Recent measurements of jet properties in Pb+Pb collisions with ATLAS

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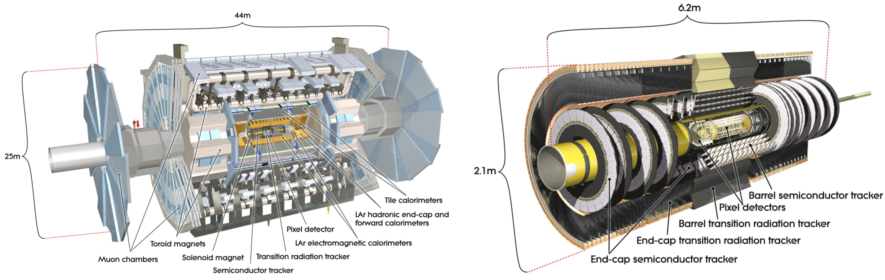
Overview

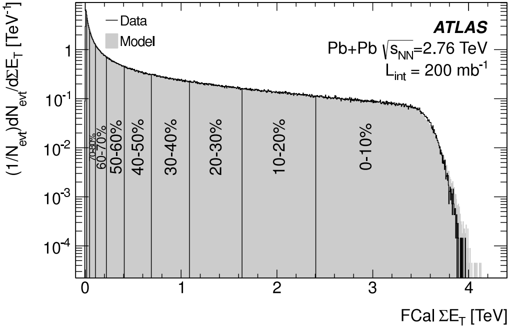
- Jet measurements in Pb+Pb collisions provide important insight on the properties of the medium created in the heavy ion collisions
- Run 1 studies of asymmetric dijet events, suppressed production of jets, production of nearby jets or measurement of jet fragmentation were presented by ATLAS (not complete list!!!)
- Run 2 measurement of the gamma+jet events has been presented recently
- These measurements provided information on the jet production rates, parton energy loss and its path length dependence and medium properties

ATLAS experiment



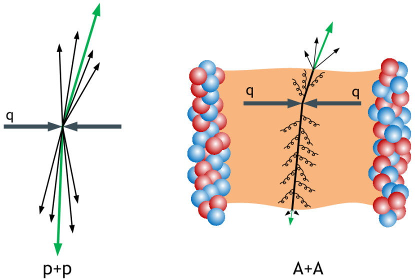
- ATLAS is multi-purpose detector well capable of measuring heavy-ion collisions
- Excellent tracking performance within $|\eta| < 2.5$. Combination of silicon pixel and strip detectors and transition radiation tracker.
- Powerful calorimeter system with fine segmentation with η coverage up to $|\eta| < 4.9$

Centrality in Pb+Pb collisions



- Centrality expresses measure of overlap of two colliding nuclei
- Is closely related to the average number of participant nucleons and number of binary inelastic collisions
- Centrality determined by the sum of E_{T} deposited in the FCAL calorimeter $(3.1 < |\eta| < 4.9)$
- Events divided into successive percentiles of the $\sum E_{\mathrm{T}}^{\mathrm{FCal}}$

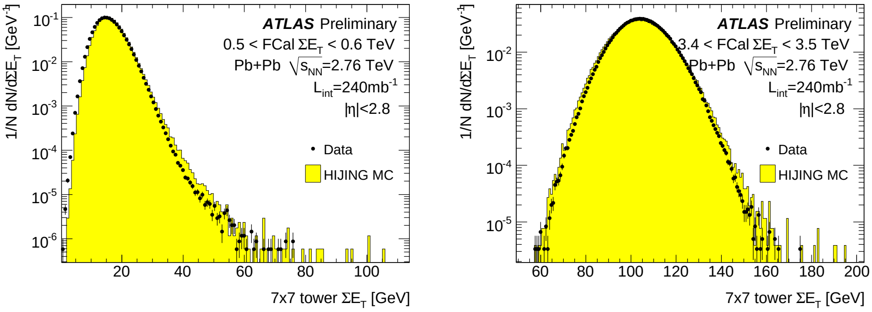
Jets in HI collisions



- Partons from the hard scattering have to traverse through the deconfined medium
- Do we observe suppression of jet yields or modification of fragmentation functions?
- Is production of the associated jets influenced by the medium?
- To quantify the effects of medium compare with *pp* data at the same energy

Jet reconstruction 1

- Reconstruction of jets in HI collisions is challenging by itself
- Presence of large underlying event background (UE) requires subtraction procedure
- Large variations of UE energy density due to geometry of the collisions and physics effects such as elliptic flow implies that UE subtraction procedure must be on the event-by-event basis



Jet reconstruction 2

- Input into the reconstruction procedure is the measured $E_{\mathrm{T}}^{\mathrm{tower}}$ distribution

$$\frac{\mathrm{d}E_{\mathrm{T}}^{\mathrm{total}}}{\mathrm{d}\eta\mathrm{d}\phi} = \frac{\mathrm{d}E_{\mathrm{T}}^{\mathrm{UE}}}{\mathrm{d}\eta\mathrm{d}\phi} + \frac{\mathrm{d}E_{\mathrm{T}}^{\mathrm{jet}}}{\mathrm{d}\eta\mathrm{d}\phi}$$

- UE background is estimated and subtracted from the jet energy in the subtraction procedure at the cell level (separately for each calorimeter layer)
- Fake jets are rejected by matching to the track jets or calorimeter clusters
- Self energy bias correction is applied
- Numerical Inversion (MC based correction) is used to get the final jet energy

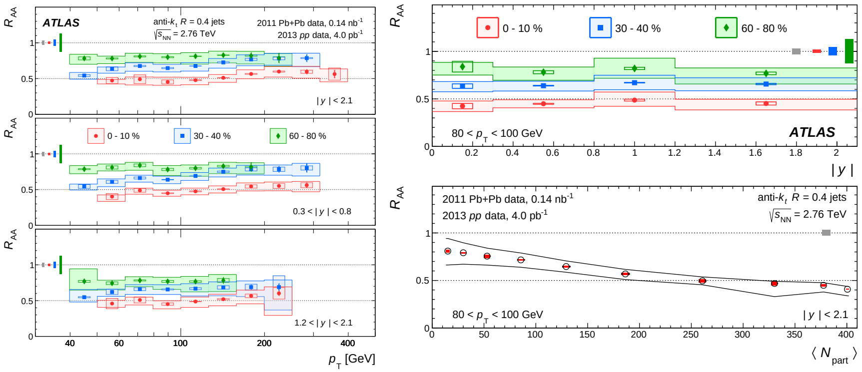
Jet R_{AA}

- Variable that expresses the size of the suppression/enhancement is the so called R_{AA} defined as

$$R_{\mathrm{AA}} = \frac{\frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N_{\mathrm{Pb+Pb}}}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}y} \Big|_{\mathrm{centr}}}{\langle T_{\mathrm{AA}} \rangle \frac{\mathrm{d}^2 \sigma_{pp}}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}y}}$$

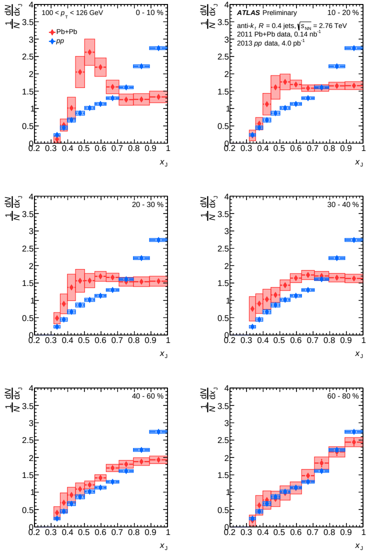
- We measured R_{AA} for anti-k_t jets using 2011 Pb+Pb and 2013 pp run, MB and jet triggered samples were combined to get continuous jet spectra $32 < p_{\mathrm{T}} < 500$ GeV
- Unfolding based on SVD method was used to account for detector effects

Jet R_{AA}



- R_{AA} plots clearly show suppression down to ≈ 0.5 for most central collisions
- Weak dependence of R_{AA} on the p_T
- No significant dependence on the y observed

Dijet asymmetry



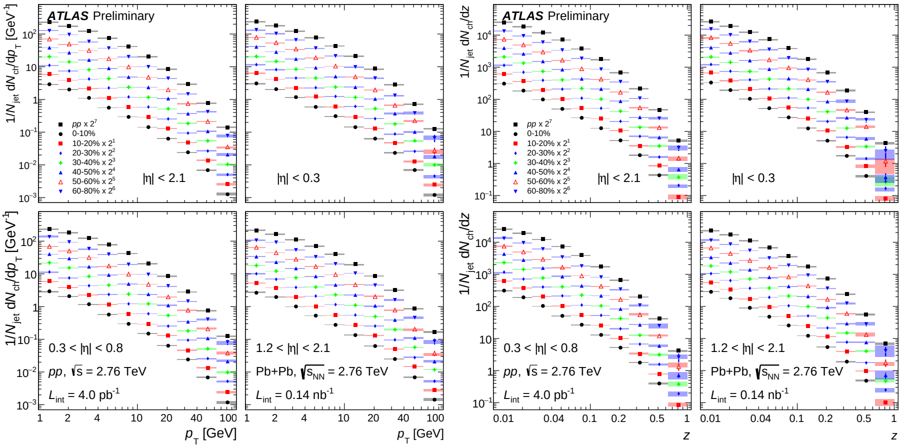
- Latest measurement of dijet asymmetry showing strong evolution of dijet asymmetry with collision centrality
- Main improvement in usage of 2D Bayesian unfolding and increase of statistics
- Plot showing $\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}x_\mathrm{J}}$, $x_\mathrm{J} = \frac{p_{\mathrm{T}_2}}{p_{\mathrm{T}_1}}$ distributions for pairs with $100 < p_{\mathrm{T}_1} < 126$ GeV for different collision centralities

- Jet Fragmentation Functions (FF) $D(p_{\mathrm{T}})$ and $D(z)$ are defined as

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

- New FF measurement of $R = 0.4$ jets measured differentially in 4 η and 4 $p_{\mathrm{T}}^{\mathrm{jet}}$ bins
- Jet substructure measured using charged tracks starting at $p_{\mathrm{T}} = 1$ GeV
- Using *pp* as a reference
- FF are background subtracted, efficiency corrected and fully unfolded with 2-D Bayesian unfolding

$D(p_\mathrm{T})$ and $D(z)$ distributions



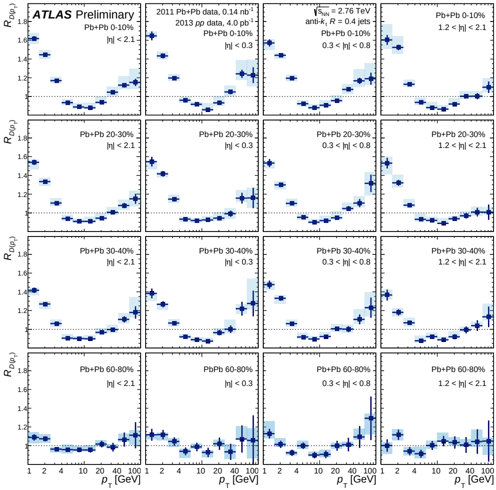
- FF for *pp* and 6 centrality bins in 4 η regions
- Inclusive in $p_\mathrm{T}^\mathrm{jet}$

inclusive midrapidity → forward

central

↓

peripheral



- $R_{D(p_{\mathrm{T}})}$ for 4 centralities in 4 η bins
- Hint of η dependence at large p_{T} observed

$D(p_{\mathrm{T}})$ Ratios (2)

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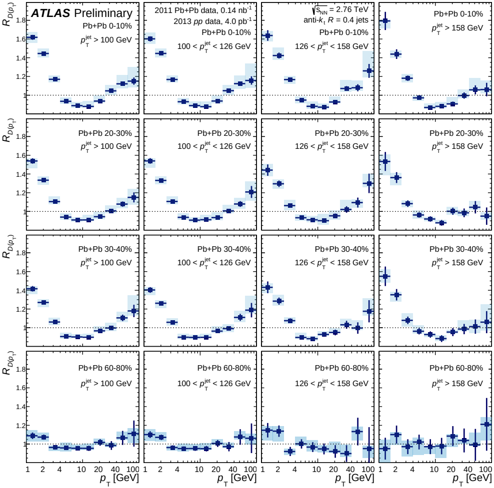
inclusive low $p_{\mathrm{T}}^{\mathrm{jet}}$ $\rightarrow$ high $p_{\mathrm{T}}^{\mathrm{jet}}$

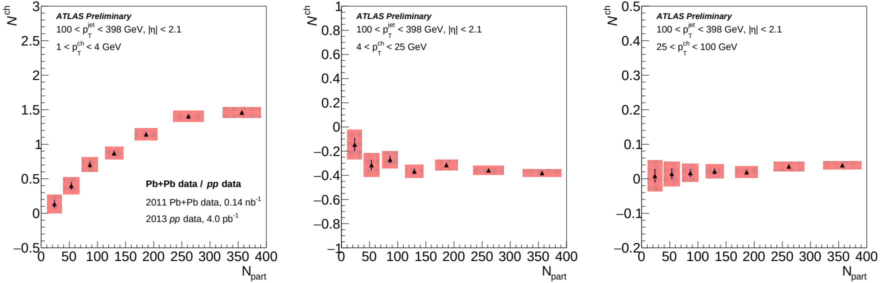
central

$\downarrow$

peripheral



- $R_{D(p_{\mathrm{T}})}$ for 4 centralities in 4 $p_{\mathrm{T}}^{\mathrm{jet}}$ bins
- No clear dependence on $p_{\mathrm{T}}^{\mathrm{jet}}$ except change of trends at highest p_{T}



- To quantify the size of enhancement/suppresion, we calculated

$$N^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) \, \mathrm{d}p_{\mathrm{T}} \qquad (1)$$

- N_{part} dependence shown for three characteristic p_{T} regions
- Tells how many extra/missing particles is in p_{T} range

FF - extra/missing momentum

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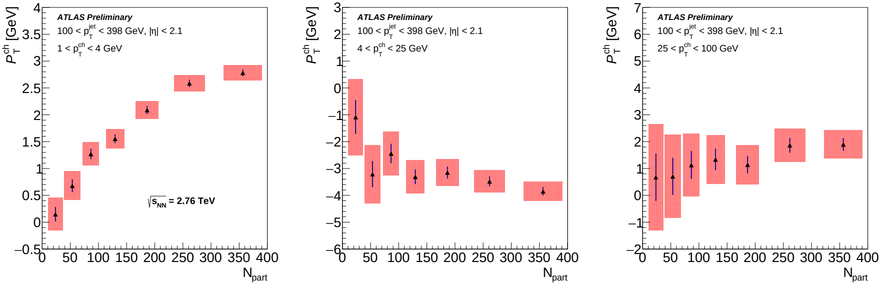
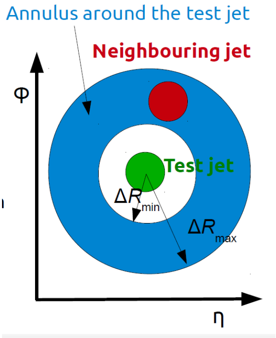


- To quantify the p_{T} flow, we calculated

$$P_{\mathrm{T}}^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) p_{\mathrm{T}} \, \mathrm{d}p_{\mathrm{T}}. \qquad (2)$$

- Tells how much p_{T} is carried by extra/missing particles in given p_{T} range



- The rate of the neighbouring jets that accompany a test jet was measured in run 1
- $R_{\Delta R}$ is defined as

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

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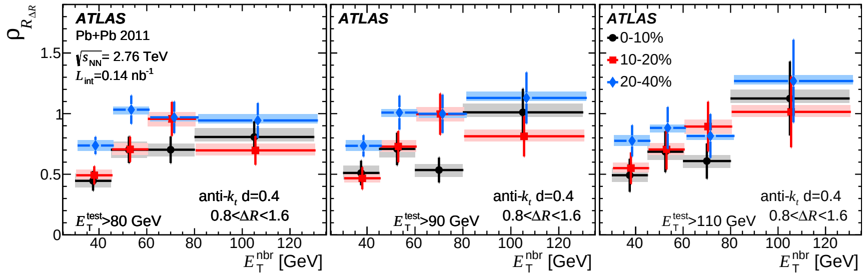
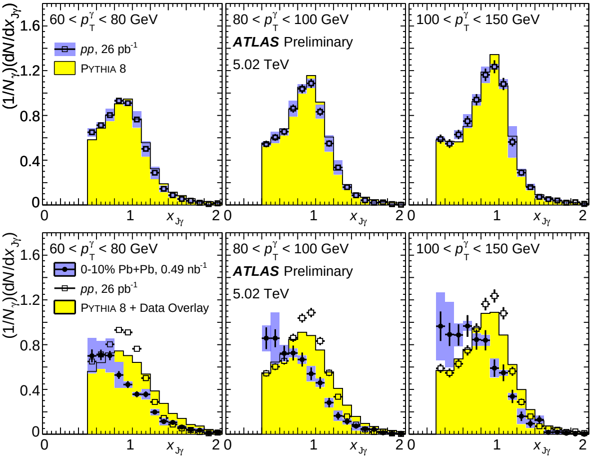


- The ratio of $R_{\Delta R}$ for three centrality bins to 40-80% centrality bin
- Suppression by a factor ≈ 2 in central collisions, no strong E_{T} dependence observed
- With increased statistics in Run 2, expect significant reduction in statistical uncertainties
- Moreover new type of jet substructure measurements possible

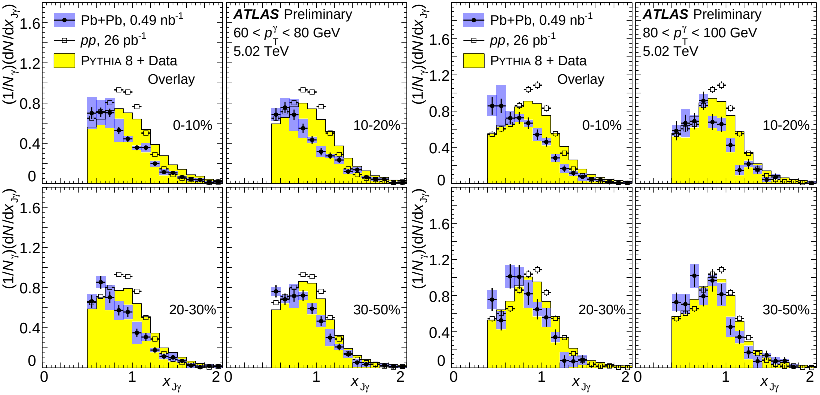
Run 2

- The main advantage of the new data is the large increase in integrated luminosity ($L_{\mathrm{int}}^{\mathrm{PbPb,run1}} = 0.15\ \mathrm{nb}^{-1}$ vs $L_{\mathrm{int}}^{\mathrm{PbPb,run2}} = 0.515\ \mathrm{nb}^{-1}$)
- Along with the increased cross section for some processes this will provide opportunity to improve statistical precision
- New channels become feasible
- All the possible collision systems, *pp*, p+Pb and Pb+Pb measured at the same energy

- First ATLAS heavy ion jet measurement from Run 2
- γ+jet p_{T} balance defined as $x_{\mathrm{J}} = \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\gamma}}$
- Measured for three bins in photon p_{T}, using $R = 0.4$ jets both in pp and Pb+Pb (four centrality intervals)
- Data compared with reconstructed Pythia8 + Geant simulation



- Comparison of x_J distributions in data and Pythia for *pp* (upper panels) and central Pb+Pb (lower panels)



- Centrality dependence for two photon p_{T} bins
- Results showing smaller shift in less central collisions

Summary

- Run 1 ATLAS jet results show significant modifications of jet production rates and jet properties in heavy ion collisions
- These are confirmed and extended by new Run 2 measurement of gamma+jet events
- Stay tuned for new results from new data that will come (hopefully) soon

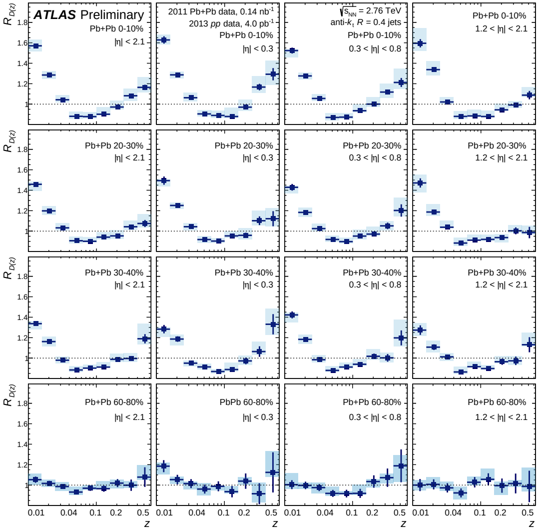
Backup

N^{ch} and $P_{\mathrm{T}}^{\mathrm{ch}}$ for $1.0 < p_{\mathrm{T}} < 100.0$ GeV

Centrality	0 – 10%	10 – 20%	20 – 30%	30 – 40%
$P_{\mathrm{T}}^{\mathrm{ch}}$ [GeV]	0.8 ± 0.7	0.9 ± 0.9	0.1 ± 1.0	-0.4 ± 1.2
N^{ch}	1.1 ± 0.1	1.0 ± 0.1	0.8 ± 0.1	0.5 ± 0.1

Centrality	40 – 50%	50 – 60%	60 – 80%
$P_{\mathrm{T}}^{\mathrm{ch}}$ [GeV]	-0.1 ± 1.6	-1.8 ± 2.1	-0.3 ± 2.7
N^{ch}	0.4 ± 0.1	0.1 ± 0.2	0.0 ± 0.2

FF $D(z)$ ratios (1)



FF $D(z)$ ratios (2)