Jet physics at LHC
(experimental overview and perspective)

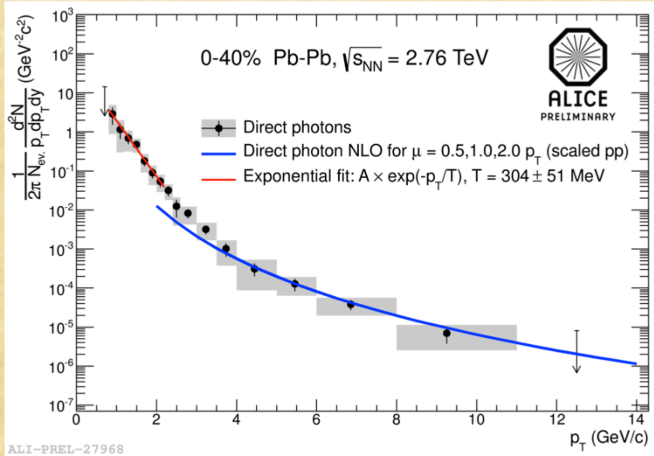
Nagoya Mini-Workshop 2012
"Phenomenology and Experiments at RHIC and LHC"

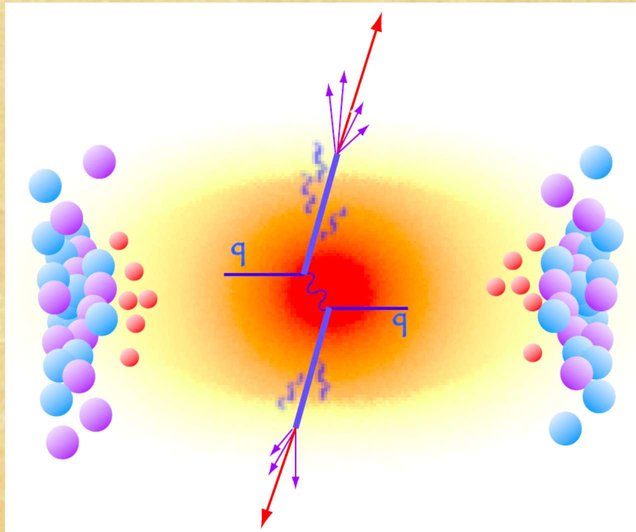
Tatsuya Chujo (Univ. of Tsukuba)
2012.09.25, Nagoya University

Jet physics at LHC

- Jet: an ideal probe for the **precision** measurements of hot and dense medium originated from known interaction (= hard scattering).
- At LHC:
  1. High statistics jet data.
  2. Variety of probes associated jets.
     - interacting/ non-interacting with medium.
     - single jets, di-jets, three-jets, γ-jet, Z-jet
  3. “Control” experiment.
     - e.g. path length (or hard scattering point)
  4. Jet-medium “response”.
     - jets strongly interact with medium.

     → modification of QGP itself (?), fate of lost energy.



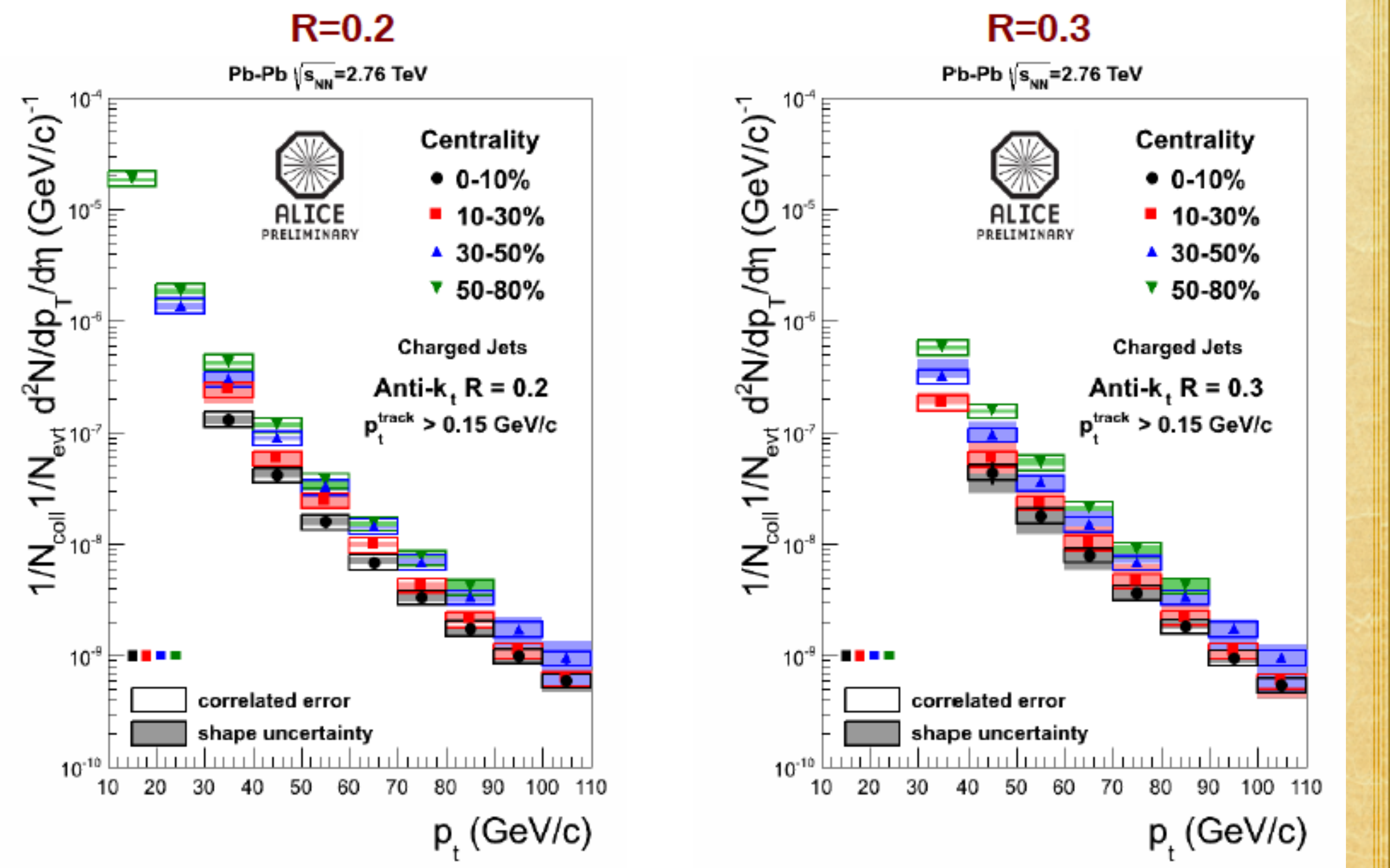


Outline

1. Jet suppression
2. Fragmentation function, jet shape, jet chemistry
3. Di-jet
4. Jet v_2
5. γ– jet, Z-jet
6. Di-hadron correlations
7. Outlook
8. Summary

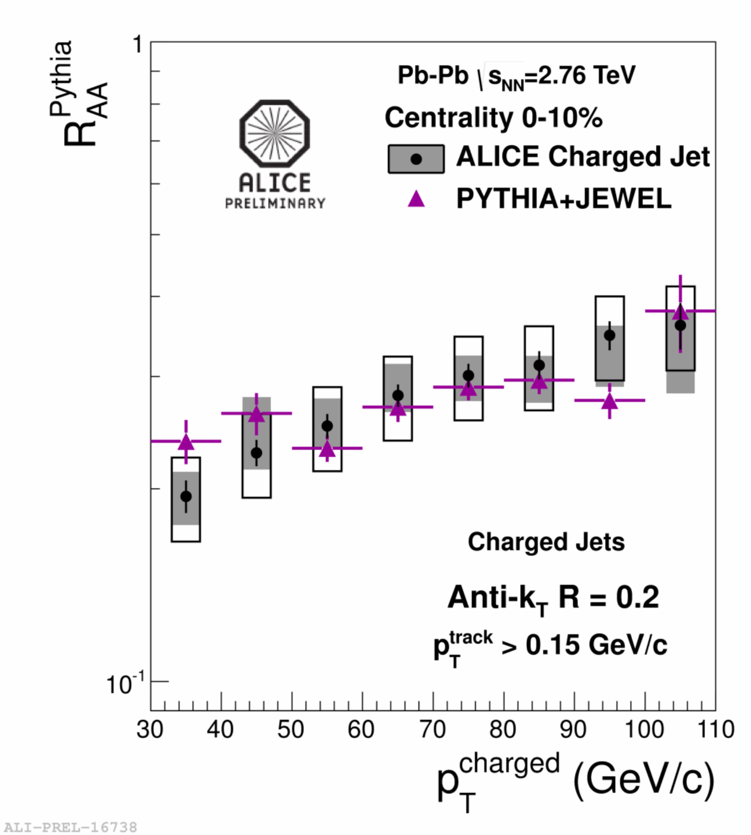
1. Jet suppression

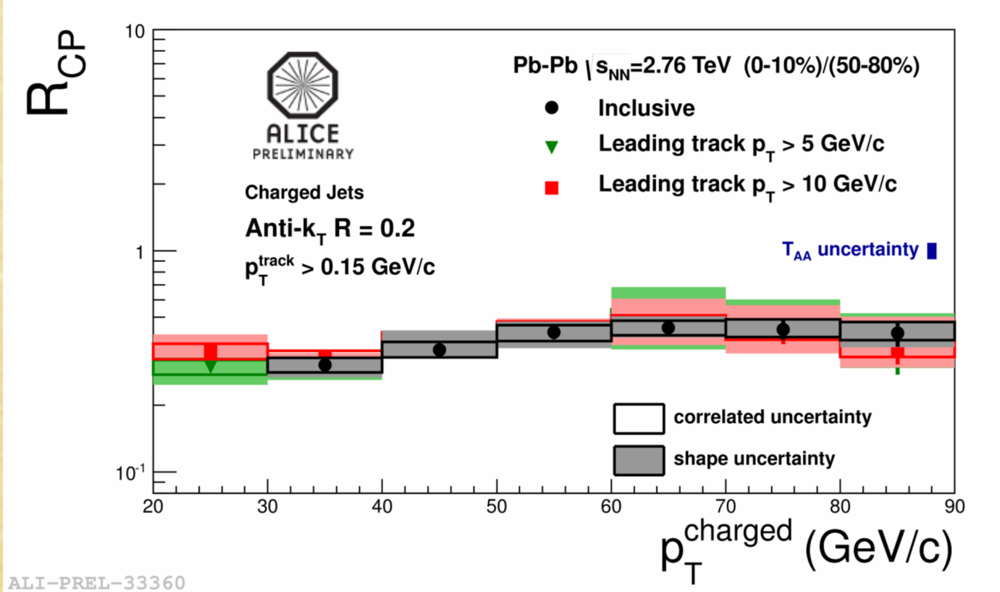
Pb-Pb jet spectrum (charged)



Jet spectra have been measured for 2 cone radii and 4 centrality bins

Charged jet R_{AA} and R_{CP}





Strong jet suppression observed for jets reconstructed with charged particles
– R_{AA} (jet) is smaller than inclusive hadron $R_{AA}(h^{\pm})$ at similar parton p_T
– data are reasonably well described by JEWEL model
K.Zapp, I.Krauss, U.Wiedemann, arXiv:1111.6838

Jet suppression

arXiv:1208.1967 [hep-ex] Submitted to Phys. Lett.B

First LHC result on jet suppression

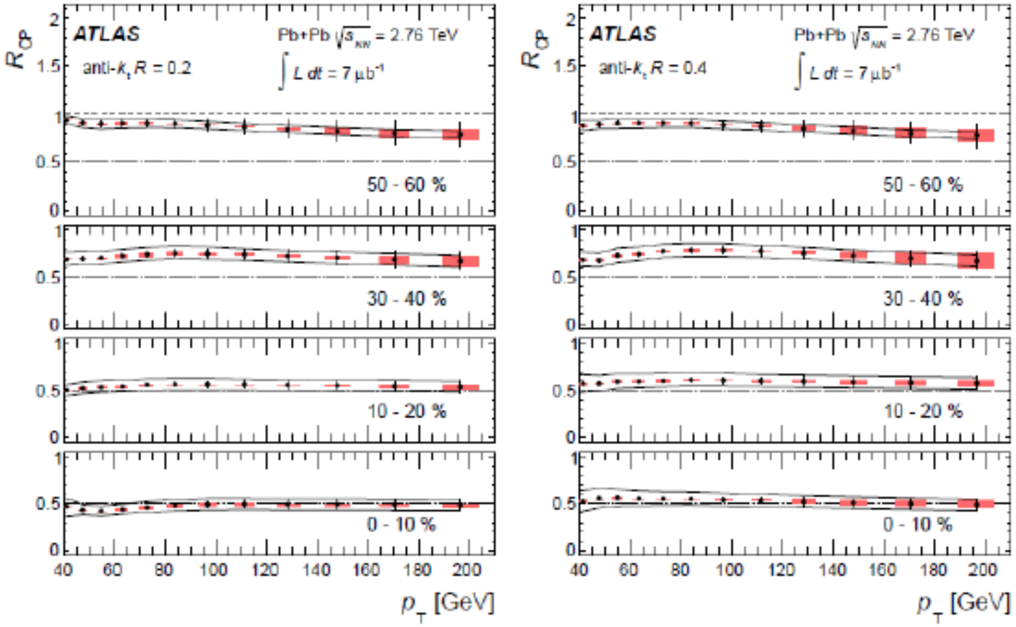
Unfolded p_T spectra

For jet sizes R=0.2, 0.3, 0.4 and 0.5

$$R_{cp} = \frac{\frac{1}{N_{coll}^{cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{coll}^{periph}} E \frac{d^3N^{periph}}{dp^3}}$$

peripheral reference: 60-80%

R=0.2

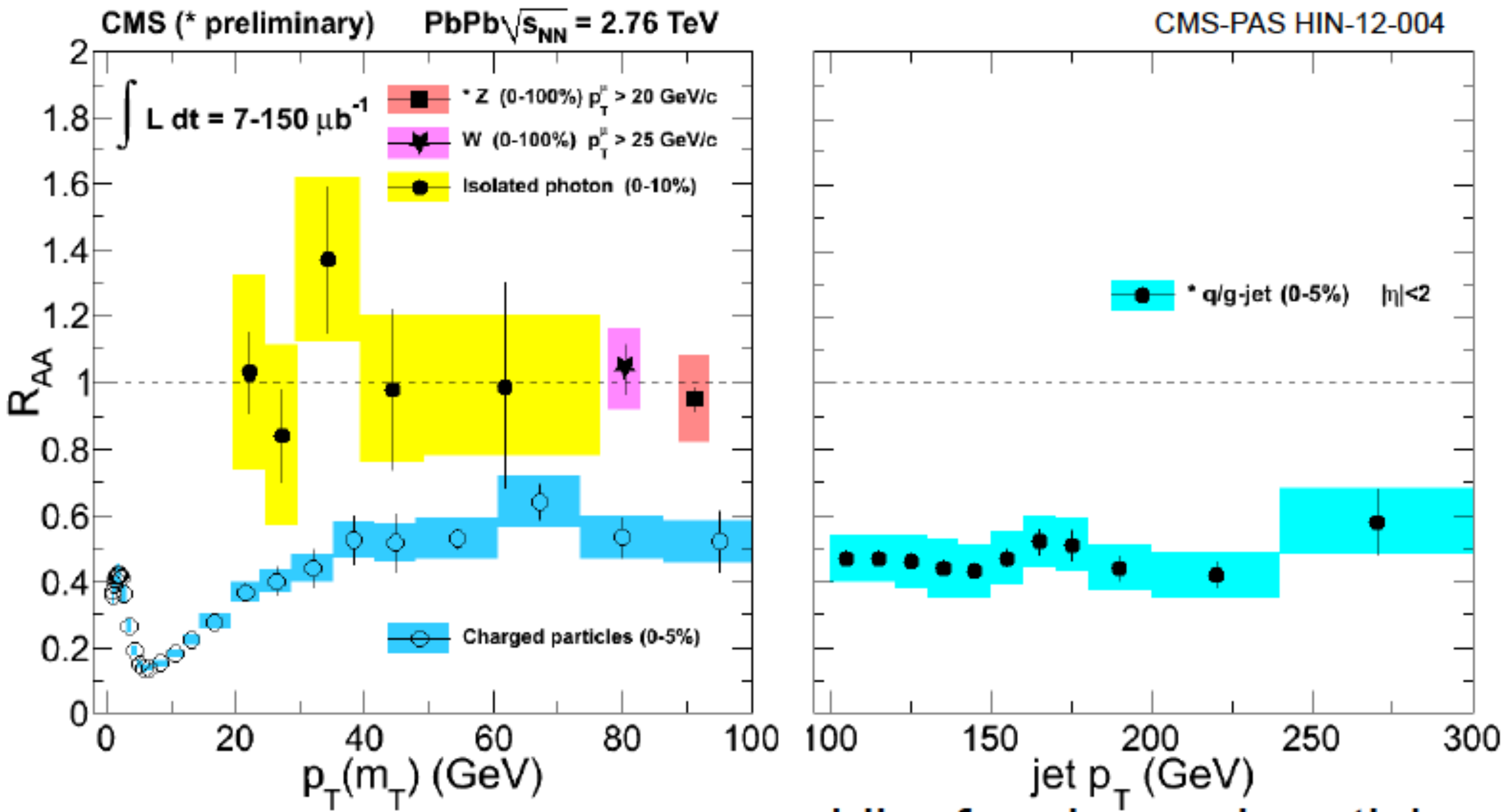


R=0.4

- **A factor of ~2 suppression in 0-10% most central collisions**
- **Suppression independent of jet p_T**

Suppression of inclusive jets

Fully unfolded inclusive jet R_{AA}
pp 2.76 TeV reference



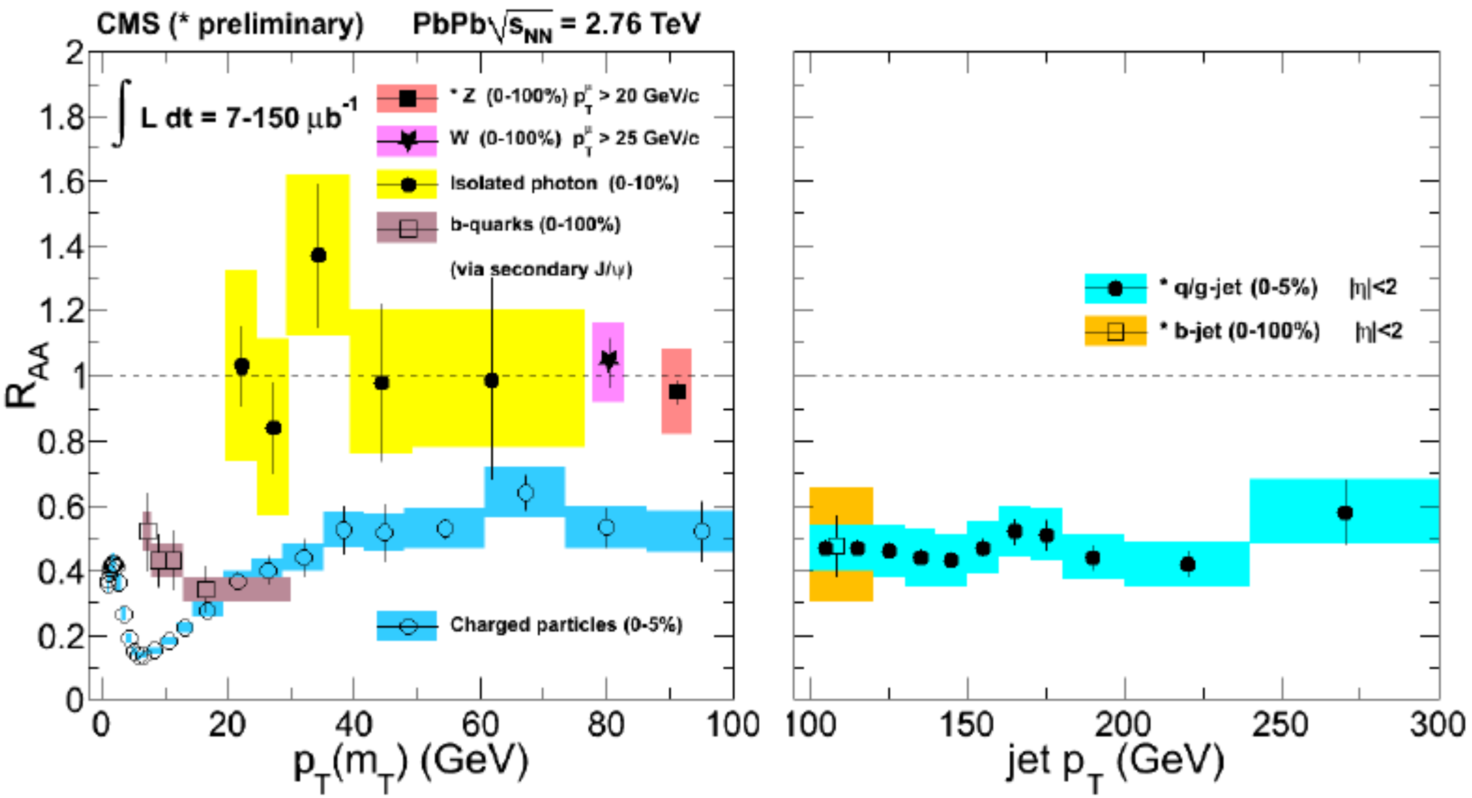
Like for charged particles, high-p_T jet R_{AA} flat at ≈ 0.5

Parton ID: b-quarks

Parallel talk
Mihee Jo (Fri)

Parallel talk
Matt Nguyen (Tue)

Poster
Jorge Robles



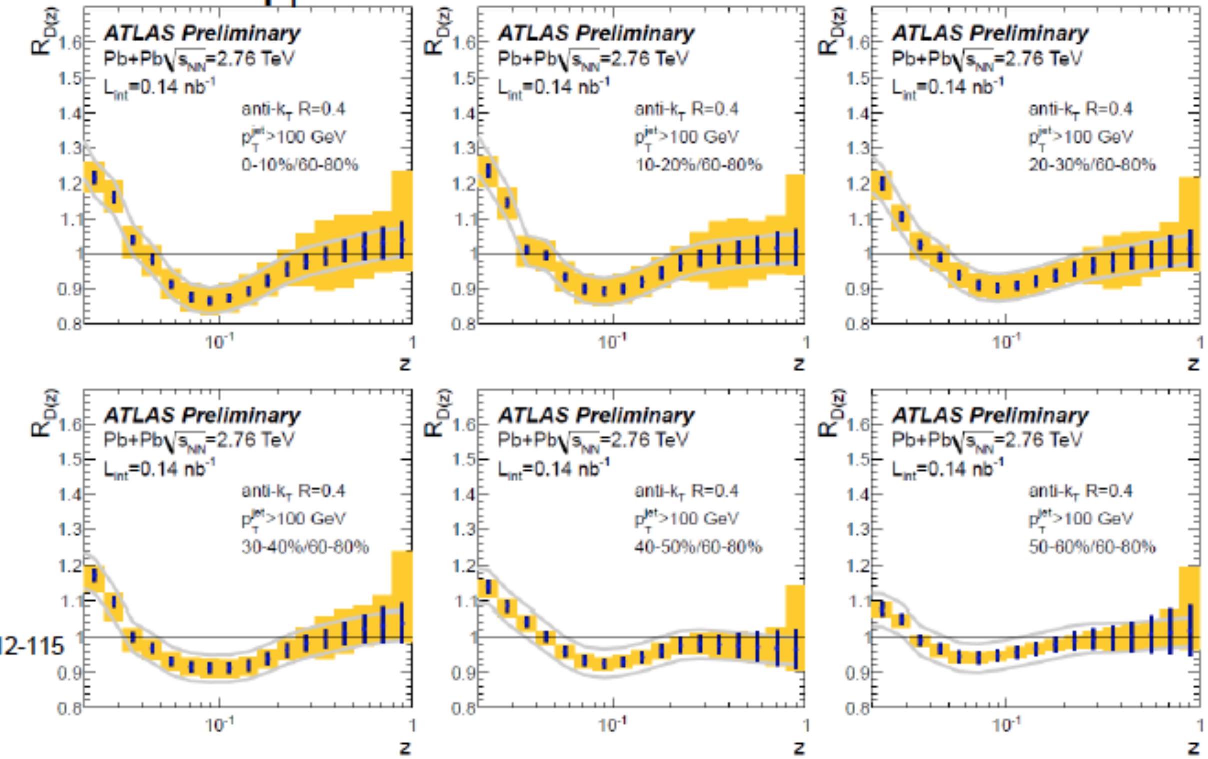
Distinct b-quark suppression pattern at low p_T

First observation of b-jet suppression at high p_T

2. Fragmentation function, jet shape & chemistry

Jet fragmentation

$p_T^{had} > 2\text{GeV}$ $\quad z \equiv \frac{p_T^{had}}{p_T^{jet}} \cos\Delta R$ $\quad R_{D(z)} \equiv D(z)_{cent} / D(z)_{60-80\%}$



ATLAS-CONF-2012-115

- Enhancement at low z, suppression at z≈0.1
- No modification at high z
- Similar results found for R=0.2 and 0.3 jets

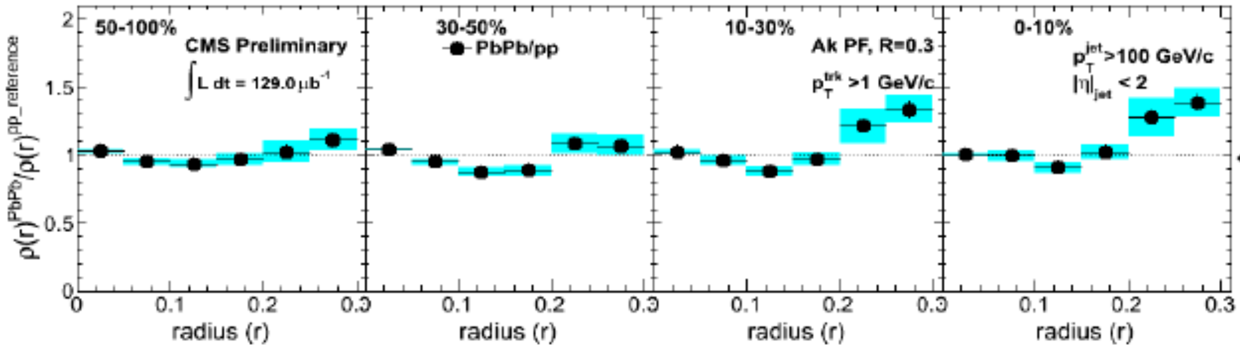
Anatomy of a jet

Ratio of PbPb/pp differential jet shapes

Parallel talk
Pelin Kurt (Wed)

Poster
Yaxian Mao

CMS-PAS HIN-12-013

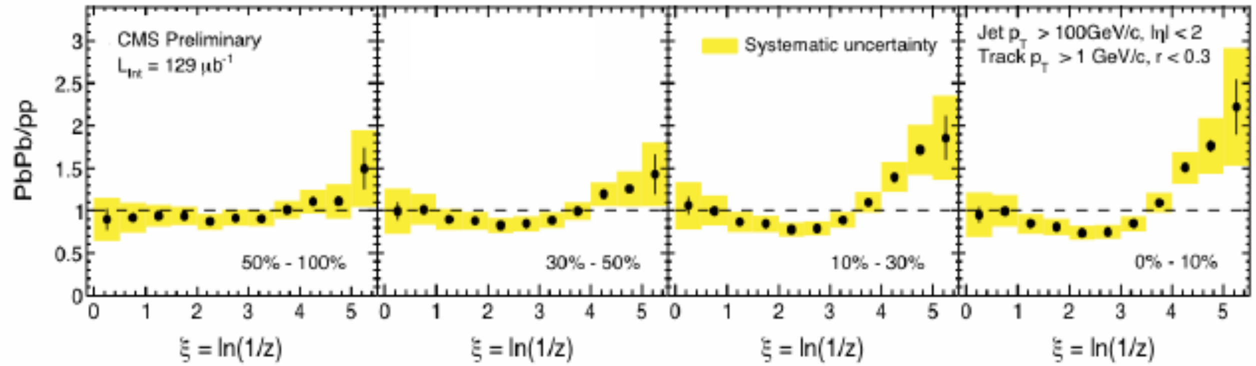


← No medium effect

Ratio of PbPb/pp fragmentation functions

CMS-PAS HIN-12-013

high p_T low p_T

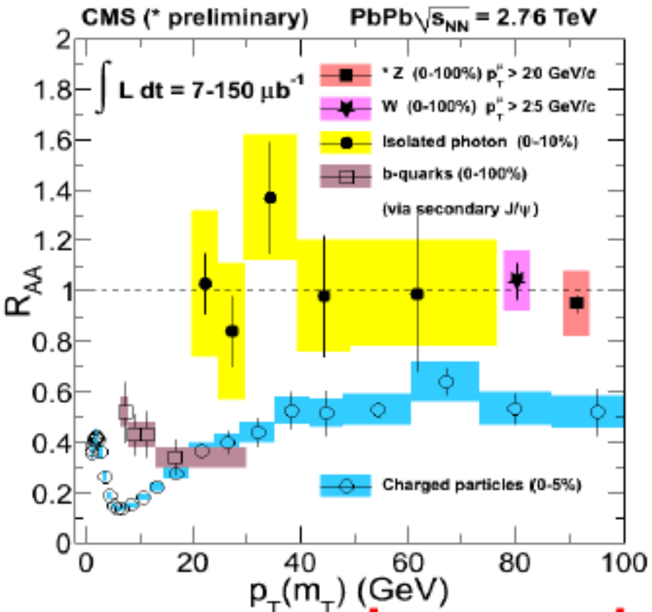


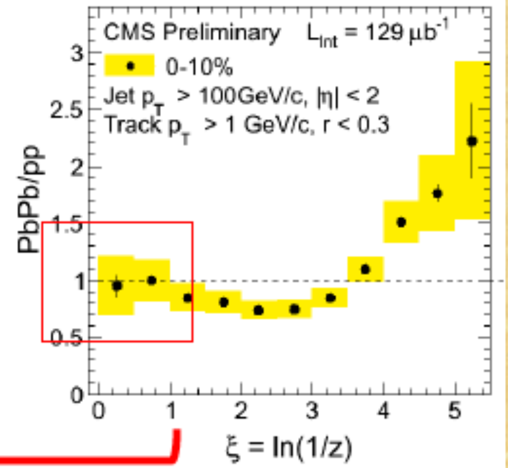
← No medium effect

$z = p_T(\text{track})/p_T(\text{jet})$

Parallel talk
Frank Ma (Wed)

A consistent view of jet quenching





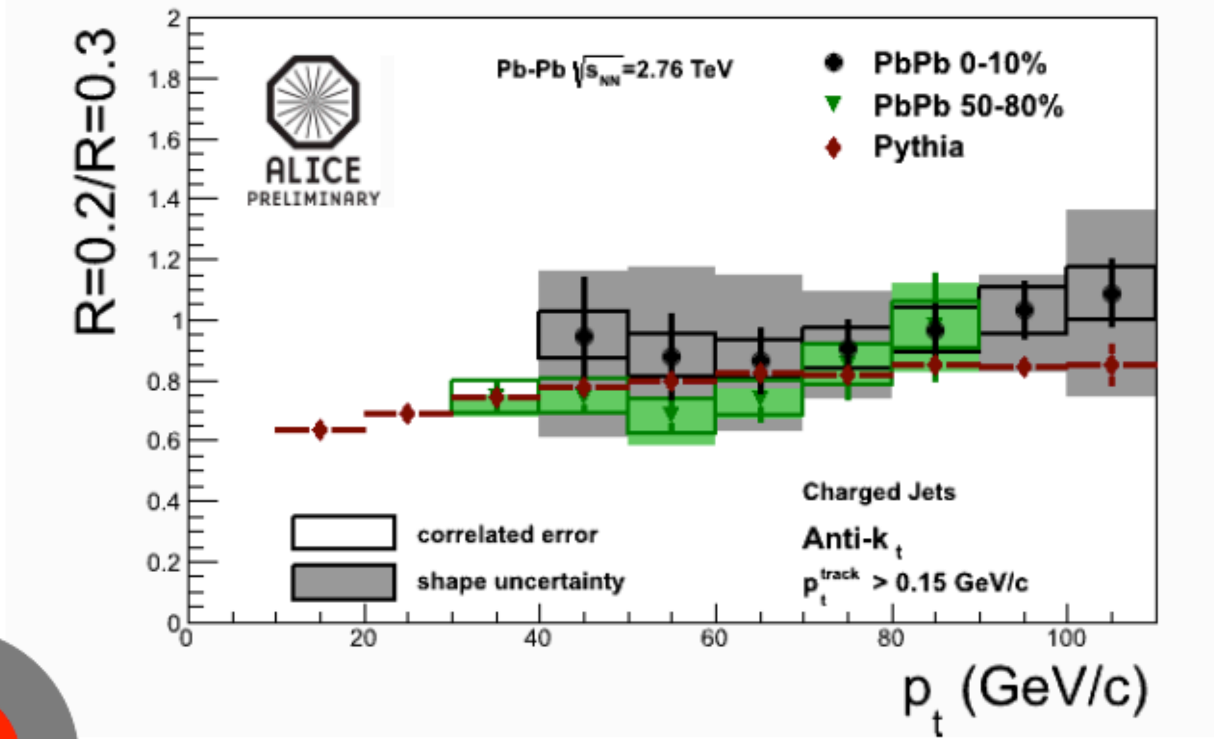
Charged particles from p_T =50-100 GeV:
z = p_T(track)/p_T(jet) = 0.4-0.6
→ ξ < 1

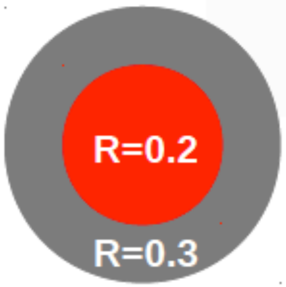
Looking at the same parton p_T range

PbPb fragmentation function = pp for ξ <1

Consistent message from charged hadron R_{AA}, inclusive jet R_{AA} and fragmentation functions!

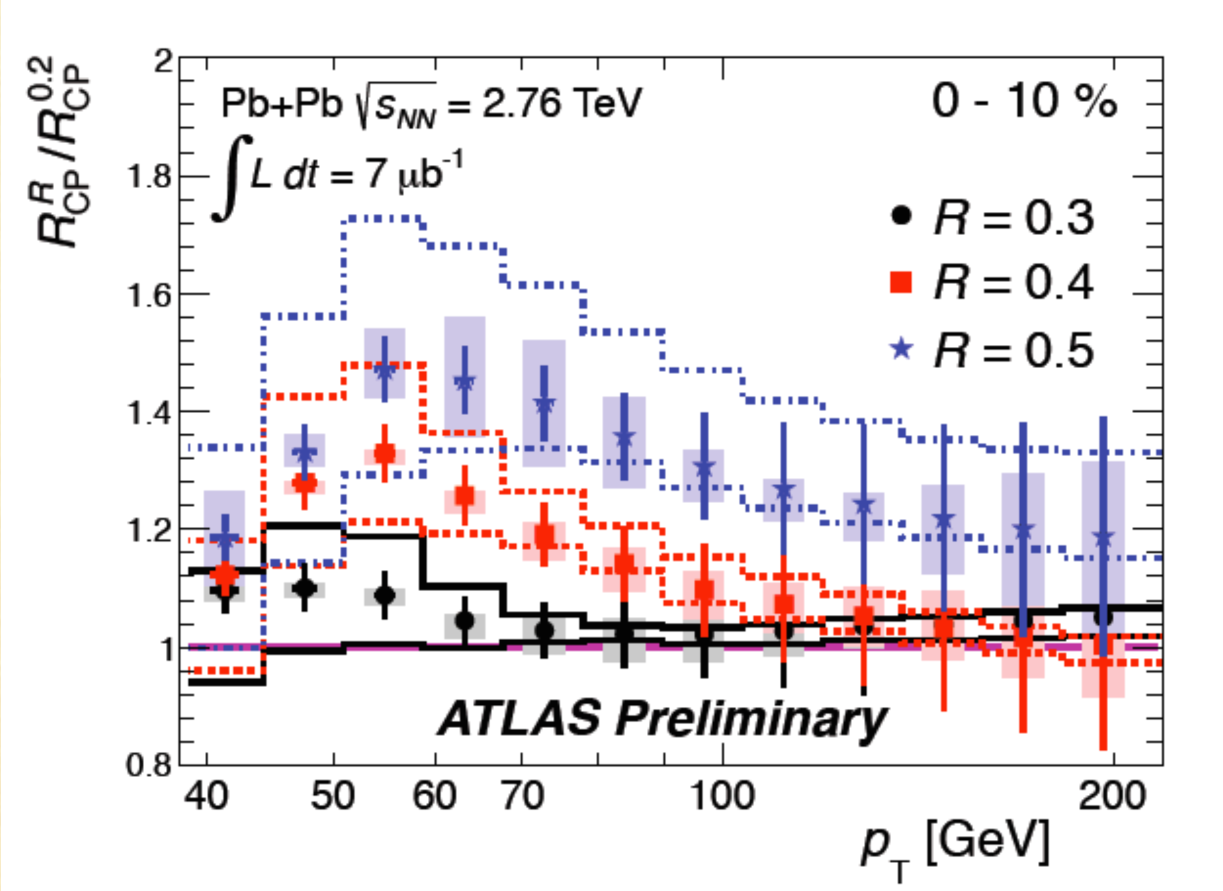
Ratio of charged jet cross section R=0.2 / R=0.3 (Pb-Pb)





Ratio R=0.2/R=0.3 consistent with vacuum jets for peripheral and central collisions

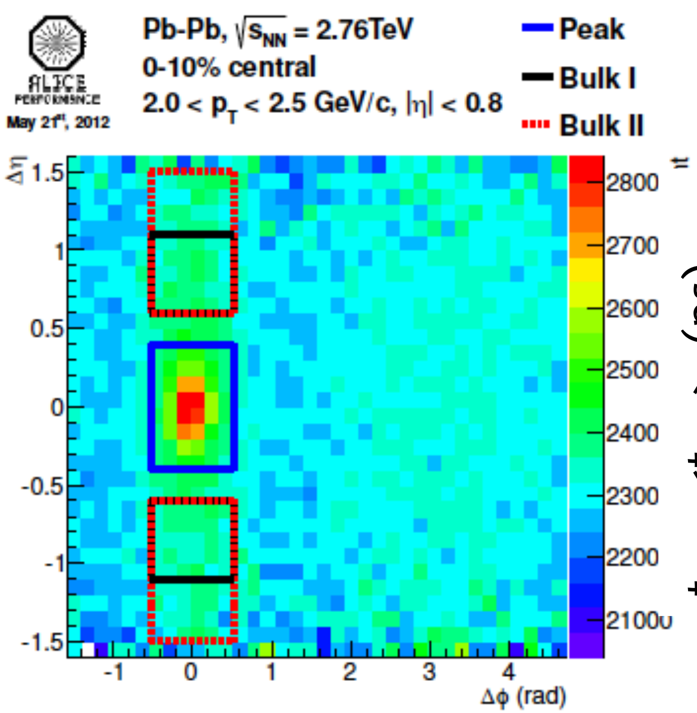
Jet R_{cp} (R=X / R=0.2) in

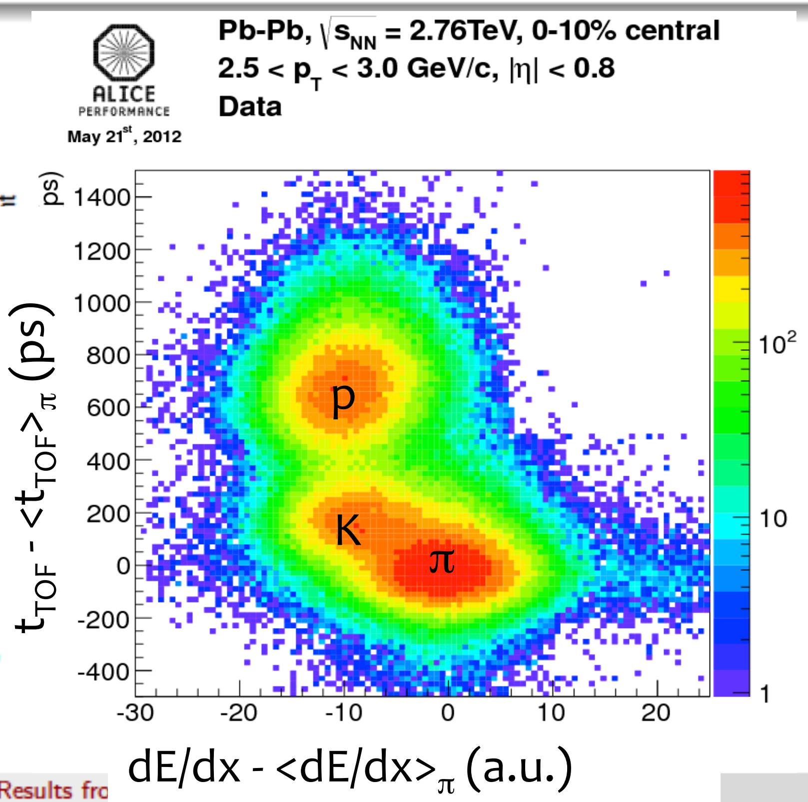


- Up to 200 GeV, in R= 0.2, 0.3, 0.4, 0.5
- Consistent with ALICE results for R=0.3.
  - (plotted oppositely for vertical axis .)

p/π ratio in Bulk and Jet region

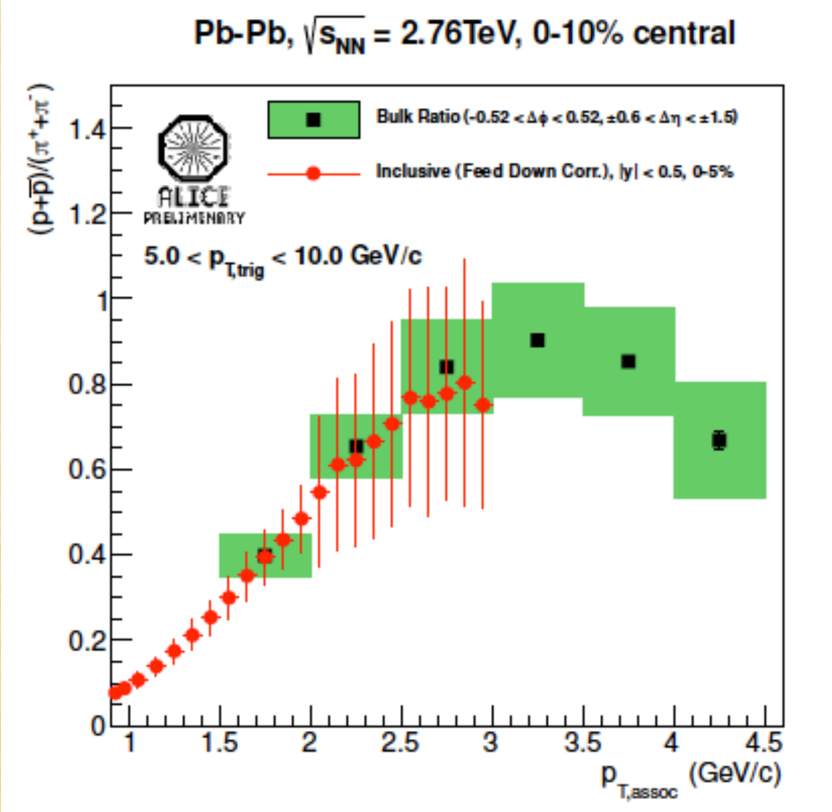
- Trigger particle (charged hadrons) $5 < p_{T,trigg} < 10$ GeV/c
- Associated particles (π or proton) $1.5 < p_{T,assoc} < 4.5$ GeV/c
  - Combined particle identification with specific energy loss in the TPC and time of flight in the TOF
  - Bulk region ($-0.52 < \Delta\phi < 0.52$ rad, $\pm 0.60 < \Delta\eta < \pm 1.50$)
  - Peak region($-0.52 < \Delta\phi < 0.52$ rad, $-0.4 < \Delta\eta < 0.4$)





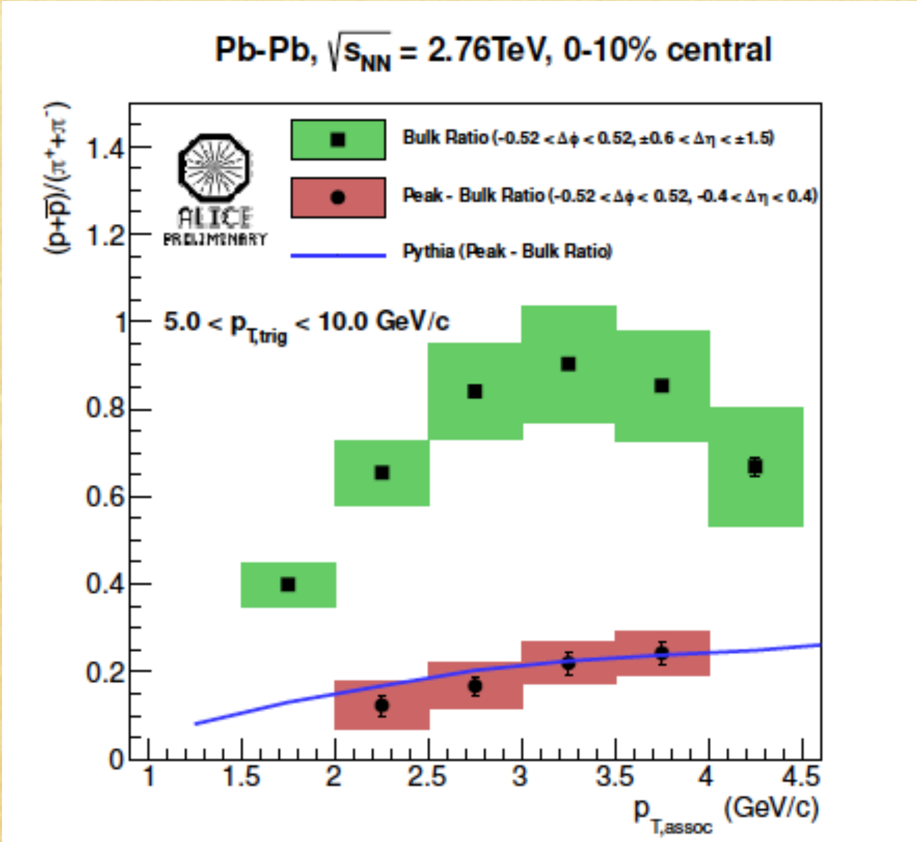
Dong Jo ,Kim (JYFL/HIP) Particle Correlation Results fro 17 / 20

p/π ratio in Bulk region



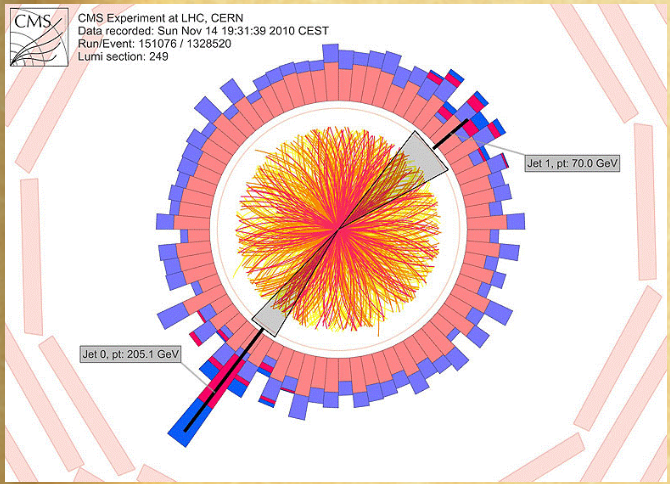
- Comparison with feed-down corrected p/π ratio, from inclusive spectra (0-5%) .
- Good agreement with "Bulk" and inclusive.

p/π ratio in Bulk and Jet region

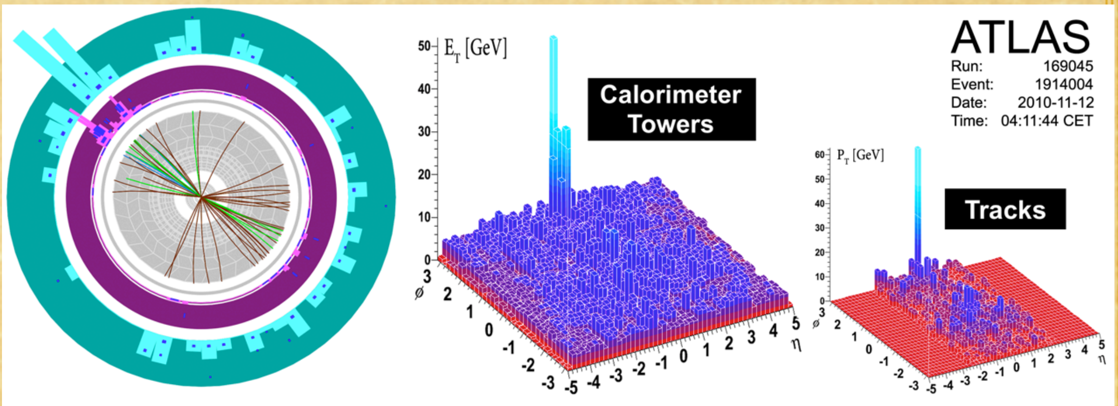


- p/π in bulk is much larger than that in jet region.
- p/π in jet region is similar as that from PYTHIA (6.4).
- No indication of medium modification of the particles of jets in the intermediate p_T region.

3. Di-jets

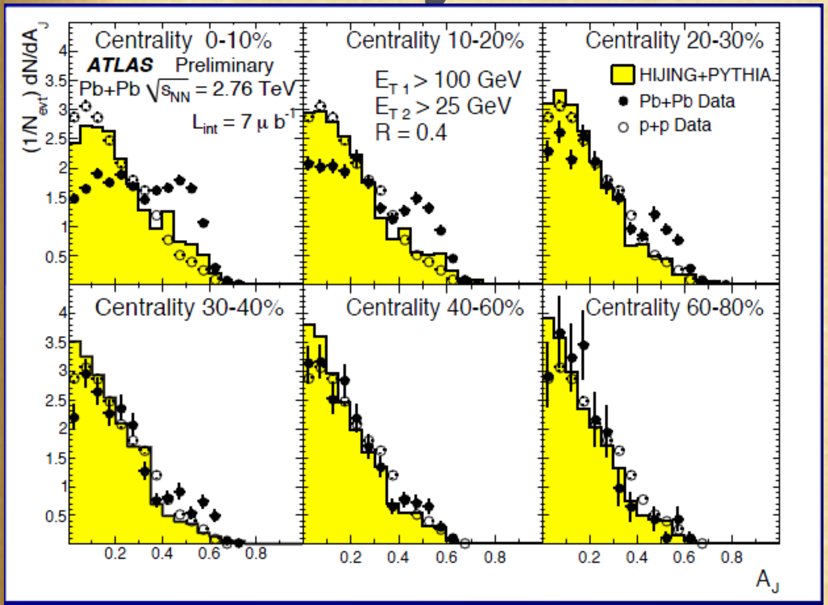


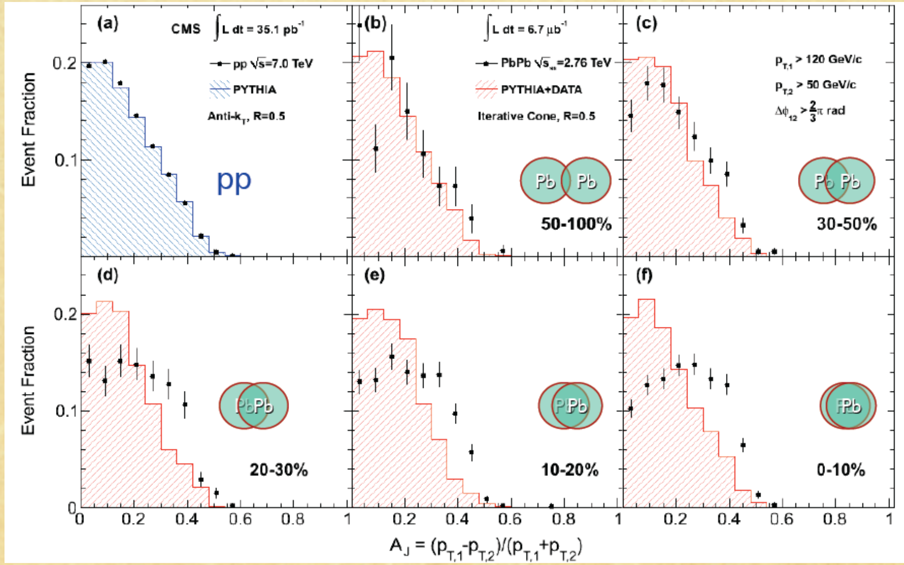
CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV



ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET
Calorimeter Towers
Tracks
E_T [GeV]
P_T [GeV]
φ
η

A_J: di-jet asymmetry





ATLAS R=0.4

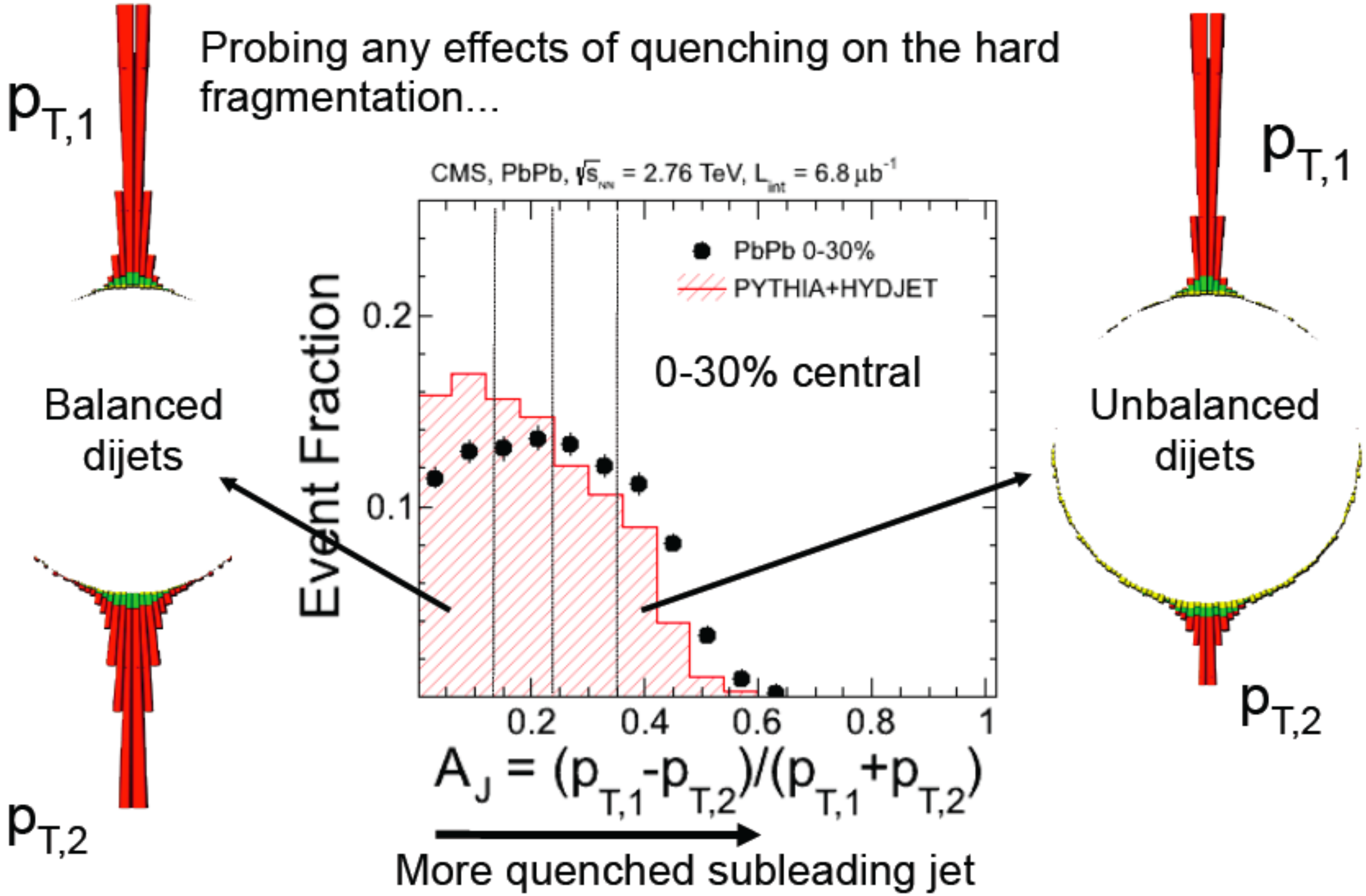
CMS R=0.5

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Quantify jet energy imbalance by the asymmetry ratio.
- Large asymmetry is seen in energy imbalance.

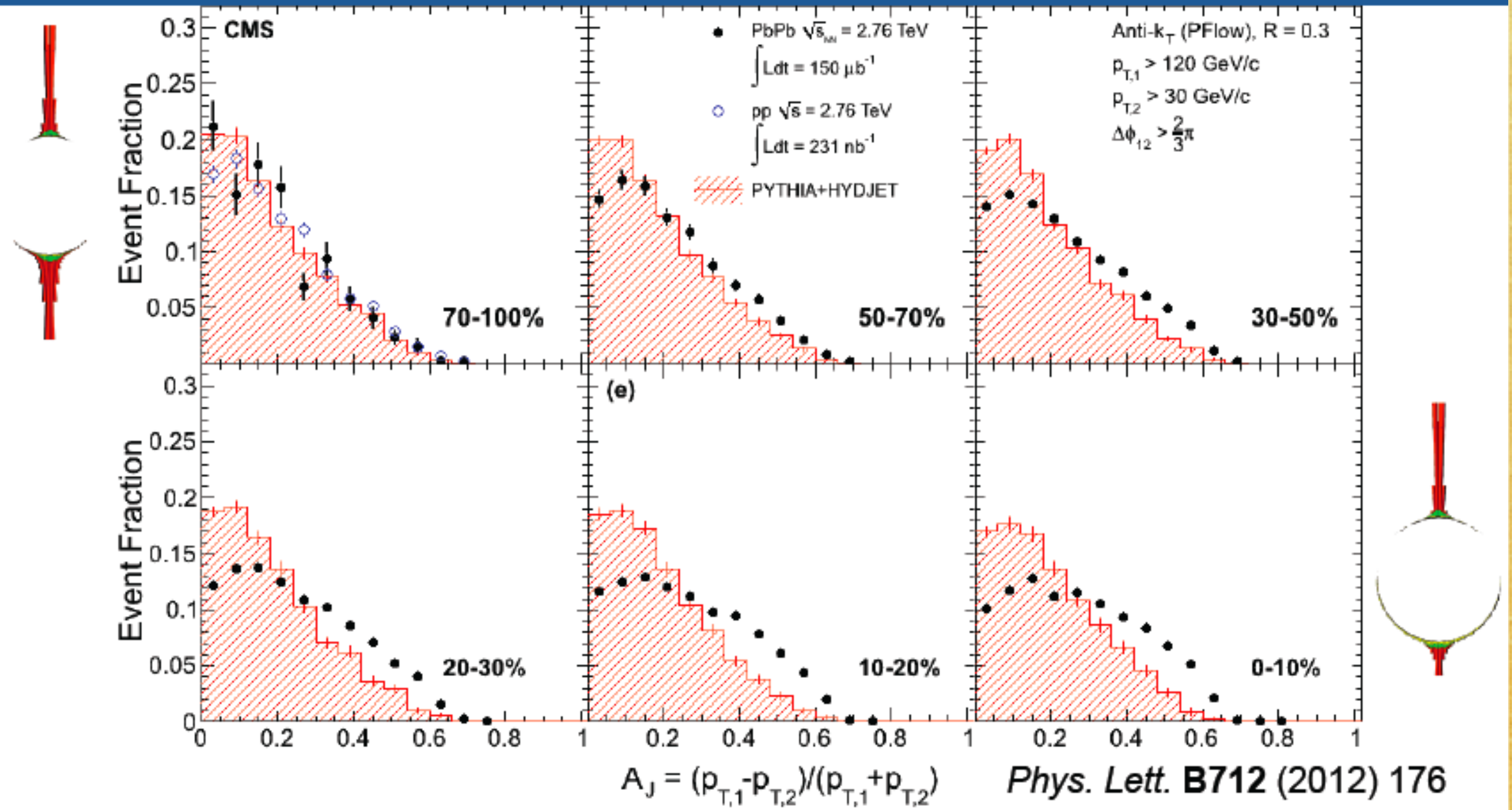
Differentiating in A_J

Probing any effects of quenching on the hard fragmentation...



Large A_J : low momentum particle (< 4 GeV/c) emitted at large angle on away side.

Results from 2011 data

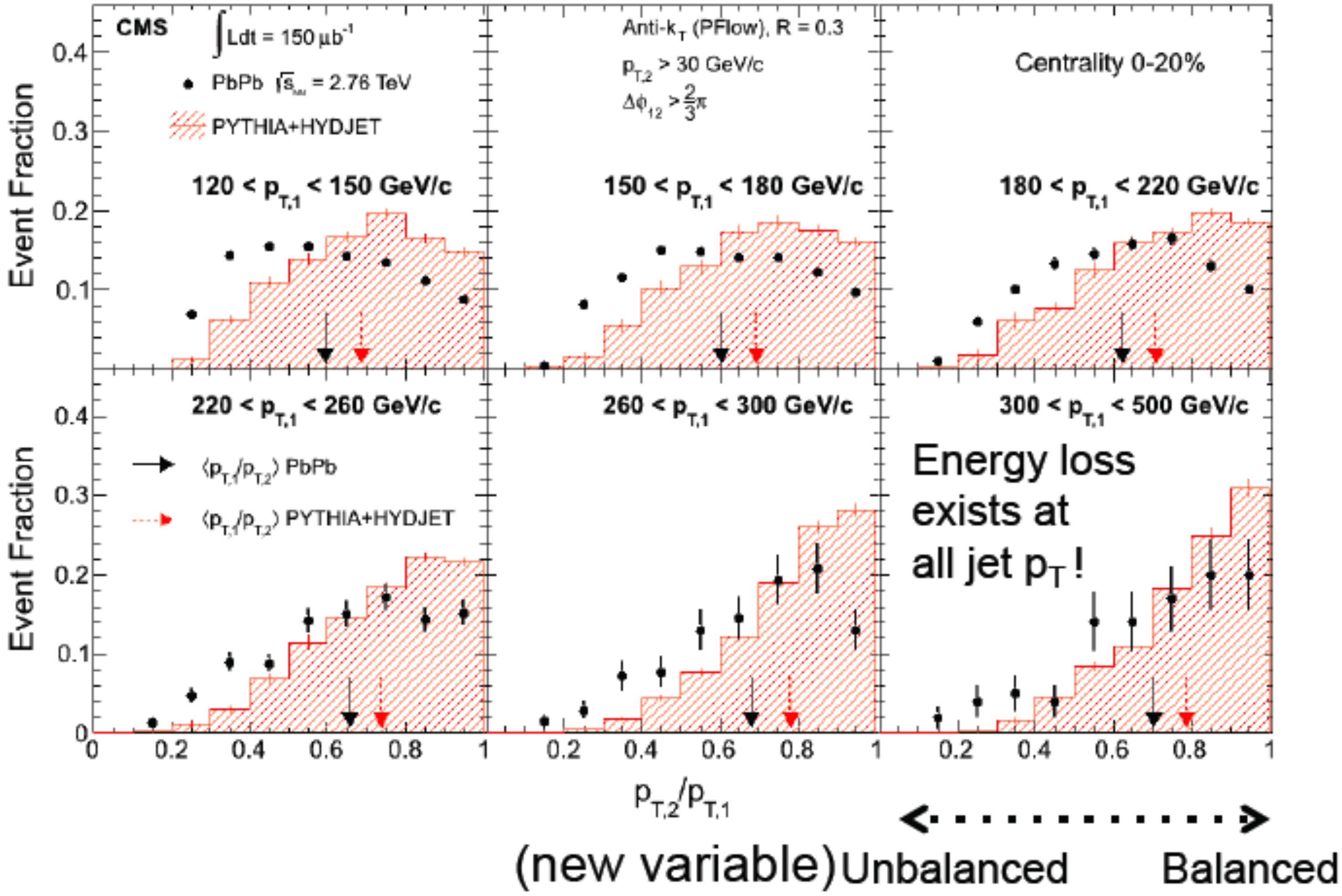


Phys. Lett. **B712** (2012) 176

Earlier results confirmed

Statistical uncertainties significantly reduced

p_T-dependence of the dijet imbalance

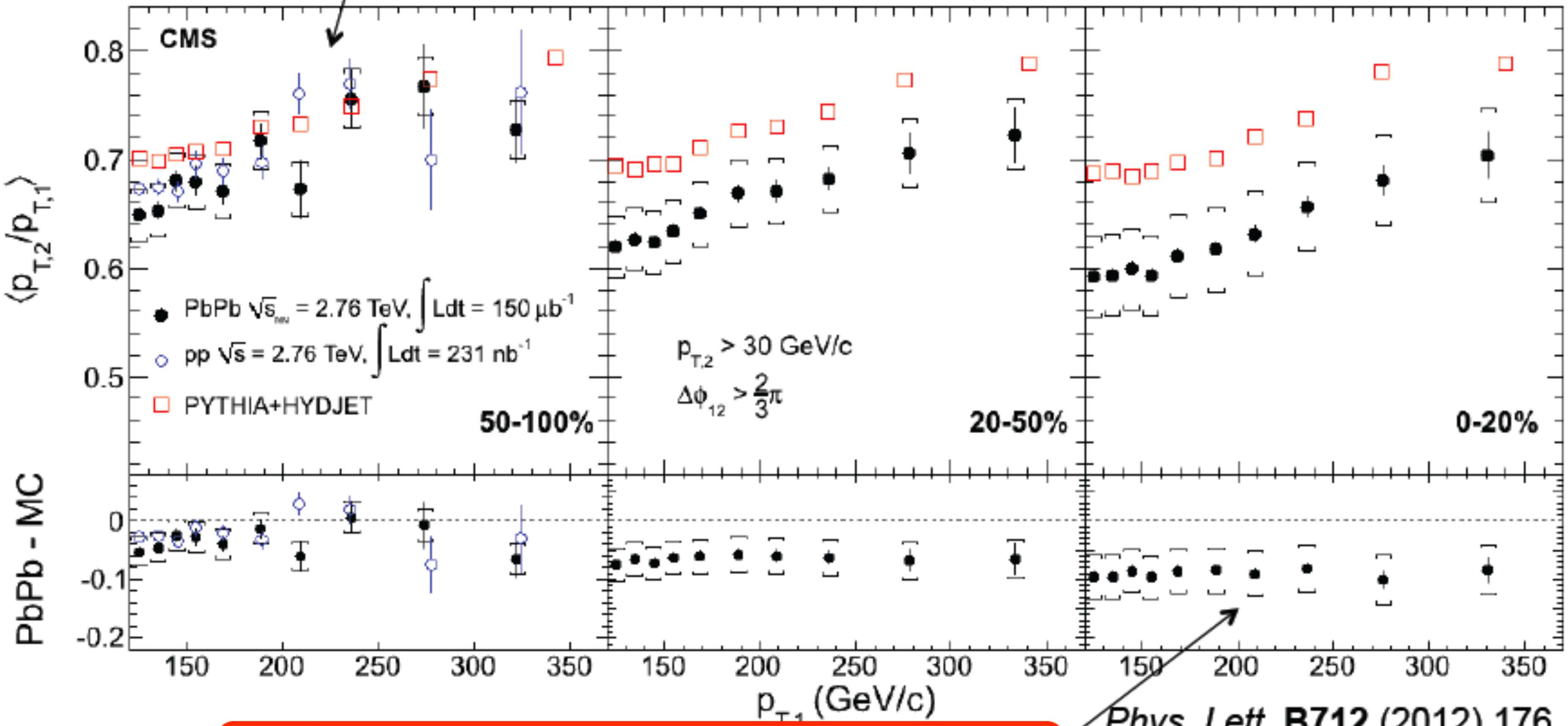


Dijets in PbPb are more imbalanced than Pythia at
all bins of leading jet p_T

Phys. Lett. **B712** (2012) 176

p_T-dependence of the dijet imbalance

Reference and pp already have an increasing trend
Differences in initial state, different jet resolution



Phys. Lett. **B712** (2012) 176

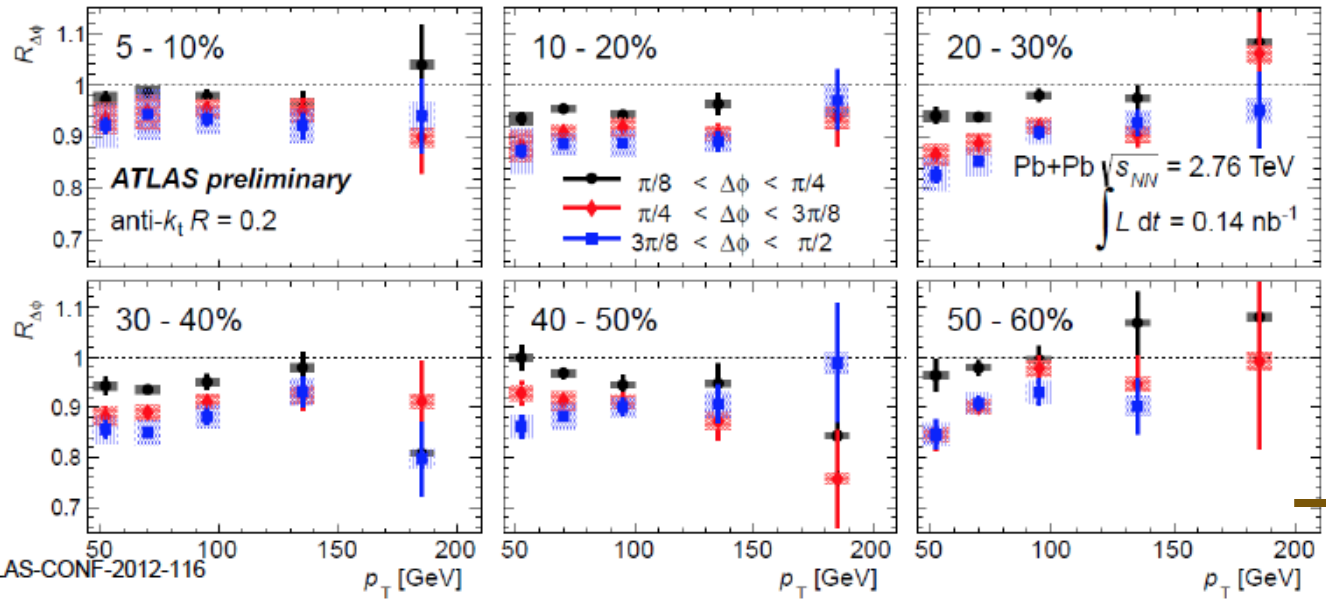
No significant dependence on jet p_T

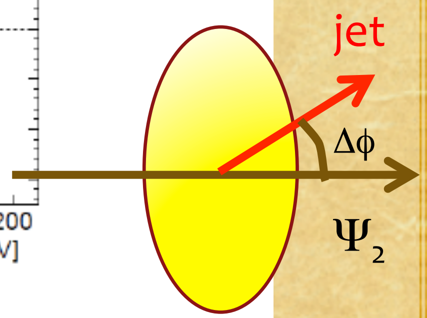
4. Jet v_2

Azimuthal dependence of jet yields

- Path length dependence of jet suppression
- Ratios of yields in different slices of $\Delta\phi = \phi^{jet} - \Psi_2$

$$R_{\Delta\phi} = \frac{\left.\frac{d^2N_{jet}}{dp_T d\Delta\phi}\right|_{\Delta\phi=\Delta\phi_i}}{\left.\frac{d^2N_{jet}}{dp_T d\Delta\phi}\right|_{\Delta\phi=0-\pi/8}}$$

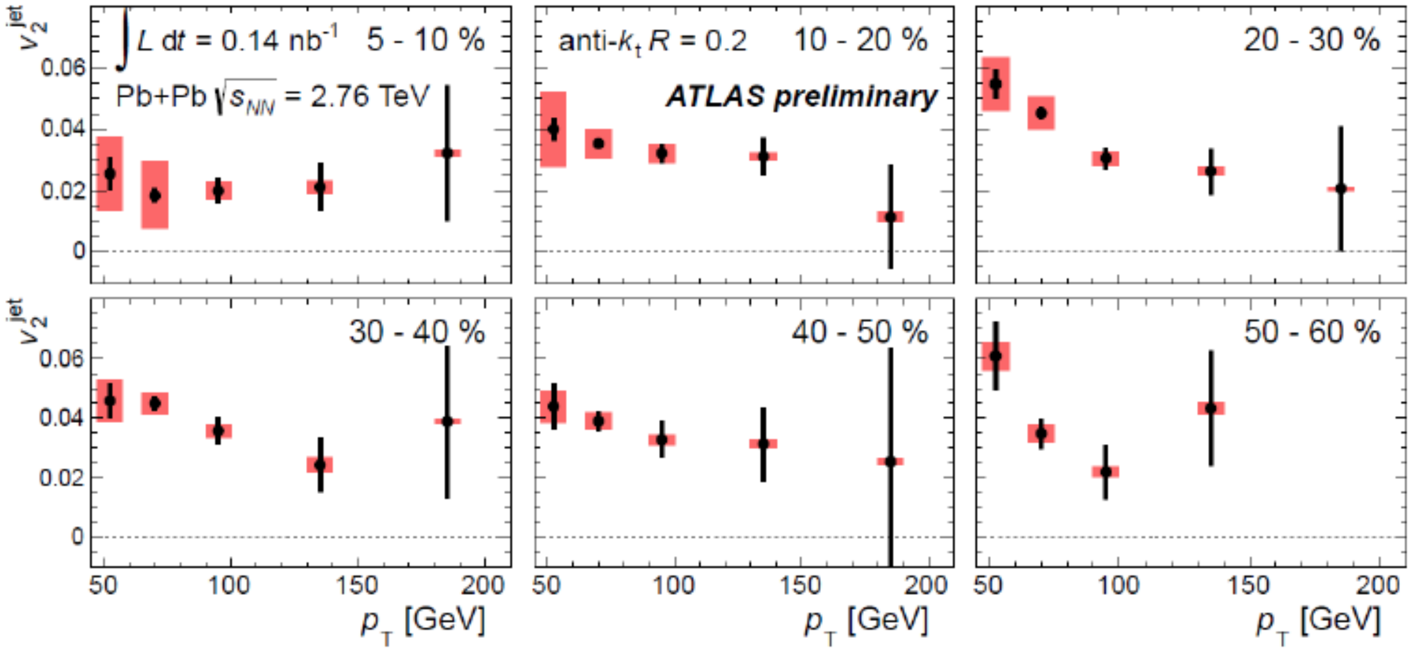




– Yields are reduced by about 15% for $3\pi/8<\Delta\phi<\pi/2$ relative to $0<\Delta\phi<\pi/8$

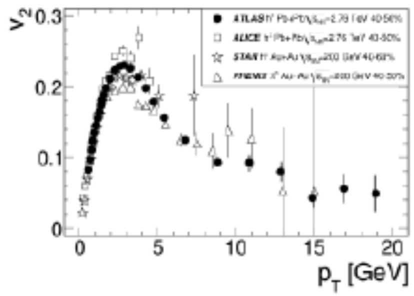
Jet v_2

- Jet v_2 measured for $45 < p_T < 210$ GeV R=0.2 jets



Charged hadrons

Phys. Lett. B707 (2012) 330-348



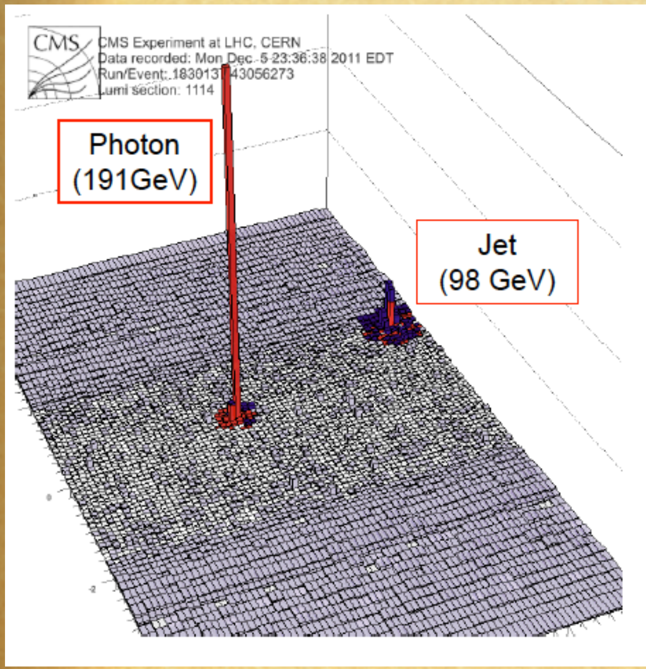
- Weak dependence on p_T above 100 GeV
- Some evidence for increase at lower p_T

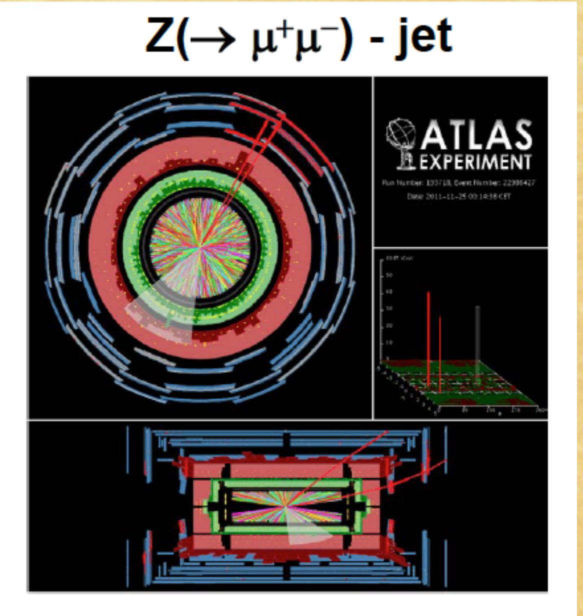
ATLAS-CONF-2012-116

QM'2012, Washington D.C. 13/08/2012 B. Wosiek

5. γ/Z-jet

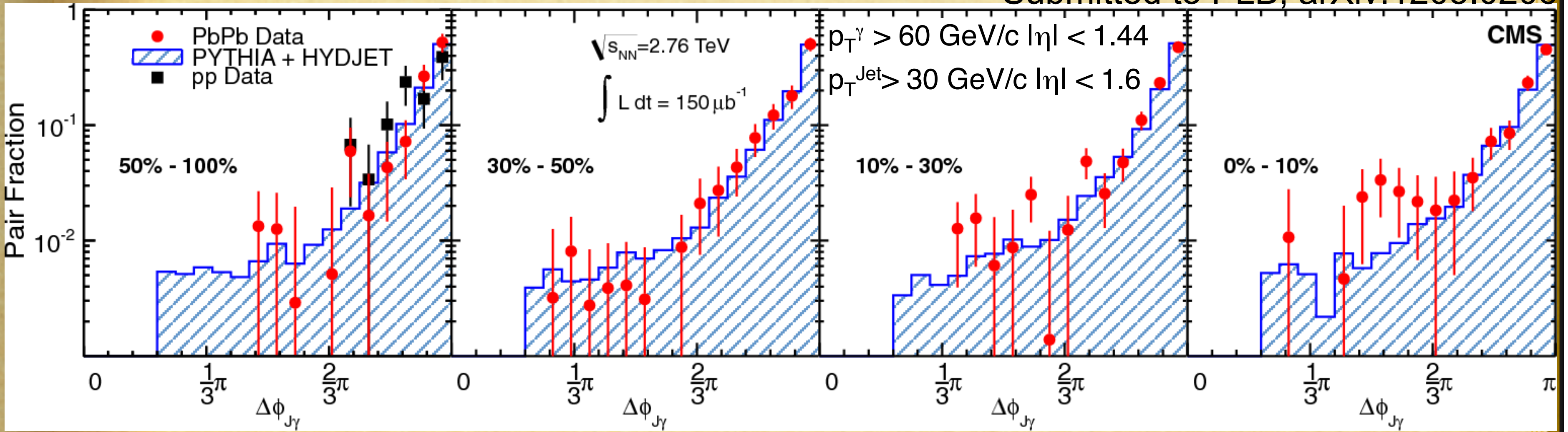
Modification of the jet energy relative to the probe not affected by the medium





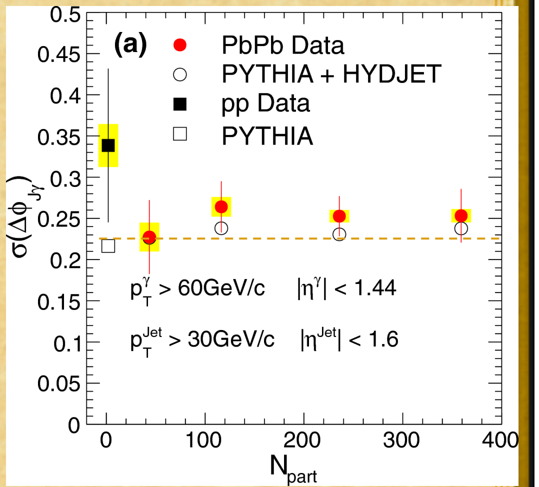
γ-Jet Angular Correlations (CMS)

Submitted to PLB, arXiv:1205.0206



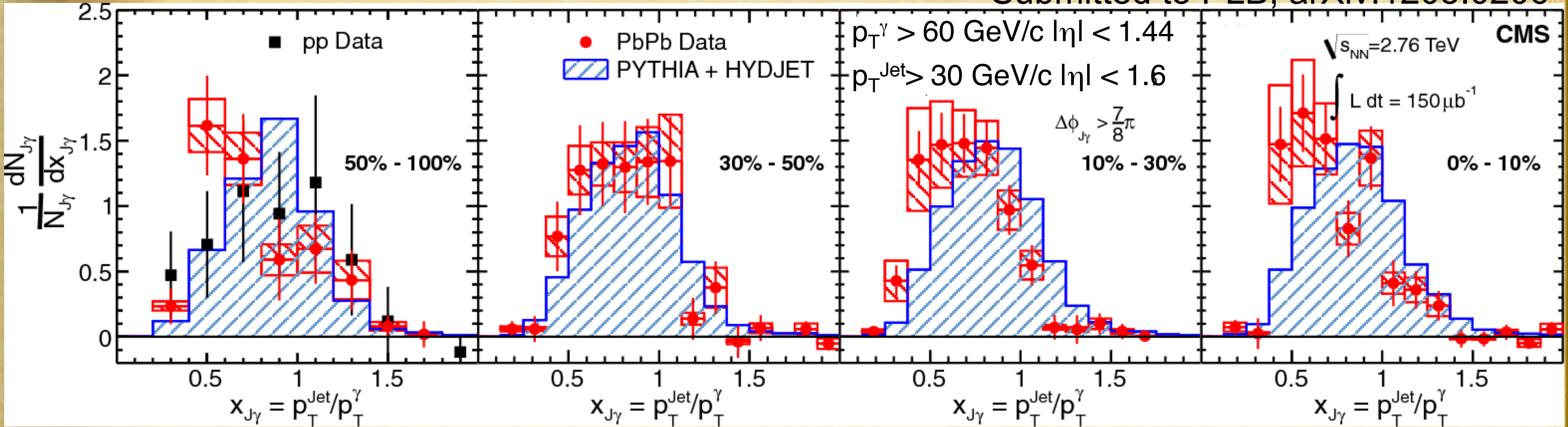
No significant angular de-correlation

is observed for γ-jet pairs



γ-Jet momentum balance

Submitted to PLB, arXiv:1205.0206

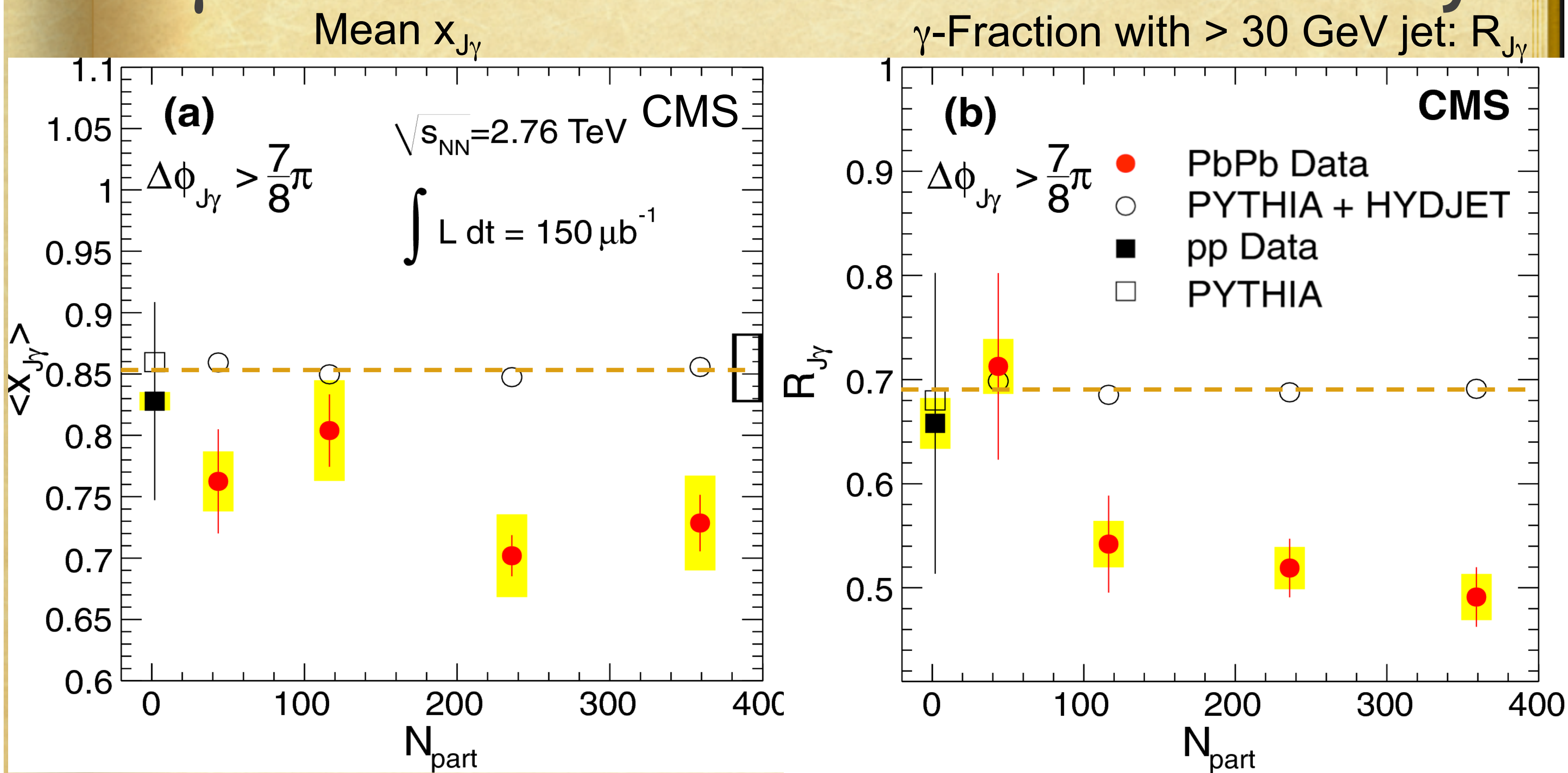


- Momentum ratio shifts/decreases with centrality
  - jets shifting below the 30 GeV p_T threshold not included

$p_T^\gamma > 60$ GeV/c $|\eta| < 1.44$

$p_T^{Jet} > 30$ GeV/c $|\eta| < 1.6$

γ-Jet Momentum Balance vs. Centrality



- Significant deviation of $\langle x_{J\gamma} \rangle$ in PbPb compared to PYTHIA + HYDJET
- The centrality dependence is mostly visible in $R_{J\gamma}$
  - jet p_T shifting below the 30 GeV threshold

$p_T^{\gamma} > 60$ GeV/c $|\eta| < 1.44$

$p_T^{Jet} > 30$ GeV/c $|\eta| < 1.6$

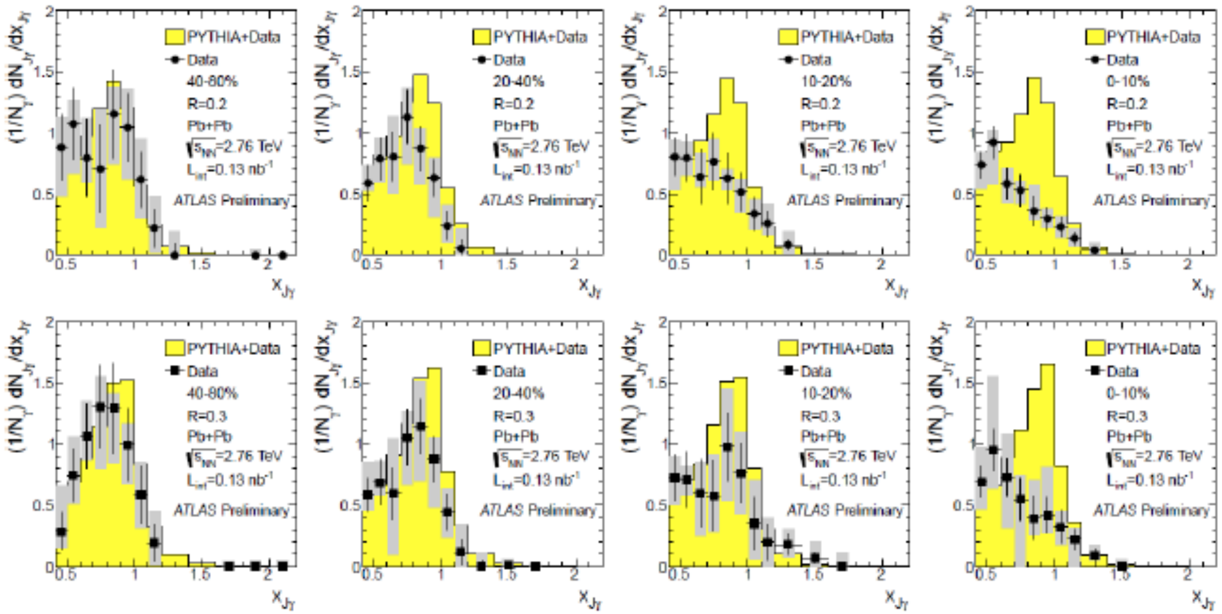
γ - jet correlations

- Large cross-section, purity 75-85%
- E_γ > 60 GeV: 60-90 GeV, $|\eta|<1.3$
- Jet: anti-kT, R=0.2, 0.3, p_T>25 GeV, $|\eta|<2.1$
- γ-jet separation $\Delta\phi > 7\pi/8$ (back-to-back)

$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$

R=0.2

R=0.3

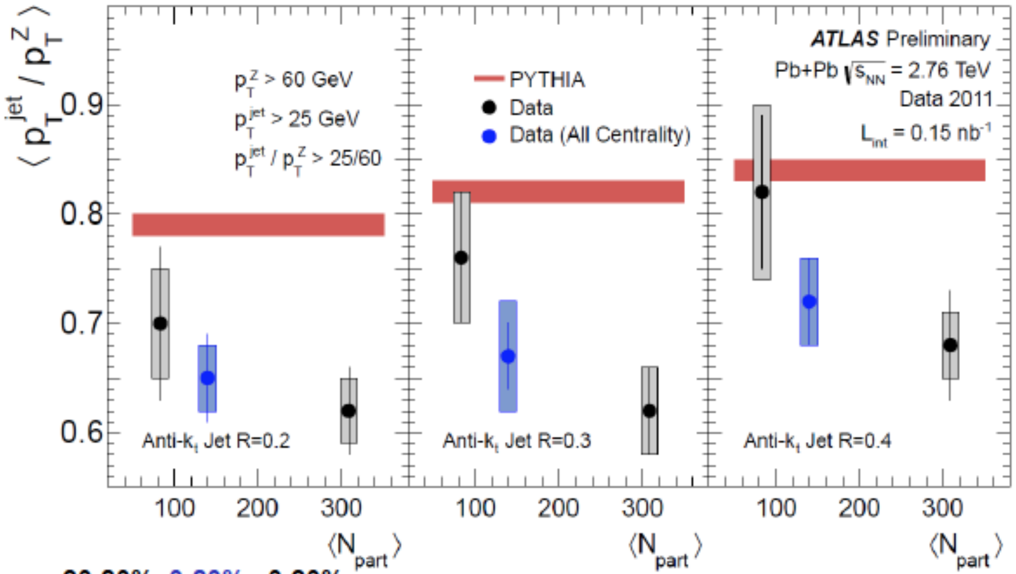


- Shape and integral compatible with PYTHIA for peripheral collisions
- With increasing centrality shift towards smaller $x_{J\gamma}$ and reduction of the integral

ATLAS-CONF-2012-121

Z - jet correlations

- $Z \to e^+e^-, \mu^+\mu^-$ $p_T > 60$ GeV
- Jet: anti-kT, R=0.2, 0.3, 0.4, p_T>25 GeV, $|\eta|$<2.1
- Z-jet separation > $\pi/2$ → 37 events for L_{int}=0.15 nb^{-1}



20-80% 0-80% 0-20%

$\langle p_T^{jet} / p_T^Z \rangle$

- Suppression of the $\langle p_T^{jet} / p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events)
- Stronger suppression for more central collisions

ATLAS-CONF-2012-119

QM'2012, Washington D.C. 13/08/2012 B. Wosiek 31

Next step of EM probe + Jet :
with reaction plane to control path length.

6. di-hadron correlations

One way to access the jet – medium interactions

Motivation of di-hadron correlation measurements

- **Probe jet medium interactions in Heavy Ion collisions(Di-hadron Tomography)**

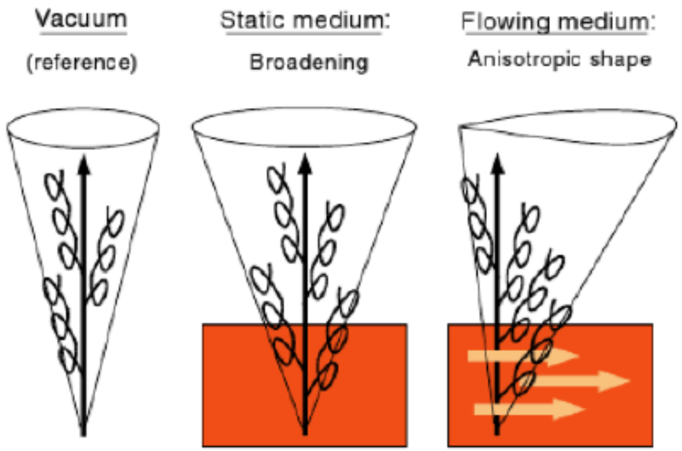


Figure: Broadening in a static medium.Longitudinal flow results in deformation of the conical jet shape

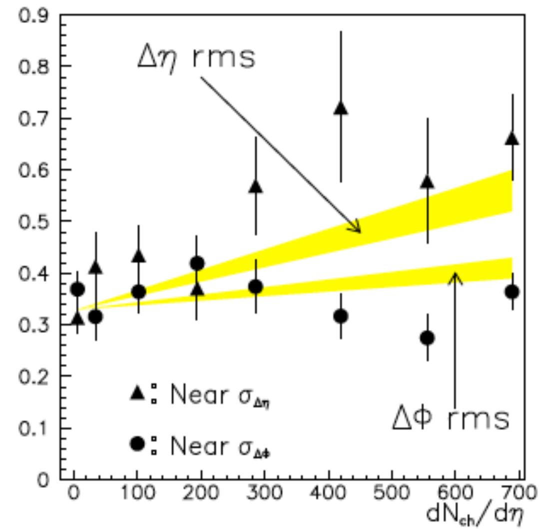
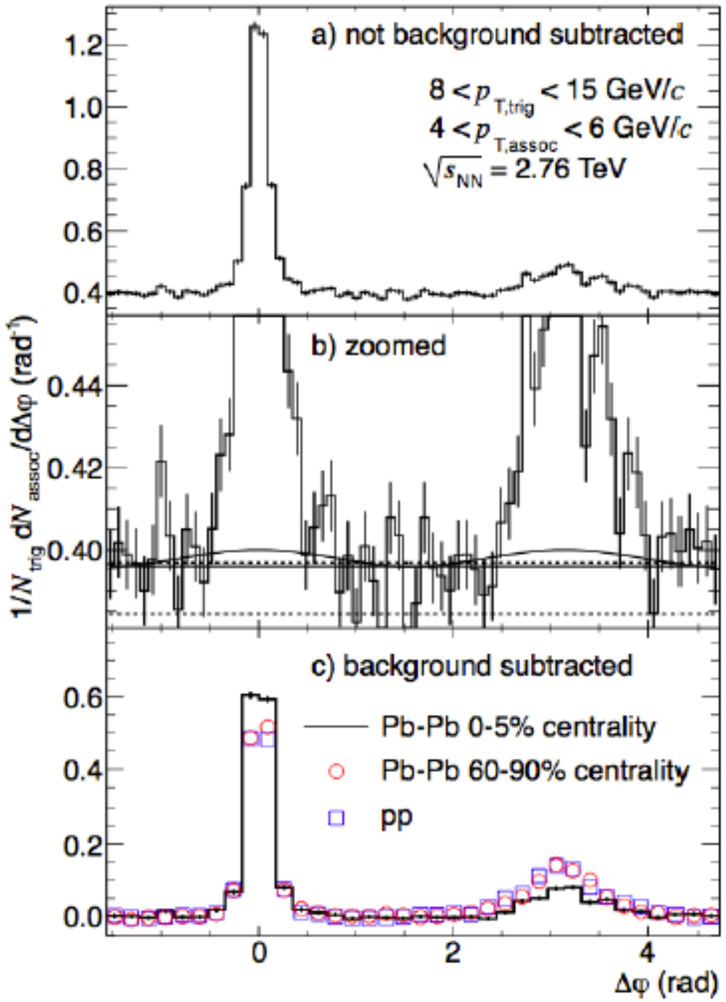


Figure: Néstor Armesto, Carlos A. Salgado and Urs Achim Wiedemann, PhysRevLett.93.242301 $(4 < p_{T,trigg} < 6 \otimes 0.15 < p_{T,assoc} < 4$ GeV$/c)$

di-hadron correlations



- Particle-yield modification in jet-like azimuthal di-hadron correlations in Pb-Pb collisions (Phys. Rev. Lett. 108, 092301 (2012), ALICE)

$$Y(\Delta\phi) = \frac{1}{N_{trigg}} \frac{dN_{assoc}}{d\Delta\phi}$$

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$

$$I_{CP} = \frac{Y_{central}}{Y_{peripheral}}$$

In $p_{\mathrm{Tassoc}} > 3$ GeV/c for higher trigger momentum bin($p_{\mathrm{Ttrigg}} > 8$ GeV/c), flow background is not very important and signal is more pronounced than the background

I_{AA}

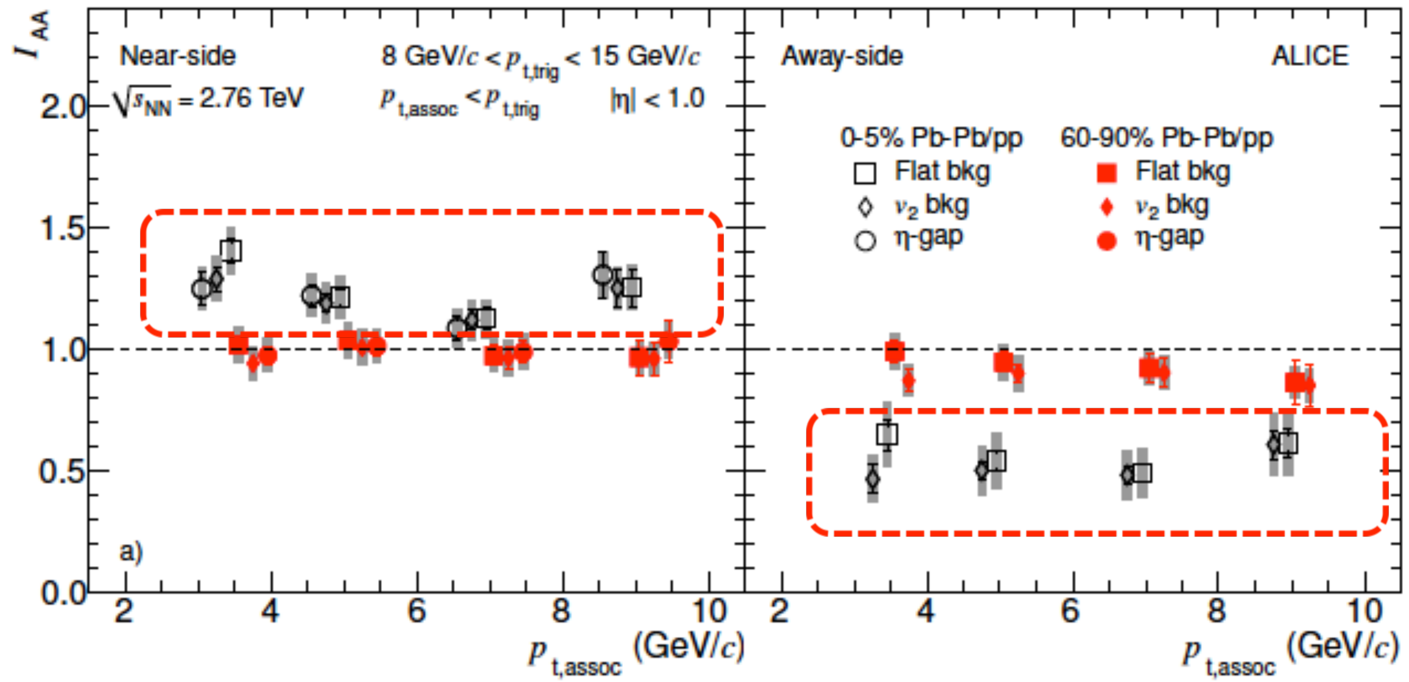
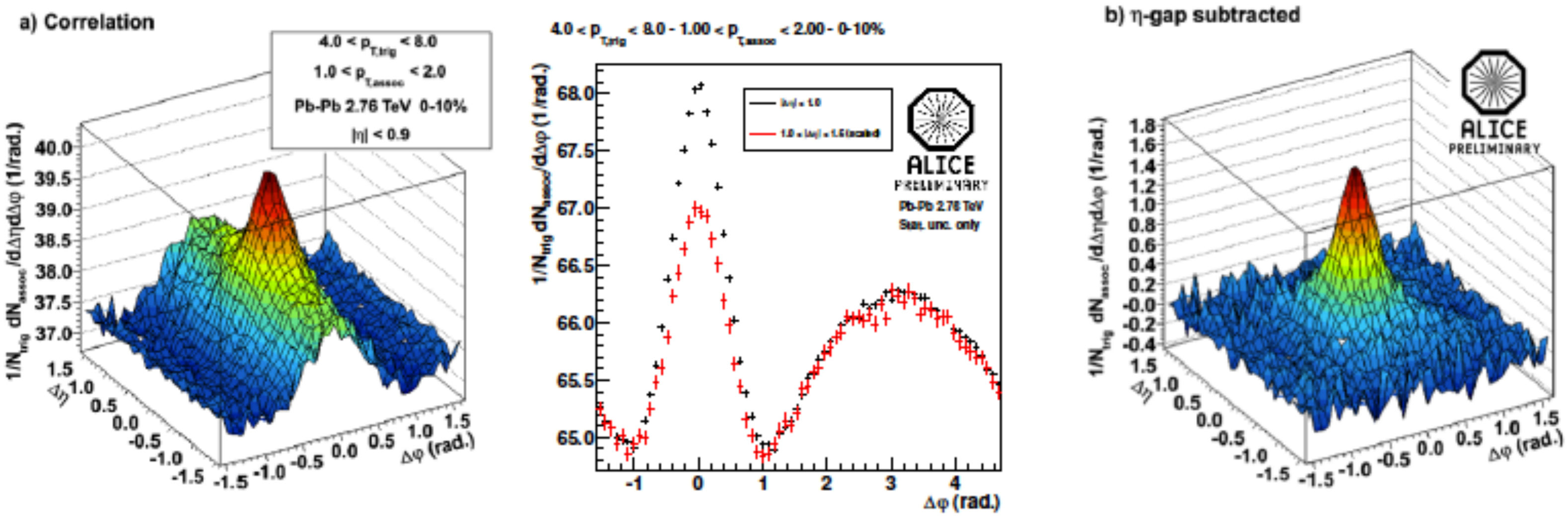


Figure: Phys. Rev. Lett. 108, 092301 (2012), ALICE

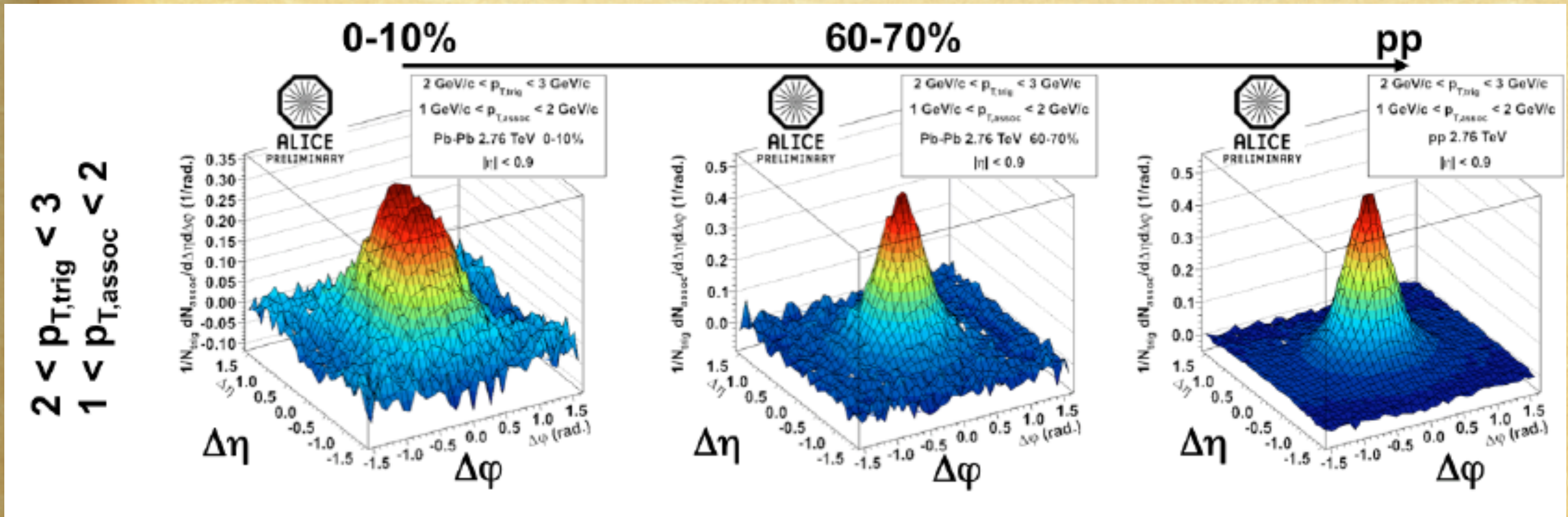
- Enhancement above unity of ~30% on the near-side (not observed at RHIC).
- Away-side suppression at LHC (less at RHIC, i.e. lager I_{AA}), while single-hadron suppression is found to be slightly larger (R_{AA} is small) than at RHIC.

Near side peak shape modification?

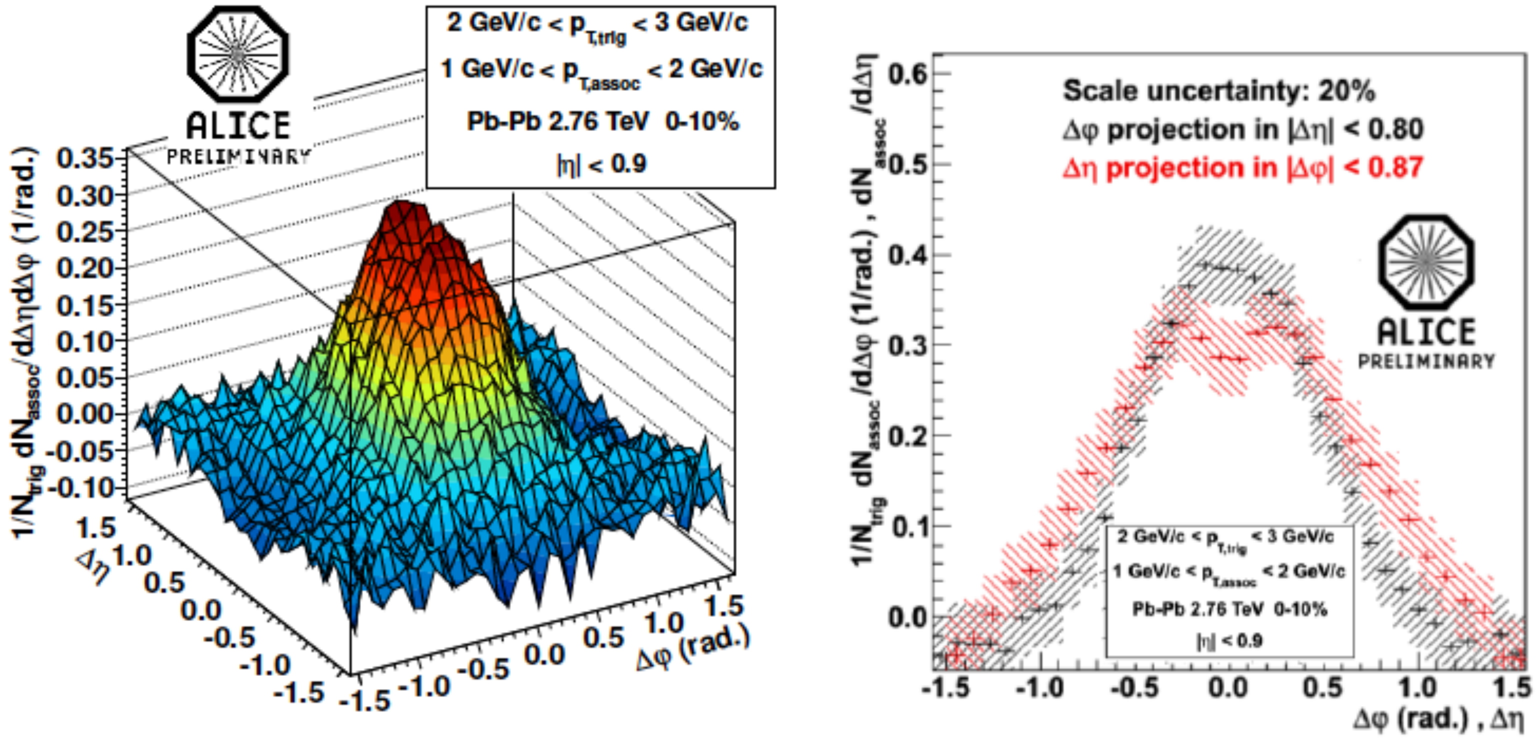
- Can we see modification of the near-side peak ?
- Estimate $\Delta\eta$-independent effects (e.g. flow) by studying the long-range correlation region ($|\Delta\eta| > 1$)
- Remove from short-range region ($|\Delta\eta| < 1$)



Near side peak shape evolutions



Closer look at low $p_{T\ trig,\ assoc}$ bin



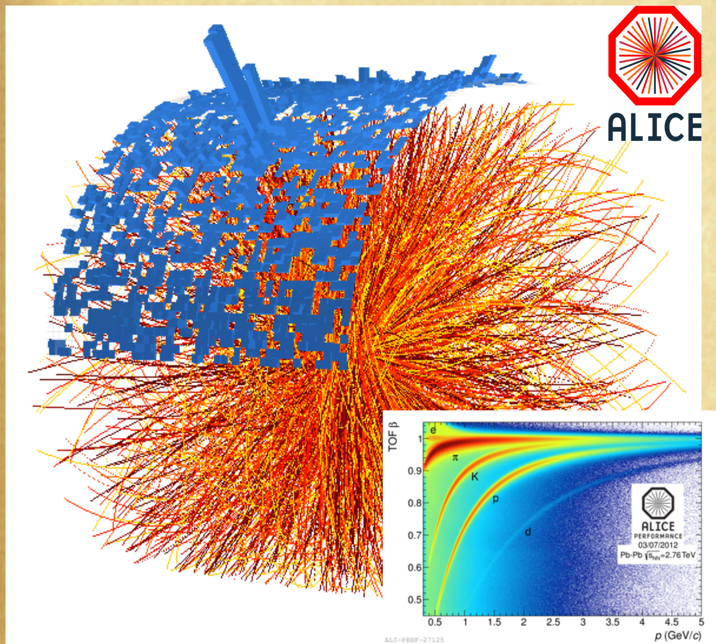
(a) $\eta - gap$ subtracted (b) $\Delta\eta, \Delta\phi$ projection

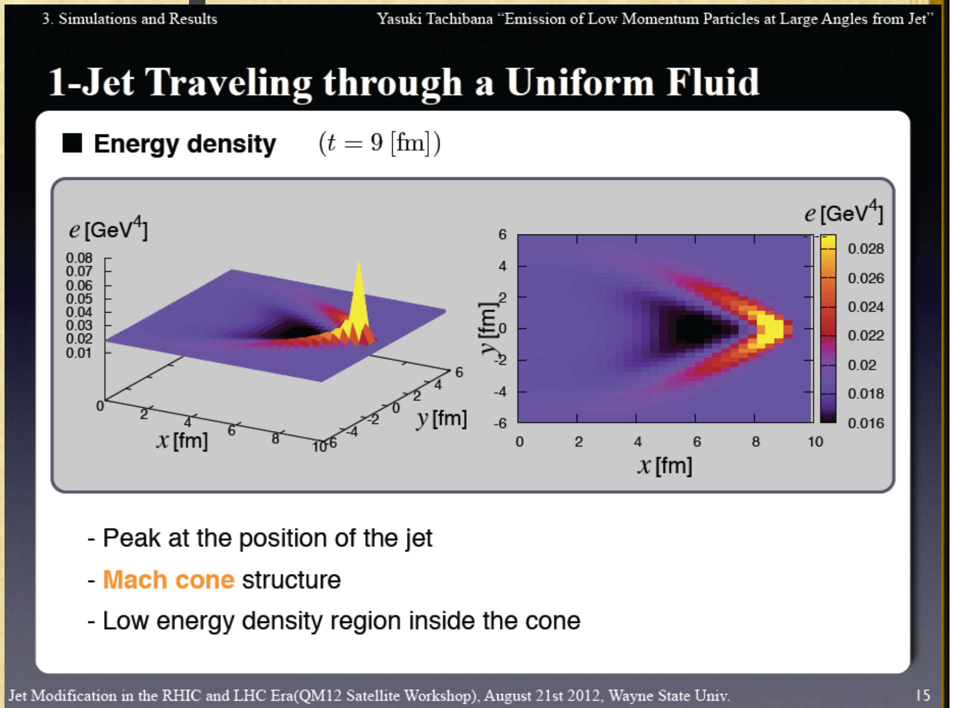
Figure: $2 < p_{T,trigg} < 3 \otimes 1 < p_{T,assoc} < 2$, 0-10% centrality

- The lowest p_T bin shows a structure with a flat top in $\Delta\eta$

7. Outlook

Medium response





3+1 hydro + jet (Tachibana, Hirano) QM2012

ALICE advantage:

- Excellent hadron PID (0.15 – 20 GeV/c), suitable detector to measure the medium response with PID, jet ID and trigger by EMCal (neutral) + TPC (charge)
- Bulk properties (PID spectra, v_2, HBT, etc.) with a large jet energy imbalance.
- ALICE can lower the jet energy threshold than those CMS & ATLAS.
- Key to access c_s, EOS?, How freeze out property changes by parton energy loss?

Path length control by "trigger" bias

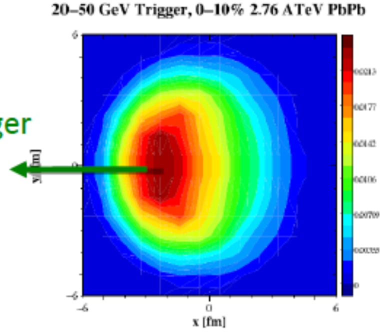
Hadron+Jet in Heavy-Ion Collisions

ALICE

- Semi-inclusive measurement: **biases are ONLY due to trigger hadron**
- Geometric bias in model calculations

distribution of vertices that generate the trigger

Hadron trigger



1.Hadron trigger: strong "surface bias"

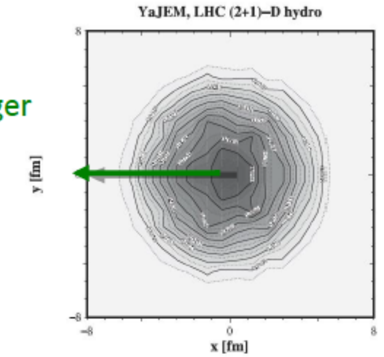
maximizes recoil path length

(T.Renk, private com.)

2.Full jet trigger: no geom. bias

(T.Renk, Phys.Rev .C85 064908)

Jet trigger



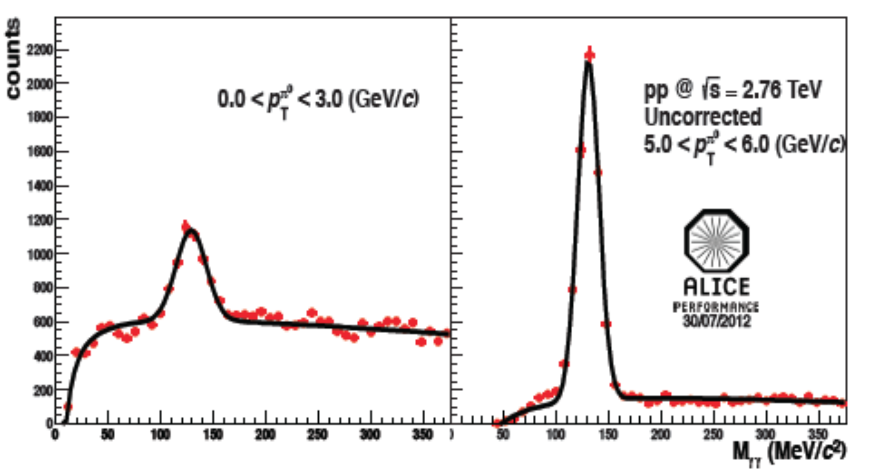
Centrality and reaction plane biases:

- finite, but only weak trigger p_T dependence for high p_T^{trig}

Leticia Cunqueiro Quark Matter 2012 4

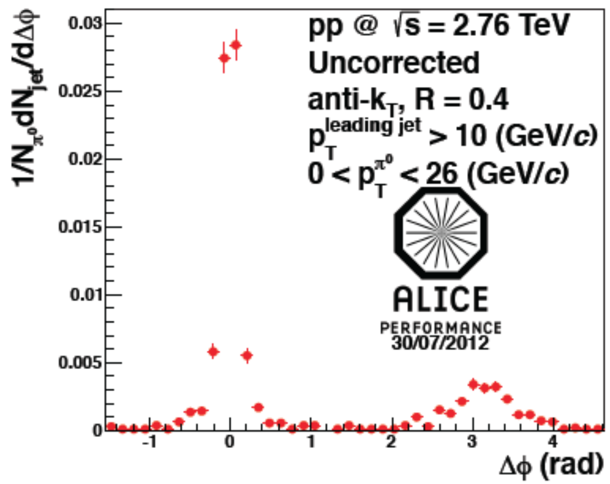
π^0 –jet (charged) correlations

D. Watanabe



In this analysis, π^0s are reconstructed up to 12GeV/c from gamma pairs with good mass resolution.

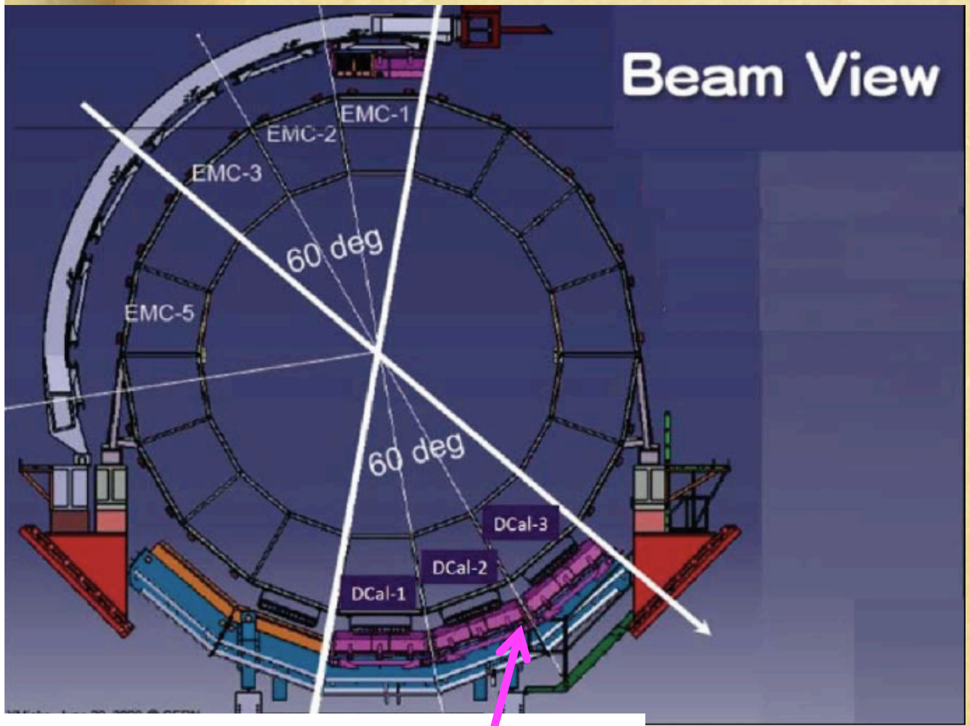
Leading Jet distribution with respect to π^0

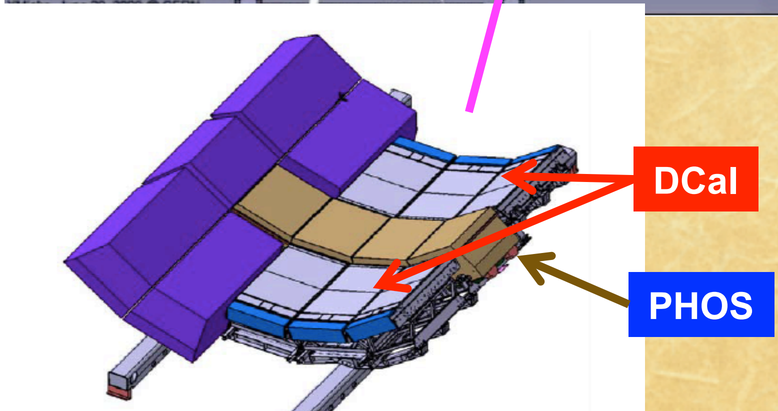


Two clear jet peaks are observed, indicating that high p_T π^0 production is related to jet production.

- π^0: EMCal triggered events, jet: charged jets.
- Towards the measurement for path length control exp.
- See D. Sakata's talk for di-jet & hadron correlations at this workshop.

ALICE Dijet Calorimeter (DCal)

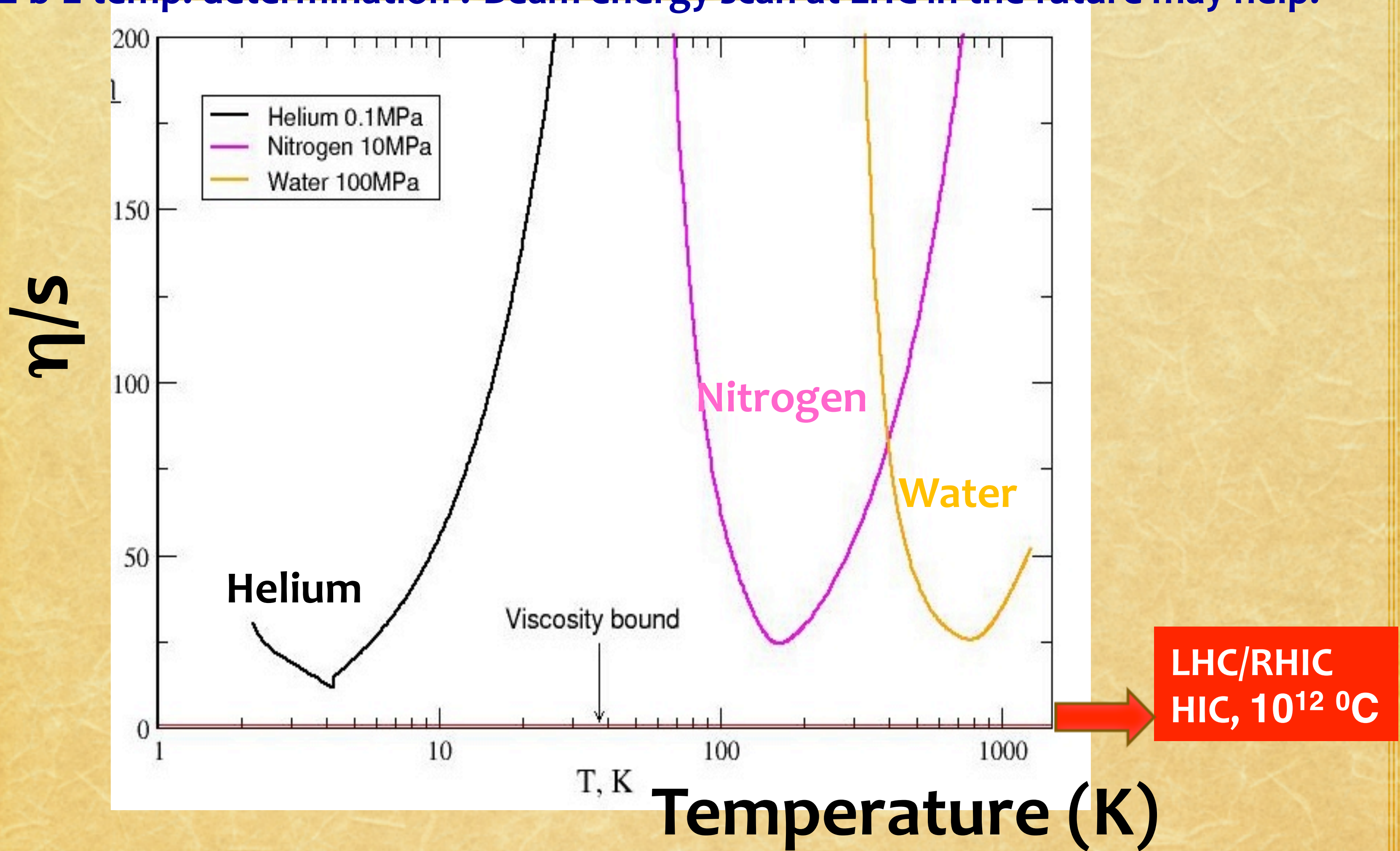




- *Extension of the acceptance of EMCal .*
- *Lead-scintillator sampling type EMC with APD readout.*
  - *EMCal: $\Delta\phi$ = 110°*
  - *DCal: $\Delta\phi$ = 60° (on opposite side of EMCal)*
  - *$\Delta\eta$ = 0.7 for both EMCal and DCal + PHOS*
  - *~10%/√E*
- *Allow back-to-back hadron-jet, di-jet measurements in ALICE, with R = 0.4, up to p_T ~ 150 GeV/c.*
- *Enhance jet, γ trigger capability.*
- *Installed in 2013-2014 (LHC long shutdown, SL1)*

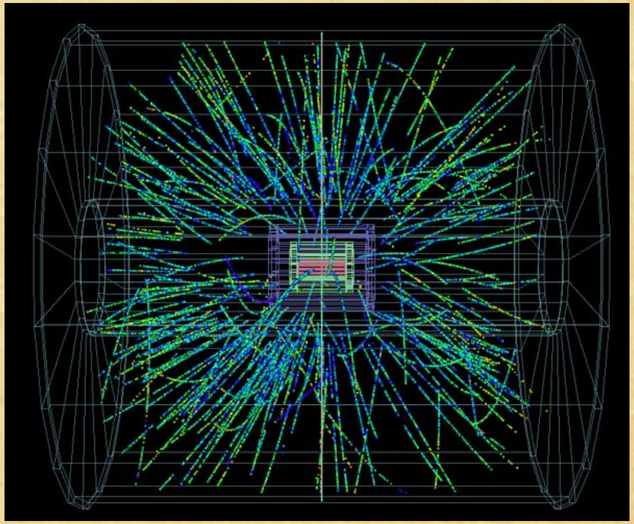
Temperature dependence of mater properties

RHIC v_2 data : $\eta/s \sim 0.1$ (suggested MC Glauber, CGC).
T_{ini} at LHC: suggested 30% higher than that at RHIC.
Any temp. dep. of matter properties ? Affect to transport coefficients (e.g. q-hat) ?
E-b-E temp. determination ? Beam energy scan at LHC in the future may help.



p+Pb at LHC, and initial conditions

- Successful p+Pb pilot run (Sep. 13, 2012)
- p+Pb Physics run (Jan. – Feb., 2013):
  - Beam energy: $\sqrt{s_{NN}}$ = 5.02 TeV
  - Expected statistics: ~ 30 nb^{-1}
    → rare probe statistics equivalent to 0.15 nb^{-1} of Pb-Pb.
- Longer plan:
  - Forward physics to determine the initial condition.
    - soft direct photon jet at low-x in forward direction.



Sep. 13, 2012 (ALICE) test run, p+Pb collisions

Summary

Jet physics at LHC

- **Many exciting data on jet from LHC.**
- **Towards more precision and controllable experiments.**
  - Medium response.
  - Control experiment (path length, temperature, …)
  - Determination of initial condition.
  - + good models and theories.

→ Keys to the precision measurements of properties QGP.