The hot and dense matter

(QGP in Heavy Ion Collisions: the soft & the hard probes)

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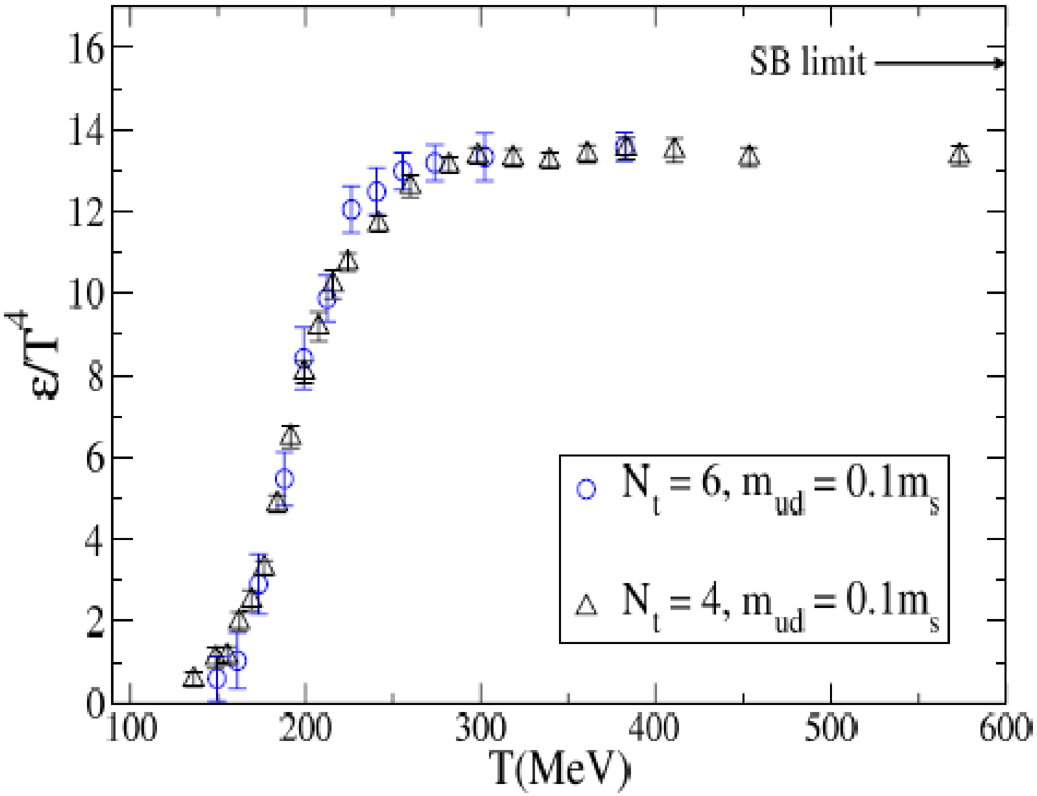
INFN Frascati

seminar@LPSC Grenoble 2013

The expected change of phase of the nuclear matter into a deconfined state



ε_c~0.3-1 GeV/fm3

T_c~170 MeV

from finite temperature Lattice QCD at null net baryon number

Stefan Boltzman: ε ~ #degrees of freedom (DF) in the system

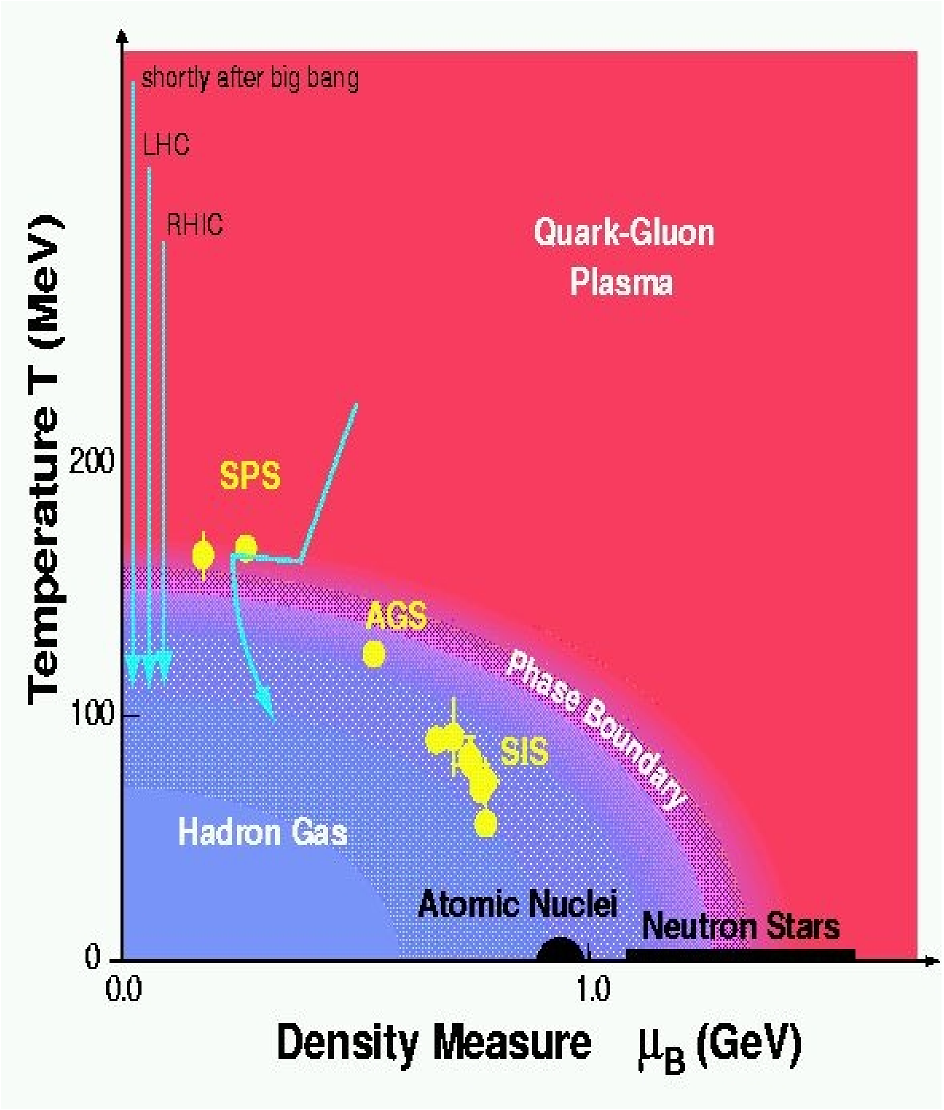
Phase transition (crossover)

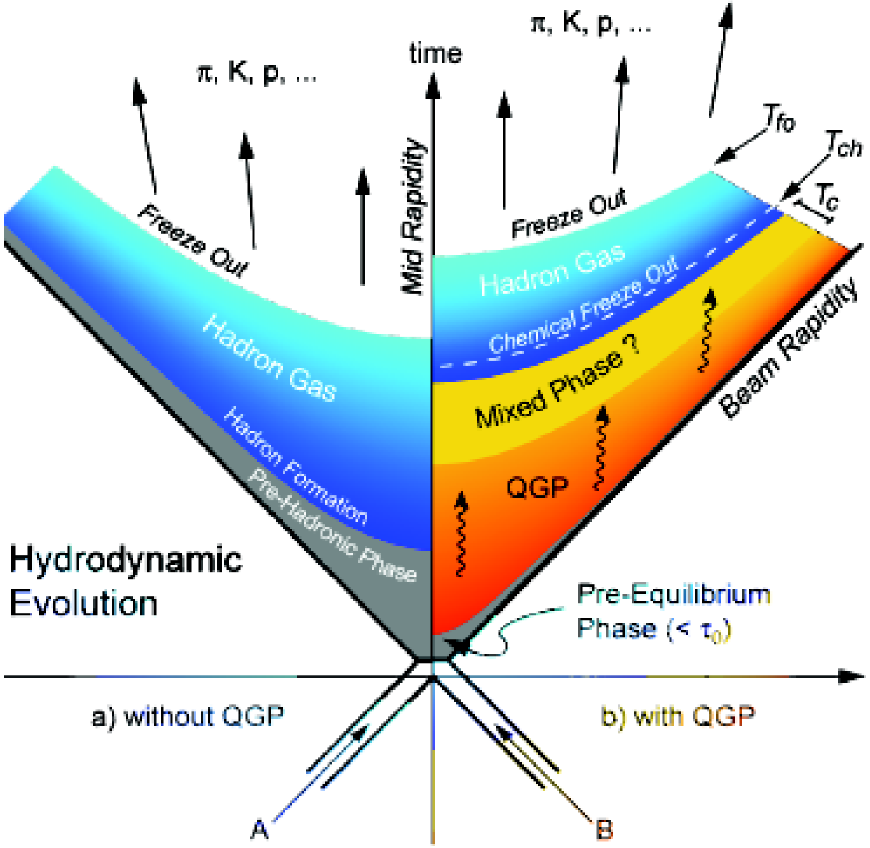
Low T: Hadron gas-->DF=3 pions

High T: QGP -->quark and gluon constituents->DF=37

(*depending on # flavours considered*)

The “standard model” of Heavy Ion Collisions

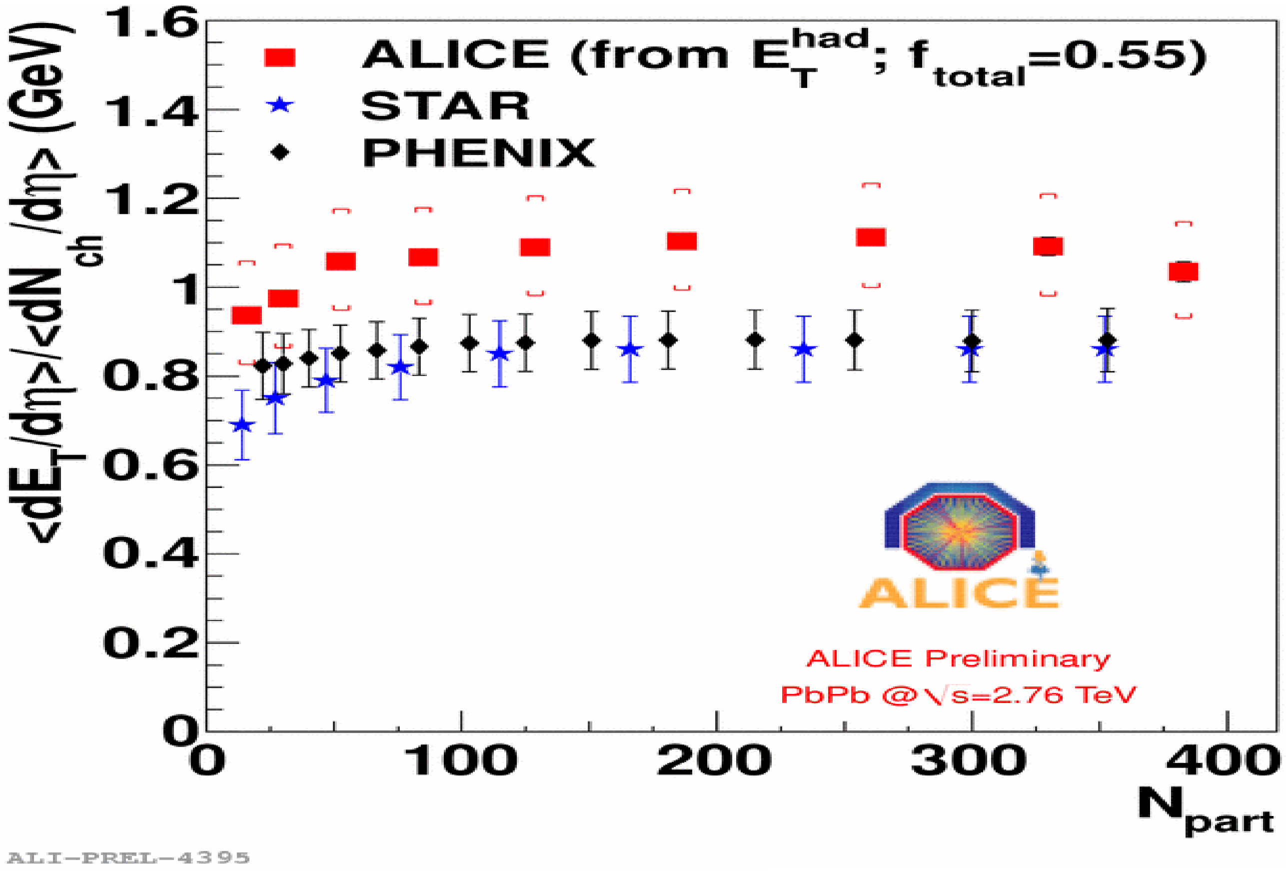




Explore different phases of the system evolution:

- Collective Motion:radial, elliptic (higher orders) flow
- Critical fluctuations
- Initial state conditions (prethermalization)
- Thermalization?
- Thermal electromagnetic radiation
- Hard probes (focus here)

Experimental measurement of the energy density



Energy density above critical is a necessary condition for the QGP formation, but not sufficient: many constituents needed to reach thermal equilibrium:

ε(7TeV)_pp>ε(0.2TeV)_AuAu

Bjorken energy density estimate:

$$\varepsilon_{Bj} = \frac{1}{\tau \pi R^2} \frac{dE_T}{d\eta}$$

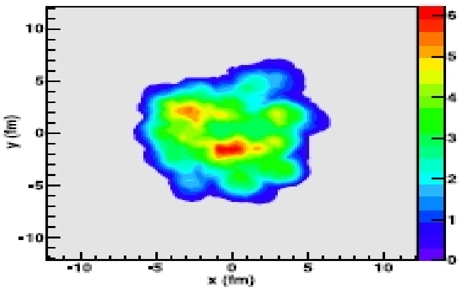
πR^{2}->area of the overlapping region

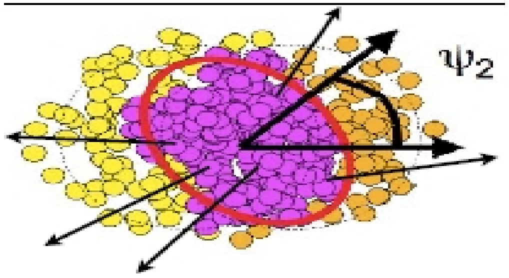
$\varepsilon_{Bj}\,\tau \sim 16$ GeV/fm^2

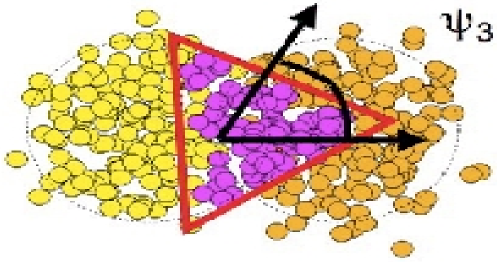
τ-->formation time, unknown, τ<1fm/c

Bjorken estimate at LHCwell above lattice critical density in a wide centrality range

Towards precise characterization of the QGP:
2 examples: vn

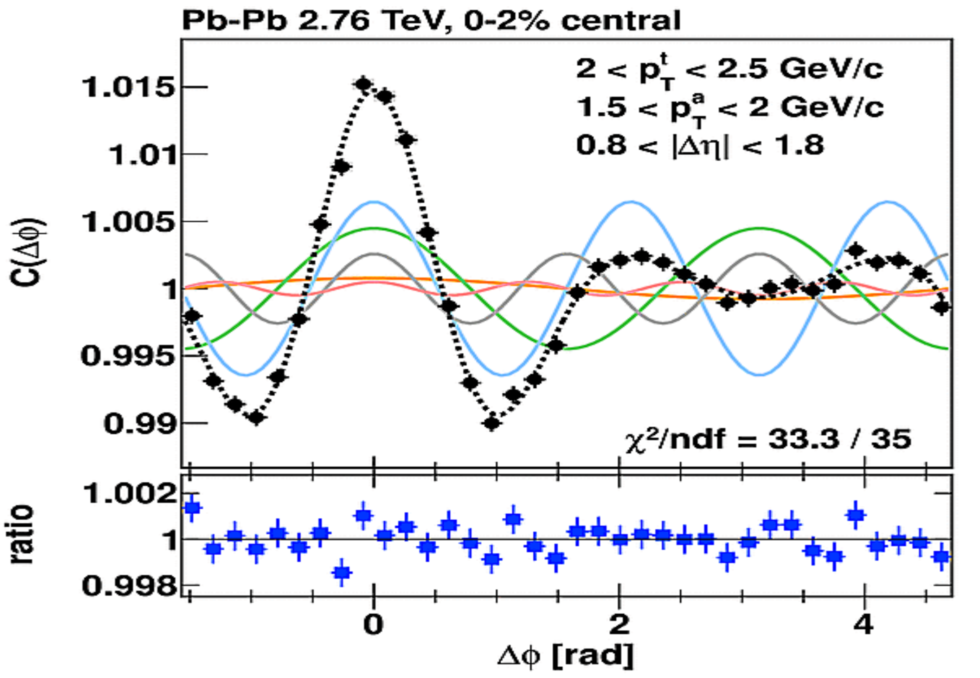






Different initial state conditions generate different symmetry planes

--> different flow coefficients vn are present in the final particle distributions



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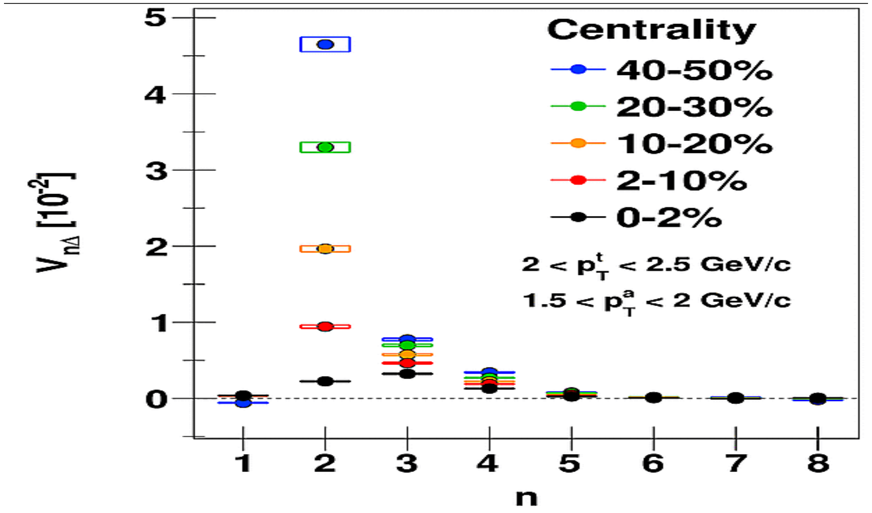

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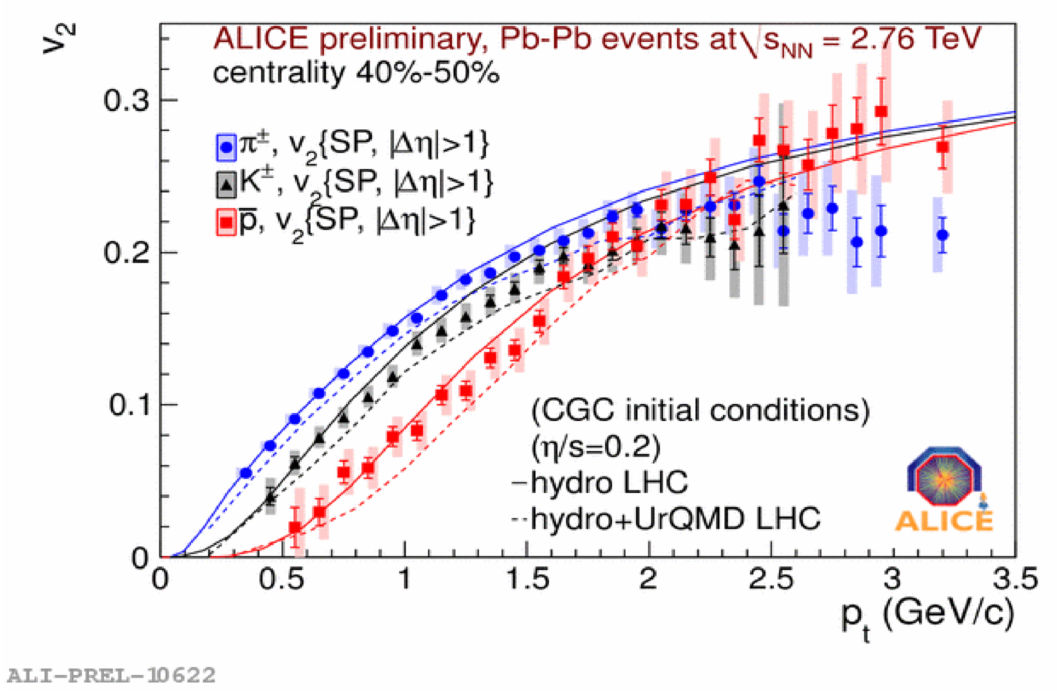
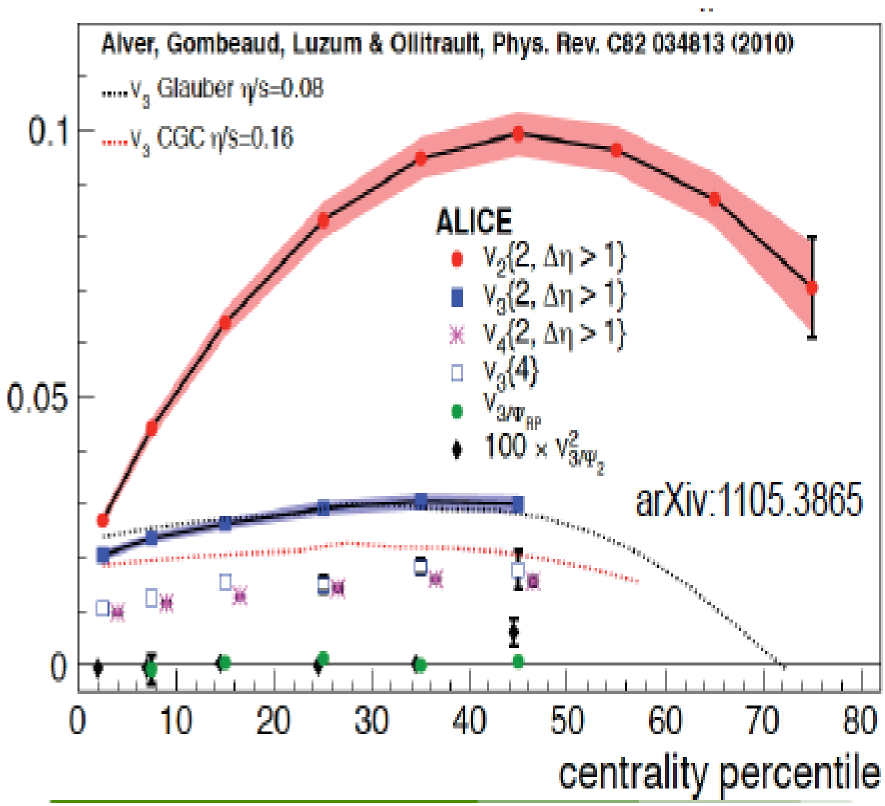
Particle correlations get contributions from up to n=5

ALICE. Phys.Lett.B 708 (2012)

Towards precise characterization of the QGP transport properties: 2 examples: vn





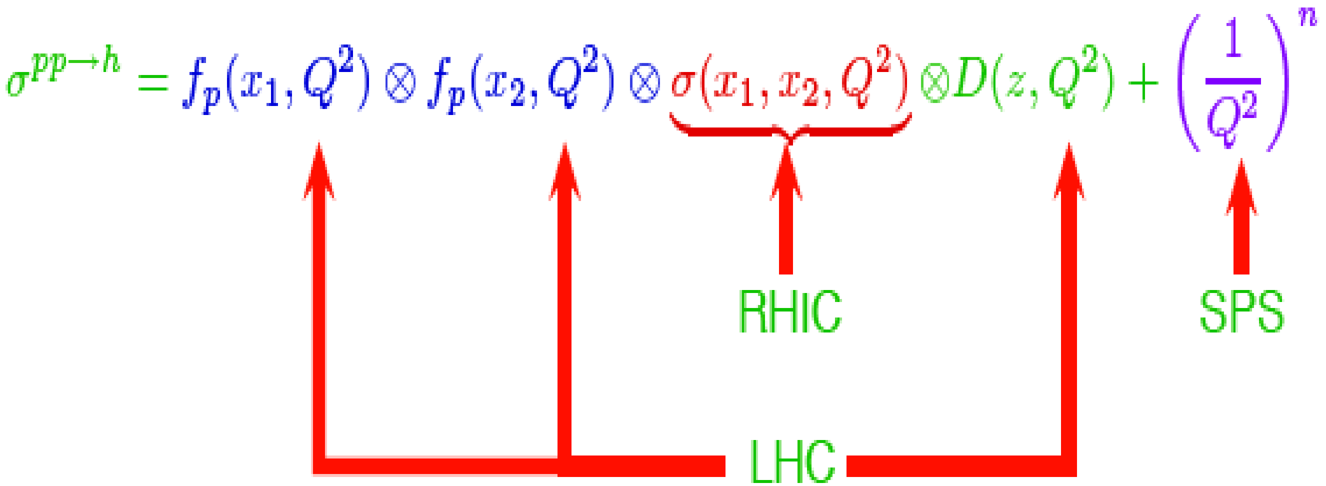
Large v2 indicates early thermalization

Great success of viscous Hydrodynamics:
Shear viscosity close to the lower bound
(AdS/CFT lower bound=0.08)

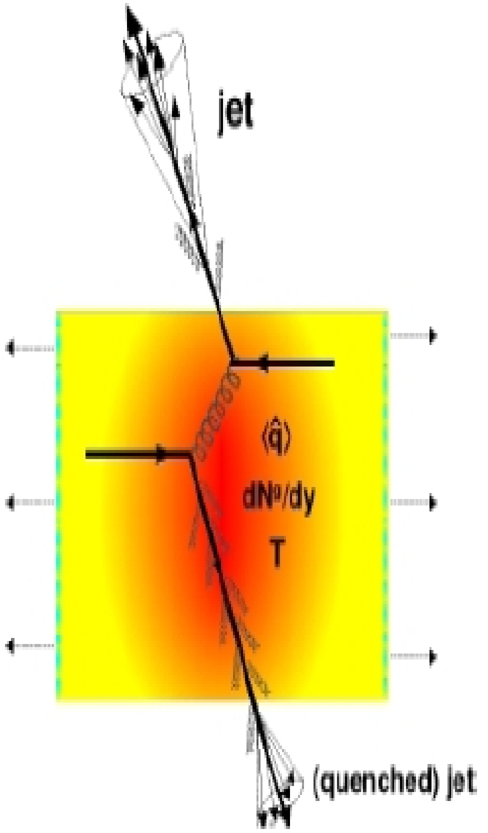
The system behaves as an almost perfect liquid!

Higher orders-->constrain initial conditions, needed for hydro calculations
-->**more precise determination of η/s**

Towards precise characterization of the QGP transport properties: 2 examples: Hard probes



$$\sigma^{pp\rightarrow h} = f_p(x_1,Q^2)\otimes f_p(x_2,Q^2)\otimes \underbrace{\sigma(x_1,x_2,Q^2)}\otimes D(z,Q^2) + \left(\frac{1}{Q^2}\right)^n$$



Early production of the hard scattering t~1/Q:

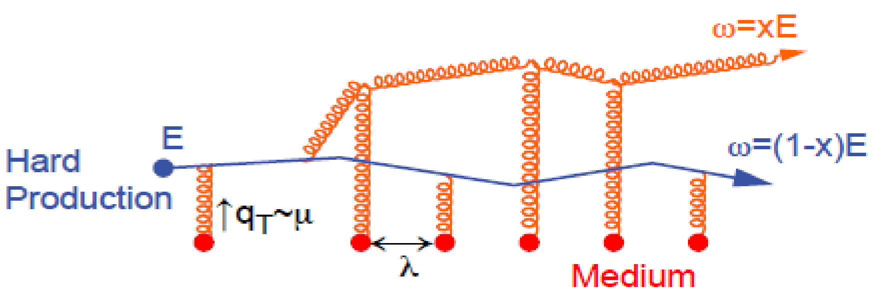
Long distance terms in the factorized Xsection above can be **directly modified by the dense medium** created in HIC

The probe production rate is the same as in vacuum -->**well calibrated probes**

Look for attenuation/absorption of the probe

The “standard” mechanisms of energy loss in medium

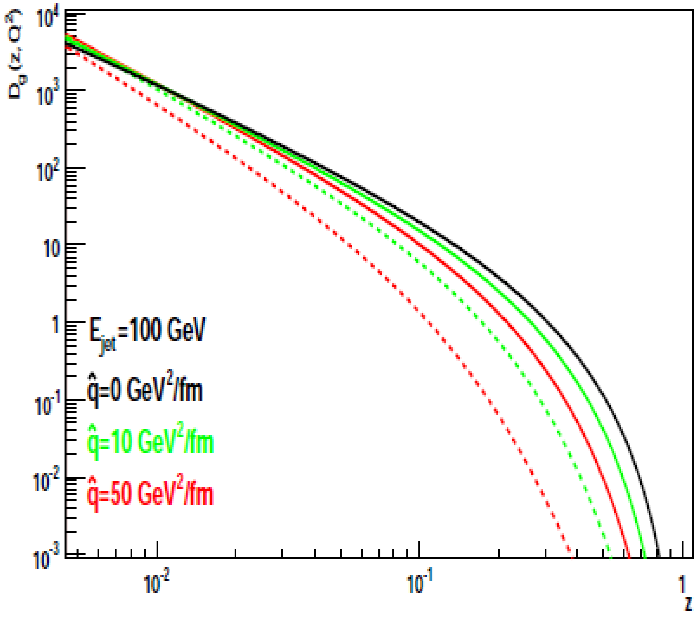
Medium-induced gluon radiation, dominant mechanism of energy loss for a high energy parton traversing a colored medium.

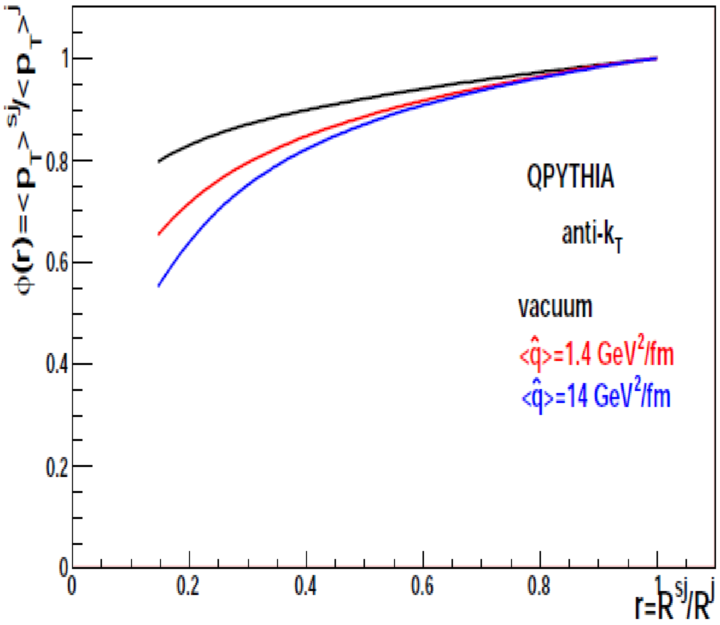


Energy loss & transverse broadening of the jet shower dynamically related by:

ΔE~qhat Δk_T

qhat characterizes the medium (encodes the info about the interactio with the colored medium): $\langle k_T \rangle$ given by the medium to the projectile per unit path length λ.





Armesto-Cunqueiro-Salgado
JHEP 0802 (2008) 048
Eur.Phys.JC63 (2009) 679-690

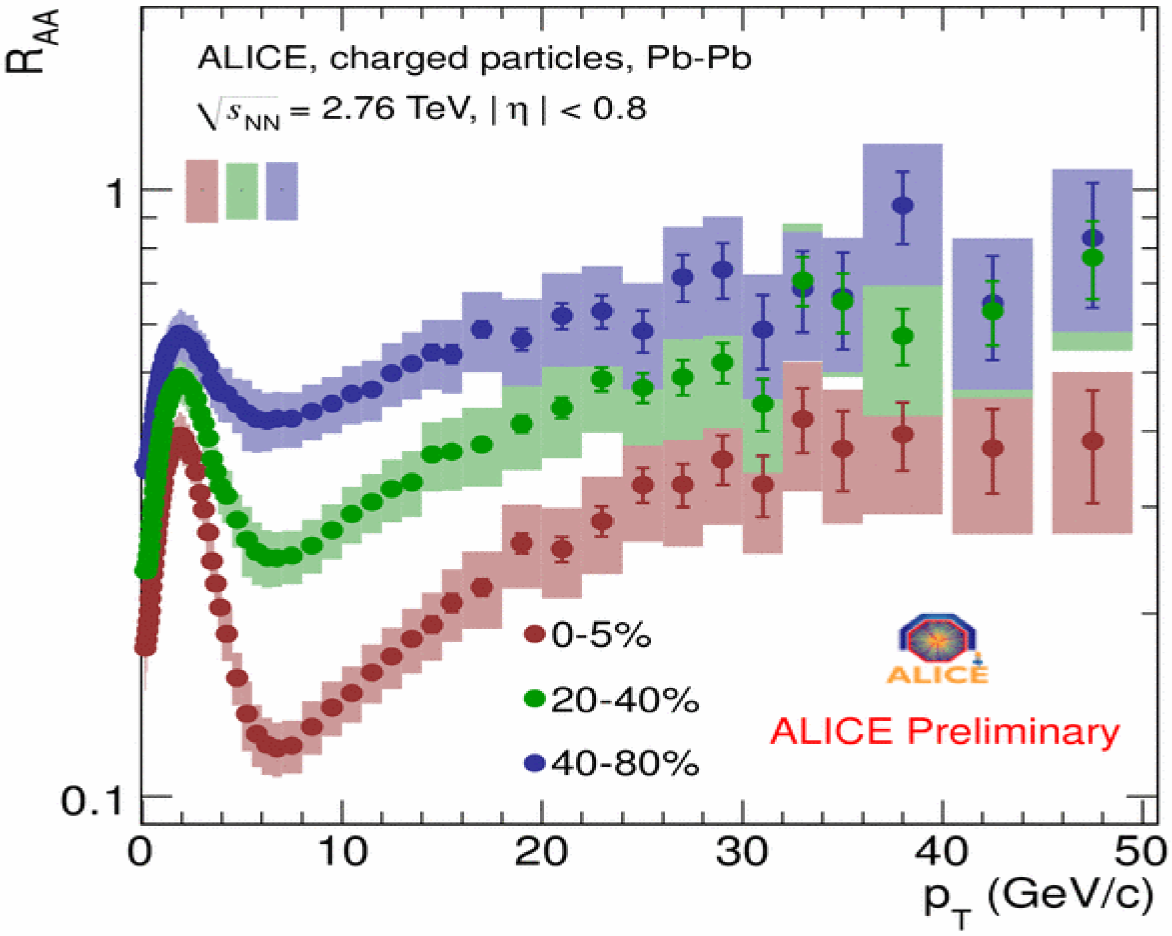
Energy degradation and moderate broadening of the transverse jet shape

Start with the “easy” thing: high pT hadrons

Measures the suppression of the yiedl in PbPb collisions with respect to the scaled yield in pp.

Nuclear Modification Factor (RAA):

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

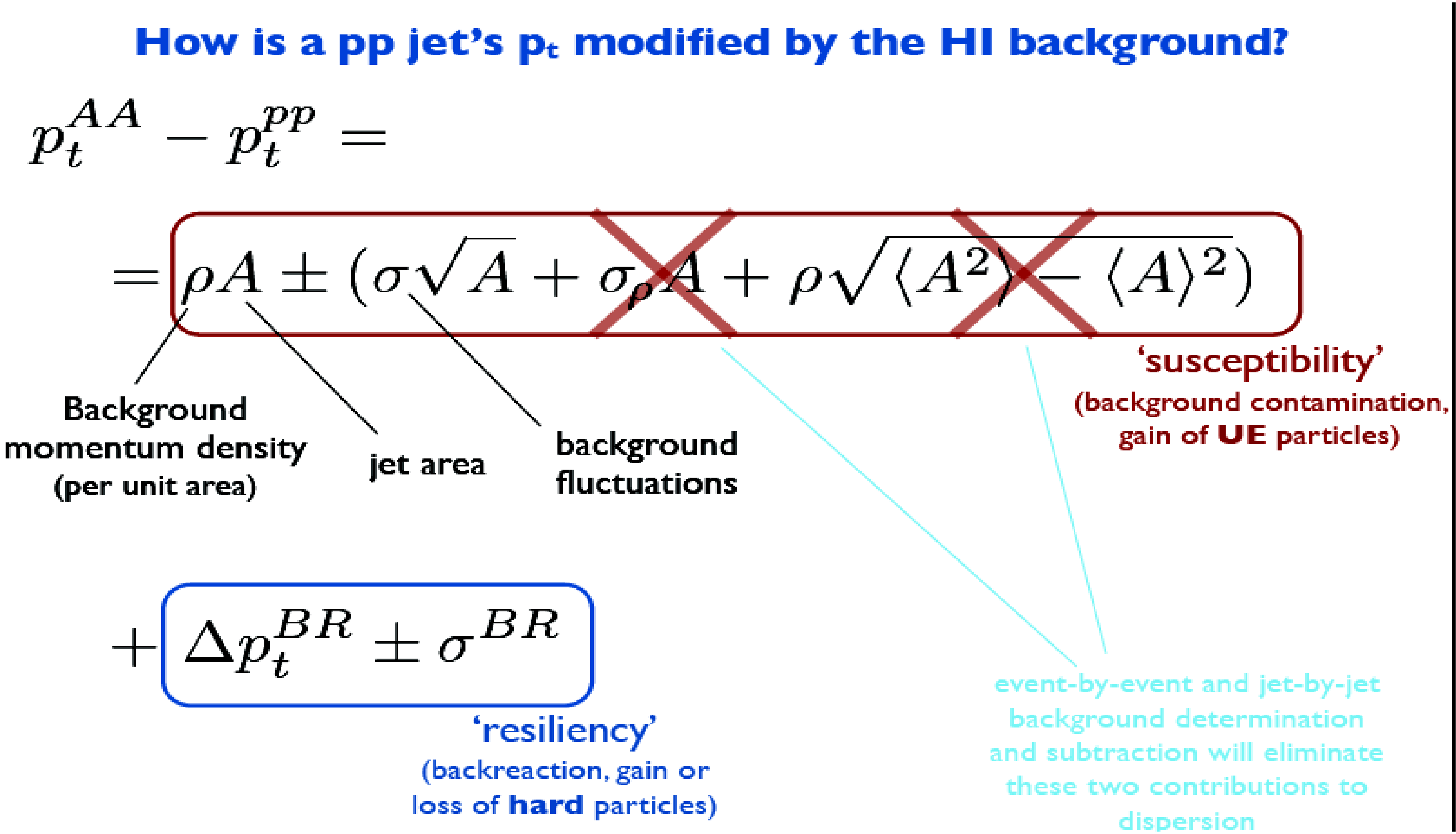


ALI-PREL-10239

Peripherals: RAA-->1

Centrals:
~1/5 suppression factor.
Larger in-medium path encountered by the hard parton.

Continue with jets: to capture the full dynamics of jet quenching, not only leading hadron suppression



How is a pp jet's p_t modified by the HI background?

$$p_t^{AA} - p_t^{pp} =$$

$$= \boxed{\rho A \pm (\sigma\sqrt{A} + \cancel{\sigma_\rho A} + \rho\sqrt{\langle A^2 \cancel{\rangle -} \langle A\rangle^2})}$$

$$+ \boxed{\Delta p_t^{BR} \pm \sigma^{BR}}$$

Background momentum density (per unit area)

jet area

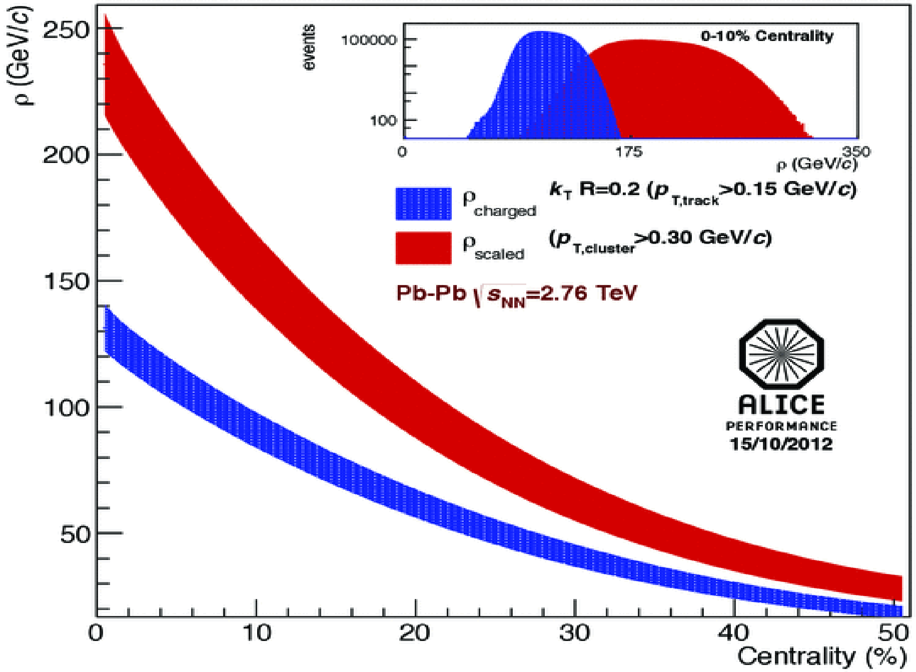
background fluctuations

'susceptibility' (background contamination, gain of **UE** particles)

'resiliency' (backreaction, gain or loss of **hard** particles)

event-by-event and jet-by-jet background determination and subtraction will eliminate these two contributions to dispersion

Ingredients



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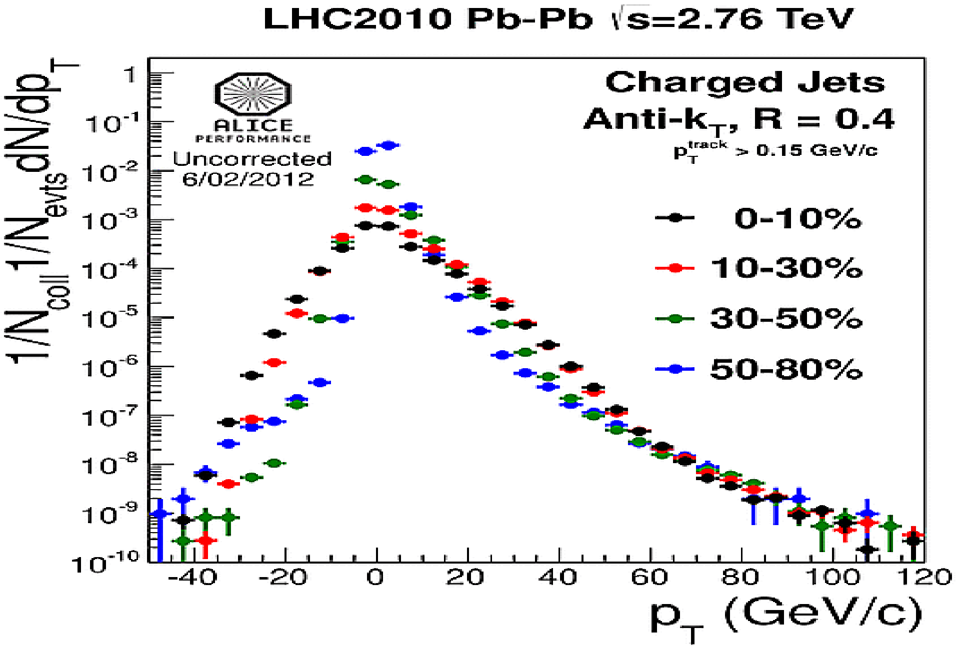

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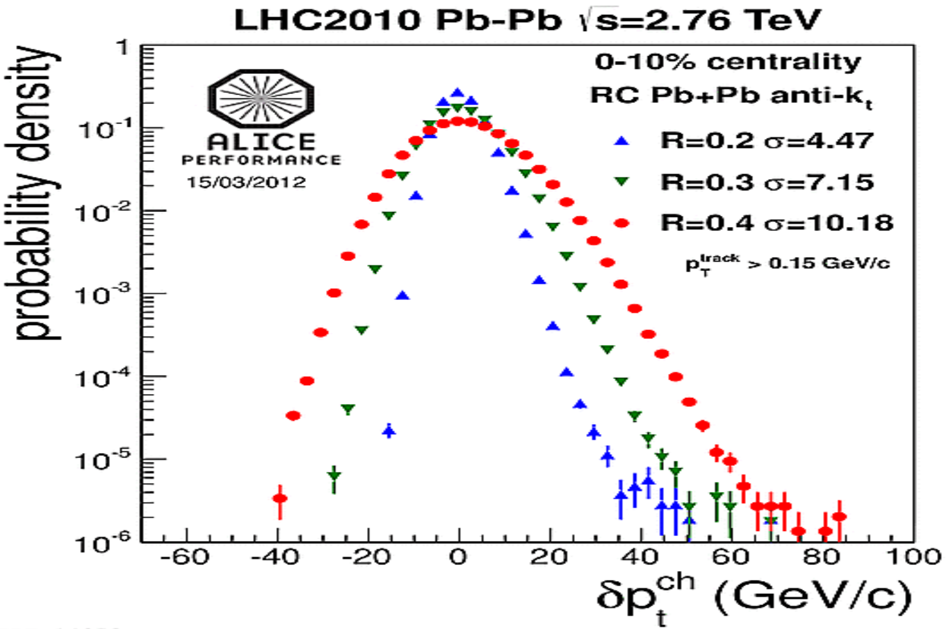

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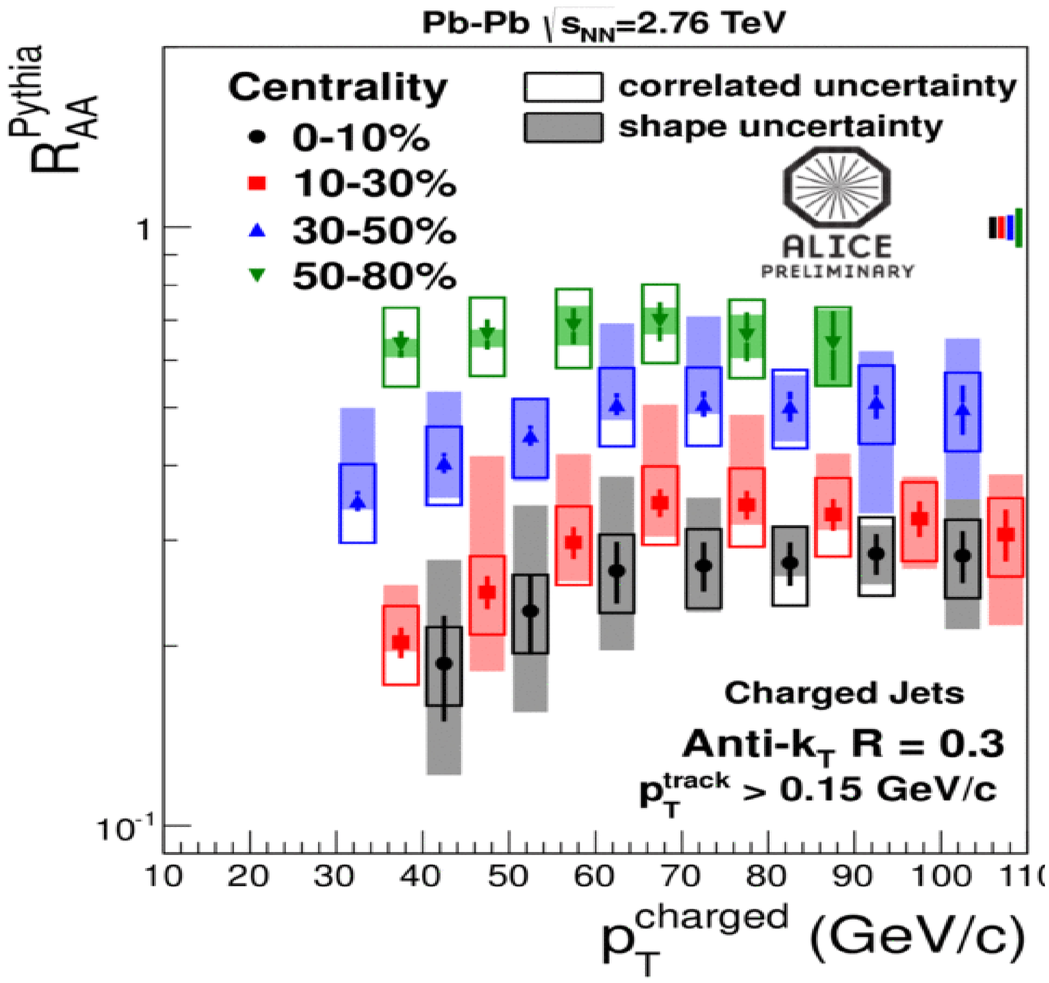
The jet energy is corrected **on average** jet-by-jet and event-by event by subtracting ρ*Areajet.

Background **region-to-region fluctuations** (deviations from the average ρ) are the main source of uncertainty and have to be corrected by unfolding.

Fluctuations smear the jet energy enhancing the yet yield up to high jet p_T

Low-moderate jet p_T is dominated by fakes

ALICE INCLUSIVE CHARGED JET SPECTRA and RAA



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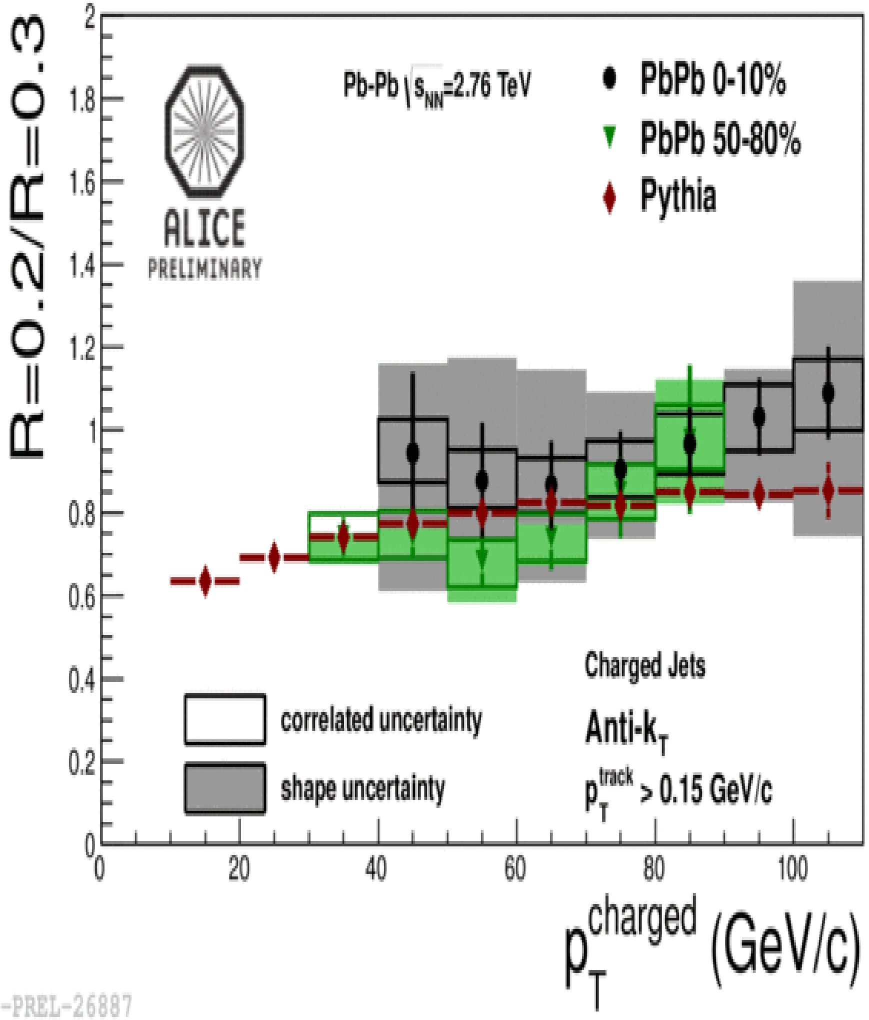


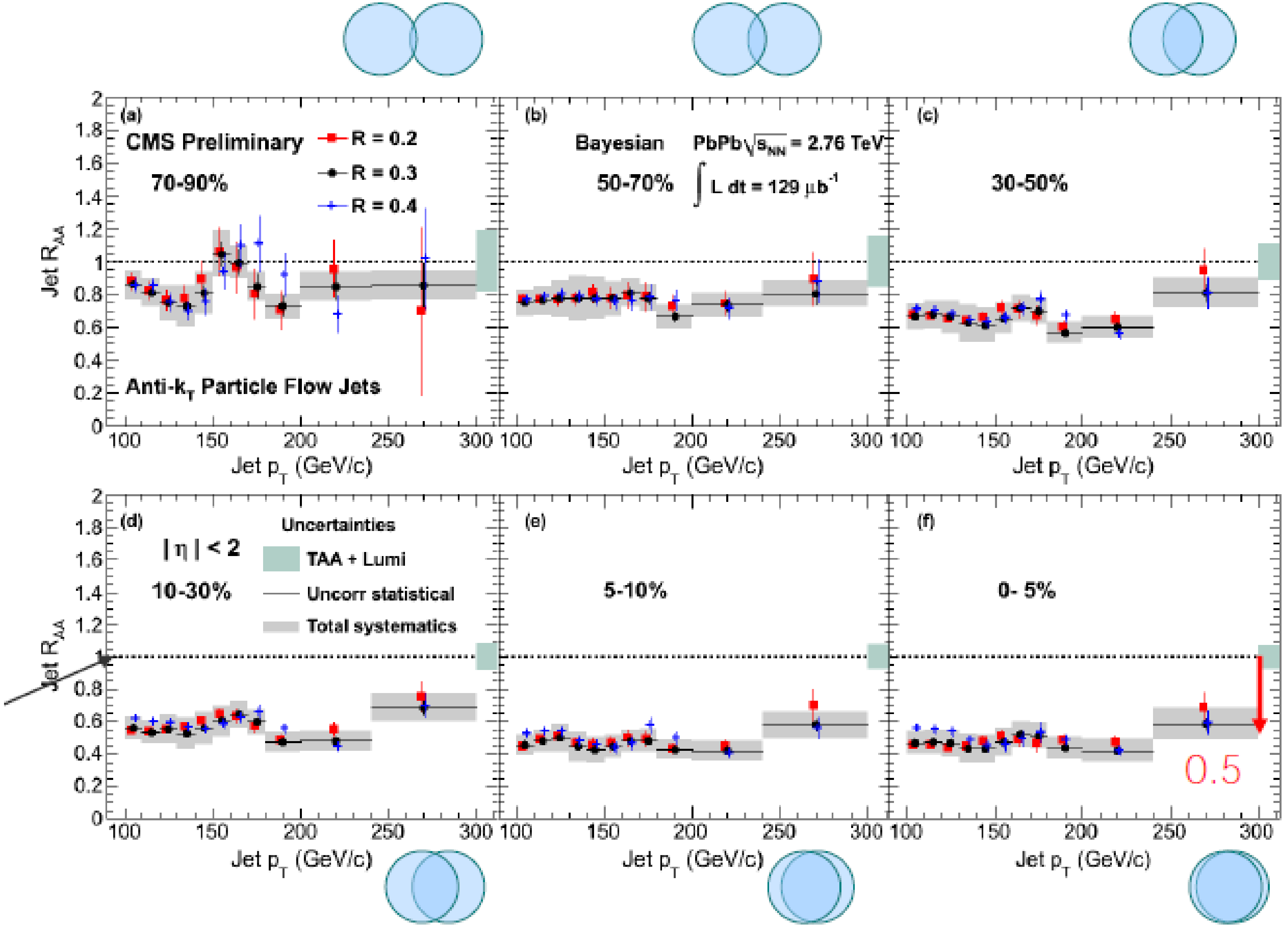
ALI-PREL-26887

I: RAA for R=0.3 is not very different to RAA for single hadrons

II:Energy distribution within a cone of R-0.3 is not very different (within large systematic errors) from PYTHIA vacuum structure.

CMS results on RAA

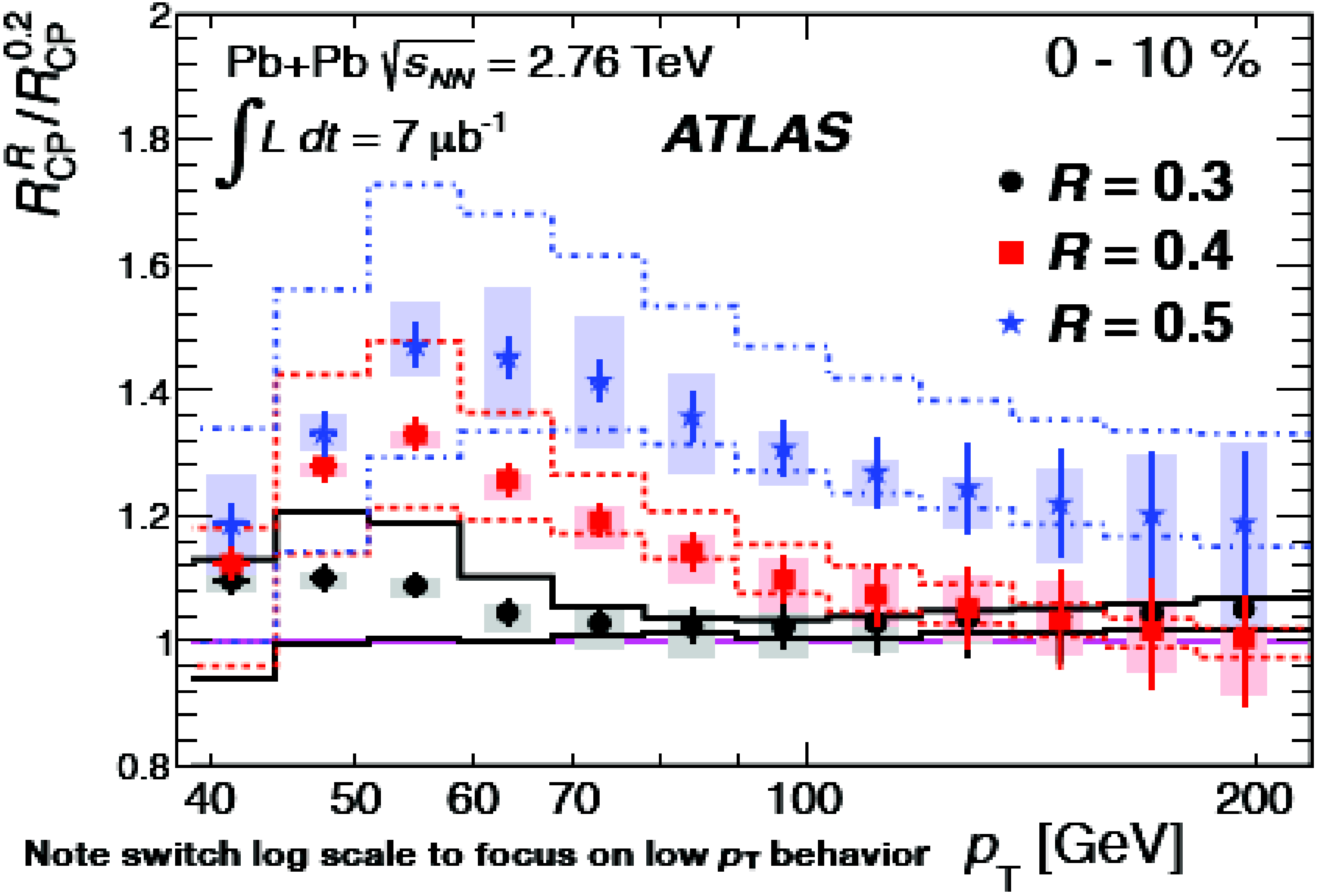
Compare PbPb to pp data



III. CMS high energy jet suppression shows no dependence with jet pT and radii R

Where does the energy go? Are jets completely absorbed by the medium?

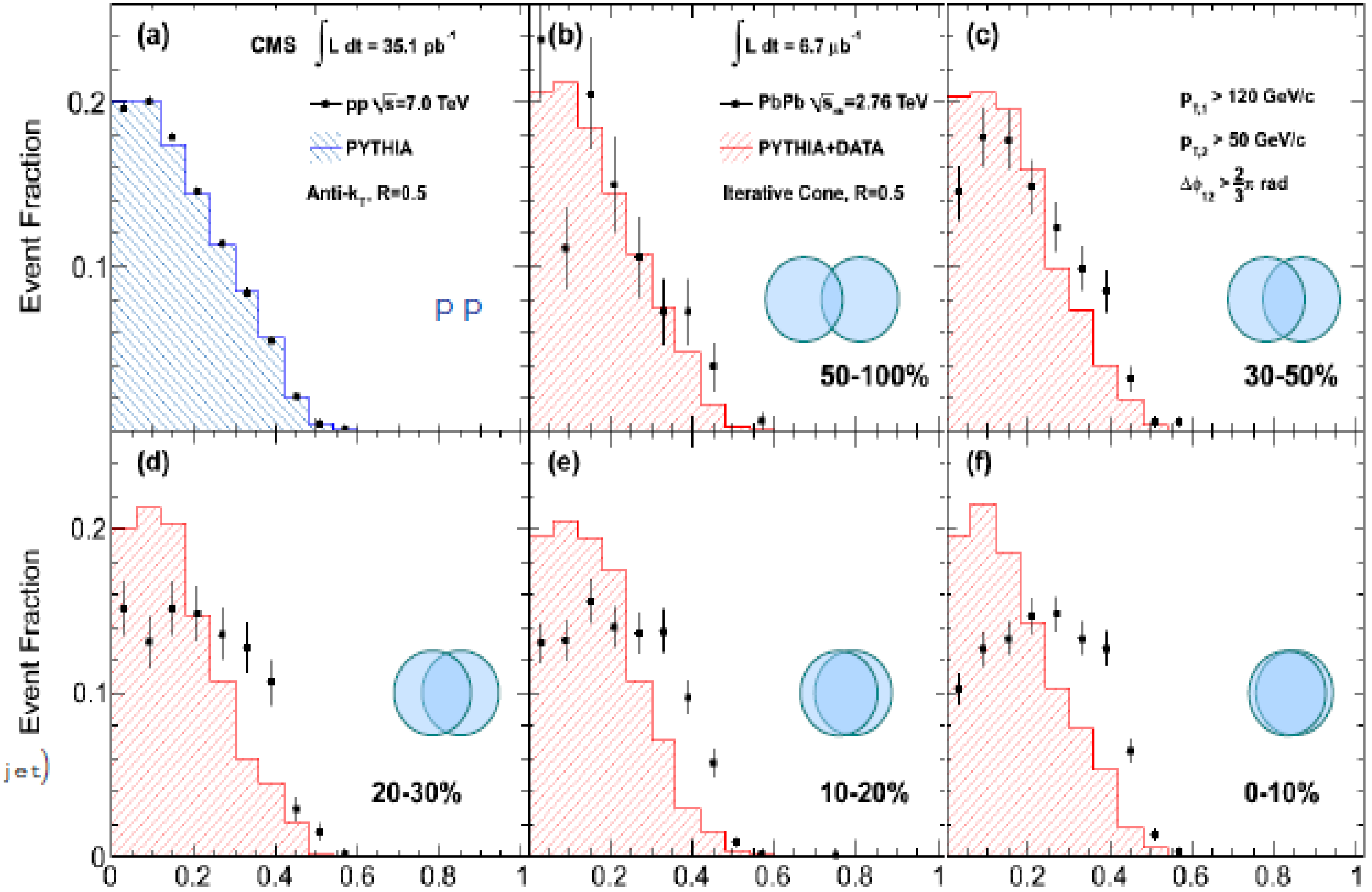
ATLAS MEASUREMENTS of low pT JET STRUCTURE



Note switch log scale to focus on low p_T behavior

Clear evidence for energy redistribution at low jet p_T<40 GeV

CMS momentum imbalance



$$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$$

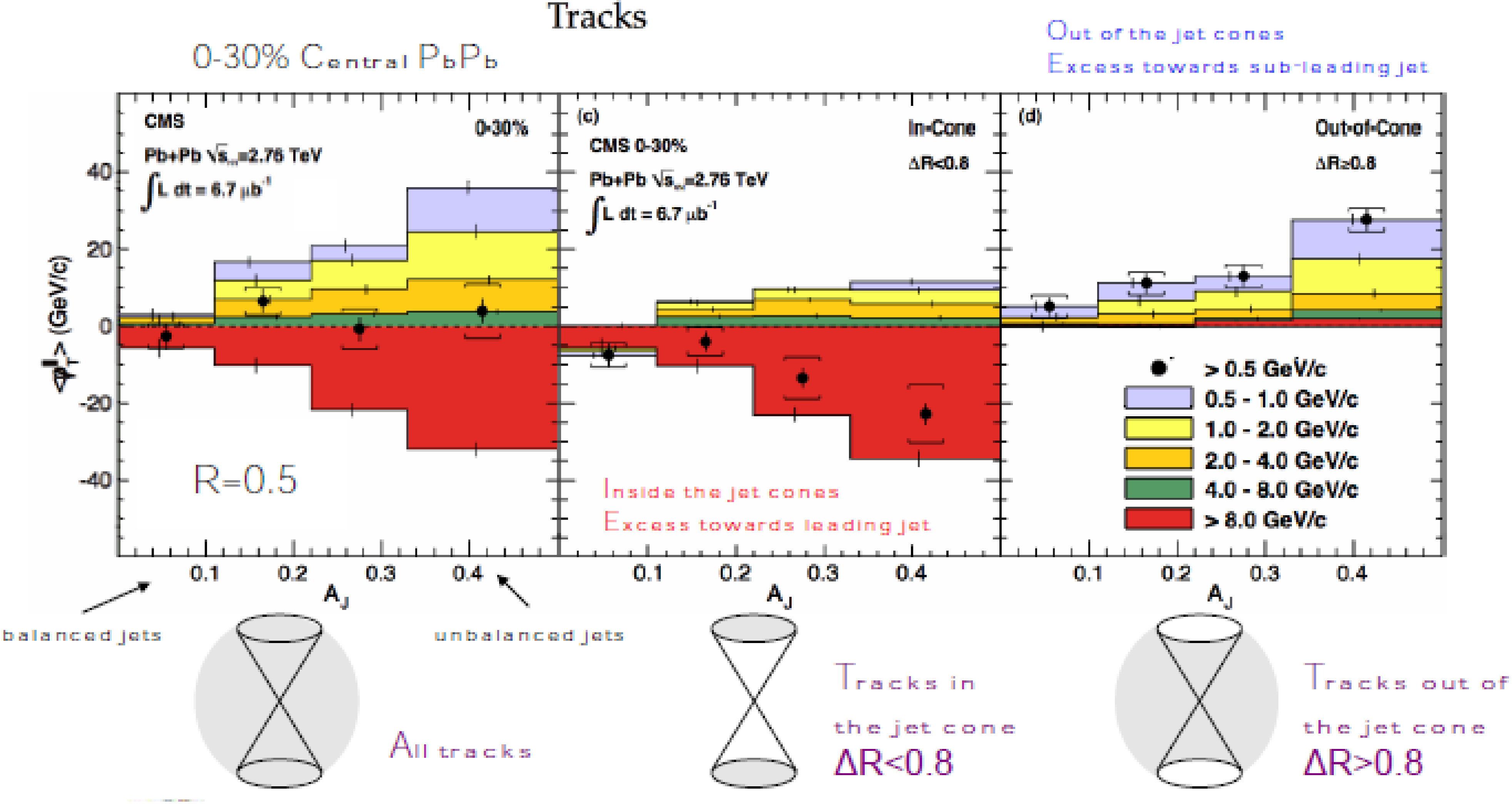
This is a striking observation but difficoult to interpret quantitatively: not a fully corrected observable,many biases imposed by the cuts on jets.

There is an excess of events (compared to vacuum fragmentation smeared with background fluctuations) with large momentum imbalance between the leading and subleading jets.

CMS missing transverse momentum

Missing $p_T^{\parallel}$:

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$



0-30% Central PbPb

Out of the jet cones

Excess towards sub-leading jet

R=0.5

Inside the jet cones

Excess towards leading jet

balanced jets

unbalanced jets

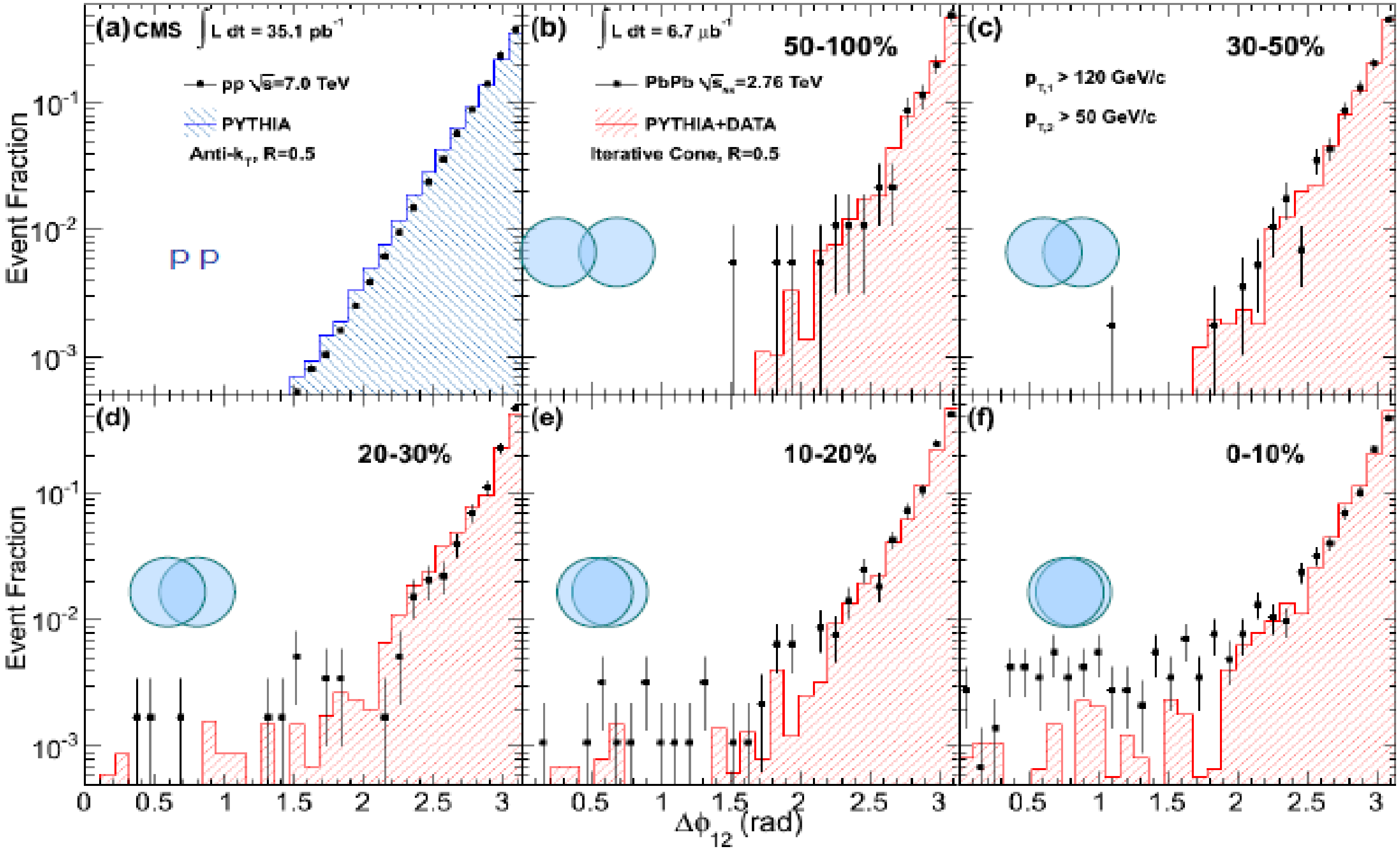
All tracks

Tracks in the jet cone $\Delta R<0.8$

Tracks out of the jet cone $\Delta R>0.8$

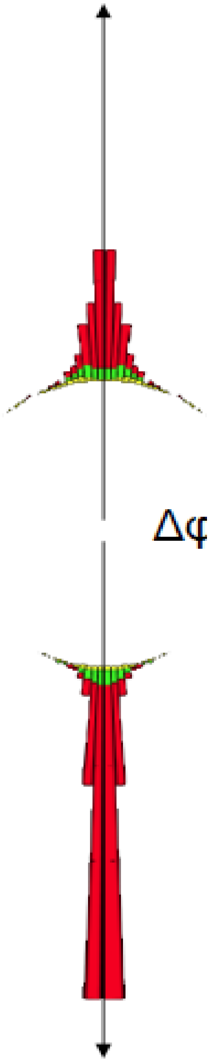
In the events with large assymetry, the momentum balance is recovered with soft particles found at large angles.

CMS accoplanarity



Jet Cone size R = 0.5

PRC 84 (2011) 024906

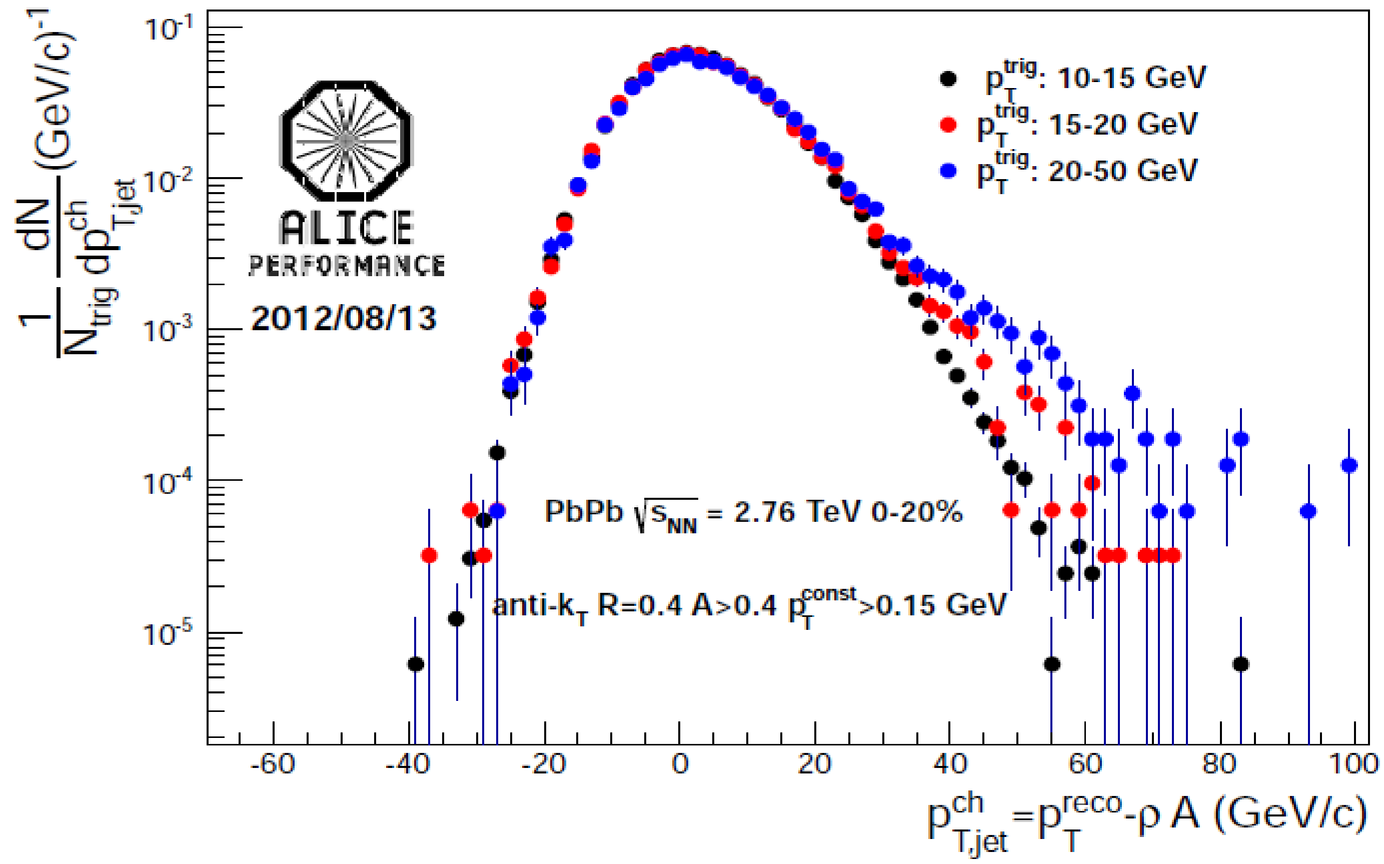


No apparent modification in the dijet Δφ distribution
(still back-to-back)

The subleading jet looses a lot of energy but its direction is not modified!

ALICE RECOIL JET DISTRIBUTION

The hadron trigger imposes maximum path length to the recoil jets

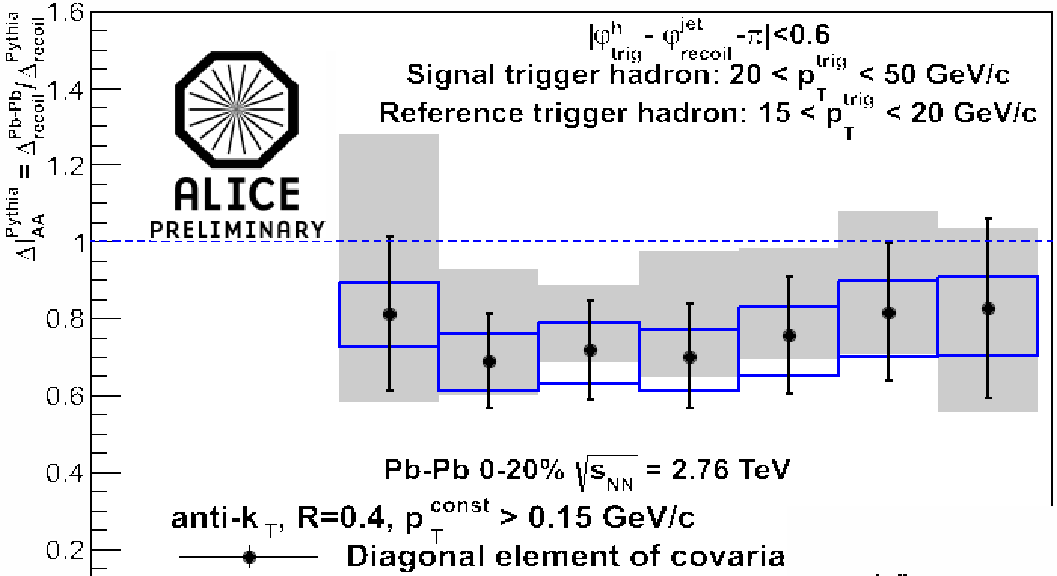


The subtraction of 2 trigger classes (being multiplicity and flow biases saturated) **removes the combinatorial background wo imposing any bias** and allows to unfold the recoil jet spectrum down to low jet p_T and

arbitrarily large R

$$\Delta_{recoil}((p_T^{trig,1}\text{-}p_T^{trig,2})-(p_T^{trig,3}\text{-}p_T^{trig,4})) = \frac{1}{N_{trig}}\frac{dN}{dp^{ch}_{T,jet}}(p_T^{trig,2}<p_T^{trig}<p_T^{trig,1})-c\frac{1}{N_{trig}}\frac{dN}{dp^{ch}_{T,jet}}(p_T^{trig,4}<p_T^{trig}<p_T^{trig,3})$$

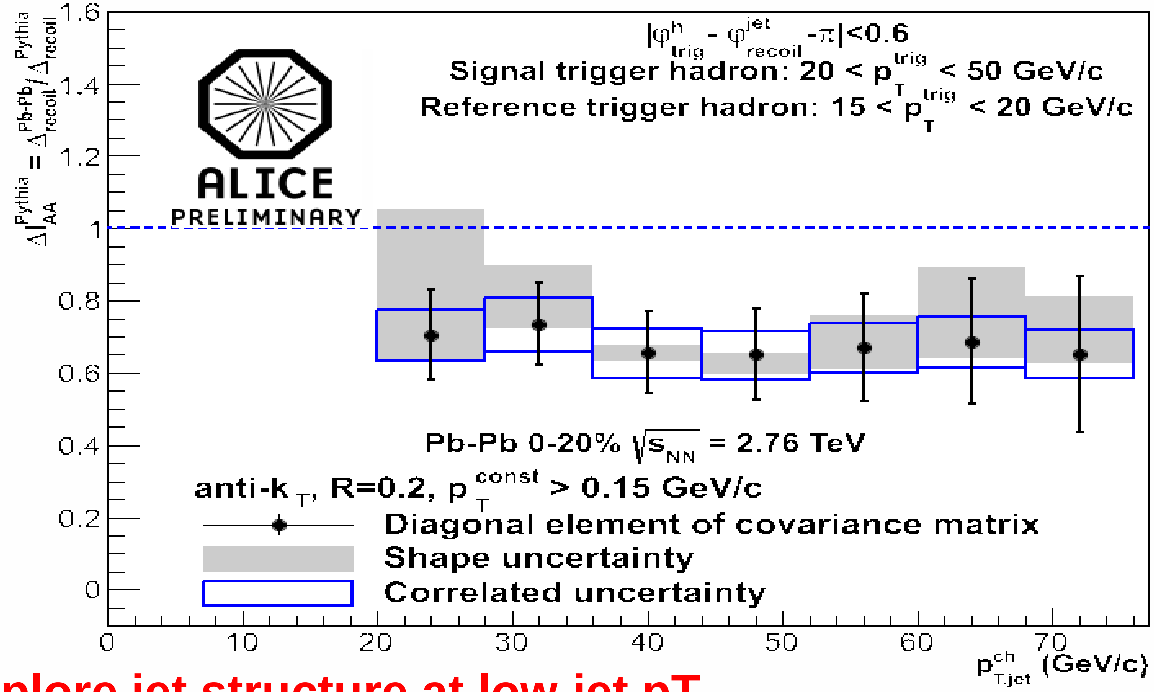
ALICE recoil jet distribution



Not much space left for energy redistribution within R=0.4

Working on reducing systematics!

The recoil spectrum is less steep than the inclusive spectrum -->smaller dynamical range to explore quenching



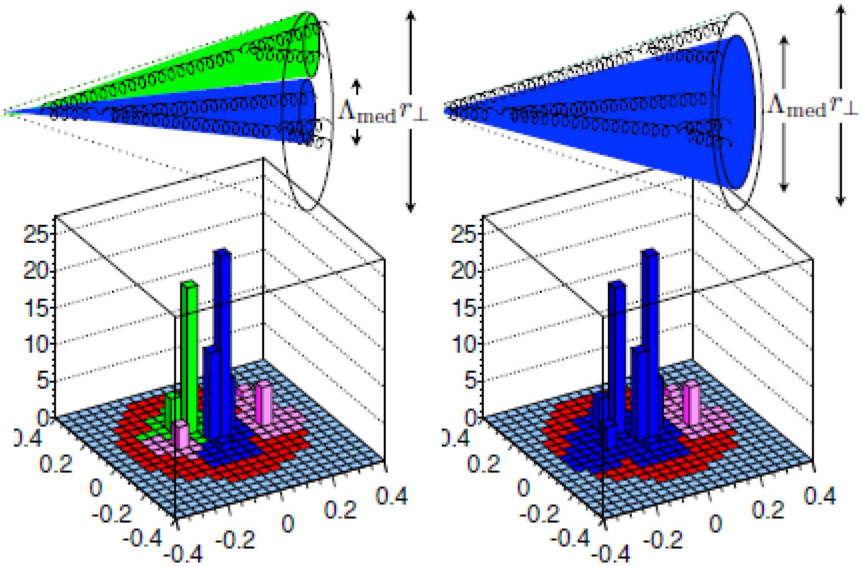
The only method that allows to explore jet structure at low jet pT and arbitrarily large R

Some final comments

1.Different collaborations: different jet pT ranges, different minimum pT cut-off, ,**different biases**, different jet finding algorithms, different input to jet finding, different background subtraction techniques,different interplay between the detector and background response....

2.What is observed so far:

- -The jet energy is not recovered within R=0.5
- -Mild modifications of fragmentation and jet shapes for high energy jets(pT>100 GeV)
- -Excess of events with large momentum imbalance where the energy is recovered at very large angle (R>0.8) in the form of very soft particles.
- -Coplanarity of dijets: the subleading looses energy but does not change direction
- -Hints for energy redistribution within R=0.5 for low energy jets.

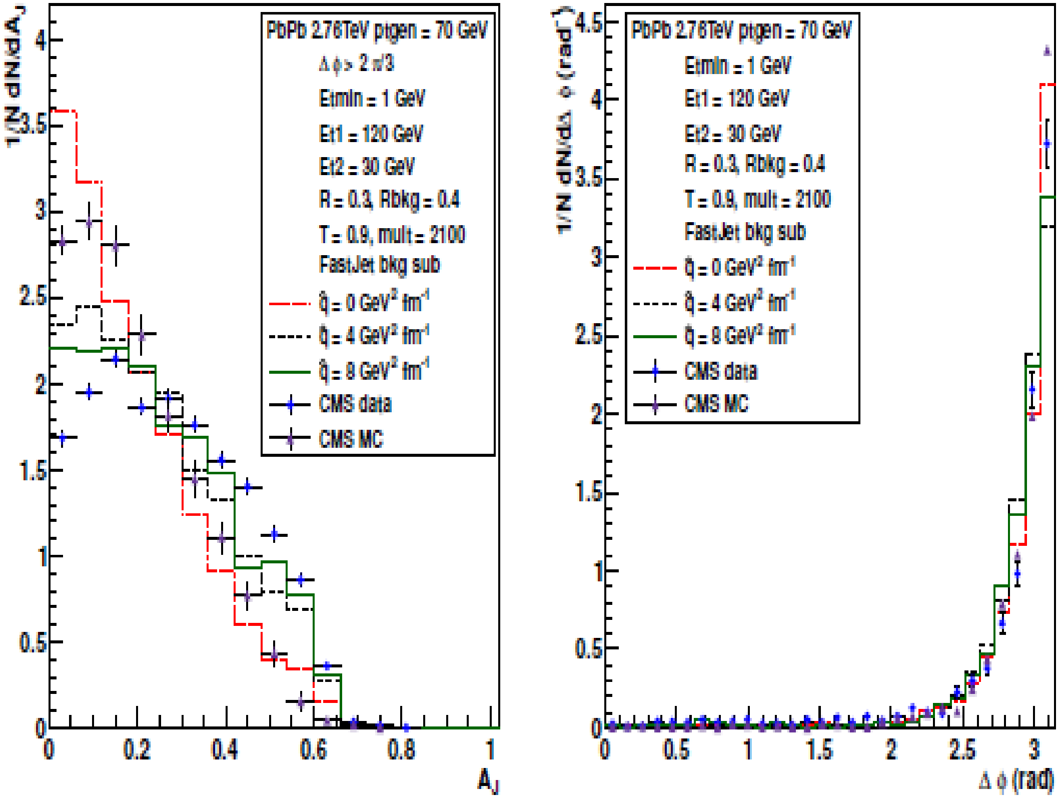


3. Interesting new pictures arising from theory: [Salgado et al,arXiv:1210.7765v2]

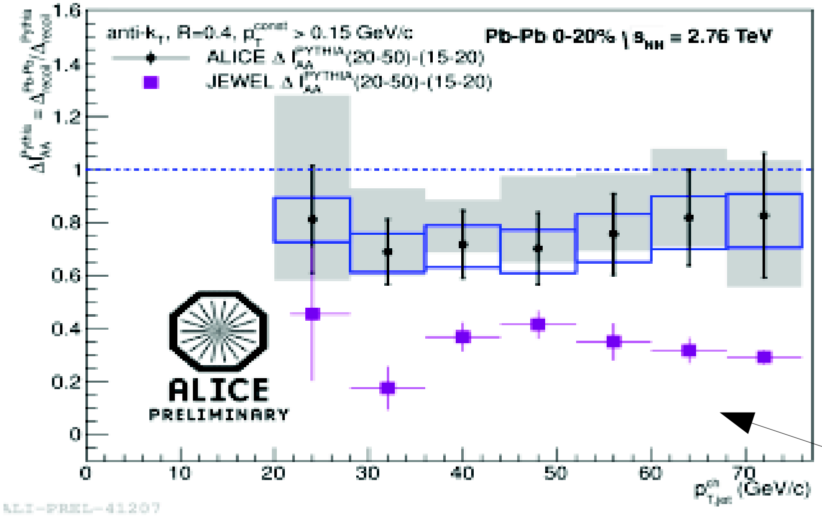
4. Comparisons to theory ongoing: lot's of joint effort to define strategies and observables

Theory-experiment comparisons

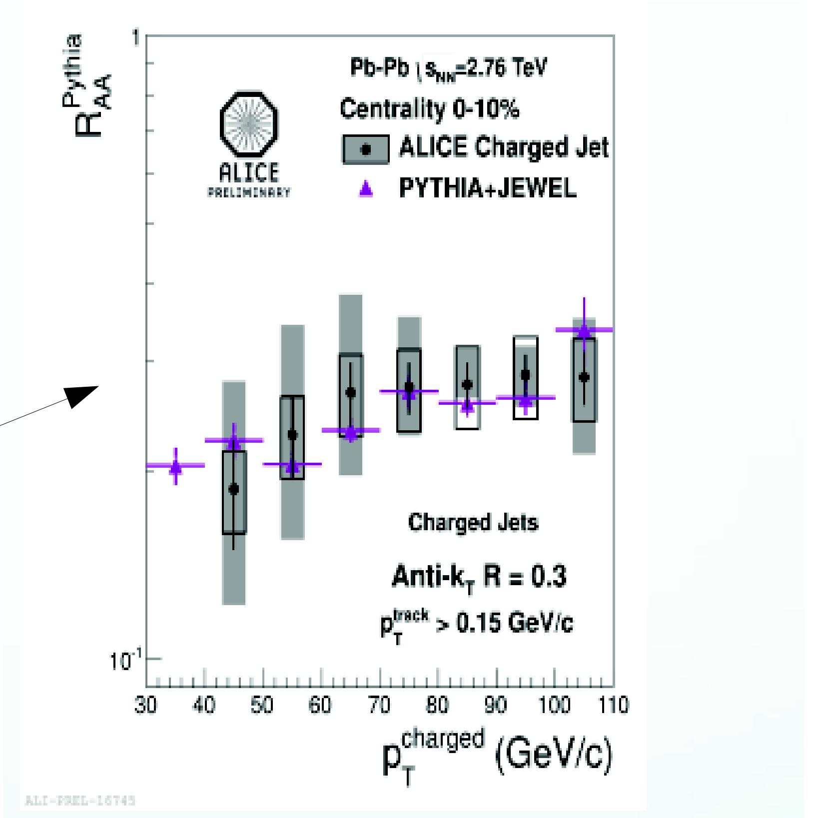
Experimental observables should be **fully corrected**. To extract quantitative info of jet quenching. -->The Aj is not corrected for background fluctuations, so theorists have to embedd their jet showers into modelled backgrounds (see left ***[Armesto-Apolinario-Cunqueiro])***



hal correlation.



Constrain theory. Left: JEWEL vs recoil. Rigth: JEWEL vs inclusive jet spectrum. Path length sampling?



Summary and outlook

LHC measures a larger,denser,longer lived and more opaque source than at RHIC

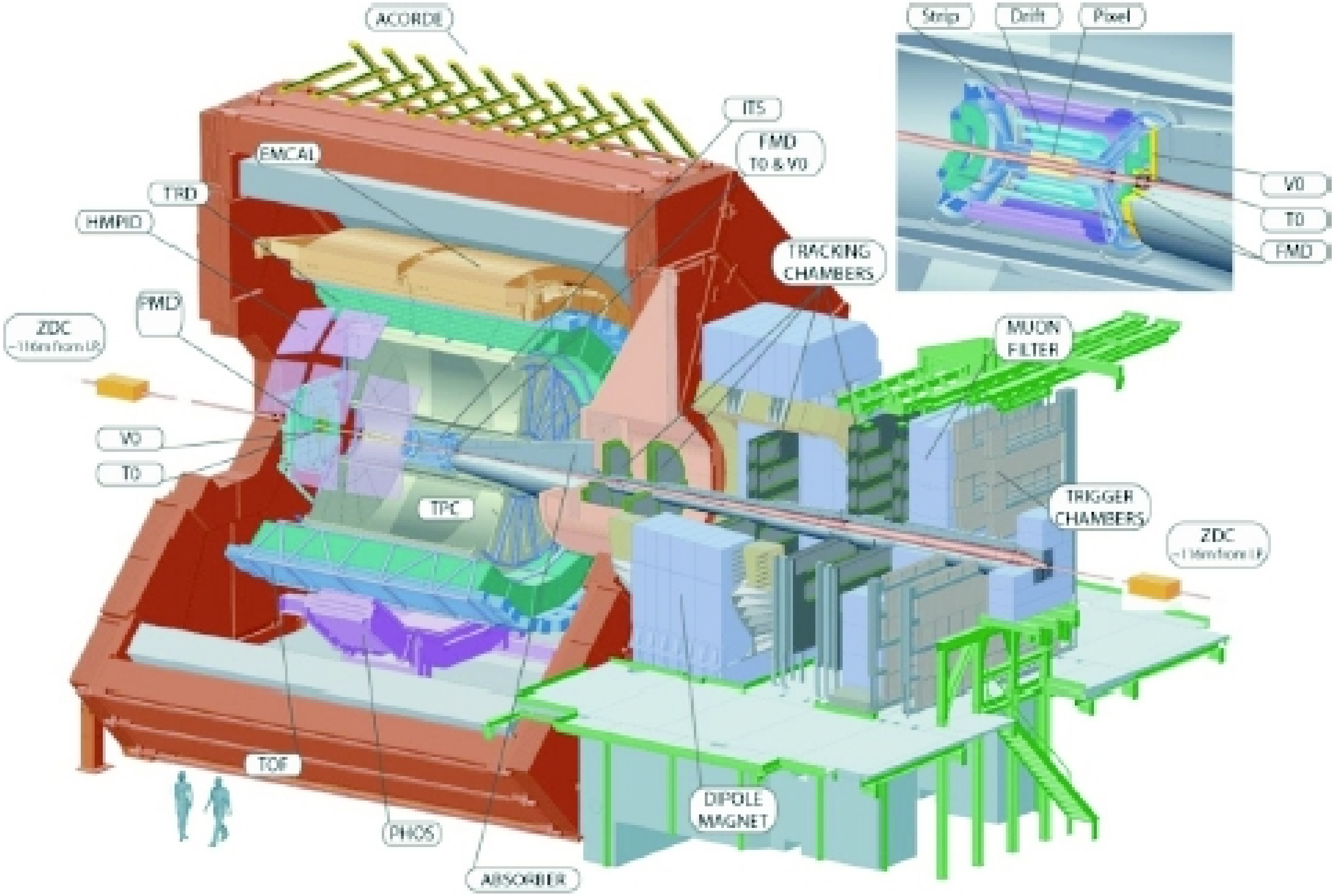
The measurements of bulk properties confirm the great success of hydrodynamics in Heavy Ion Collisions.

-->precision measurements of shear viscosity η/s

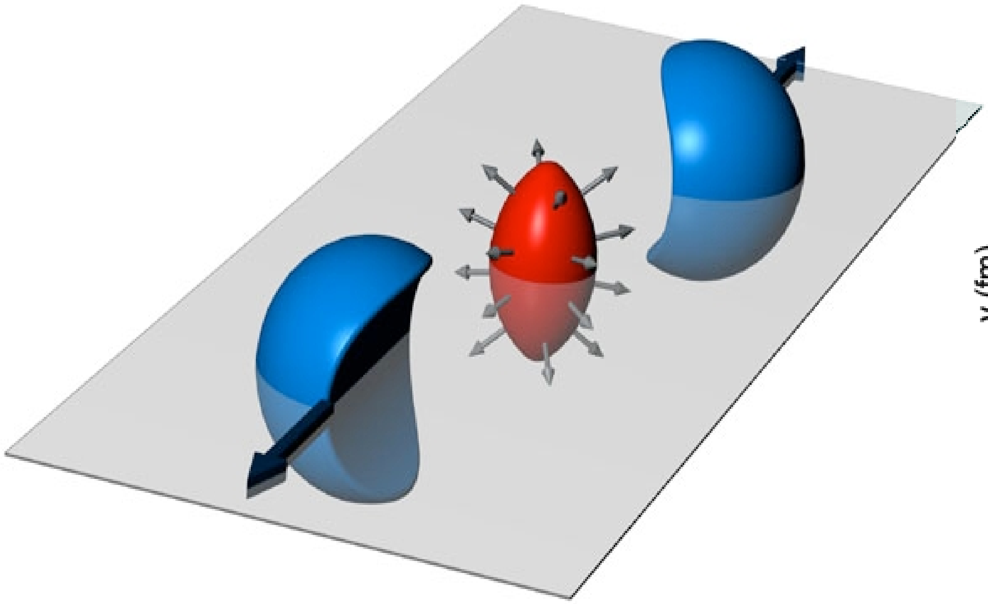
Towards a quantitative characterization of the fundamental "transport" properties of the medium

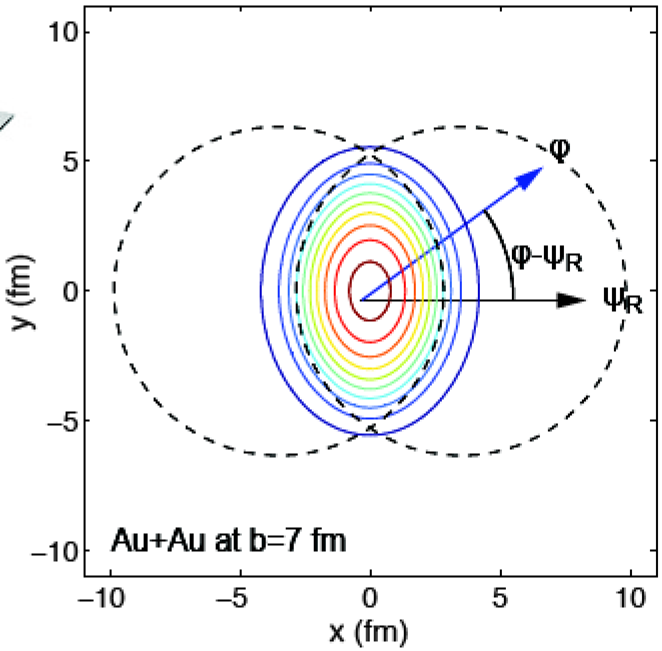
-->Jets are great tools but there is a long road ahead

The ALICE experiment



The elliptic flow: early thermalization





Almond shape overlapping region in coordinate space → Interactions generate pressure gradients → anisotropy in momentum space

Fourier expansion to describe angular dependence of particle density wrt reaction plane →

$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

$$v_2 = \langle\cos[2(\varphi - \psi_R)]\rangle$$

The dependence on the jet R

δp_T measures the difference between the measured jet p_T and the original parton p_T

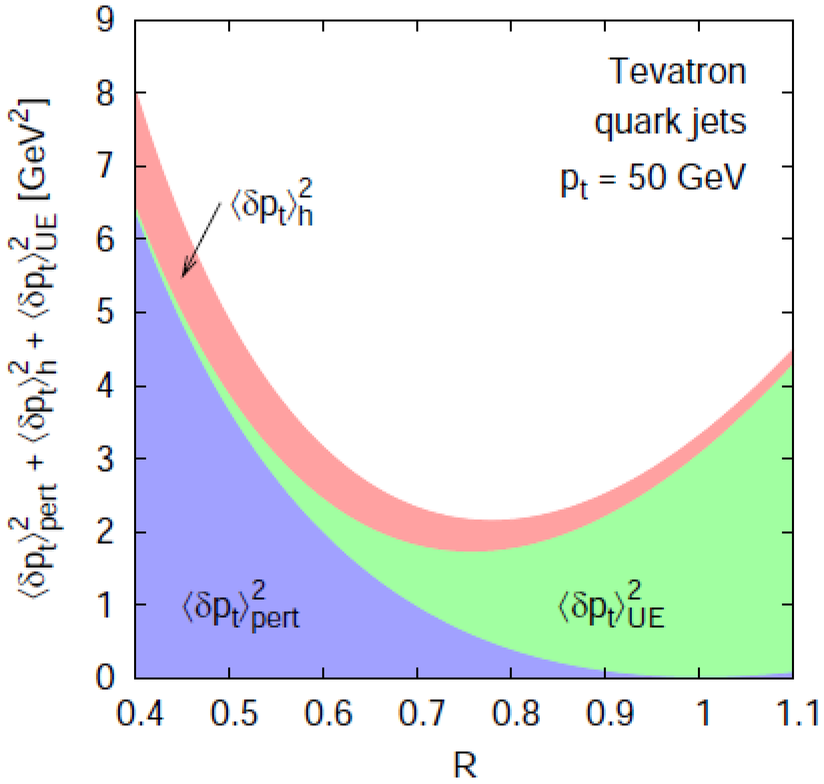
$$<\delta p_T> = <\delta p_T^H> + <\delta p_T^P> + <\delta p_T^{UE}>$$

Har radiation, UE and hadronization splash out

$$<\delta p_T^P> \approx \log R + \mathcal{O}(1)$$

$$<\delta p_T^{UE}> \approx R^2 + \mathcal{O}(R^4)$$

$$<\delta p_T^H> \approx -\frac{1}{R} + \mathcal{O}(R)$$



Note that the UE (*underlying event:energy in the pp event which is not correlated with the hard scattering*) enters as ~R^2

In heavy ions, this constraints us to low-moderate jet R~0.4

In pp, no limit (except for acceptance) on maximum R.

Combinatorial background and unfolding

The unfolding is a **linear** method that **conserves** total number of jets.

If in your measured sample at a certain jet p_T you have large contribution from **fake jets** (soft particles clusterd by the algorithm, uncurrelated with hard processes) and they enter the unfolding,
then the **unfolded solution will be wrong.**

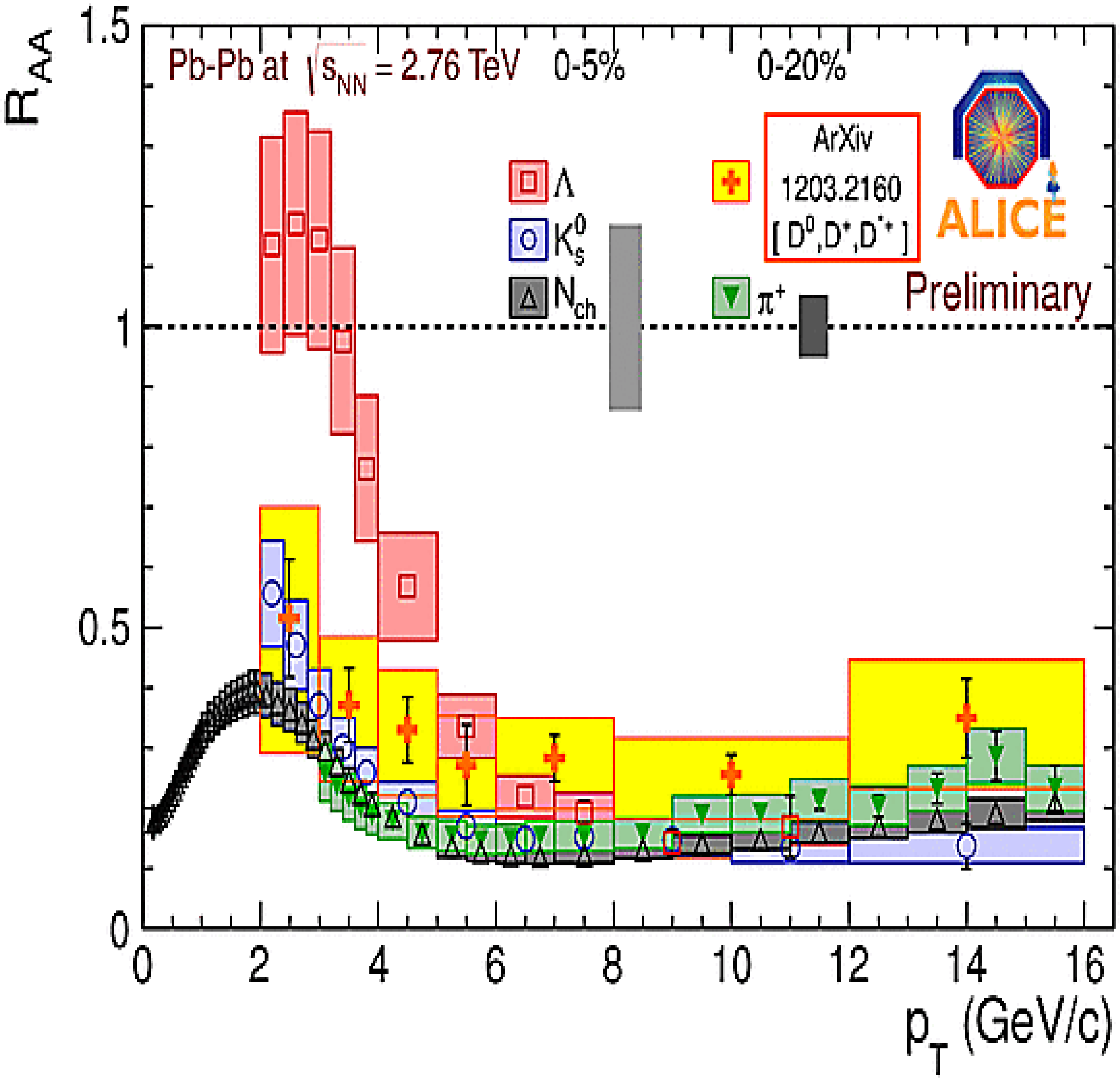
I HIC we are interested on looking to low energy jets, which are expected to be modified more by the medium, and we are interested on large R to explore energy redistirbution at large angles.

-the unfolding of the inclusive spectrum is limited in min p_T and R

Different approaches to the problem:

-Introduce biases: require a leading hadron of more than X GeV
(but this biases your jet fragmentation)
-consider correlation measurements to suppress combinatorial background
-tagging on heavy flavour jets?

PID RAA



ALI-PREL-14286

Dead cone effect?

$$\omega \frac{dI}{dw}\Big|_{HEAVY} = \frac{\omega \frac{dI}{dw}\big|_{LIGHT}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

Implies lower heavy quark energy loss in matter

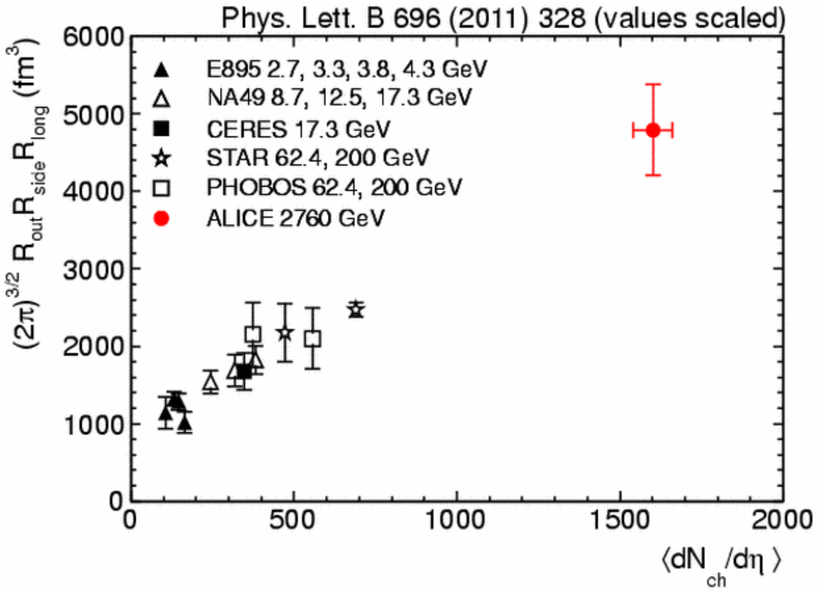
Dokshitzer PLB (2001) 519 199

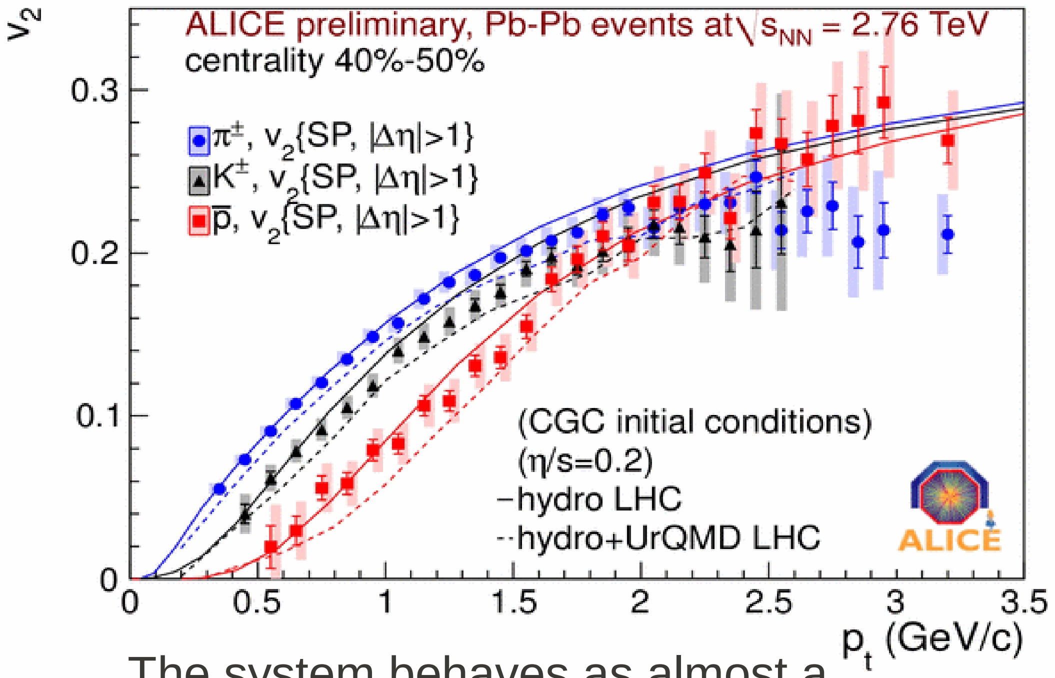
Similar suppression at high p_T for all particle species, including charm.

Experimental characterization of the System II

Pion interferometry: 2pion BE correlations: larger and longer lasting system than at RHIC. V~500 fm^3, τ~11 fm/c (*from Bang to freezout*)

Great success of **viscous hydrodynamics** Large v2->early thermalization





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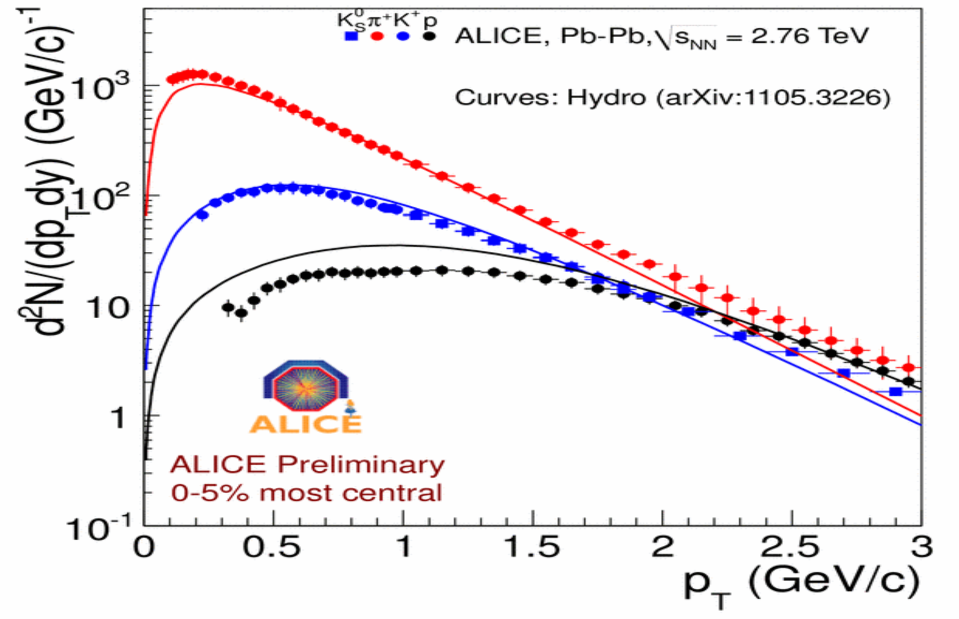
The system behaves as almost a **perfect liquid**: shear viscosity close to ADS/CFT bound.

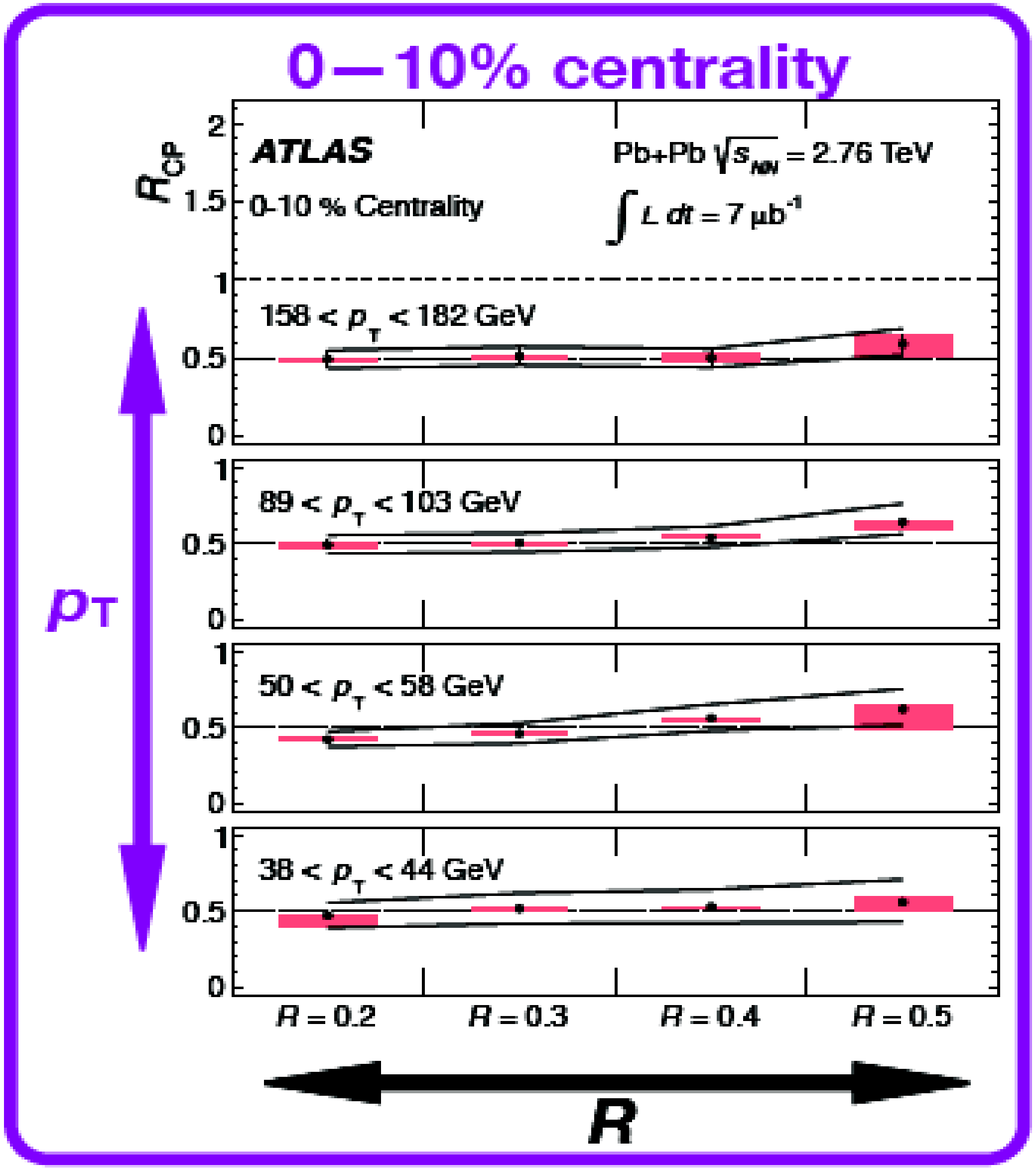


ALI-PREL-6358

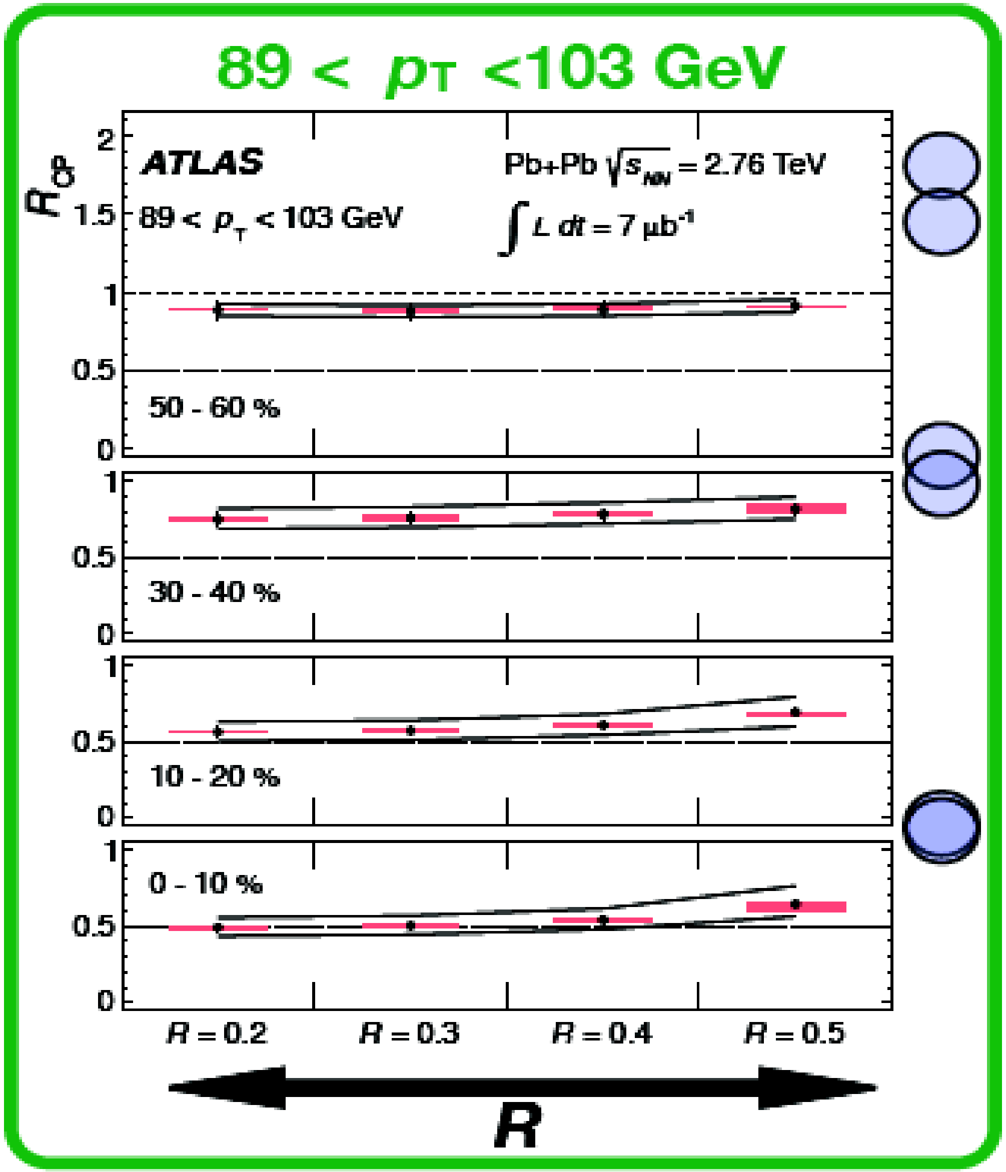
Fits of hermal boosted models to **particle spectr**a:temperature at the kinetic freezout and radial velocity of the system.

T_{kin}=80 MeV & β_c=0.6c

ATLAS RCP and R dependence



0—10% centrality



89 < p_T <103 GeV

Some change in the suppression observed at larger R~0.5-->but also large systematics