# Overview of ALICE results

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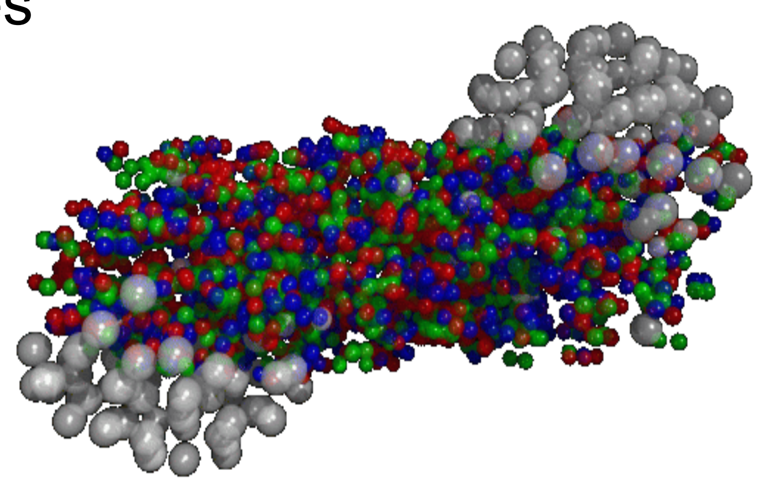
*for the ALICE Collaboration*

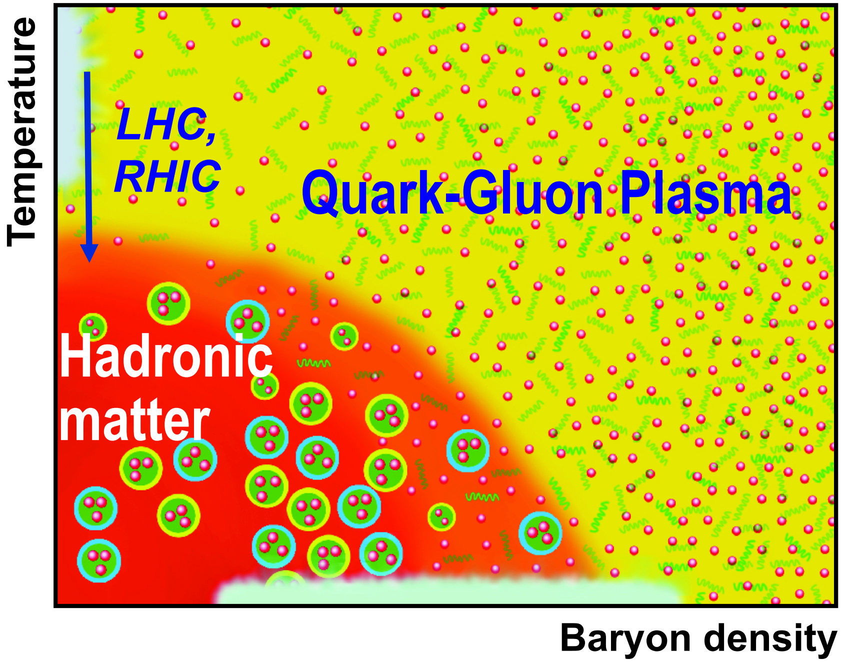
# Outline

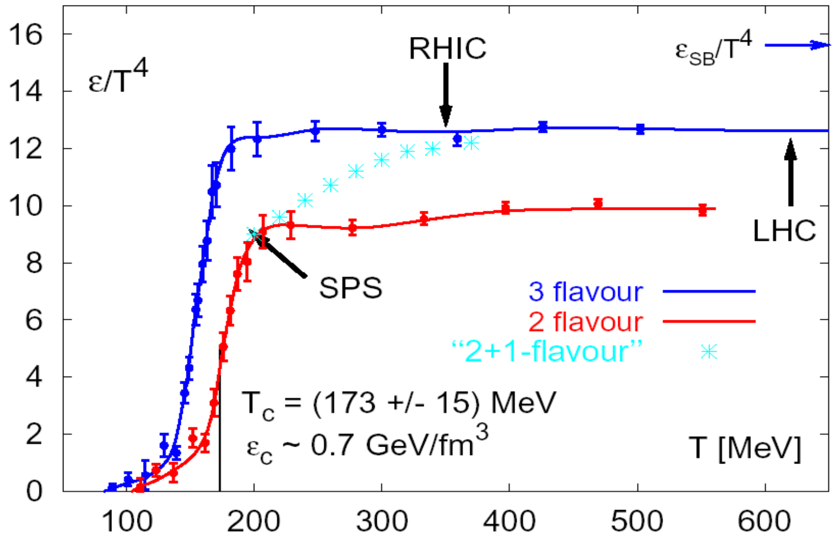
- Strongly interacting matter in extremes
- ALICE experiment — Massimo Masera
- Recent measurements
  - Global event observables
  - CNM effects (p-Pb results)
  - Jet quenching — Leticia Cunqueiro Mendez
  - Heavy flavour — Cristina Terrevoli, Lizardo Valencia Palomo
- Conclusions



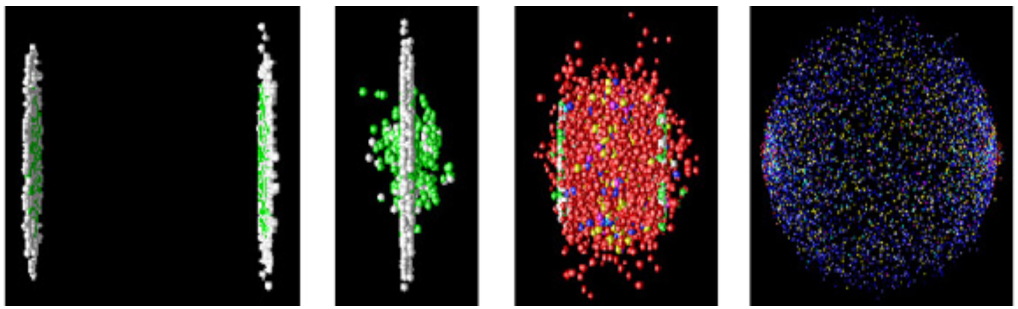
*Impossible to cover all of this in 20 min*
*→ Concentrate on selected highlights*

# Matter in extremes: the QGP

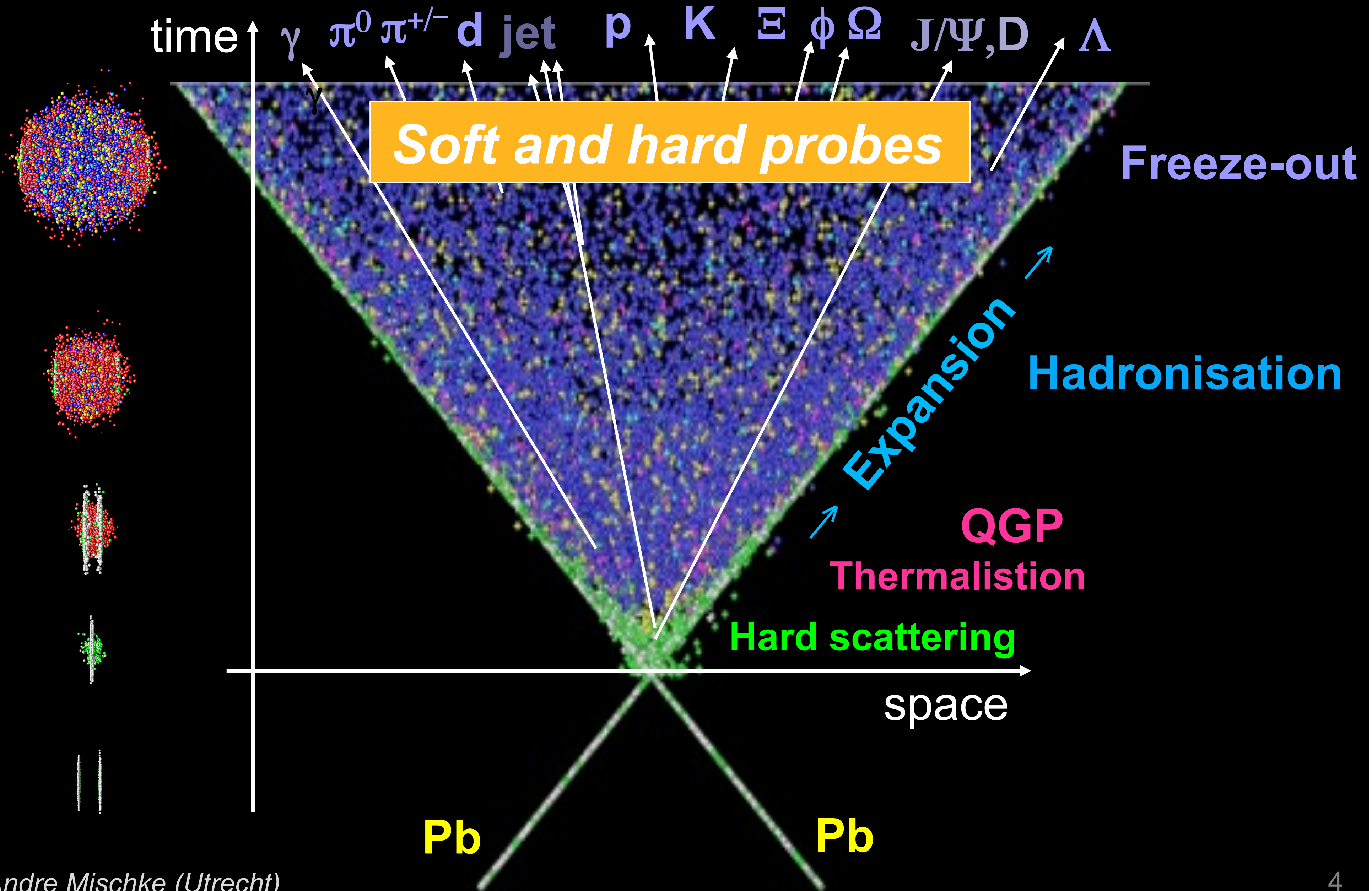


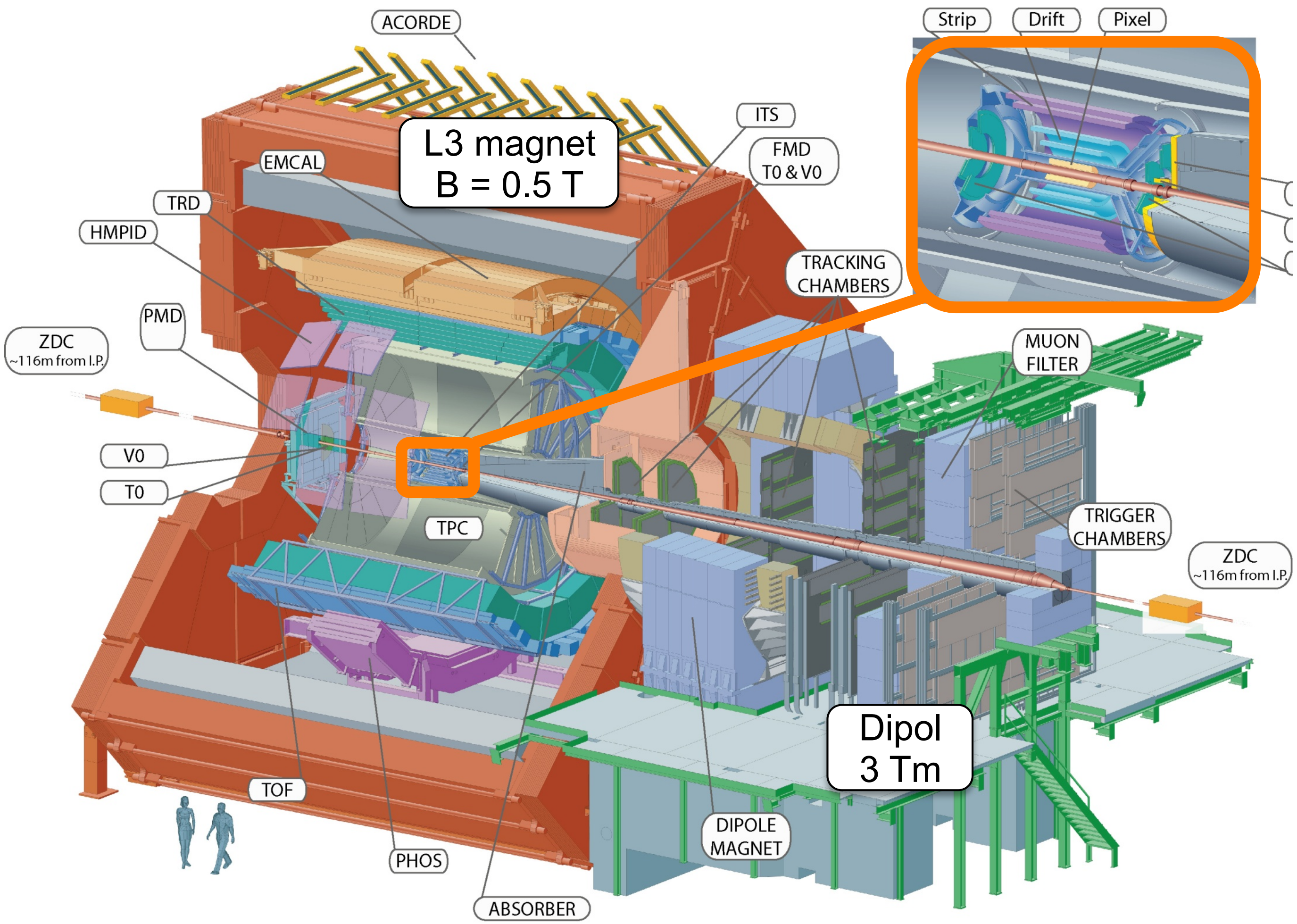

- Study strongly interacting matter under extreme conditions: high temperature and high density
- Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the Quark-Gluon Plasma
- Experimental access via high energy heavy-ion collisions



# Space-time evolution of a heavy-ion collision



# A Large Ion Collider Experiment




Performance, see talk by Massimo Masera

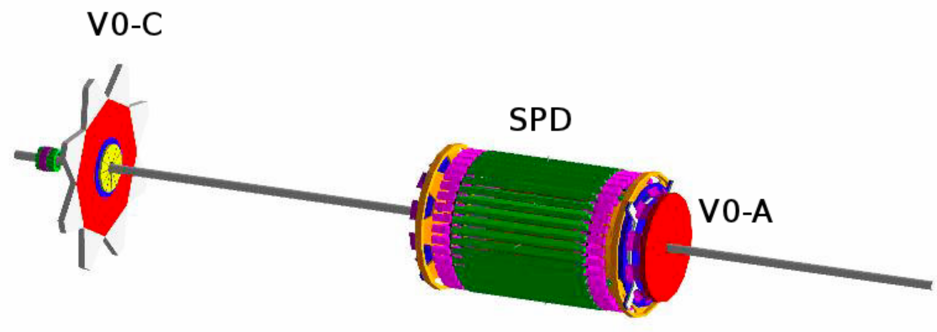
## Sub-detector systems

ITS, TPC, TOF, HMPID, TRD, FMD, PMD, T0, V0, ZDC, EMCAL, DCAL, PHOS, Muon arm, DAQ, HLT (High Level Trigger)

- PID over a very broad momentum range (> ~100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage ($|\eta| < 0.9$) and $-4 < \eta < -2.5$ in forward region

# Trigger and data samples

- Minimum bias, based on interaction trigger:
  - SPD or V0-A side or V0-C side
  - at least one charged particle in 8 $\eta$ units
  - 95% efficient on $\sigma_{inel}$
- Vertex determination: SPD
- Centrality in Pb-Pb: Glauber fit to VZERO signal amplitude
- Single-muon trigger
  - forward muon in coincidence with MB




| System | $\sqrt{s_{NN}}$ (TeV) | Year | Integrated luminosity |
|---|---|---|---|
| Pb-Pb | 2.76 | 2010 | 10 $\mu b^{-1}$ |
| Pb-Pb | 2.76 | 2011 | 0.1 $nb^{-1}$ |
| p-Pb | 5.02 | 2013 | 30 $nb^{-1}$ |

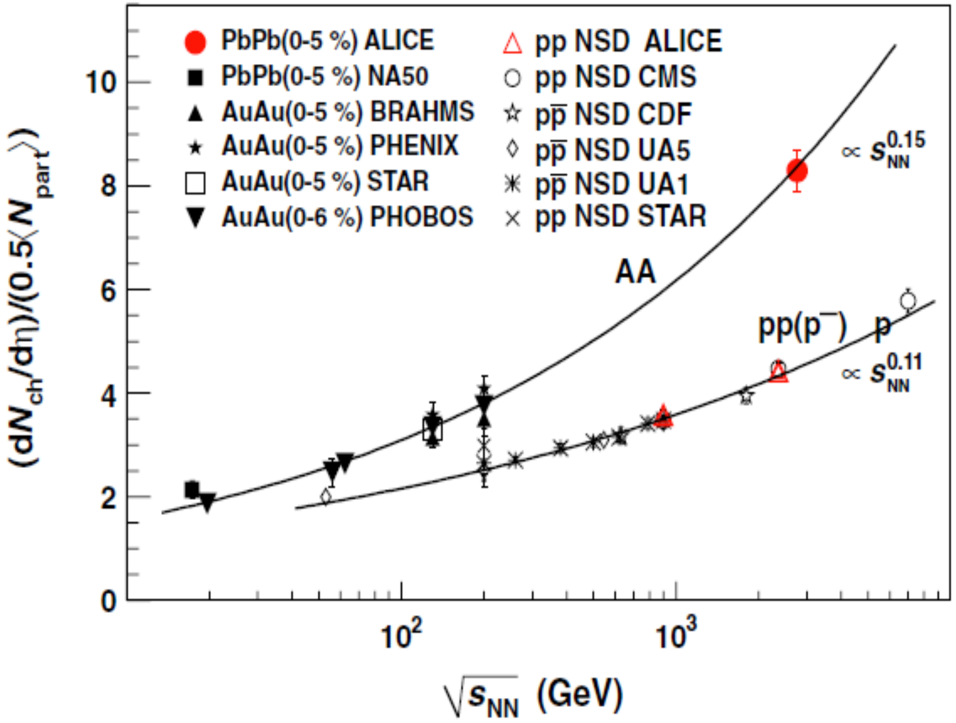
In addition (not covered in this talk),
pp collisions at $\sqrt{s}$ = 0.9, 2.76, 7 and 8 TeV

# Global event observables

# Charged particle multiplicity

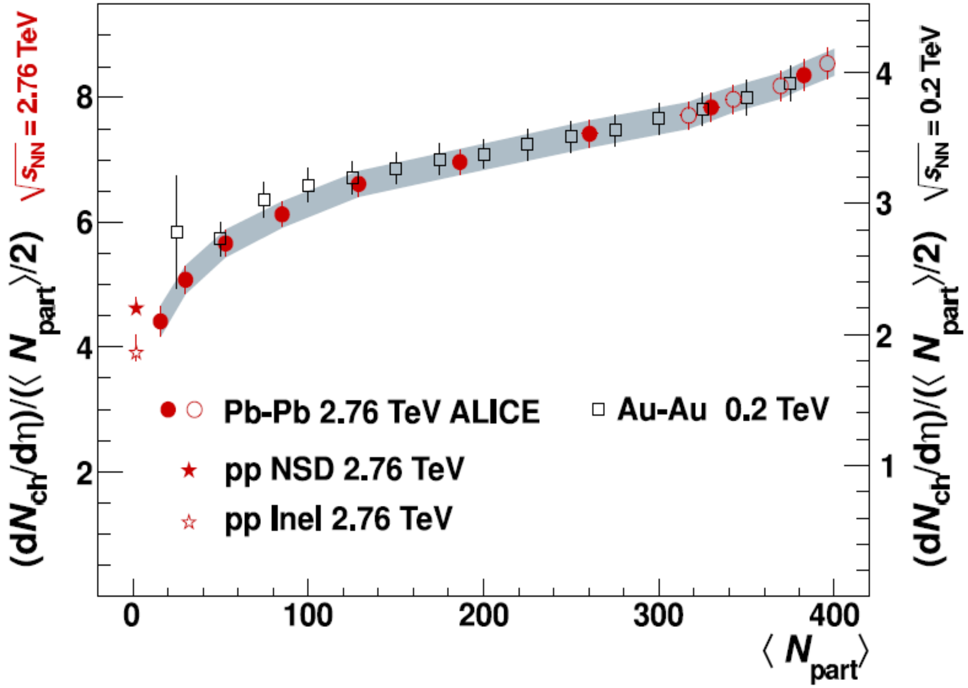
## vs. cms energy

Phys. Rev. Lett. 105, 252301 (2010)




## vs. number of participants

Phys. Rev. Lett. 106, 032301 (2011)




- Power law dependence fits well and faster in Pb-Pb ~$s^{0.15}$ than in pp ~$s^{0.11}$
- Multiplicity ~ 2 x $N_{RHIC}$
- Energy density ~ 3 x $\varepsilon_{RHIC}$

- Very similar centrality dependence at LHC and RHIC

  Once corrected for difference in absolute values

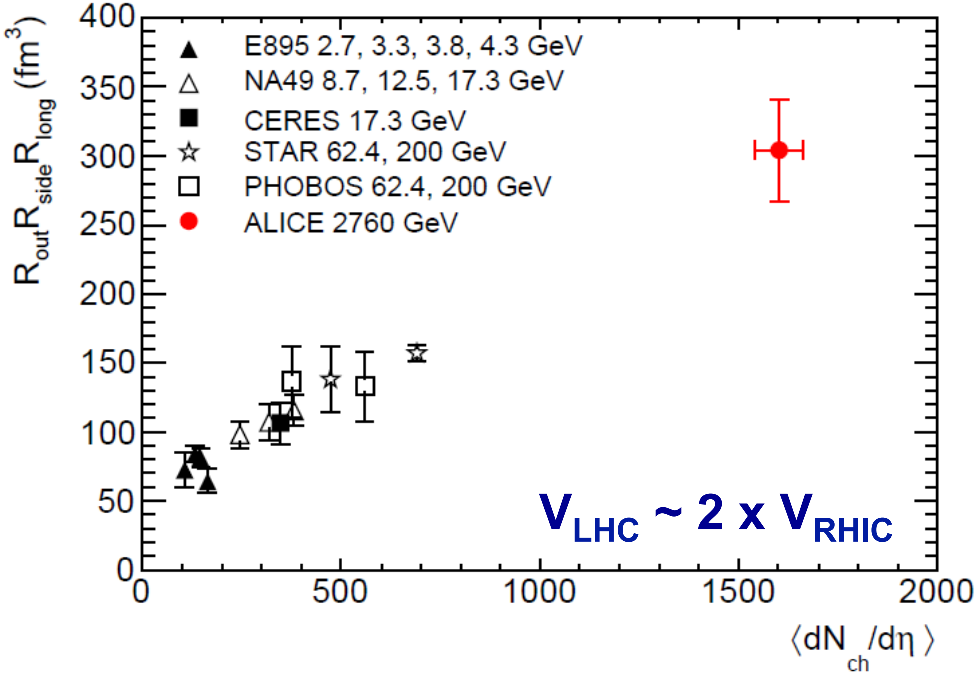
**Denser and hotter system**

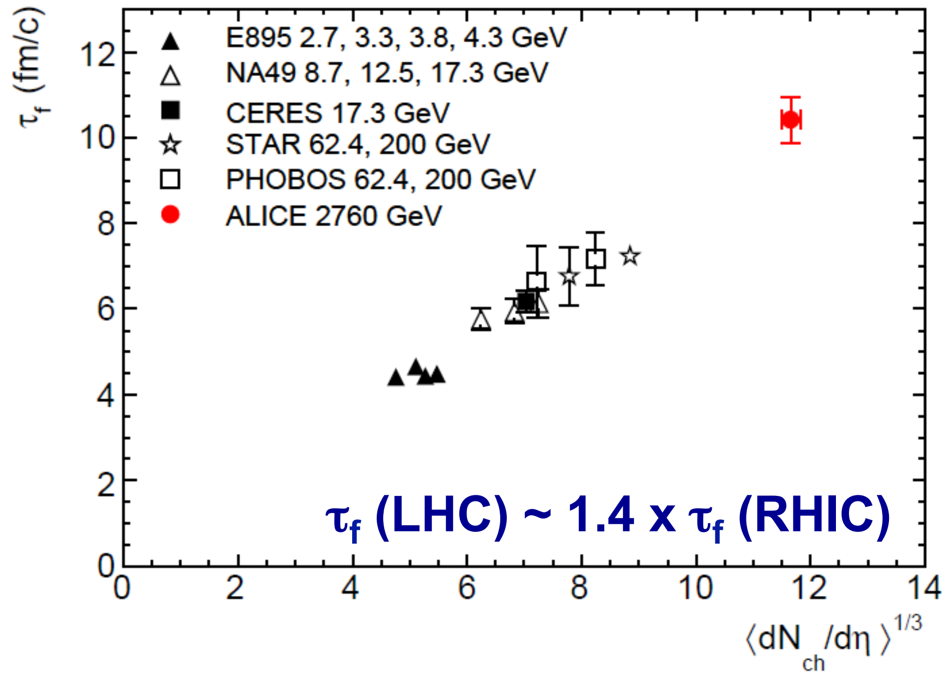
# System size and lifetime

System size

Lifetime

Phys. Lett. B 696, 328 (2011)

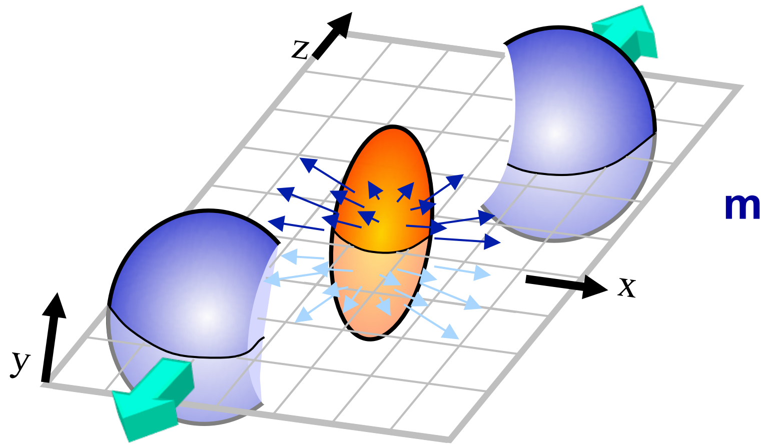


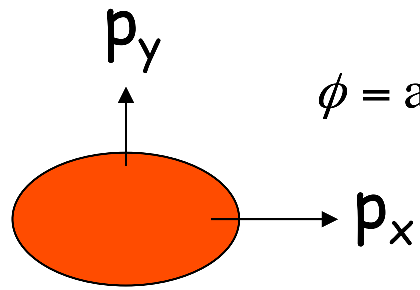

- From Bose-Einstein Correlations analysis (HBT)
- 2 × freeze-out volume and 1.4 × lifetime compared to RHIC

**Fireball has larger volume and longer lifetime**

# Azimuthal anisotropy




**pressure and multiple collisions**




$$\phi = \operatorname{atan}\frac{p_y}{p_x}$$

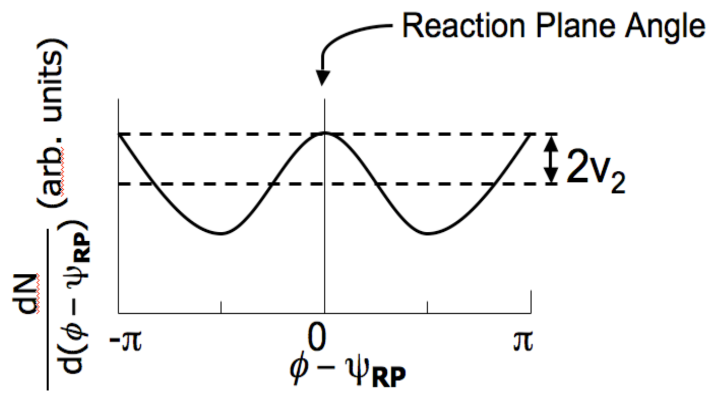
*coordinate space: initial anisotropy*

*momentum space: final anisotropy*

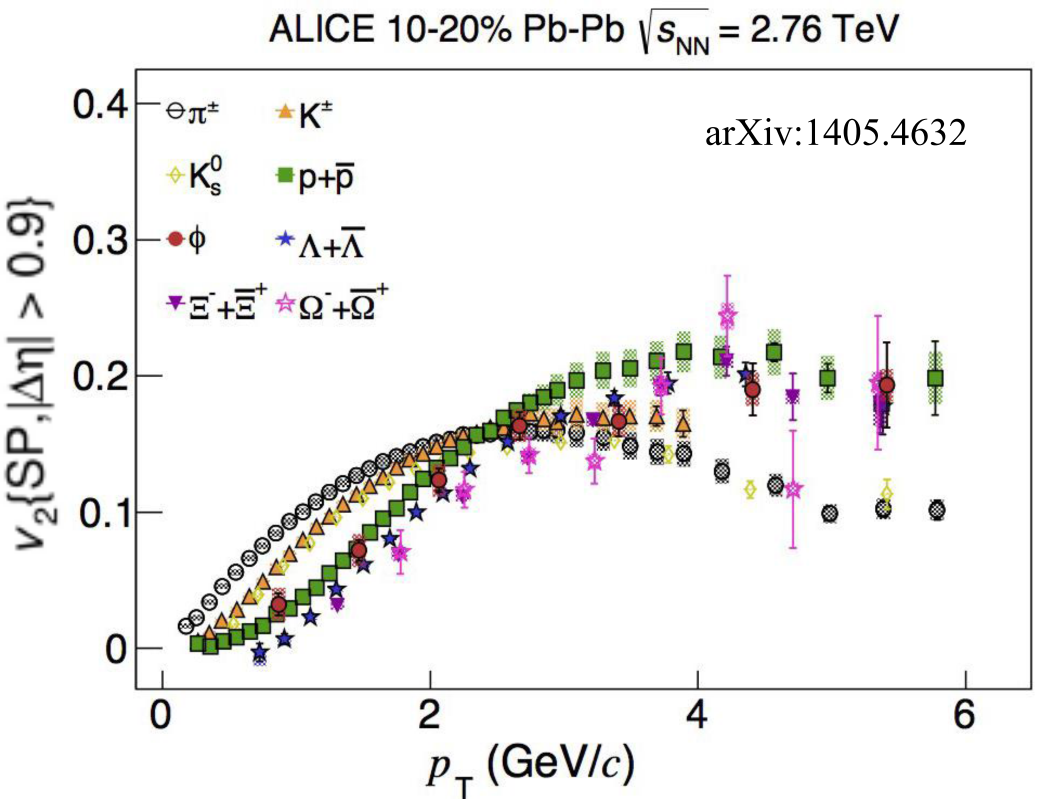
- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective flow → anisotropy in momentum space
- Fourier decomposition:

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

$$v_n = \langle \cos(n[\varphi-\psi_n]) \rangle$$



# $v_2$ of identified particles in Pb-Pb



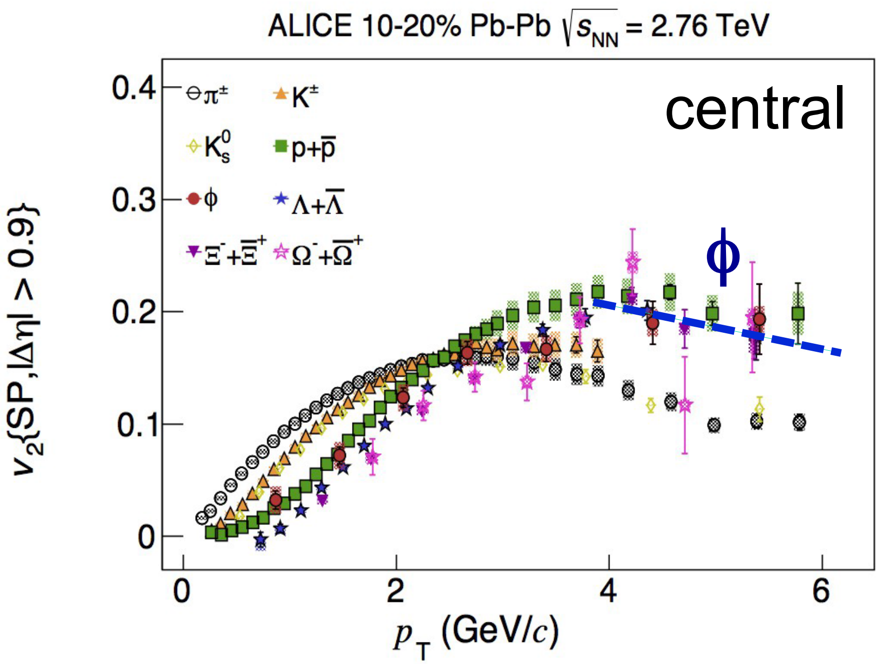

## Why?

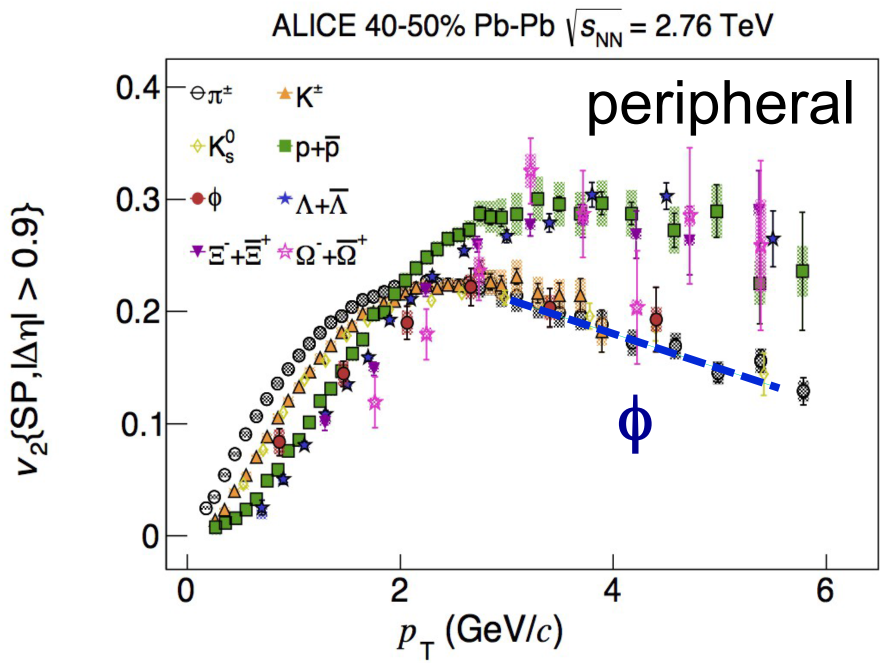
- Constraints on initial conditions, such as particle production mechanisms
- Probes freeze-out conditions of the system
- Checks number of constituents quarks scaling

- Low $p_T$: mass ordering observed → interplay between radial and elliptic flow
- Qualitative description with hydrodynamical calculations and hadronic cascade model → small $\eta/s$ favoured
- High $p_T$: particles tend to group into mesons and baryons

# $v_2$ of identified particles: $\phi$ mesons

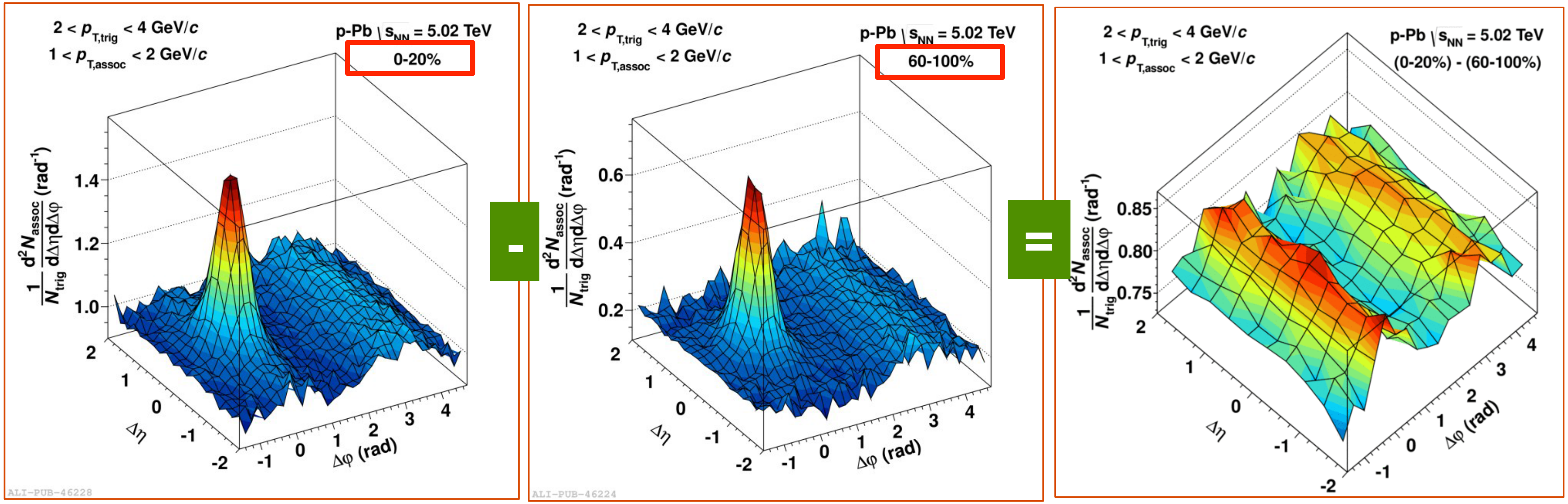
*$\phi$ (heavy meson) is of particular interest as testing ground for mass ordering and baryon-meson grouping*



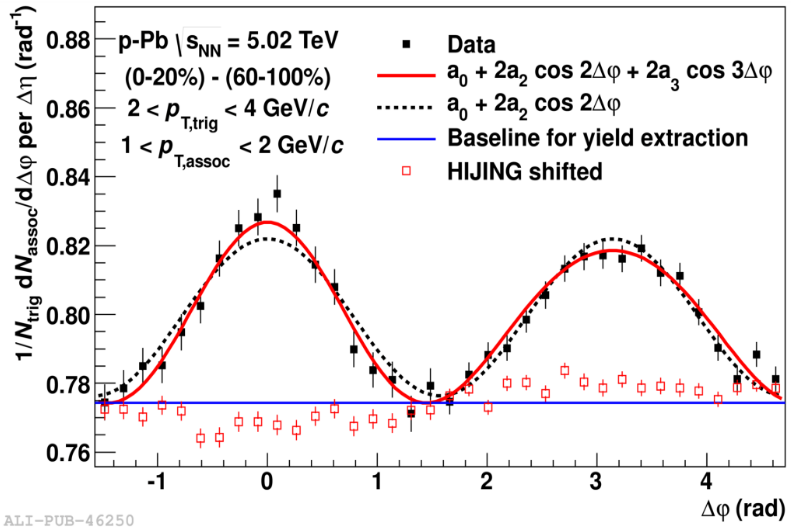




- $v_2$ follows baryons for central collisions and shift progressively to mesons for peripheral collisions
- Mass (and not number of constituent quarks) is main driver for $v_2$ in central Pb-Pb → consistent with hydrodynamic picture
- Scaling with number of quark constituents violated by 20%, in particular in central collisions

# Di-hadron correlations in p-Pb




**Double ridge structure** described by both colour glass condensate (initial state effect) and hydrodynamics (final state effect)
Phys. Lett. B 719, 29 (2013)

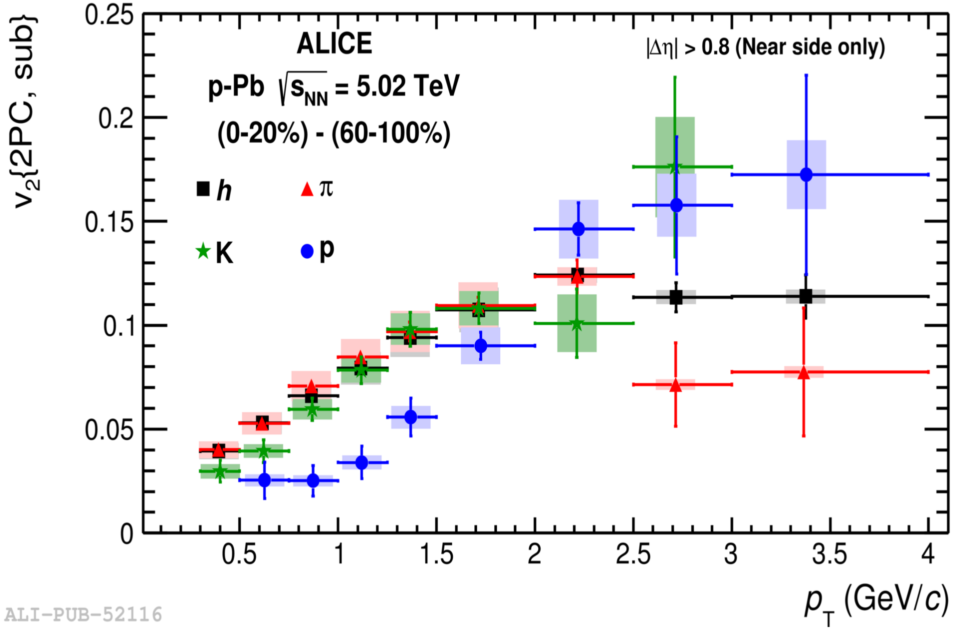



Unexpected underlying azimuthal anisotropy in high-multiplicity events: two long-range structures (double ridge)

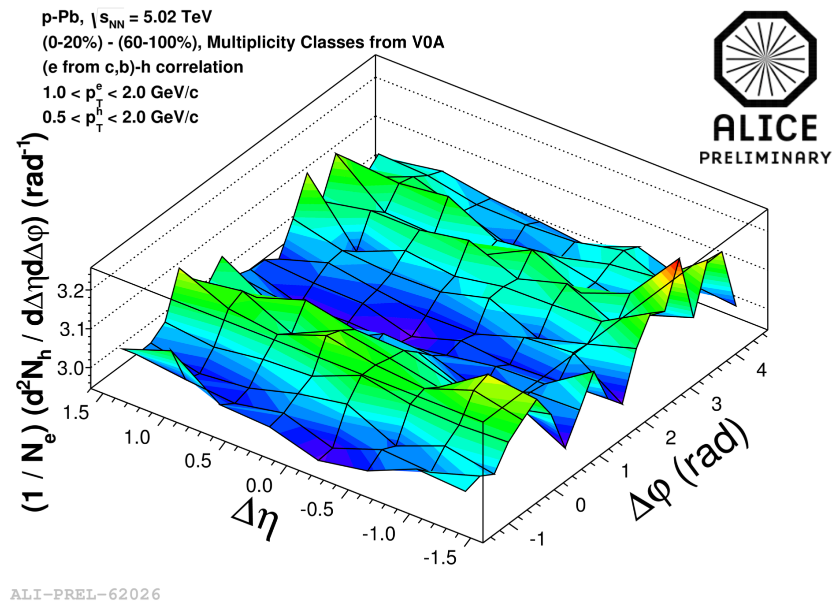
# Di-hadron correlations in p-Pb (cont'd)

## h - π,K,p correlations

Phys. Lett. B 726, 164 (2013)




## Heavy-flavour decay $e^{\pm}$ - h correlations

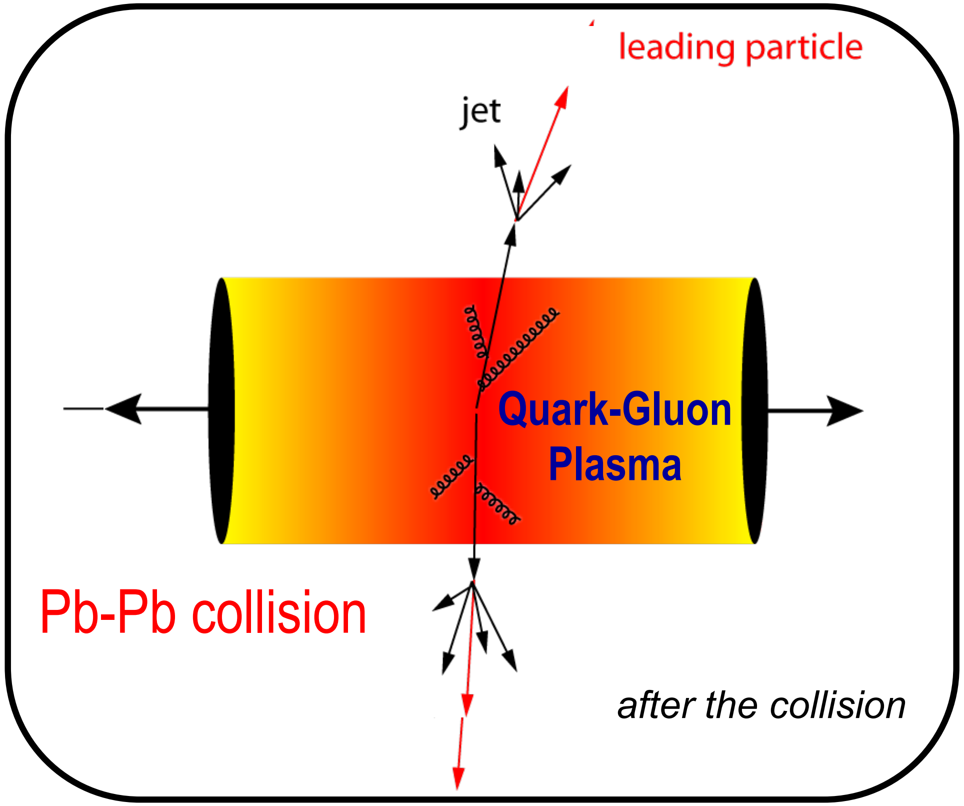



- $v_2$ obtained from two-particles correlations
  - Mass ordering at low $p_T$
  - Crossing at $p_T \sim 2$ GeV/c
- Qualitatively similar to Pb-Pb and consistent with hydro calculations

Double ridge structure also observed in the correlation of heavy-flavour decay electrons and hadrons
→ Suggests that the mechanism generating the double ridge is also at work for heavy flavours

# Jet quenching

# Probing hot QCD matter with hard probes




Quantify medium effects with nuclear modification factor

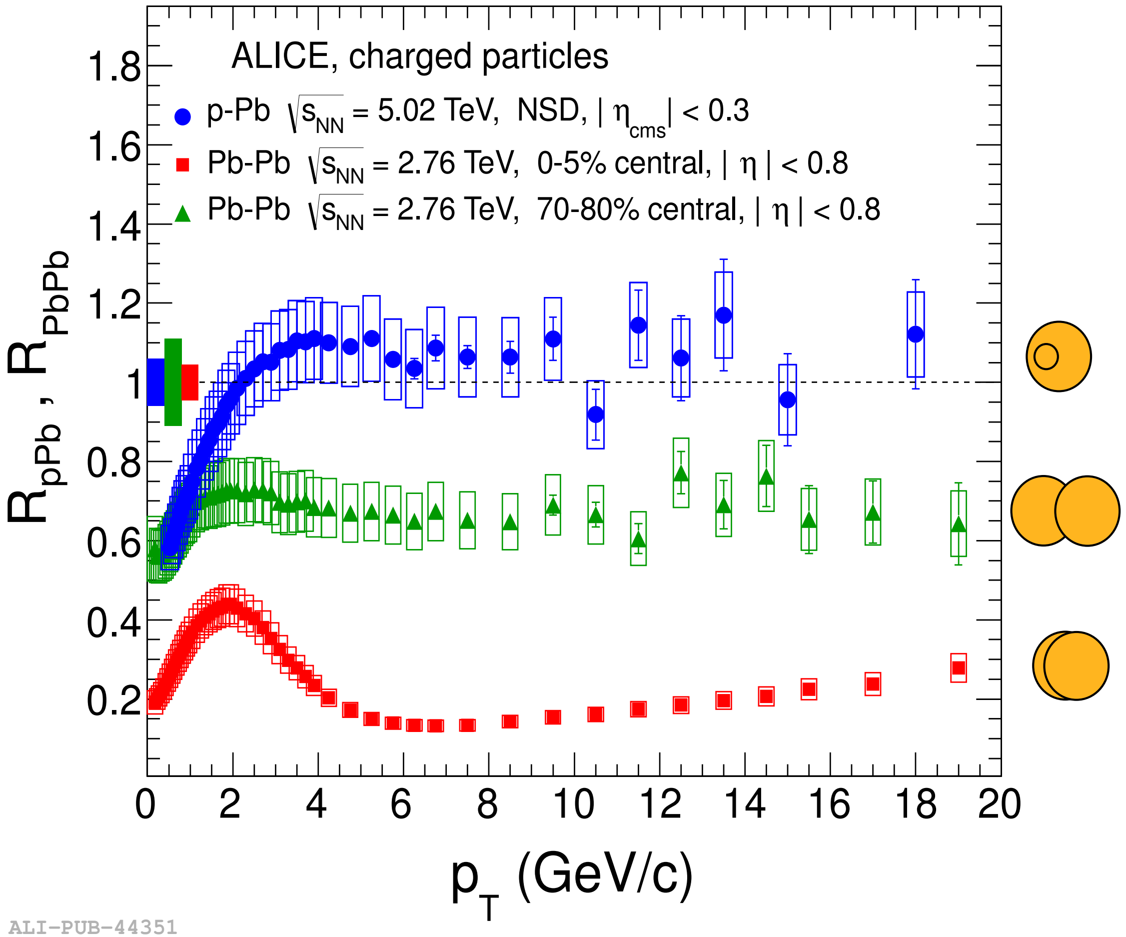
$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{bin} \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

if $R_{AA} = 1 \rightarrow$ no nuclear effects
if $R_{AA} \neq 1 \rightarrow$ (hot or cold) medium effects

- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile
- Heavy-ion collision
  - hard processes serve as calibrated probe (pQCD)
  - traverse through the medium and interact strongly
  - suppression pattern provides density measurement
  - General picture: parton energy loss through medium-induced gluon radiation and collisions with medium constituents

# High-$p_T$ particle production

Phys. Rev. Lett. 110, 082302 (2013)

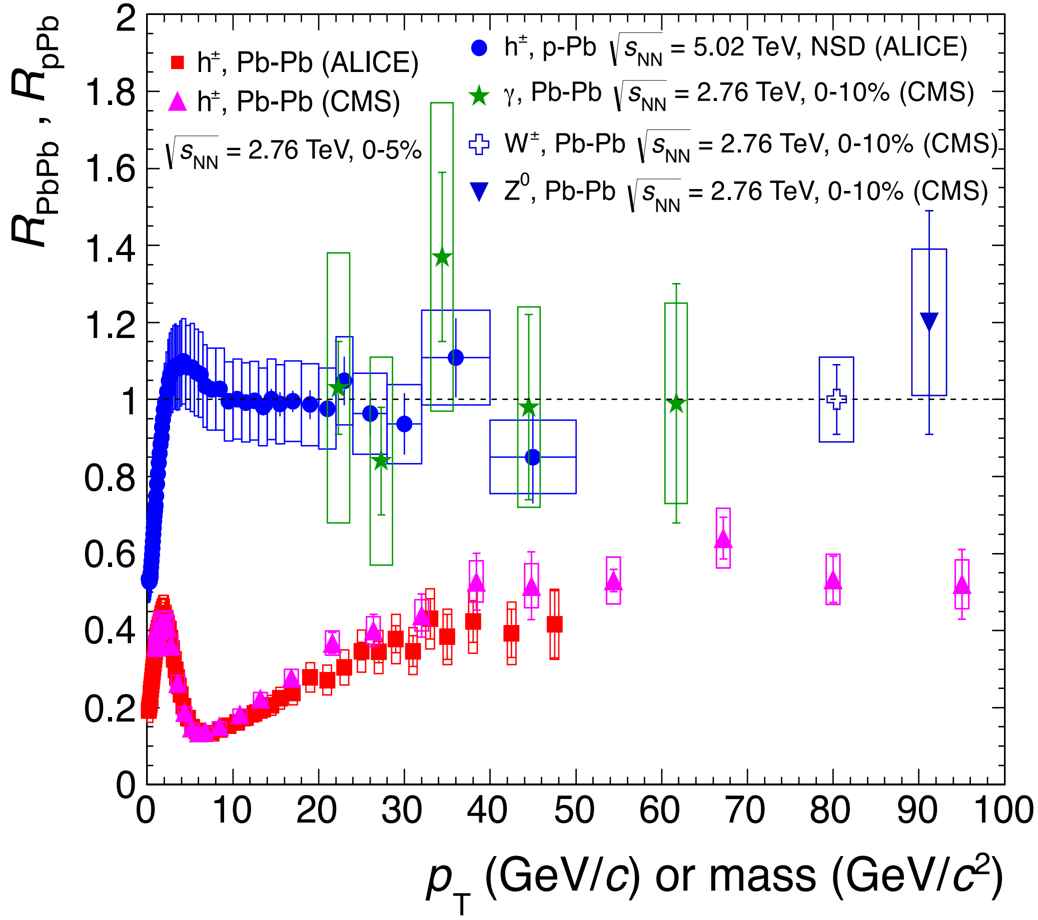



**p-Pb ($p_T$ > 2 GeV/c)**
- Binary scaling ($R_{pPb}$ ~ 1)
- Absence of nuclear modification
- Initial state effects small

**Pb-Pb – suppression**
- Increases with centrality
- Not initial state
- Final state effect; due to hot and dense QCD matter

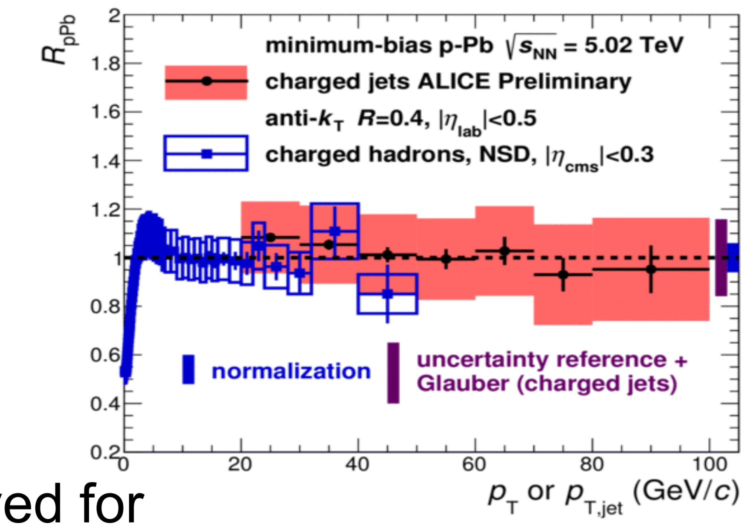
# High-$p_T$ particle production (cont'd)

Eur. Phys. J. C 74, 3054 (2014)



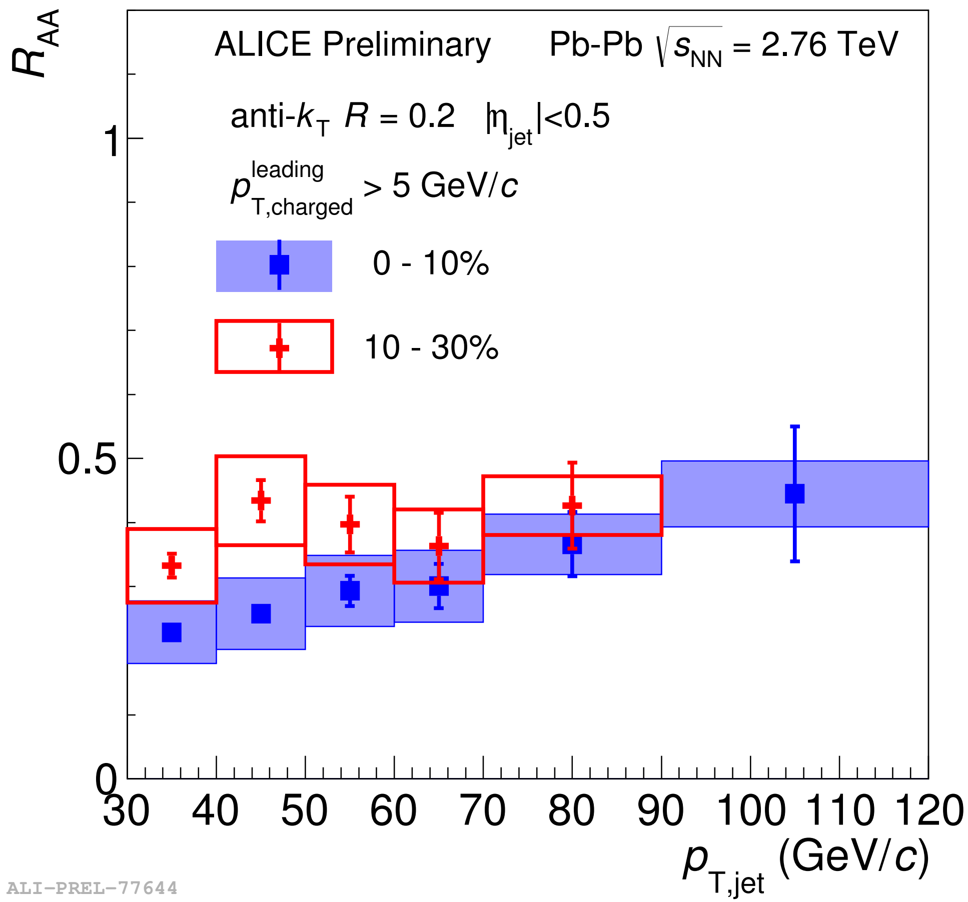

$Z^0 \rightarrow \mu^+\mu^-$
$W \rightarrow \mu\nu$ using single muon recoil against missing $p_T$

Z, W and γ production in Pb-Pb consistent with $N_{coll}$ scaling ($R_{AA} \approx 1$)
→ not sensitive to the medium




No modifications observed for charged jets up to 100 GeV/c

# Jets in Pb-Pb




See talk by
Leticia Cunqueiro Mendez

**Expectation:**

Jet fragmentation is modified by the medium

- suppression of jet yield
- broadening of jet shape
- di-jet imbalance

**Findings:**

- Strong suppression of jet yields in most central Pb-Pb collisions
→ Moderate increase of $R_{AA}$ with increasing $p_T$

- Dependence on centrality class
→ Jet energy is moved from high to low $p_T$ and from small to large angles (with respect to the jet axis)

# Heavy flavour

# Hierarchy of parton energy loss

(1) Radiative parton energy loss is colour charge dependent (Casimir coupling factor $C_R$)

*R. Baier et al., Nucl. Phys. B483, 291 (1997) ("BDMPS")*

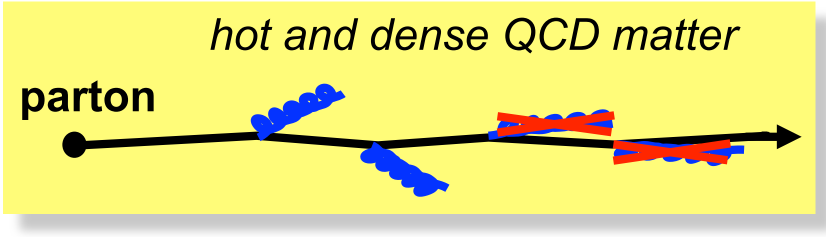
$$\langle \Delta E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

(2) Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

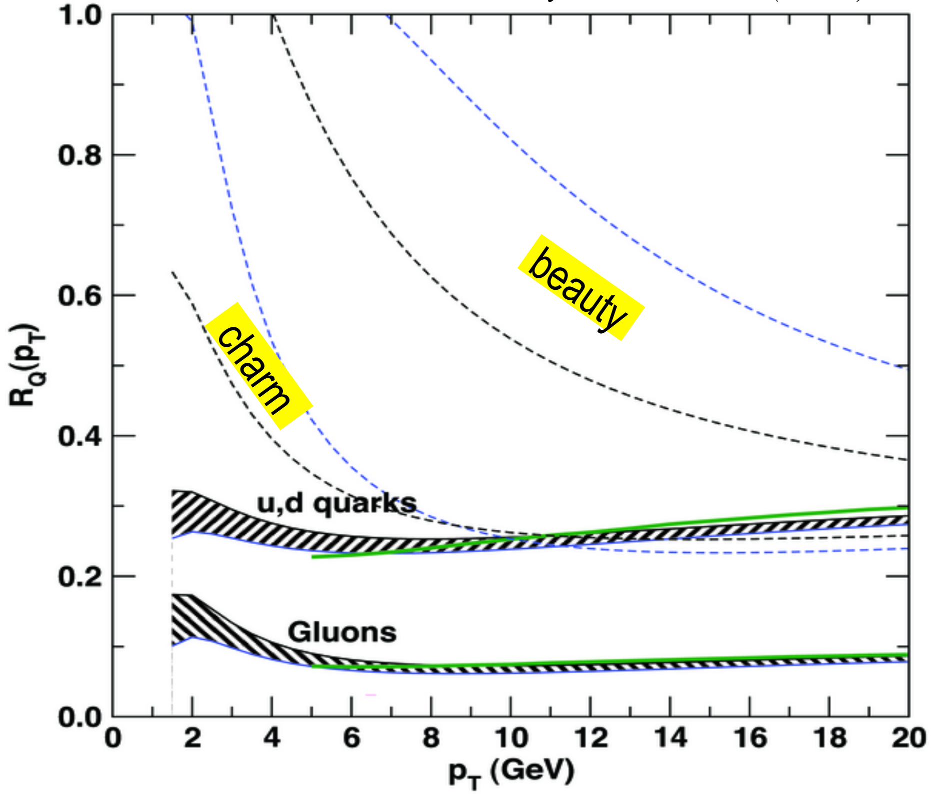
*Y. Dokshitzer, D. Kharzeev, PLB 519, 199 (2001), hep-ph/0106202*

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

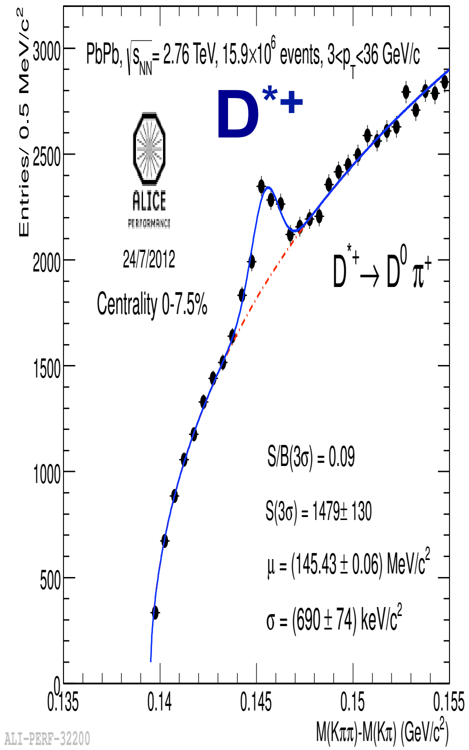
$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

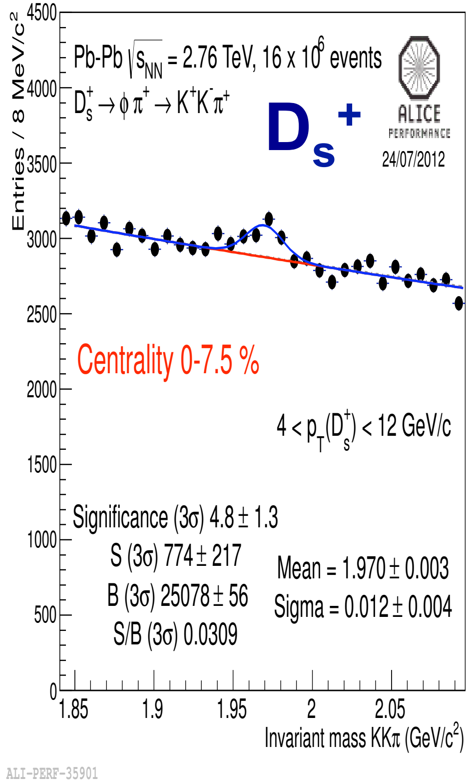


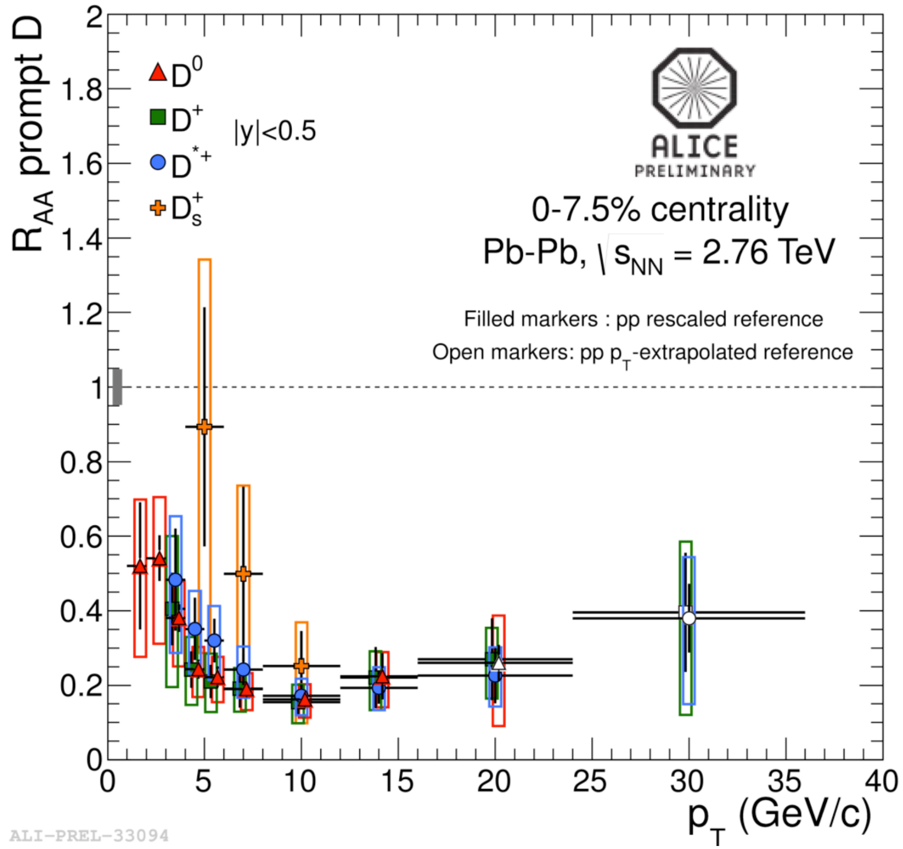

*S. Wicks et al., Nucl. Phys. A784, 426 (2007)*



# Prompt D meson $R_{AA}$ in Pb-Pb



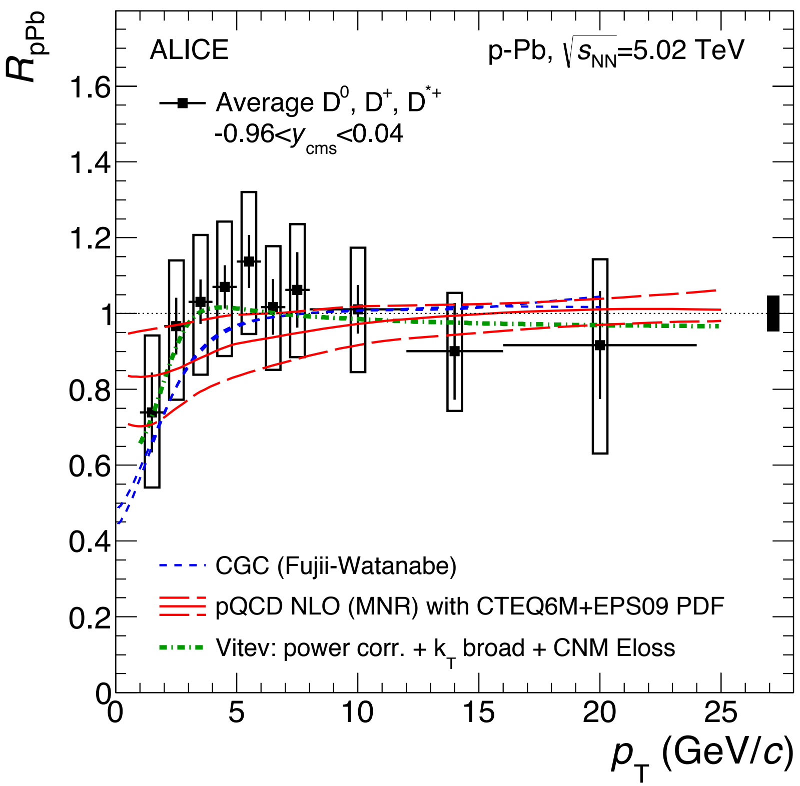



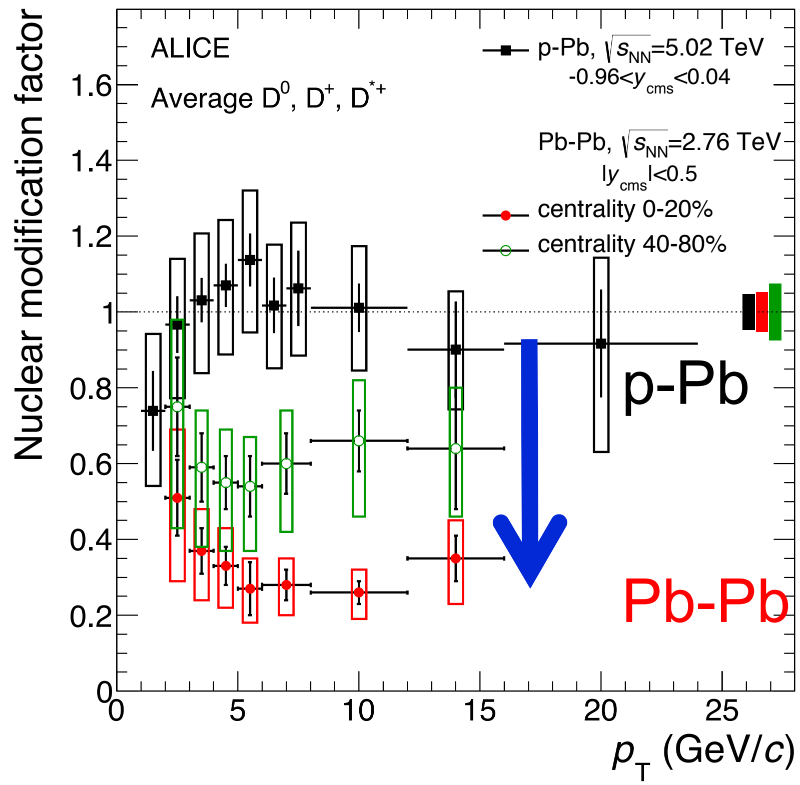

- First $D_s^+(c\bar{s})$ measurement in heavy ion collisions
- Expectation: enhancement of strange D meson yield at intermediate $p_T$, if charm hadronizes via recombination in the medium
- Strong suppression (factor 4-5) above 5 GeV/c in most central Pb-Pb, compared to binary scaling from pp

See talk by Cristina Terrevoli

# D mesons: initial state effects

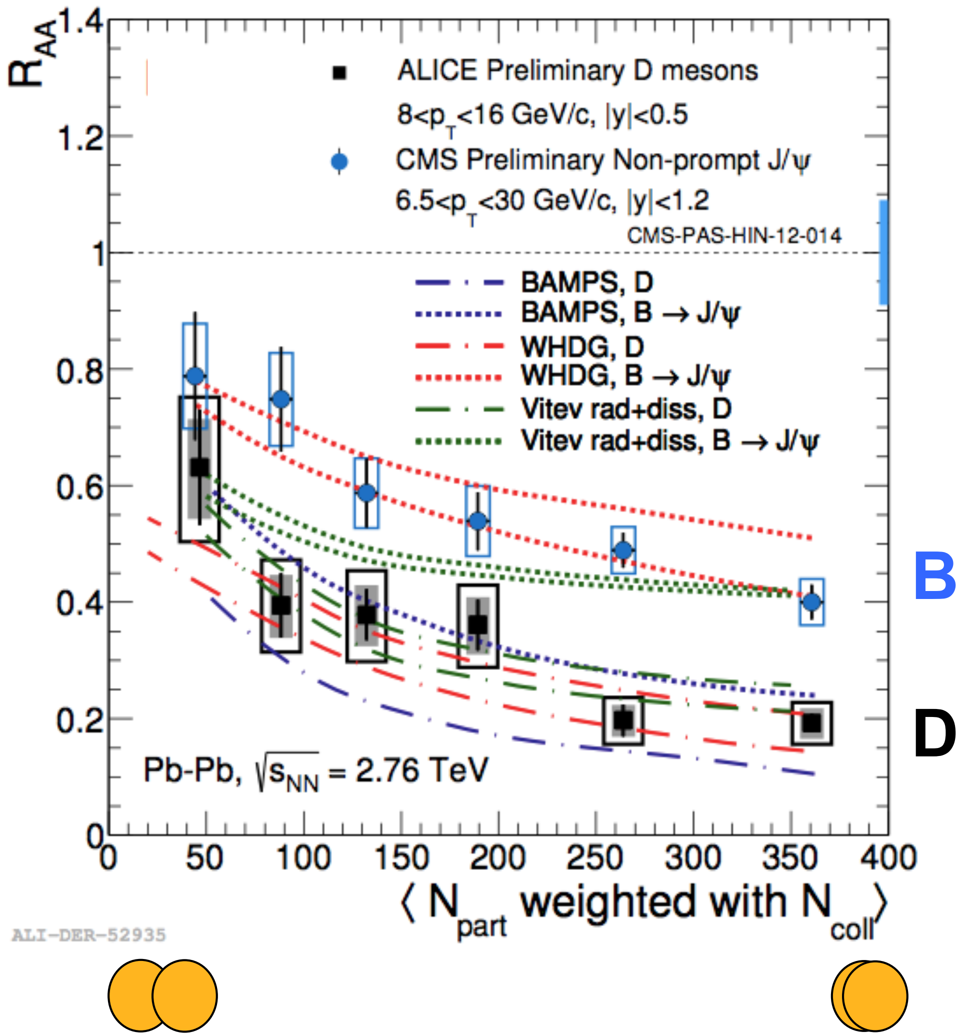
arXiv:1405.3452



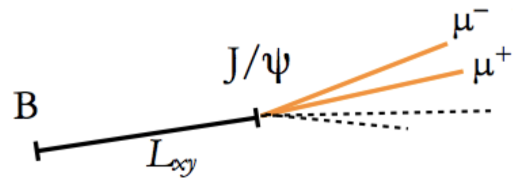




- Important baseline measurement of **cold nuclear matter effects** (e.g., Cronin effect, nuclear shadowing, gluon saturation)
- D meson $R_{pA}$ shows consistency with unity and predictions from shadowing and CGC model predictions
- **High-$p_T$ suppression of particle yield in Pb-Pb is a final state effect**

# $R_{AA}$ of D and B mesons

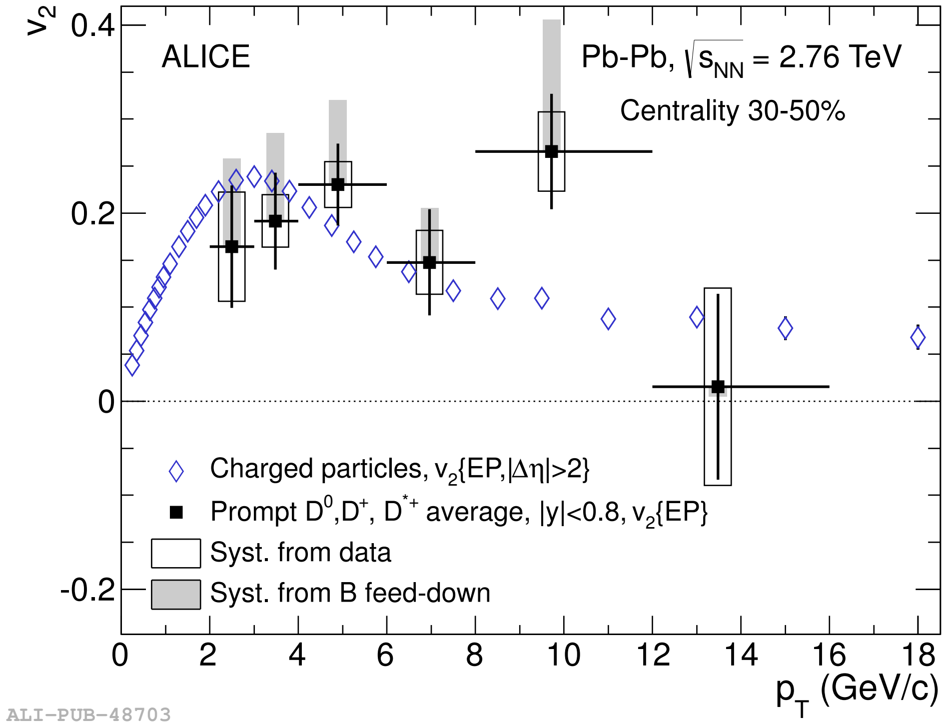


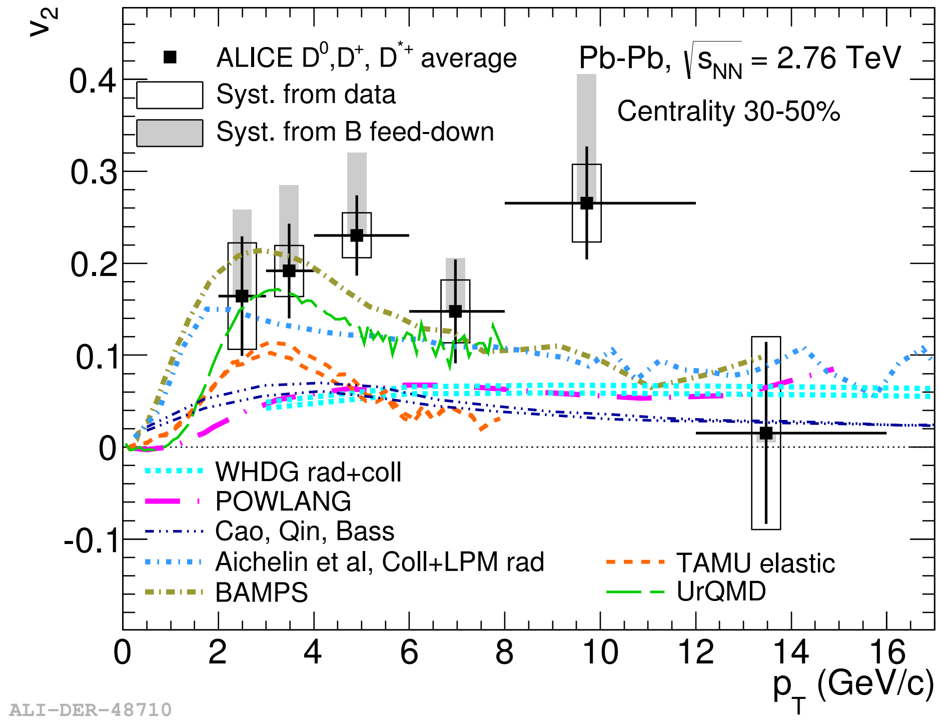

- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson $\langle p_T \rangle$ ~10 GeV/c
- First indication for the mass dependence of the parton energy loss: $R_{AA}^D < R_{AA}^B$
- Consistent with the expectation $\Delta E_c > \Delta E_b$



# Azimuthal anisotropy of D mesons

Phys. Rev. Lett. 111, 102301 (2013)

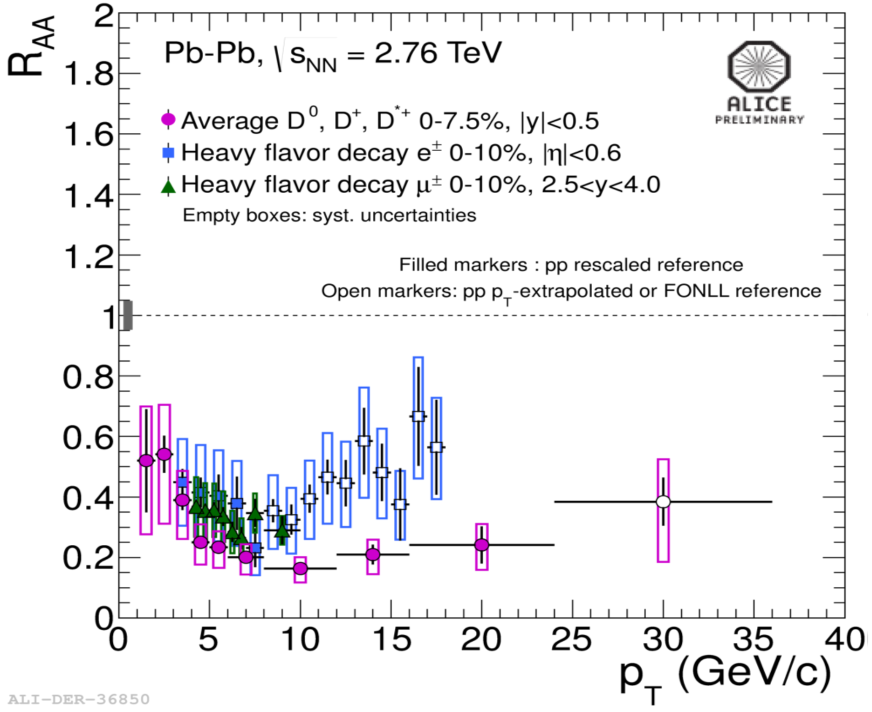


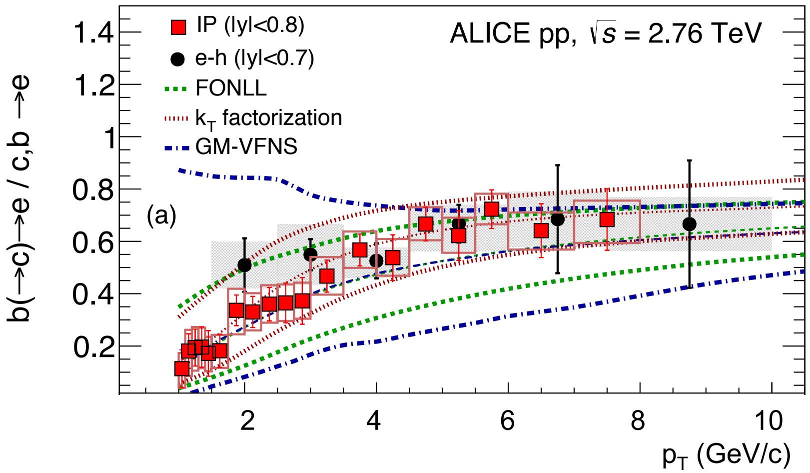




- Due to the large mass, long thermalisation process is expected for heavy quarks → less influenced by collective expansion
- Indication (3-5σ confidence level) for non-zero charm elliptic flow in the $p_T$ range 2-6 GeV/c

→ Significant interaction of charm quarks with the medium

# Heavy flavour decay muons and electrons



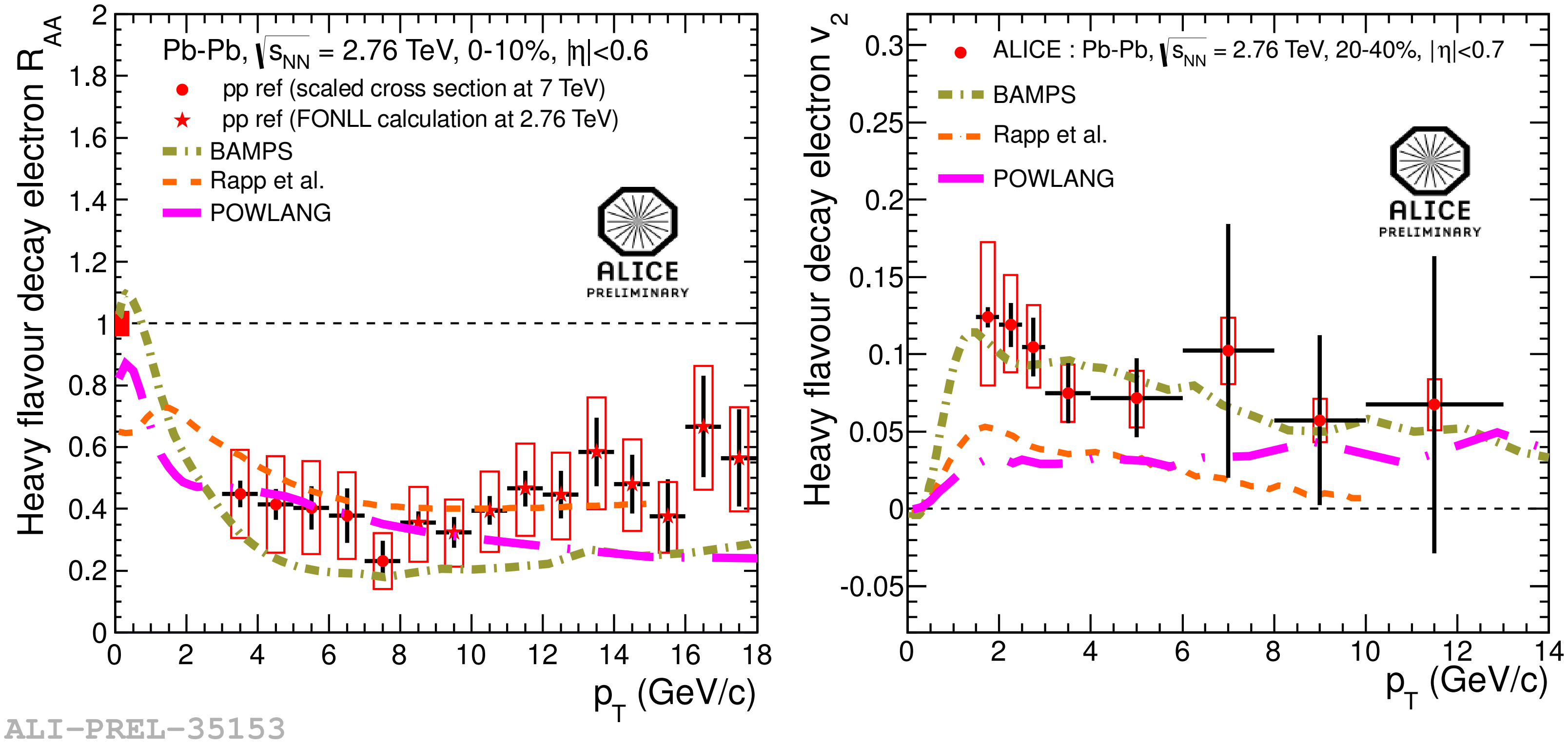




- Strong suppression of high-$p_T$ muon yield from heavy flavour decays
- No significant dependence on $p_T$ in $4 < p_T < 10$ GeV/c
- Similar to single electron and D meson $R_{AA}$ at central rapidity
- $R_{AA}^{single\ e} > R_{AA}^{D}$ at $p_T > 8$ GeV/c due to beauty contribution

Relative beauty contribution to single electron yield from electron-hadron azimuthal correlations

1405.4144, PLB in press

# Single electron $R_{AA}$ and $v_2$ at mid-rapidity



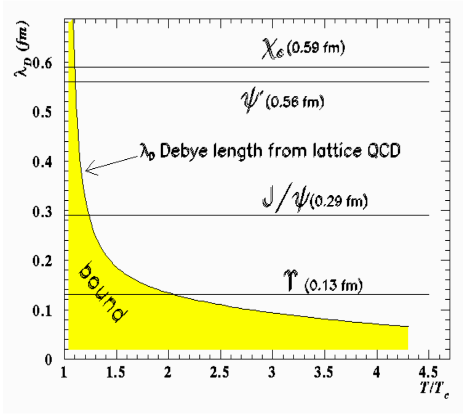

- Strong suppression of single electron yield up to 18 GeV/*c*

**Energy loss models need to simultaneously describe $v_2$ and $R_{AA}$**; → more difficult with more precision and more observables, such as azimuthal angular correlations

→ suggests strong re-interactions within the medium

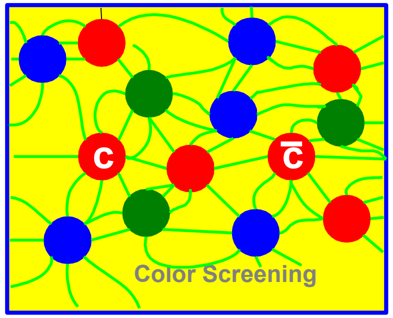
# Quarkonia production in hot QCD matter

- Colour screening length $\lambda_D$ in the deconfined medium decreases with temperature



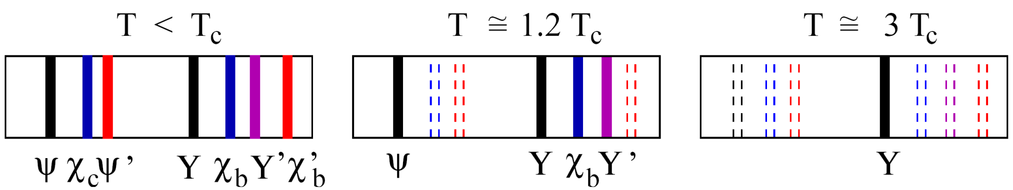

- Quarkonia "melt" when their binding distance becomes bigger than screening length → yields suppressed (one of the first QGP signatures)

*T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416*



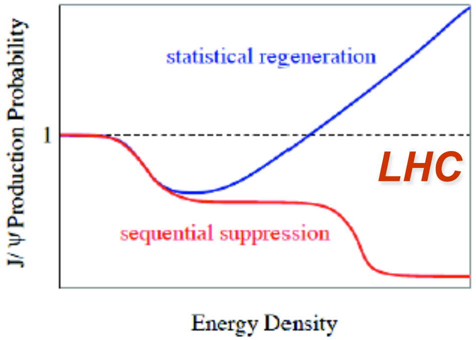

- Screening at different temperature for different states (binding energy) → sequential suppression of the quarkonium states → QCD thermometer

*S. Digal, P. Petreczky and H. Satz, Phys. Rev. D 64 (2001) 0940150*



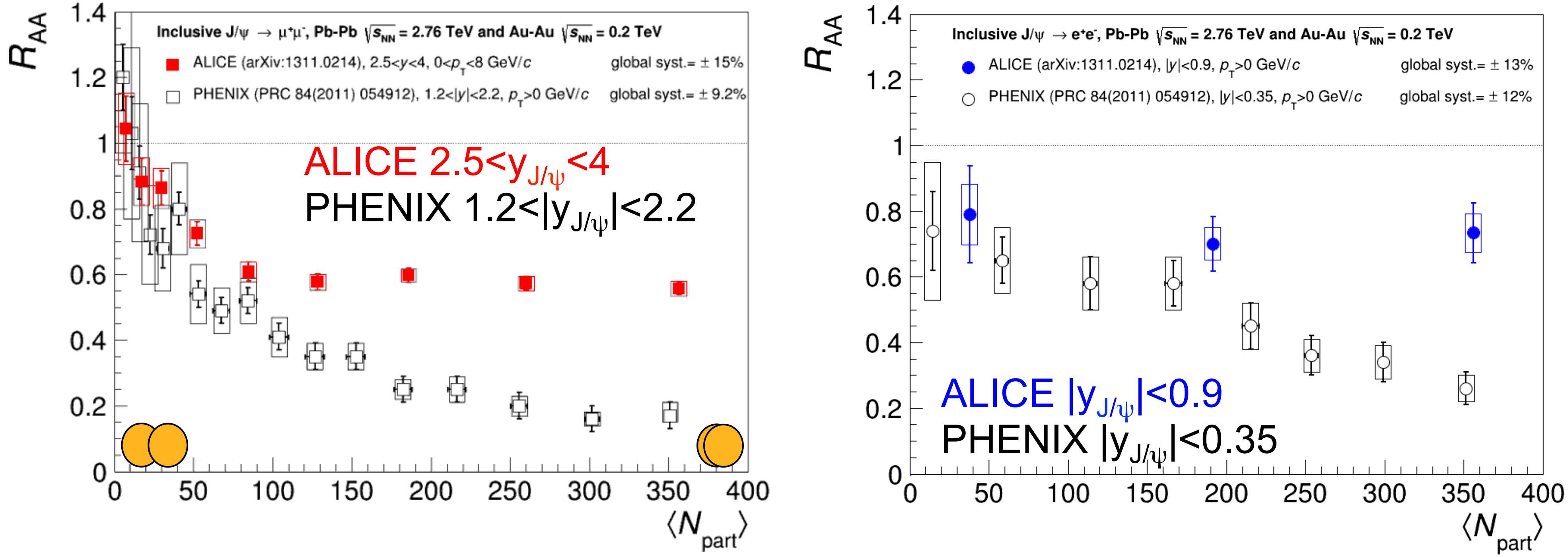

- Enhancement via (re-)generation of quarkonium states due to large heavy quark multiplicity

*A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Phys. Lett. B 571(2003) 36*



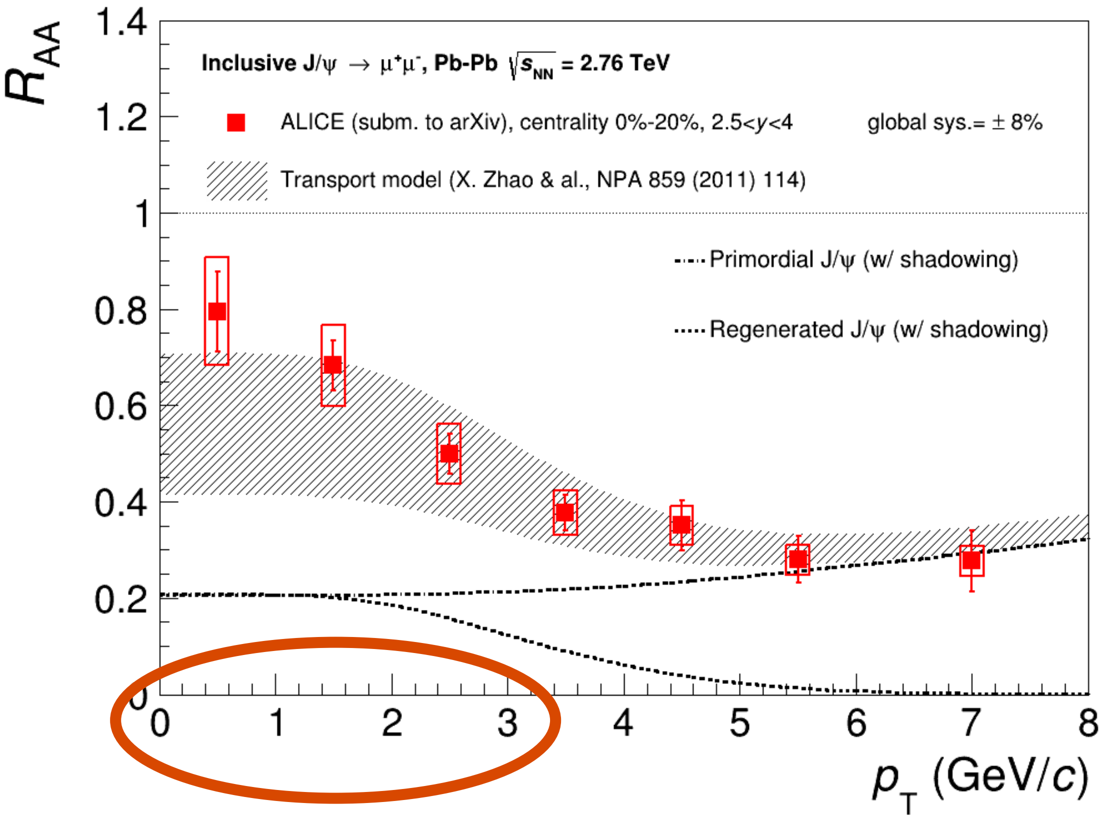
# J/ψ production in Pb-Pb

Phys. Lett. B 734, 314 (2014)




- Clear J/ψ suppression with almost no centrality dependence above $N_{part}$~100.
- Less suppression at mid-rapidity wrt. forward rapidity for central events
- Data show weaker centrality dependence and smaller suppression for central events compared to RHIC results

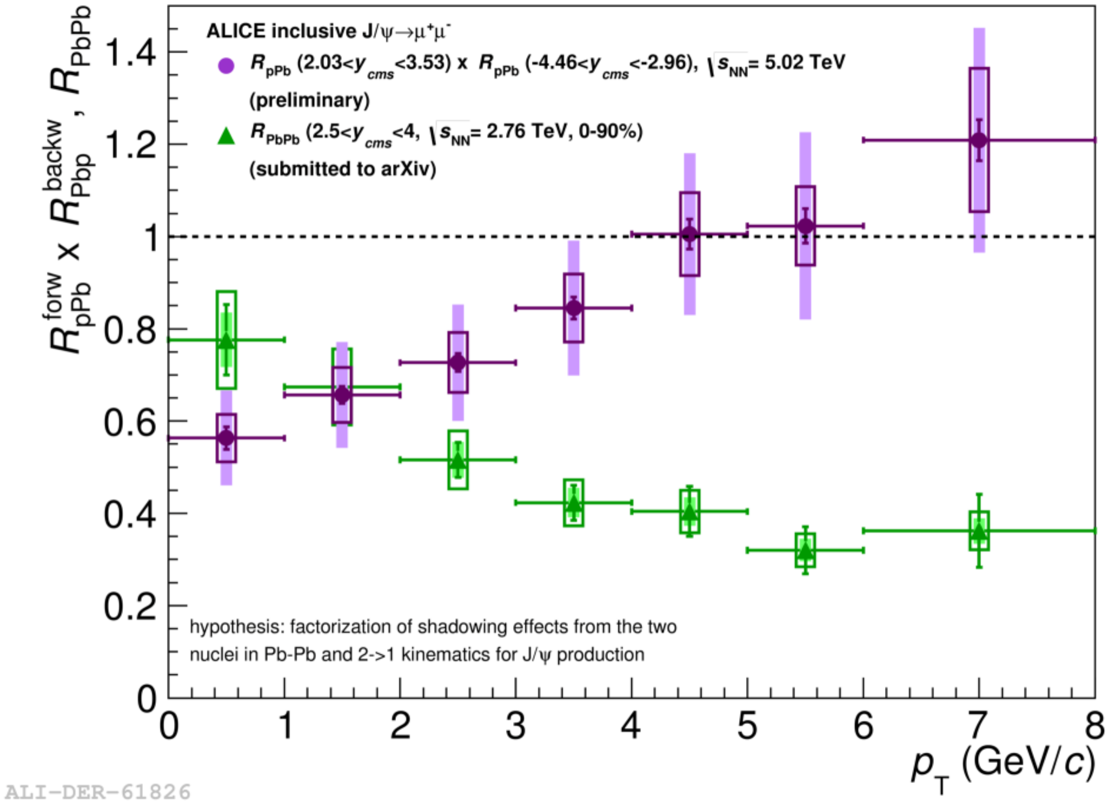
# J/ψ melting vs. regeneration




- Enhanced production at low $p_T$
- Comparison with transport model calculations: sizeable QGP regeneration component needed

Liu, Qiu, Xu and Zhuang, PLB 678 (2009) 72
Zhao and Rapp, NPA 859 (2011) 114
Andronic et al., arXiv:1210.7724

# J/ψ forward vs. backward rapidity




- Small CNM effects at high $p_T$ (> 4-6 GeV/c) → evidence of hot matter effects in Pb-Pb
- At low $p_T$: similar (or lower) suppression in Pb-Pb relative to shadowing expectation

Not shown: Stronger suppression of ψ(2S) in p-Pb relative to J/ψ
→ Not described by initial state CNM effect and coherent energy loss
→ Final state effects?

See talk by
Lizardo Valencia Palomo

# Conclusions

- LHC ideal for studying the properties of hot dense QCD matter
  - $\varepsilon_{initial} \gg \varepsilon_{critical}$, large volume, long lifetime, high production rates for rare probes
- Many results from Pb-Pb data from Run-1
  - High degree of collectivity → perfect liquid
  - Parton-medium interaction → parton energy loss mechanisms
- p-Pb collisions
  - More than control measurements; mechanisms at work not fully understood
- Precision measurements needed to gain more insights into energy loss mechanisms and further constraint model calculations
- Many more exciting results ahead of us
  - LHC Run-2 (5.1 TeV, 2015-2017)
  - After detector upgrades (2018/19)