Overview of ALICE results

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for the ALICE Collaboration

Outline

- Introduction and detector description
- Selected Pb-Pb results
  - Global properties and particle spectra
  - Anisotropic flow
  - Heavy flavour and quarkonia
  - Charmonium production in ultra-peripheral collisions
- p-Pb highlights
- pp highlights
- Conclusions

Introduction

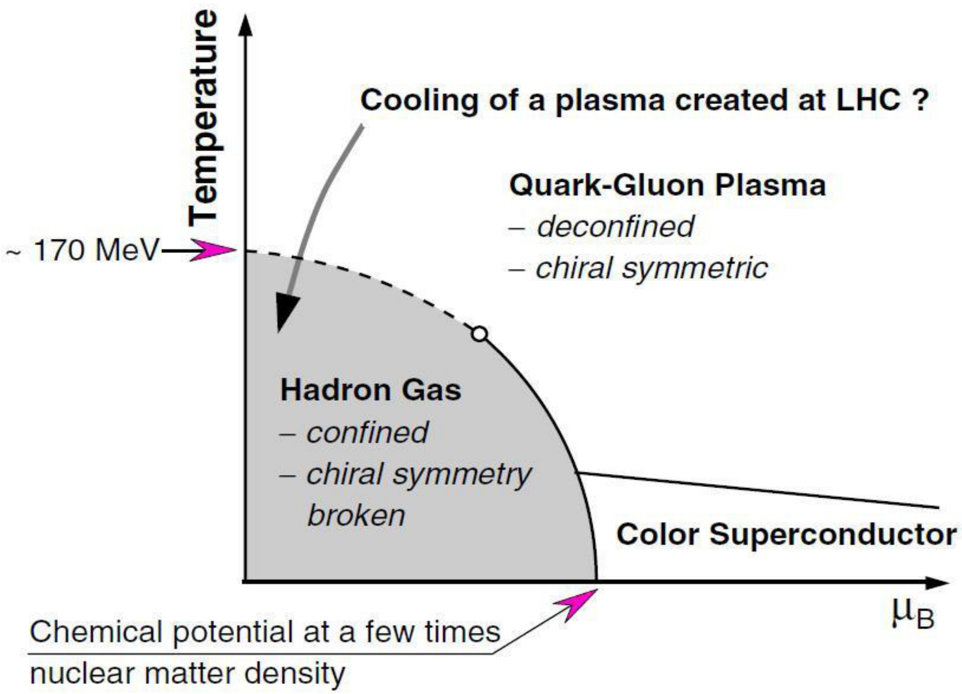
The ALICE physics goal

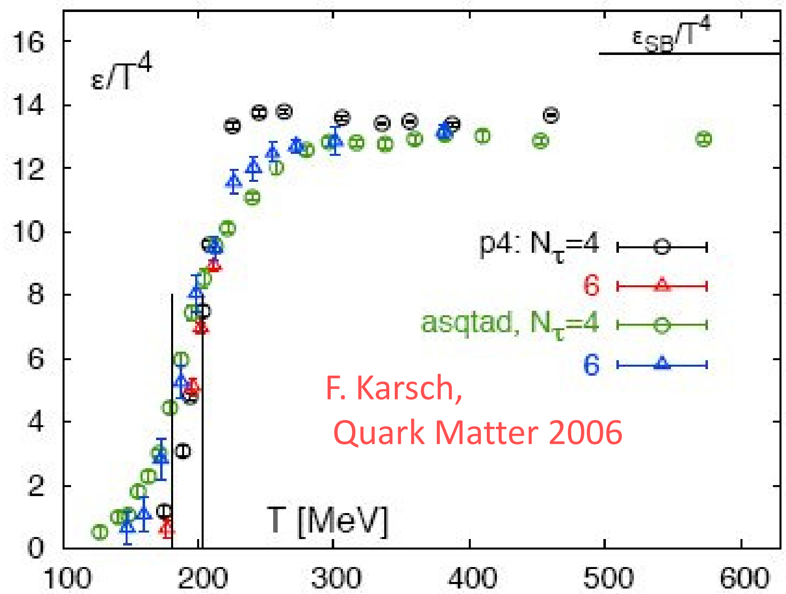
Study the hot and dense medium formed in **ultra-relativistic heavy-ion collisions** at the LHC

QCD asymptotic freedom -> transition to a **deconfined state of nuclear matter** with partonic degrees of freedom (**Quark Gluon Plasma**, QGP)

Lattice QCD predicts transition at T ~ 170 MeV (ε ~ 0.7 GeV/fm^3)

Early indications of QGP formation came from experiments at RHIC and SPS





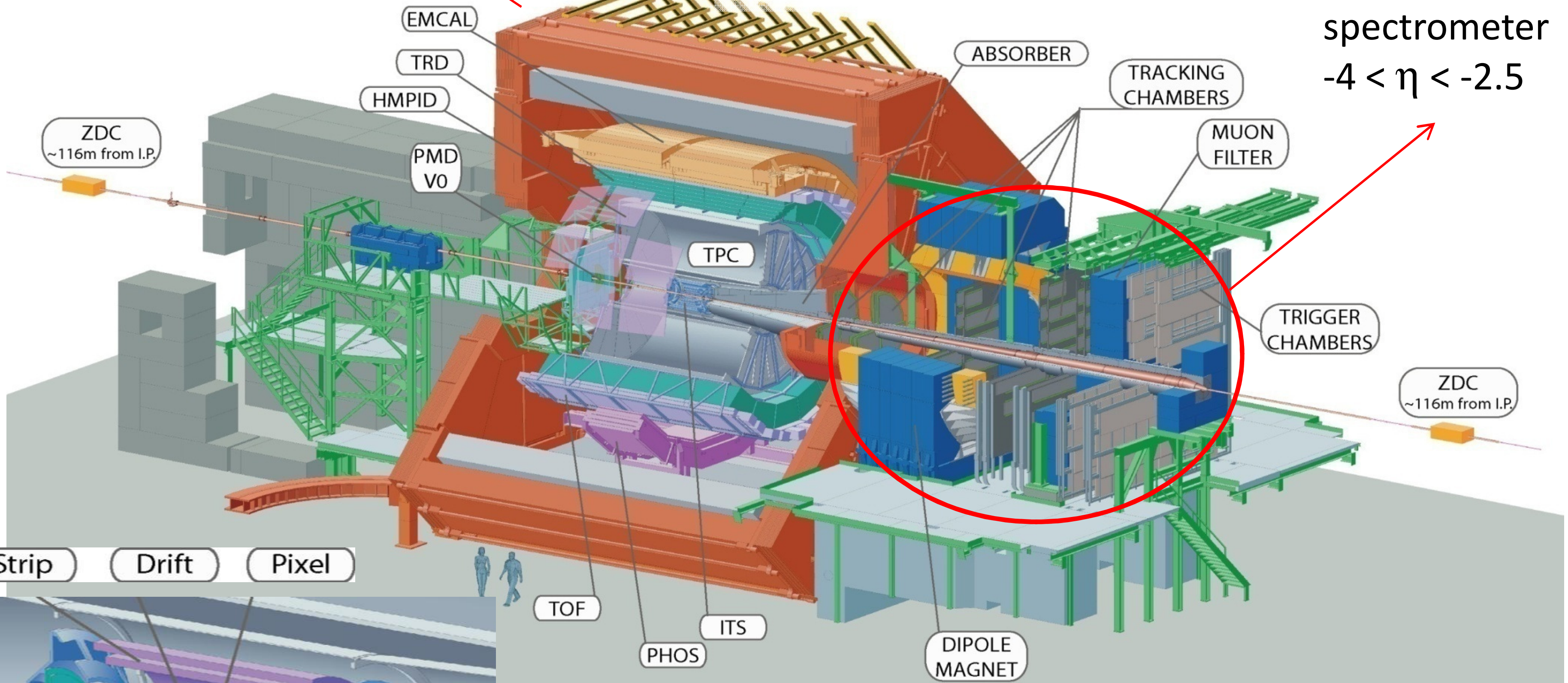
A Large Ion Collider Experiment

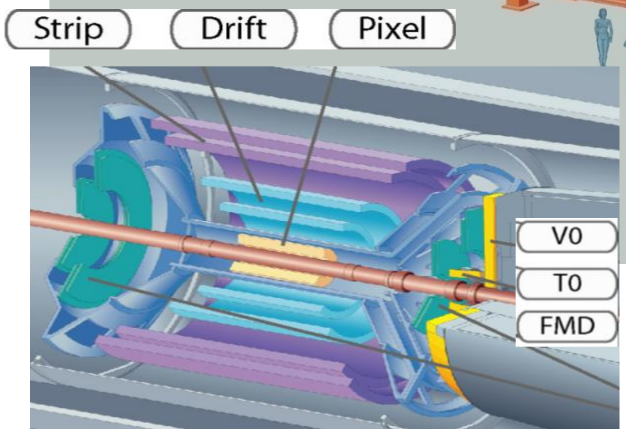
Central Barrel $|\eta| < 0.9$
2π tracking & PID

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

Collaboration:
~ 1200 Members
132 Institutes
36 countries

Muon spectrometer
$-4 < \eta < -2.5$

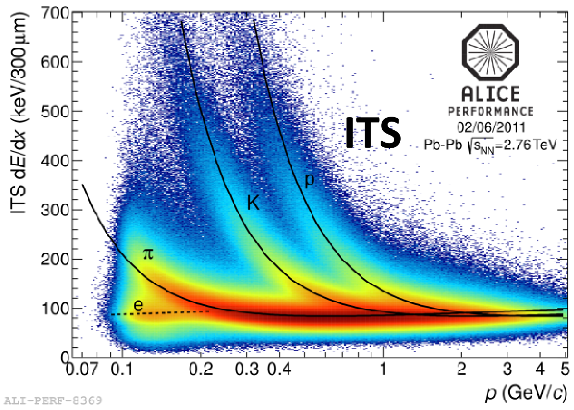


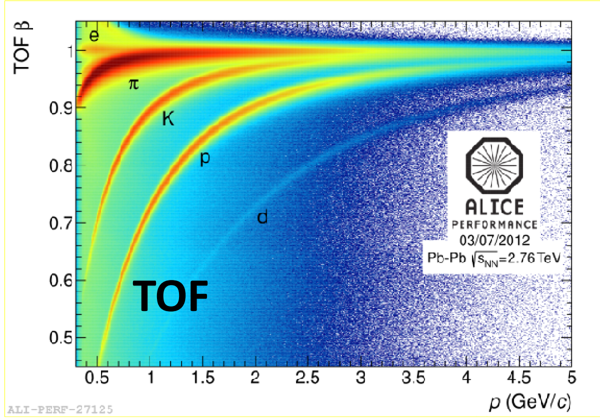


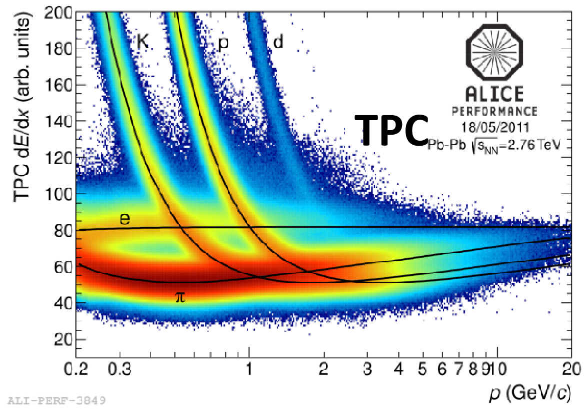
ACORDE (cosmics)
VZERO scint. (centrality)
η: -1.7– -3.7, 2.8–5.1

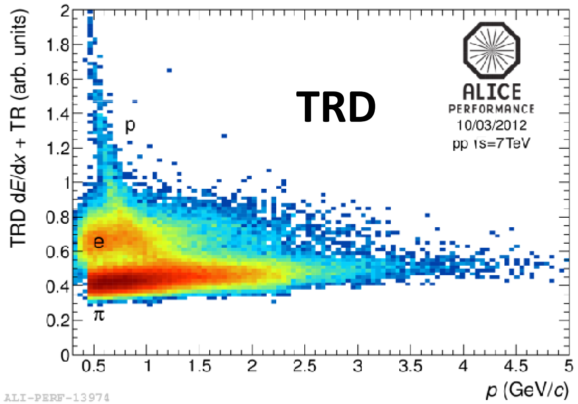
T0 (timing)
ZDC (centrality)
FMD (N_{ch} $-3.4<\eta<5$)
PMD ($N\gamma$, N_{ch})

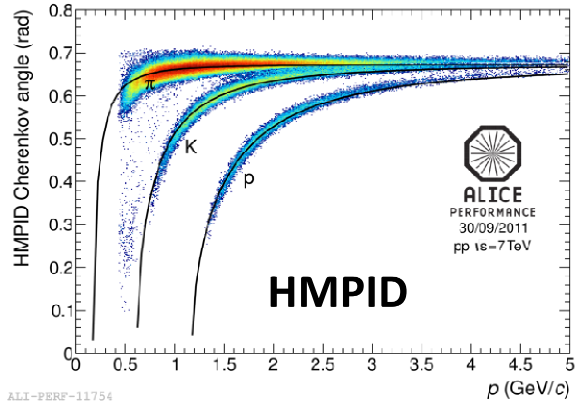
ALICE performance

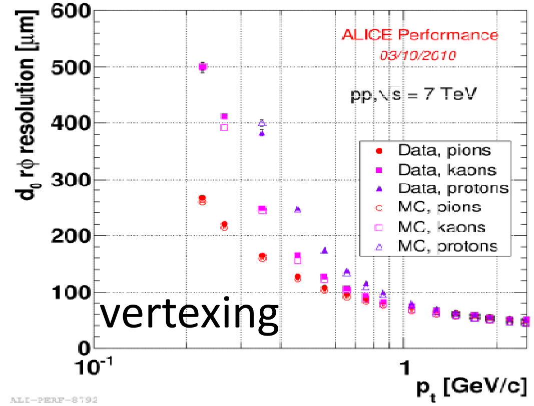












Central Barrel →
- particle identification (~ all known techniques)
- excellent vertexing capability
- tracking down to ~ 100 MeV/*c*

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

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

ALICE data taking during LHC Run I

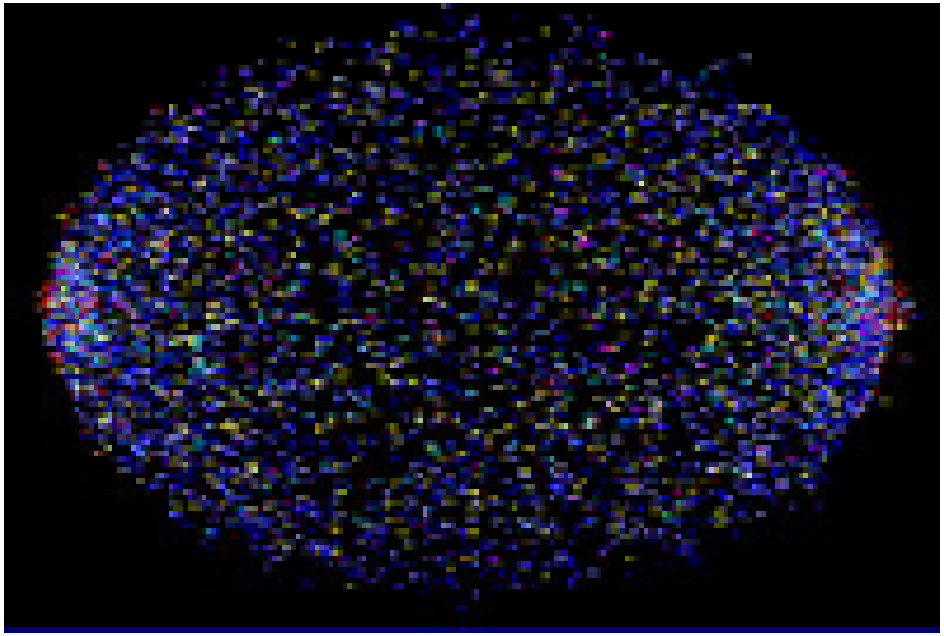
- **Two Pb-Pb runs** at $\sqrt{s_{NN}}$ =2.76 TeV:
  - in 2010 – commissioning and first data taking (mostly min. bias trigger)
  - in 2011 – several dedicated triggers

- **pp data** in 2009-2013:
  0.9, 2.76, 7 and 8 TeV
  → reference for Pb-Pb data, but also pp physics

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

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

Pb-Pb results



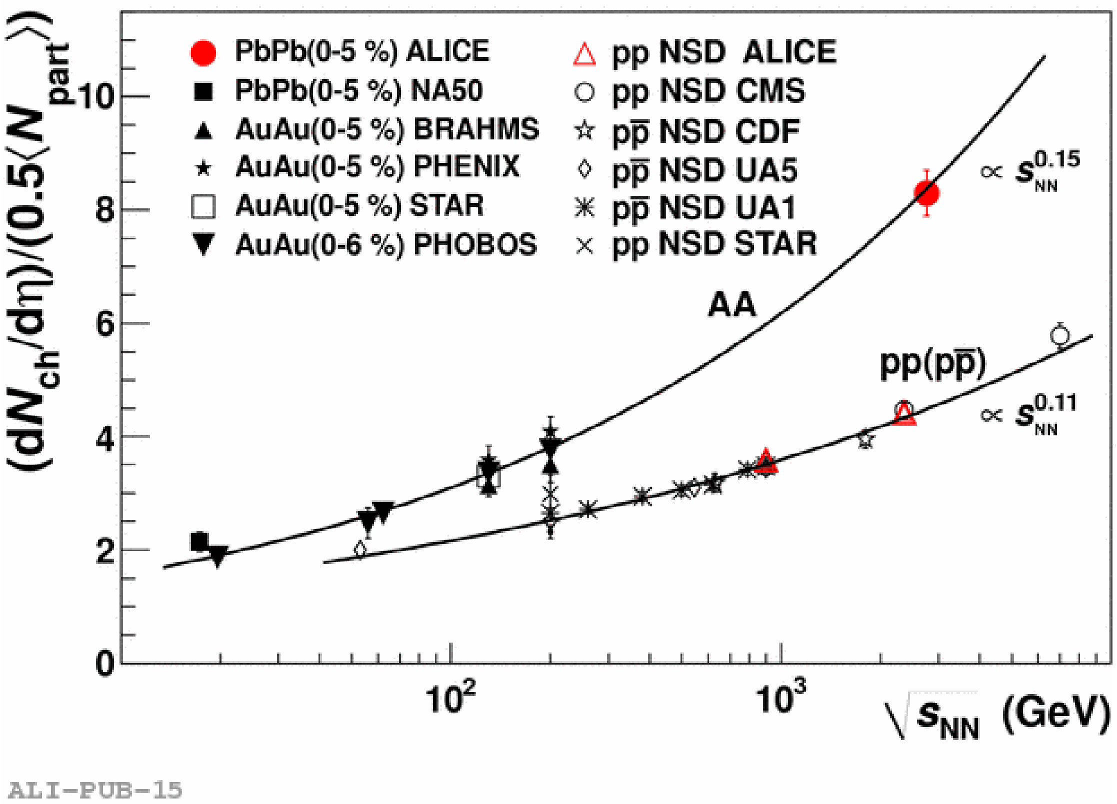
Global event observables: multiplicity, energy density

PRL 105, 252301 (2010)

Charged particle density at mid-rapidity per participant nucleon pair is :

~2x larger than in pp

~2x larger than at RHIC (Au-Au)



Energy density:

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

> 10 GeV/fm^3

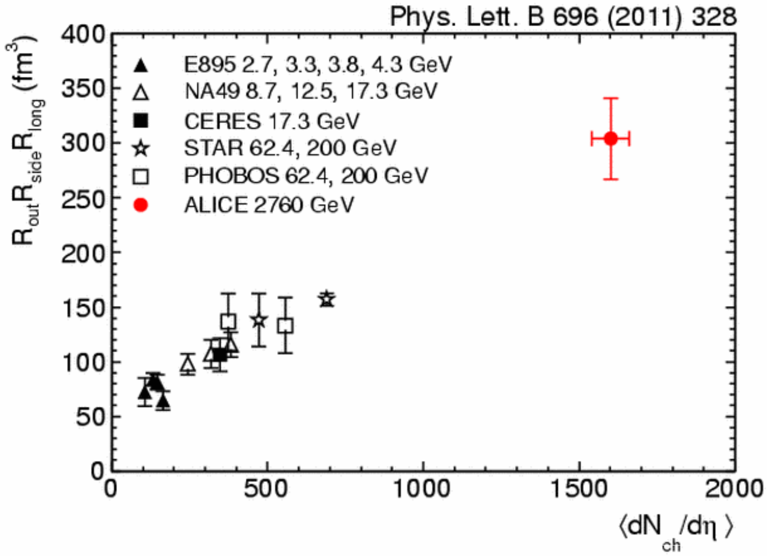
(3x larger than at RHIC)

Global event observables: fireball size, lifetime, temperature

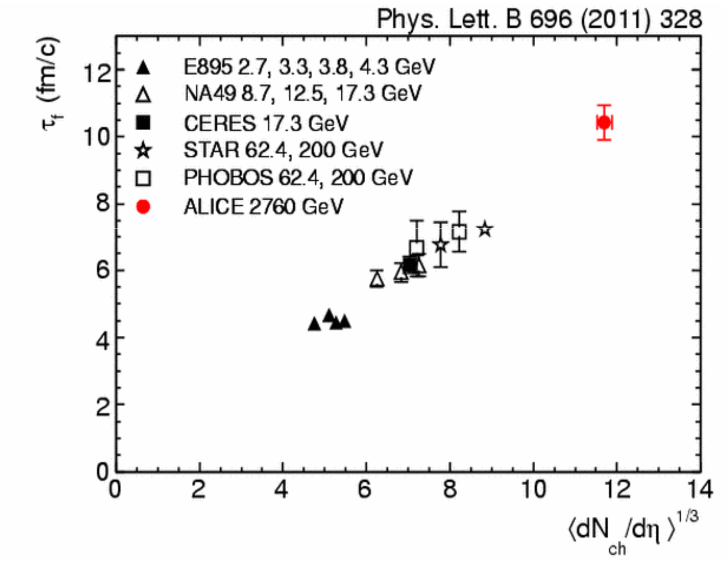
Fireball volume and lifetime studied via
identical pion interferometry

Volume R^3 ~ **300 fm³** ~ 2x larger than at RHIC

Lifetime **~ 10 fm/c** ~ 1.2x larger than at RHIC

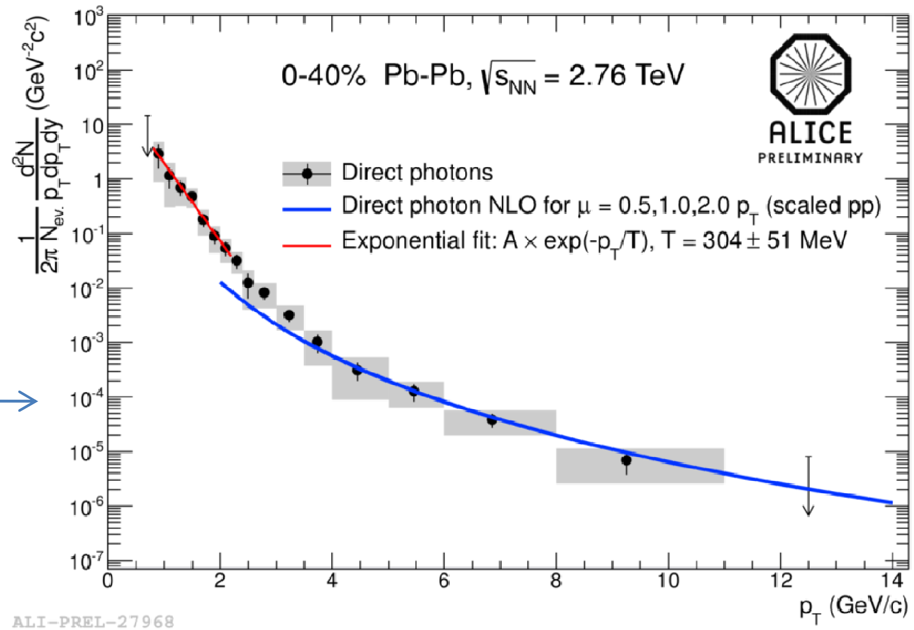


ALI-PUB-174



ALI-PUB-181

Fireball temperature from exponential fit to the **direct photon spectrum** at low p_T

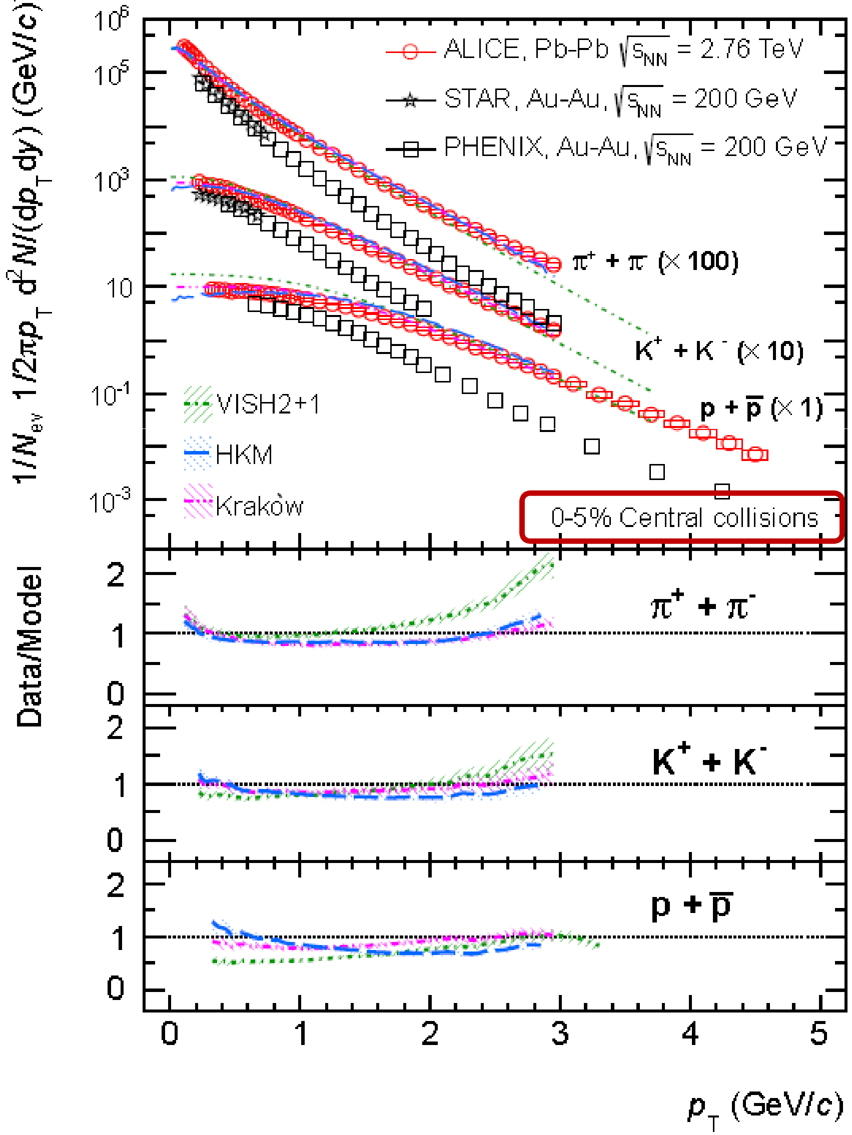


ALI-PREL-27968

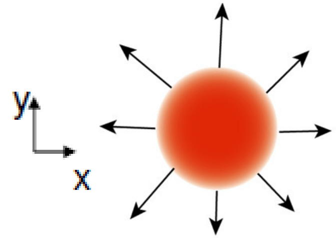
Temperature = 304 ± 51 MeV
~ 1.4x larger than at RHIC

Particle spectra: radial flow

PRL 109, 252301 (2012)



Low p_T spectra : **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

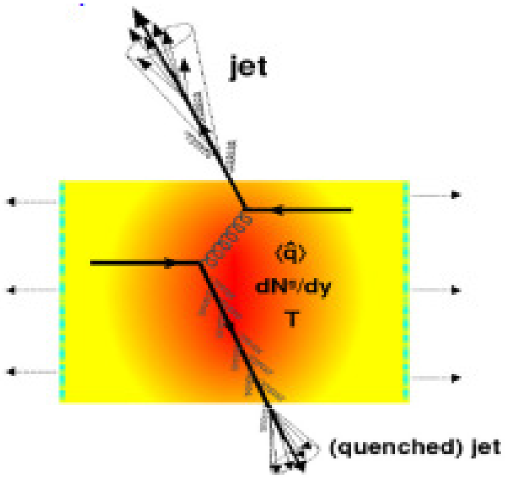
E. Schnedermann, et al.; Phys. Rev. C48, 2462 (1993):

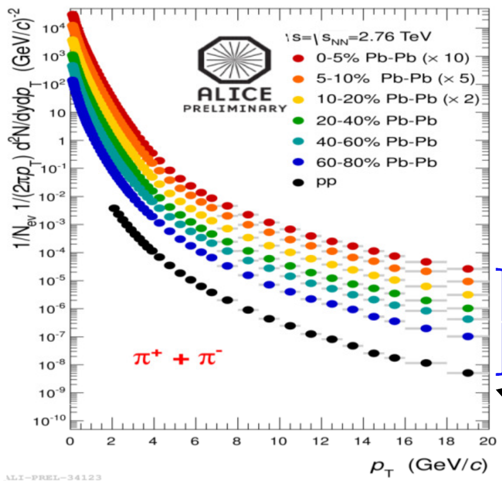
→ Radial flow velocity **<β> ≈ 0.65**
(10 % larger than at RHIC)

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

High p_T particle spectra: nuclear modification factor

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





Pb-Pb at different centralities

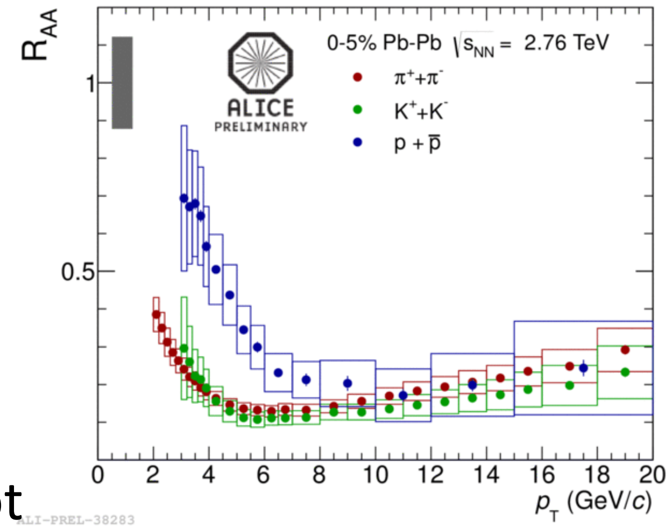
Reference: pp collisions

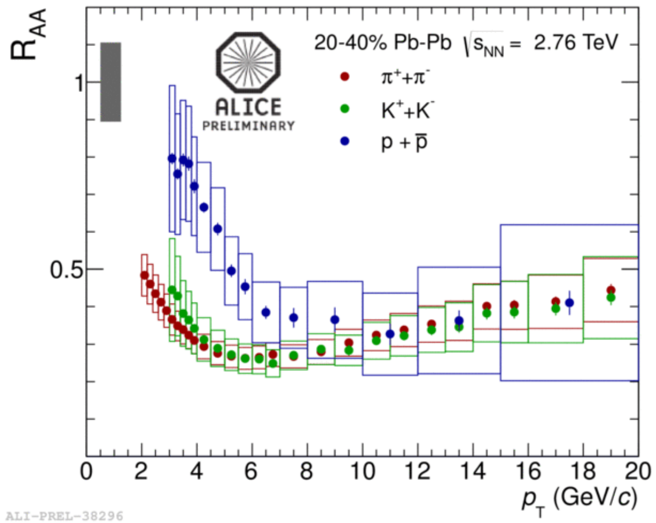
Nuclear modification factor:

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

- **Strong suppression**
- The $\mathbf{R_{AA}}$ for (anti-)p, π^+ and K are **compatible above ~7 GeV/c**

  → this suggests that the medium does not affect the fragmentation strongly



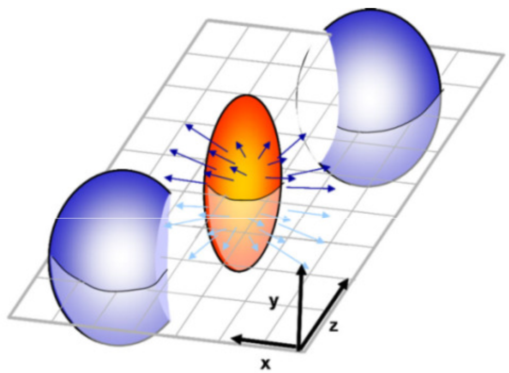


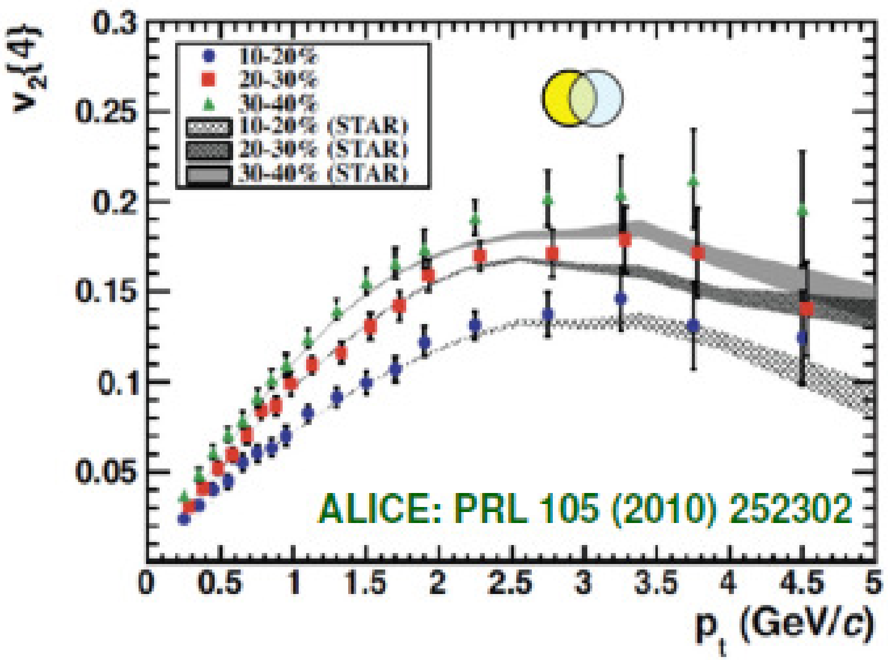
Elliptic flow

- **Sensitivity to initial anisotropy** is a measure of the importance of collective phenomena
- In non-central collisions, pressure gradients convert the spatial anisotropy in **momentum anisotropy**
- Elliptic flow (v_2) = **2nd harmonic coefficient in Fourier decomposition** of particle azimuthal distribution w.r.t. reaction plane (RP)

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

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



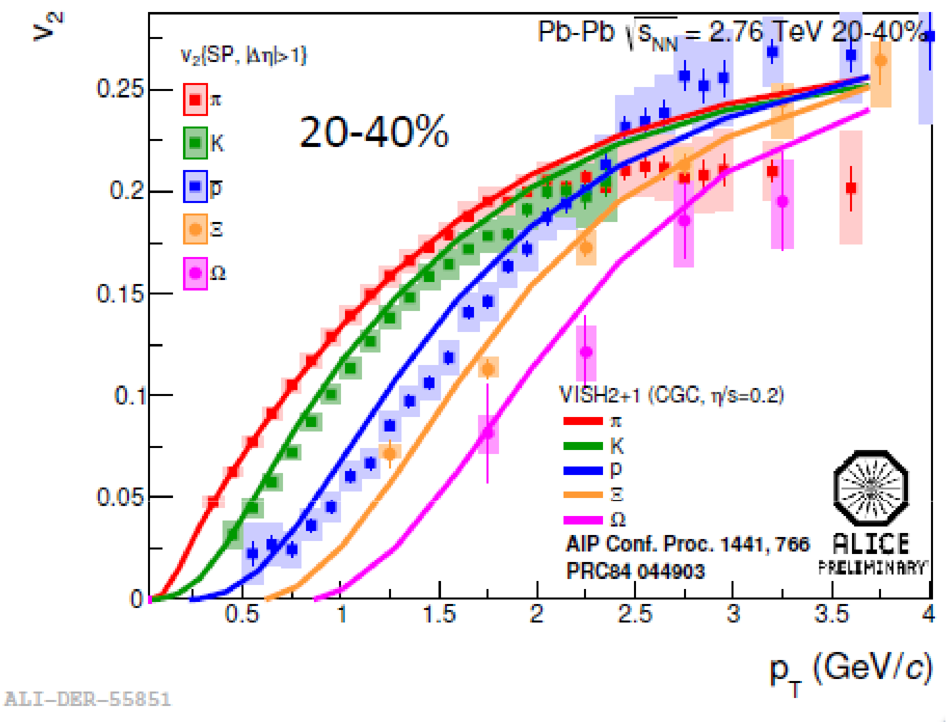


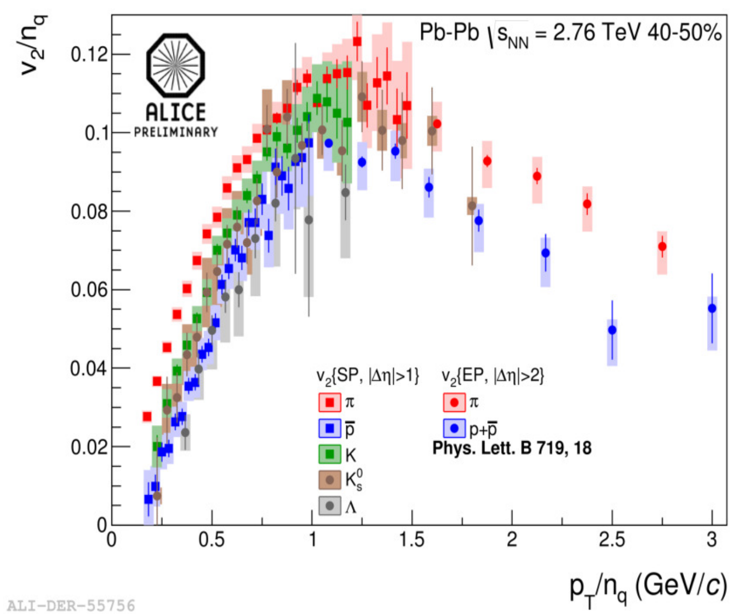
v_2 vs. p_T for non-identified charged particles in Pb-Pb collisions, was measured for three different centrality intervals

v_2 vs. p_T does not change between RHIC (200 GeV) and LHC (2.76 TeV) energy

Elliptic flow for identified particles

- v_2 shows **mass ordering** up to multi-strange baryons
- v_2 vs. p_T described by **hydrodynamical models**





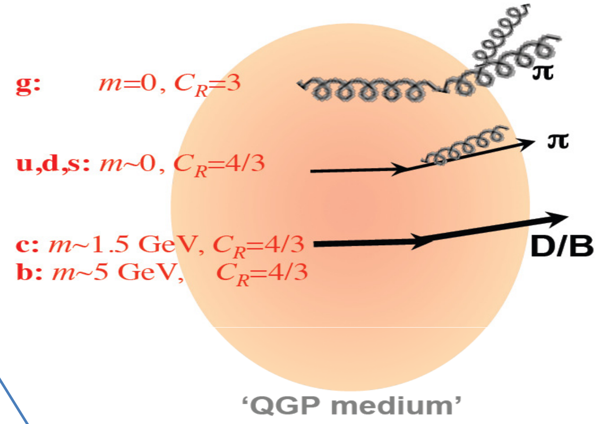
- **v_2/n_q scaling** (seen at RHIC) is less obvious (still, within 20%) at LHC
- at large p_T/n_q protons have smaller v_2 than pions

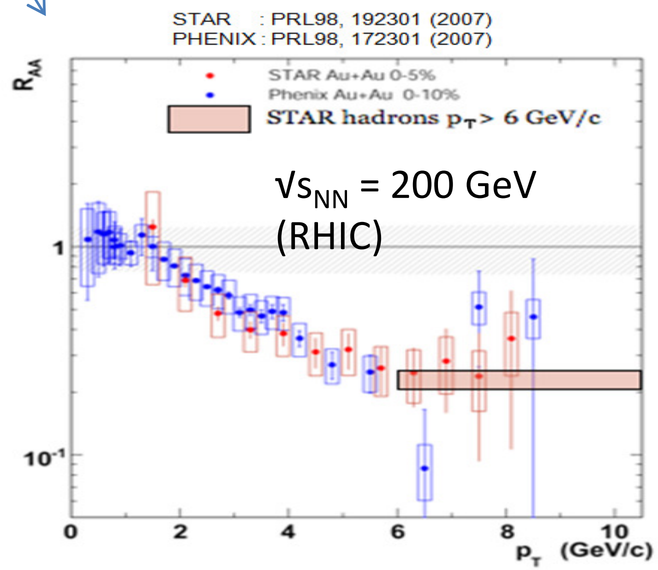
Open heavy flavour

- Particles containing **heavy quarks** (c,b) are produced in the early stages of the collision (high Q^2)
  -> tool to study the **parton-medium interaction**, via the **energy loss** mechanism

- **$R_{AA} \neq 1$ if medium effects** are present
  (seen at RHIC with non-photonic electrons)
- Energy loss is predicted to vary with
- the colour charge ($\Delta E_q < \Delta E_g$)
- the mass ($\Delta E_{u,d,s} > \Delta E_b > \Delta E_c$)

  -> Prediction: $\mathbf{R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}}$

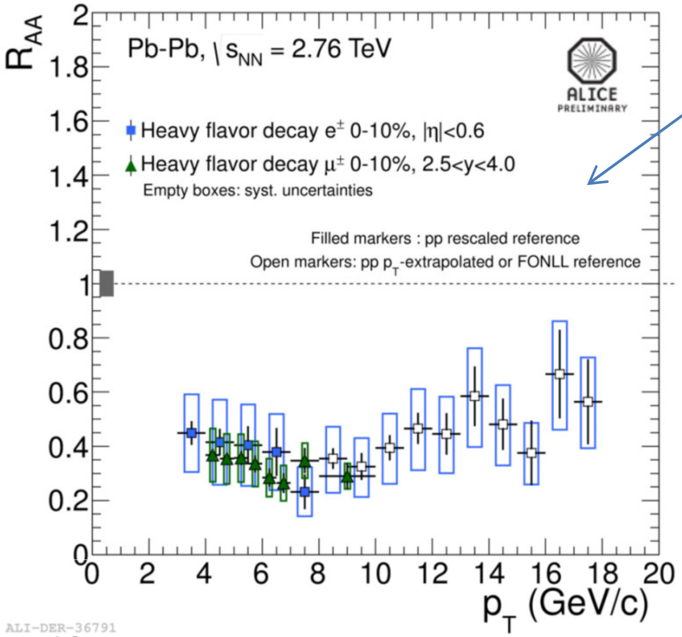




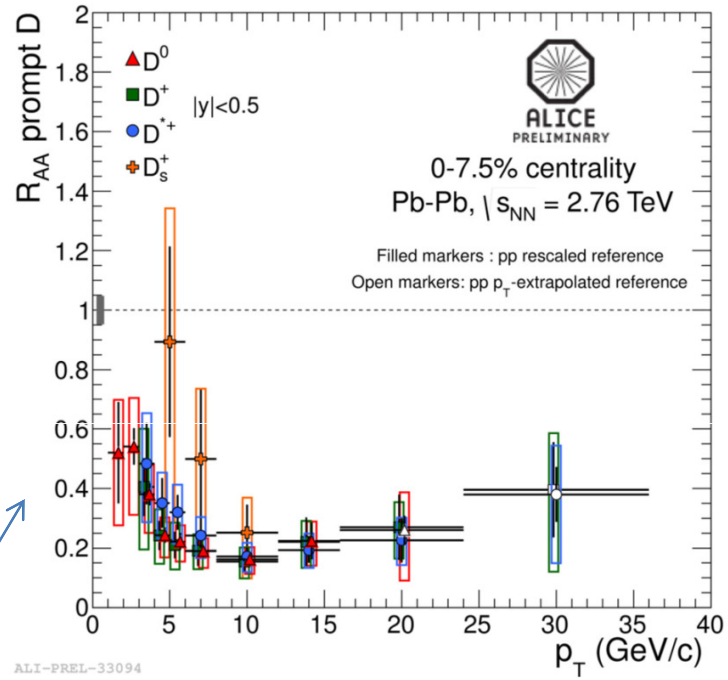
- Heavy flavour **detection in ALICE**

- **Midrapidity**:
  - D-meson hadronic decays
  - electrons from semileptonic decays
- **Forward rapidity**
  - muons from semileptonic decays

Open heavy flavour R_{AA}

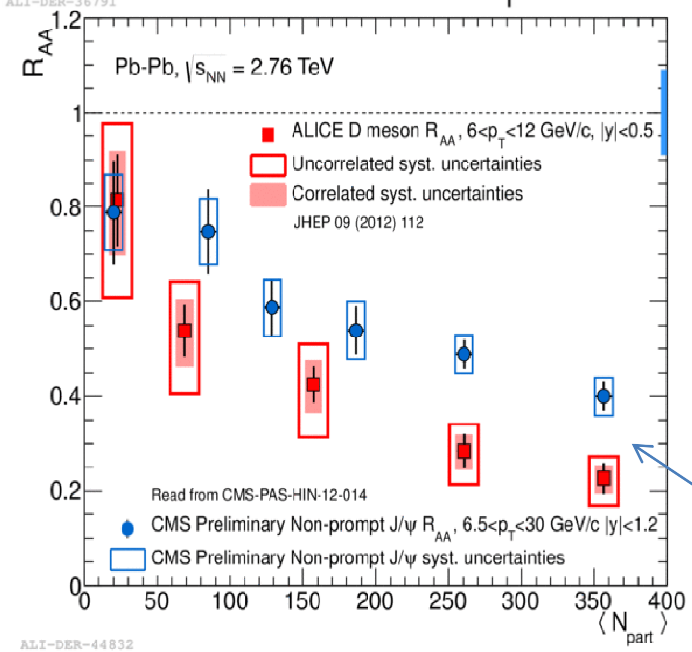


Similar **suppression** (by a factor 2-4) for muons (2.5<y<4) and electrons (|y|<0.6) from HF decay



Large suppression for D^0, D^+, D^{*+}, consistent within uncertainties for the three species

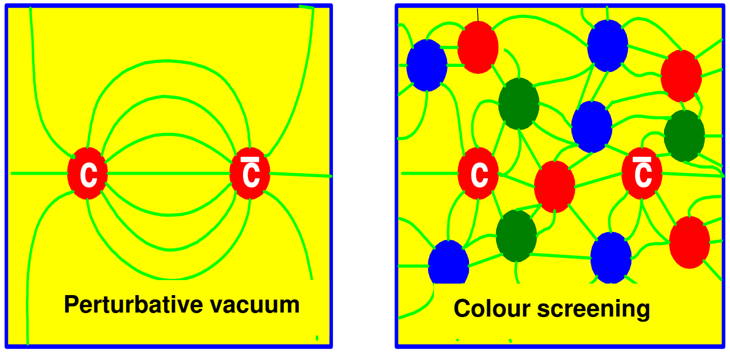
Hint for larger D_s^+ R_{AA} at low p_T
(not conclusive with current uncertainties)



D meson R_{AA} is smaller than that of J/ψ from B (CMS), as expected from the **mass dependence of heavy quark energy loss**

Quarkonium production

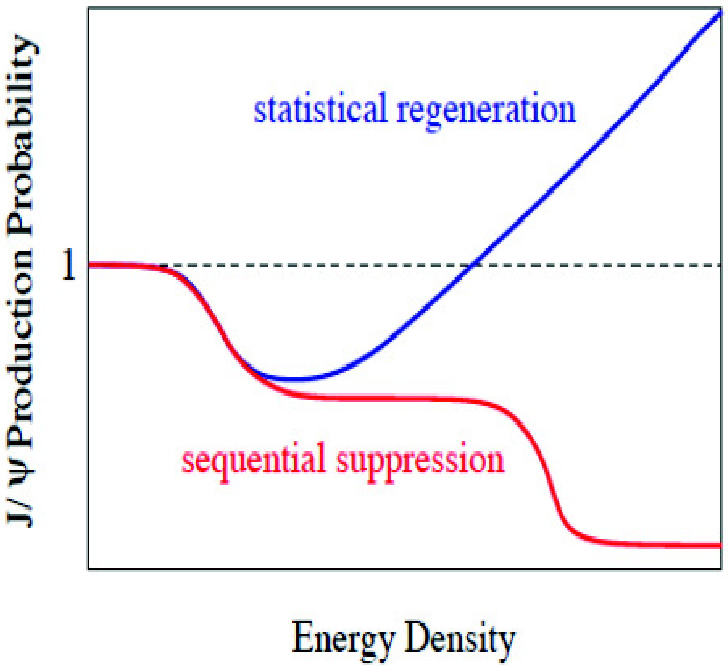
Resonance melting by colour screening in a Quark Gluon Plasma: one of the first proposed signatures of deconfinement.



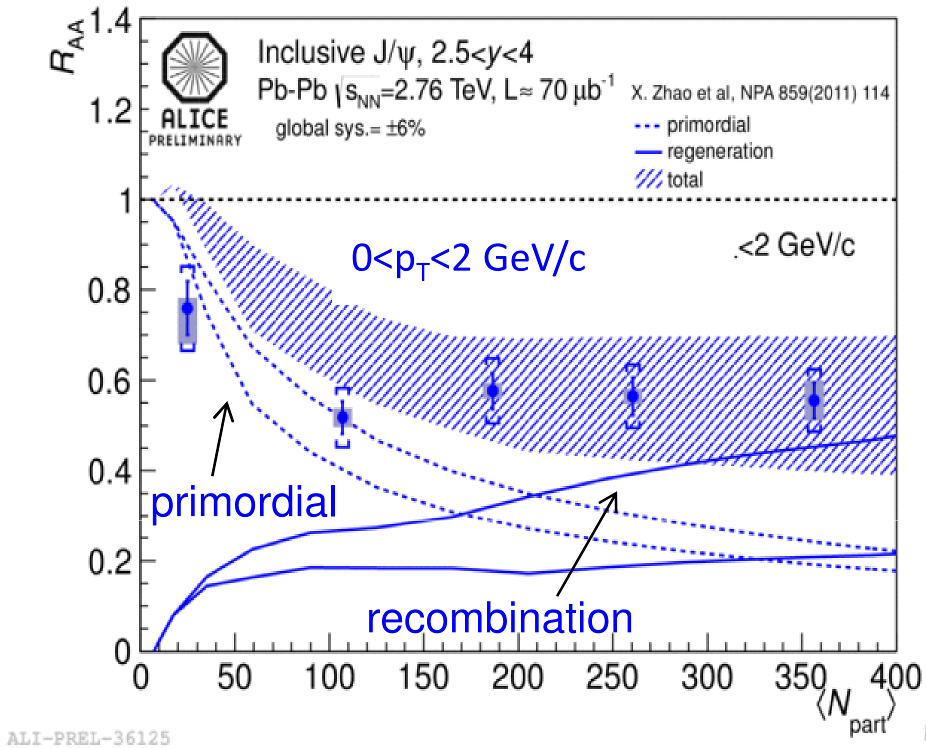
Sequential suppression of quarkonium states as the energy density increases
-> **thermometer of the plasma**

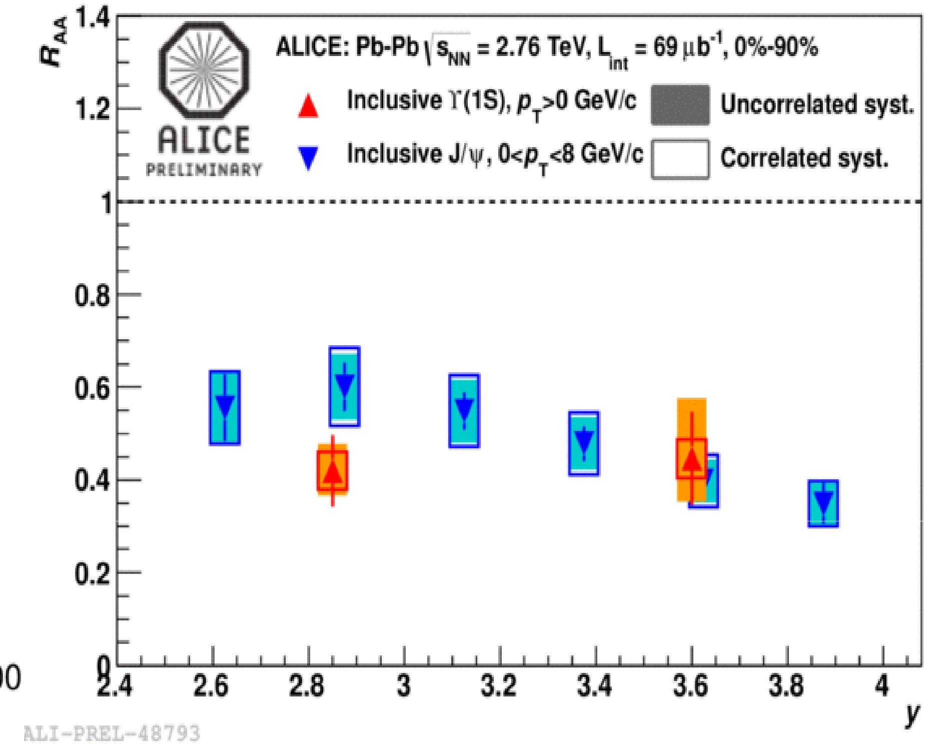
J/ψ suppression beyond cold nuclear matter effects observed at SPS and RHIC (but similar magnitude in spite of different energy densities).

J/ψ regeneration by recombination of cc pairs might play a role at low to intermediate p_T, and even become dominant at LHC energies



Quarkonium production: J/ψ and ϒ R_{AA}

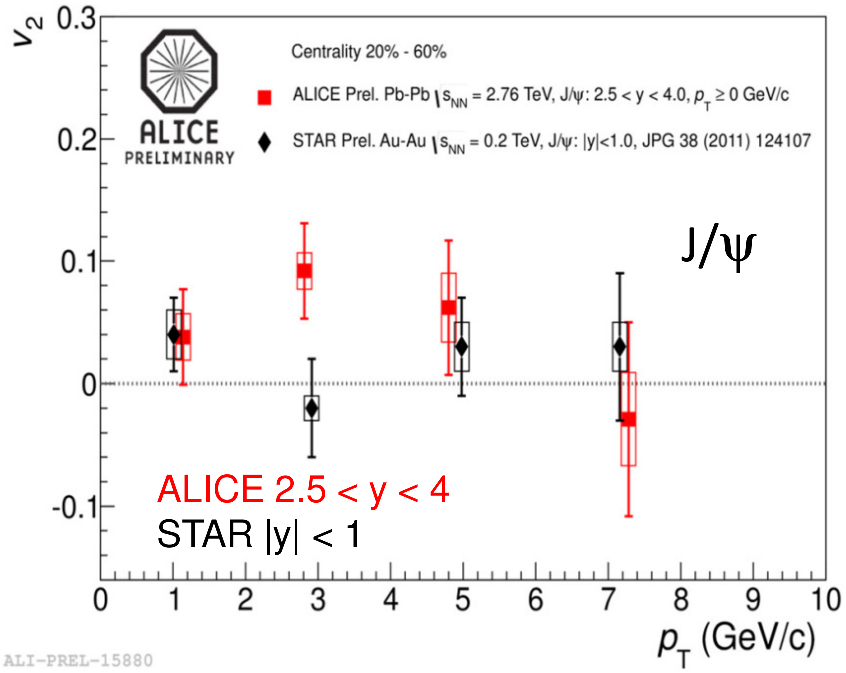


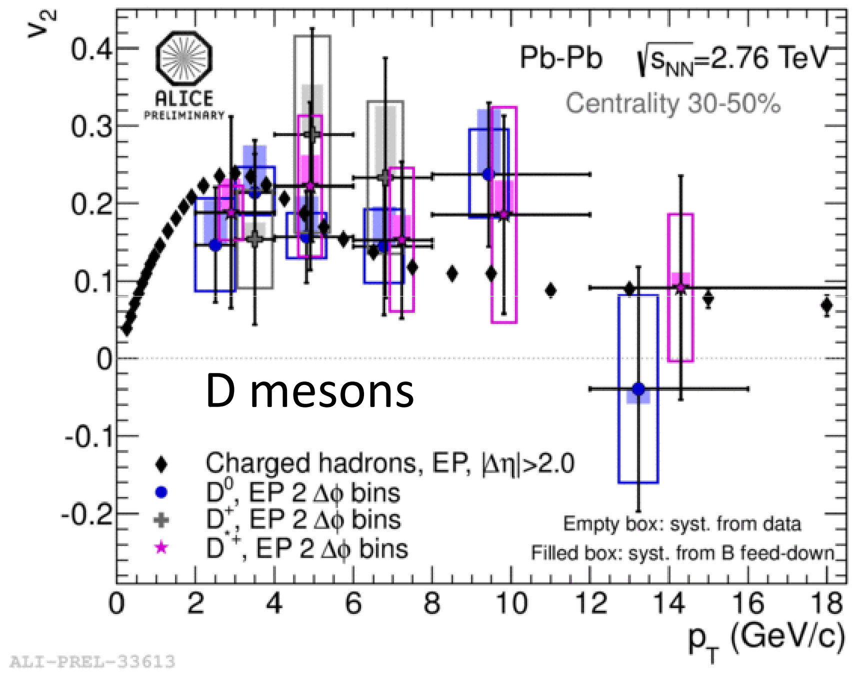


- **Inclusive J/ψ R_{AA} vs centrality (and p_T)** is in reasonable agreement with models including J/ψ **regeneration**
- **Weak rapidity dependence of ϒ suppression**; similar magnitude as J/ψ (CAVEAT: inclusive measurement, no feed-down separation)
- **Results from p-Pb are also available** -> address cold nuclear matter effects

J/ψ and D meson elliptic flow (v_2)

D mesons and regenerated J/ψs should have a significant v_2 if charm quarks participate in the collective motion





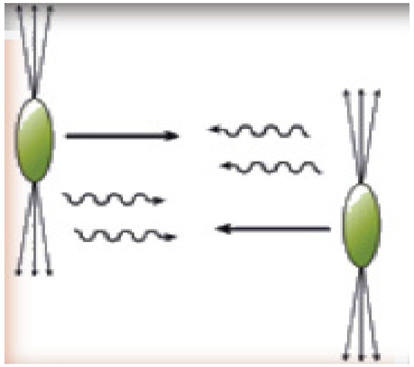
J/ψ:
hint for non-zero v_2 at intermediate p_T
(not seen at lower $\sqrt{s}$)

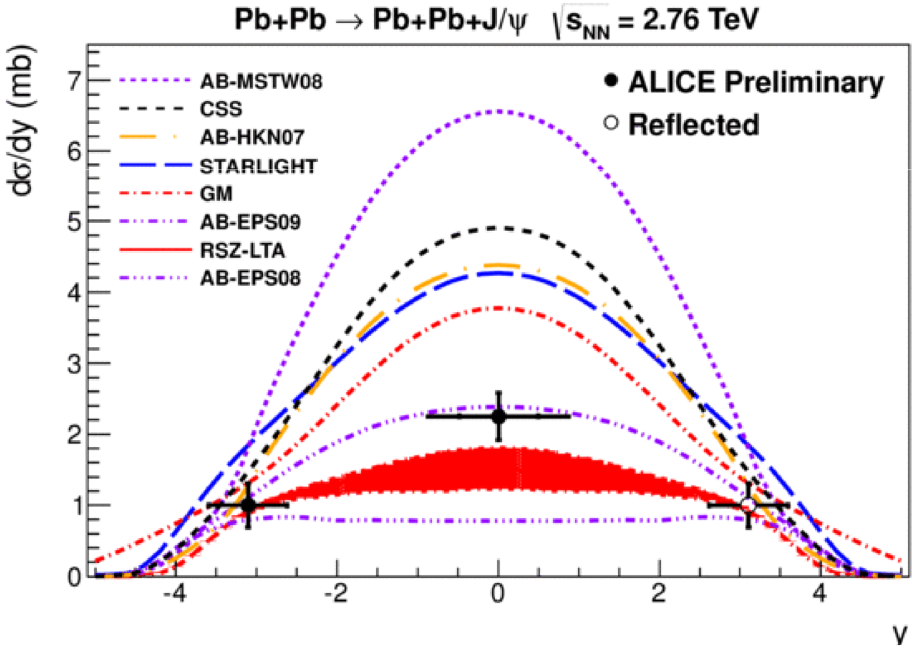
D mesons:
indication of **non-zero v_2** at intermediate p_T ;
simultaneous description of R_{AA} and v_2
is a **challenge for models**

J/ψ coherent photoproduction in ultra-peripheral Pb-Pb

In ultra-peripheral collisions ions interact via their clouds of **virtual photons** (hadronic processes are strongly suppressed)

Production of vector mesons containing heavy flavour in photo-nuclear processes is a powerful tool to **study the gluon distribution function in the nuclei down to x~10^{-4}**





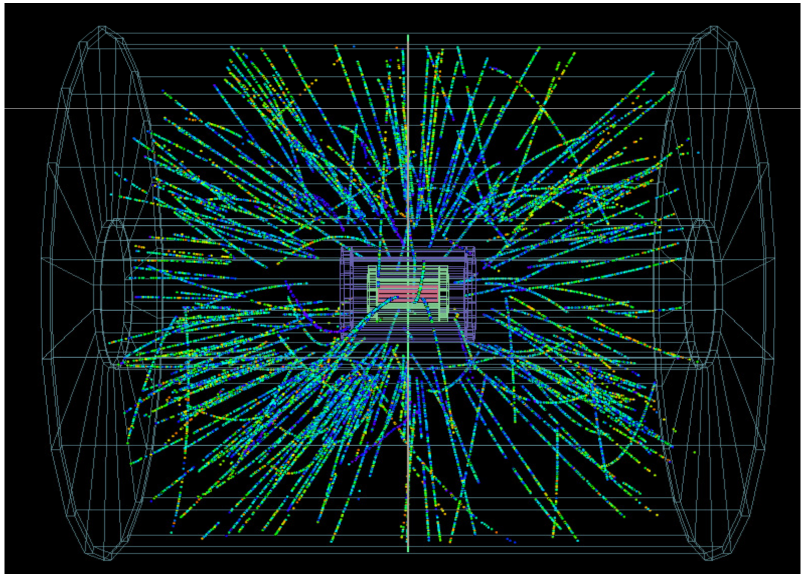
Forward rapidity:
PLB 718 (2013) 1273

Mid-rapidity: Preliminary

First measurement of coherent J/ψ photoproduction at both forward and mid-rapidity

Rapidity dependence is reproduced by the AB-EPS09 partonic model (**dσ/dy α g(x)²**)

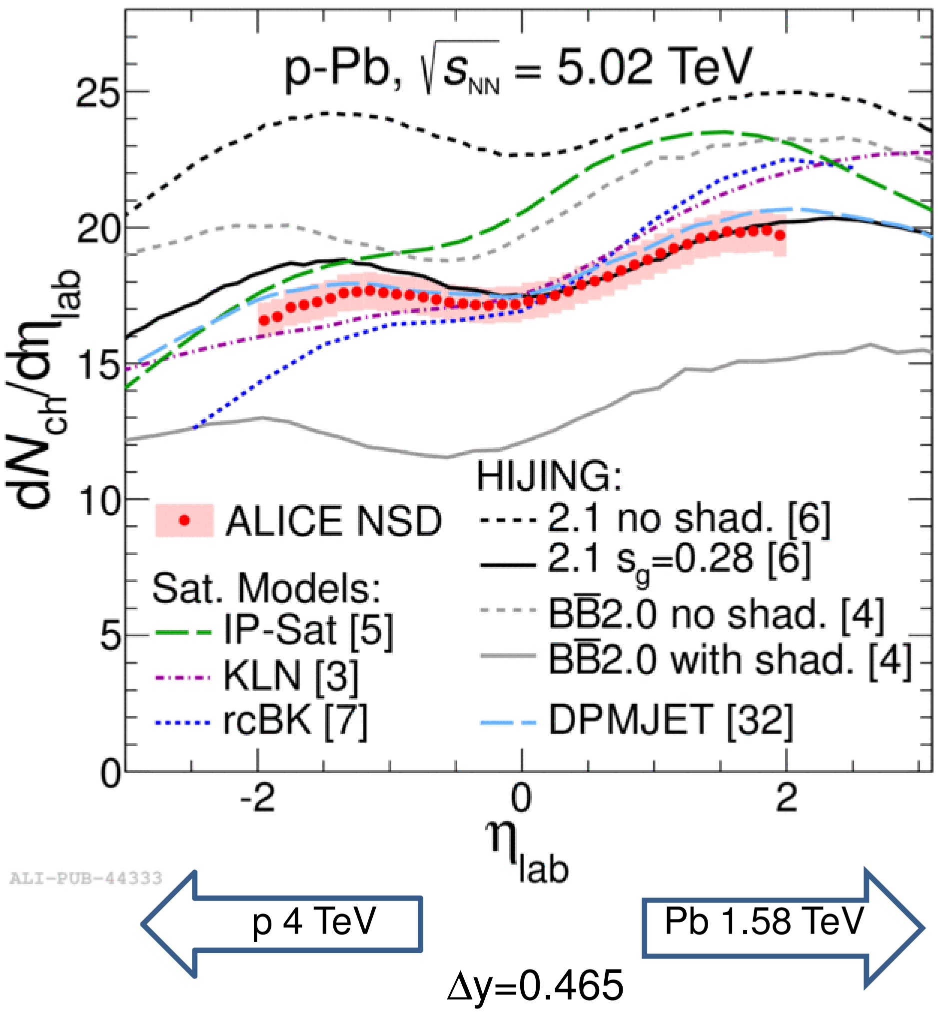
p-Pb highlights
(global event properties only)



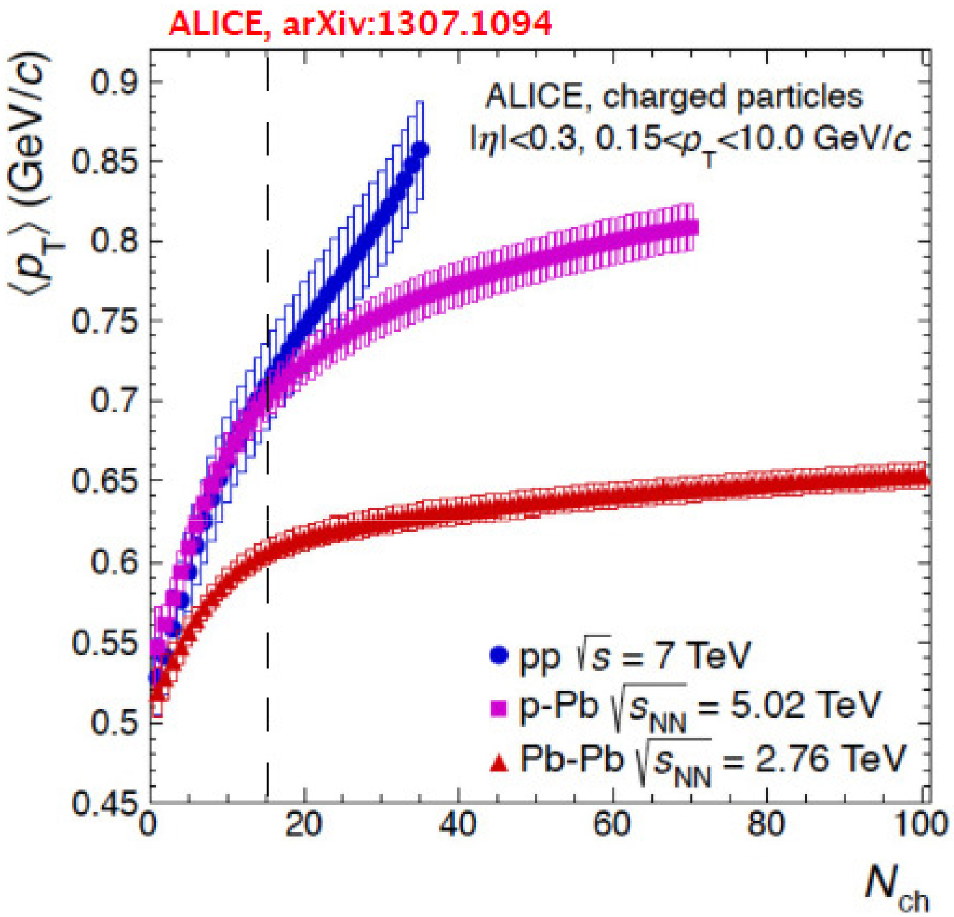
Charged particle multiplicity

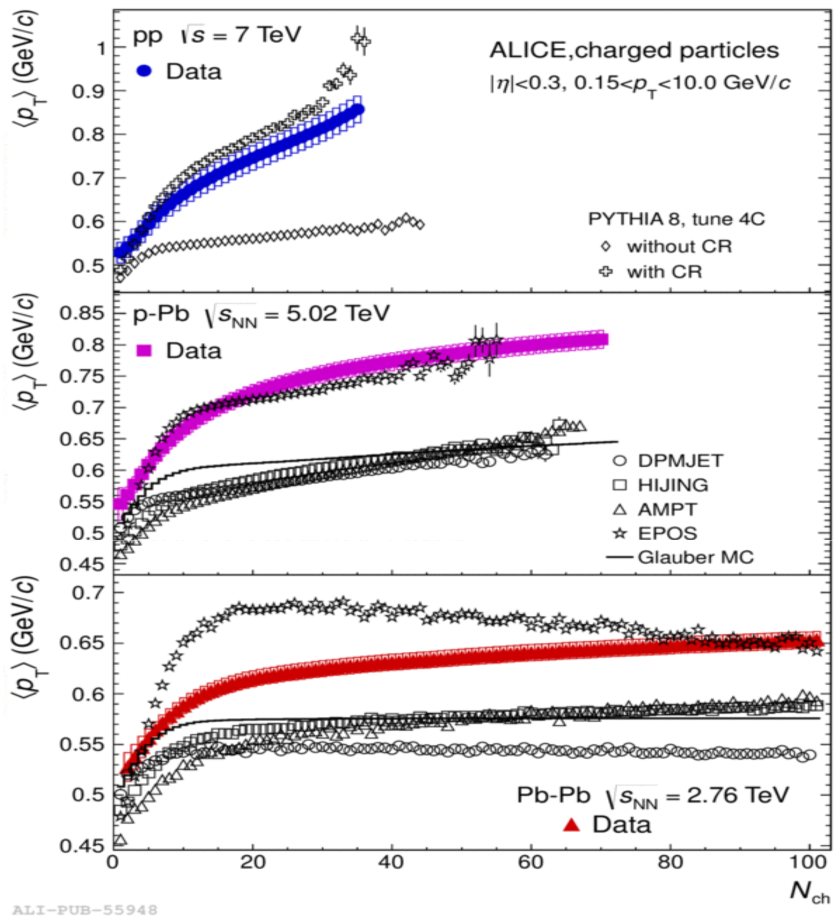
- Normalization: NSD
- All models within 20%
- Saturation models too steep with η_{lab}
- pQCD models (HIJING, DPMJET) in agreement with data
- Where shadowing is included, strong yield reduction (~ 30%)

PRL 110, 032301 (2012)



<p_T> vs charged particle multiplicity





- p-Pb follows pp up to N_{ch} ~14
- **Superposition of independent pp collisions** (Glauber approach), with measured <p_T> from pp, is **lower than p-Pb data**

- **Collective final state effects?**
- Color reconnections between hadronizing strings?
- Coherent effects between strings formed in different p-N collisions?

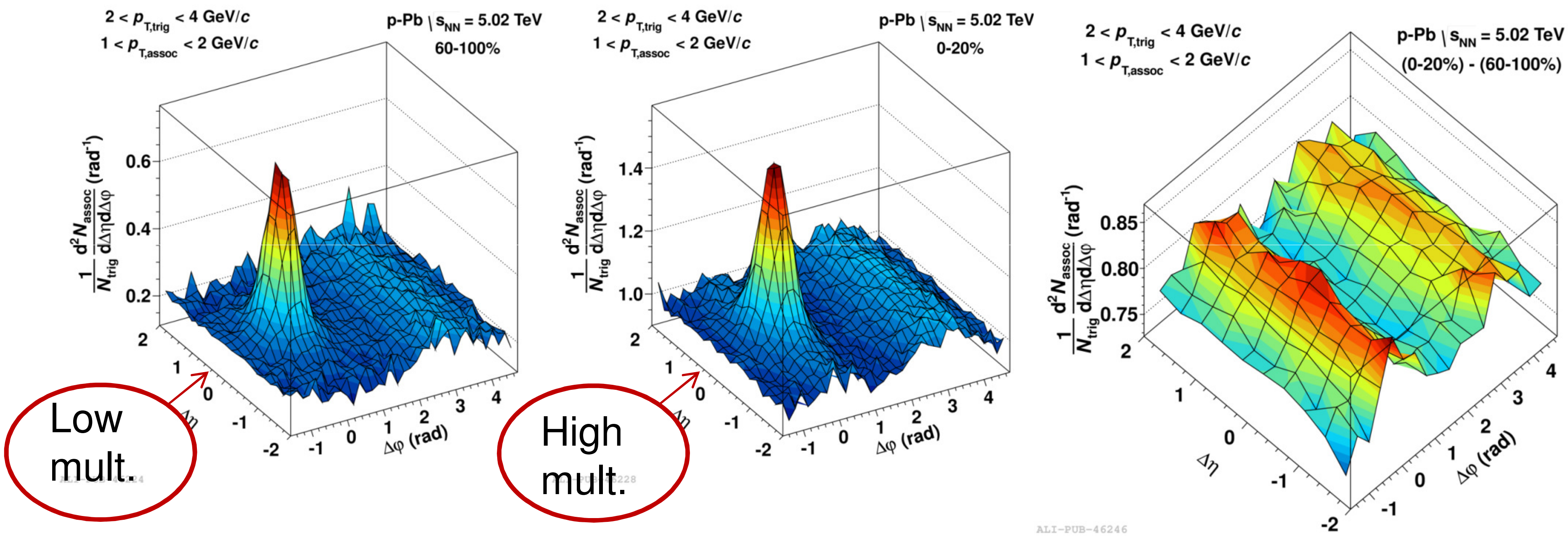
Long range correlations vs multiplicity

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 the two VZERO arms

Phys. Lett. B 719 (2013) 29

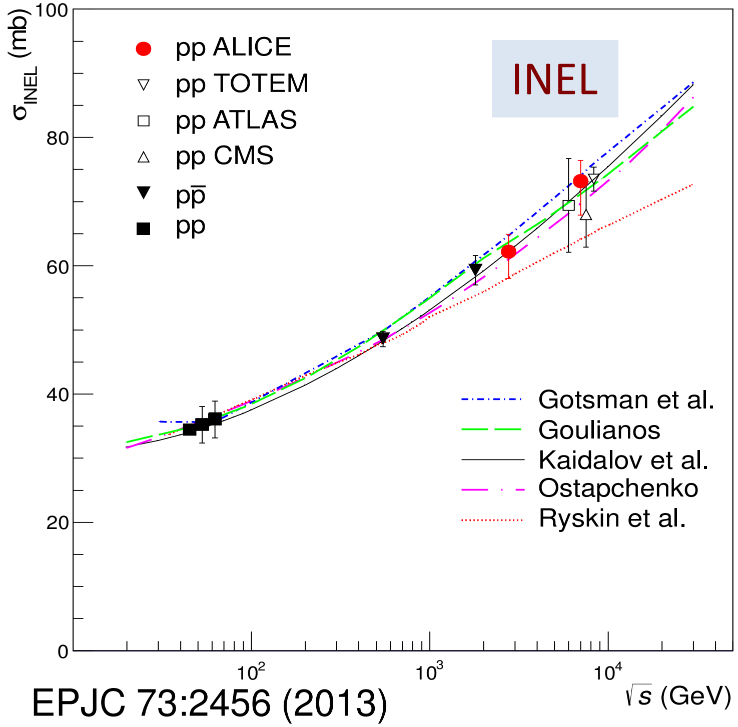


- **Low-multiplicity p-Pb**: pp-like (jet-like) correlation
- **High multiplicity p-Pb:** near-side ridge appears; higher yields on near and away side
- Subtracting the per-trigger yield of the low multiplicity class to that of the high multiplicity class, **a double ridge structure appears**
  -> similar to Pb-Pb, where it is ascribed to collective effects. **Unexplained** in p-Pb.

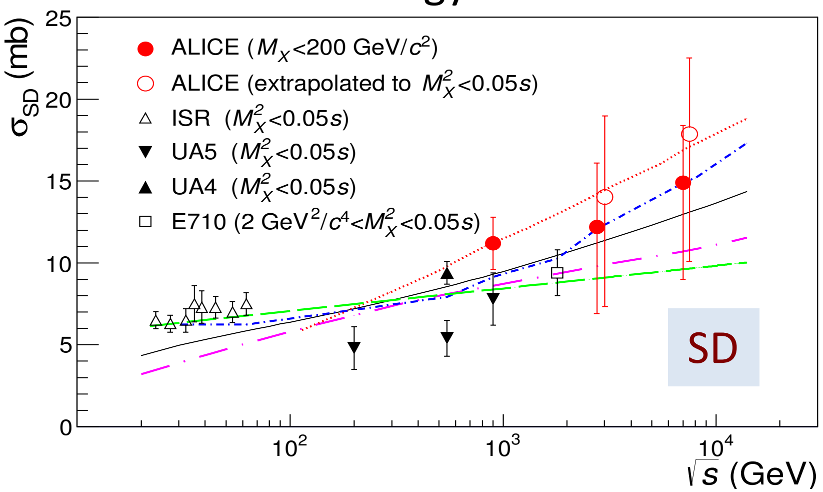
pp highlights

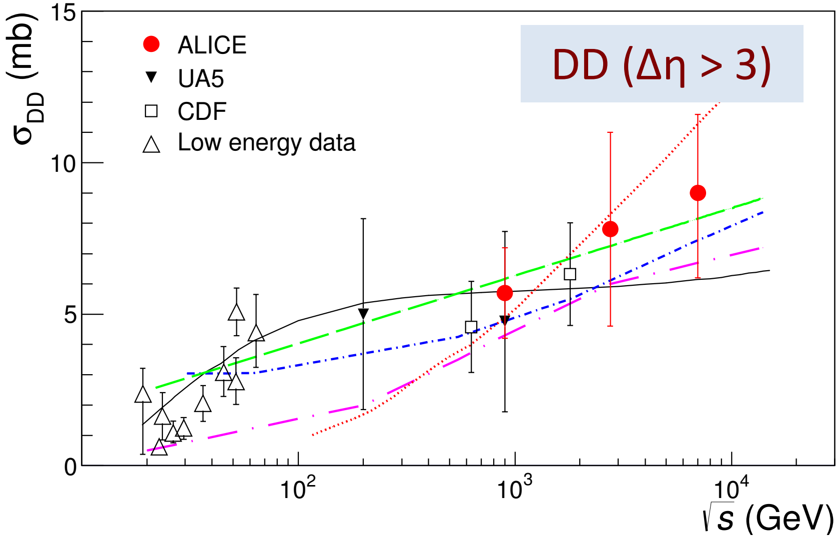
Inelastic and diffractive cross sections

- Relative rates of single and double-diffraction determined via a **study of pseudorapidity gaps**
- The inelastic cross section is obtained from the visible cross section determined in a vdM scan corrected by the trigger efficiency, determined via a **simulation tuned on diffraction data**
- Results on the **inelastic cross section** at 7 TeV **consistent with ATLAS, CMS and TOTEM**
- Results on single diffraction **consistent with UA5** at √s = 0.9 TeV
- We do not observe variations of relative rates of SD and DD with energy



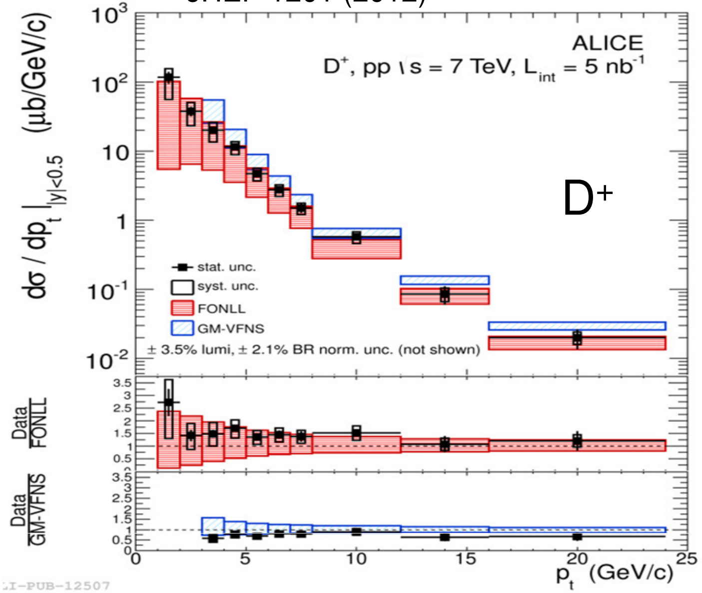
EPJC 73:2456 (2013)

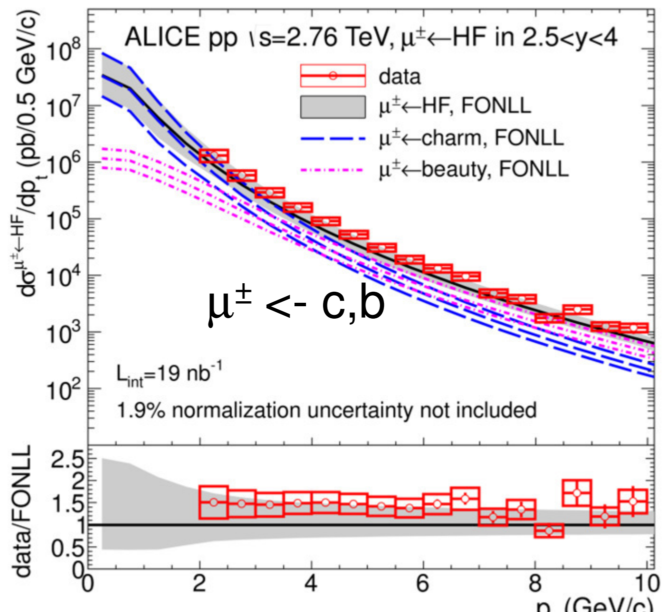




Heavy flavour cross sections

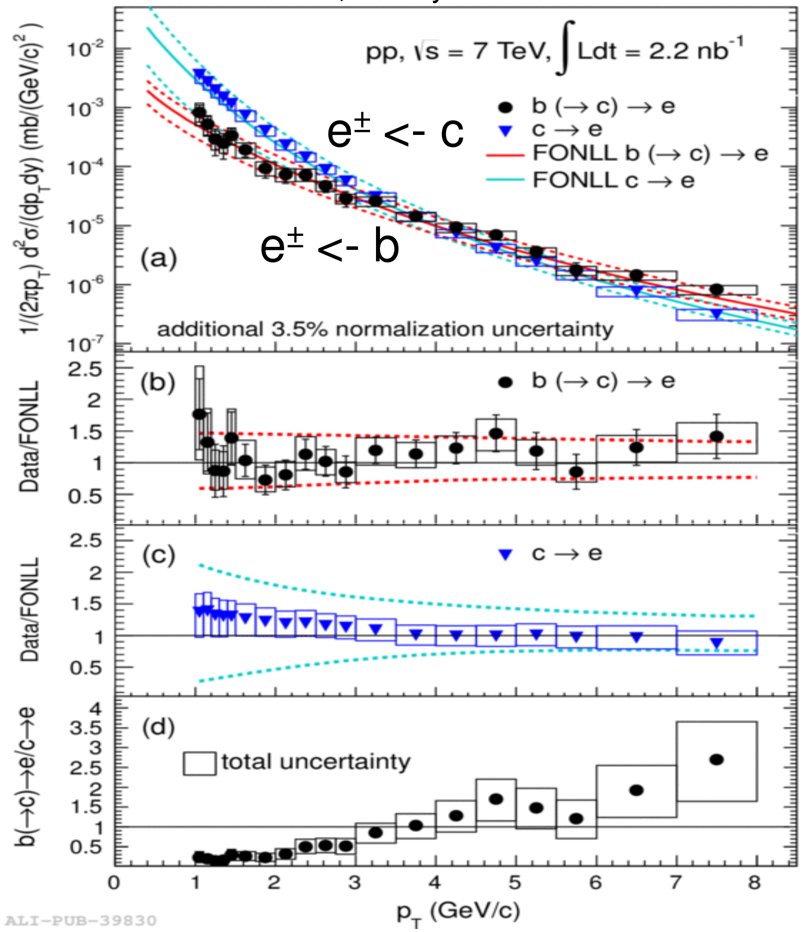
JHEP 1201 (2012)





PRL 109 (2012) 112301

arXiv:1205.5423, acc. by PRD



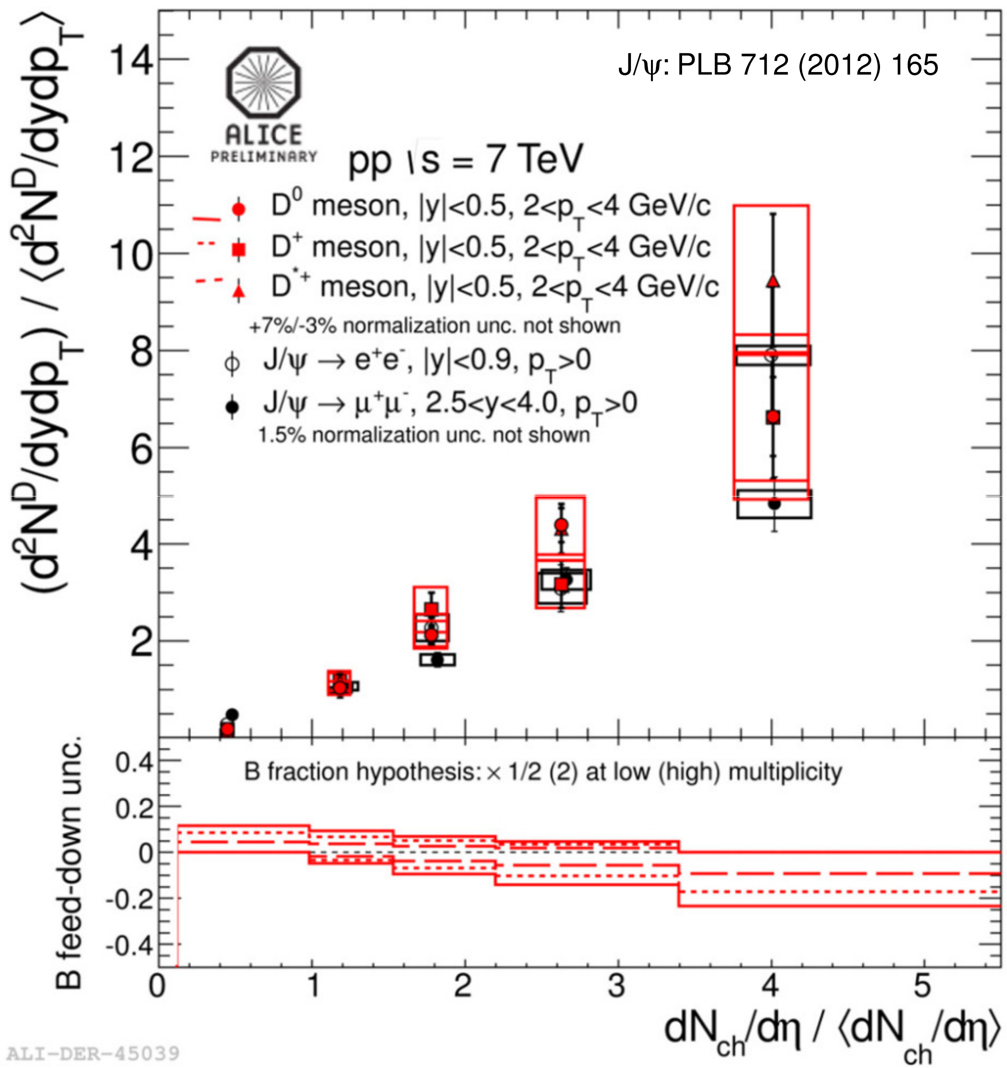
- Measurement of **D meson cross sections down to low p_T**
- The measured cross sections are **reproduced by pQCD** within uncertainties

Multiplicity dependence of J/ψ and D mesons

- **Linear increase** of D meson and J/ψ production vs the underlying min bias event multiplicity

- For J/ψ , the results are not reproduced by Phythia 6.4

- Measurement may provide insights on the **interplay between hard and soft regime**



Conclusions

- ALICE has provided a wealth of results, trying to characterise the hot and dense medium formed in heavy-ion collisions. Many of them were left out from this talk: strange and multi-strange particles, resonances, higher armonics anisotropic flow, jets, correlations, EM dissociation cross sections...

- Analysis of the 2013 p-Pb run is well advanced, providing insights on cold nuclear matter effects
  -> collective behaviour in p-Pb?

- pp measurements are crucial to the ALICE physics program, both as a reference for Pb-Pb and as a field of study in his own right