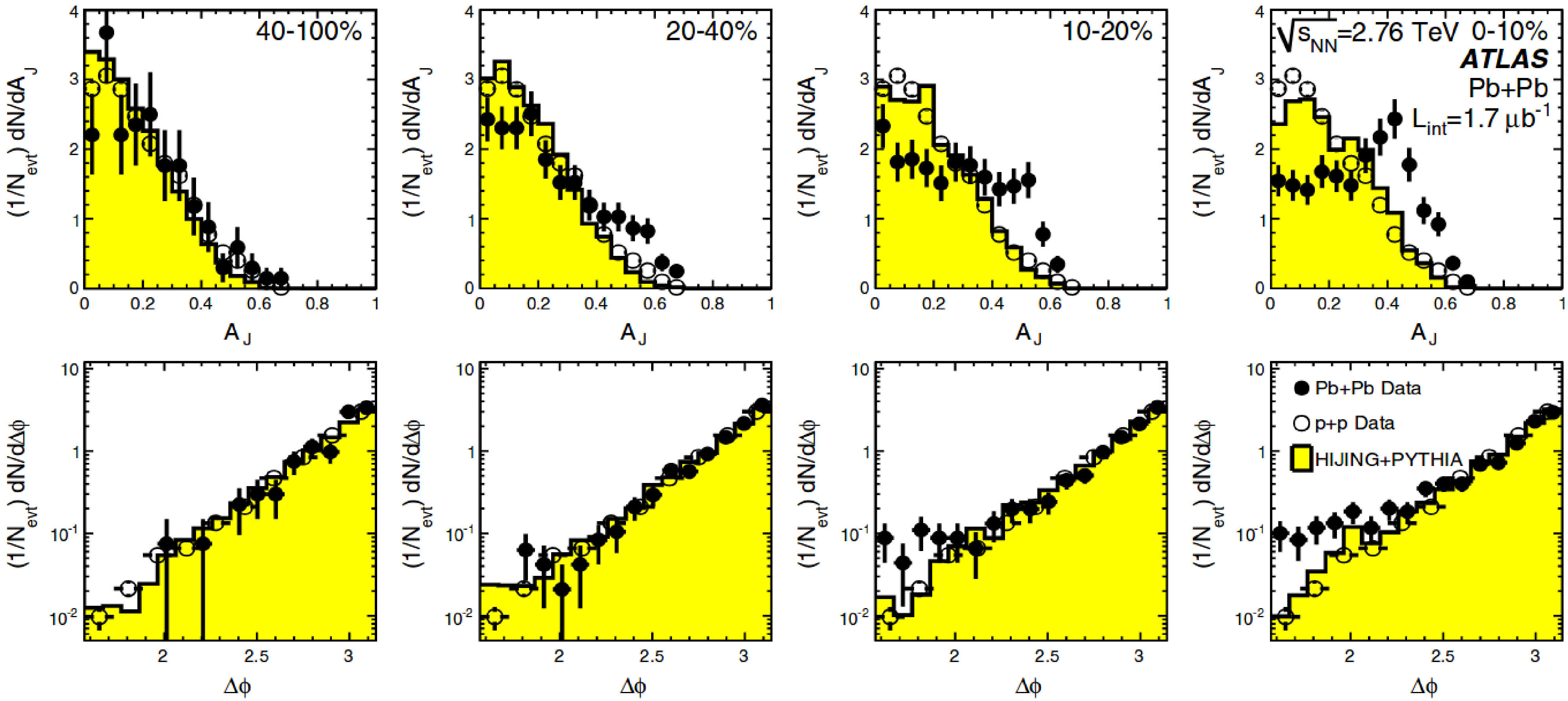
9.4.2018

Jets in *pp*, *p*+Pb, Pb+Pb collisions

- In heavy-ion collisions the strongly interacting deconfined matter (Quark-Gluon plasma - QGP) is created
- The main motivation is to understand better the modification of jet properties: a parton with high momentum is traversing the hot and dense medium and looses its energy by radiating gluons = **jet quenching**
- To fully understand jet quenching phenomenon, in addition to jet suppression it is necessary to measure jet fragmentation i.e. possible modifications of parton showers through interactions in the plasma
- We obtained the final result on the jet Fragmetation Funcions (FF) for **Pb+Pb @ 2.76 TeV** and ***p*+Pb @ 5.02 TeV** with new *pp* @ 5.02 TeV reference and first preliminary result for **Pb+Pb @ 5.02 TeV** with *pp* reference at corresponding energy
- **Pb+Pb @ 5.02 TeV** was done with large p_T range
- We obtained preliminary R_{AA} @ 5.02 TeV for jets

Discovery of jet quenching on LHC



PRL 105 (2010) 252303 (>500 citations)

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

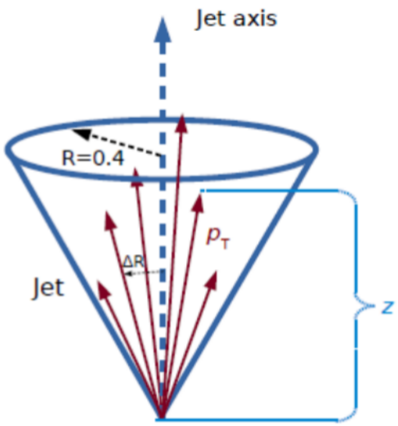
Used data and MC

- **Pb+Pb @ 2.76 TeV** (2011), L_{int} = 0.15 nb^{-1}
  - ***pp* @ 2.76 TeV** (2013), L_{int} = 4 pb^{-1}
  - Pb+Pb data are compared to MC, where MC PYTHIA 6 di-jet events were embedded into real MB Pb+Pb events
- **Pb+Pb @ 5.02 TeV** (2015), L_{int} = 0.49 nb^{-1}
  - ***pp* @ 5.02 TeV** (2015), L_{int} = 25 pb^{-1}
  - Pb+Pb utilize POWHEG+PYTHIA8 with overlayed MinBias Pb+Pb collisions
  - *pp* utilize PYTHIA8 with the A14 ATLAS tune and the NNPDF23LO pdfs
- ***p*+Pb @ 5.02 TeV** (2013), L_{int} = 28 nb^{-1}
  - ***pp* @ 5.02 TeV** (2015), L_{int} = 25 pb^{-1}
  - *p*+Pb and *pp* measurements utilize PYTHIA 6 (embedded into real MB *p*+Pb), PYTHIA 8 and HERWIG++ samples

Jet fragmentation in Pb+Pb @ 2.76 TeV and @ 5.02 TeV, *p*+Pb @ 5.02 TeV

arXiv:1702.00674 **ATLAS-CONF-2017-005** **ATLAS-CONF-2017-004**

- 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 y and p_T for Pb+Pb and differentially in p_T for p+Pb
- Jets measured using charged tracks starting at p_T = 1 GeV for p+Pb @ 5.02 TeV and Pb+Pb @ 2.76 TeV and p_T = 4 GeV for Pb+Pb @ 5.02 TeV
- FF are background subtracted, corrected for tracking efficiency and fully unfolded with 2D Bayesian unfolding
- The jet spectra for the normalisation were unfolded using 1D Bayesian unfolding for both Pb+Pb FF and using bin-by-bin correction for p+Pb

Unfolded fragmentation functions *pp* and *p*+Pb

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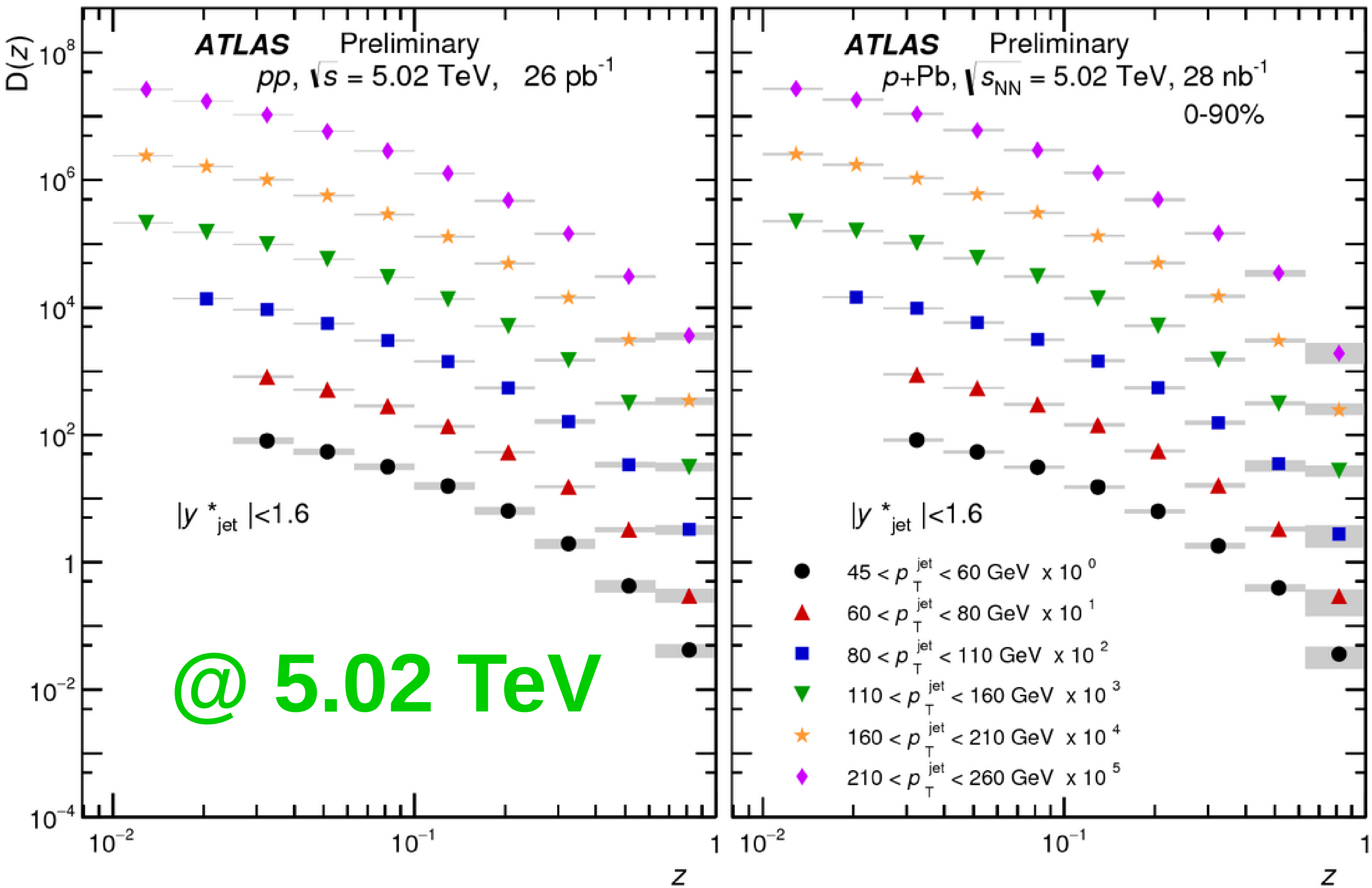

Spectra have similar shape, ratios are needed to see the modifications:

$$R_{D(z)} \equiv \frac{D(z)_{p\mathrm{Pb}}}{D(z)_{pp}}$$

$R_{D(pT)}$ for different p_T bins

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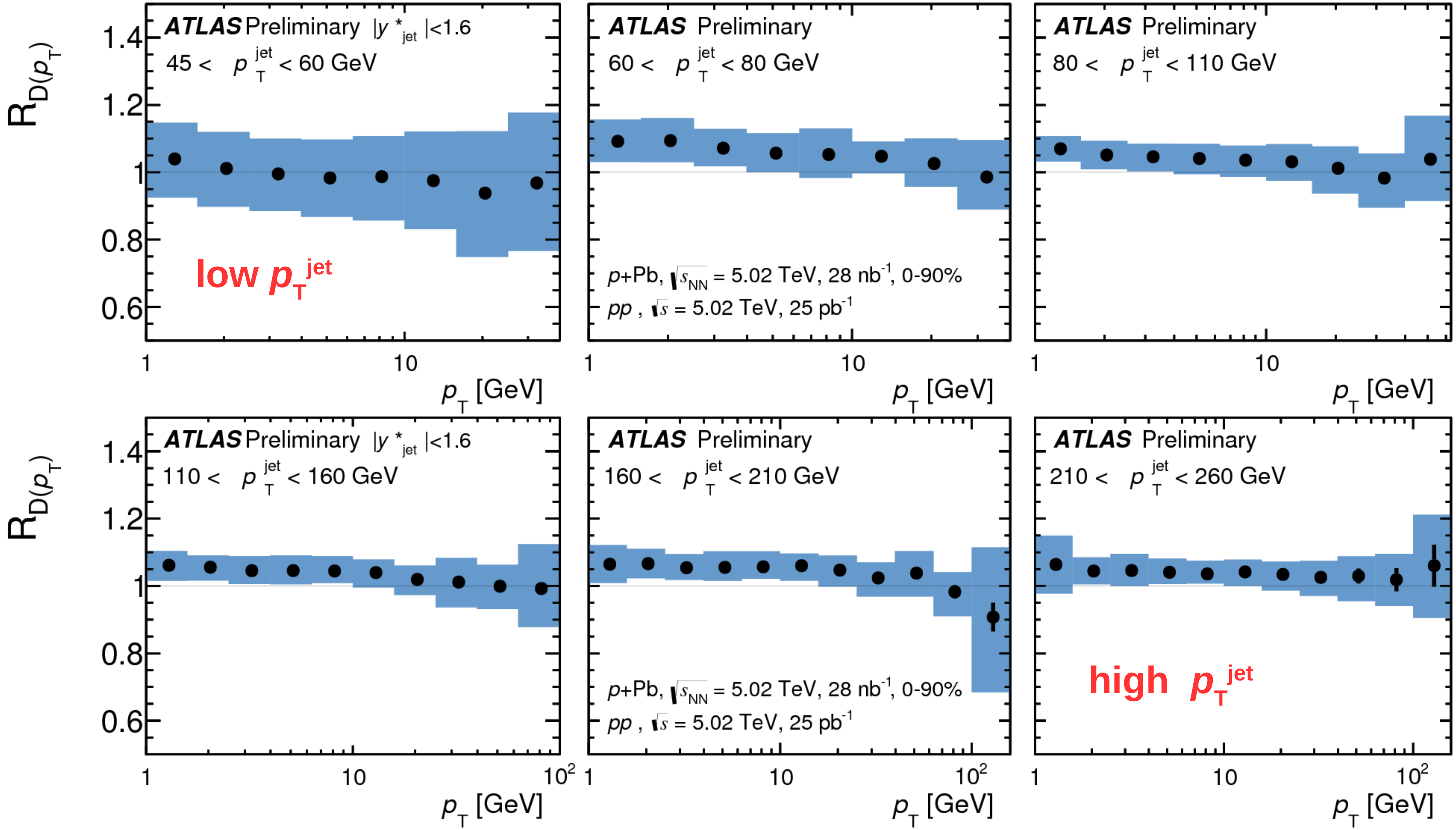
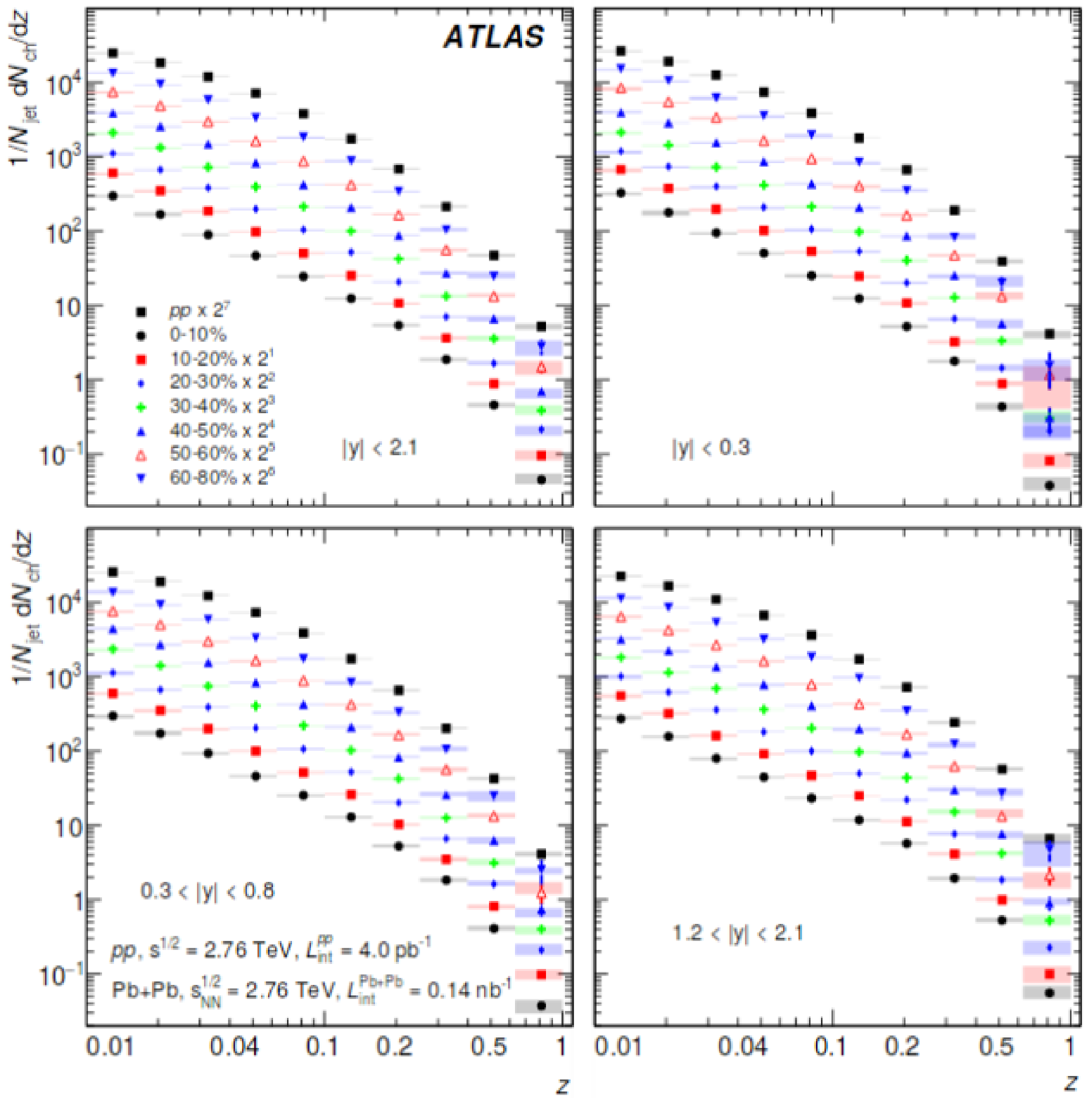
p+Pb @ 5.02 TeV with new *pp* reference @ 5.02 TeV

- No modification of the fragmentation fuctions is observed



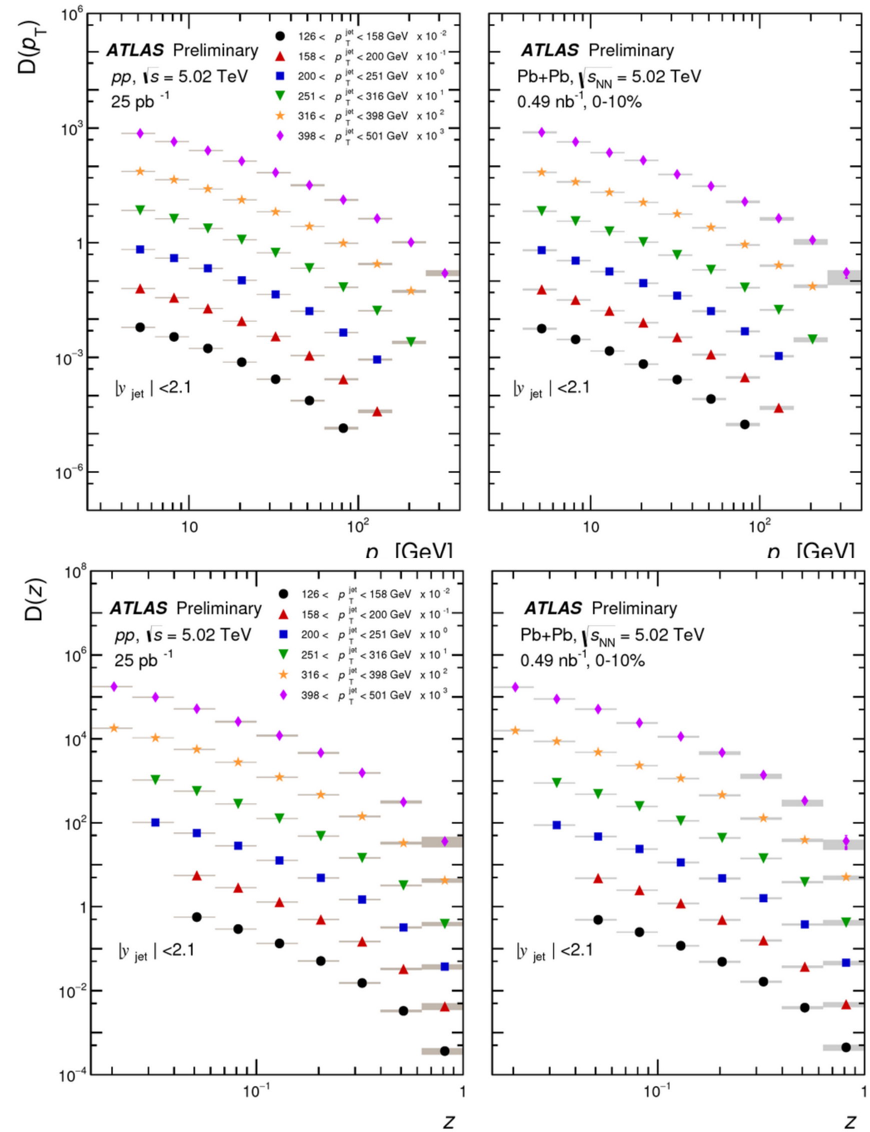
Comprehensive Pb+Pb fragmentation functions

Pb+Pb and *pp* @ 2.76 TeV



arXiv:1702.00674

Pb+Pb and *pp* @ 5.02 TeV

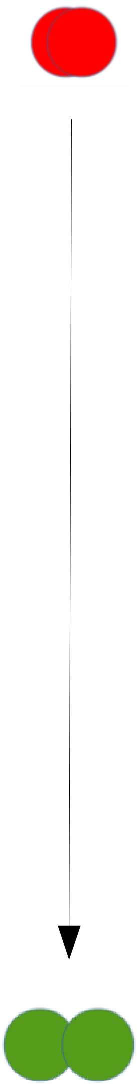


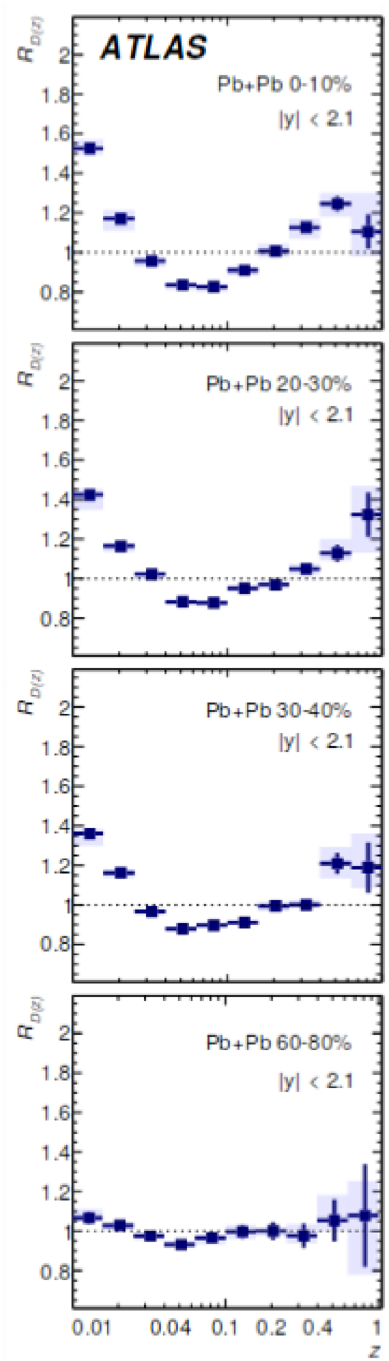
ATLAS-CONF-2017-005

Spectra have similar shape, ratios are needed to see the modifications:

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

Jet fragmentation ratios Pb+Pb





Ratios of *D*(z) for 4 centralities

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

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

@ 2.76 TeV

arXiv:1702.00674

Centrality dependence

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

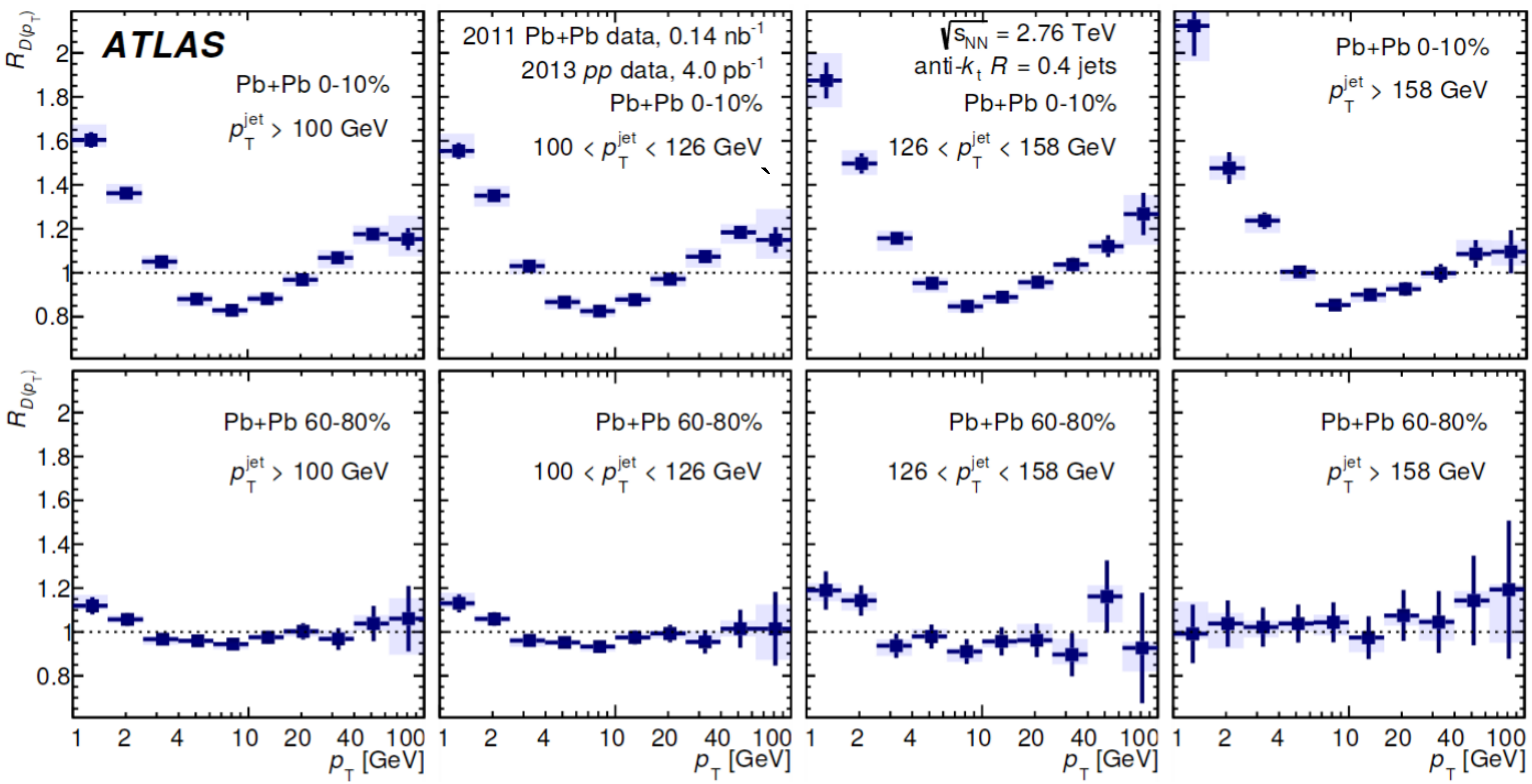
Similar observation for $D(p_T)$

arXiv:1702.00674

Jet fragmentation ratios Pb+Pb

@ 2.76 TeV

Ratios of $D(p_T)$ for 2 centralities and 4 p_T bins



Jet p_T dependence

- No significant dependence on jet p_T
- Enhancement at low p_T is larger for bigger p_T^{jet} interval in the central events

100 < p_T^{jet} < 398 GeV

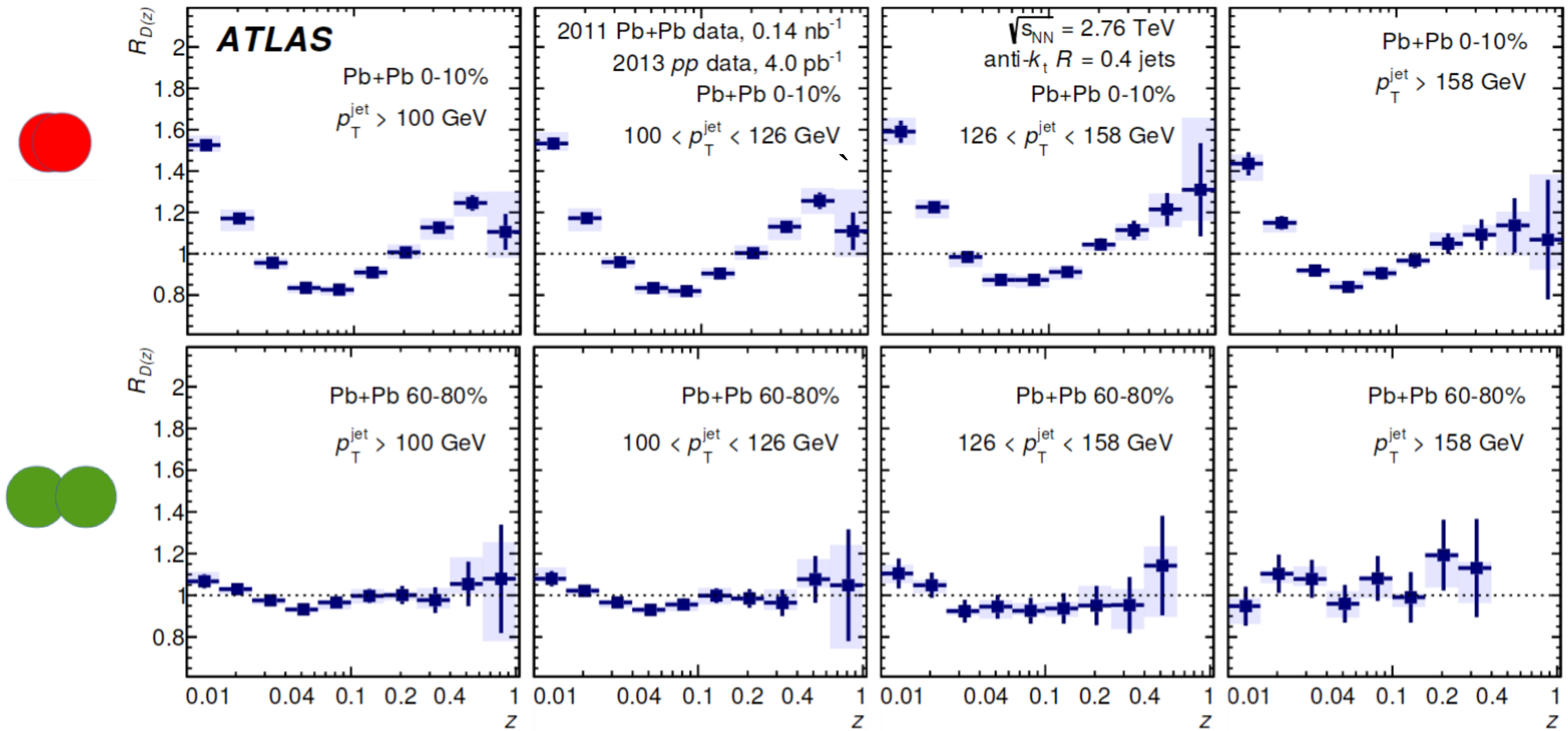
$|y|$ < 2.1

arXiv:1702.00674

Jet fragmentation ratios Pb+Pb

Ratios of *D*(z) for 2 centralities and 4 p_T bins

@ 2.76 TeV



Jet p_T dependence

- No significant dependence on jet p_T

100 < p_T^{jet} < 398 GeV

|*y*| < 2.1

Jet fragmentation – flow of particles

Pb+Pb @ 2.76 TeV

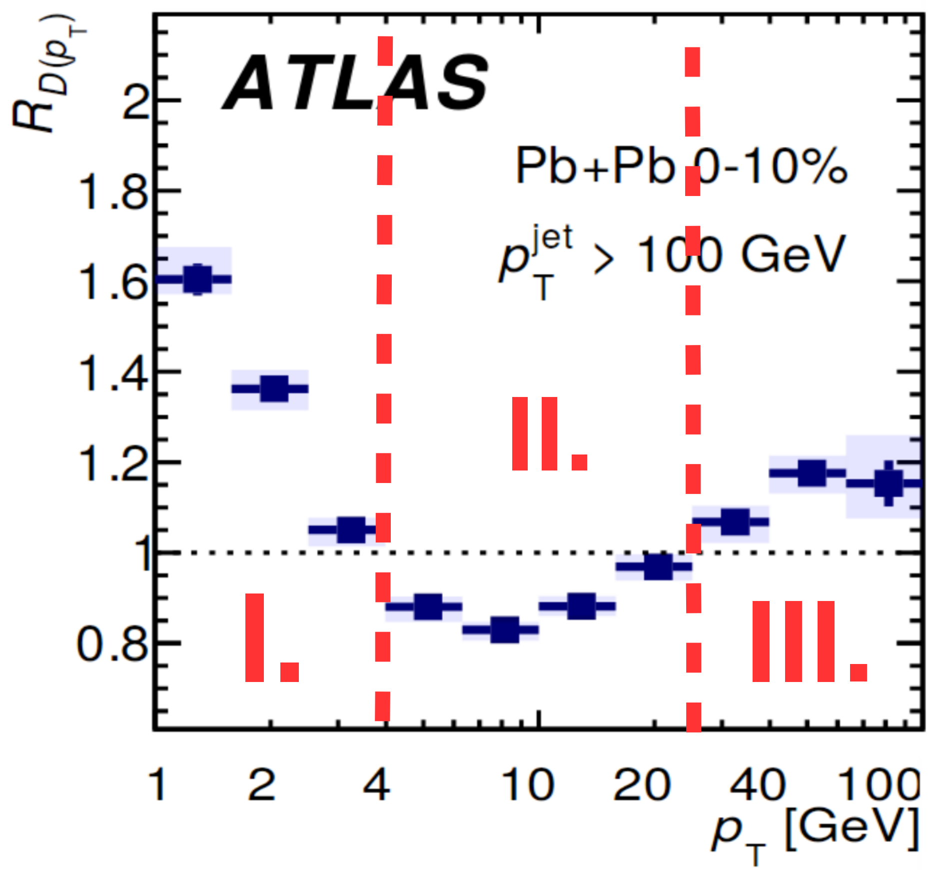
arXiv:1702.00674

- To quantify the flow of particles as a function of N_{part}:

$$N^{ch} \equiv \int_{p_{T,min}}^{p_{T,max}} \left(D(p_T)|_{cent} - D(p_T)|_{pp} \right) dp_T$$

- Values $p_{T,min}$ and $p_{T,max}$ set accordingly where $R_{D(pT)}$ is above or under unity

- Three p_T intervals:
  - I. 1 – 4 GeV
  - II. 4 – 25 GeV
  - III. 25 – 100 GeV



Jet fragmentation – flow of particles

Pb+Pb @ 2.76 TeV

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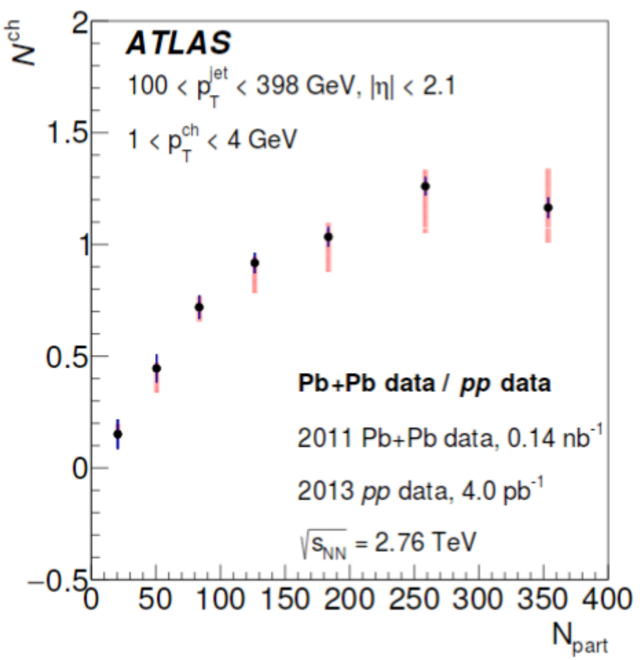
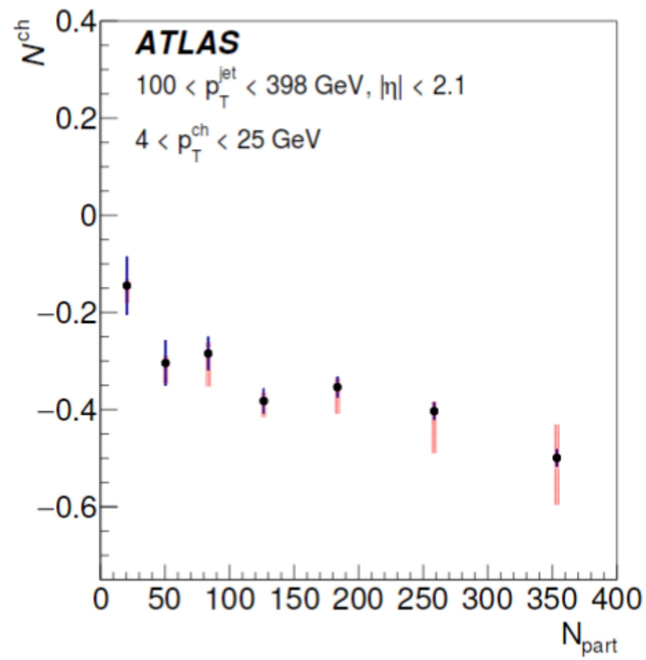
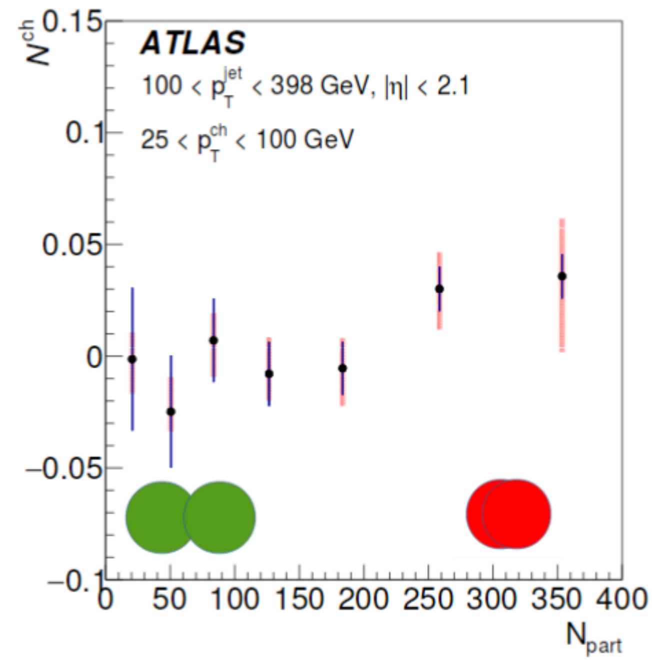
I.



II.



III.



- Tells us how many extra/missing particles are present in a given p_T range
- Observed a clear increase of yields of particles with low tranverse momenta as the collision's centrality increases
- Particles with p_T > 25 GeV do not exhibit noticeable variations with centrality

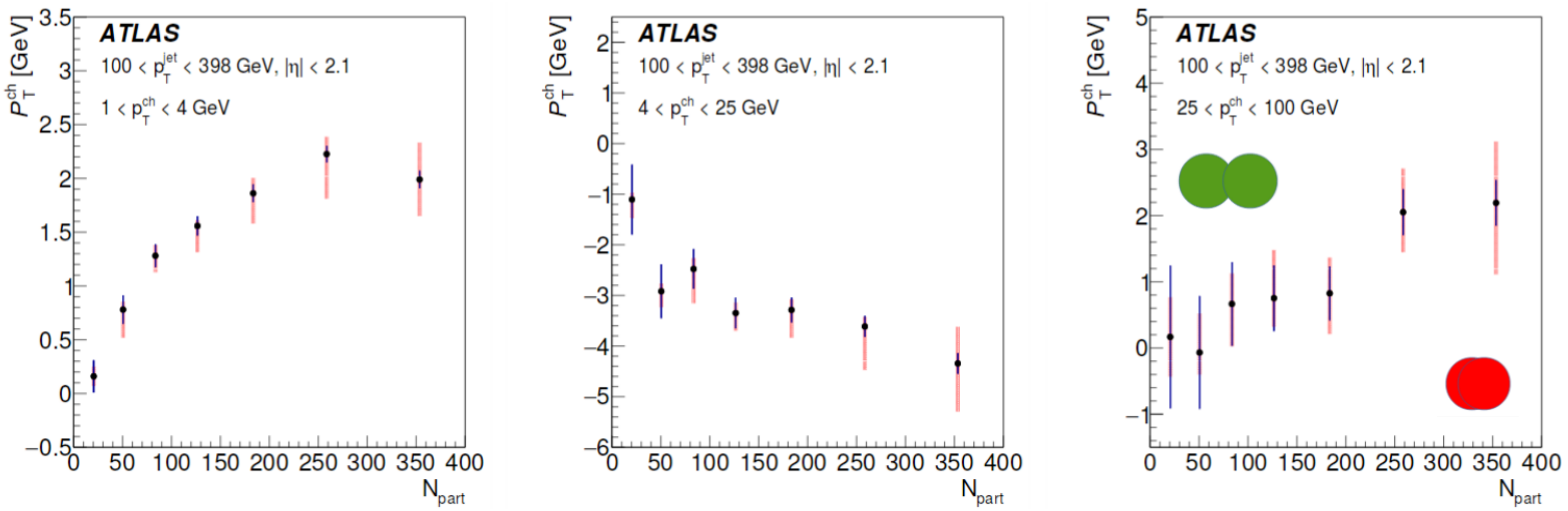
Jet fragmentation – flow of momentum

Pb+Pb @ 2.76 TeV **arXiv:1702.00674**

- The flow of momentum as a function of N_{part}:

$$P_{\mathrm{T}}^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) p_{\mathrm{T}}\, \mathrm{d}p_{\mathrm{T}}$$

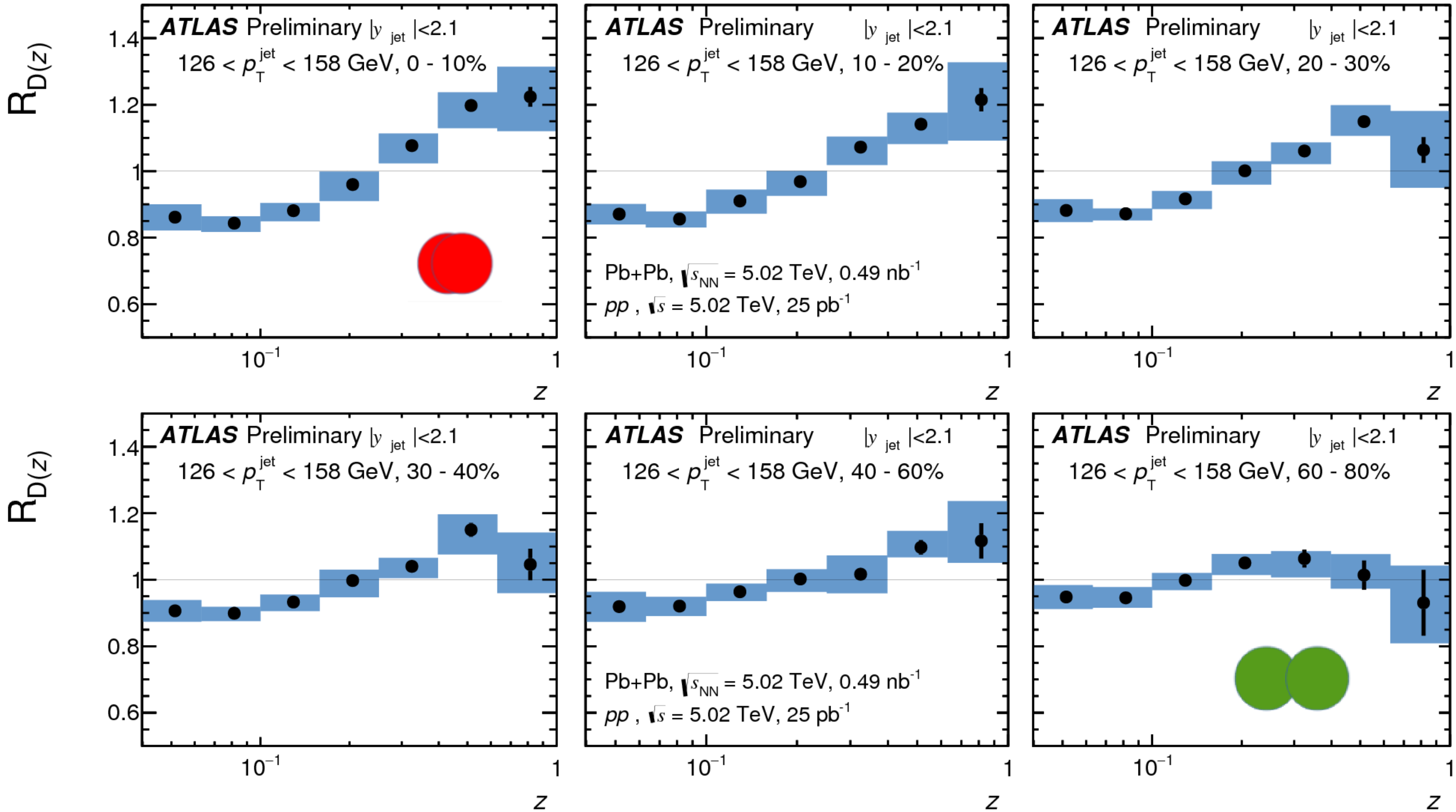
I. **II.** **III.**



- Tells us how much p_T is carried by extra/missing particles in a given p_T range
- The changes in the total transverse momentum follow the trends seen in the yields.

Jet fragmentation ratios Pb+Pb

Ratios of *D*(z) for 6 centralities in one p_T bin **@ 5.02 TeV**



Centrality dependence

- Enhancement at high z
- Suppression at intermediate z

$126 < p_T < 158$ GeV

- Cut on $p_T^{trk} > 4$ GeV
- Missing the low p_T enhancement

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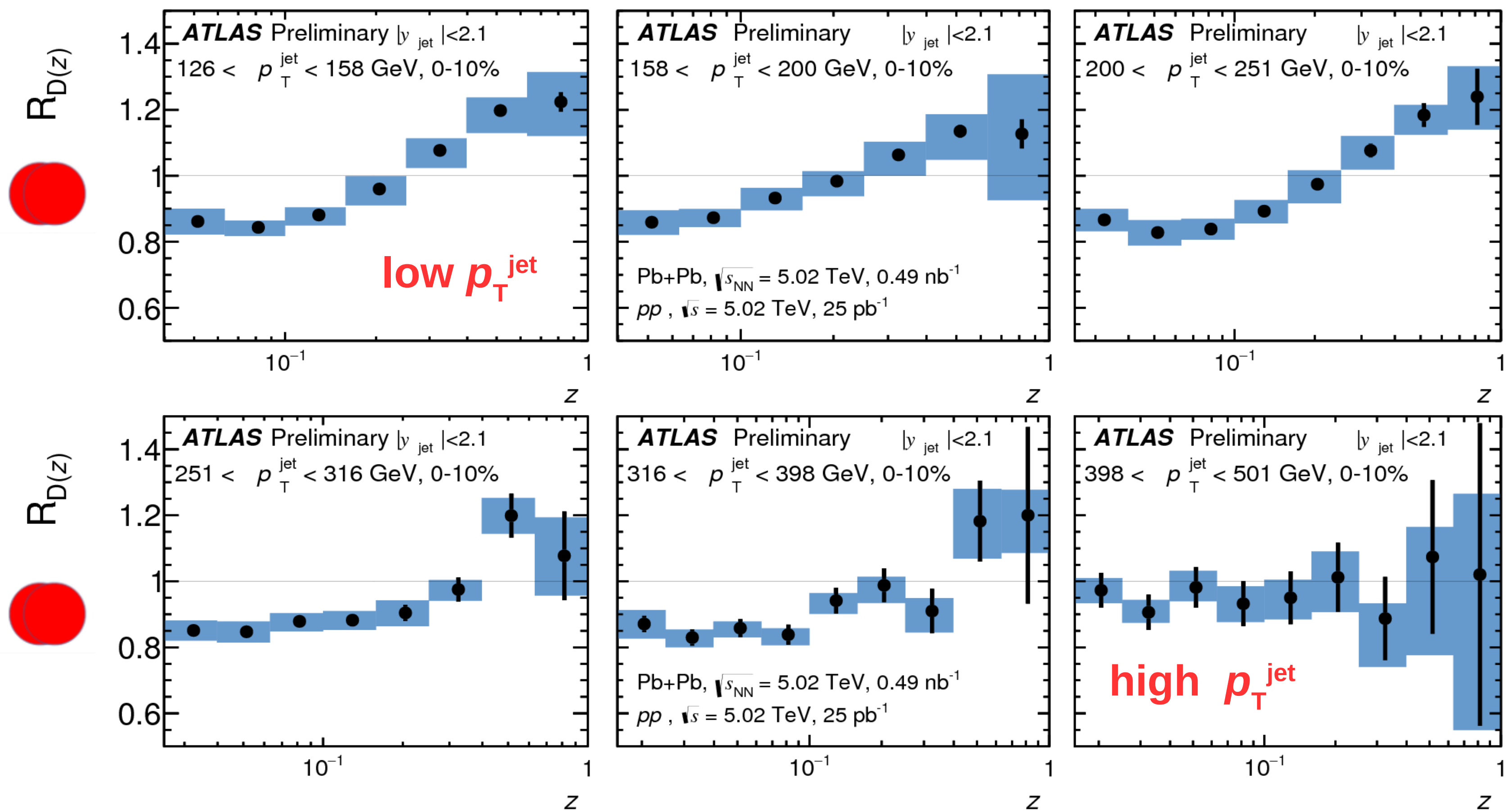
Jet fragmentation ratios Pb+Pb

Ratios of *D*(z) for central events and 6 p_T bins **@ 5.02 TeV**



Centrality dependence

- Enhancement at high z
- Suppression at intermediate z

Jet p_T dependence

- No significant dependence on jet p_T

126 < p_T < 501GeV

- Cut on p_T^{trk} > 4 GeV
- Missing the low p_T enhancement

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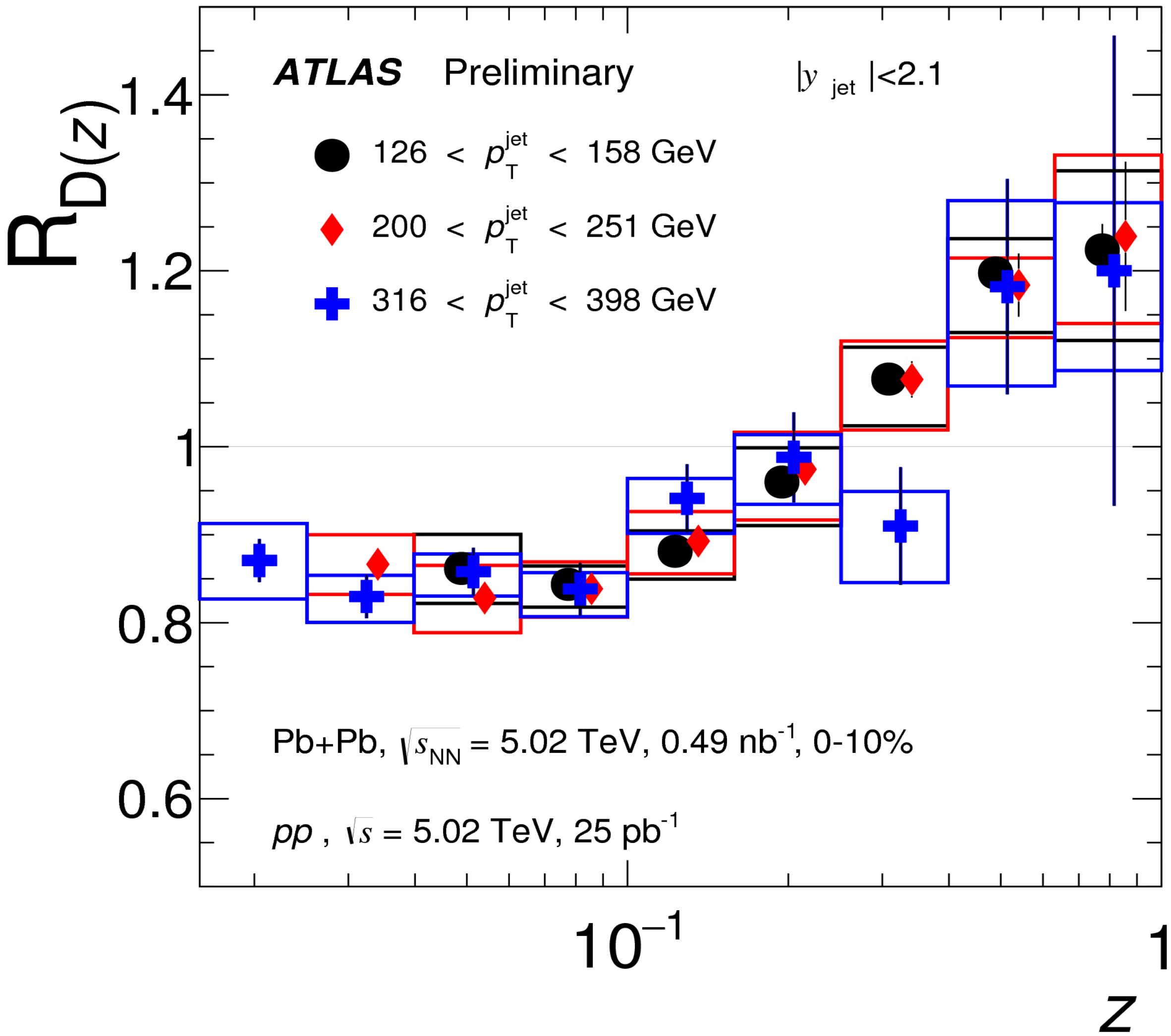
Jet fragmentation ratios Pb+Pb



@ 5.02 TeV

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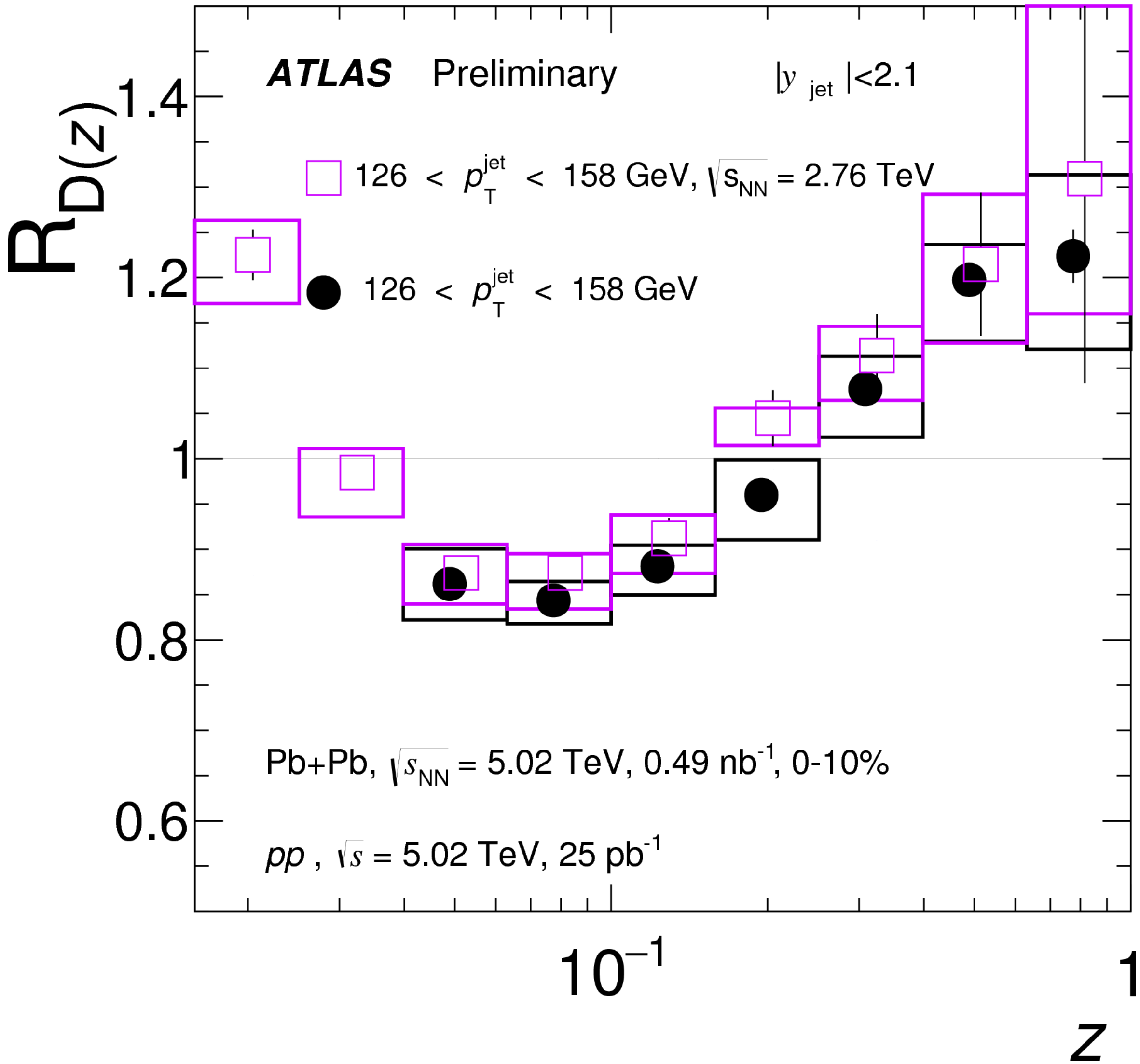
Cut on $p_T^{trk} > 4$ GeV

$126 < p_T^{jet} < 398$ GeV

No significant dependence on jet p_T

Comparison of $R_{D(z)}$ ratios of three p_T^{jet} bin selections as a function of z.

Comparison of $R_{D(z)}$ in Pb+Pb



@ 2.76 TeV

@ 5.02 TeV

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Cut on $p_T^{trk} > 1$ GeV for **2.76 TeV**

Cut on $p_T^{trk} > 4$ GeV for **5.02 TeV**

$126 < p_T^{jet} < 158$ GeV

No observed dependence on √s

Inclusive jets suppression

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

Jet yield in heavy ion collisions

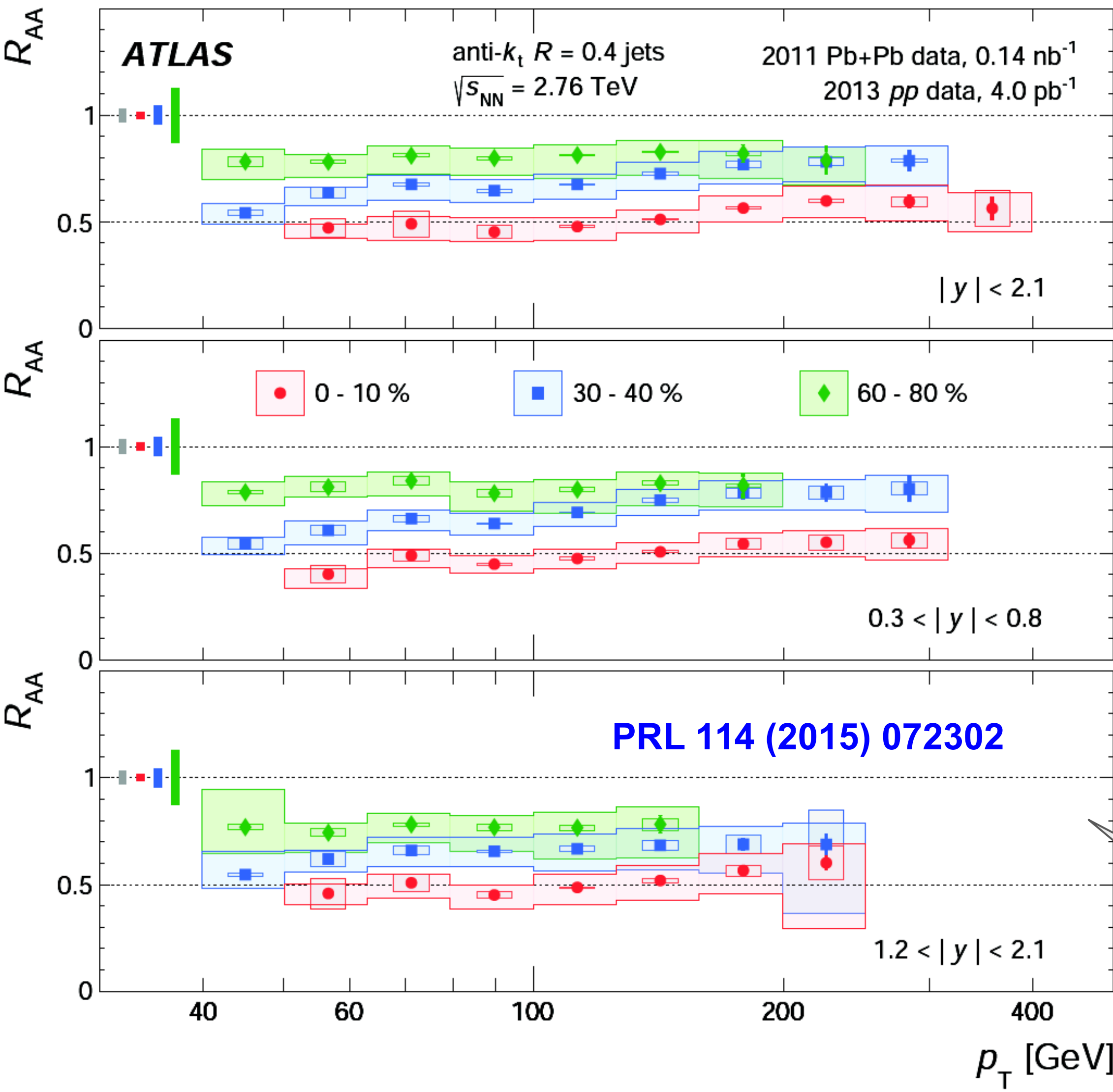
Nuclear tickness fuction

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 R_{AA} @ 2.76 TeV

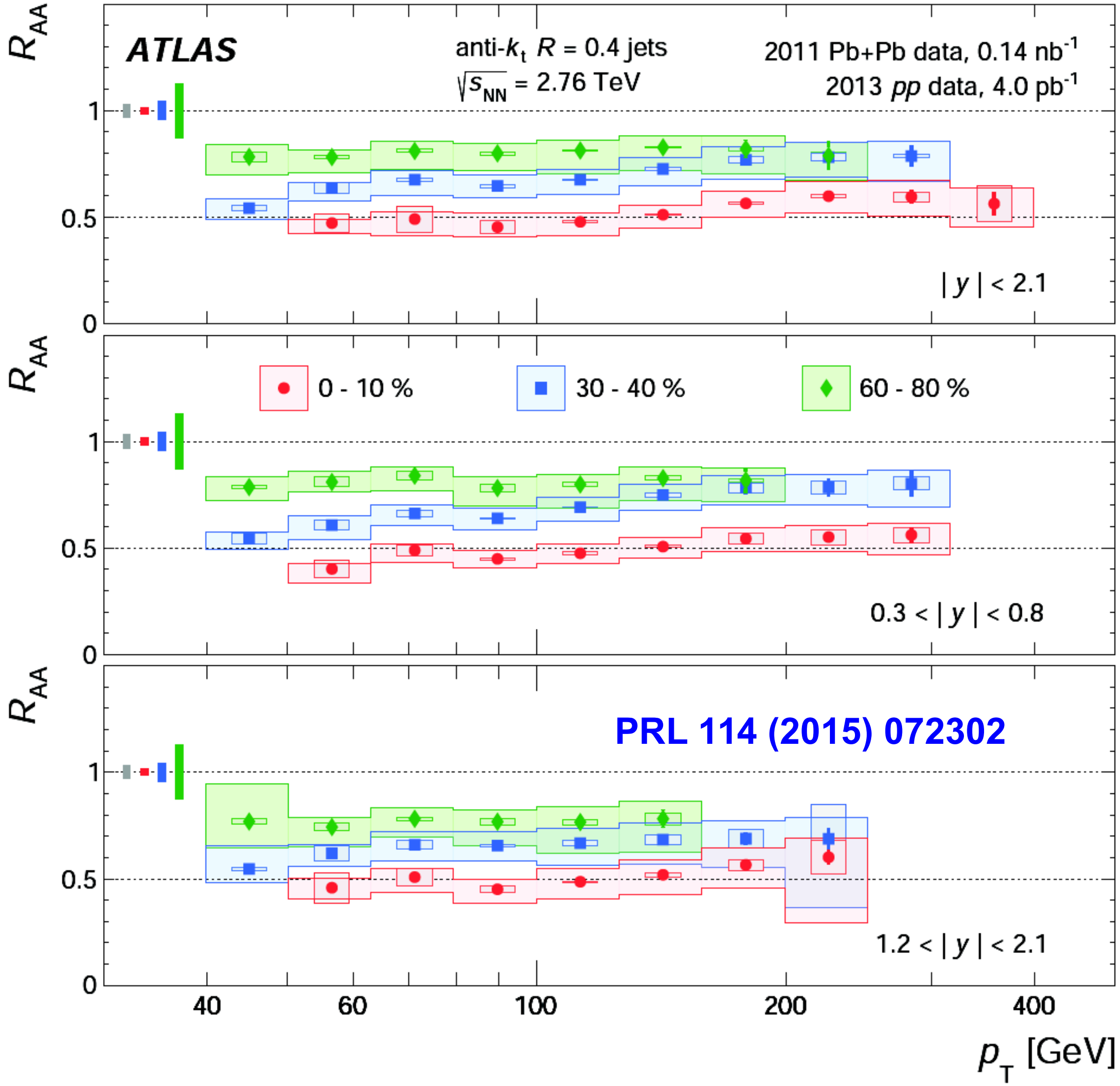


$$R_{AA} = \frac{\frac{1}{N_{evnt}} \frac{d^2 N_{jet}^{PbPb}}{dp_T dy}\Big|_{cent}}{\langle T_{AA} \rangle_{cent} \times \frac{d^2 \sigma_{jet}^{pp}}{dp_T dy}}$$

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

Angerami, Cole, Kosek, Spousta

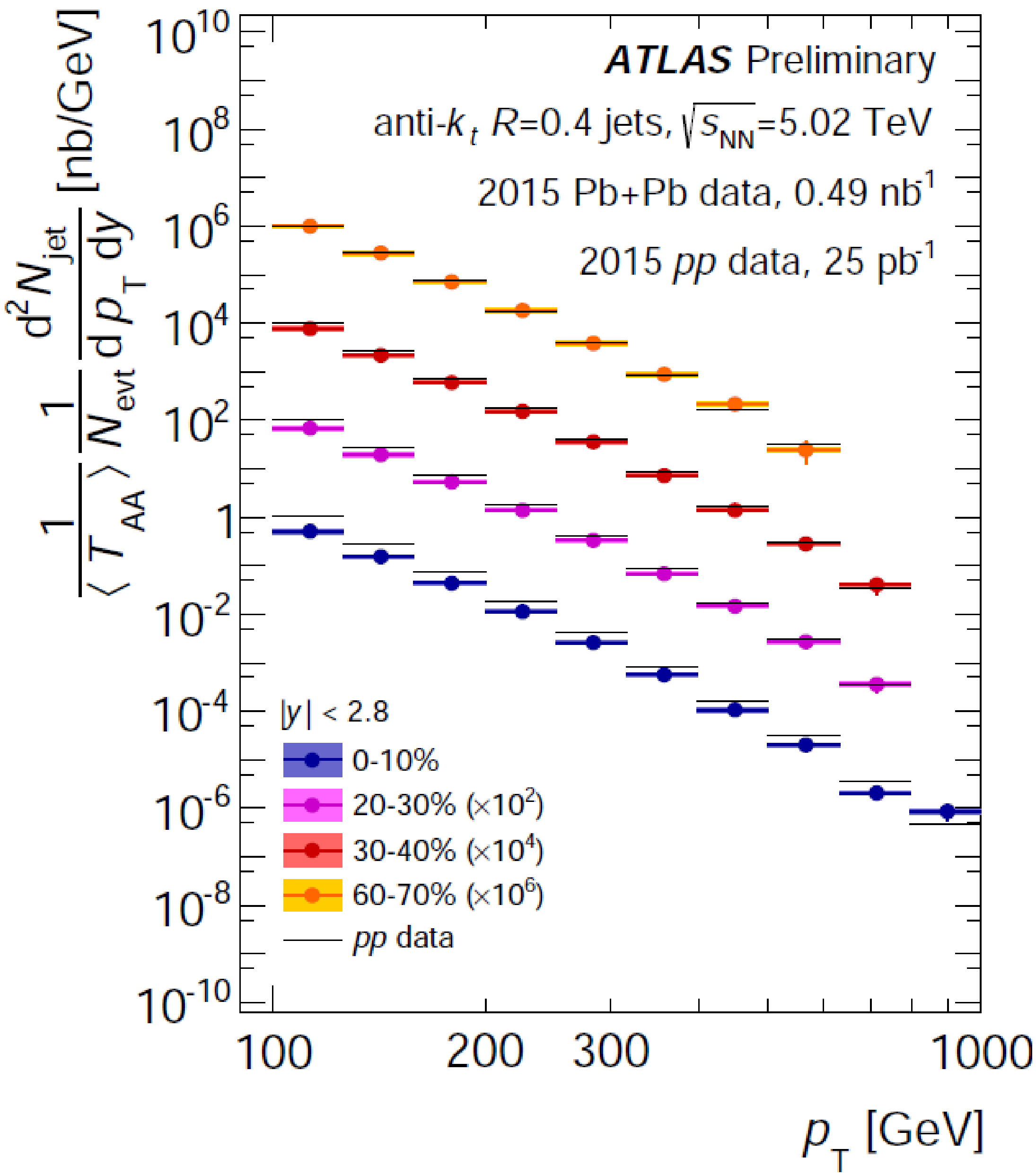
Jet R_{AA} @ 2.76 TeV



- Goal of the new analysis:
  - Repeat measurement for new energy @ 5.02 TeV
  - Extend the measurement to higher jet momenta
  - Extend the measurement to higher jet rapidities

Jet R_{AA} @ 5.02 TeV

Slovák, Spousta, Havener



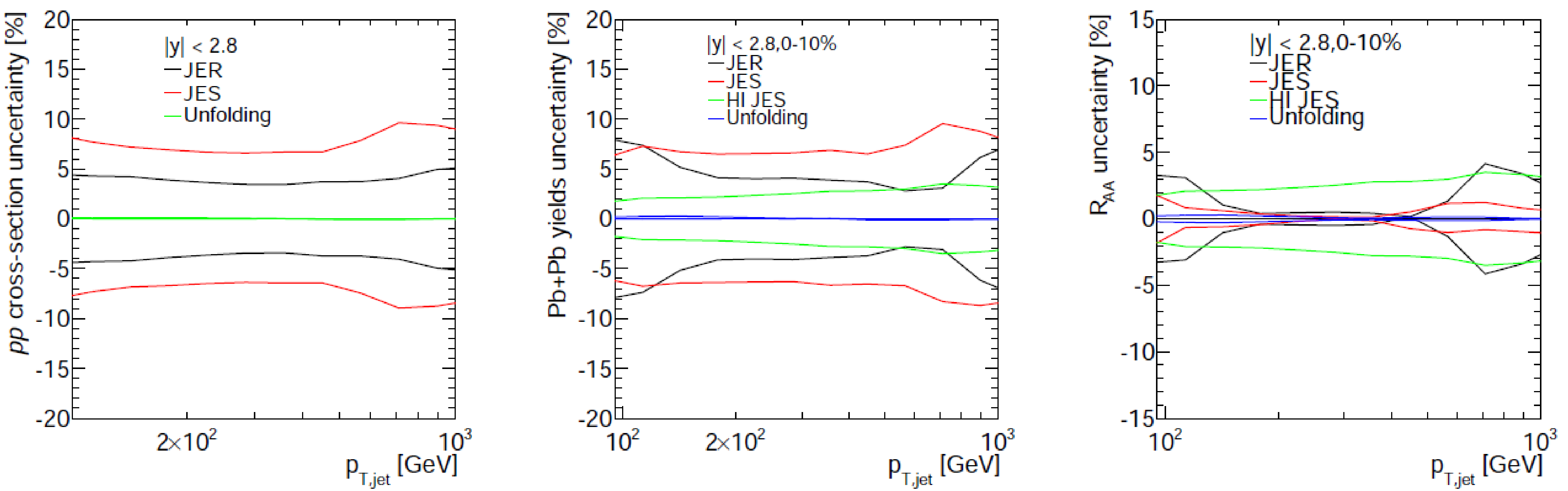
Kinematics region:

- R = 0.4 jets with p_T > 100 GeV
- Six bins in rapidity: $|y|<0.3$, $0.3<|y|<0.8$, $0.8<|y|<1.2$, $1.2<|y|<1.6$, $1.6<|y|<2.1$, $2.1<|y|<2.8$, $|y|<2.1$, $|y|<2.8$
- Eight bins in centrality: 0-10% to 70-80%
- 1D Bayesian unfolding

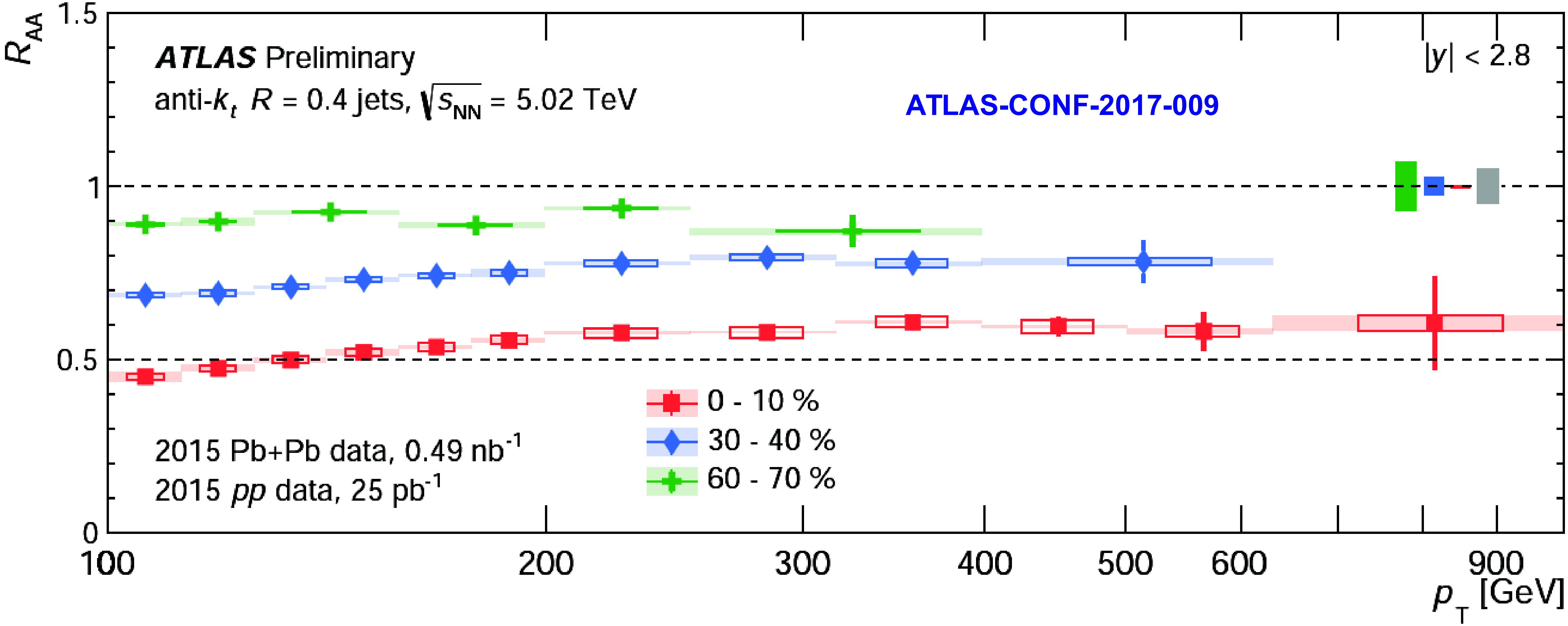
ATLAS EXPERIMENT

Systematical uncertainties

- Jet energy scale:
  - Standard *pp* component + 5 TeV flavor a HI cross-calibration
  - HI uncertainties due to jet quenching
- Jet energy resolution - standard *pp* a HI part
- Luminosity
- Uncertainty on T_{AA}
- Unfolding – results unfolded with not weighted response matrix

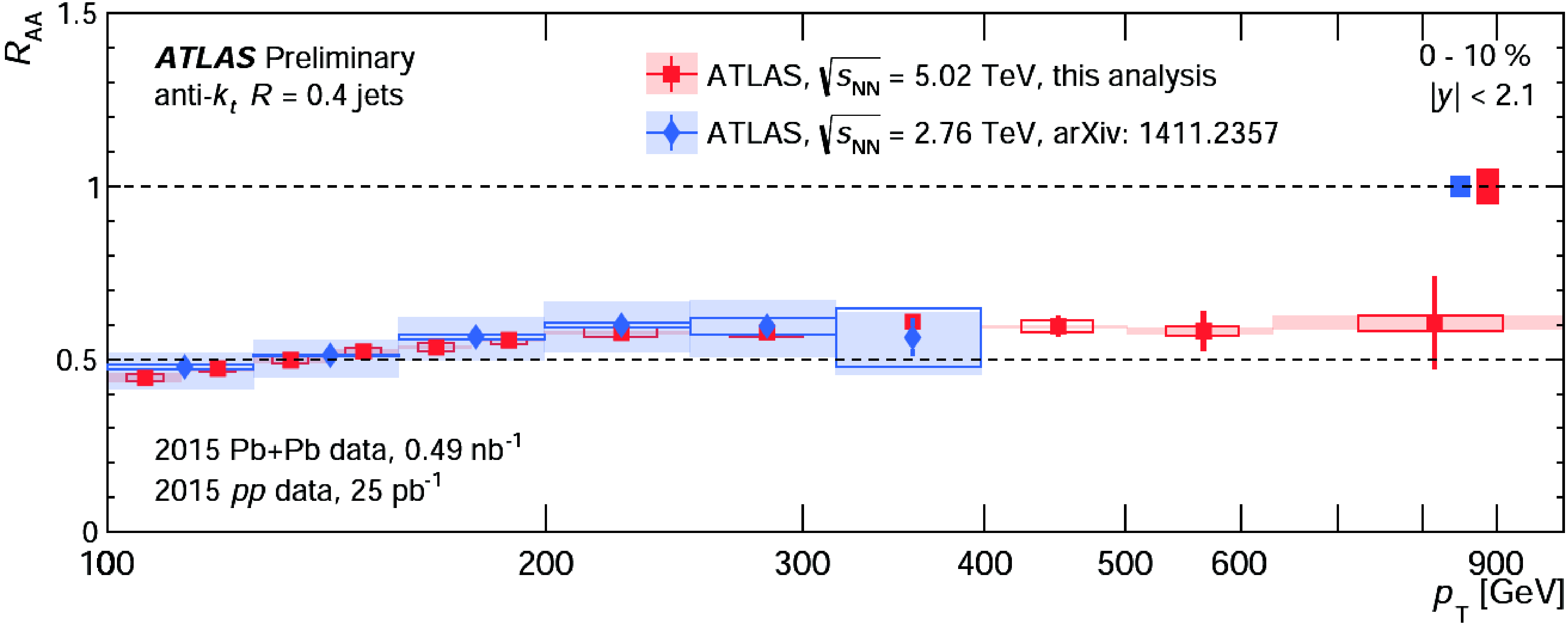


Jet R_{AA} @ 5.02 TeV p_T-dependence



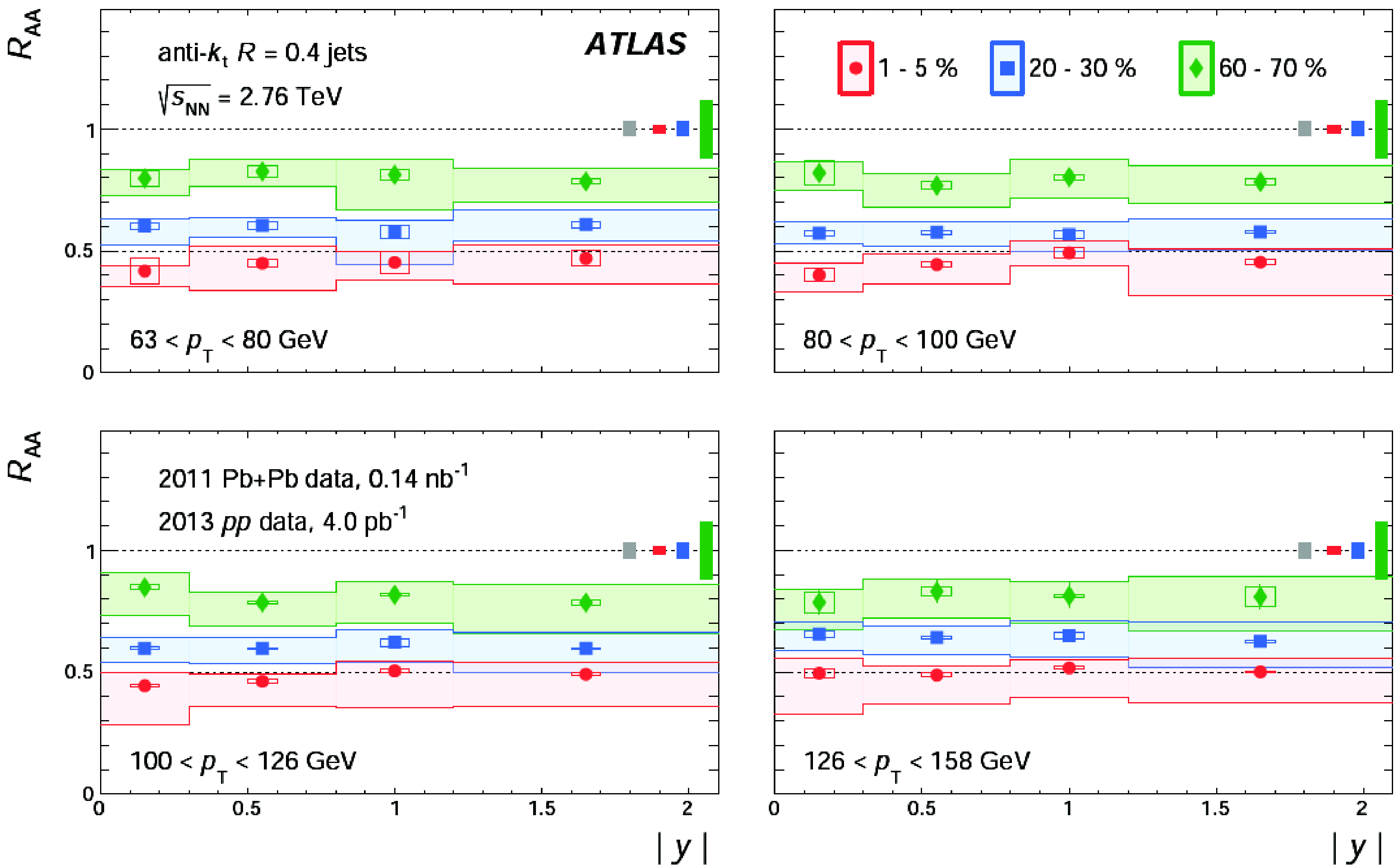
- R_{AA} measured for jets with p_T **100 GeV - 1 TeV** in rapidity $|y| < 2.8$.
- The central events suppressed by factor ~ 2. For jets within 100 ~ 200 GeV we observe a modest grow, then R_{AA} is flat.

Jet R_{AA} @ 5.02 TeV and @ 2.76 TeV



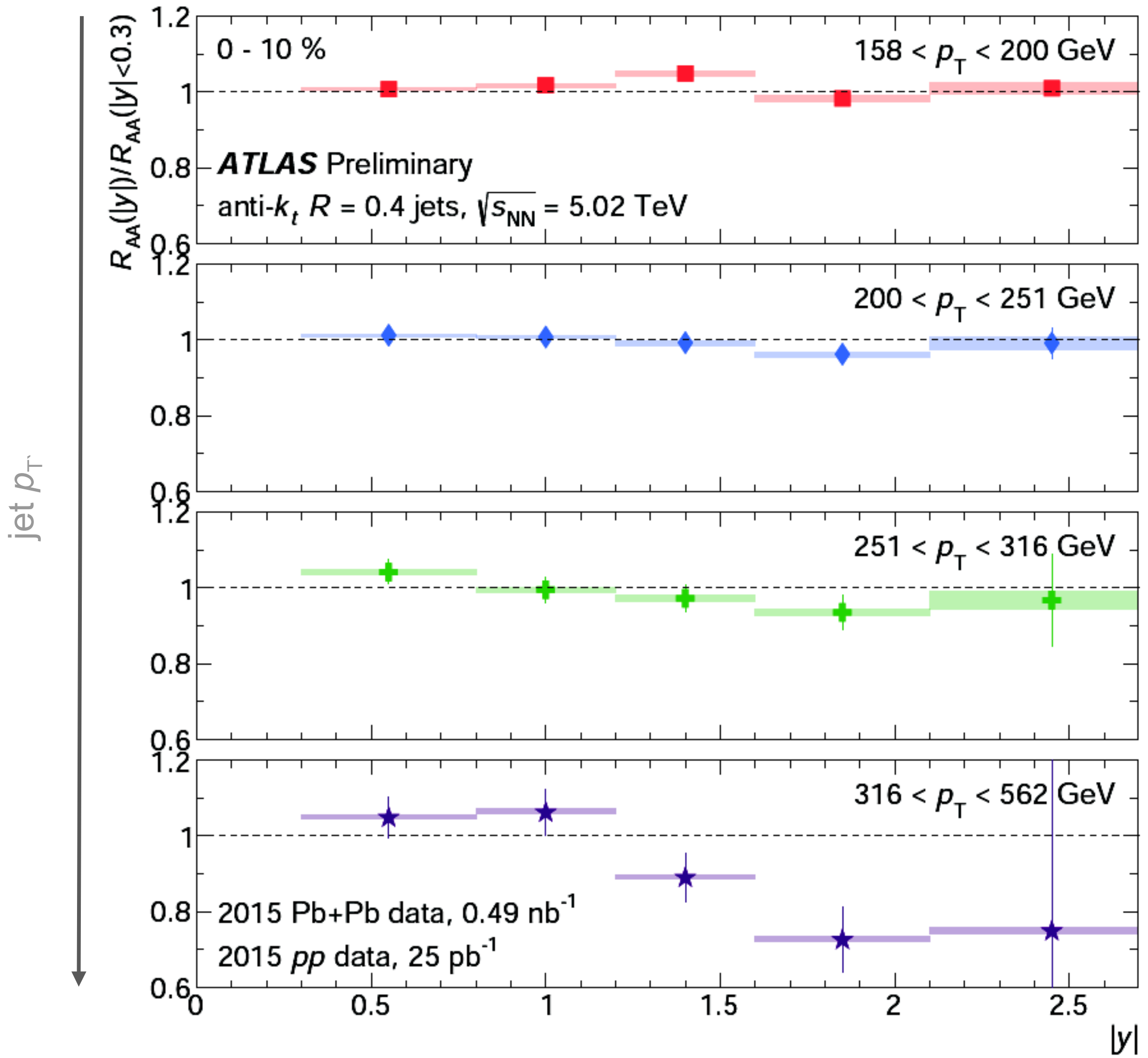
- The magnitude of jet suppression is the same within the systematic uncertainties for both measurement
- A significant reduction of systematic uncertainties for the new measurement mainly due to the fact than *pp* and Pb+Pb data were taken in the same period.

Jet R_{AA} @ 2.76 TeV – dependence on y



No rapidity dependence observed

Jet R_{AA} @ 5.02 TeV – dependence on y

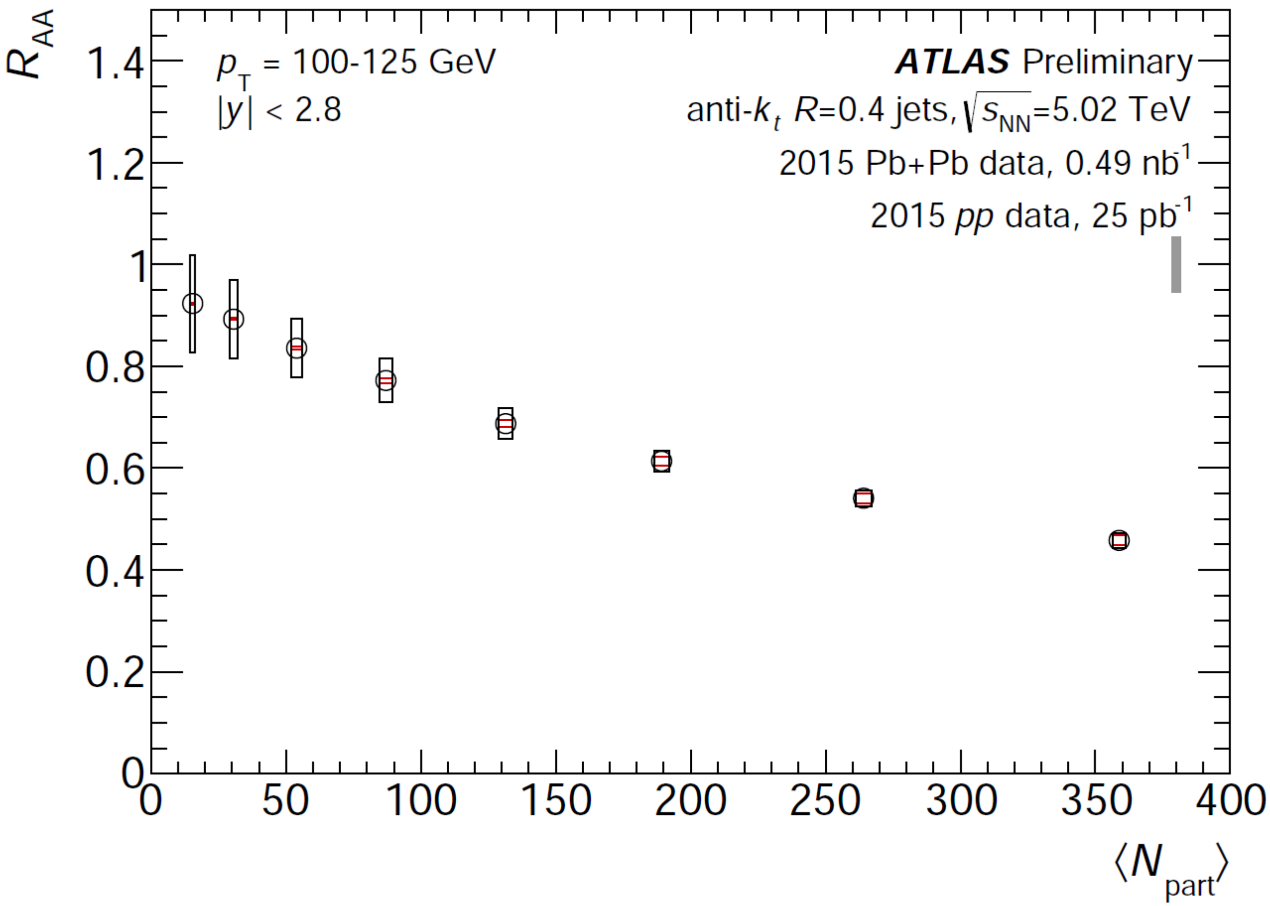


The vertical axis describes the ratio of R_{AA} for a given rapidity and R_{AA} for jets with $|y| < 0.3$.

$$\frac{R_{AA}(y)}{R_{AA}(|y| < 0.3)}$$

With increasing momentum R_{AA} is getting smaller in the forward rapidity as compared to the mid-rapidity region.

Jet R_{AA} @ 5.02 TeV – dependence on N_{part}



100 < p_T^{jet} < 125 GeV
|y| < 2.8

$<N_{part}>$ = the average number of participating nucleons for a given centrality interval.

Smooth decrease of R_{AA} with increasing centrality.

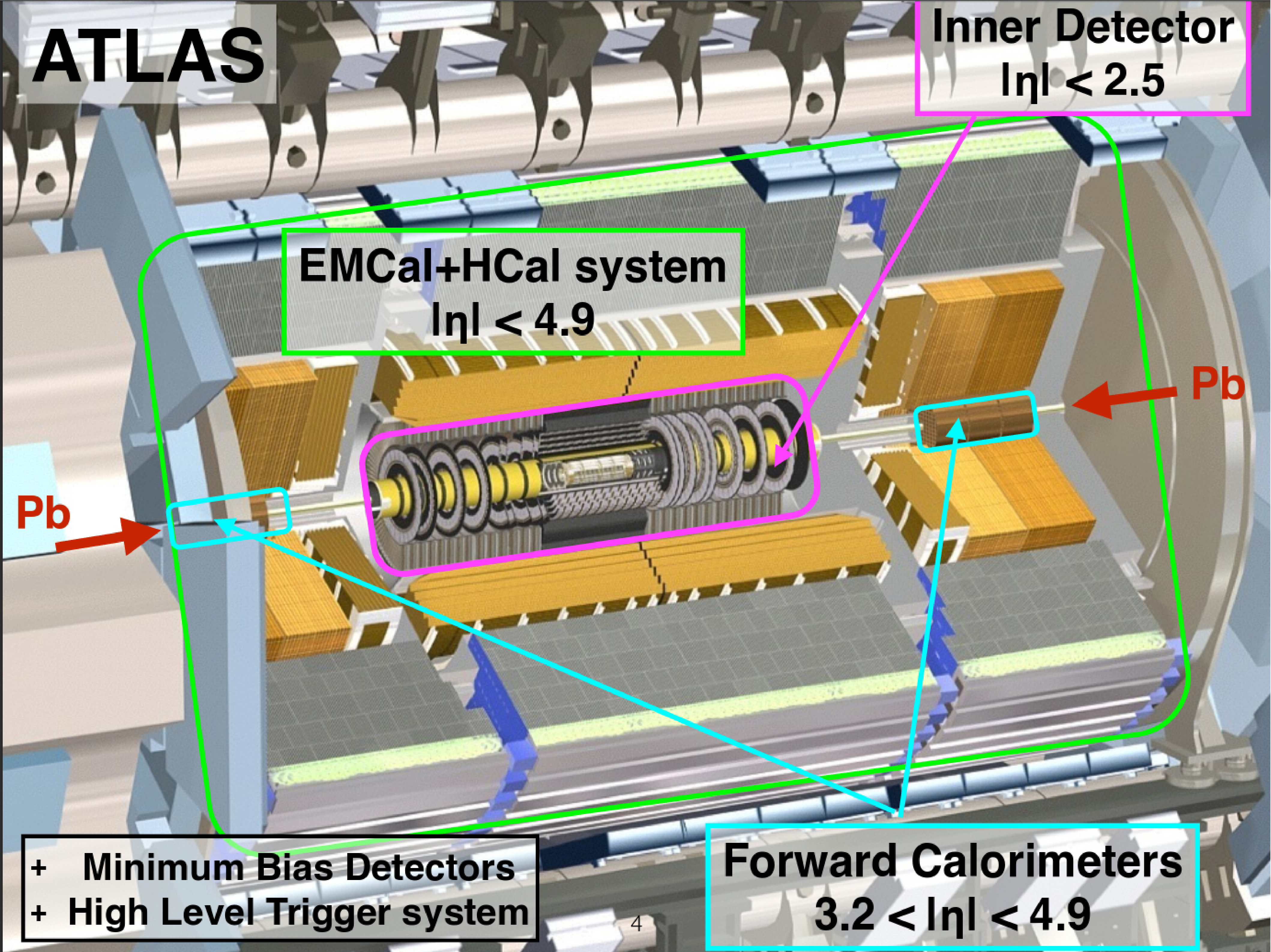
Summary

- We have presented a measurement of fragmentation variables in Pb+Pb collisions @ 2.76 TeV, @ 5.02 TeV, *p*+Pb collisiton @ 5.02 TeV and *pp* collisions for the reference measurement at corresponding energy

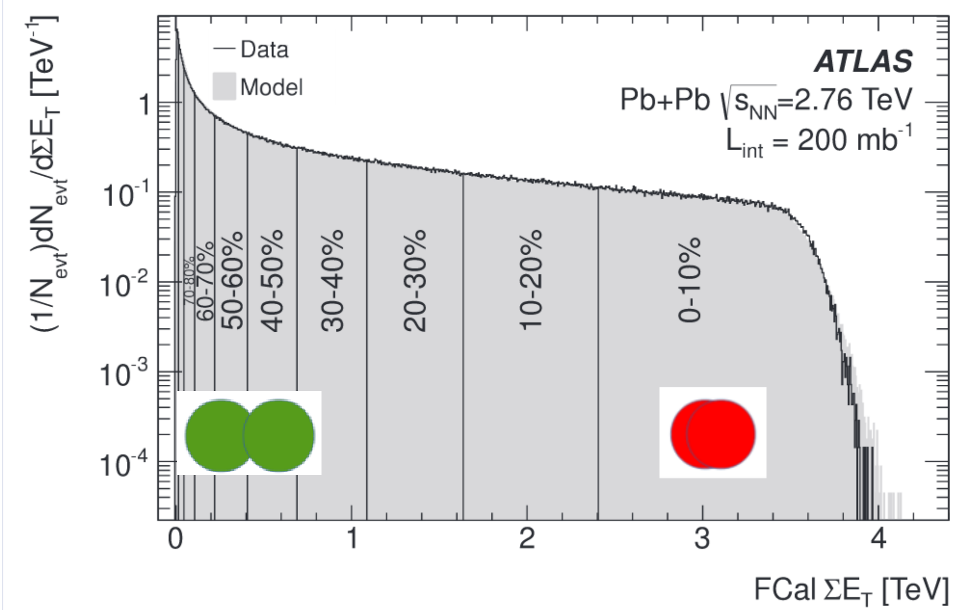
- Pb+Pb @ 2.76 TeV and @ 5.02 TeV: - clear centrality dependence
  - no observed dependence on $\sqrt{s}$
  - Pb+Pb @ 2.76 TeV – hint of rapidity dependence
    - Observed a increase of yields of particles and transverse momentum as centrality increases for particles with low tranverse momenta
  - Pb+Pb @ 5.02 TeV - we observe the lack of p_T dependence

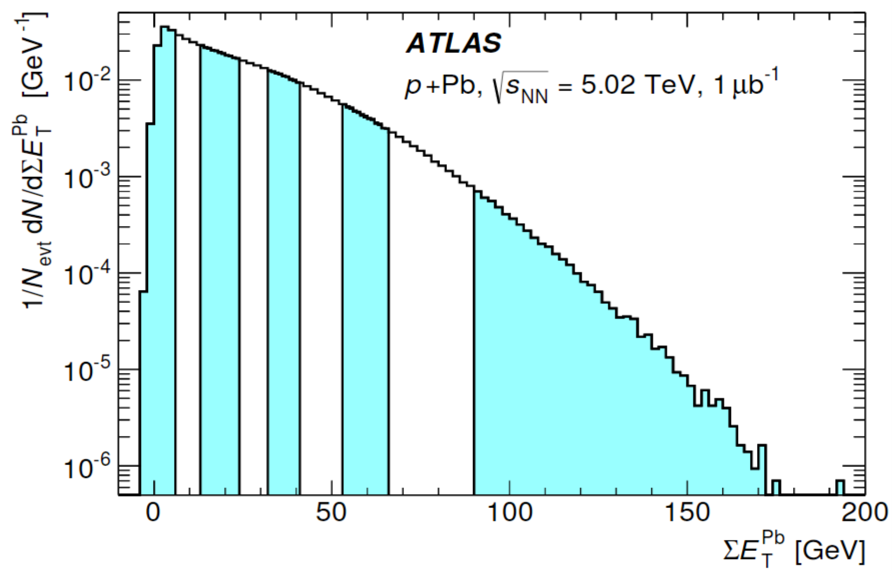
- We have presented a measurement of nuclear modification factor in Pb+Pb collisions @ 5.02 TeV and *pp* collisions for the reference measurement at corresponding energy where we observed:
  - a significant suppression up to ~ 1 TeV
  - rapidity dependence of R_{AA} for jets with high momentum
  - a quantitative comparison with the measurement at 2.76 TeV

Back up


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

Centality



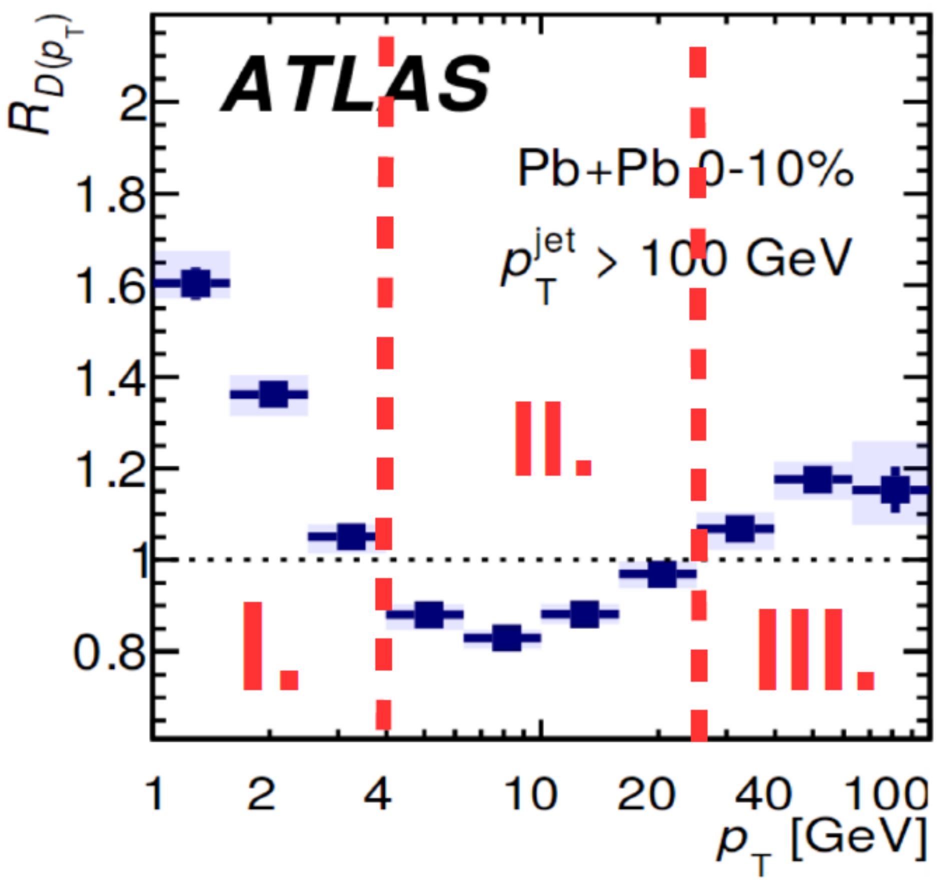


- Centrality express measure of everlap of two colliding nuclei
- Determined by the sum of the transverse energy deposited in the Forward calorimeters
- It is closely related to the average number of participant nucleons and number of binary inelastic collisions
- Events divided into succesive percintiles of the $\sum E_{\mathrm{T}}^{\mathrm{FCal}}$

- In Pb+Pb collisions use sum of the transverse energy in both sides
- In p+Pb collisions use sum of the transverse energy on Pb-going side only

Jet Fragmentation

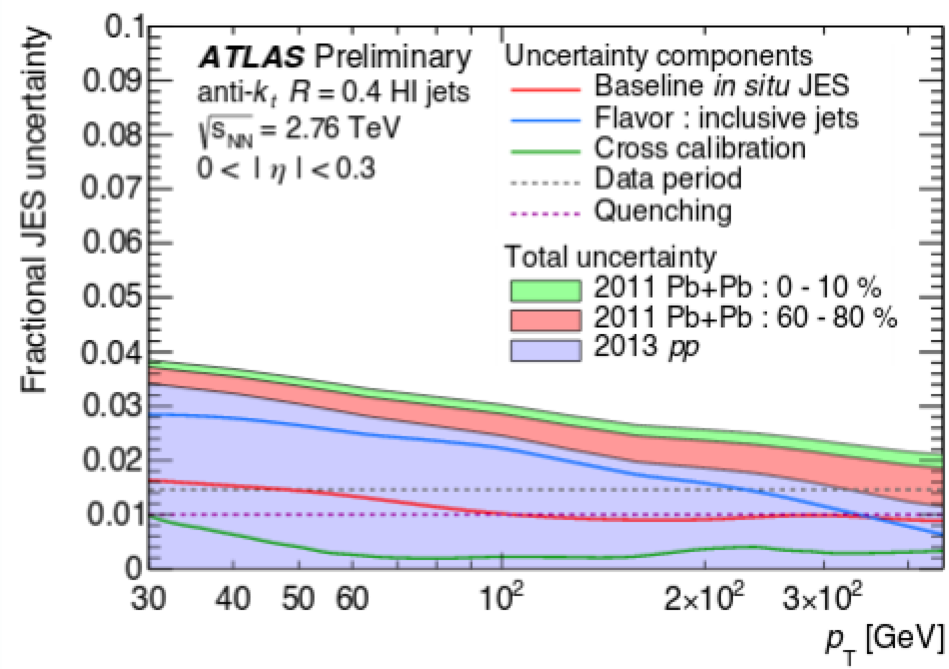
- Energy lost by parton is transvered mainly to the soft particles **(I.)**
- The modification on the middle and high p_T is caused by the different quenching of quark and gluon jets **(II. + III.)**



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

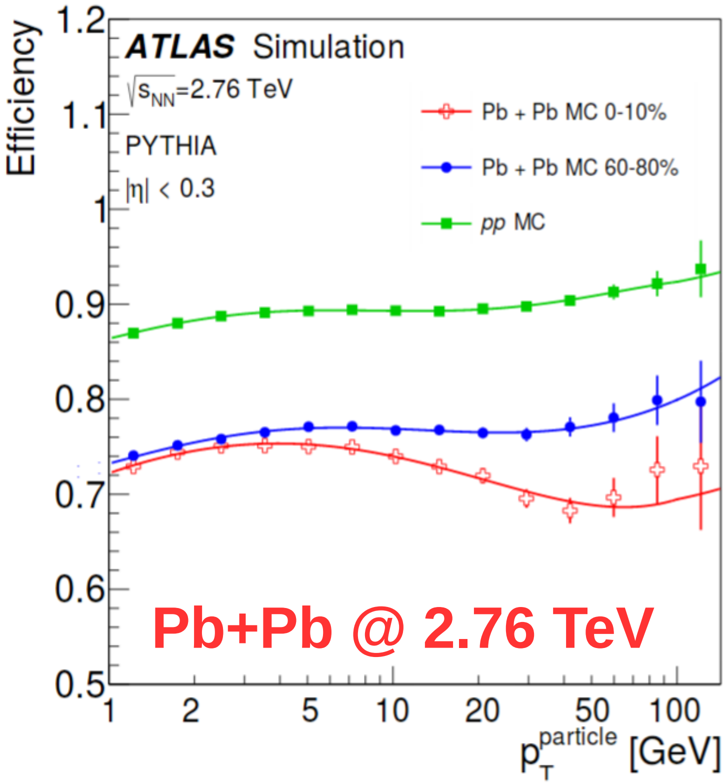


JER:

- 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

Tracking reconstruction

arXiv:1702.00674



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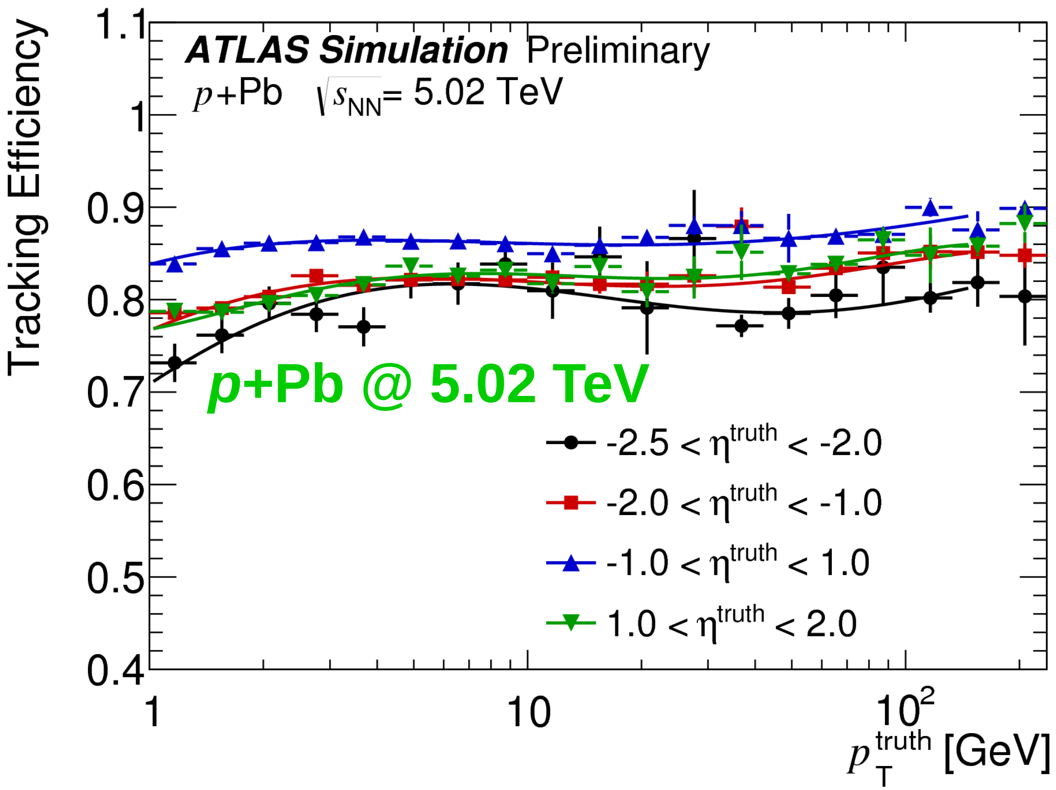

- Tracks with deffirent p_T are used :

  p_T > 1 GeV for Pb+Pb @ 2.76 TeV and *p*+Pb @ 5.02 TeV

  p_T > 4 GeV for Pb+Pb @ 5.02 TeV
- Tracking efficiency is parametrized as a function of track p_T and track η

Comparison of *pp* results to different theoretical calculation

pp @ 5.02 TeV

Significant differences between theory and data

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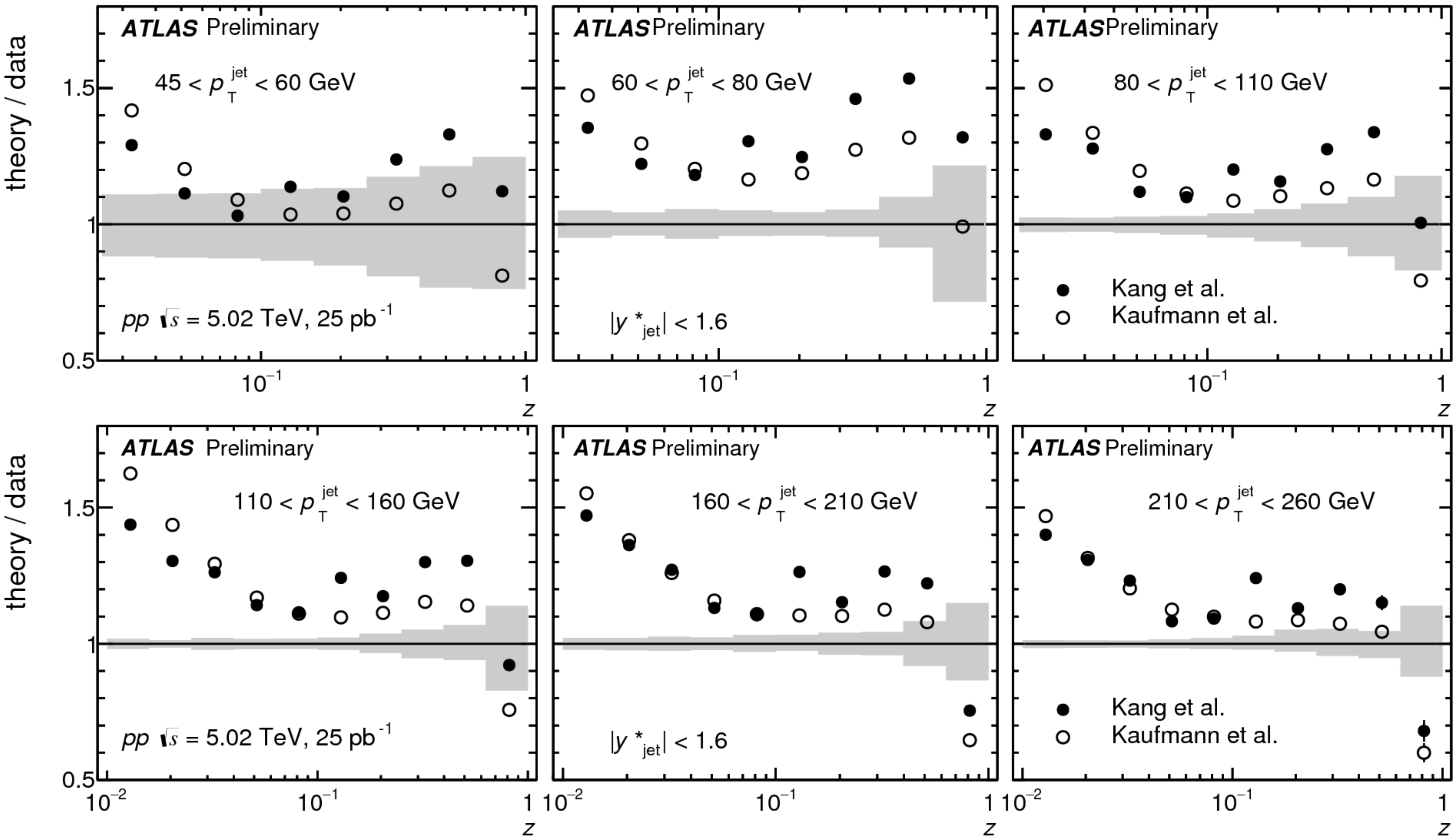
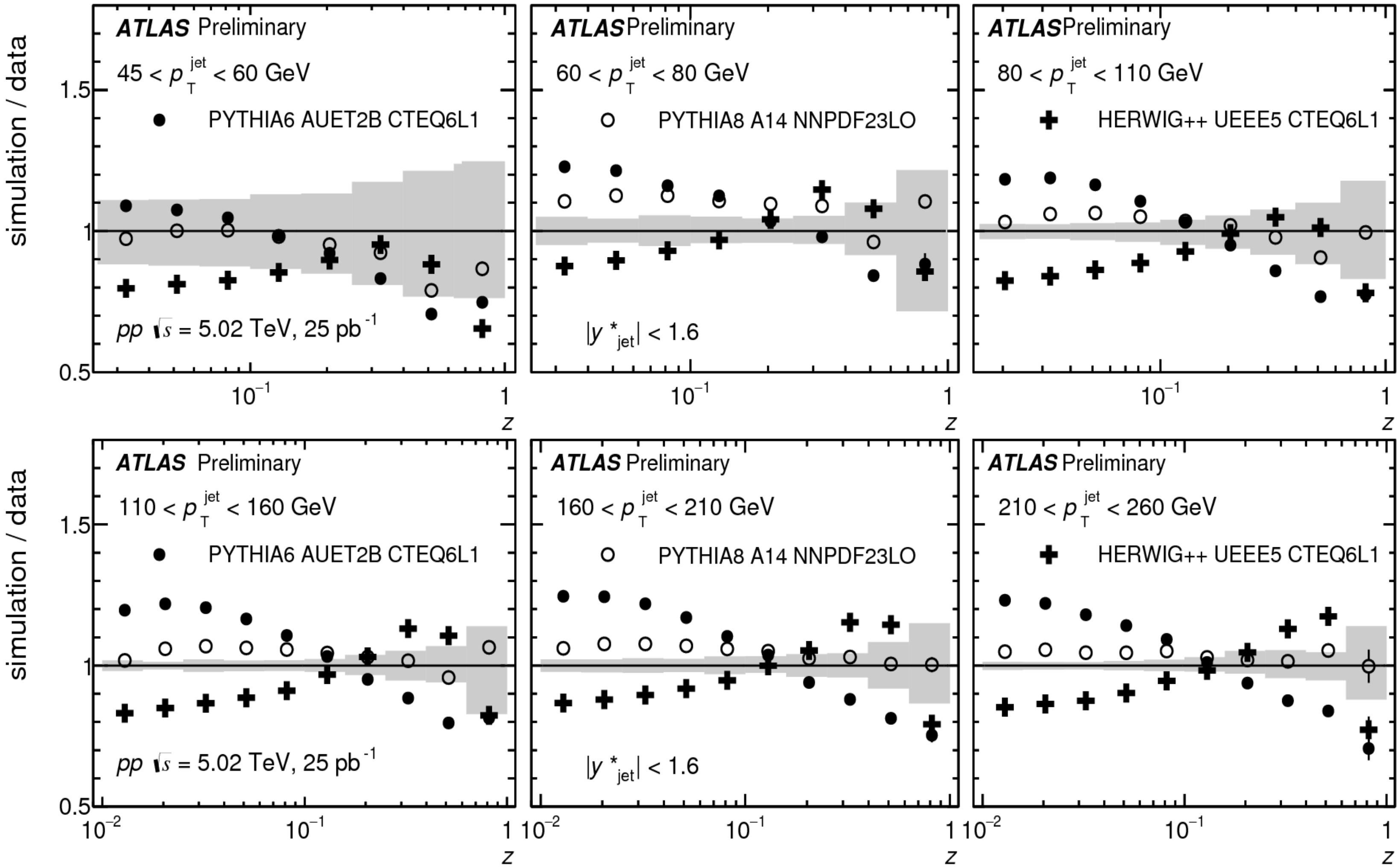


Comparison of *pp* results to different theoretical calculation

***pp* @ 5.02 TeV**

- Significant differences between MC models
- PYTHIA8 describes the data in the best way

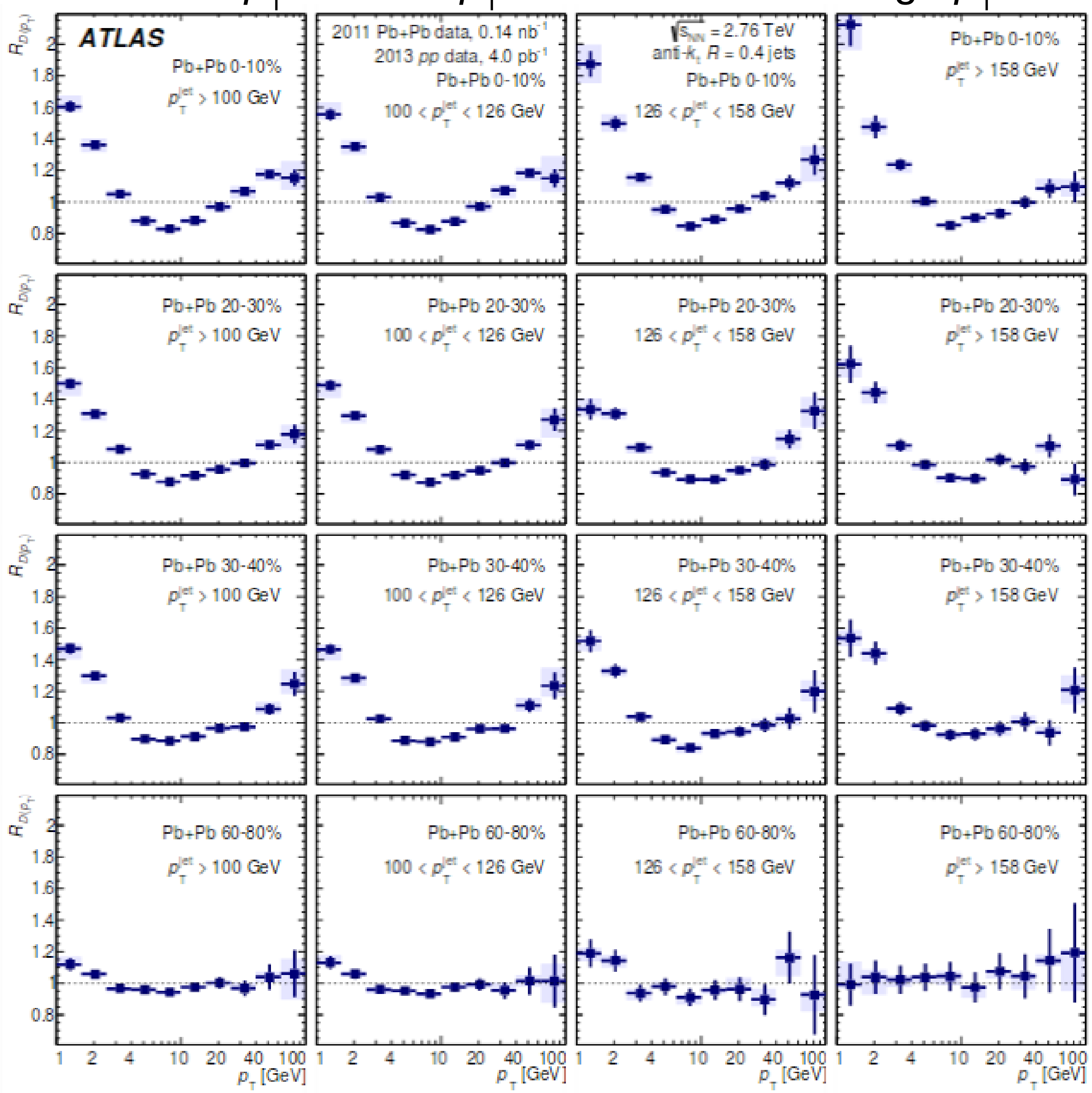
ATLAS-CONF-2017-004



Jet fragmentation ratios Pb+Pb

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

Inclusive p_T^{jet} | low p_T^{jet} | → | high p_T^{jet}



@ 2.76 TeV

arXiv:1702.00674

100 < p_T < 300 GeV

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

Similar observation for *D*(z)

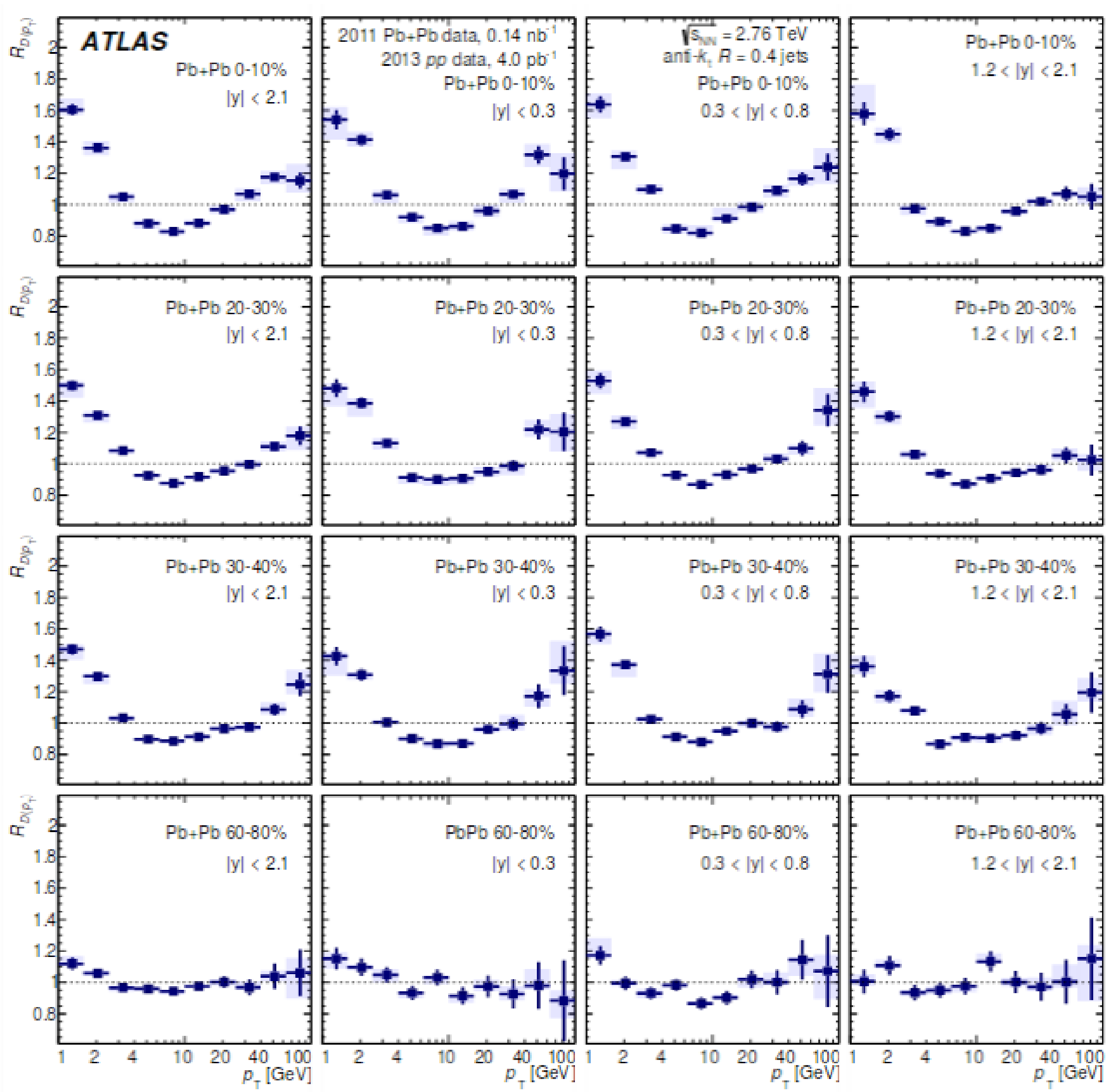
Jet fragmentation ratios Pb+Pb

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

$|\eta|<2.1$ less forward → more forward

@ 2.76 TeV

arXiv:1702.00674

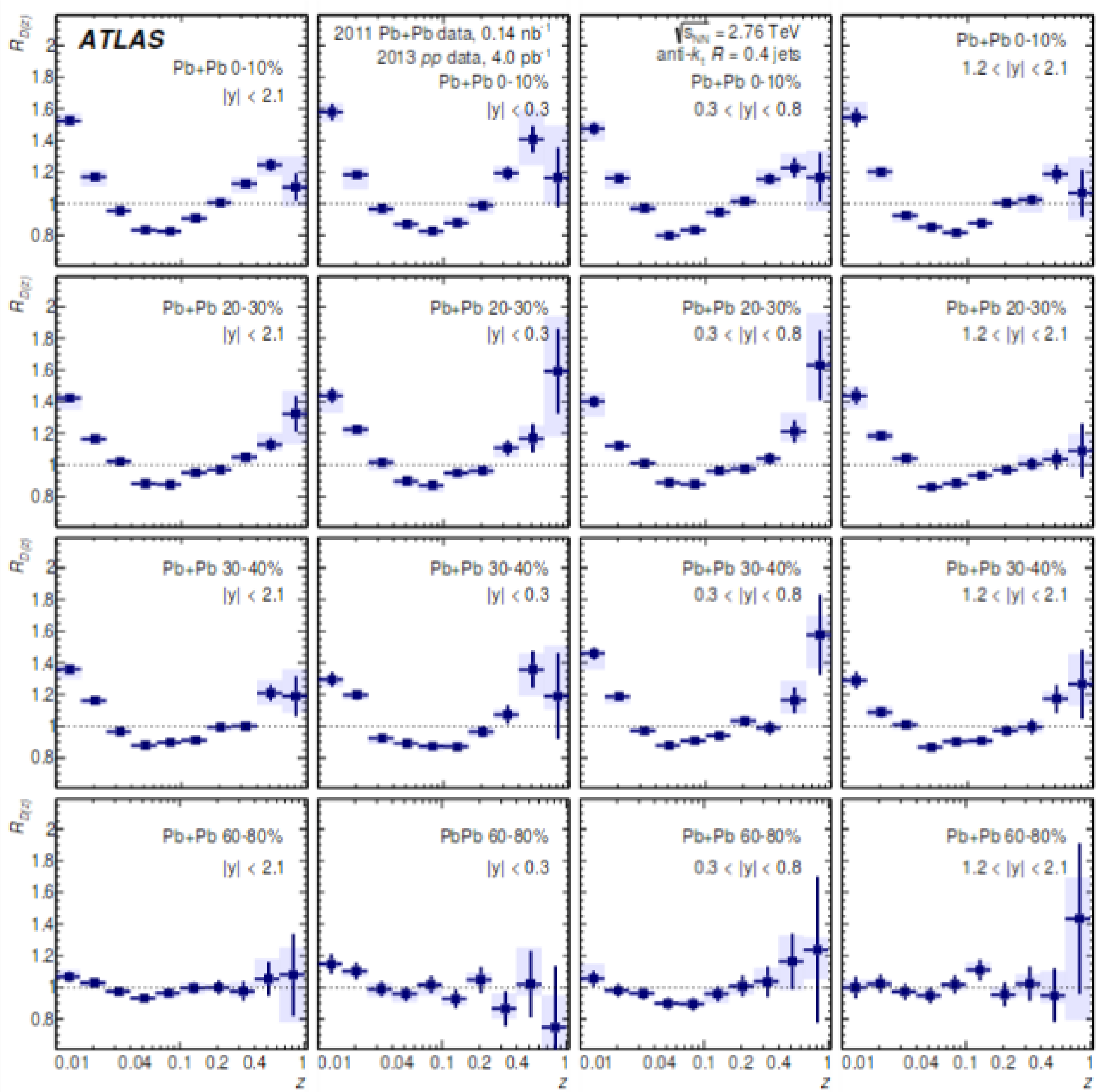


Rapidity dependence

- Hint of rapidity dependence
- Consistent with change of flavour composition as suggested in ArXiv:1504.05169

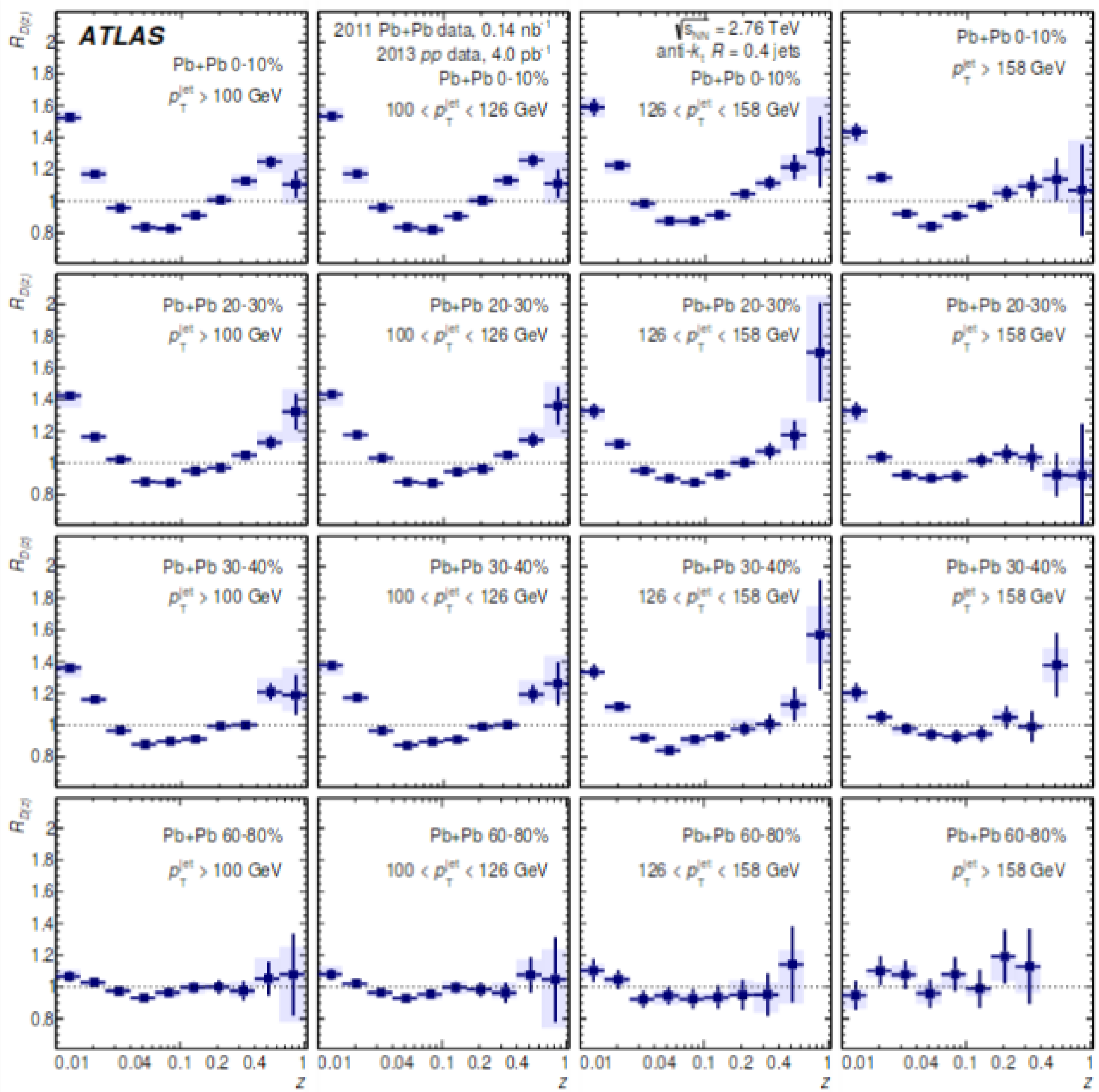
Same observation for *D(z)*

Jet fragmentation Pb+Pb @ 2.76 TeV



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

Jet fragmentation Pb+Pb @ 2.76 TeV



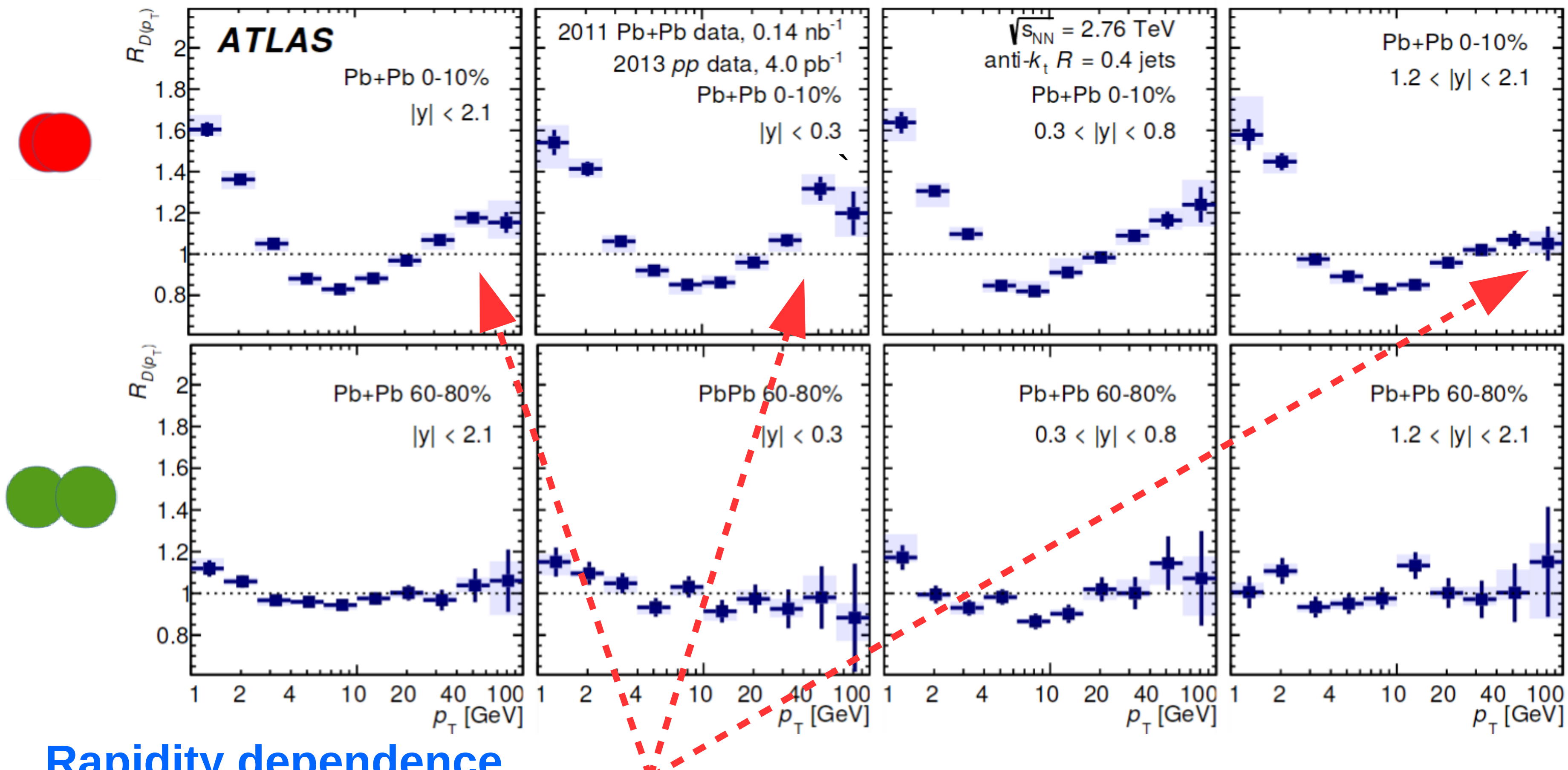
- Ratios of FF $D(z)$ for different centrality and p_T bins

Jet fragmentation ratios Pb+Pb

arXiv:1702.00674

Ratios of $D(p_T)$ for 2 centralities and 4 pseudorapidity bins

@ 2.76 TeV



Rapidity dependence

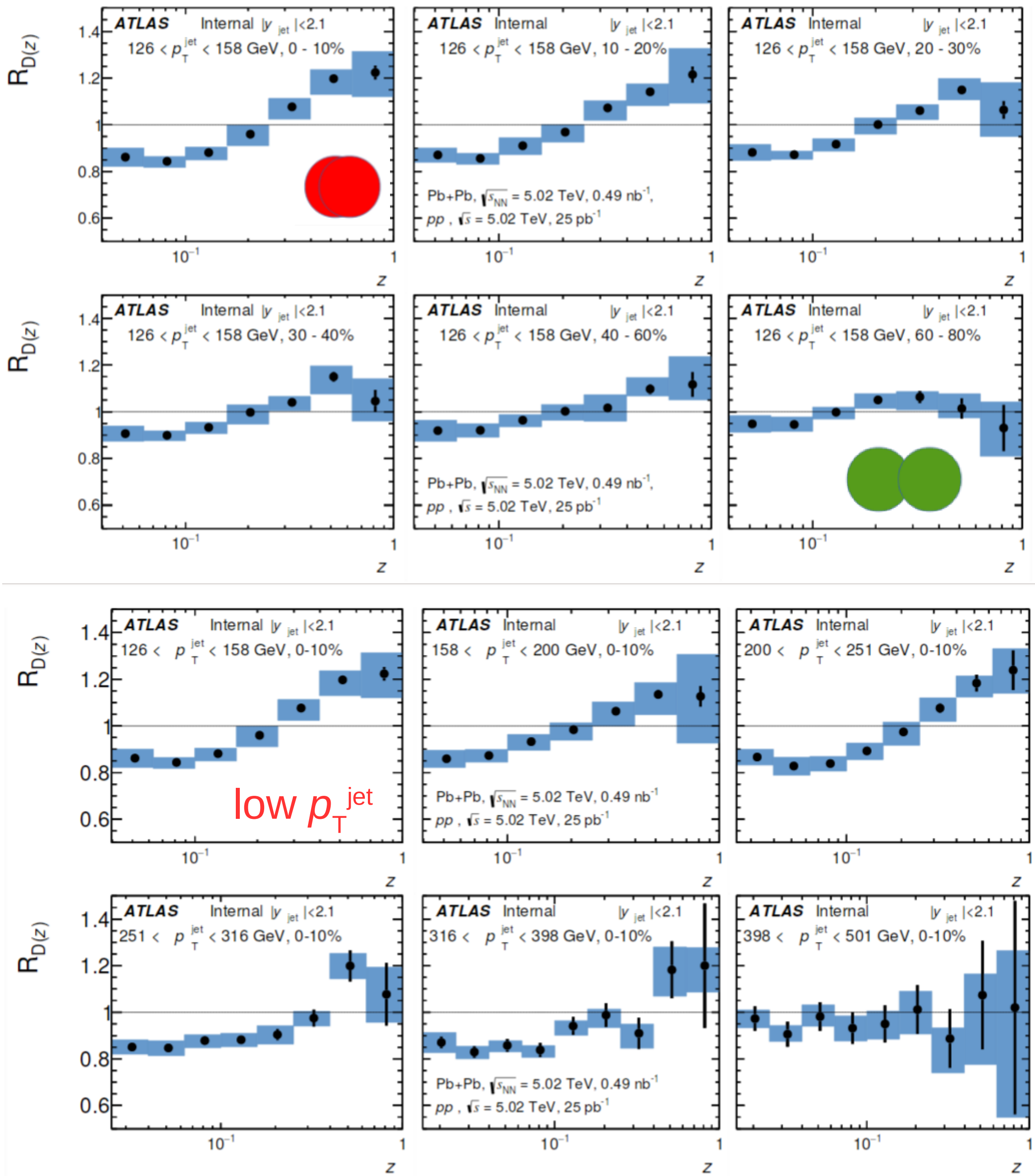
- Hint of rapidity dependence
- Consistent with change of flavour composition as suggested in ArXiv:1504.05169

$100 < p_T < 300$ GeV

Same observation for *D*(z)

Jet fragmentation ratios Pb+Pb

Ratios of *D*(z) for 6 centralities and 6 p_T bins



high p_T^{jet}

@ 5.02 TeV

ATLAS-CONF-2017-005

$126 < p_T < 501$GeV

- Cut on $p_T^{trk} > 4$ GeV
- Missing the low p_T enhancement

Centrality dependence

- Enhancement at high p_T
- Suppression at intermediate p_T

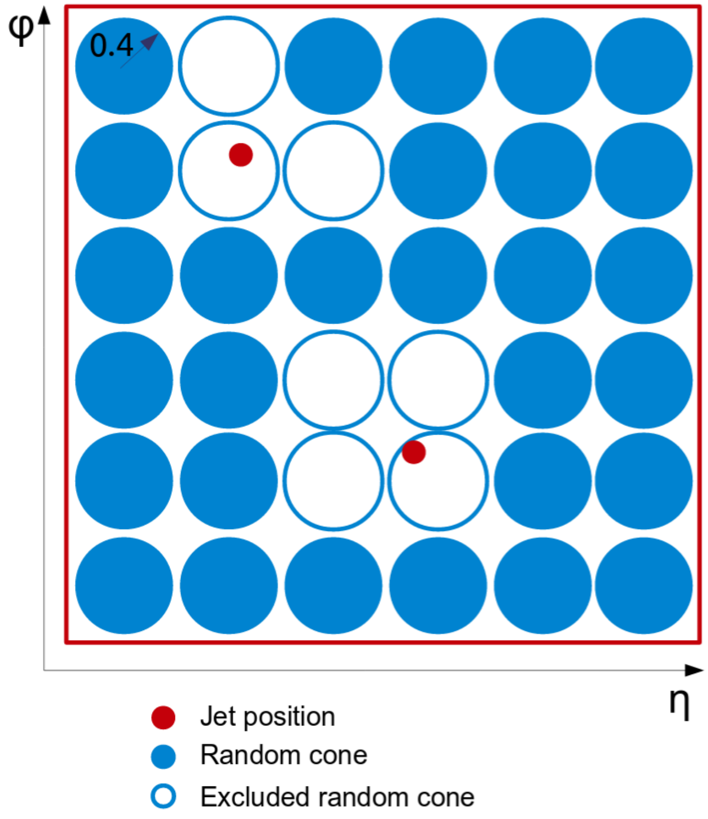
Jet p_T dependence

- No significant dependence on jet p_T

UE subtraction

$$\frac{\mathrm{d}n_{\mathrm{ch}}^{\mathrm{UE}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{ch}}} = \frac{1}{N_{\mathrm{cone}}}\frac{1}{\varepsilon}\frac{\Delta N_{\mathrm{ch}}^{\mathrm{cone}}(p_{\mathrm{T}}^{\mathrm{ch}}, p_{\mathrm{T}}^{\mathrm{jet}}, \eta^{\mathrm{jet}})}{\Delta p_{\mathrm{T}}^{\mathrm{ch}}}$$

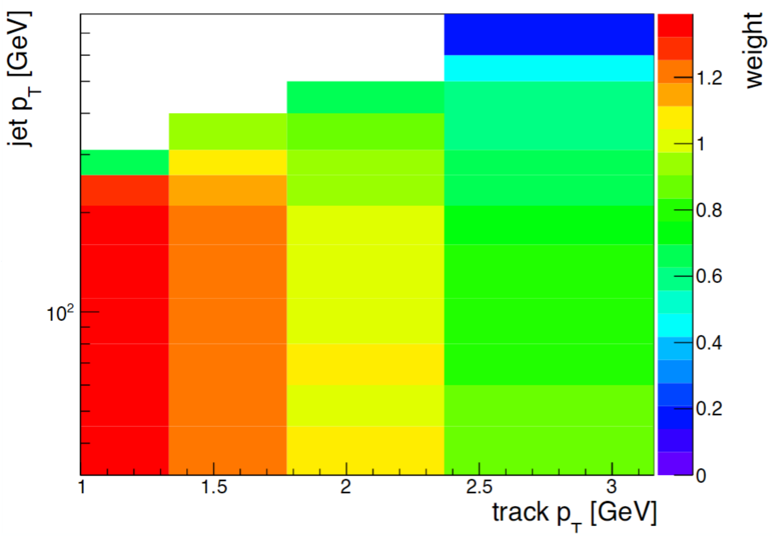
- Use grid of cones to estimate UE below a certain threshold: 3.5 GeV for p+Pb, 8 GeV for Pb+Pb
- Above those thresholds there is negligible UE, verifed with overlay MC samples
- Cones with a track p_{T} bigger then certain threshold are omitted to exclude real jets

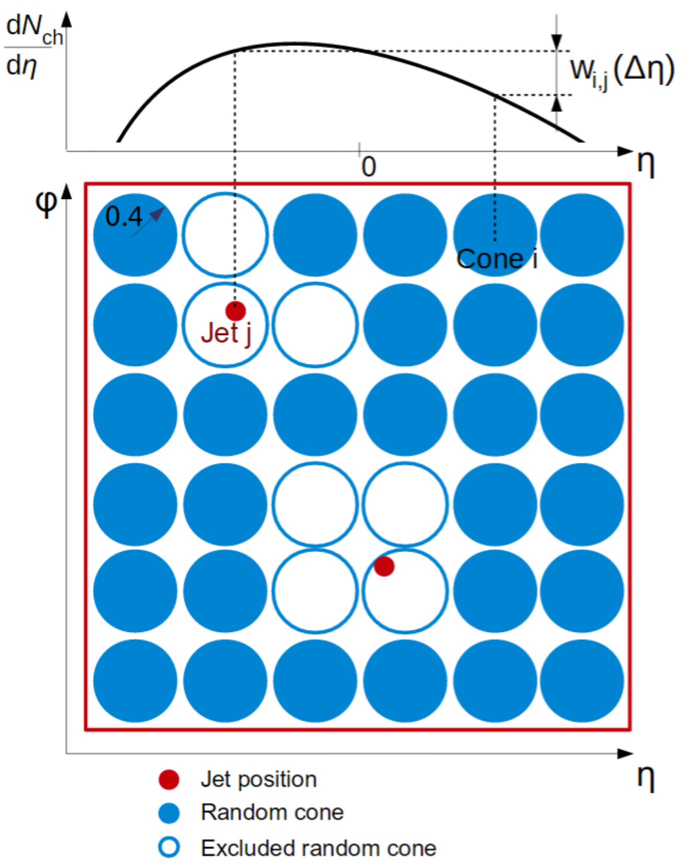


UE subtraction

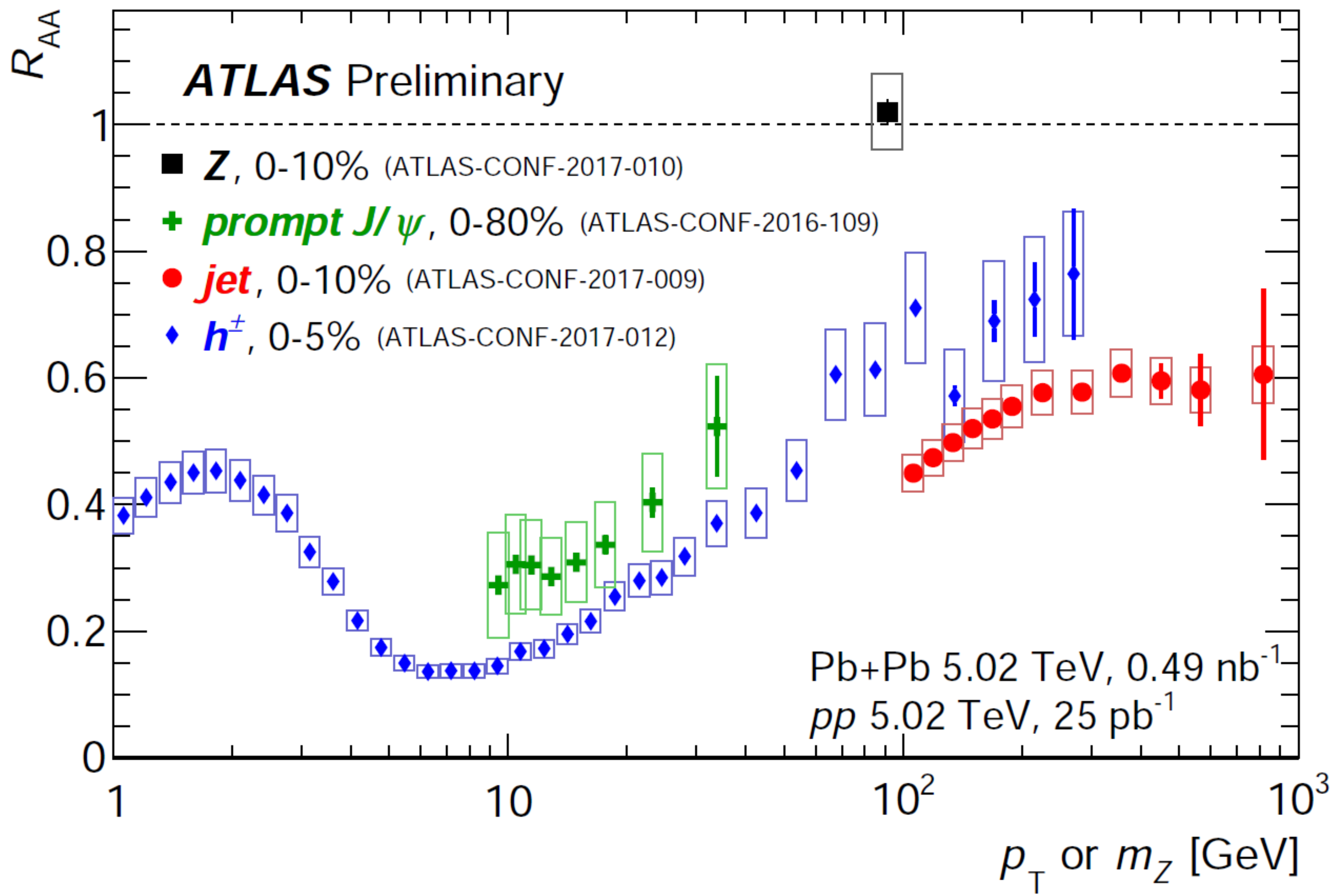
$$\frac{dn_{ch}^{UE}}{dp_T^{ch}} = \frac{1}{N_{cone}} \frac{1}{\varepsilon} \frac{\Delta N_{ch}^{cone}(p_T^{ch}, p_T^{jet}, \eta^{jet})}{\Delta p_T^{ch}}$$

- Correct UE distribution for difference between jet rapidity and cone rapidities
- Correlation between UE and JER corrected for by a multiplicative factor on the UE, $w_{UE}(z)$
  - Events with larger UE have worse JER
  - Also corrects for fakes below a certain threshold



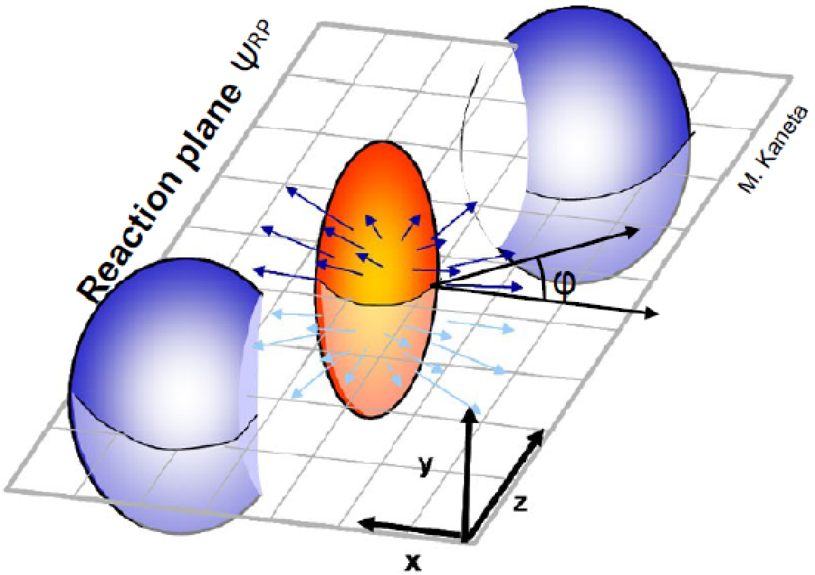


$$w_{UE}(p_T) = \frac{dn_{ch}^{UE}/dp_T^{ch}}{D(p_T)_f}|_{MC}$$



R_{AA}
ATLAS Preliminary
Z, 0-10% (ATLAS-CONF-2017-010)
prompt J/ψ, 0-80% (ATLAS-CONF-2016-109)
jet, 0-10% (ATLAS-CONF-2017-009)
$h^{\pm}$, 0-5% (ATLAS-CONF-2017-012)
Pb+Pb 5.02 TeV, 0.49 nb^{-1}
pp 5.02 TeV, 25 pb^{-1}
0
0.2
0.4
0.6
0.8
1
1
10
10^2
10^3
p_T or m_Z [GeV]

Eliptický tok

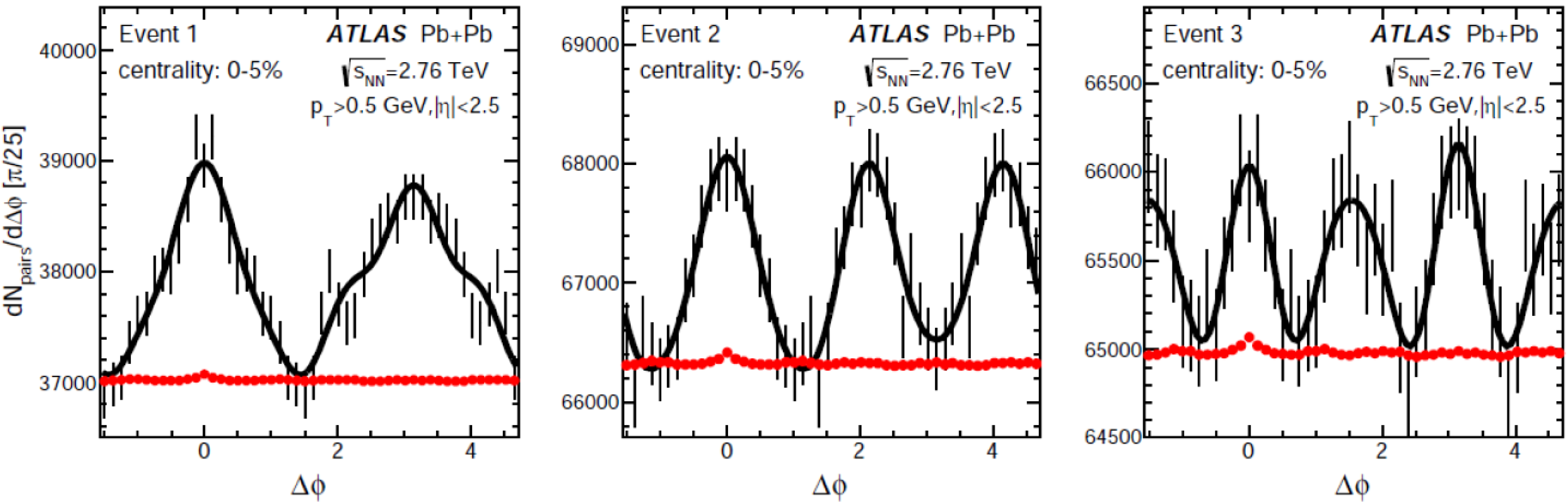


- V dekonfinovaná hmotě panují gradienty tlaku díky počáteční prostorové nesymetrii.
- Dekonfinovaná hmota se rozpíná **v různých směrech různě**.
- Tato různost lze charakterizovat například pomocí Fourierova rozvoje v úhlové vzdálenosti vzhledem k rovině interakce. Omezíme se na první netriviální člen tohoto rozvoje:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = N_0\Big(1 + 2v_2 \cos 2(\phi - \Phi^{RP})\Big) \qquad v_2 = \Big\langle \cos 2(\phi - \Phi^{RP}) \Big\rangle$$

… jeho velikost se nazývá eliptický tok (v_2)

Eliptický tok



- Tato modulace je typicky vyhodnocována statisticky (tedy průměr z vícero událostí).
- Je však často viditelná i "pouhým okem" v každé události zvlášť … tj. velmi silný rys!
- Kdyby těžko-intové srážky byly prostou superpozicí mnoha pp srážek, tak bychom nic takového nepozorovali.