Jet measurements in heavy ion collisions with the ATLAS detector

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on behalf of the ATLAS Collaboration

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Introduction

- Jet production and properties are modified in heavy ion collisions
- 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 this de-confined medium
- Study of **jets in p+Pb** collisions should tell us about e.g.:
  - initial state effects
  - correlations between soft and hard processes
- LHC **heavy ion runs** & ATLAS:
  - Run 1: Pb+Pb: $\sqrt{s_{NN}} = 2.76$ TeV, $L_{int} = 0.15$ nb^{-1}

    pp: $\sqrt{s} = 2.76$ TeV, $L_{int} = 4.2$ pb^{-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, $L_{int} = 28$ nb^{-1}

Inclusive jet suppression in Pb+Pb collisions

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

Jet yield in heavy ion collisions

Nuclear tickness fuction

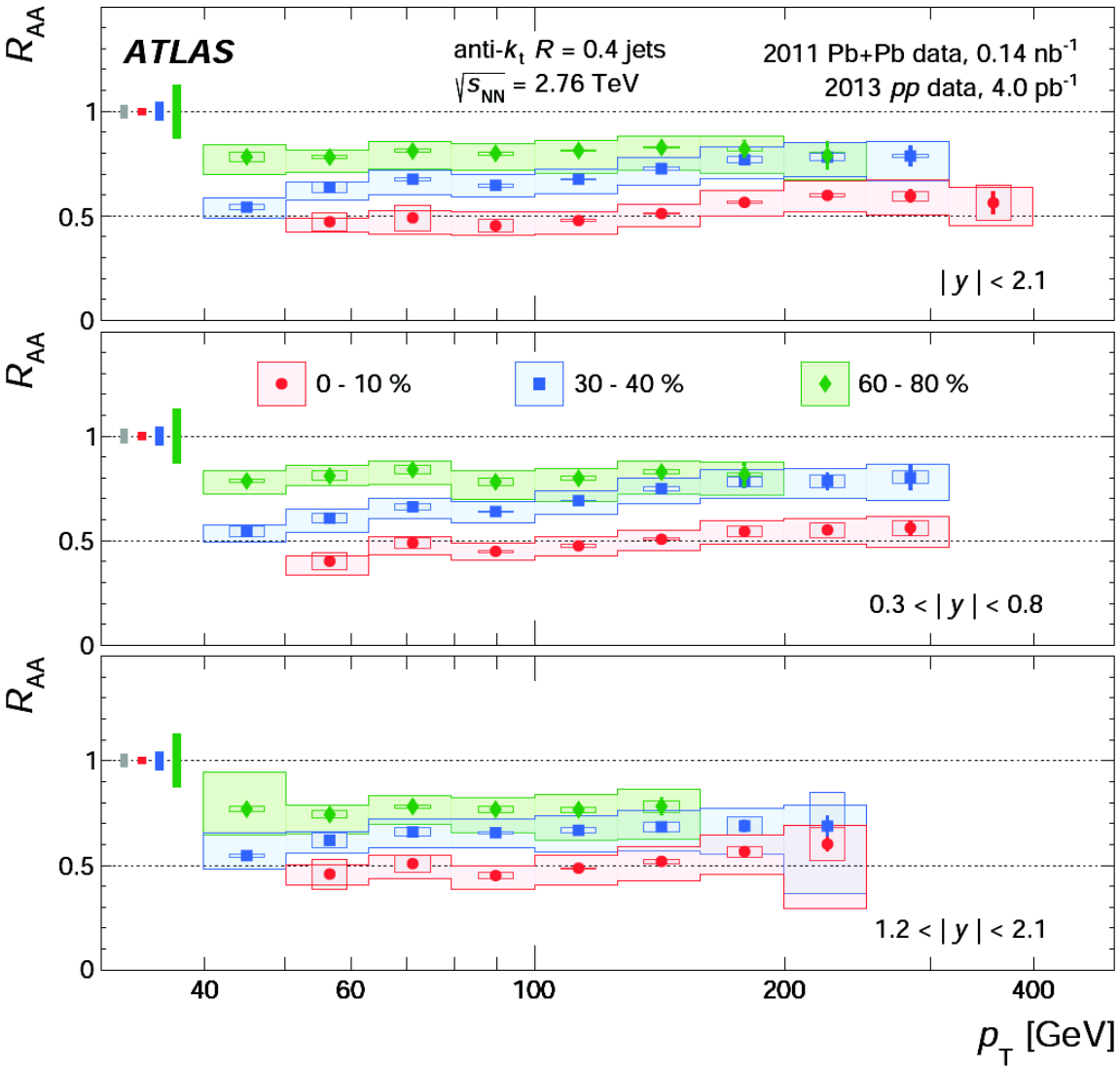
Jet cross-section in *pp* collisions

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

PRL 114 (2015) 072302

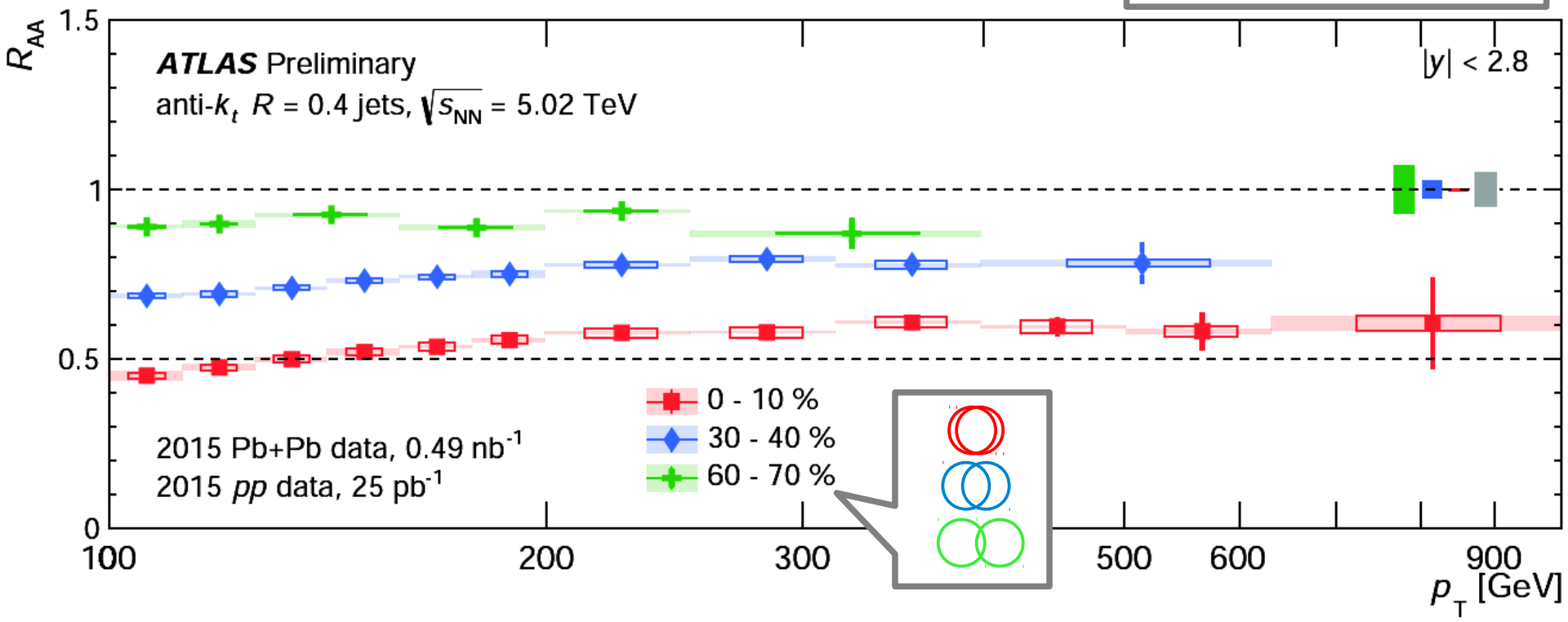


$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{evnt}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2\sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

- A **factor of two** suppression of jet yield in 0-10% central collisions ( ).
- A **modest grow** of jet R_{AA} with increasing jet p_T.
- Still significant **suppression even for 60-80%** centrality bin ( ).
- Practically **no rapidity dependence**.

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

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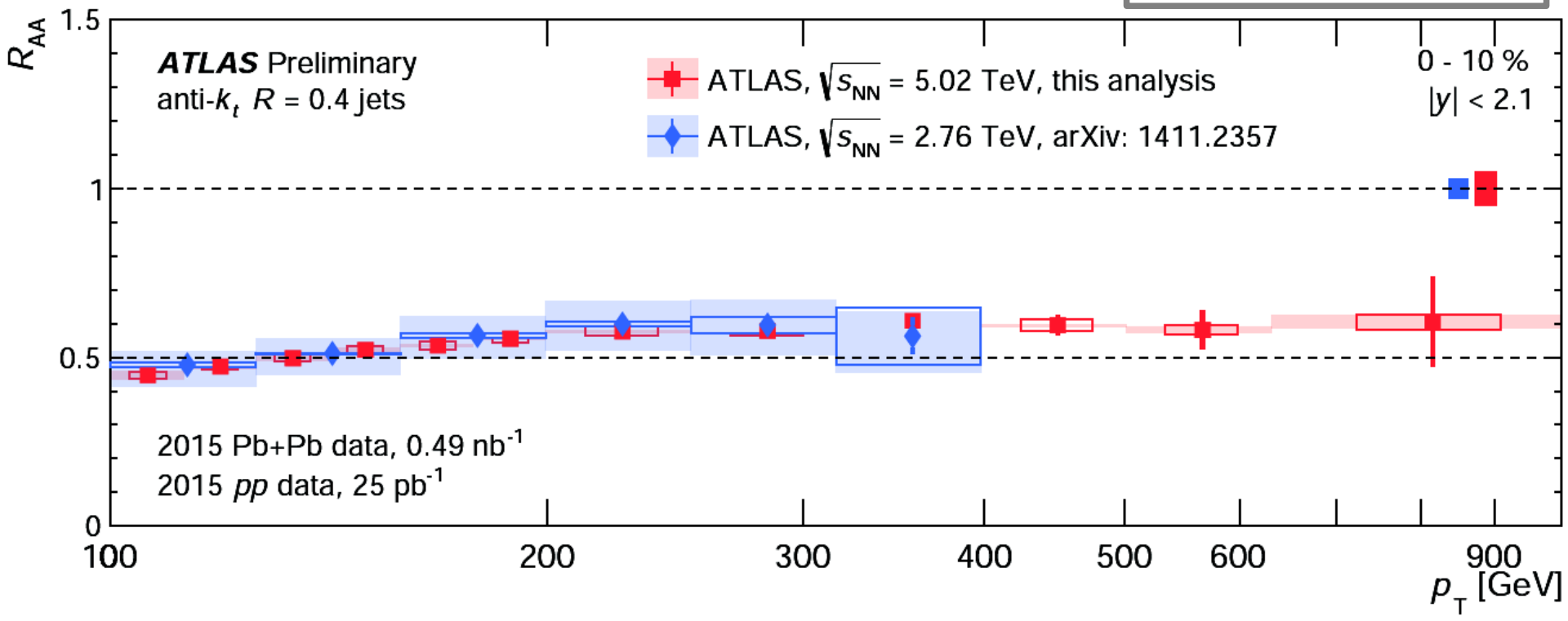
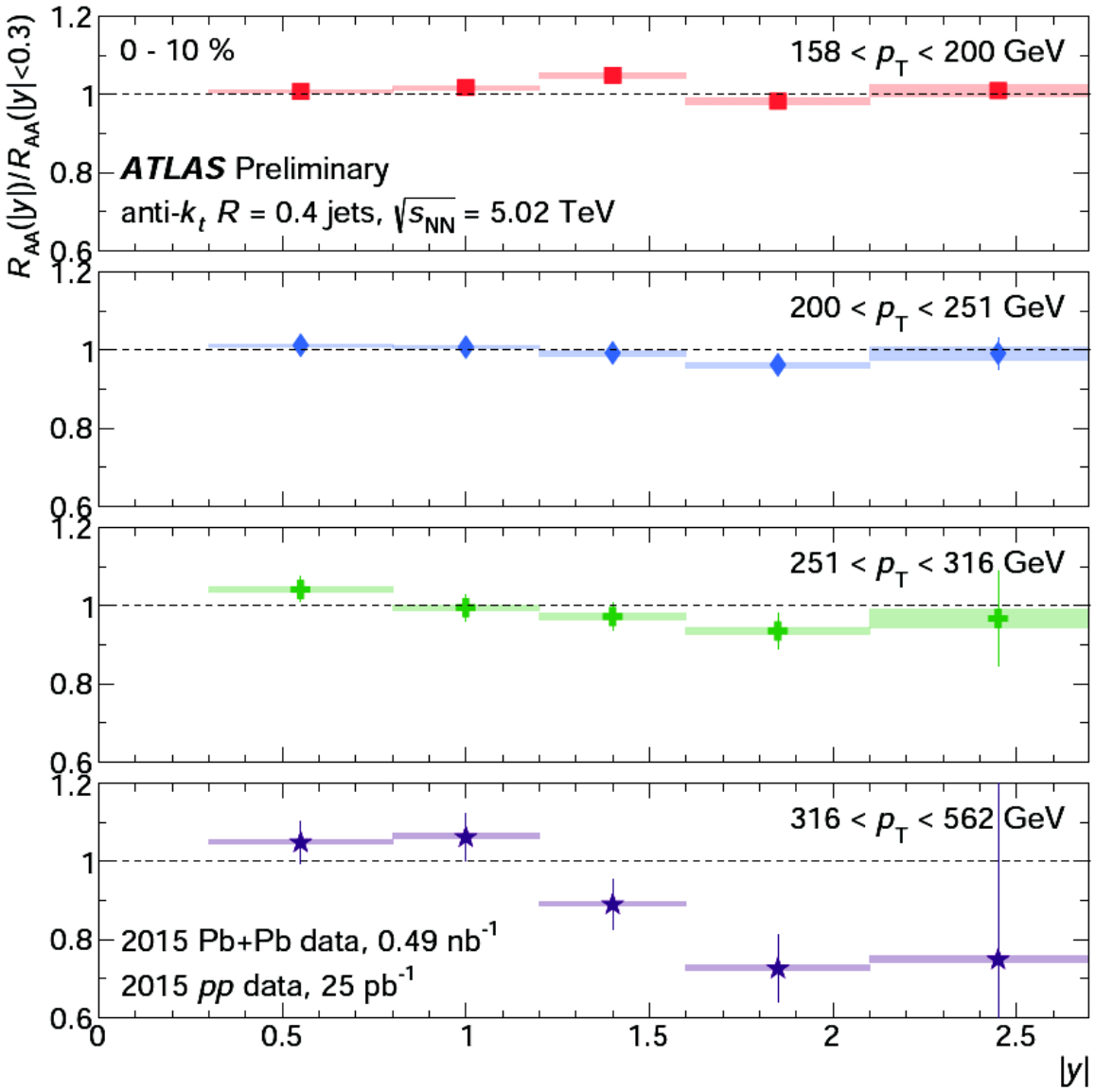


- **Same magnitude** of R_{AA} within systematic uncertainties seen at the two different center-of-mass energies.

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 fragmentation at 2.76 TeV

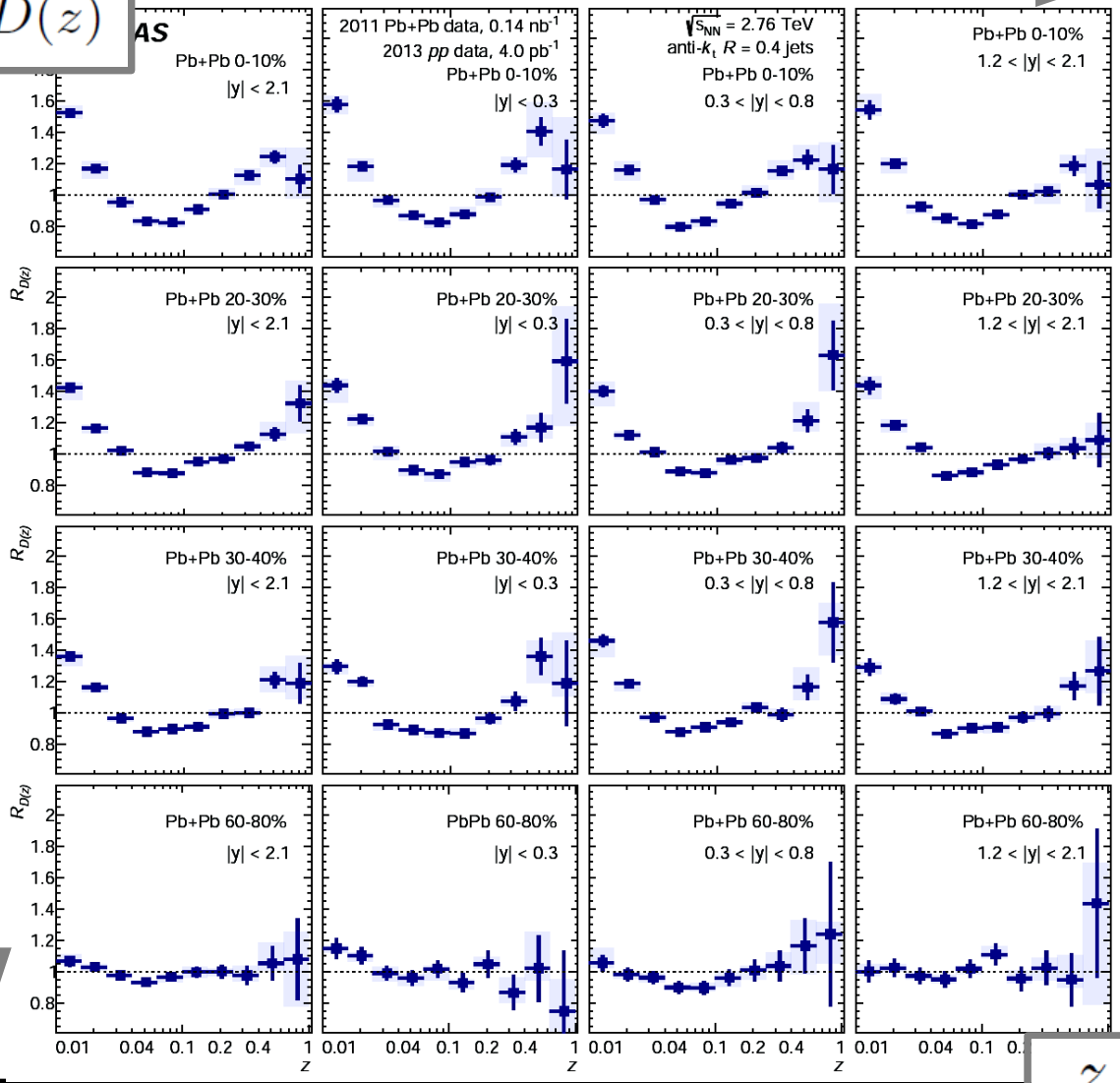
now published

EPJC 77 (2017) no.6, 379

$R_{D(z)}$

rapidity of jet

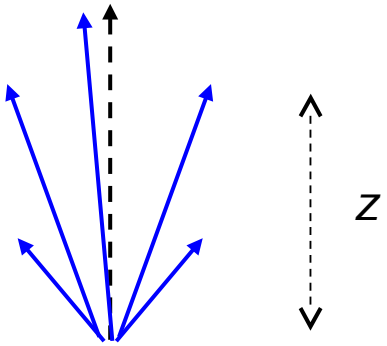
centrality



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

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

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



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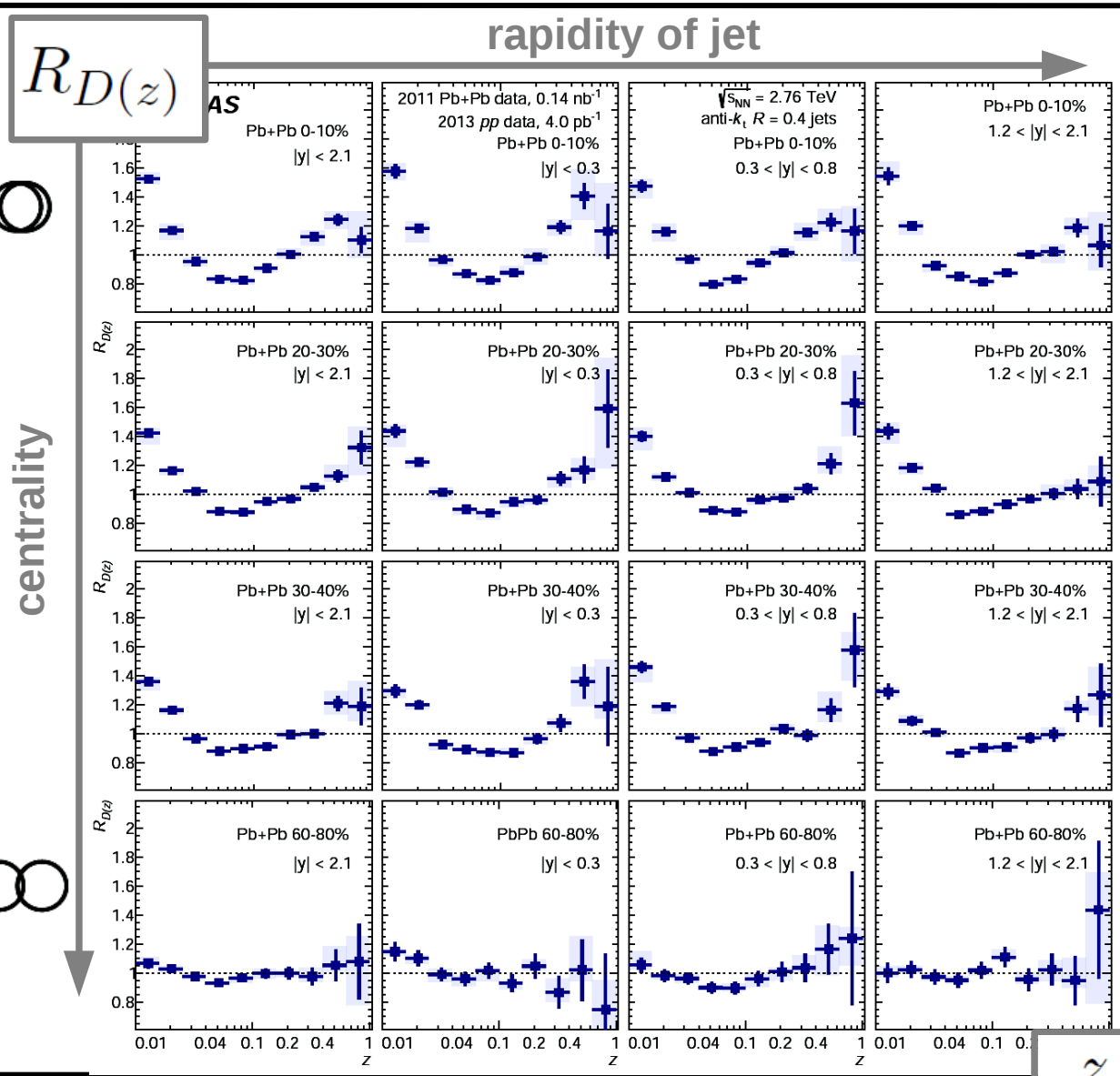


Centrality dependence

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

Rapidity dependence

- No rapidity dependence except for the highest z values (hint of a smaller enhancement for more forward jets)

Jet p_T dependence

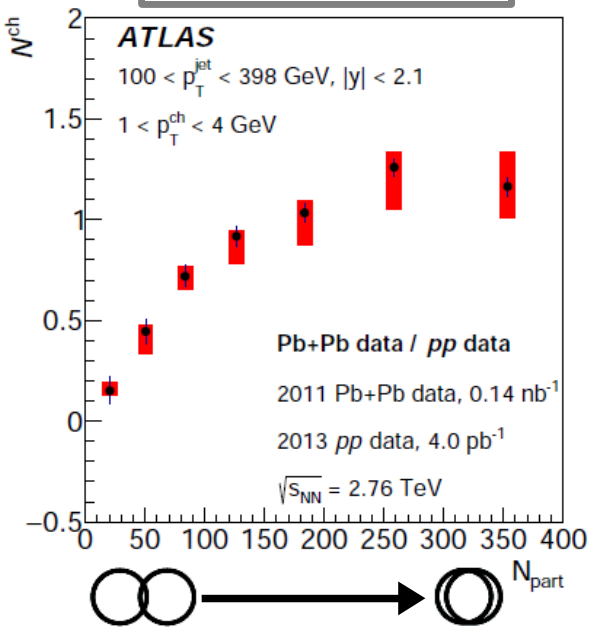
- No significant dependence on jet p_T (not shown here)

Jet fragmentation at 2.76 TeV

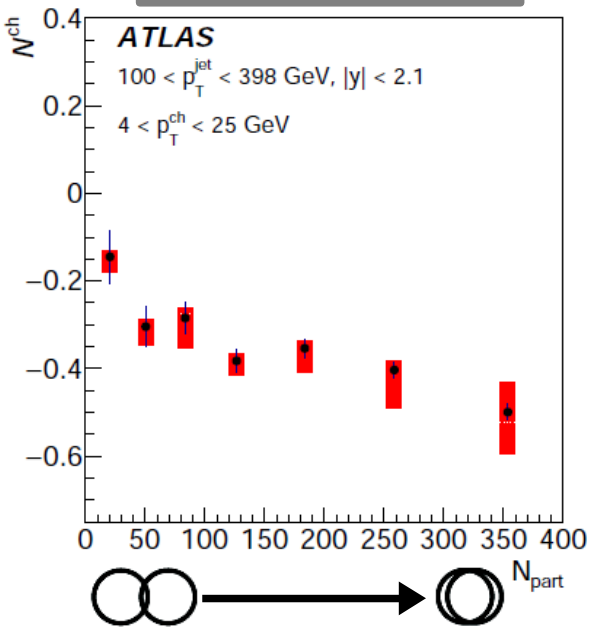
now published

EPJC 77 (2017) no.6, 379

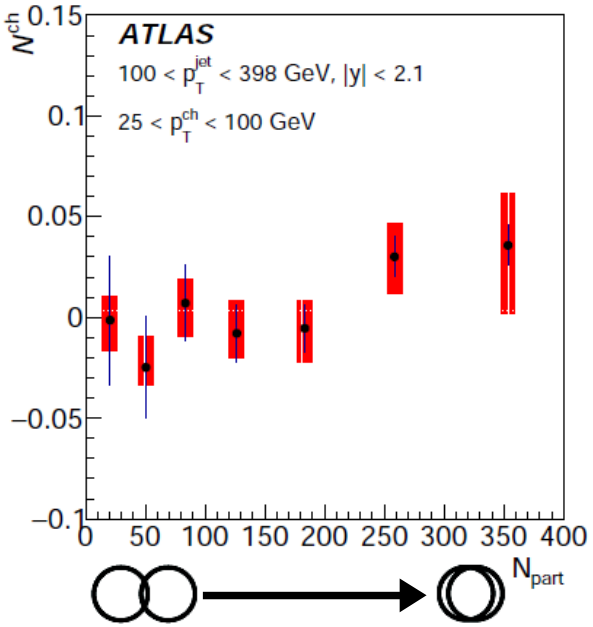
$1 < p_T^{ch} < 4$ GeV



$4 < p_T^{ch} < 25$ GeV



$25 < p_T^{ch} < 100$ GeV

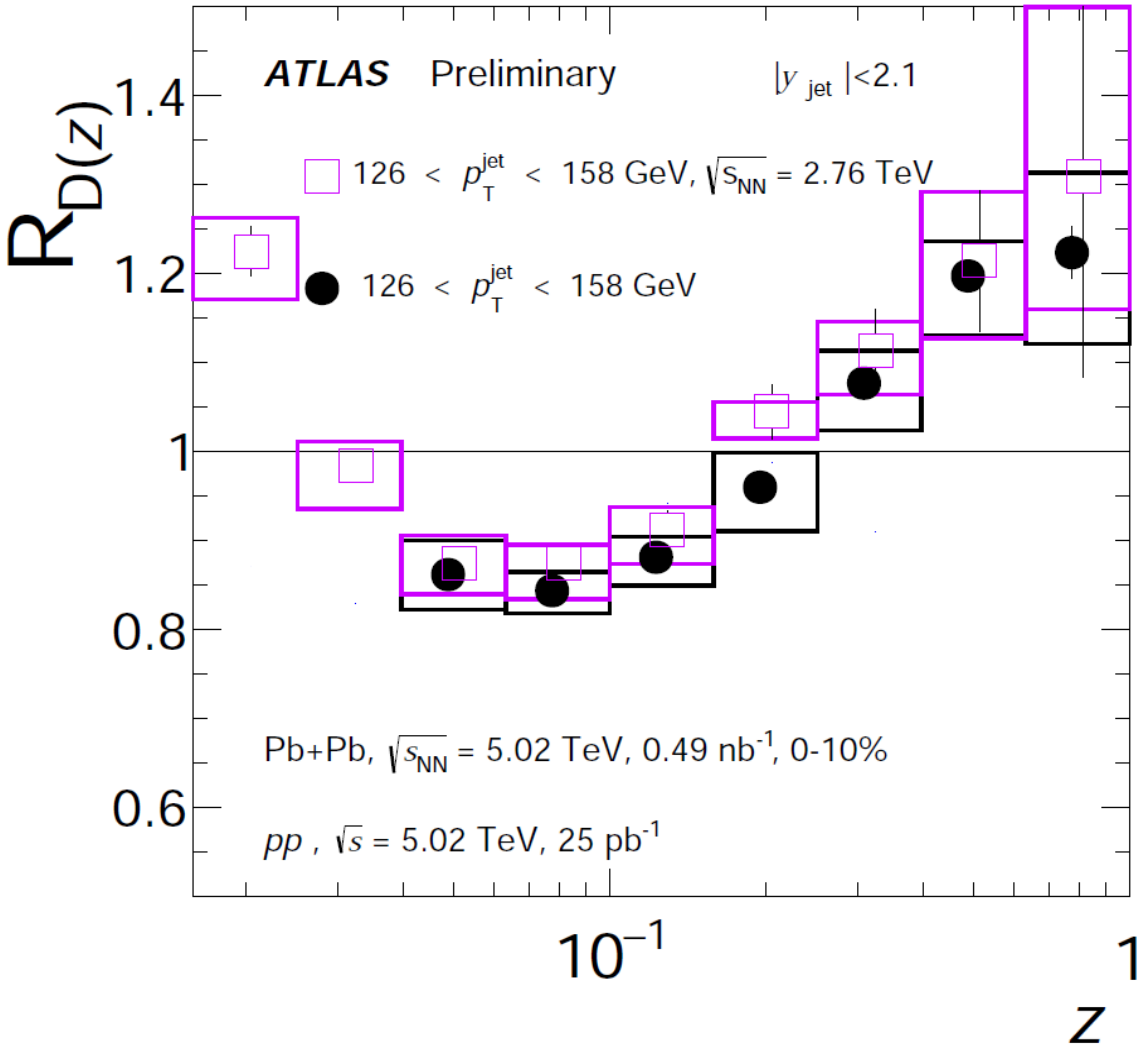


- To quantify the flow of particles: $N^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) \mathrm{d}p_{\mathrm{T}}$

  … quantifies number of missing/extra particles
- Also measured was first moment (see backup)

Jet fragmentation at 5.02 TeV

ATLAS-CONF-2017-005

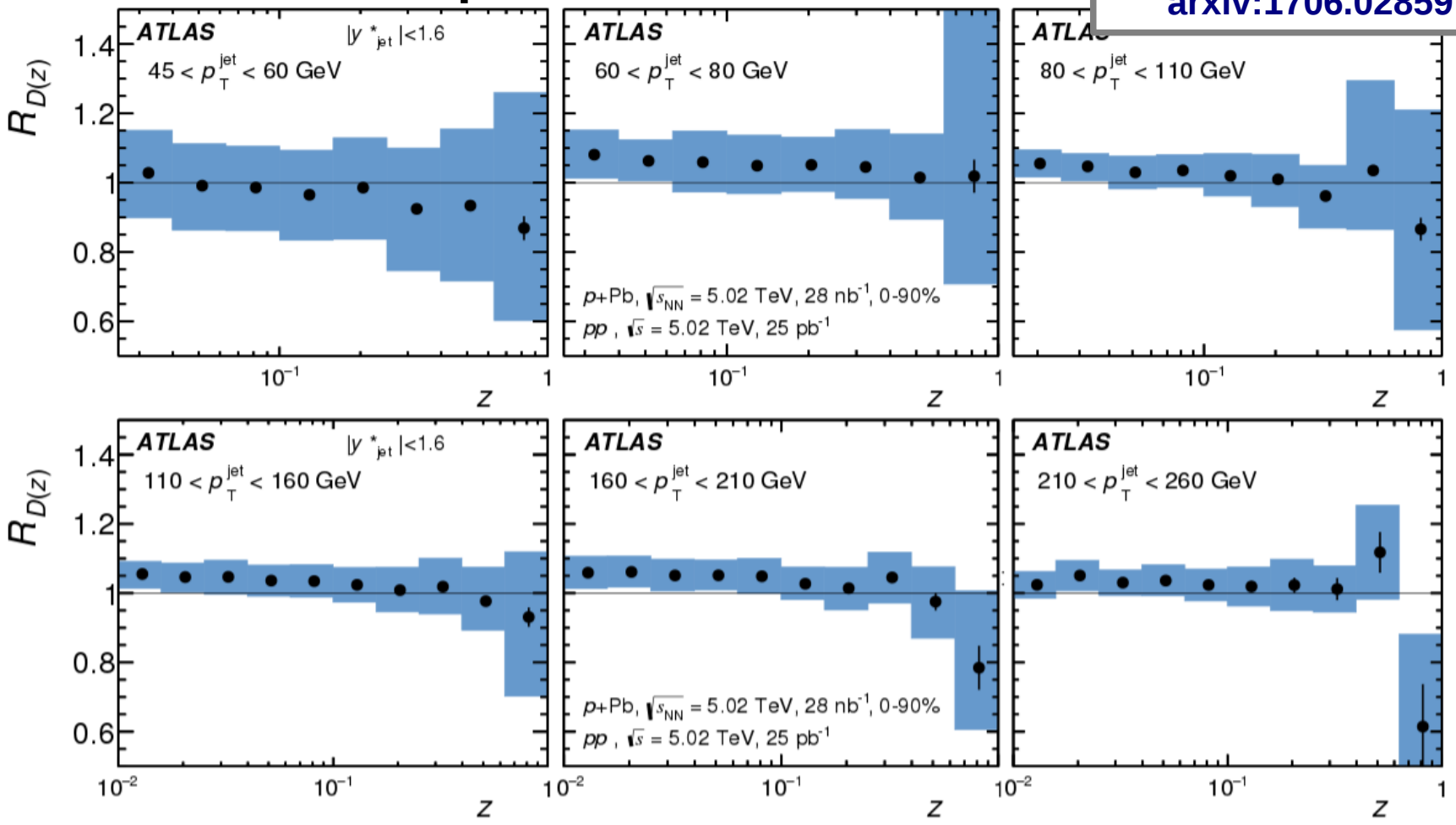


- Ratios of $D(z)$ distributions for tracks with p_T>4 GeV.
- 5.02 TeV measurement **agrees with 2.76 TeV** measurement at the comparable z domain

Jet fragmentation in p+Pb at 5.02 TeV

final

arxiv:1706.02859

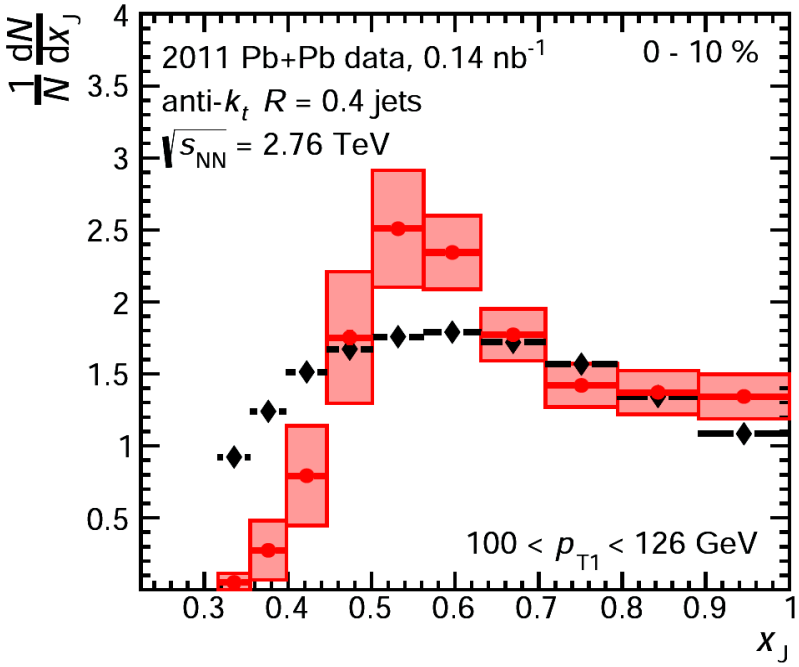


- Ratios of $D(z)$ and $D(p_T)$ distributions measured **in 5.02 TeV p+Pb** collisions.
- **No modifications** of the jet internal structure seen in the p+Pb environment.

Dijet production

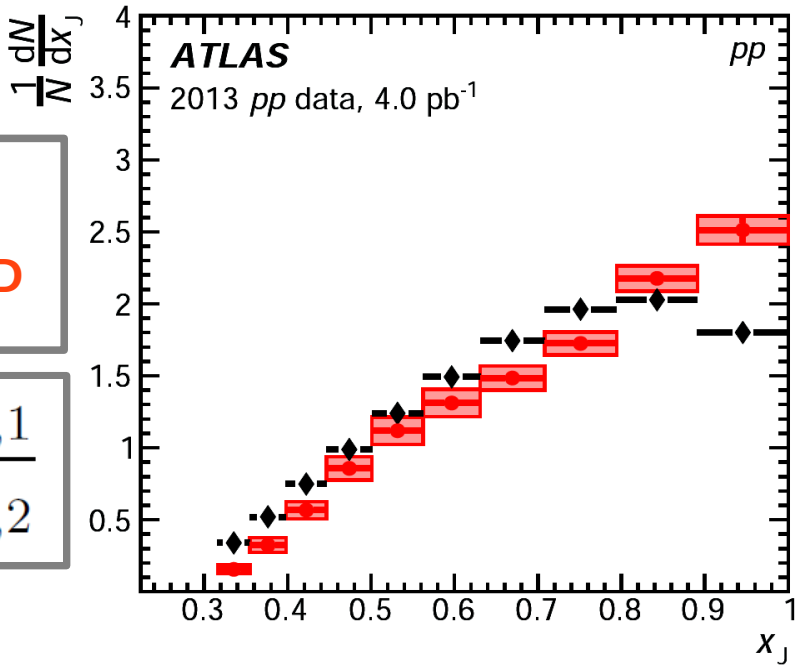
final

arxiv:1706.09363



RAW
UNFOLDED

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



- Fully **particle-level corrected** dijet asymmetry measurement
- Uses 2D bayesian unfolding to correct for the detector effects in p_{T1} and p_{T2} simultaneously
- Energy loss **very different for two jets** in the system

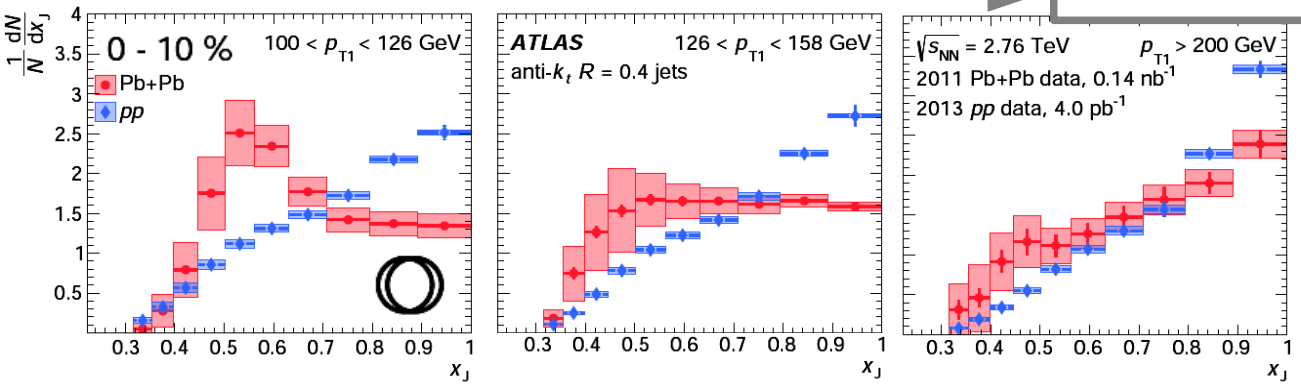
Dijet production

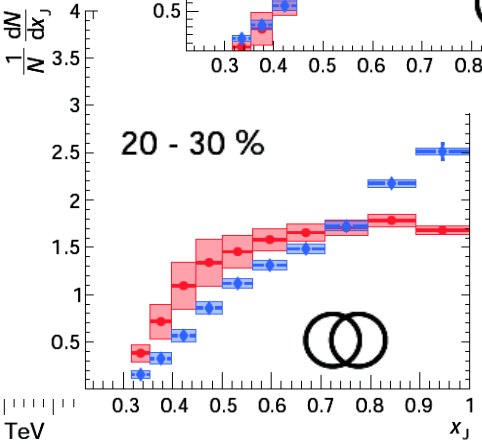
final

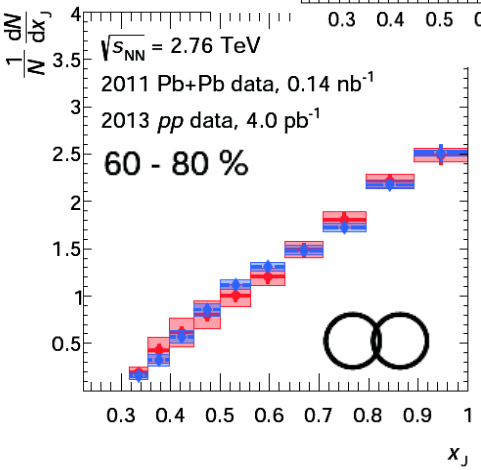
pt of jet

centrality

arxiv:1706.09363







Pb+Pb

pp

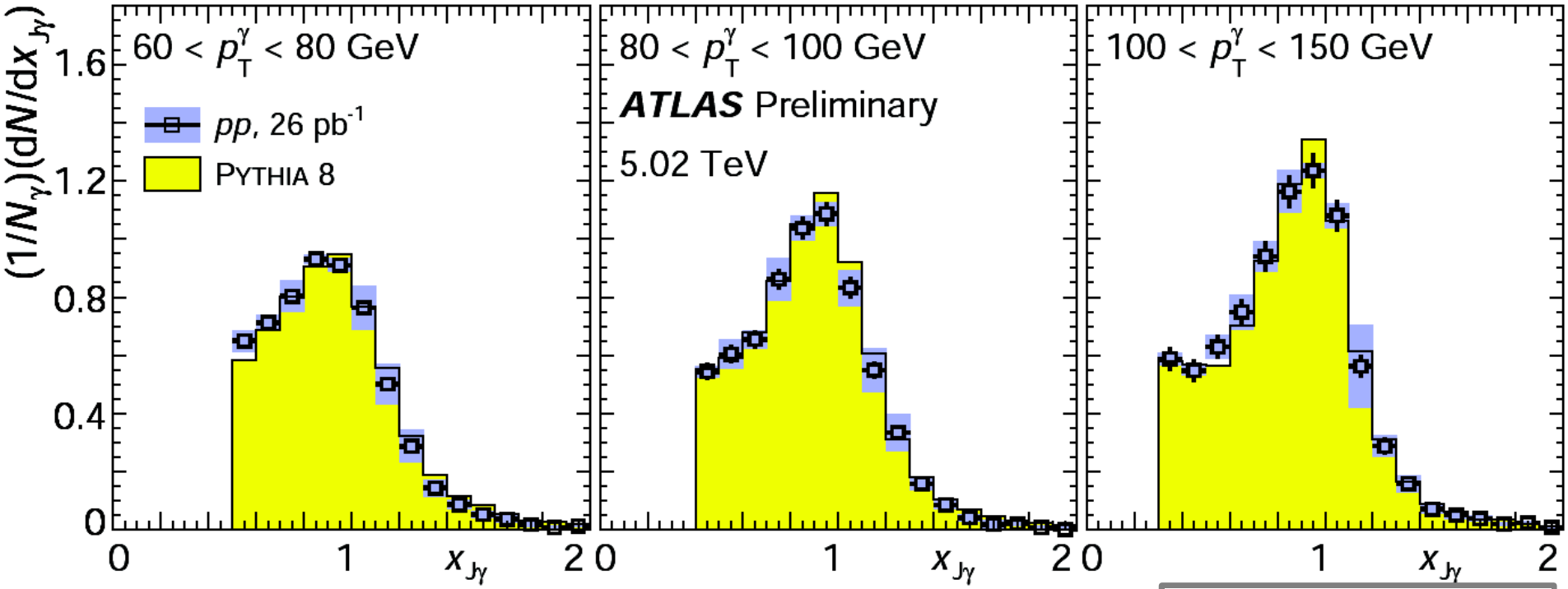
Pronounced jet pt dependence, high-pt jets almost unmodified

Clear centrality dependence.
0-10%: most proable value ~0.5.
60-80%:consistent with pp.

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

Gamma-jet production

ATLAS-CONF-2016-110

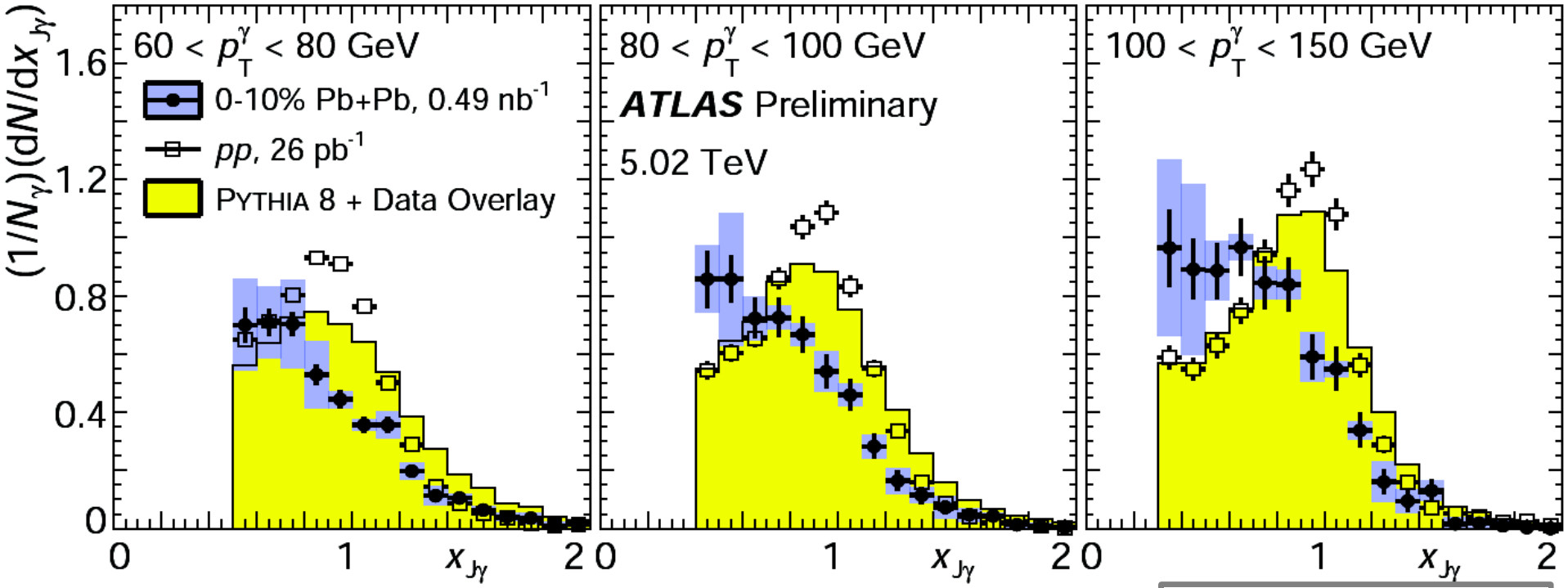


$$x_{\mathrm{J}\gamma} = \frac{p_{\mathrm{T,jet}}}{p_\gamma}$$

- Good agreement between PYTHIA8 and *pp* data
- Not unfolded for the detector response

Gamma-jet production

ATLAS-CONF-2016-110



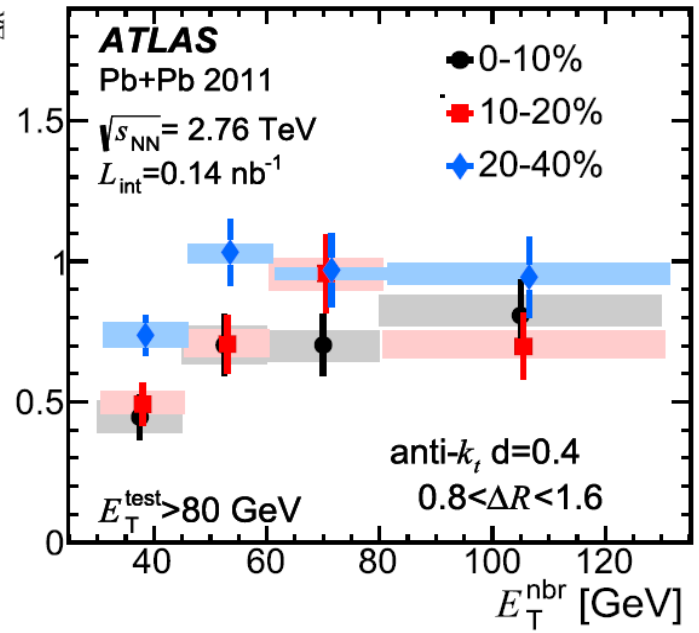
$$x_{\mathrm{J}\gamma} = \frac{p_{\mathrm{T,jet}}}{p_\gamma}$$

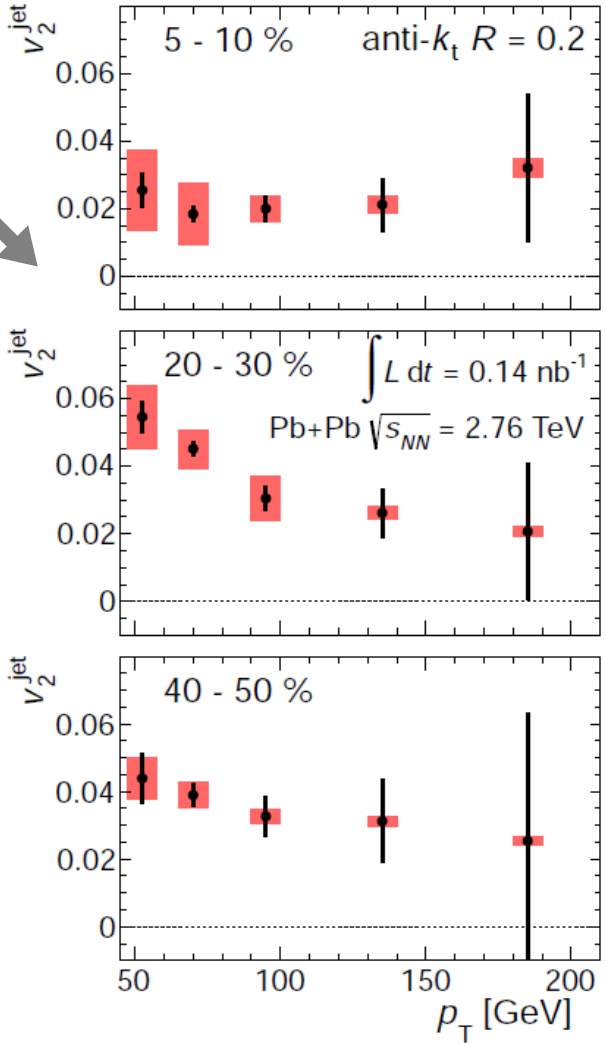
- Clear modification (downward shift) due to the parton **energy loss of the balancing jet**.
- Not shown is centrality dependence – smaller effect in less central collisions

Other published jet results with Pb+Pb collisions (2013+)

- Jet R_{CP} (PLB 719 (2013) 220)
- Azimuthal angle dependence of inclusive jets (PRL 111 (2013) no.15, 152301)
- Jet fragmentation I. (PLB 739 (2014) 320)
- Small angle jet pairs (PLB 751 (2015) 376)

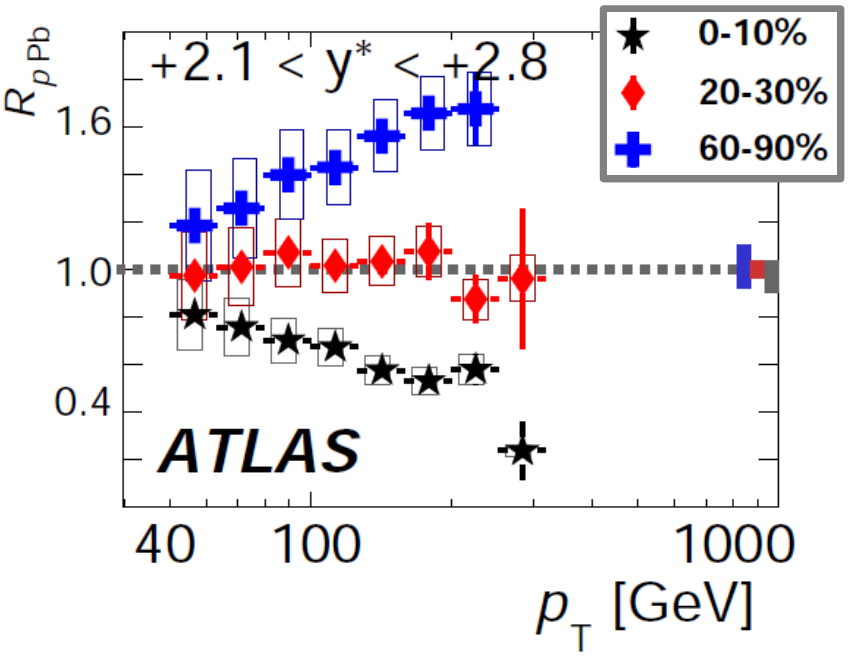
Central-to-peripheral ratio of nearby jet yield

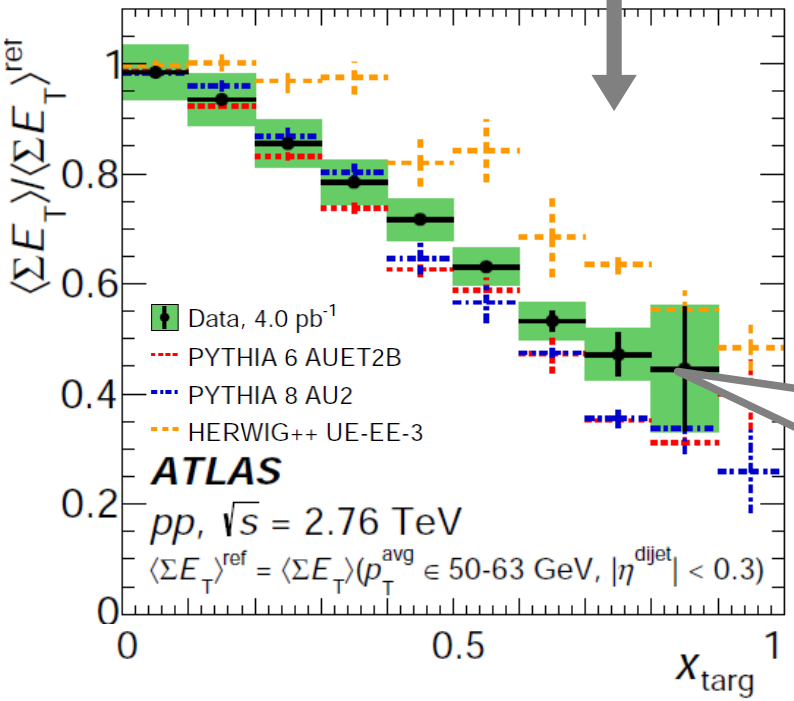




Other jet results with p+Pb and *pp* collisions

- Jet production in p+Pb (PLB 748 (2015) 392)
- Jet and forward E_T correlations in *pp* (PLB 756 (2016) 10)





Forward UE production **depleted if x-target is large,** but only a modest variation with varying x-projectile (not shown)

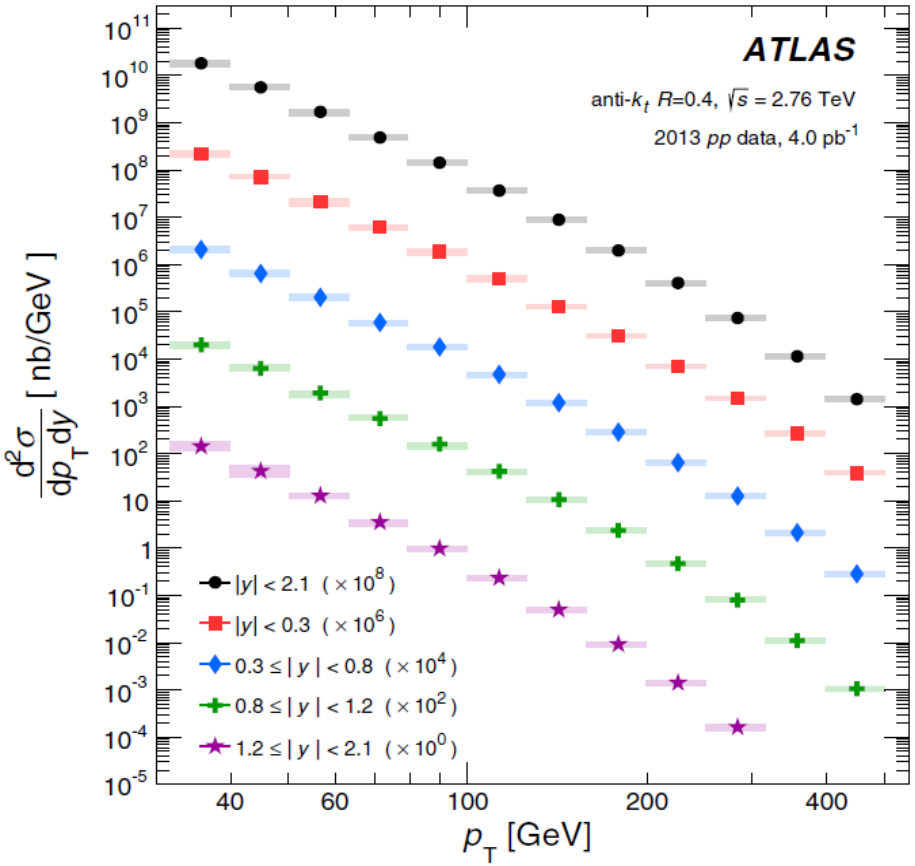
Summary

- Jet R_{AA} measured differentially in centrality, rapidity and up to 1 TeV
- Jet internal structure measured differentially centrality, jet pt and rapidity in *pp*, Pb+Pb, and *p*+Pb collisions
- Fully corrected di-jet measurement exhibits very pronounced difference between Pb+Pb and *pp* collisions
- Uncorrected photon-jet measurement exhibits a significant suppression of balancing jet

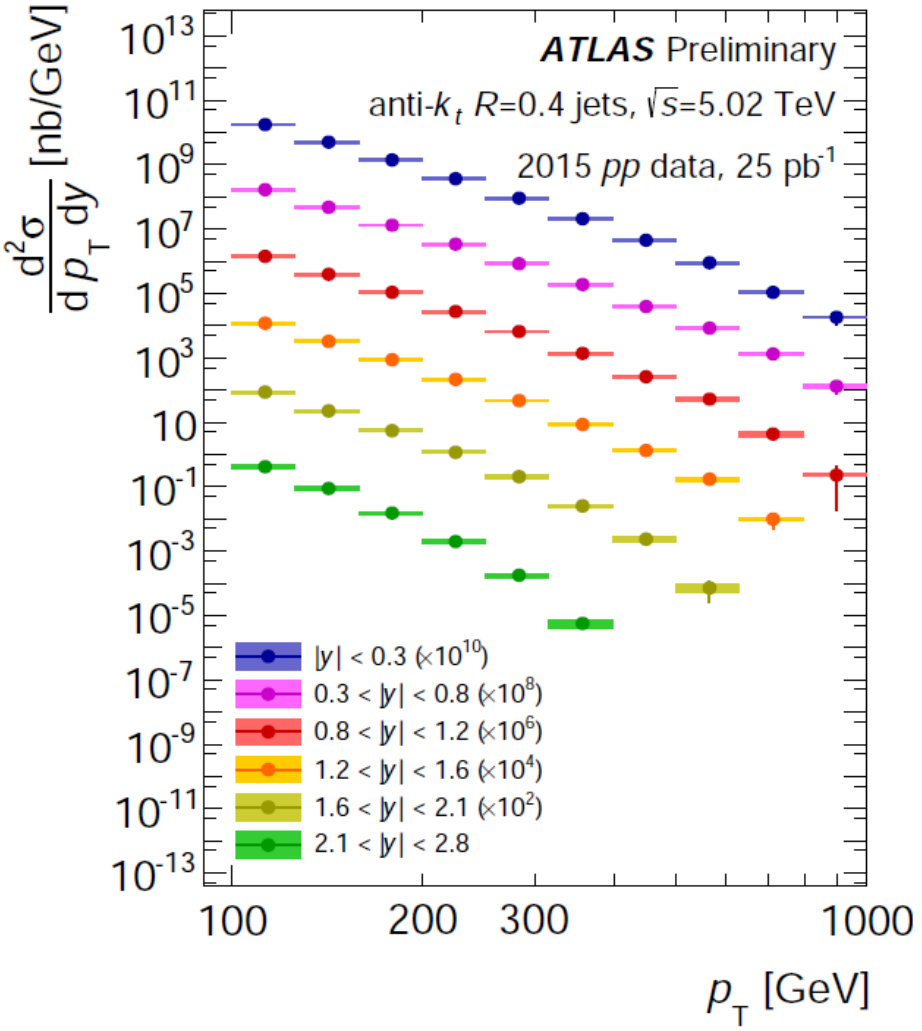
Backup slides

Jet cross-section in pp collisions

2.76 TeV

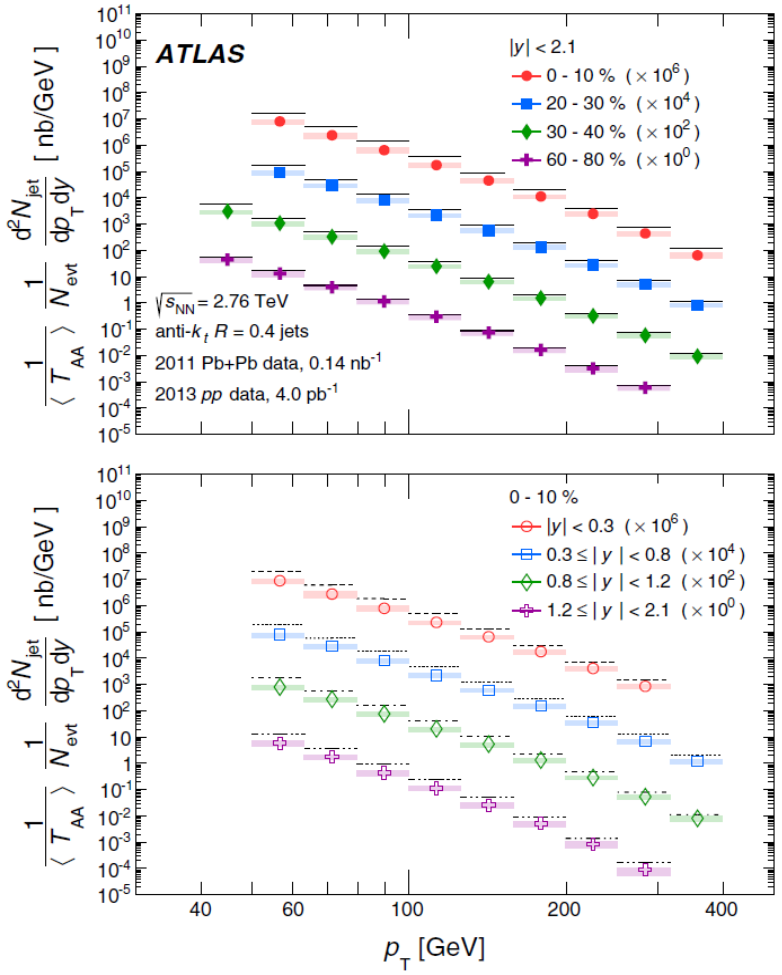


5.02 TeV



Jet yeilds in Pb+Pb collisions

2.76 TeV



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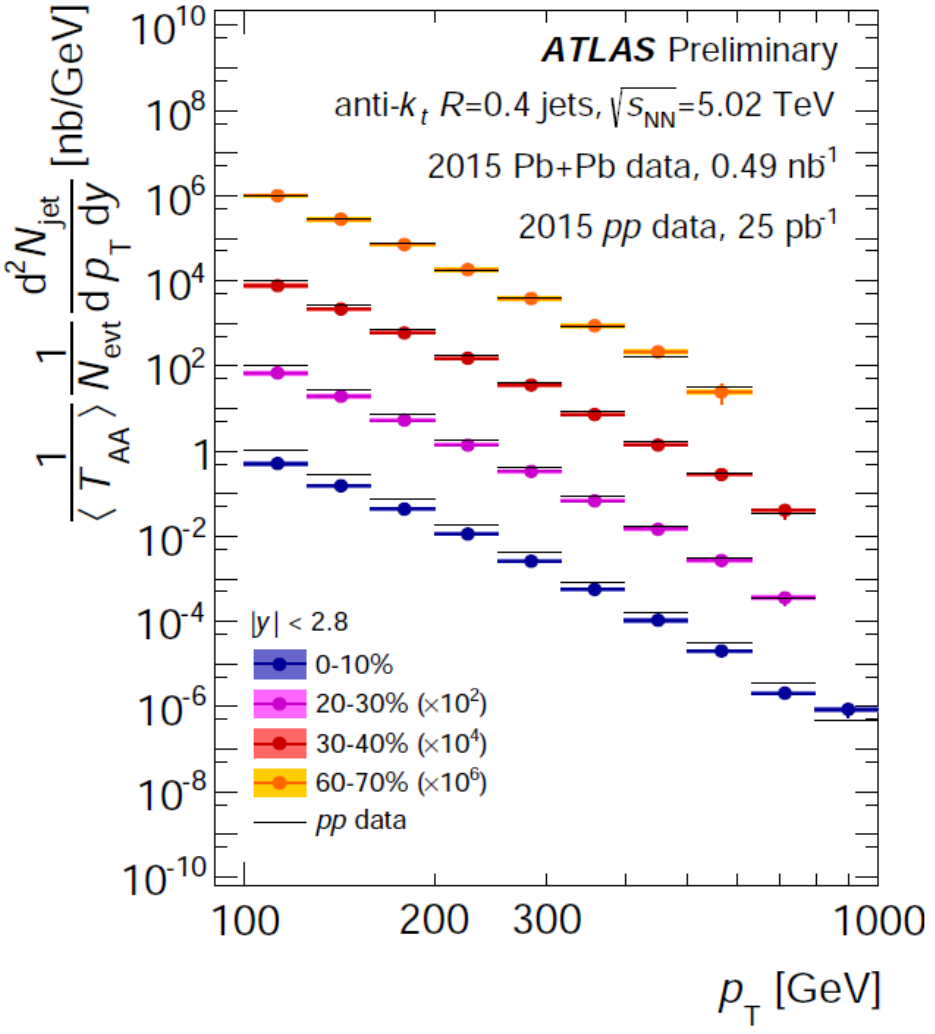


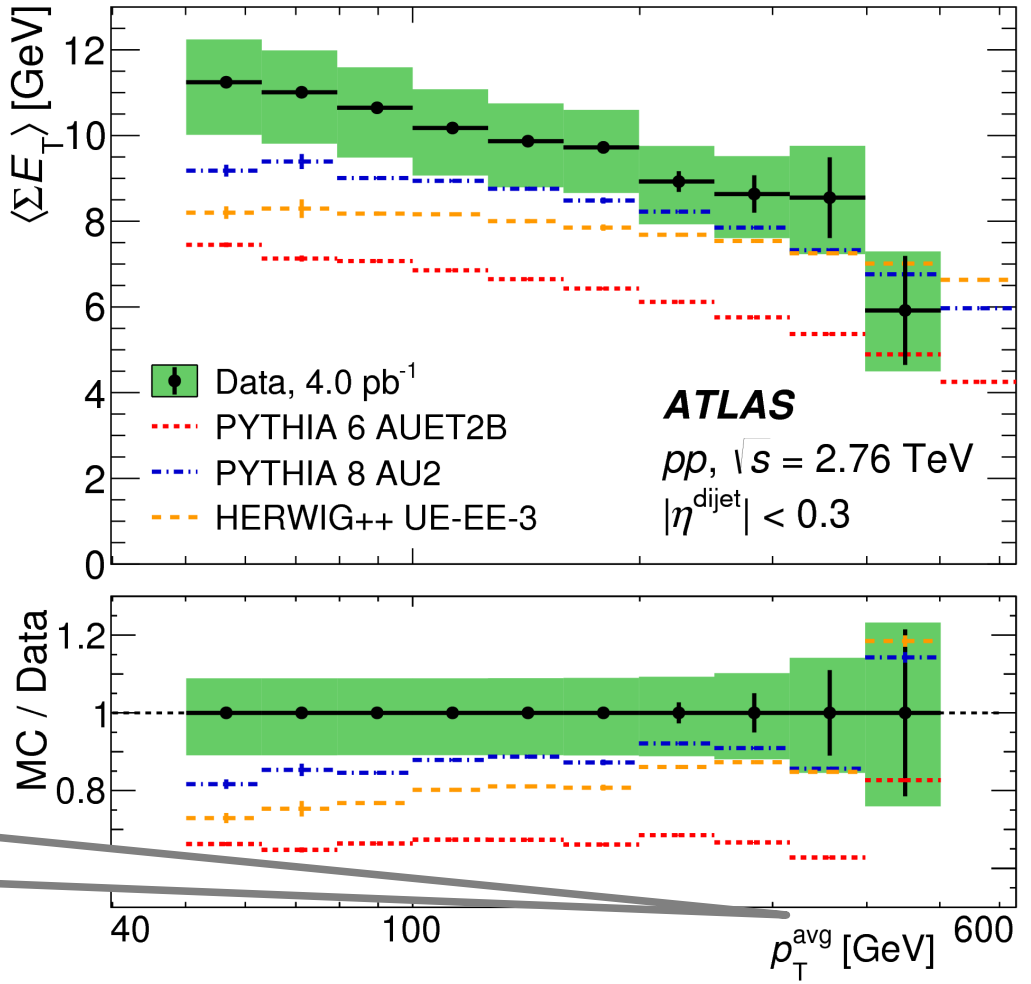
Correlations between soft and hard production in *pp*

PLB 756 (2016) 10-28

- **What is measured**: correlation between the dijet kinematics and the magnitude of the UE in the forward region **in *pp* collisions**
- **Motivation**: modeling of particle production, reference measurement to **better understand the centrality in p+Pb**

$\langle \Sigma E_T \rangle$ of UE in the forward region ($-4.9<\eta<-3.2$)

$(p_{T1}+p_{T2})/2$ of dijet



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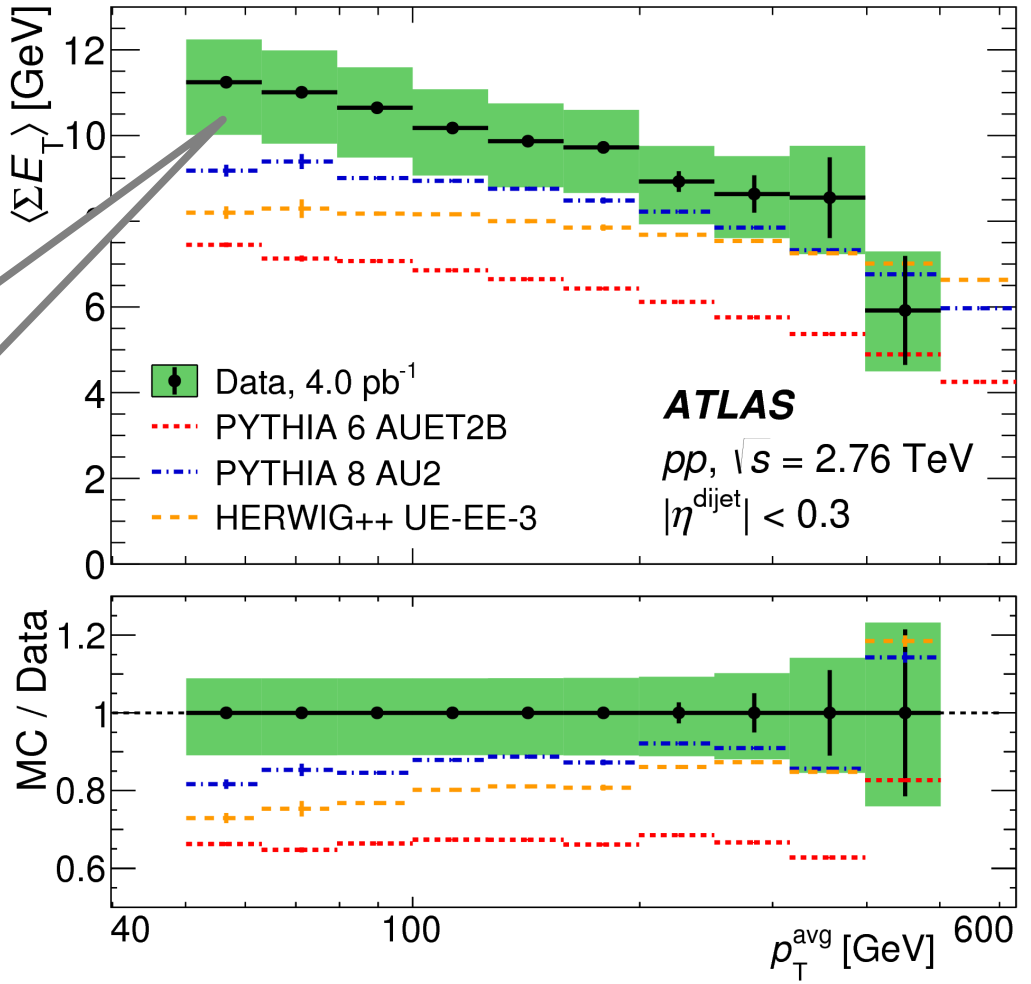
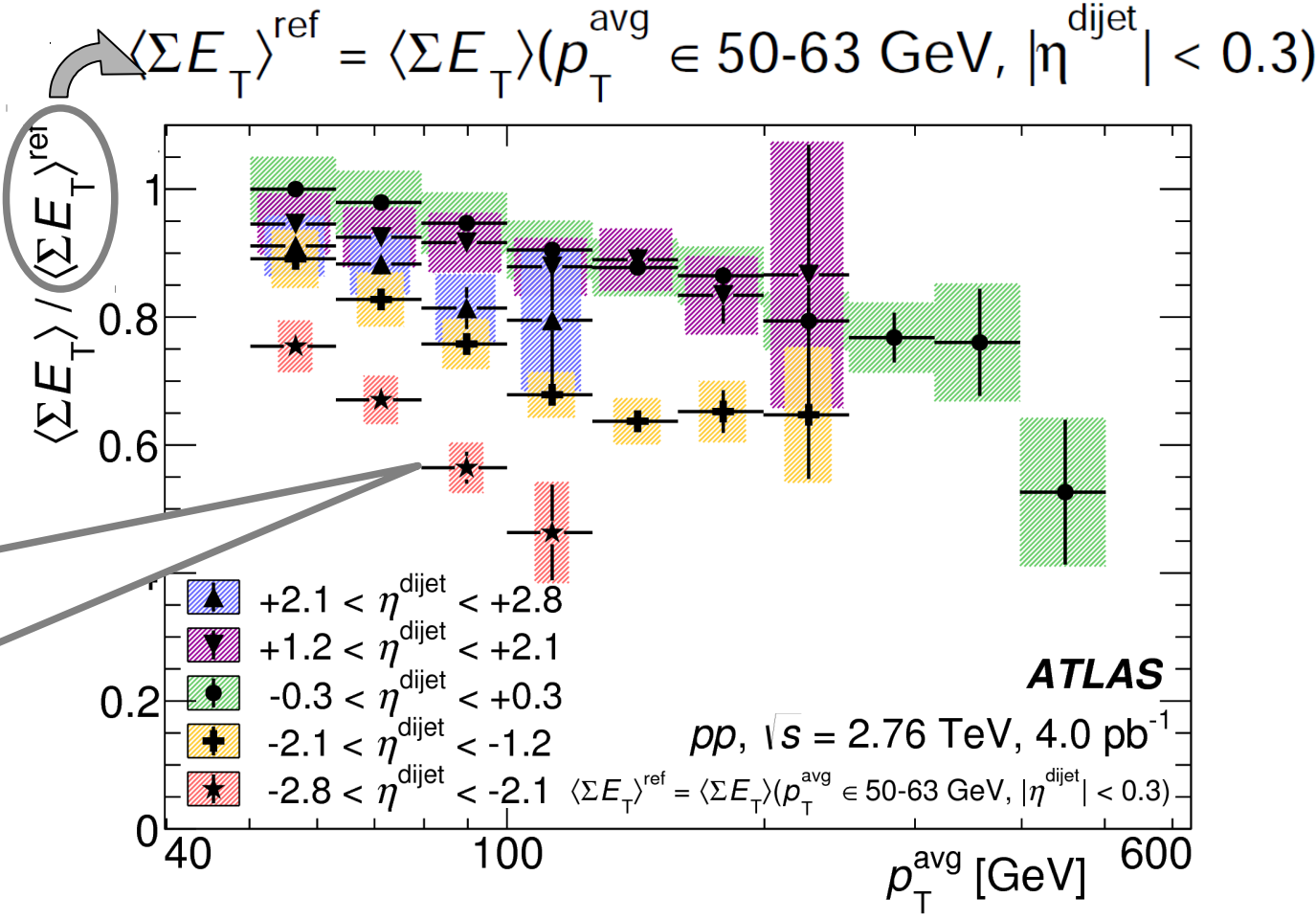
Anti-correlation between "soft production" and "hard production"



Correlations between soft and hard production in *pp*

PLB 756 (2016) 10-28



Anti-correlation is **stronger** when η_{dijet} approaches the $\Sigma \mathbf{E_T}$ **measuring region**

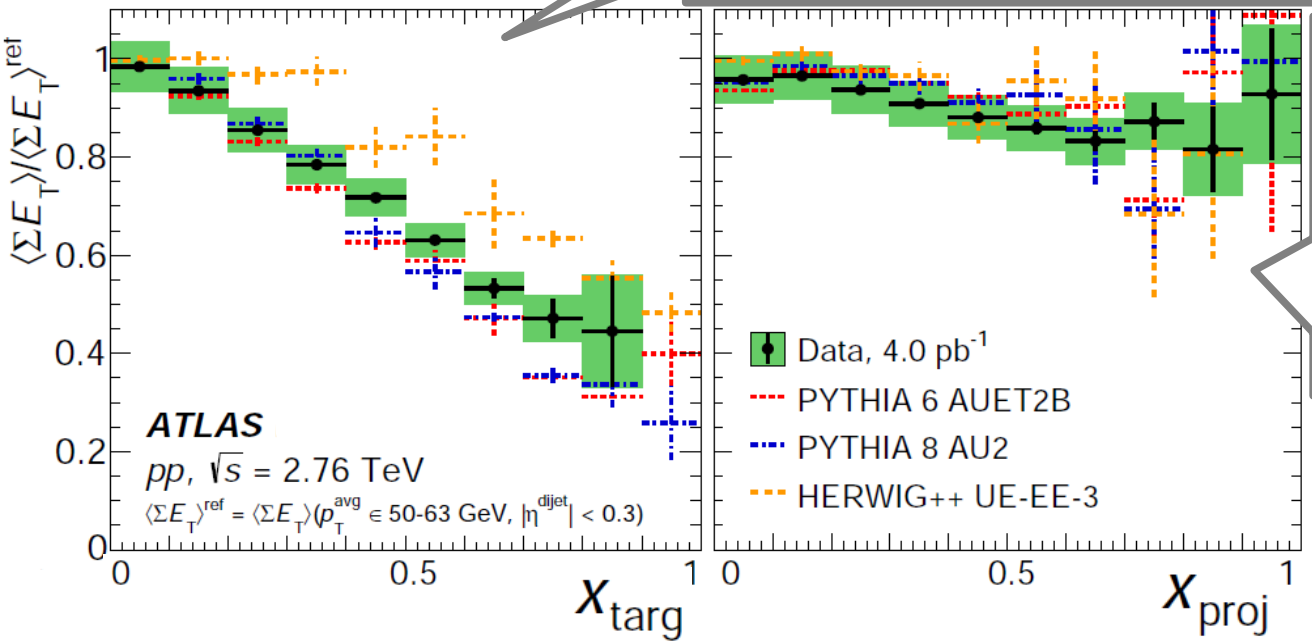
… this can be evaluated as a function of x-target and x-projectile (~ Bjorken x)

Correlations between soft and hard production in *pp*

PLB 756 (2016) 10-28

$$x_{\mathrm{proj/trag}} = \frac{p_{\mathrm{T}}^{\mathrm{avg}}}{\sqrt{s}}\left(e^{\pm\eta_1} + e^{\pm\eta_2}\right)$$

Forward UE production **depleted if x-target is large**



… but only a modest variation with varying x-projectile

The target is the analogue of the nucleus **in p+Pb** collisions, projectile analogue of proton … small sensitivity of ΣE_T to x-projectile suggests that effects seen in p+Pb jets are **not due to trivial anti-correlation in individual nucleon-nucleon collisions** (e.g. “energy conservation”)**.**

Correlations between soft and hard production in *pp*

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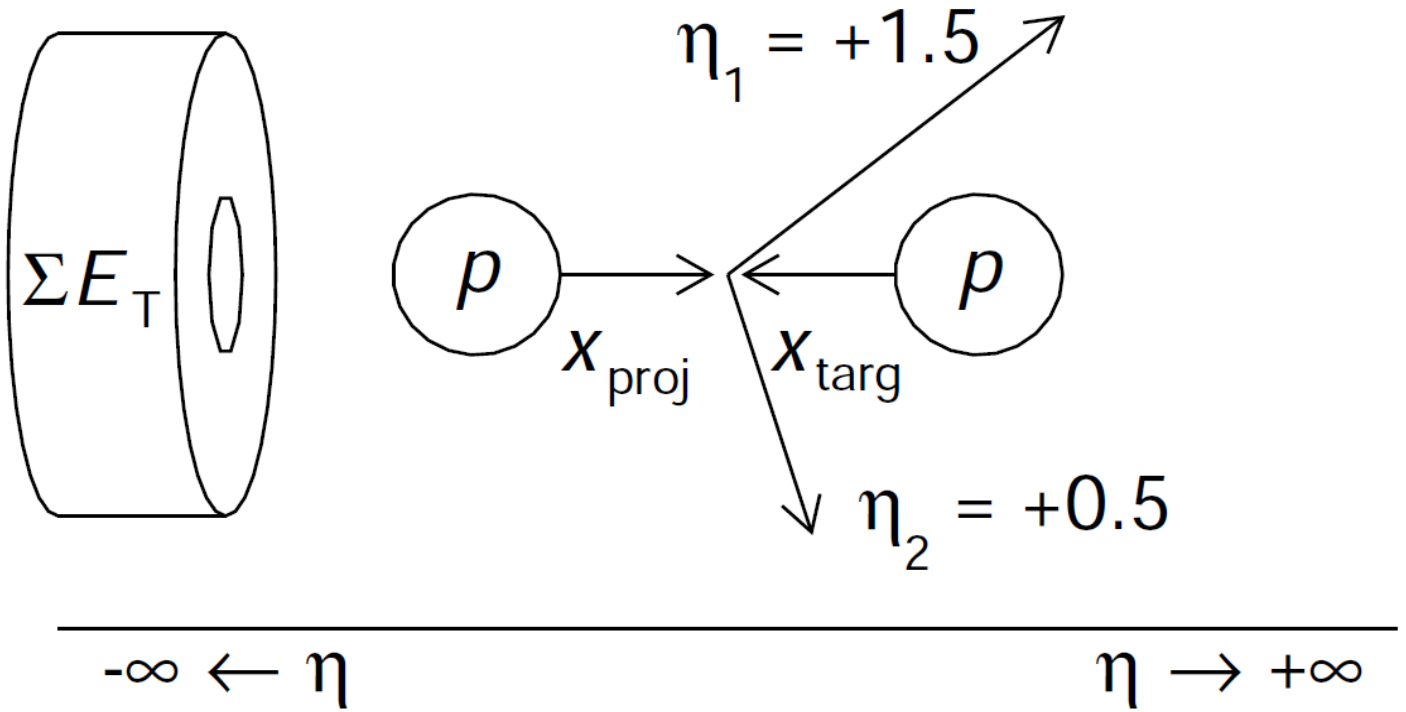

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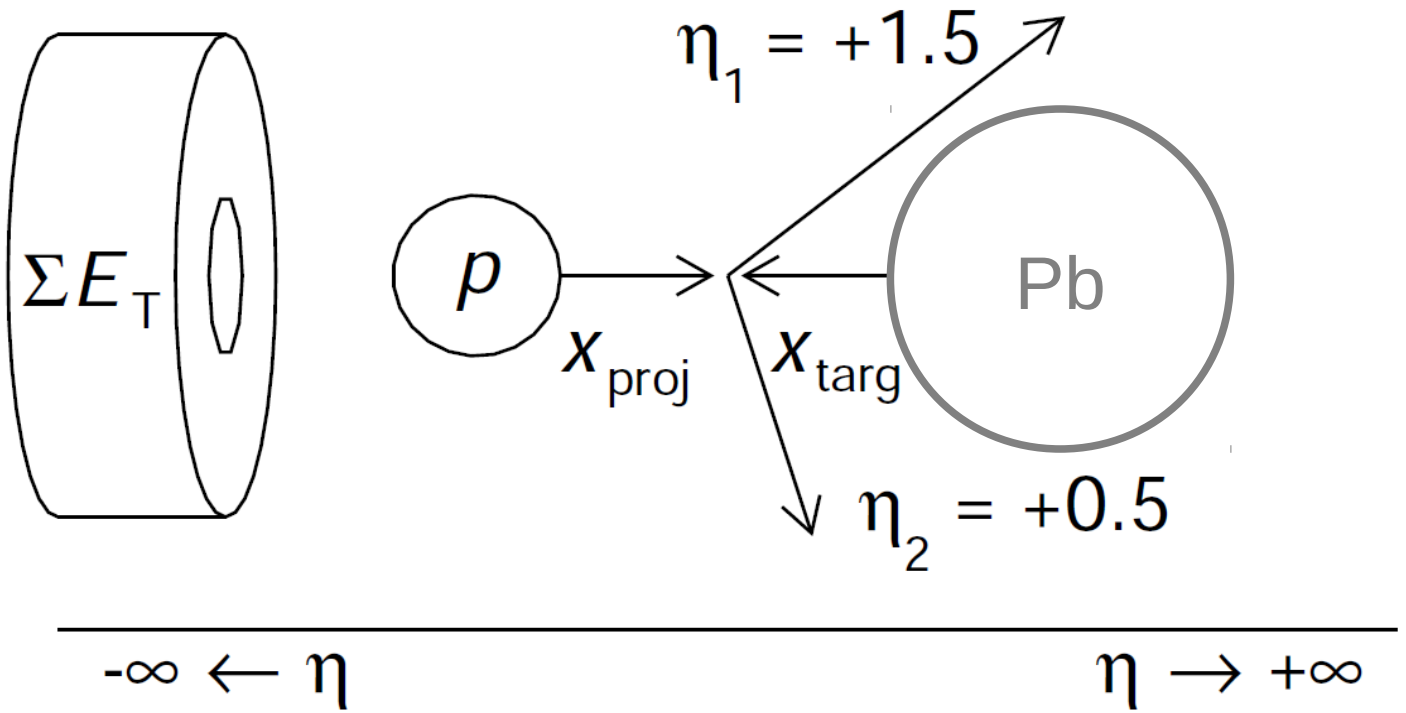

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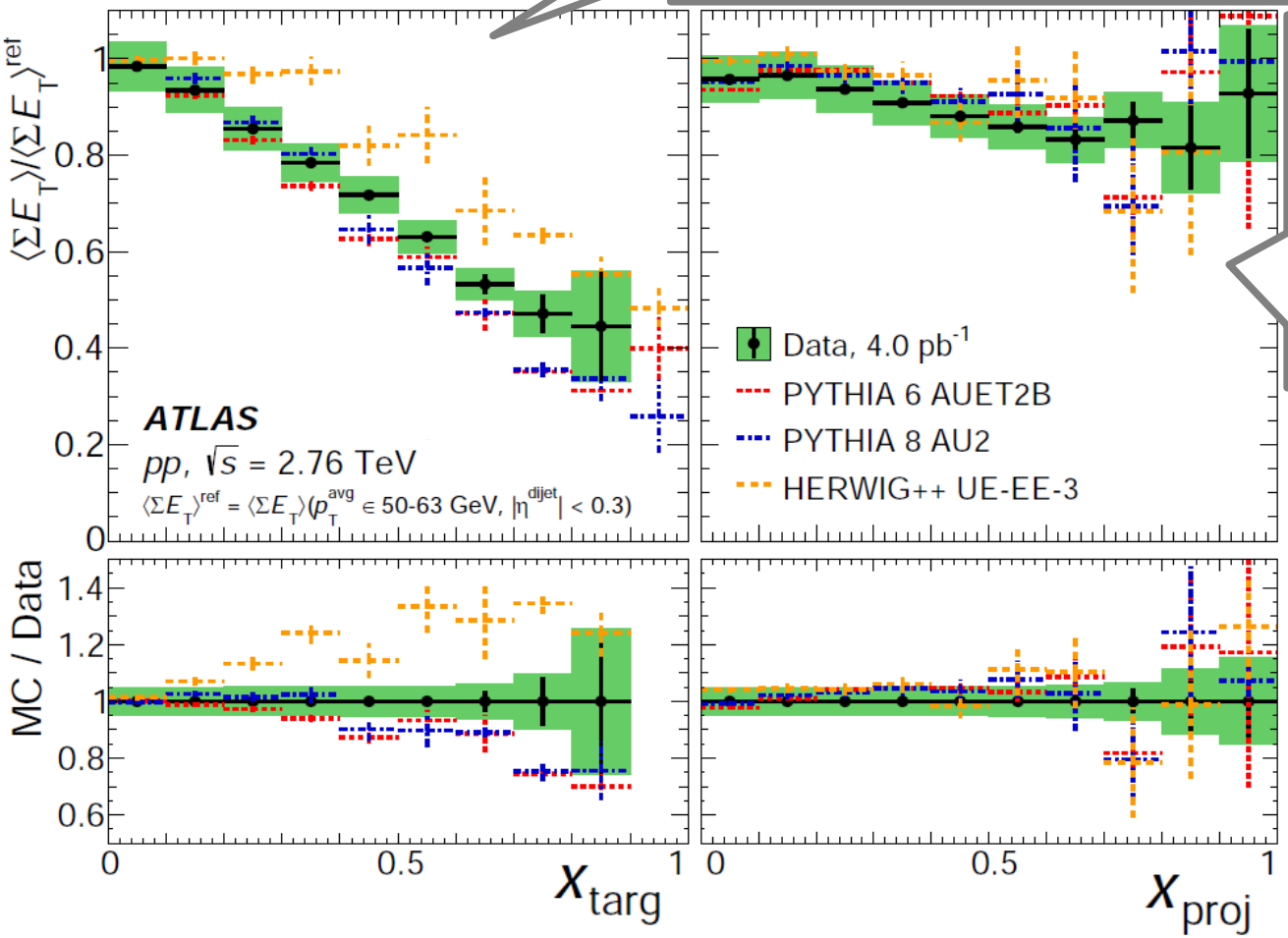
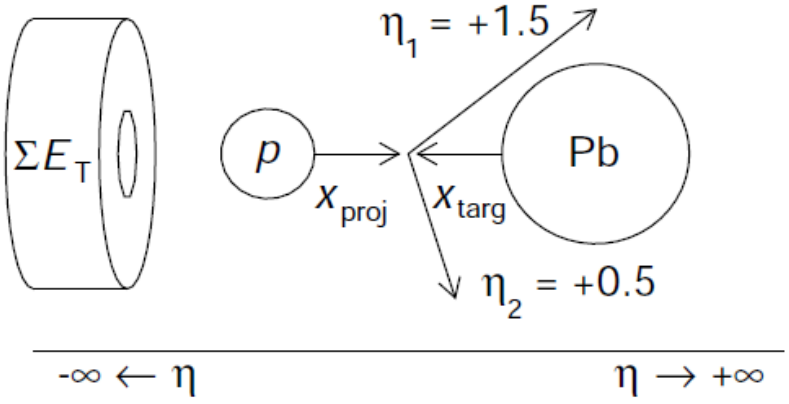
Forward UE production
depleted if x-target is large



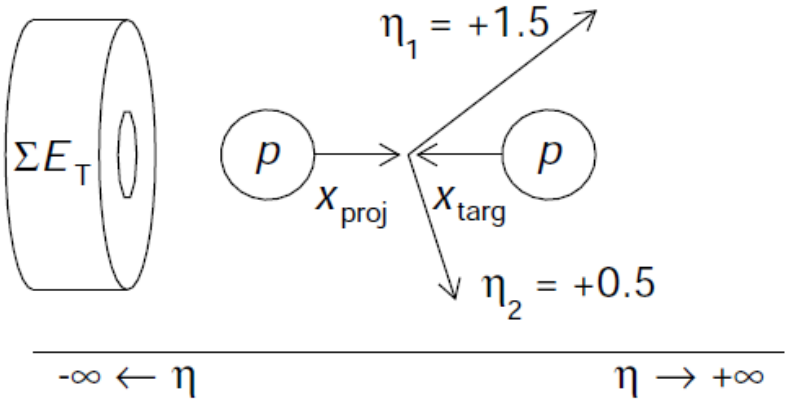
… but only a modest variation with varying x-projectile

Correlations between soft and hard production in *pp*

(a) *p*+Pb collision



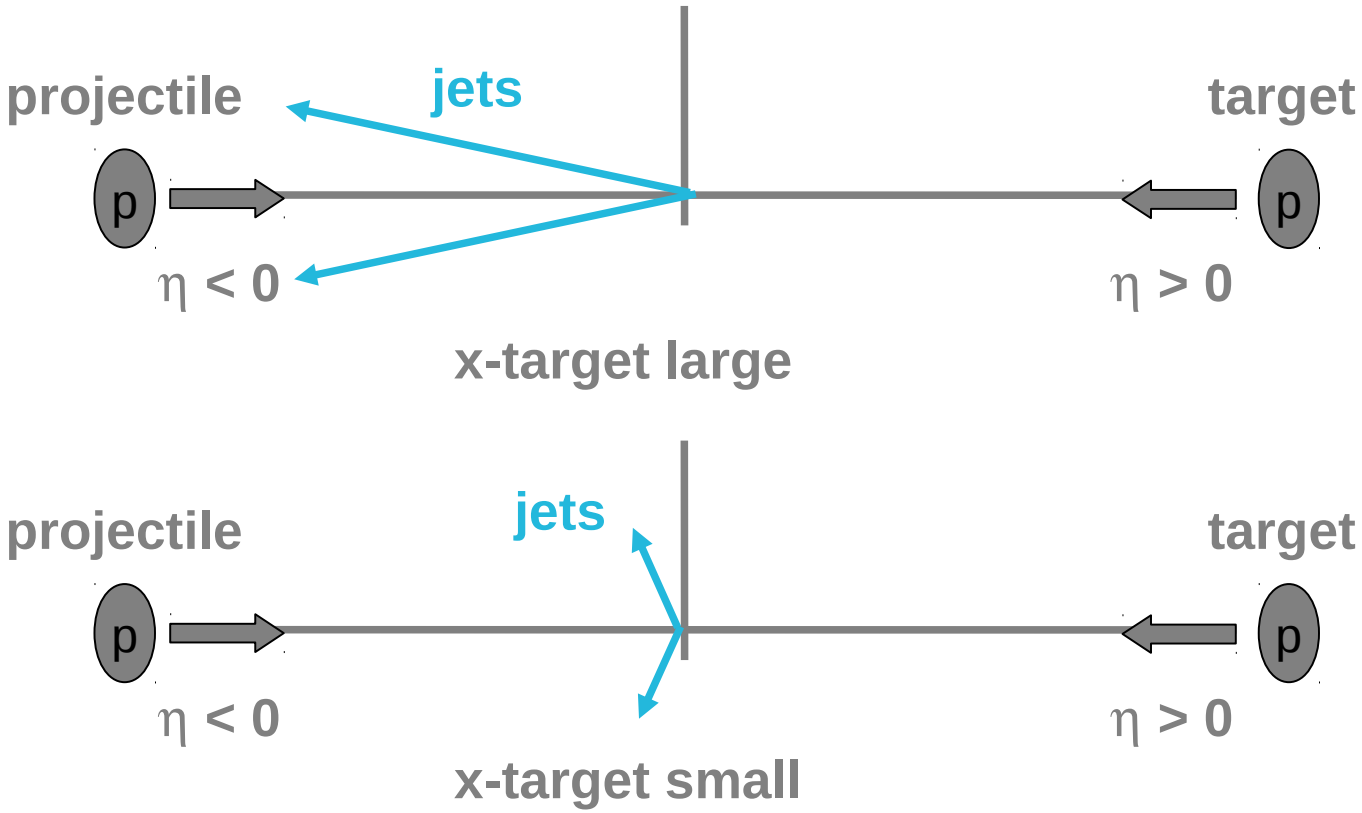
(b) *pp* collision



Correlations between soft and hard production in *pp*

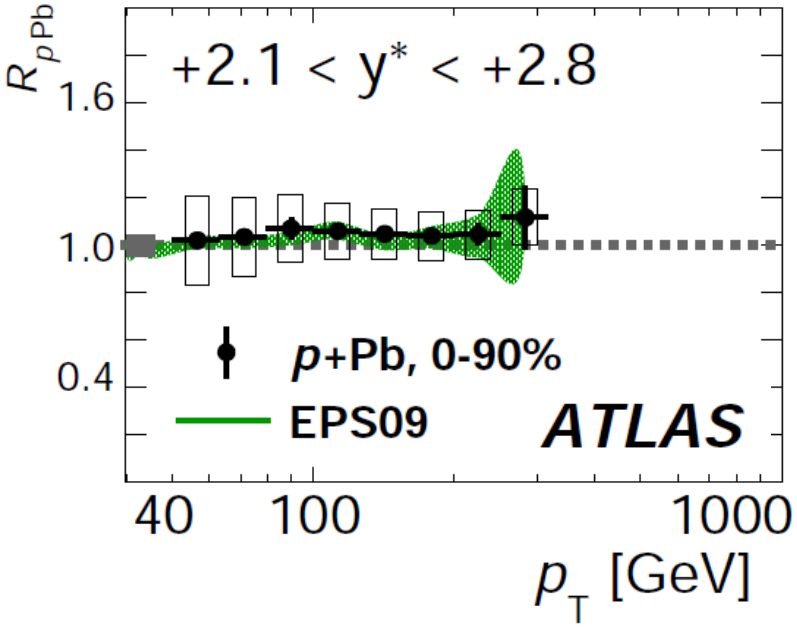
- Anti-correlation can be evaluated also **as a function of x**-projectile and x-target
- Example of configurations:

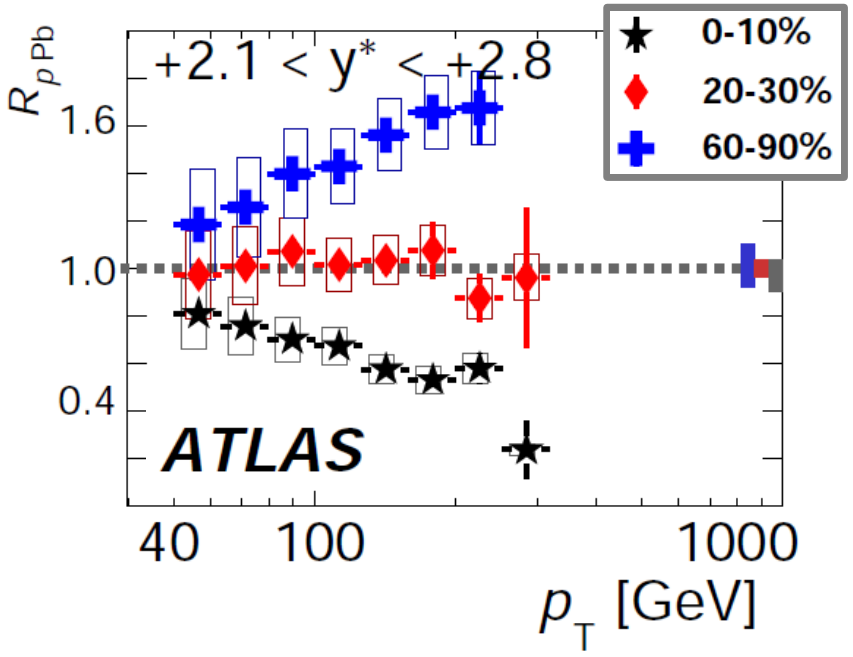
$$x_{\mathrm{proj/trag}} = \frac{p_{\mathrm{T}}^{\mathrm{avg}}}{\sqrt{s}}\left(e^{\pm\eta_1} + e^{\pm\eta_2}\right)$$



Inclusive jets

PLB 748 (2015) 392-413

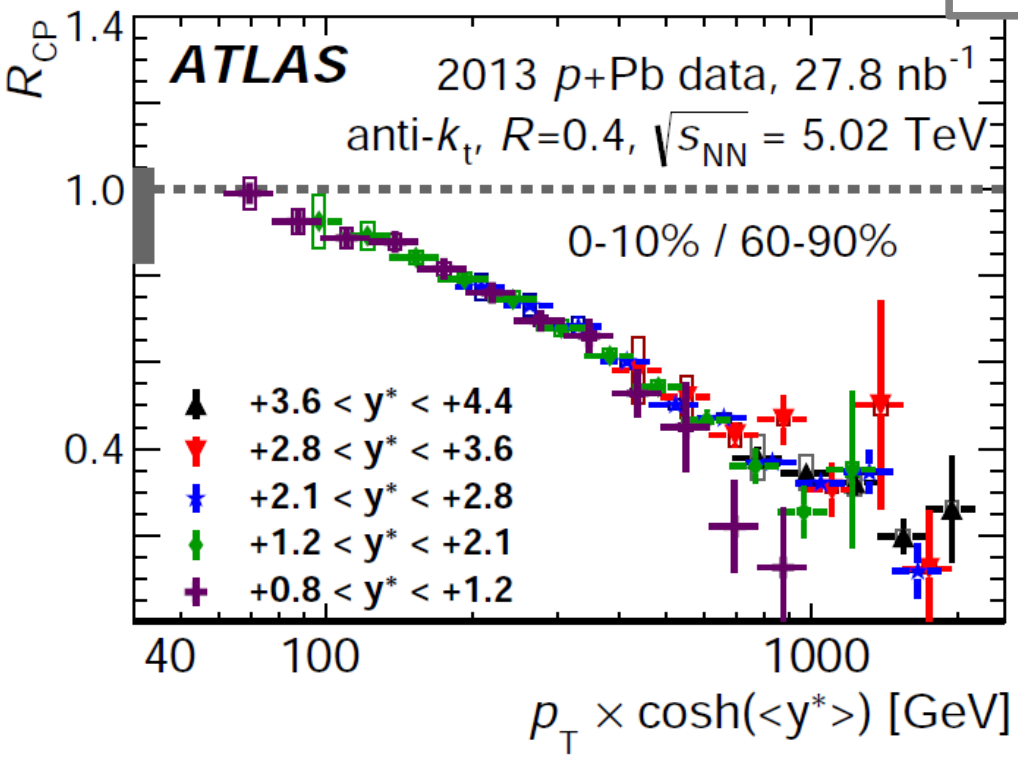




R_{pPb} for jets: While the R_{pPb} is consistent with unity when evaluated inclusively in centrality (left), it is **not unity when evaluated differentially in the centrality** (right).

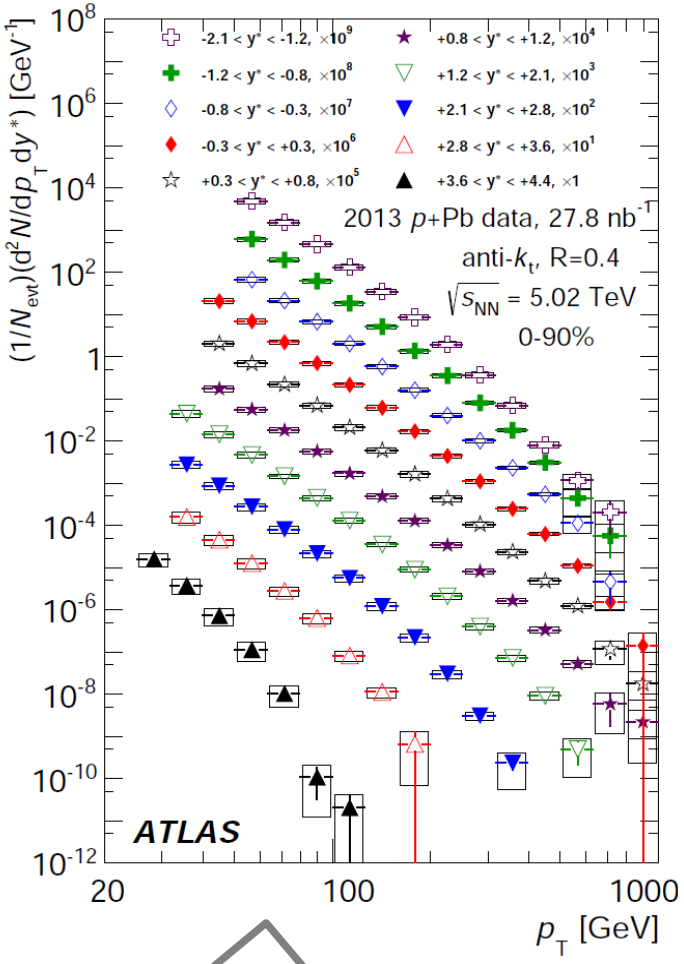
Inclusive jets

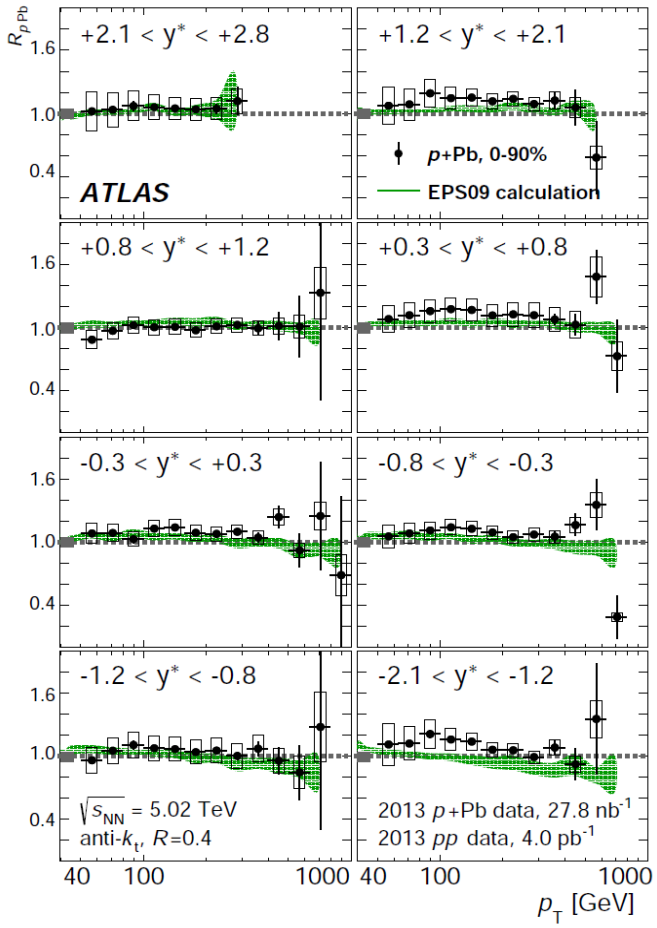
PLB 748 (2015) 392-413



- R_{CP} / R_{pPb} scales with the total momentum of a jet for jets in the positive forward region suggesting a **dependence on *x* of parton in proton**.
- How much of the centrality dependence (= dependence on ΣE_T in the negative forward region) comes from the dependence of ΣE_T on *x* in individual NN collision?

Jet yields and R_{pPb}





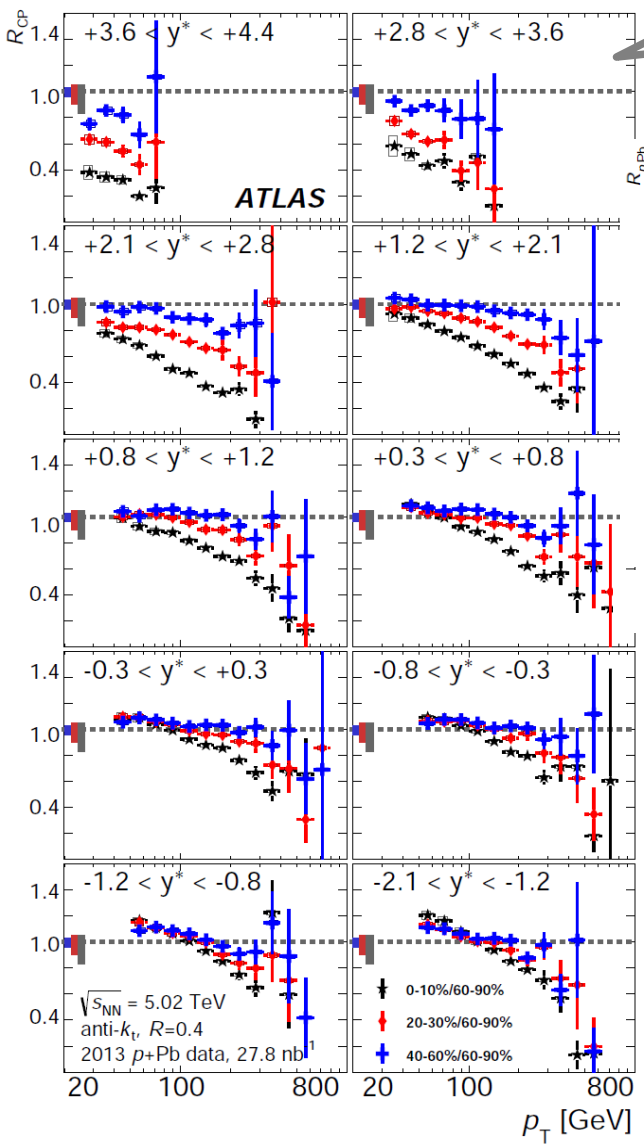
arXiv:1412.4092

- 0-90% R_{pPb} compared to NLO with EPS09 nPDFs
- R_{pPb} does not differ much from unity if measured inclusively in centrality, **but** ...

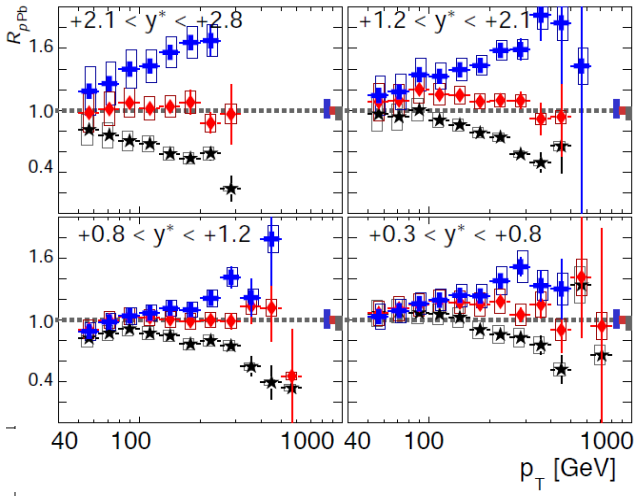
0-90% jet yields

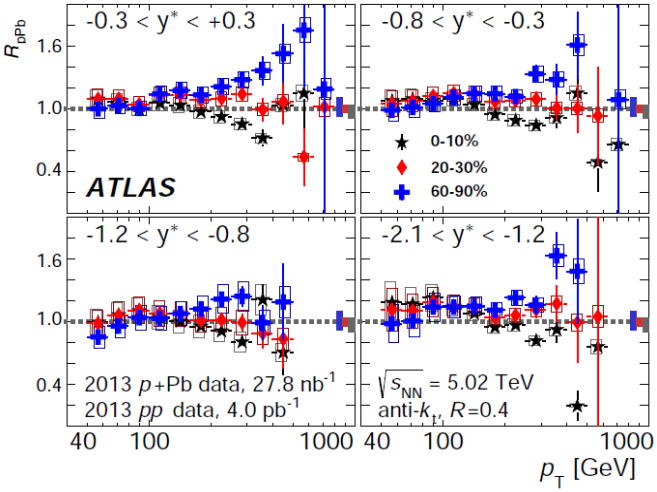
$$R_{\mathrm{pPb}} \equiv \frac{1}{T_{\mathrm{pA}}} \frac{(1/N_{\mathrm{evt}})\ \mathrm{d}^2N_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}dy^*}{\mathrm{d}^2\sigma^{pp}_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}dy^*}$$

Jet R_{pPb} and R_{CP}



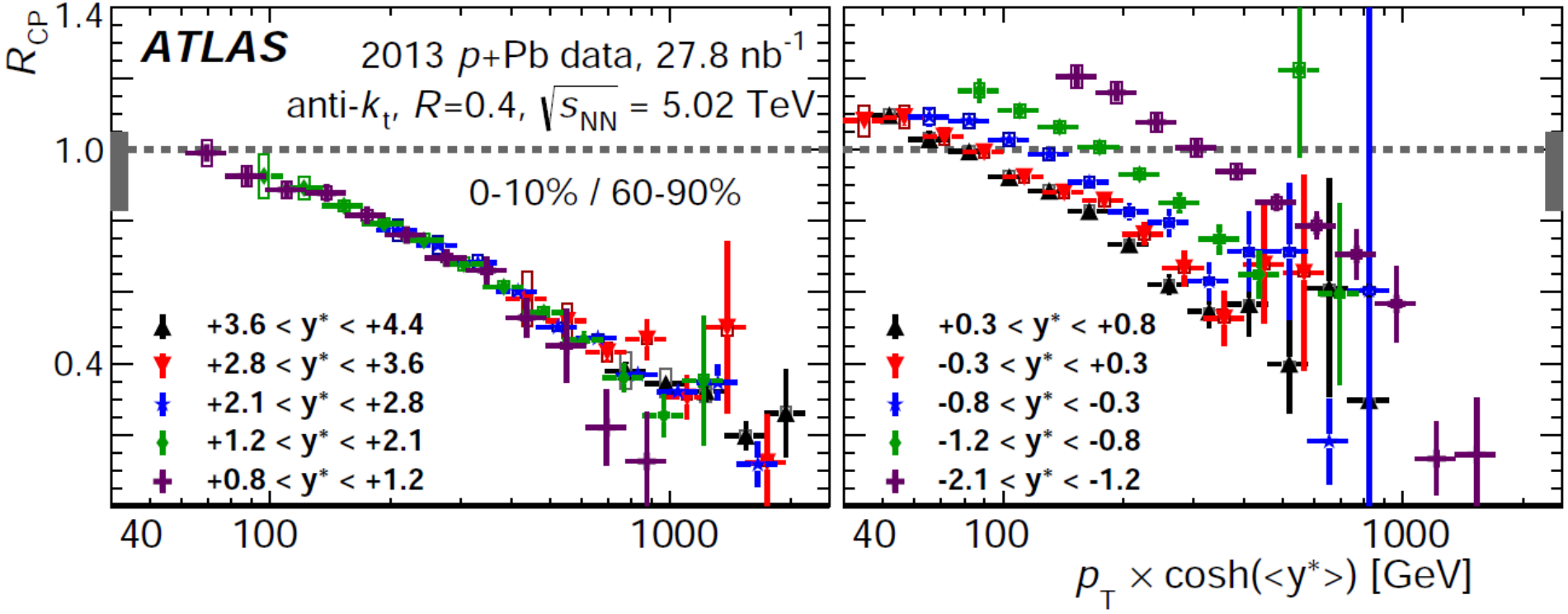
R_{CP} R_{pPb}



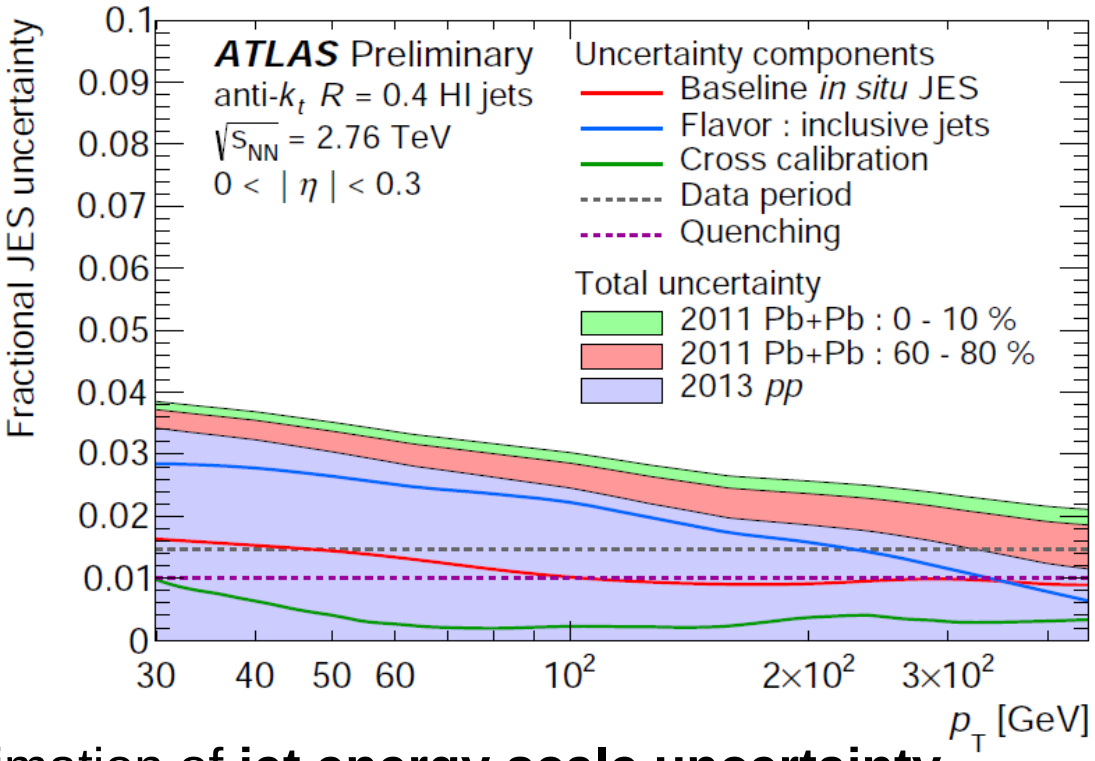


- **R_{CP} strongly varies with centrality** exhibiting decrease with increasing pt in all three centrality bins.
- If R_{pPb} is unity and R_{CP} decreases then there must be **enhancement in peripheral collisions** wrt to pp. Indeed, this is observed.
- The use of Glauber-Gribov only amplifies these effects.

Jet R_{pPb} and R_{CP}

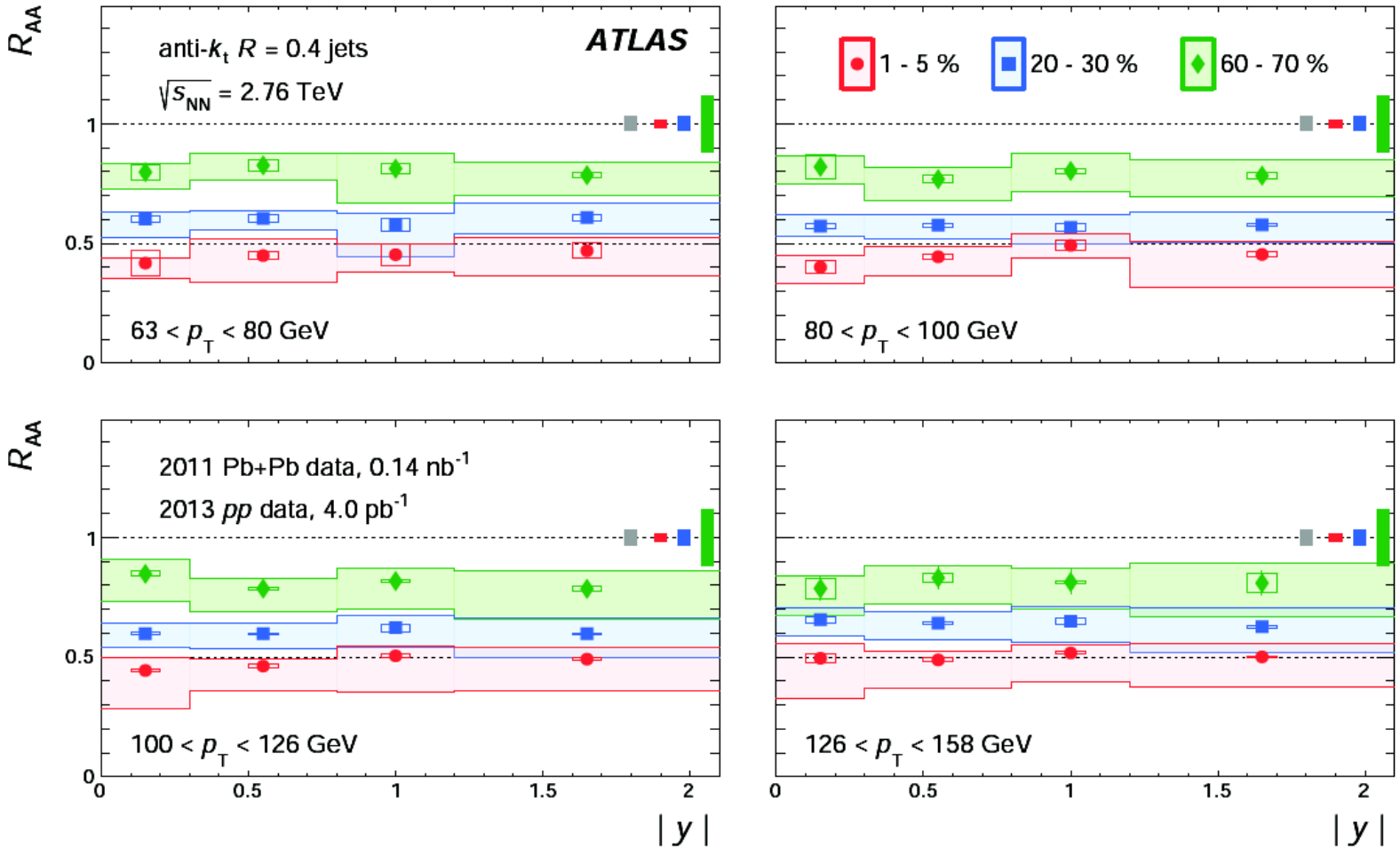


Inclusive jet suppression

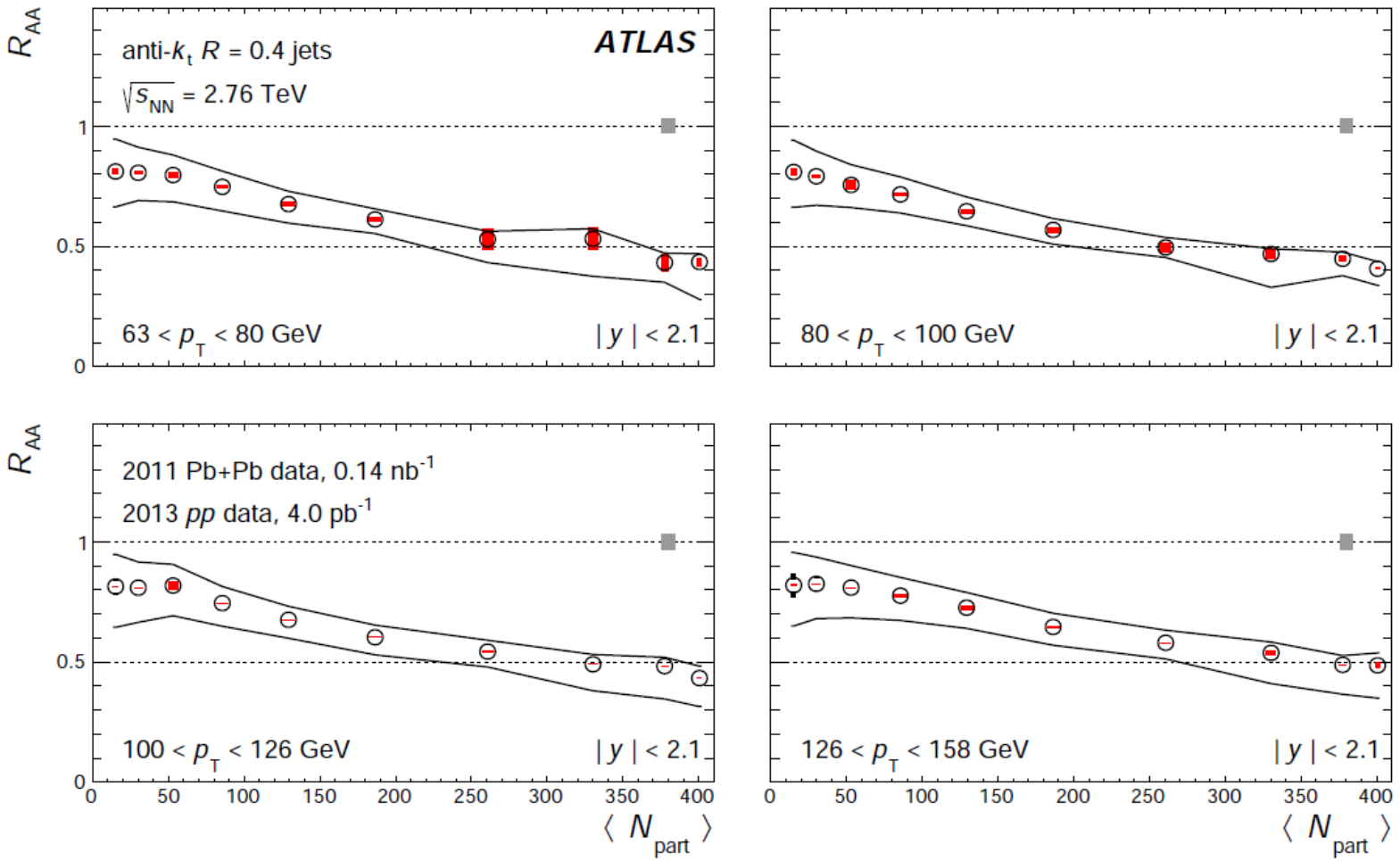


- Detailed estimation of **jet energy scale uncertainty**.
- Using ***in situ*** techniques (γ+jet and Z+jet) and limits on the impact of modified fragmentation on jet energy scale.
- Same level of **rigor as in precision pQCD** measurement should be a standard for precision HI measurements in the run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

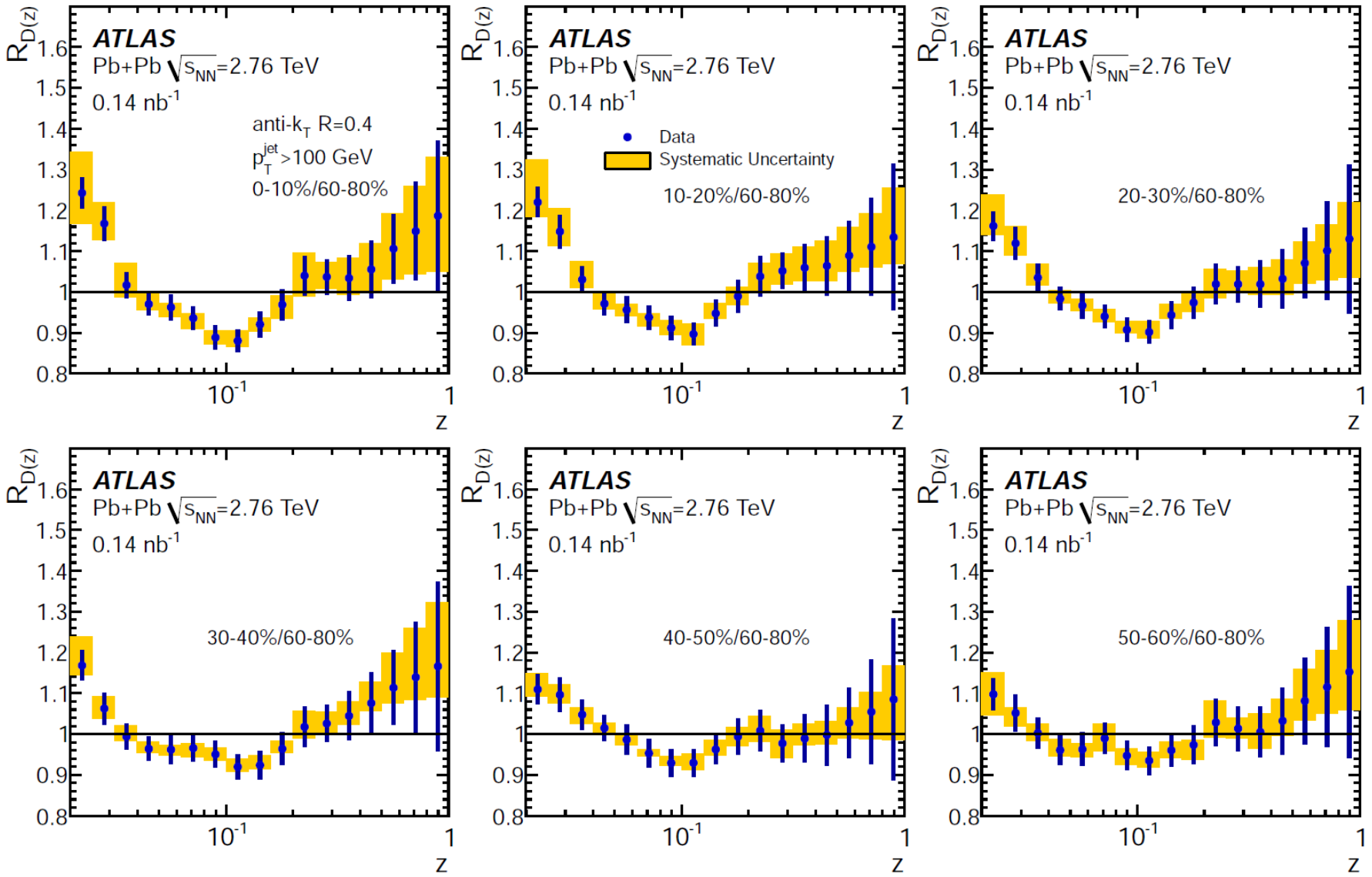
Jet R_{AA}


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 |

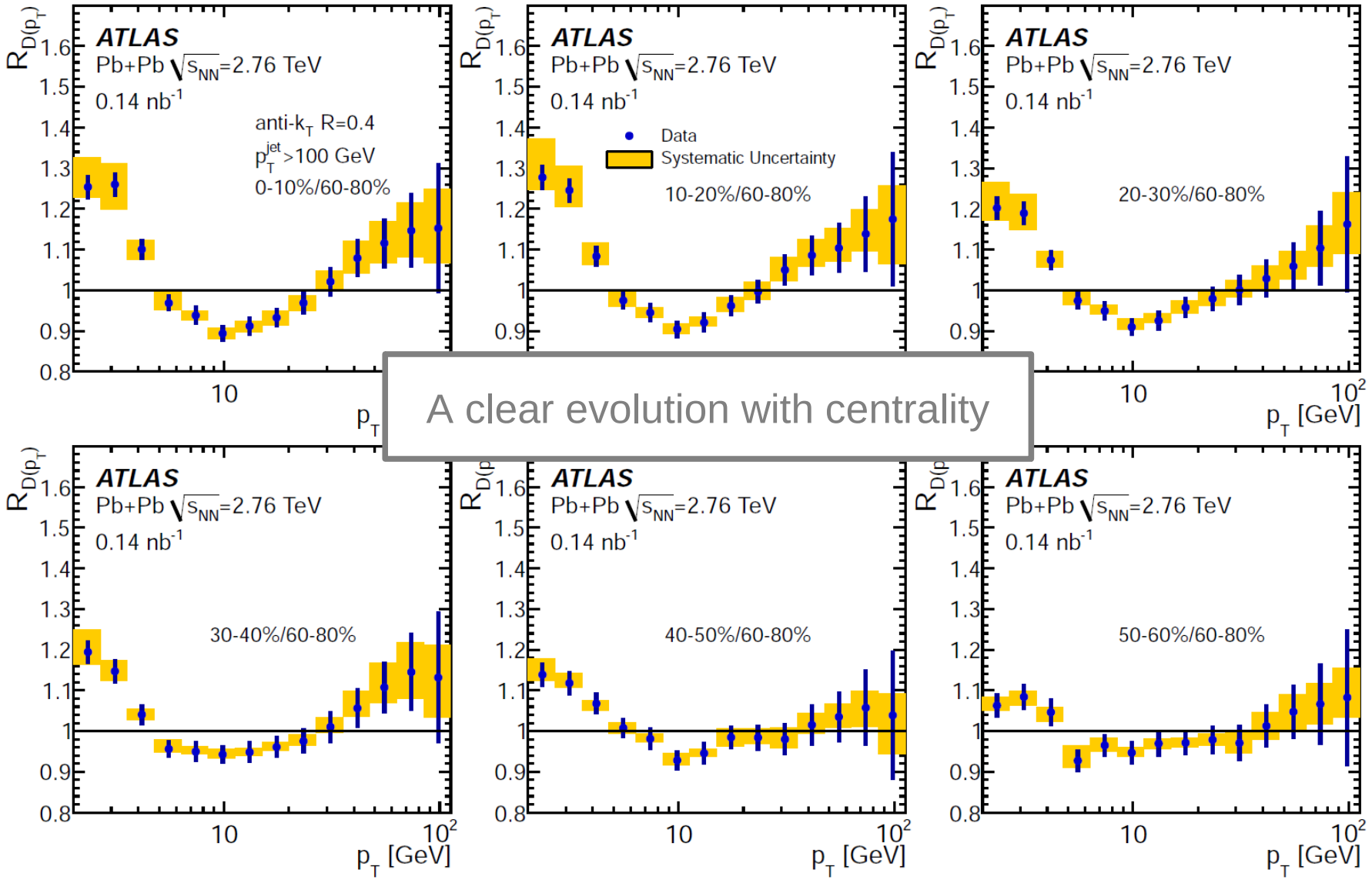
Jet R_{AA}


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} ⟩

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



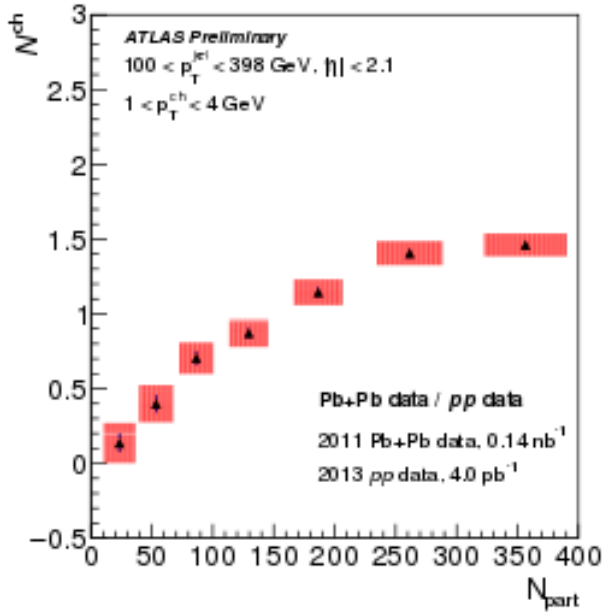
$R_{D(pt)}$ in Pb+Pb for R=0.4 jets

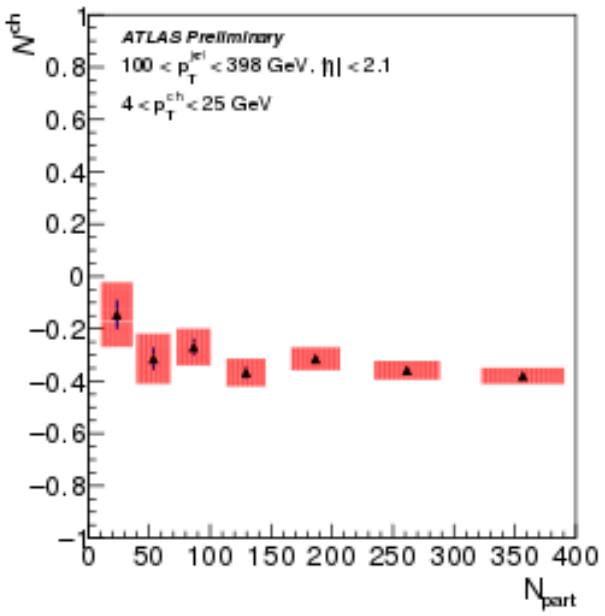


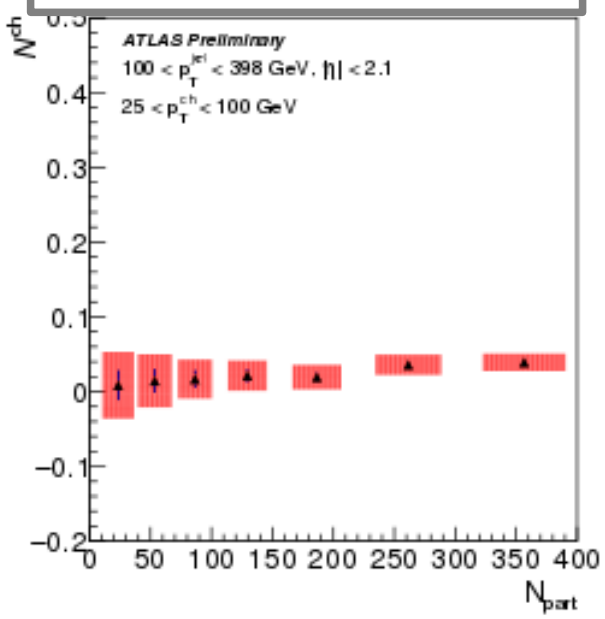
A clear evolution with centrality

Jet fragmentation – flow of particles

EPJC 77 (2017) no.6, 379







- To quantify the flow of particles:

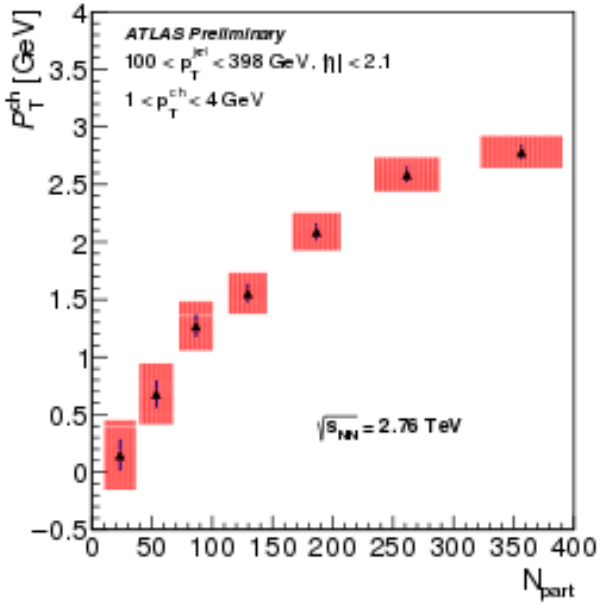
$$N^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) \mathrm{d}p_{\mathrm{T}}$$

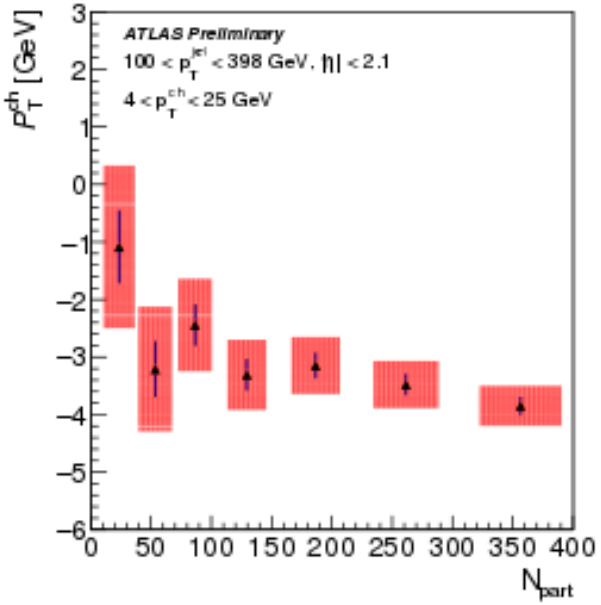
… as a function of N_{part}

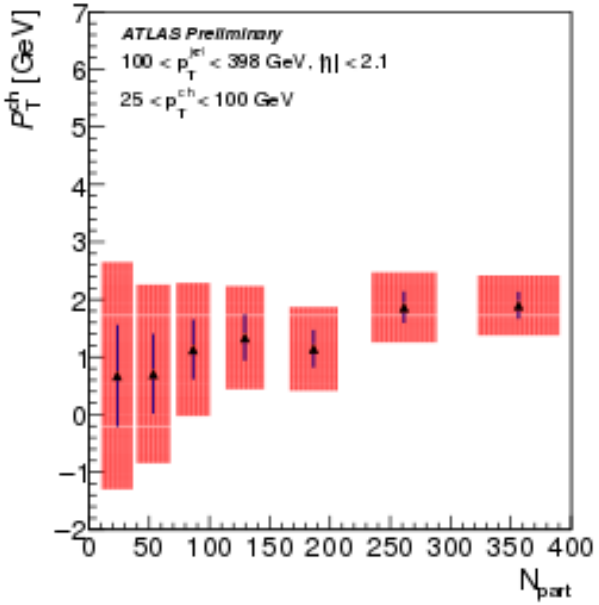
Tells us how many extra/missing particles is present in a given p_T range

Jet fragmentation – flow of energy

EPJC 77 (2017) no.6, 379







- To quantify the flow of momentum:

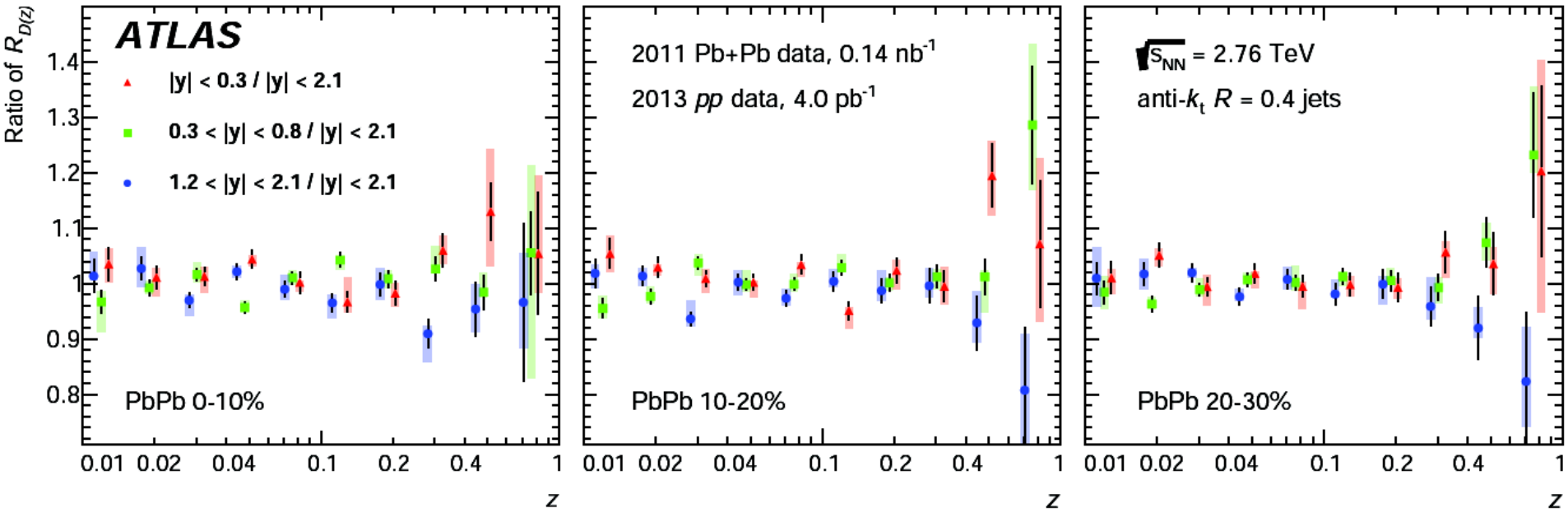
$$P_{\mathrm{T}}^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) p_{\mathrm{T}} \, \mathrm{d}p_{\mathrm{T}}$$

… as a function of N_{part}

Tells us how much p_T is carried by extra/missing particles in a given p_T range

Jet fragmentation at 2.76 TeV

EPJC 77 (2017) no.6, 379

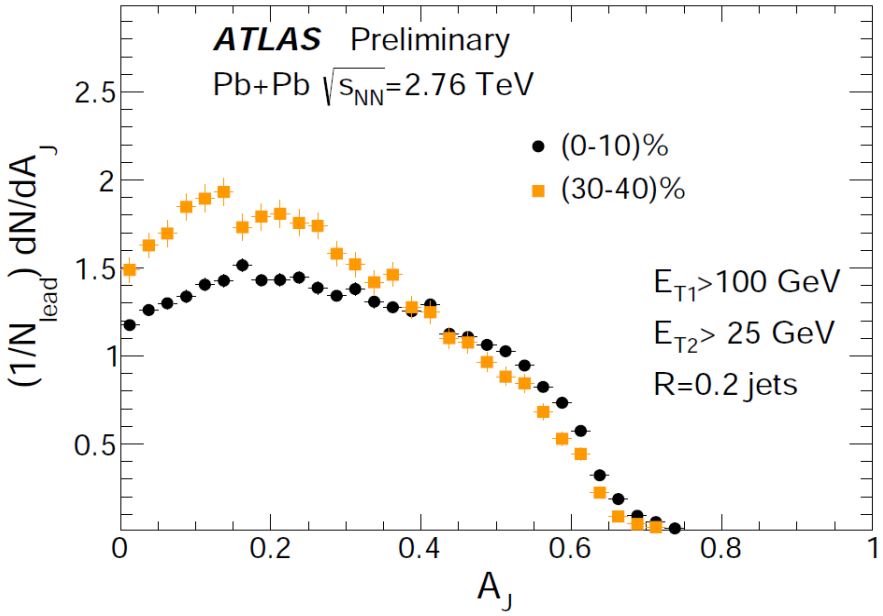


Sign of a larger enhancement at high z in the mid-rapidity region as compared to the forward rapidity region (explanation for this proposed in arXiv:1504.05169).

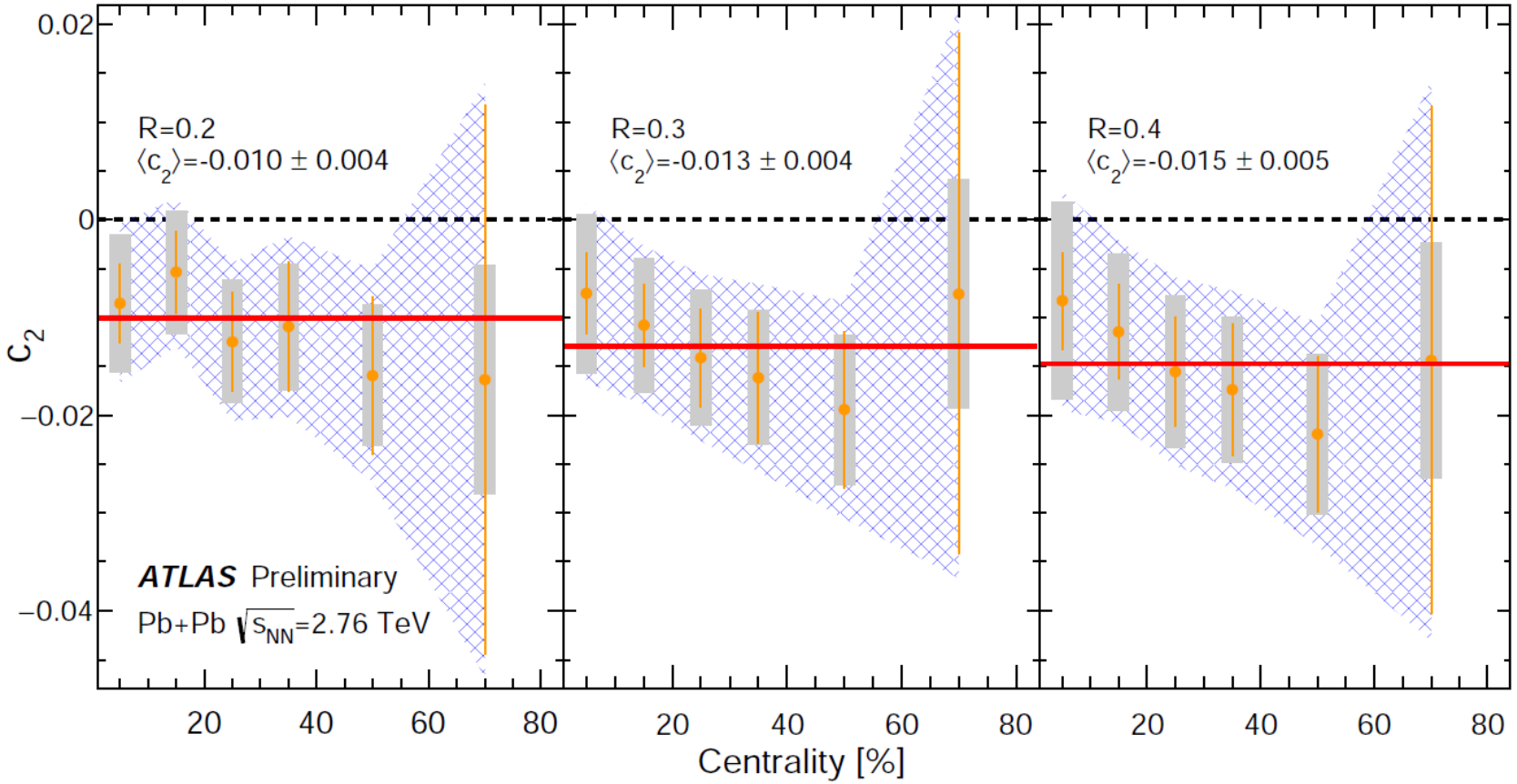
Jet event shape correlations

- Study the dependence of the dijet asymmetry on the **angle between the leading jet and second order event plane =>** help constraining the **path length dependence** of the jet quenching.
- Evaluating second Fourier coefficient of mean A_J:

$$\langle A_J \rangle(\phi^{\mathrm{Lead}} - \Psi_2) = A_J^0 \left(1 + 2c_2^{\mathrm{obs}} \cos(2 \times |\phi^{\mathrm{Lead}} - \Psi_2|)\right)$$



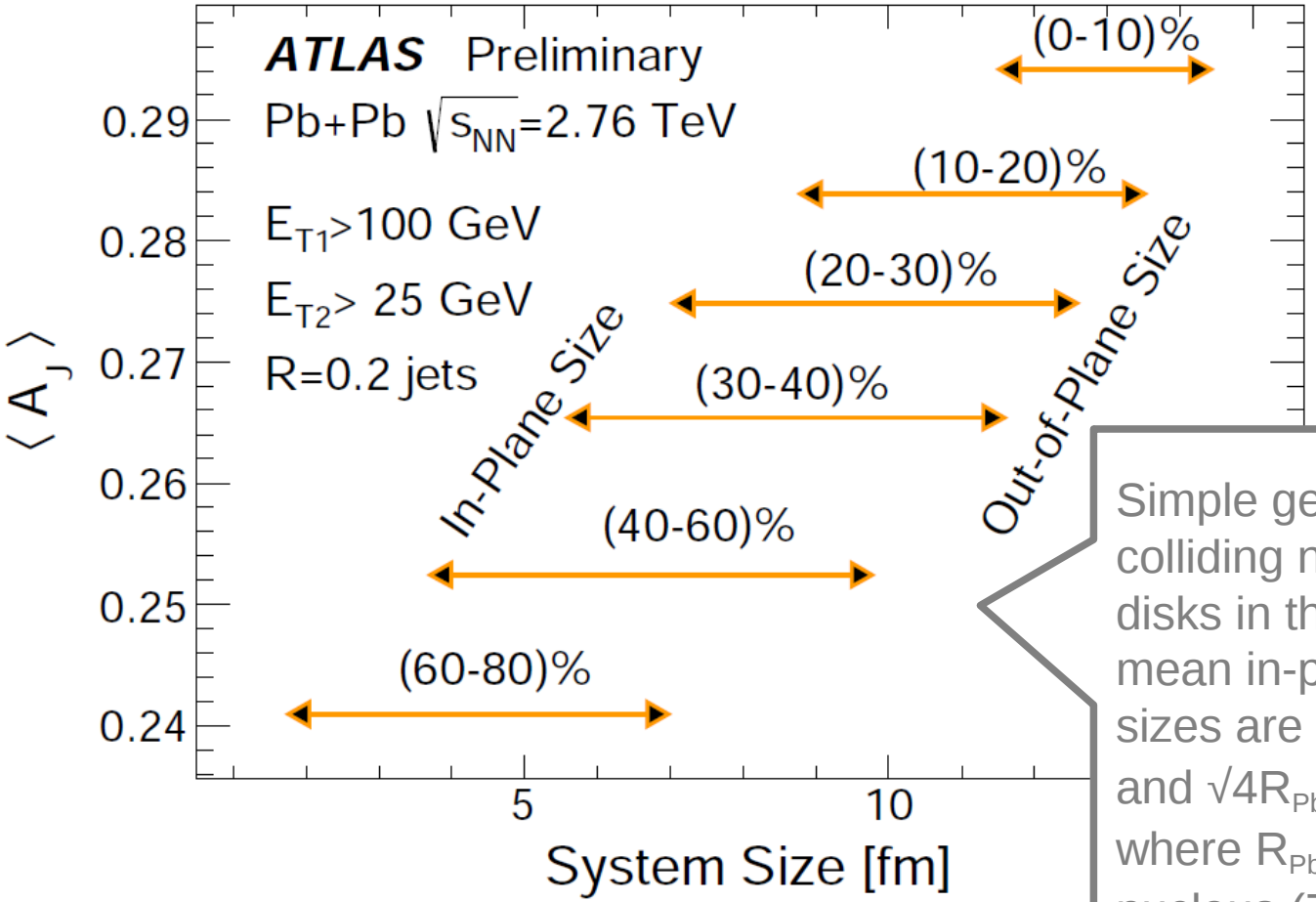
Jet event shape correlations



$$c_2 = \frac{c_2^{\text{obs}}}{\text{Res}\{2\Psi_2\}}$$

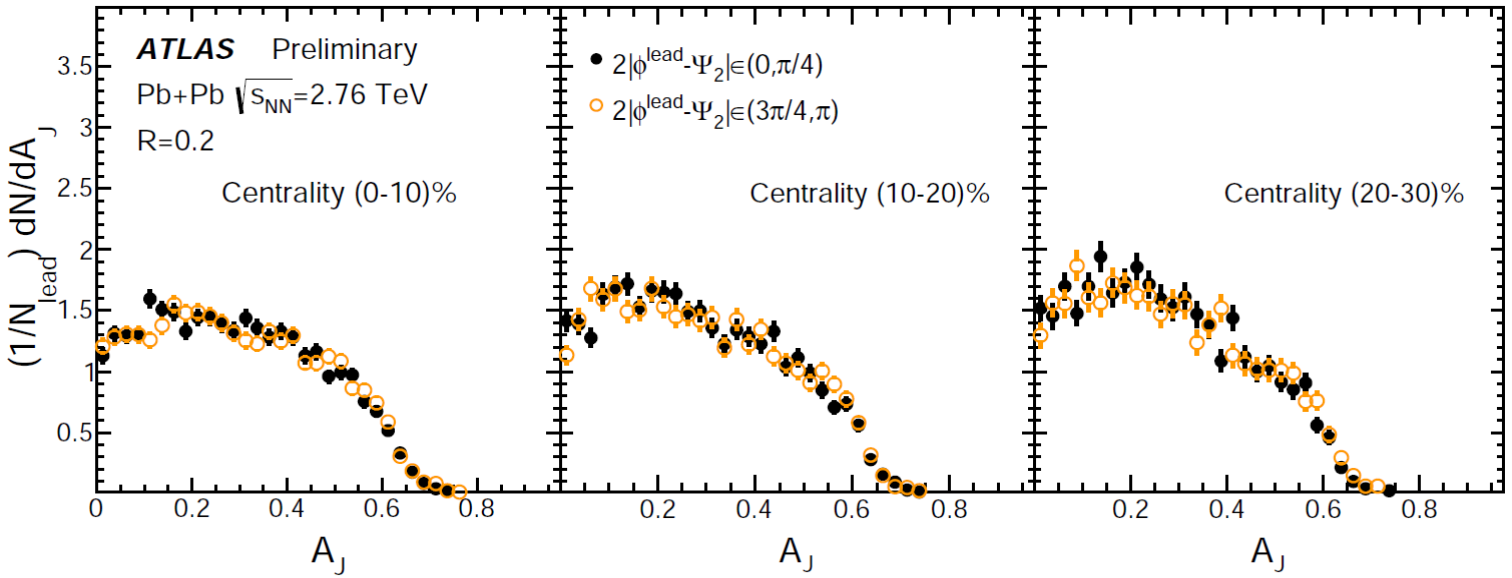
c_2 small (<2%), negative indicating slightly larger A_J for leading jets oriented out-of-plane than for jets oriented in-plane.

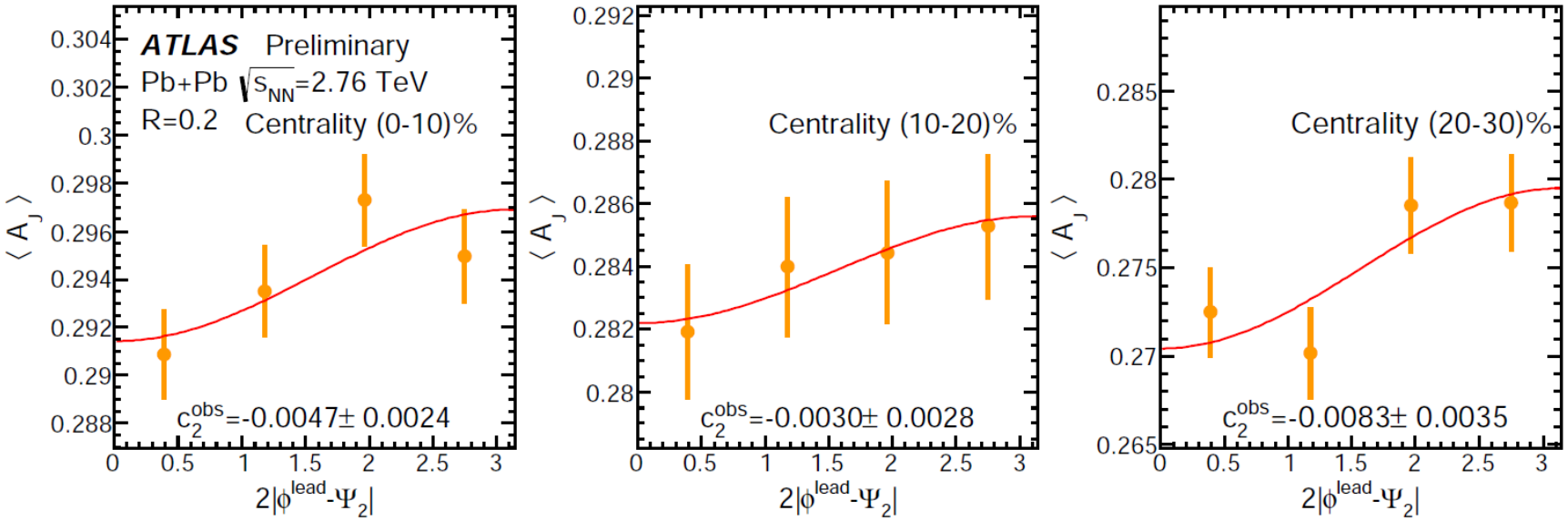
Jet and event shape correlations, system size from a simple model



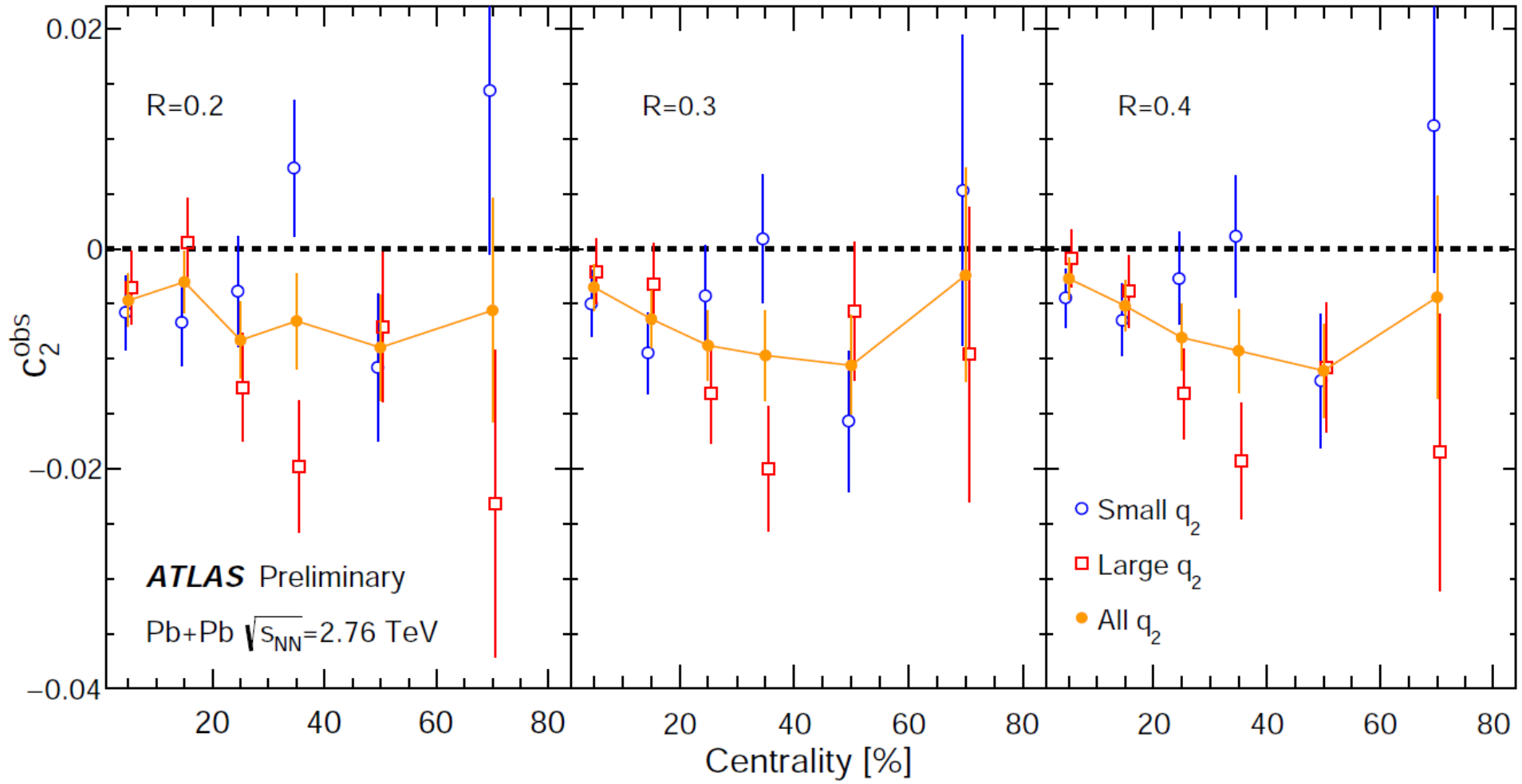
Simple geometric picture: The colliding nucleons are treated as disks in the transverse plane. The mean in-plane and out-of plane sizes are obtained as $2R_{Pb}$-$\langle b_{imp} \rangle$ and $\sqrt{4R_{Pb}^2 - \langle b_{imp} \rangle^2}$ respectively, where R_{Pb} is the radius of the Pb nucleus (7.4 fm) and $\langle b_{imp} \rangle$ is the mean impact parameter for the given centrality interval.

Jet and event shape correlations





Jet and event shape correlations, c_2 differentially in q_2



Neighboring jet production

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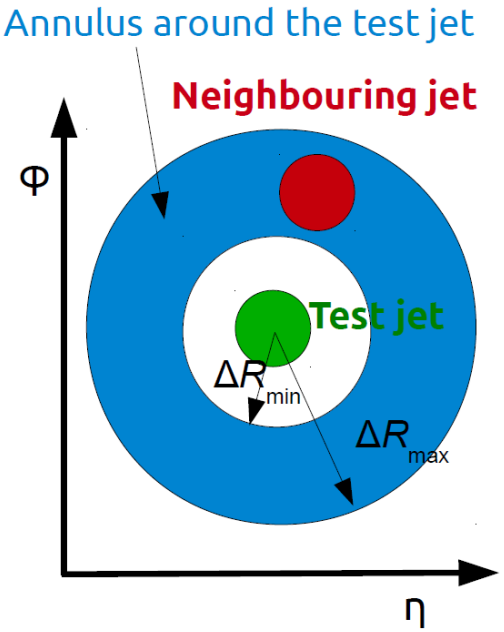
- Neighboring jet production quantified using quantity previously measured at Tevatron

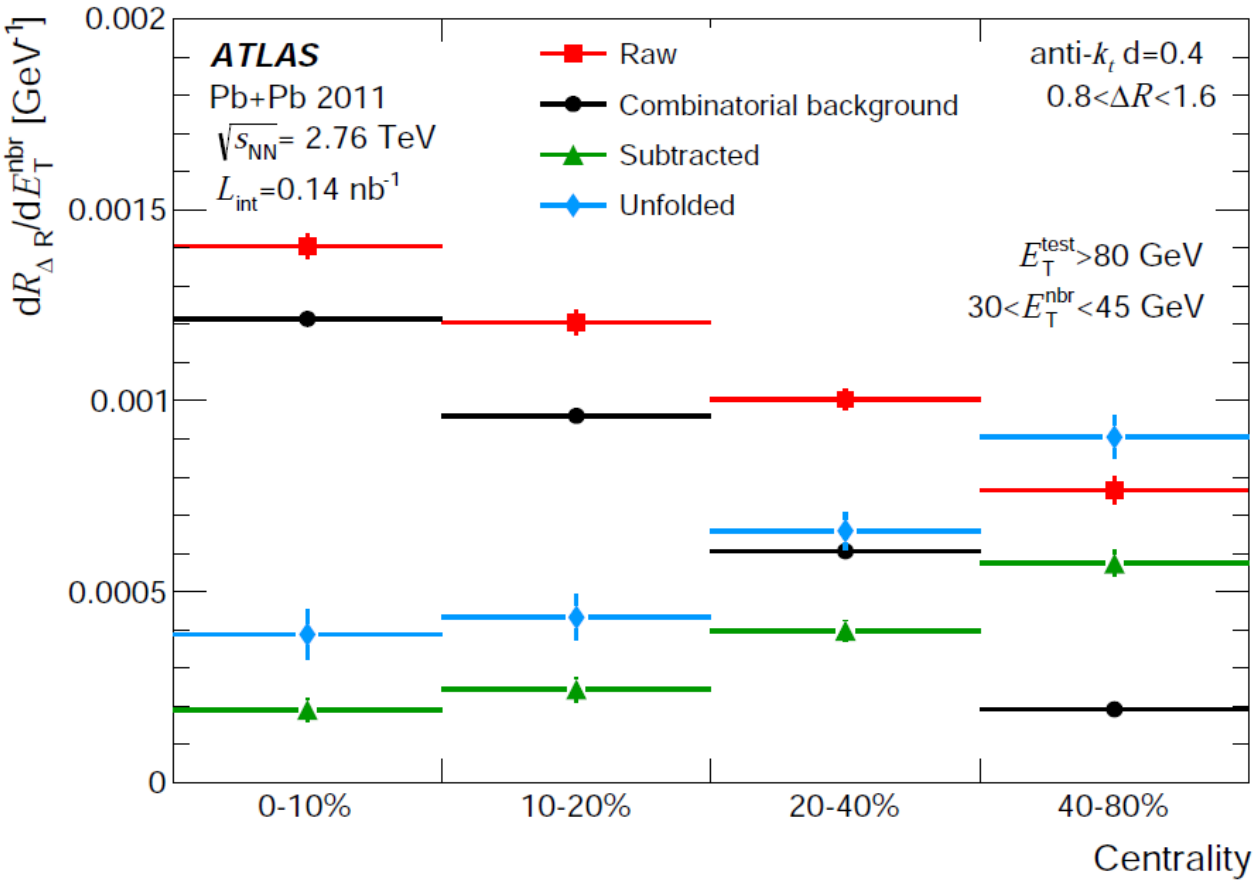
$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}},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



… the rate of **neighboring jets that accompany** a given **test jet**.

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

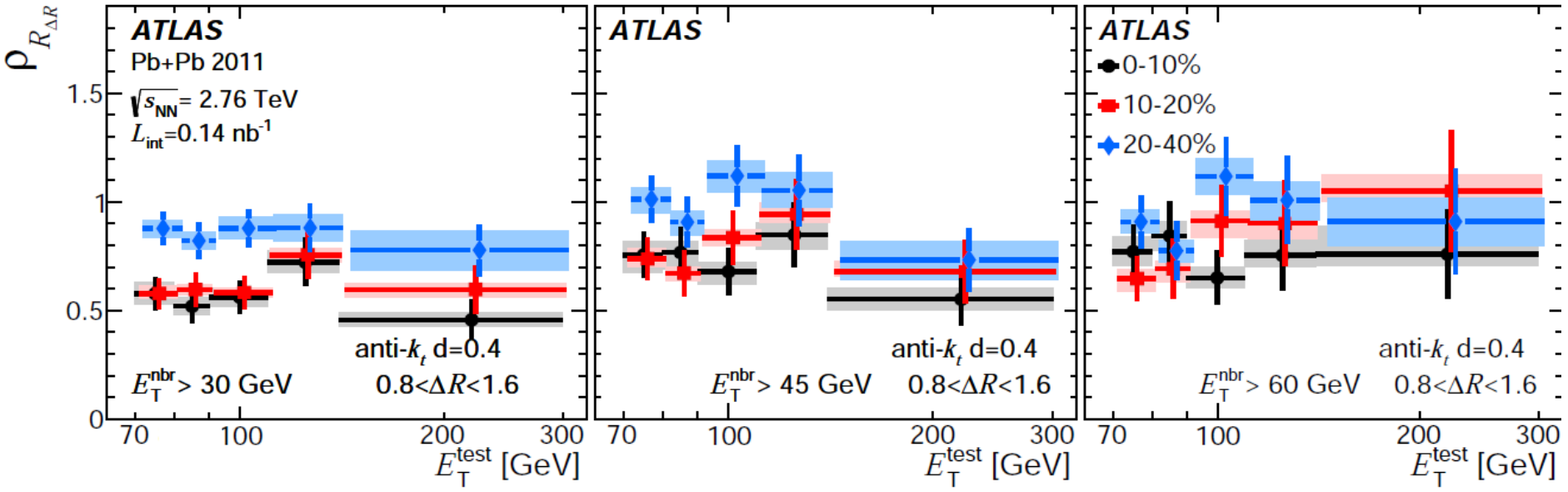
Correction flow for neighboring jet yields



Example of the correction flow for the most "difficult" case of lowest E_T bins

Unfolded = *k* * (Raw – Combinatorics)

Central-to-peripheral ratios



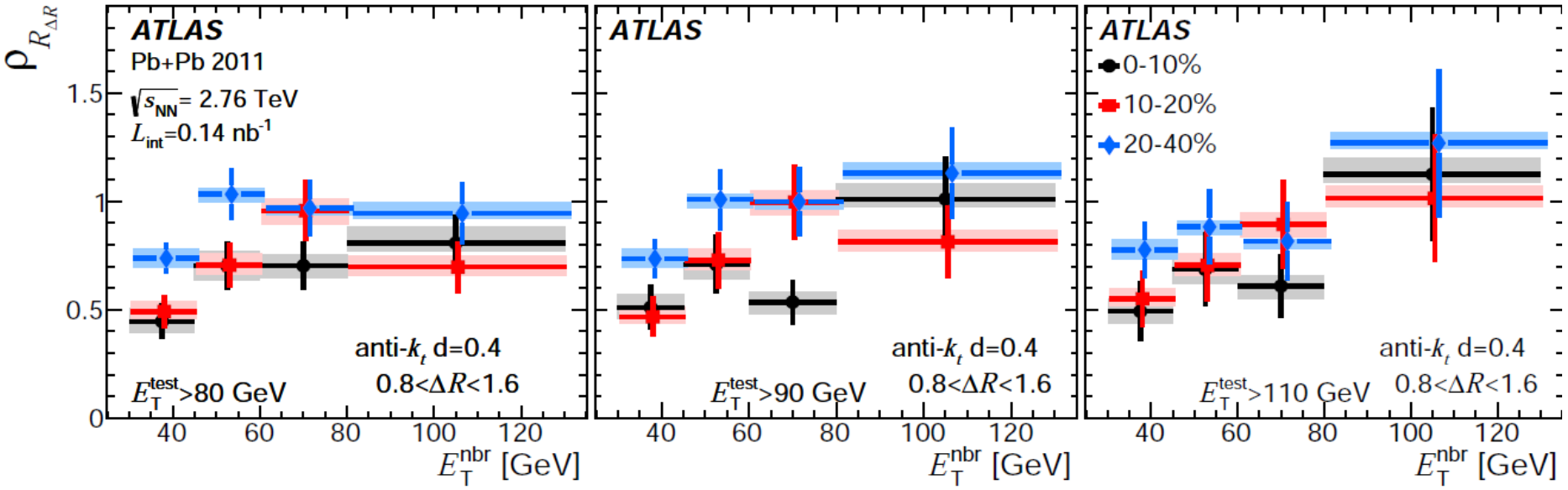
Central to peripheral ratio of $R_{\Delta R}$ as a function of test jet E_T.

–> suppression factor of about 0.5

–> suppression rather flat with E_T

} similar trends as in the inclusive jet R_{CP}

Central-to-peripheral ratios



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

Decrease of suppression with increasing jet E_T … may be expected for the configuration of magnitude of neighboring jet E_T approaching the magnitude of test jet E_T (the per-test jet normalization in the $R_{\Delta R}$ effectively removes the suppression).