Jet physics in Heavy Ion Collisions at the LHC

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Jets in Heavy Ions

A multi-scale problem

Hard process → **scales is O(p_T^{jet})** → **perturbative QCD**

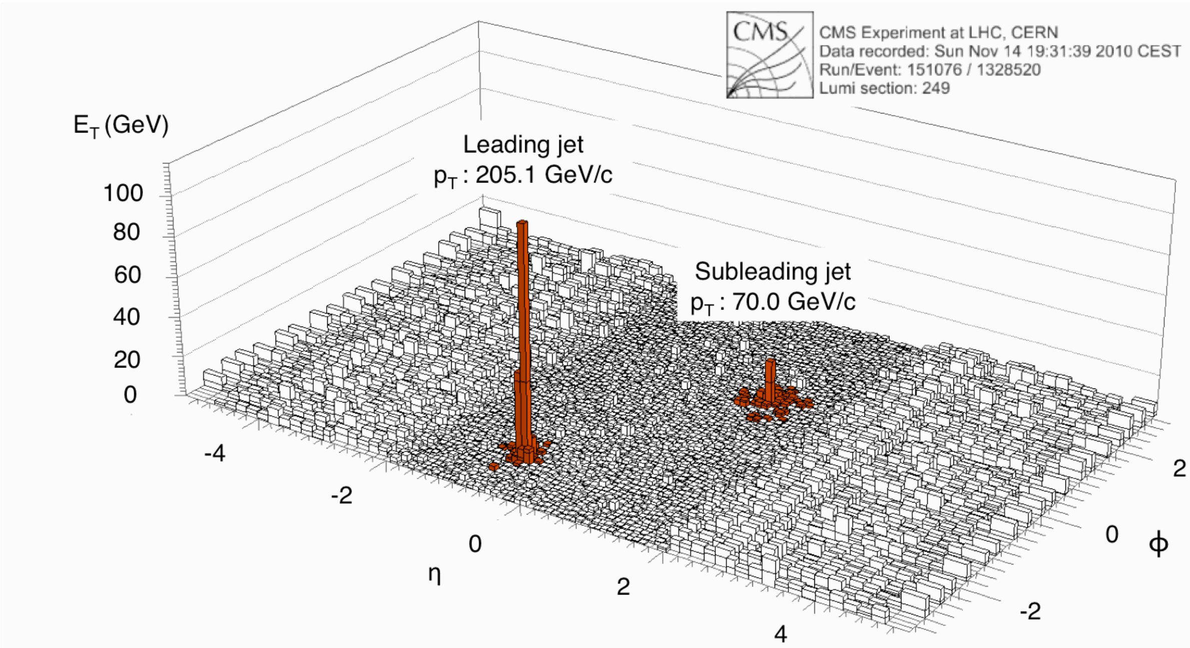
-Vacuum DGLAP evolution
-Medium-induced gluon emission
-Collisional energy loss
-Large angle scattering (Moliere)

Soft exchanges of energy and momentum between jet fragments and medium constituents → **scale is O(T^{medium})** → **strongly coupled description**

-Drag force
-Sound waves
-Diffusion wakes
-Heating up the plasma…

Other relevant scales: hadronization, resolution parameter of the medium…

Jets in Heavy Ions

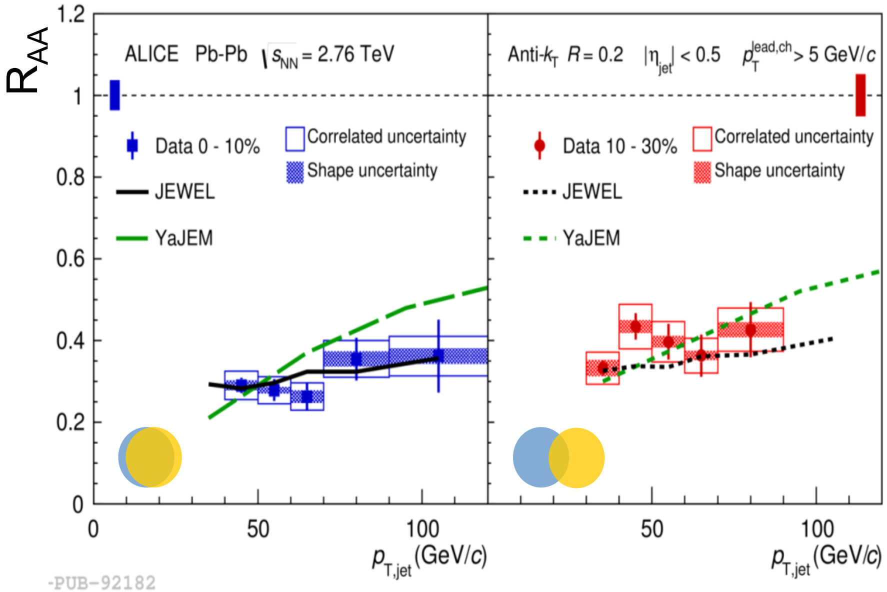


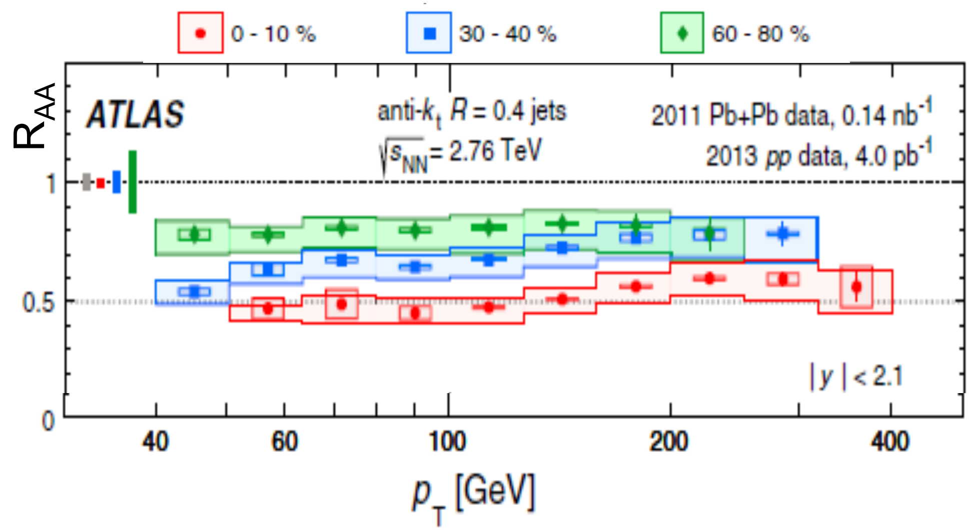
Hard Jets are clearly visible in event displays but accurate measurement of the energy of such jets is **challenging** due to large and inhomogeneous underlying event background:

Differentiate hadronic component of a jet from that of the background
Suppress the combinatoric component
Keeping IRC safety, that may play a key role in uncovering nature of jet quenching

Inclusive jet yield suppression relative to pp

ALICE: PLB 746 (2015) 1





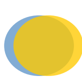
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

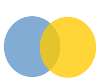
The medium is opaque in a large kinematic range:

Inclusive jet yields are suppressed relative to pp

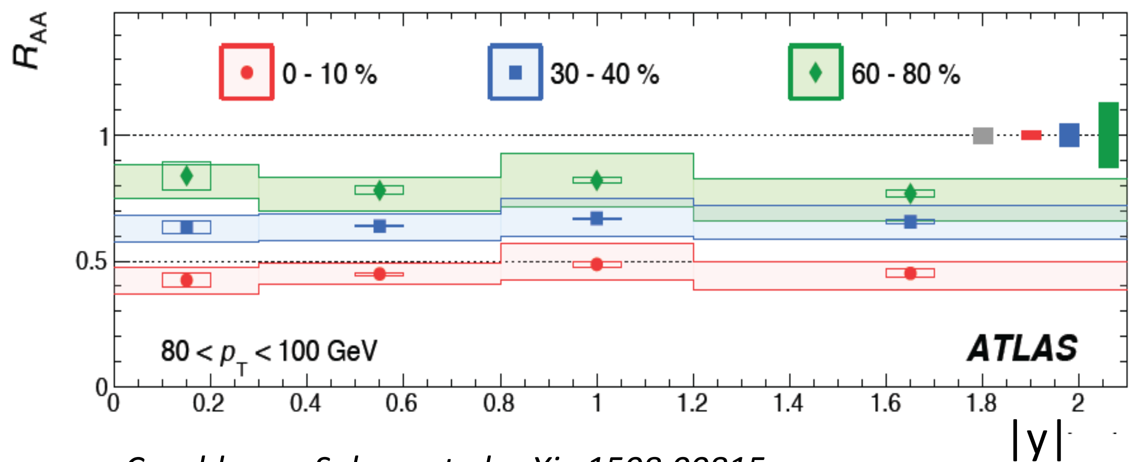
Modest p_T dependence

No strong constraint on jet quenching models since R_{AA}(jets)~R_{AA}(hadrons)

Note:  Central or head-on collisions, larger in medium path length

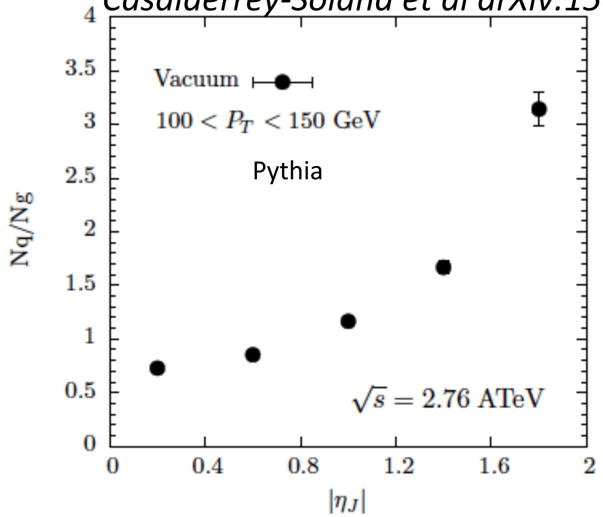
 Peripheral, less in medium path length

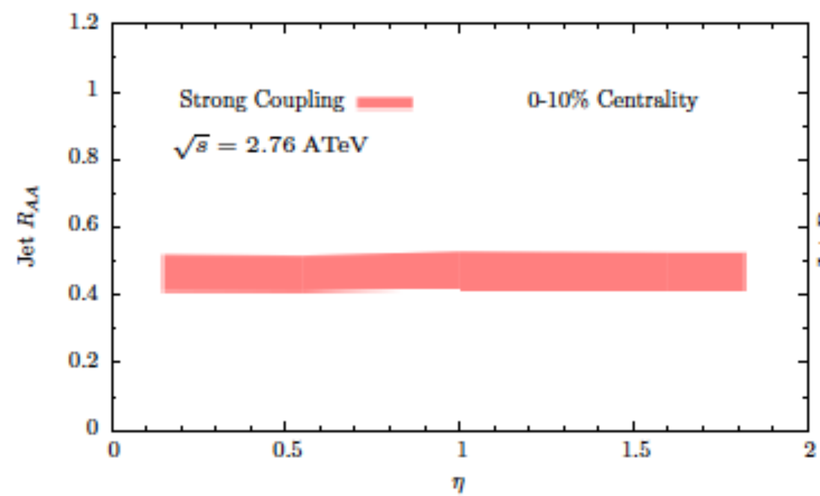
Inclusive jet yield suppression relative to pp



Suppression strongly dependent on centrality but constant with rapidity

Casalderrey-Solana et al arXiv:1508.00815

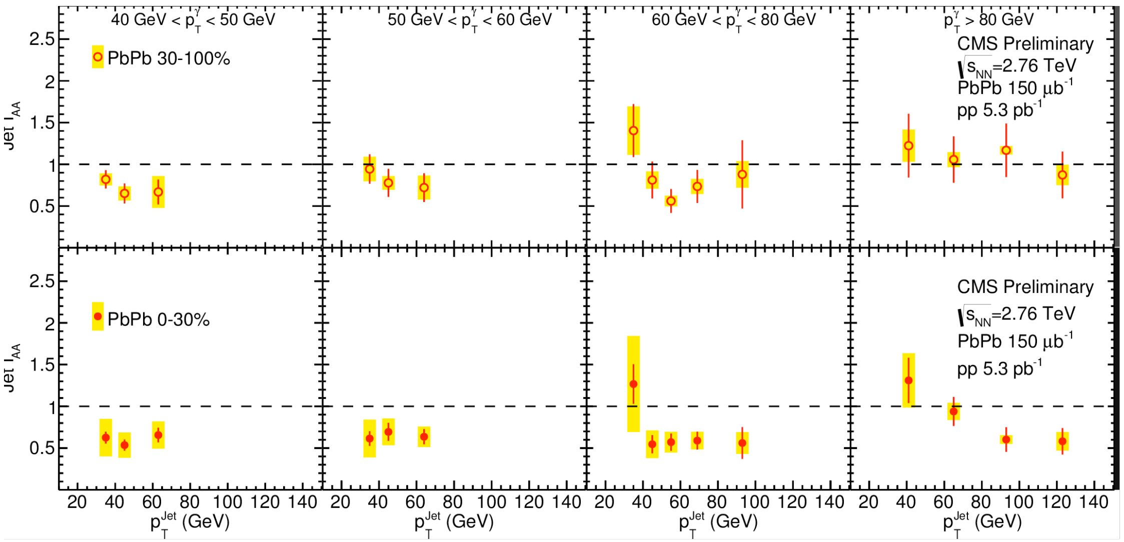




Strong change of species + strong change of quenching + different underlying spectrum = coincidental flatness?

Semi-inclusive jet yield suppression

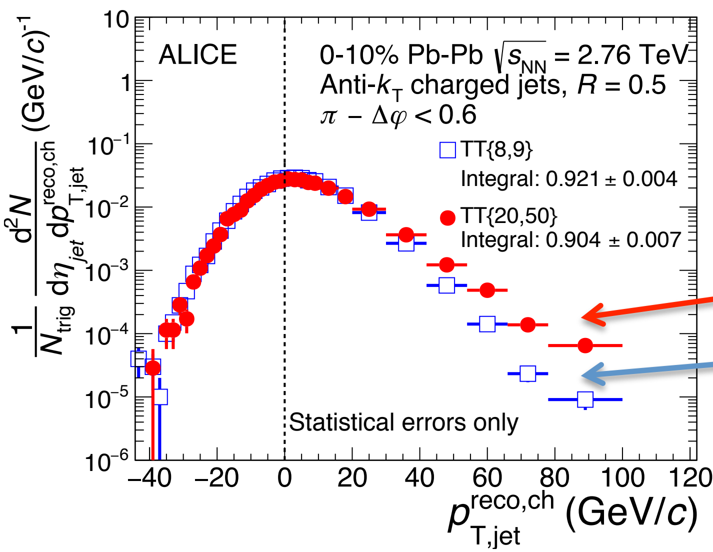
Photon (color transparent) trigger



Semi-inclusive yields of jets recoiling from a high p_T trigger

Dijet-like topologies to reduce combinatorial background

Hadron trigger



Difference of semi-inclusive recoil yields in two bins of hadron trigger p_T

ALICE, arXiv:1506.03984

$$\Delta_{recoil} = \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}^{AA}}{dp_{T,jet}^{ch}\, d\eta_{jet}}\bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}^{AA}}{dp_{T,jet}^{ch}\, d\eta_{jet}}\bigg|_{p_{T,trig} \in TT_{Ref}} .$$

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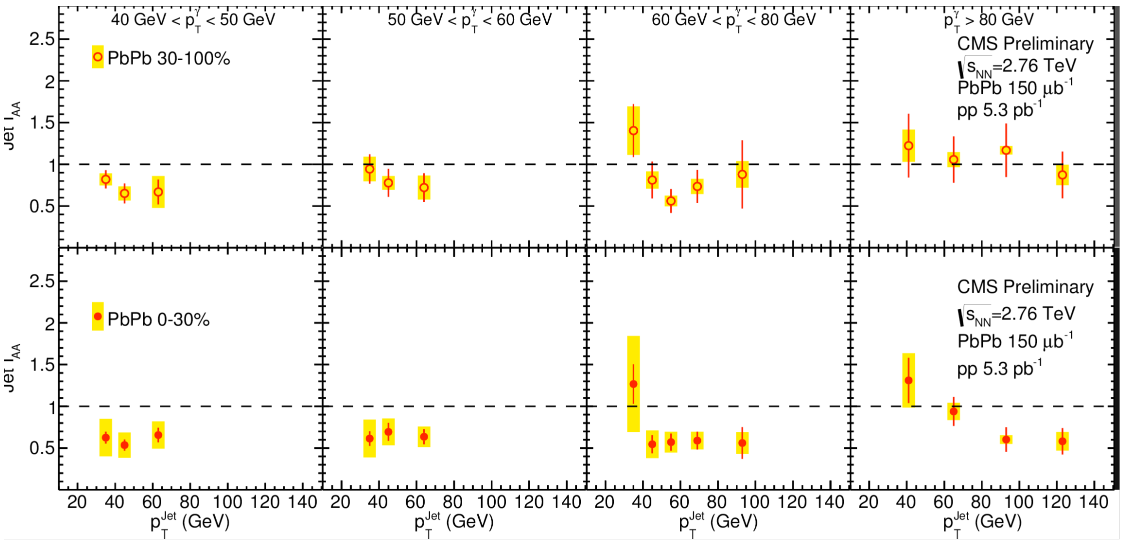

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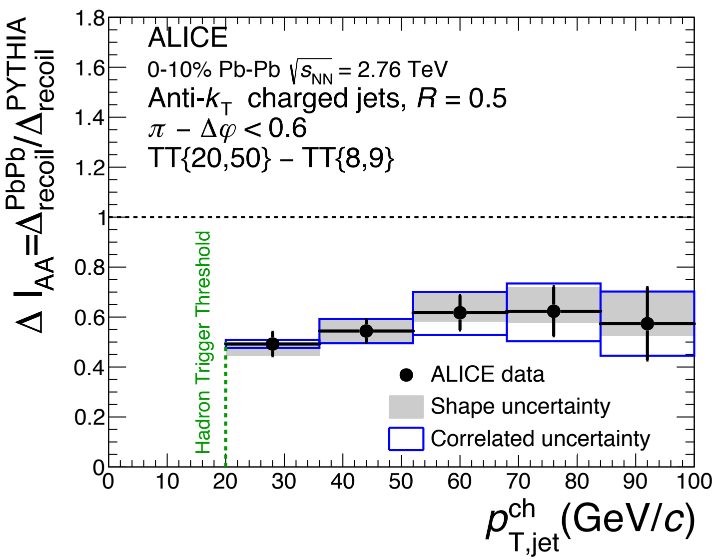

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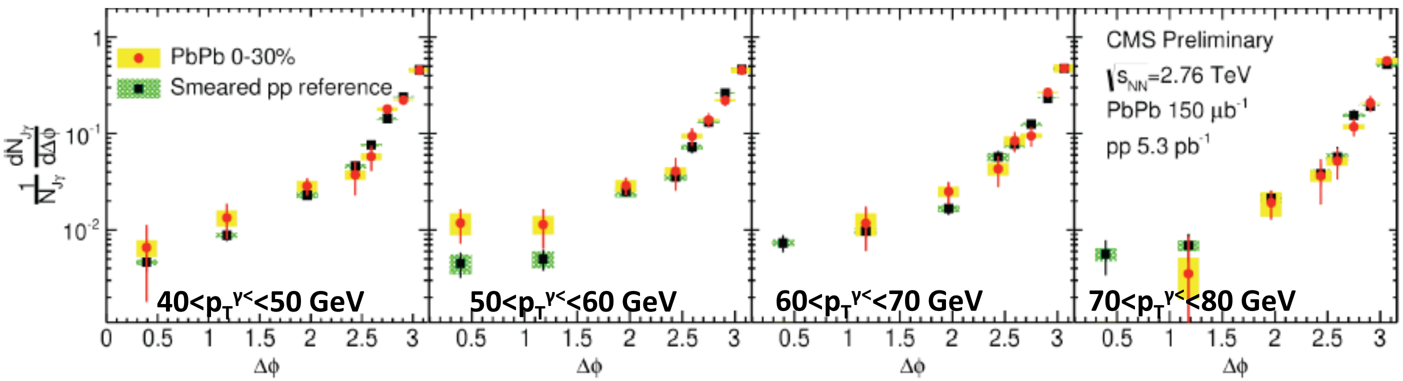
New techniques and observables to measure jet quenching down to low jet p_T and large resolution R=0.5 in a IRC safe way

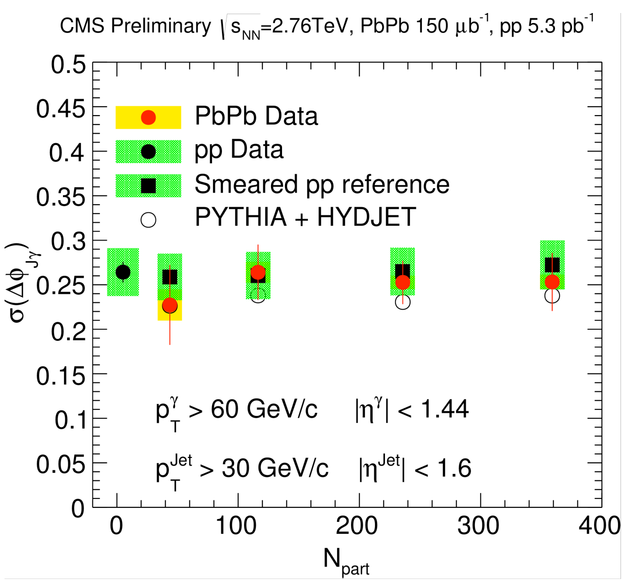
Inter-jet modifications

Azimuthal correlation between photons and recoiling jets

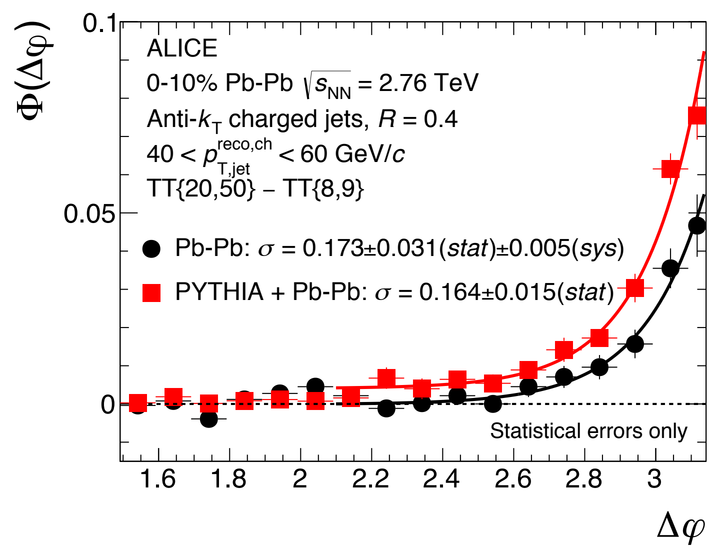


Does the loss of energy cause a deflection of the jet axis?

Width of the azimuthal correlation between photons and jets

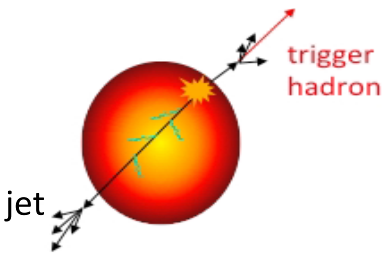


Azimuthal correlations between high p_T hadrons and recoiling jets



Bulk unmodified: width of the correlation in Pb-Pb compatible with the vacuum reference

Inter-jet: looking for the quasi-particles



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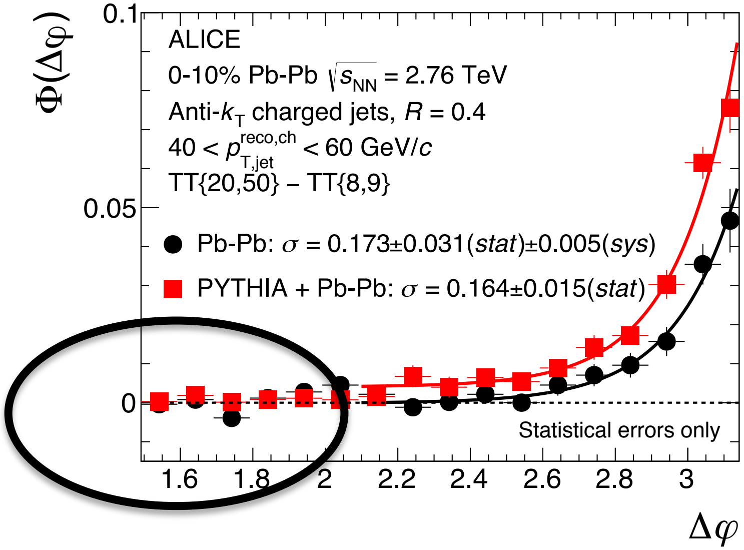
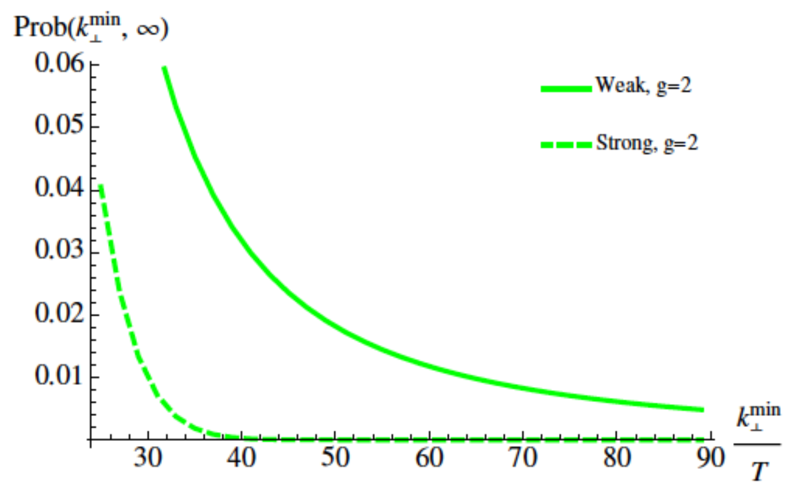


Inspect large angle deflections using semi-inclusive hadron-jet coincidence measurements plus new techniques for combinatorial background suppression

D'Eramo et al, JHEP 1305 (2013) 031



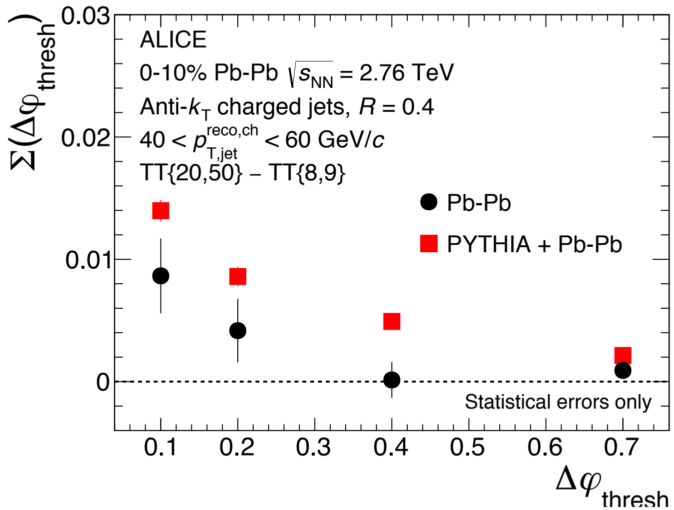
At short enough distances (large k_T), the strongly coupled liquid can be described by weakly interacting quasiparticles

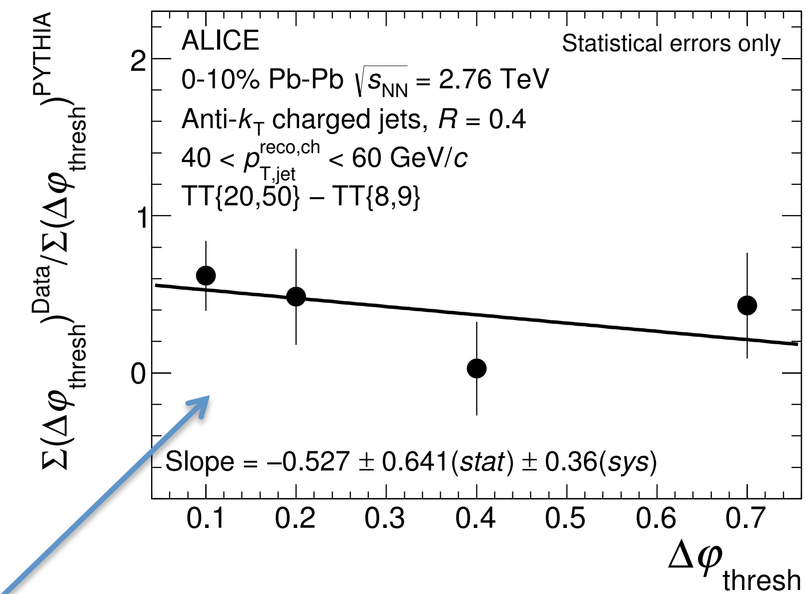
$$\Phi(\Delta\varphi) = \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

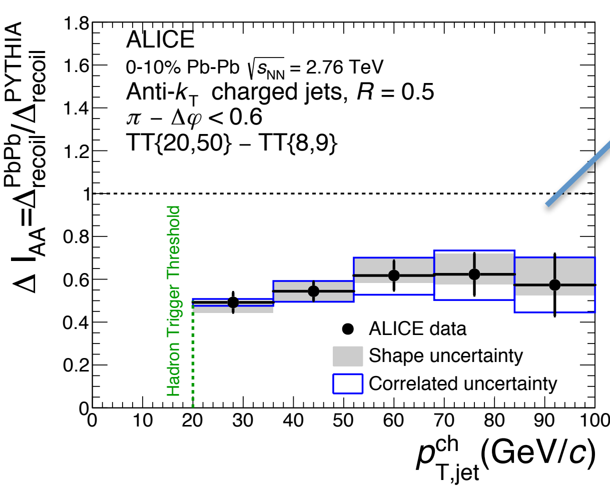
Inter-jet: looking for the quasi-particles

$$\Sigma\left(\Delta\varphi_{\mathrm{thresh}}\right) = \int_{\pi/2}^{\pi-\Delta\varphi_{\mathrm{thresh}}} \mathrm{d}\Delta\varphi\,[\Phi(\Delta\varphi)]$$

ALICE, arXiv:1506.03984







Absolute value of the ratio consistent with recoil jet suppression

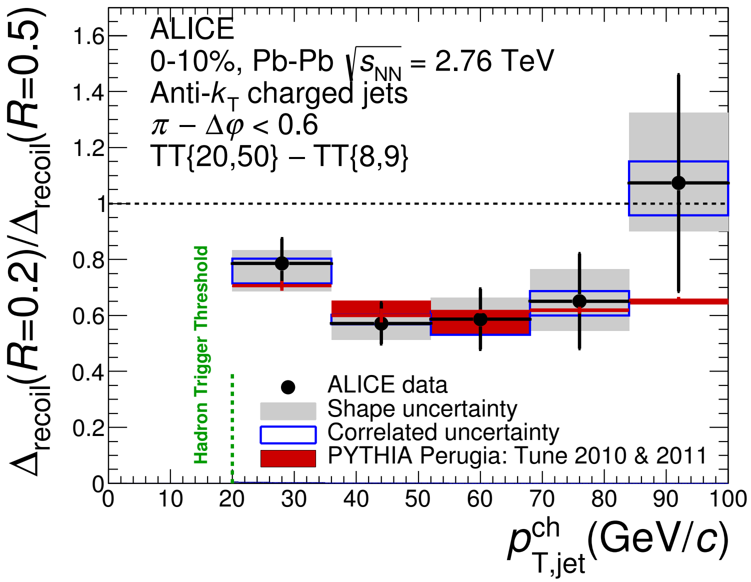
No enhancement of the tails relative to vacuum reference

Increase stat.precision with Run2

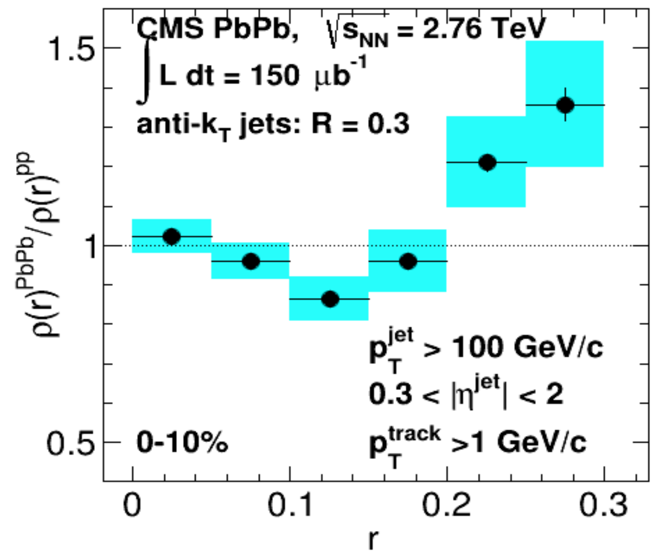
Theory calculations ongoing

Intra-jet modifications

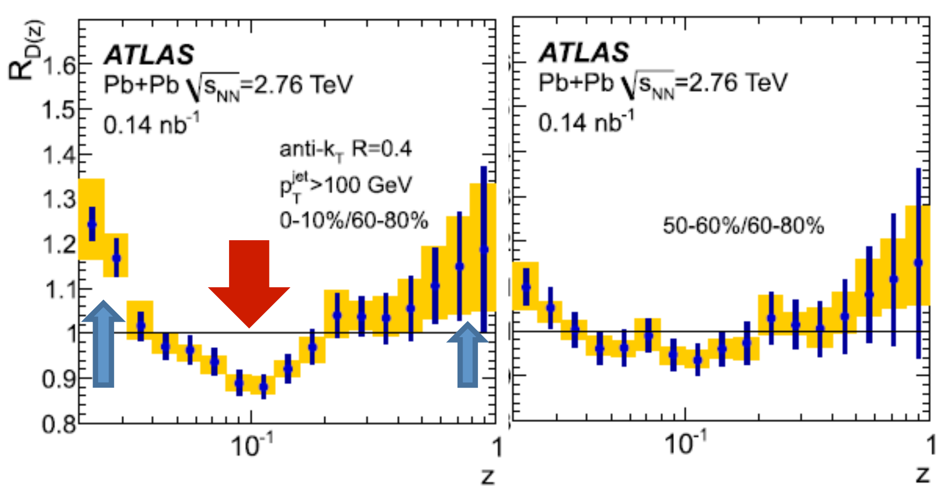
Ratio of recoil yields with different R



Energy contained in concentric subcones



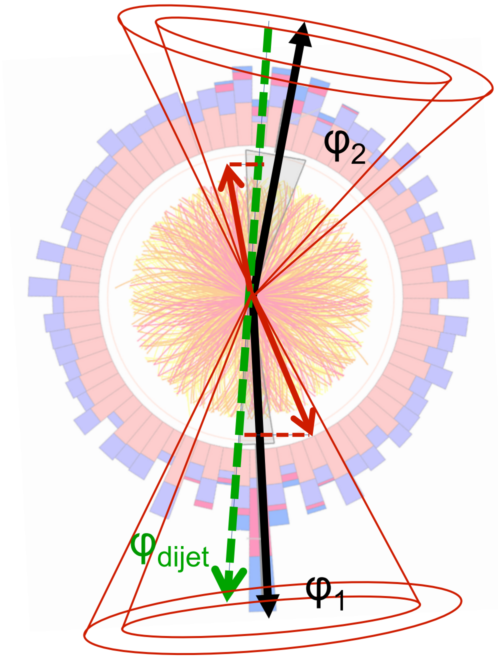
Fragmentation functions



Although jet yield is strongly suppressed, redistribution of energy within the jet core is compatible with few GeVs

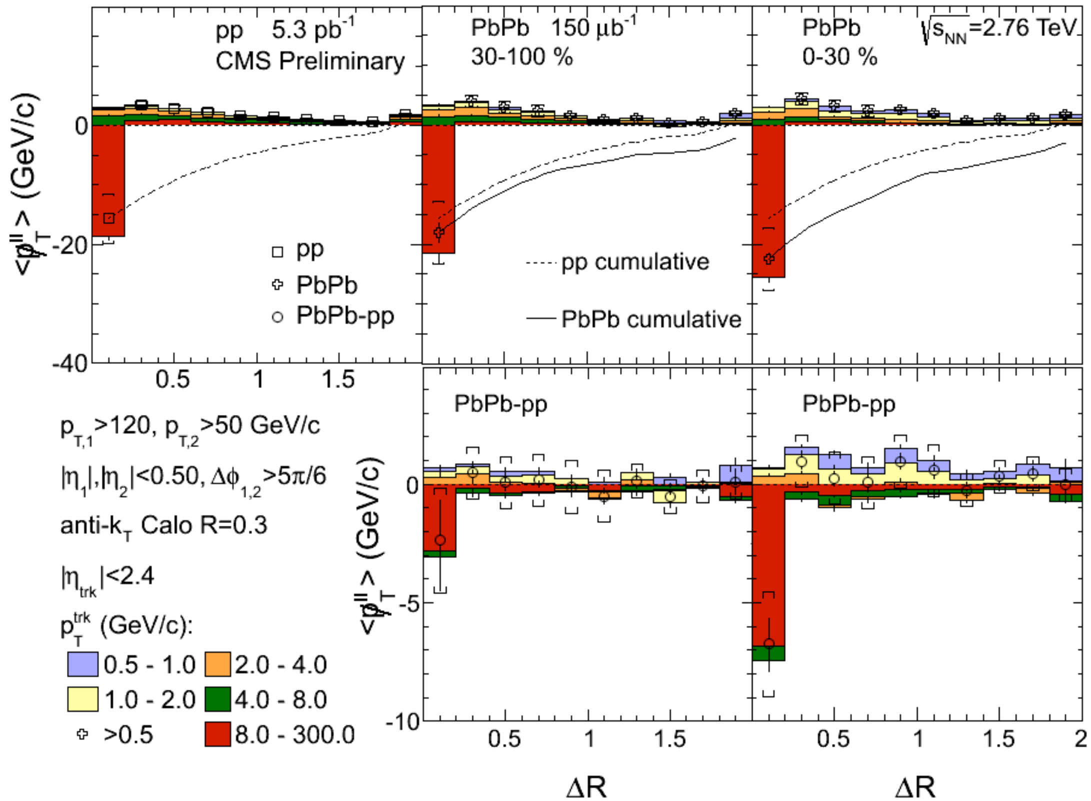
First generation of jet shape measurements

Can the lost energy be found?



courtesy Y. J. Lee (CMS)

$p_{T,1}$>120, $p_{T,2}$> 50 GeV/c, $|\eta_{1,2}|$< 0.5, $\Delta\phi_{1,2}$ > 5π/6



Missing p_T:

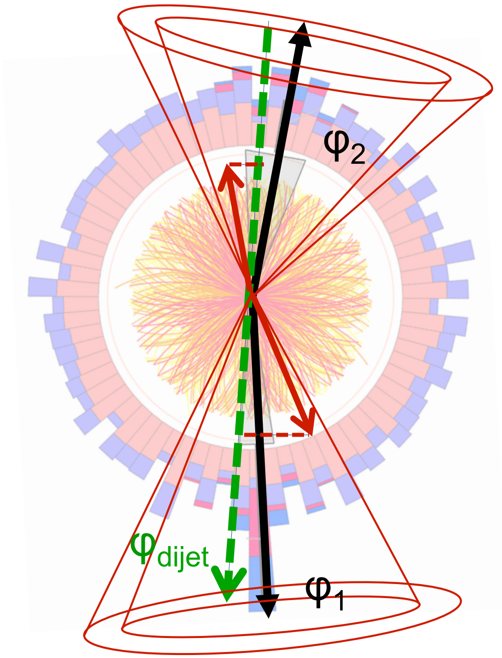
$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Dijet}}\right)$$

Cancels combinatorial background by symmetry

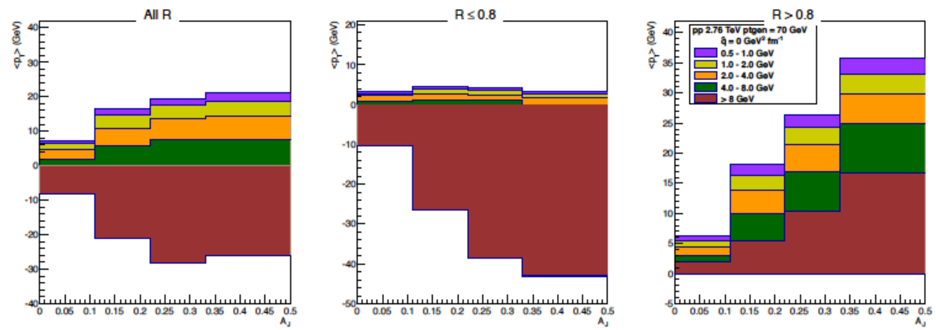
The extra imbalance at low ΔR relative to pp is compensated by an excess of soft particles in subleading jet direction extending to large ΔR.

Cummulative curves show rate of recovery of balance

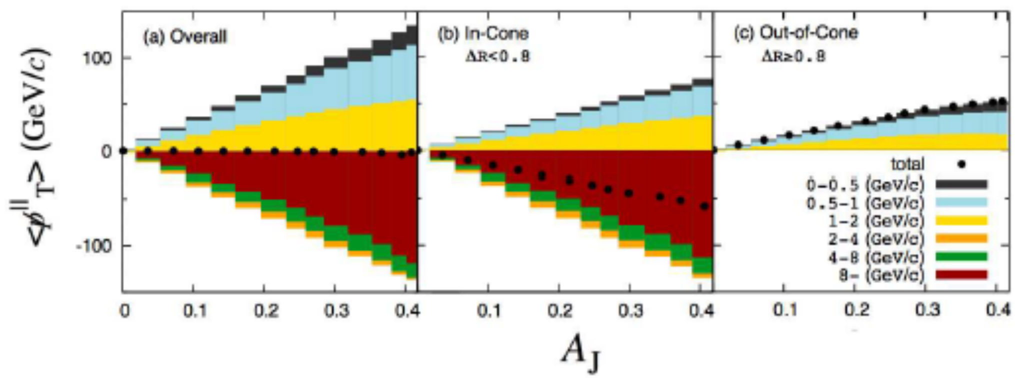
Can the lost energy be found?



qPythia JHEP 1302 (2013) 022



Hydro model 1404.1706



Missing p_T:

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Dijet}}\right)$$

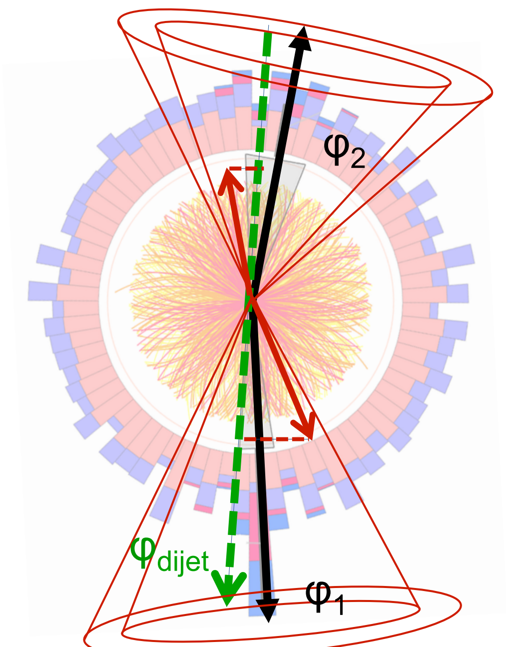
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Different physics mechanisms can qualitatively explain this behaviour:

In-medium gluon radiation: the quenching of the 3rd jet produces an excess of soft particles at large ΔR from subleading jet

Hydro back-reaction: transport of the deposited energy and momentum by the collective flow in the QGP fluid

Can the lost energy be found?



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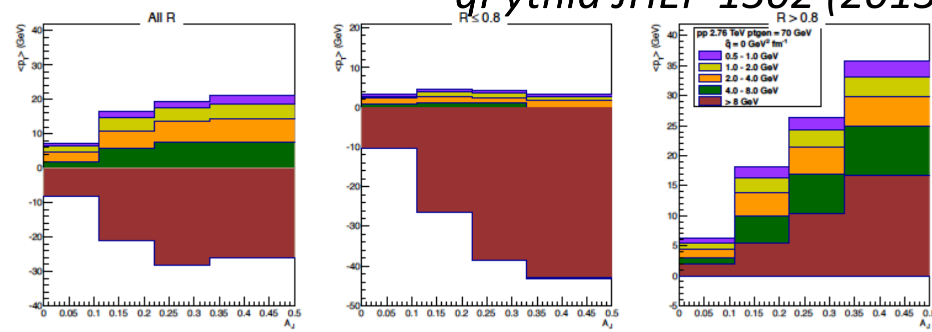

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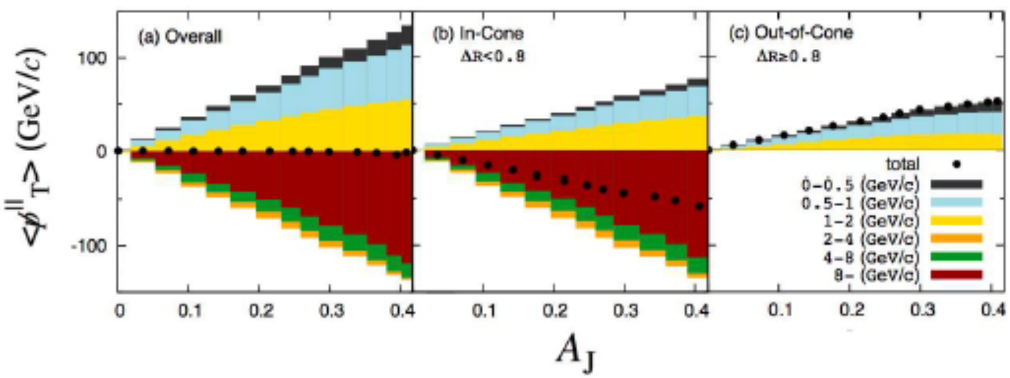

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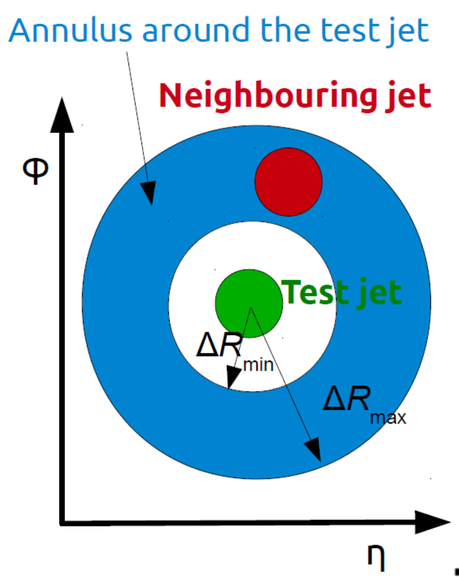
Different physics mechanisms can qualitatively explain this behaviour:

In-medium gluon radiation: the quenching of t… …t large ΔR from subleading jet

Hydro backreaction: transport of the deposited … flow in the QGP fluid

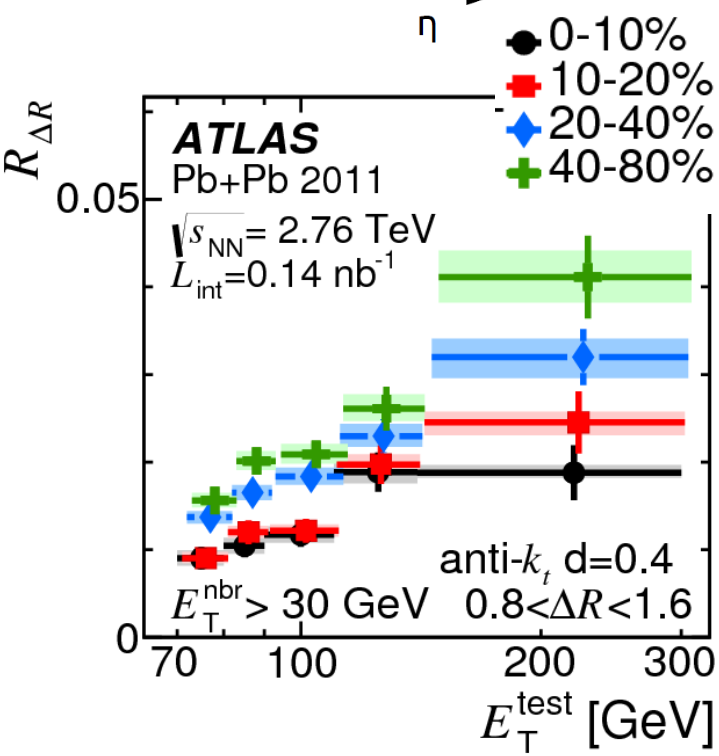
What is the source of the signal, third or subleading jet?

Neighbouring jets: gaining control on the third jet



Production of neighbouring jets quantified using a rate of jets accompanying a given test jet (trigger jet)

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

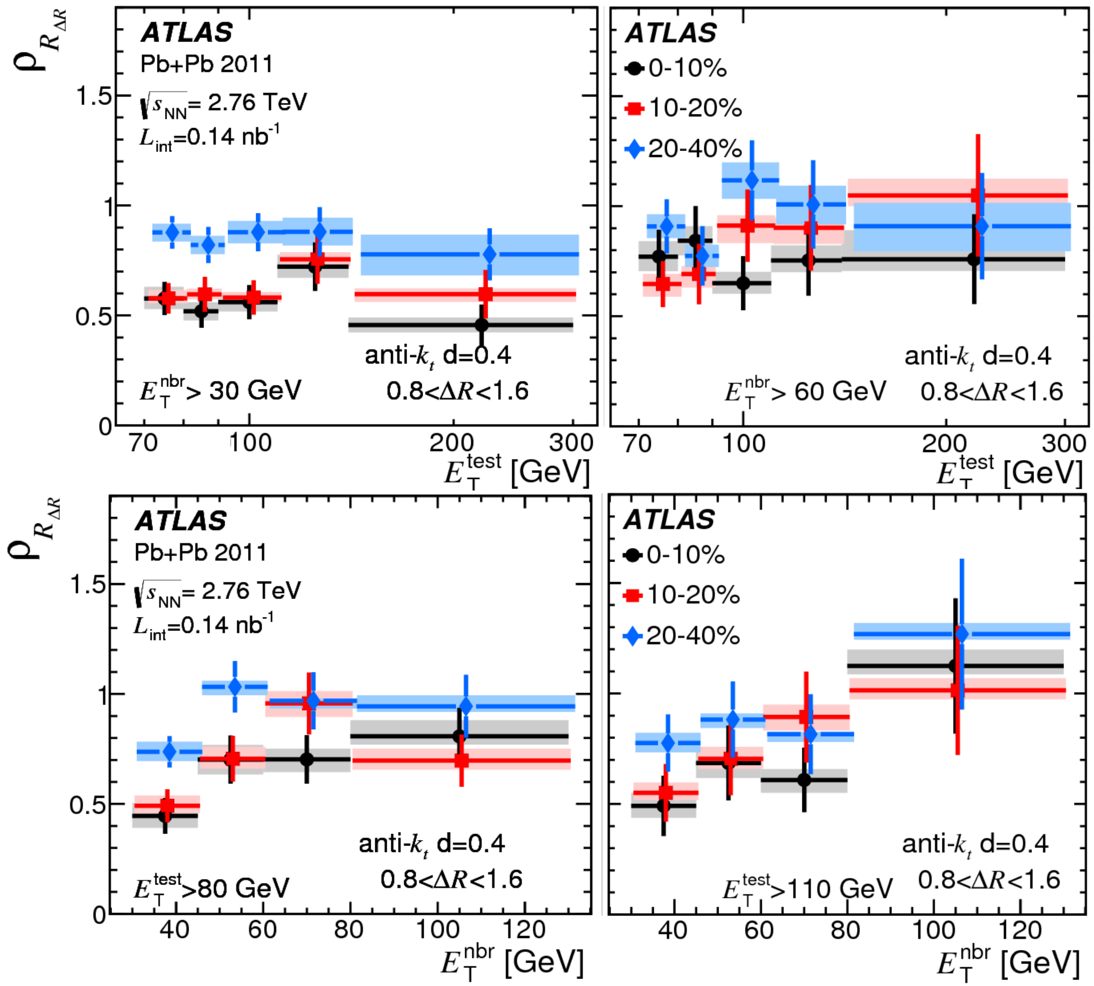


The semi-inclusive rate of neighbouring jets increases with the Q^2 of the process (with energy of the test or trigger jet).

Neighbouring jets: gaining control on the third jet

Nuclear modification factor $\rho_{R\Delta R}$

$\rho_{R\Delta R} = R_{\Delta R}(\text{central})/R_{\Delta R}(\text{peripheral})$



Modest dependence of suppression on the p_T of the test jet, as for inclusive rates.

Approching zero suppression when $E^{nbr} \sim E^{test}$

Quenching of two jets is uncorrelated

Outline

Jets in Heavy Ions: **multiscale problem**, from weakly to strongly coupled.

Jet yields are strongly suppressed up to very high momentum: **medium is opaque**.

No hints for medium induced **acoplanarity.**

The inspection of the tails can **uncover the quasiparticles** in the QGP fluid, statistical precision needed.

Intrajet structure modified, first generation of jet shapes.
New opportunities and observables to probe **different aspects of substructure** in Run2.

Can the lost energy be recovered and characterized? Role of third jets?

More differential observables, multijet structures etc pose strong constrains to theories of jet quenching

Efforts to define observables that allow for a clean experimen-theory comparison

Many new physics to explore with Run2: substructure, coherence, flavour hierarchy…