Recent Pb-Pb and p-Pb results from ALICE

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Summary

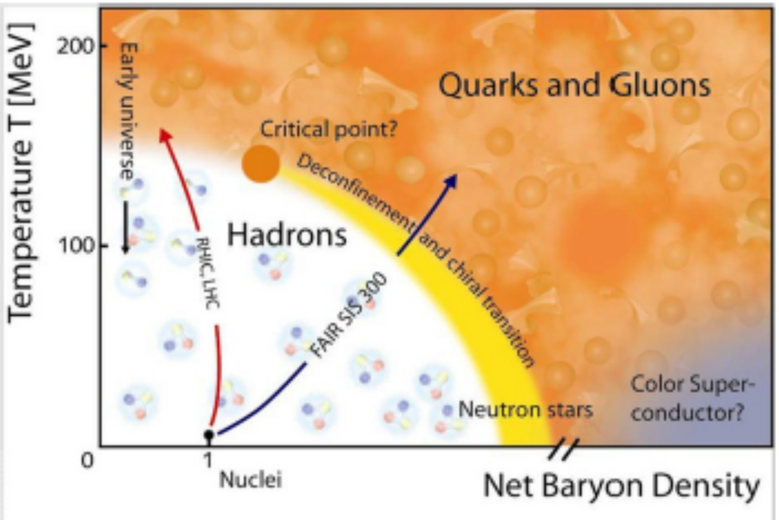
- Few words about ALICE
- ALICE Pb-Pb results: a selection
  - Global properties
  - Anisotropic flow
  - High-p_T particles
  - Heavy Flavors
  - Quarkonia
- ALICE p-Pb results
  - First results from Pilot Run
- Conclusions and perspectives

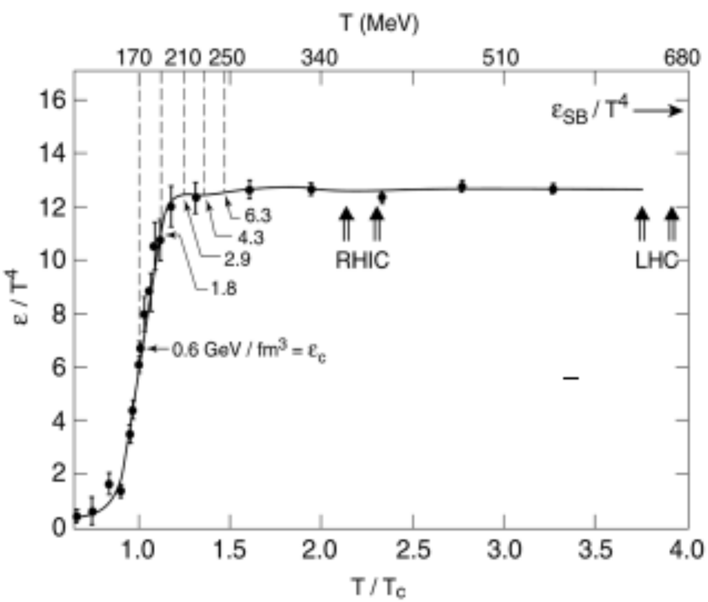
FEW WORDS ABOUT ALICE

ALICE motivation

heavy-ion collisions at the LHC energy regime

- Basic idea: compress large amount of energy in a very small volume
  - ⇨ produce a "fireball" of hot matter:
  - ⇨ temperature $O(10^{12}$ K)
    - ✓ *~ 10^5 x T at centre of Sun*
    - ✓ *~ T of universe 10 μs after Big Bang*



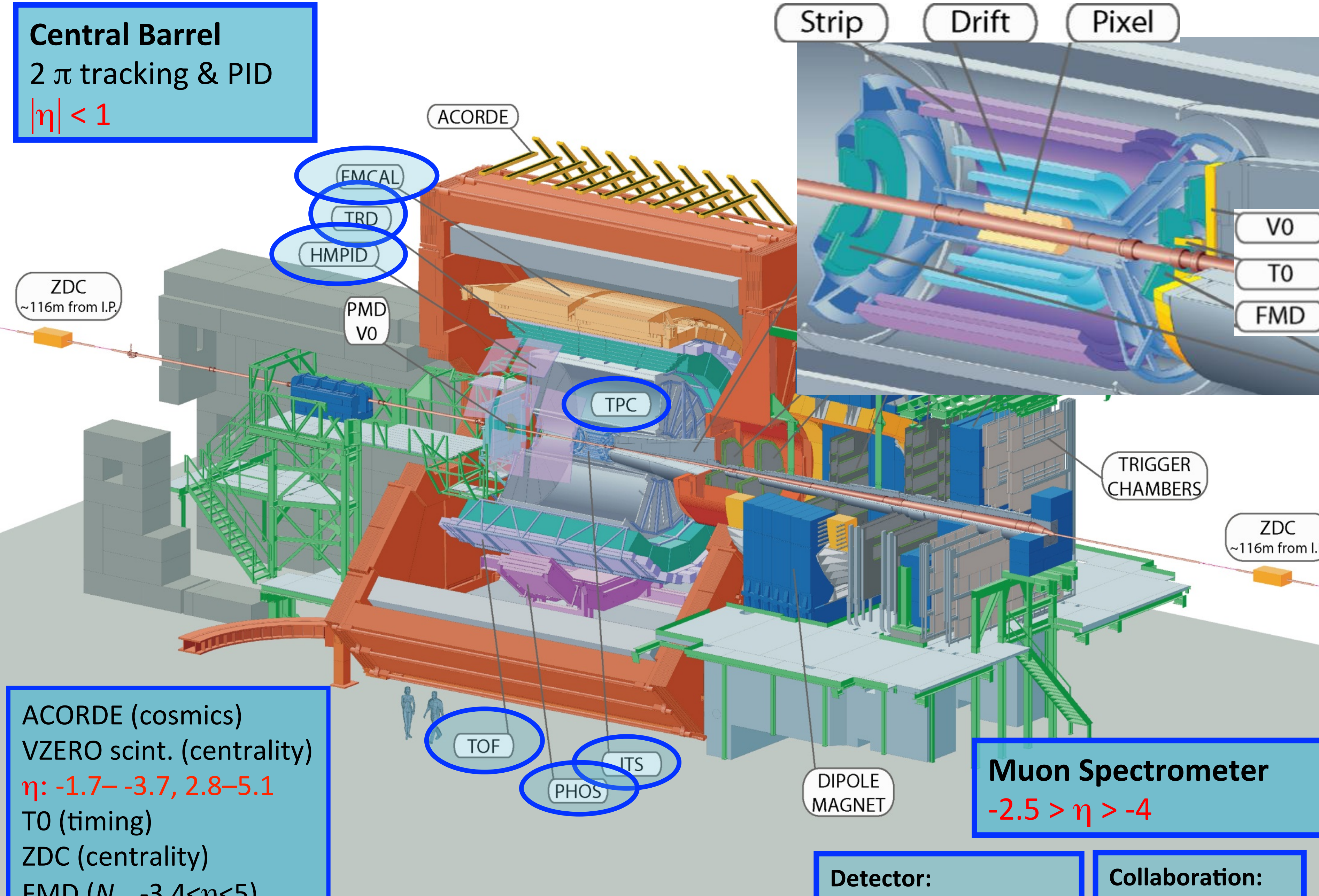


- Study nuclear matter at extreme conditions of temperature and density

Produce a state where quarks and gluons are deconfined (Quark Gluon Plasma) and study its properties

- ⇨ Phase transition predicted by Lattice QCD calculations
  - ✓ $T_C \approx 170$ MeV $\rightarrow \varepsilon_C \approx 0.6$ GeV/fm^3

Central Barrel
2 π tracking & PID
|η| < 1



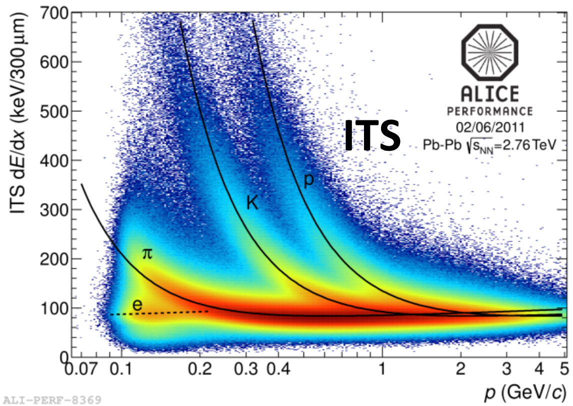
ACORDE (cosmics)
VZERO scint. (centrality)
η: -1.7– -3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD (N_{ch} -3.4<η<5)
PMD ($N\gamma$, N_{ch})

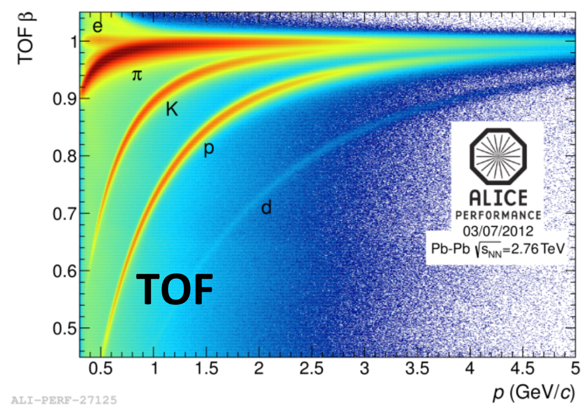
Muon Spectrometer
-2.5 > η > -4

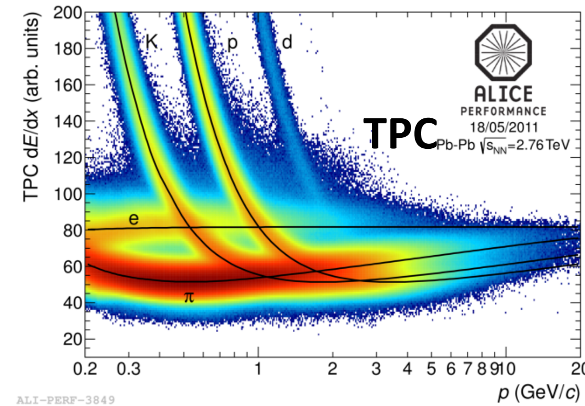
Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

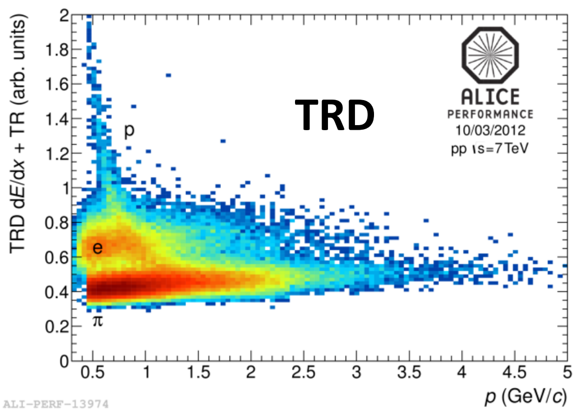
Collaboration:
~ 1200 Members
132 Institutes
36 countries

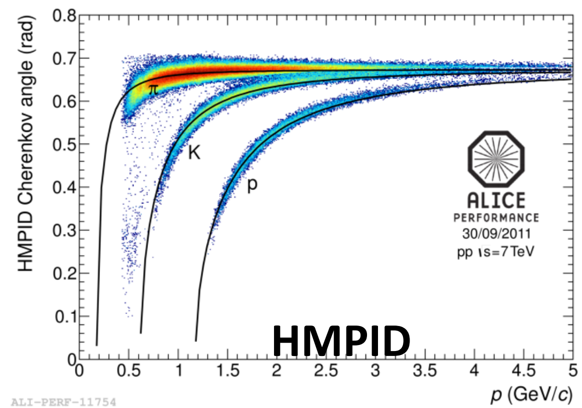
ALICE: main features and performance

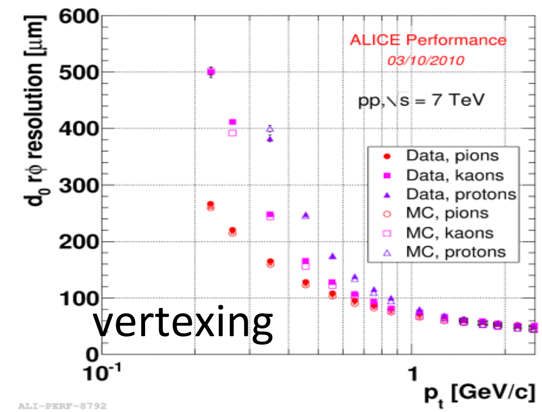












Central Barrel →
- particle identification (practically all known techniques)
- excellent vertexing capability
- efficient tracking – down to ~ 100 MeV/*c*

Forward det. →
- particle detection over a large rapidity range

Muon Arm & C.B. →
- quarkonia detection down to p_T=0

ALICE Data Taking

- Two Pb-Pb runs at 2.76 TeV (N-N c.m. energy) :
  - in 2010 – commissioning and the first data taking
  - in 2011 – (energy scaled) above nominal luminosity!

- pp data taken at different c.m. energies in 2009-2013:
  - 0.9, 2.36, 2.76, 7 and 8 TeV
  - → reference for HI data *and* genuine pp physics

- p-Pb : Pilot run in September 2012, run (p-Pb *and* Pb-p) in Jan-Feb 2013

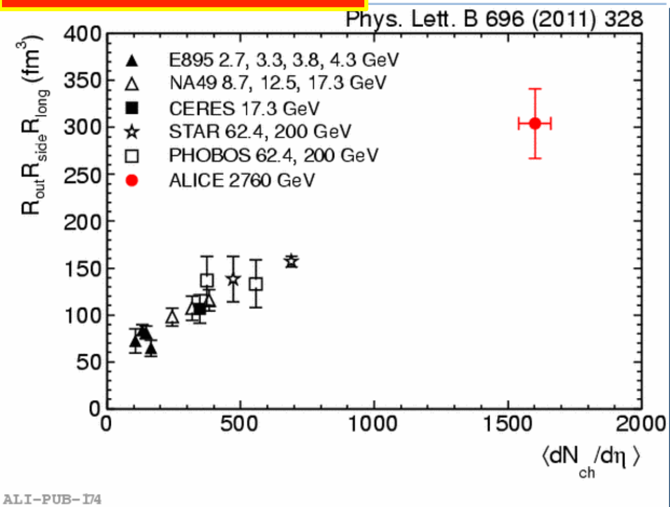
→ *Thanks to machine people for the superb LHC performance!!!*

year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 10 μb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

GLOBAL PROPERTIES

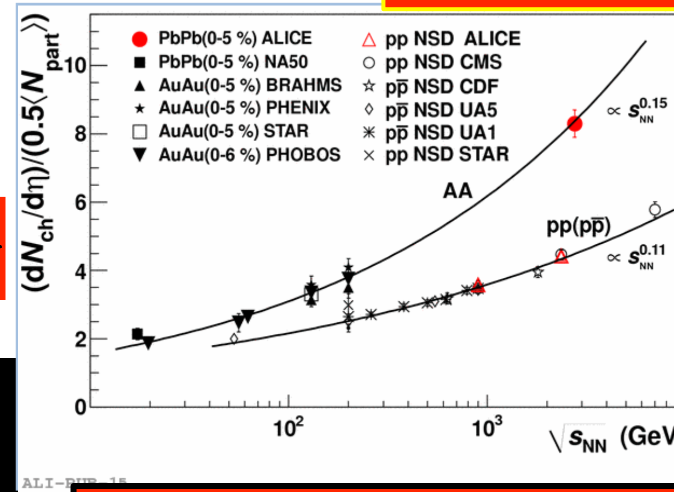
Global properties

Phys. Lett. B 696 (2011) 328

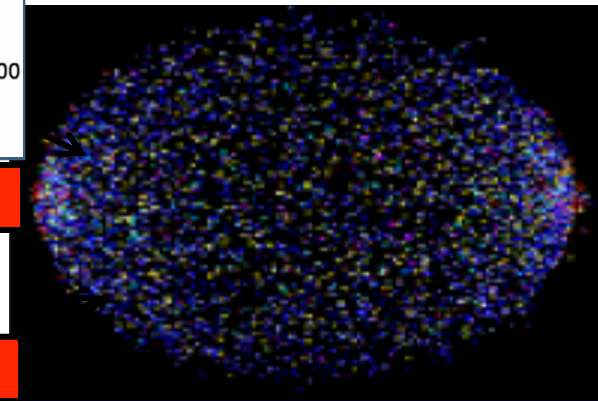


Volume ~ 2 x RHIC (R^3 ~ 300 fm^3)

PRL 105, 252301 (2010)



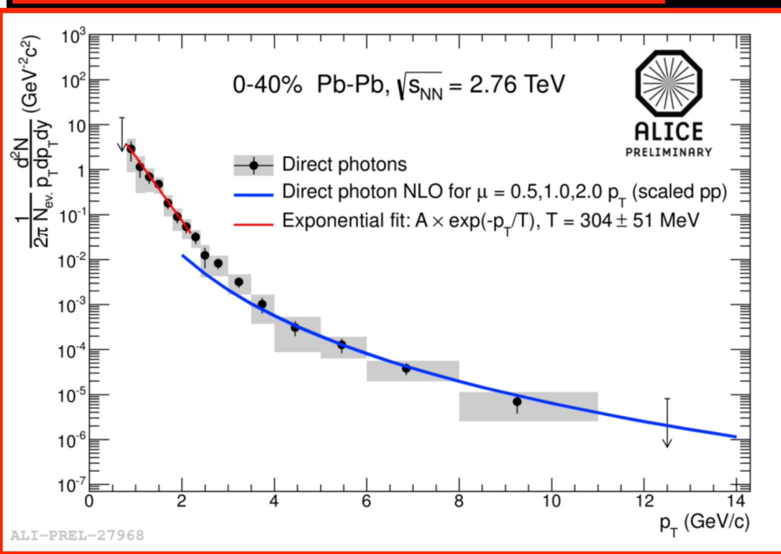
$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$



Energy density ~ 3 x RHIC ~ 10 GeV/fm^3

Photon T = 304±51 MeV ~ 1.4 x T_{RHIC}

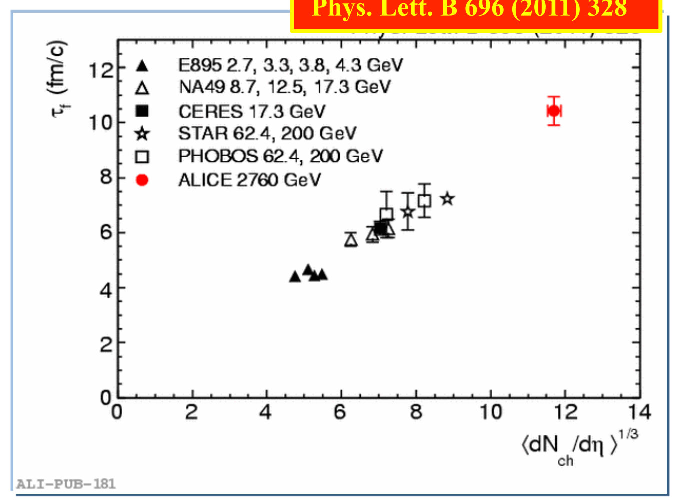
Lifetime: +20% wrt RHIC(~ 10 fm/c)



At LHC the fireball is hotter, larger and lasts more

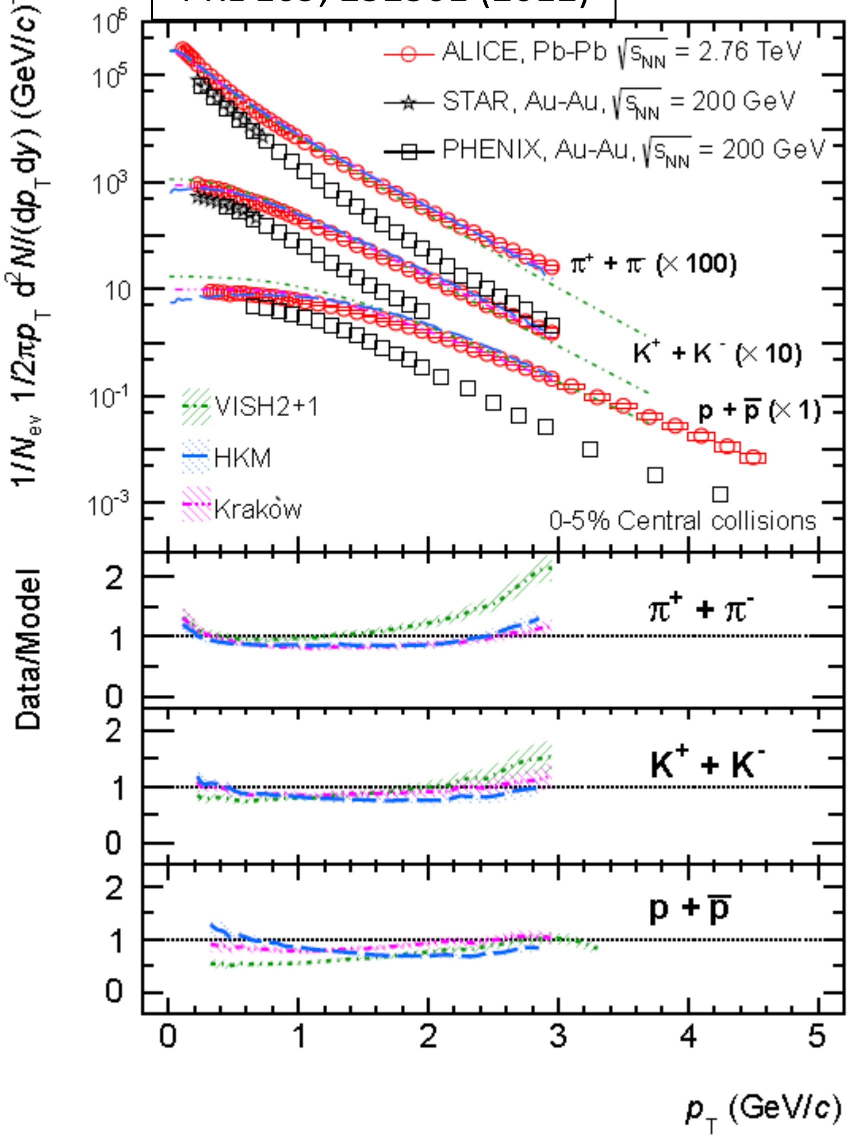
NEW!

Phys. Lett. B 696 (2011) 328

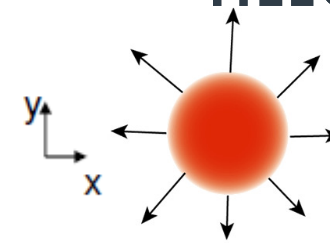


Low-p_T particle production

PRL 109, 252301 (2012)



Central collisions: radial flow



(low) p_T spectra : superposition of collective motion of particles on top of thermal motion

Collective motion is due to high pressure arising from compression and heating .

"Blast-Wave" fit to p_T spectra [1]:

→ Radial flow velocity <β> ≈ 0.65 (10 % larger than at RHIC)

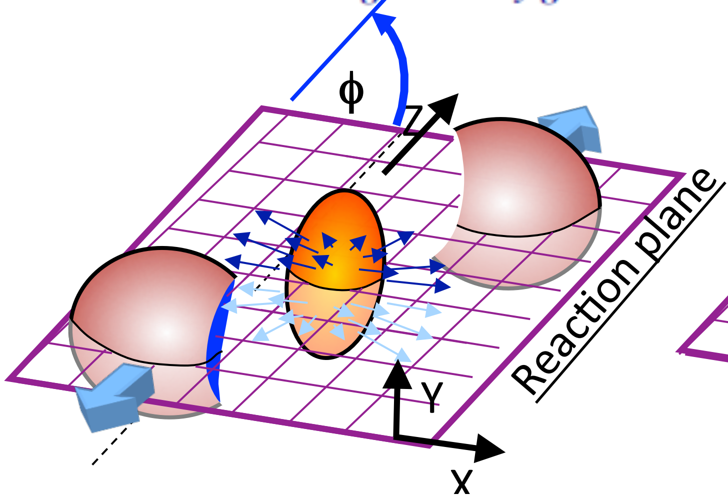
→Kinetic freeze-out temp. T_K ≈ 95 MeV (same as RHIC within errors)

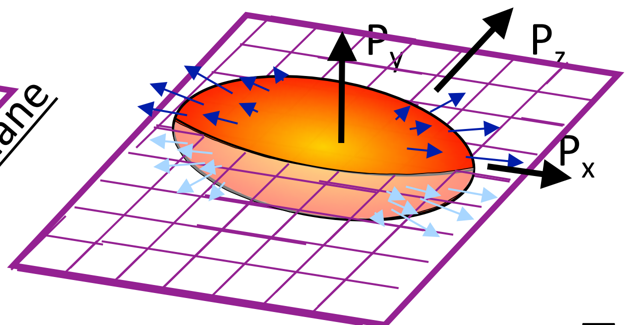
[1] E. Schnedermann, et al.; Phys. Rev. C48, 2462 (1993)

ANISOTROPIC FLOW

Elliptic flow

- In heavy ion collisions with b≠0 the impact parameter selects a preferred direction in the transverse plane
- Re-scatterings among produced particles convert the initial geometrical anisotropy into an observable momentum anisotropy
  - ⇨ Large mean free path
    - ✓ *Particles stream out isotropically, no memory of the initial eccentricity*
  - ⇨ Small mean free path:
    - ✓ *Larger density gradient "in plane" -> larger pressure gradient "in plane"*

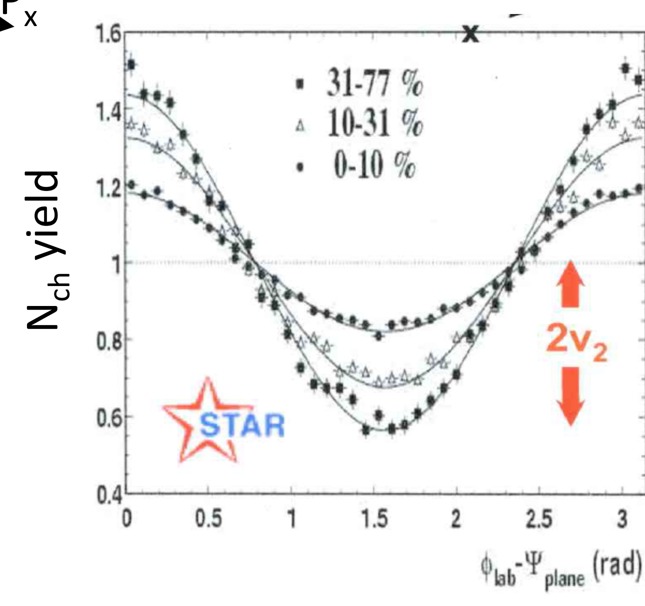




- Elliptic flow (v_2) = 2[nd] harmonic coefficient in the Fourier decomposition of particle azimuthal distributions w.r.t. the reaction plane (RP)

$$\frac{dN}{d(\varphi-\psi_{RP})} \propto 1+2\sum_{n=1} v_n \cos(n[\varphi-\psi_{RP}])$$

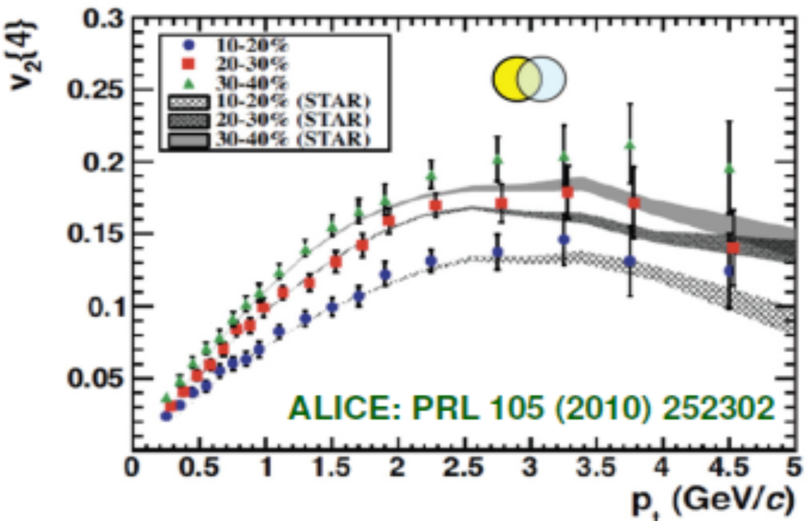
$$v_2 = \langle \cos[2(\varphi-\Psi_{RP})] \rangle$$



- Large elliptic flow observed at RHIC
  - ⇨ Consistent with strongly coupled medium with low shear viscosity (ideal fluid)

v_2: selected ALICE results

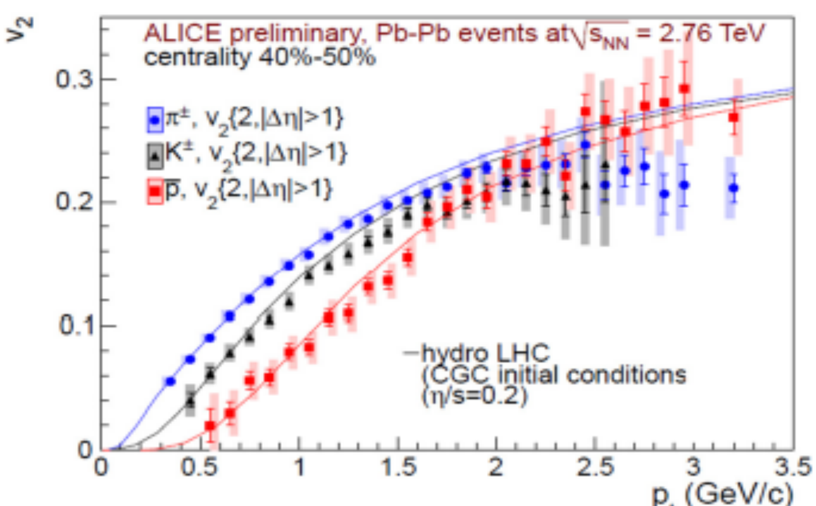
Large elliptic flow oberved at RHIC → consistent with strongly coupled medium with low shear viscosity (ideal fluid)



v_2 for non-identified particles:

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



v_2 for identified particles:

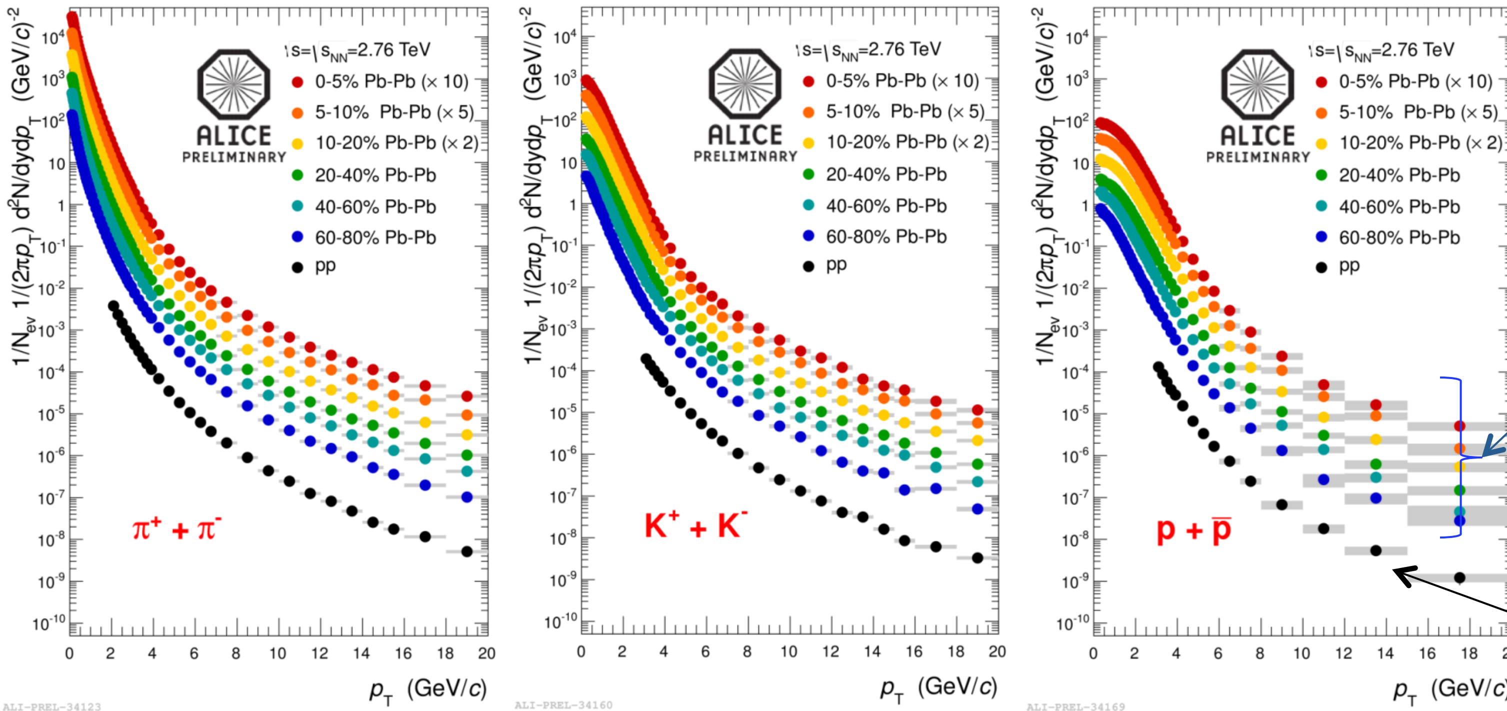
Stronger mass dependence of the elliptic flow as compared to RHIC:

→ Due to the larger radial flow?

→ Some deviation from hydrodynamic predictions for (anti) protons in close-to-central collisions: rescattering?

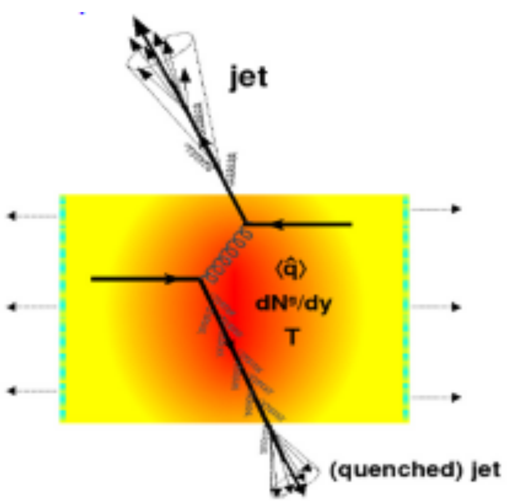
PARTICLE SPECTRA AT HIGH P_T

Particle spectra at high p_T



Pb-Pb at different centralities

Reference: pp collisions



Parton energy loss:

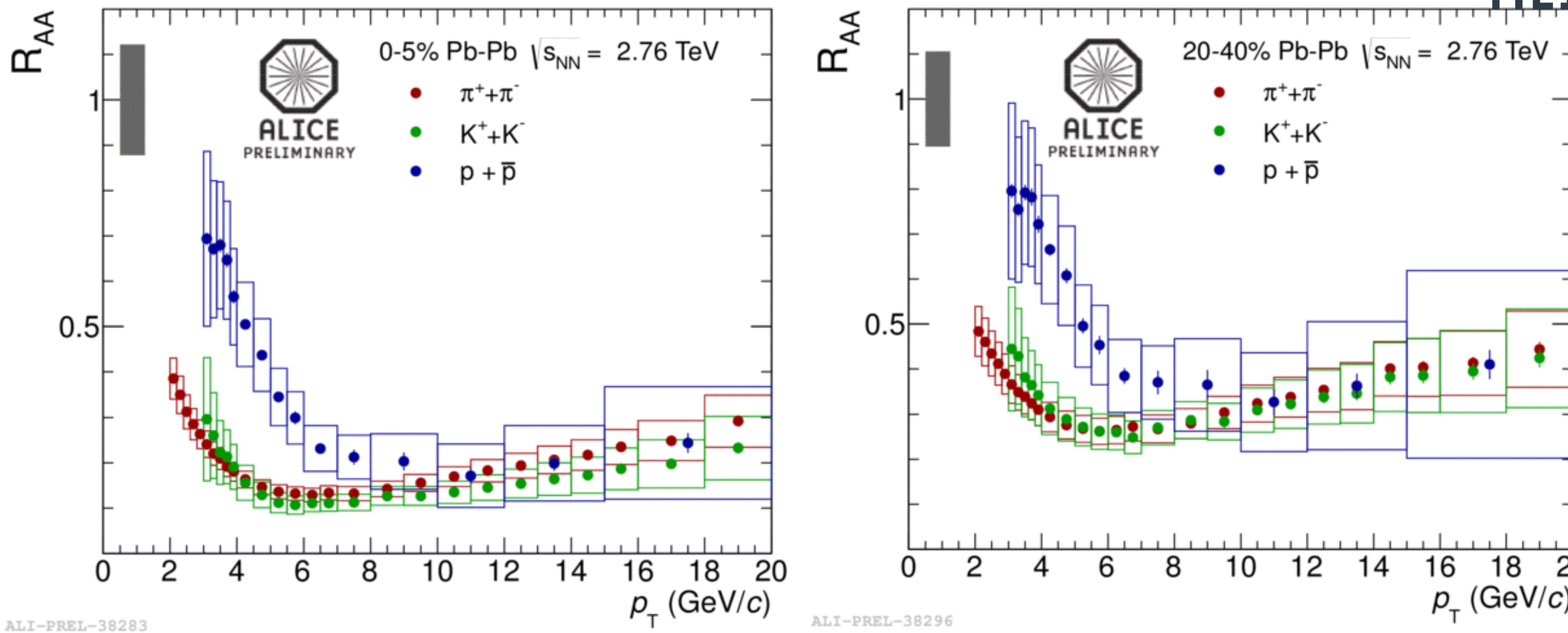
A parton passing through the QCD medium undergoes energy loss which results in the suppression of high-p_T hadron yields

Related observable:

nuclear modification factor R_{AA}

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

R_{AA} for identified particles



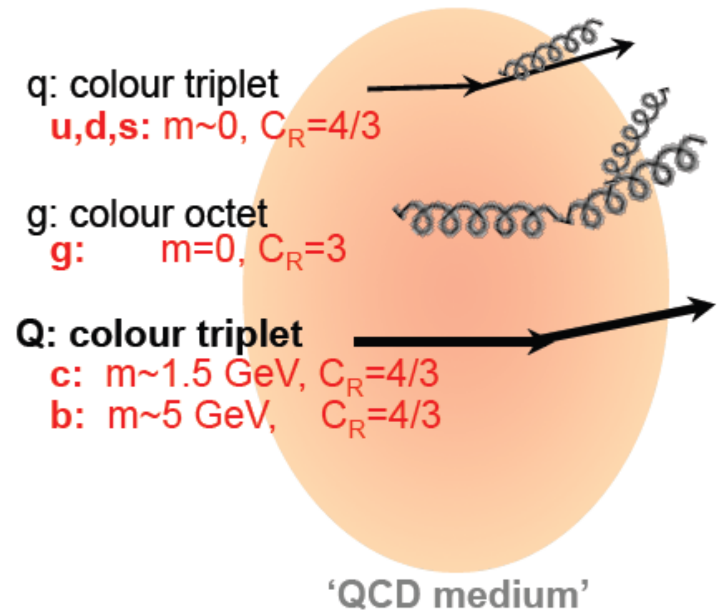
- First measurement of (anti-)proton, K and π at high p_T *(>7 GeV/c) :*
  - *The R_{AA} indicates strong suppression, confirming the indications from previous measurements for non-identified particles*
  - *The R_{AA} for (anti-)protons, charged pions and K are compatible above ~7 GeV/c → this suggests that the medium does not affect the fragmentation strongly.*

OPEN HEAVY FLAVORS

Heavy Flavor

Heavy quarks produced in the early stages of the collisions (high Q2) → effective probe of the high-density medium created in heavy-ion collisions

In-medium energy loss expected to be smaller for heavy quarks than for light quarks and gluons due to color charge and dead cone effect [1]



Parton Energy Loss by

- medium-induced gluon radiation
- collisions with medium gluons

$$\Delta E(\varepsilon_{medium};C_R,m,L)$$

pred: $\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$

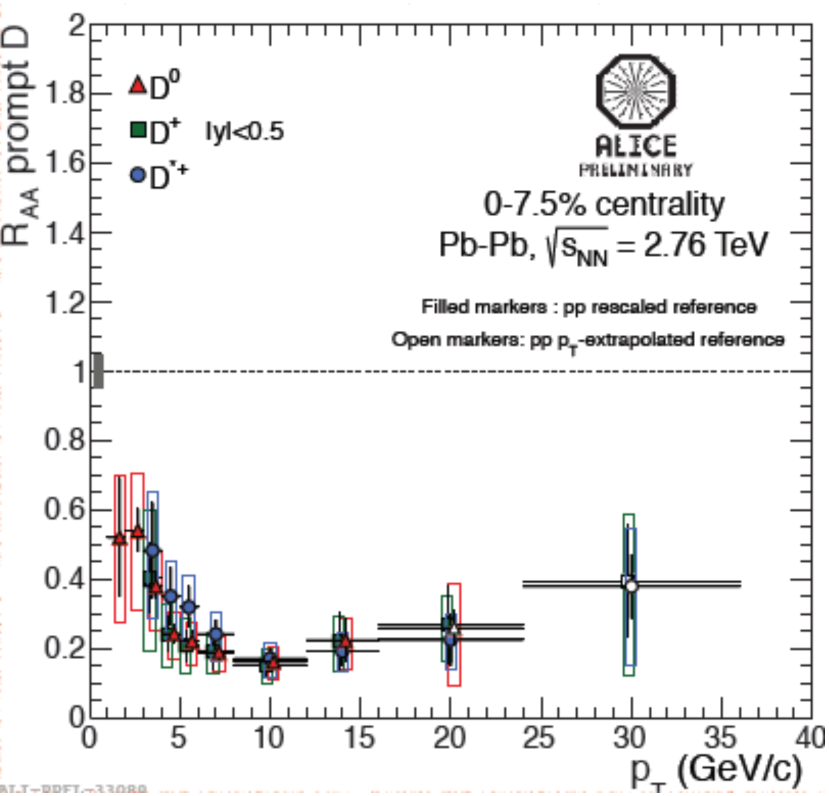
→ $R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$

Heavy Flavor detection in ALICE:

- Midrapidity:
  - D-mesons hadronic decay
  - electrons from semileptonic decays
- Forward rapidity
  - muons from semileptonic decays

[1] Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

D meson R_{AA}

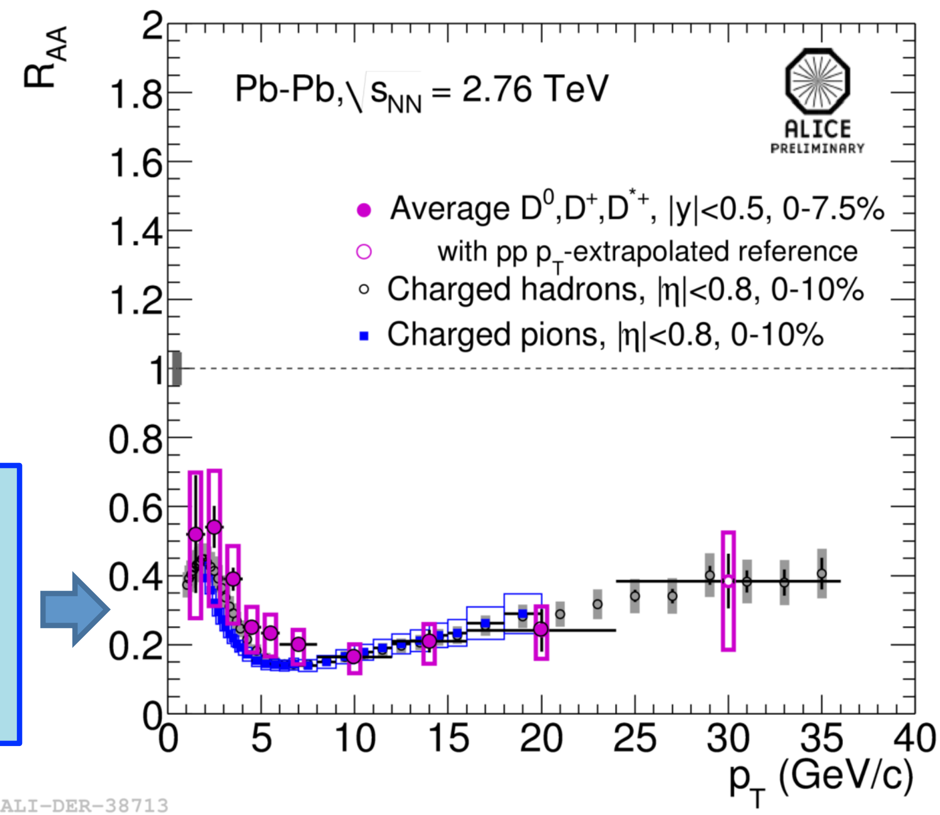


- D^0, D^+ and D^{*+} R_{AA} compatible within uncertainties in the measured range [1,36] GeV/*c*.
- Suppression up to a factor 5 for D^0, D^+ and D^{*+} at $p_T \sim 10$ GeV/c.

Average D-meson R_{AA}:

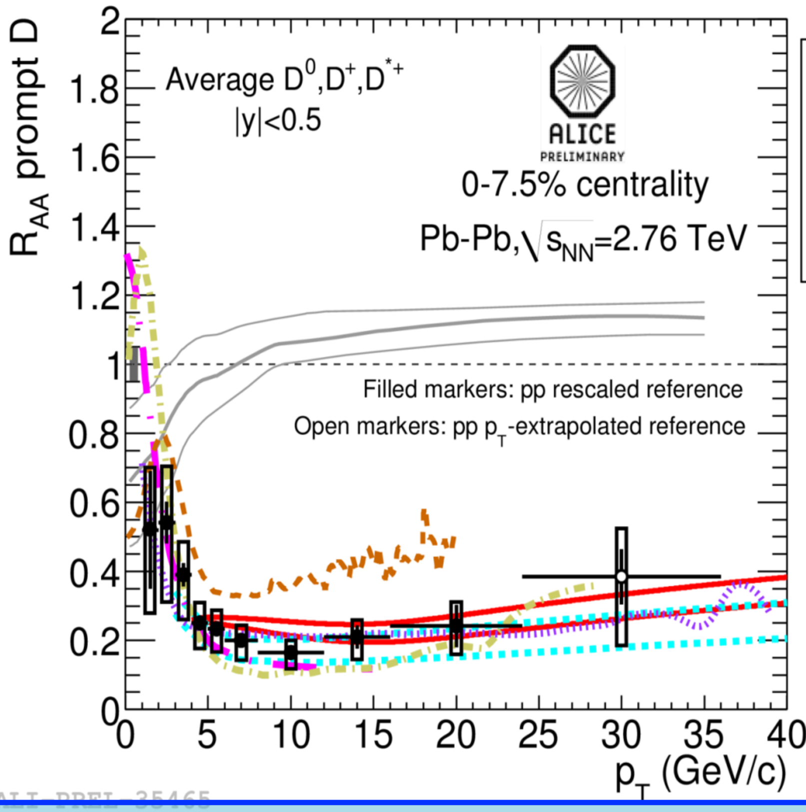
– $p_T < 8$ GeV/*c* hint of slightly less suppression than for light hadrons

– $p_T > 8$ GeV/*c* both (all) very similar.



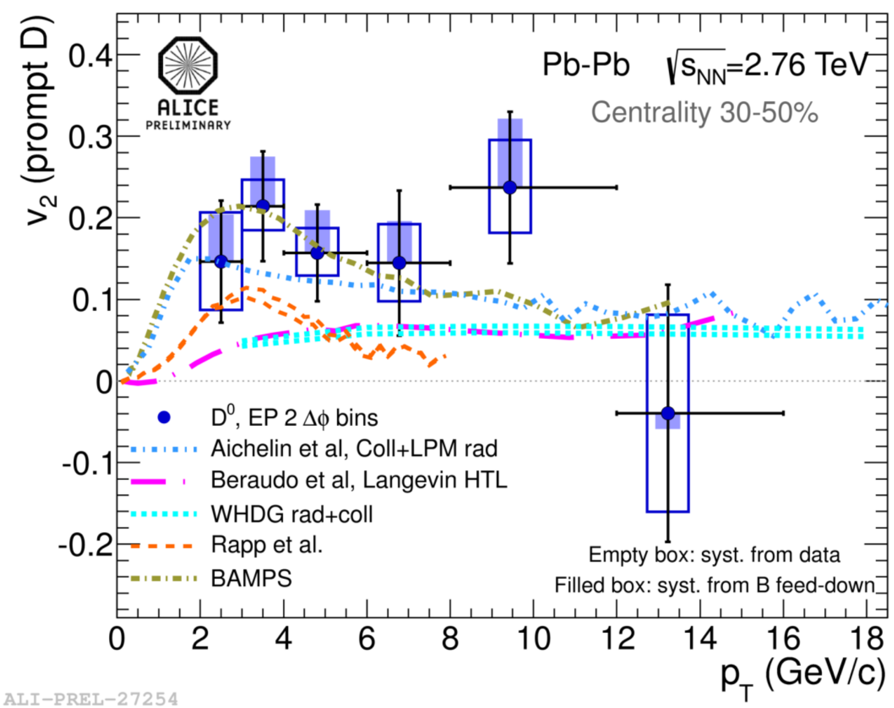
D meson elliptic flow

Together with R_{AA} , *also v2* is sensitive to medium transport properties



Low- *pT v2:* pressure gradient in medium expansion→ degree of thermalization

High *pT v2:* path - length dependence of energy loss



- Non-zero D meson v_2 observed;

Comparable to that of light hadrons

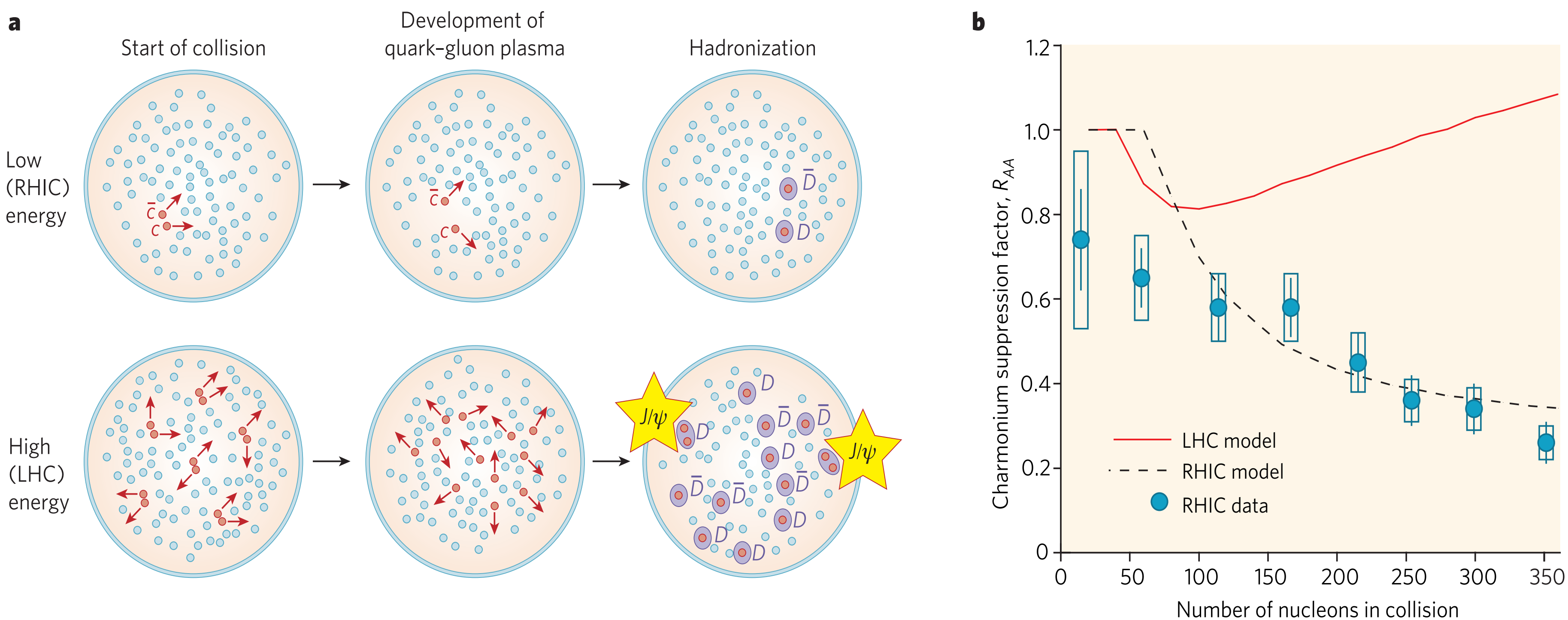
- Simultaneous description of R_{AA} and v_2

c-quark transport coefficient in medium

CHARMONIUM

J/ψ

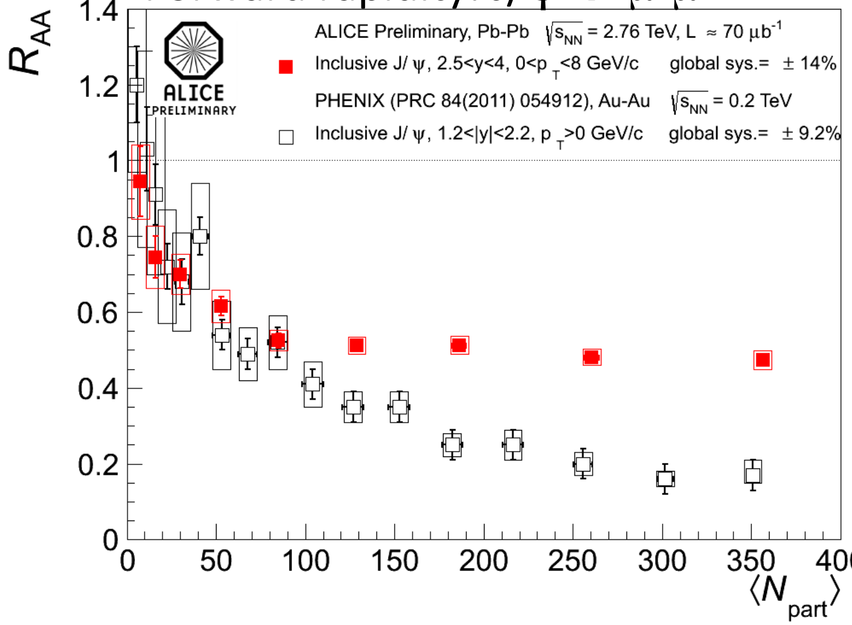
- **SPS & RHIC energies:** Quarkonia suppression via colour screening
  → probe of deconfinement (Matsui and Satz, PLB 178 (1986) 416)
- **LHC energies :** Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity (A. Andronic et al.; PLB 571(2003) 36)



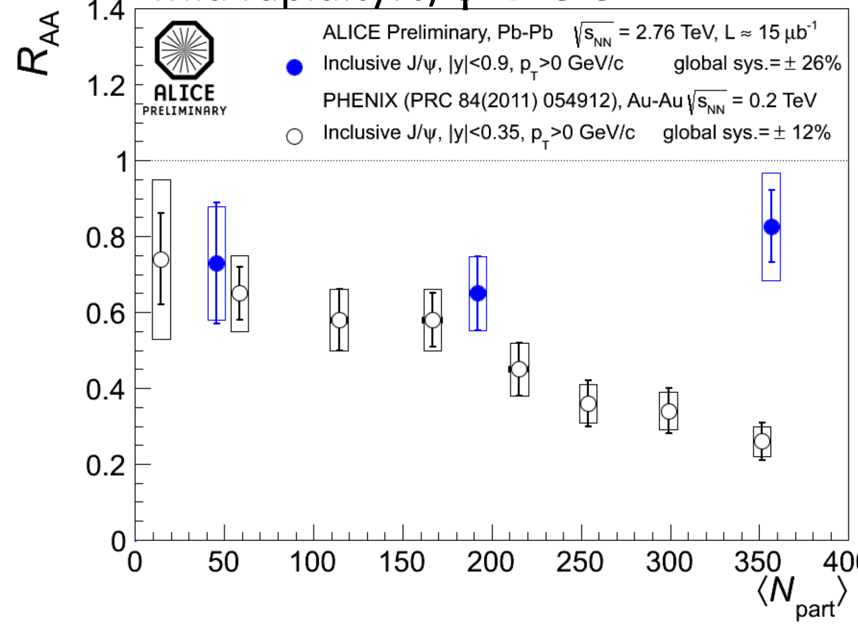
Braun-Munzinger & Stachel, Nature Vol. 448 (2007)

J/ψ : R_{AA} vs $\langle N_{part} \rangle$

Forward rapidity: $J/\psi \rightarrow \mu^+\mu^-$



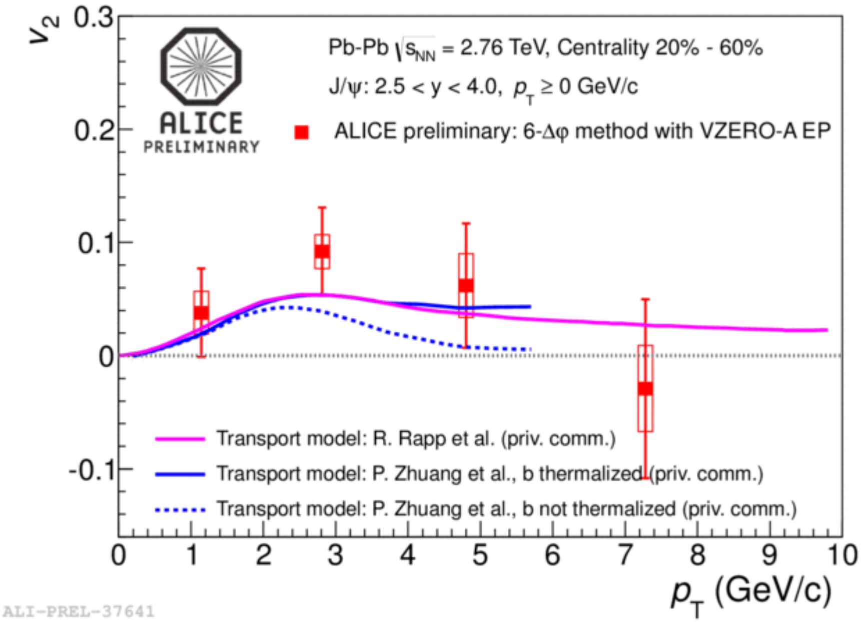
Mid rapidity: $J/\psi \rightarrow e^+e^-$

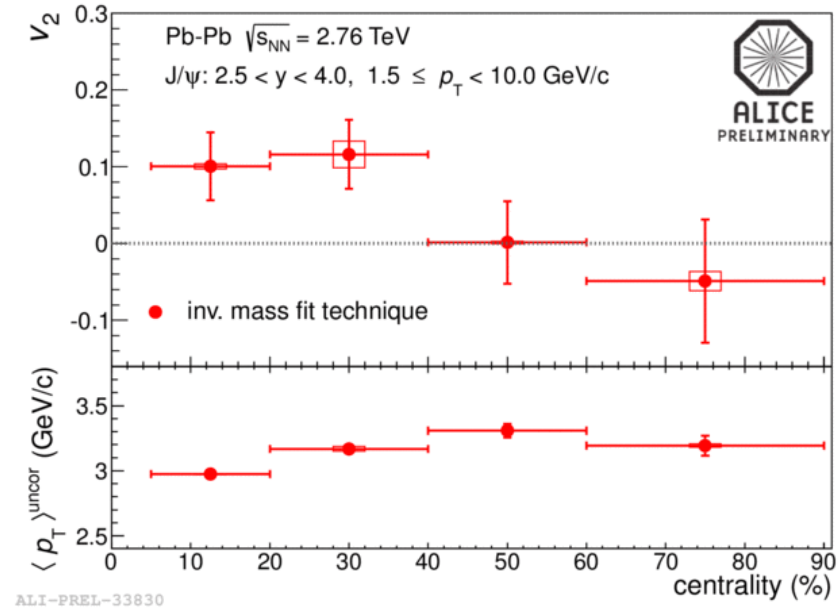


- Comparison with RHIC (PHENIX)
  - Stronger centrality dependence at lower energy; systematically larger R_{AA} values for central events in ALICE
  - Behaviour qualitatively expected in a (re)generation scenario
    → Look at theoretical models

J/ψ : hint for non-zero elliptic flow at LHC

- Flow studies Complements indications obtained from R_{AA} studies

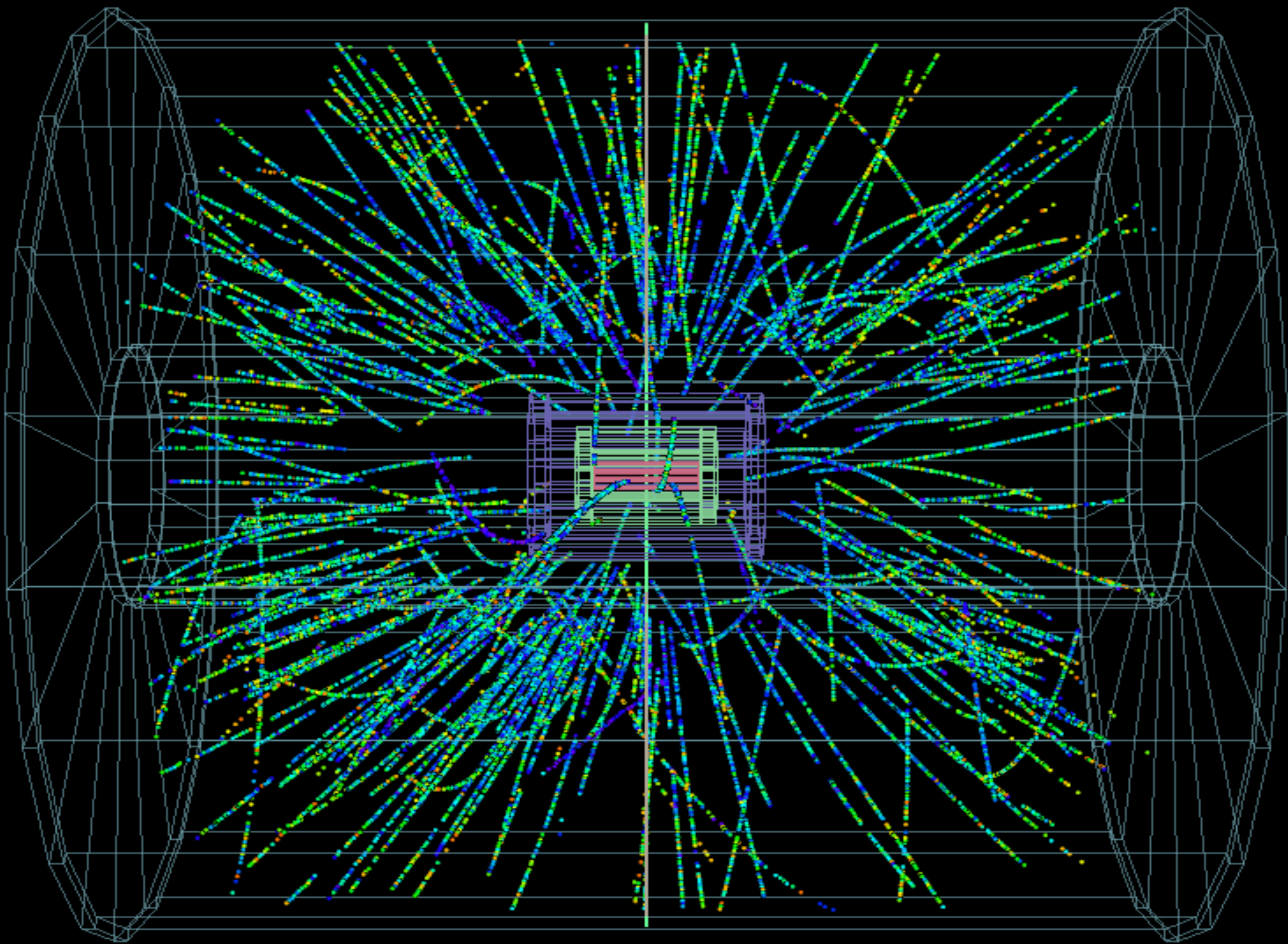




- STAR: v_2 compatible with zero everywhere
- ALICE: for the first time, hint for non-zero v_2 in both
  - 20-60% central events in $2<p_T<4$ GeV/c
  - 5-20% and 20-40% central events for $1.5<p_T<10$ GeV/c
  - Significance up to 3.5 σ for chosen kinematic/centrality selections
- Qualitative agreement with transport models including regeneration

RESULTS FROM THE PROTON-LEAD PILOT RUN

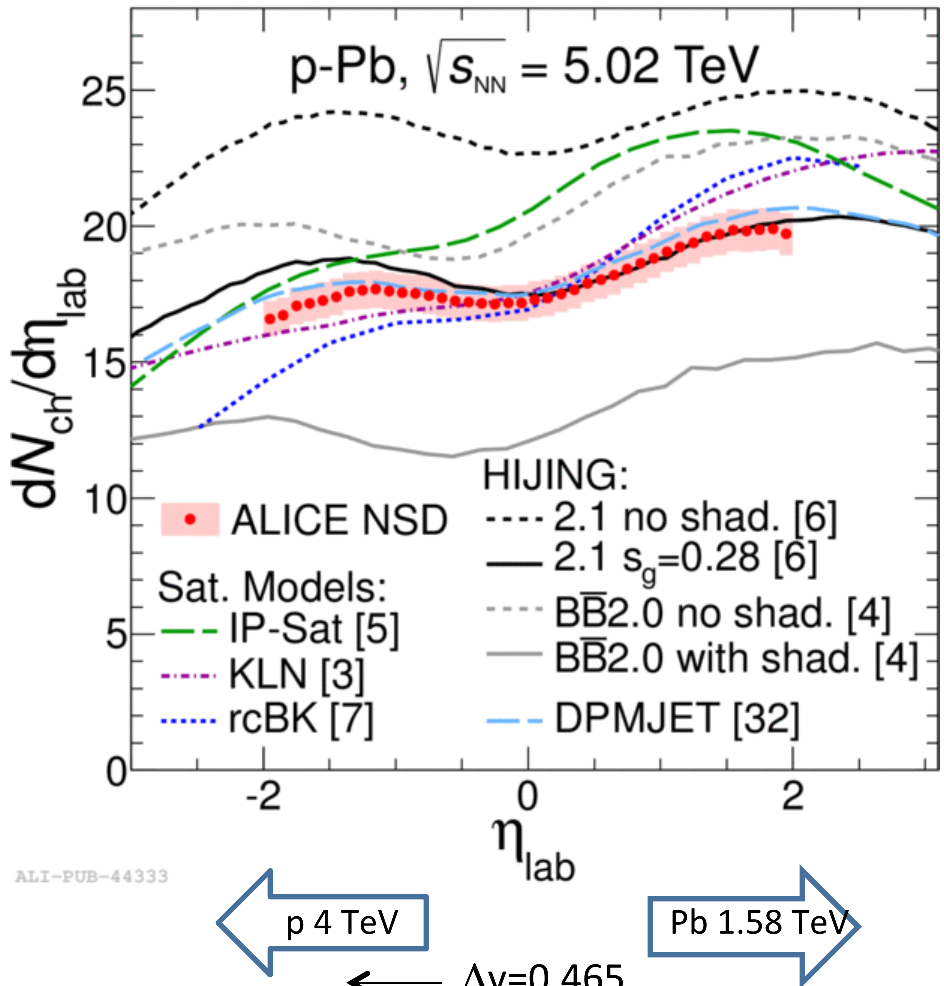
First p-Pb collisions in ALICE with the “pilot” run on September 12, 2012



Charged particles η distribution

- Normalization: NSD
- All models within 20%
- Saturation models too steep with η_{lab}
- pQCD models (HIJING, DPMJET) in agreement with data
- Where shadowing is included, strong yield reduction (~ 30%)

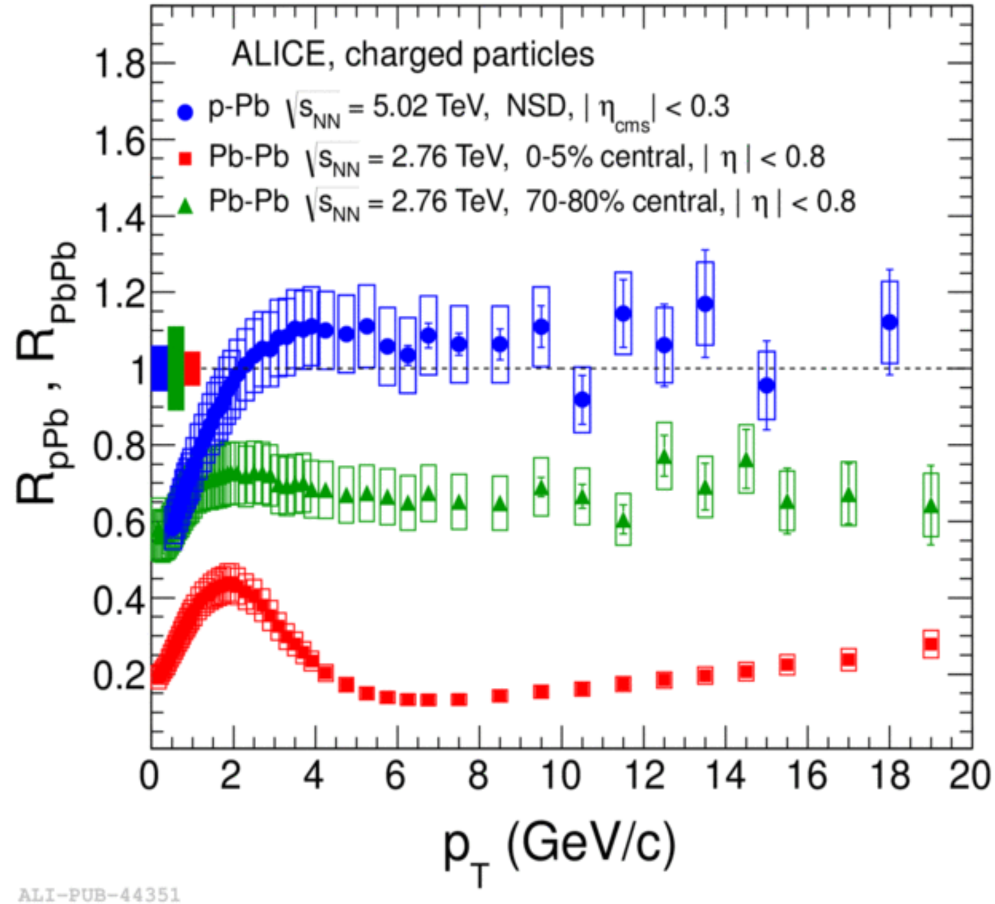
PRL 110, 032301 (2012)



Nuclear modification factor

- R_{pPb} compatible with 1 for p_T above 2-3 GeV/c.
- Binary scaling is preserved, no (or small) initial state effect.
- No (or weak) sign of Cronin effect
- Very different from R_{PbPb} :
  → indication that suppression in Pb-Pb is not an initial state effect

arXiv:1210.4520

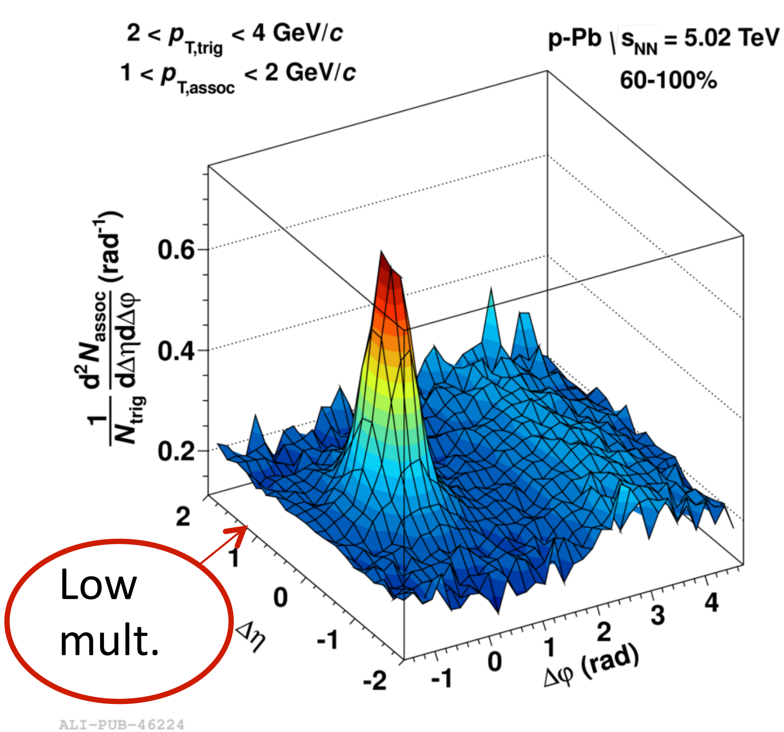


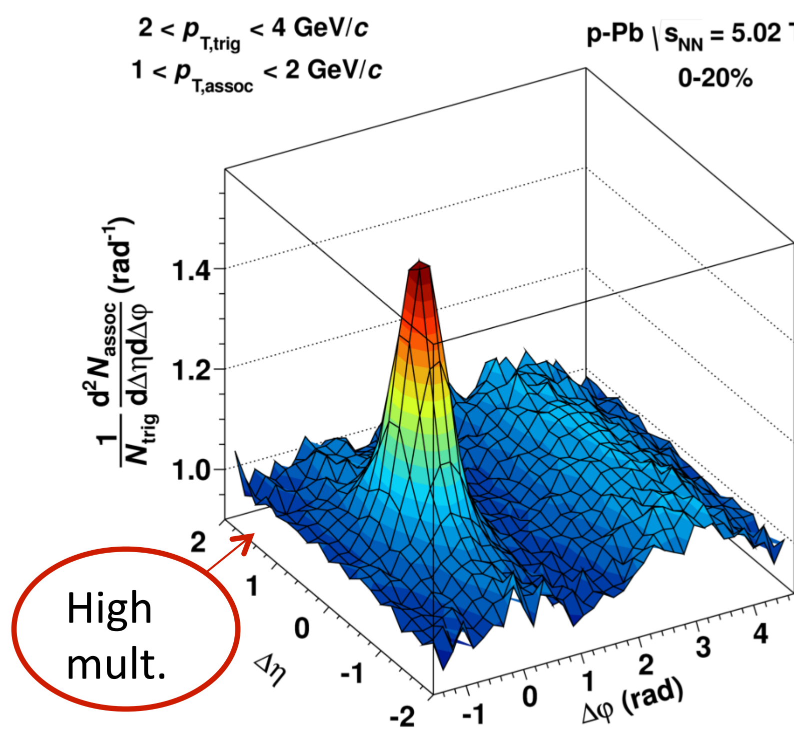
Long-range correlations vs multiplicity

Associated yield per trigger particle:

$$\frac{1}{N_{trig}}\frac{d^2N_{ass}}{d\Delta\eta\Delta\phi}=\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Multiplicity classes defined from the sum of the signals from VZERO-A ($2.8<\eta_{lab}<5.1$) and VZERO-B ($-3.7<\eta_{lab}<-1.7$)





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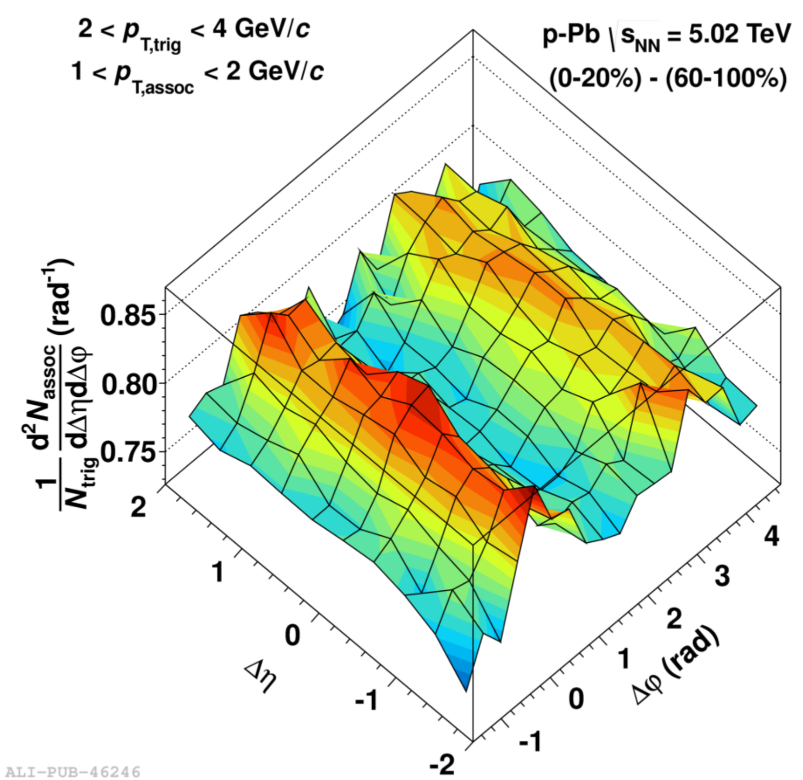
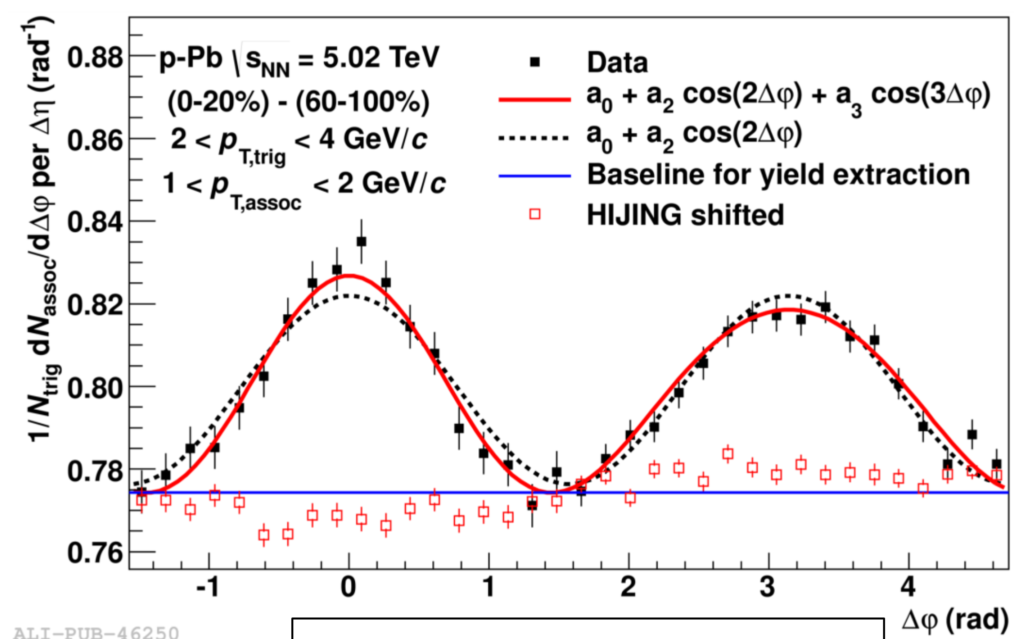
Low-multiplicity p-Pb: pp-like (jet-like) correlation

High multiplicity p-Pb: near-side ridge appears; higher yields on near and away side

The two ridges

To quantify the change from low to high multiplicity, the per-trigger yield for the low mult. class (60-100%) is subtracted from the per-trigger yield of the high-mult. class (0-20%)





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→ The near-side ridge is accompanied by a similar structure on the away side!
→ Origin of the effect to be understood; not predicted by Hijing.
→ Effect also observed by ATLAS (arXiv:1212.5198)

CONCLUSIONS AND PERSPECTIVES

Conclusions and plans

- ALICE is obtaining a remarkable amount of physics results from the first two LHC heavy-ion runs:
  - bulk, soft probes, correlations;
  - high-p_T probes;
  - heavy-flavours and quarkonium ;
- First p-Pb results from Pilot Run …. more to come……
- Entering the precision measurement era of QGP
  - before LS2 (2018): Pb–Pb collisions at higher energy.
- Upgrade for the LHC high-luminosity heavy-ions era:
  - ambitious physics programme
    - detailed detector upgrade plan for improved vertexing (ITS) and tracking (TPC)
    - increased rate capability of all subdetectors and DAQ
  - other possible upgrades (FOCAL, MFT, VHMPID) under consideration.

BACKUP SLIDES

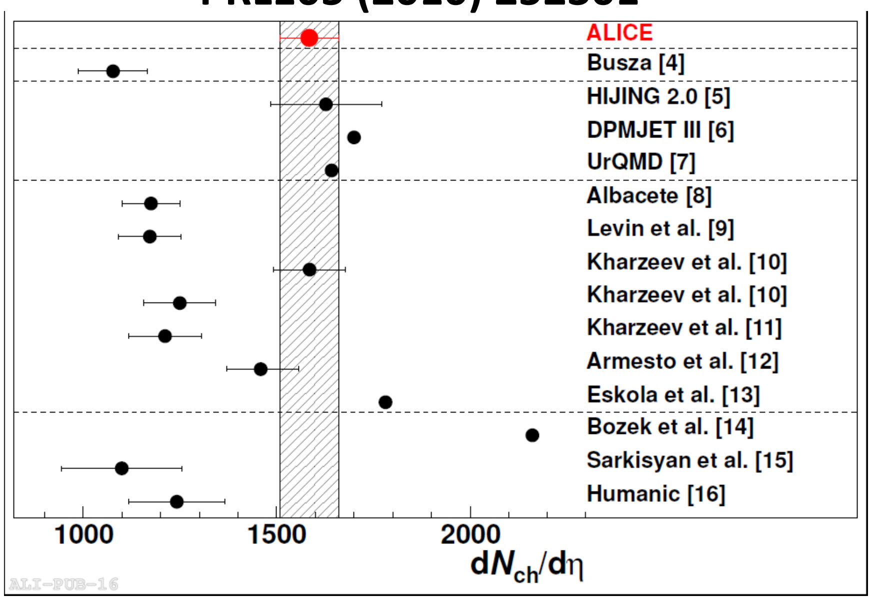
Charged multiplicity (central collisions)

ALICE

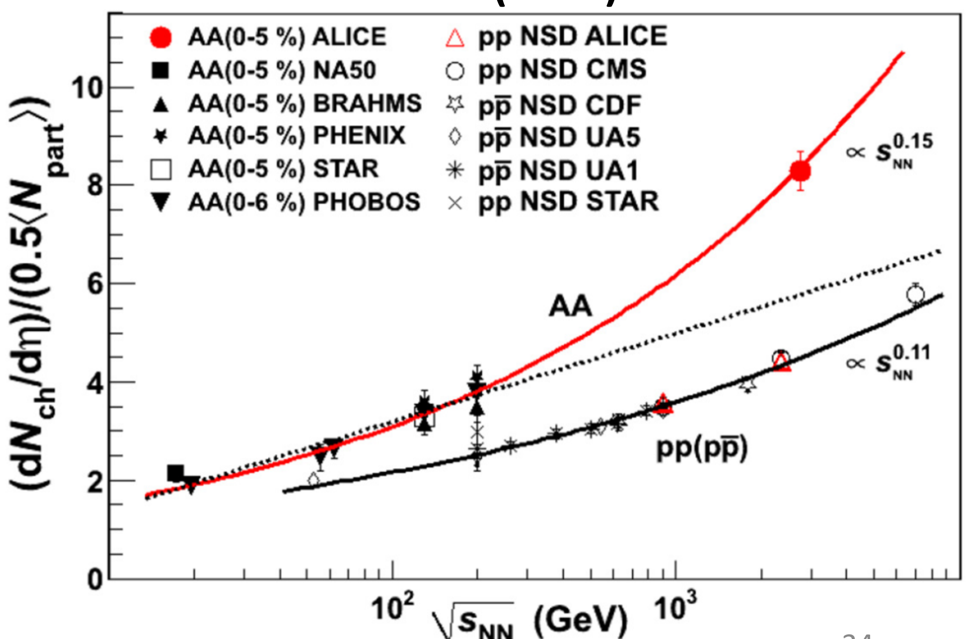
- **Quantitative Difference from RHIC**
  - **$dN_{ch}/d\eta$ ~ 1600 ± 76 (syst)**
    - on high side of expectations
    - growth with √s faster in AA than pp :
      -'nuclear amplification'
  - **Energy density ≈ 3 x RHIC** (fixed τ)
    - lower limit, likely τ_0(LHC) < τ_0(RHIC)

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$

PRL105 (2010) 252301



PRL105 (2010) 252301

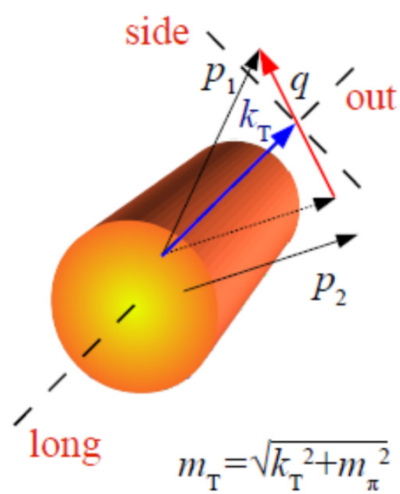


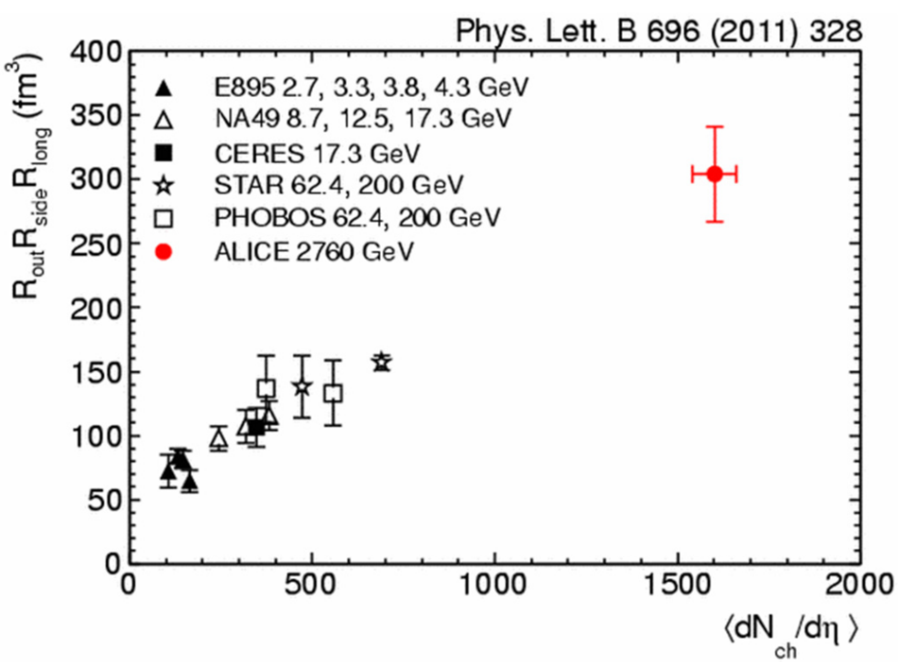
System Size

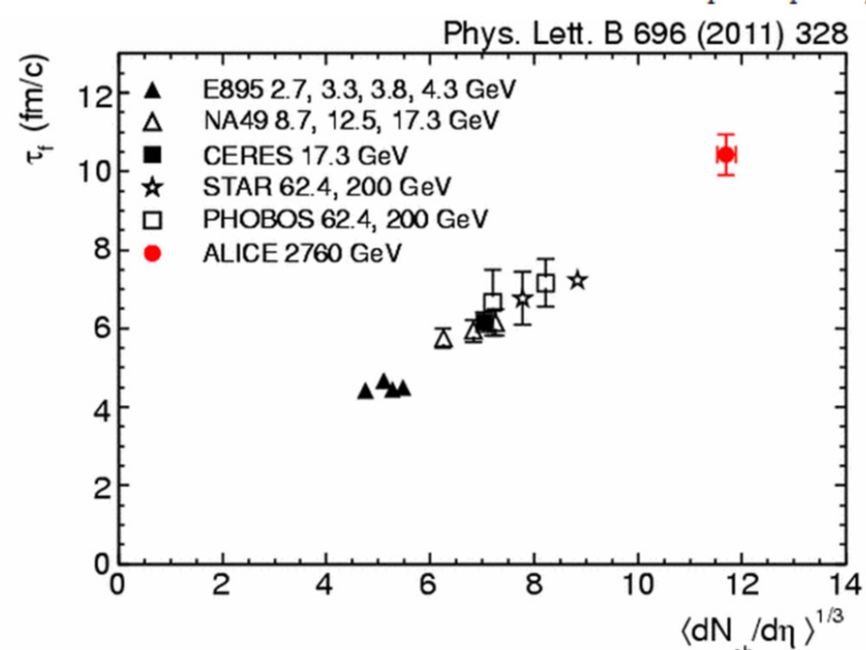
- Spatial extent of the particle emitting source extracted from interferometry of identical bosons
- Two-particle momentum correlations in 3 orth. directions -> HBT radii (Rlong, Rside, Rout)

→ Size: twice w.r.t. RHIC

→ Lifetime: 40% higher w.r.t. RHIC

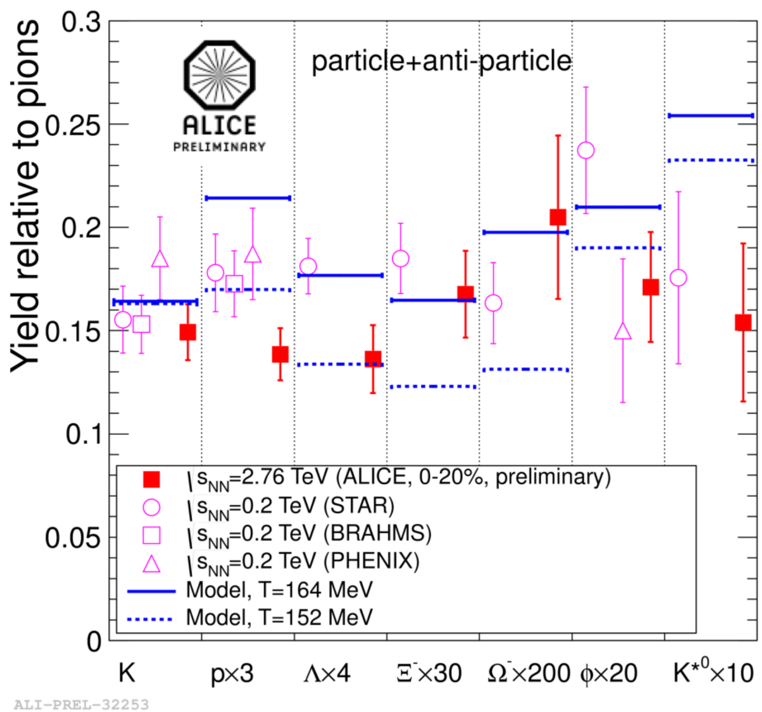


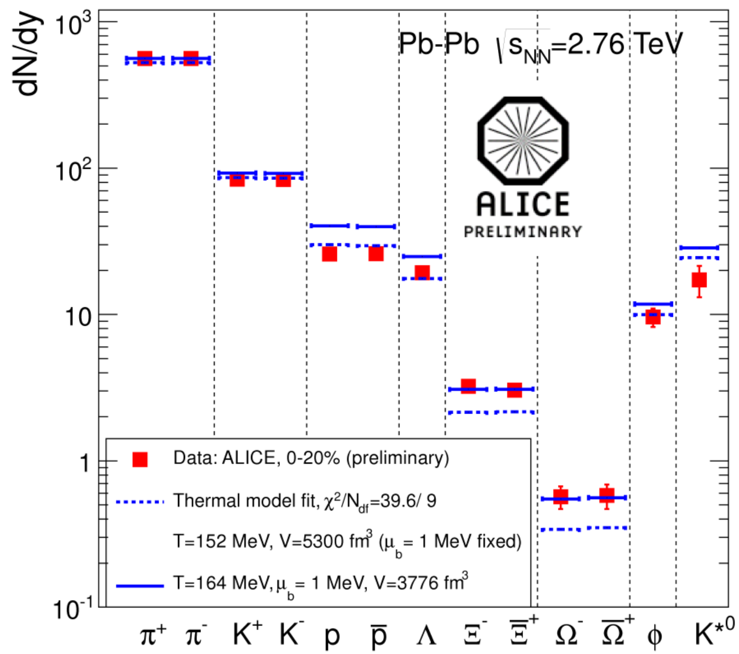




Particle yields and ratios

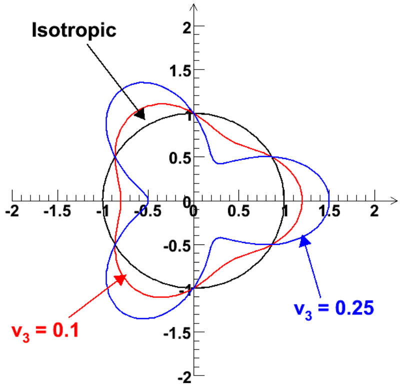
- Extracted from p_T- integrated identified particle spectra.
- Comparison /Fit with Thermal/ Statistical models work well at RHIC → info on chemical freezout temperature and baryochemical potential





Predicted temperature T=164 MeV
A.Andronic, P.Braun-Munzinger, J.Stachel NP A772 167
Thermal fit (w/o res.): **T=152 MeV** (χ^2/ndf = 40/9)
Ξ and Ω significantly higher than statistical model

p/π and Λ/π ratios at LHC lower than RHIC
Hadronic re-interactions ?
F.Becattini et al. 1201.6349 J.Steinheimer et al. 1203.5302



Fluctuations → v_3 ….(+ 3 v_3 cos(3(φ−ψ)))

→ "ideal" shape of participants' overlap is ~ elliptic; no odd harmonics expected participants' plane coincides with event plane

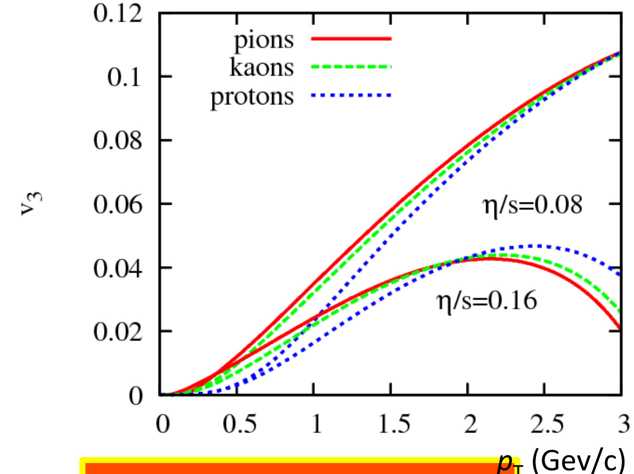
→ but fluctuations in the initial position of the partecipant nucleons give:

- plane ≠ event plane
- v_3 ("triangular") harmonic appears

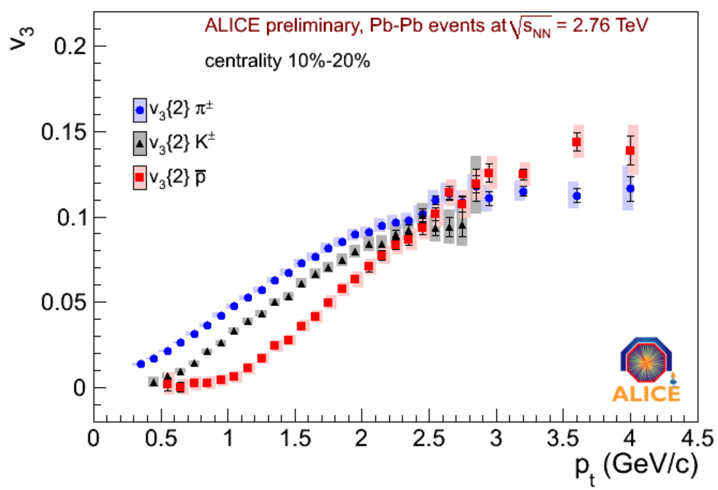
[B Alver & G Roland, PRC81 (2010) 054905]

→ and indeed, $v3 \neq 0$!

v_3 sensitive to η/s: viscosity to entropy ratio



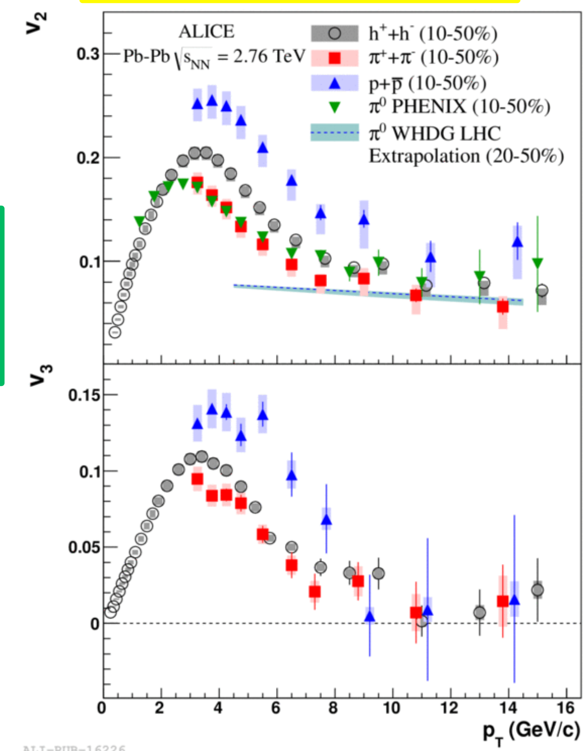
ALICE: PRL 107 (2011) 032301



Similar v_2 trend, mass ordering;

fluctuations discriminate & constrain models:large sensitivity to viscosity

PLB 719 (2013) 18-28



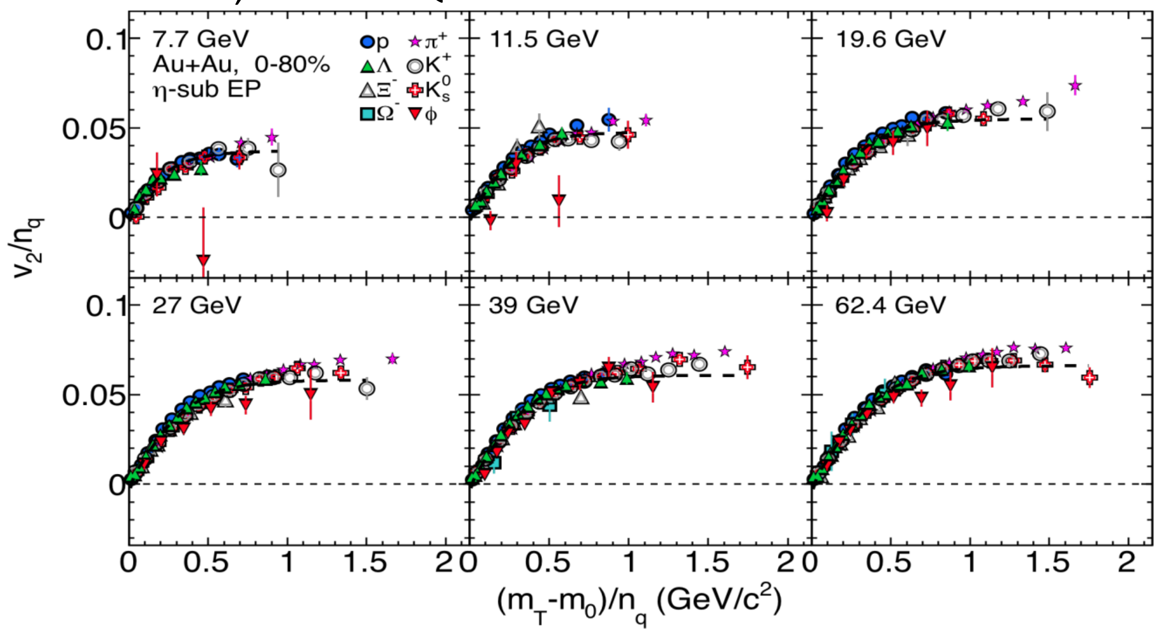
v_3 has weaker centrality dependence than v_2 when calculated wrt participants plane, v_3 vanishes (as expected, if due to fluctuations…).

Progress in precision measurements of η/s

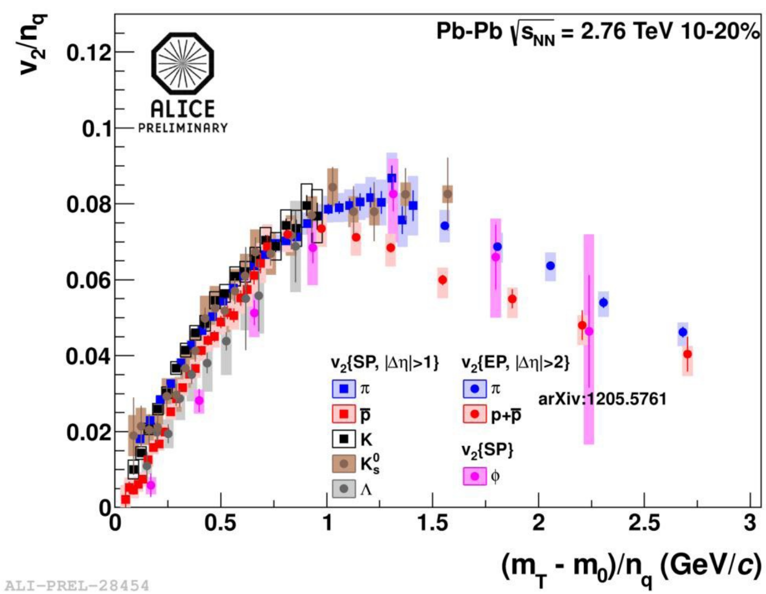
NCQ Scaling

ALICE

STAR, S. Shu at QM 2012

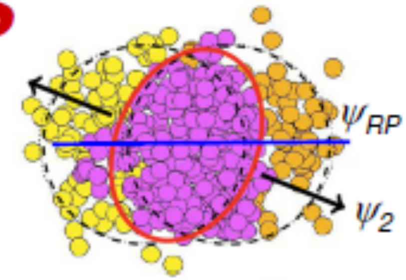


At RHIC energies:
NCQ scaling holds quite well, also for close-to-central collisions (at least at low pT)

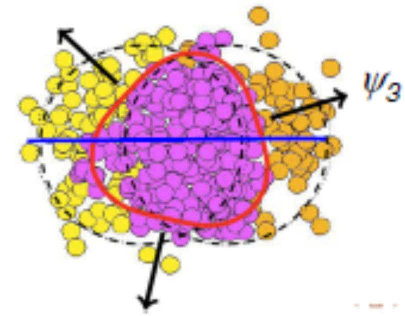


At LHC energies:
Some deviations from NCQ scaling appear for close-to-central collisions: due to stronger radial flow or Jet quenching/rescattering?

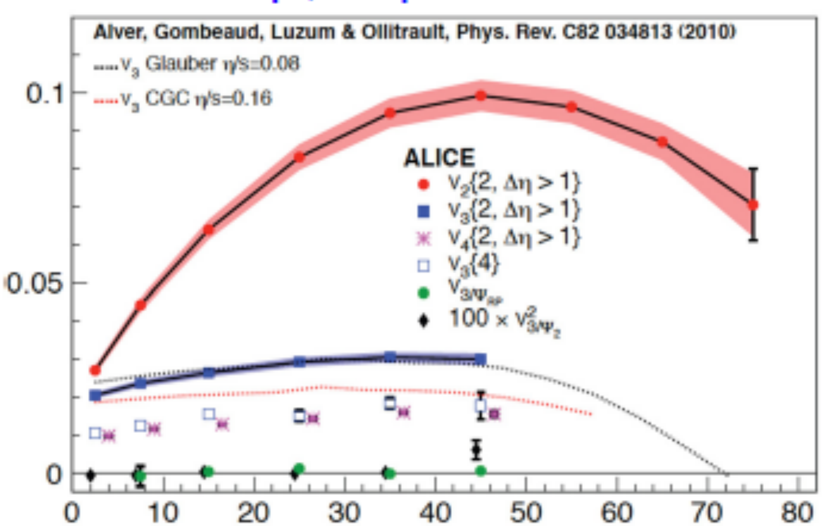
Higher harmonics



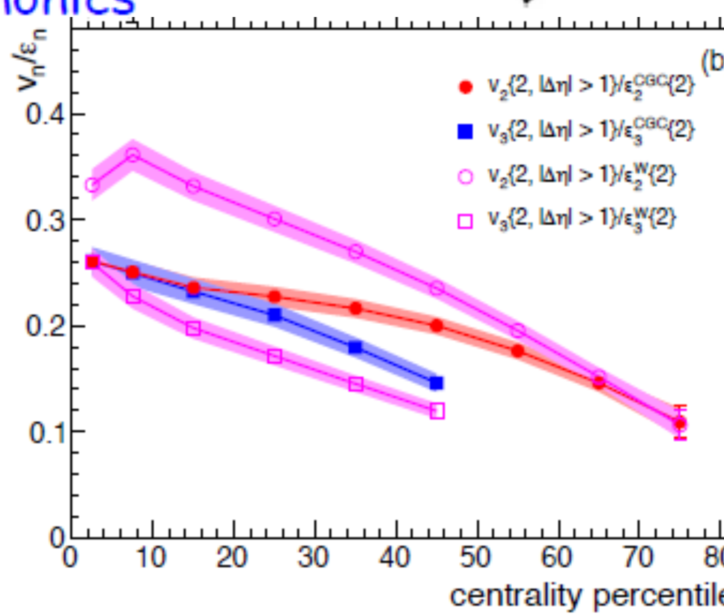
- Fluctuations in the initial nucleon distribution
  - ⇨ Event-by-event fluctuation of the symmetry plane Ψ_n w.r.t. Ψ_{RP}
- Odd harmonics are not null
- In particular, v_3 ("triangular") harmonic appears
  - ⇨ v_3 has weaker centrality dependence than v_2
  - ⇨ When calculated w.r.t. participant plane, v_3 vanishes (as expected, if due to fluctuations)



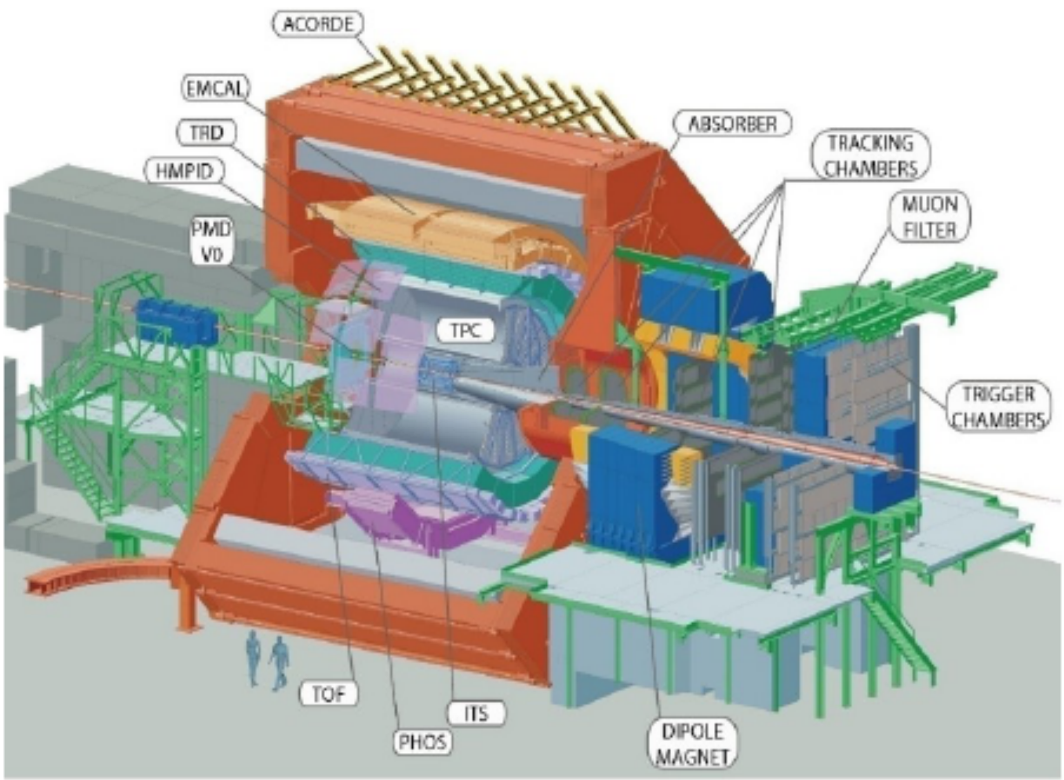
- Similar p_T dependence for all harmonics

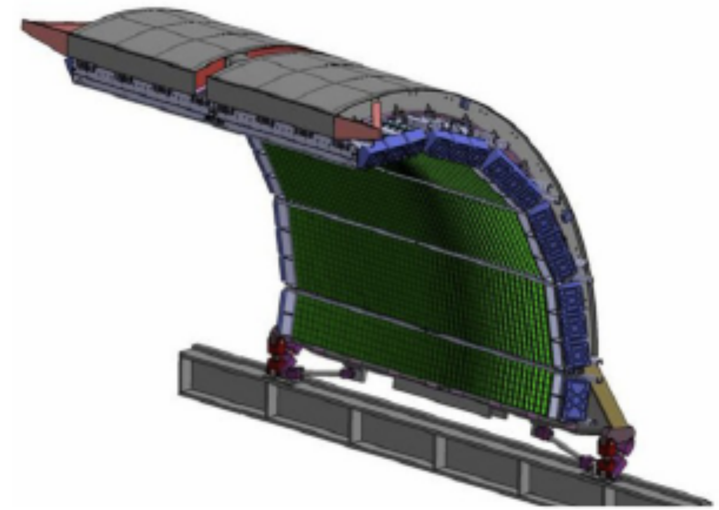


ALICE:arXiv:1105.3865



Jet Reconstruction in ALICE





Energy and direction of neutral particles

EMCal: Pb-scintillator sampling calorimeter which covers:

$|\eta| < 0.7,\ 80° < \varphi < 180°$

- 11520 towers with each covers $\Delta\eta \times \Delta\varphi \sim 0.014 \times 0.014$

4-momenta of charged particles

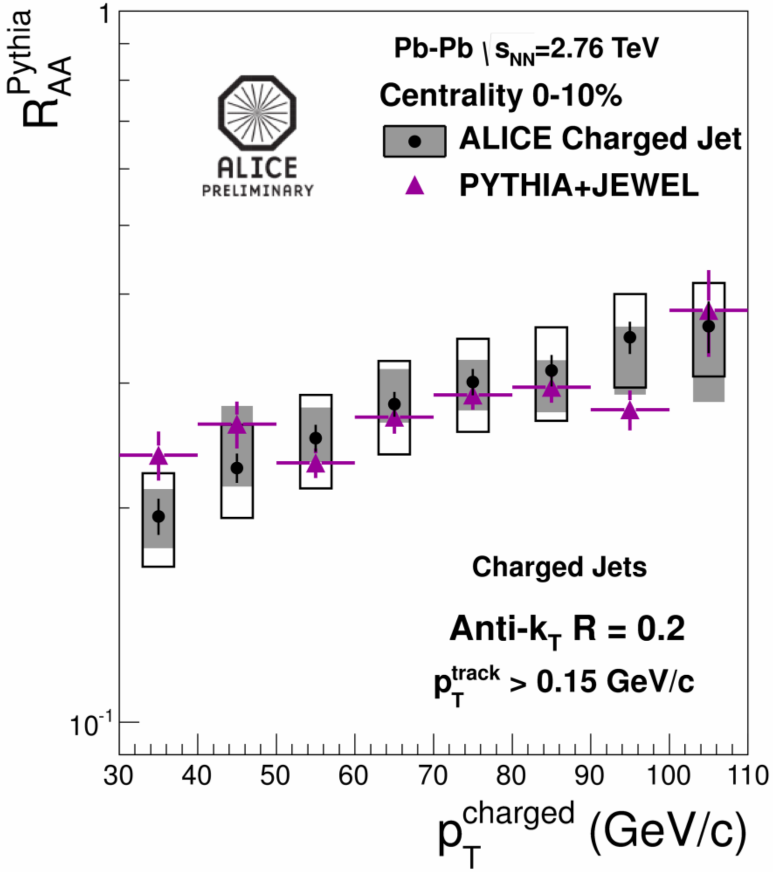
Tracking: $|\eta| < 0.9,\ 0 < \varphi < 360°$

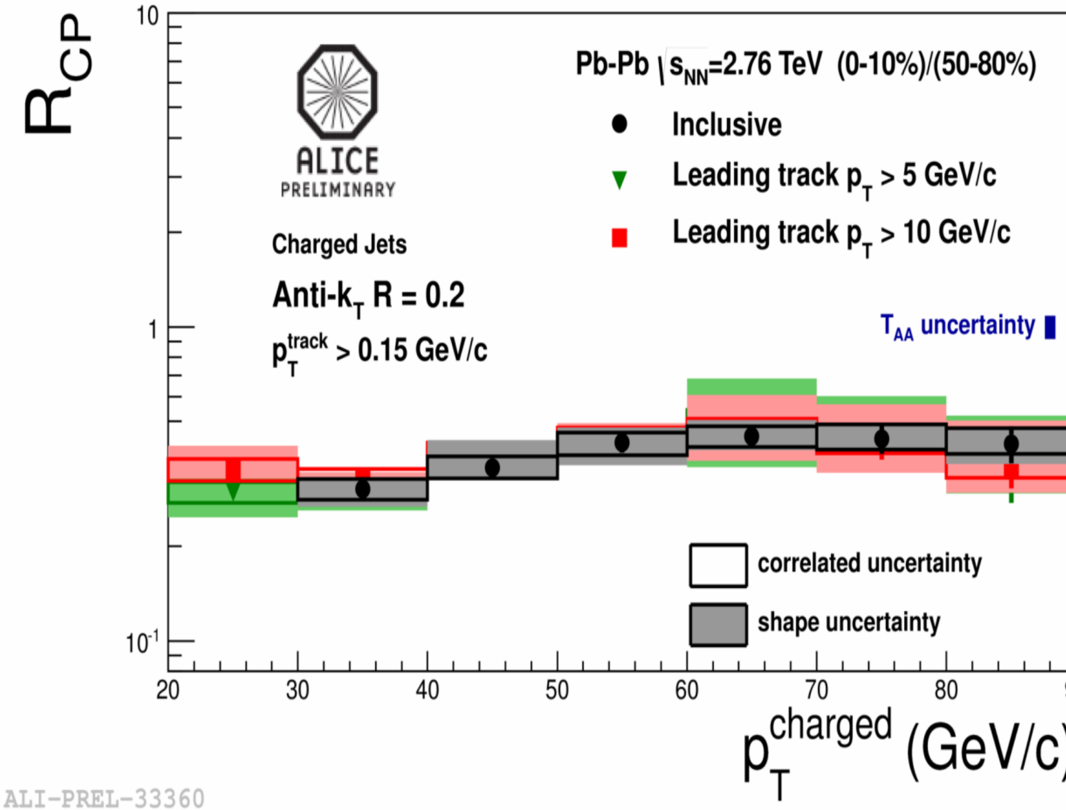
TPC: gas detector

ITS: silicon detector

Charged constituents → **JET** ← **Neutral** constituents

Charged jet: R_{AA} and R_{CP}





Strong jet suppression observed for jets reconstructed with charged particles

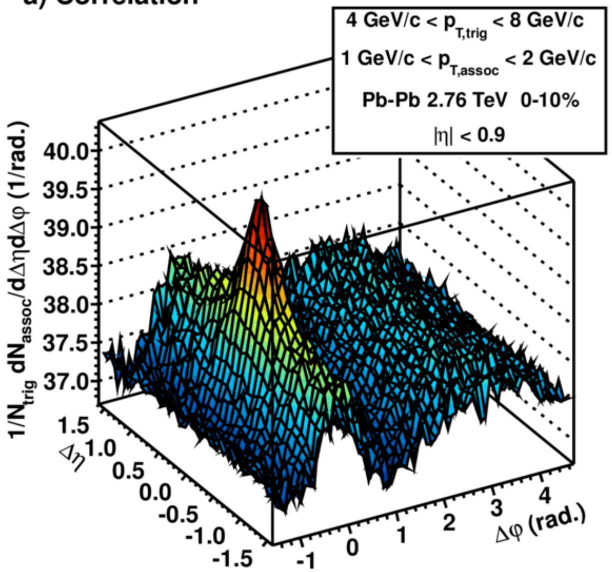
– R_{AA} (jet) is smaller than inclusive hadron $R_{AA}(h^{\pm})$ at similar parton p_T

– data are reasonably well described by JEWEL model

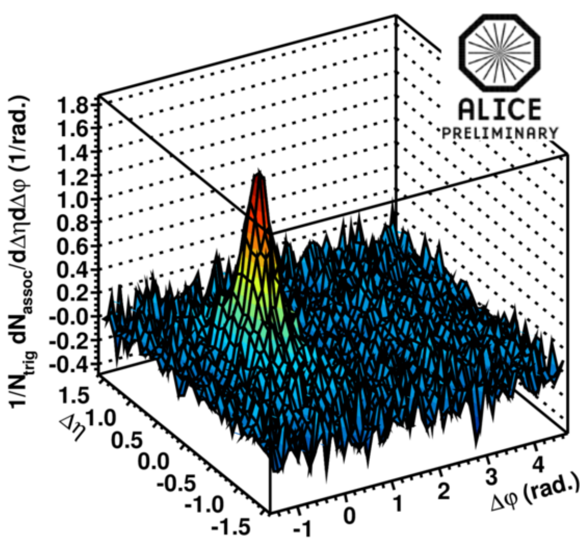
K.Zapp, I.Krauss, U.Wiedemann, arXiv:1111.6838

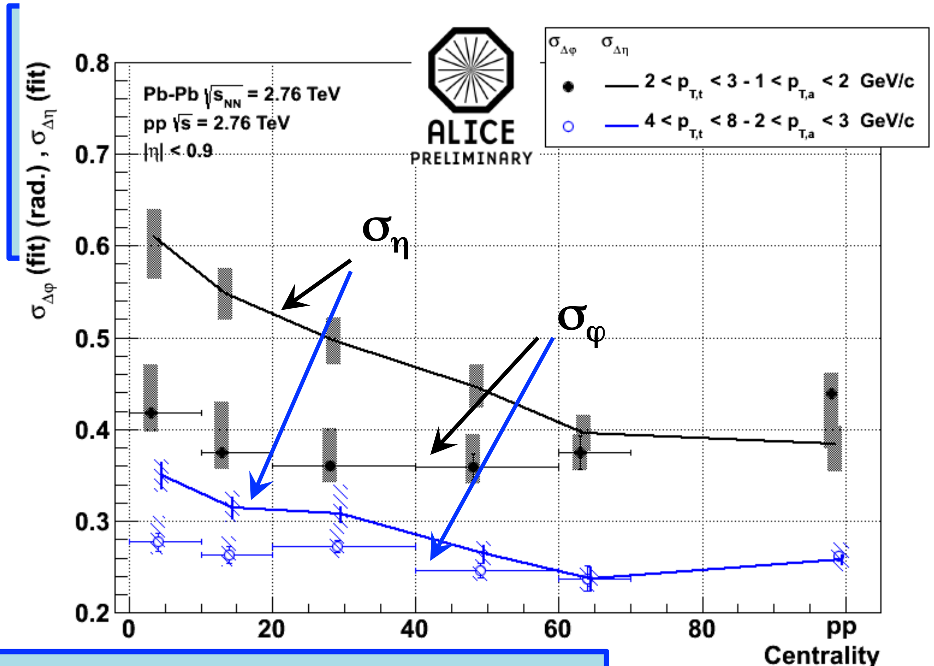
Near-side (jet-like) structure

a) Correlation



b) η-gap subtracted

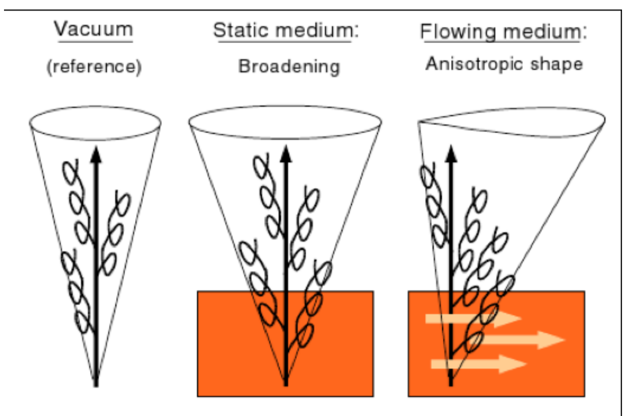




Evolution of near-side-peak σ_η and σ_φ with centrality: Strong σ_η increase for central collisions

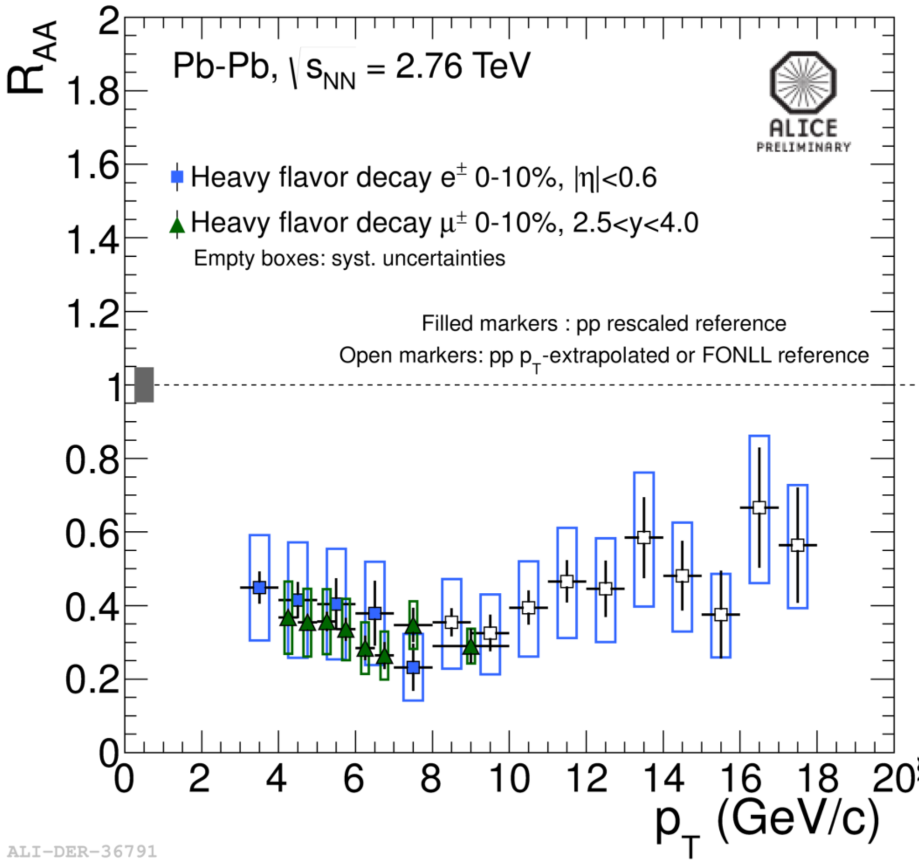
Interesting: AMPT describes the data very well

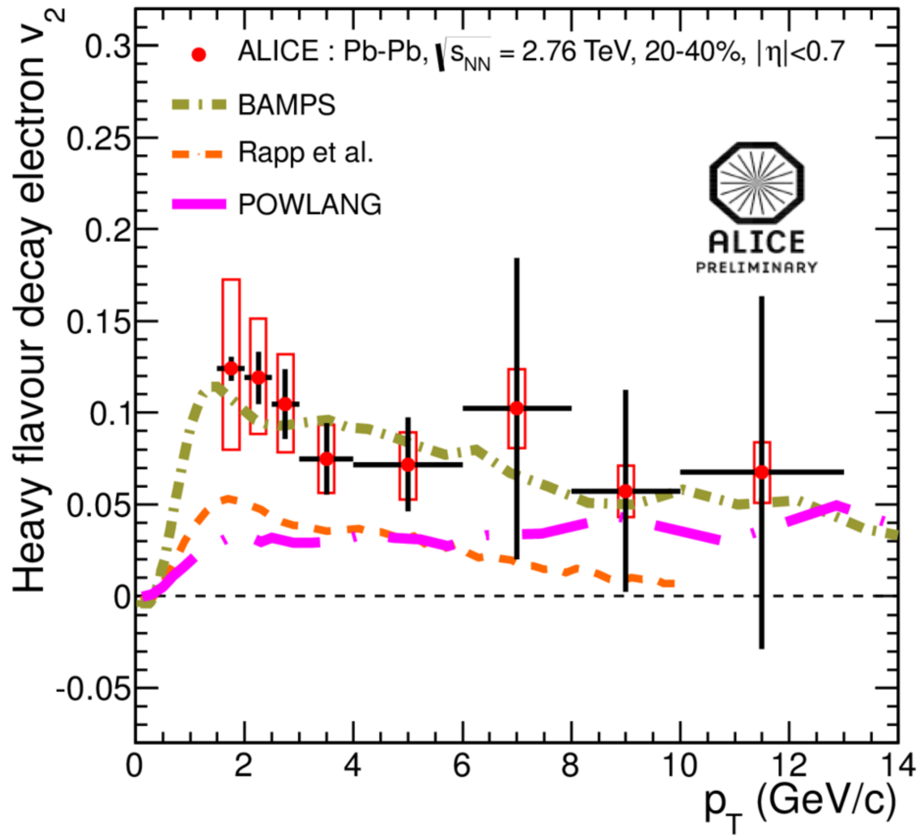
Influence of flowing medium?



N.Armesto et al., PRL 93, 242301

Heavy-flavor e(μ) R_{AA} & v_2





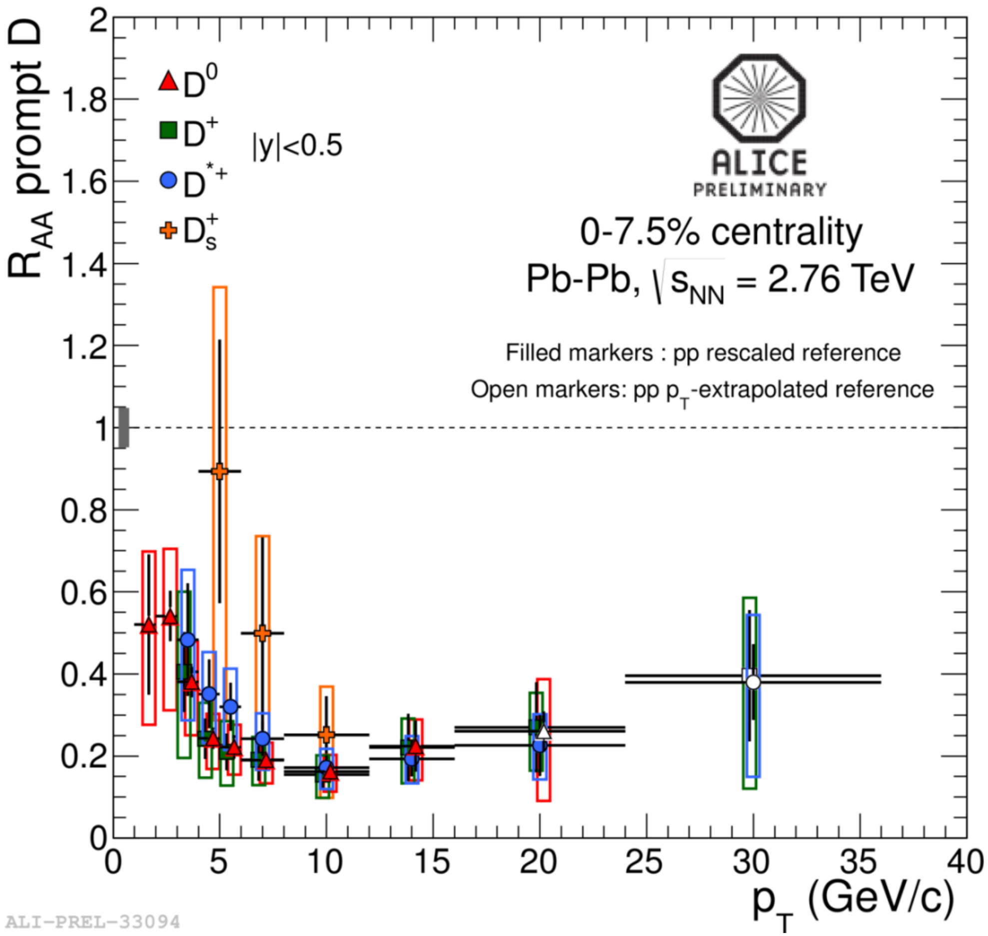
- HF electrons:
  - Strong suppression up to p_T 18 GeV/*c* in 0–10% centrality
  - Non-zero v_2 in 20–40% centrality class

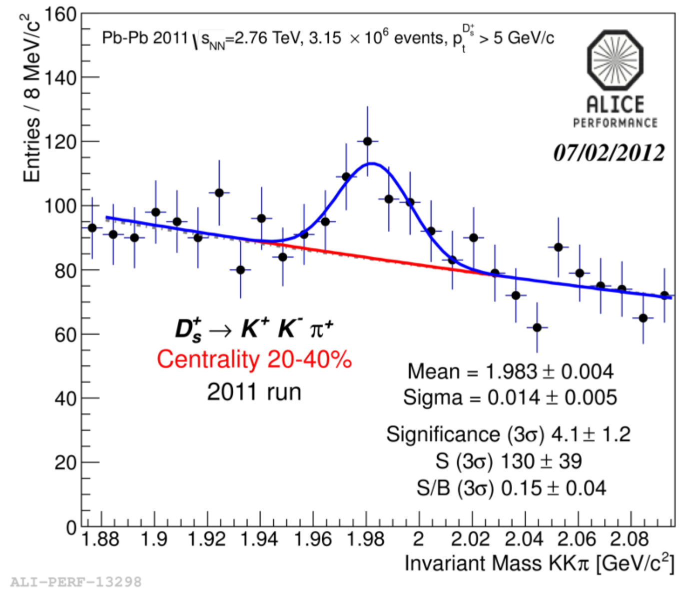
→Ongoing effort to separate beauty contribution…

- HF muons : Suppression in forward region very similar to that of electrons

… adding D_s to charm R_{AA}

The relative yield of D^+_s with respect to non-strange D meson expected to be enhanced in Pb-Pb collisions in the intermediate momentumrange if charm quarks hadronize via recombination in the medium [1]



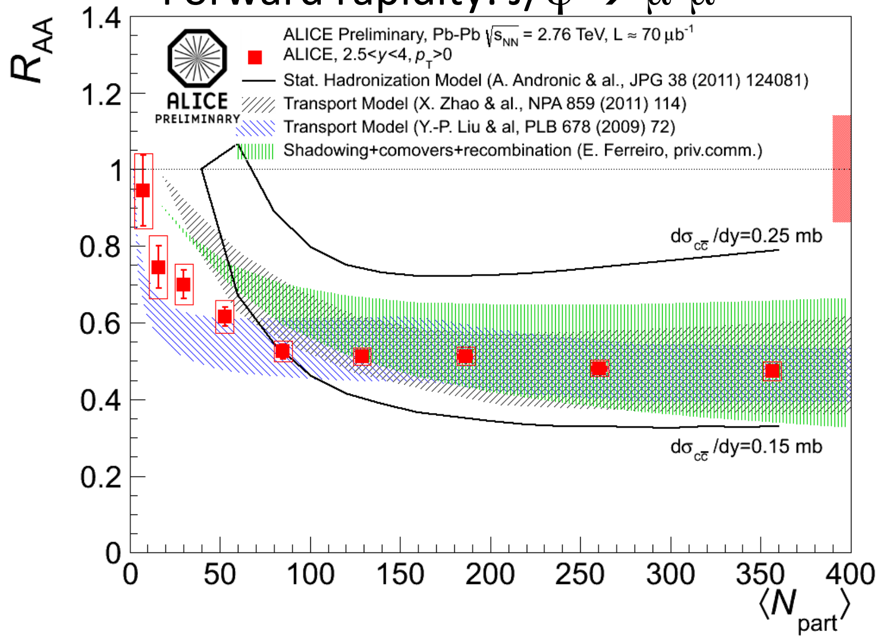


Strong suppression (~ 4–5) at p_T above 8 GeV/c ; uncertainty will improve with future pp and Pb–Pb data taking

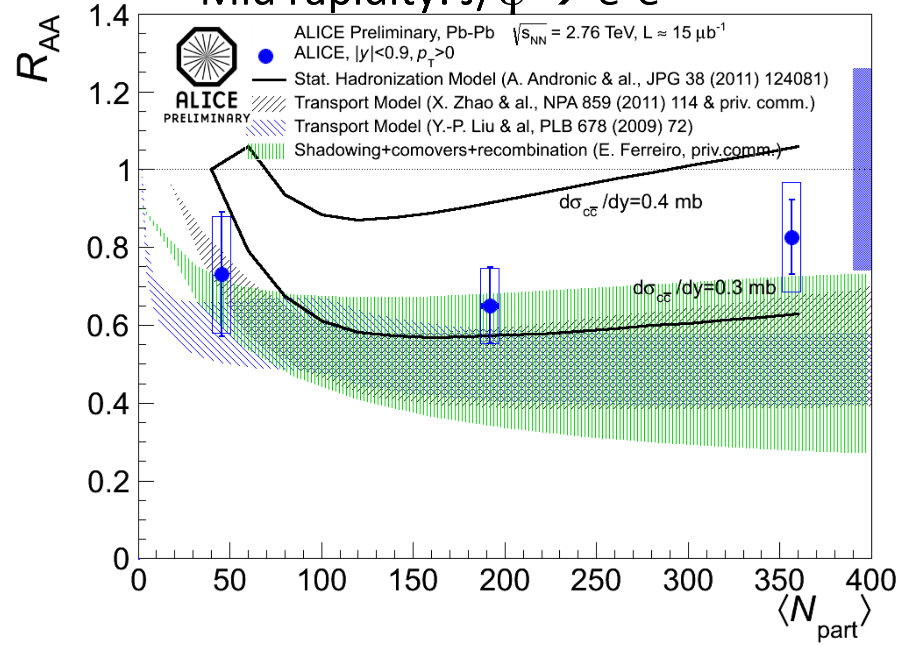
[1] I. Kuznetsova, J. Rafelski, Eur.Phys.J.C51:113-133,2007; M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th].

J/ψ : R_{AA} vs $\langle N_{part} \rangle$

Forward rapidity: J/ψ → $\mu^+\mu^-$



Mid rapidity: J/ψ → e^+e^-

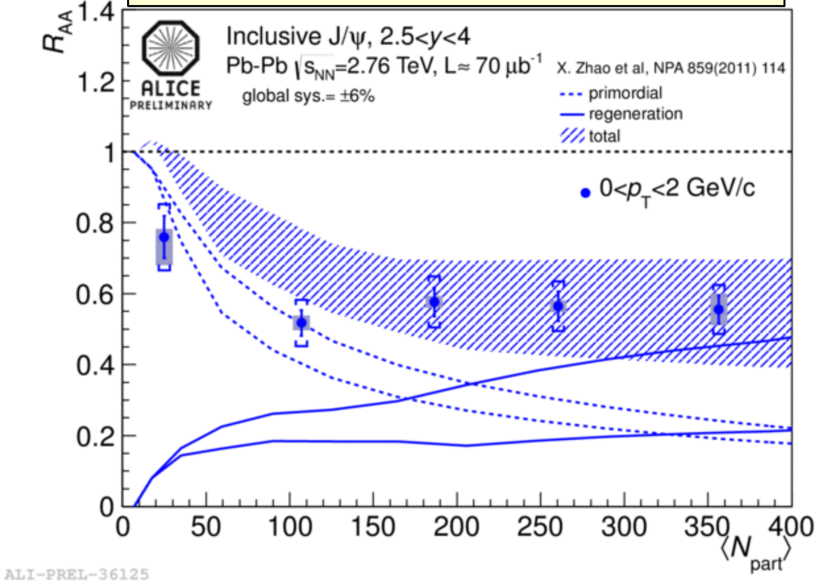


- Comparison with models
  - X.Zhao and R.Rapp, Nucl. Phys. A859(2011) 114
  - Y.Liu, Z. Qiu, N. Xu and P. Zhuang, Phys. Lett. B678(2009) 72
  - A. Capella et al., Eur. Phys. J. C58(2008) 437 and E. Ferreiro, priv. com.
- Models including a large fraction (>50% in central collisions) of J/ψ produced from (re) combination or models with all J/ψ produced at hadronization can describe ALICE results for central collisions in both rapidity ranges

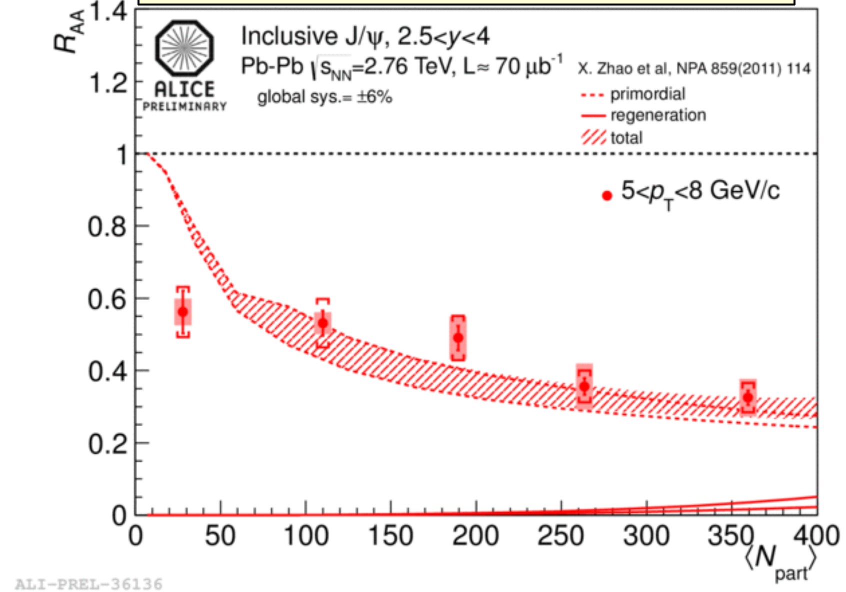
J/ψ : R_{AA} vs $\langle N_{part} \rangle$ in p_T bins

- J/ψ production via (re)combination should be more important at low transverse momentum → Compare R_{AA} vs $\langle N_{part} \rangle$ for J/ψ in different p_T intervals:

→ low-p_T (0<p_T<2 GeV/c)



→ high-p_T (5<p_T<8 GeV/c)



- Different suppression pattern for low and high-p_T J/ψ → smaller R_{AA} for high p_T J/ψ
- In the models, ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible → fair agreement from N_{part}~100 onwards