

Jets and charged particles in p+Pb and Pb+Pb collisions with the ATLAS Experiment

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on behalf of the ATLAS Collaboration

Charles University
in Prague

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Introduction

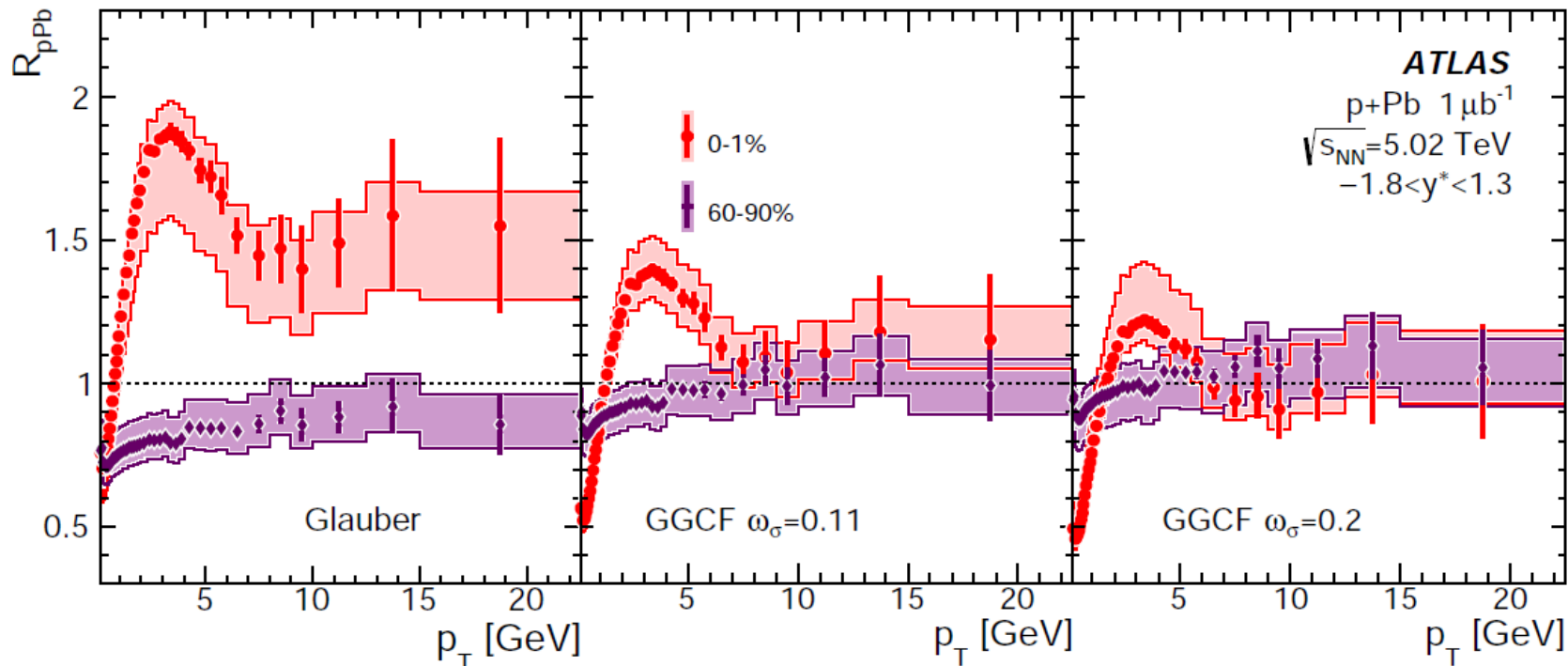
- Jet production and properties are modified in heavy ion collisions
- Study of **jets in Pb+Pb** collisions should tell us about e.g.:
 - properties of de-confined matter created in heavy ion collisions
 - radiation of energetic color charges in this de-confined medium
- Study of **jets in p+Pb** collisions should tell us about e.g.:
 - initial state effects
 - correlations between soft and hard processes
- LHC **heavy ion runs** & ATLAS:
 - Run 1: Pb+Pb: $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, $L_{int} = 0.15 \text{ nb}^{-1}$
 pp : $\sqrt{s} = 2.76 \text{ TeV}$, $L_{int} = 4.2 \text{ pb}^{-1}$
 p +Pb: $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $L_{int} = 29 \text{ nb}^{-1}$
 - Run 2: Pb+Pb: $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $L_{int} = 0.5 \text{ nb}^{-1}$
 pp : $\sqrt{s} = 5.02 \text{ TeV}$, $L_{int} = 28 \text{ nb}^{-1}$

Physics of p +Pb collisions

Inclusive charged particles

arXiv:1605.06436

$$R_{pPb}(p_T, y^*) = \frac{1}{\langle T_{Pb} \rangle} \frac{1/N_{evt} d^2 N_{pPb}/dy^* dp_T}{d^2 \sigma_{pp}/dy^* dp_T}$$

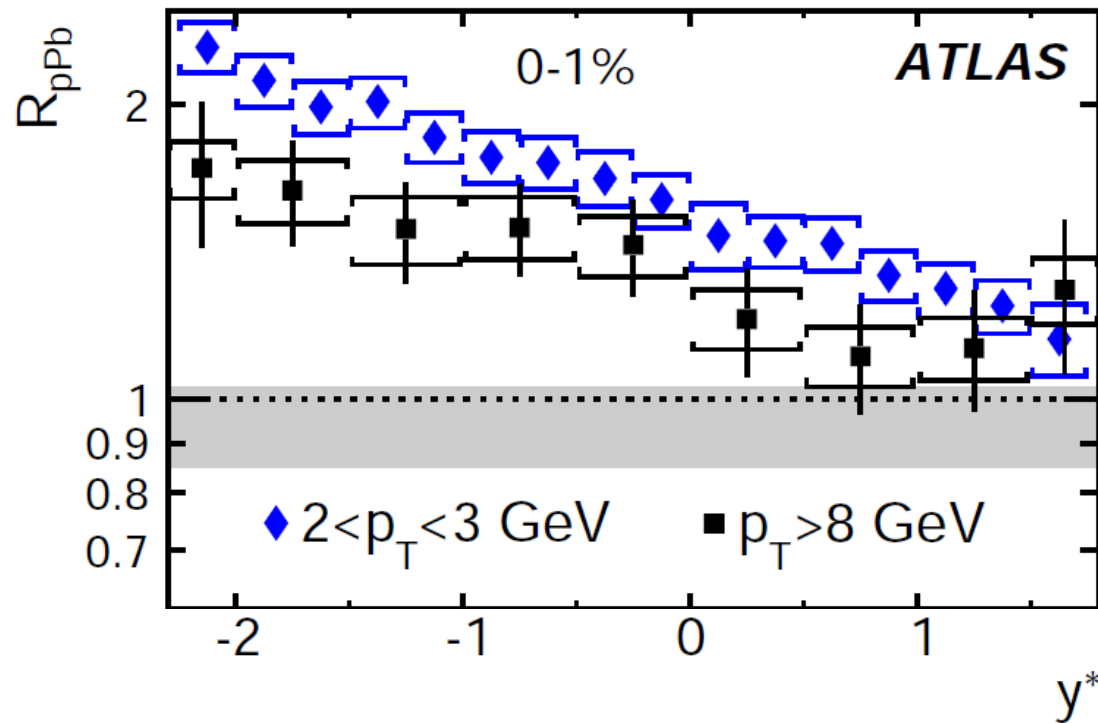


- Clear Cronin peak in central collisions
- Magnitude of R_{pPb} strongly **depends on** the choice of the **Glauber model**

Inclusive charged particles

arXiv:1605.06436

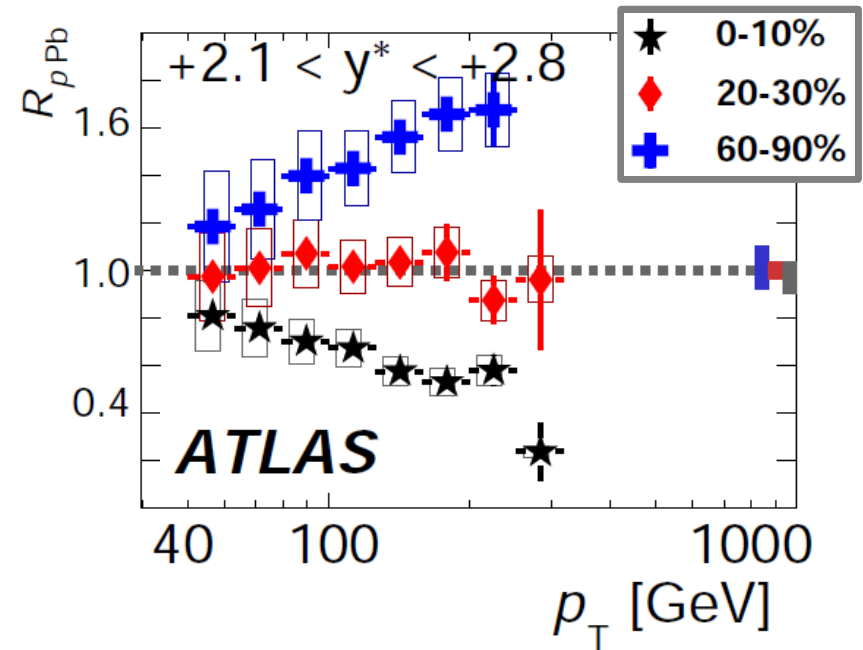
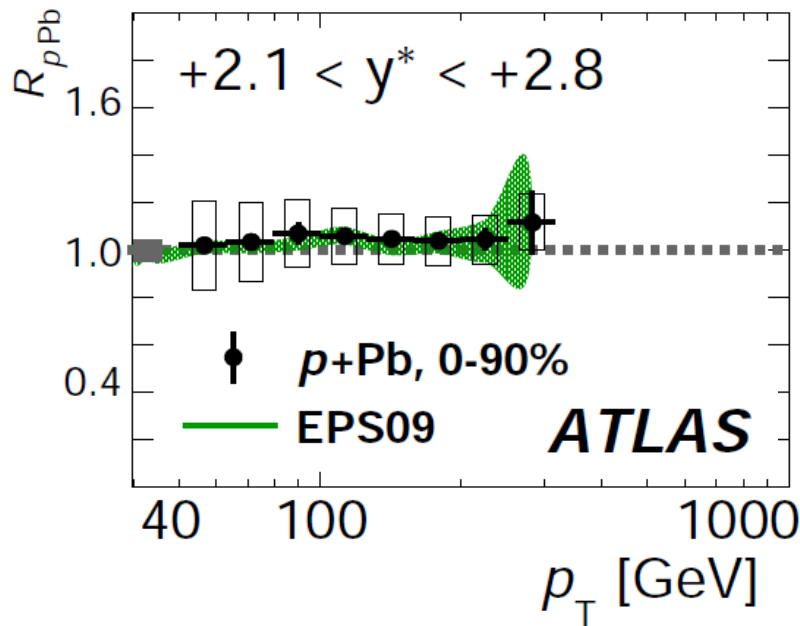
$$R_{pPb}(p_T, y^*) = \frac{1}{\langle T_{Pb} \rangle} \frac{1/N_{evt} d^2 N_{pPb}/dy^* dp_T}{d^2 \sigma_{pp}/dy^* dp_T}$$



- Magnitude of R_{pPb} **increases with y^*** towards Pb-going direction (both in **peaking region** and **plateau region**)

Inclusive jets

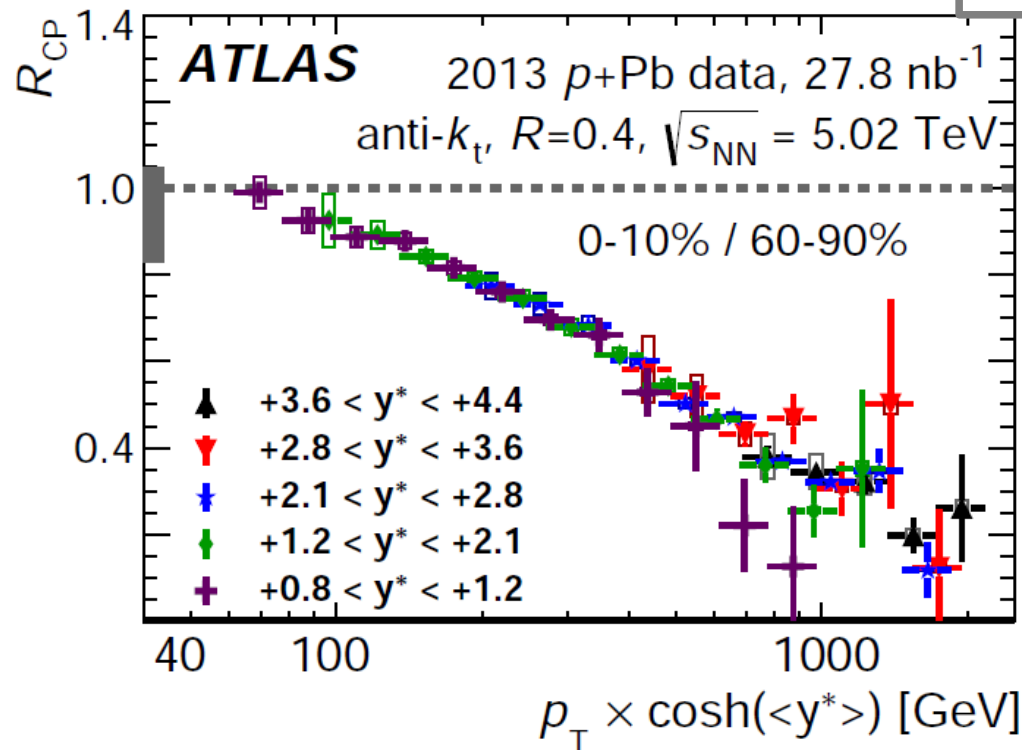
PLB 748 (2015) 392-413



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?

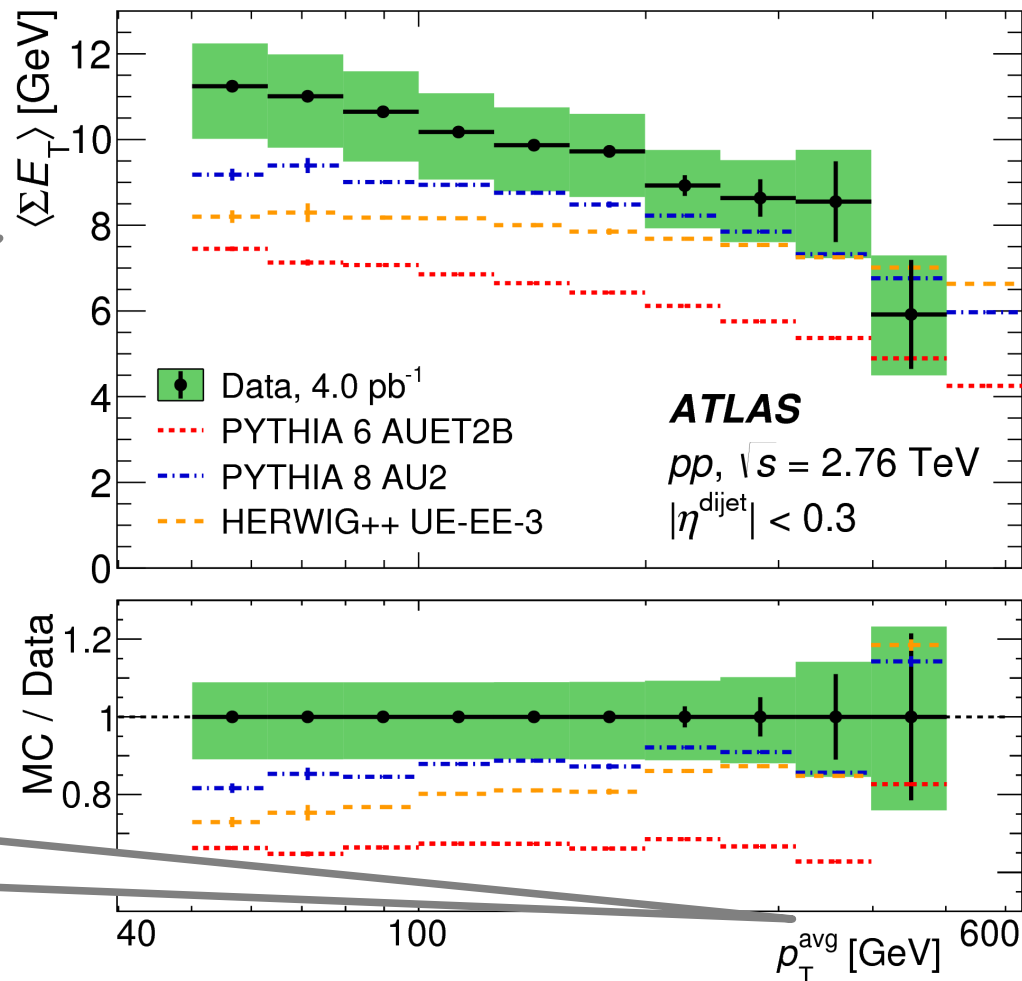
Correlations between soft and hard production in pp

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

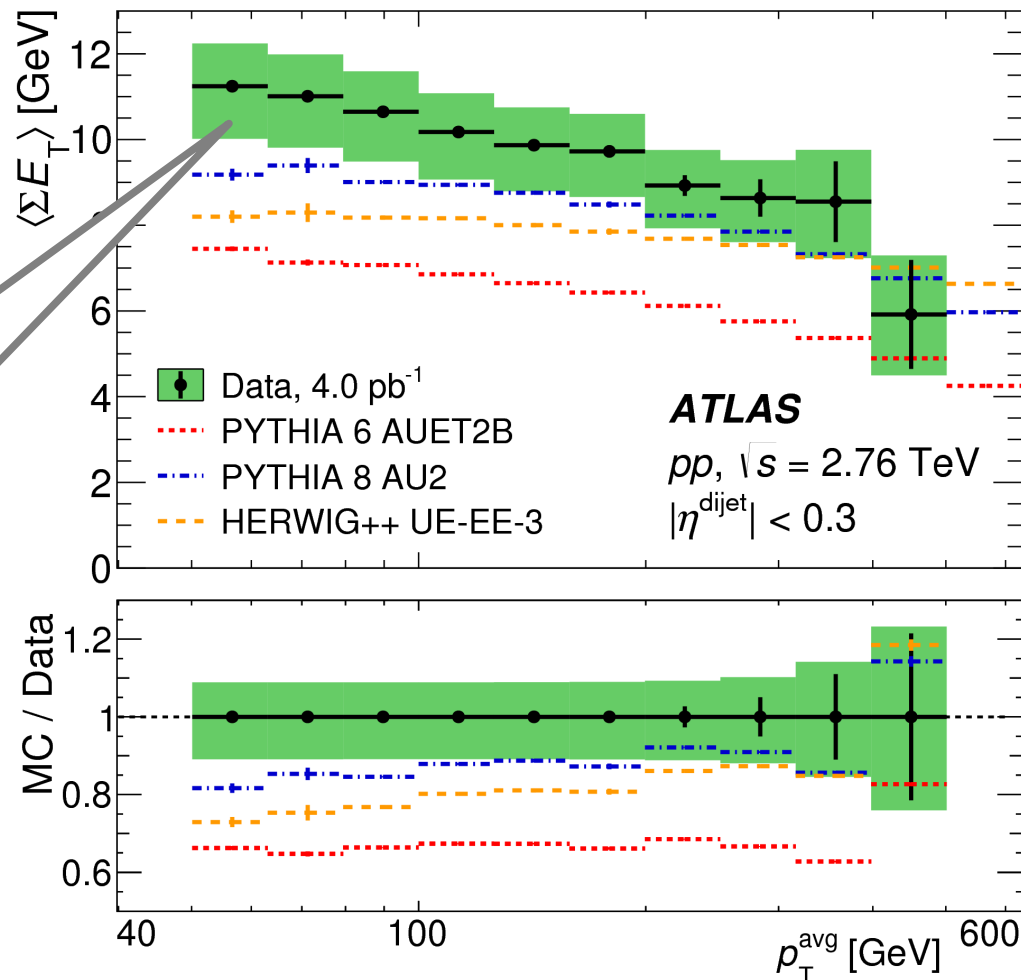


Correlations between soft and hard production in pp

PLB 756 (2016) 10-28

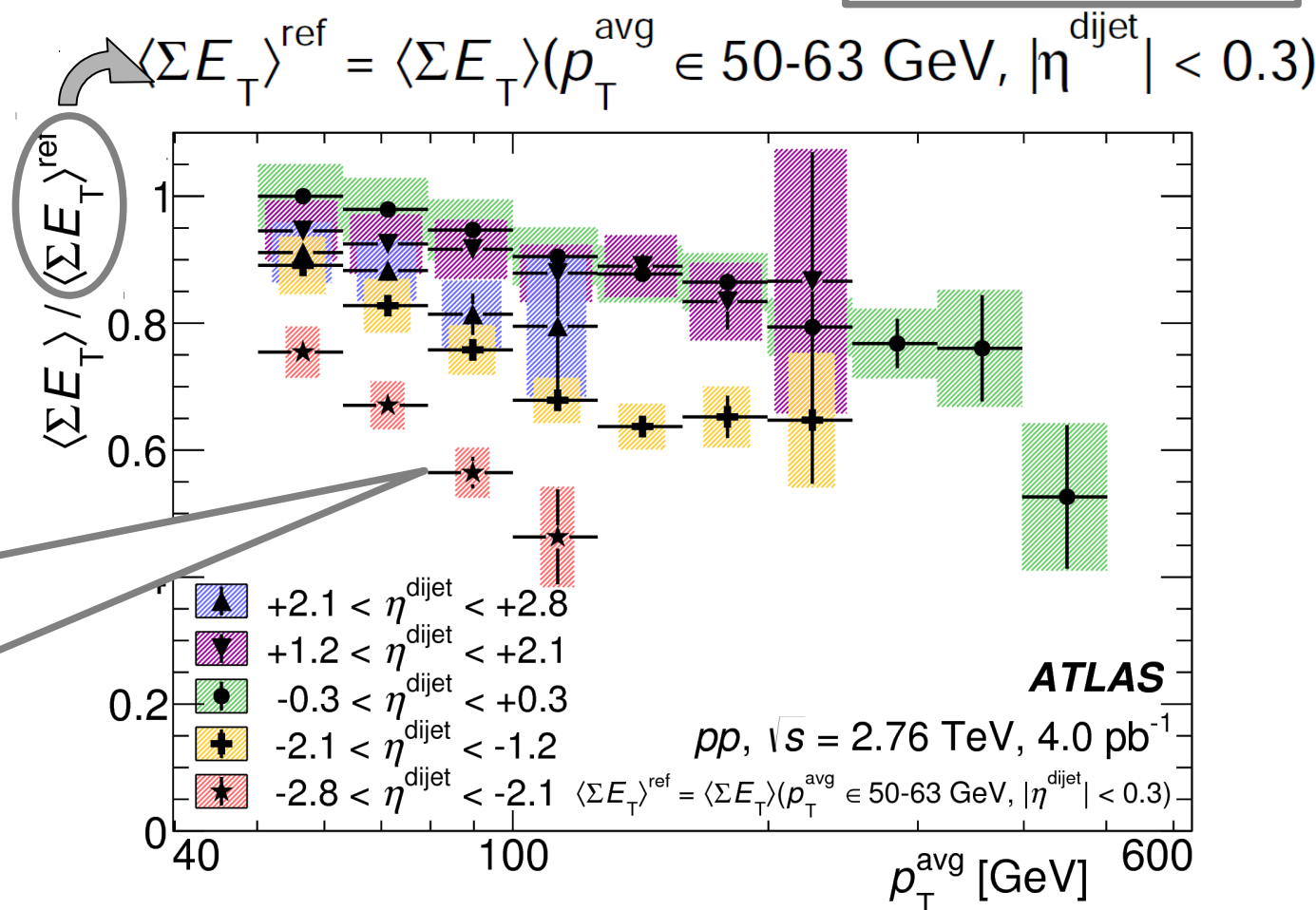
- **What is measured:** correlation between the dijet kinematics and the magnitude of the UE in the forward region in pp collisions
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Anti-correlation between
“soft production”
and “hard production”



Correlations between soft and hard production in pp

PLB 756 (2016) 10-28



Anti-correlation is **stronger** when η_{dijet} approaches the ΣE_T measuring region

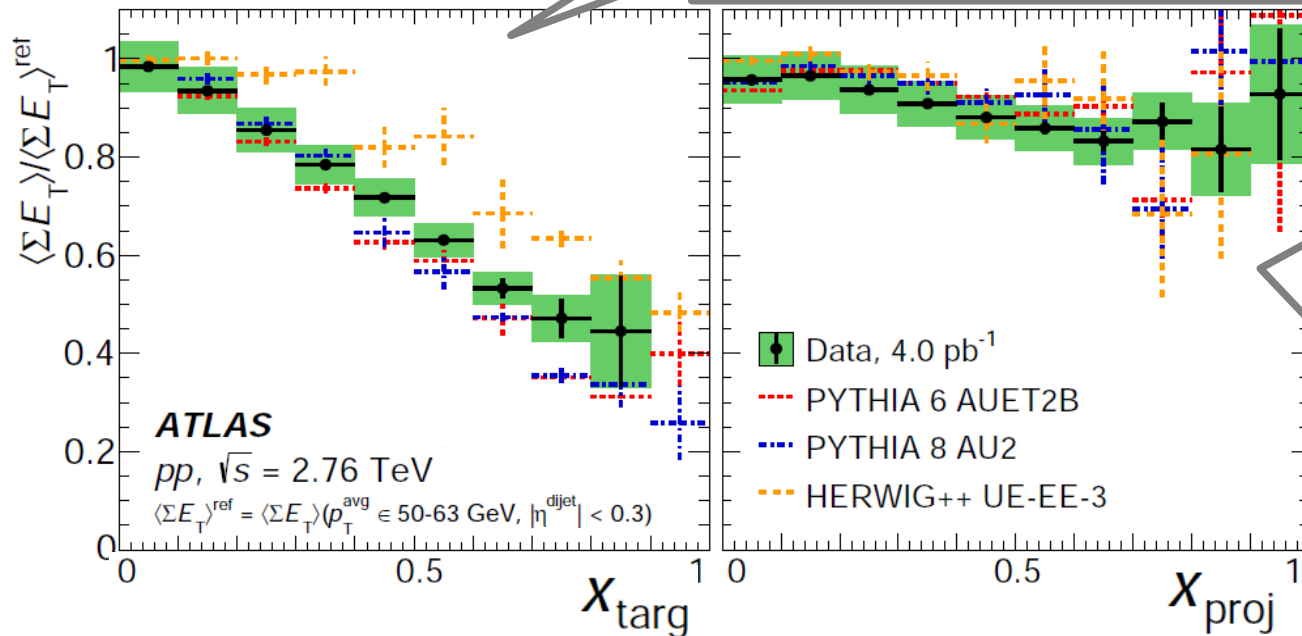
... this can be evaluated as a function of x-target and x-projectile (\sim Bjorken x)

Correlations between soft and hard production in pp

PLB 756 (2016) 10-28

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

Forward UE production
depleted if x-target is large



... but only
a modest
variation with
varying
x-projectile

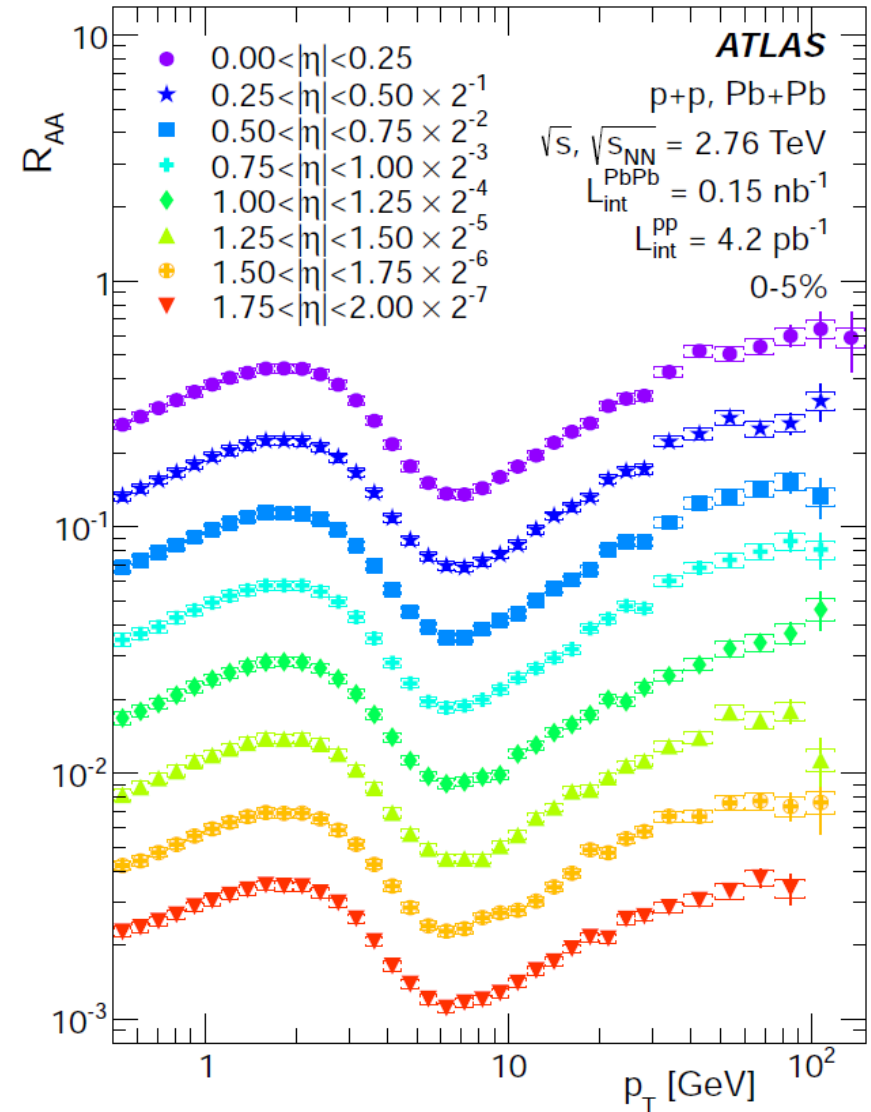
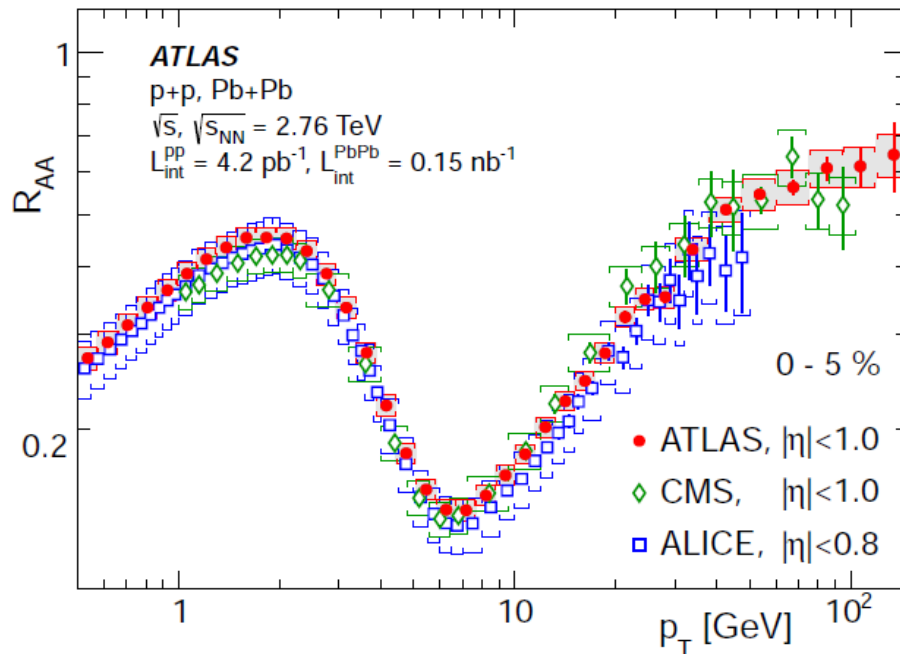
The target is the analogue of the nucleus in **p+Pb** collisions, projectile analogue of proton ... small sensitivity of ΣE_{T} to x-projectile suggests that effects seen in p+Pb jets are **not due to trivial anti-correlation in individual nucleon-nucleon collisions** (e.g. “energy conservation”).

Physics of Pb+Pb collisions

Charged particle spectra at high- p_T

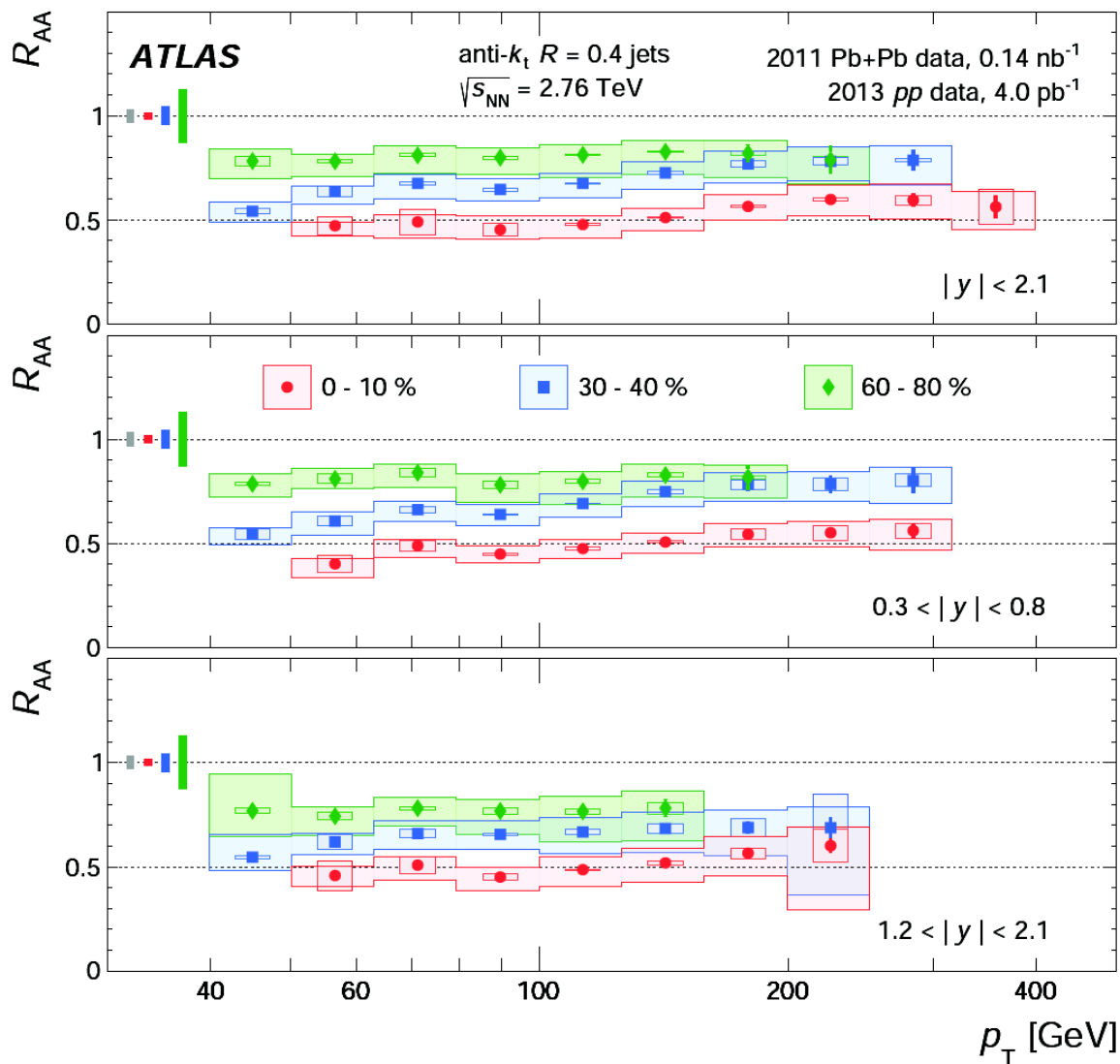
JHEP09 (2015) 050

- Charged particle R_{AA} at **up to 150 GeV**.
A **flattening** of R_{AA} at high- p_T seen.
- R_{AA} differentially in **pseudorapidity**.
No obvious pseudorapidity dependence observed which is consistent with observation made in jet R_{AA} .



Inclusive jet suppression

PRL 114 (2015) 072302



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

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

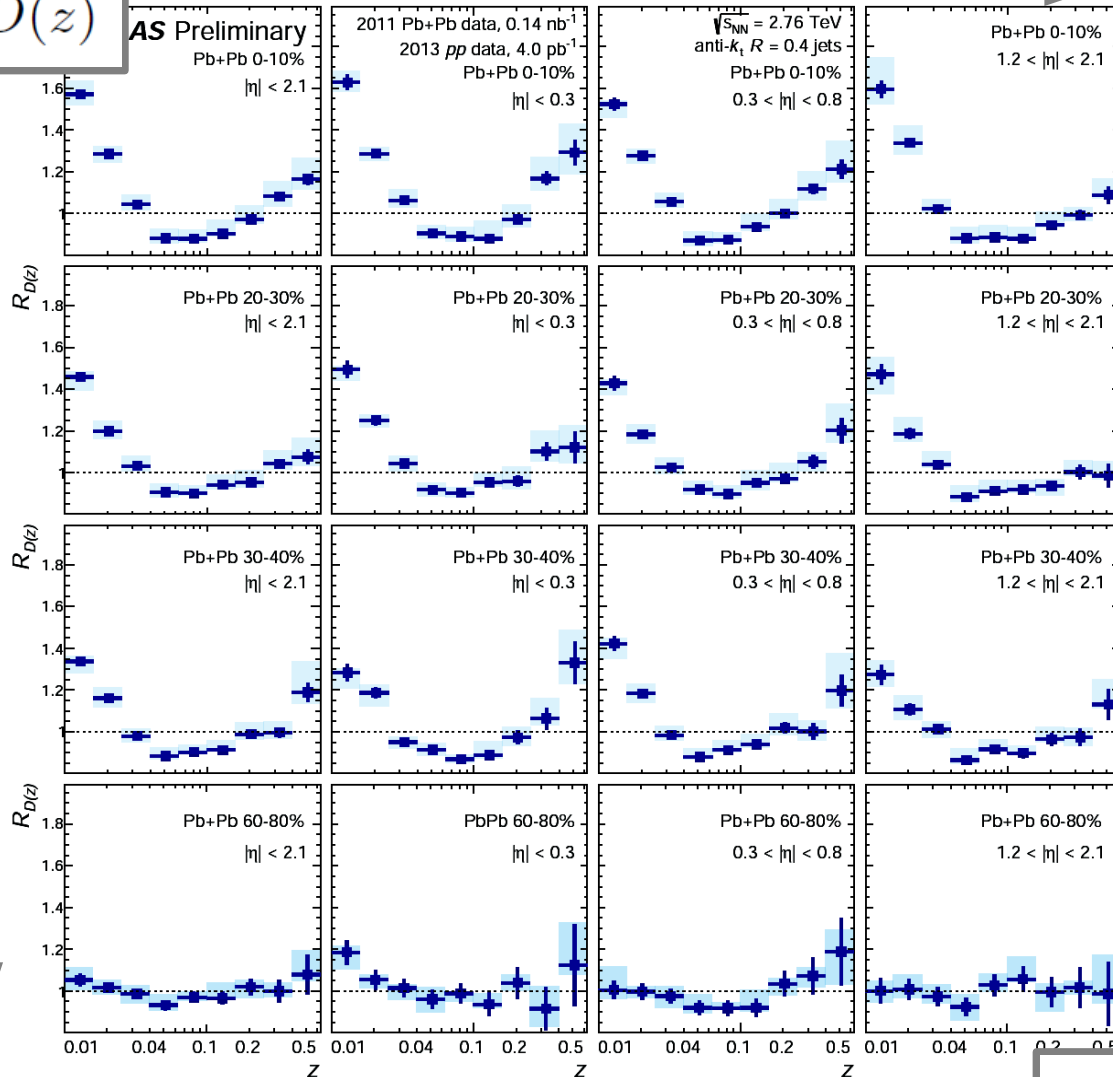
Jet fragmentation

ATLAS-CONF-2015-055

$R_D(z)$

pseudorapidity of jet

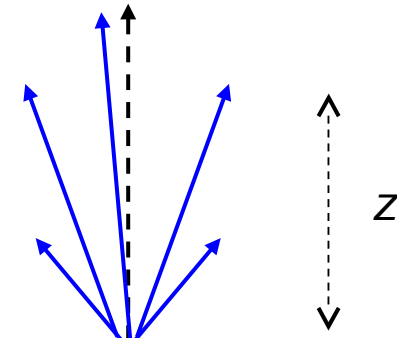
centrality



$$R_D(z) = \frac{D(z)|_{\text{cent}}}{D(z)|_{pp}}$$

$$D(z) = \frac{1}{N_{jet}} \frac{dN}{dz}$$

$$z = \frac{p_T}{p_T^{jet}} \cos \Delta R$$



z

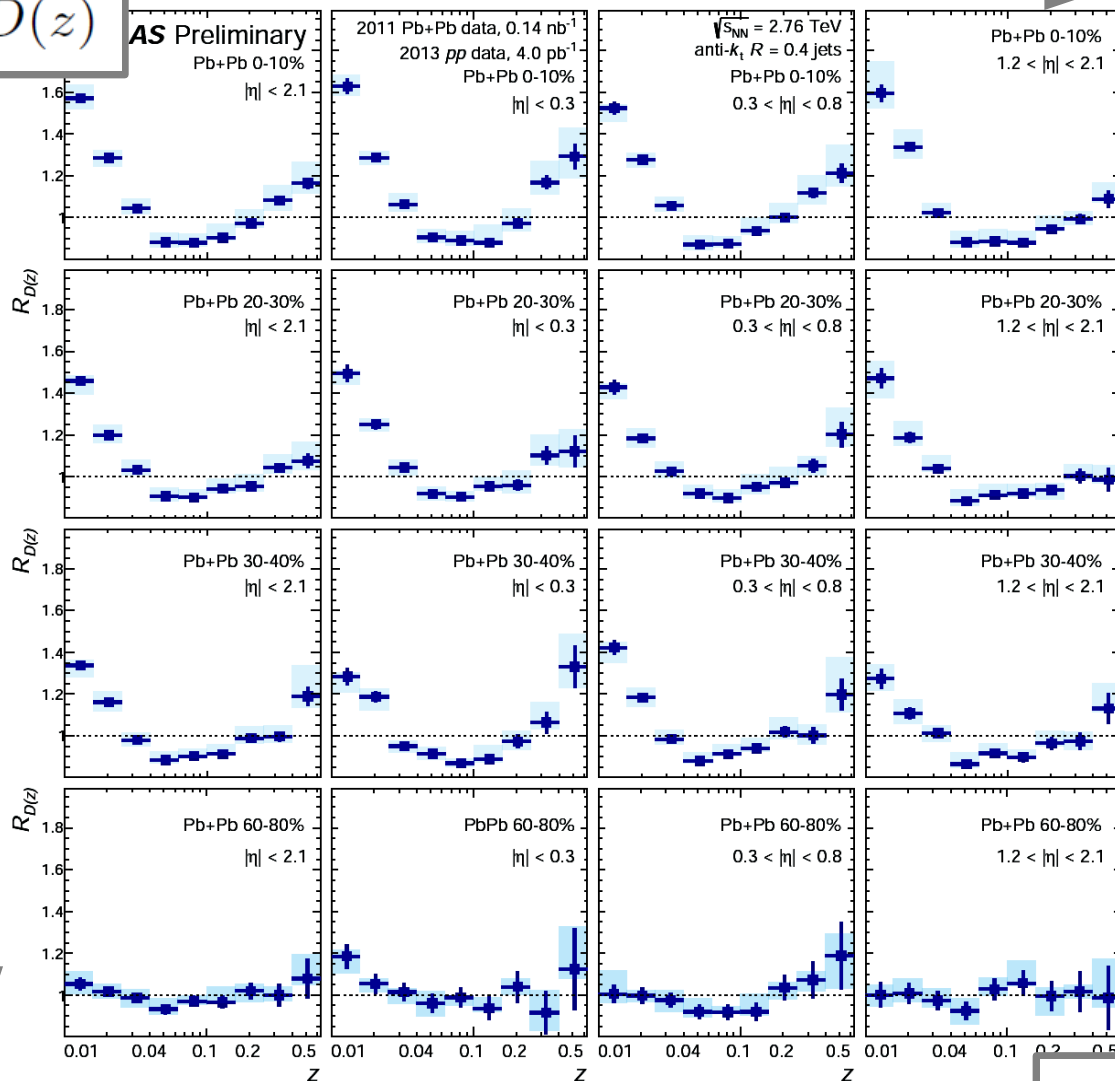
Jet fragmentation

ATLAS-CONF-2015-055

$R_D(z)$

pseudorapidity of jet

centrality



Centrality dependence

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

Jet pt dependence

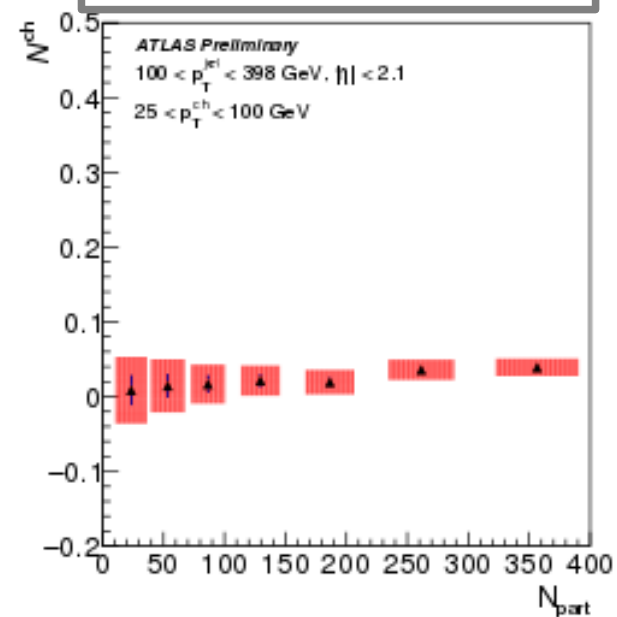
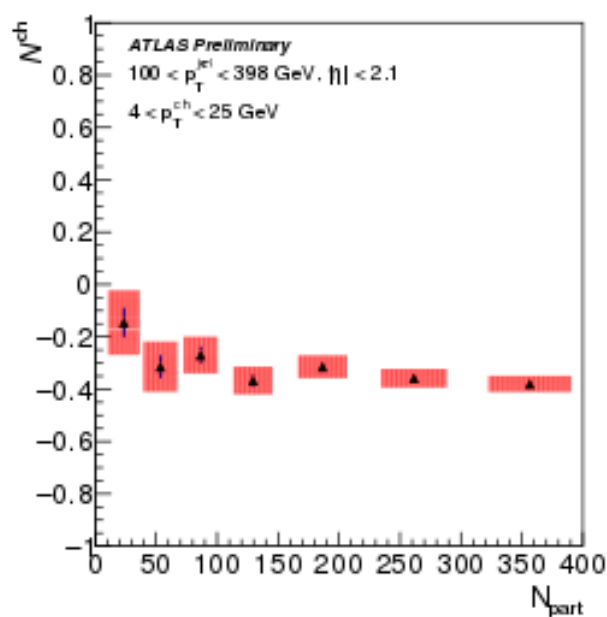
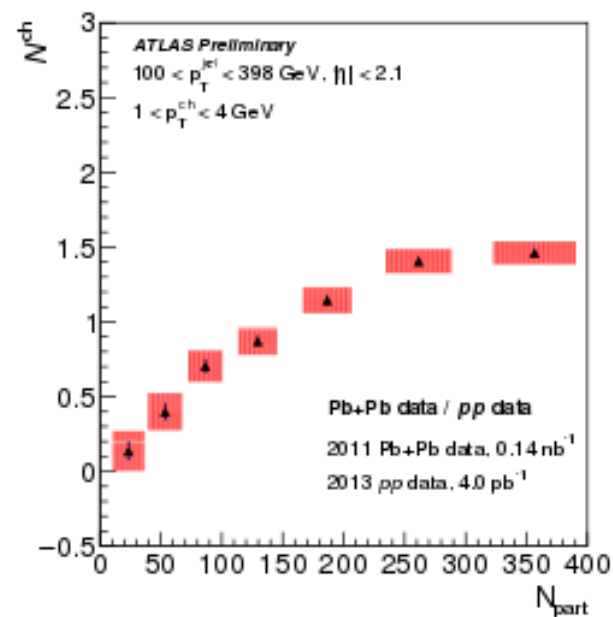
- No significant dependence on jet pt

Rapidity dependence

Hint of a difference in the enhancement for different rapidity ... consistent with prediction in arXiv:1504.05169

z

Jet fragmentation – flow of particles



- To quantify the flow of particles:

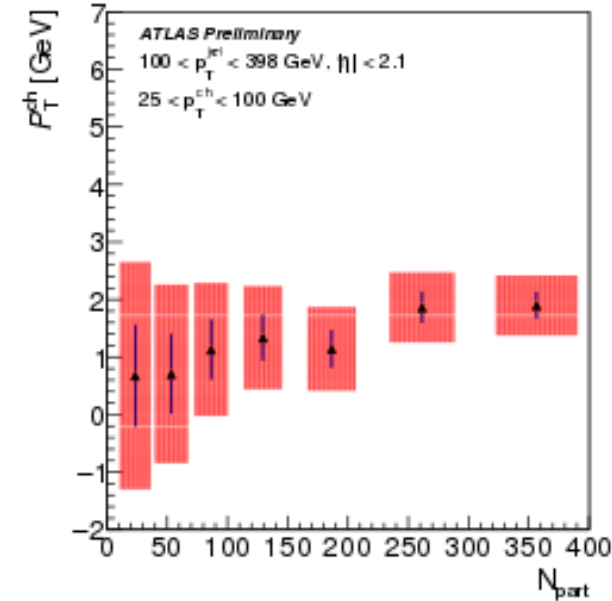
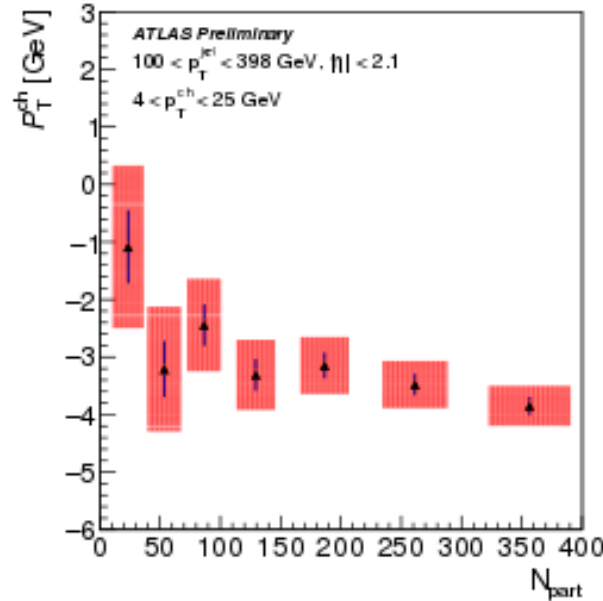
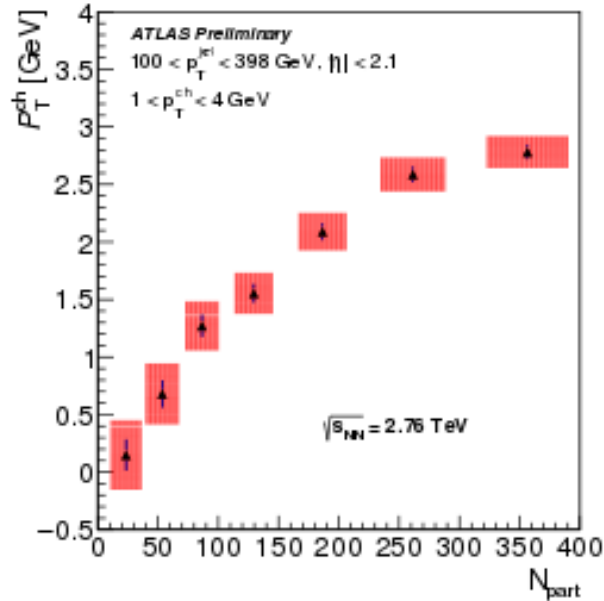
$$N^{\text{ch}} \equiv \int_{p_{T,\text{min}}}^{p_{T,\text{max}}} \left(D(p_T)|_{\text{cent}} - D(p_T)|_{\text{pp}} \right) dp_T$$

... 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

ATLAS-CONF-2015-055



- To quantify the flow of momentum:

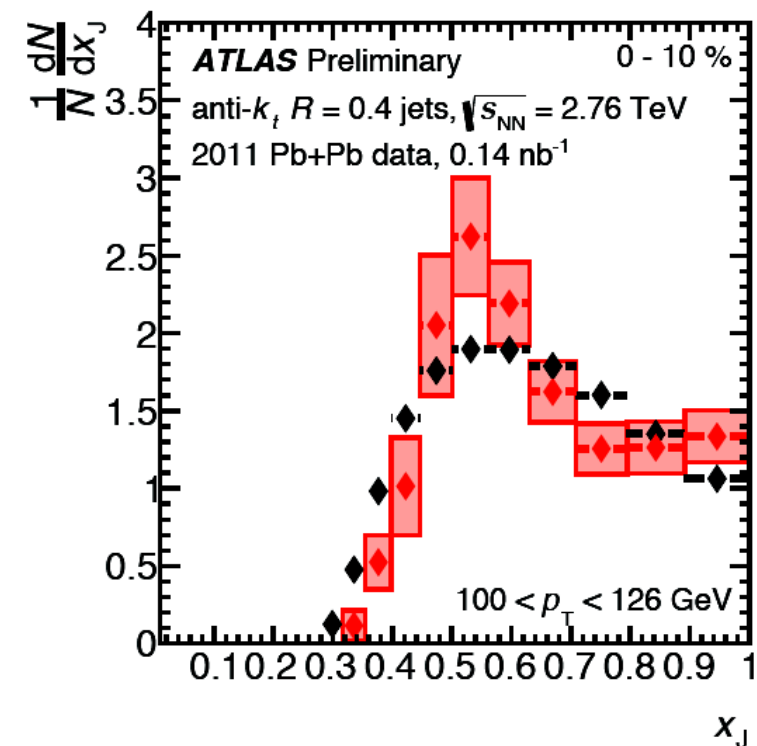
$$P_T^{\text{ch}} \equiv \int_{p_{T,\text{min}}}^{p_{T,\text{max}}} \left(D(p_T)|_{\text{cent}} - D(p_T)|_{\text{pp}} \right) p_T dp_T$$

... as a function of N_{part}

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

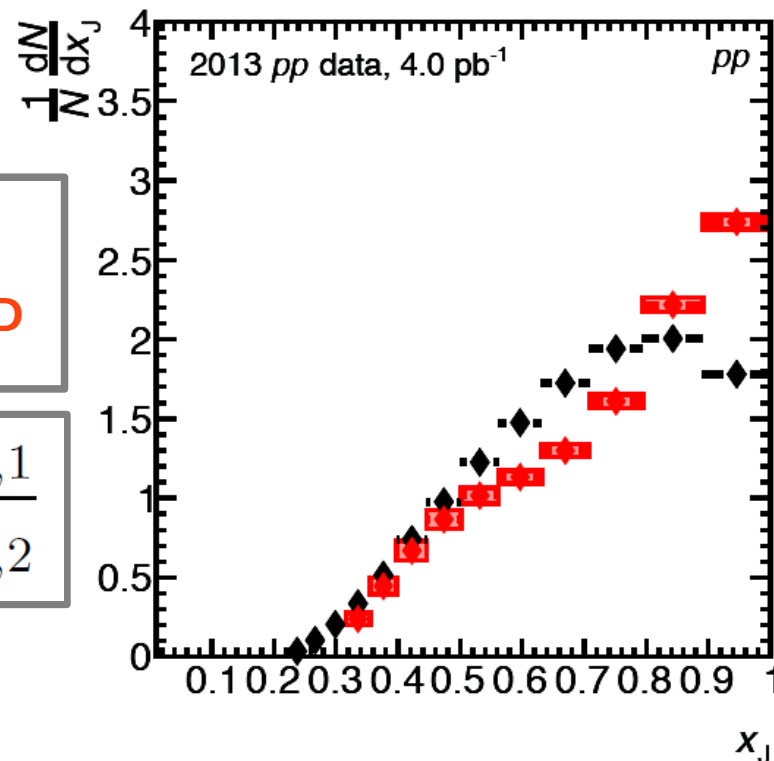
Dijet production

ATLAS-CONF-2015-052



RAW
UNFOLDED

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



- Updated dijet asymmetry measurement
- Uses 2D bayesian unfolding to correct for the detector effects in $p_{T,1}$ and $p_{T,2}$ simultaneously
- Energy loss very different for two jets in the system

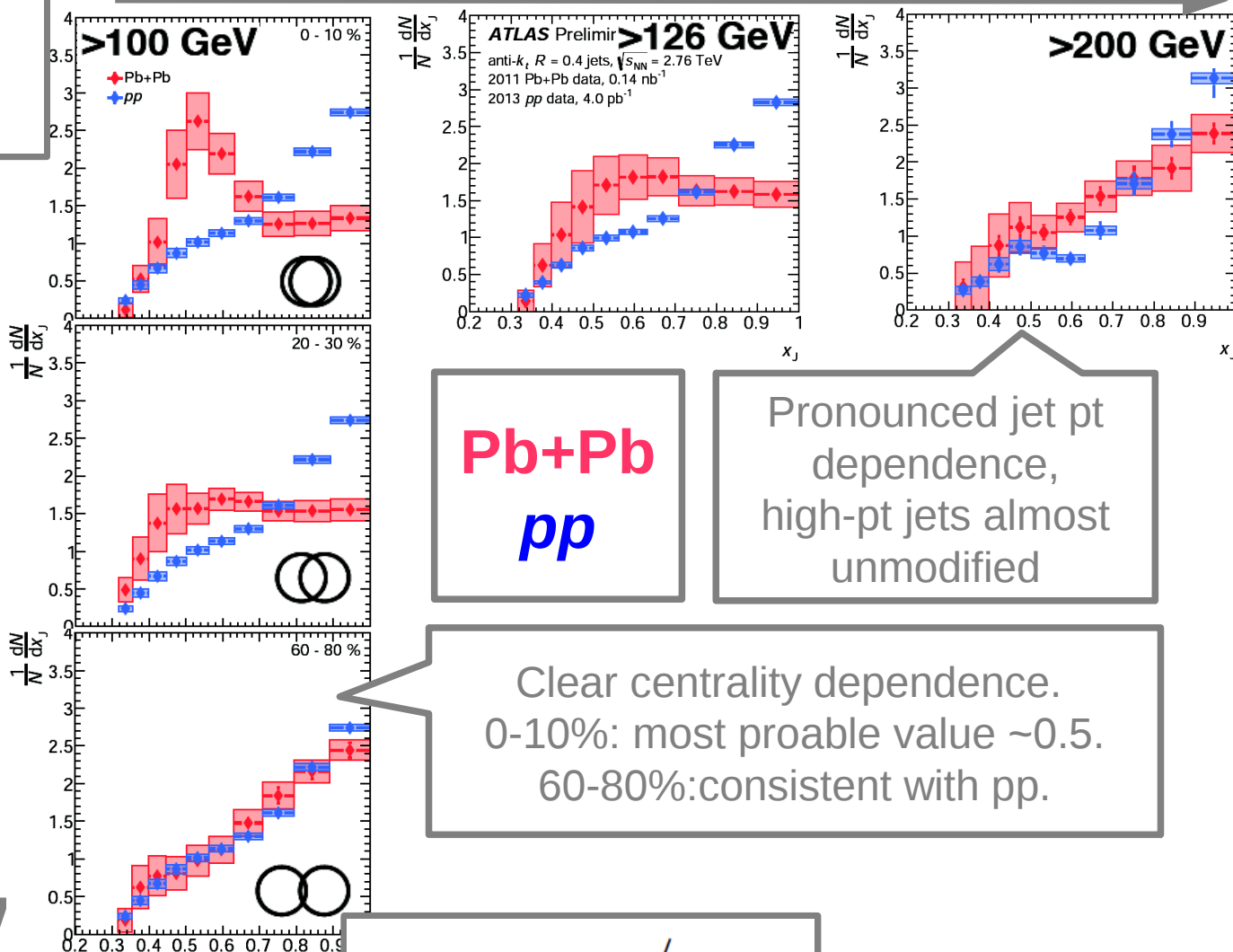
Dijet production

ATLAS-CONF-2015-052

$$\frac{1}{N} \frac{dN}{dx_J}$$

pt of jet

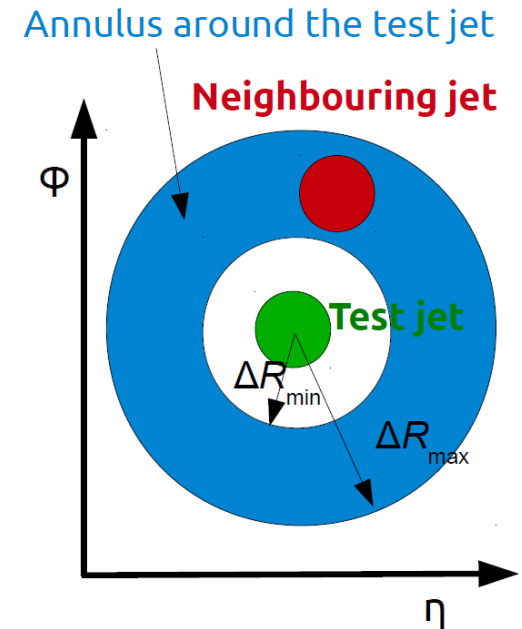
centrality



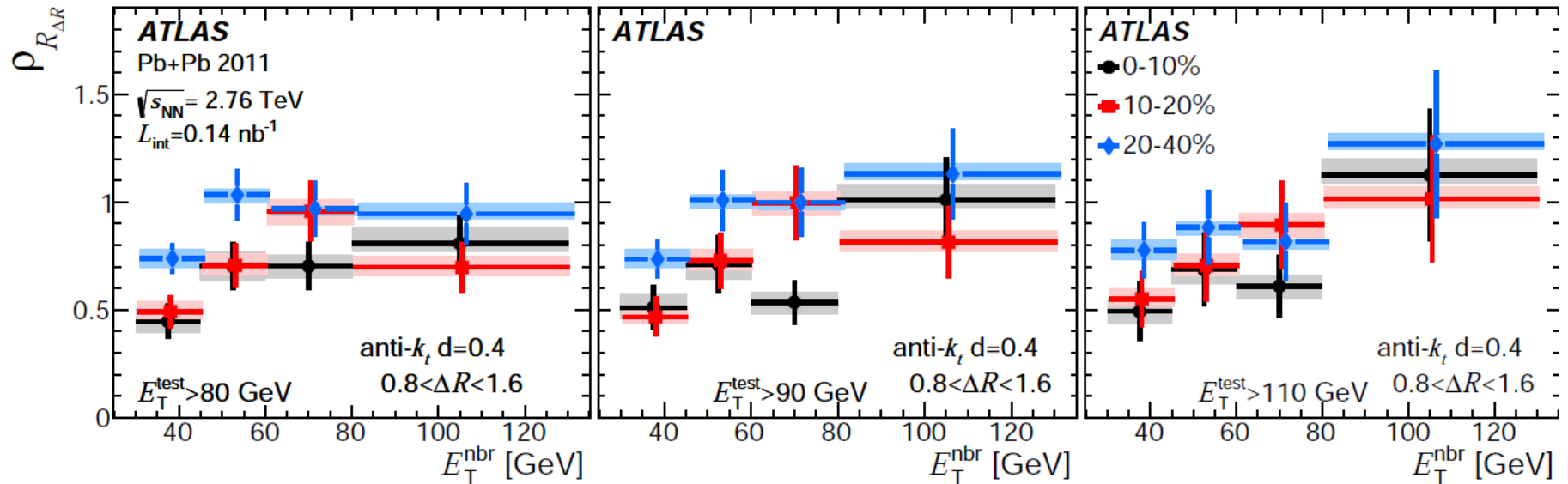
- Neighboring jet production quantified using quantity previously measured at Tevatron

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

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



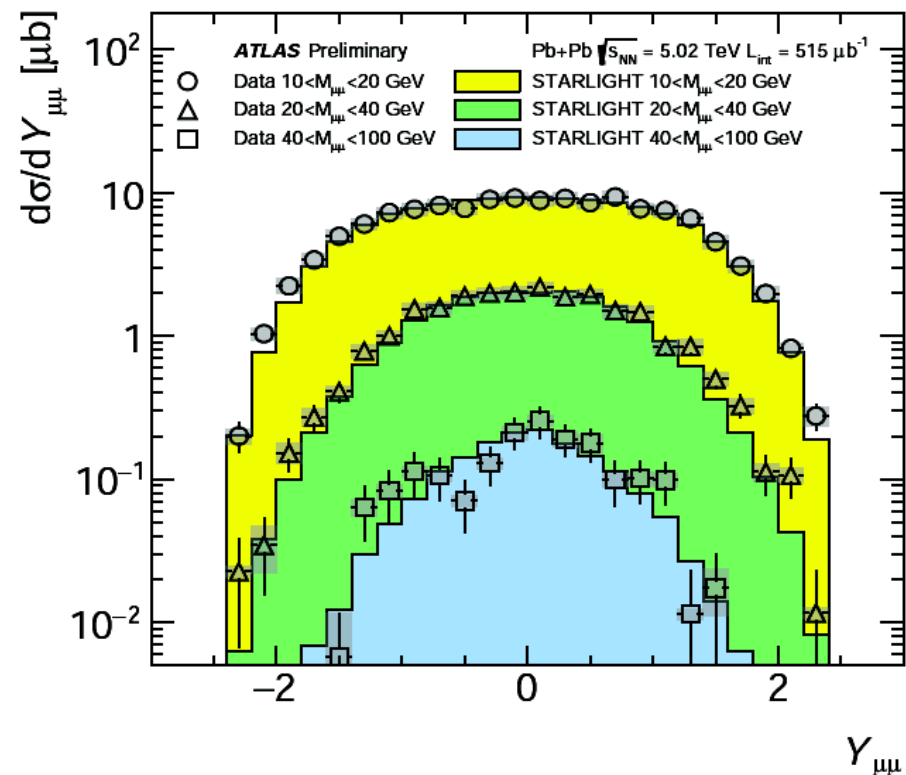
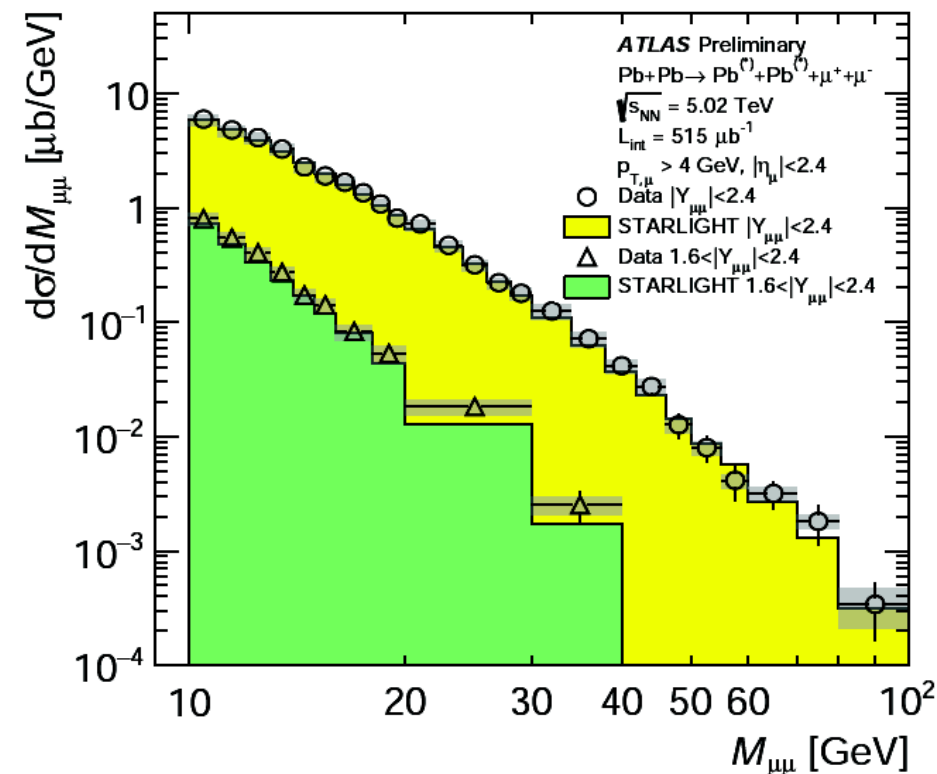
- To quantify the centrality dependence the central-to-peripheral ratios, $\rho(R_{\Delta R})$, also evaluated.



- Central-to-peripheral ratio of $R_{\Delta R}$ as a function of neighboring jet E_T .
- Decrease of suppression with increasing jet E_T .

Di-muons in ultra-peripheral collisions in run 2

ATLAS-CONF-2016-025



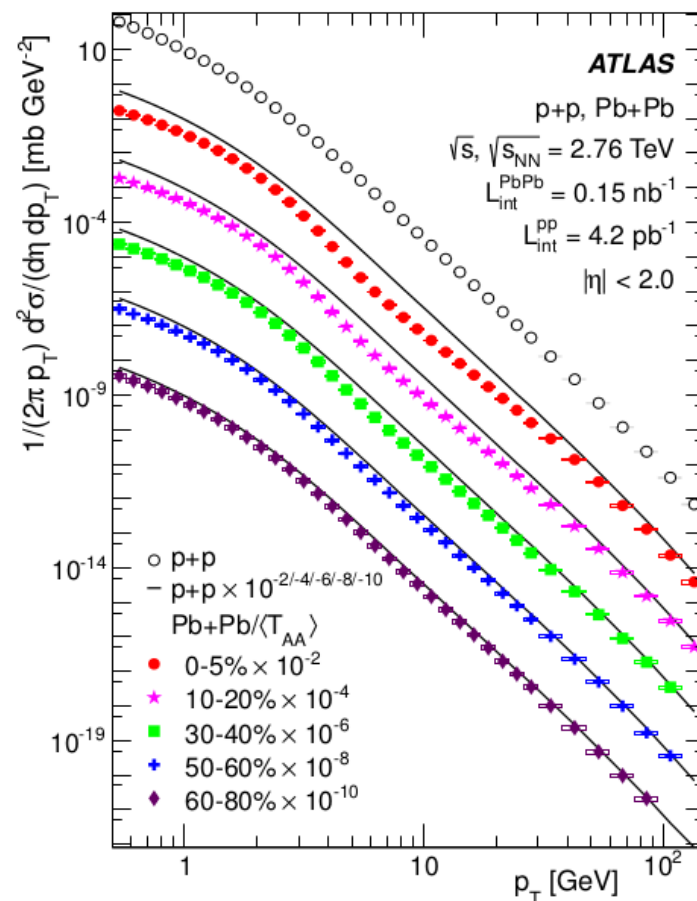
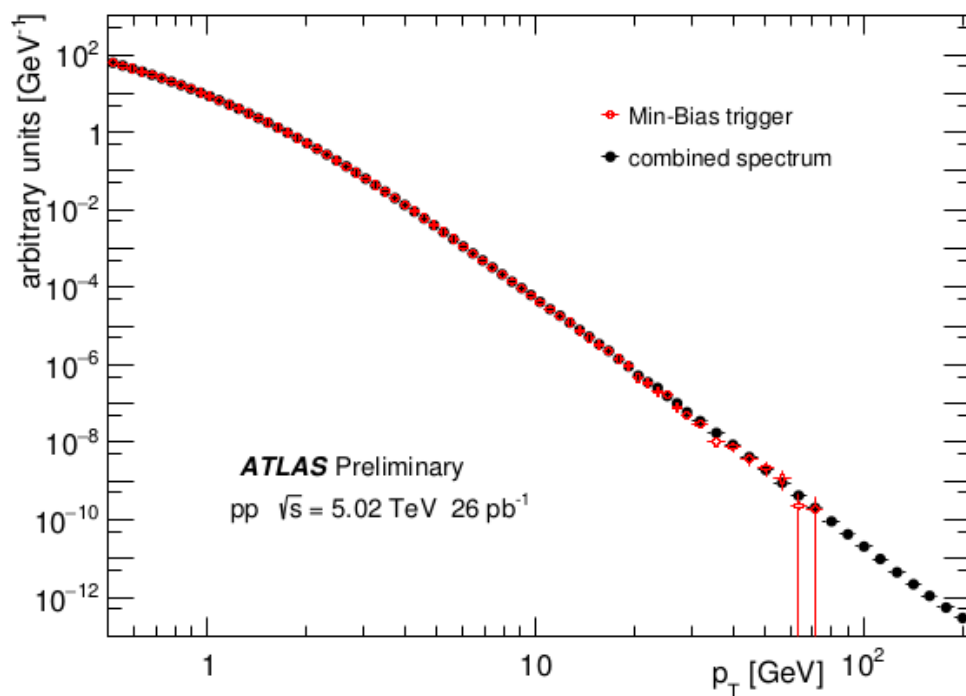
- Di-muons produced in the electromagnetic interaction between the two nuclei
- The photon flux well modeled by STARLIGHT 1.1

Outlook

Charged particles

Run 1

Run 2



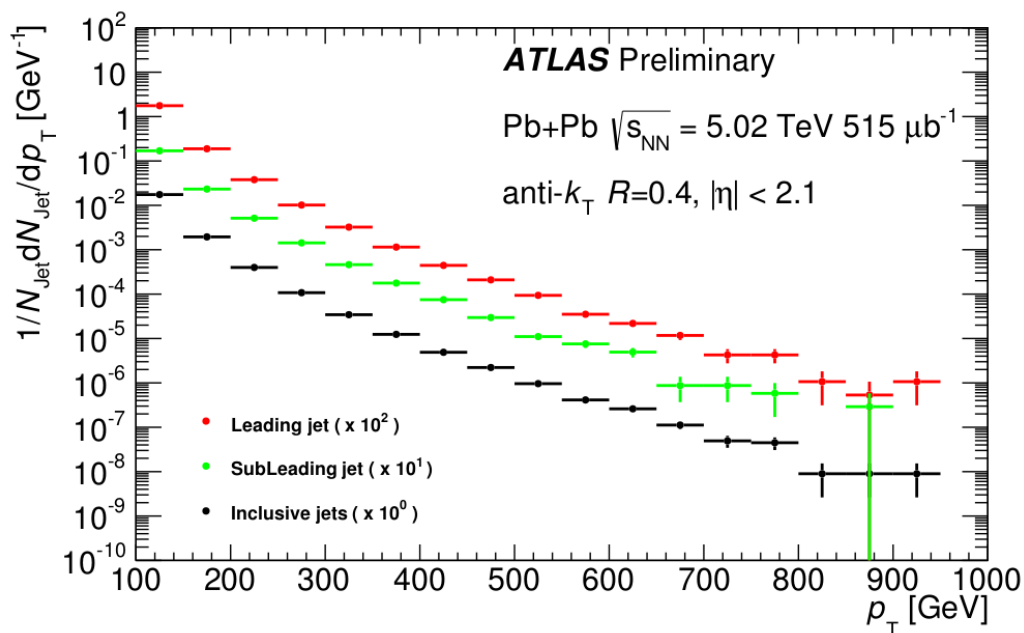
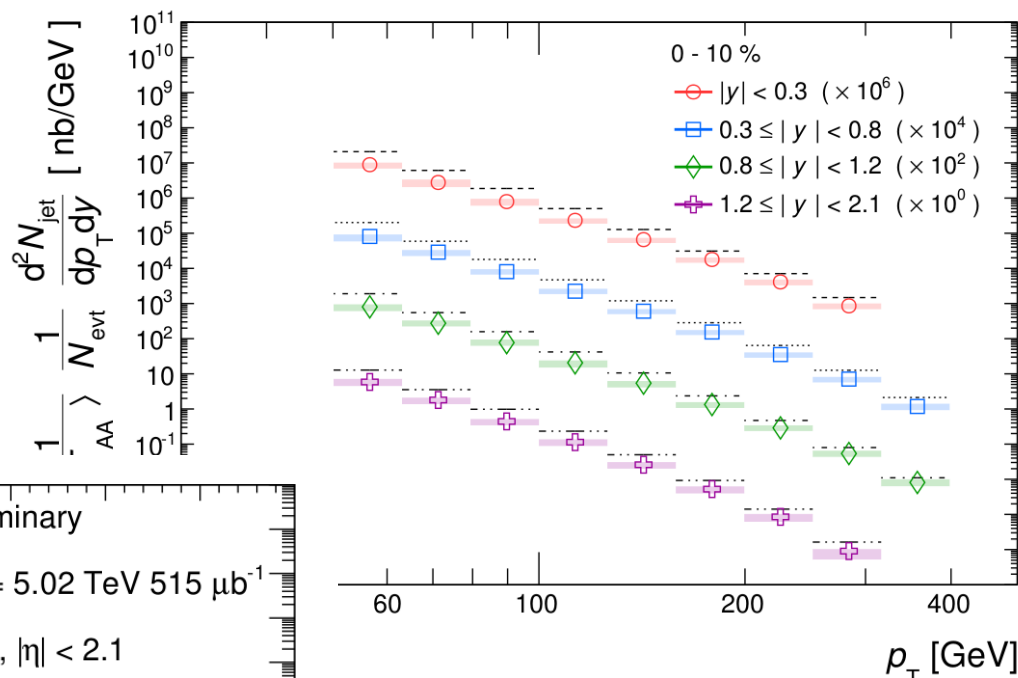
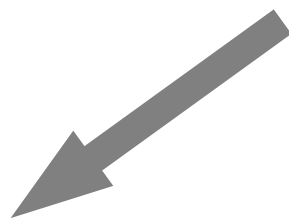
... great statistics
up to 200 GeV

Outlook

Jets

Run 1

Run 2



... may double the pt reach

Summary

- p+Pb collisions:

- Inclusive jet R_{pPb} is centrality and pseudorapidity dependent
- Pseudorapidity dependent anti-correlation between “soft” and “hard” production seen in pp collisions have implications for p+Pb physics
- Charged particle production ... dependence on the Glauber model

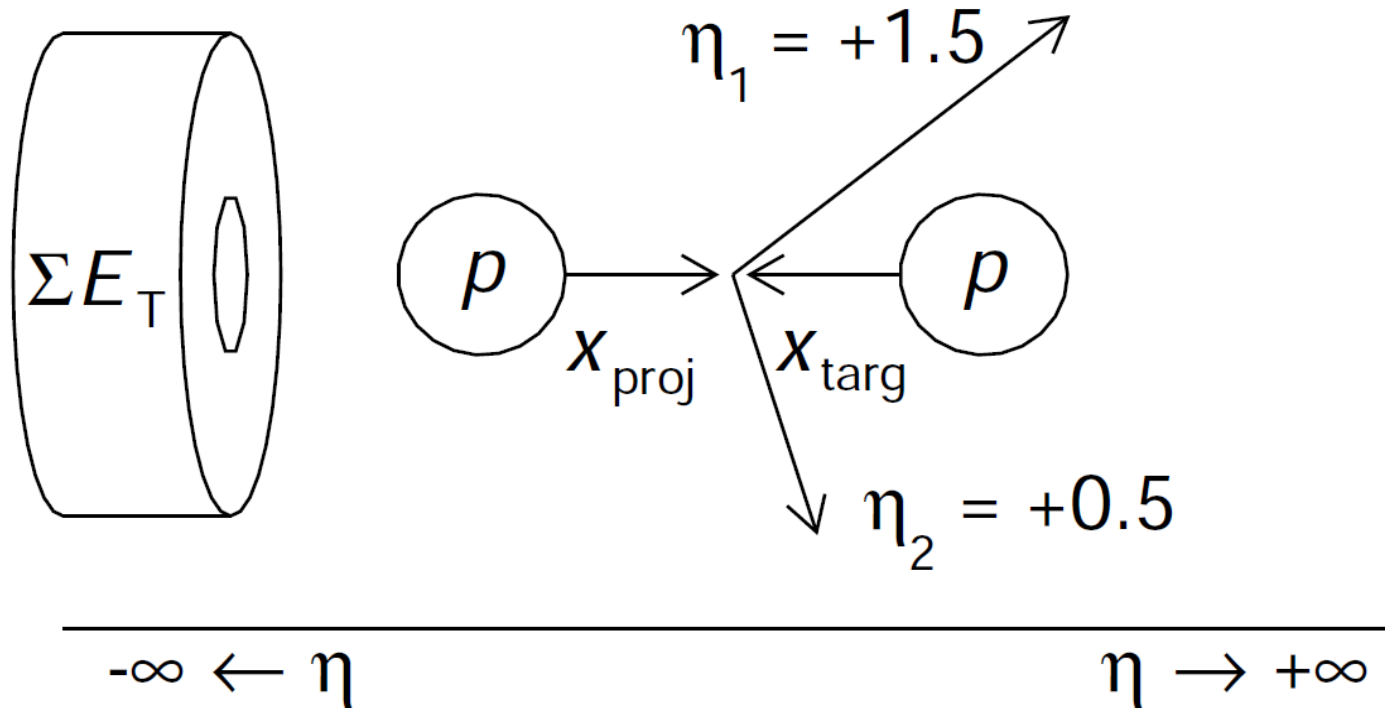
- Pb+Pb collisions:

- Charged particle R_{AA} measured up to 150 GeV, jet R_{AA} up to 400 GeV ... almost no y dependence, sizable suppression even for 60-80%
- Jet internal structure measured differentially in jet p_t and rapidity
- First fully corrected di-jet measurement exhibits very pronounced difference between Pb+Pb and pp collisions
- Production of nearby jets quantified

Backup slides

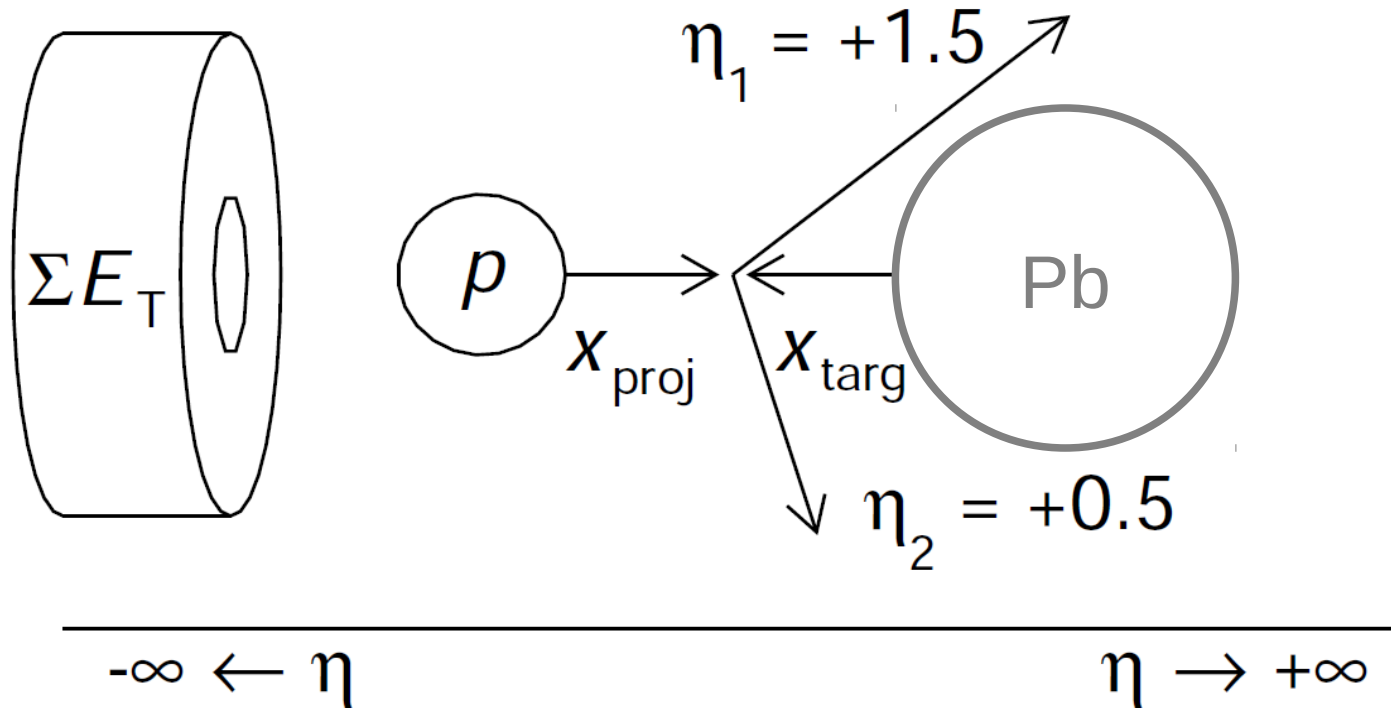
Correlations between soft and hard production in pp

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



Correlations between soft and hard production in pp

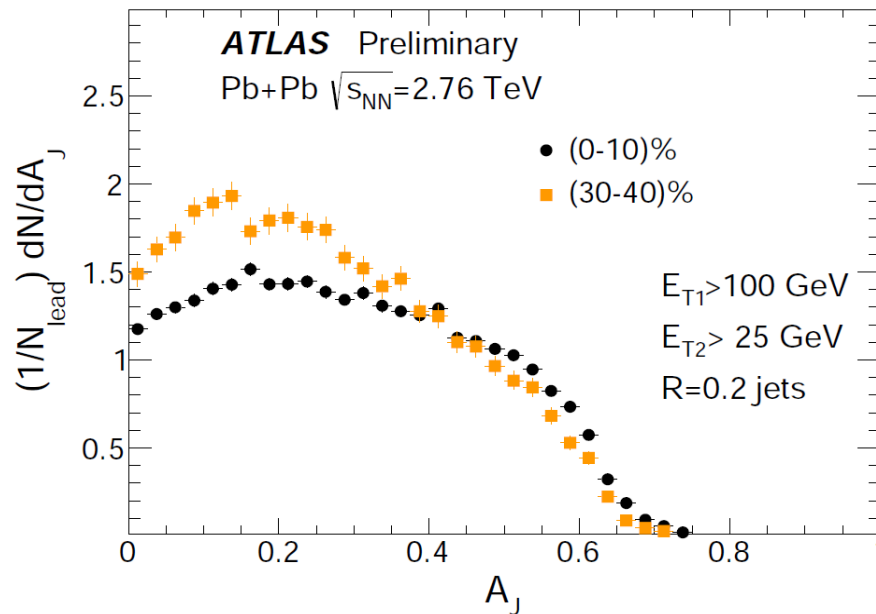
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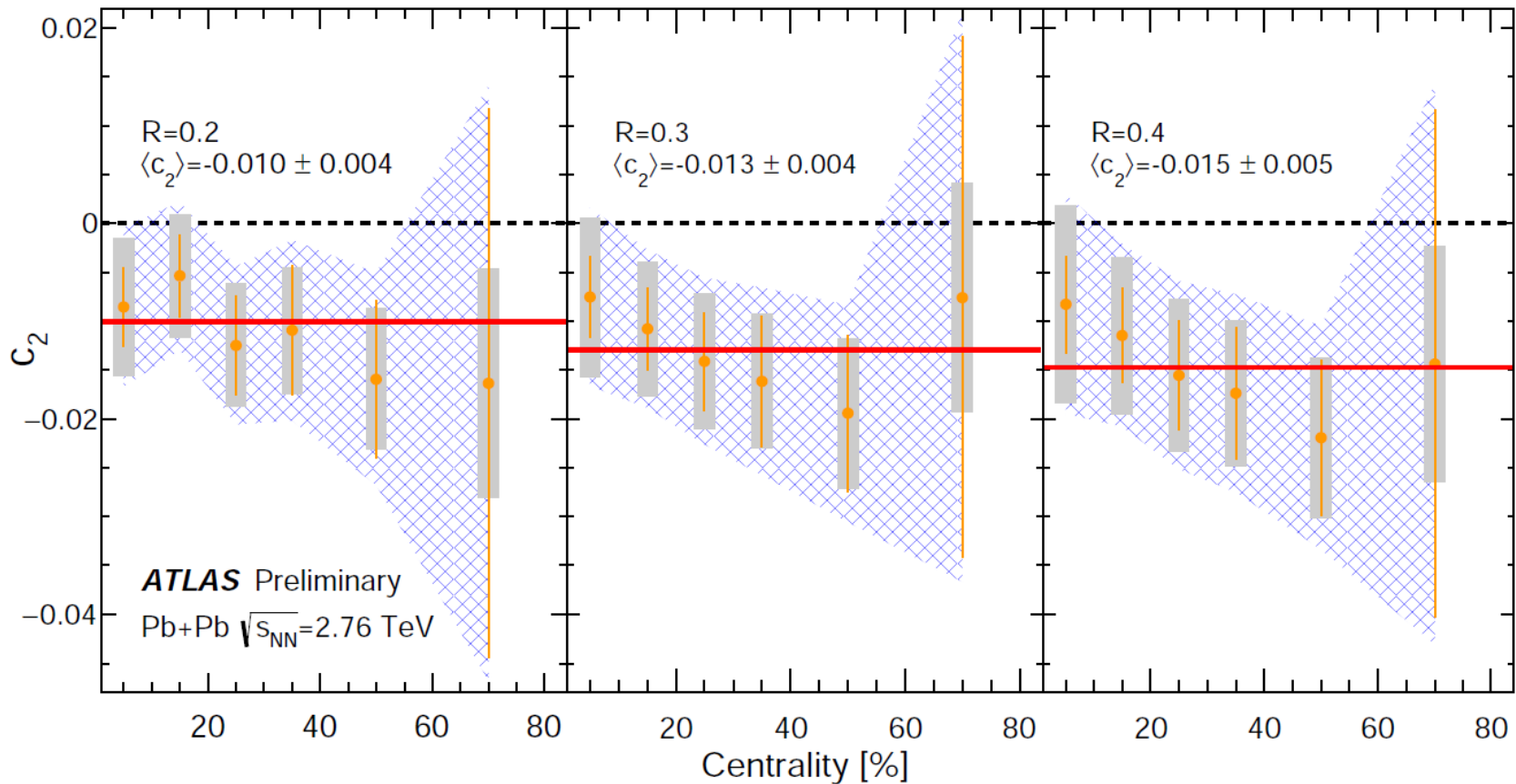
Jet event shape correlations

- 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 :

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



Jet event shape correlations



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

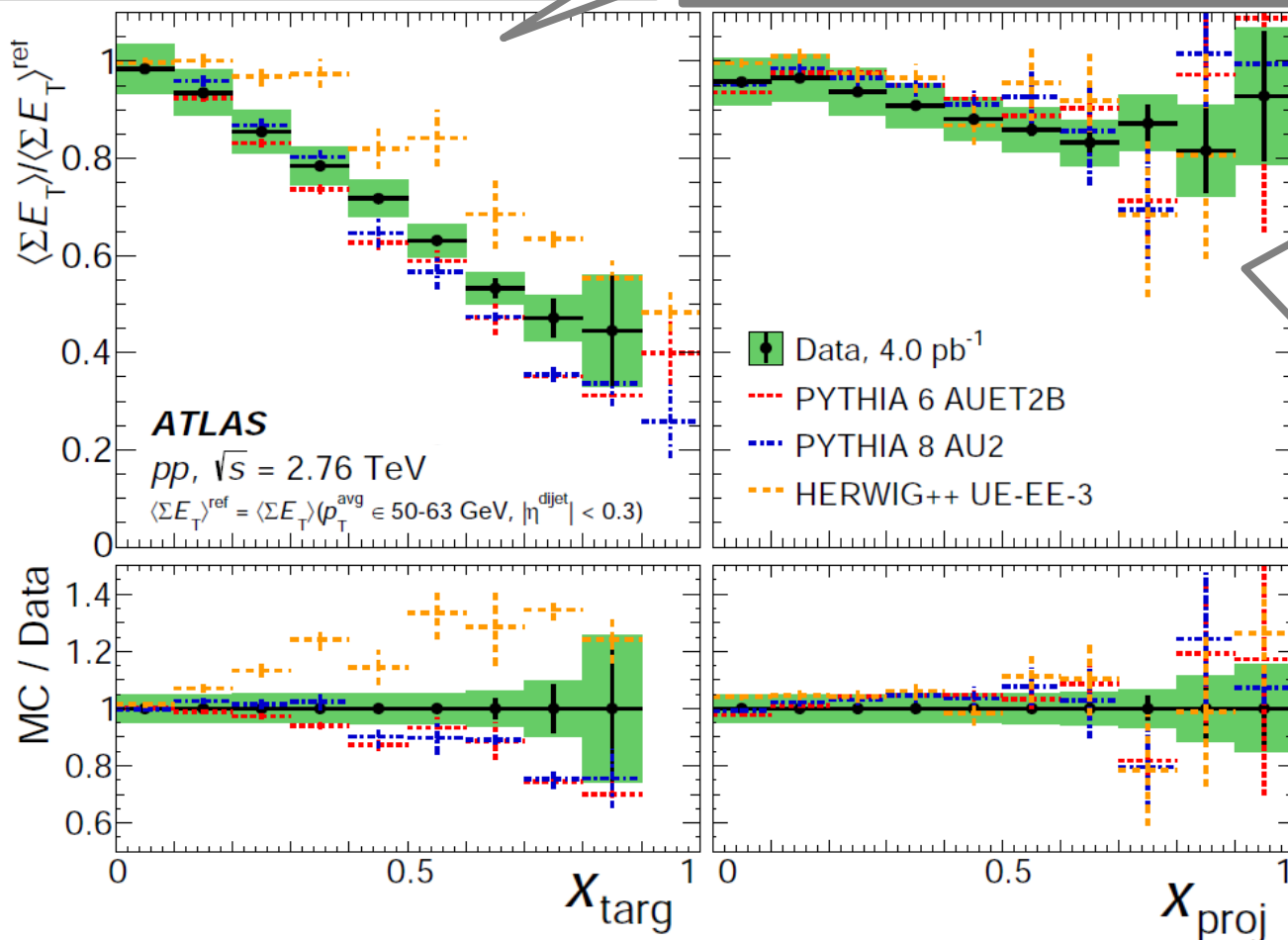
c_2 **small (<2%), negative** indicating slightly larger A_J for leading jets oriented out-of-plane than for jets oriented in-plane.

Correlations between soft and hard production in pp

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

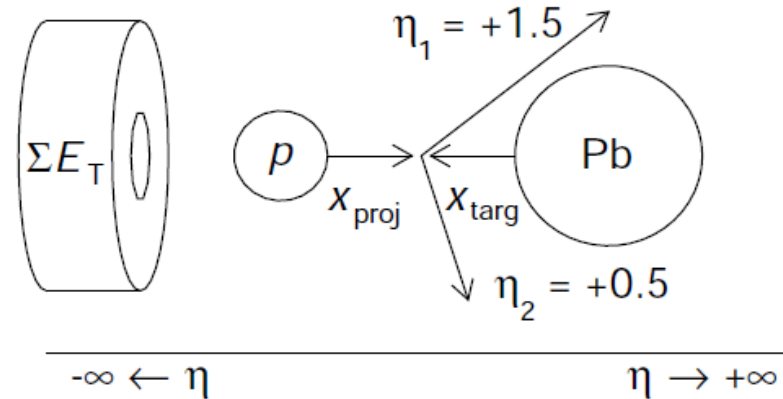
Forward UE production
depleted if x-target is large

... but only
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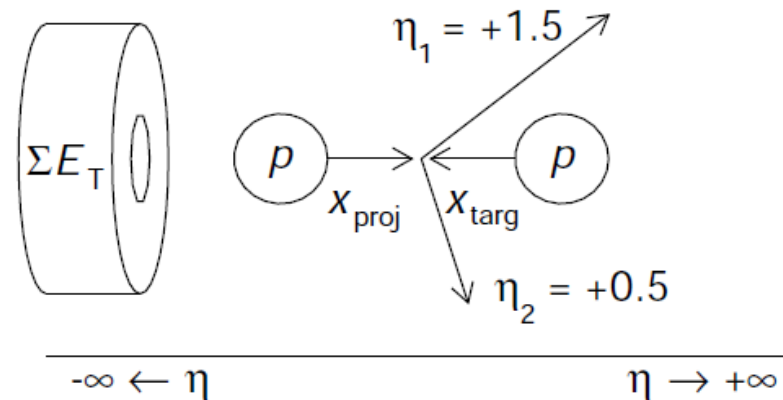


Correlations between soft and hard production in pp

(a) p +Pb collision



(b) pp collision

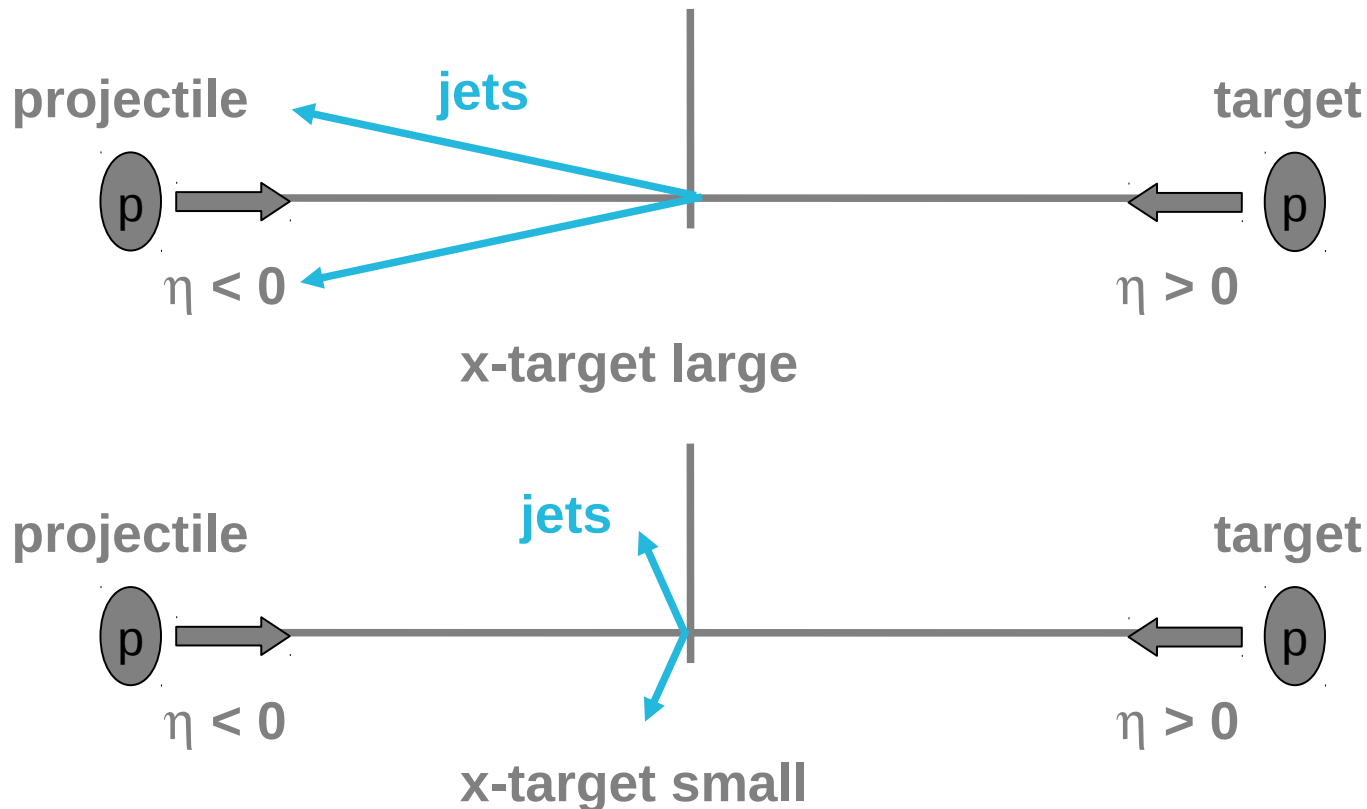


Correlations between soft and hard production in pp

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

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

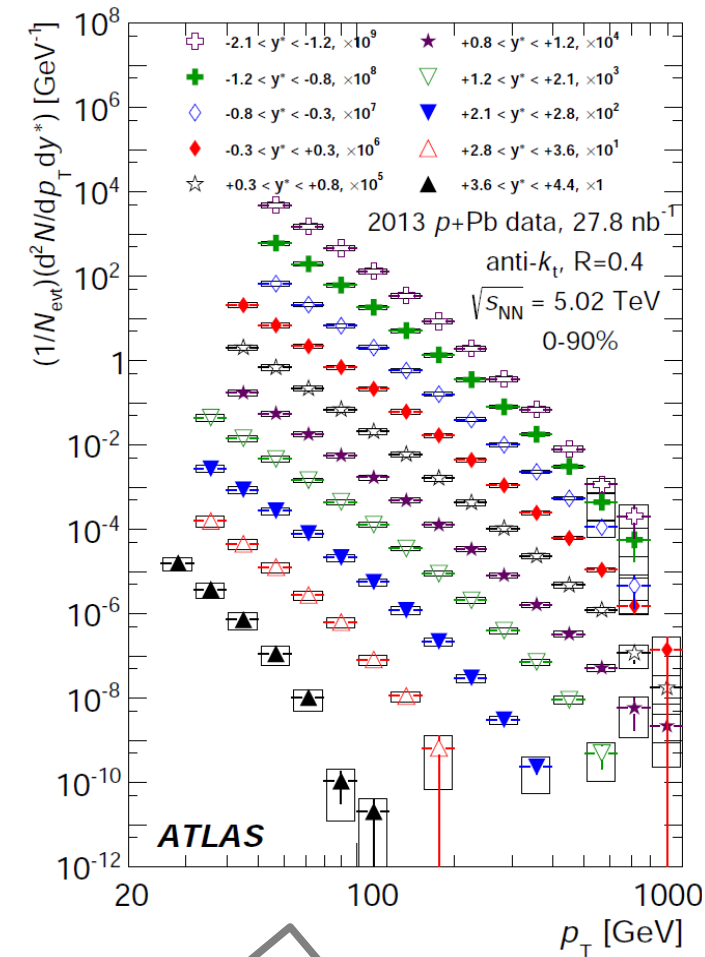
- Example of configurations:



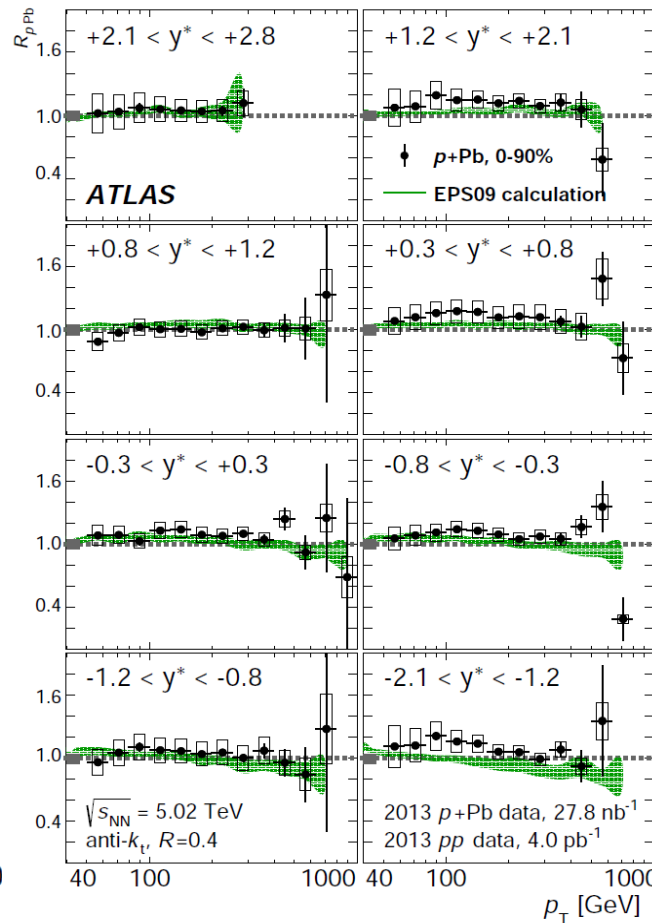
Jet yields and R_{pPb}

[arXiv:1412.4092](https://arxiv.org/abs/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 ...**

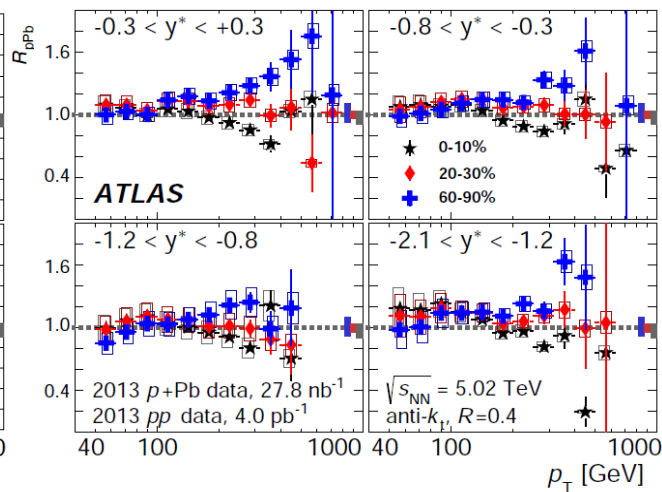
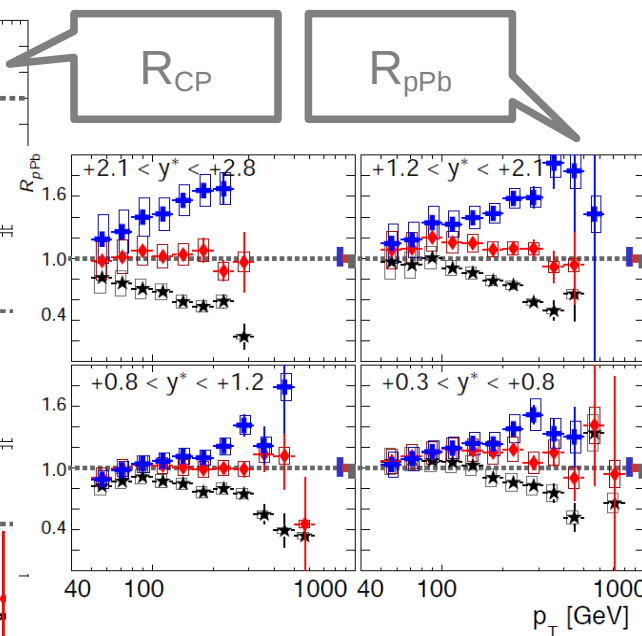
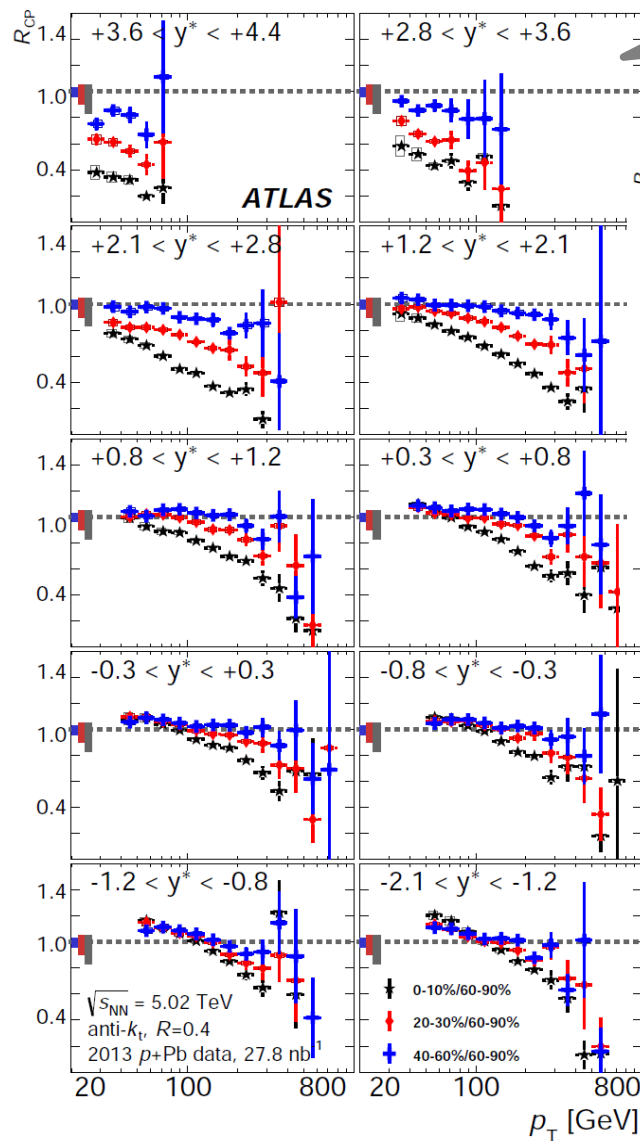


0-90% jet yields



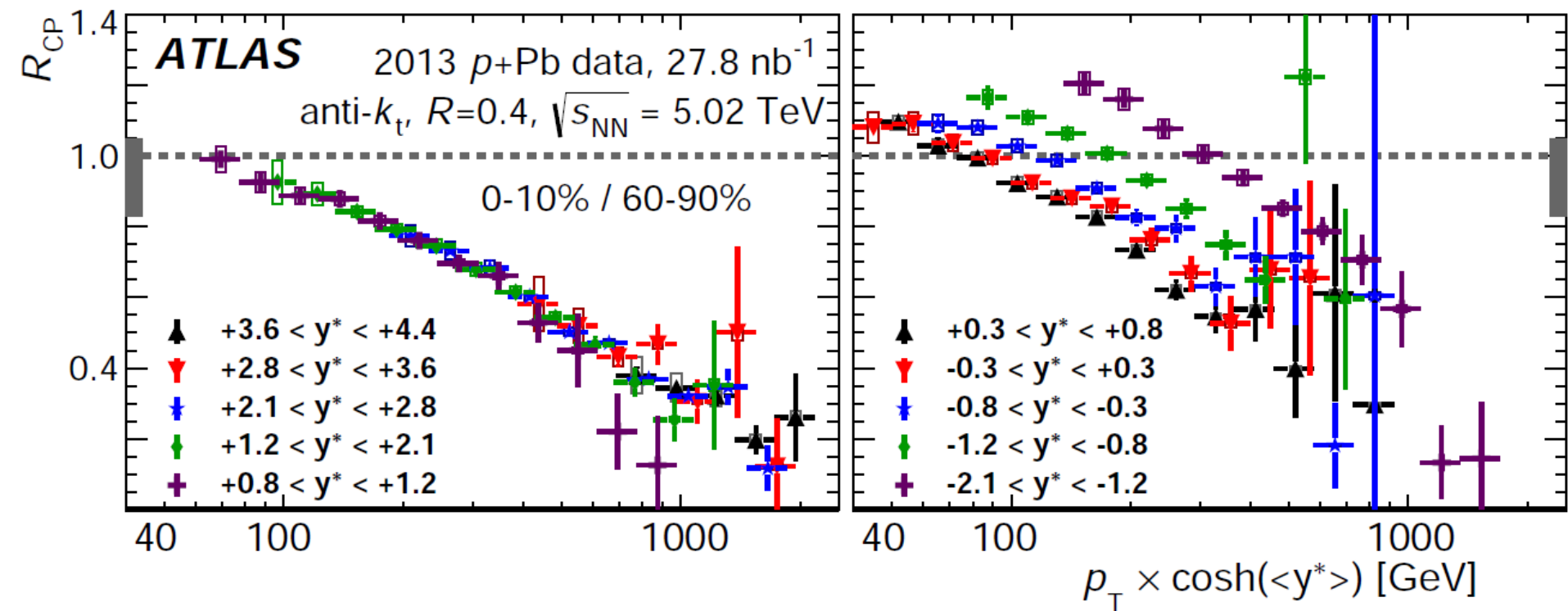
$$R_{pPb} \equiv \frac{1}{T_{pA}} \frac{(1/N_{evt}) \frac{d^2 N_{jet}}{dp_T dy^*}}{d^2 \sigma_{jet}^{pp} / dp_T dy^*}$$

Jet R_{pPb} and R_{CP}

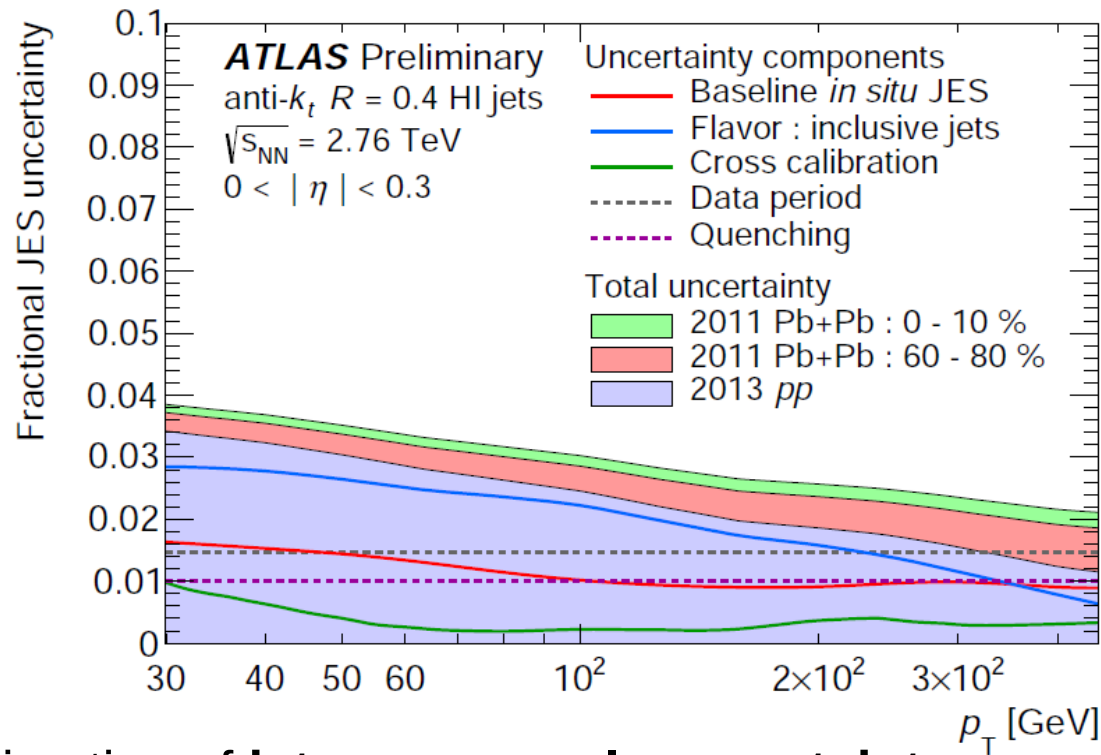


- R_{CP} strongly varies with centrality exhibiting decrease with increasing p_T in all three centrality bins.
- If R_{pPb} is unity and R_{CP} decreases then there must be **enhancement in peripheral collisions** wrt to pp . Indeed, this is observed.
- The use of Glauber-Gribov only amplifies these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

Jet R_{pPb} and R_{CP}

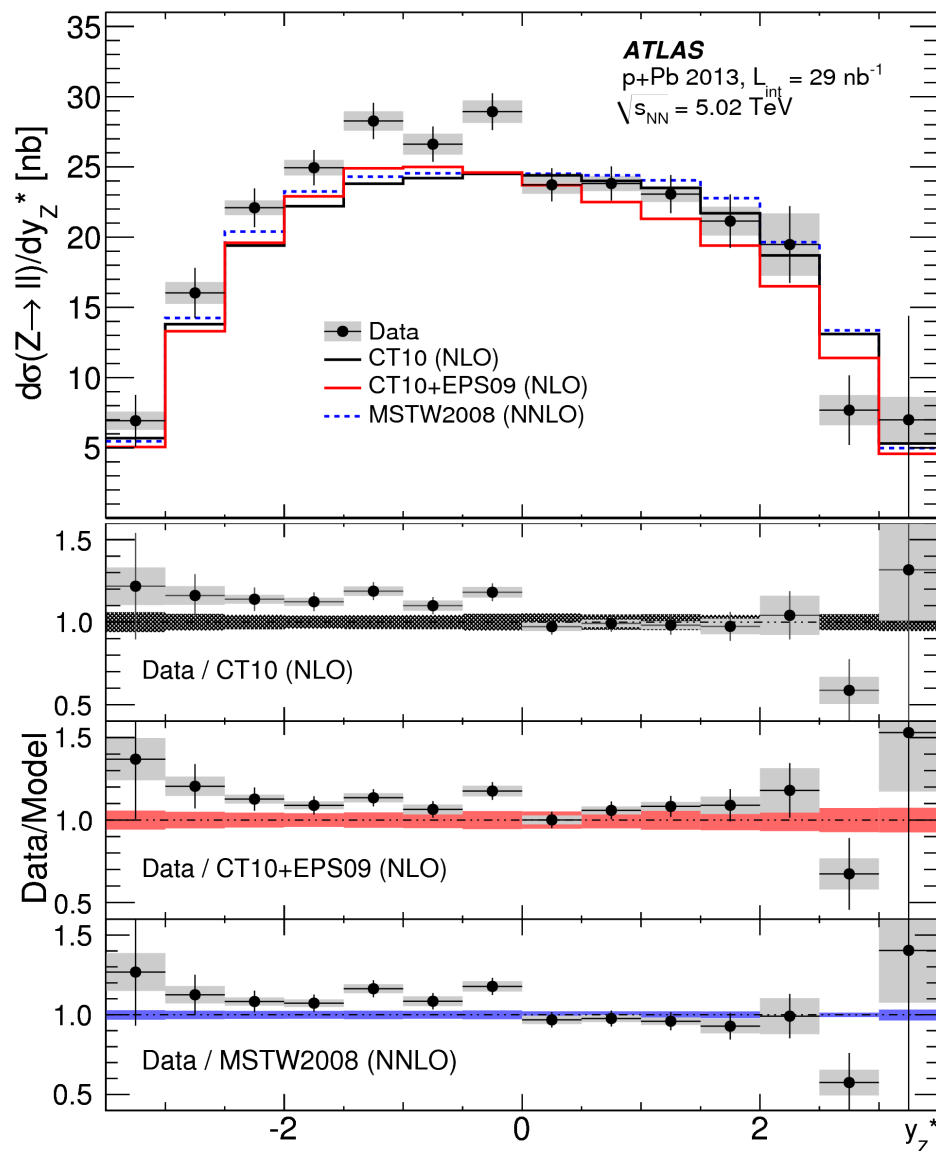


Inclusive jet suppression



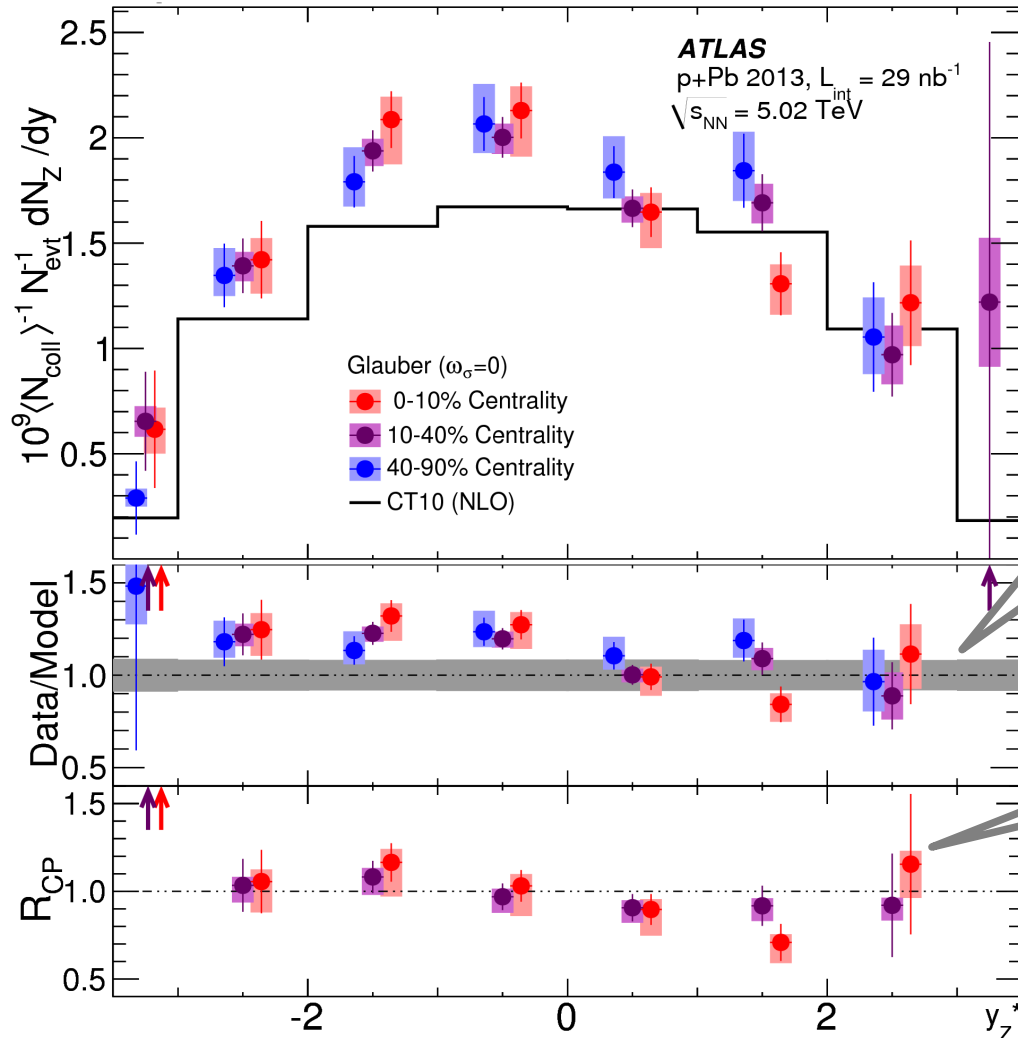
- Detailed estimation of **jet energy scale uncertainty**.
- Using ***in situ*** techniques (γ +jet and Z+jet) and limits on the impact of modified fragmentation on jet energy scale.
- Same level of **rigor as in precision pQCD** measurement should be a standard for precision HI measurements in the run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

Z boson production in p+Pb



$$x_{Pb} = \frac{m_{\ell\ell} e^{-y_z^*}}{\sqrt{s_{\text{NN}}}}$$

Z boson production in p+Pb

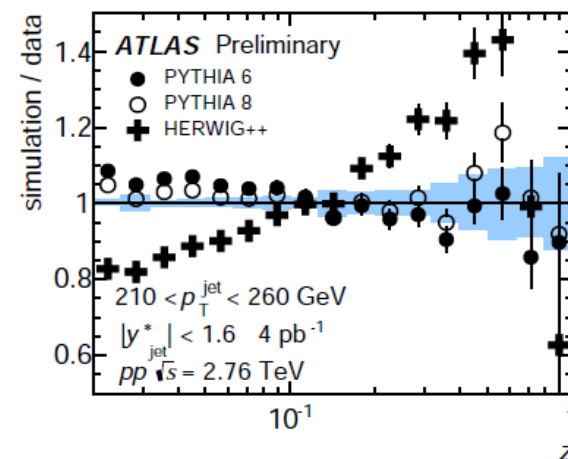
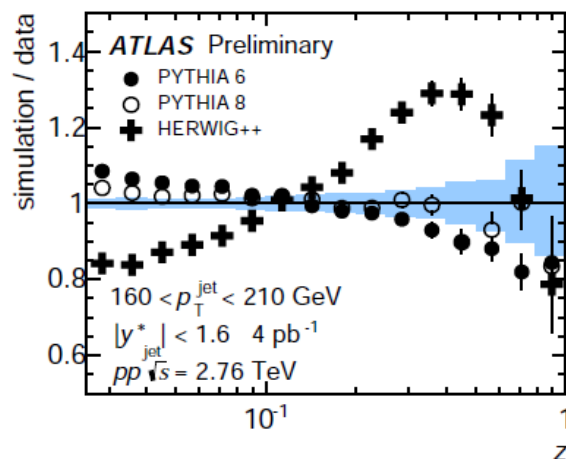
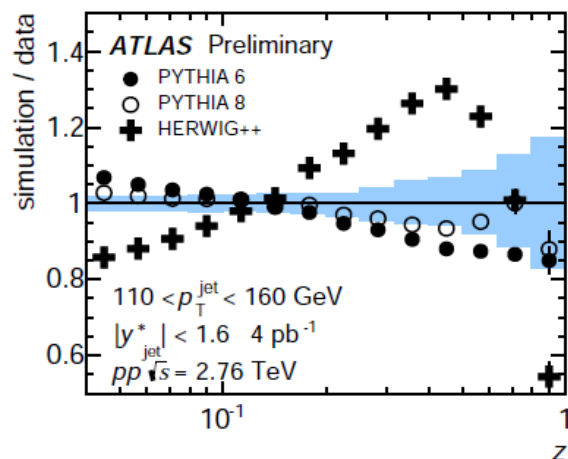
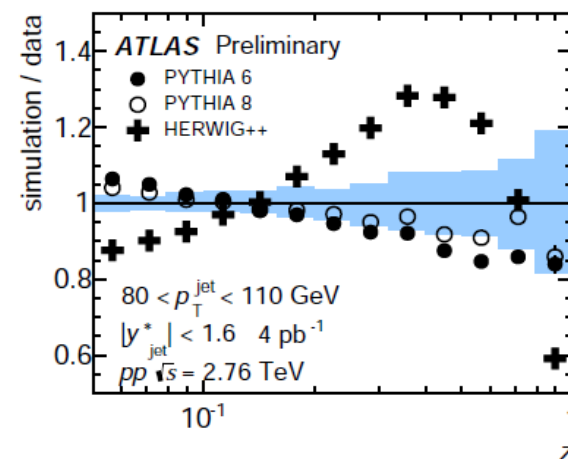
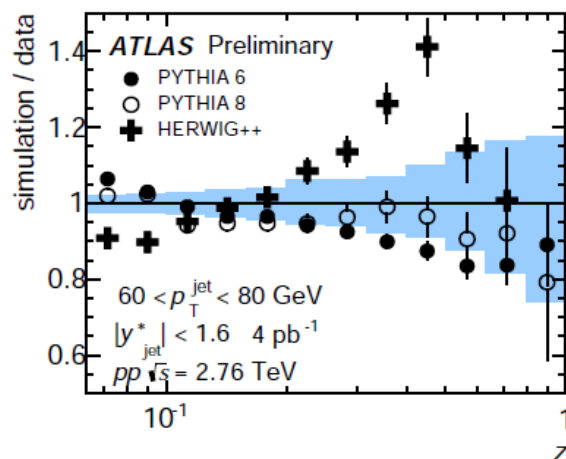
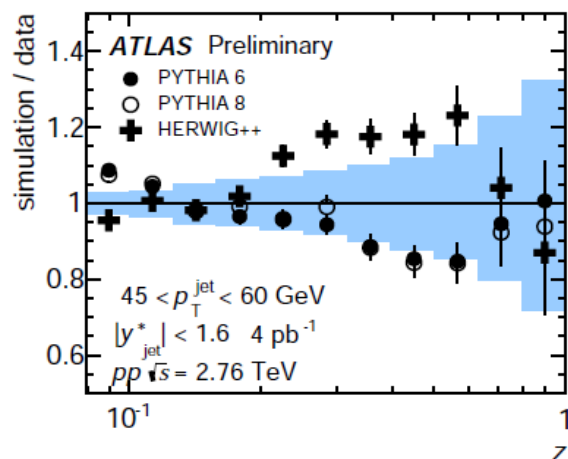


Agreement of the data with NLO CT10 in the forward region may be accidental
 \leq centrality dependence of the yields is seen

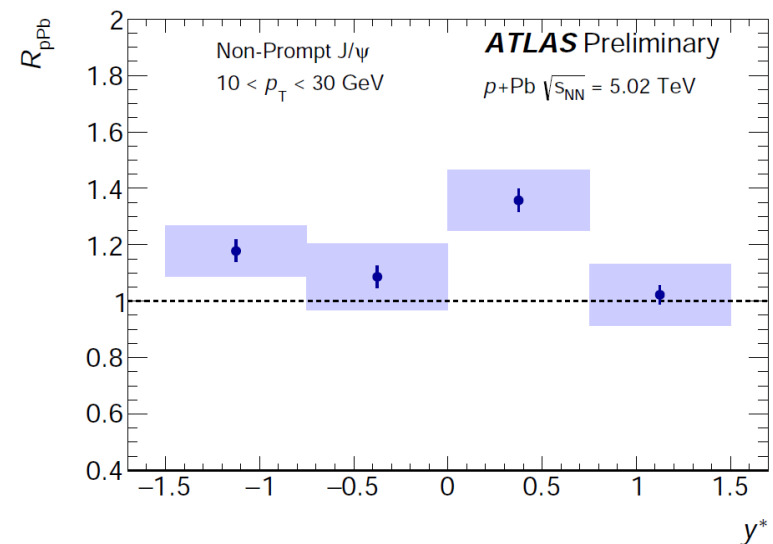
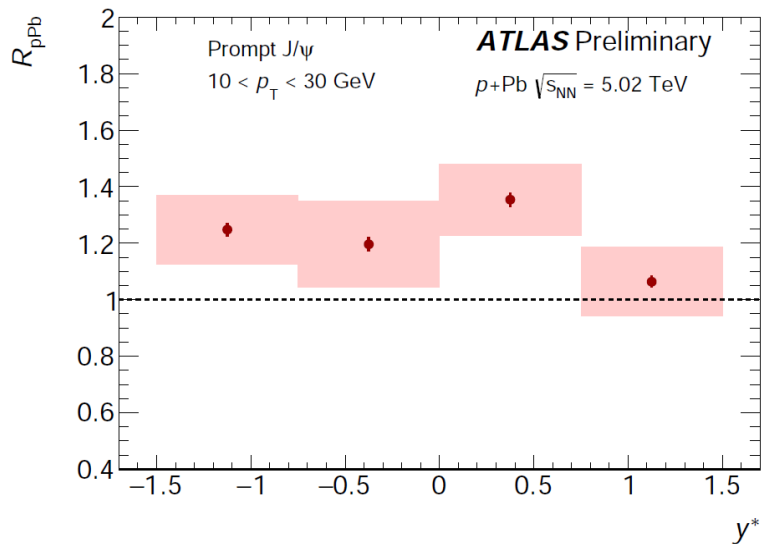
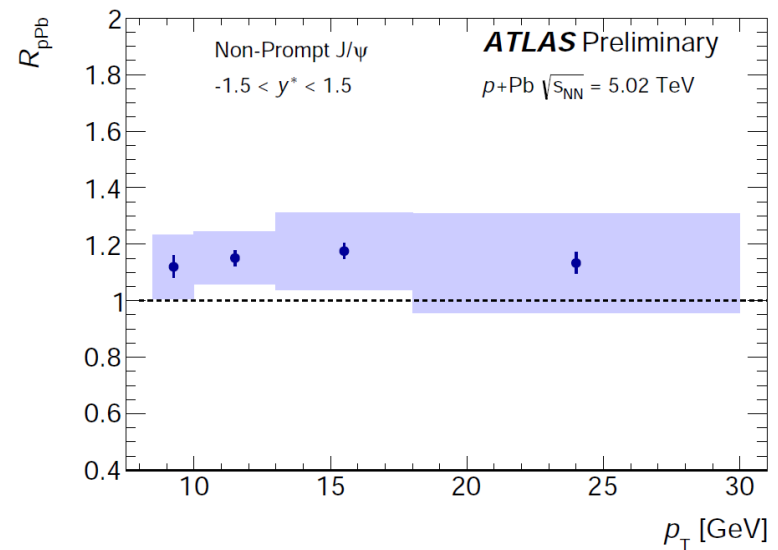
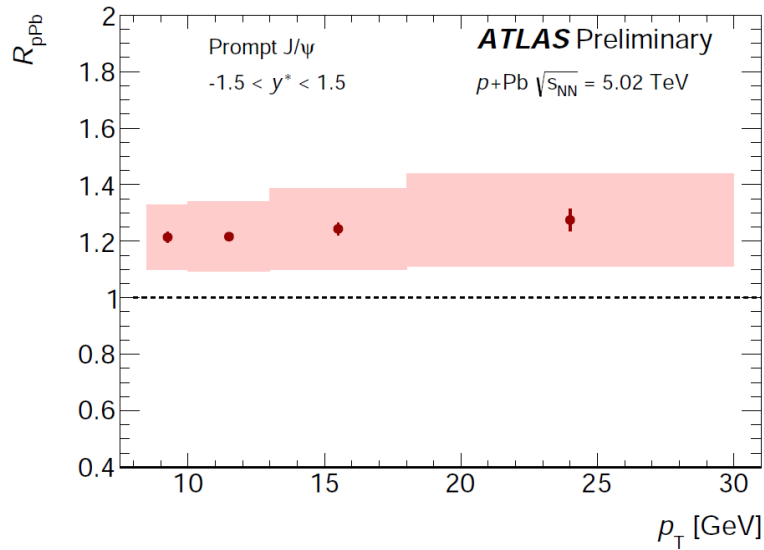
More central collisions, more nuclear matter involved \Rightarrow expect larger modification

$$R_{\text{CP}}(y_Z^*) = \frac{\langle N_{\text{coll}} \rangle^{\text{peripheral}}}{\langle N_{\text{coll}} \rangle^{\text{central}}} \times \frac{dN_Z^{\text{central}}/dy_Z^*}{dN_Z^{\text{peripheral}}/dy_Z^*}$$

Fragmentation functions in different generators

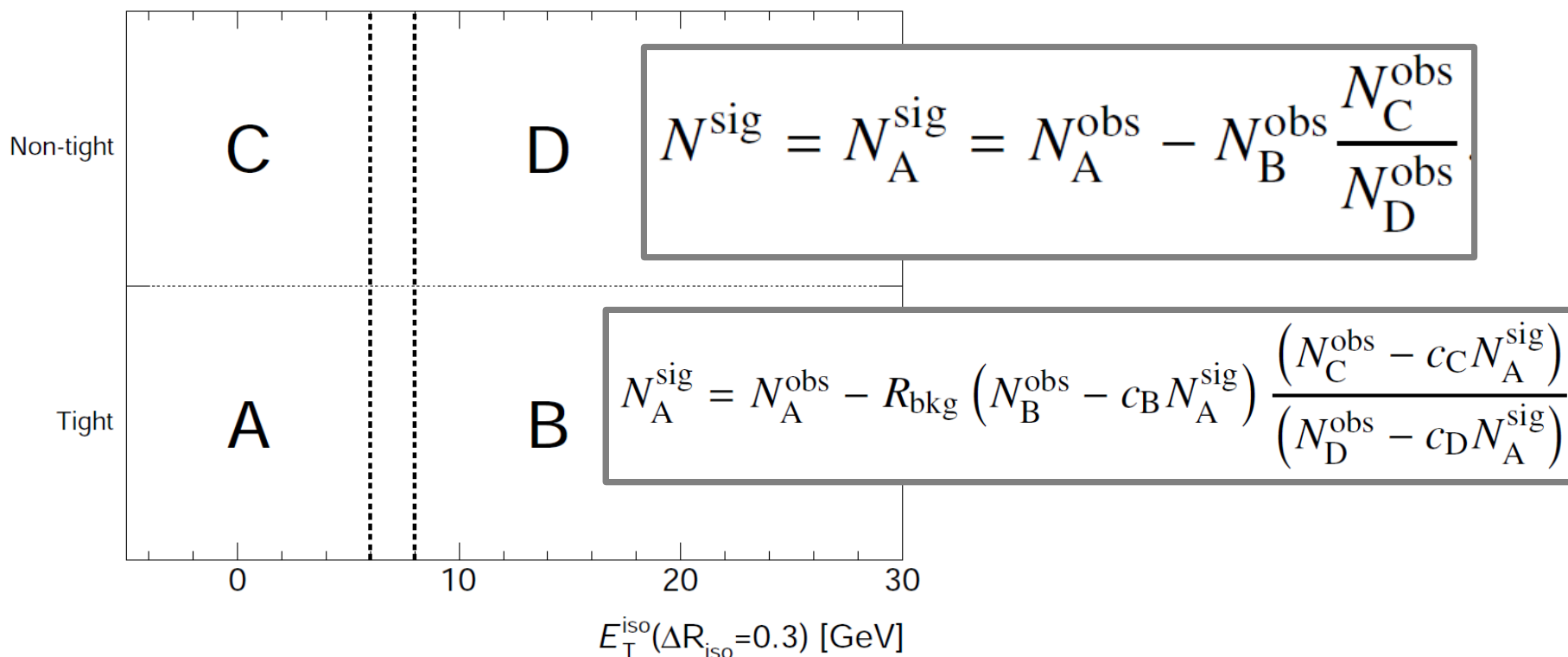


J/Psi and Psi(2) in p+Pb

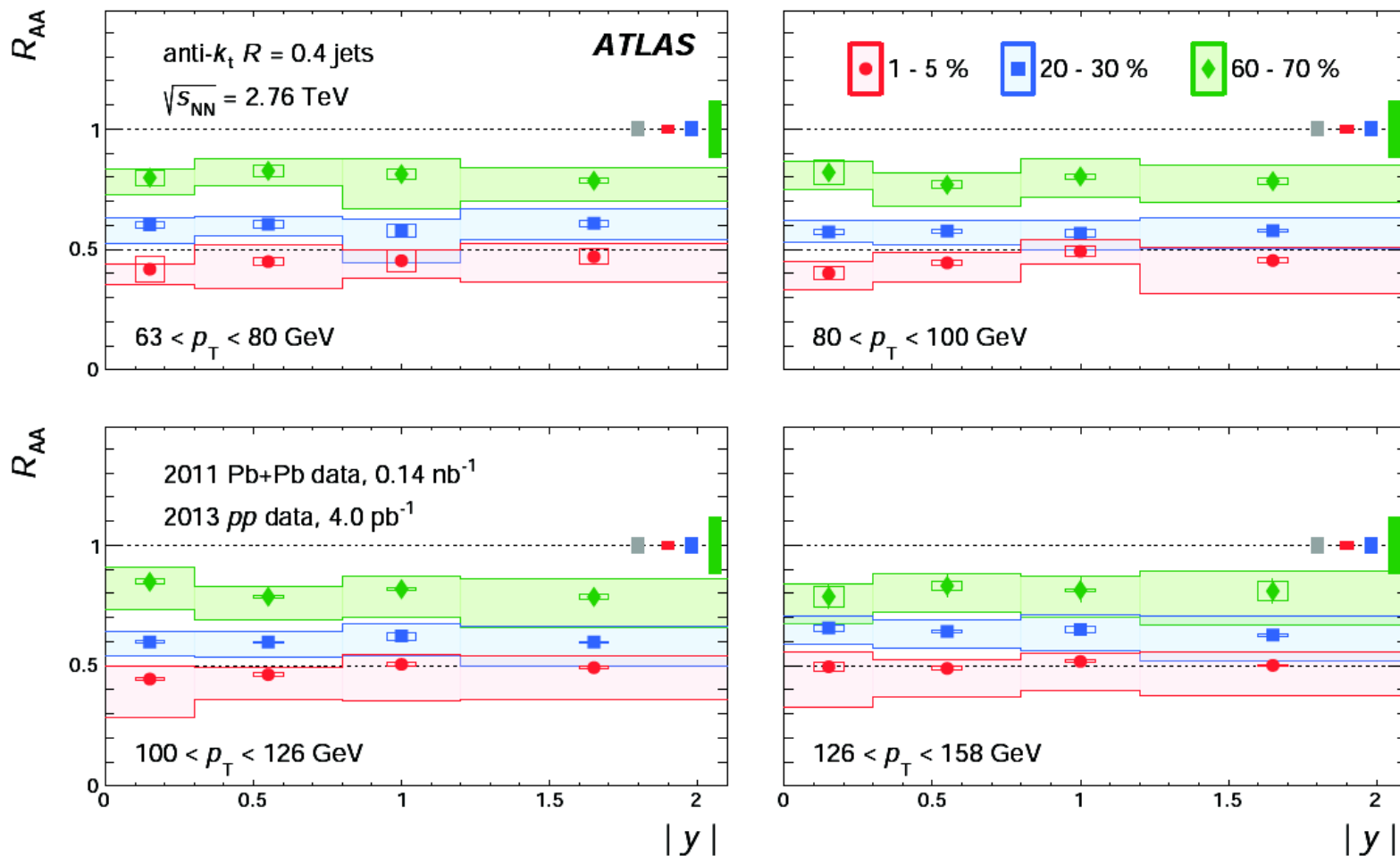


Isolated prompt photons

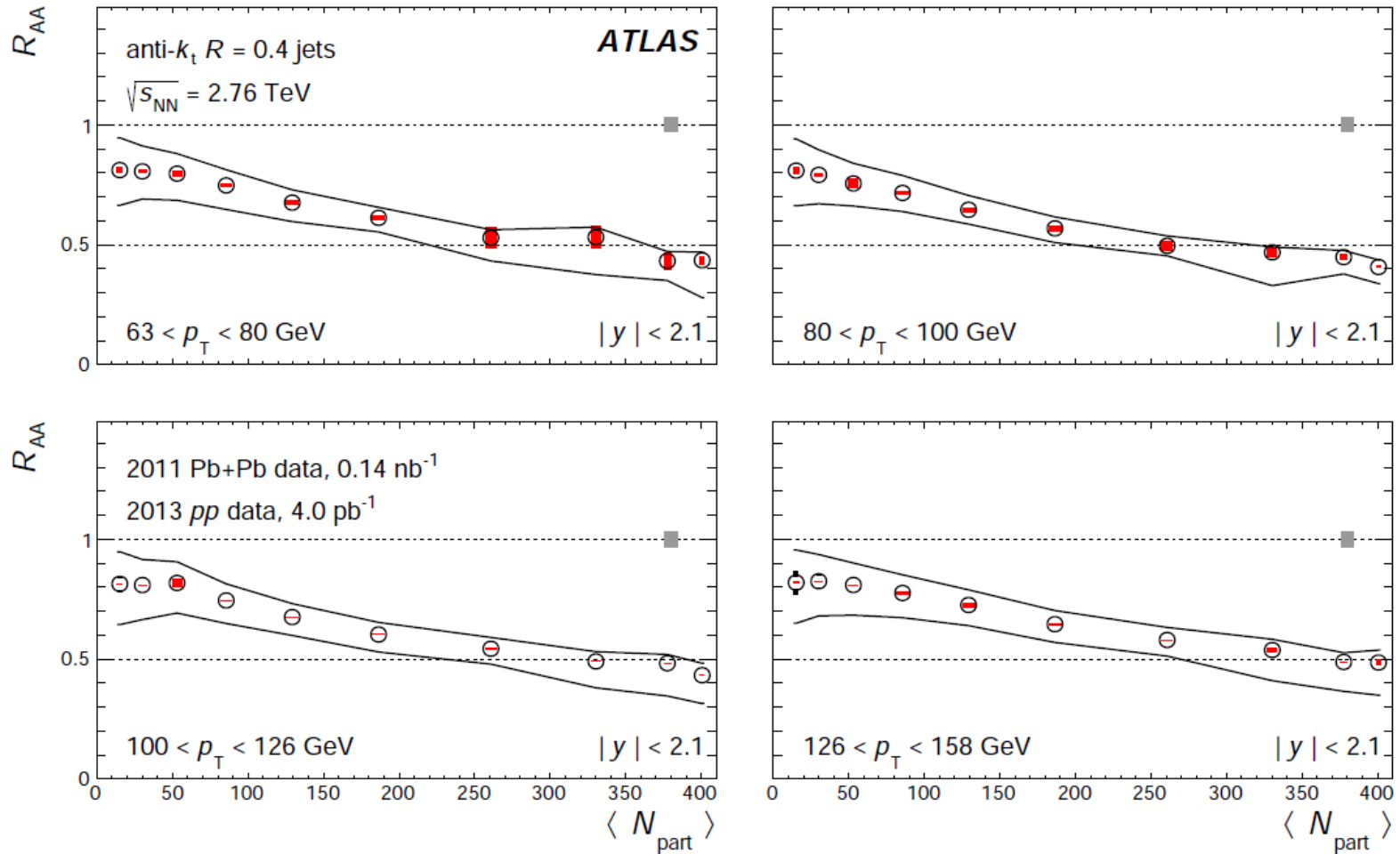
$$\frac{1}{N_{\text{evt}}(C)} \frac{dN_{\gamma}}{dp_T}(p_T, \eta, C) = \frac{N_A^{\text{sig}} \mathcal{U}(p_T, \eta, C) \mathcal{W}(p_T, \eta, C)}{N_{\text{evt}}(C) \epsilon_{\text{tot}}(p_T, \eta, C) \Delta p_T}$$



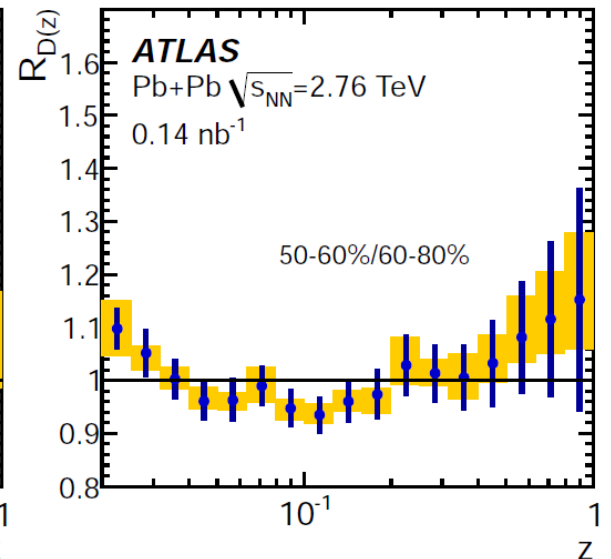
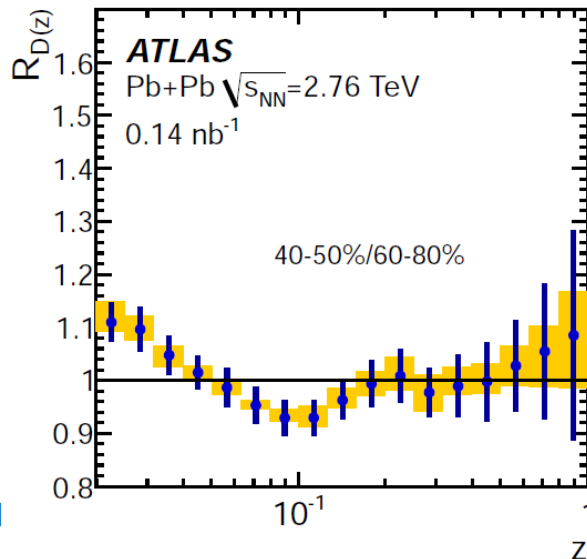
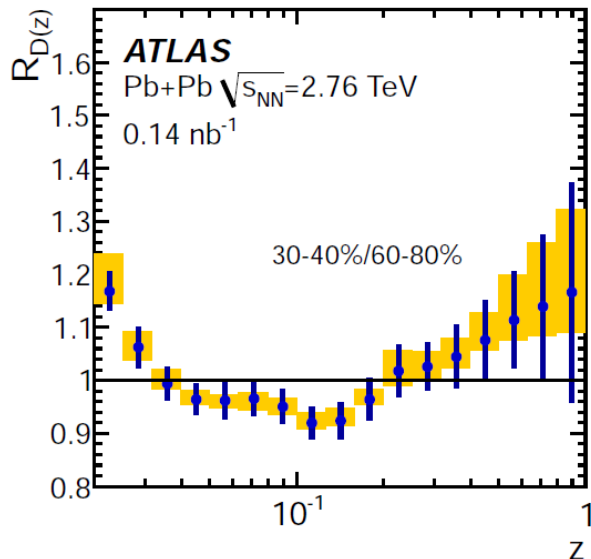
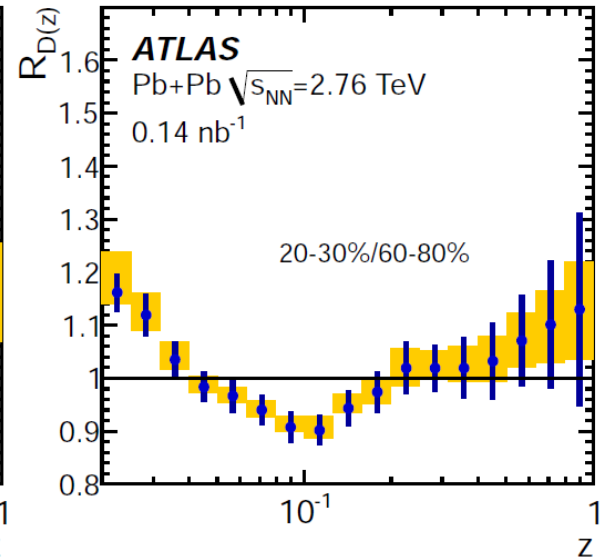
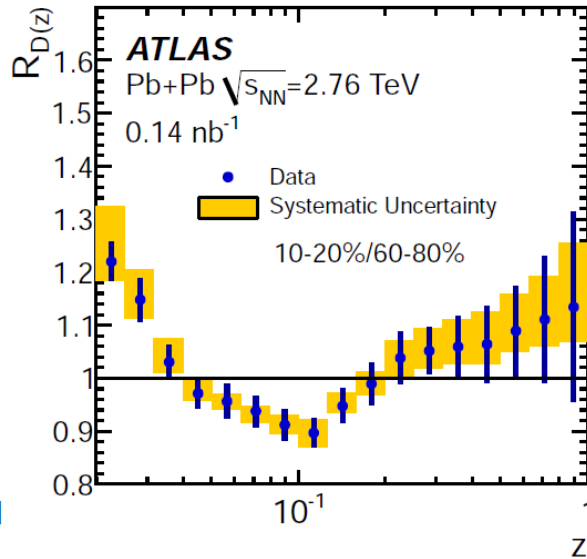
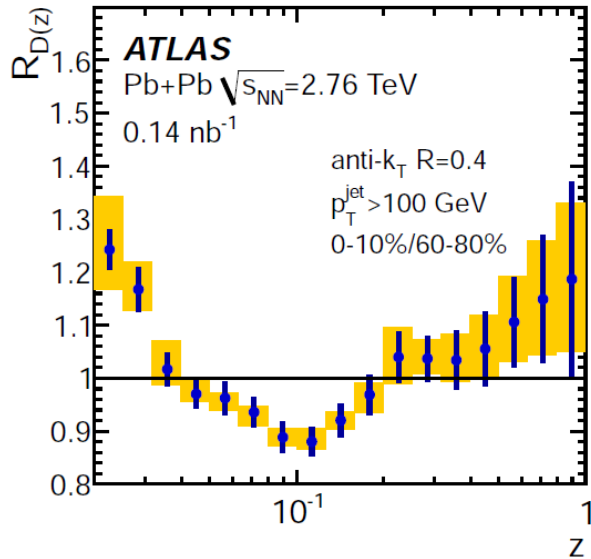
Jet R_{AA}



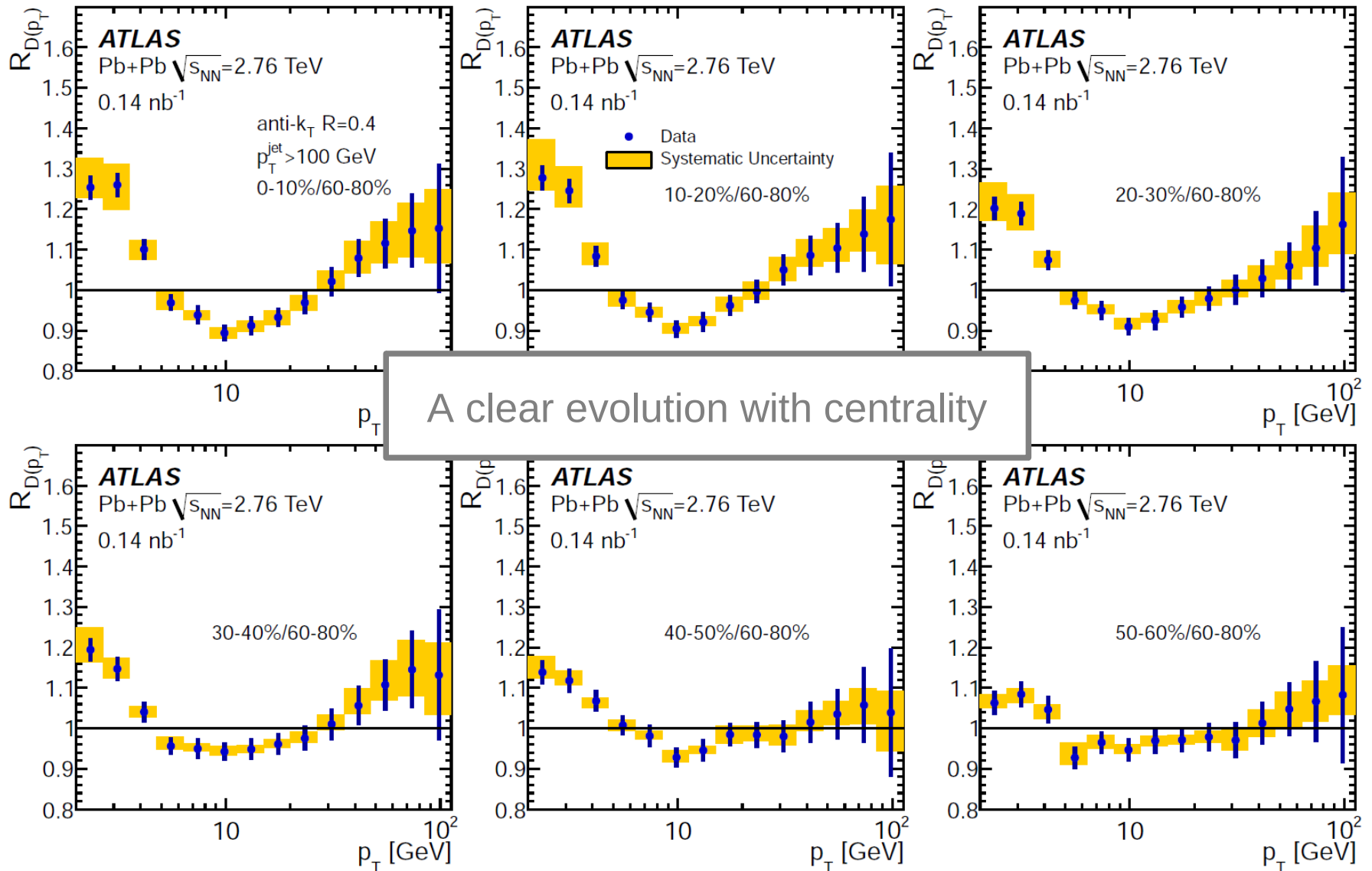
Jet R_{AA}



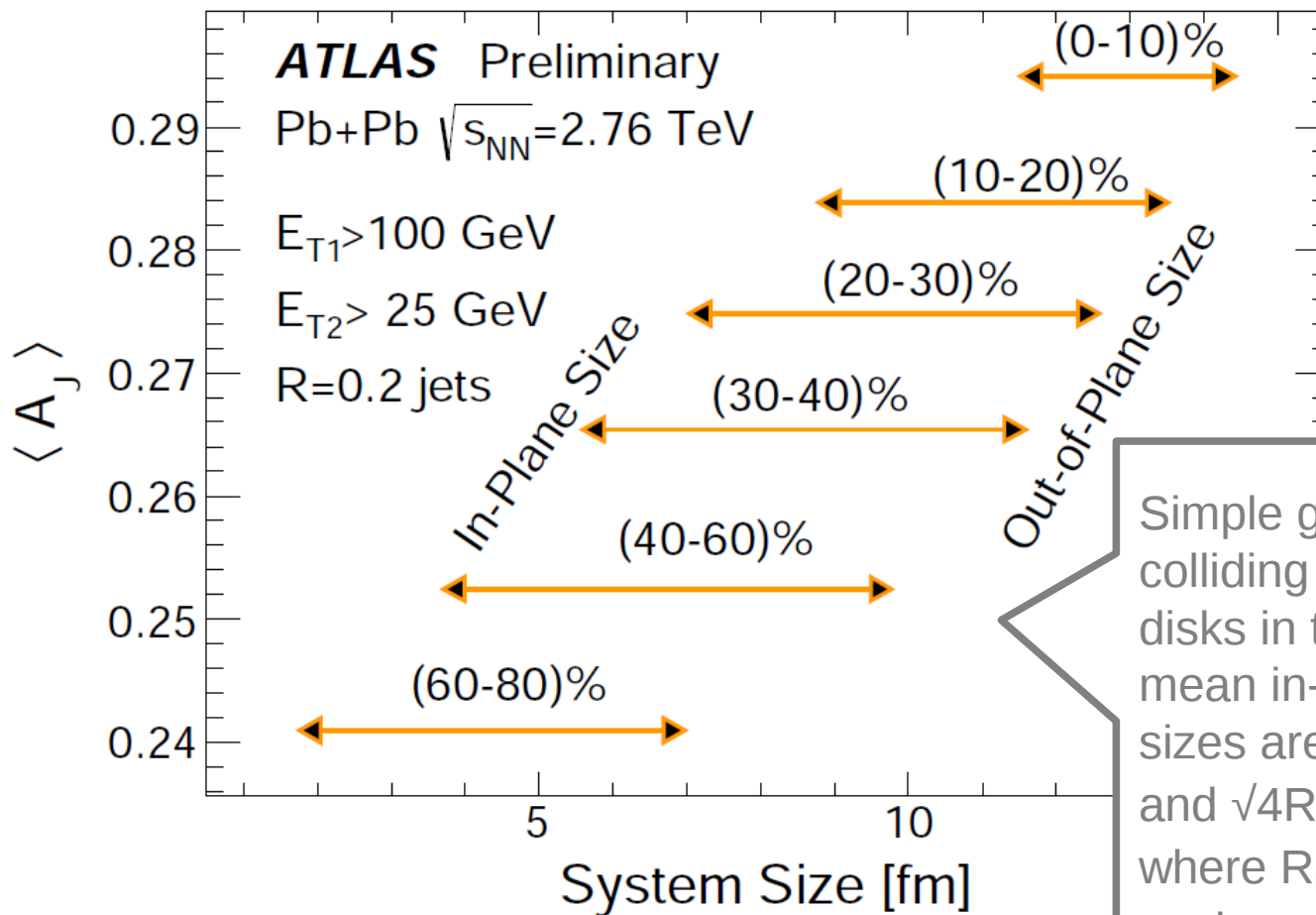
$R_{D(z)}$ in Pb+Pb for $R=0.4$ jets



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

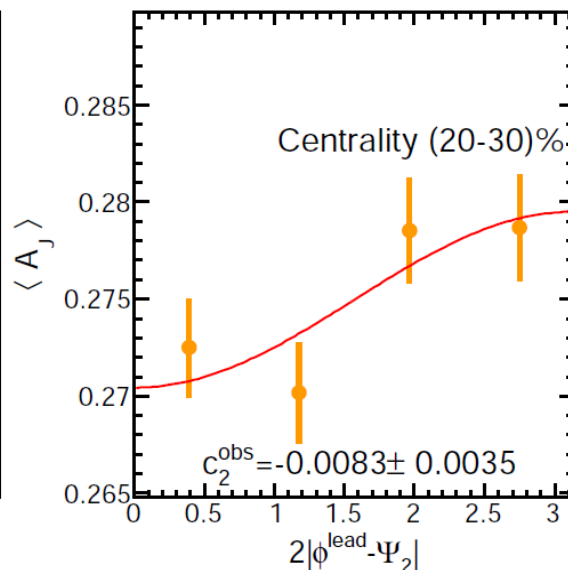
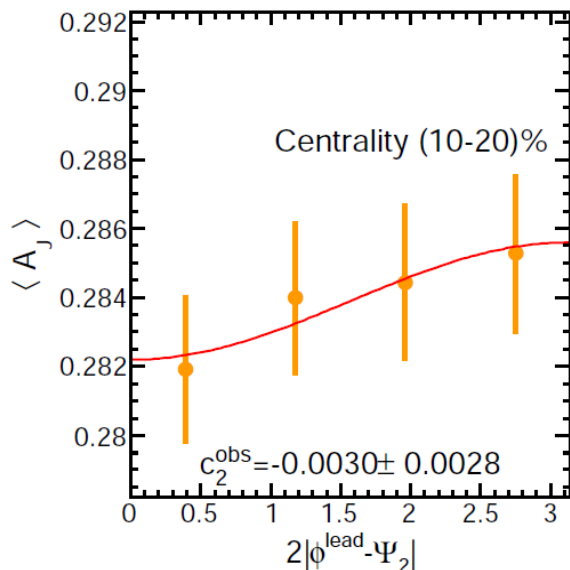
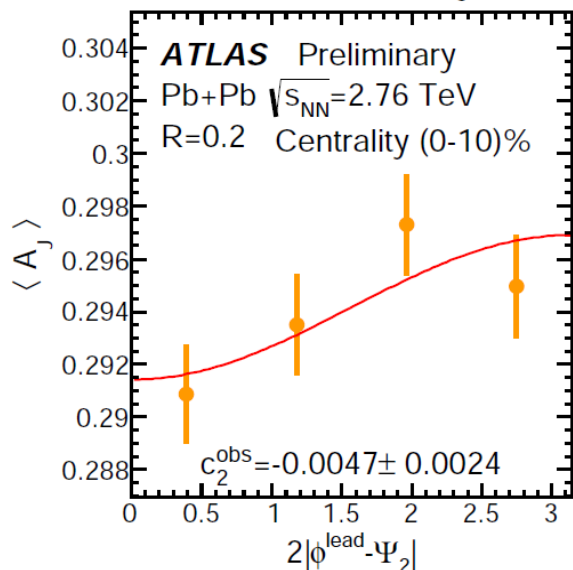
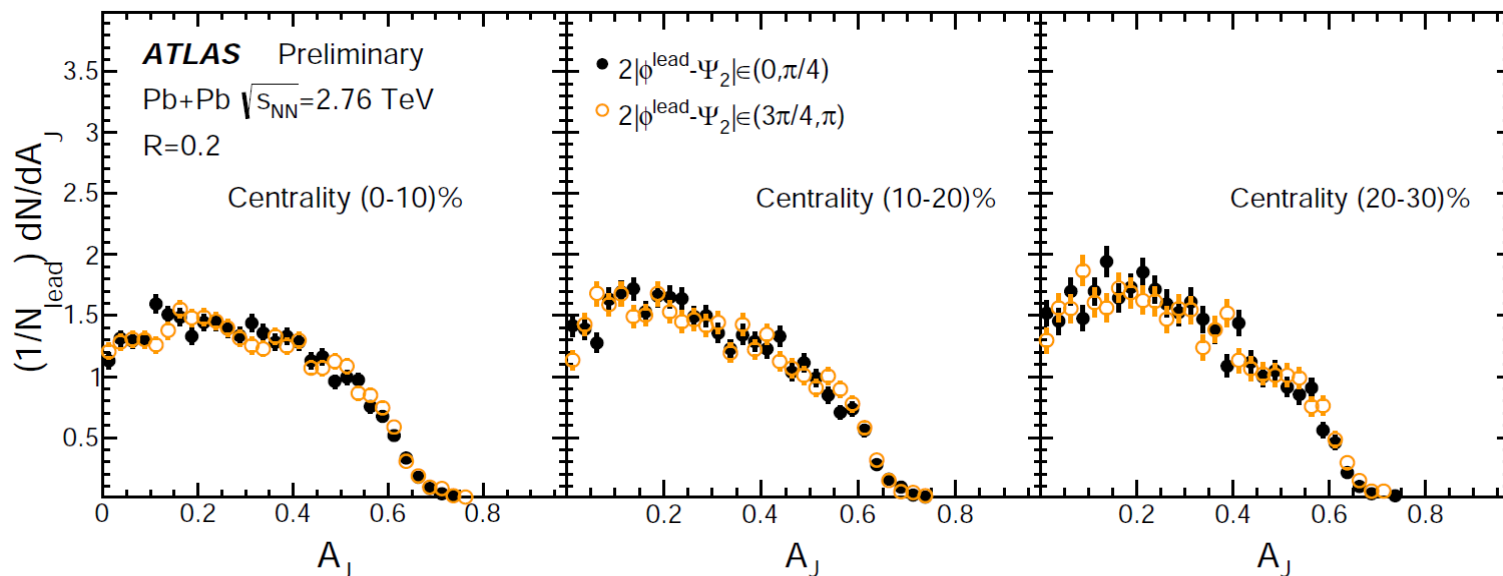


Jet and event shape correlations, system size from a simple model

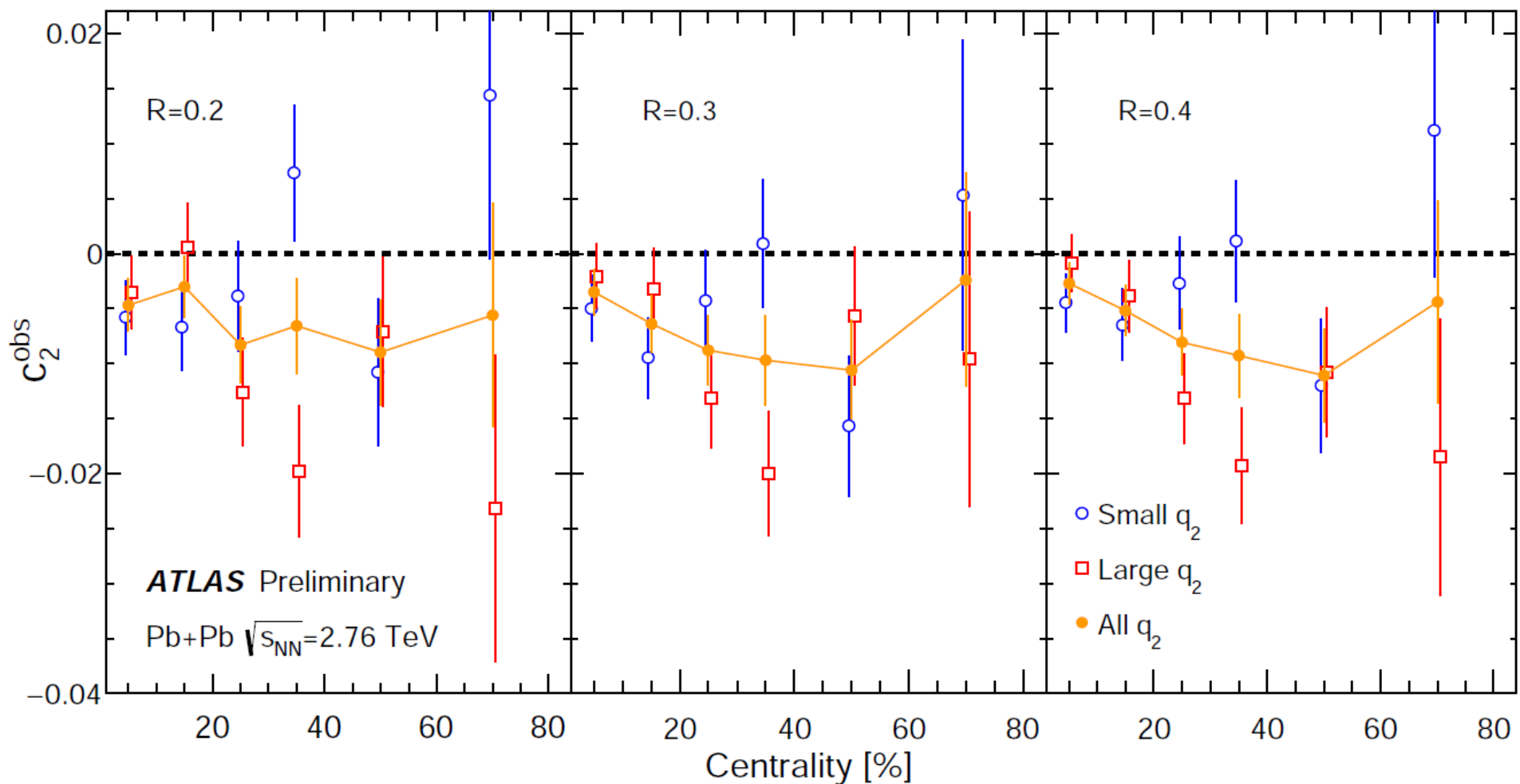


Simple geometric picture: The colliding nucleons are treated as disks in the transverse plane. The mean in-plane and out-of plane sizes are obtained as $2R_{Pb}-\langle b_{imp} \rangle$ and $\sqrt{4R_{Pb}^2-\langle b_{imp} \rangle^2}$ respectively, where R_{Pb} is the radius of the Pb nucleus (7.4 fm)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

- Neighboring jet production quantified using quantity previously measured at Tevatron

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

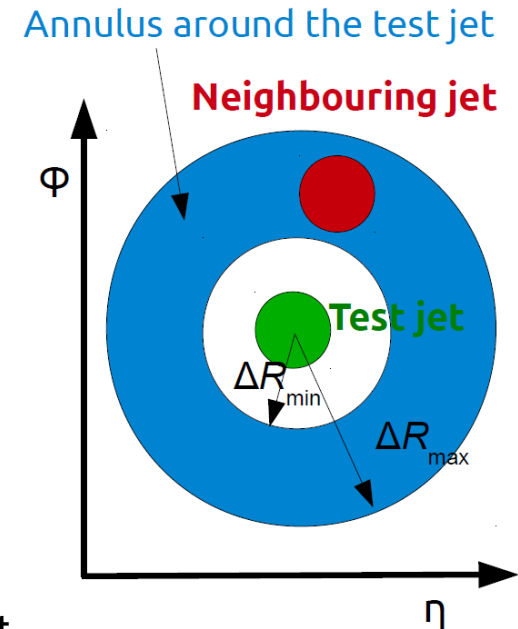
... the rate of neighboring jets that accompany a given test jet.

- $R_{\Delta R}$ evaluated also differentially in neighboring jet E_T

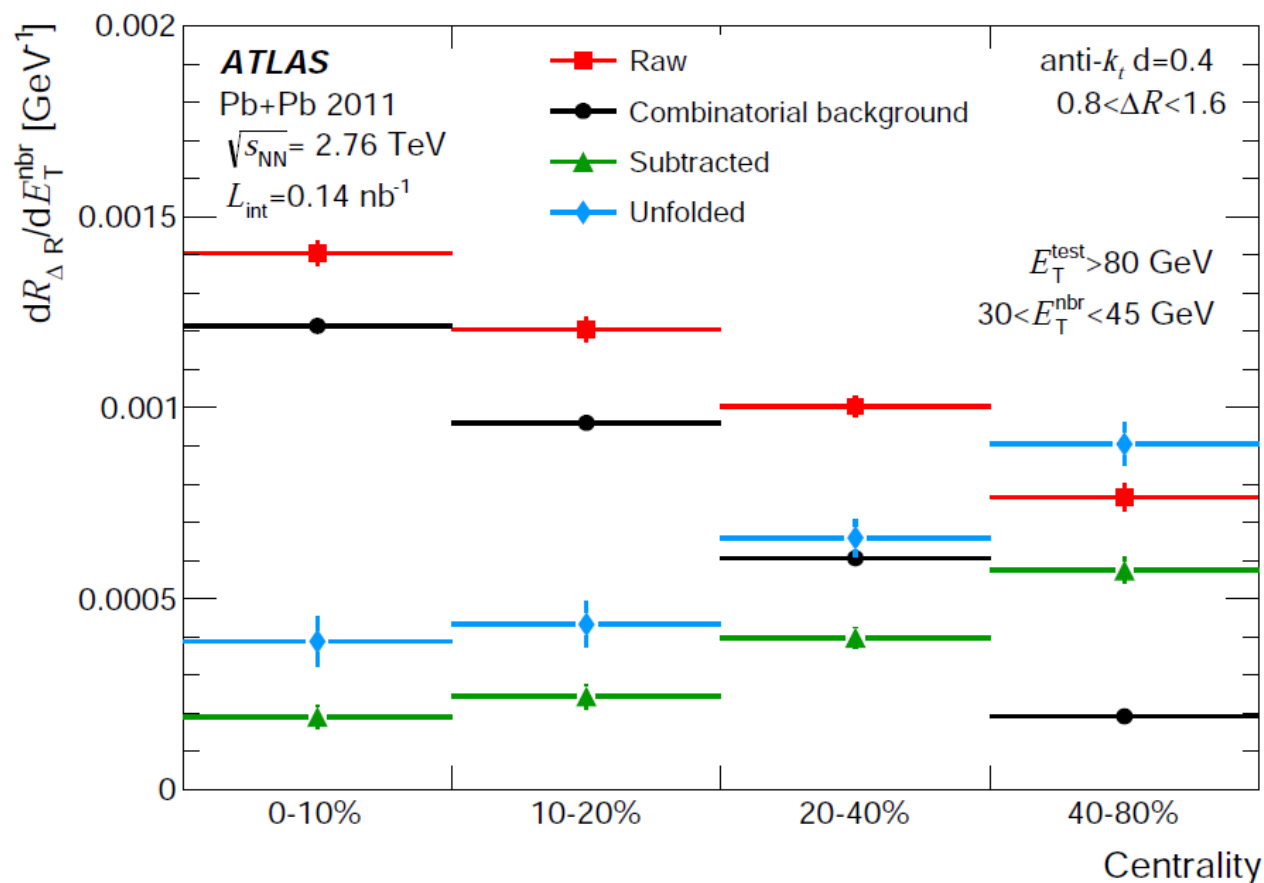
$$\frac{dR_{\Delta R}}{dE_T^{\text{nbr}}} = \frac{1}{dN_{\text{jet}}^{\text{test}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet}}^{\text{test}}} \frac{d^2 N_{\text{jet},i}^{\text{nbr}}}{dE_T^{\text{test}} dE_T^{\text{nbr}}} (E_{T,\text{min}}^{\text{test}}, E_T^{\text{nbr}}, \Delta R)$$

... which are the E_T spectra of the third (or n^{th}) jet given the test jet E_T

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



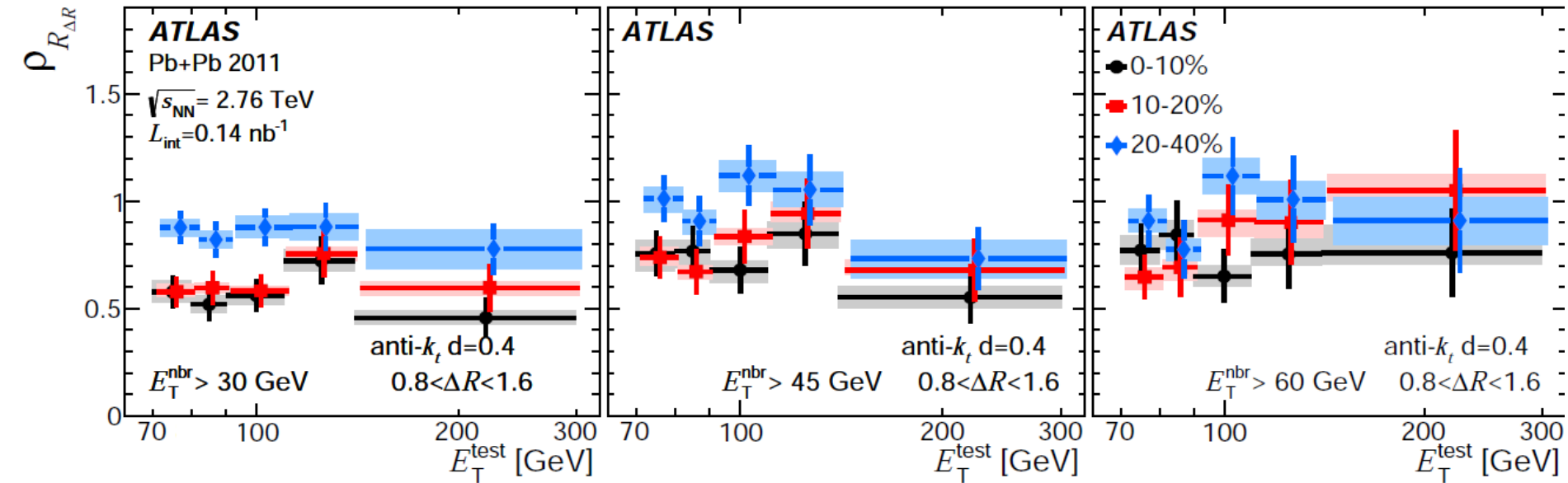
Correction flow for neighboring jet yields



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

$$\text{Unfolded} = k * (\text{Raw} - \text{Combinatorics})$$

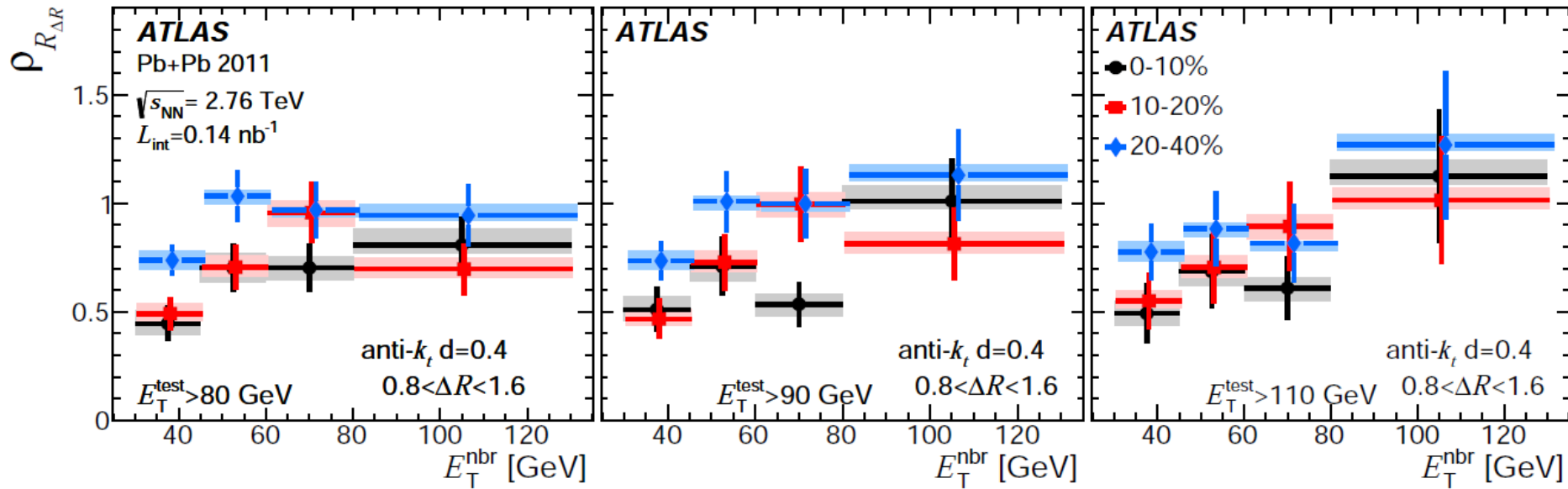
Central-to-peripheral ratios



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).