Review of recent results on jet physics in Heavy Ion from LHC (compared to RHIC)

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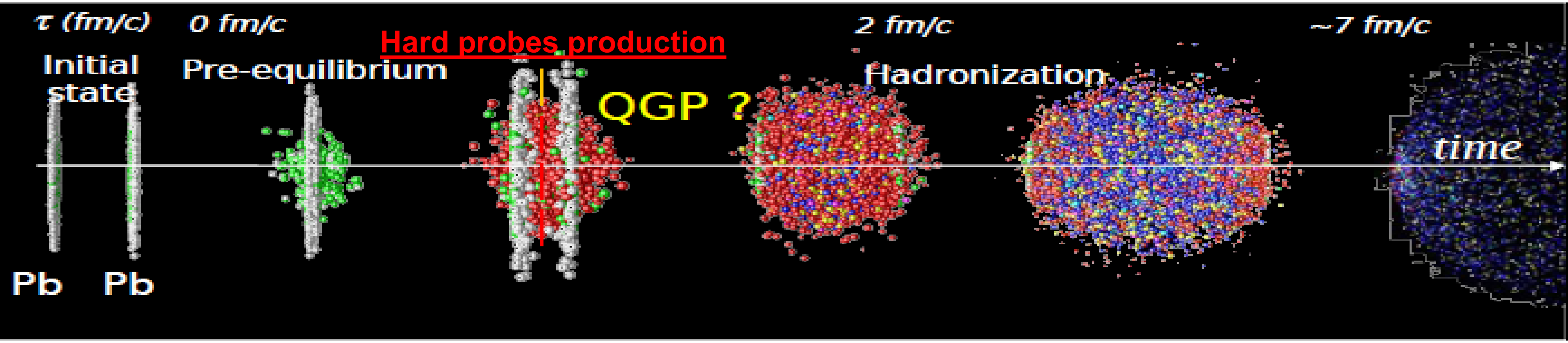
Physics motivation



Jets are produced very early and are sensitive to early stage of the collision

➔This allows to probe and study the QGP by using jet properties

- pp: Study jet production (ex. Cross section measurements) : test pQCD
- pA / dA: Are they affected by Cold Nuclear Mater effects ?
- A-A Study in medium energy loss
  - Path length dependence
  - Broadening of shower
  - Leading hadron vs. softening of FF
    - Probe ex. the density of the medium

This can be studied by using various observables, in this talk we will mainly discuss: nuclear modification factors, h-jet azimuthal correlations, di-jet asymmetry and jet FF.

Subatech

Nuclear Modification Factors

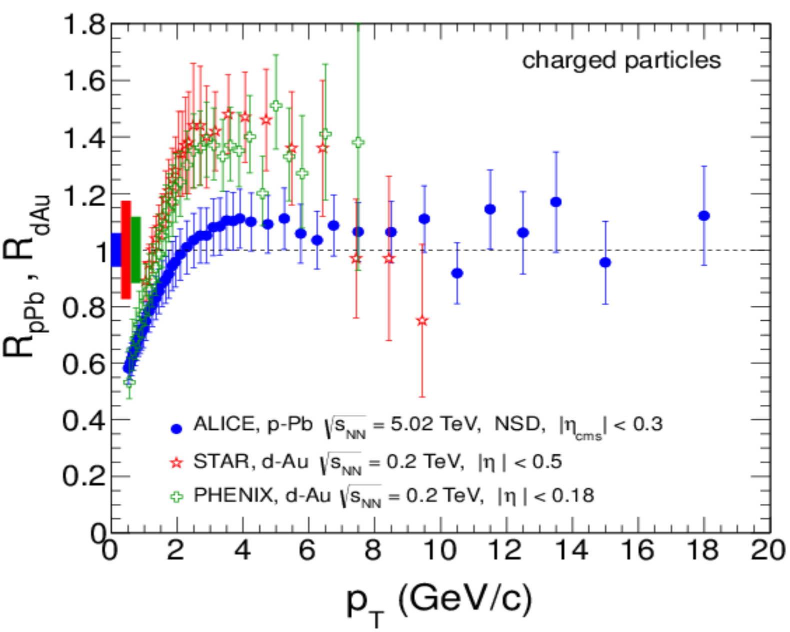
$$R_{AA} = \frac{Yield(AA)}{Yield(pp)}$$

$$R_{AA}(,p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp}{dN_{pp}/dp}$$

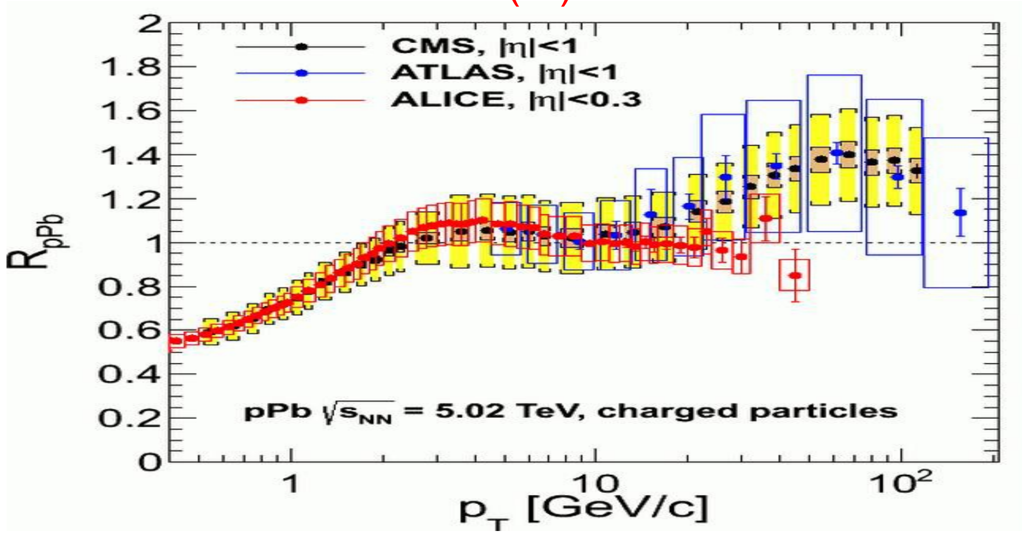
In absence of nuclear modifications, hard processes are expected to follow N_{col} scaling ➔ $_{RAA} = 1$

Single particle RpPb & RdA

RHIC: $R_{dAu} > 1$ at high p_T
=> CNM effects (Cronin / Shadowing)



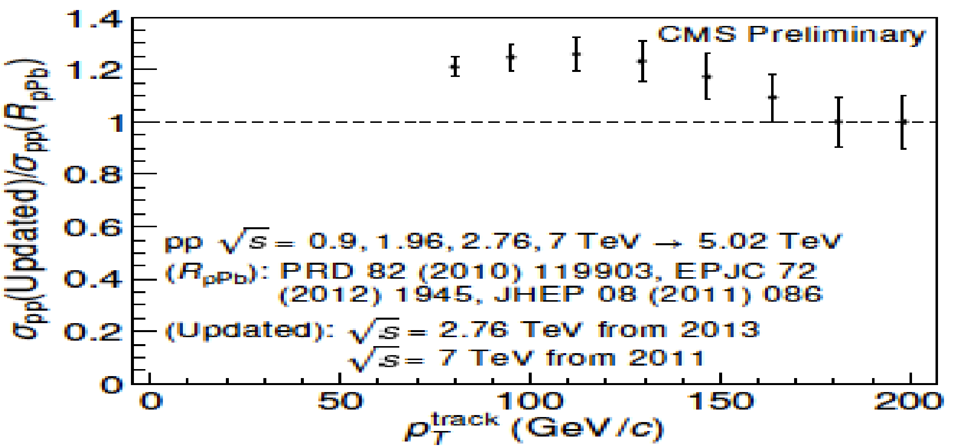
LHC: High-p_T charged particles follow binary scaling.
Initial state effects are small(er)



Tension at high p_T between ALICE and ATLAS/CMS

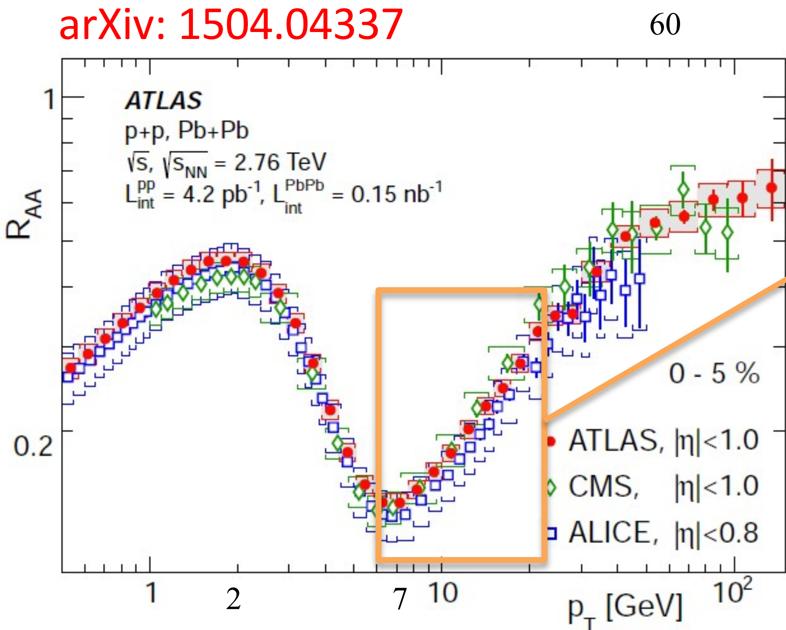
ALICE / CMS difference
Likely due to pp reference
CMS: new pp@5 TeV
interpolation (used for Jet FF)

Issue solved?



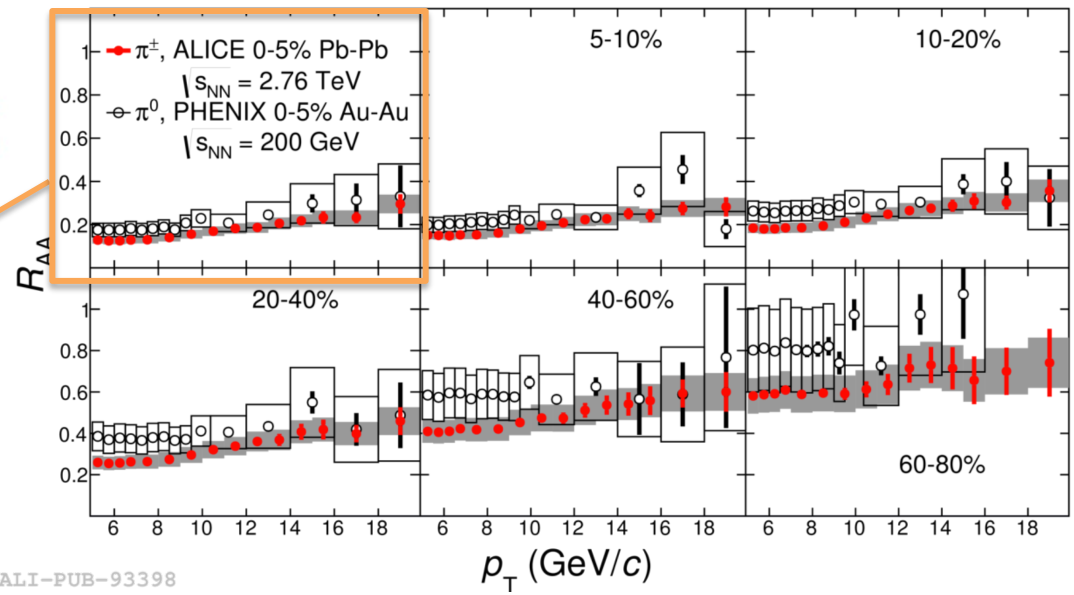
single particle R_{AA} at high p_T

arXiv: 1504.04337



arXiv:1506.07287

PRC 87 (2013) 034911



LHC:

R_{AA} = 0.55 +/- 0:01(stat) +/-0.04(syst:).

A lot of models describing the trend of R_{AA} with different set of parameters

R_{AA} not enough to really constrain the transport coefficients

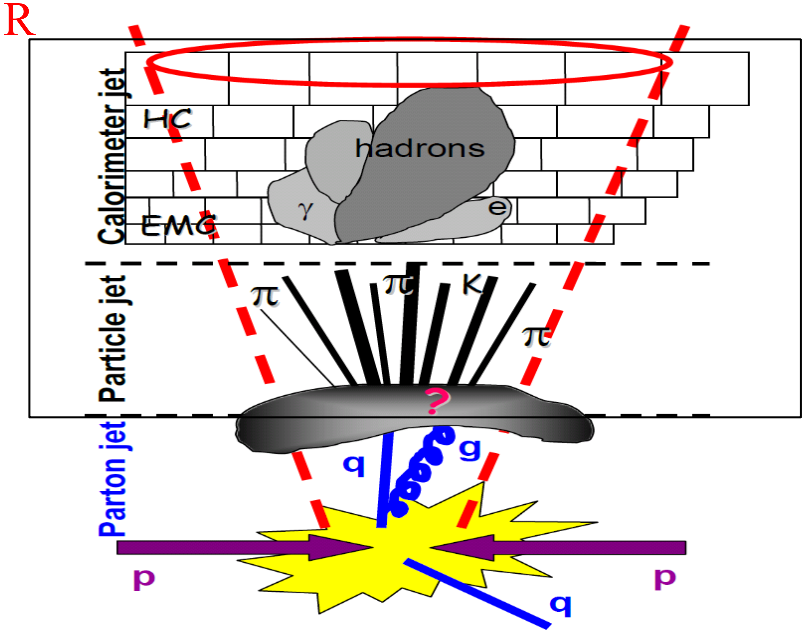
LHC RUN 2: evolution of the shape at higher p_T ?

RHIC:

Similar R_{AA} values in central collisions at LHC and RHIC: with a much harder spectrum at LHC

➔ larger ΔE at LHC

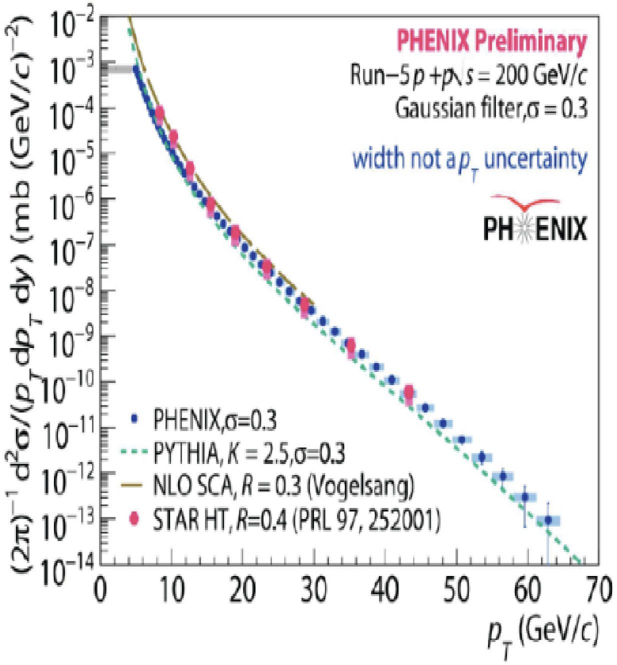
Jets Measurements



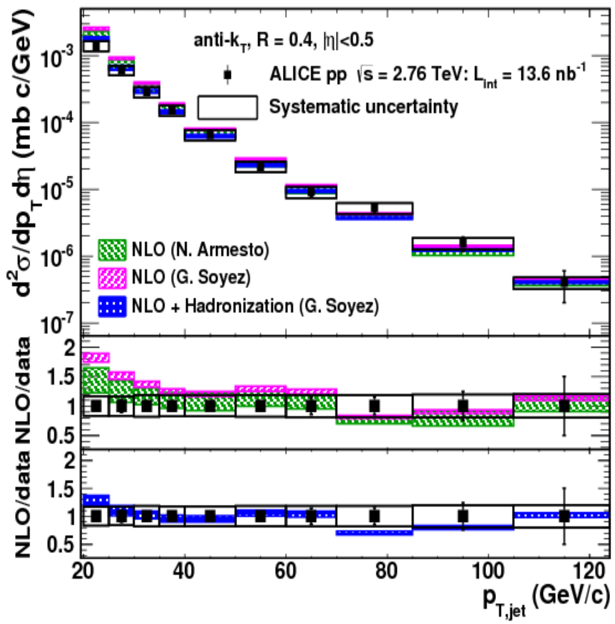
“Cone like” or sequential reconstruction algorithms (k_T and anti-k_T are used in the following analyses).

Jet production cross-sections in pp collisions

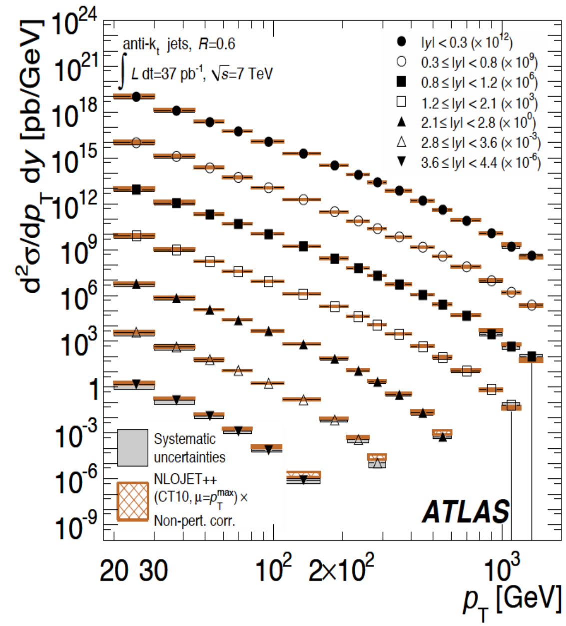
- RHIC : STAR & PHENIX
- ALICE: Full jets
- ATLAS



PLB 722, 262 2013



Phys.Rev. D86 (2012) 014022

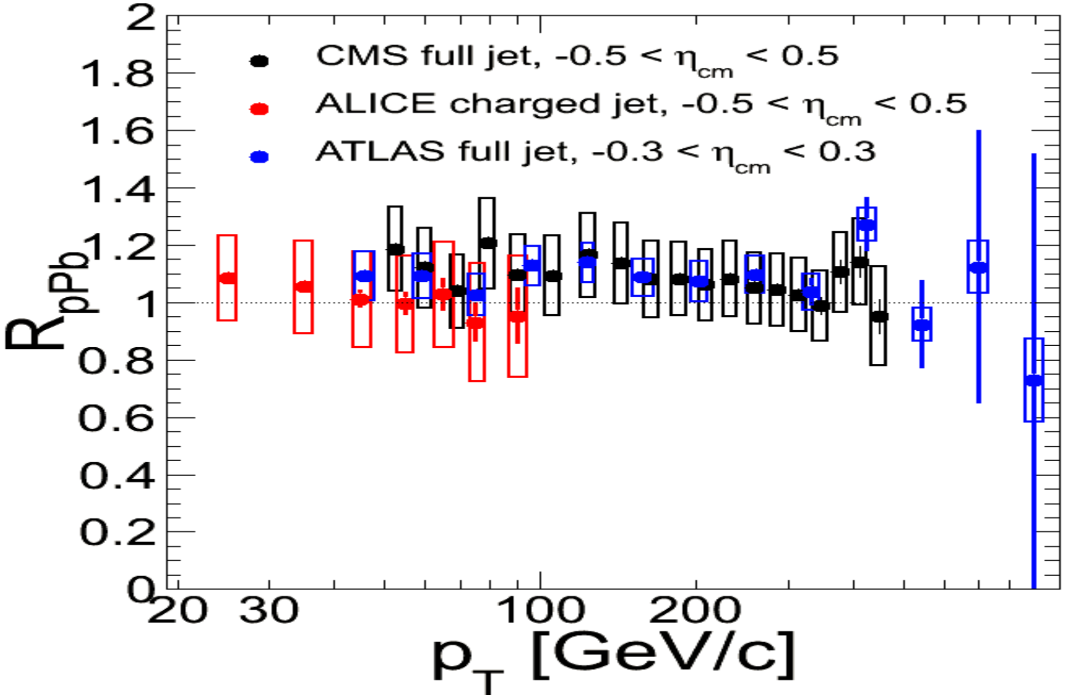


Good agreement with NLO pQCD over a broad kinematic range

Important reference for p-Pb & Pb-Pb analyses

Jet R_{pA} @ LHC

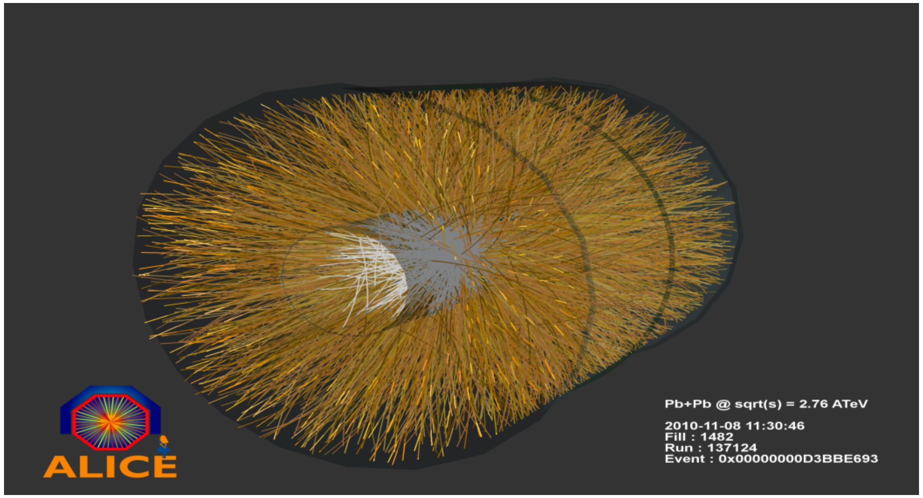
$$R^{jet}_{pA} = \frac{dN^{jet}_{pA}/dp^{jet}_{T}}{N_{coll}\, dN^{jet}_{pp}/dp^{jet}_{T}} \cdot \frac{N^{event}_{pp}}{N^{event}_{pA}}$$

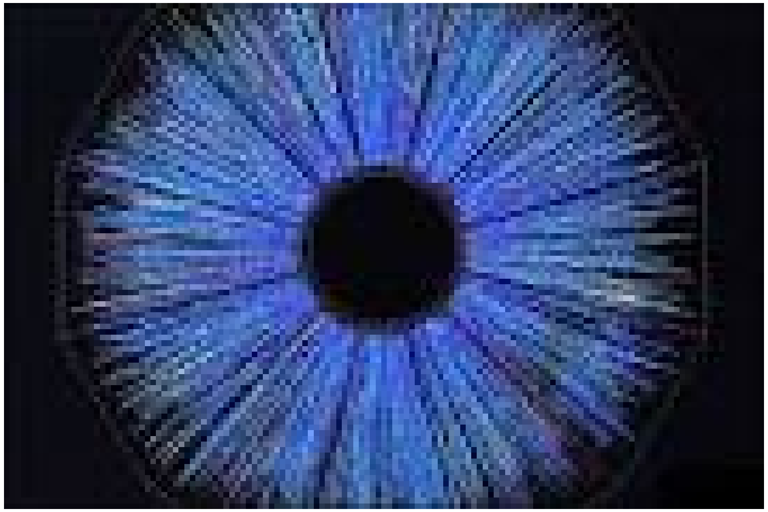


jet yield in p-Pb compatible with what is expected from a superposition of independent pp collisions

Consistent with no CNM effects

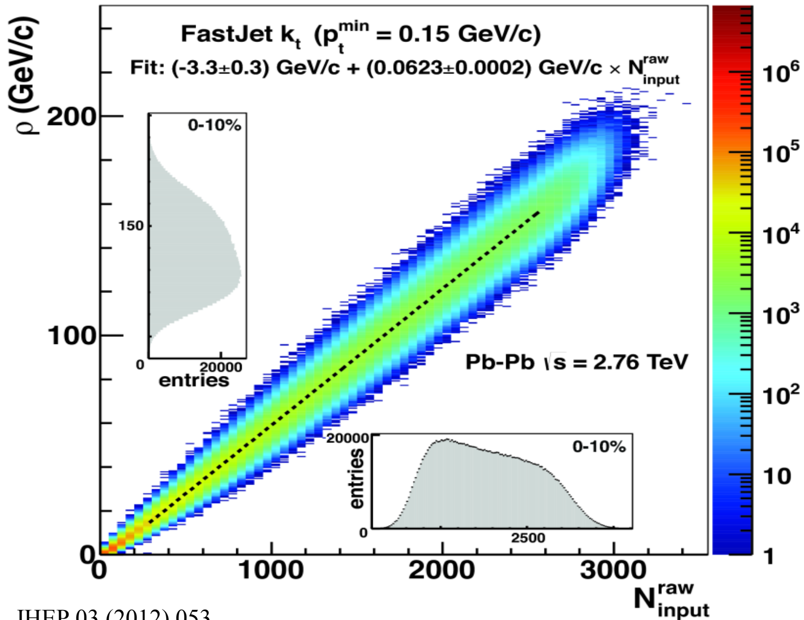
Results from nucleus nucleus collisions





Background and its fluctuations in Pb-Pb

Ex of ALICE



JHEP 03 (2012) 053

$$\rho = median\left(\frac{p_T^{jet,i}}{A_i^{jet}}\right)$$

Larger background fluctuations (σ) for larger R, while larger R should be preferred to recover as much information as possible of the jet property.

➔ Background density scales with event multiplicity

ρ ~ N ⟨pT⟩

➔ ρ = 200 GeV/c for most central collisions PbPb collisions at LHC

➔ ρ has large event by event up/down fluctuations

Ex: σ_{ch} ≈ 10 GeV/c for R=0.4

➔Smaller R ➔ less background fluctuation

➔Limit R to resonable values 0.2<R<0.5

➔ jets studies are challenging.... In heavy ions Especially at low p_T

Jet
Nuclear Modification Factor

$$R_{AA} = \frac{Yield(AA)}{Yield(pp)}$$

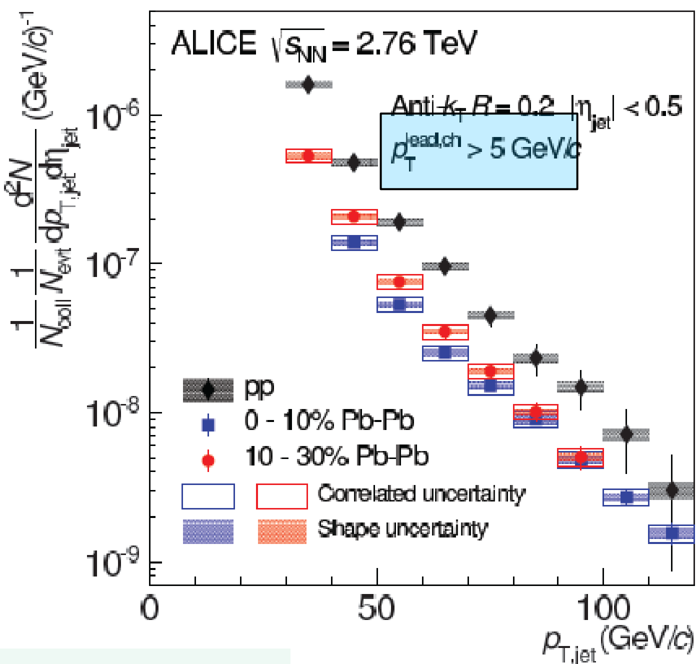
$$R_{AA}(,p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp}{dN_{pp}/dp}$$

In absence of nuclear modifications, hard processes are expected to follow N_{col} scaling ➔ $_{RAA}$ = 1

ALICE: Full jet spectrum & R_{AA} in PbPb collisions

- Full jet spectrum in Pb-Pb: large and fluctuating background (JHEP03 (2012) 053)

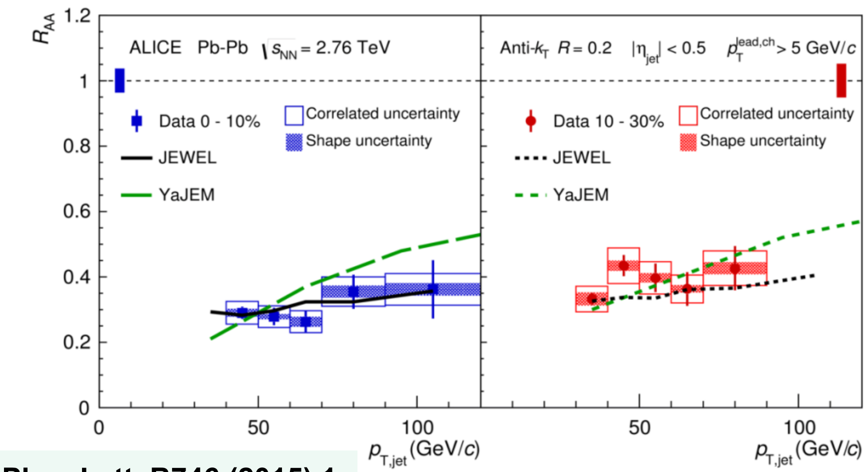
$$p_{T,jet} = p_{T,\mathrm{rec}} - \rho A$$



Phys.Lett. B746 (2015) 1

Strong suppression observed in spectra and R_{AA}

- Full jet R_{AA}:



Phys.Lett. B746 (2015) 1

Leading track p_T cut ➔ fragmentation bias

- Suppression quantified by R_{AA} for different centralities:
- 0-10% R_{AA}~ 0.28+/-0.04
- 10-30%R_{AA}~ 0.35+/-0.04
- Both models use a fit to hadron R_{AA} to adjust their parameters.

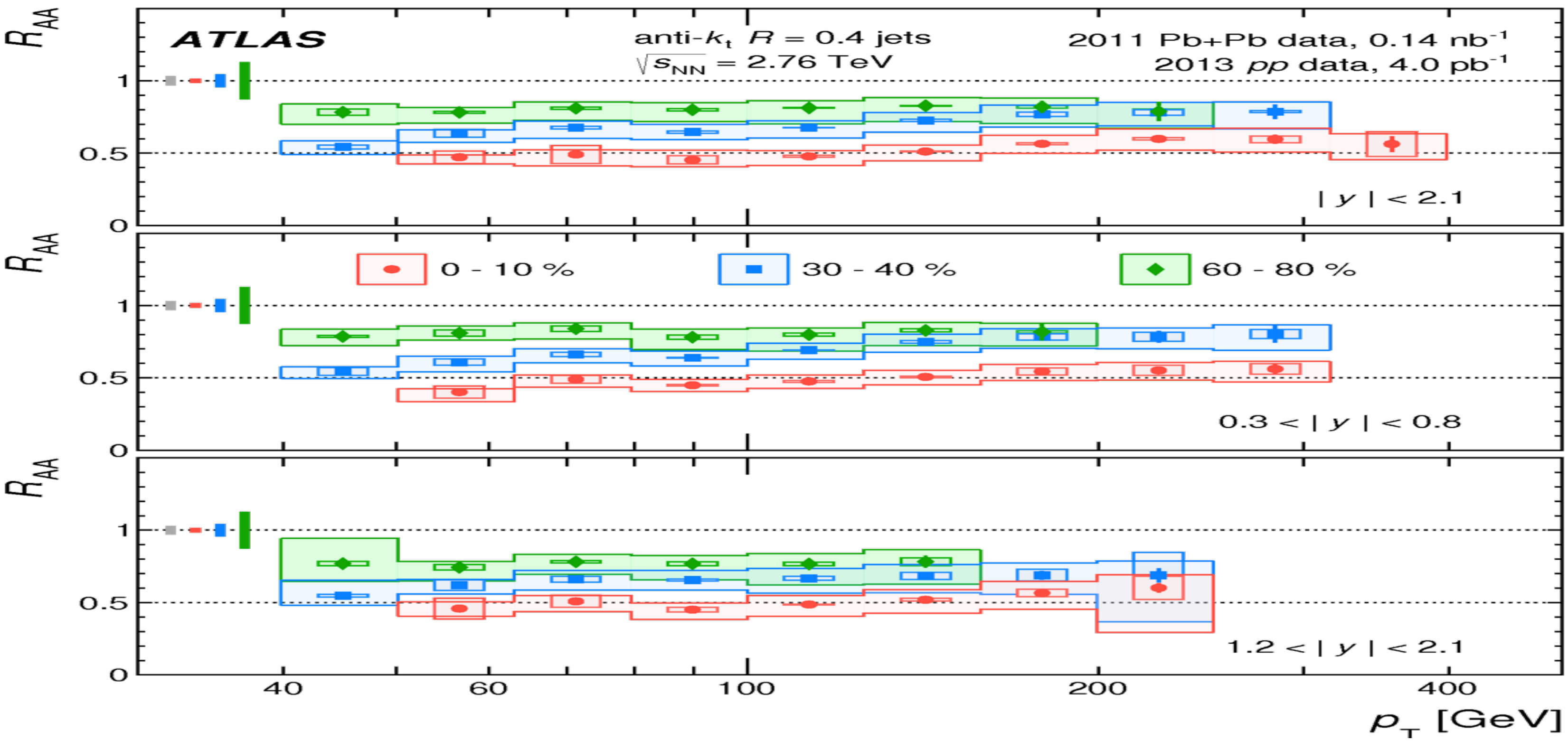
Both models are in agreement with data
(slight **deviation of YaJEM at high p_T in central collisions)**

ATLAS: Inclusive jet suppression

Suppression (~ **factor 2** in 0-10% centrality) of inclusive jets from 40 to **400 GeV/c** for different rapidity bins

No or small dependence on rapidity ➔ not enough to constrain gluon/quark jet ratio (which varies with y)

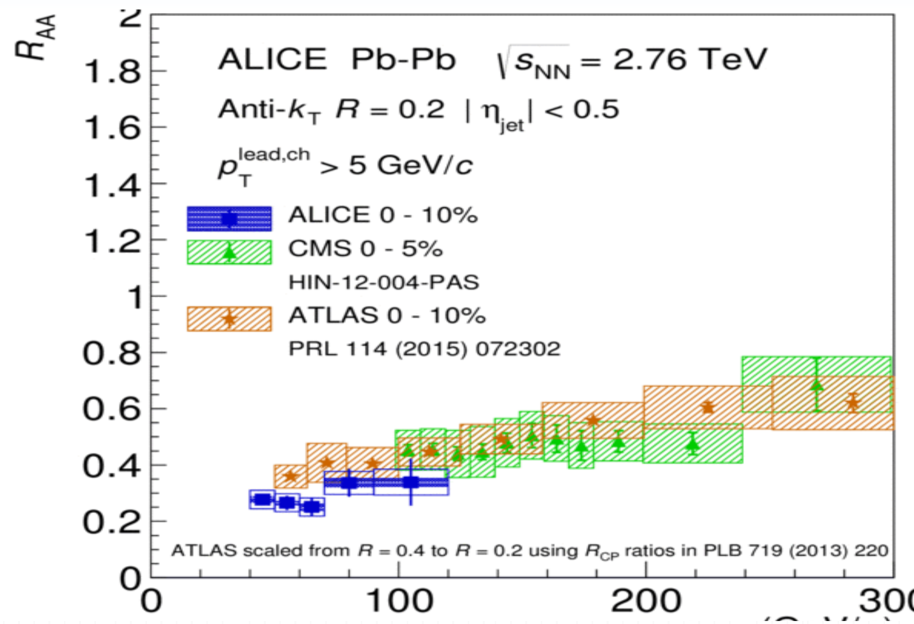
Phys. Rev. Leh. 114 (2015) 072302



jet RAA: LHC vs RHIC

LHC:
- Full jet R_{AA} in central Pb-Pb collisions,
- Different jet reconstruction technics (ATLAS: Calo Jets, CMS: PF jets, ALICE: Ch+En Jets) used by the different experiments
- R=0.2

NB: ATLAS scaled from R=0.4 to R=0.2

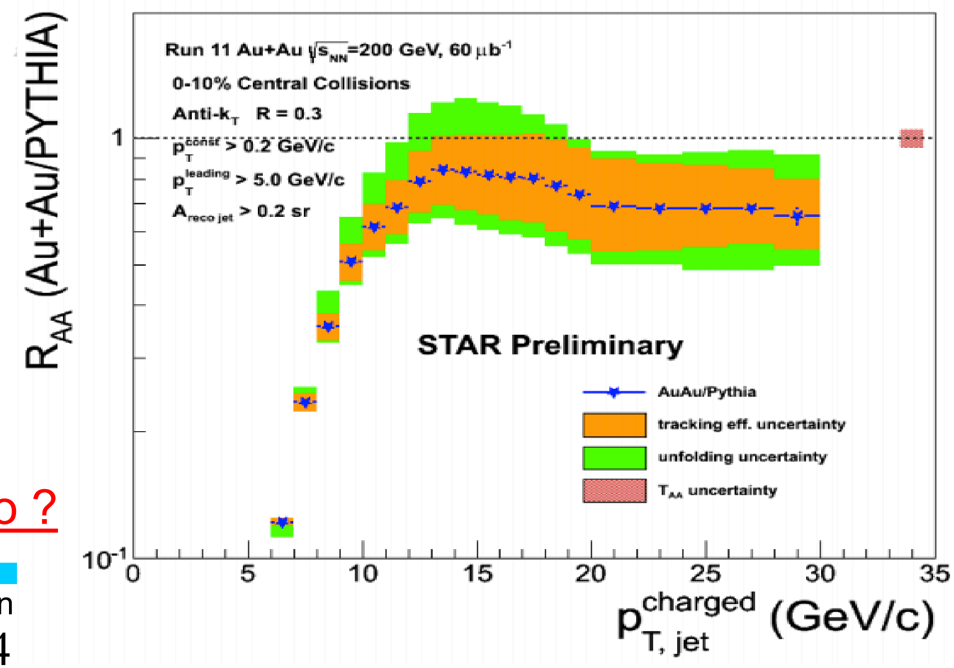


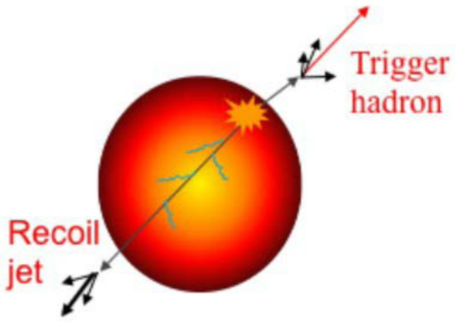
Results at LHC are in fair agreement

RHIC:
Smaller suppression of inclusive jet yield at RHIC
Jets are also less suppressed than hadrons at RHIC

Jet RAA expected to be one if all the jet energy is measured

Where did the energy go ?





Surface bias effect: the parton producing the jet is biased towards higher in-medium path length
Trigger Hadron: close to the surface

Hadron-jet Azimuthal Correlations

Recoil jet measurement provides us with a good handle on the combinatorial background and allows to go to larger R

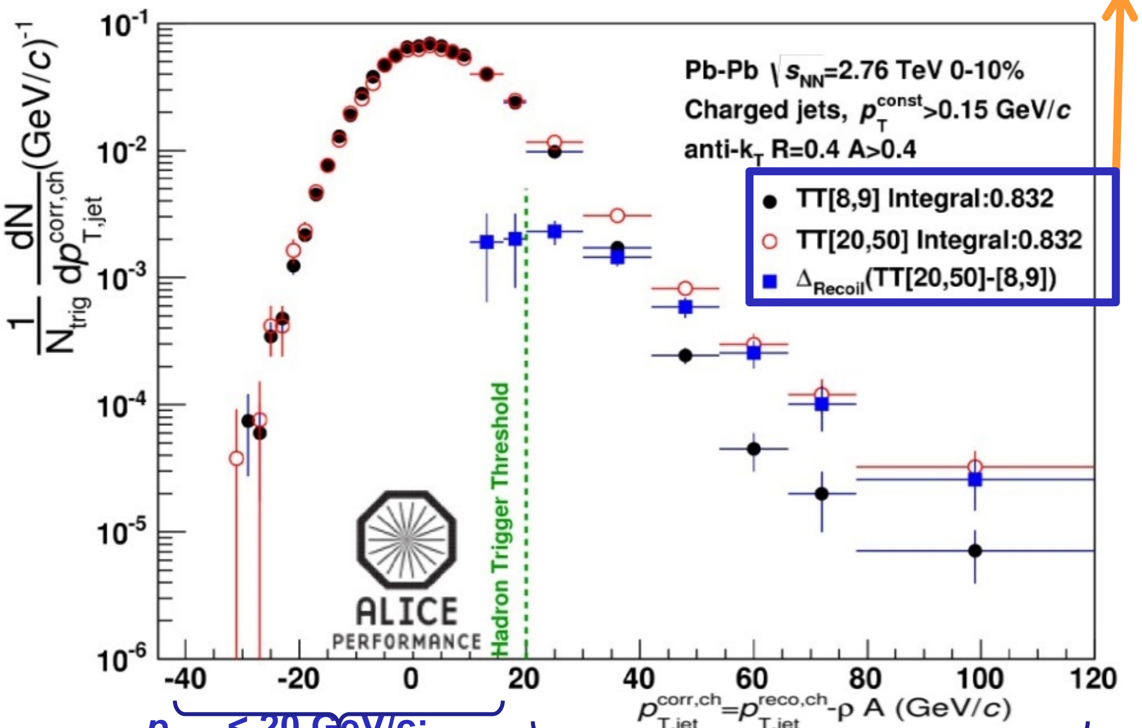
Bonus: **No fragmentation bias on recoil side**

ALICE vs STAR: Hadron-jet correlations

ALICE:

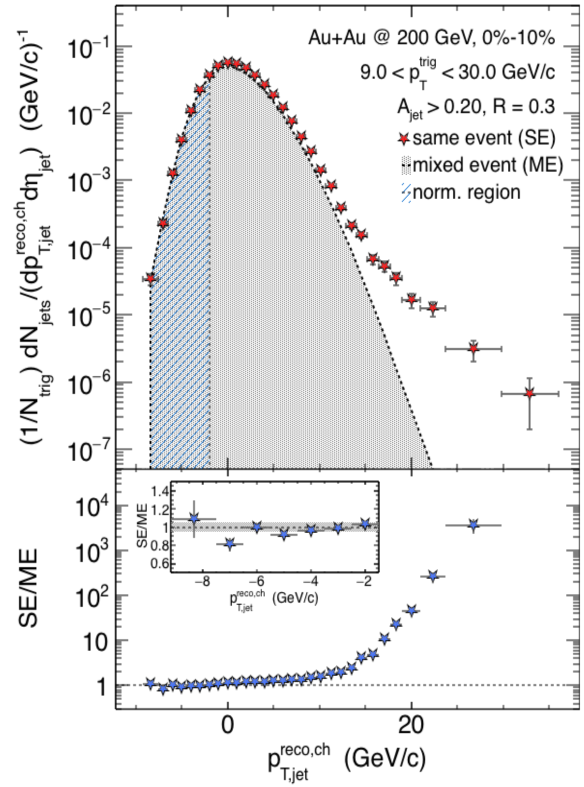
Low $p_{T,trig}$ (TT*[8, 9]) trigger recoil jet spectrum as a reference (dominated by combinatorial jet).
High $p_{T,trig}$ (TT[20, 50]) trigger recoil jet spectrum mainly from hard (high Q^2) process (signal).
Δ_{Recoil} is defined as the difference of these two spectra to remove bkg and uncorrelated component.

* TT for triggered track



$p_{T,jet}$ < 20 GeV/c:
Shape does not change with $p_{T,trig}$
➔ Combinatorial background

$p_{T,jet}$ > 20 GeV/c:
Recoil jet spectrum evolves with $p_{T,trig}$

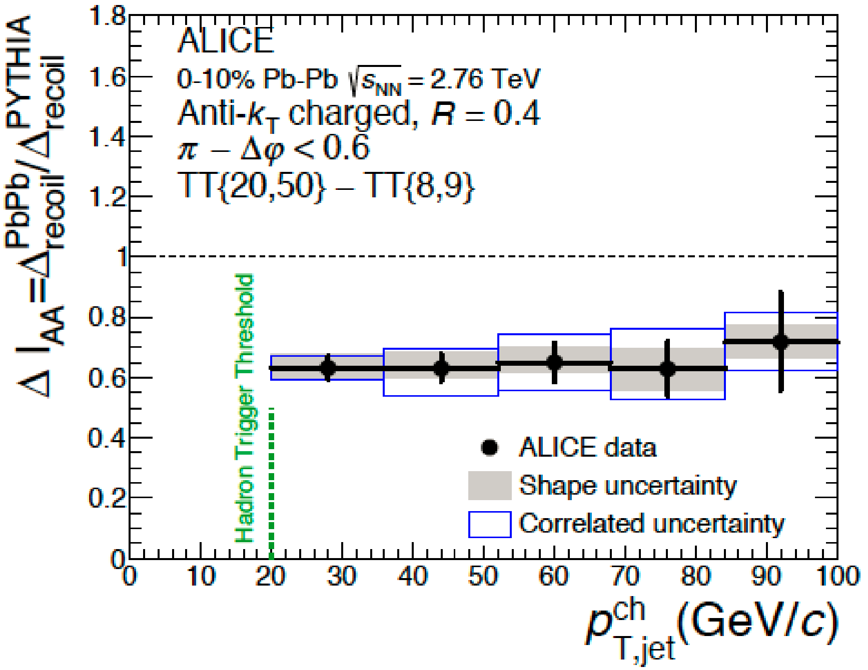


STAR: Mixed events describe the combinatorial background
➔Trigger-correlated jet distribution: subtract ME from data
Comparable to ALICE h+jet

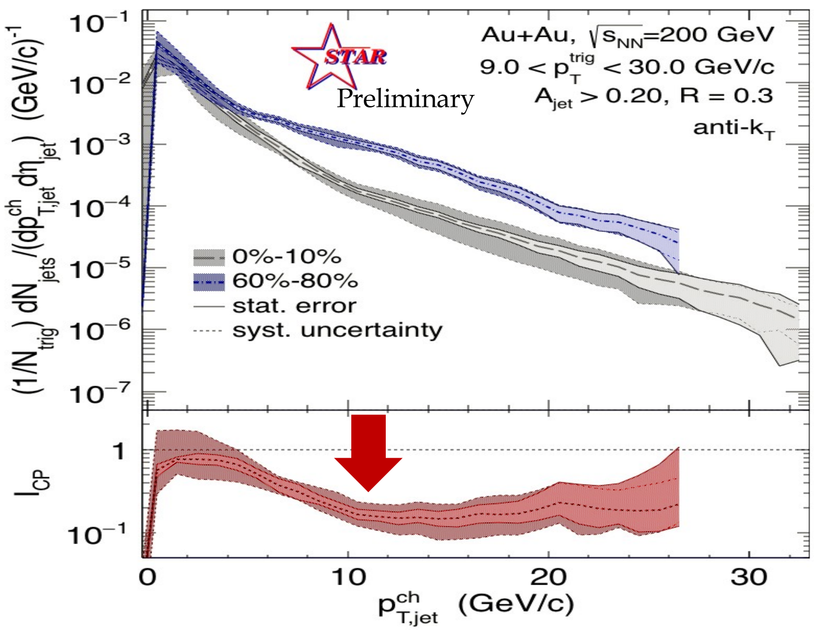
Hadron-jet correlations at RHIC

ALICE

arXiv:1506.03984



STAR



STAR: Nuclear modification factor "I_{CP}":

- close to 1 at low p_T
- large suppression at p_T > 10 GeV/c: I_{CP} ~ 0.2

ALICE: Recoil jet yields are suppressed (~0.6) (conditional yield) independently of R and slowly decreases with jet p_T

Larger suppression at RHIC compared to LHC

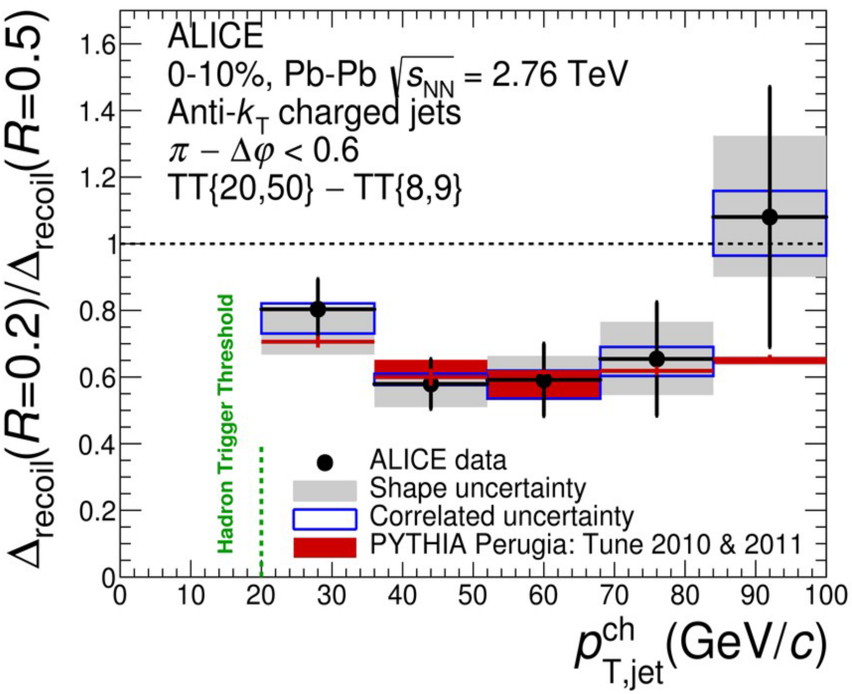
However: different kinematics and cuts

Constant ΔE ~ 8 GeV

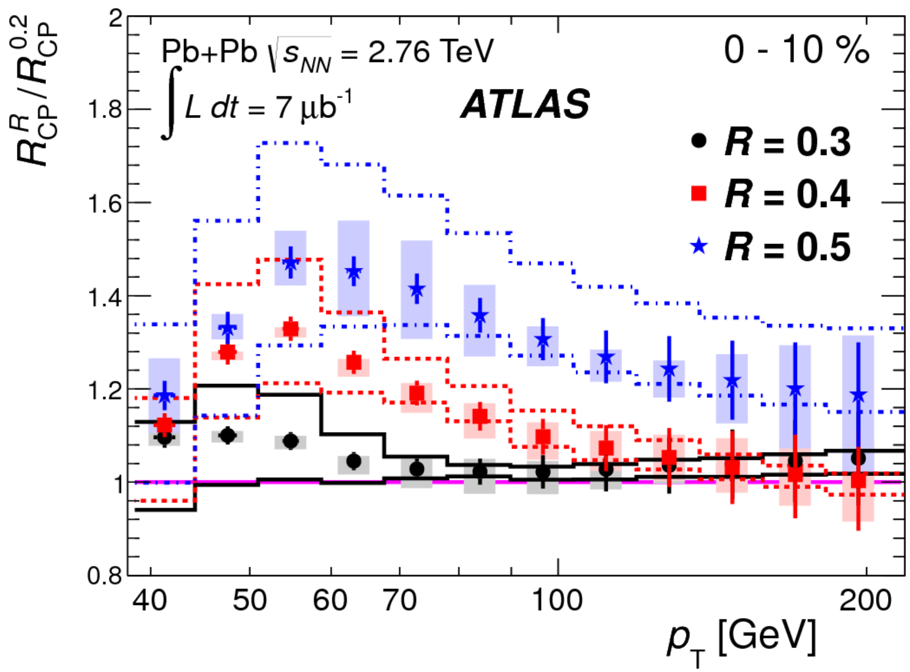
Cone size dependence

First step towards measuring internal jet structure
Measure jets with different resolution parameters

ALICE: 1506.03984



ATLAS: Phys. Rev. C 86, 014907 (2012)



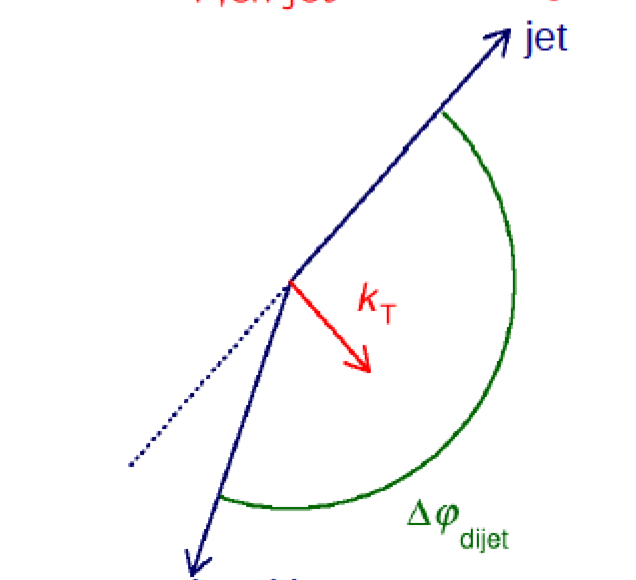
No evidence for jet broadening for R<0.5

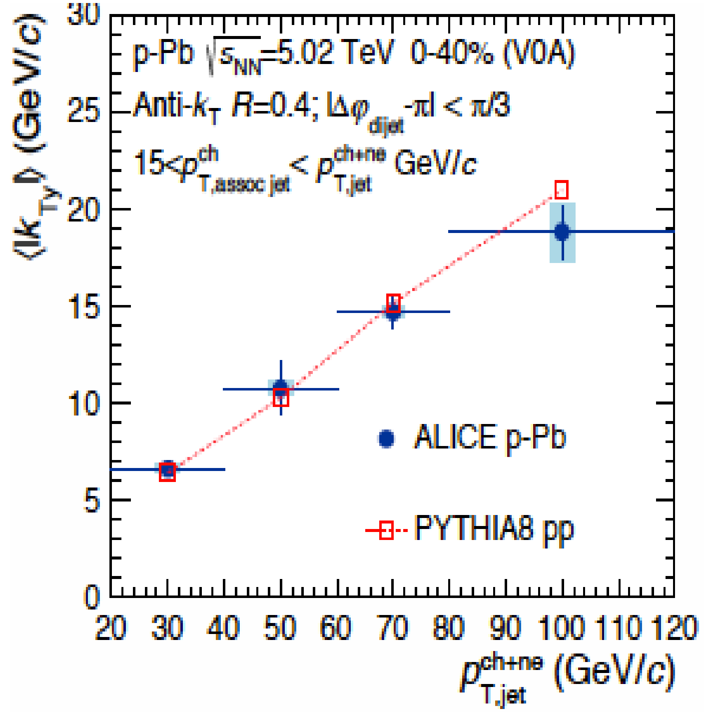
Excess observed for R=0.5

Jet acoplanarity:Inter jet broadning in p-Pb

Sources of acoplanarity in pp: intrinsic k_T, 3-jet events, hard FSR, ISR
Additional sources in p-Pb: interaction of the partonic projectile with the nuclear medium.

$$k_T = p_{T,\mathrm{ch\ jet}}^{\mathrm{trigger}} \sin(\Delta\varphi_{\mathrm{dijet}})$$





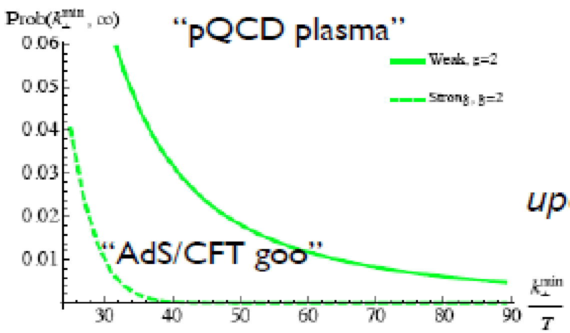
STAR: small k_T broadning

ALICE : charged jets

No modification of di-jet k_T

medium induced acoplanarity

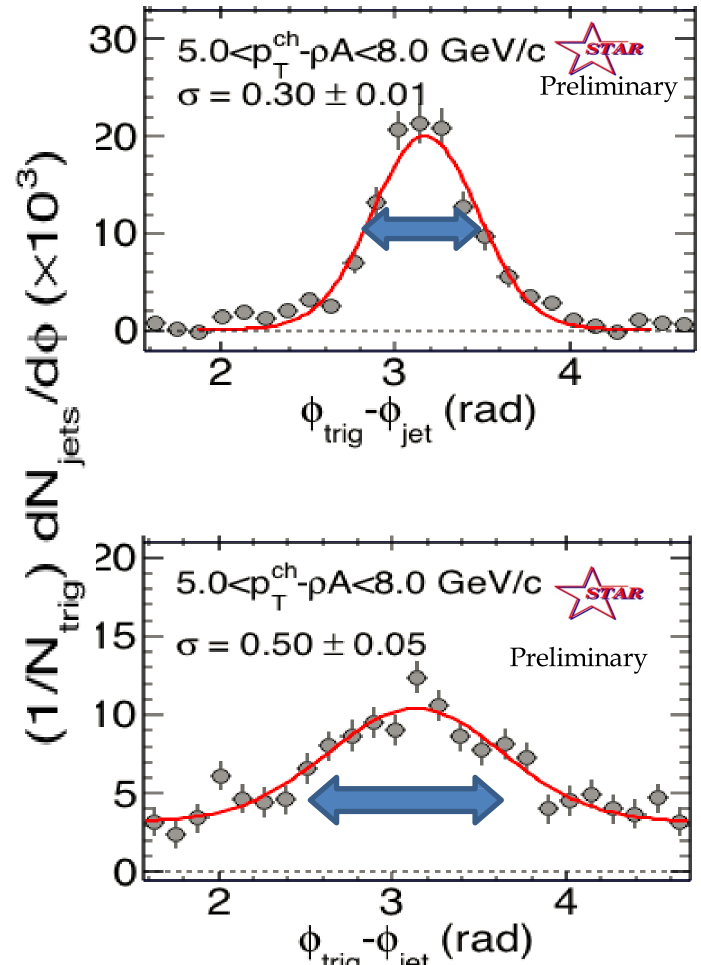
Large angle inter-jet scattering

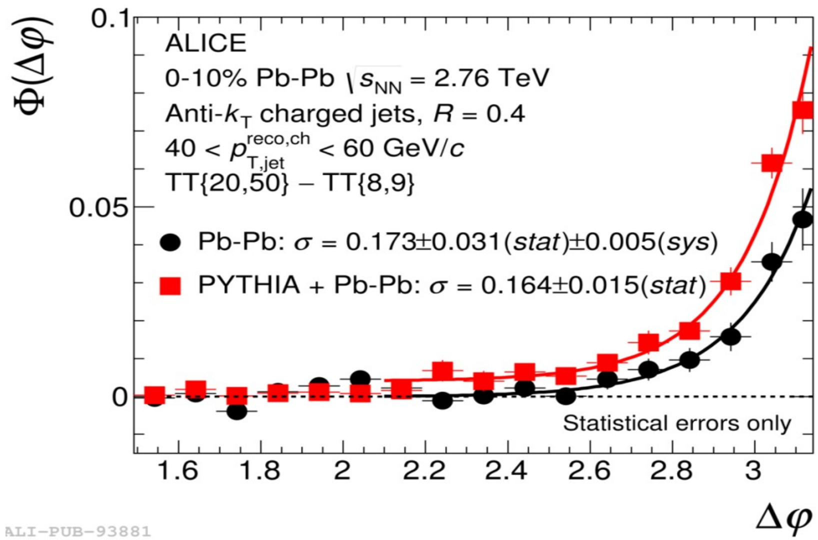


D'Eramo, Rajagopal, '12
updated calculation underway

ALICE : Width (σ) consistent in Pb+Pb with PYTHIA embedded data

➔ No evidence of medium-induced acoplanarity of recoil jets



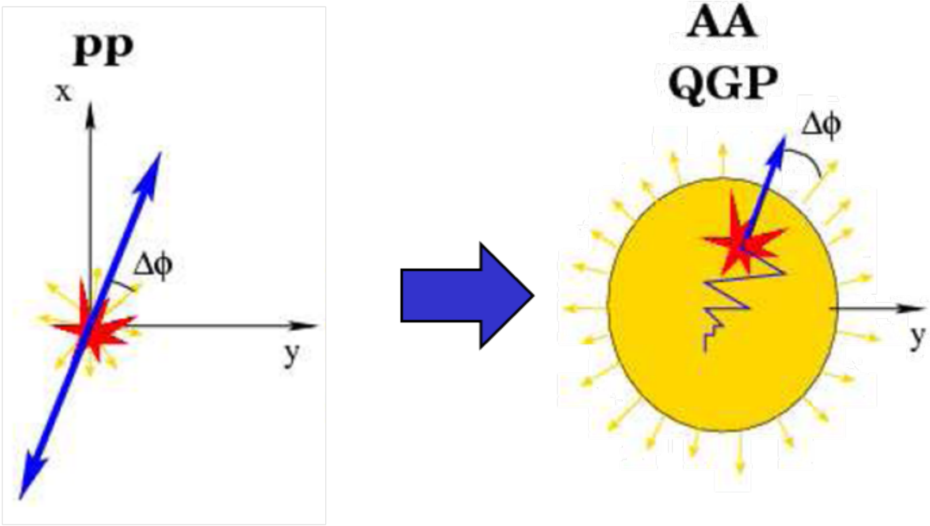


STAR: High-p_T trigger: no broadening with central

Low-p_T trigger: broadening with centrality

➔ Broadening in central collisions at RHIC for very low pt jets? Work ongoing

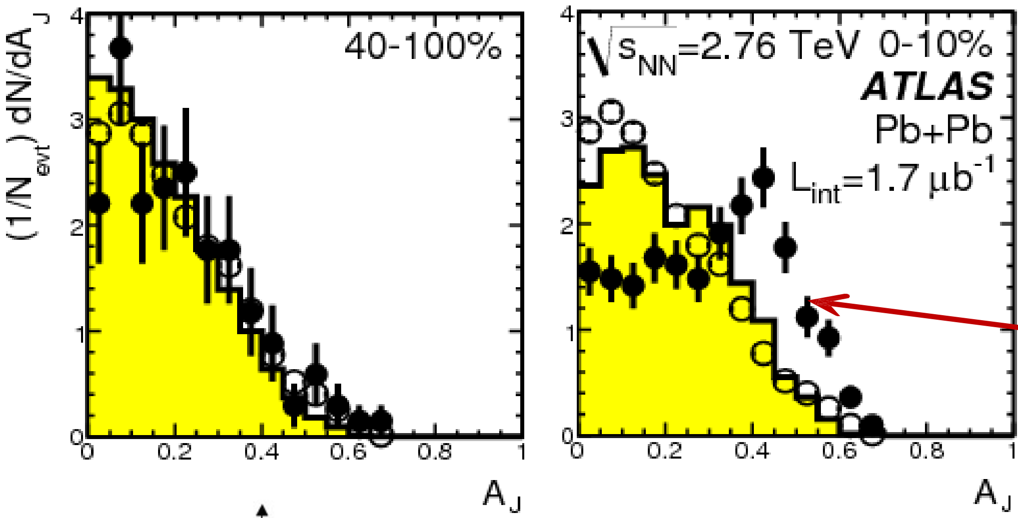
Di-jets Asymmetry



$$A = \frac{(pT_1 - pT_2)}{(pT_1 + pT_2)}$$

Di-jet asymmetry in Pb+Pb collisions

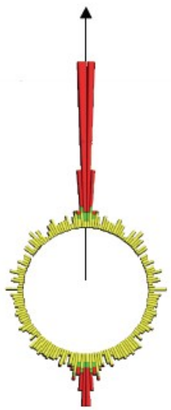
ATLAS: *PRL 105 (2010) 252303*

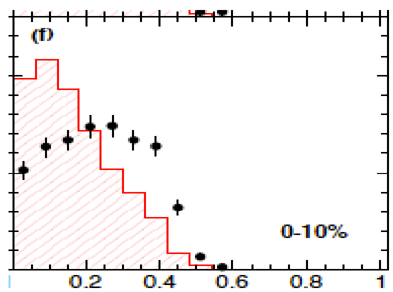


First heavy ion jet measuments at LHC

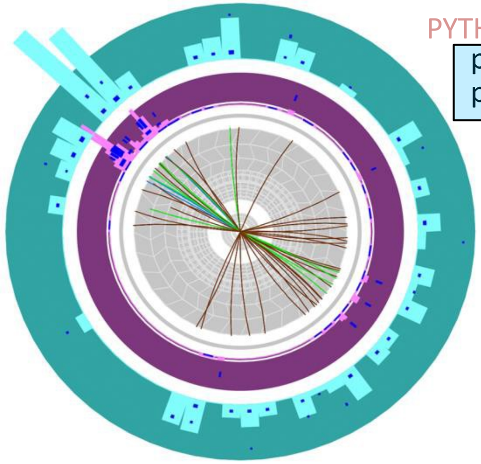
$$A = \frac{(pT_1 - pT_2)}{(pT_1 + pT_2)}$$

di-Jet asymmetry observed in central Pb+Pb collisions by ATLAS and CMS



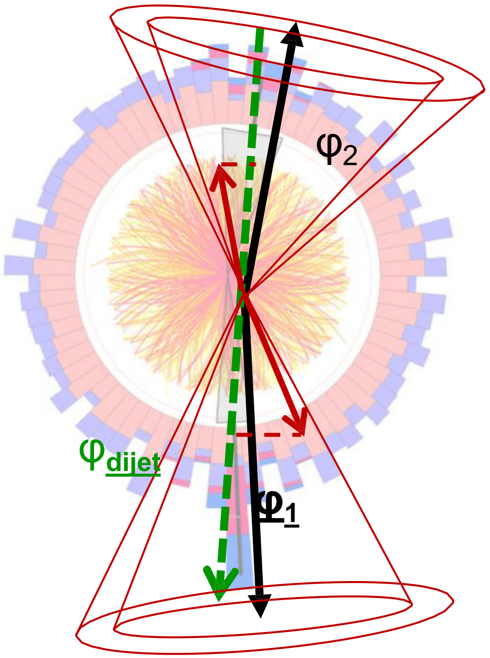


CMS: PRC 84 (2011)024906

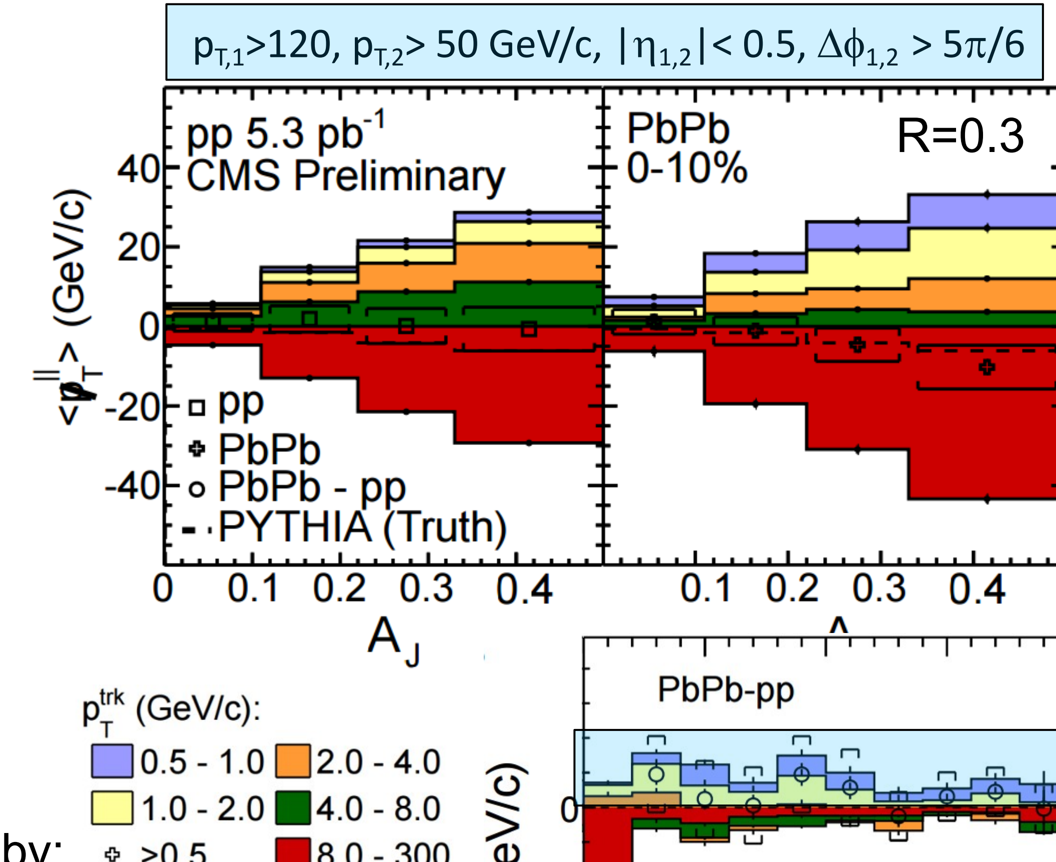


Assymetry : **Probing** differences in quenching **between the two parton showers**

CMS: Where did the energy go?



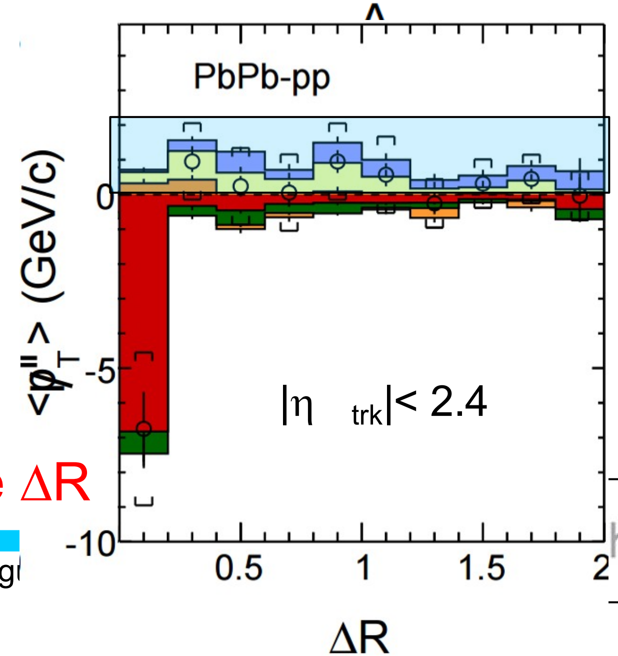
courtesy Y. J. Lee (CMS)



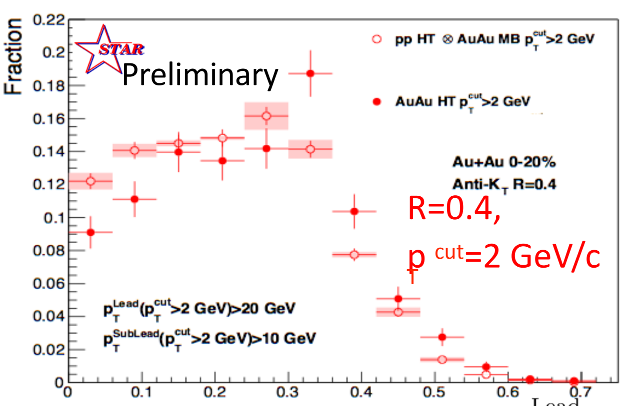
Missing p_T

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

- increases with A_J and is balanced by:
  - 2-8 GeV/c particles in pp
  - p_T < 2 GeV/c particles in 0-10% Pb+Pb
- high p_T imbalance at small R compensated by low p_T particles in subleading jet direction extending to large ΔR

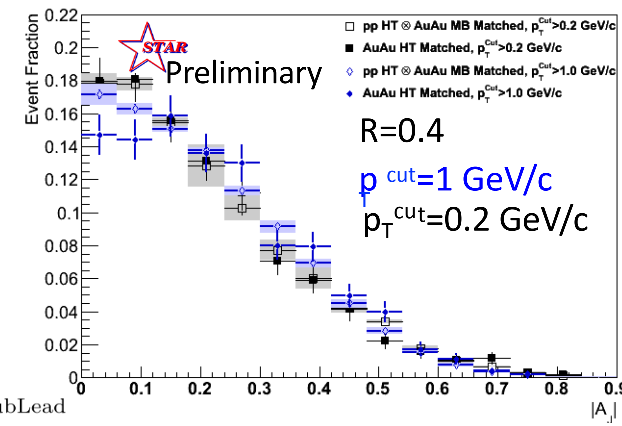


STAR: di-jets: properties of radiated energy



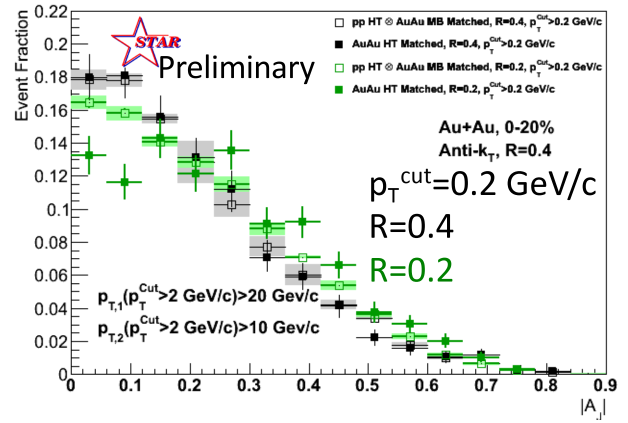
$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$

Imbalanced



Imbalanced

Balanced



Imbalanced

Balanced

Find jet **with high p_T cut on constituents** ➔ reduce combinatorial background
rerun jet finder for identified jets **with looser p_T cut** or different radius

Momentum **balance restored** with R=0.4, p_T^{cut} = 0.2 GeV

Imbalance with:

- increasing p_T^{cut} ➔ Jet softening
- decreasing radius ➔ jet broadening **(between 0.2 and 0.4)**

Different modification of jet structure at RHIC and LHC

BUT **Non negligible jet p_T** biases possibles (cuts & low p_T jets ➔ background ?)

ATLAS: Path length effects on di-jet production

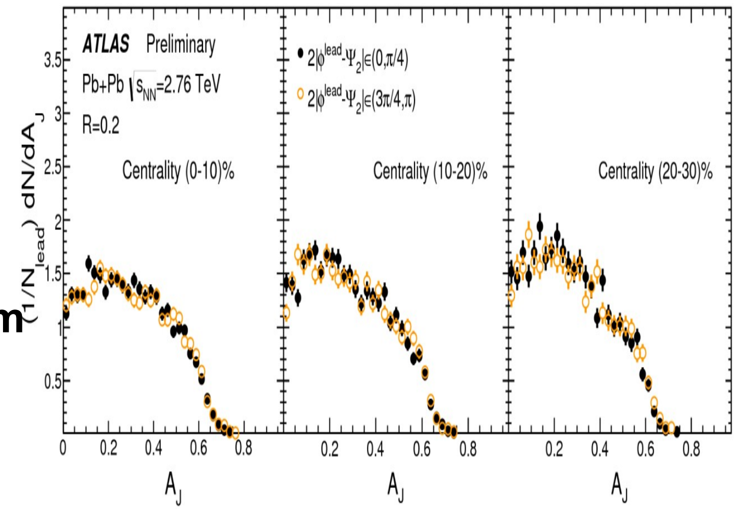
Goal : constrain path length dependence of enrgy loss

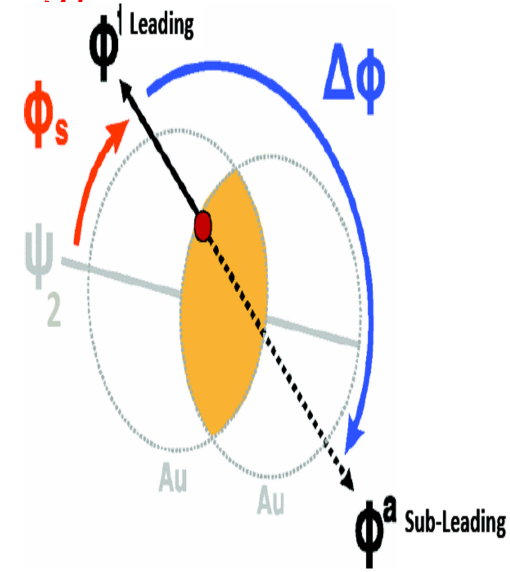
ATLAS-CONF-2015-021

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

Previous study of jet production vs. event plane showed modest path length dependence ($v_{2\ jet}$~2-5%)

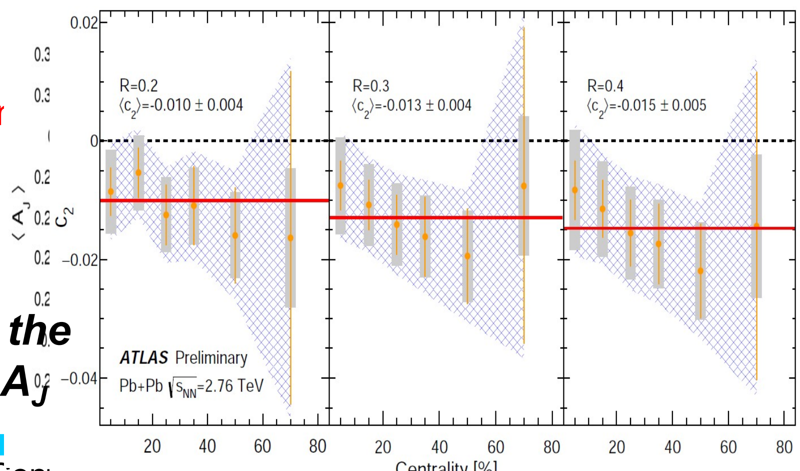
ATLAS: *PRL 111 (2013)152301*





Study un-equal path lengths of the showers in the medium

- Selecting on the angle between the leading jet and 2nd order Event−Plane angle Ψ2, provides control on the path length traversed by the jet pair.
- Jet pairs that are Out−of−Plar are expected to traverse more medium than In−Plane.

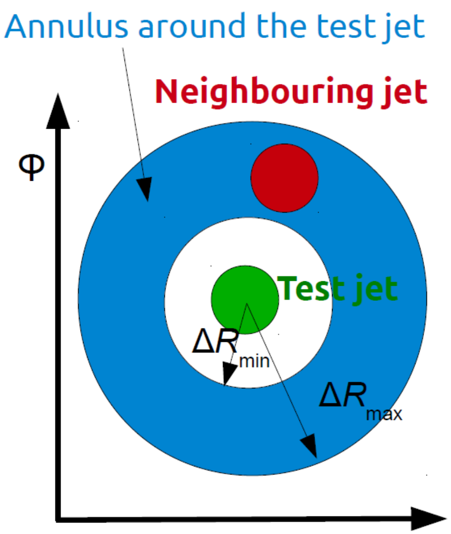


Extract c2 that quantifies the EP angle dependence of A_J

➔ c_2 is small (<2%) and negative

➔ larger A_J for leading jets oriented out-of-plane than for in-plane ones

ATLAS: Neighbouring jet production in Pb-Pb collisions

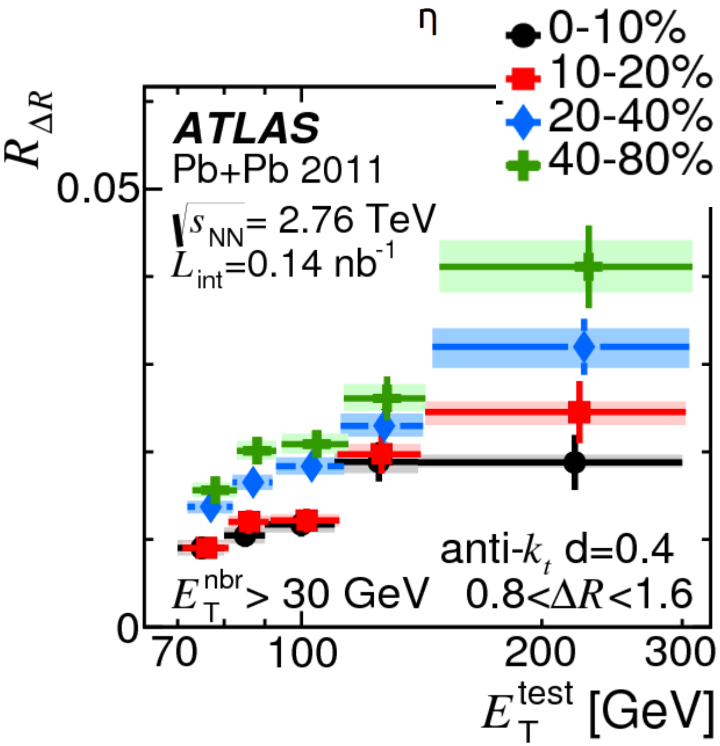


Goal: probe differences in quenching that do no primarily result from difference in path length. (fluctuations of energy loss)

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

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

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



Study its dependence on:

- **E_T of test jet:**

Suppression of neighbouring jet production in central Pb-Pb is:

~ independent of test jet E_T & similar to inclusive jets

- **E_T of neighbouring jet**

Nuclear modification factor for neighbouring jets approaches 1 when $E_{T\,test} \approx E_{t\,nbr}$

Fragmentation Functions

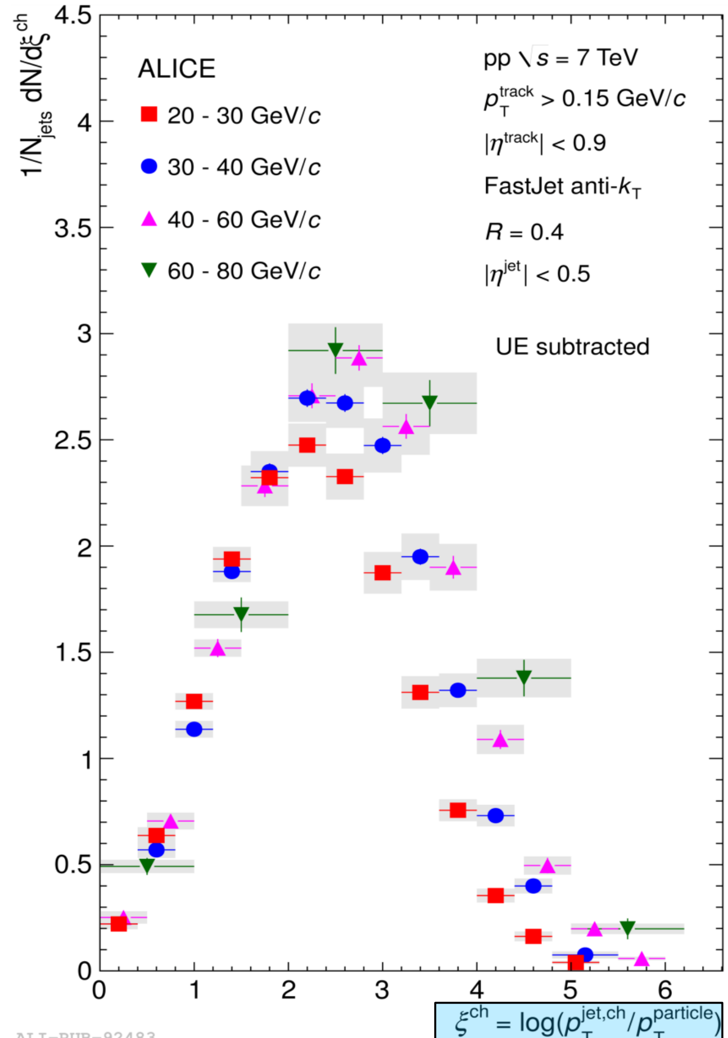
Study the momentum distribution of tracks in jets

ALICE:Jet fragmentation functions in pp

arXiv:1411.4969

- Charged jets in pp collisions @ 7 TeV:

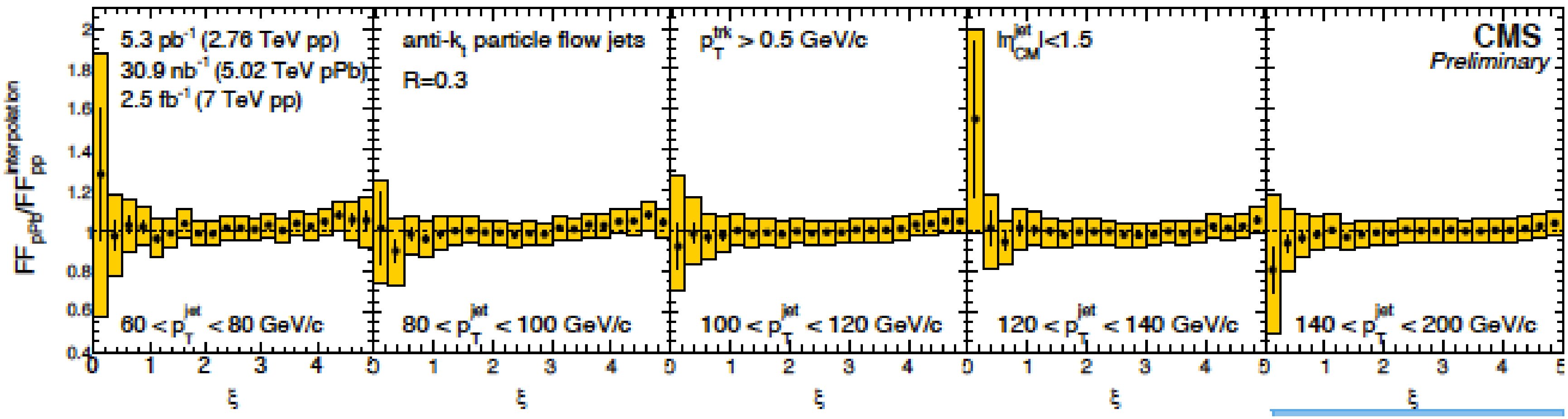
For **ξ < 2 scalling**
At higher ξ , maximum :'**hump-backed plateau' ➔ suppression of low momentum particle** production by QCD coherence
With **increasing jet pT,** the **area** of the distributions **increases (higher** particle **multiplicity** in jets),
maximum shifts to higher values of ξ
This observation is in qualitative agreement with **MLLA**

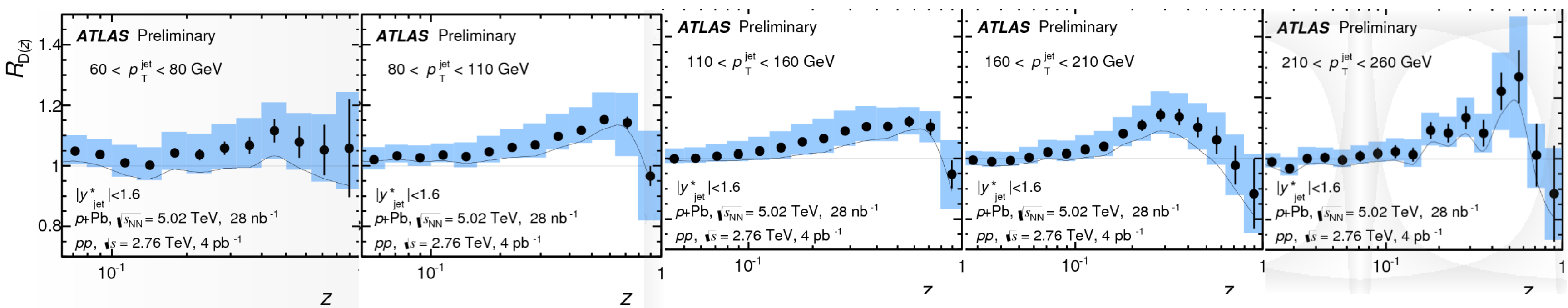


Measurement challenging in Pb-Pb collisions (large heavy ion background and fluctuations).

CMS/ATLAS: FF in pA

Reduce background ➔ high p_T jets needed



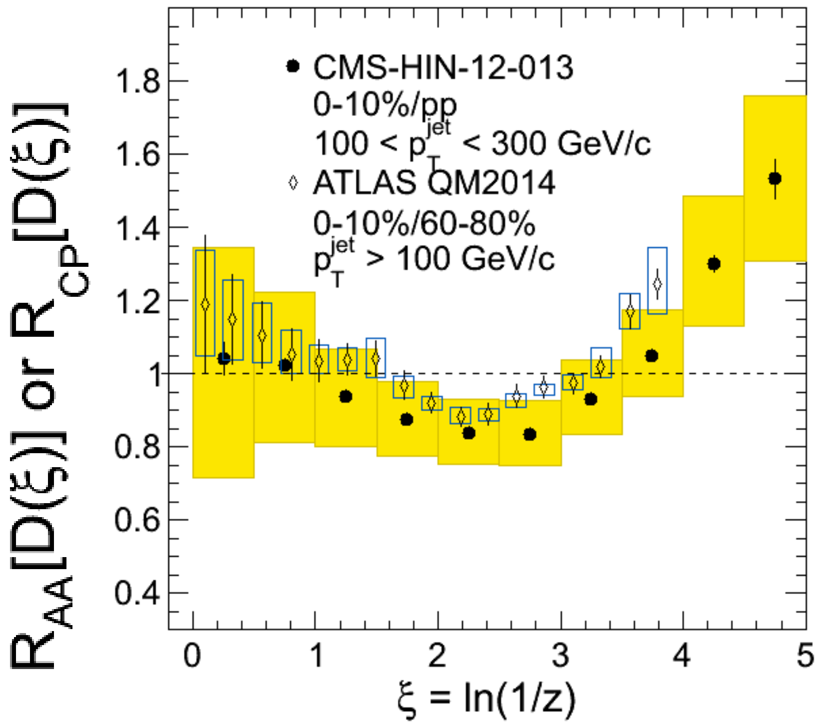


CMS: no modification of fragmentation functions (within uncertainties). Coherent with R_{pPb} (jets)=1 if R_{pPb} (charged) will move to ~1

ATLAS: suggestion for a hardening of the FF

➔ Also commes from the interpolation method used for the pp reference ?

FF in PbPb



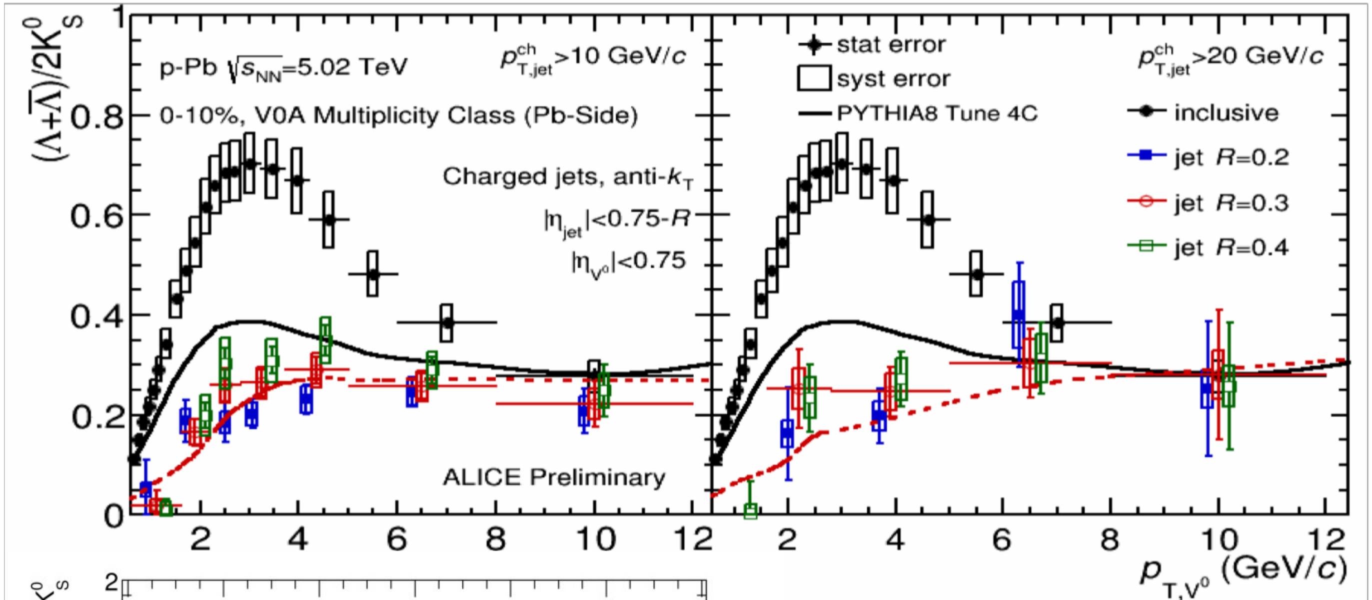
Z = p||Trk / pJet

Qualitative agreement between ATLAS and CMS
Small modifications:
Depletion from 3-4 GeV to 40-50 GeV (2-3% of the total jet energy)
Enhancement below 3-4 GeV (~ 2% of the jet energy)
➔ Need to improve systematics

Exclusive measurements

Strange particle production in jets

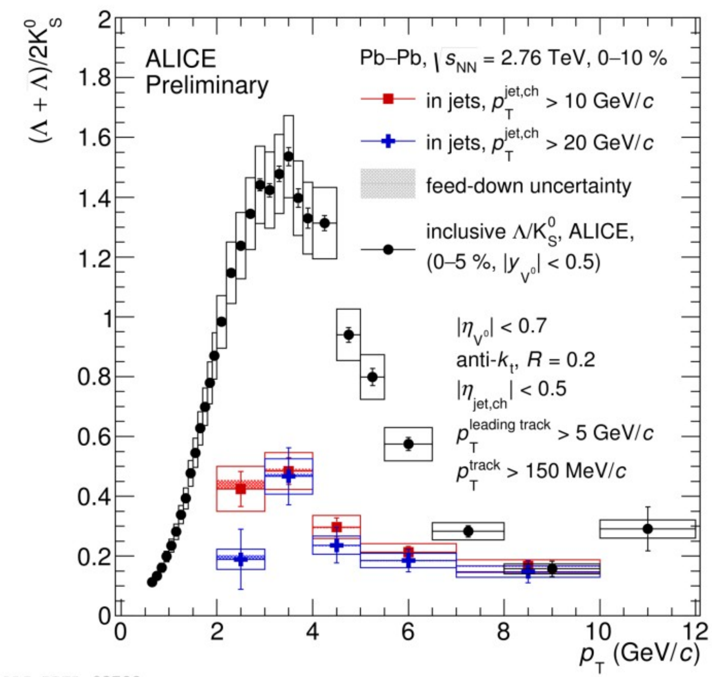
$p_{T,\,jet}$> 10 GeV/c $p_{T,\,jet}$> 20 GeV/c



V0s in PYTHIA

inclusive

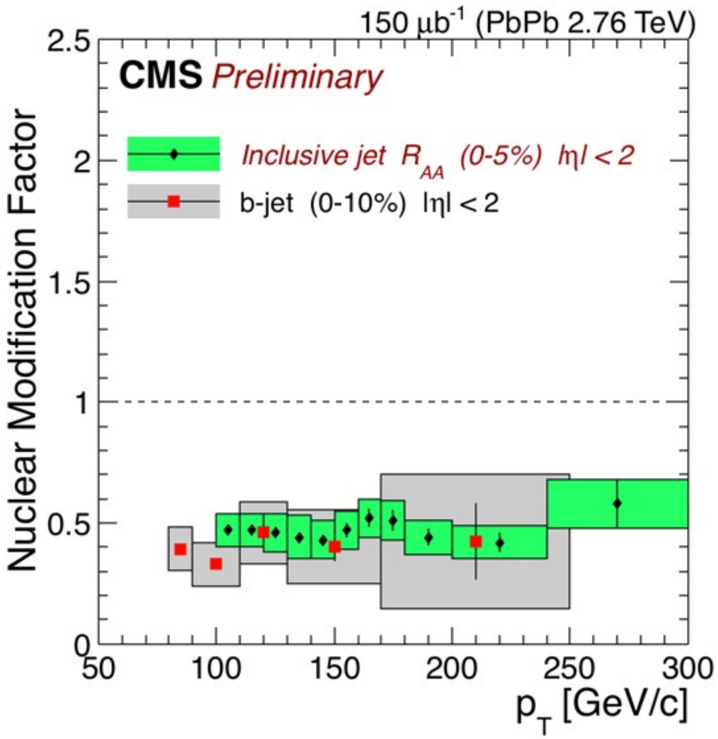
in jets (R=0.3)



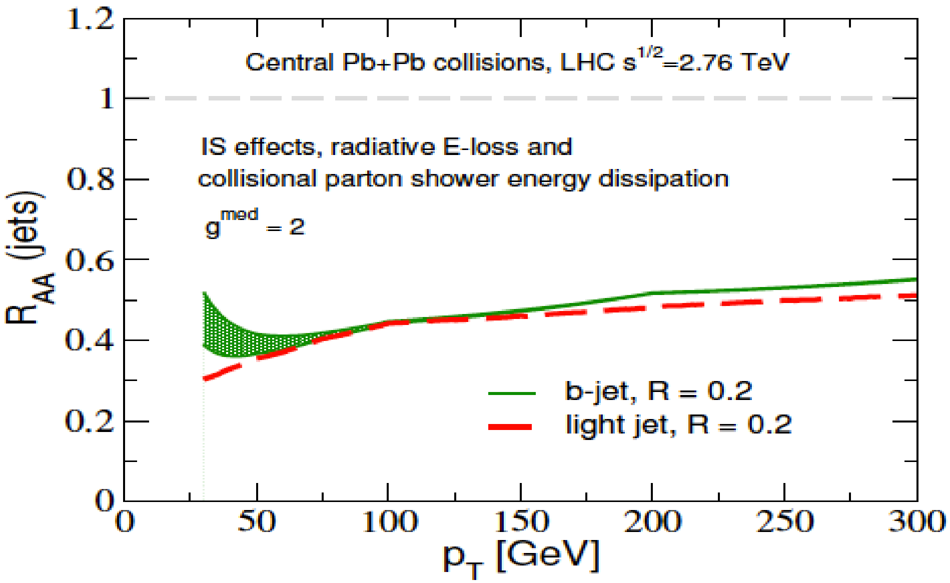
Λ/K^0 ratio in charged jets in p-Pb and Pb-Pb are significantly lower than for inclusive particles

➔Jet composition is not influenced by the enhanced baryon/meson production in the bulk.

B-jets



PRL 113 (2014) 132301



b-jet R_{AA} decreases with centrality down to ~0.4 in 0-10%

Similar suppression to inclusive jets for p_T>80 GeV/c

➔ Mass effects might appear at lower p_T

Summary

A lot of results on jets from both LHC RUN 1 and RHIC

→In general good consistency between experiments

More **differential observables** are needed in order to better understand and constrain energy loss mechanisms

Theory / Experiments comparisons are very important
→Are we really comparing the same observables ?
→ Interactions between theorists / experimentalists are crutial.

Outlook

The LHC run 2 is just starting… (STAR / ALICE upgrades)

- Increased luminosity ➔ more statistics will be availible
- Redo Run 1 measurements to reduce the systematics incertenties
- new observables are under study (ex PID in jets, HF jets, quark / gluon jets tagging, sub-jets, …

➔ many new exiting results **are expected soon** ➔ Stay tuned !

Backup

How much energy is lost ?

- Jets are very collimated in pp slightly less so in PbPb
- Modification of energy within the jet is 1-2 GeV
- Significant fraction of jet's energy is lost
  - Suppression of semi-inclusive jets: 8 GeV
  - Dijet asymmetry: 10-20 GeV [1107.1964]