ALICE 実験・最新結果で迫るQGPの姿

~ Properties of QGP at LHC revealed by the recent ALICE results ~

Heavy Ion Café

Tatsuya Chujo (Univ. of Tsukuba)

2012.06.16 @ Sophia Univ.

ALICE (+CMS, ATLAS) 実験・重イオンデータ最新結果で迫るQGPの姿

~ Properties of QGP at LHC revealed by the recent LHC heavy ion data ~

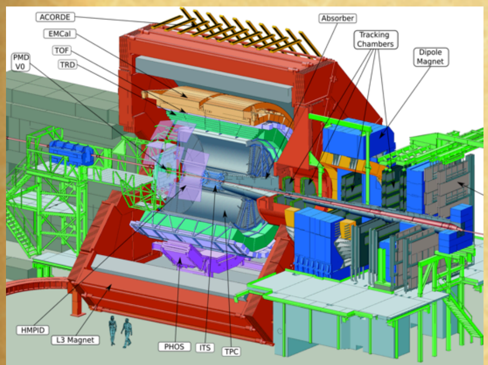
Heavy Ion Café

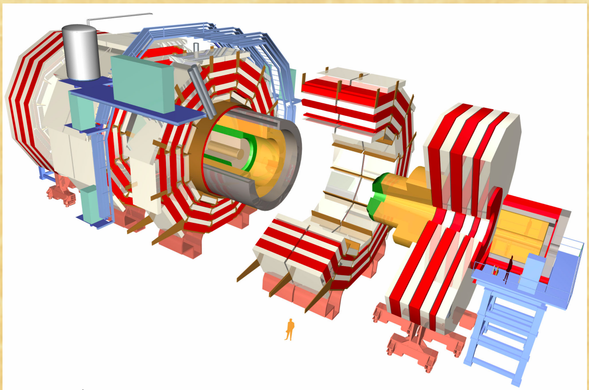
Tatsuya Chujo (Univ. of Tsukuba)

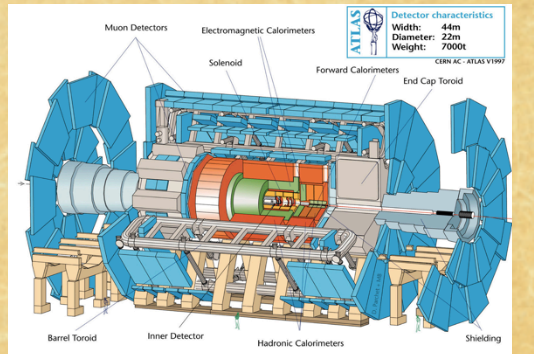
2012.06.16 @ Sophia Univ.

Objectives of this talk

- This is neither a ALICE nor a LHC experiment overview talk.
- Rather, a talk by showing the most recent results from LHC experiments (with my personal bias).
  - adopted the many other's slides presented at Hard Probe 2012, and recent conferences.
  - Try to simulate theorists, experimentalists by many new and exciting data.
- Tried to cover all topics, but might be not so comprehensive.

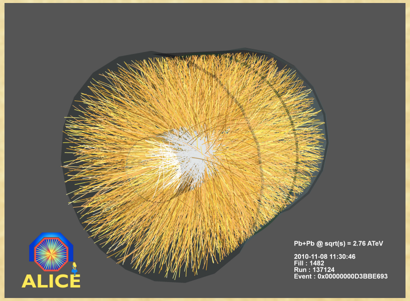


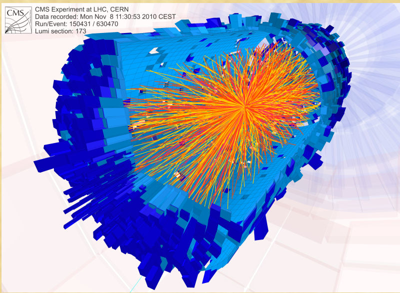


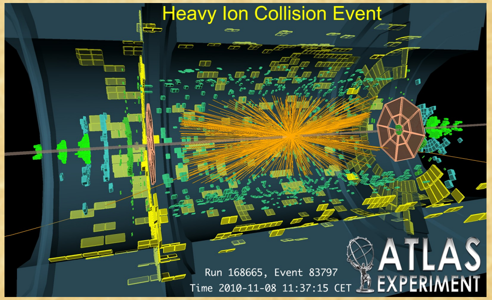


Menu

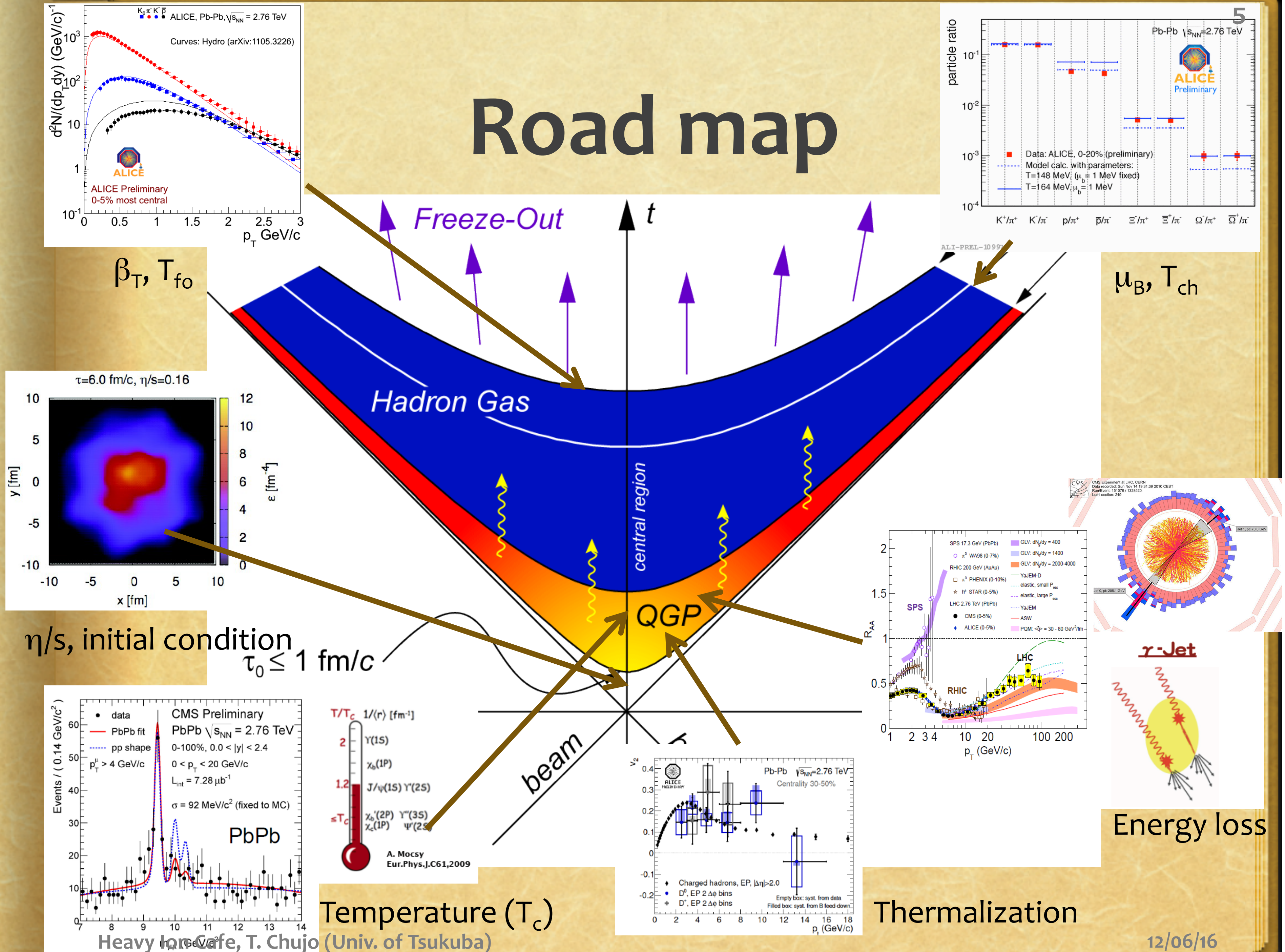
1. Low p_T single particle production
2. HBT
3. Flow and higher harmonics
4. High p_T single particle production
5. Di-hadron correlations
6. Jets (single jet, di-jet, γ-jet)
7. Heavy Flavor
8. Quarkonia
9. Summary





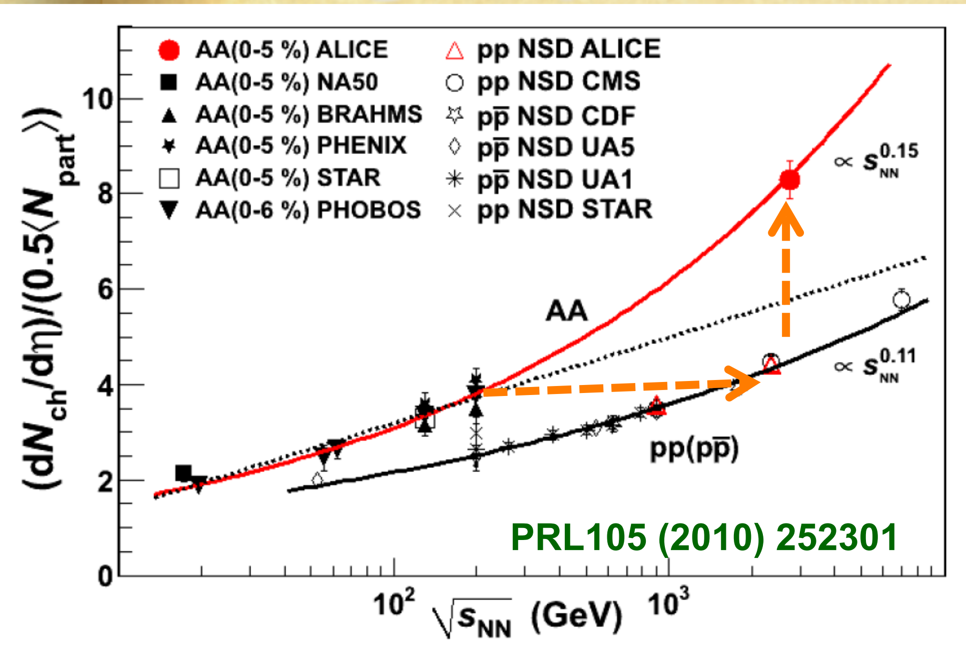


Road map

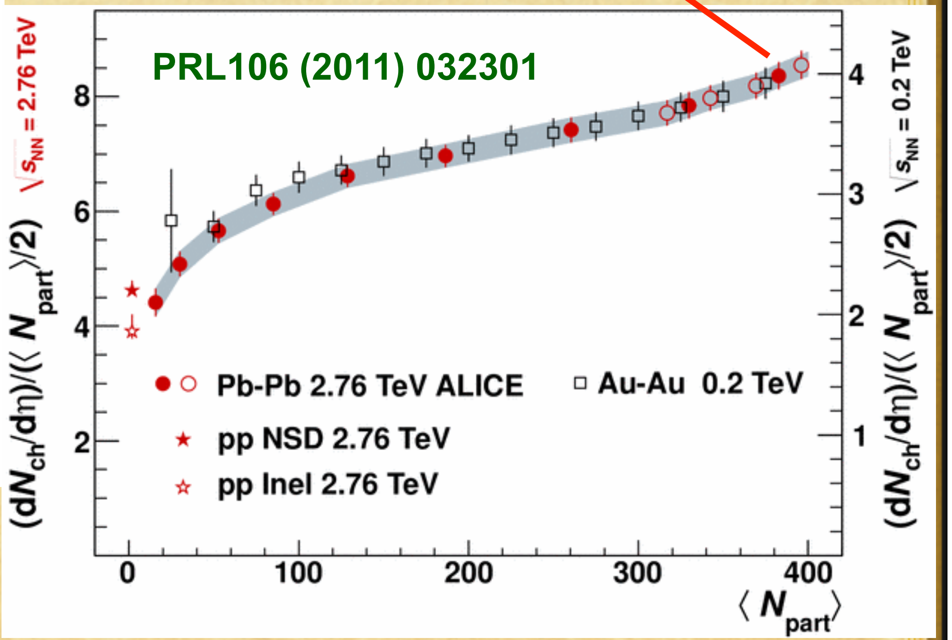

Freeze-Out
t
Hadron Gas
central region
QGP
beam
$\tau_0 \leq 1$ fm/c
β_T, T_{fo}
μ_B, T_{ch}
η/s, initial condition
Temperature (T_c)
Thermalization
Energy loss
γ-Jet
ALICE, Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Curves: Hydro (arXiv:1105.3226)
ALICE Preliminary
0-5% most central
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
Data: ALICE, 0-20% (preliminary)
Model calc. with parameters:
T=148 MeV, (μ_b = 1 MeV fixed)
T=164 MeV, μ_b = 1 MeV
τ=6.0 fm/c, η/s=0.16
CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
PbPb
A. Mocsy
Eur.Phys.J.C61,2009
Centrality 30-50%
SPS
RHIC
LHC

1. Low p_T single particle production

Charged particle multiplicity; $dN_{ch}/d\eta$



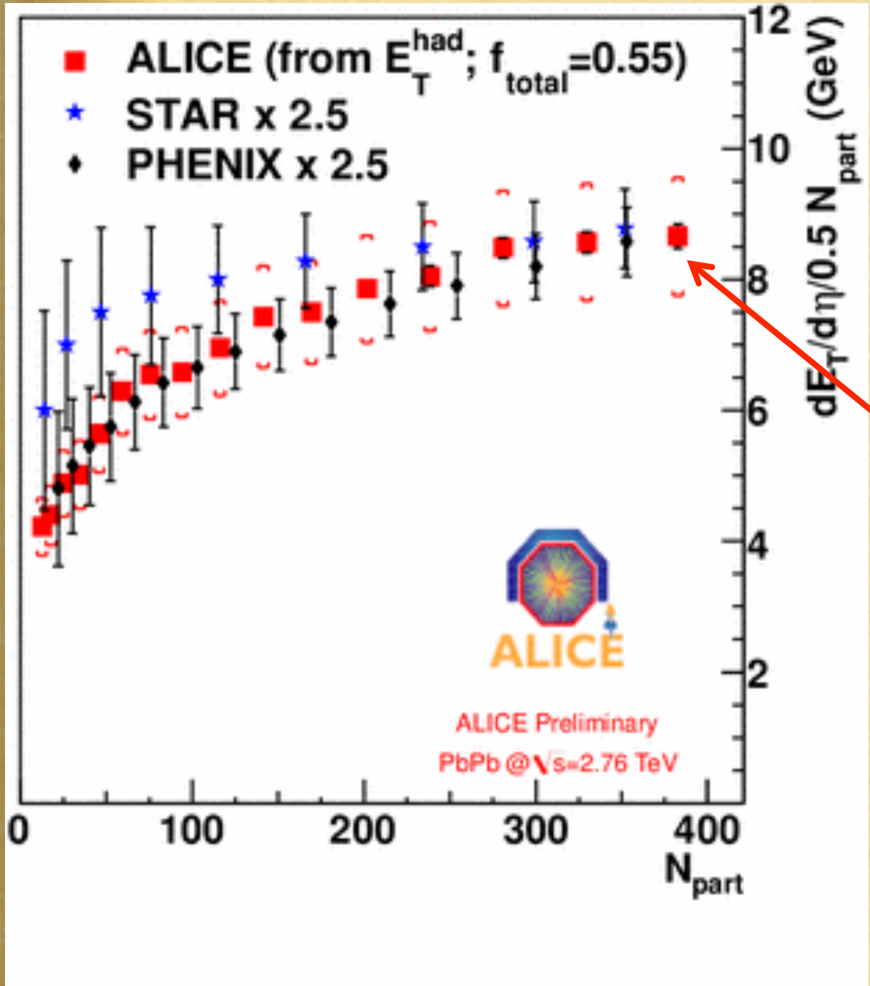
$\varepsilon_{Bj}\tau \cong 15\ \mathrm{GeV/(fm^2c)}$



- $dN_{ch}/d\eta = 1584 \pm 76$
- $(dN_{ch}/d\eta)/(N_{part}/2) = 8.3 \pm 0.4$
  - **≈ 2.1 x central AuAu at $\sqrt{s_{NN}}$=0.2 TeV**
  - **≈ 1.9 x pp (NSD) at √s=2.36 TeV**
- Stronger rise with √s in AA w.r.t. pp
- Stronger rise with √s in AA w.r.t. log extrapolation from lower energies

- **Very similar centrality dependence at LHC & RHIC**
  - ⇨ After scaling RHIC results (x2.1) to the multiplicity of central collisions at the LHC

Energy density from E_T



- From RHIC to LHC:
  - increase in $dE_T/d\eta$ per participant pair by a factor 2.5
  - Similar centrality dependence

- Energy density of the medium from Bjorken formula

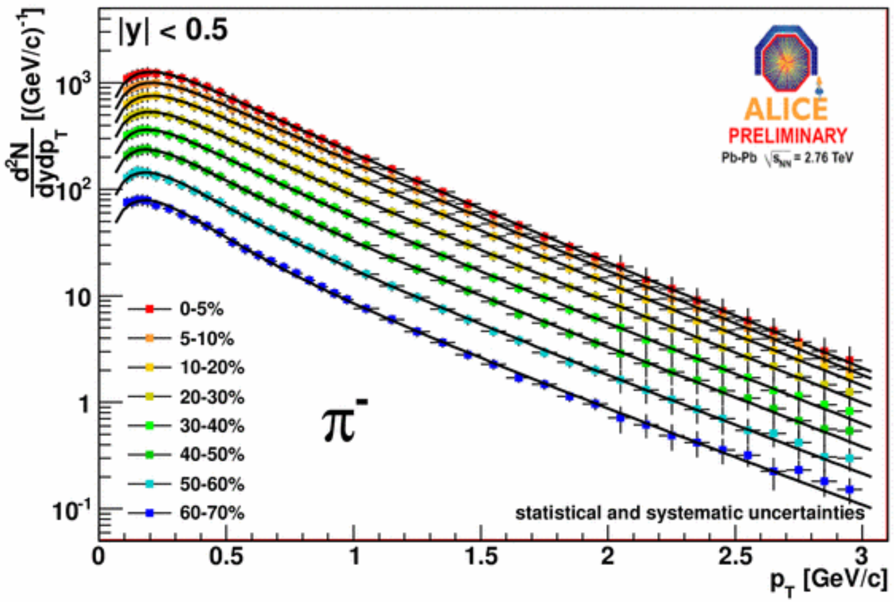
$$\varepsilon_{Bj} = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \qquad R = 1.12 A^{1/3}\ fm$$

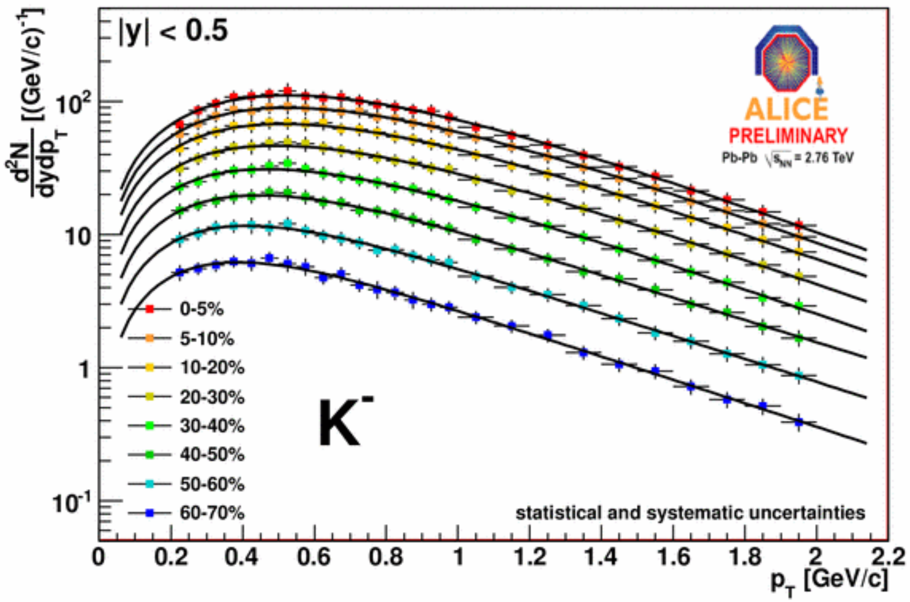
$$\varepsilon_{Bj} \tau \cong 16\ \mathrm{GeV/(fm^2c)}$$

  - Where τ = (unknown) formation time

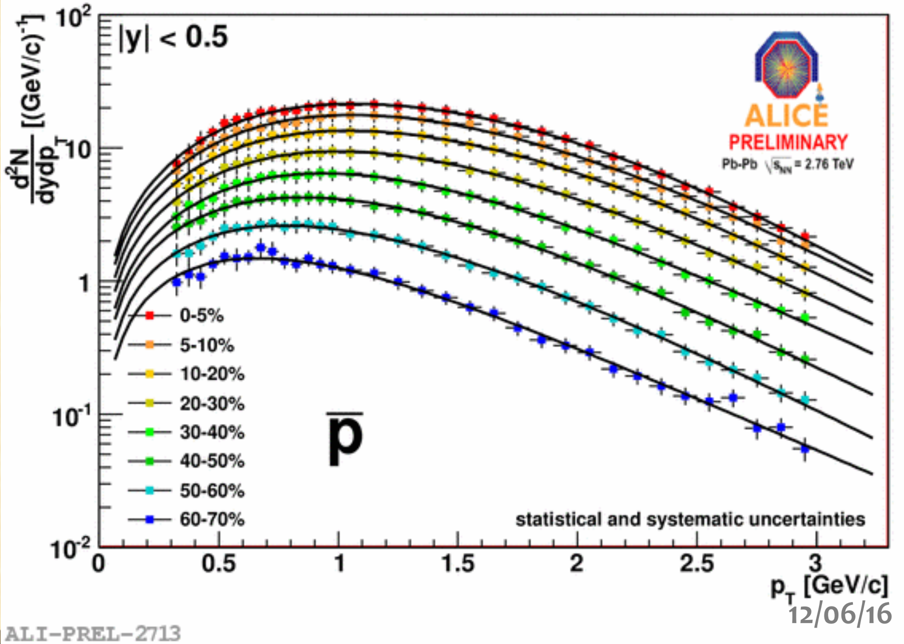
  - $\approx 3 \times \varepsilon_{Bj}\tau$ at RHIC
  - RHIC: $\varepsilon\tau$ =5.4±0.6 GeV/(fm²c)

Identified hadron spectra at LHC

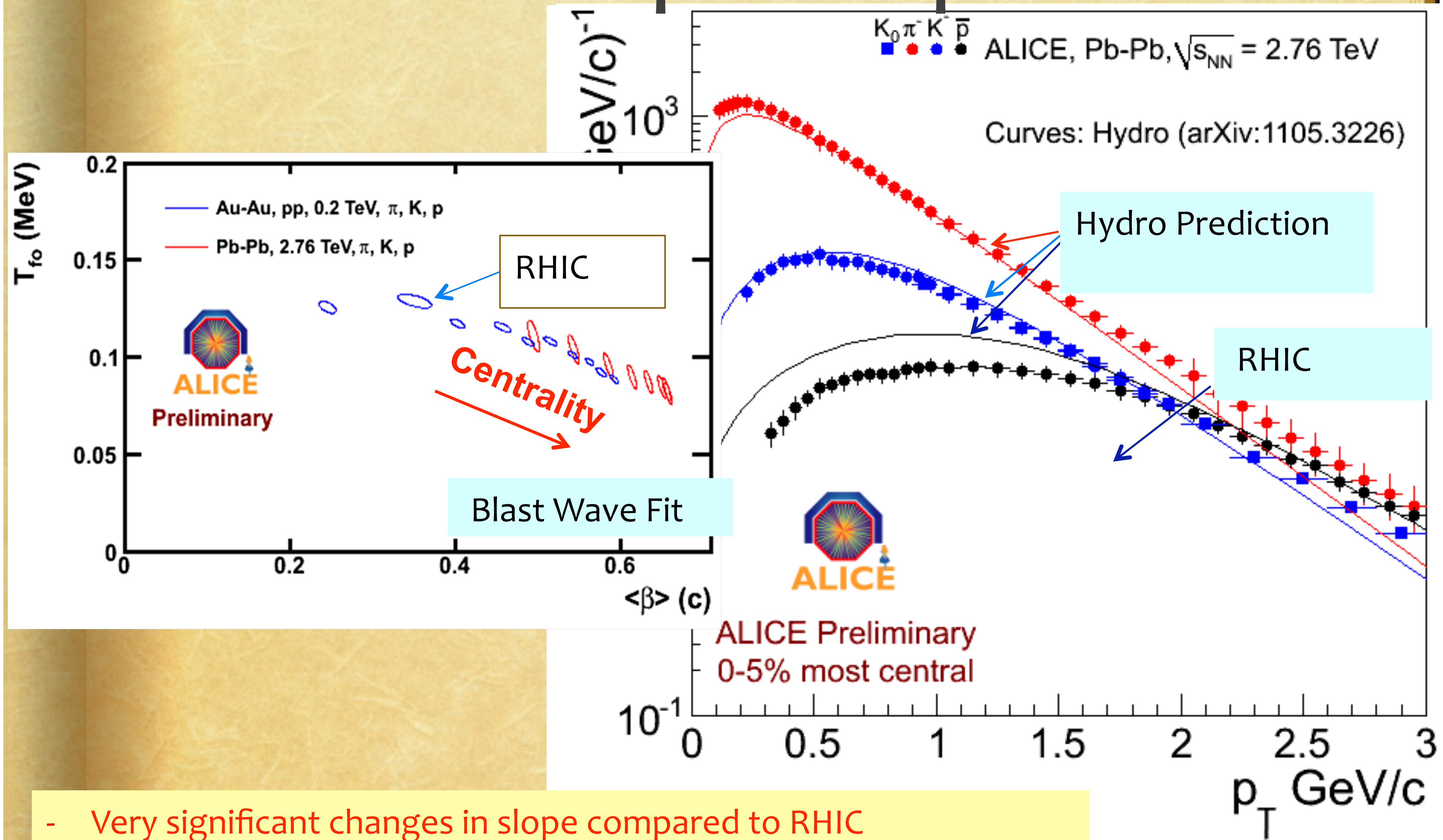




- ALICE data (combined analysis with ITS, TPC and TOF).
- Lines = blast-wave fits
  - ⇨ Parameters of the system at the kinetic freeze-out (T_{fo}, β_T)



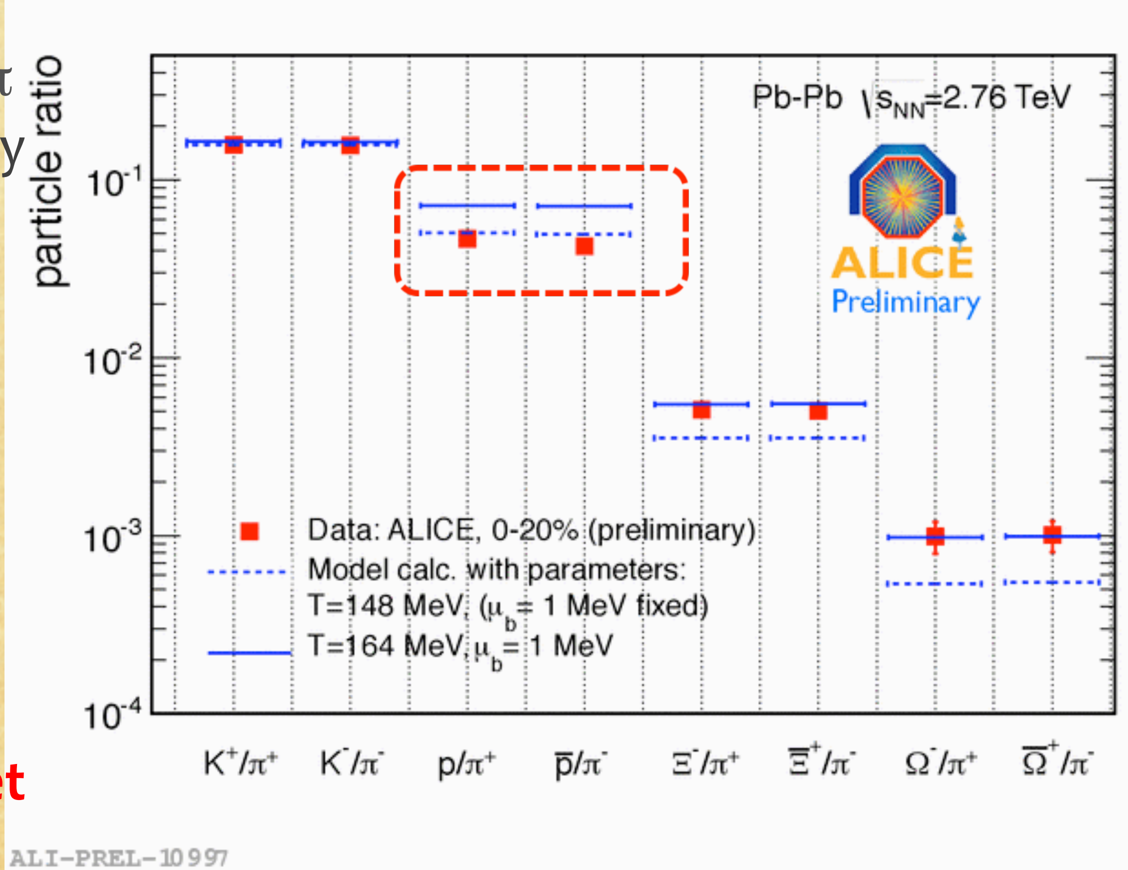
Identified particle spectra



- Very significant changes in slope compared to RHIC
- Most dramatically change for protons
- Very strong radial flow, β ≈ 0.66 (10% higher than RHIC)
- **Even larger than predicted by most recent hydro (e.g. protons)**

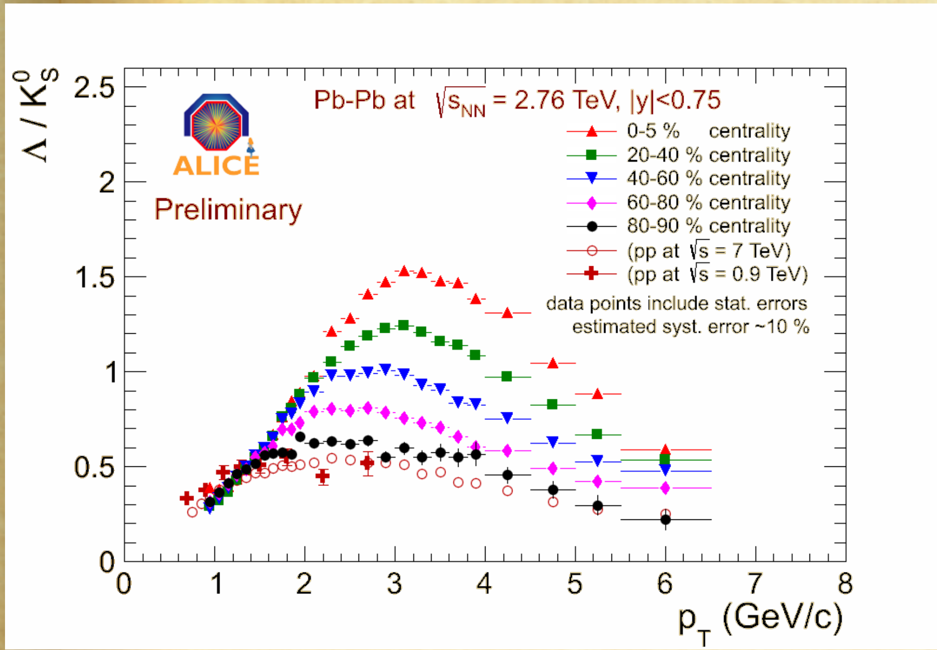
Thermal Model Comparison

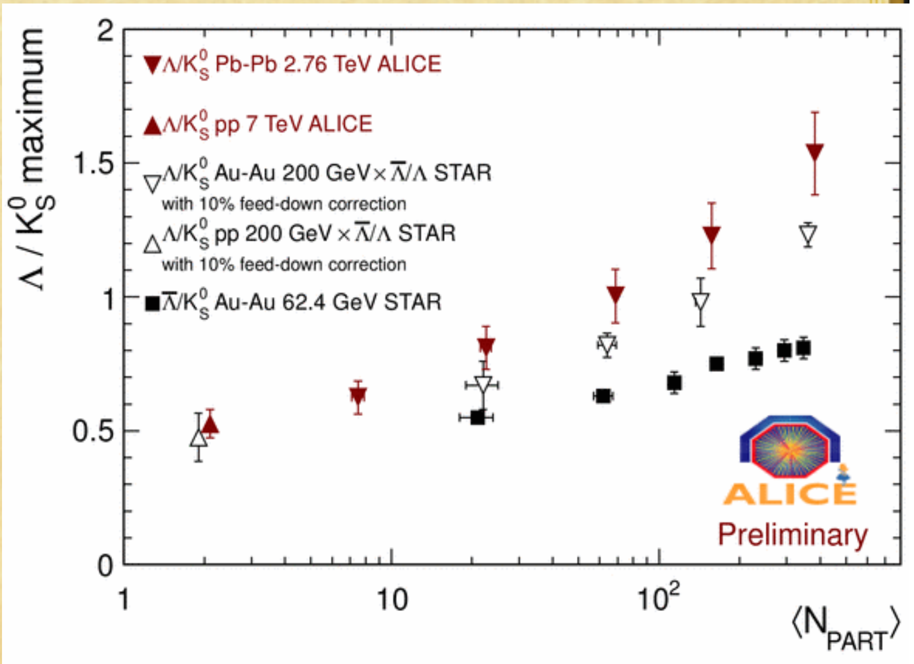
- All ratios other than p/π are predicted accurately
- γ_s=1
- **Protons: different T_{ch} than strange/multi-strange? Model may yet improve?**



A. Andronic et al, PLB 673: 142-145 (2009)

Intermediate p_T: Λ / K^0_S

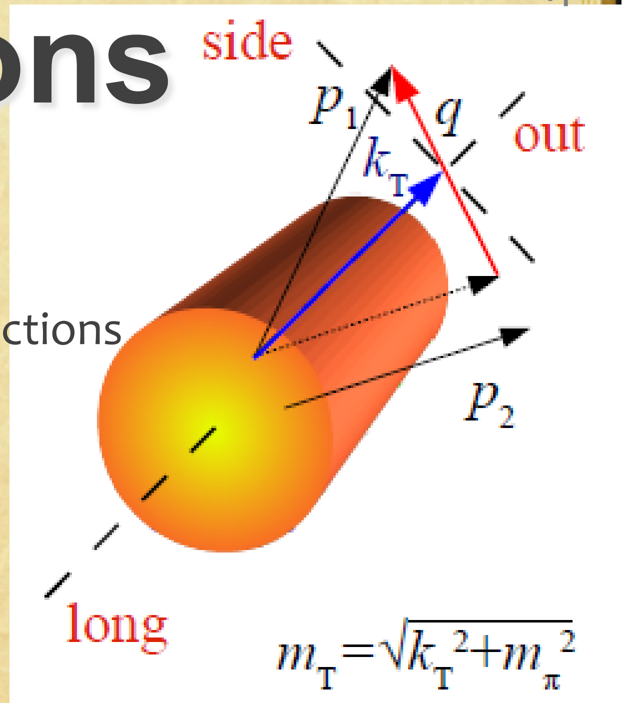




- Mid-p_T region: 2 <p_T <5 GeV/c
- Ratio >1 for spectra in 0-40% central collisions
- Maxima similar to 200 GeV RHIC at low N_{part}; possibly above RHIC at N_{part}>30

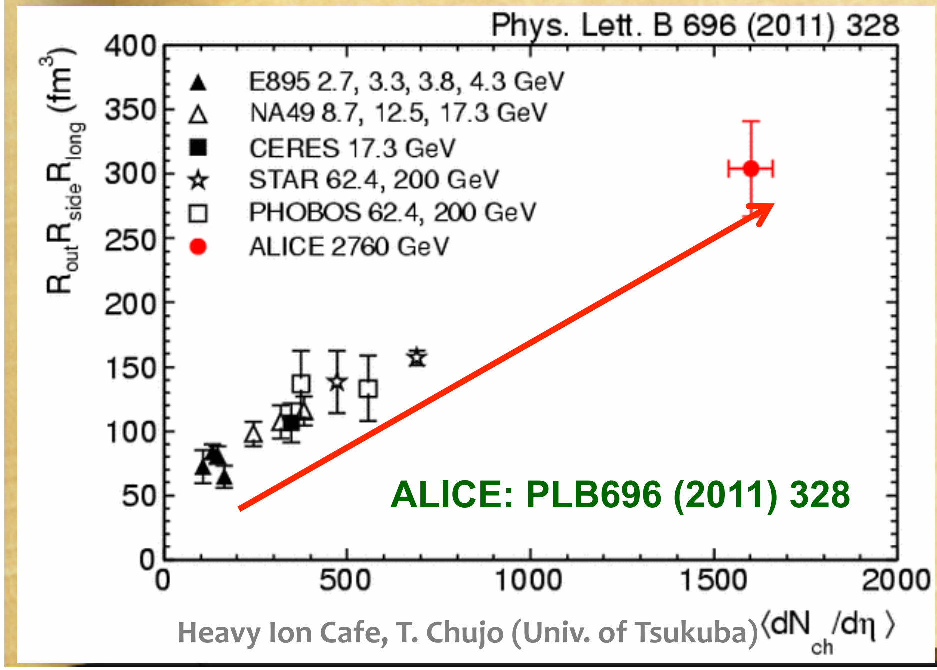
2. HBT

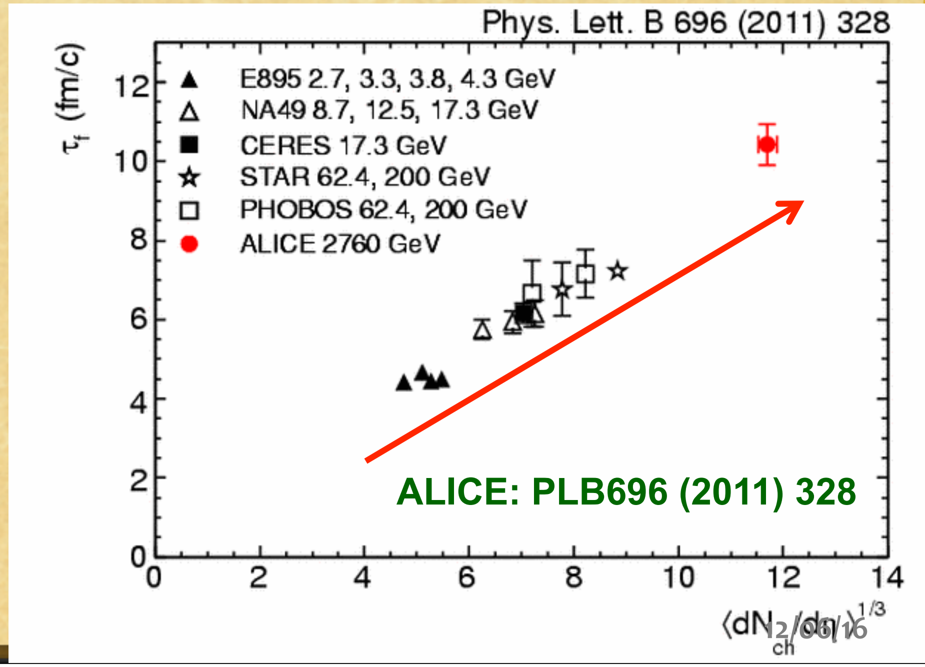
HBT correlations



- Spatial extent of the particle emitting source extracted from interferometry of identical bosons
  - Two-particle momentum correlations in 3 orthogonal directions → HBT radii (R_{long}, R_{side}, R_{out})
  - **Volume: x2 compared to RHIC**
  - **Lifetime from R_{long}: 40% higher than that at RHIC**

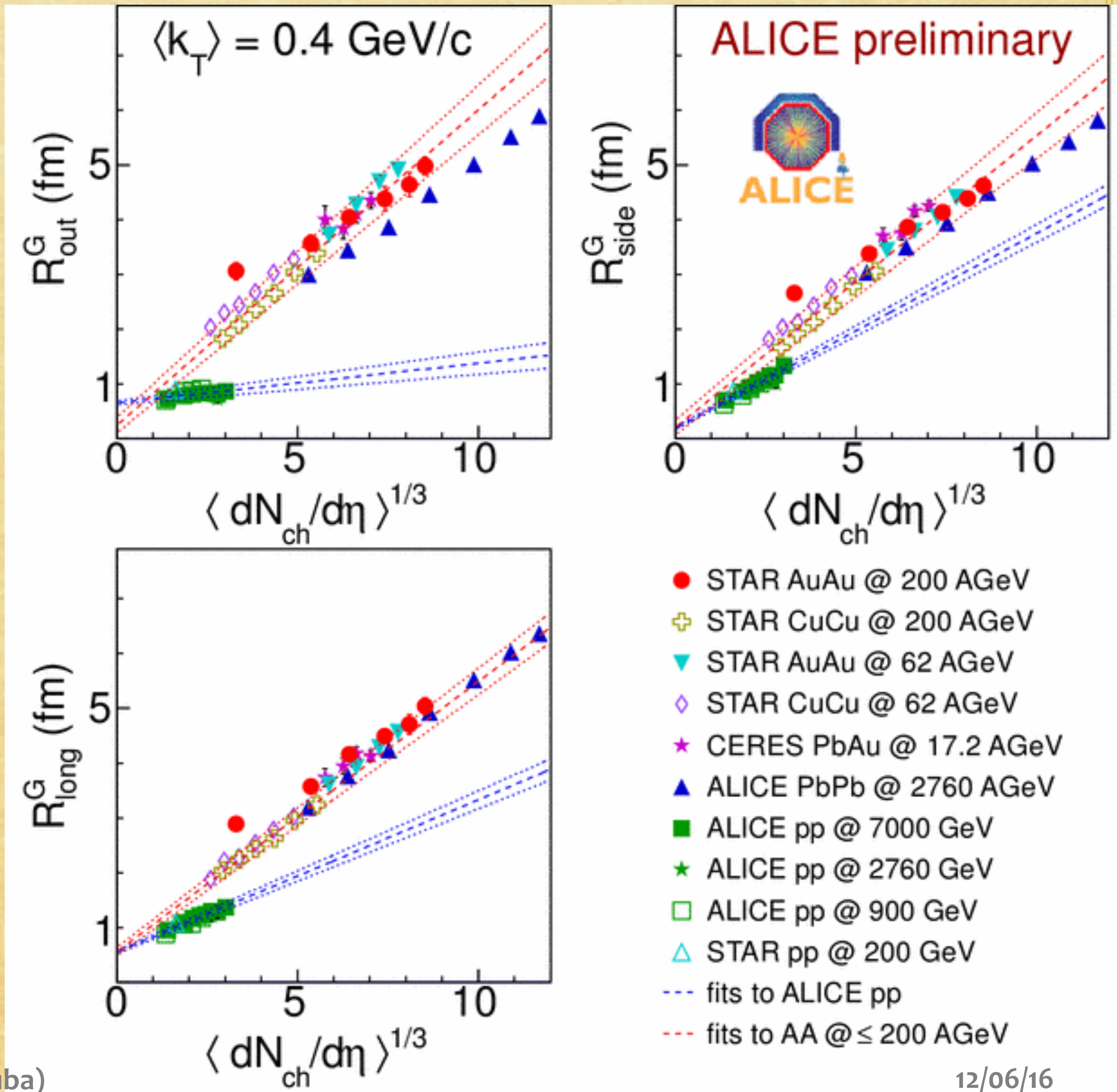
$$R^2_{\rm long}(k_T) = \frac{\tau_f^2 T}{m_T}\frac{K_2(m_T/T)}{K_1(m_T/T)},$$



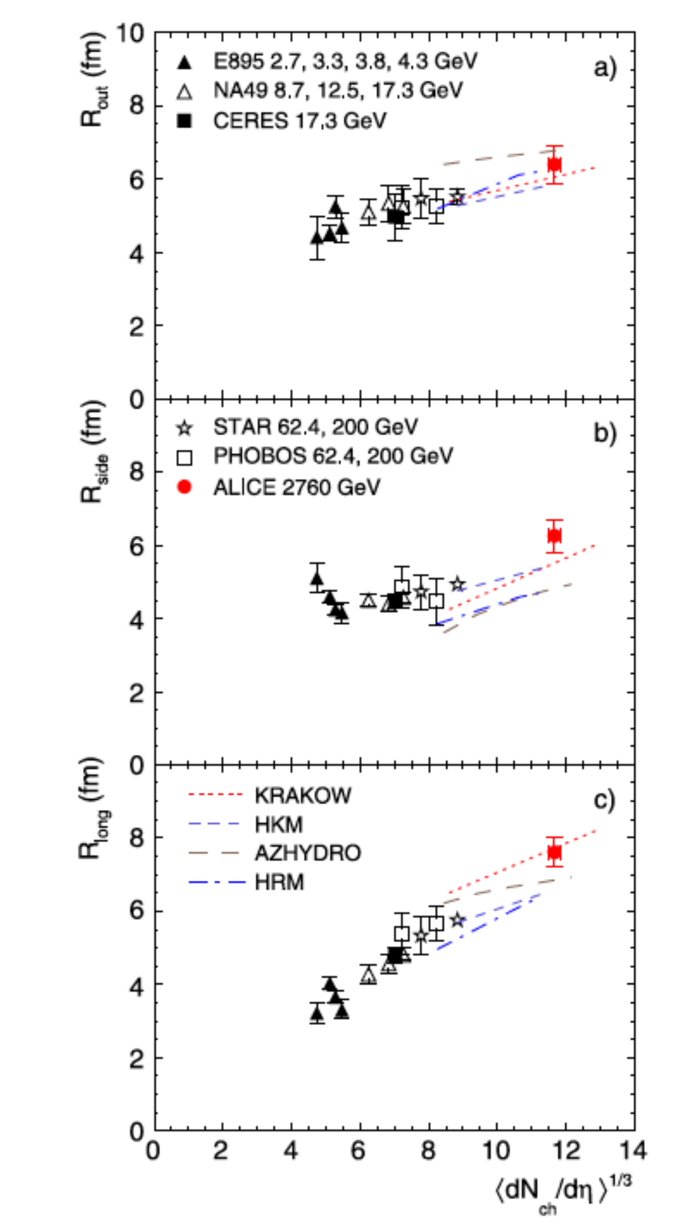


System size vs. multiplicity

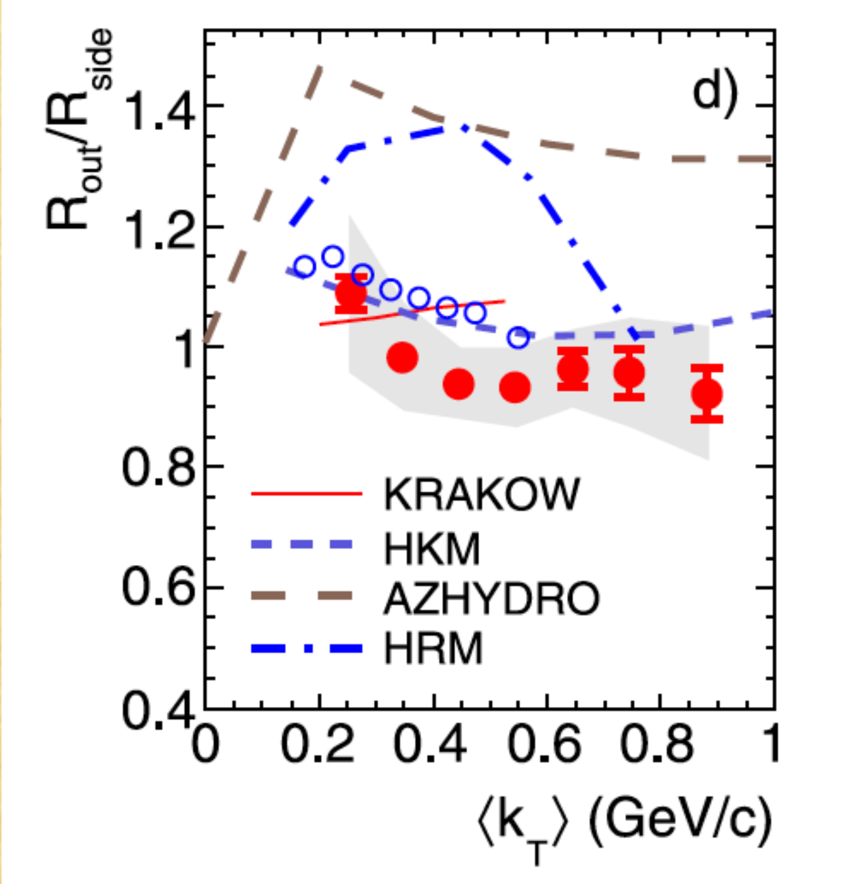
- HBT radii scale linearly with $\langle N \rangle^{1/3}$ in pp and PbPb, but with different slopes.
- HBT radii in PbPb vs. trend from lower energy AA:
  - R_{long}: perfectly agree
  - R_{side}: reasonably agree
  - R_{out}: clearly below the trend



HBT vs. Hydro

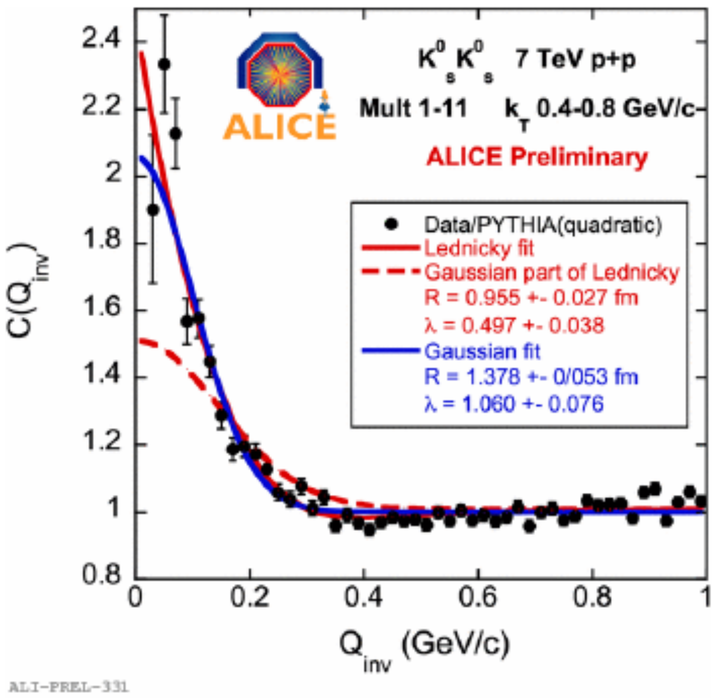


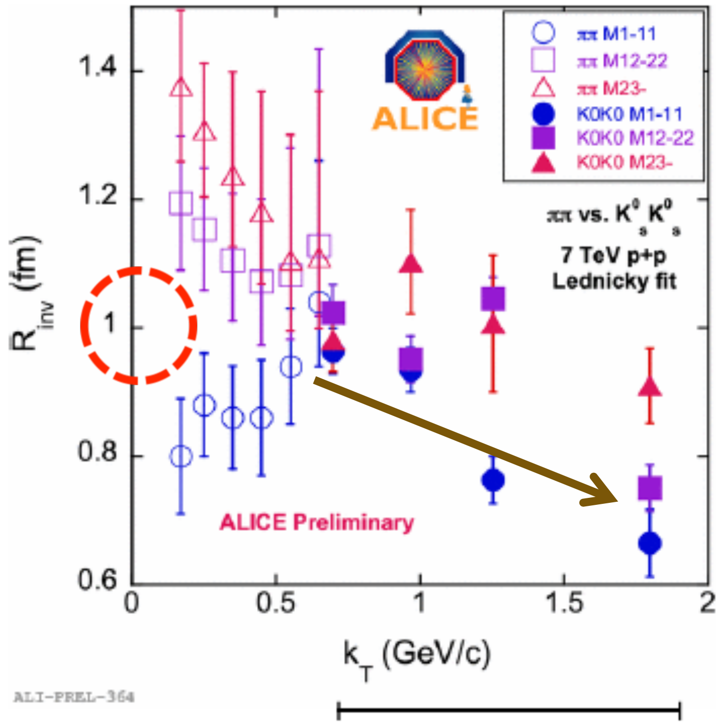
- Behaviour of all 3 radii in qualitative agreement with hydro expectations
- R_{out}/R_{side}: some model cannot describe the data.



ALICE: PLB696 (2011) 328

K^0_s HBT in p+p 7 TeV (1D)





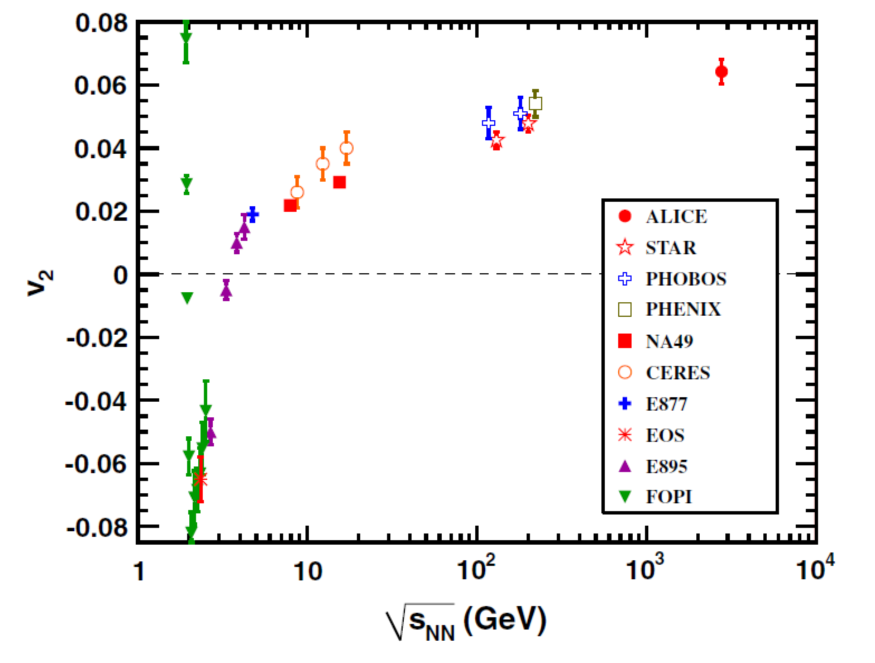
Extended k_t coverage

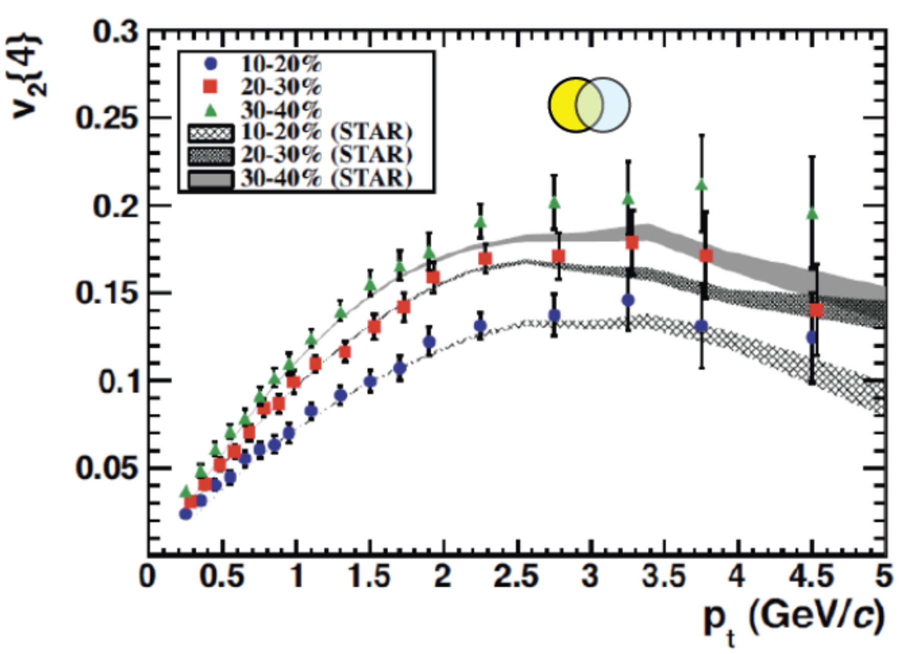
- Baseline estimated with PYTHIA.
- Strong interactions significant.
- Radii consistent with that from pion-pion channel.
- Low M Radii rise with kt for pions but not for K^0_S.
- Also being done in Pb-Pb 2.76 TeV!

Indication of k_T dep. of R_{inv} in p+p (radial flow)?

3. Flow & higher harmonics

v_2 at LHC (early results)

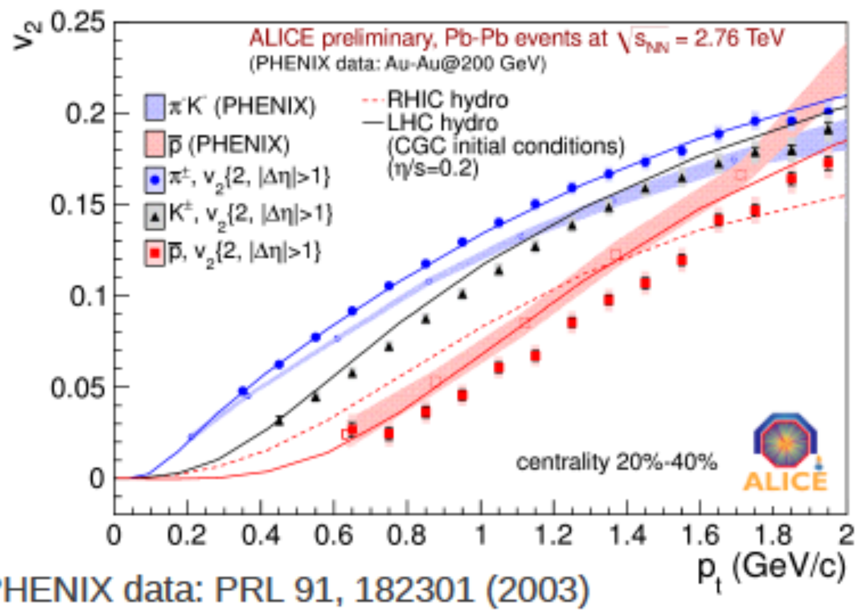




PRL 105 (2010) 252302

- At LHC, p_T integrated v_2 increases by 30% compared to RHIC data at $\sqrt{s_{NN}}$=200 GeV.
- v_2 vs. p_T does not change within uncertainties between $\sqrt{s_{NN}}$=200 GeV and 2.76 TeV
  - 30% increase of p_T integrated flow explained by higher mean p_T due to stronger radial flow at higher energies

Identified particle v_2



PHENIX data: PRL 91, 182301 (2003)
STAR data: PRC 77, 054901 (2008)
Hydro: Heinz et. al, arXiv:1105.3226

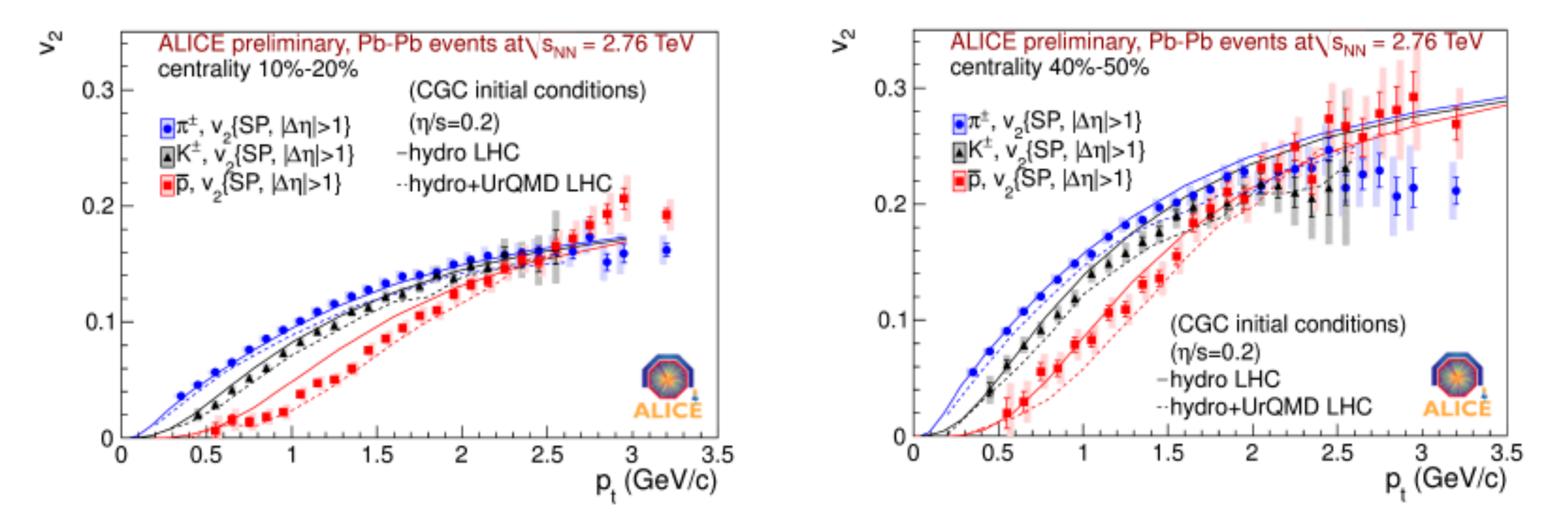
Comparison with PHENIX results and hydro

- Large mass splitting at LHC compared to RHIC as predicted by hydrodynamics models.
- Pion v_2: described well by hydro. predictions with MC-KNL CGC initial conditions and $\eta/s = 0.2$.
- (K and) Anti-protons: overestimated by the same calc. for central collisions.
  - ✓ Larger radial flow than in the Hydro model
  - ✓ Rescatterings in the hadronic phase play an important role (arXiv:1108.5323)

Identified particle v_2

10-20%

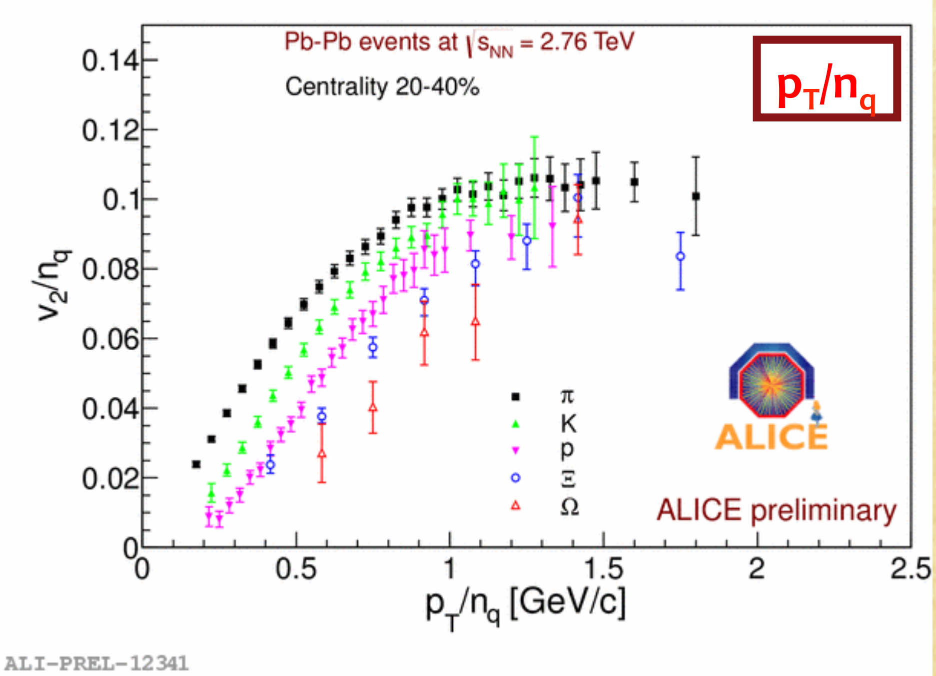
40-50%

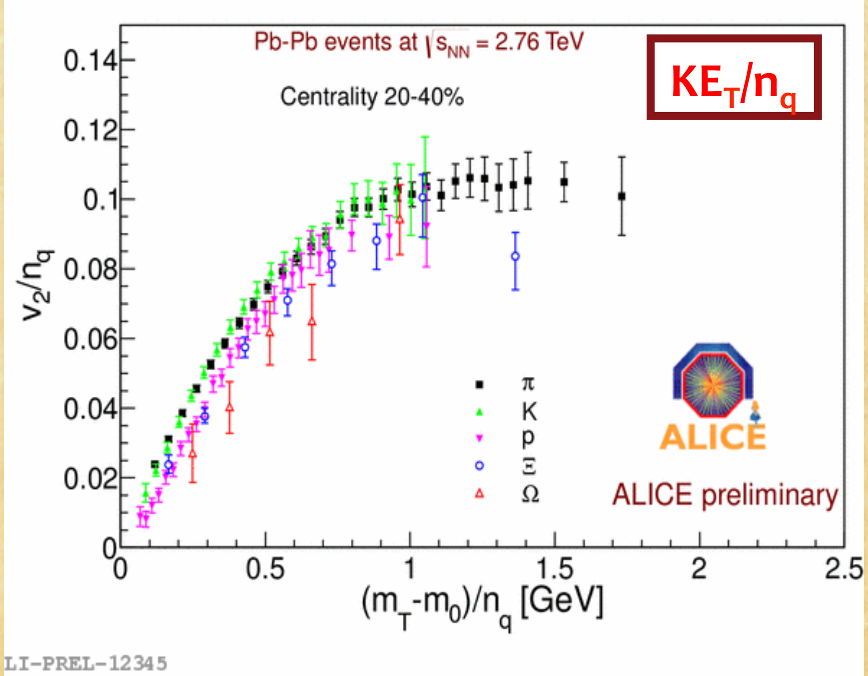


VISHNU: Heinz et. al, arxiv:1108.5323

Anti-proton v_2 is better reproduced by hydro calc. followed by the UrQMD afterburner model for central collisions..

Quark number scaling of v_2 with strangeness

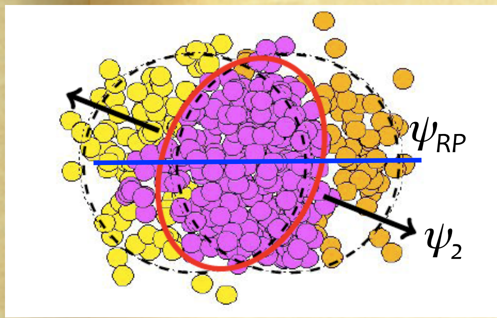


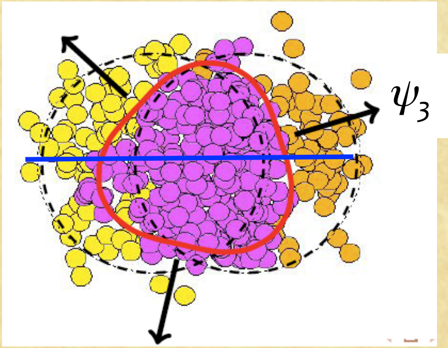


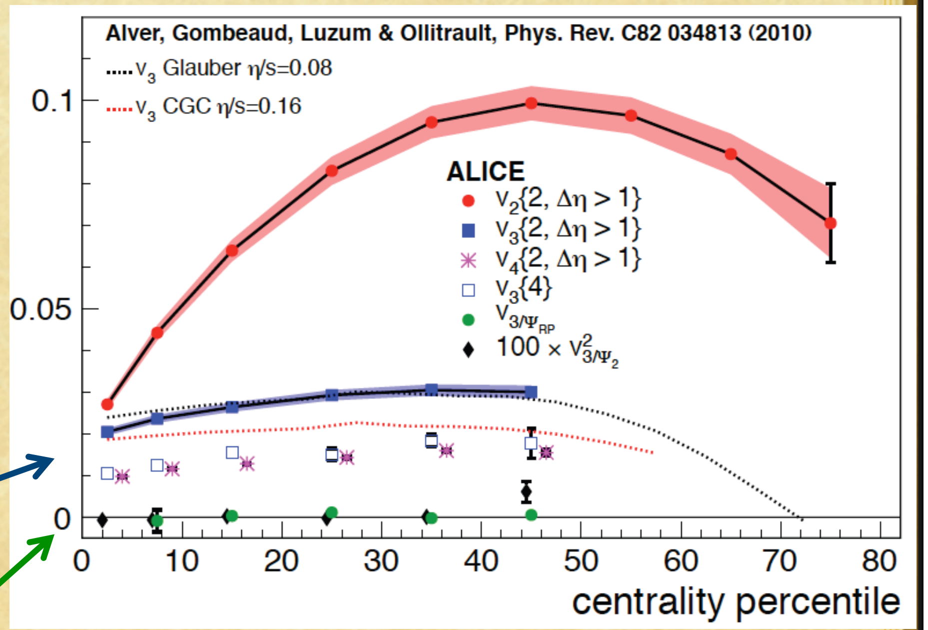
- Just simple p_T/n_q scaling does not work at LHC.
- Scaling works better as a function of transverse energy, but not perfect.

Higher order harmonics; v_n

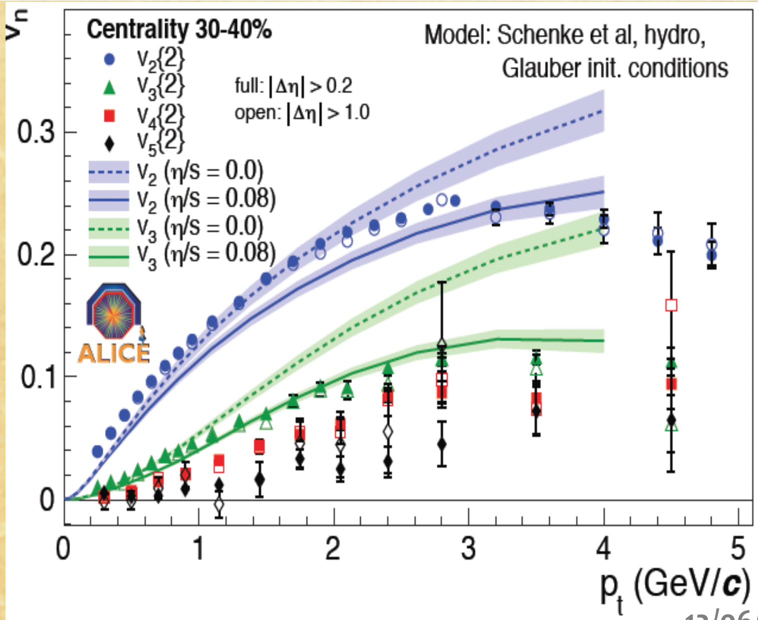
PRL 107, 032301 (2011), ALICE





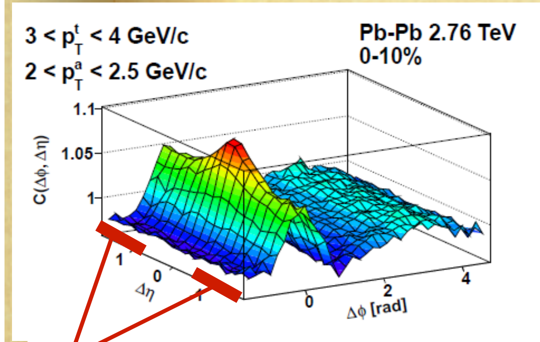


- v_3 ("triangular") harmonic:
  - v_3 has weaker centrality dependence than v_2
  - When calculated w.r.t. participant plane, v_3 vanishes due to fluctuations.
  - well described by Glauber with η/s = 0.08.



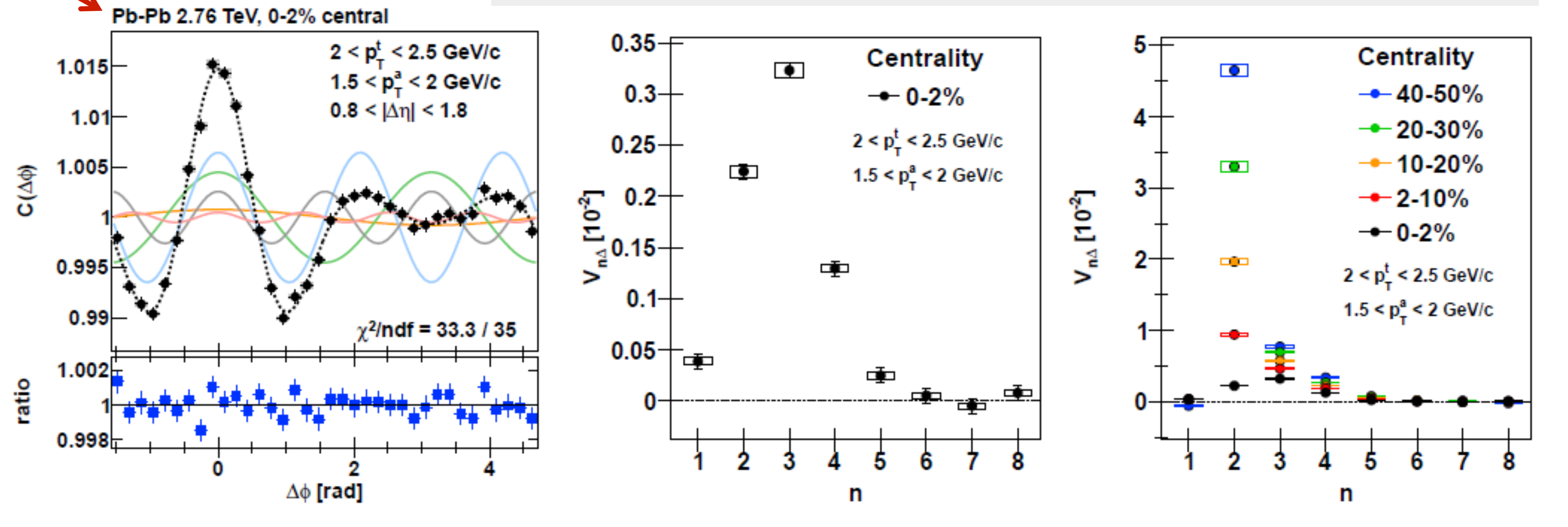
- p_T dependence for v_2, v_3, v_4, v_5
  - **v_3 sensitive to shear viscosity η/s and to initial conditions (Glauber, CGC) .**
  - No simultaneous description of v_2 and v_3 with the same η/s.

Fourier decomposition in di-hadron corr.



- Extract 1D Δφ correlations by integrating the C(Δη,Δφ) in 0.8<|Δη|<1.8 range and do a Fourier decomposition

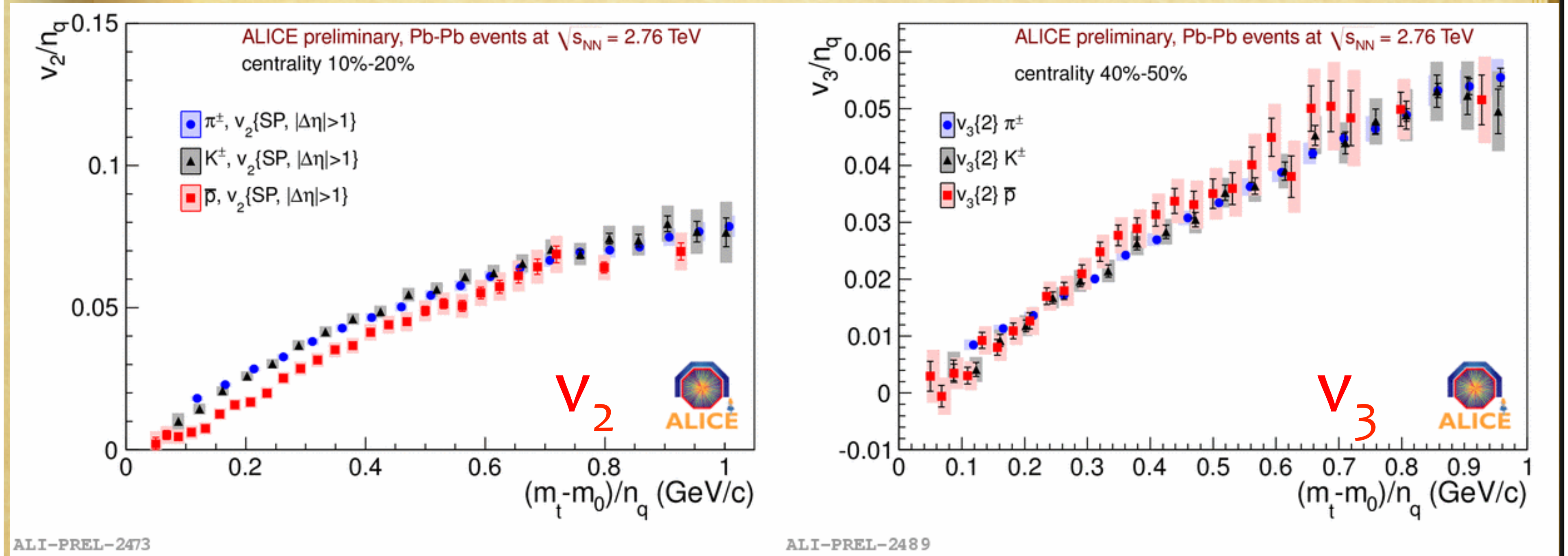
$$C(\Delta\varphi) = \frac{1}{\Delta\eta_{\max} - \Delta\eta_{\min}} \int_{\Delta\eta_{\min}}^{\Delta\eta_{\max}} C(\Delta\eta, \Delta\varphi) \propto 1 + 2\sum_{n=1} v_{n\Delta} \cos(n\Delta\varphi)$$



- 5 components describe completely the correlations at large Δη and low p_T
  - ⇨ Strong near-side ridge + double-peaked structure on away side

arXiv:1109.2501

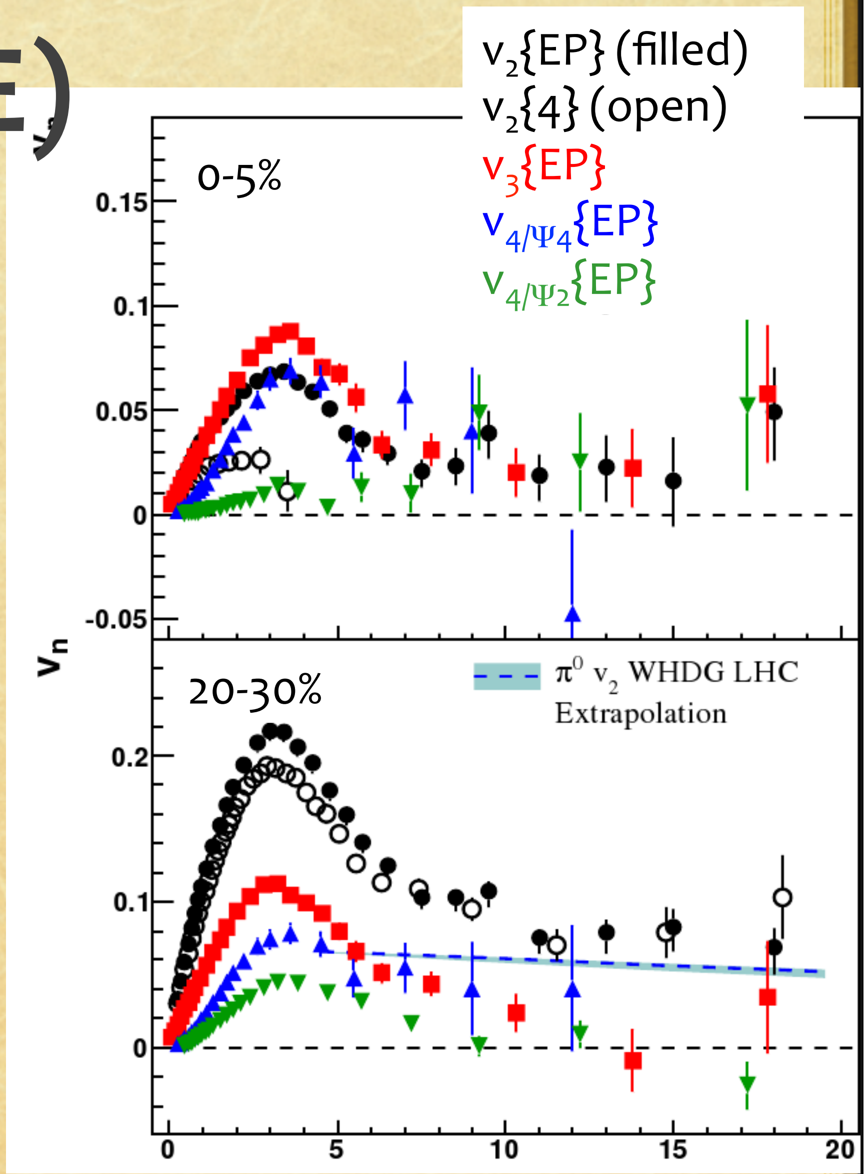
Quark number scaling; v_2 & v_3



- v_2 scaling with number of constituent quarks (NCQ).
  - Holds for π and K, but anti-protons do not follow the scaling.
    - Breakup more pronounced for more central collisions.
- v_3 scaling with NCQ: marginal (coincidence?)

Flow (v_2, v_3, v_4) at High p_T (ALICE)

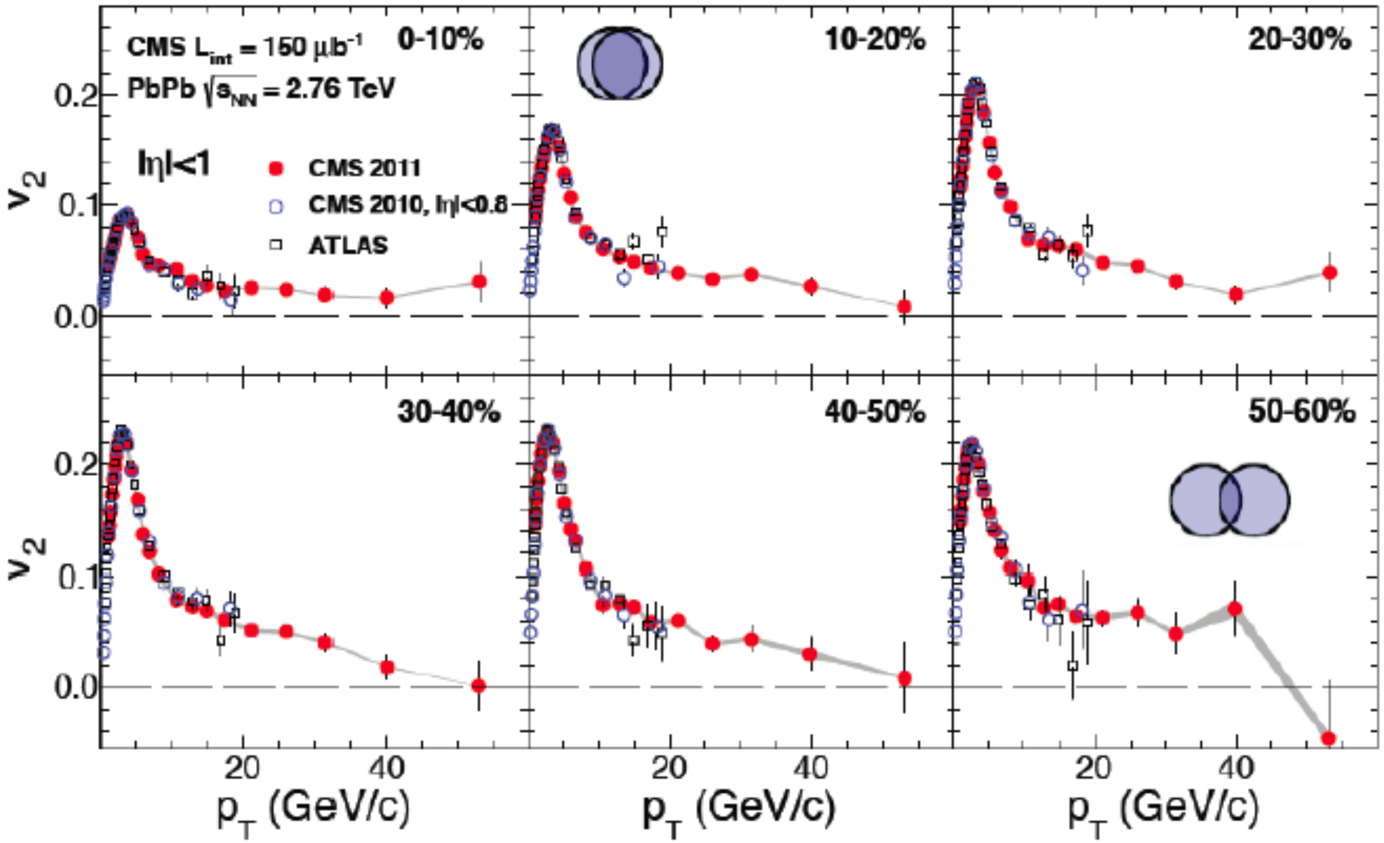
- v_2, v_3, v_4 were measured up to 20 GeV/c in 6 centrality classes (0-5% to 40-50%).
- **v_2 flattens at high p_T, stays positive and increases towards mid-centrality**
  - Path-length dependent quenching
  - Described by WHDG calculation
- v_3 shows weak centrality dependence
- v_4 consistent with 0 within (large) uncertainties for p_T > 8 GeV/c.

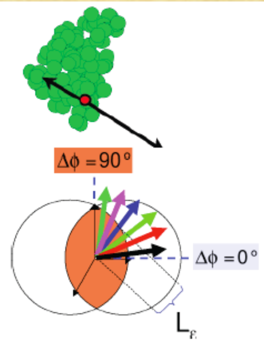


ALICE arXiv:1205.5761 p_T (GeV/c)

v_2 beyond p_T > 20 GeV/c (CMS)

arXiv:1204.1850



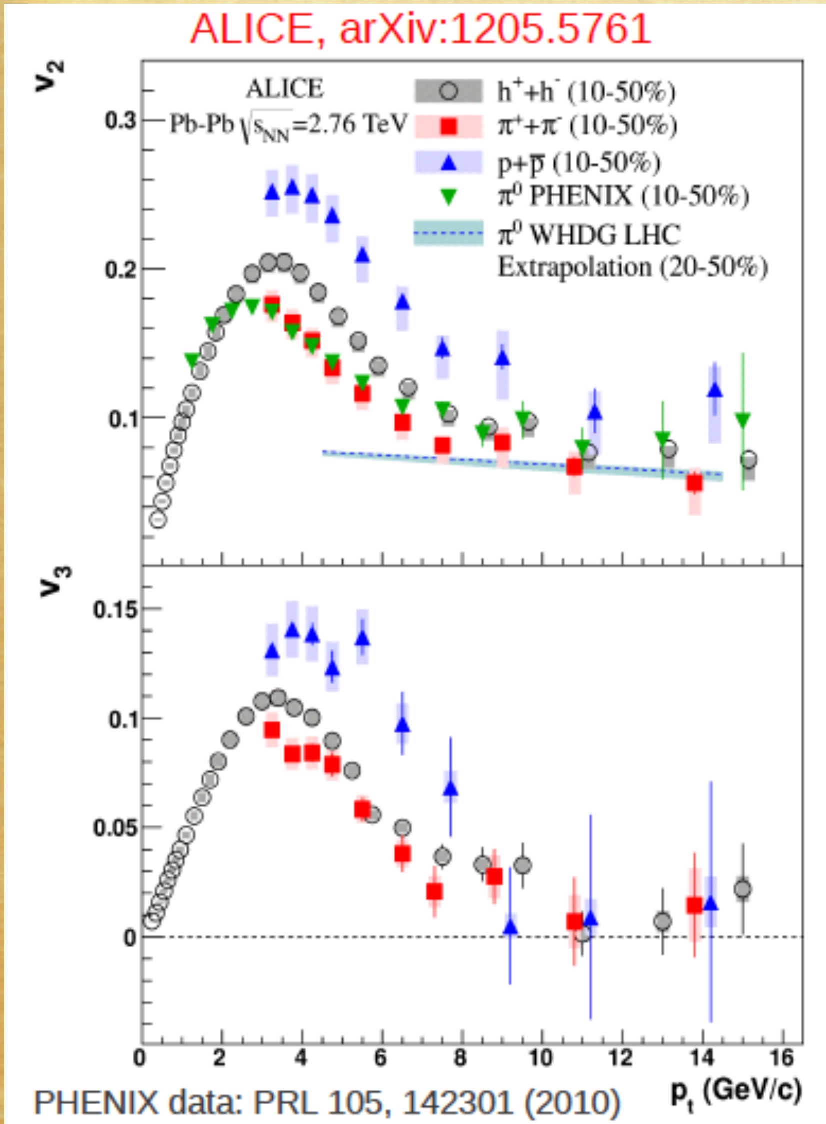


$\Delta E \sim L^{\alpha}$:
α = 1 for QCD, collisional
α = 2 for QCD, radiative
α = 3 for AdS/CFT

First v_2 measurements for p_T > 20 GeV/c
Gradual decrease of v_2 above 10 GeV/c

Charles Maguire (Vanderbilt) 25 Hard Probes 2012 (Sardinia)

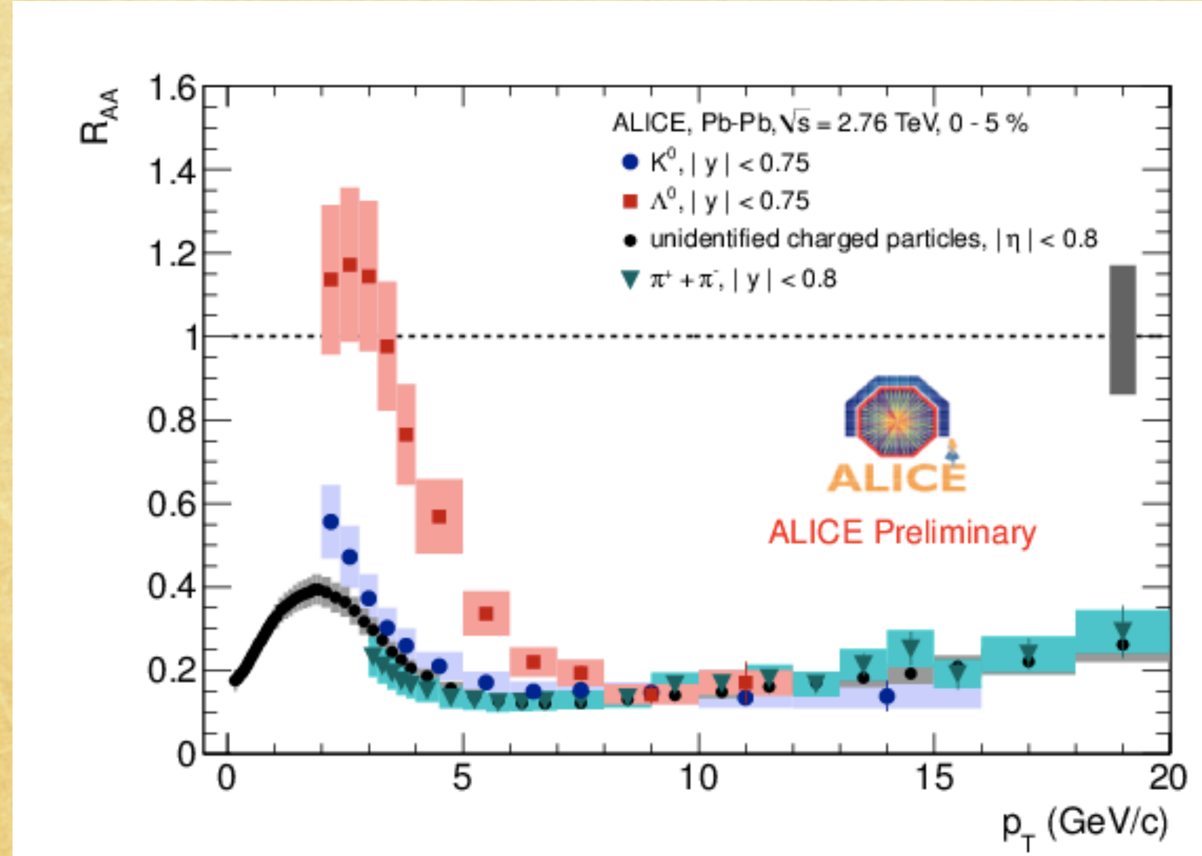
PID v_n at high p_T (ALICE)



- (Anti-) proton v_2 and v_3 higher than that of pions out to at least p_T = 8 GeV/c.
  - Particle type dep. persists out to high p_T.
- Charged pion v_2: reproduced by WHDG π^0 predictions for p_T > 7 GeV/c.
- Charged pion v_2 (ALICE) ~ π^0 v_2 (PHENIX).

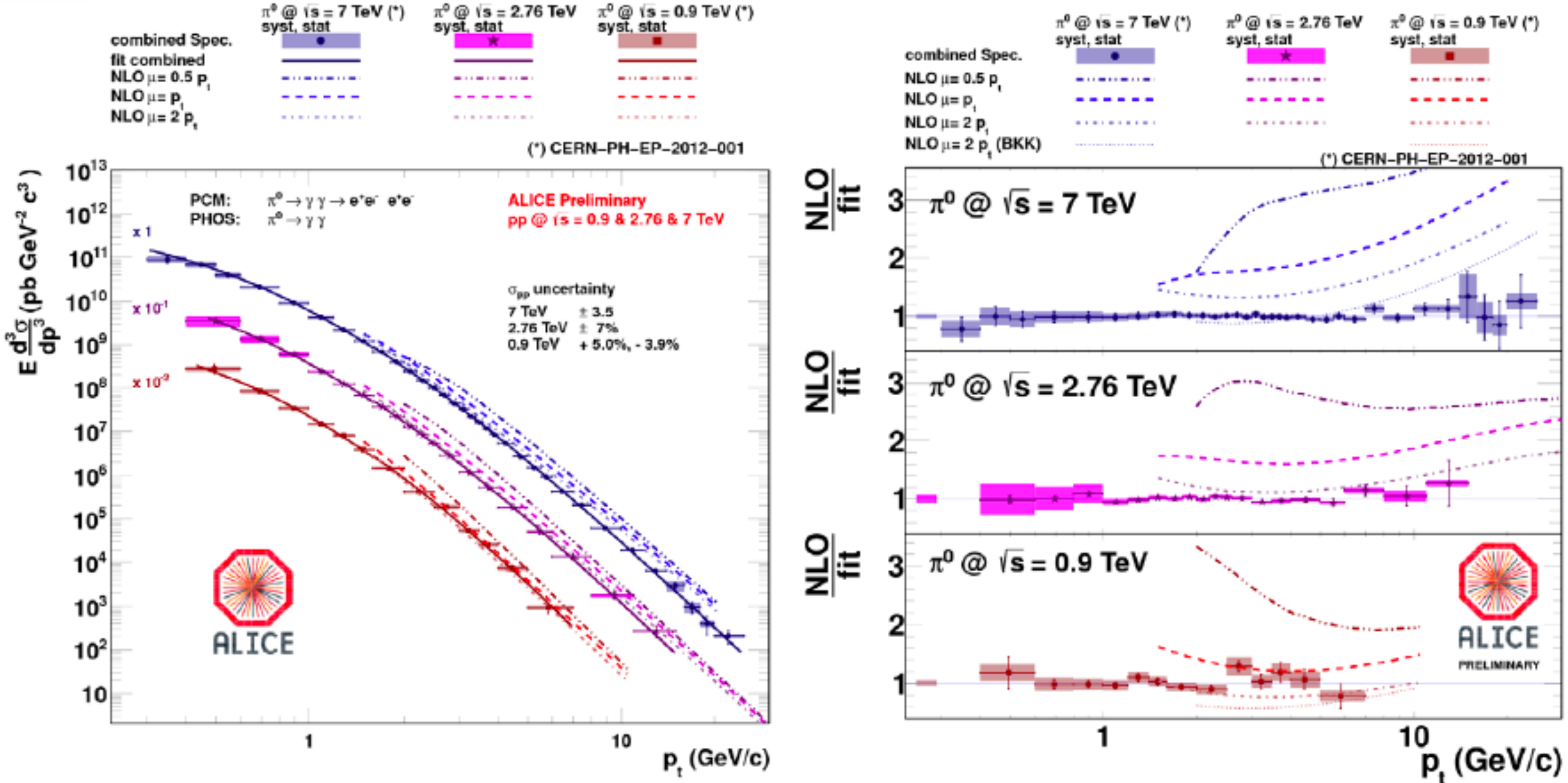
4. High p_T single hadron production from hard scattering

R_{AA} for light quark hadrons



- Light quark hadrons with p_T > 8 GeV/c are equally suppressed
- This seem to indicate that medium interactions do not affect fragmentation for p_T > 8 GeV/c - fragmentation occurs into vacuum

π^0 spectrum in pp @ 0.9, 2.76, 7 TeV

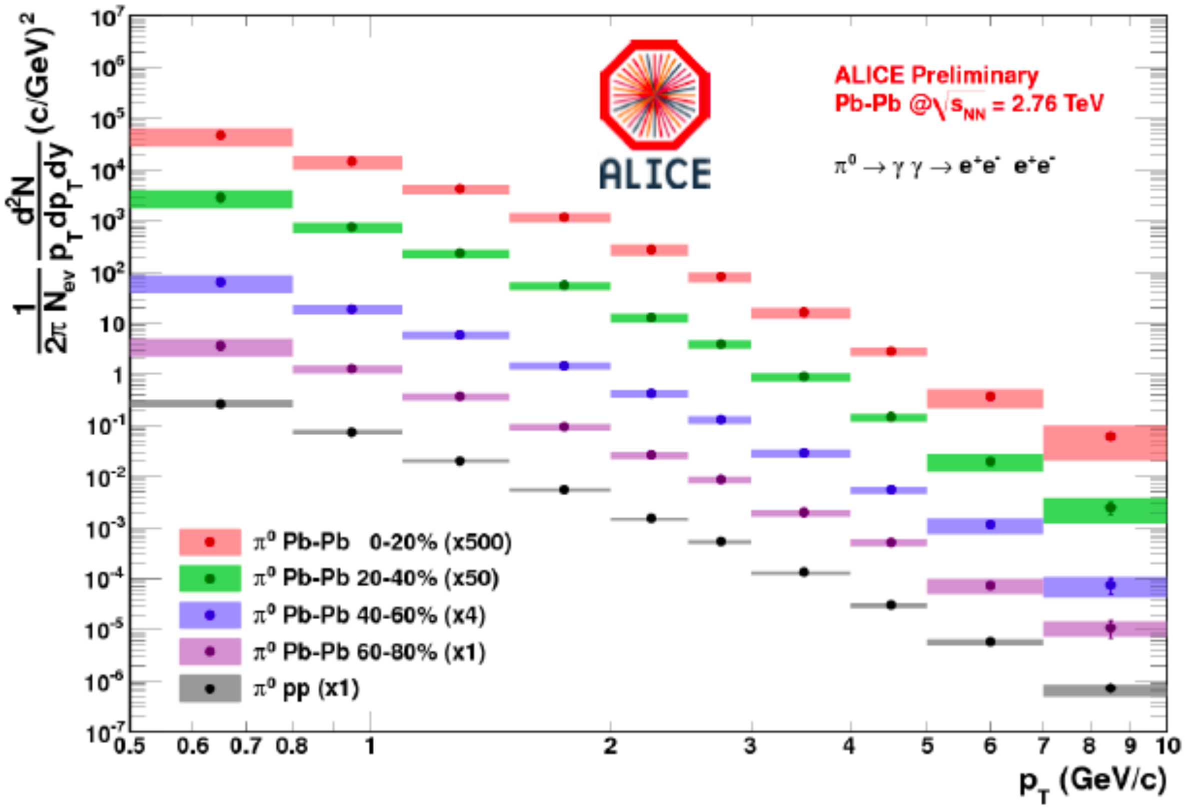


pQCD NLO calculations [*] can reproduce data at √s=900 GeV, but overestimate π^0 spectrum at √s=2.76 and 7 TeV.

[*] P. Aurenche et al., Eur. Phys. J. C13, 347-355 309 (2000).

ALICE data: CERN-PH-EP-2012-001, arXiv.1205.5724

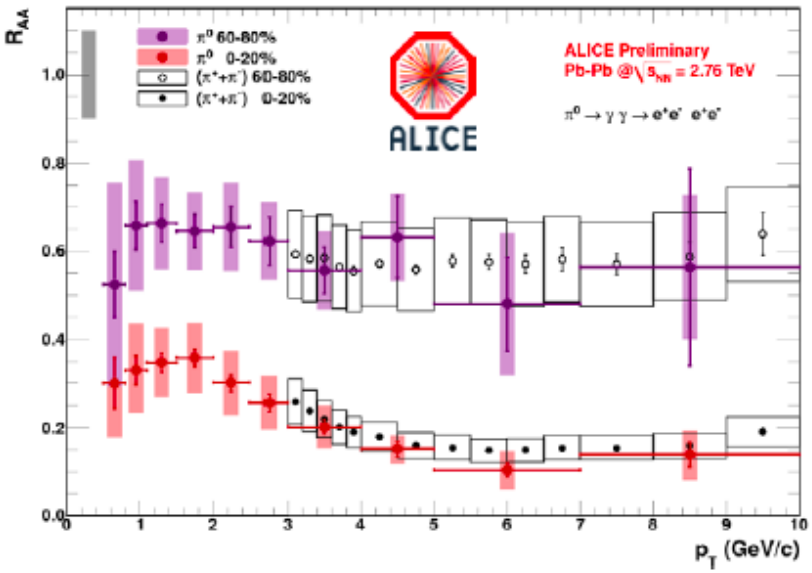
π^0 spectrum in Pb-Pb @ 2.76 TeV



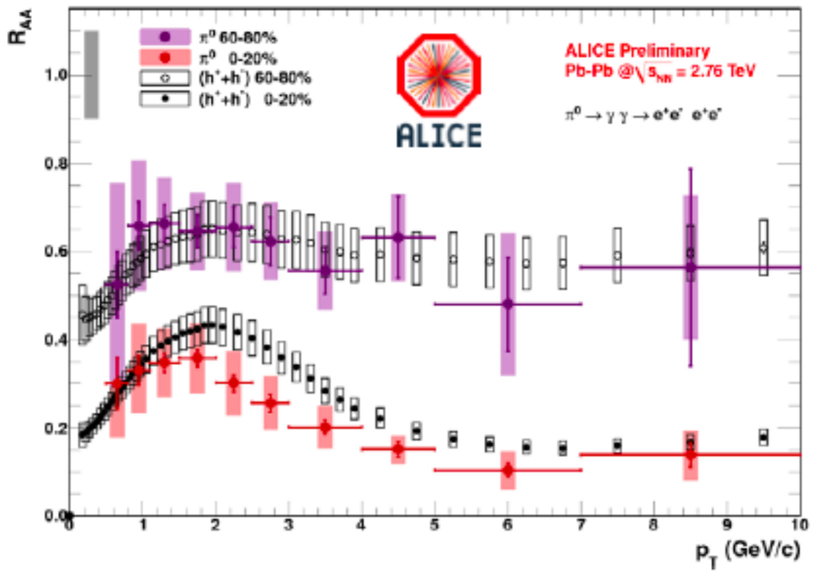
The first result on π^0 production in 4 centrality classes was obtained via photon conversion [G.Conesa Balbastre et al., ALICE collaboration. J. Phys. G: Nucl. Part. Phys. 38 (2011) 124117]

R_{AA} for π^0, $\pi^\pm$ and charged particles in Pb-Pb @ 2.76 TeV

comparison w/ charged pions



comparison w/ h^{+-}

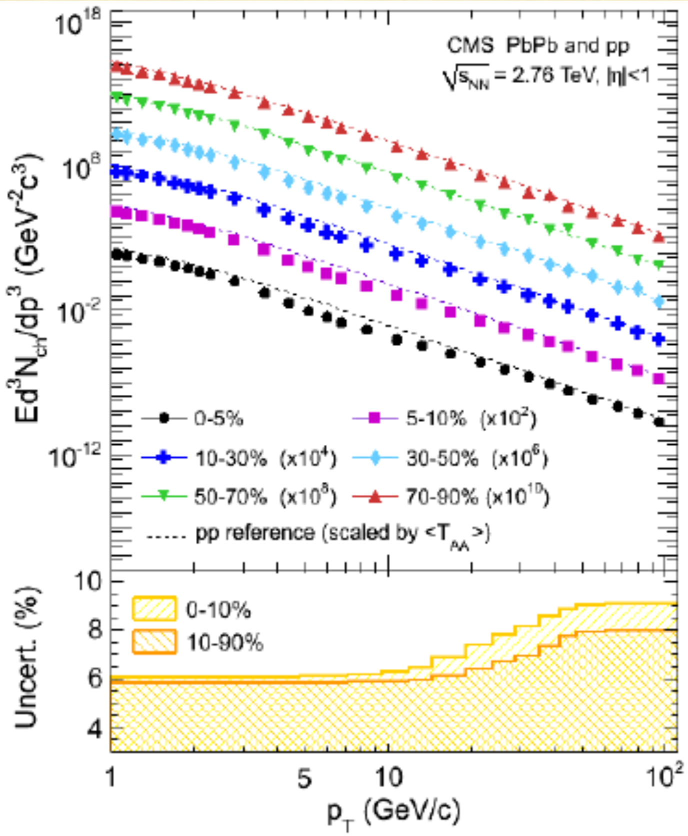


- Neutral and charged pions have similar suppression in Pb-Pb collisions, as expected
- At lower p_t, neutral pions are slightly more suppressed in the most central collisions compared to unidentified charged particles.

→ affected by baryons

28.05.2012 pi0,eta @ HP2012 17

h^{+-} spectra in Pb-Pb (CMS)

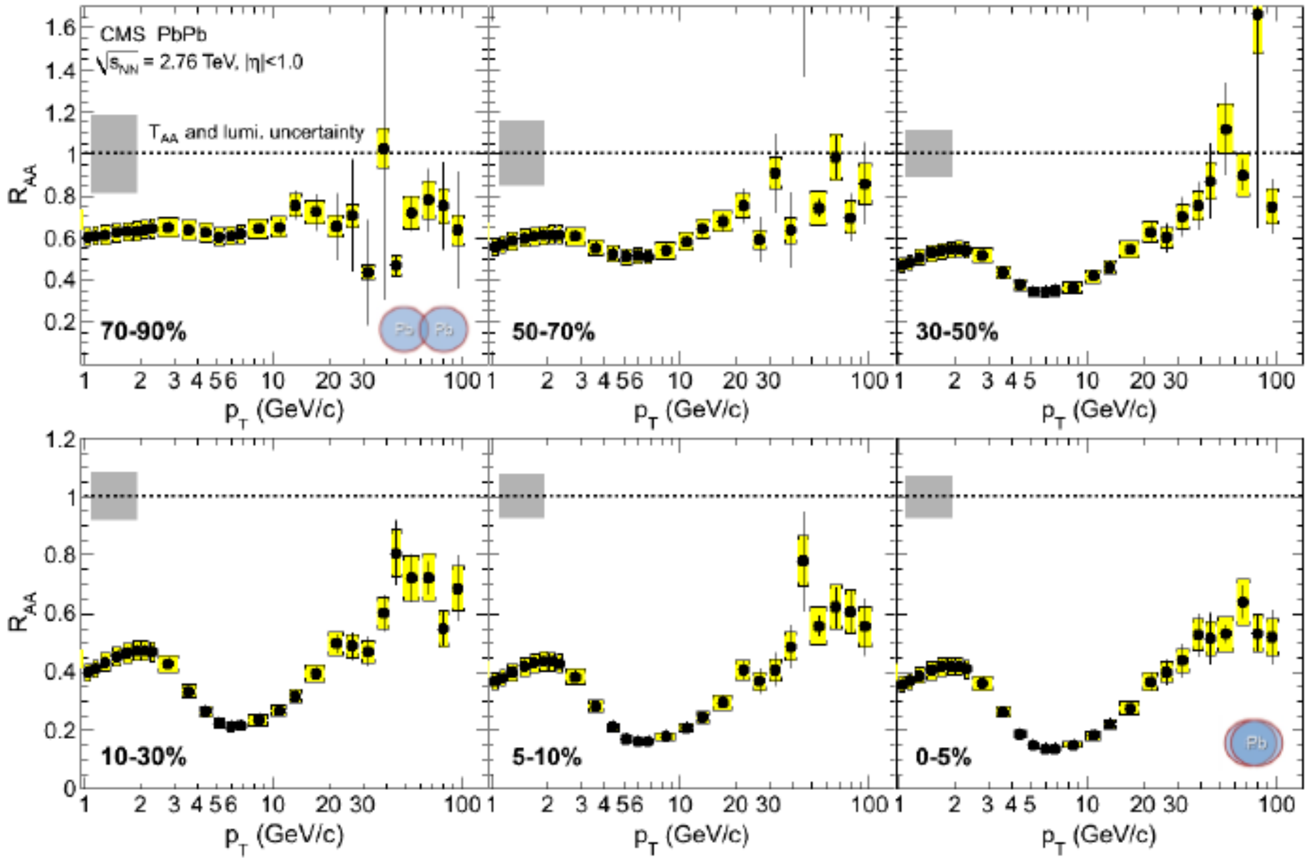


- Measured up to 100 GeV/c in six centrality bins
- Uses full 2011 run statistics at high p_T (150 μb^{-1})

EPJC 72 (2012) 1945

Krisztián Krajczár (MIT) Hard Probes 2012, 27 May – 1 June, Cagliari, Sardinia 10

Charged Particle R_{AA} (CMS)

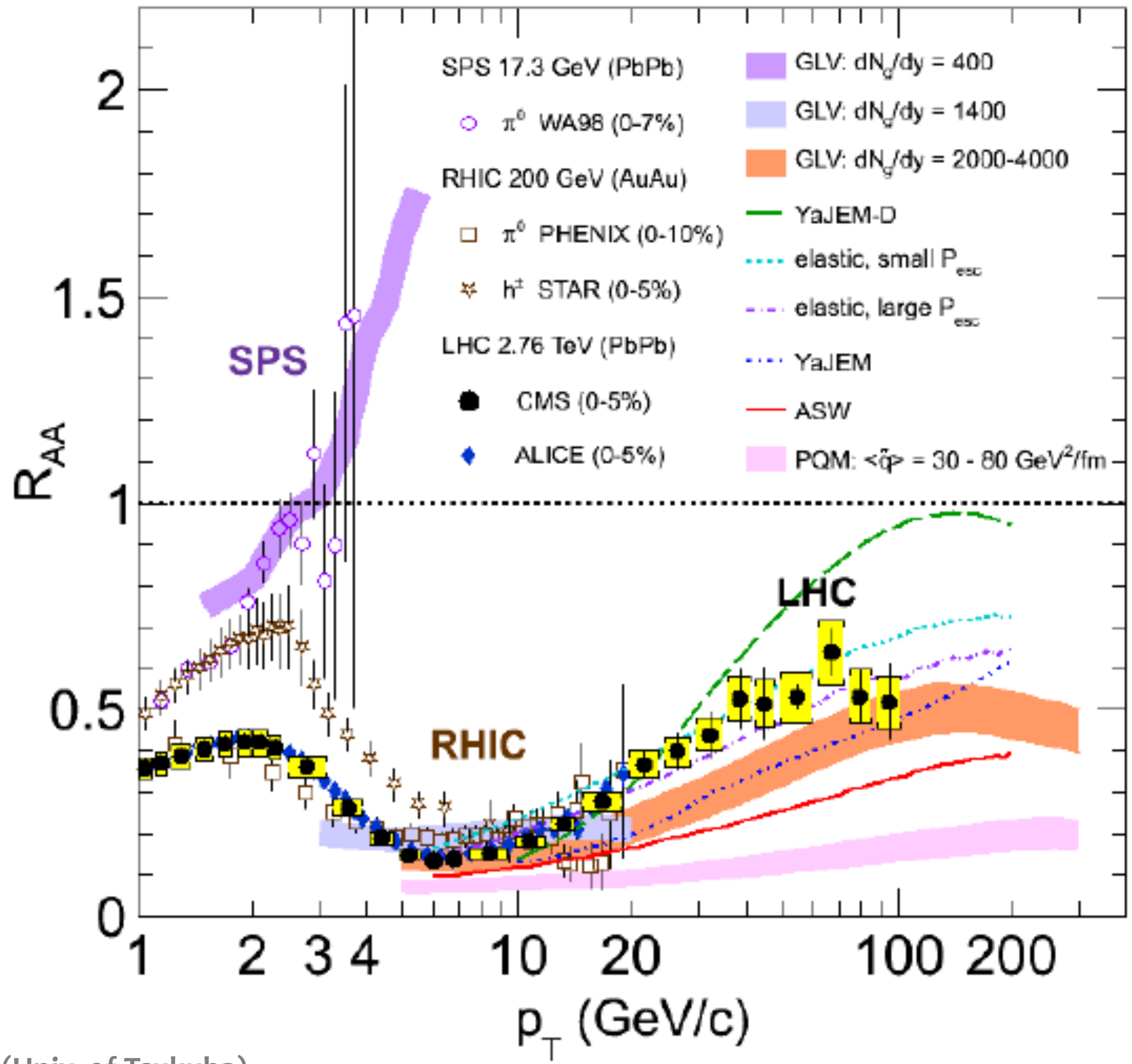


- Dip structure develops as a function of centrality
- R_{AA} increases at high p_T

EPJC 72 (2012) 1945

Krisztián Krajczár (MIT) Hard Probes 2012, 27 May – 1 June, Cagliari, Sardinia 12

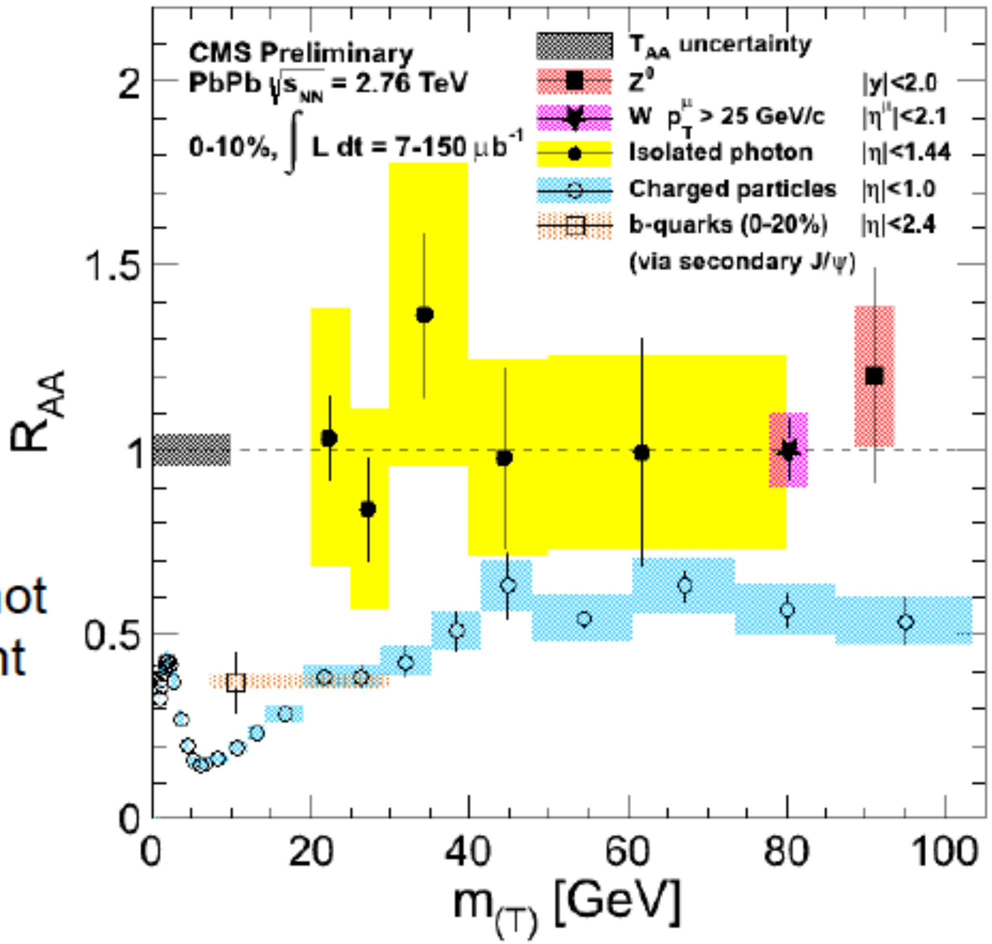
Charged particle R_{AA} compared to models



Heavy Ion Cafe, T. Chujo (Univ. of Tsukuba)

EPJC 72 (2012) 1945

Summary of CMS R_{AA} results

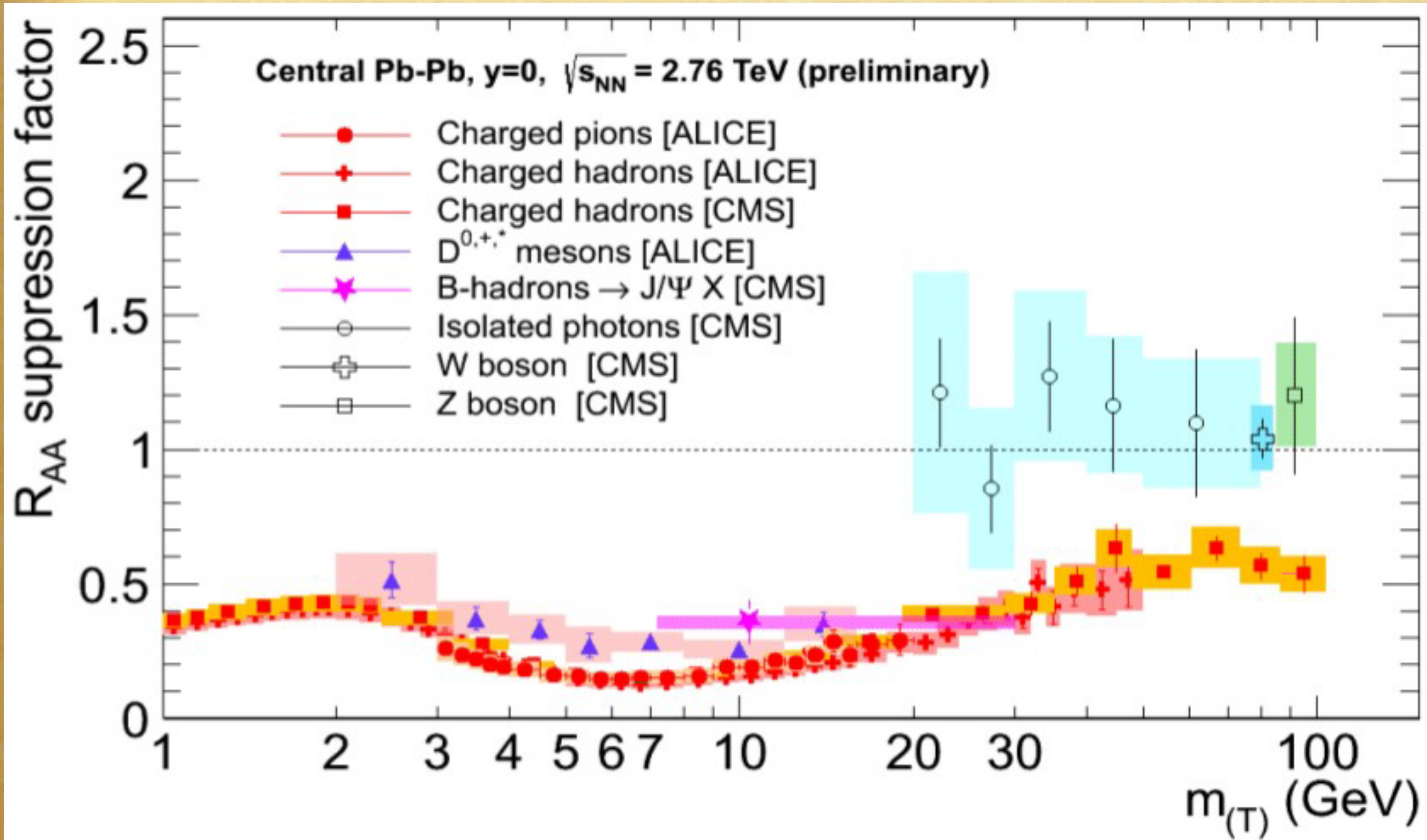


b-quarks are quenched (but not as much as light hadrons)
arxiv:1201.5069

Colorless probes are unsuppressed
Phys. Lett. B (2012) 710
Phys. Rev. Lett. (2011) 106

Strong quenching for light hadrons
Eur. Phys. J. C. (2012) 72

Summary of R_{AA} (LHC)



5. di-hadron correlations

Motivation of di-hadron correlation measurements

- Study the jet properties in pp
- **Probe jet medium interactions in Heavy Ion collisions(Di-hadron Tomography)**

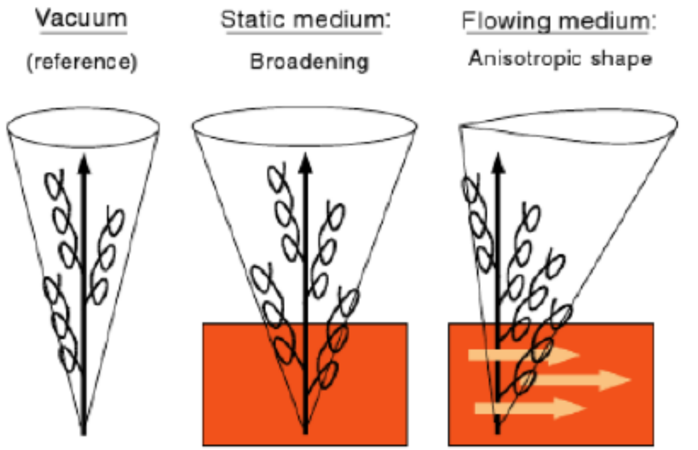


Figure: Broadening in a static medium.Longitudinal flow results in deformation of the conical jet shape

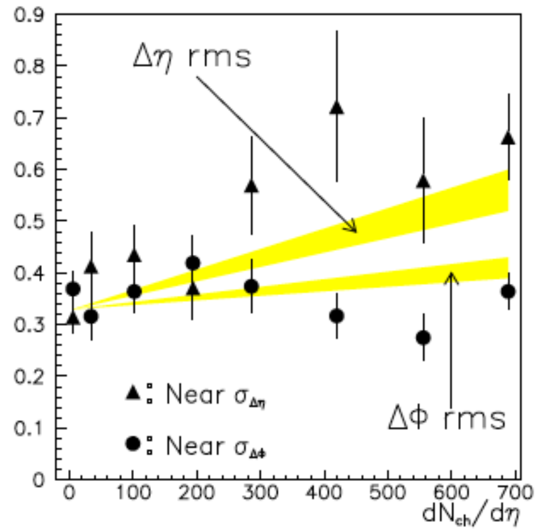
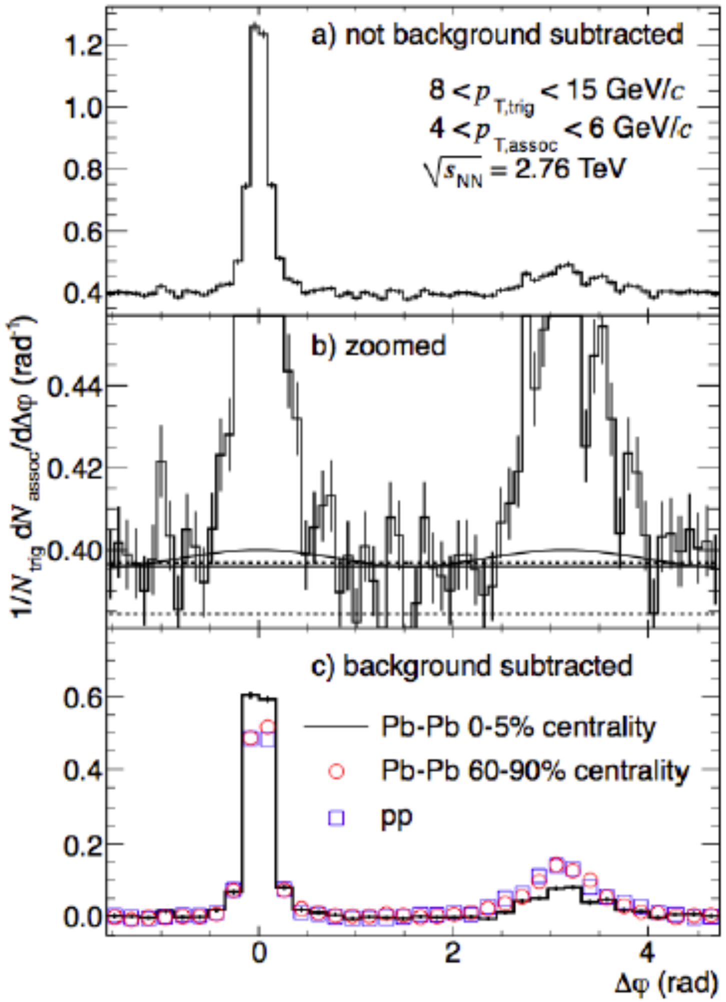


Figure: Néstor Armesto, Carlos A. Salgado and Urs Achim Wiedemann, PhysRevLett.93.242301 $(4 < p_{T,trigg} < 6 \otimes 0.15 < p_{T,assoc} < 4\ \mathrm{GeV}/c)$

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}

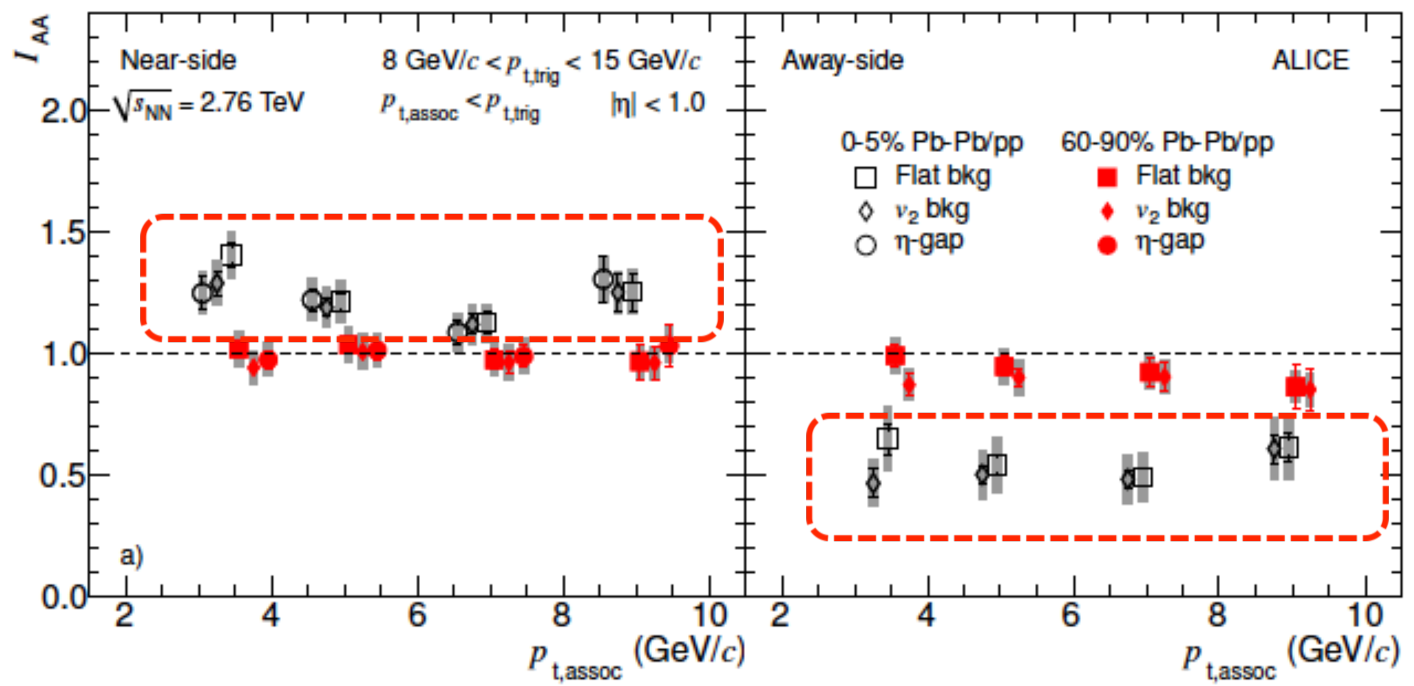
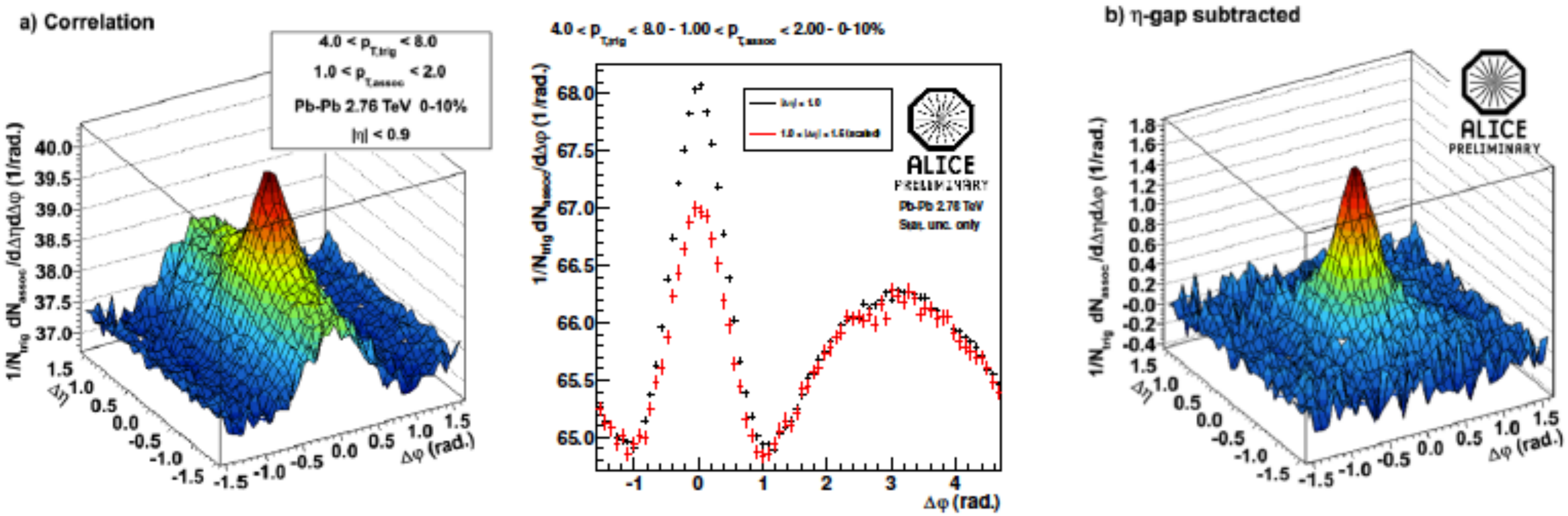


Figure: Phys. Rev. Lett. 108, 092301 (2012), ALICE

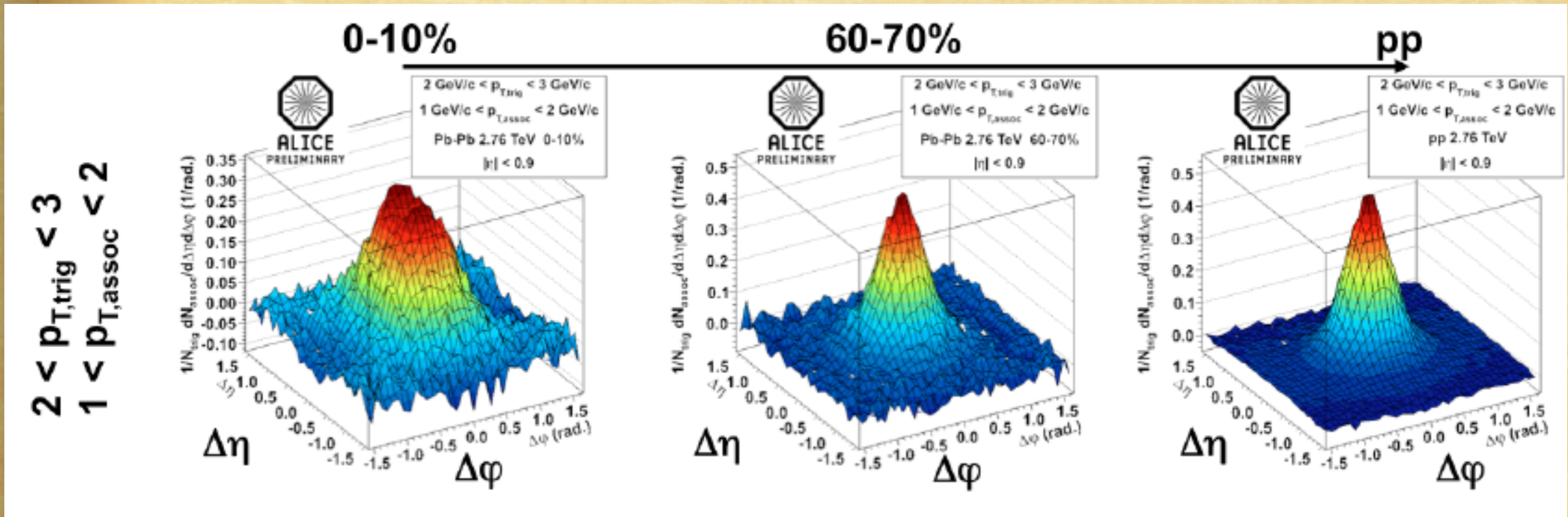
- Enhancement above unity of 20-30% on the near-side (not observed at RHIC).
- Away-side suppression at LHC (less at RHIC, i.e. lager I_{AA}), while single-hadron suppression is found to be slightly larger (R_{AA} is small) than at RHIC.

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



Characterize the near-side jet shape

- Quantification with rms ($\approx \sigma$) and excess kurtosis K
  - K = $\mu_4/\mu_2{}^2$ - 3 (μ_n, nth moment) , measure of the peakedness
  - Laplace: K=3, Gaussian: 0, semi-circle: -1, uniform -1.2
- rms determined with two independent methods: fitting and projections
- Near-side peak fitted with 2×2D Gaussians
- 4 shape parameters: $\sigma_{\Delta\eta}, \sigma_{\Delta\phi}, K_{\Delta\eta}, K_{\Delta\phi}$

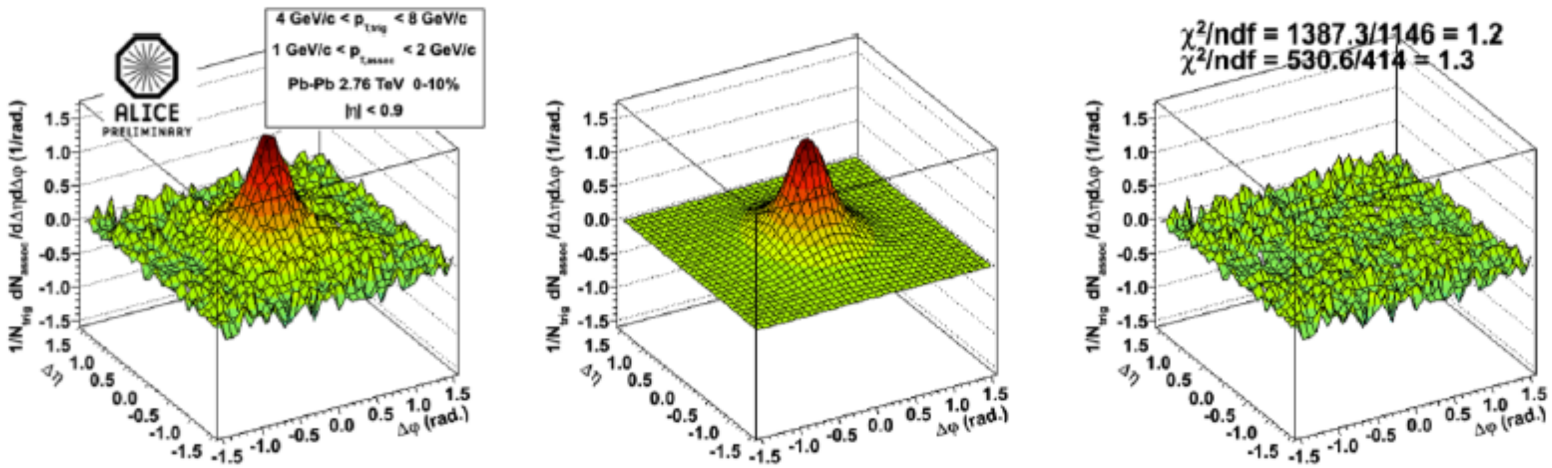
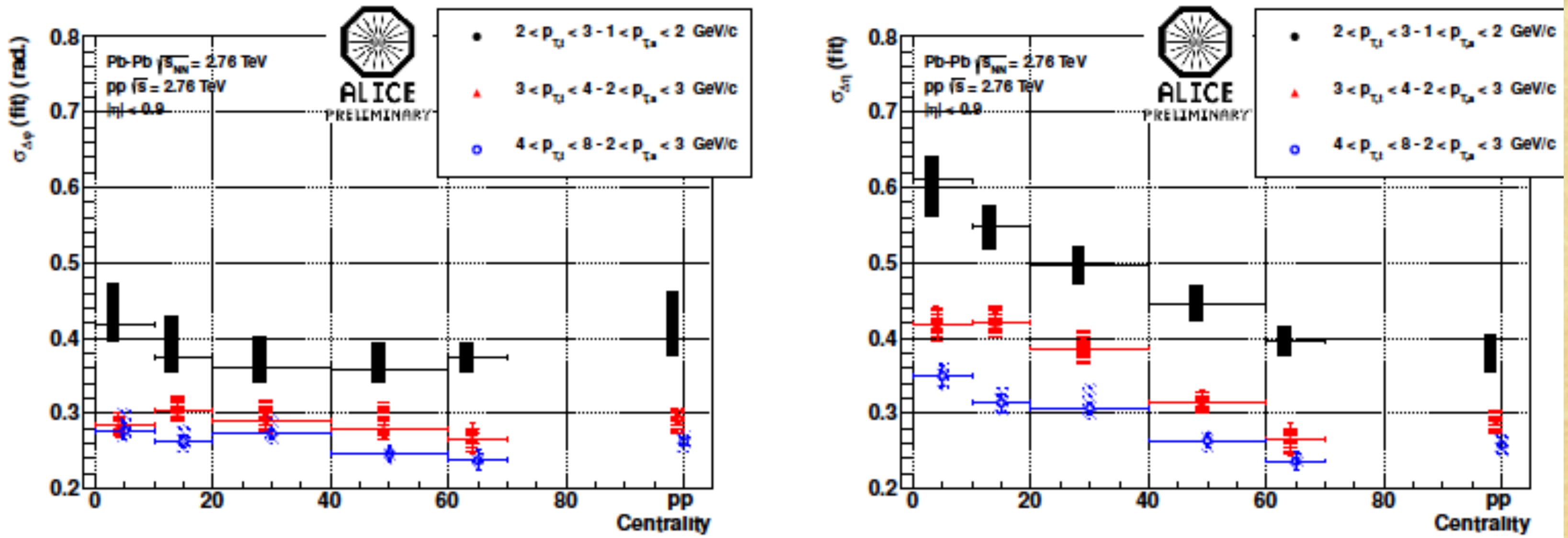


Figure: Left:Data Middle:Fit Right:Residual

Near Side Peak, σ (fit)

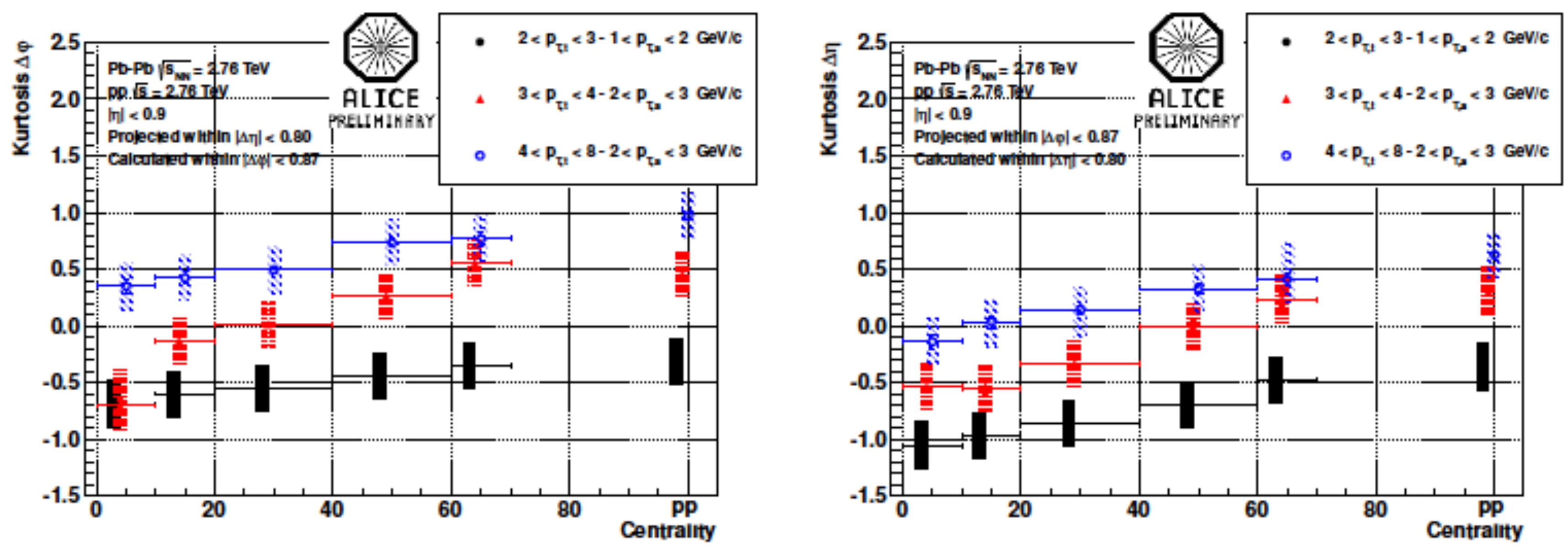


(a) $\sigma_{\Delta\phi}$ (b) $\sigma_{\Delta\eta}$

Figure: Near side peak width

- No significant centrality dep. of $\sigma_{\Delta\phi}$.
- **Significant increase of $\sigma_{\Delta\eta}$ towards central collisions.**
- Smooth continuation from peripheral to pp.

Near Side Peak, kurtosis

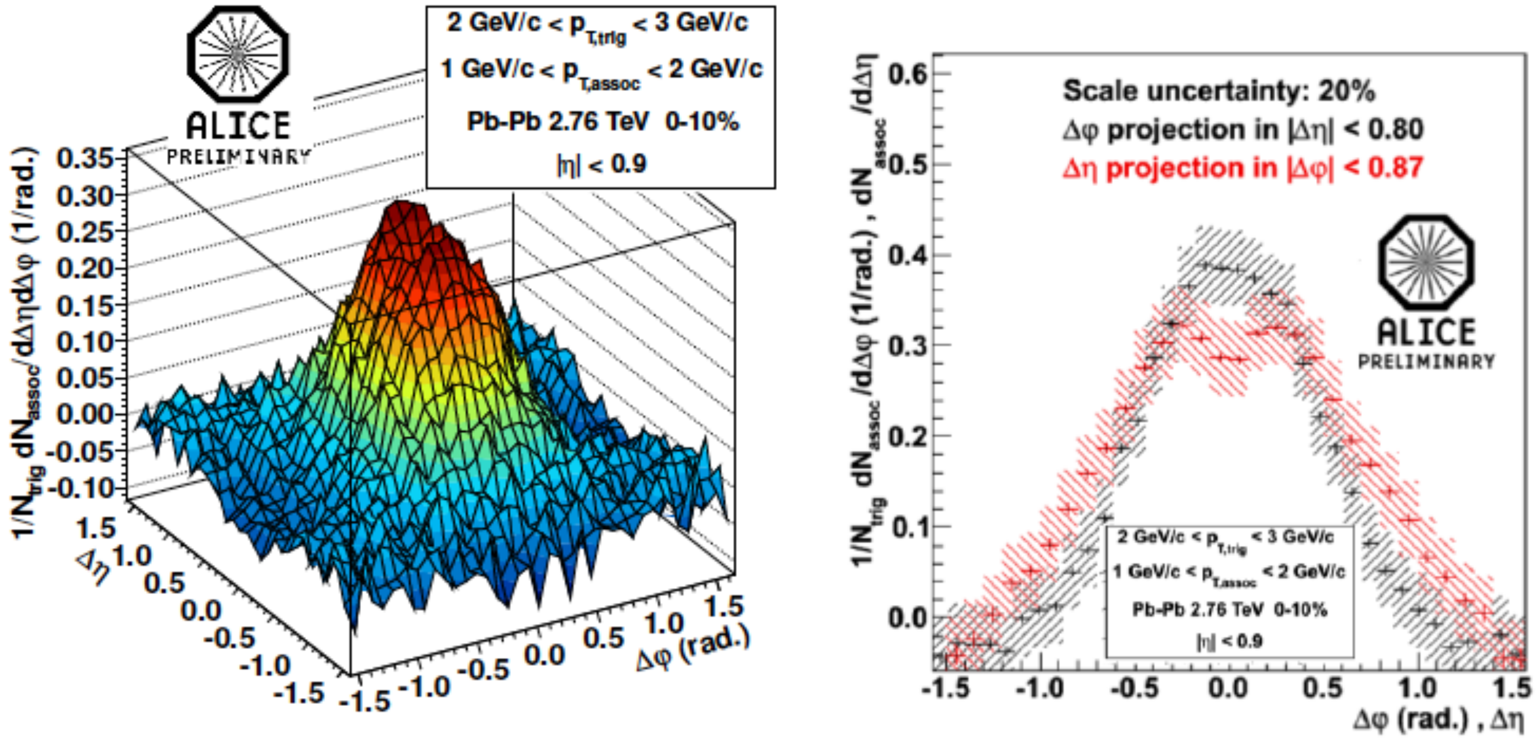


(a) kurtosis $\Delta\phi$ (b) kurtosis $\Delta\eta$

Figure: Near side, Peakness

- Clear p_T dependence: increase with p_T.
- Centrality dependence: decreases from pp to peripheral, central collisions.

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



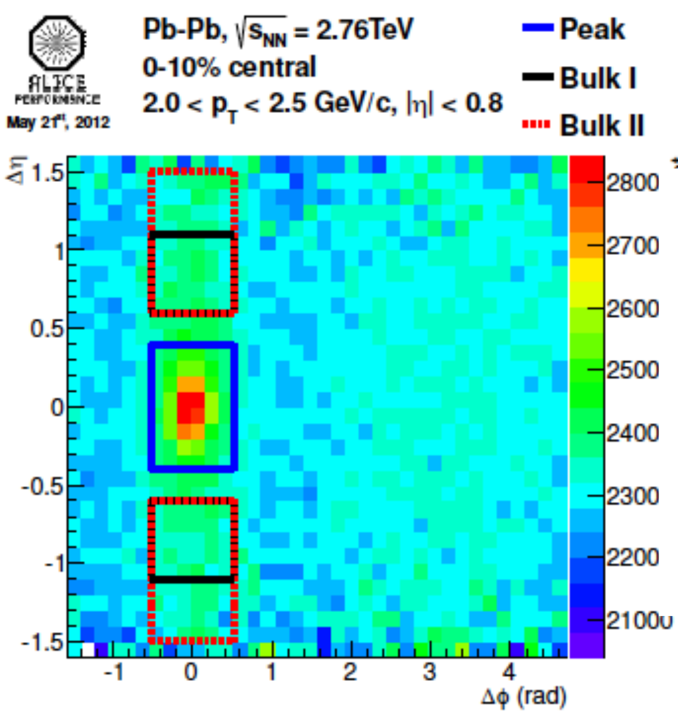
(a) $\eta - gap$ subtracted (b) $\Delta\eta, \Delta\phi$ projection

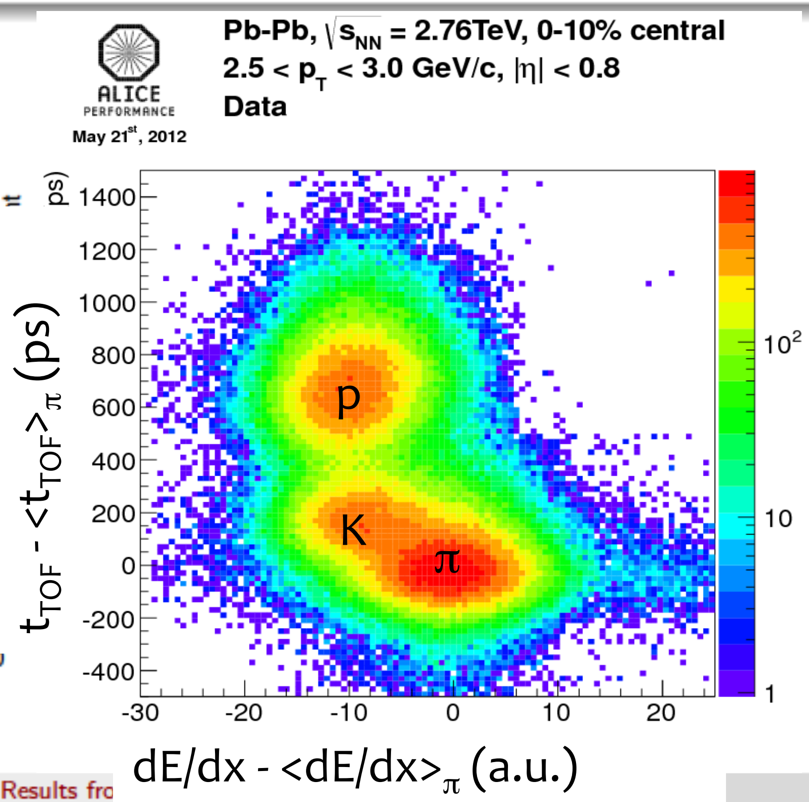
Figure: $2 < p_{T,trigg} < 3 \otimes 1 < p_{T,assoc} < 2$, 0-10% centrality

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

p/π ratio in Bulk and Jet region

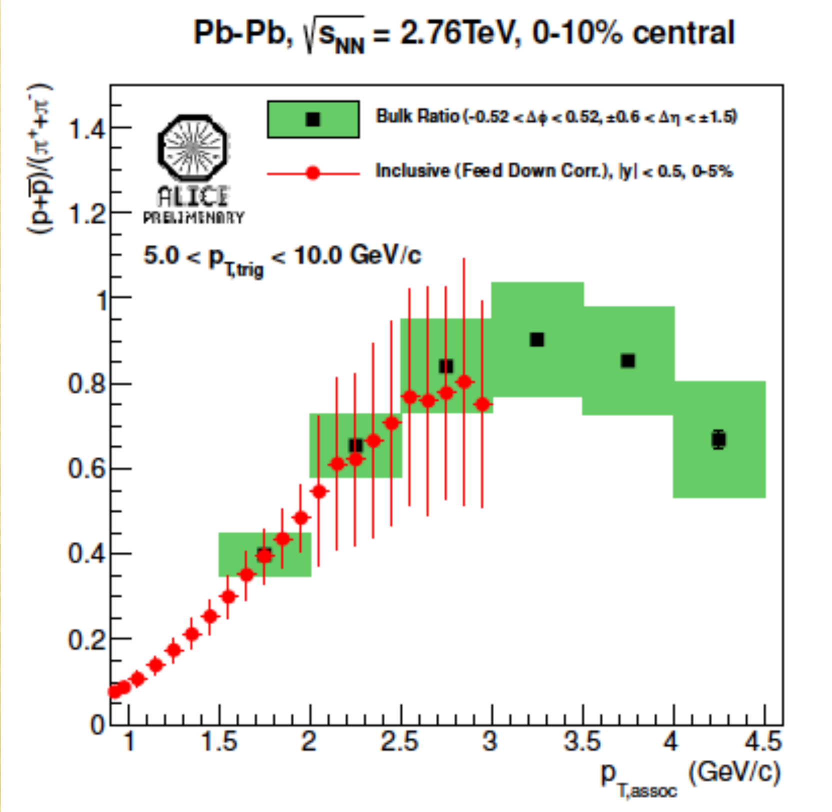
- Trigger particle (charged hadrons) $5 < p_{T,trigg} < 10$ GeV/c
- Associated particles (π or proton) $1.5 < p_{T,assoc} < 4.5$ GeV/c
  - Combined particle identification with specific energy loss in the TPC and time of flight in the TOF
  - Bulk region ($-0.52 < \Delta\phi < 0.52$ rad, $\pm 0.60 <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





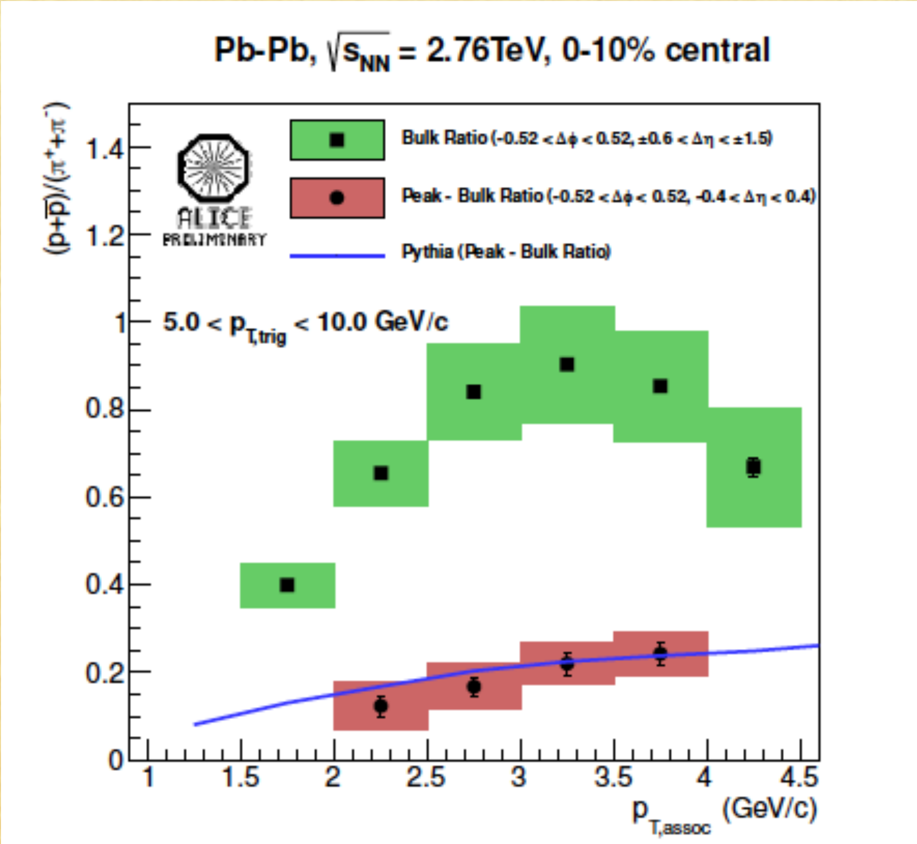
Dong Jo ,Kim (JYFL/HIP) Particle Correlation Results fro 17 / 20

p/π ratio in Bulk region



- Comparison with feed-down corrected p/p ratio, from inclusive spectra (0-5%) (QM2010 prel.).
- 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.

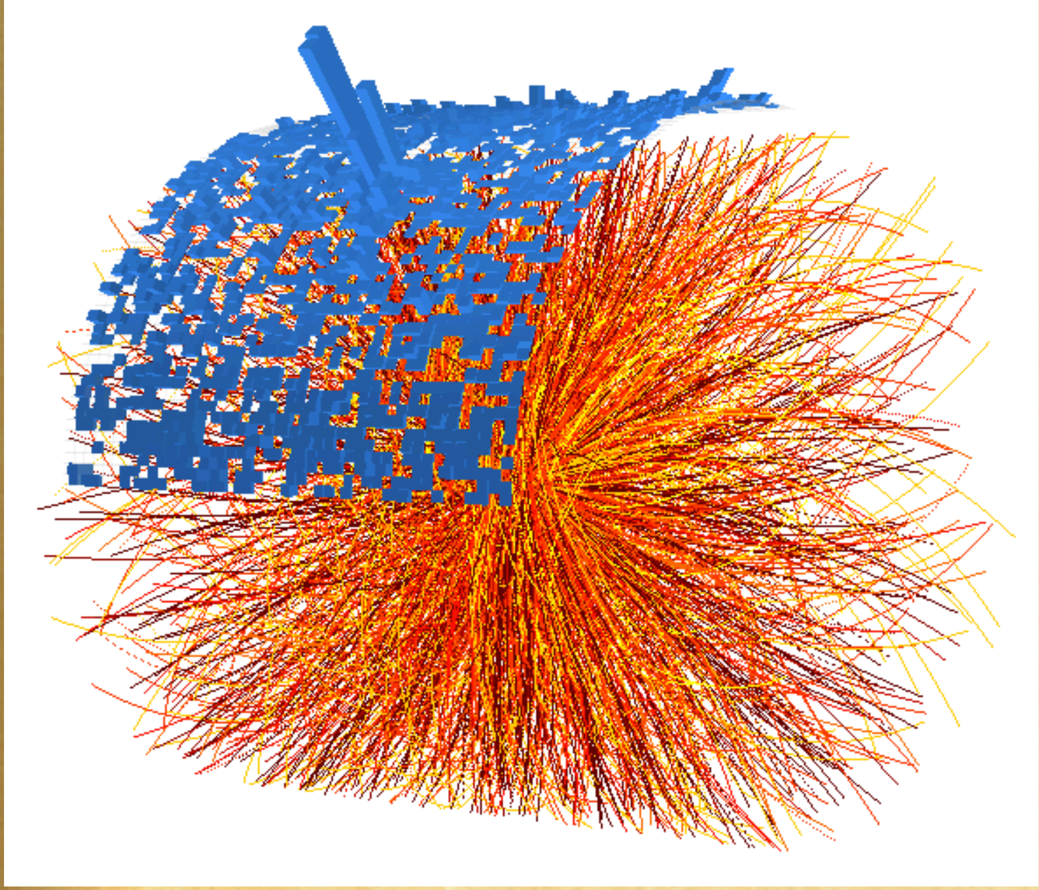
6. Jets

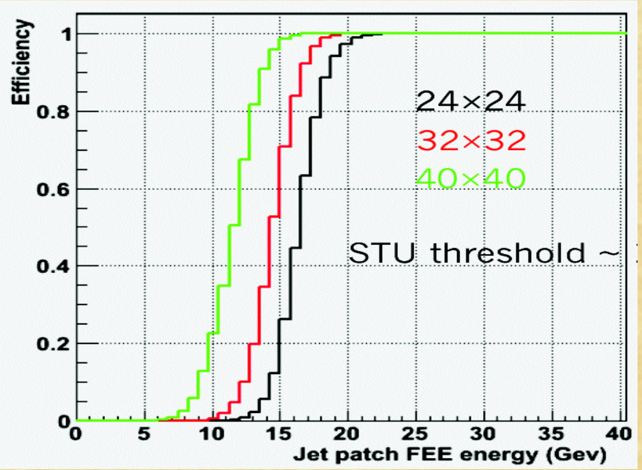
Single jet, di-jets, γ-jet

6.1 Single jet

(ALICE, ATLAS)

Jet trigger in 2.76 TeV Pb+Pb in ALICE





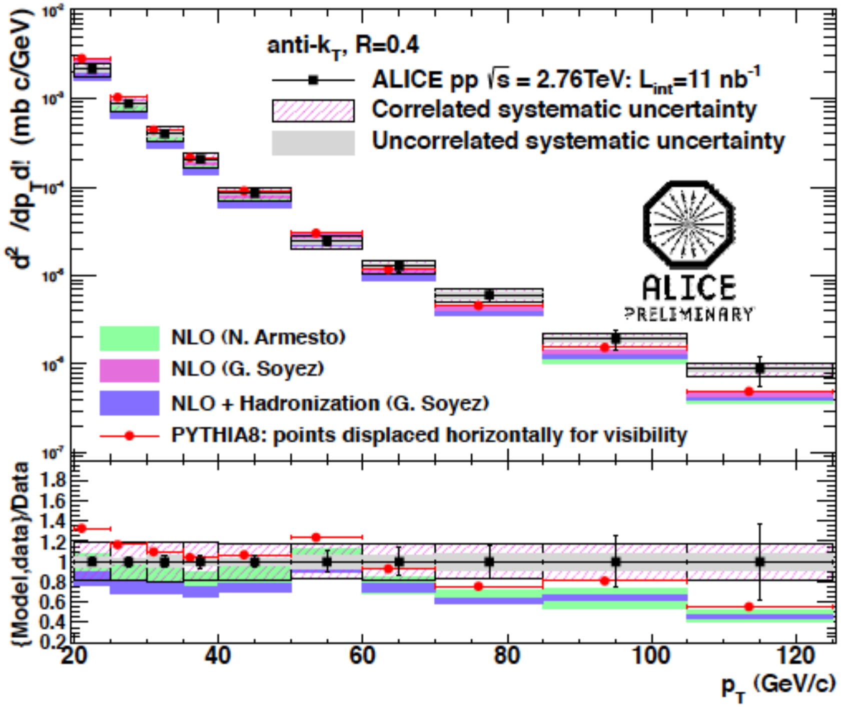
L1 jet trigger

Jet energy with EMCal + TPC tracking

- For 2011 run, all of EMCal is installed and trigger was in use.

Jet spectra in p+p 2.76 TeV (ALICE, charged + neutral jets)

Inclusive jet cross-section in pp √s = 2.76 TeV (R=0.4)



Green and magenta bands: NLO on Parton level

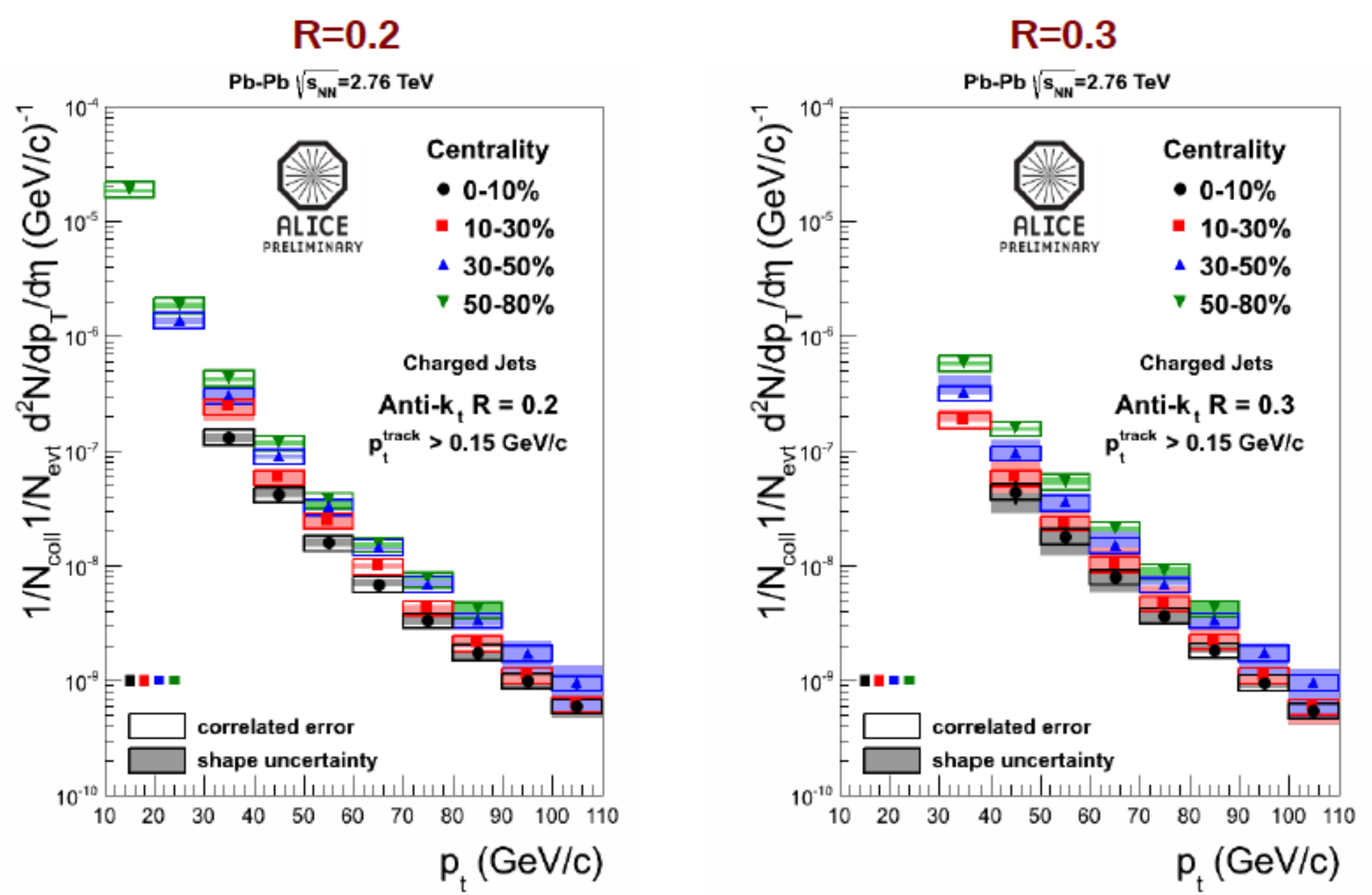
Blue band: NLO + hadronization

Red points: Pythia8. Shifted horizontally for visibility

Good agreement between data and NLO calculations as well as Pythia8 prediction within both experimental and theoretical uncertainties

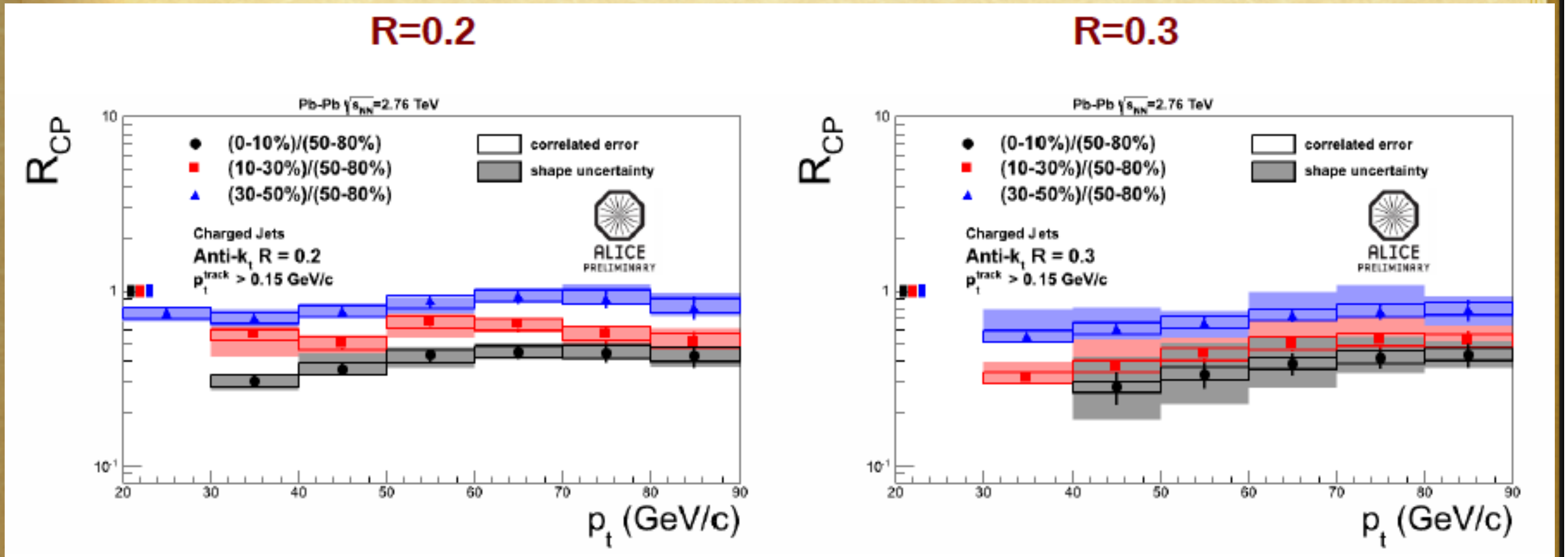
5/28/12 Rongrong Ma, Hard Probes, Cagliari, Italy 11

Pb-Pb jet spectrum (charged)



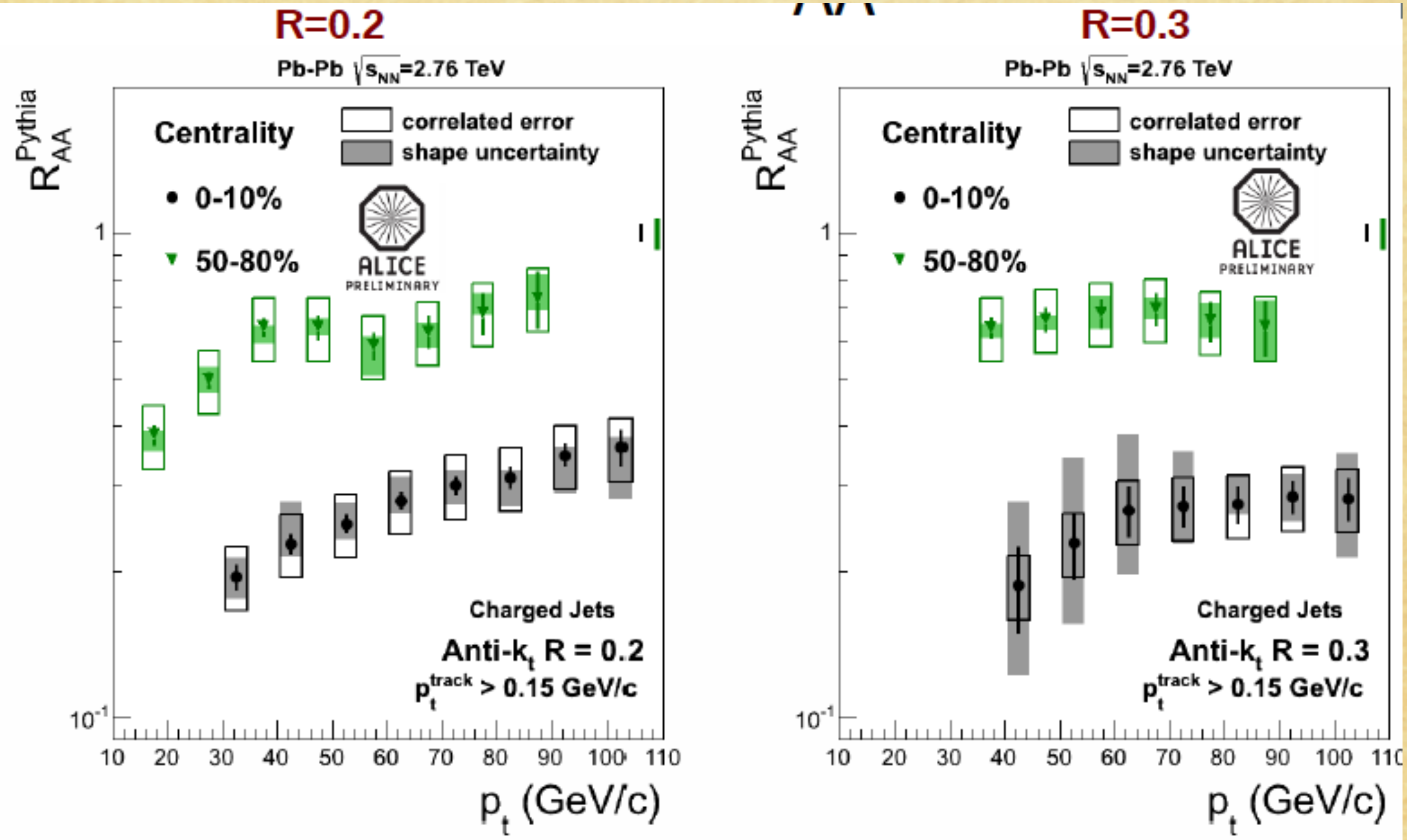
Jet spectra have been measured for 2 cone radii and 4 centrality bins

Jet (charged) R_{cp}



- Observed jet suppression for central collisions.
- Weak p_T dependence.
- R_{cp} ~ 0.5 for central, close to unity for peripheral.

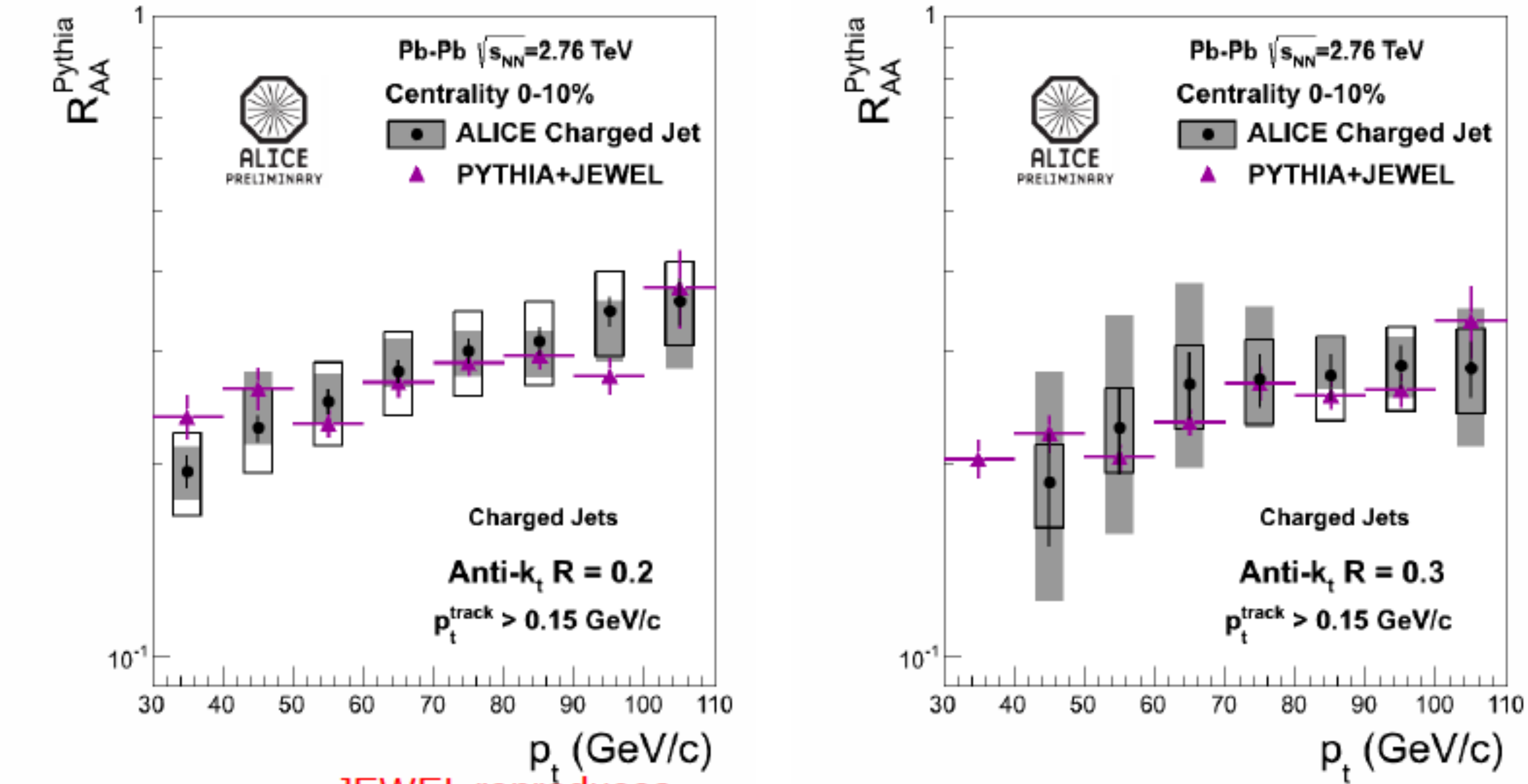
Jet (charged) R_{AA}



- Large jet suppression for central.
- Note that using PYTHIA for p+p reference.

Model Comparison

Jet R_{AA}: ALICE vs JEWEL



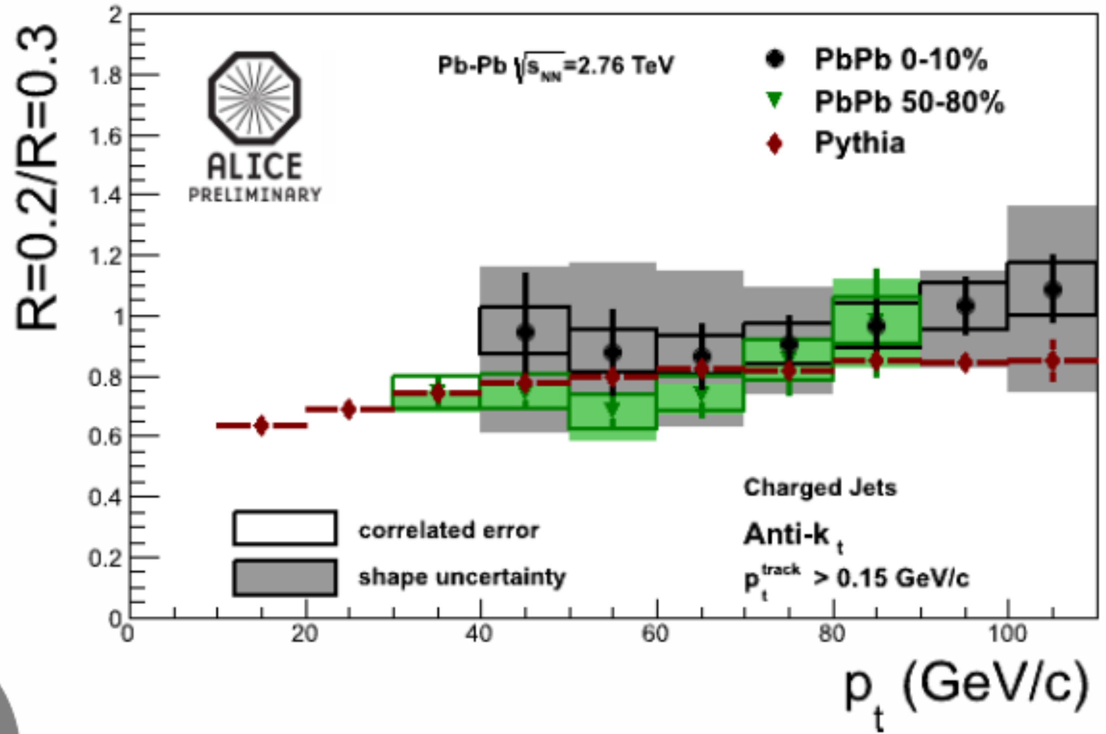
JEWEL reproduces

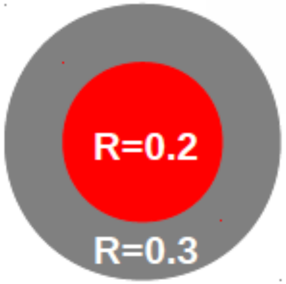
→ Hadron R_{AA} (*Zapp, Krauss Wiedemann arXiv:1111.6838*)

→ Charged jet R_{AA} for R=0.2 and R=0.3

JEWEL jet results: private communication

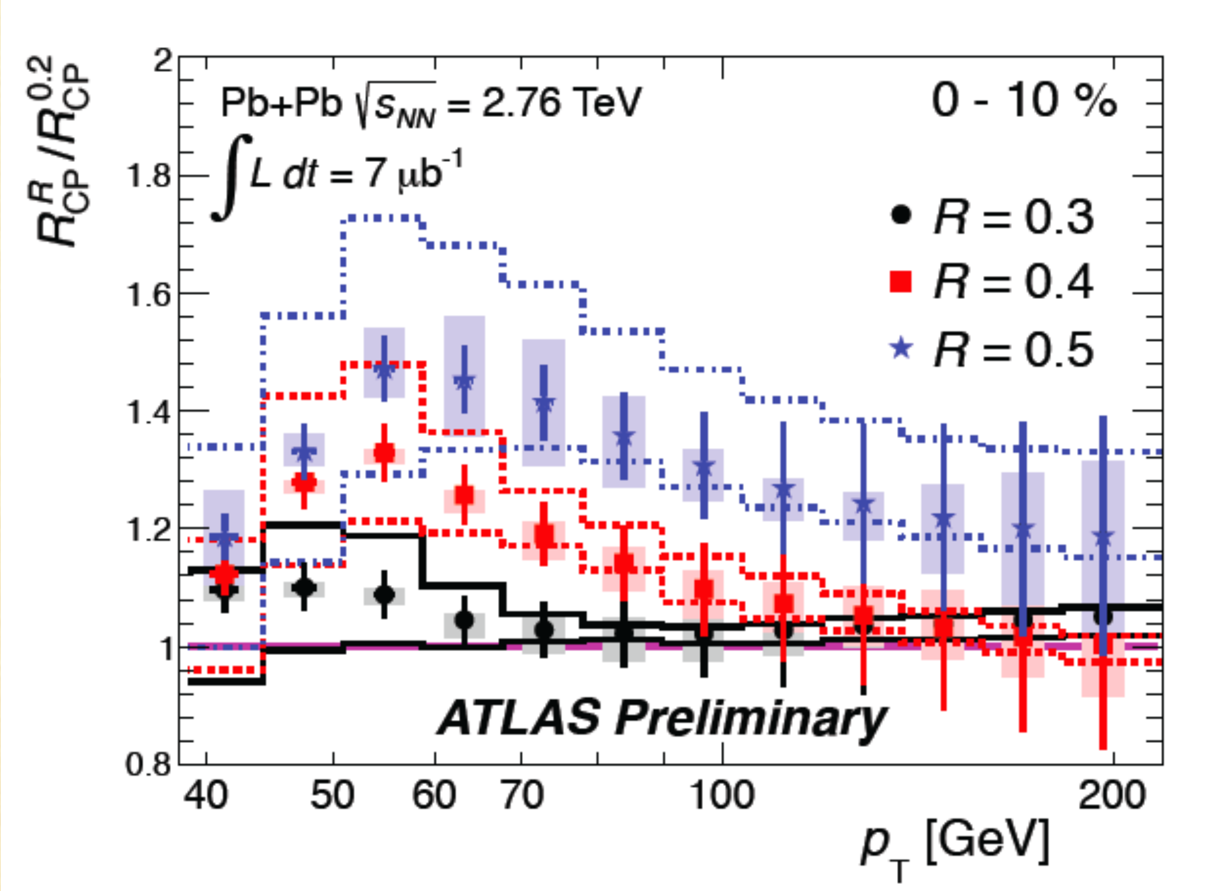
Ratio of jet cross section R=0.2 / R=0.3 (Pb-Pb)



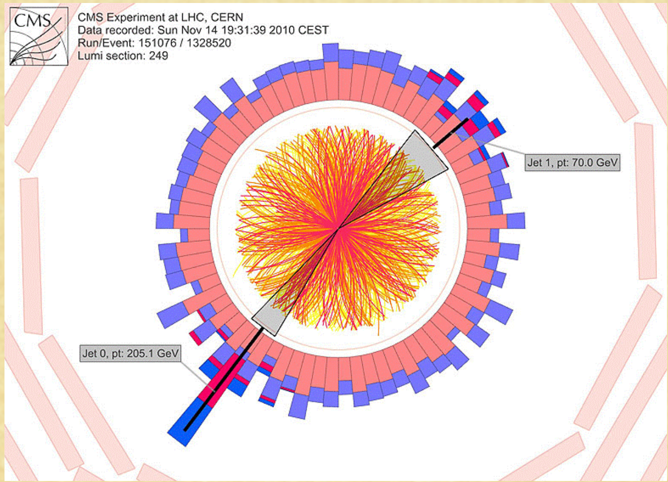


Ratio R=0.2/R=0.3 consistent with vacuum jets for peripheral and central collisions

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

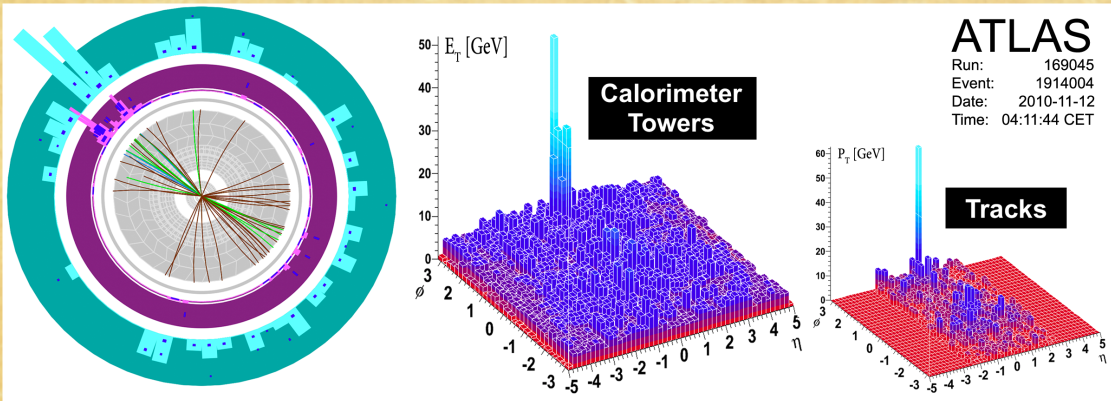


- Up to 200 GeV, in R= 0.2, 0.3, 0.4, 0.5
- Consistent with ALICE results for R=0.3.
  - (plotted oppositely for vertical axis .)

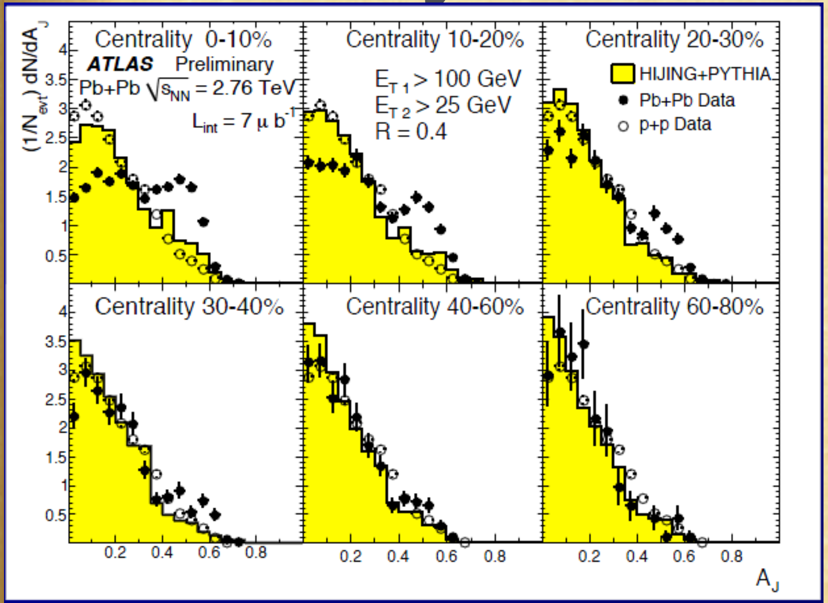


6.2 Di-jets

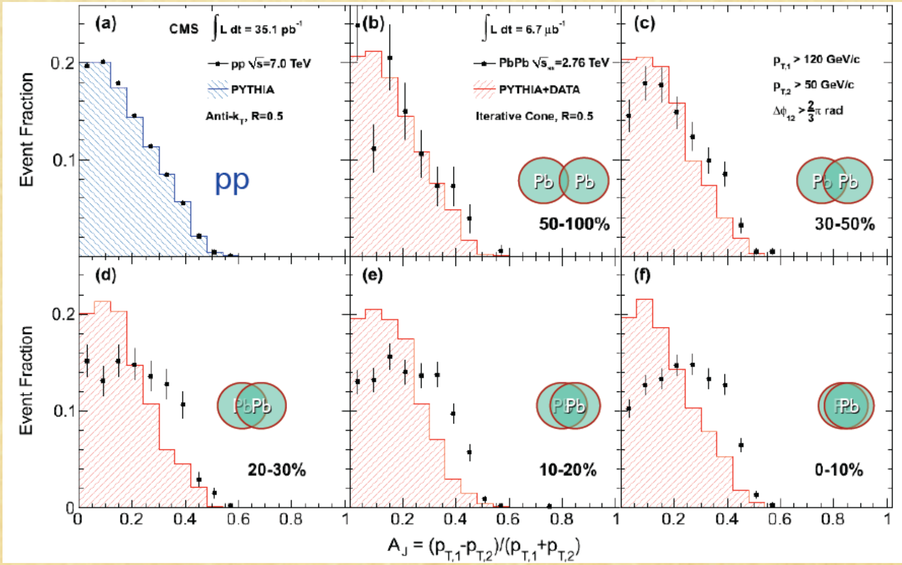
(ATLAS, CMS)



A_J: di-jet asymmetry



ATLAS R=0.4



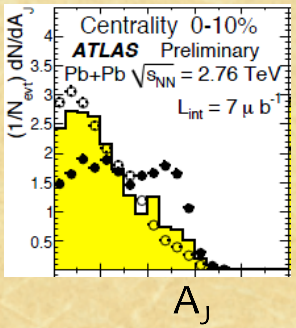
CMS R=0.5

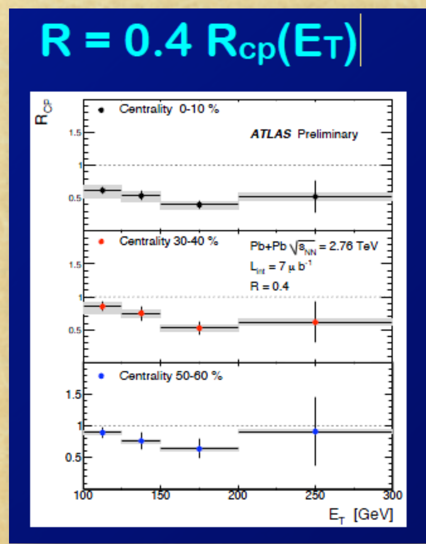
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

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

Highlights on jets at QM2011

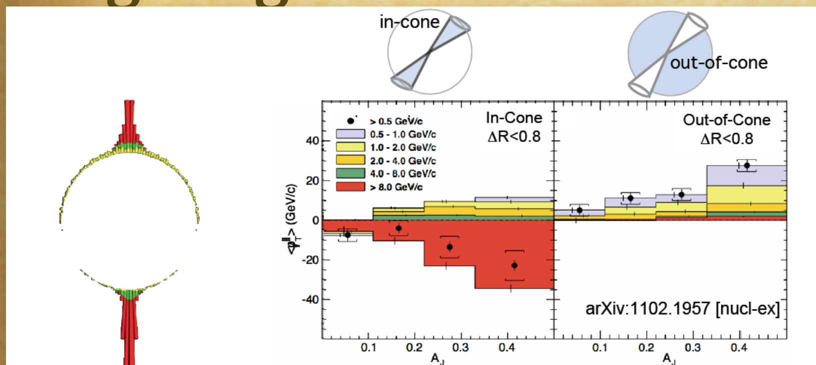
1. Extremely large energy loss on the away side jets.
   - Large energy asymmetry in central Pb+Pb.
   - Jet R_{cp} ~ 0.5.

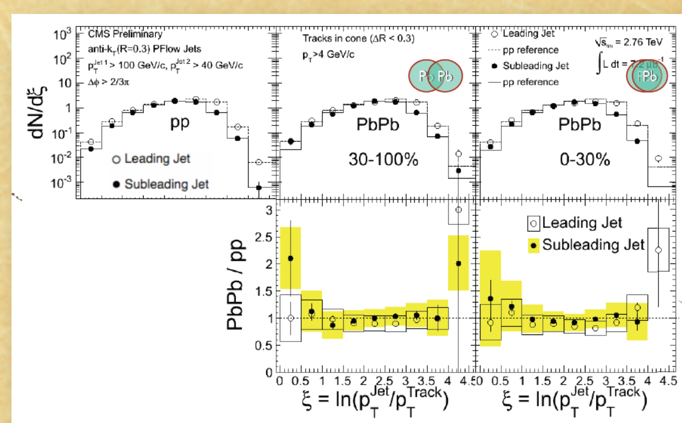




2. Little modification of jet shape
   - both near and away side.
   - Both transverse (j_T) and longitudinal (FF).
   - No broadening of jets.

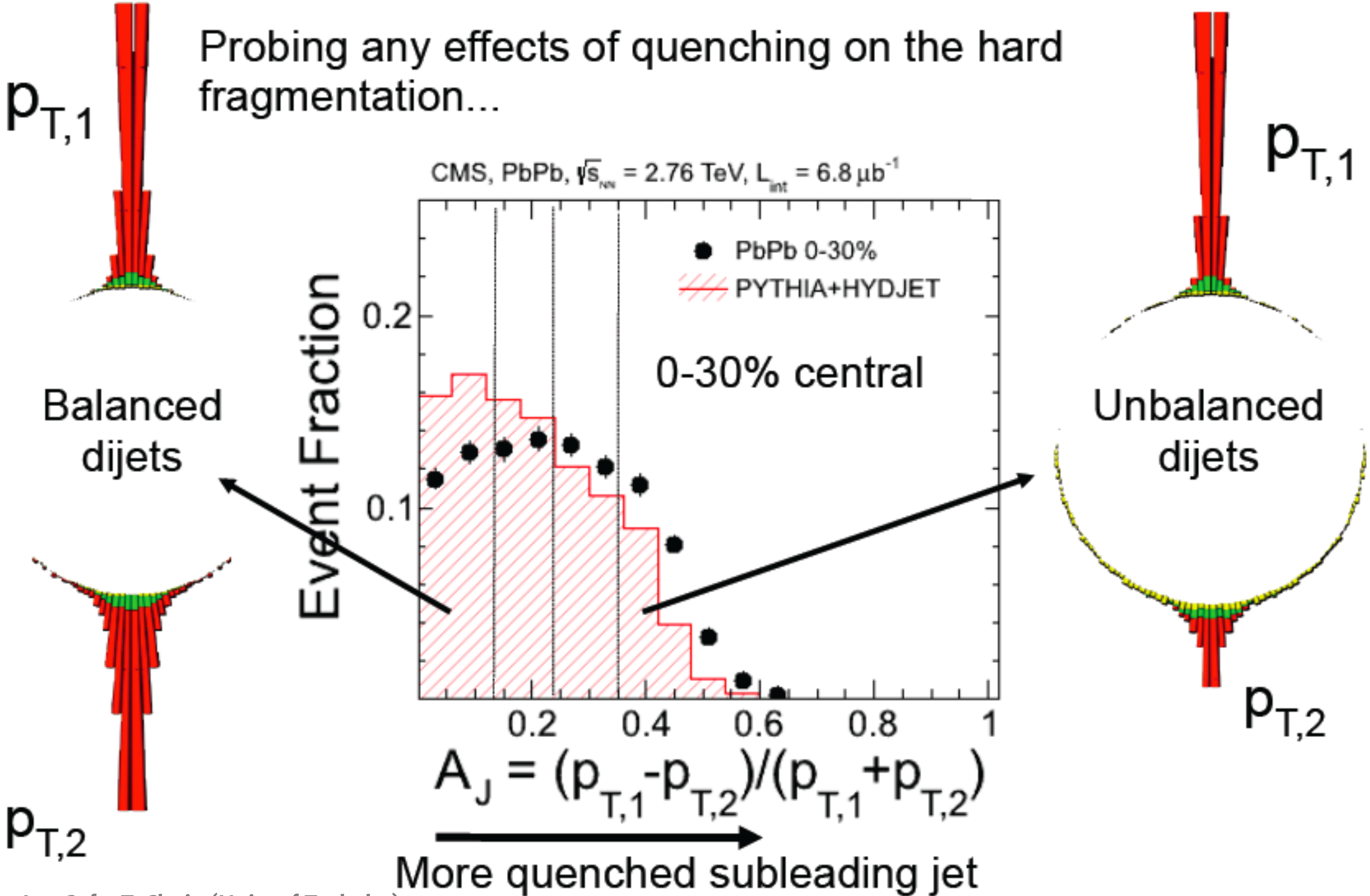
3. **Lost energy is used for the low p_T bulk particle production at large angle!**



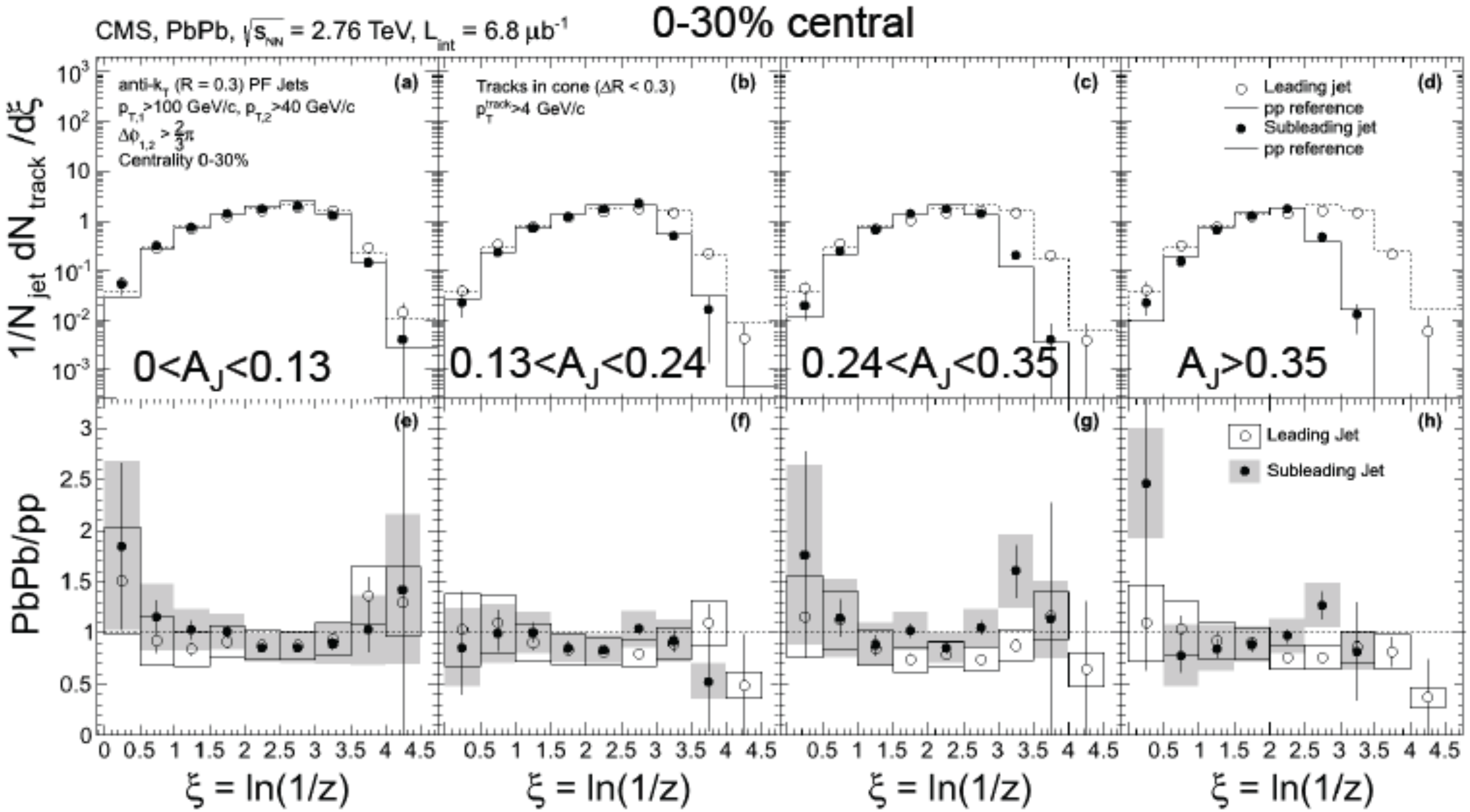


Differentiating in A_J

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



PbPb results in A_J bins

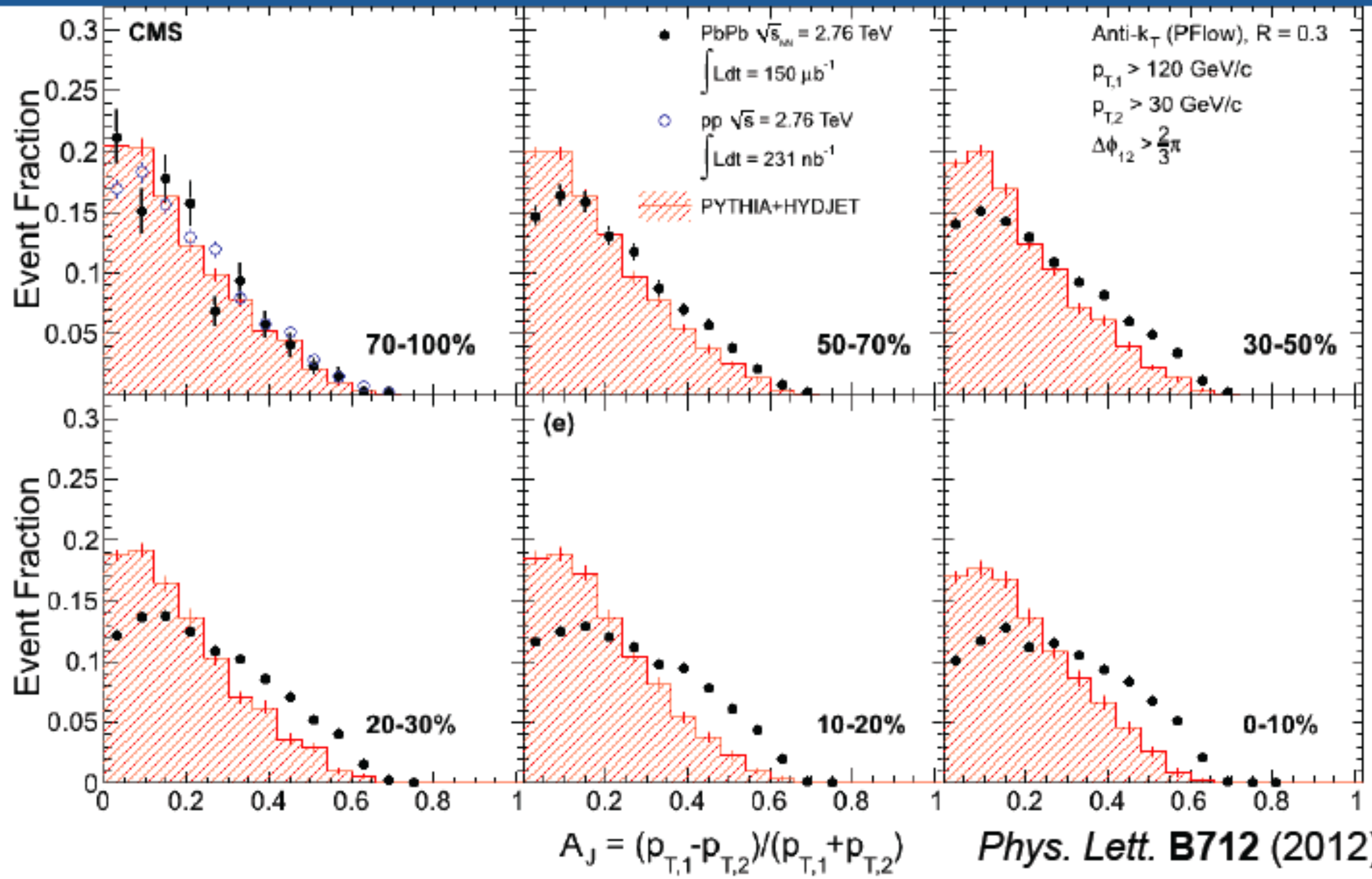


$$z = \frac{p_{\parallel}^{track}}{p^{jet}}$$

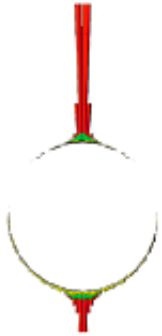
Structure of reconstructed jets resemble those that were produced in vacuum, despite the energy loss

arXiv:1205.5872

Results from 2011 data



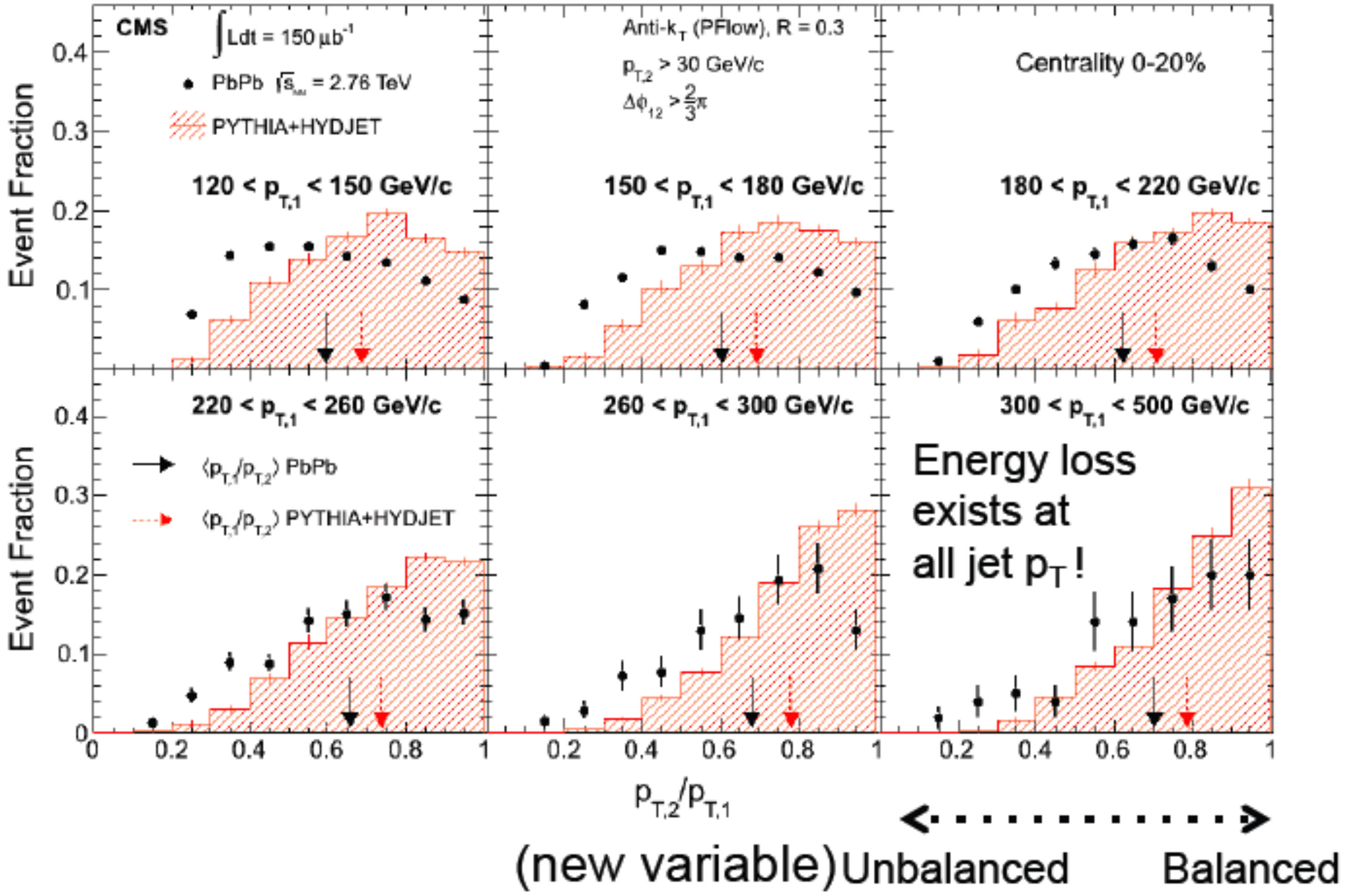
Phys. Lett. **B712** (2012) 176



Earlier results confirmed

Statistical uncertainties significantly reduced

p_T-dependence of the dijet imbalance

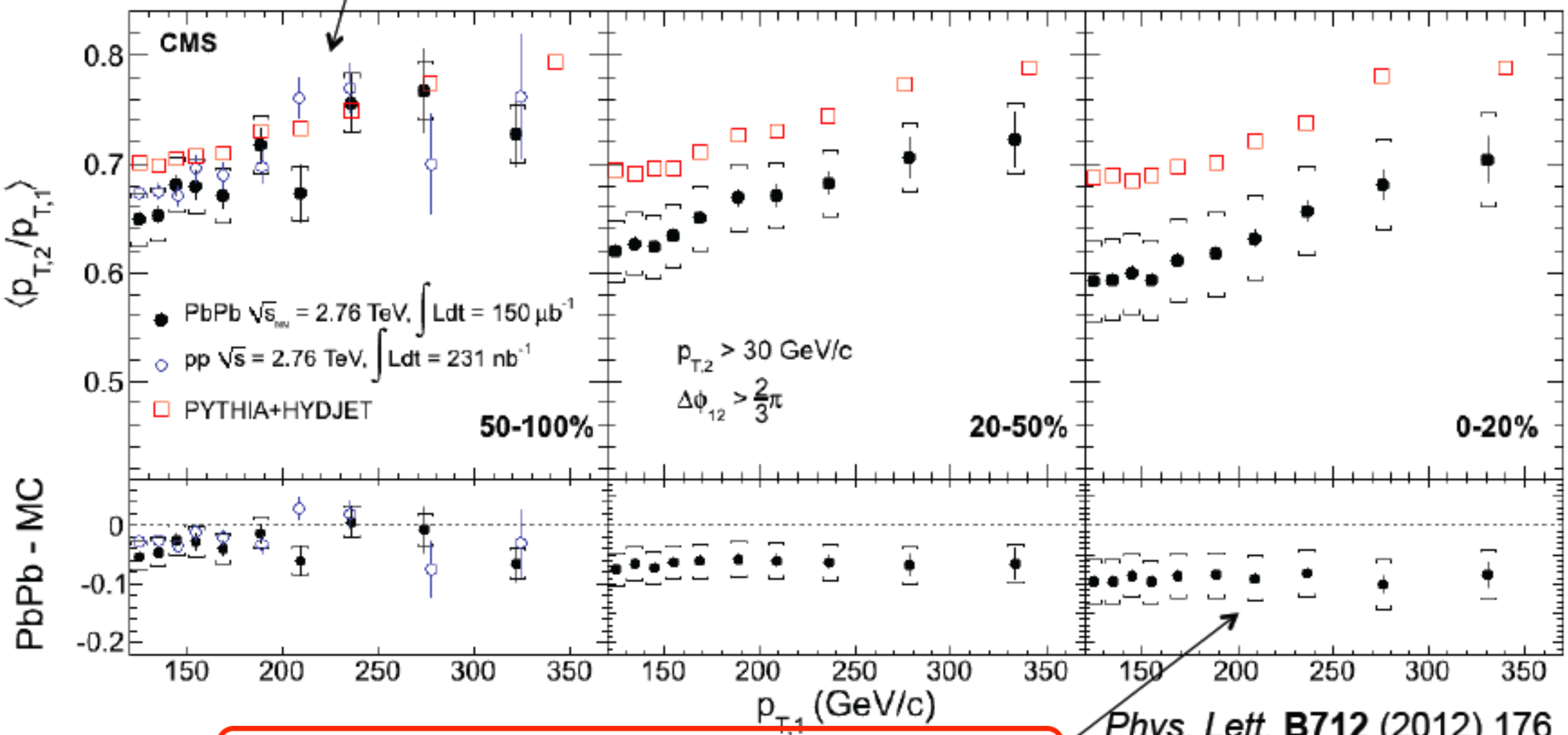


Dijets in PbPb are more imbalanced than Pythia at **all bins of leading jet p_T**

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

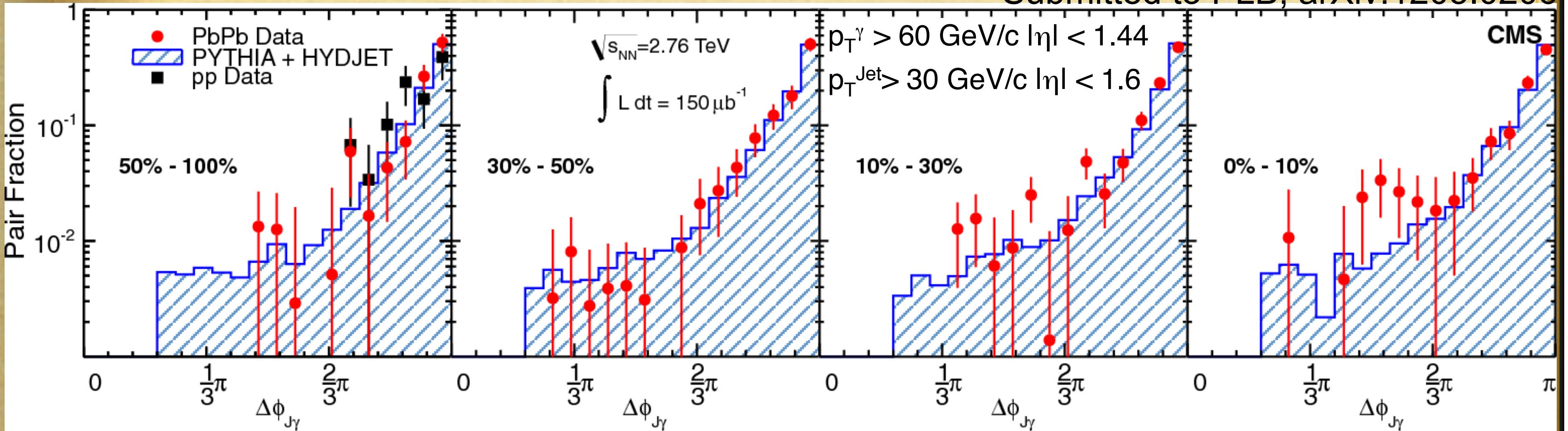
No significant dependence on jet p_T


γ-Jet
✓Quark Jet
✓Small Xsection
✓Experimentally challenging

6.3 γ-jet
(CMS)

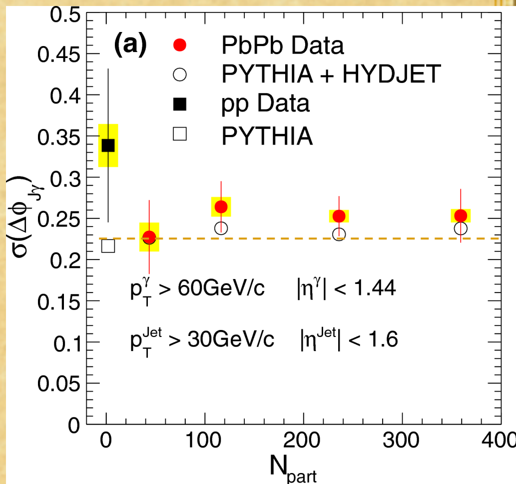
γ-Jet Angular Correlations (CMS)

Submitted to PLB, arXiv:1205.0206



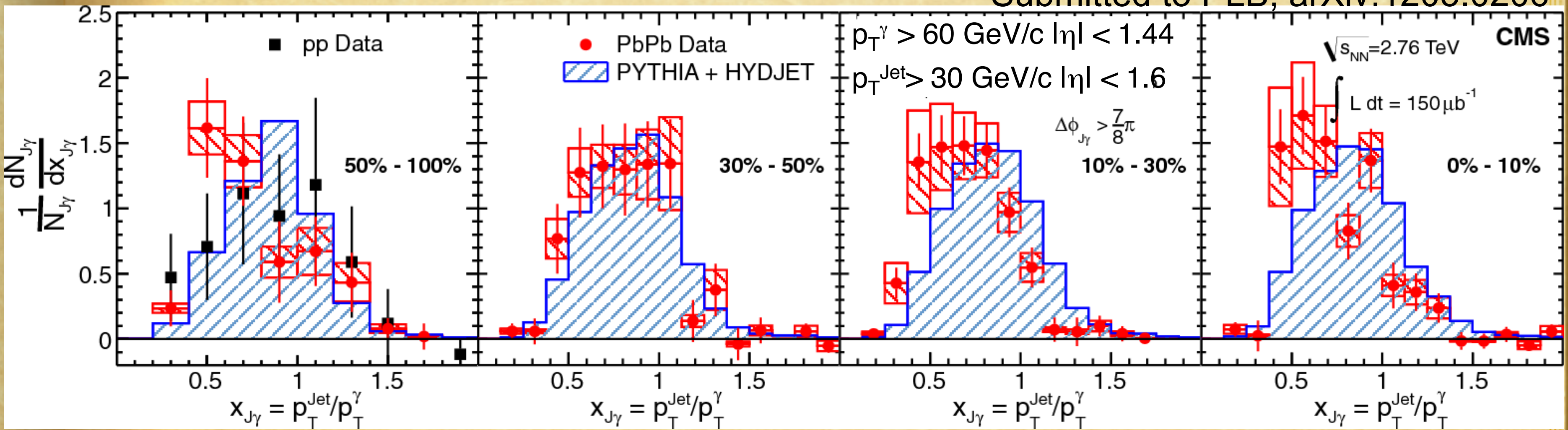
No significant angular de-correlation

is observed for γ-jet pairs



γ-Jet Momentum Balance (CMS)

Submitted to PLB, arXiv:1205.0206



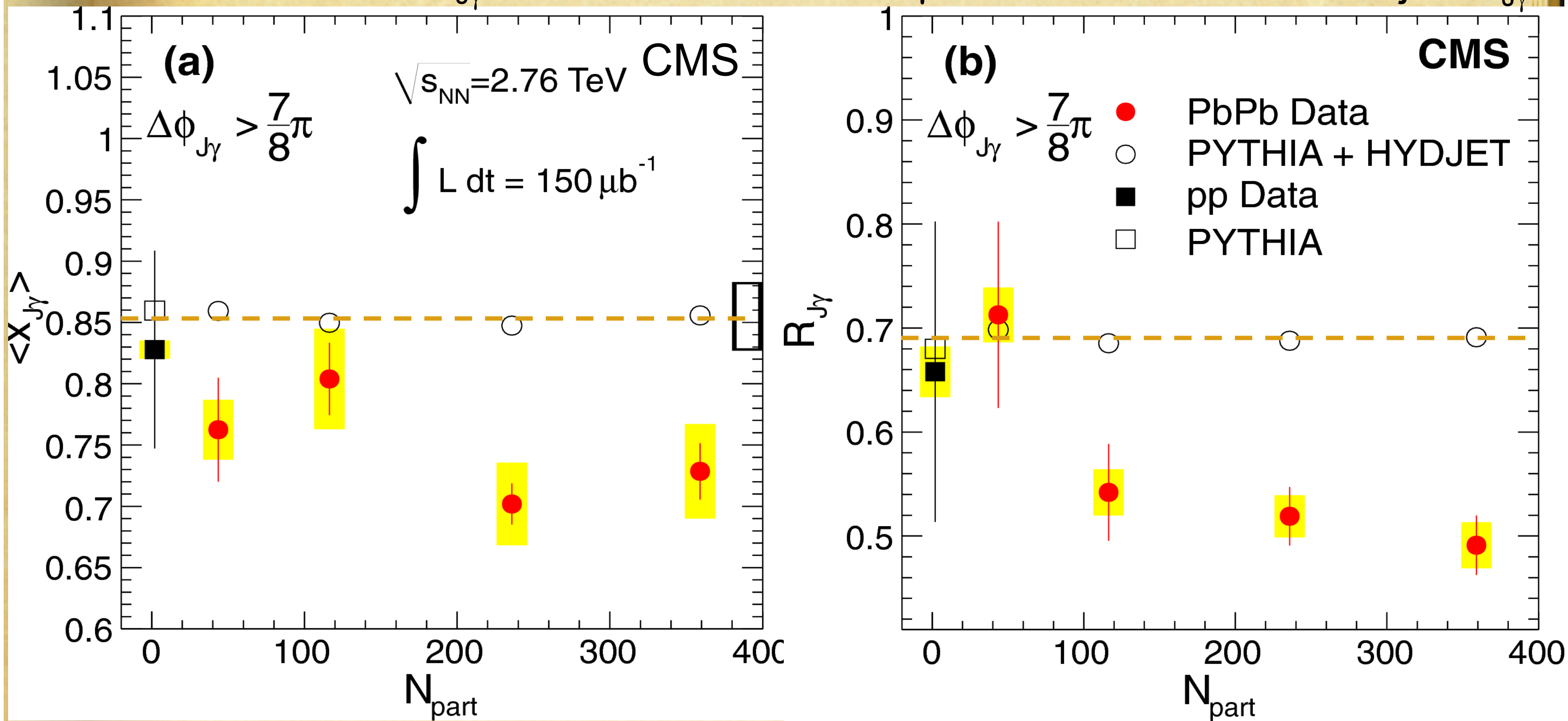
- Momentum ratio shifts/decreases with centrality
  - jets shifting below the 30 GeV p_T threshold not included

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

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

γ-Jet Momentum Balance vs. Centrality

Mean $x_{J\gamma}$ γ-Fraction with > 30 GeV jet: $R_{J\gamma}$



- 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^{γ} > 60 GeV/c $|\eta| < 1.44$

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

7. Heavy Flavor

Heavy Quark Energy Loss in Medium

Heavy Quark Energy Loss in Medium

Radiative energy loss via gluon radiation

Color charge dependence of energy loss

gluon radiation spectrum by the parton propagation in the medium:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$\text{where} \quad C_R = 3 \;\; for\; g, \;\; \frac{4}{3} \;\; for\; q$$

Dead Cone Effect

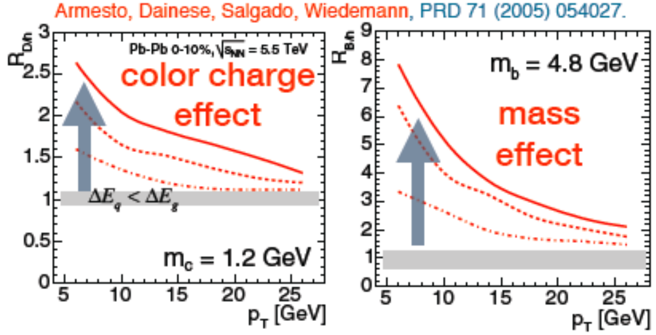
- In vacuum, gluon radiation is suppressed at angles smaller than M_Q/E_Q (ratio of the quark mass to its energy)
- In medium, dead cone implies lower energy loss for massive partons

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

$$\Rightarrow R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA} \qquad R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$R_{D/h}$: R^D_{AA}/R^h_{AA}

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.



Elastic energy loss is not negligible?

Simon Wicks, William Horowitz, Magdalena Djordjevic, Miklos Gyulassy, Nucl.Phys.A784:426-442,2007

Collisional dissociation probability of heavy mesons in the QGP?

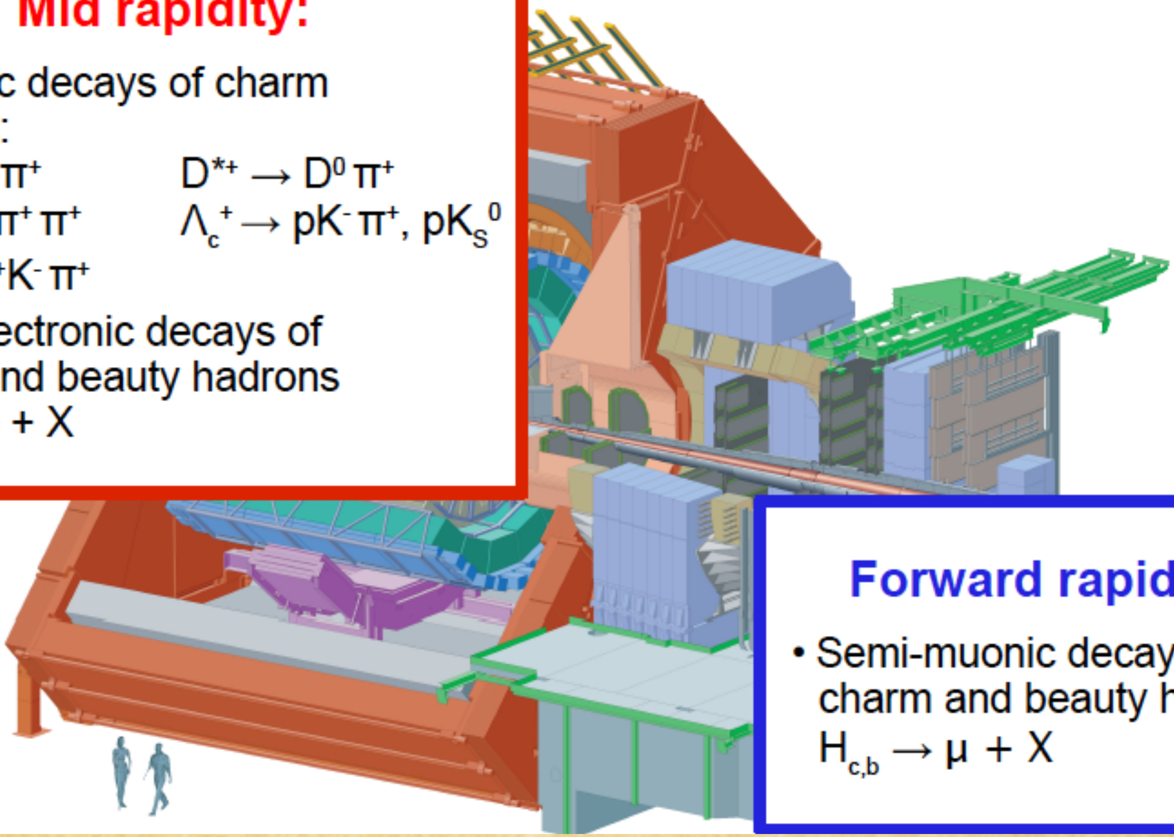
I Vitev, A Adil and H van Hees, J. Phys. G: Nucl. Part. Phys. 34 (2007) S769–S773

Proton-proton collisions: provide important test of pQCD in a new energy domain and heavy ion reference

Heavy Flavor Program in ALICE

Mid rapidity:

- Hadronic decays of charm hadrons:
  $D^0 \rightarrow K^- \pi^+$ $D^{*+} \rightarrow D^0 \pi^+$
  $D^+ \rightarrow K^- \pi^+ \pi^+$ $\Lambda_c^+ \rightarrow pK^- \pi^+, pK_S^0$
  $D_s^+ \rightarrow K^+ K^- \pi^+$
- Semi-electronic decays of charm and beauty hadrons
  $H_{c,b} \rightarrow e + X$

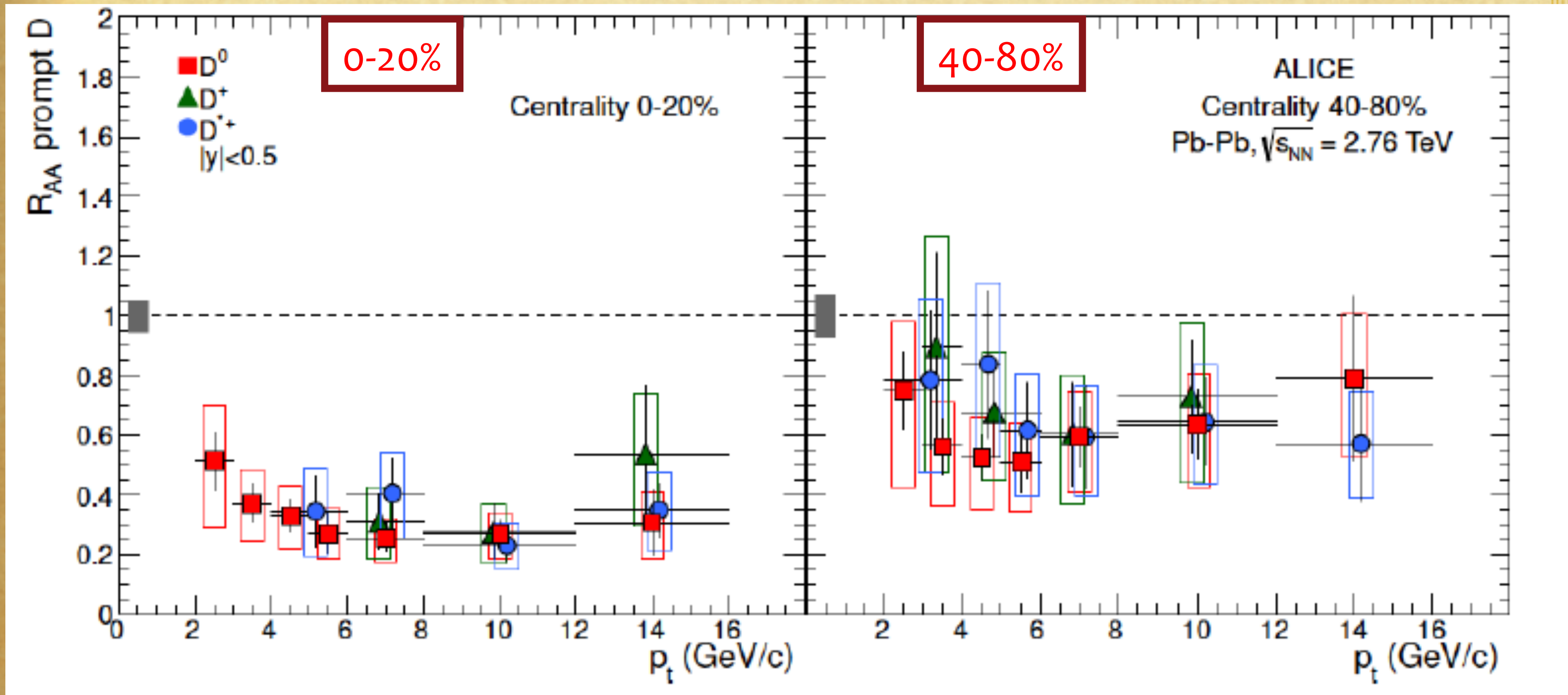


Forward rapidity:

- Semi-muonic decays of charm and beauty hadrons
  $H_{c,b} \rightarrow \mu + X$

D meson R_{AA} (|y| < 0.5)

arXiv:1203.2160

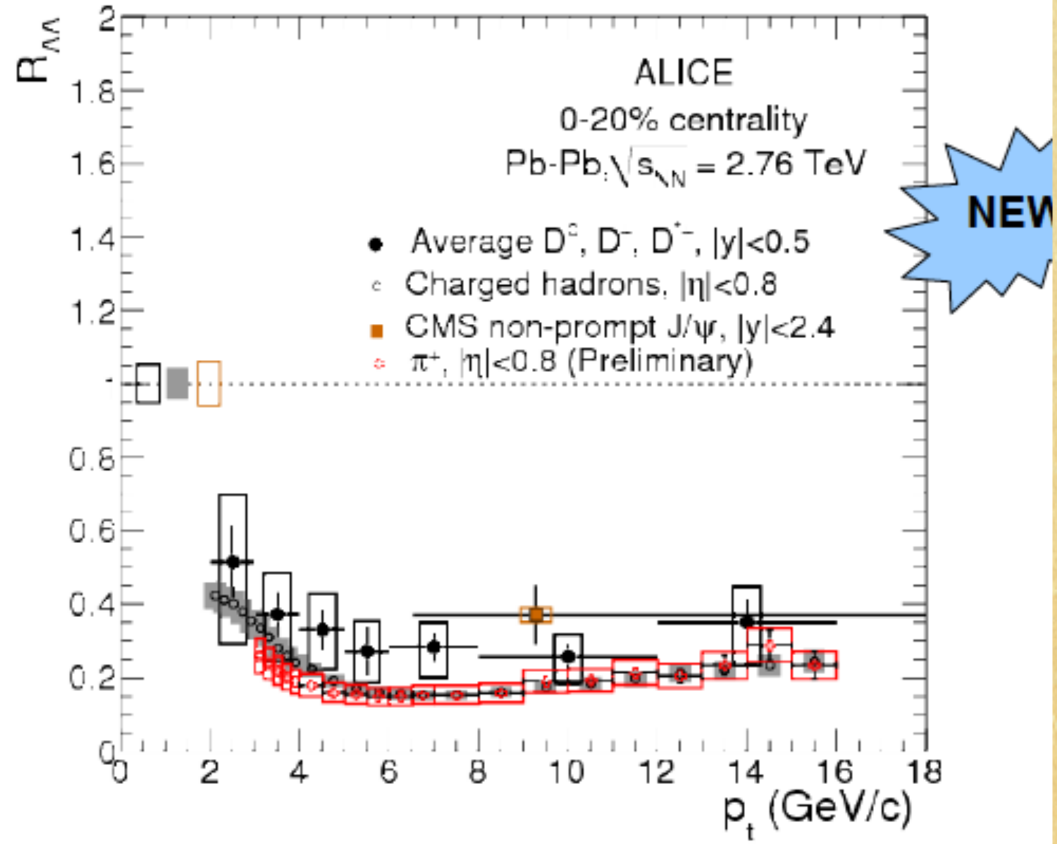


- D^0, D^+, D^* compatible
- Strong suppression in central collisions

R_{AA} compilation (D, B, light hadrons)

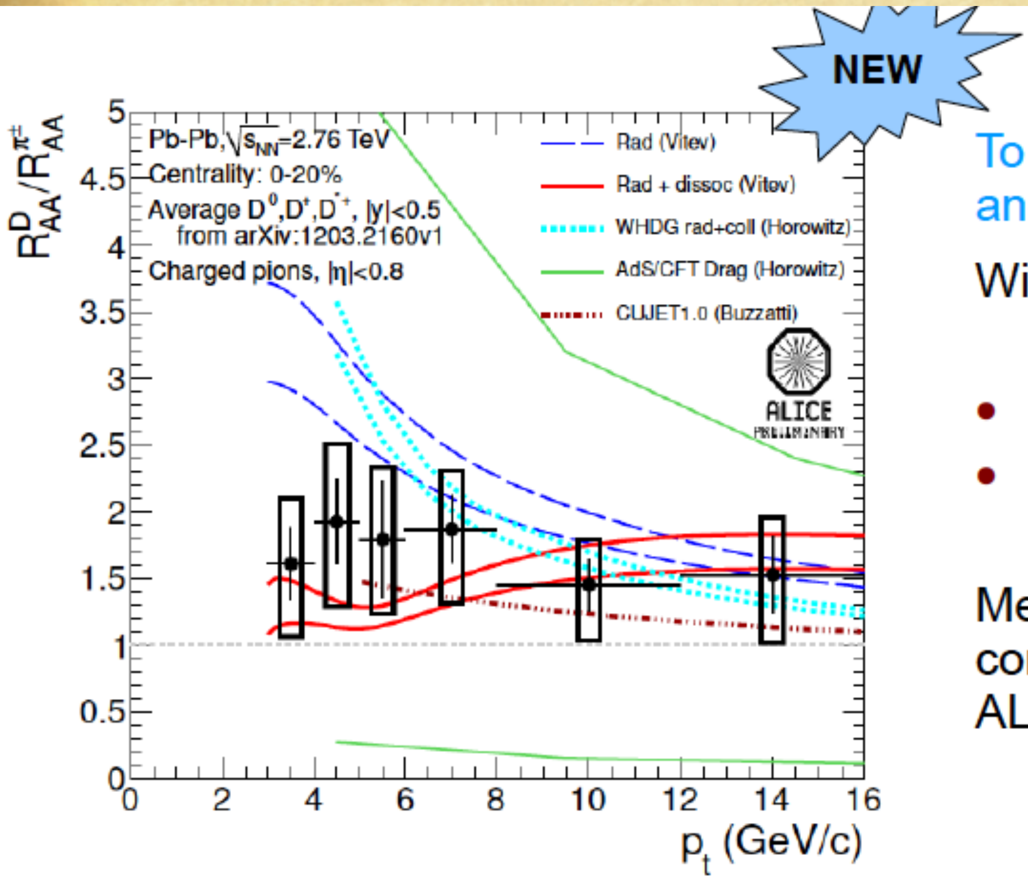
- Charged hadrons
- Identified pions
- D mesons (charm)
- B → J/ψ (beauty) CMS

arXiv:1201.5069



- Charm and beauty: no evidence of mass effects yet (dead cone)
- Pions, charm, beauty R_{AA}: hit of a hierarchy?

R_{AA} ratio (D/π^0)



To compare charm mesons and pions → ratio of R_{AA}'s

With the current uncertainties:

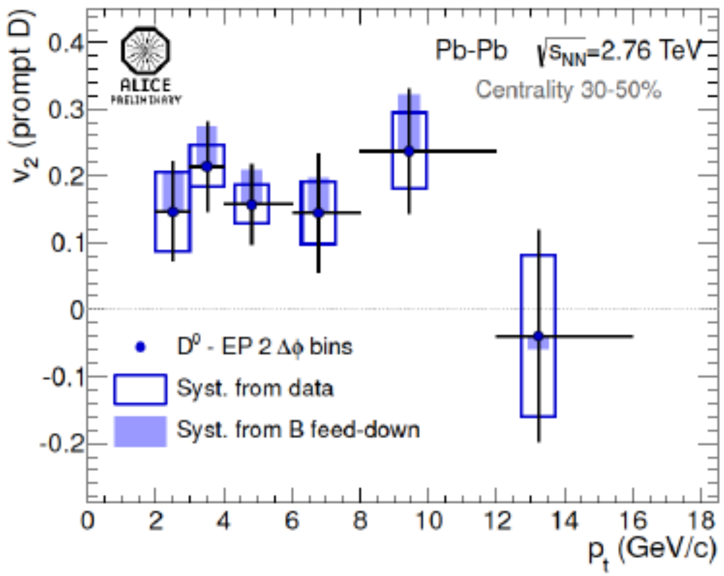
- Hint of R > 1
- Color charge effect?

Measurements are not yet conclusive → in reach for ALICE ! More precision !

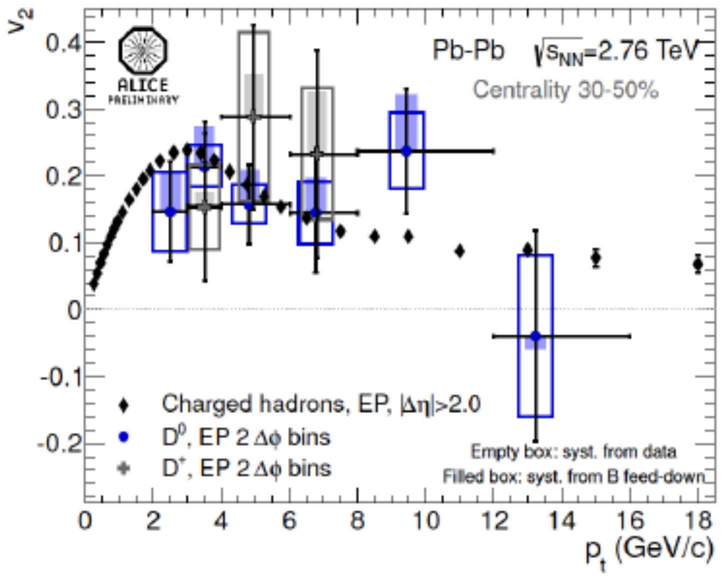
S.Masciocchi@gsi.de ALICE Heavy flavours, HP2012 26

v_2 for D

- D^0 v_2 in 30-50% centrality



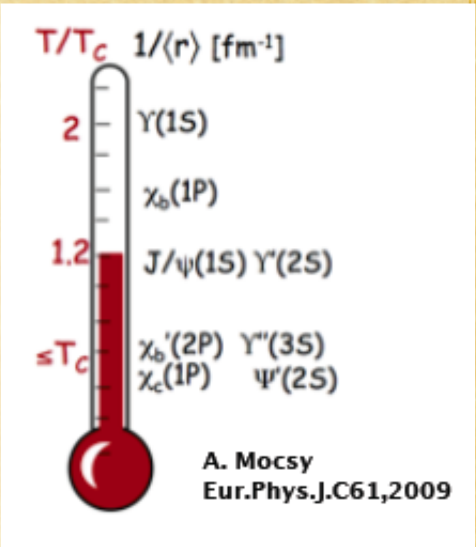
- D meson compared to charged hadrons



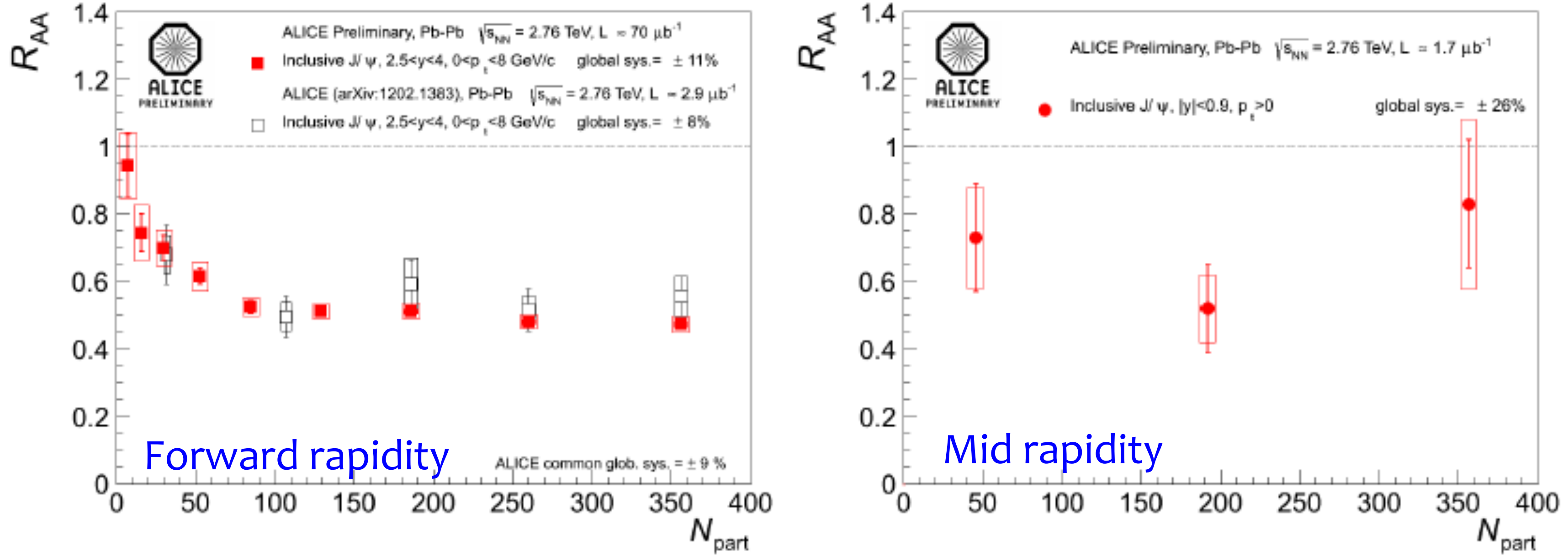
- Indication for non zero D meson v_2 (3σ in $2 < p_t < 6$ GeV/c)
- Hint of centrality dependence: D^0 v_2 flow larger in less central collisions
- Comparable with charged hadrons elliptic flow

S.Masciocchi@gsi.de

8. Quarkonia


T/Tc 1/⟨r⟩ [fm-1]
2
Υ(1S)
χb(1P)
1.2
J/ψ(1S) Υ'(2S)
≤Tc
χb'(2P) Υ''(3S)
χc(1P) ψ'(2S)
A. Mocsy
Eur.Phys.J.C61,2009

J/ψ R_{AA} vs. centrality



Clear J/Ψ suppression at forward rapidity.

→ almost no centrality dependence above N_{part} ~ 100.

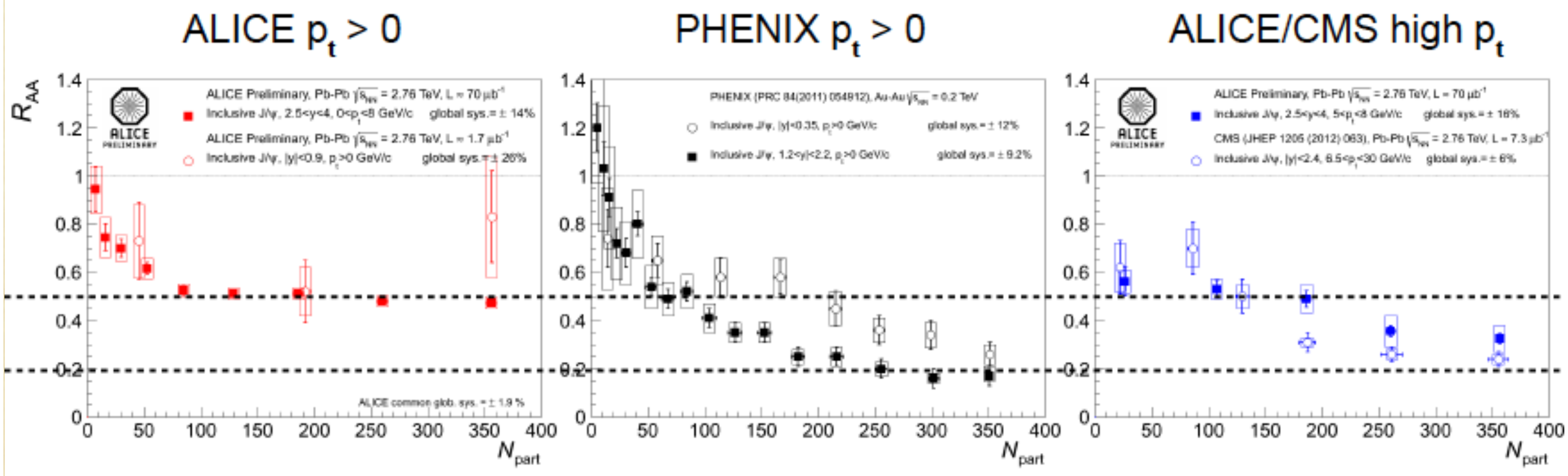
At mid rapidity, similar pattern but but large uncertainties prevent a firm conclusion.

ALICE inclusive J/ψ → $\mu^+\mu^-$ $R_{AA}^{0\text{-}90\%}$ = 0.497 ± 0.006 (stat.) ± 0.078 (sys.)

→ good agreement with 2010 results: $R_{AA}^{0\text{-}80\%}$ = 0.545 ± 0.032 (stat.) ± 0.084 (sys.)

ALICE inclusive J/ψ → e^+e^- $R_{AA}^{0\text{-}80\%}$ = 0.66 ± 0.10 (stat.) ± 0.24 (sys.)

J/ψ R_{AA} vs. centrality



At low-pt, ALICE $R_{AA} \geq 0.5$, no centrality dependence

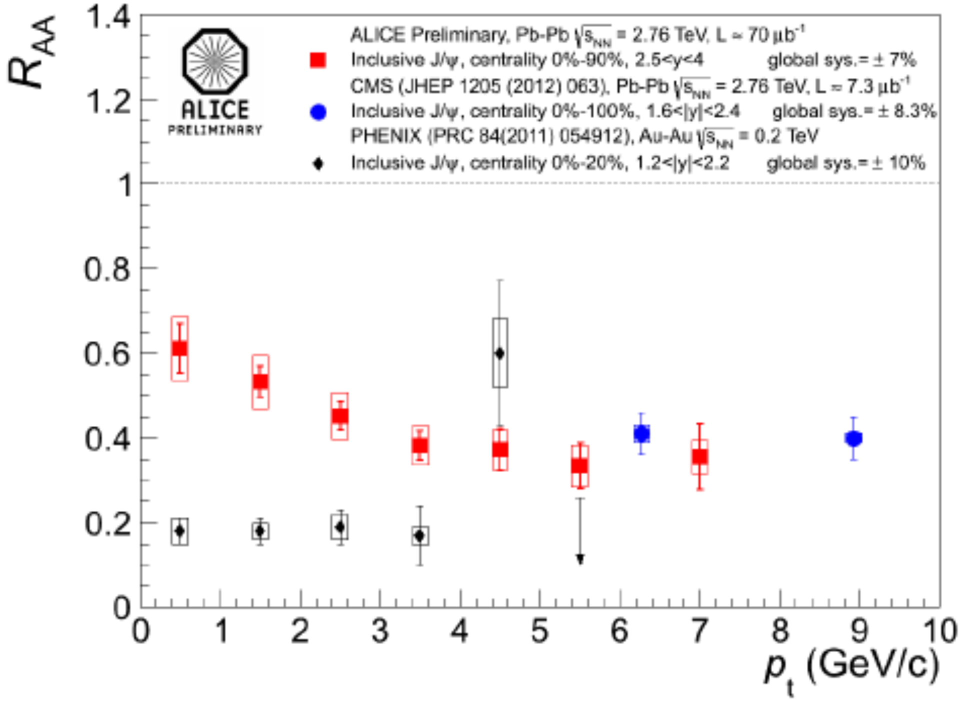
→ behavior clearly different to the one observed in PHENIX where a larger suppression and a strong centrality dependence is seen

At high-p_t, larger suppression seen both by ALICE and CMS

→ behavior is similar to the one observed at low energy

Indication that the suppression is p_t dependent

J/ψ R_{AA} vs. p_T

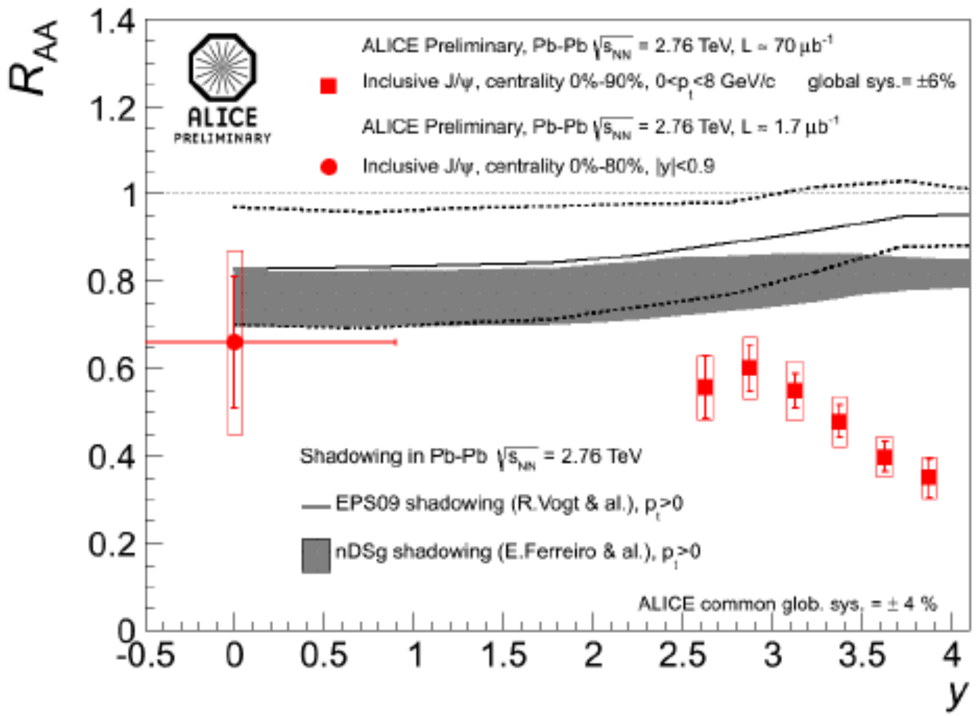


◀ ALICE inclusive J/ψ → μ+μ- at forward rapidity.
R_{AA} ~ 0.6 at low-pt down to R_{AA} ~ 0.35 at high-p_t. Suppression increases with increasing p_t.

◀ Agreement with CMS data at high-p_t (1.6<|y|<2.4) .

◀ PHENIX measured larger suppression at low-p_t (0-20% central, 1.2<|y|<2.2)

J/ψ R_{AA} vs. y



◀ Inclusive J/ψ measured in ALICE at both mid and forward rapidity.
R_{AA} decrease of 40% from y=2.5 to y=4.
Possible flat dependence toward mid rapidity.

◀ Suppression beyond the current estimate of shadowing at forward rapidity.

→ importance to measure cold nuclear matter effects.

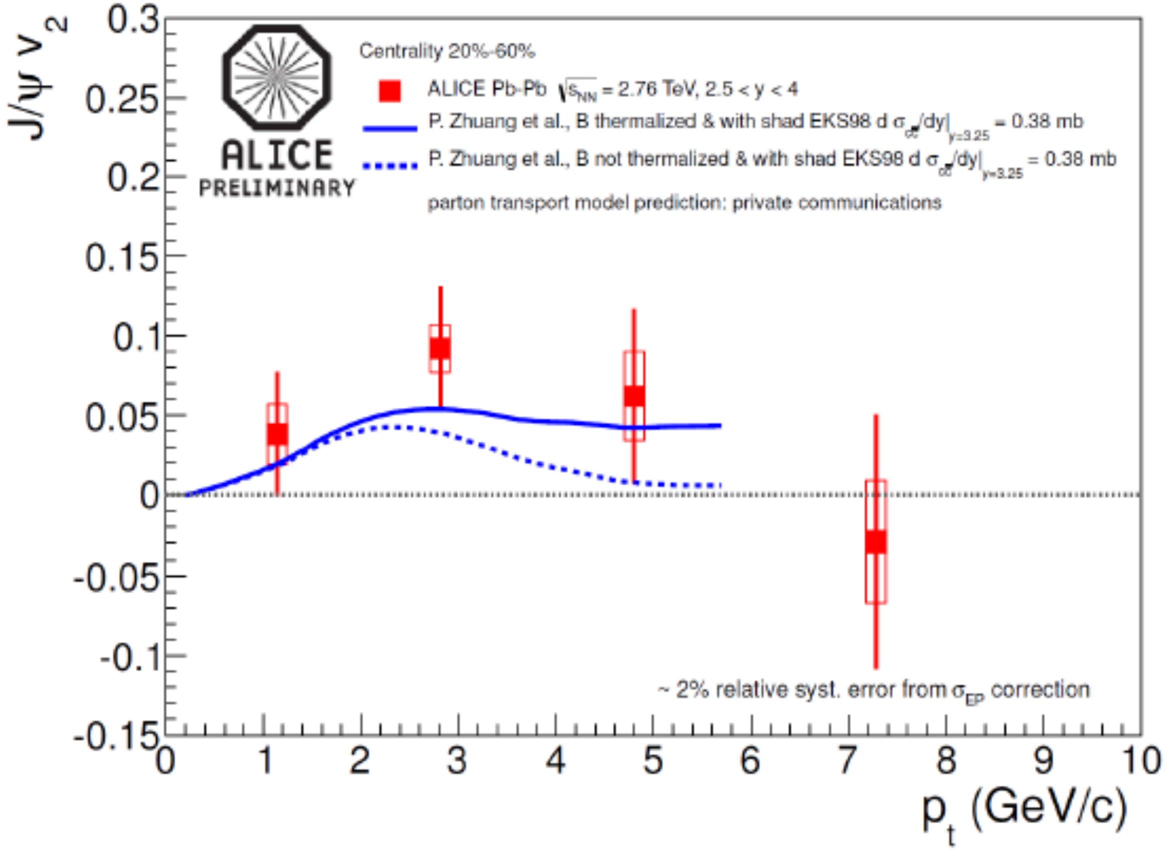
C.Hadjidakis, Poster Session , may 29th

J/ψ v_2 (20-60%)

J/Ψ v_2 as a function pt for 20%-60% most central Pb-Pb collisions

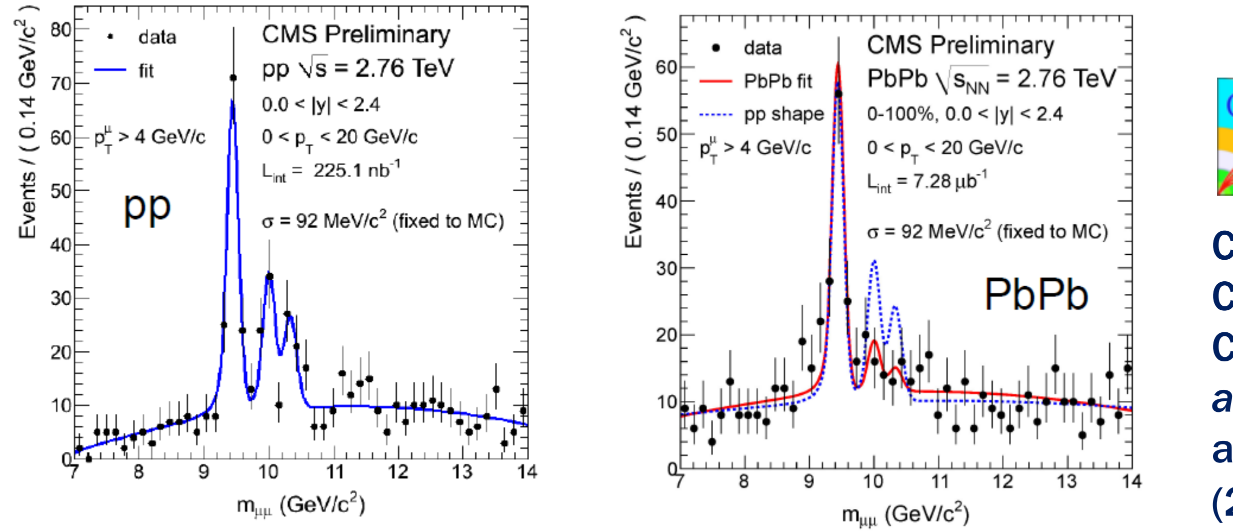
Clear hint of non-zero J/Ψ v_2 at intermediate p_t (2-4 GeV/c): significance = 2.2 σ

Model prediction for v_2 shown here succeeds well at reproducing J/ψ R_{AA}.



Higher Υ States Suppression (CMS, early results)

- Higher excited states : melt earlier (expectation)



$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

CMS-PAS-HIN-10-006
CMS-PAS-HIN-11-007
CMS (S. Chatrchyan *et al.*), arXiv:1105.4894 [nucl-ex] (2011)

- Υ(1s) suppressed by 0.6 ± 0.15

- Υ(2s, 3s) further suppressed; 2.4σ effect

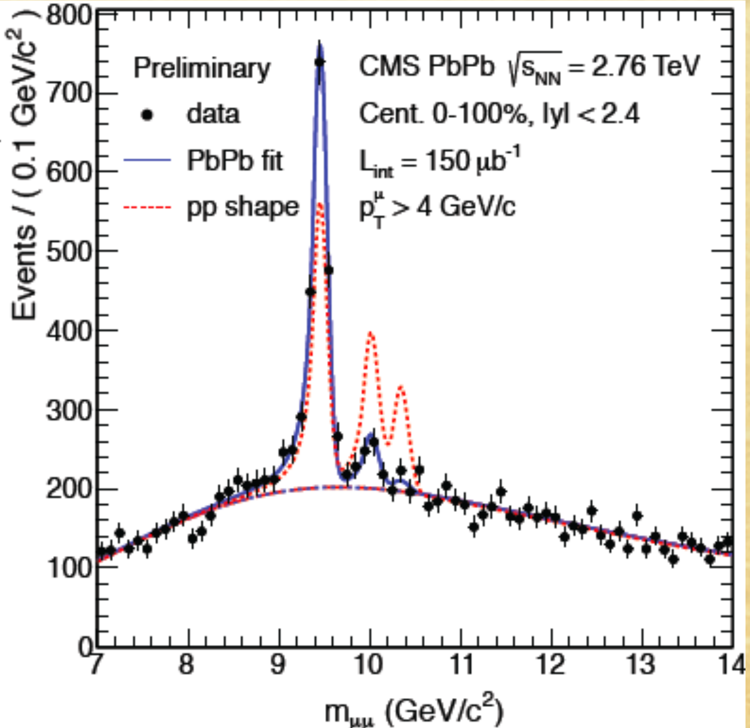
New results on Υ states

◉ First separate measurement, in HI collisions, of the relative suppression of Υ(2S) and Υ(3S) excited states wrt to the ground state

◉ Suppression pattern as expected in the sequential melting scenario

Υ(3S)>Υ(2S)>Υ(1S)

◉ No centrality dependence, within uncertainties, of the [Υ(2S)/Υ(1S)]$_{PbPb}$ / [Υ(2S)/Υ(1S)]$_{pp}$



0-100%:

$$\frac{[\Upsilon(2S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(2S)/\Upsilon(1S)]|_{pp}} = 0.21 \pm 0.07 \pm 0.02 \ (5.4\sigma \text{ significance})$$

$$\frac{[\Upsilon(3S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(3S)/\Upsilon(1S)]|_{pp}} < 0.1 \ (95\% C.L.)$$

14

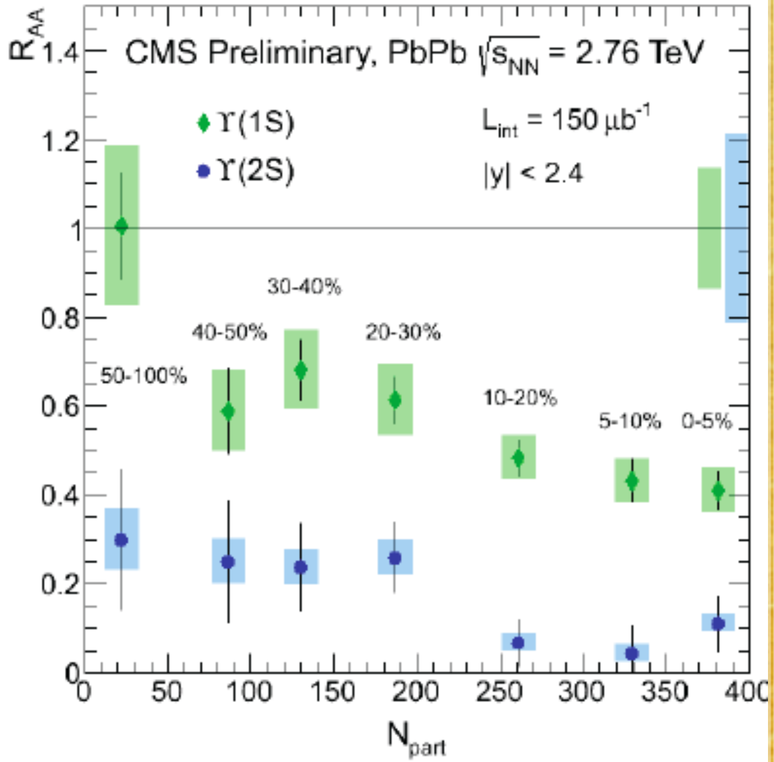
R_{AA}: Υ (1S), Υ (2S)

◉ R_{AA}: Υ(1S)

- ➡ detailed centrality study
- ➡ decrease of suppression from ~0.4 in 0-5% to ~1 in 50-100%

◉ R_{AA}: Υ(2S)

- ➡ first time measured in HI collisions
- ➡ more suppressed than the ground state and still suppressed in 50-100% centrality bin

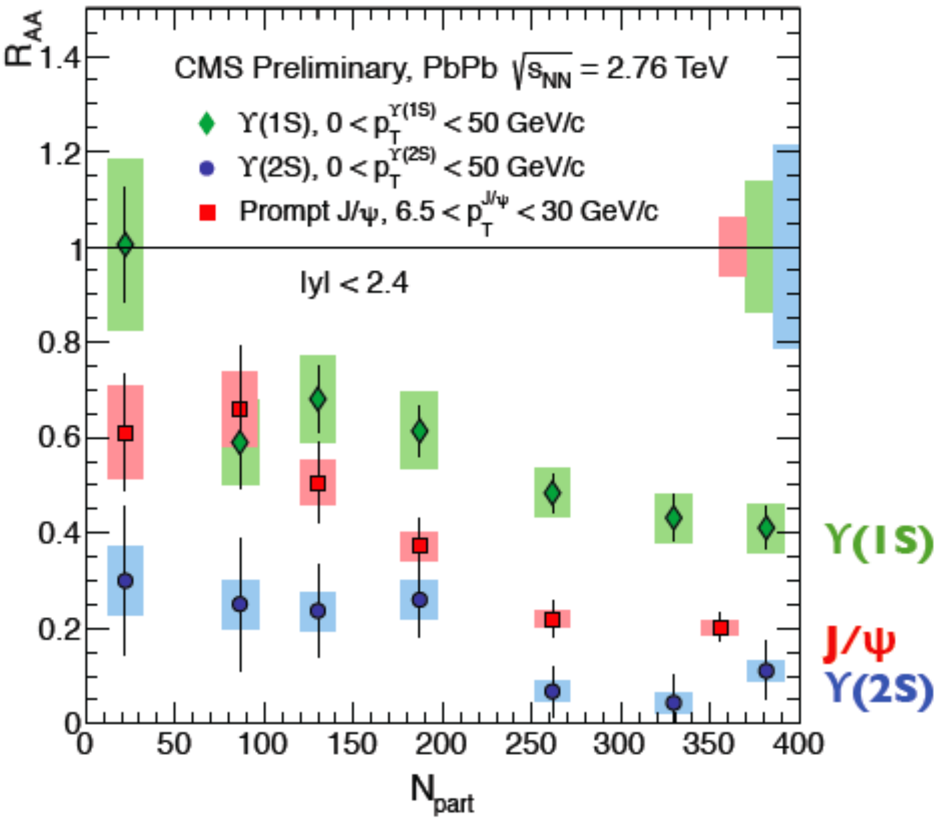


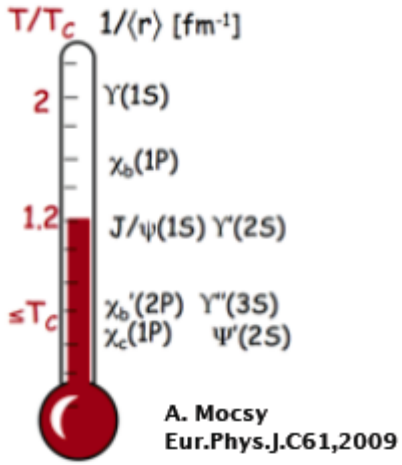
0-100%

$$R_{AA}|^{\Upsilon(1S)} = 0.53 \pm 0.07 \pm 0.07$$

$$R_{AA}|^{\Upsilon(2S)} = 0.13 \pm 0.04 \pm 0.02$$

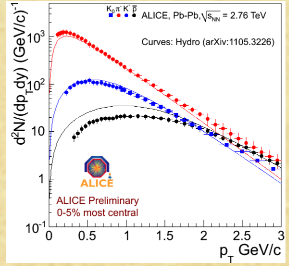
R_{AA} (J/ψ, ϒ(1S), ϒ(2S)) vs. centrality



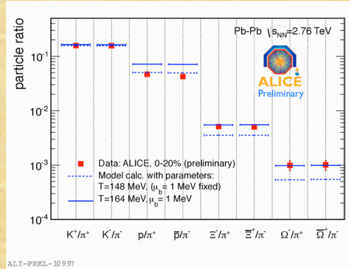


- Suppression pattern in most central collisions, as expected from sequential melting

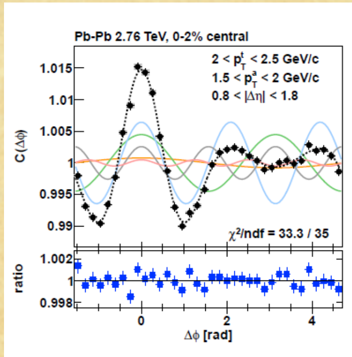
10. SUMMARY (1)



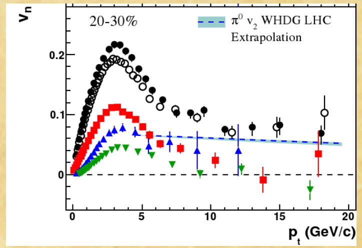
- Period of rich harvest of LHC new data!



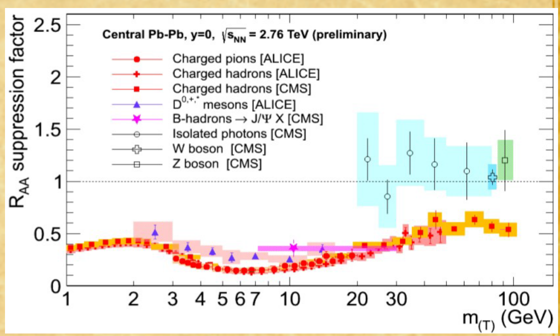
- Complimentary HI results by ALICE, ATLAS, CMS
  → New understanding.



1. **Low p_T single particle spectra**
   - proton spectra: hydrodynamics cal. overestimates.
   - p/π ratio: fail to reproduced by thermal model.
   - Stronger baryon enhancement at LHC than RHIC?



2. **Flow and higher harmonics**
   - v_2, v_3 : η/s and initial conditions, quark number scaling.
   - non-zero v2 @ p_T > 20 GeV, constraint to energy loss model (path length dep.)



3. **High p_T single particle spectra**
   - same suppression for light hadrons (dip at p_T ~ 6 GeV/c), stronger than that at RHIC, rising at higher p_T (< 100 GeV/c)
   - photon, Z, W boson: no suppression

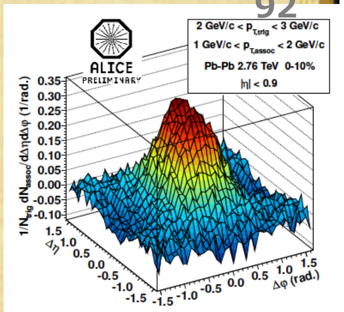
Summary (2)

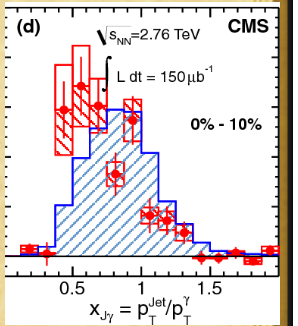
4. **Di-hadron correlations**
   - I_{AA}, near side enhancement.
   - indication of near side jet shape modification in η.
   - p/π ratio in jets is same as in the vacuum fragmentation.

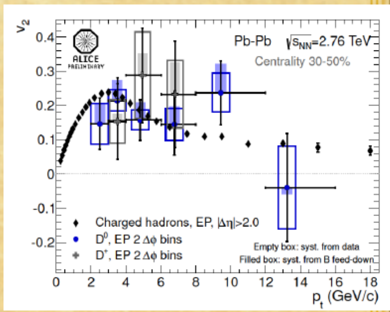
5. **Jet**
   - Jet R_{AA} ~0.5.
   - Di-jet: large A_J in all p_T up to 200 GeV. No indication of modified FF.
   - γ-jet: calibrated jet energy by gamma, towards precise jet energy loss.

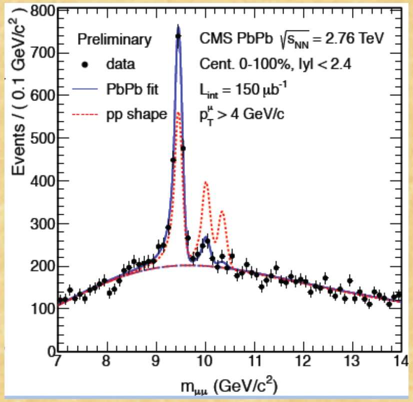
6. **Heavy Flavor**
   - D meson suppression observed, R_{AA} (D) > R_{AA} (π), hint of color charged effect
   - non-zero v2 of D mesons.

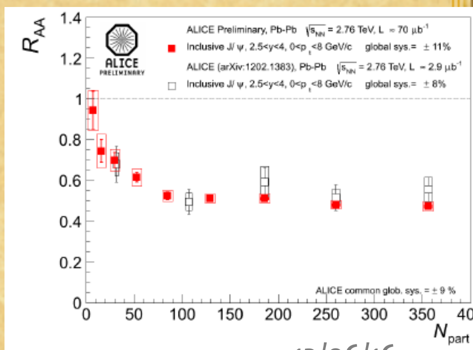
7. **Quarkonia**
   - J/ψ R_{AA} vs. pT, y, centrality.
   - non-zero v2 of J/ψ.
   - Sequential melting of excited Υ states.



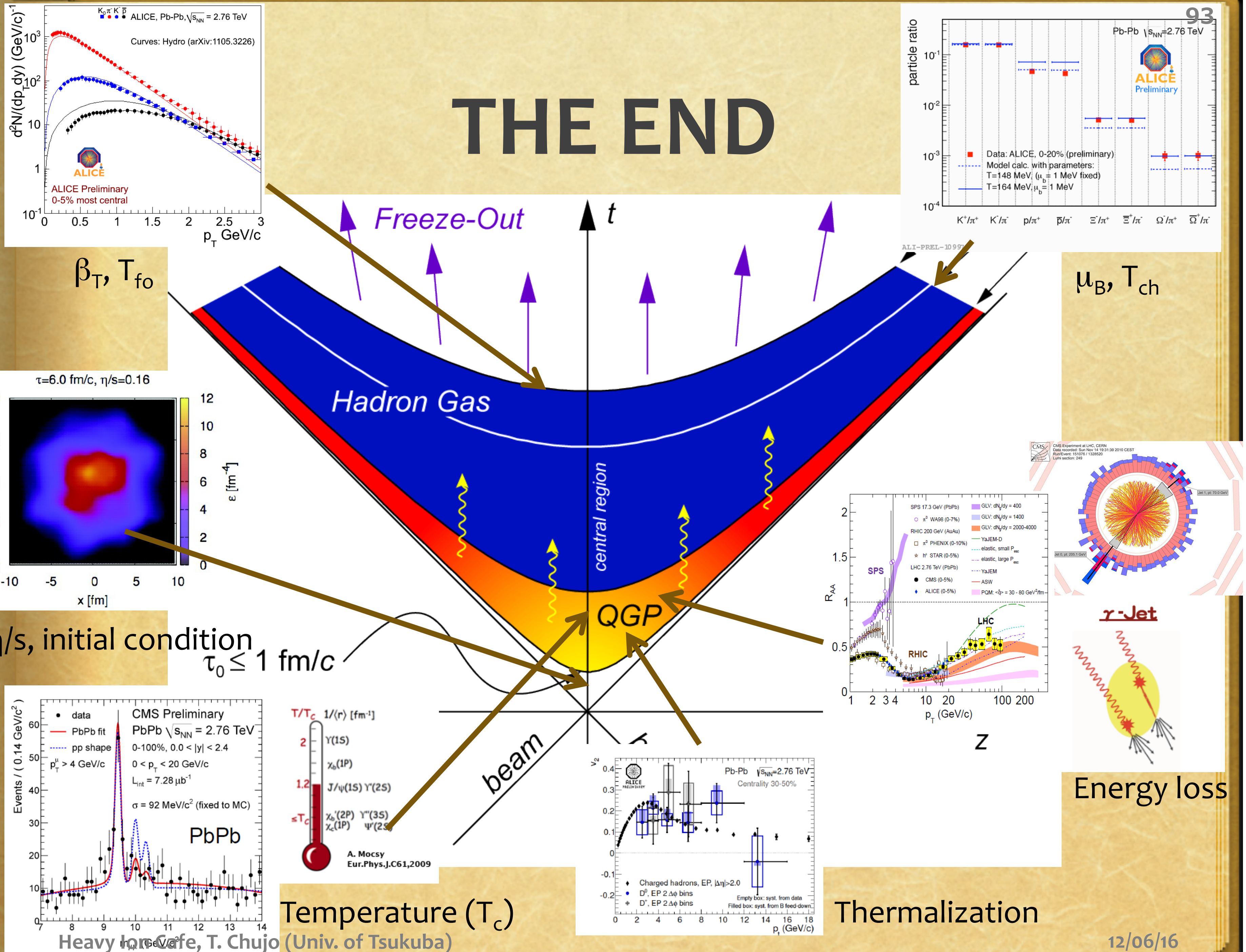








THE END



Freeze-Out
t
Hadron Gas
central region
QGP
beam
z
$\tau_0 \leq 1$ fm/c
β_T, T_{fo}
μ_B, T_{ch}
η/s, initial condition
Temperature (T_c)
Thermalization
Energy loss
γ-Jet
ALICE, Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Curves: Hydro (arXiv:1105.3226)
ALICE Preliminary
0-5% most central
p_T GeV/c
τ=6.0 fm/c, η/s=0.16
x [fm]
y [fm]
ε [fm^{-4}]
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
particle ratio
Data: ALICE, 0-20% (preliminary)
Model calc. with parameters:
T=148 MeV, μ_b = 1 MeV fixed)
T=164 MeV, μ_b = 1 MeV
CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0-100%, 0.0 < |y| < 2.4
0 < p_T < 20 GeV/c
L_{int} = 7.28 μb^{-1}
σ = 92 MeV/c^2 (fixed to MC)
data
PbPb fit
pp shape
p_T^{μ} > 4 GeV/c
PbPb
Events / (0.14 GeV/c^2)
A. Mocsy
Eur.Phys.J.C61,2009
SPS
RHIC
LHC
R_{AA}
p_T (GeV/c)
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
Centrality 30-50%
Charged hadrons, EP, |Δη|>2.0
v_2