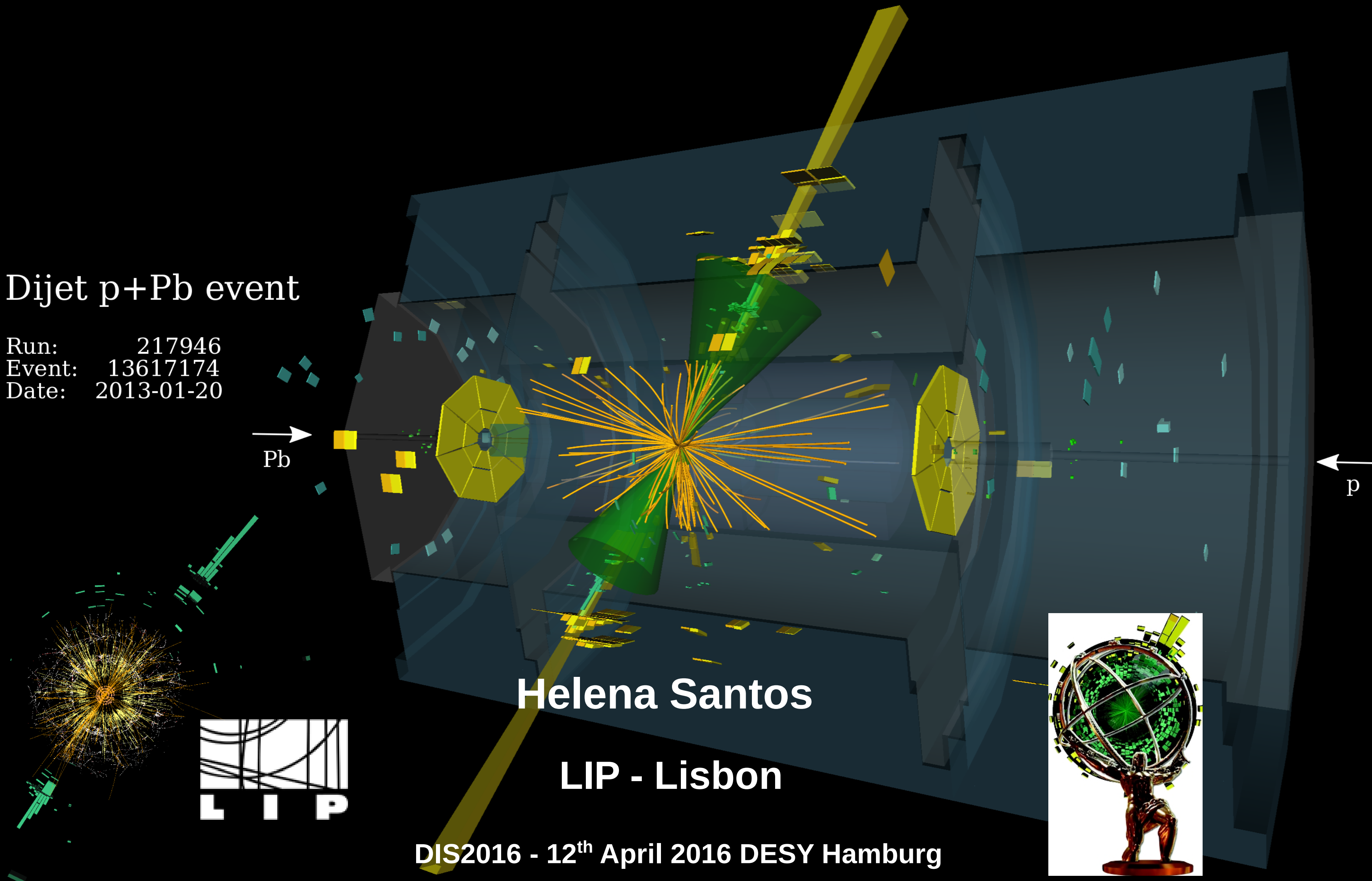
Jet measurements in p+Pb and Pb+Pb with the ATLAS Experiment at the LHC



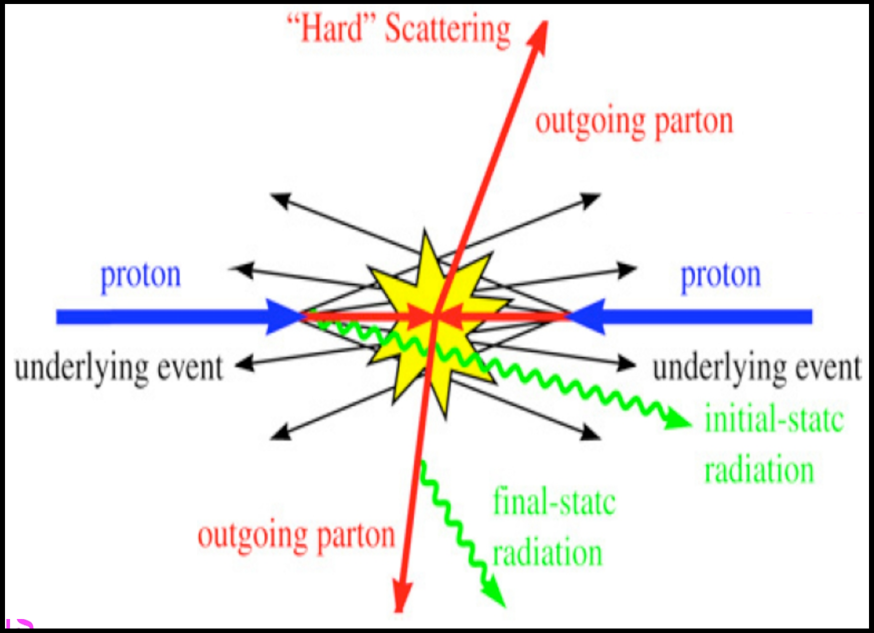
Helena Santos

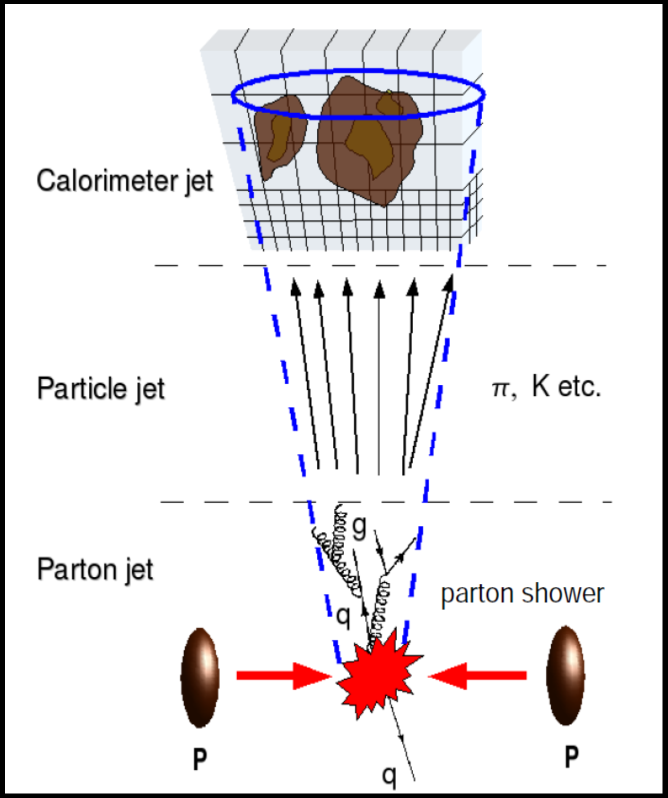
LIP - Lisbon

DIS2016 - 12th April 2016 DESY Hamburg

Jets in p+p – a baseline for HI

The common picture (p+p):

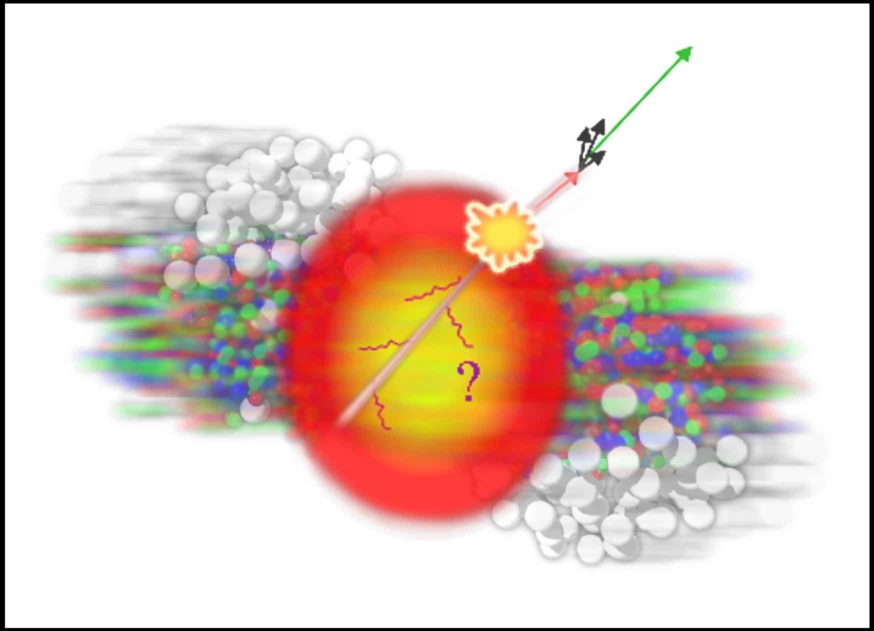


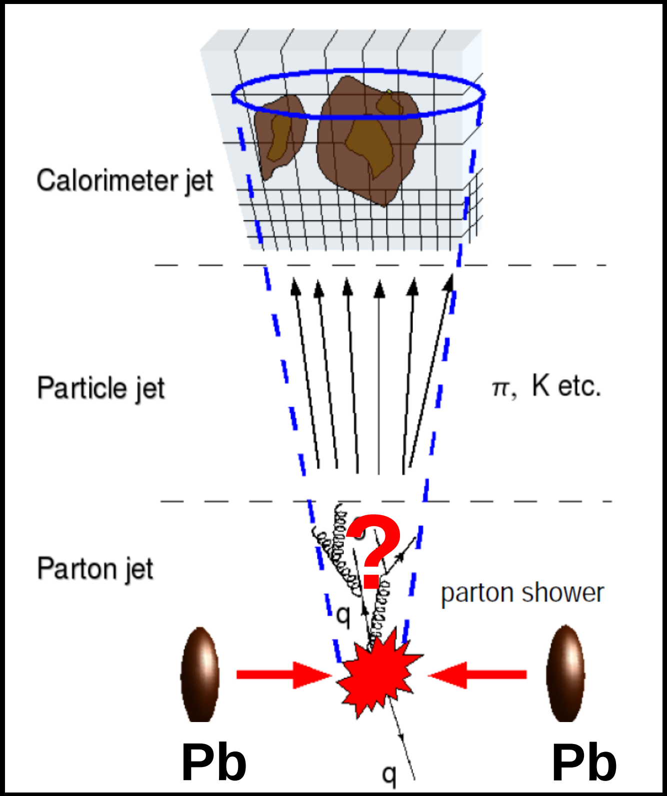


Jets produced in vacuum are well understood and constitute a reliable baseline to study medium-dependence effects.

Jets as probes of hot matter

Quark Gluon Plasma is opaque to coloured partons.
How do parton showers in the hot and dense medium differ from those in vacuum?



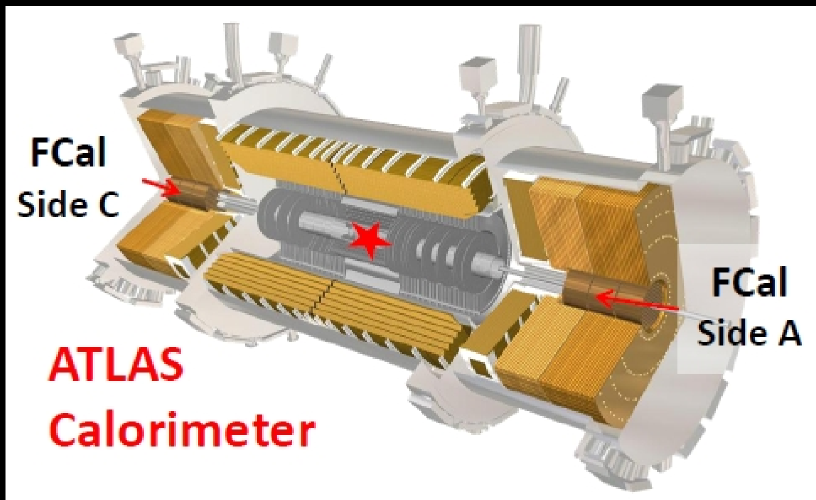


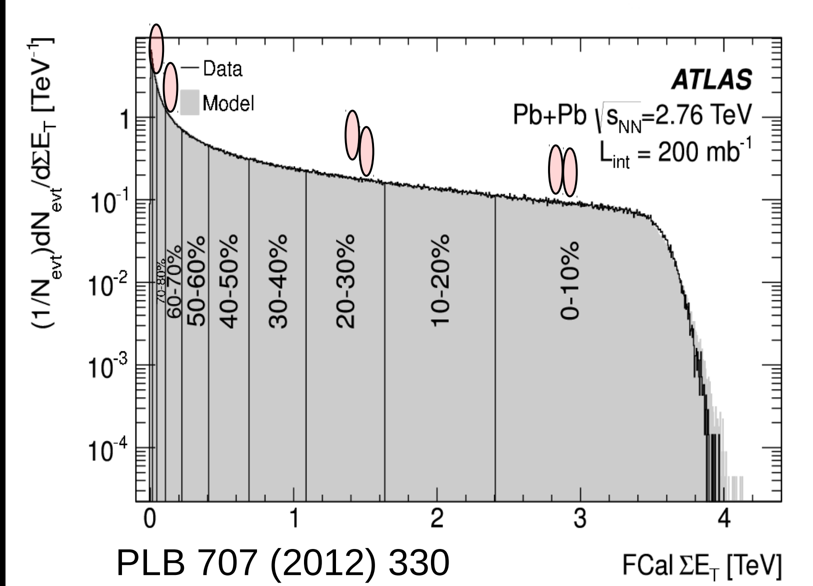
What is expected:

Partons lose energy, resulting in jet “quenching”.

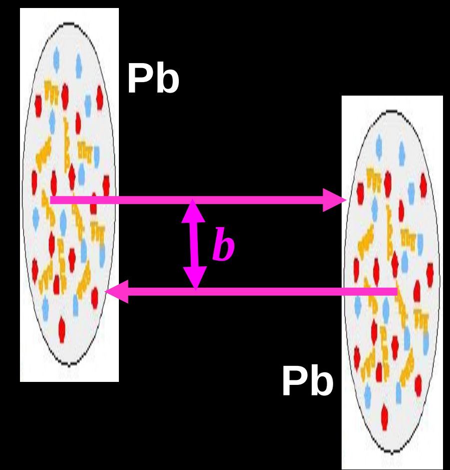
Jets probe the very first phase of the collision → they carry relevant information about the QGP .

Collisions "Centrality"





HI collision's dynamics controlled by impact parameter "b"

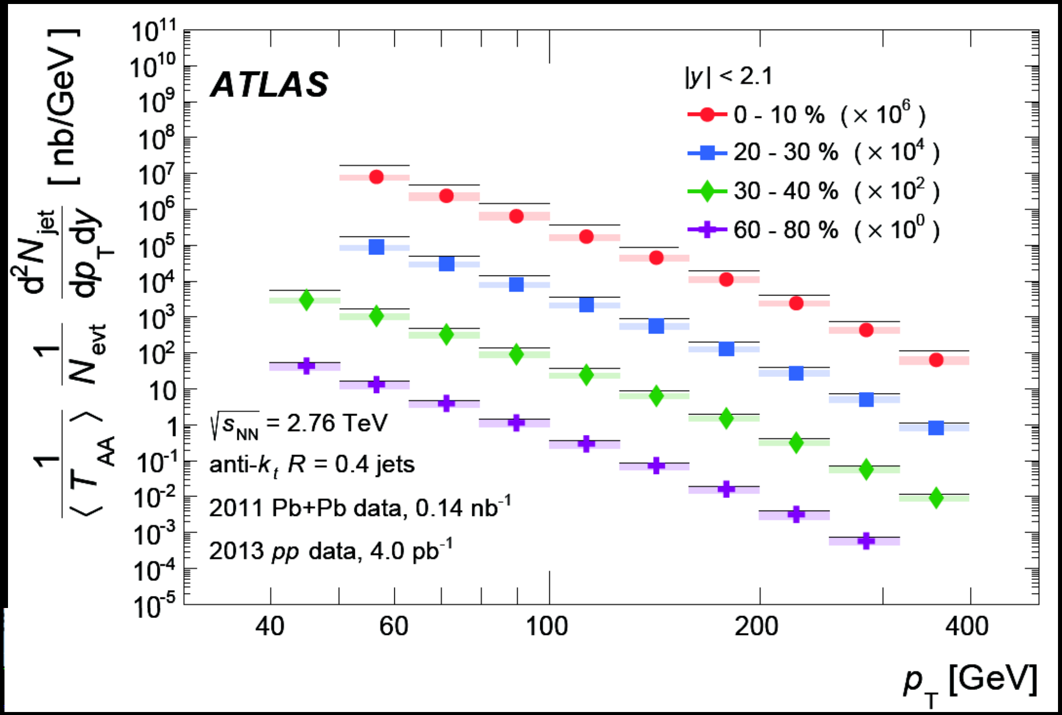


Transverse energy, E_T, measured in the forward calorimeters, FCal

Nuclear thickness function:
$\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{pp}$.
Will be used to measure the nuclear modification factor R_{AA}.

Jet production as a function of p_T

PRL 114 (2015) 072302



Different colours, different centralities ($|y| < 2.1$).

per-event jet yield scaled by $1/\langle T_{AA} \rangle$.

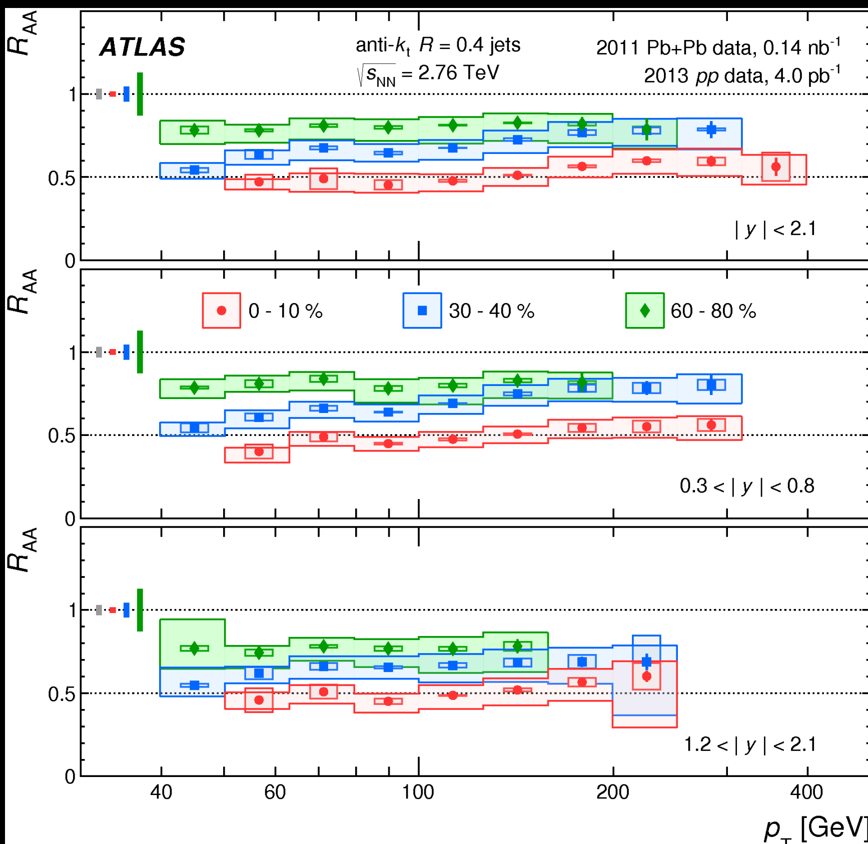
pp reference denoted by **black** line.

- **Pb+Pb** @ 2.76 TeV, 140 μb^{-1}; anti-k_T jets with R=0.4; iterative subtraction of underlying event, correction for particle flow.

- Jet spectra were corrected for jet energy resolution by SVD (singular value decomposition) unfolding and for reconstruction inefficiency.

Jet R_{AA}

$$R_{AA} = \frac{\left.\frac{1}{N_{evt}} \frac{d^2 N_{jet}}{dp_T dy}\right|_{cent}}{\langle T_{AA} \rangle_{cent} \times \frac{d^2 \sigma^{pp}_{jet}}{dp_T dy}}$$



PRL 114 (2015) 072302

Comparison of **Pb+Pb** yields to **p+p** yields in different centralities and different y intervals.

- **Jets in Pb+Pb are suppressed relatively to p+p up to a factor of 2.**
- **Slight rise with p_T at mid−central and central collisions.**
- **No dependence on rapidity.**

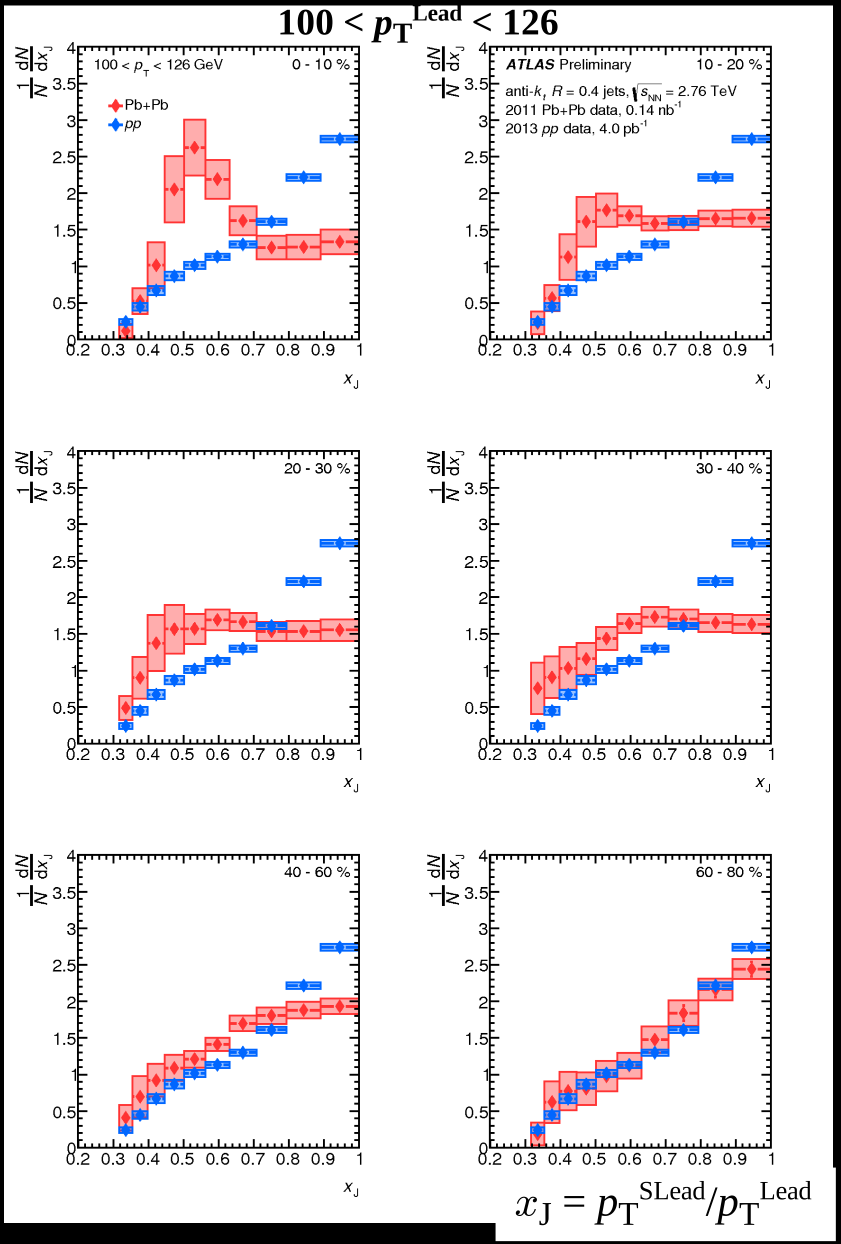
Dijet asymmetry

Dijet asymmetry probes differences in quenching between the two parton showers.

Dijets were corrected for jet energy resolution by 2D Bayesian unfolding.

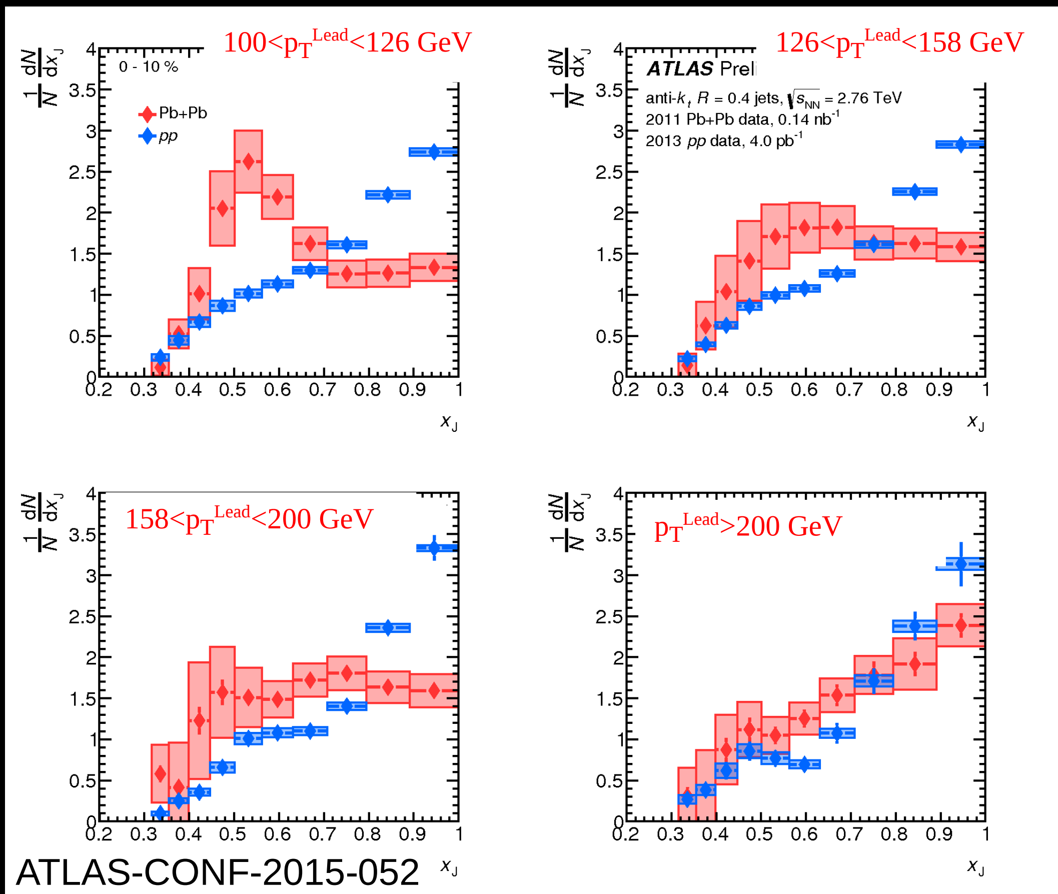
- **Enhancement of asymmetric dijets in Pb+Pb, relative to p+p as the centrality increases.**

ATLAS-CONF-2015-052

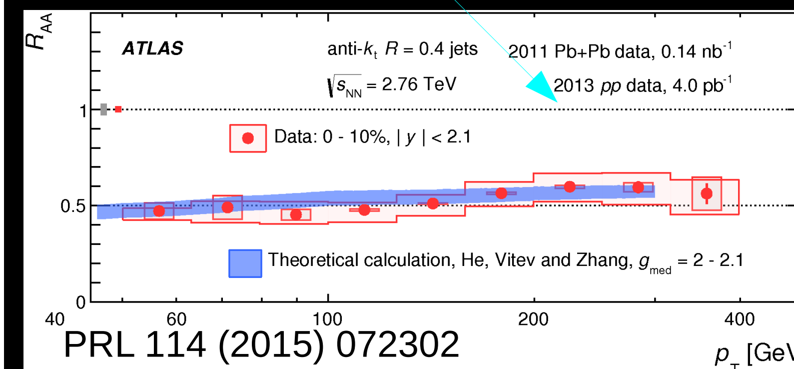


Dijet asymmetry in central collisions

p_T^{Lead} dependence in 0-10% centrality



Clear dependence with p_T of the leading jet, in contrast to single jets. R_{AA} shows very weak p_T dependence.

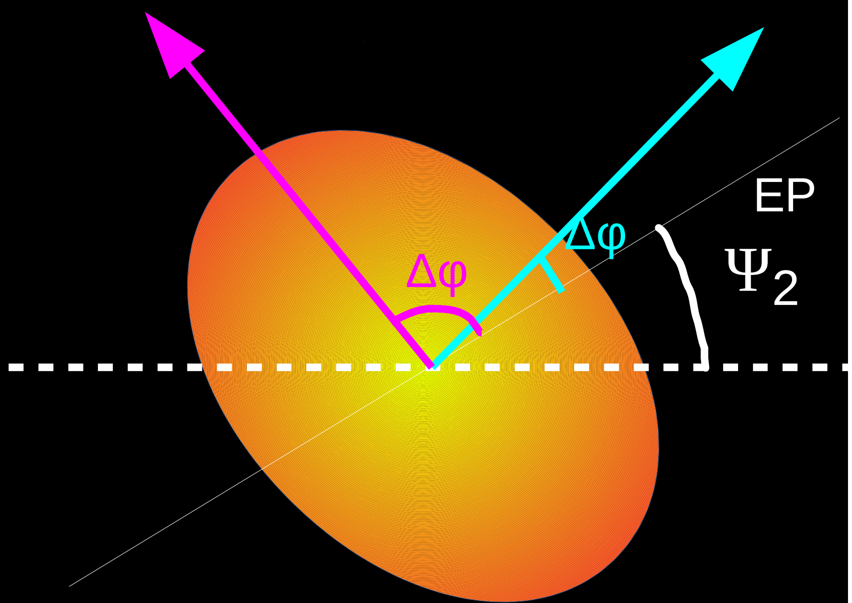


Much smaller modification at high p_T^{Lead}.

Possible effect from flavour composition. Relative quark/gluon mix in dijets changes with p_T^{Lead}.

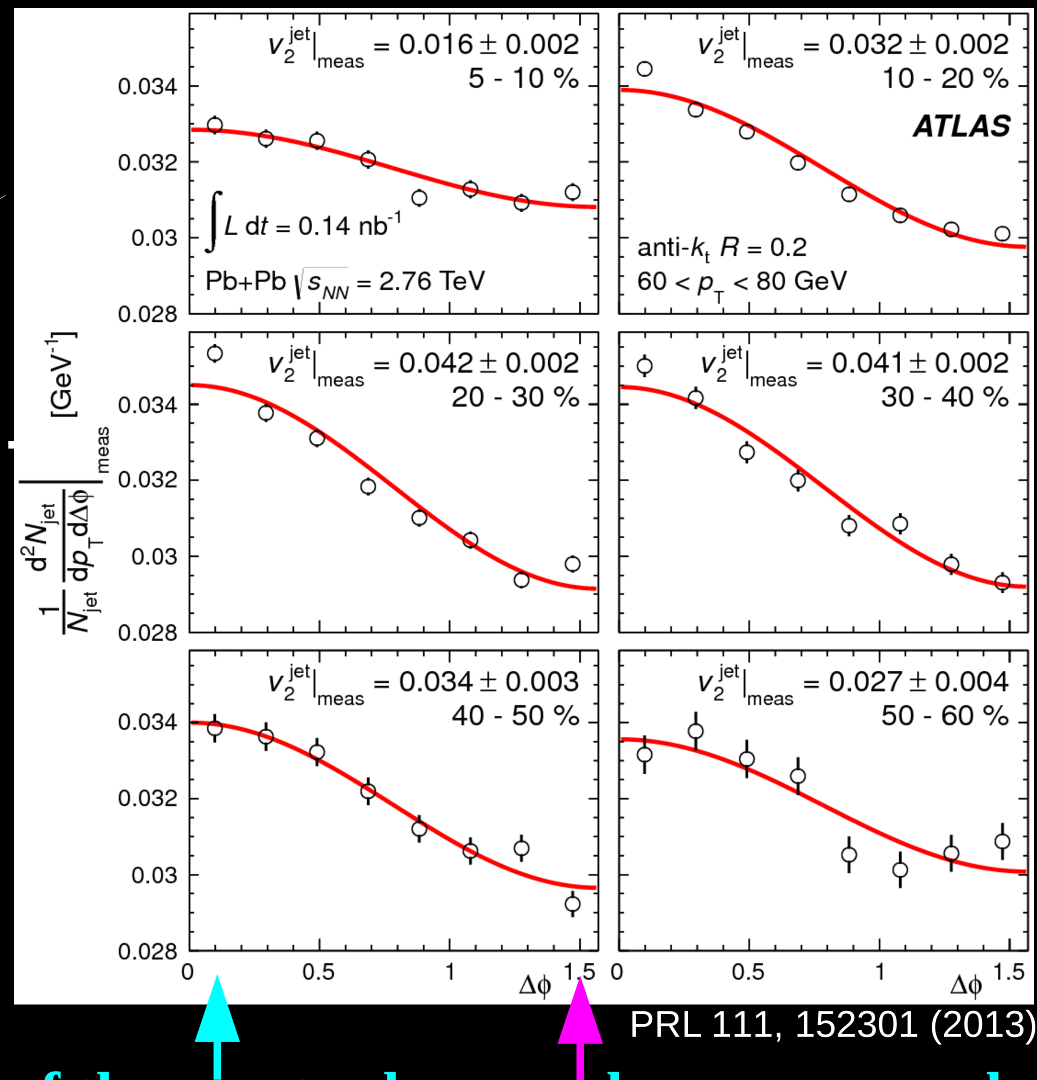
Path length dependence of quenching

Explore new observables that provide insight into the physical mechanisms responsible for jet quenching



Unequal path lengths of the showers in the medium

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$



PRL 111, 152301 (2013)

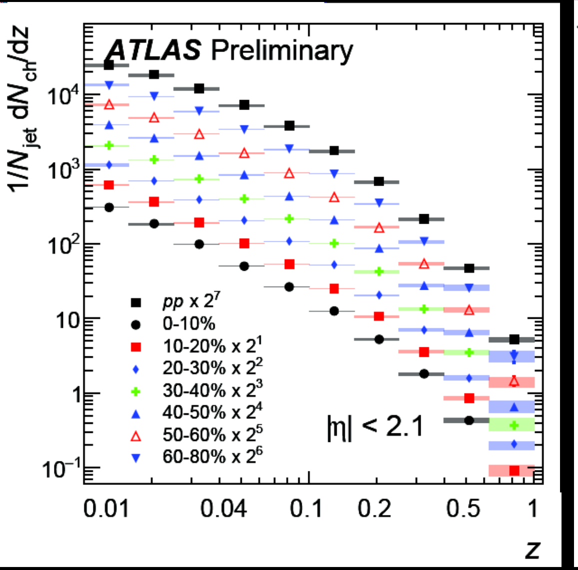
Jets produced in the direction of the event−plane are less suppressed

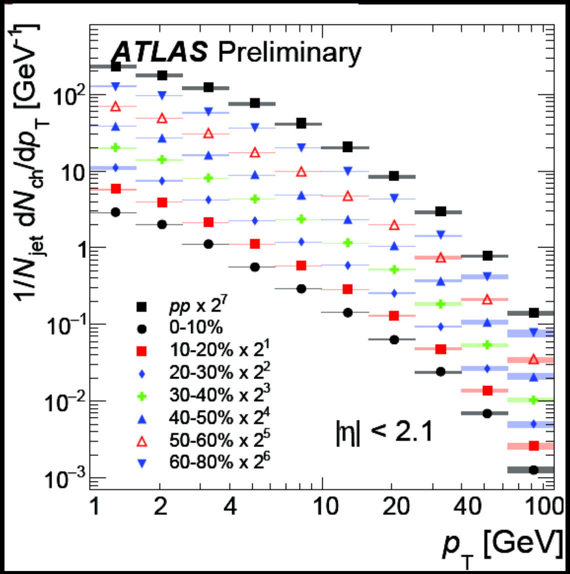
Jet fragmentation functions

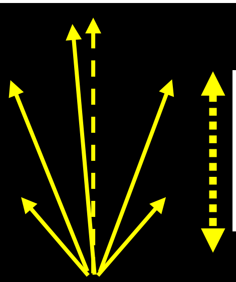
Jet internal structure is crucial to understand energy loss

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

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







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

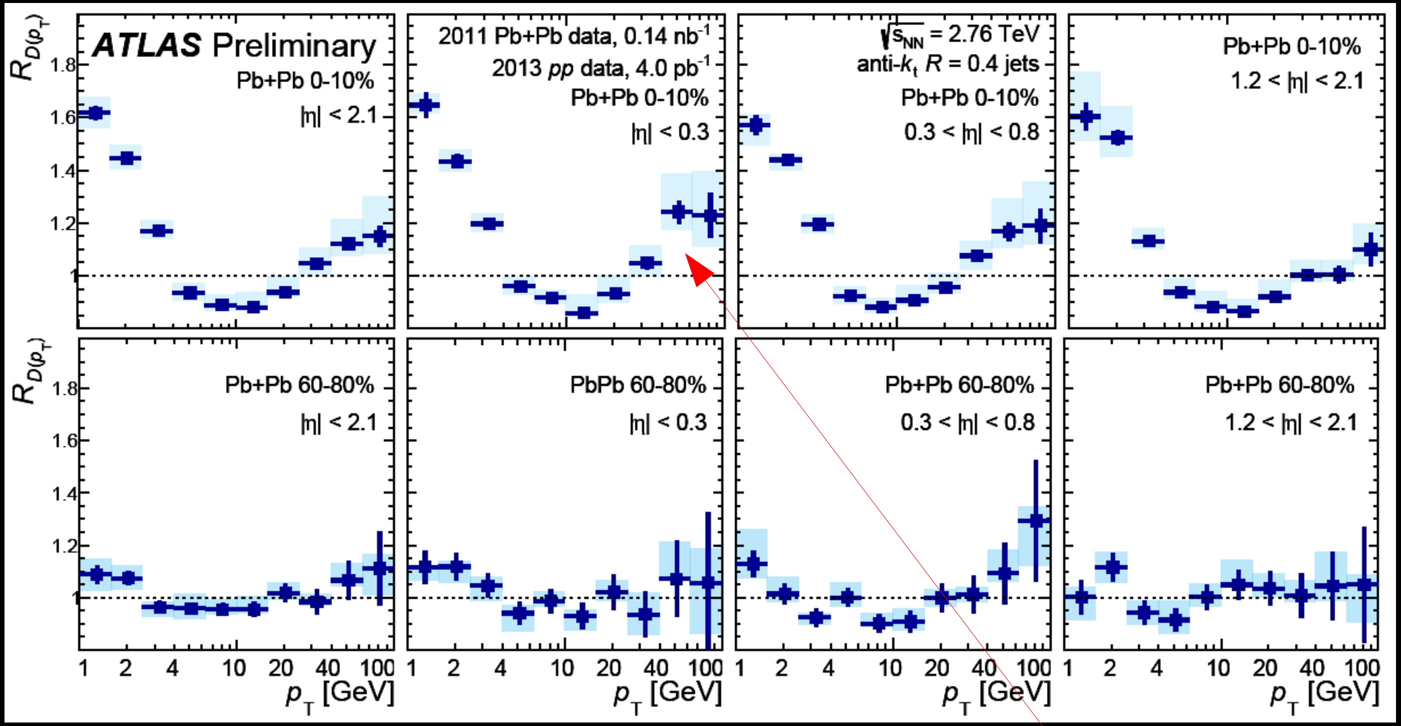
- N_{ch} is the number of charged particles associated to a jet.
- anti-k_T jets with R=0.4.
- Jet structure measured using charged tracks with $p_T > 1$ GeV.
- FF are background subtracted, corrected for reconstruction inefficiency and unfolded with 2D Bayesian method.

ATLAS-CONF-2015-055

$R_{D(p_T)} = D(p_T)_{cent} / D(p_T)_{p+p}$

Rapidity dependence of jet substructure modification

|η|<2.1 |η|<0.3 0.3<|η|<0.8 1.2<|η|<2.1



0-10%

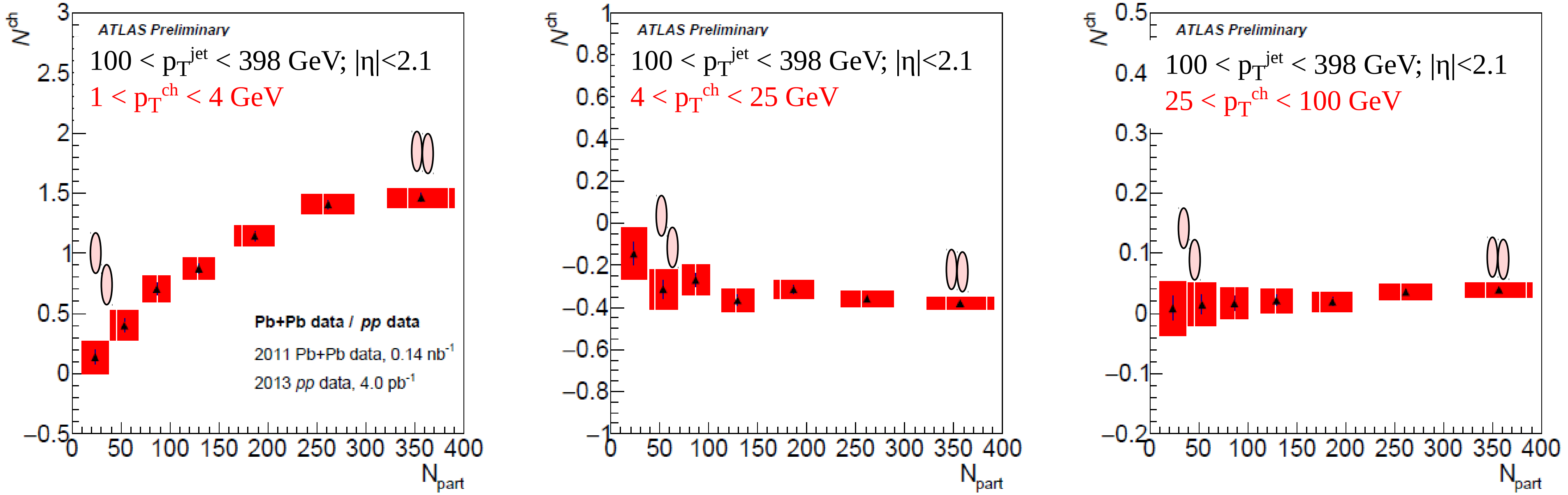
60-80%

ATLAS-CONF-2015-055

In central collisions (0-10%):

- **Enhancement of fragment yield for $p_T^{ch} < 4$ GeV; enhancement at $p_T^{ch} > 25$ GeV, mainly at mid-rapidity.**
- **Depletion at $4 < p_T^{ch} < 25$ GeV.**

extra/missing particles



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

in a given centrality/N_{part} bin

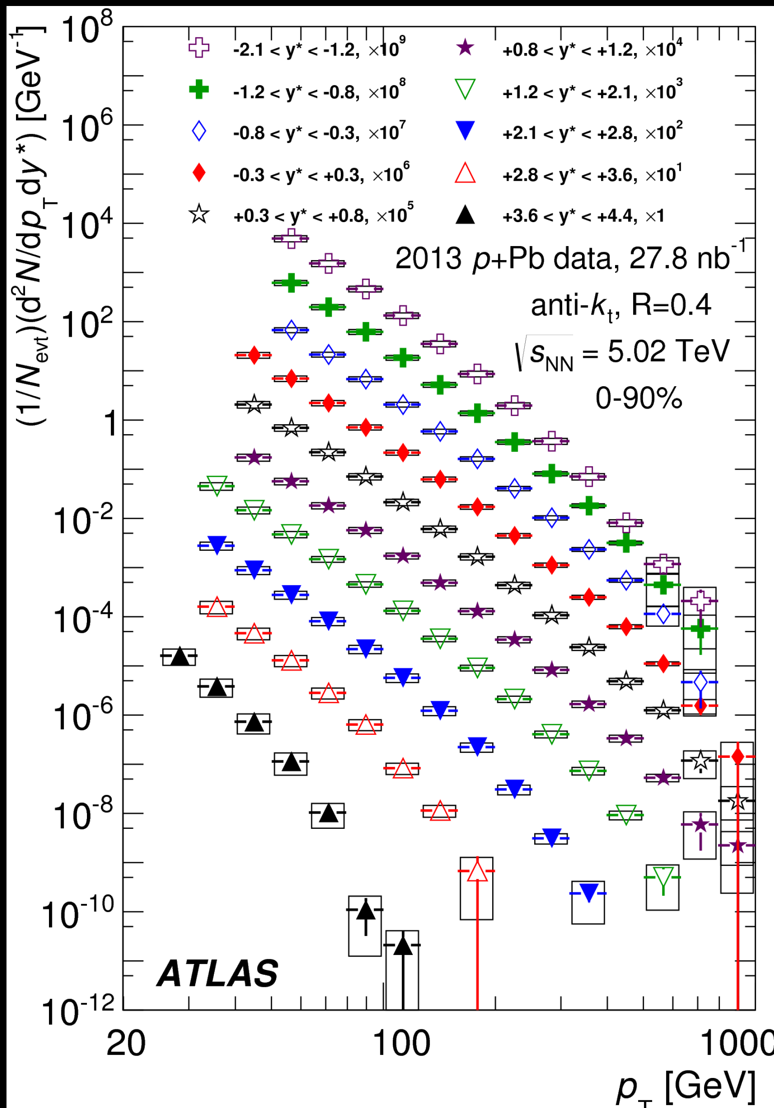
Tells how many extra/missing particles is in charged particle p_T range

- **A clear increase of yields of particles with low transverse momentum as the collision's centrality increases is observed**
- **Particles with p_T^{ch}>4 GeV do not exhibit noticeable variations with centrality**

ATLAS-CONF-2015-055

Jets in cold nuclear matter

Jets production as a function of p_T



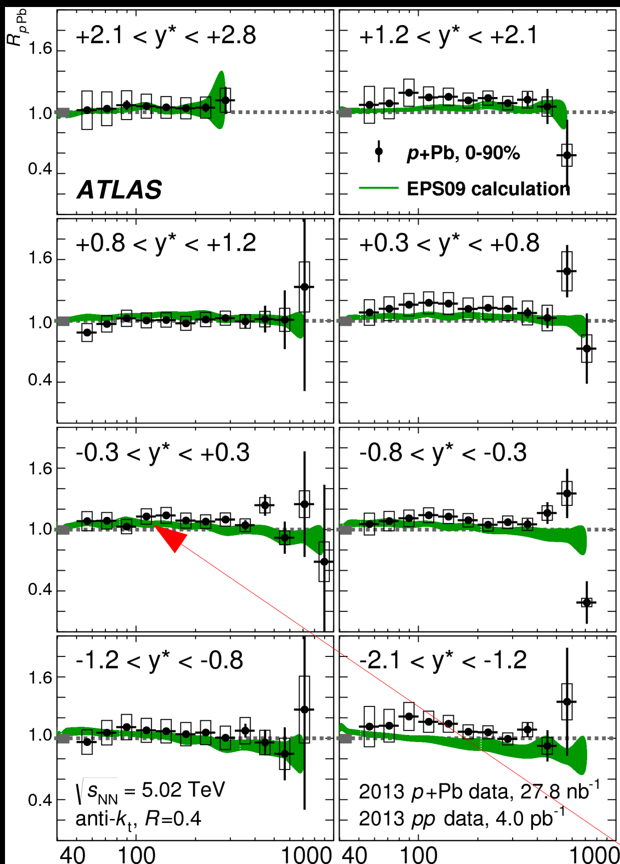
Phys. Lett. B 748 (2015) 392

- **p+Pb** @ 5.02 TeV, 28 nb^{-1};
- $y^* = y - 0.465$
- anti-k_T jets with R=0.4;

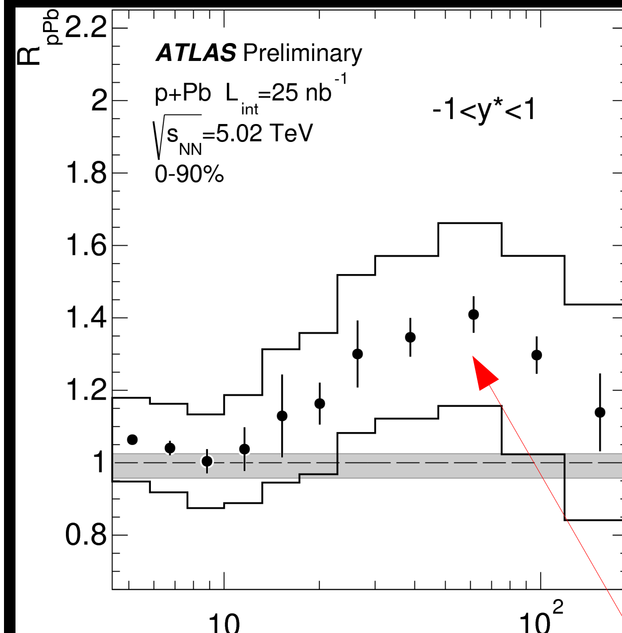
iterative subtraction of underlying event;

Yields relative to p+p: R_{pPb}

$$R_{p\text{Pb}}(p_{\text{T}}, y^{\star}) = \frac{1}{\langle T_{\text{Pb}} \rangle} \frac{1/N_{\text{evt}}\, \mathrm{d}^2 N_{p\text{Pb}}/\mathrm{d}y^{\star}\mathrm{d}p_{\text{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y^{\star}\mathrm{d}p_{\text{T}}}$$



PLB 748 (2015) 392



ATLAS-CONF-2014-029

- pPb @ 5.02 TeV, 28 nb^{-1}; anti-k_T jets with R=0.4; iterative subtraction of underlying event;
- pp @ 2.76 TeV, 4.0 pb^{-1}; anti-k_T jets with R=0.4; subtraction of contribution from in-time pile-up.
- Comparison of p+Pb yields to pp yields in 0-90%

  left: Jets RpPb

  right: Hadrons RpPb

How to conciliate unmodified jet R_{pPb} with clear enhancement in charged hadrons R_{pPb}?

Summary

Inclusive jets in Pb+Pb are suppressed relatively to p+p up to a factor of 2.

No dependence on rapidity.

Enhancement of asymmetric dijets in Pb+Pb, relatively to p+p as the centrality increases.

Clear dependence with the p_{T} of the leading jet, in contrast to inclusive jets.

Jets produced in the direction of the event−plane are less suppressed

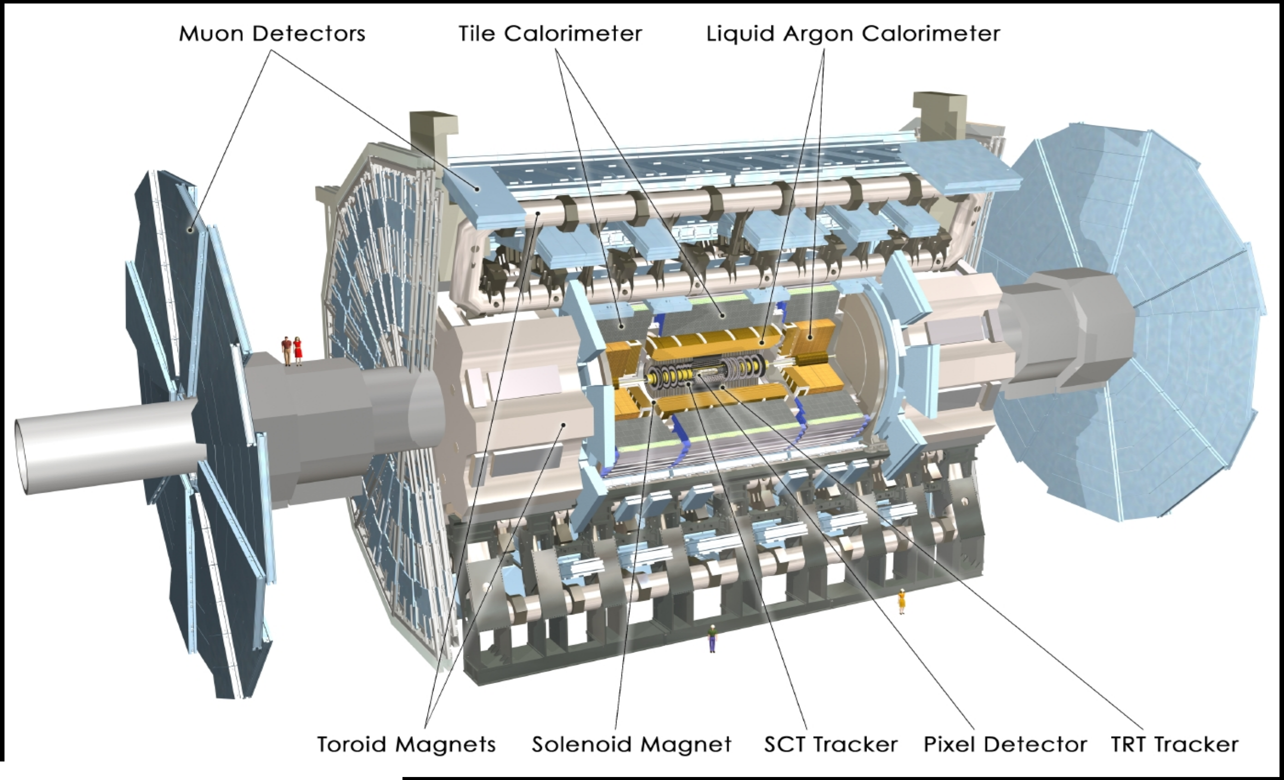
Internal jet structure shows enhancement of particle yields at low $p_{\mathrm{T}}^{\mathrm{ch}}$; enhancement at high $p_{\mathrm{T}}^{\mathrm{ch}}$, mainly at mid-rapidity; depletion at intermediate

Unmodified inclusive jet R_{pPb} in contrast with clear enhancement in charged hadrons R_{pPb}.

Pb+Pb and p+p @ 5.02 TeV results coming soon. Stay tuned!

Backup

ATLAS



η coverage:
Inner Tracker (-2.5, 2.5)
Muon Spectrometer (-2.7, 2.7)
EM Calorimeter (-3.2, 3.2)
HAD Calorimeter (-4.9, 4.9)

Measurements in three colliding systems:

Pb+Pb @ 2.76 & 5.02 TeV

p+Pb @ 5.02 TeV

p+p @ 2.76, 5.02, 7, 8, & 13 TeV

Jet reconstruction

Jets are reconstructed using anti-k_T algorithm (R=0.2, 0.3, and 0.4).

- Inputs are 0.1x0.1 ($\Delta\eta$x$\Delta\phi$) calorimeter towers or ID tracks.
- Average background (UE) estimated event-by-event per calorimeter sampling layer and per 0.1 η strip and subtracted. The estimates account for azimuthal modulation and exclude jet candidates.

Detector response evaluated using PYTHIA embedded in Minimum Bias Pb+Pb data → Reliable UE fluctuations.

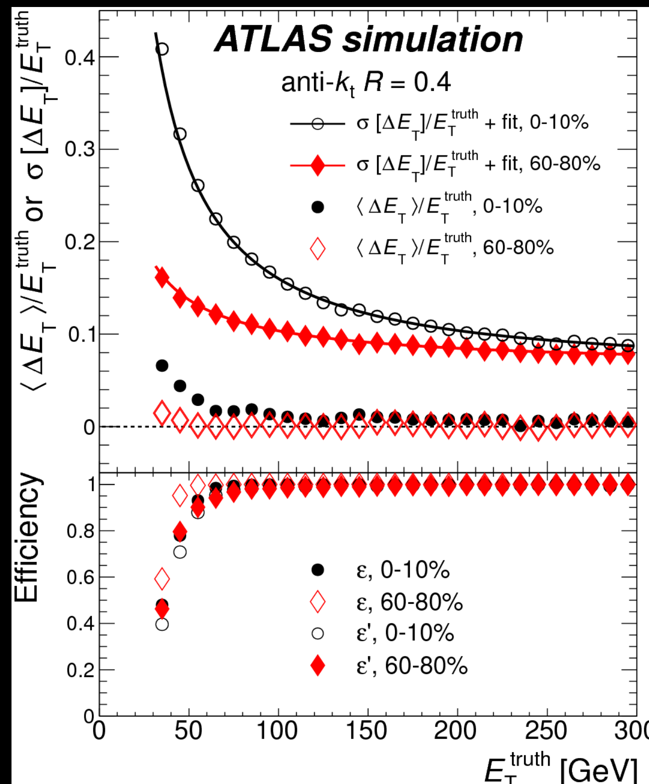
Exhaustive studies of jet energy scale (JES):

- Determine 'in situ' response and uncertainties using direct balance methods in γ/Z+jet events in high statistics 8 TeV pp data.
- Evaluated response to jets of different flavour and parton showers produced by different generators.
- Estimated effects on JES when measuring jets modified due to quenching using measurements of fragmentation function.

Performance of jet reconstruction

Performance is evaluated using pp hard scattering events from Pythia overlying on top of HIJING MB events without quenching.

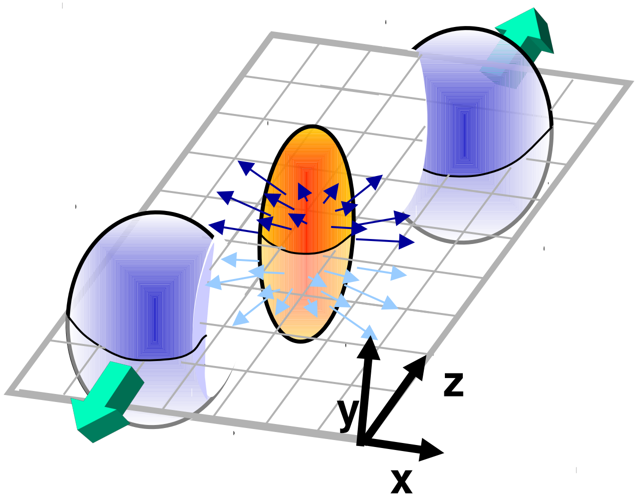
PLB 719 (2013) 220



JER is well described by where parameter *b* is consistent with the result from the fluctuation analysis.

The performance have been also verified using data overlay with similar results.

Azymuthal dependence of jet yields



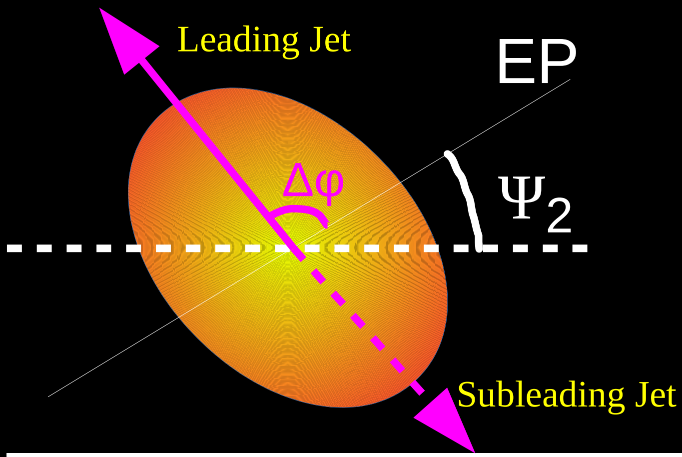
Anisotropic spatial collective motion is described by a Fourier expansion of particle distribution in azimuthal angle φ

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$

v_2 is associated with elliptic shape of nuclear overlap.

- Jets measured at different azimuthal angles relative to the Event-Plane, $\Delta\varphi \equiv \varphi - \Psi_2$, result from partons that traverse different path lengths.
- Measurement constrains models of path length dependence of the energy loss.
- Interplay between “soft” and “hard” probes of heavy ion collisions.

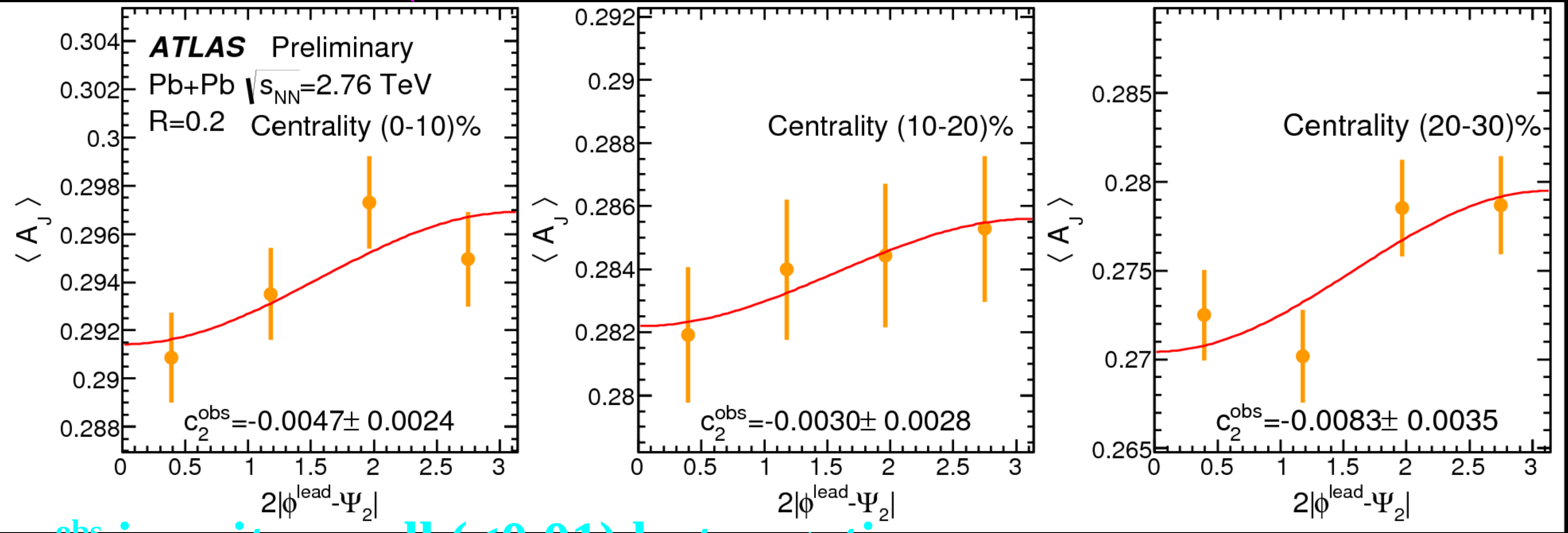
Dijet asymmetry vs. Event-Plane



$$A_J = \frac{E_T^{\text{lead}} - E_T^{\text{sublead}}}{E_T^{\text{lead}} + E_T^{\text{sublead}}}$$

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

c_2^{obs} quantifies the EP angle dependence of A_J



c_2^{obs} is quite small (<0.01) but negative

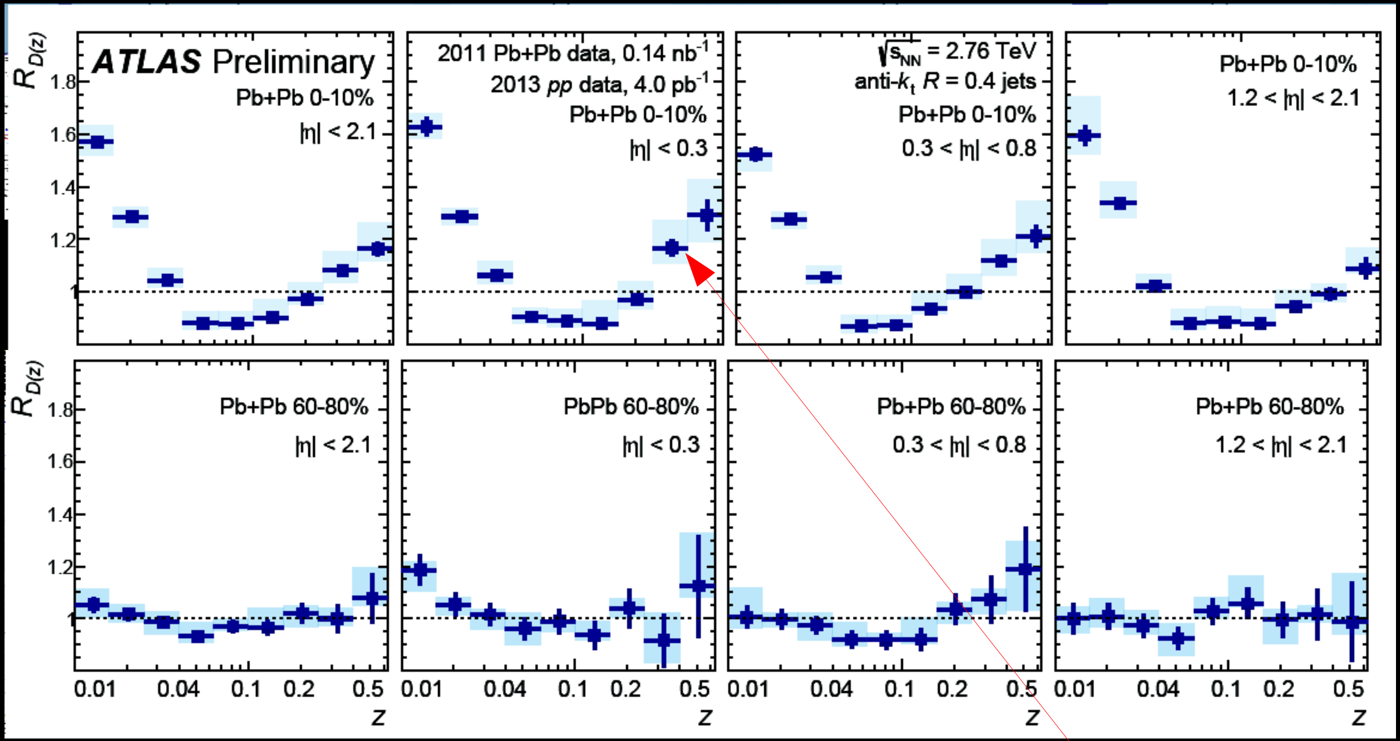
ATLAS-CONF-2015-021

→ the asymmetry is larger when the leading jet is Out−of−Plane

$R_{D(z)} = D(z)_{cent} / D(z)_{p+p}$

Rapidity dependence of jet substructure modification

|η|<2.1 |η|<0.3 0.3<|η|<0.8 1.2<|η|<2.1



0-10%

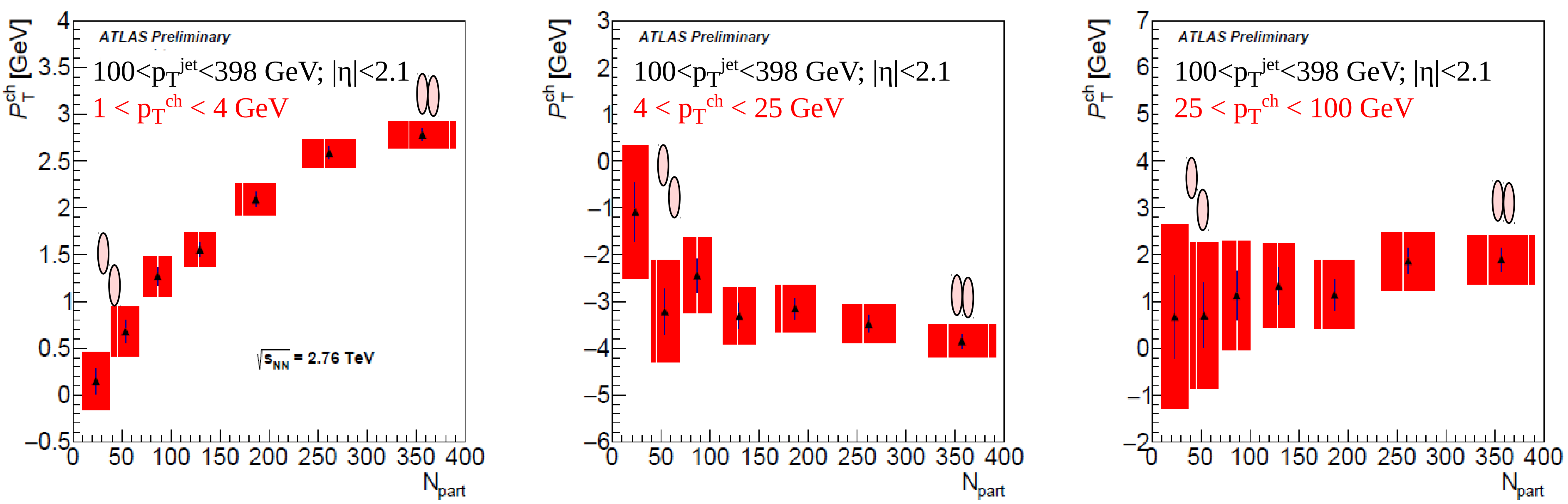
60-80%

ATLAS-CONF-2015-055

In central collisions (0-10%):

- Enhancement at low z; enhancement at high z, mainly at mid-rapidity.
- Suppression at intermediate z.

p_T of extra/missing particles



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

in a given centrality/N_{part} bin

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

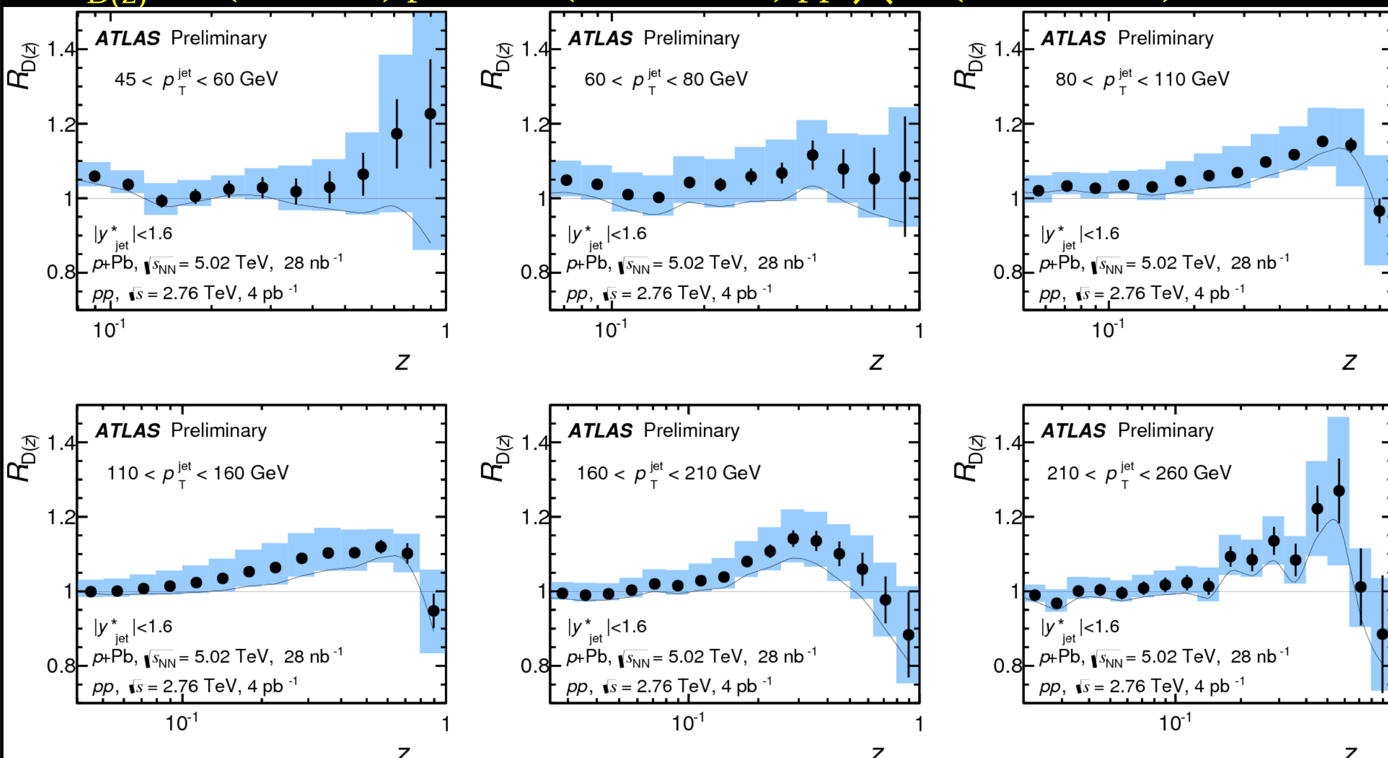
p_T flow follows the same trend of particle yields

ATLAS-CONF-2015-055

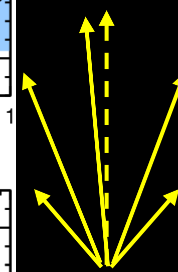
Jet fragmentation in p+Pb - $R_{D(z)}$

MC-based extrapolation used to transform 2.76 TeV data to 5.02 TeV

$R_{D(z)}$ = D(z; 5 TeV) p+Pb / D(z; 2.76 TeV) pp $\times$ [D(z; 2.76 TeV) PYTHIA / D(z; 5 TeV) PYTHIA]



$$D(z) \equiv \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$



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

ATLAS-CONF-2015-022

A possible z-dependent excess is not excluded

Results with pp@5.02 TeV are coming soon.

Acknowledgements

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

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