Jet Measurements in Heavy Ions with the ATLAS Experiment

Helena Santos

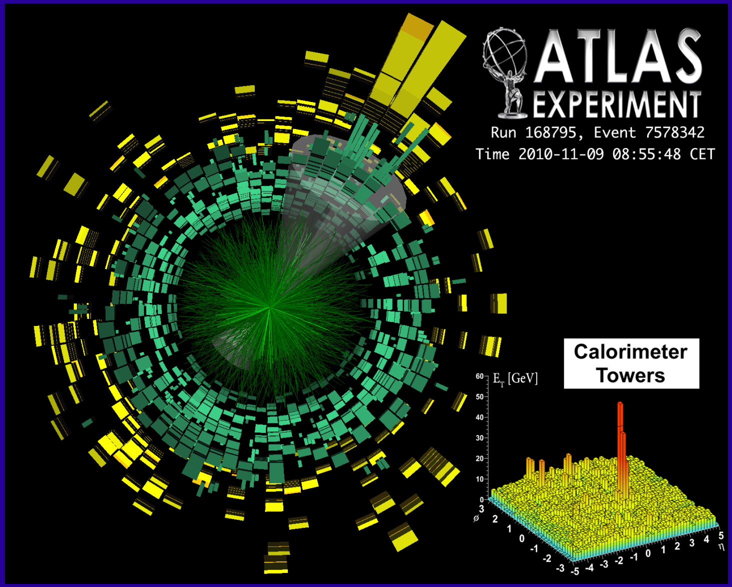
LIP, FCUL

on behalf of the ATLAS Collaboration

ICHEP 2020, 28 July-6 August, Prague

Jets in HI collisions

First insight of jets produced at LHC indicated a large dijet asymmetry



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$x_J = p_{T2}/p_{T1}$

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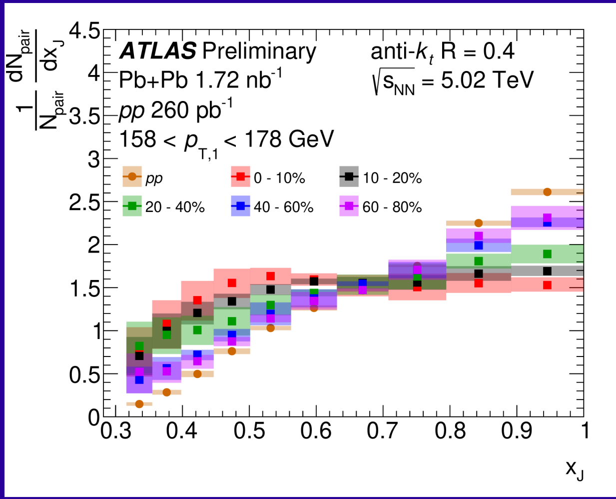

- The dijet momentum-balance in peripheral collisions is well compatible with pp collisions.
- Imbalance increases with increasing centrality.

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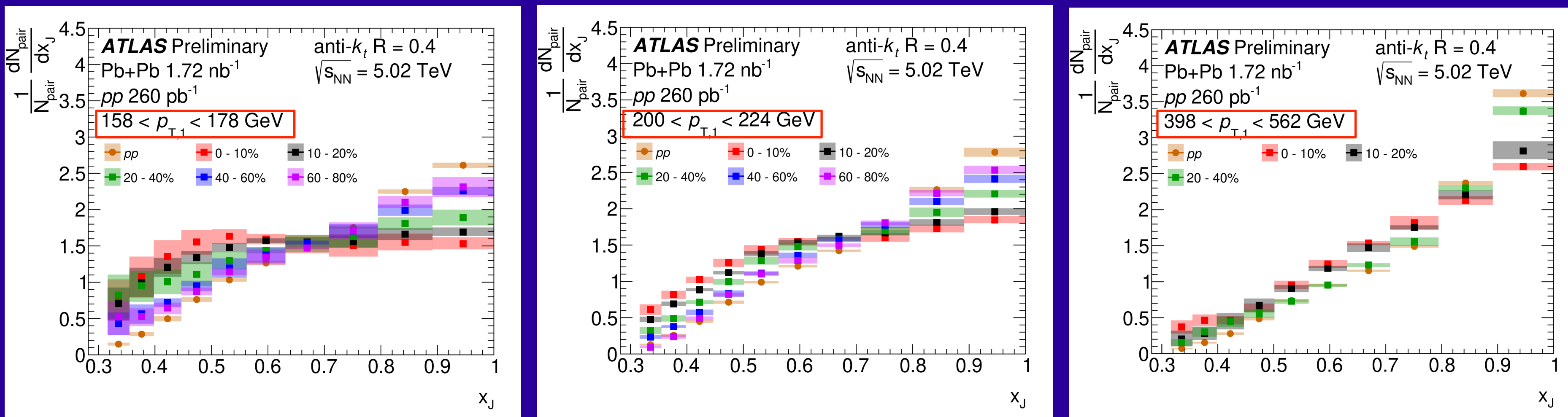

- The momentum-balance in peripheral collisions is well compatible with pp collisions.
- Imbalance increases with increasing centrality.
- The imbalance is weaker with increasing leading jet p_T.

Inclusive jet production in Pb+Pb

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

Nuclear thickness function $\langle N_{coll} \rangle / \sigma_{NN}$

Cross section in *pp* collisions (in vacuum)

- Nuclear modification factor quantifies the change of yields, w.r.t. the production in vacuum.
- Any deviation from unity indicates suppression or enhancement of yields.

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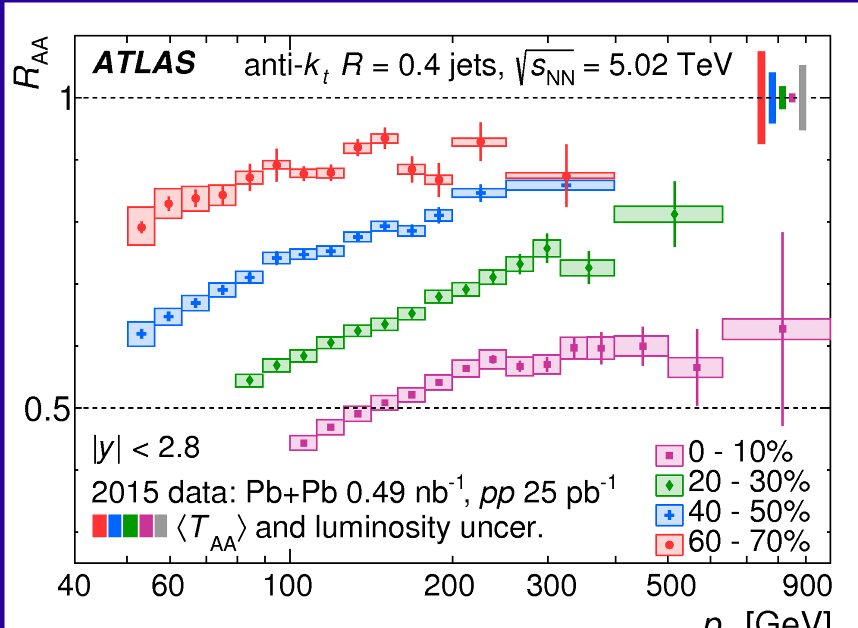

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Jets are suppressed by a factor of two in central Pb+Pb collisions with clear dependence on transverse momentum, p_T.

Path length dependence of quenching

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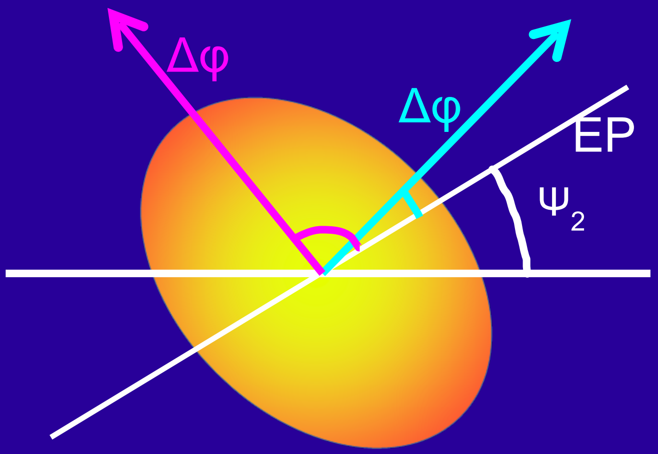

Unequal path lengths of the showers in the medium

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{n} v_n \cos(n(\phi - \Psi_n)),$$

Path length dependence of quenching

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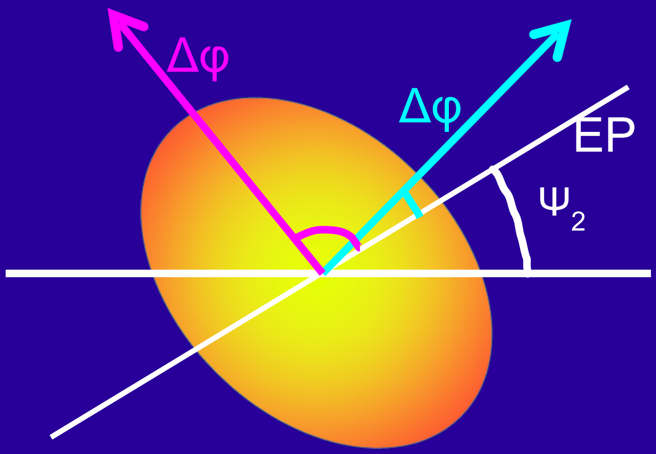
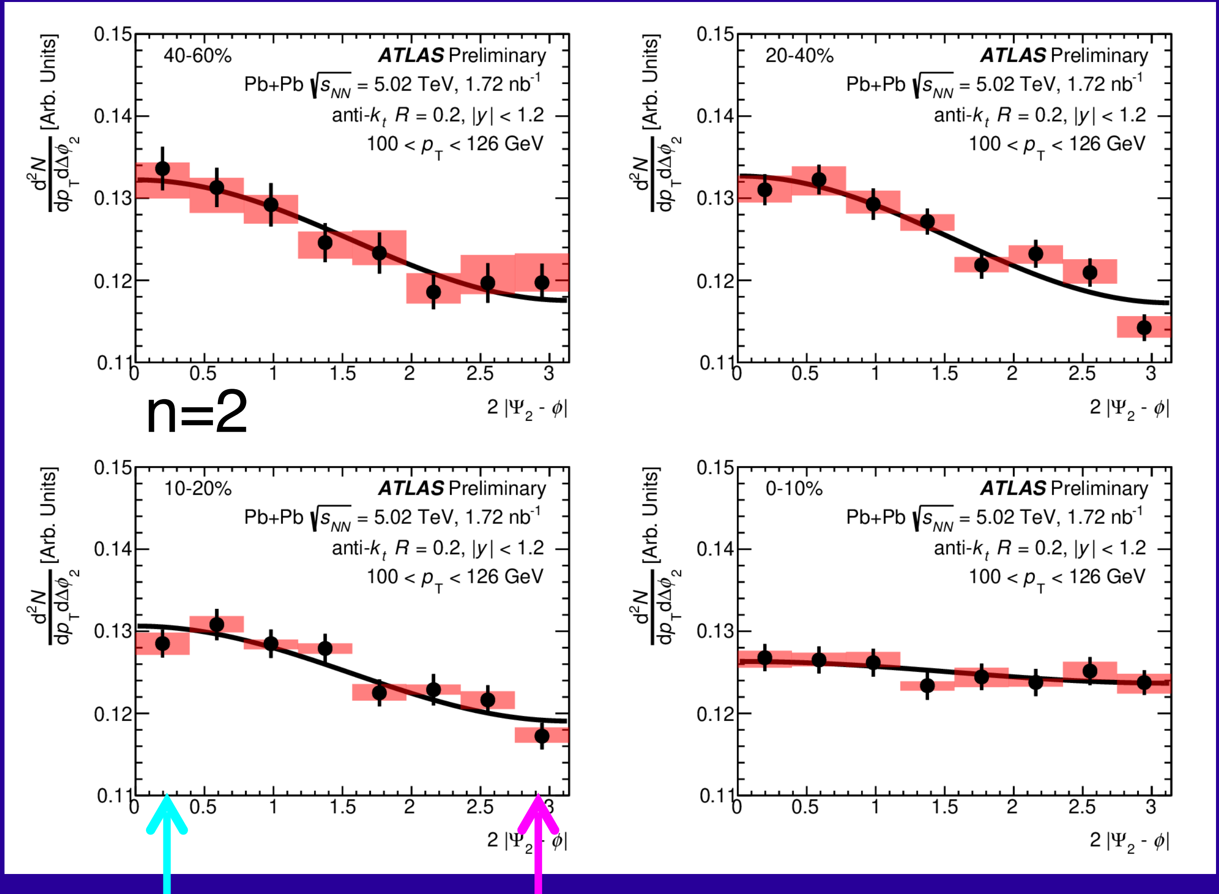


Unequal path lengths of the showers in the medium

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{n} v_n \cos(n(\phi - \Psi_n)),$$

R=0.2 jets with
$100 < p_T < 126$ GeV
Unfolded in p_T and $\Delta\varphi_n$

Angular distribution of jets with respect to Ψ_2



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

Path length dependence of quenching

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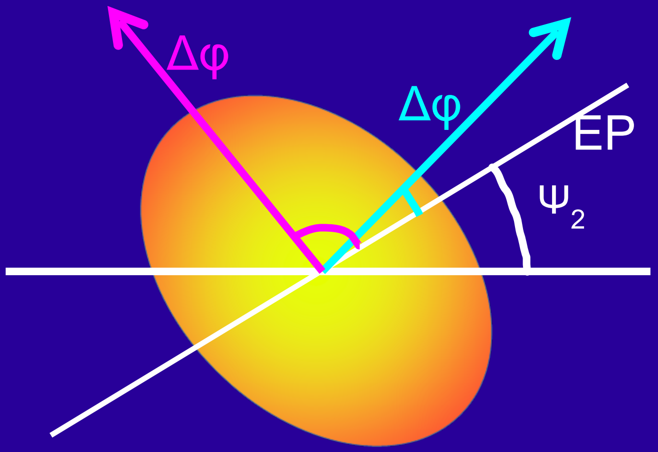

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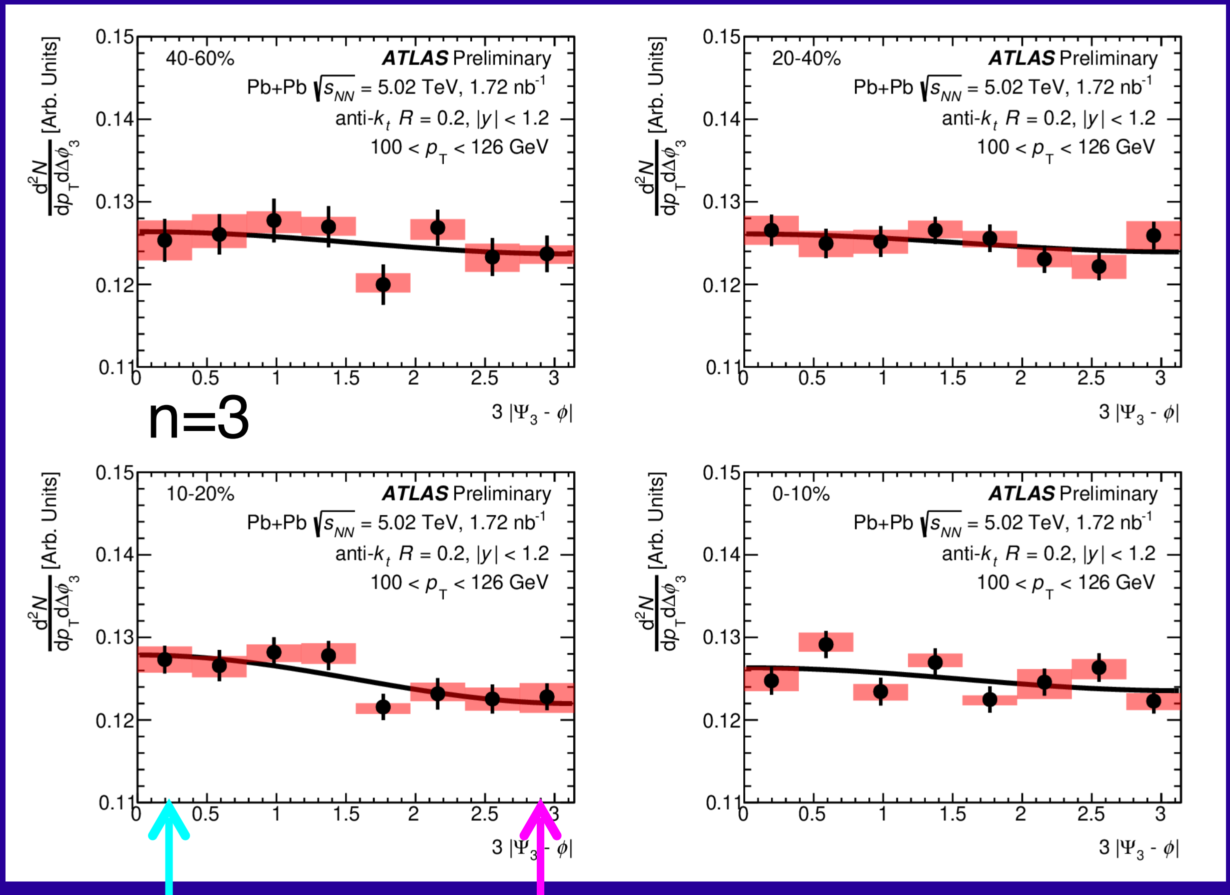
Angular distribution of jets with respect to Ψ_3



Smaller effect for n=3

Jet v_n

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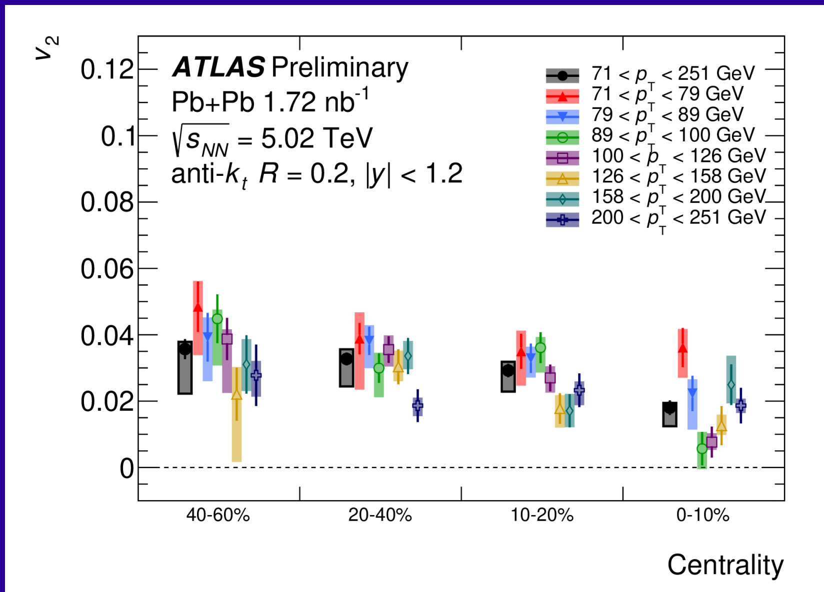
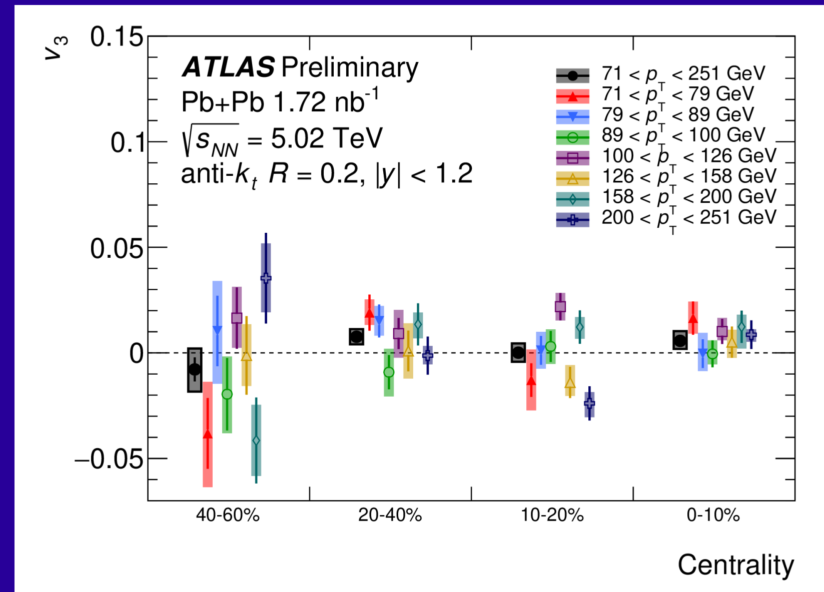
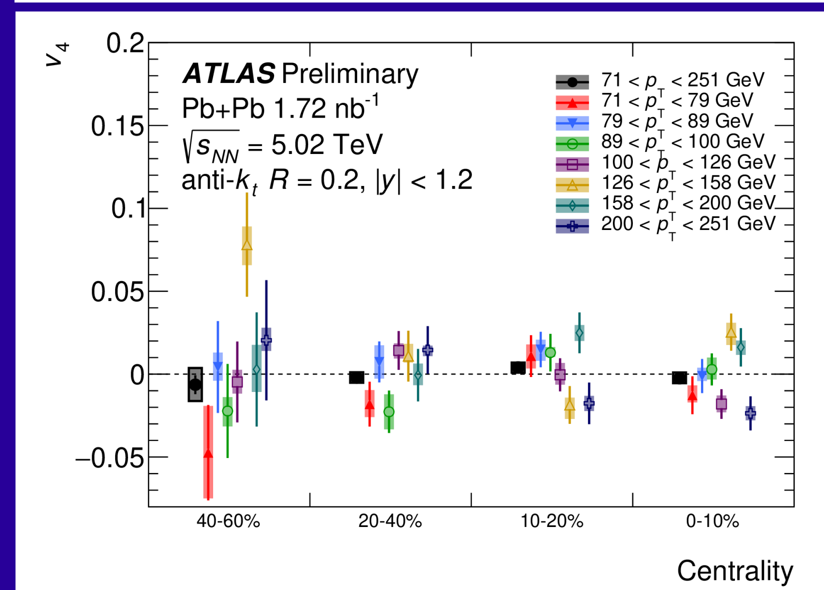
The v_2, v_3 and v_4 values for R=0.2 jets as a function of centrality



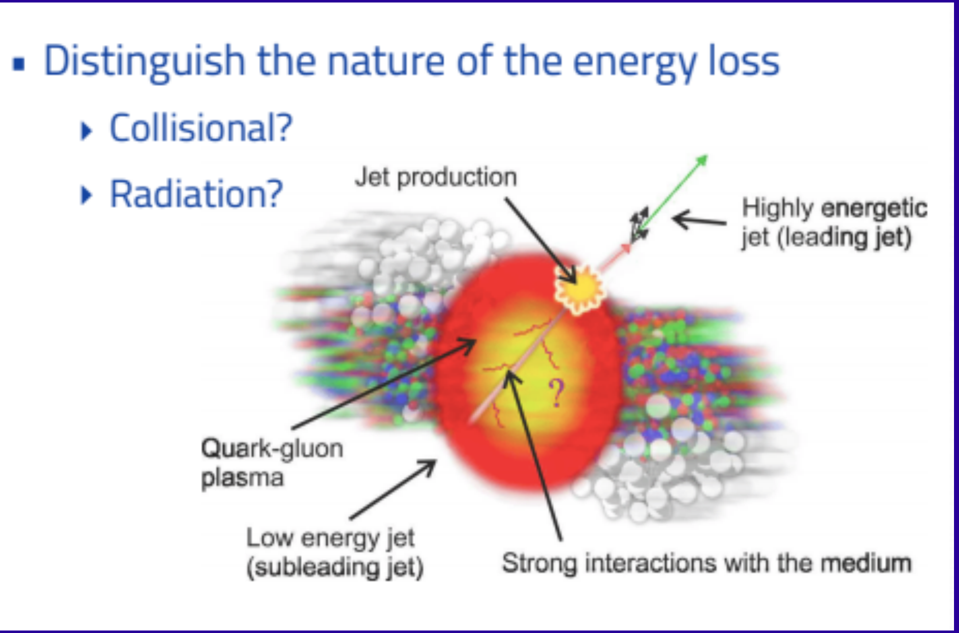




- Positive v_2, up to 4%.
- No dependence on the jet p_T within uncertainties.
- v_3 and v_4 compatible with 0.

A deeper insight

How is the parton shower modified in the hot and dense QCD medium?

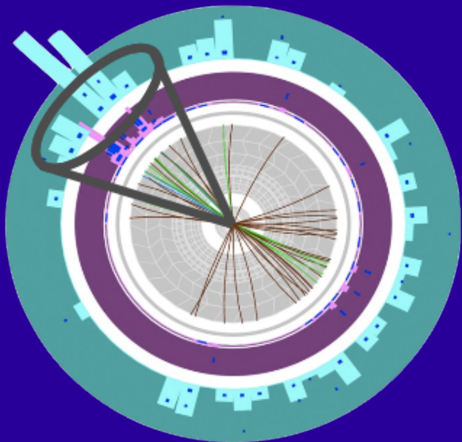


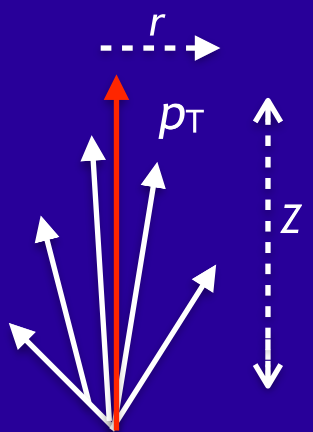
What is the resolution scale of the quark-gluon plasma?

Does the jet suppression depend on substructure?

Inclusive fragmentation functions

Does the jet suppression depend on jet structure?

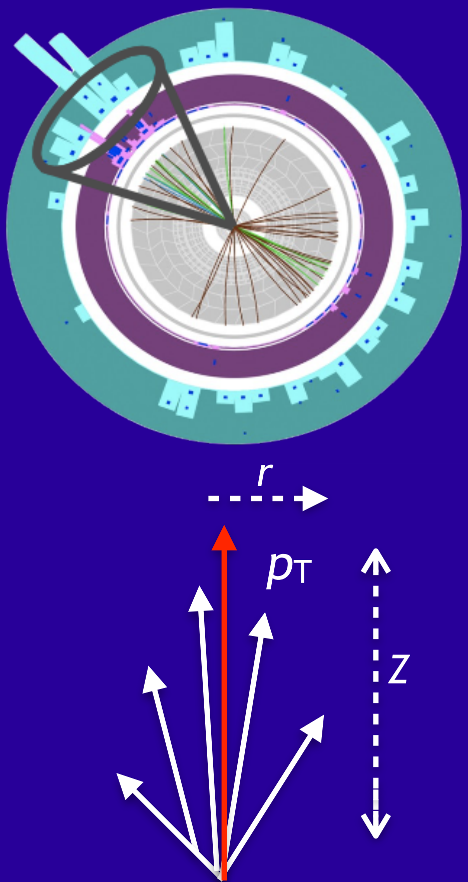




$$z \equiv p_{\mathrm{T}} \cos \Delta R \,/\, p_{\mathrm{T}}^{\mathrm{jet}}$$

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

Inclusive fragmentation functions



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

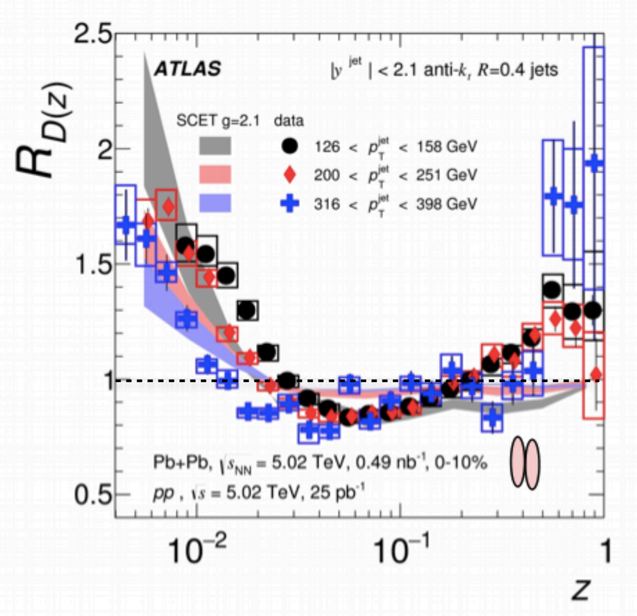
Does the jet suppression depend on jet structure?

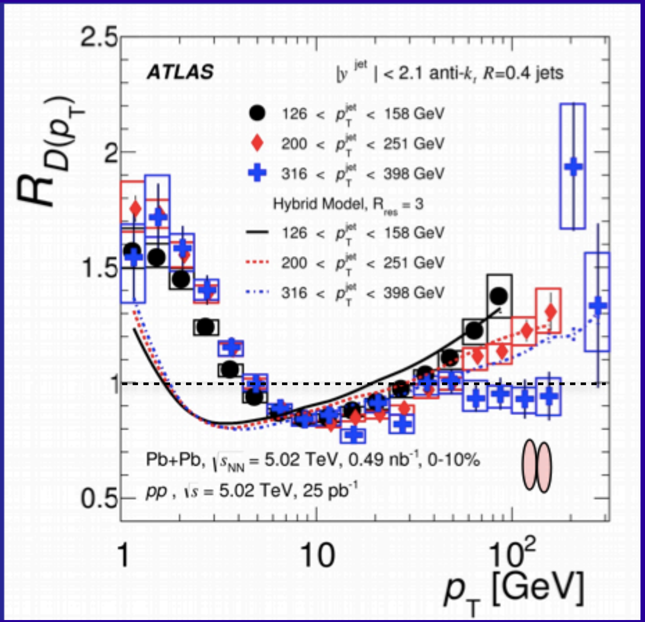
Shower in medium

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

Shower in vacuum

Phys. Rev. C 98, (2018) 024908

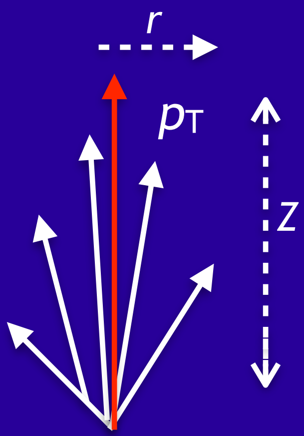




- Enhancement at low and high-z(p_T).
- Suppression at intermediate z(p_T).
- D(z,(p_T)) modifications do not scale with $p_{T,jet}$ at low-z(high-p_T).

How do particles re-distribute within the jet and beyond?

Study *FF* as a function of the angular distance between the charged particle and the jet axis.



$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\,\mathrm{d}p_{\mathrm{T}}}$$

$$r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

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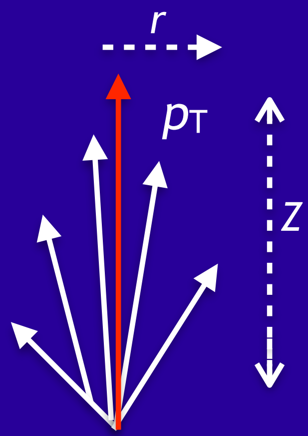

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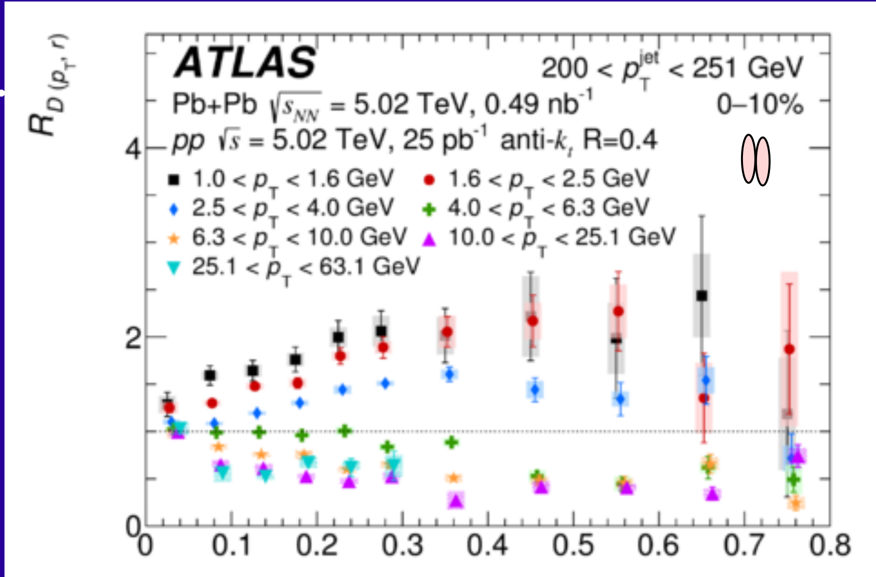

Phys. Rev. C 100 (2019) 064901

In central collisions $R_{D(p_{\mathrm{T}},r)}$ is above unity at all r for all $p_{\mathrm{T}} < 4$ GeV —> Energy lost by jets is being transferred to particles with $p_{\mathrm{T}} < 4$ GeV with larger radial distance.

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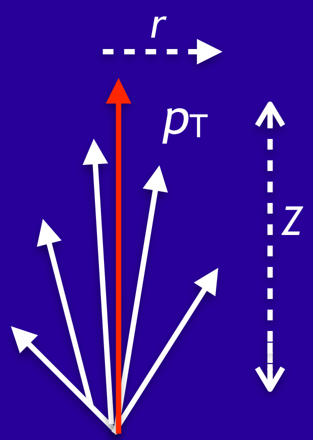

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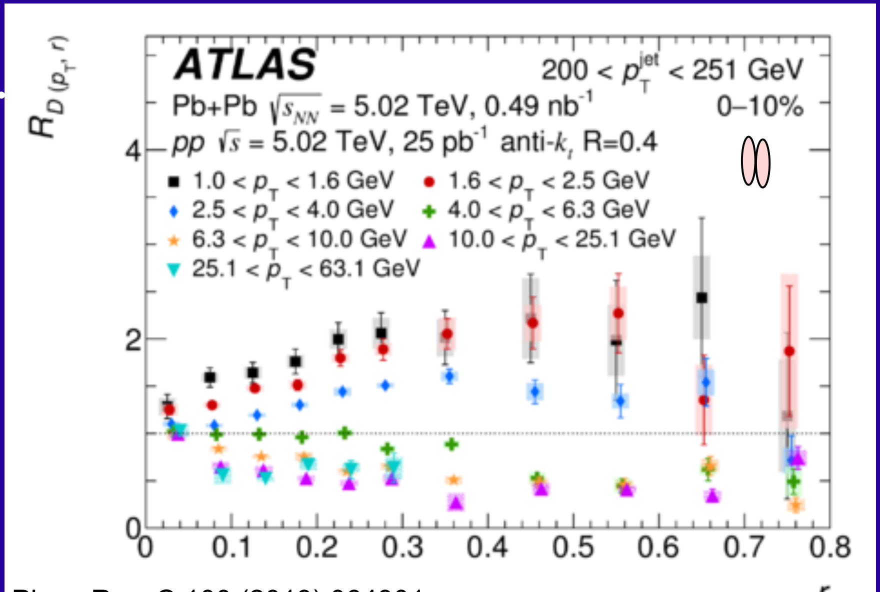

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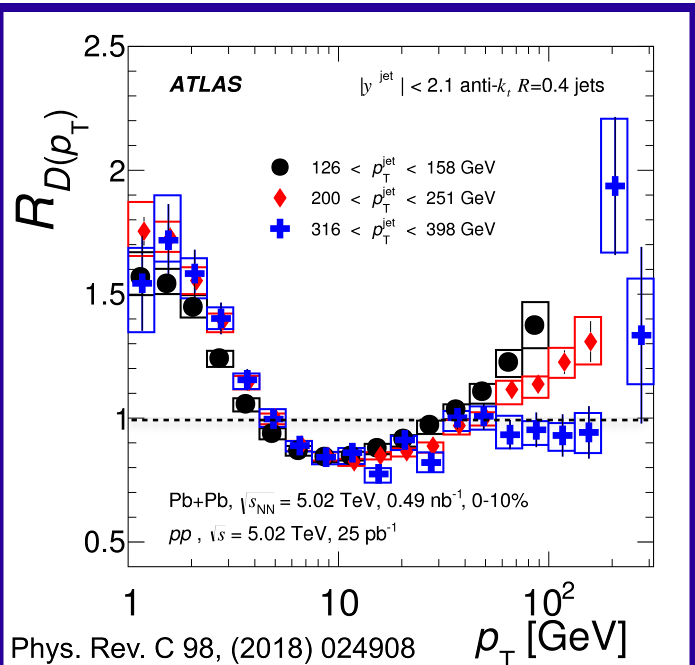

Phys. Rev. C 98, (2018) 024908

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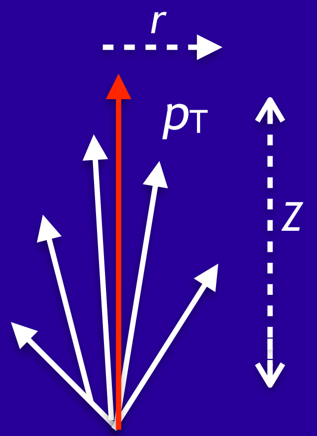

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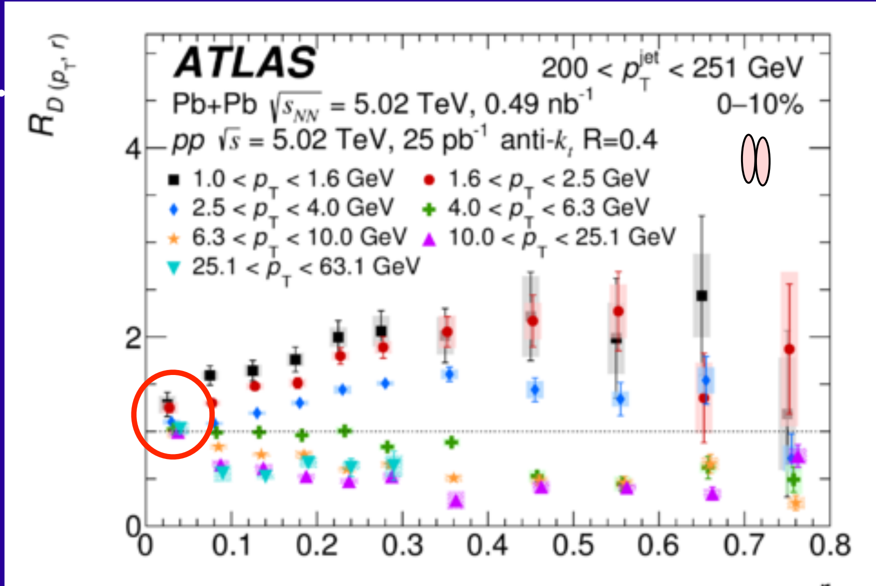

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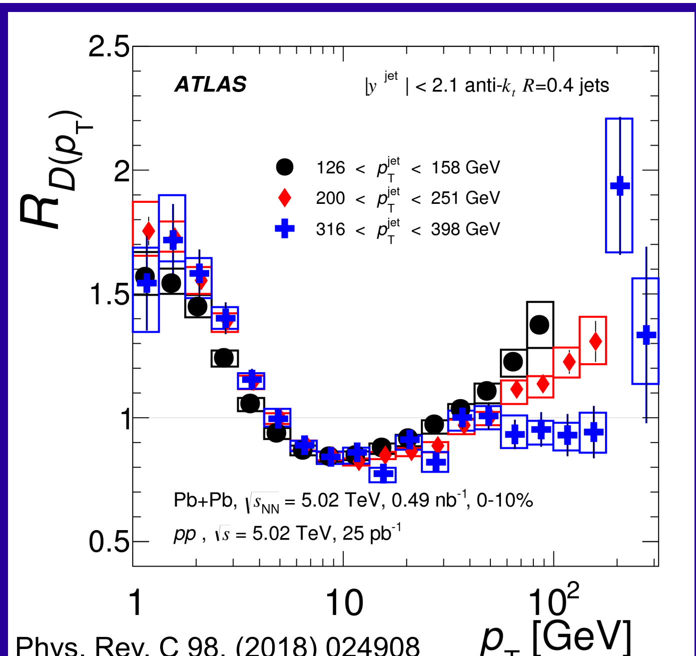
Jet core remains unmodified.



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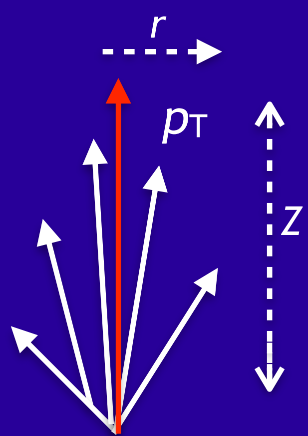

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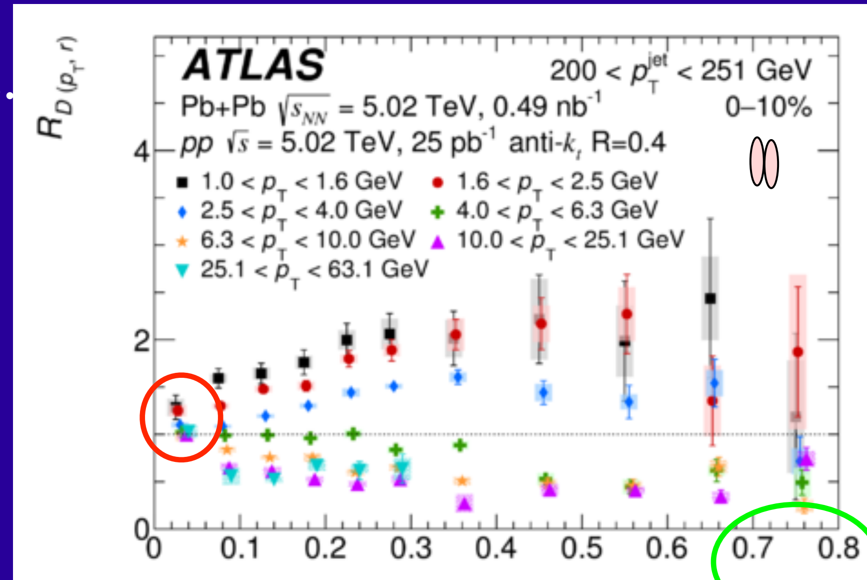

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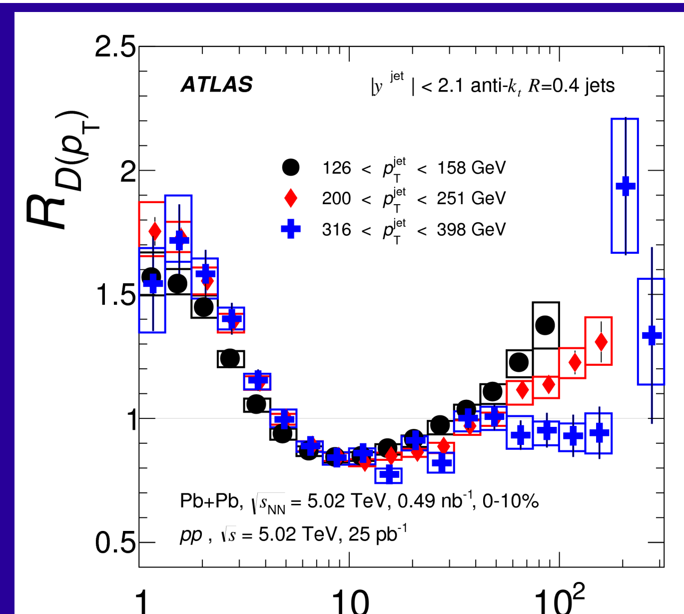
Yield of soft particles starts to drop down when r –> 0.8.



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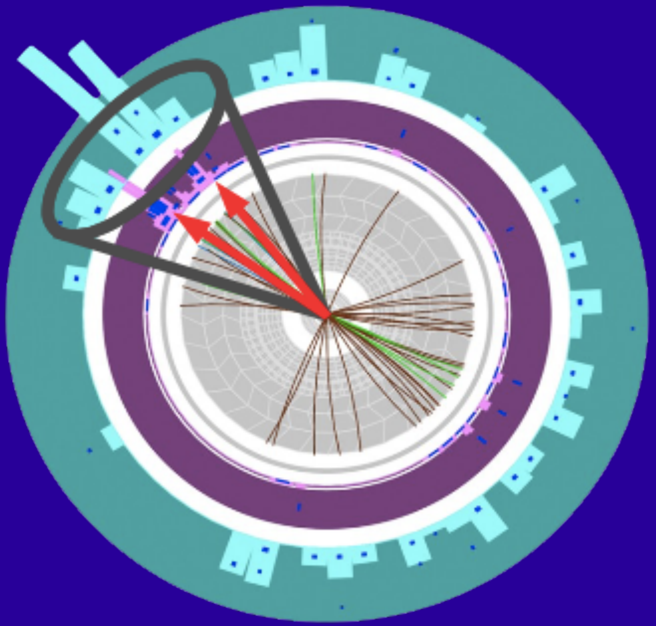
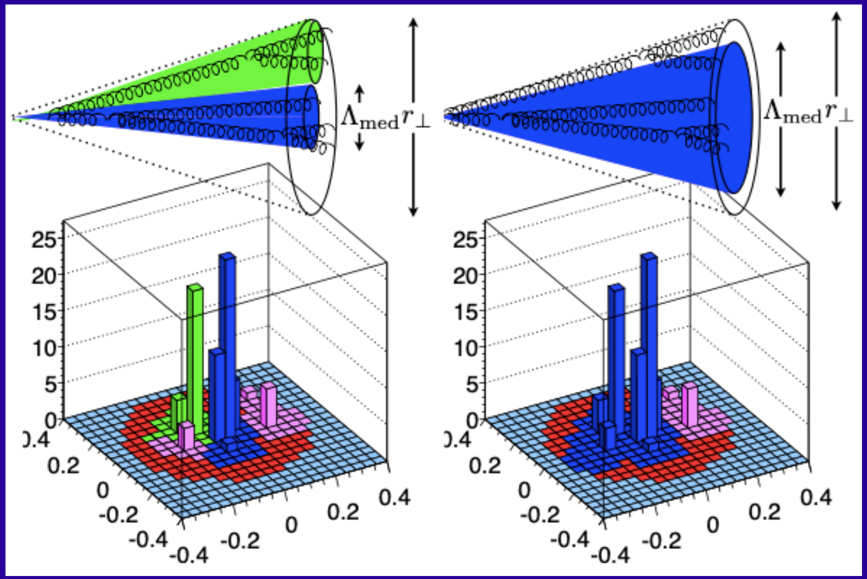
What can be learnt from large-*R* jets?

Measure jet R_{AA} as a function of jet sub-structure using sub-jets





J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

recluster jets and remove soft contributions

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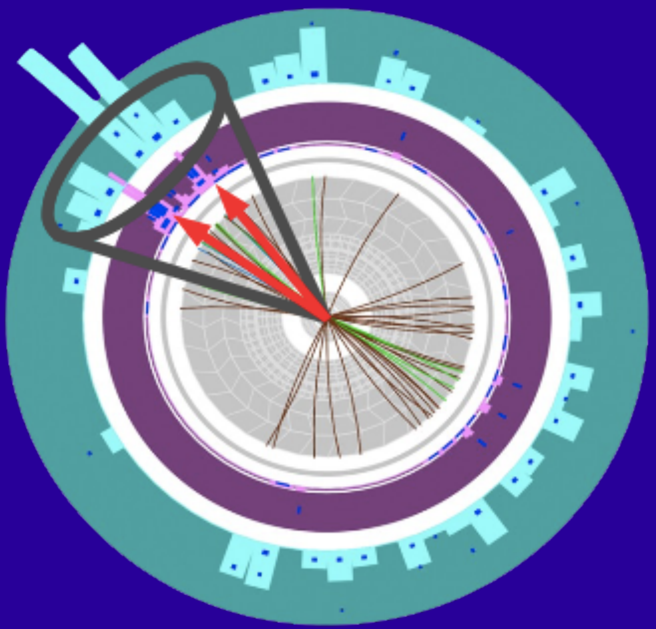

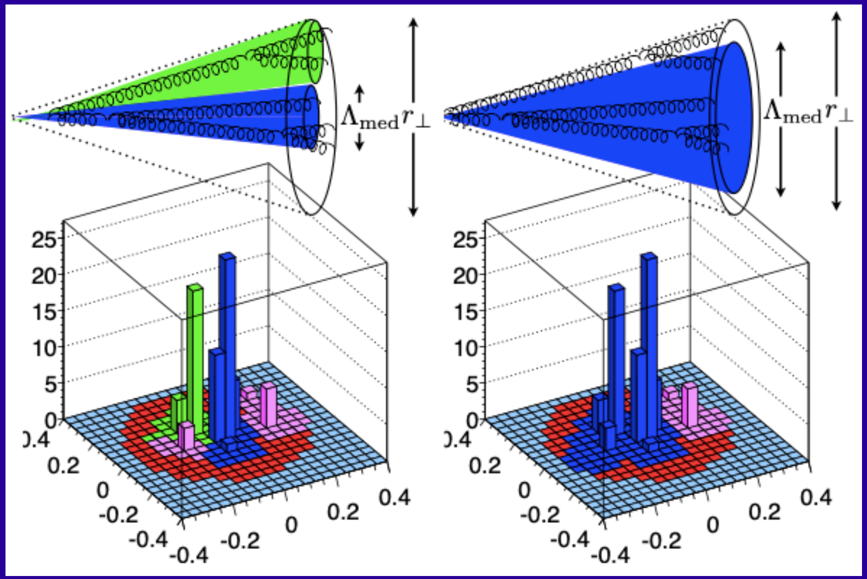

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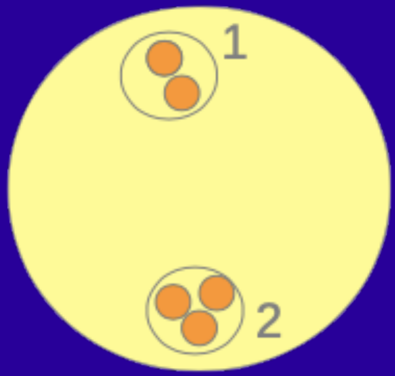
reclusters jets and remove soft contributions

$R = 0.2$ jets with $p_T > 35$ GeV

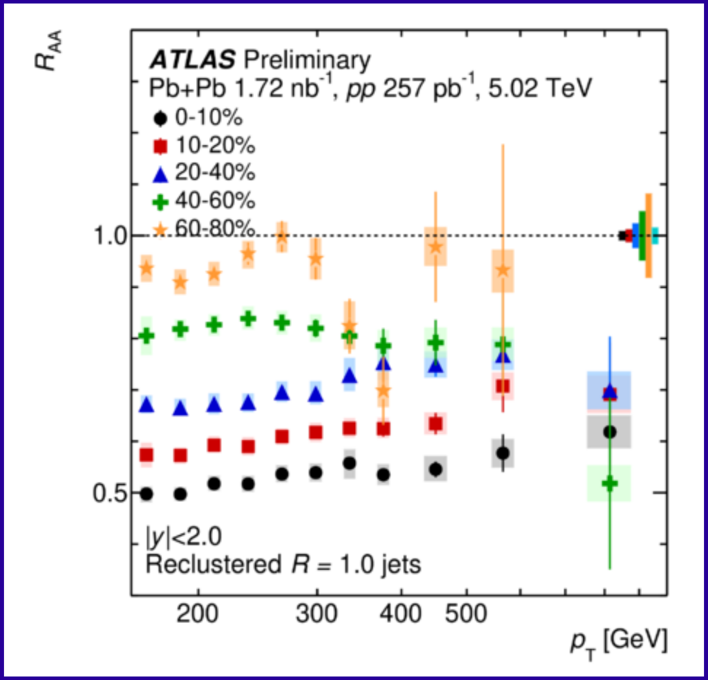
reclustered into anti-k_t $R = 1.0$

Allows the study of k_t sppliting scale

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

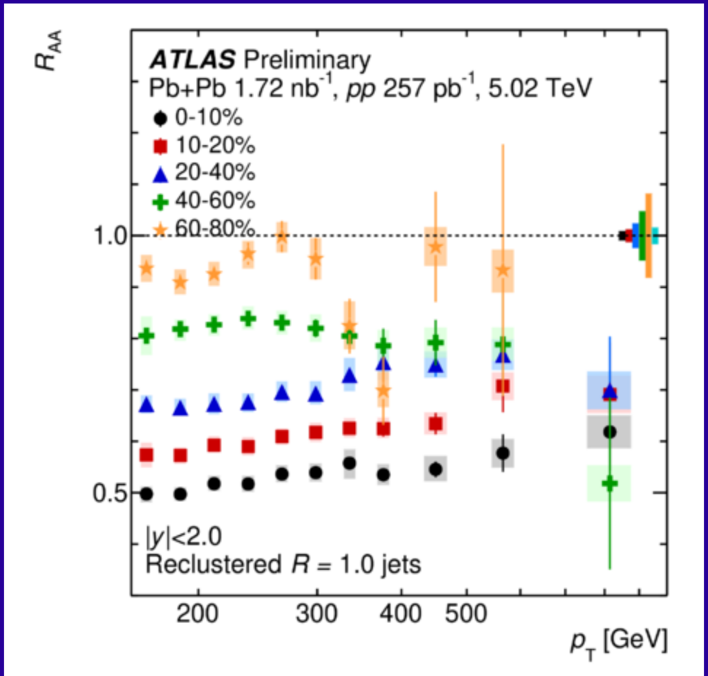


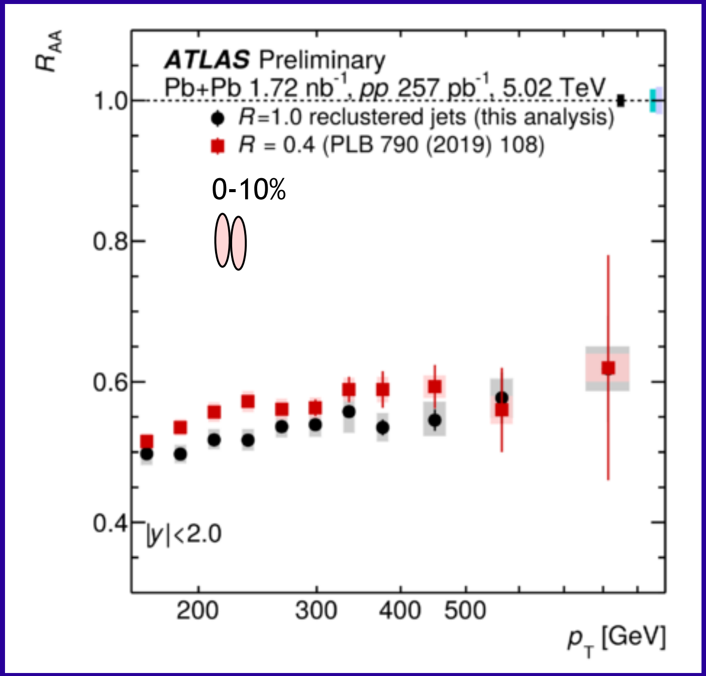
R_{AA} as a function of jet p_T



- Large-*R* (re-clustered with 0.2 jets and soft particles removed) jets are increasingly suppressed with centrality.

R_{AA} as a function of jet p_T

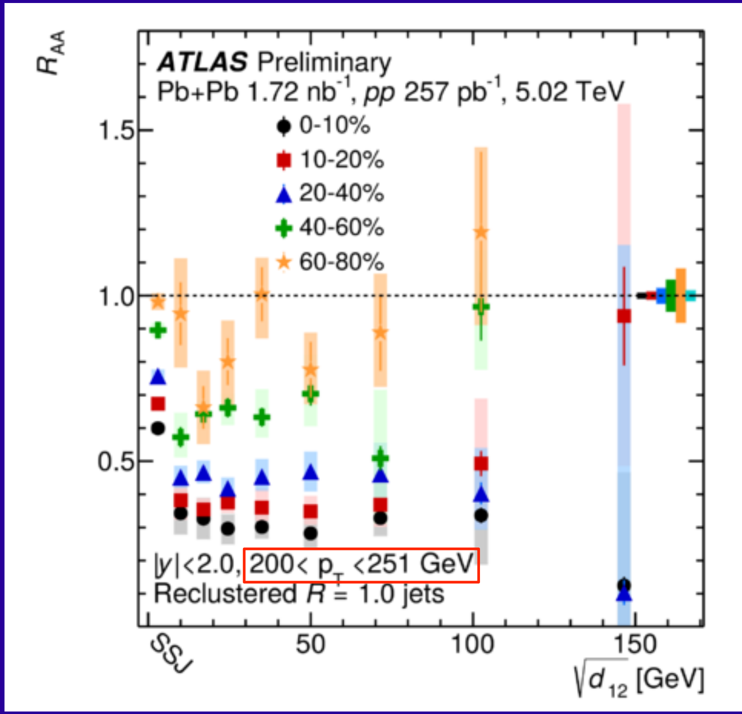




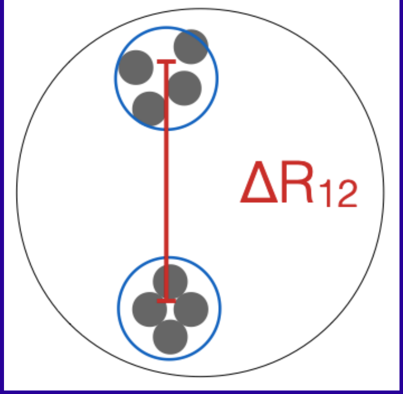
ATLAS-CONF-2019-056

- Large-*R* (re-clustered with 0.2 jets and soft particles removed) jets are increasingly suppressed with centrality.
- R = 0.4 jets slightly less suppressed, but trend is similar.

R_{AA} as a function of jet sub-structure



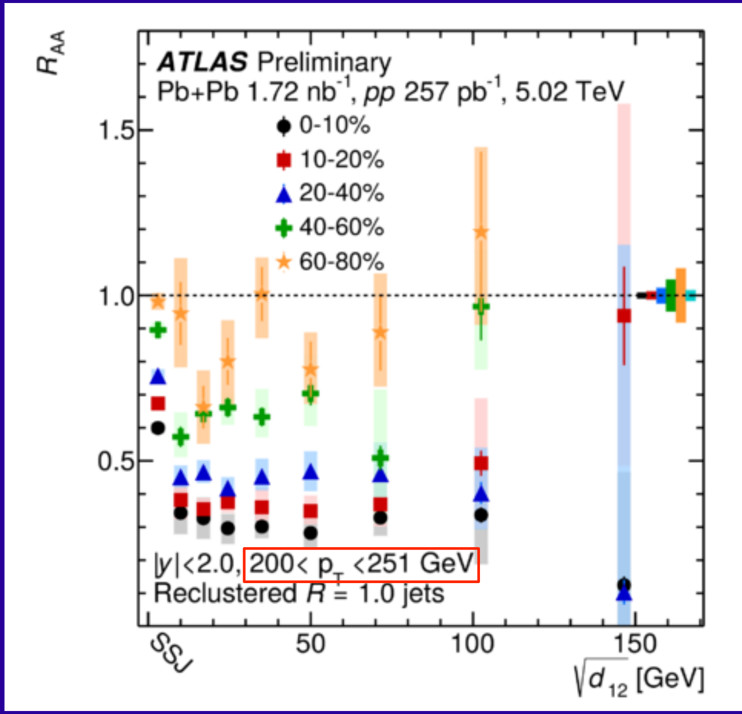
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

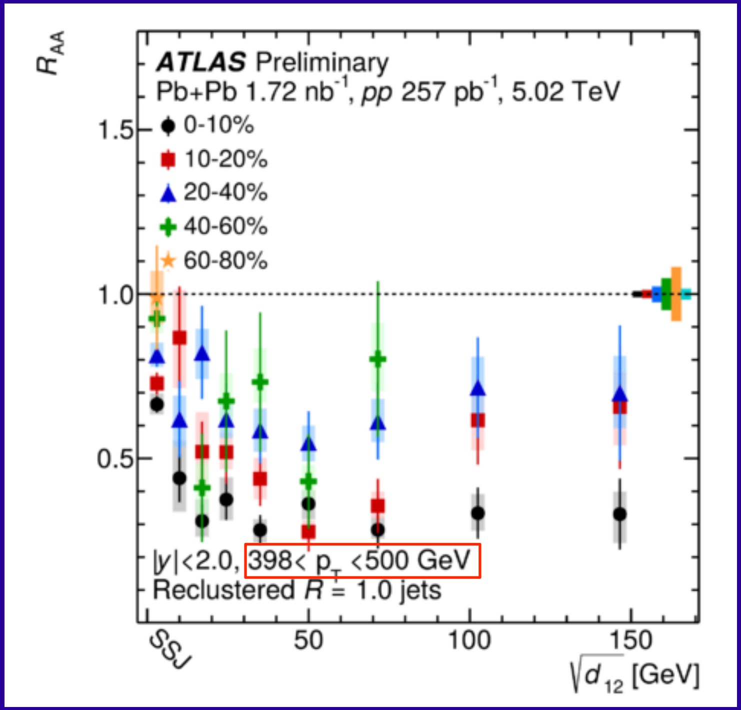


The lowest $\sqrt{d_{12}}$ interval is populated with jets with single "isolated" sub-jet - SSJ

- Significant change of the R_{AA} magnitude between jets with SSJ and those with more complex sub-structure.
- Then R_{AA} is not dependent on $\sqrt{d_{12}}$.

R_{AA} as a function of jet sub-structure





ATLAS-CONF-2019-056

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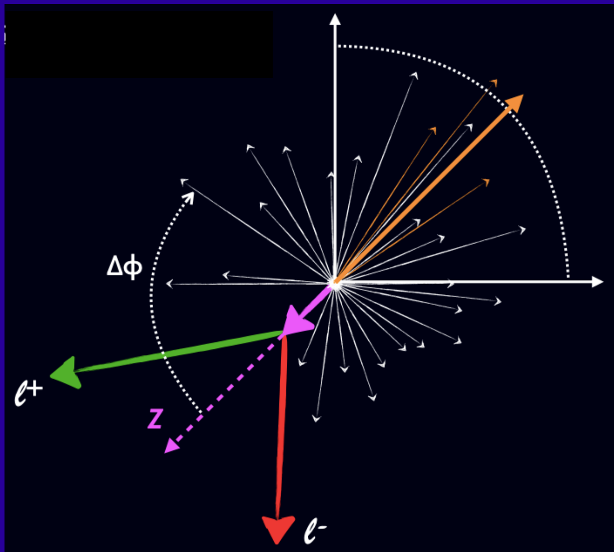
- Significant change of the R_{AA} magnitude between jets with SSJ and those with more complex sub-structure.
- Then R_{AA} is not dependent on $\sqrt{d_{12}}$.
- This behaviour is not dependent on jet p_T (up to 500 GeV).

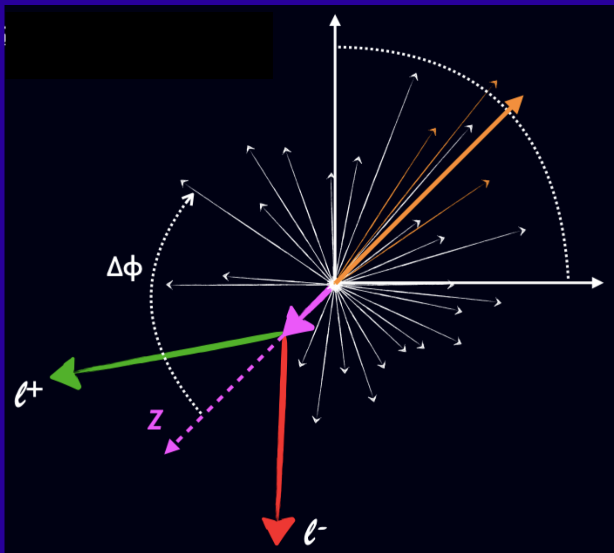
Z-recoil particles



The Z boson tags the initial energy, direction, and flavour of the opposing parton before it starts to shower and propagate through the QGP.

Access to low-p_T ranges not reached by reconstructed jets —> precious for understanding the mechanisms of the parton energy loss.

Z-recoil particles



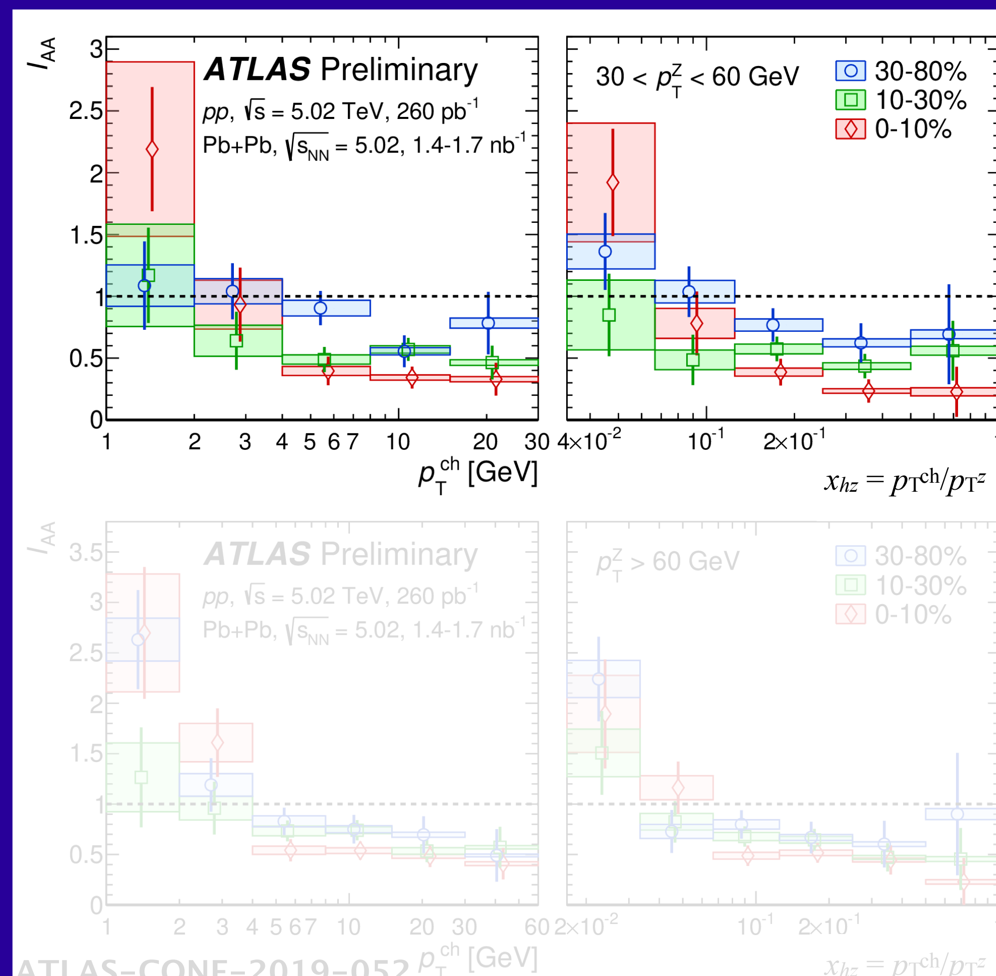
Charged particles
- p_T^{ch} > 1 GeV
- $|\Delta\varphi| > 3\pi/4$
- $|\eta| < 2.5$

p_T^{ch}-dependent enhancement/ suppression pattern

- $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$
- $76 < m_Z < 106$ GeV
- $p_T^Z > 30$ GeV

Measure the average number of charged particles per Z and

I_{AA} = yield in Pb+Pb / yield in *pp*



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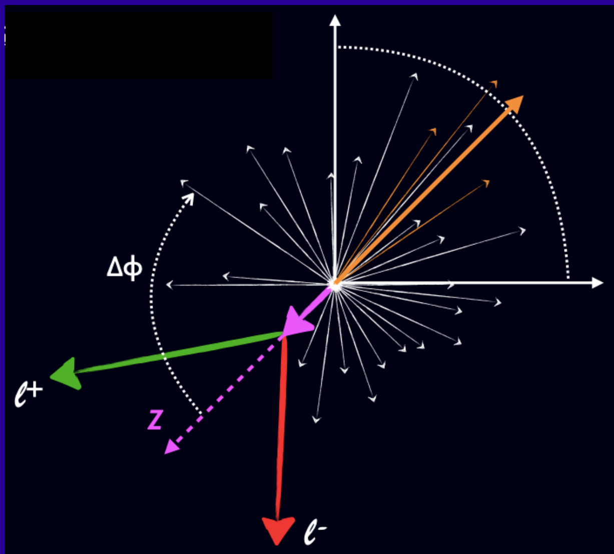

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- p_T^{ch} > 1 GeV
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p_T^Z plays a role in the enhancement/suppression pattern

- *Z* —> *ee* or *Z* —> *μμ*
- 76 < m_Z < 106 GeV
- p_T^Z > 30 GeV

Measure the average number of charged particles per Z and

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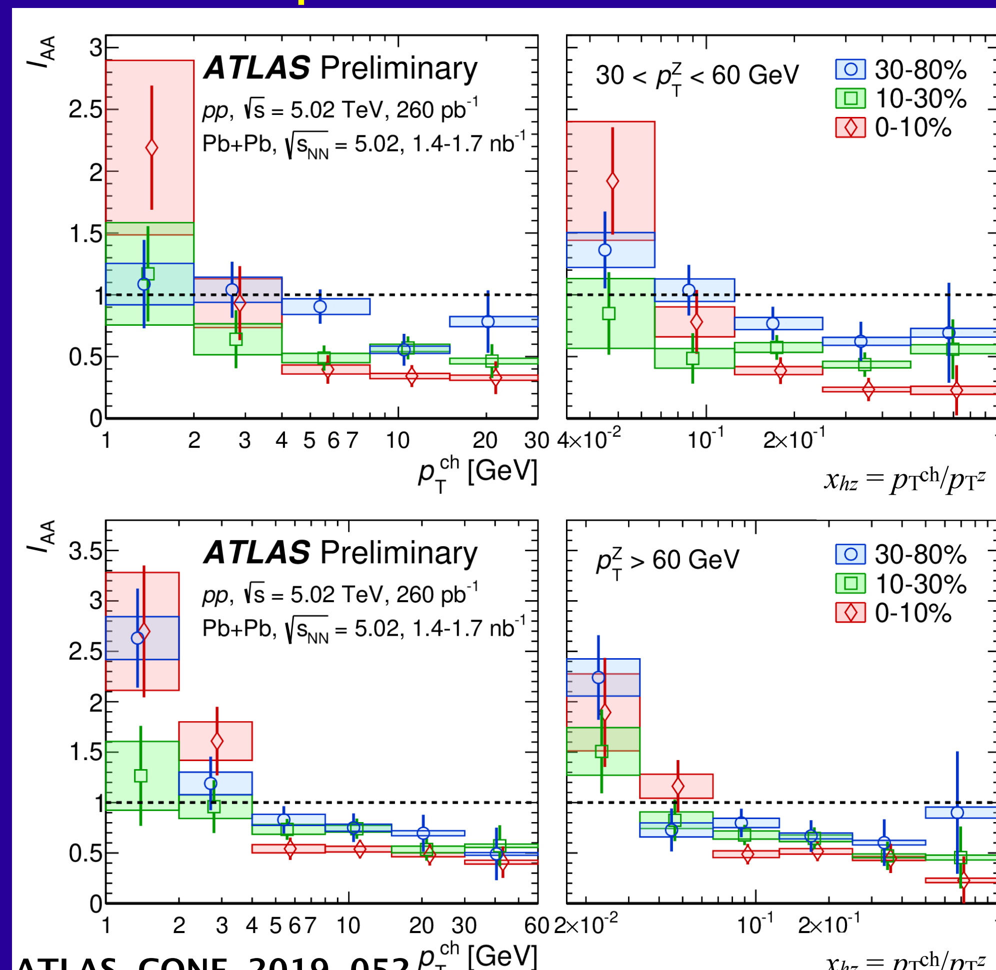
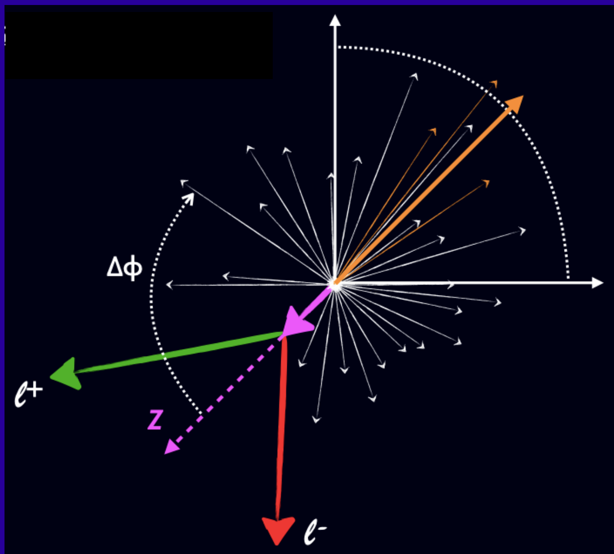


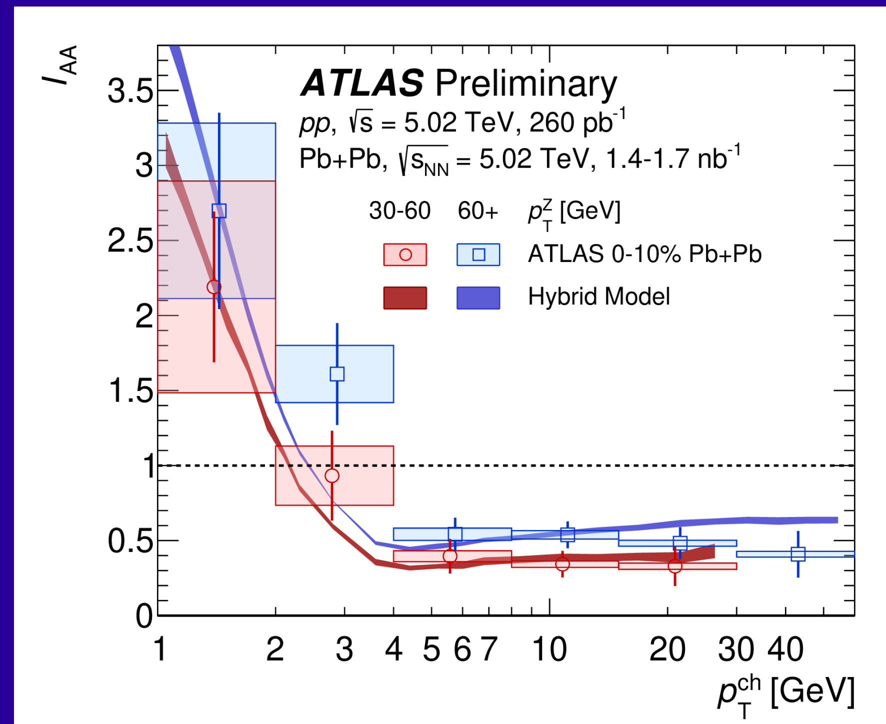
ATLAS-CONF-2019-052

Z-recoil particles



Charged particles

- $p_T^{ch} > 1$ GeV
- $|\Delta\varphi| > 3\pi/4$
- $|\eta| < 2.5$



- $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$
- $76 < m_Z < 106$ GeV
- $p_T^Z > 30$ GeV

Measure the average number of charged particles per Z and

I_{AA} = yield in Pb+Pb / yield in pp

Good agreement with the predictions of the Hybrid model (JHEP 03 (2016) 053) in the entire p_T^{ch} range and for both p_T^Z selections.

Highlights

- Inclusive jets in Pb+Pb are suppressed relatively to *pp* up to a factor of 2.
- Evidence of path length dependence of jet energy loss.
- Jet substructure strongly modified in Pb+Pb collisions with onset at 4 GeV.
- Reclustered R=1.0 jets with single sub-jet less quenched than those with more complex substructure.
- Suppression of high-p_T hadrons in Z-tagged hadron yields; enhancement at low-p_T.

Backup

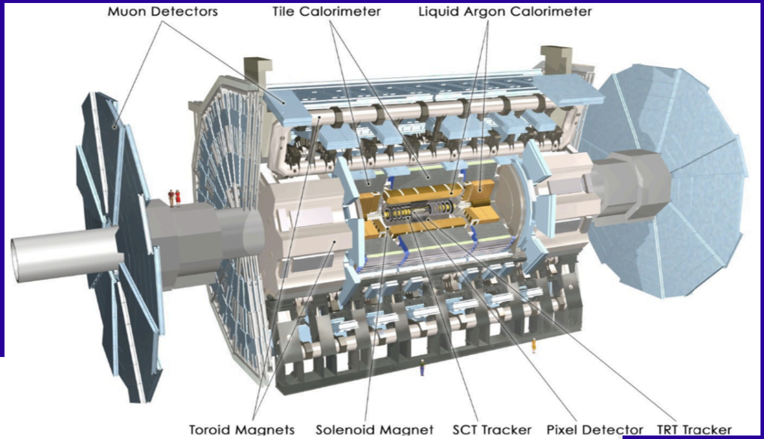
Data summary

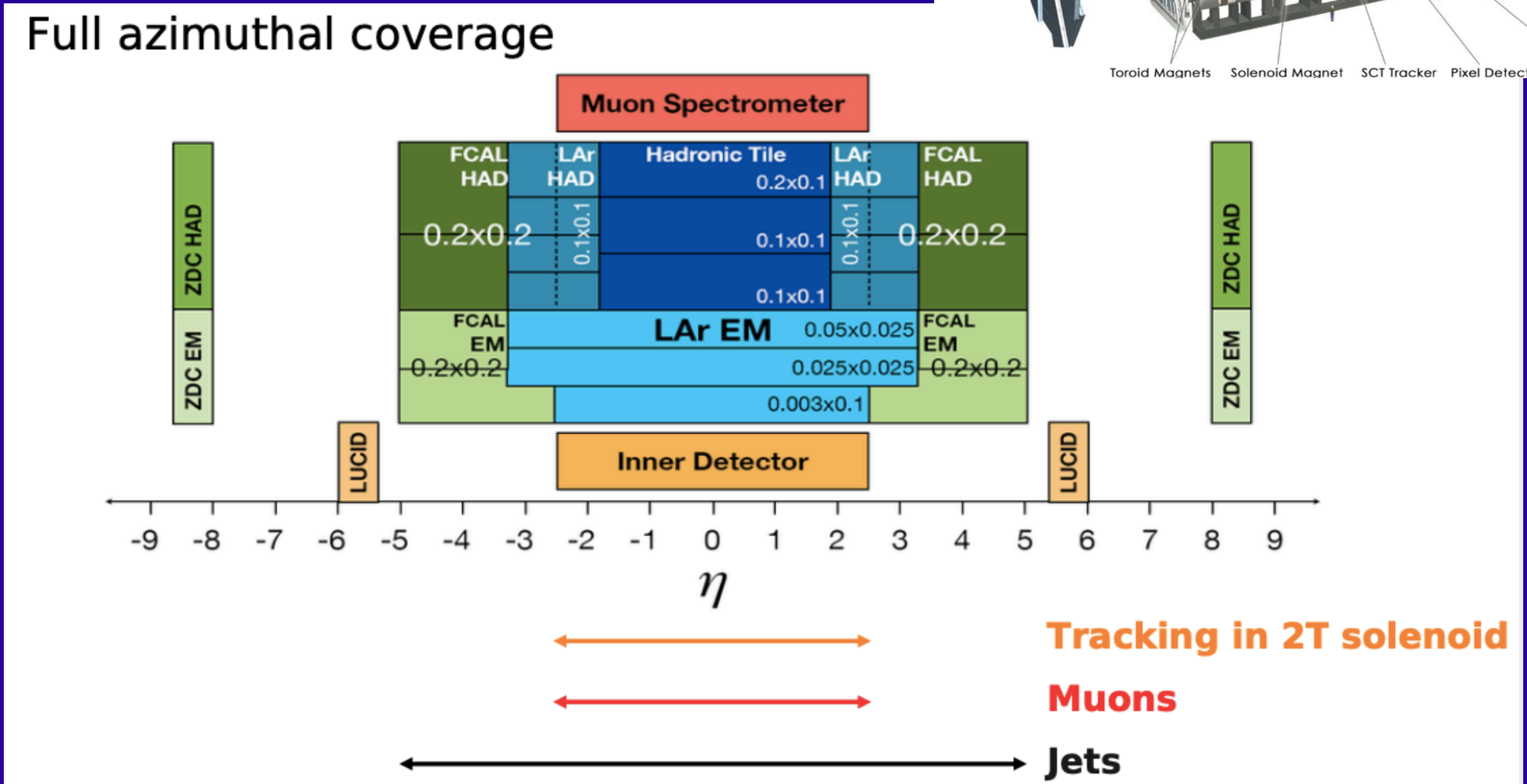
Run 2 datasets

System	Year	Collision energy (TeV)	Luminosity
PbPb	2015	5.02	0.49/nb
pPb	2016	5.02	0.5/nb
pPb	2016	8.16	180/nb
pp (low μ)	2017	13	150/nb
XeXe	2017	5.44	3/μb
pp	2017	5.02	272/pb
pp (low μ)	2018	13	11/pb
PbPb	2018	5.02	1.73/nb

The ATLAS Detector

An excellent detector for the LHC Heavy-Ion program, with enourmous trigger capabilities

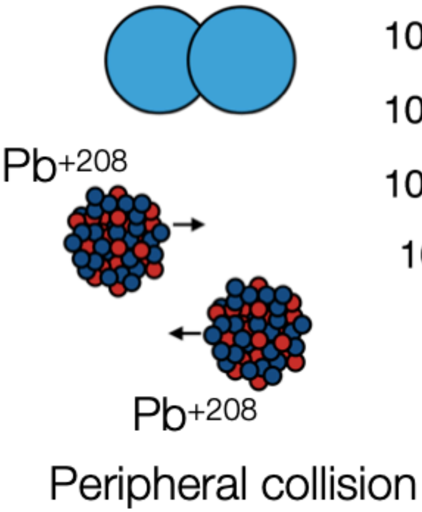


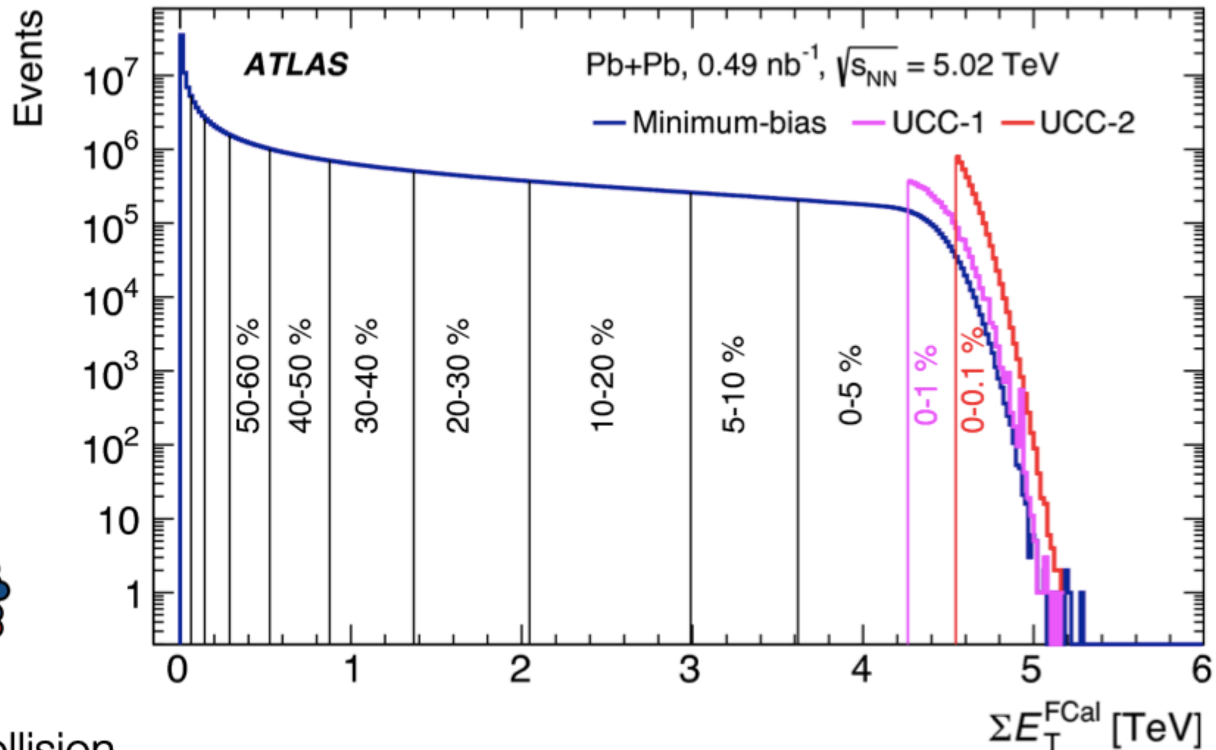


Collisions Centrality

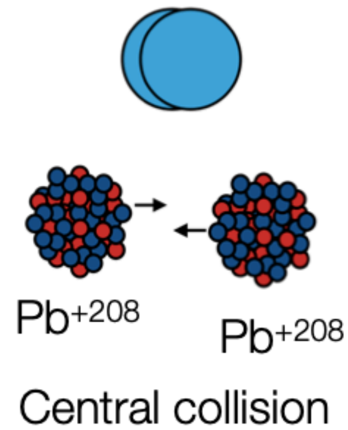
Centrality in Heavy Ion collisions

2015 Pb+Pb data





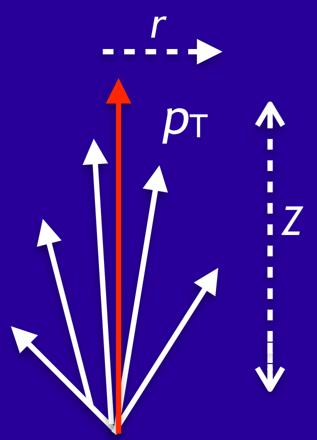
Negligible pile-up!



Centrality is parametrized using the energy deposited in the Forward calorimeter (|η|>3.2)

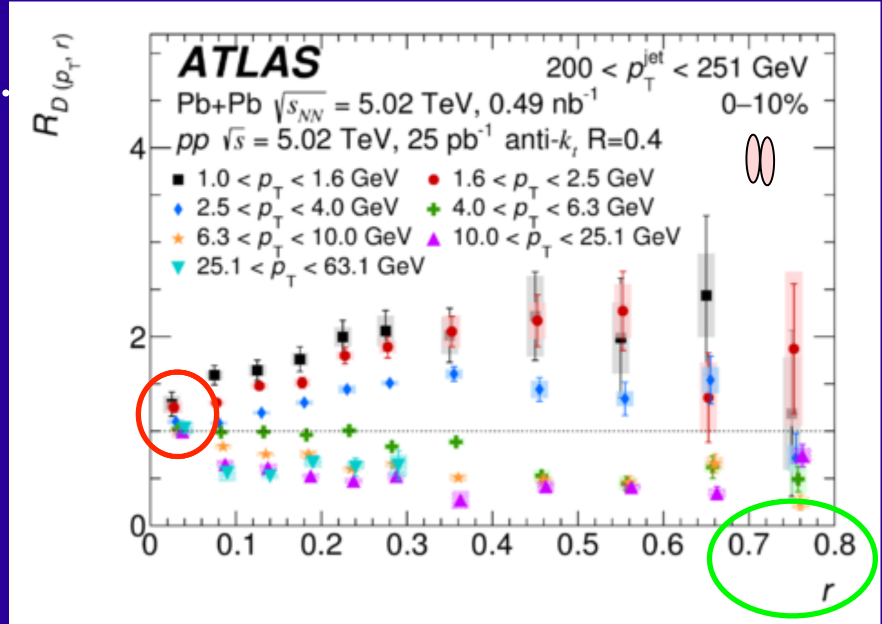
How do particles re-distribute within the jet and beyond?

Study *FF* as a function of the angular distance between the charged particle and the jet axis.



$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\,\mathrm{d}p_{\mathrm{T}}}$$

$$r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

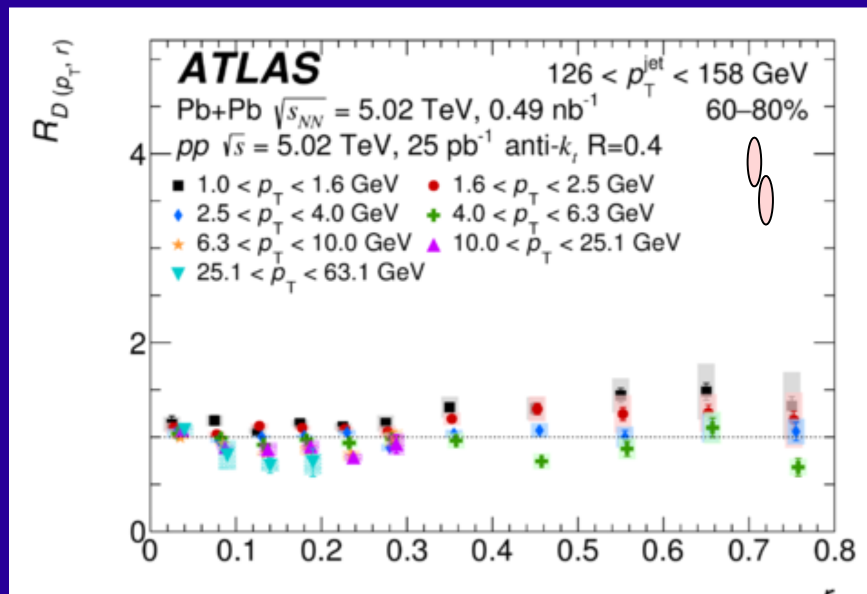


In central collisions $R_{D(p_T,r)}$ is above unity at all r for all $p_T < 4$ GeV —> Energy lost by jets is being transferred to particles with $p_T < 4$ GeV with larger radial distance.

Jet core remains unmodified.

Hints for drop down when r —> 0.8.

$R_{D(p_T,r)}$ has no significant dependence on r in peripheral collisions.



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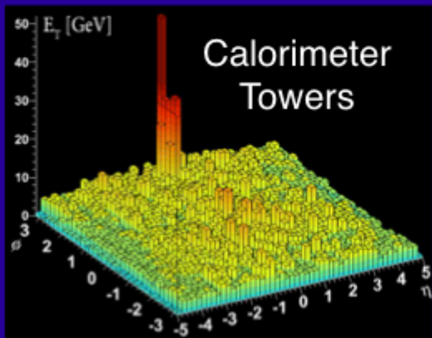
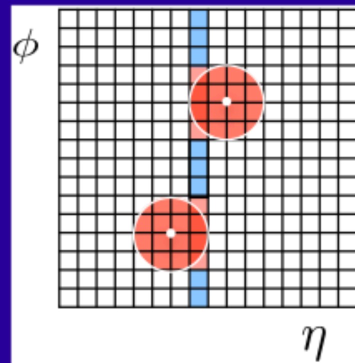
Jet reconstruction

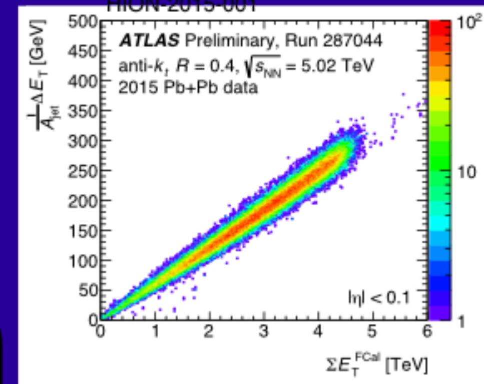
AtlasPublicEventDisplays



ATL-COM-PHYS-2011-1733



HION-2015-001



Calorimeter towers

+

Anti-k_t Algorithm

→ Jets →

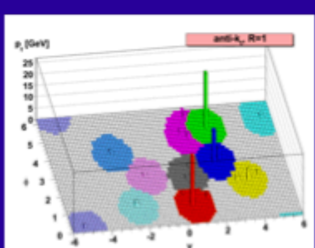
Average E_T density: ρ(η, layer)

+

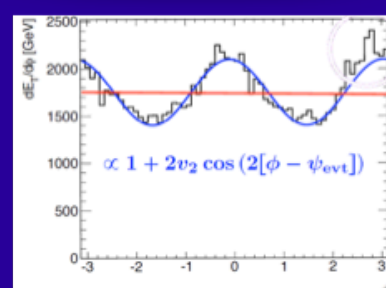
Flow modulation (v_2, v_3, v_4)

→ Reconstructed Jets

← Iterative subtraction



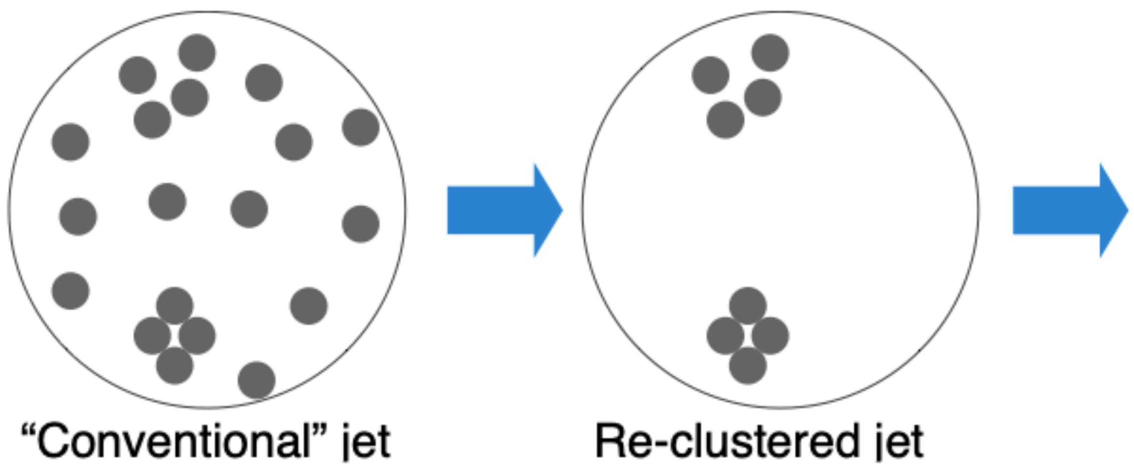
arXiv - 0802.1189



ATL-COM-PHYS-2012-628

Large R jets reconstructed from R = 0.2 jets

Cal. towers & UE subtraction → R=0.2 jets anti-k_t jets $p_T > 35$ GeV → re-clustering with anti-k_t R=1.0 → Sub-jets → re-clustering with k_t algorithm → Splitting scale $\sqrt{d_{12}}$

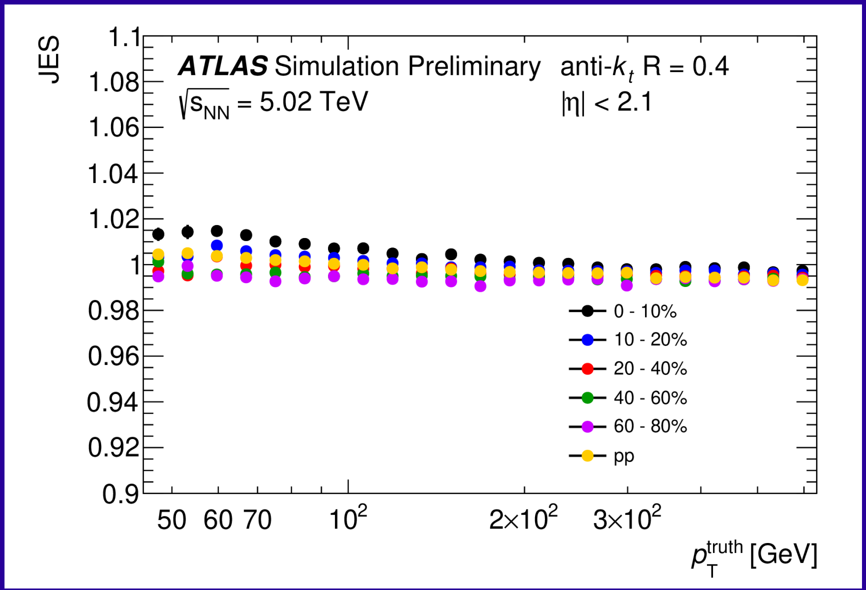


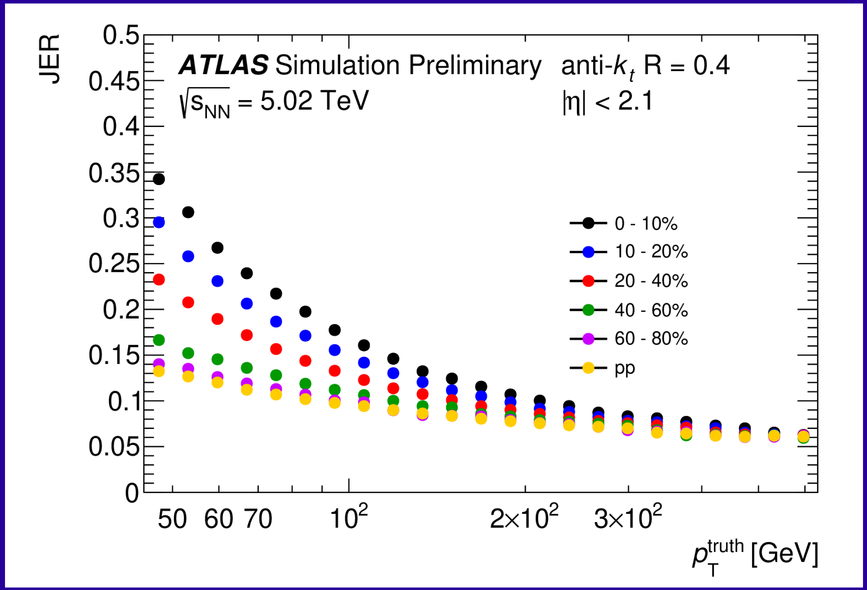
Different jets than the conventional R=1.0.

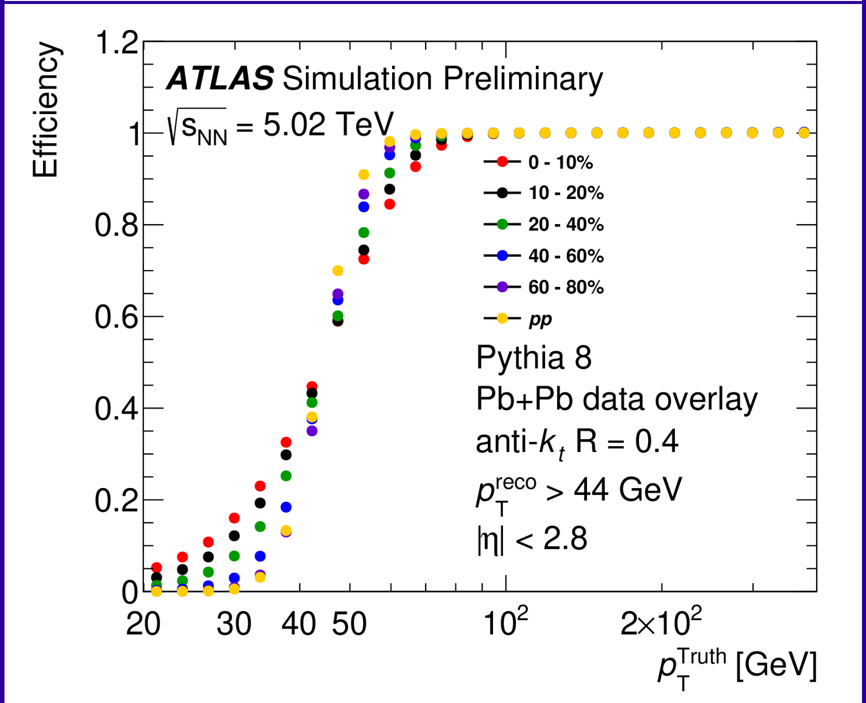
Trimming & 35 GeV threshold remove soft components.

M. Rybar QM19

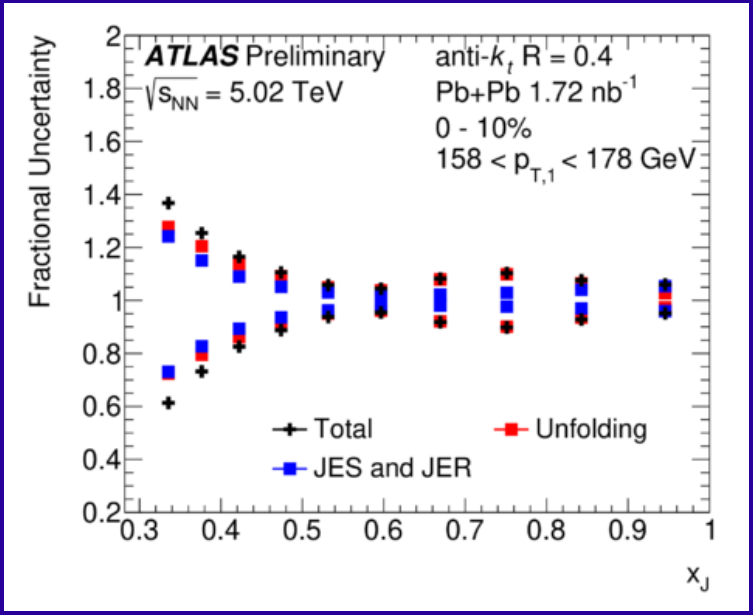
Reconstruction performance

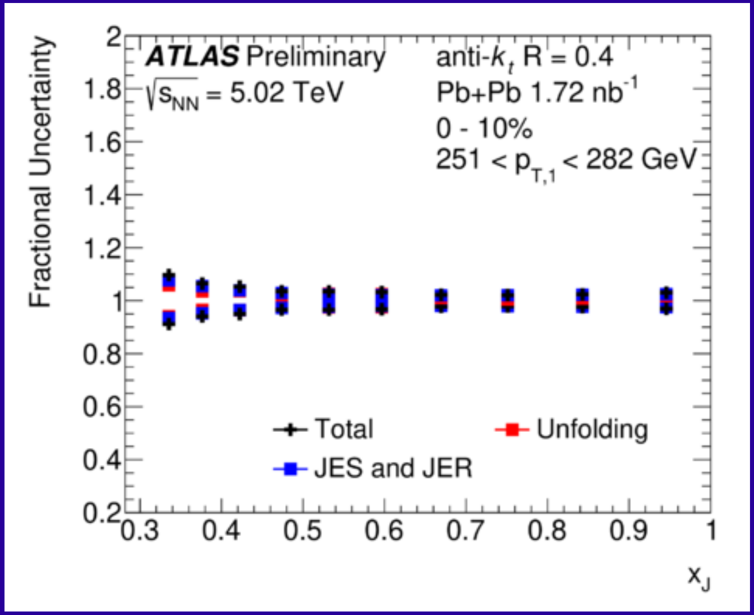




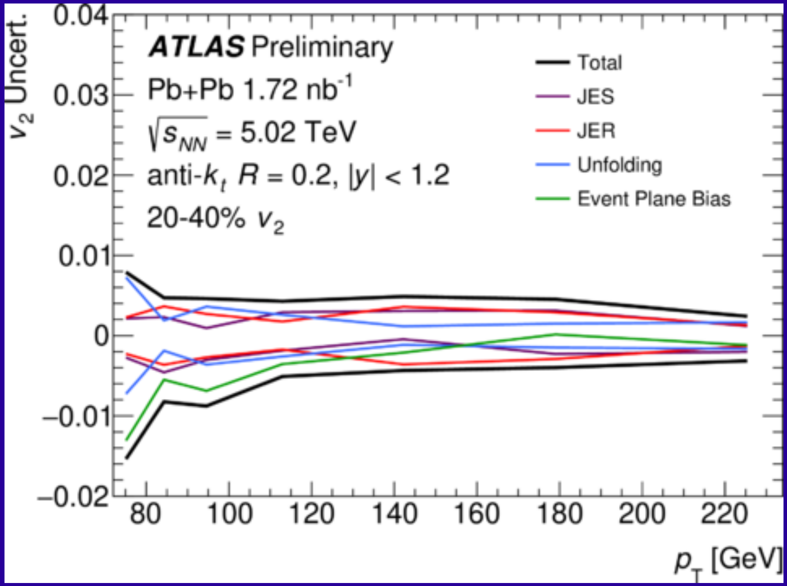


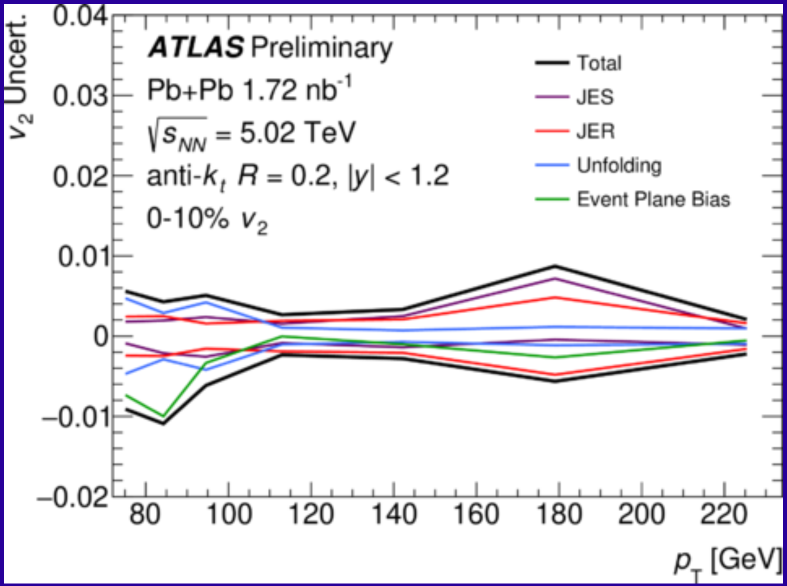
Systematic uncertainties on dijet p_T-balance



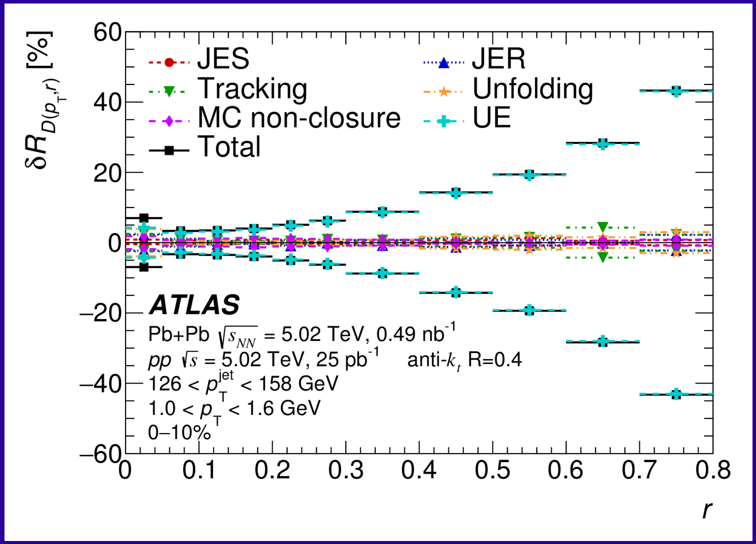


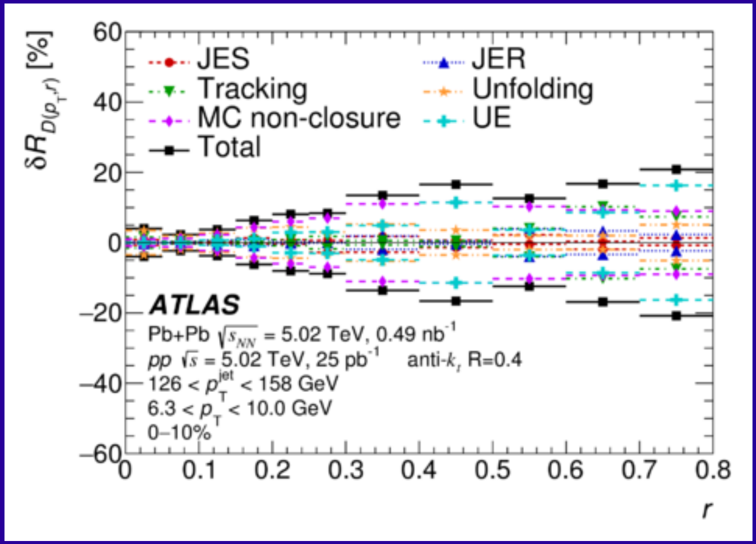
Systematic uncertainties on jet-v_n





Systematic uncertainties on $R_{D(p_T,r)}$





Systematic uncertainties on R_{AA} (R=1.0)