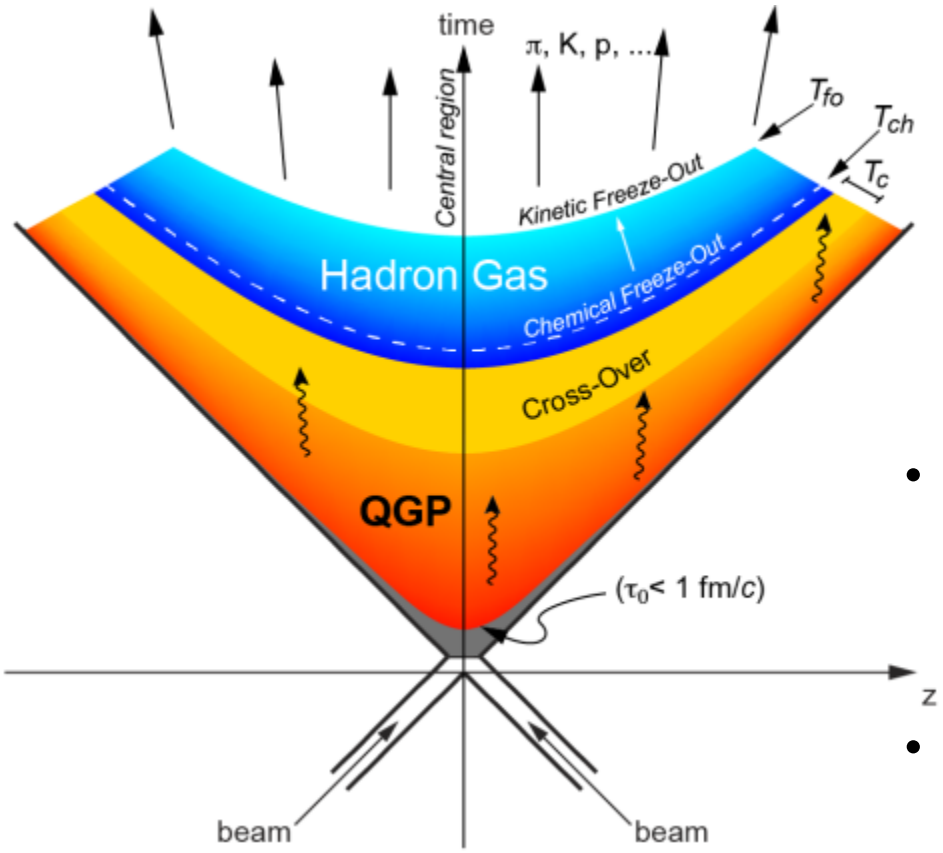
Heavy flavour production in Pb-Pb collisions at the LHC measured by ALICE

Dieter Roehrich
University of Bergen, Norway
for
the ALICE collaboration

- Heavy quarks
  - Probe of deconfinement
    - Quarkonia - temperature measurements and phase boundary
    - Energy loss of heavy quarks in the QGP
- Measurement of open heavy flavours and quarkonia in ALICE
- Results
  - Nuclear modification factor
  - Elliptic flow
- Conclusions & outlook

Heavy quarks and heavy-ion collisions



- **Early production in high-Q^2 processes**
  - **pQCD applicable for cross-sections**
  - **negligible thermal production ($m_{c,b}$>>T)**
    → number of c,b quarks is conserved

  → well calibrated probe

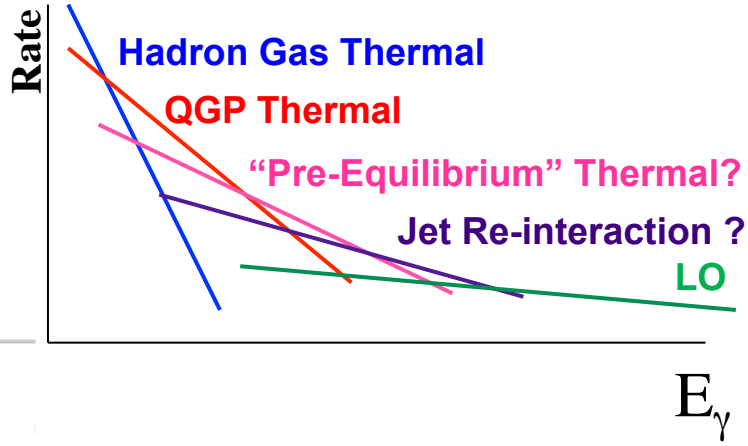
- **Heavy quark modification of the kinematics and hadronization**

  → information on the QGP properties

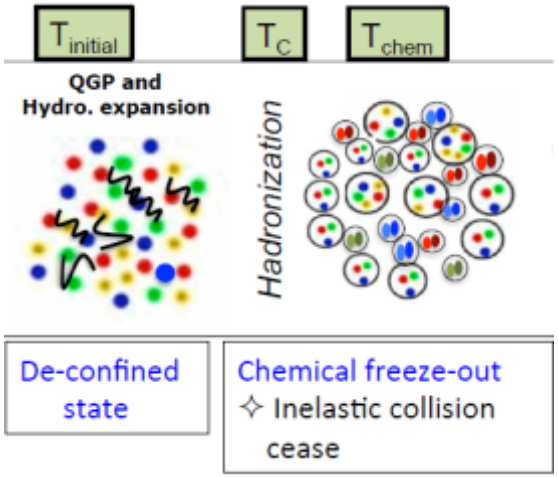
- **Copious heavy quark production at LHC**
  - **in central Pb-Pb collisions at 5.5 TeV: ~100 $c\bar{c}$ and 5-6 $b\bar{b}$**

Temperature measurements and phase boundary

- **Thermal photon production**
  - **Direct photon p_T spectrum - a "thermometer" for QGP**

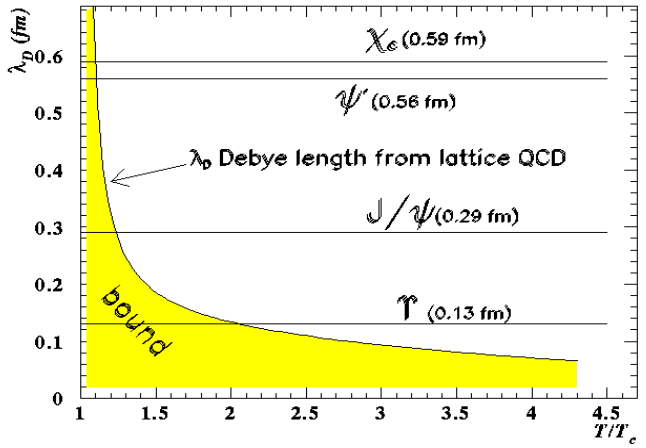


- **Chemical freeze-out temperature**

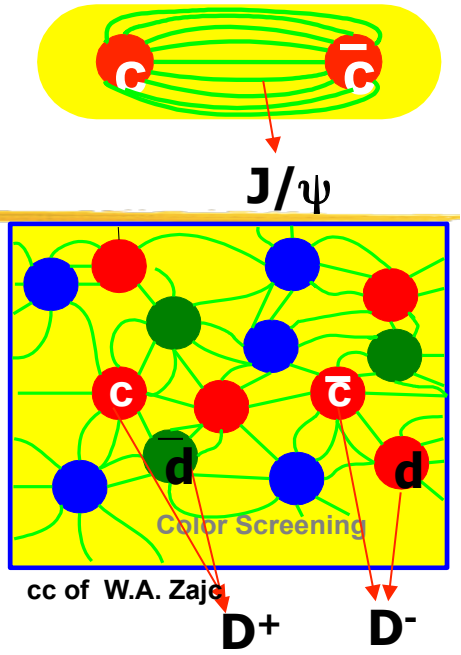


- **Quarkonium**
  - **Sequential melting - a QGP "thermometer"**

Matsui, Satz PLB178 (1986)



Quarkonia

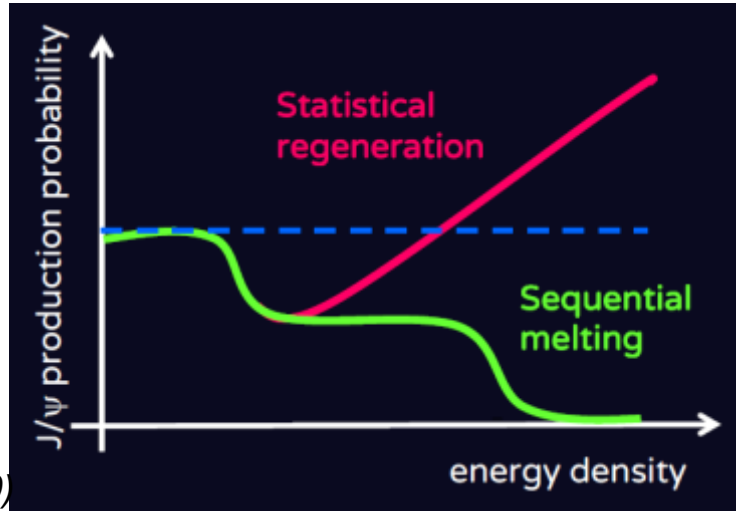


- **Quarkonium suppression: quarkonium production is suppressed via color screening in the QGP***

- **Sequential melting: differences in the quarkonium binding energies lead to a sequential melting with increasing temperature** ⟶**

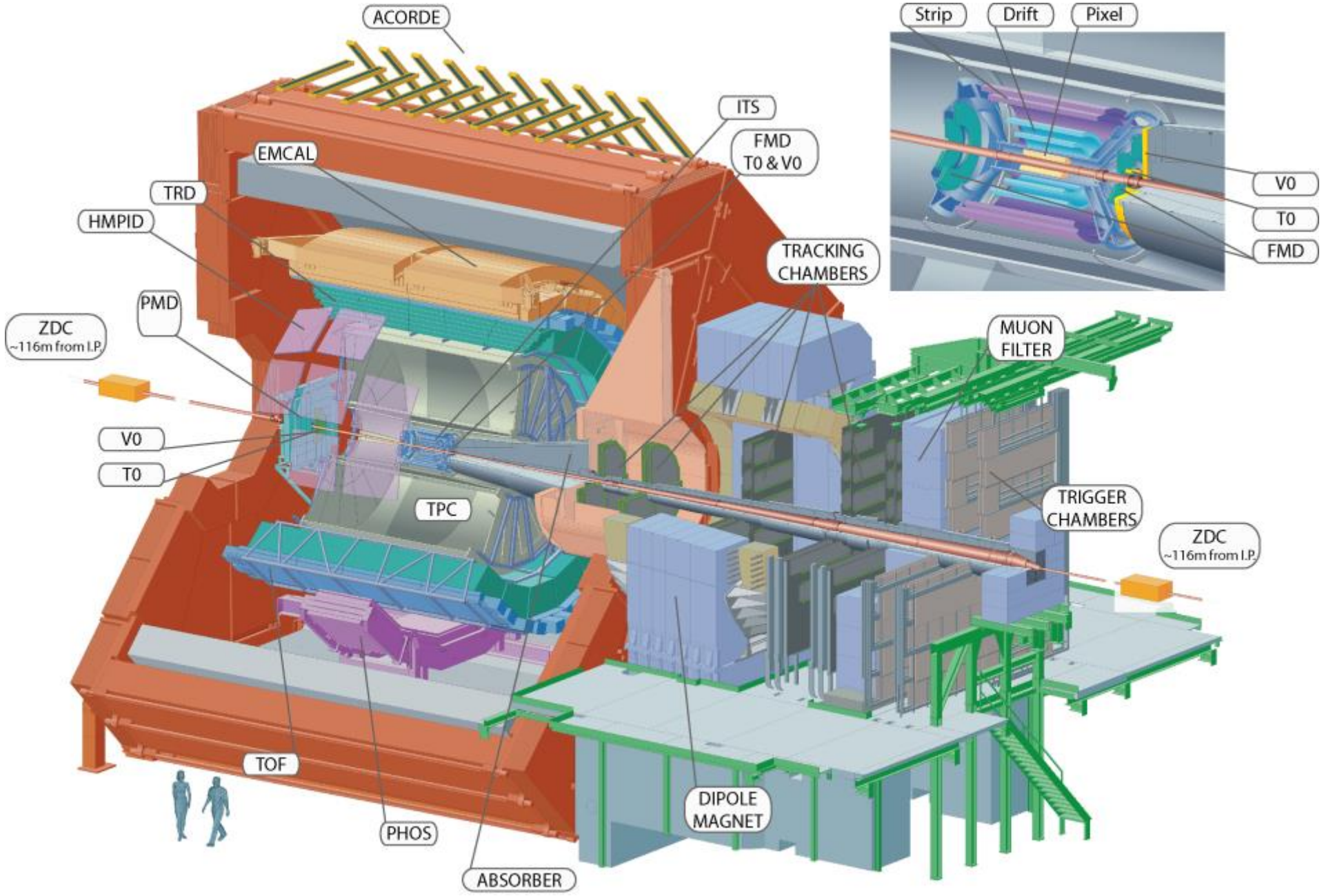
$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

- **Regeneration: increasing $c\bar{c}$ multiplicity with increasing c.m. energy → enhanced quarkonium production via (re)combination at hadronization or during QGP phase*****

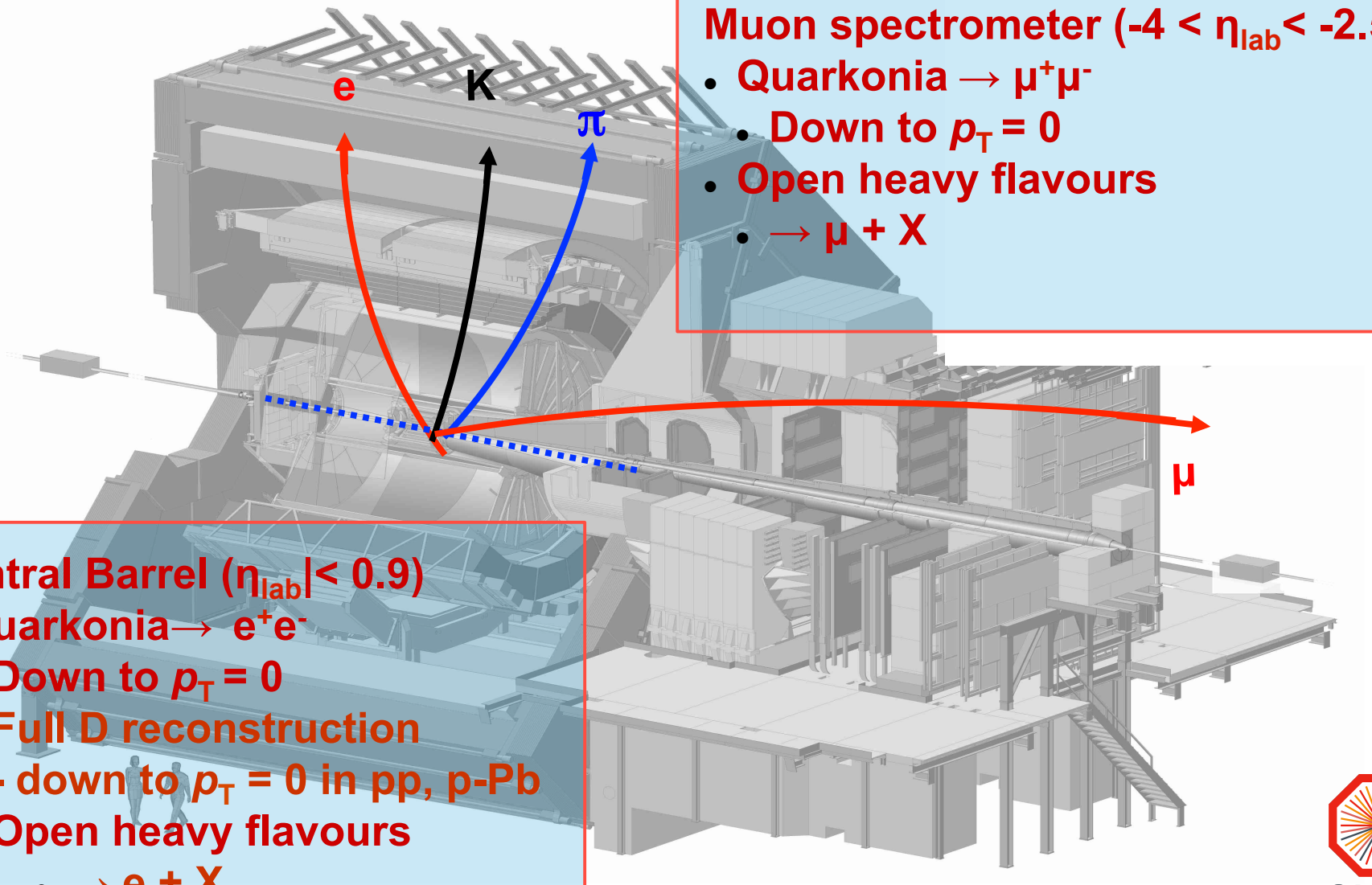


** Matsui, Satz PLB178(1986),*
***Karsch, Satz Z.Phys.C51 (1991) 209, Digal, Petreczcy, Satz (2001)*
****Braun-Munzinger, Stachel PLB490(2000), Thews et al. PRC62(2000)*

ALICE set-up


ACORDE
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
V0
T0
TPC
MUON
FILTER
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
TOF
PHOS
DIPOLE
MAGNET
ABSORBER
Strip
Drift
Pixel
V0
T0
FMD

Open heavy flavours and quarkonia in ALICE



Muon spectrometer ($-4 < \eta_{lab} < -2.5$)

- Quarkonia → $\mu^+\mu^-$
  - Down to $p_T = 0$
- Open heavy flavours
  - → μ + X

Central Barrel ($|\eta_{lab}| < 0.9$)

- Quarkonia→ e^+e^-
  - Down to $p_T = 0$
  - Full D reconstruction
    - down to $p_T = 0$ in pp, p-Pb
  - Open heavy flavours
    - → e + X

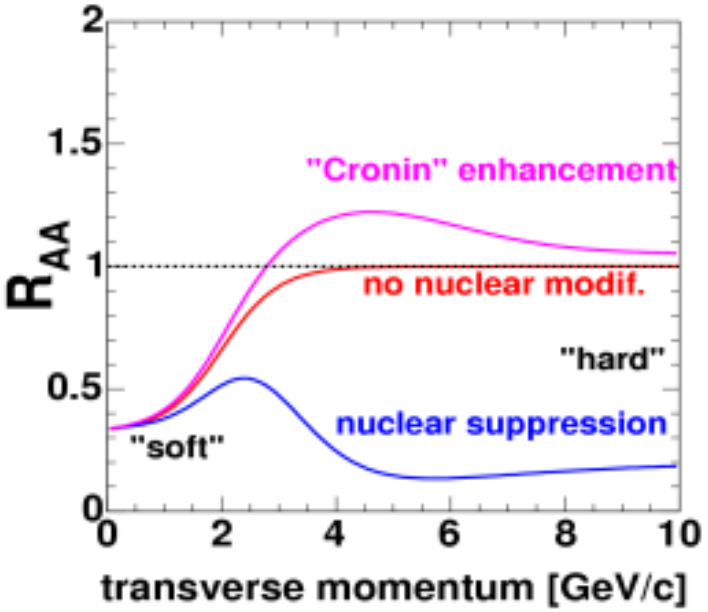
ALICE

Energy loss – quantitative measurements

Hadron p_T spectra

- **Nuclear Modification Factor R_{AA}**

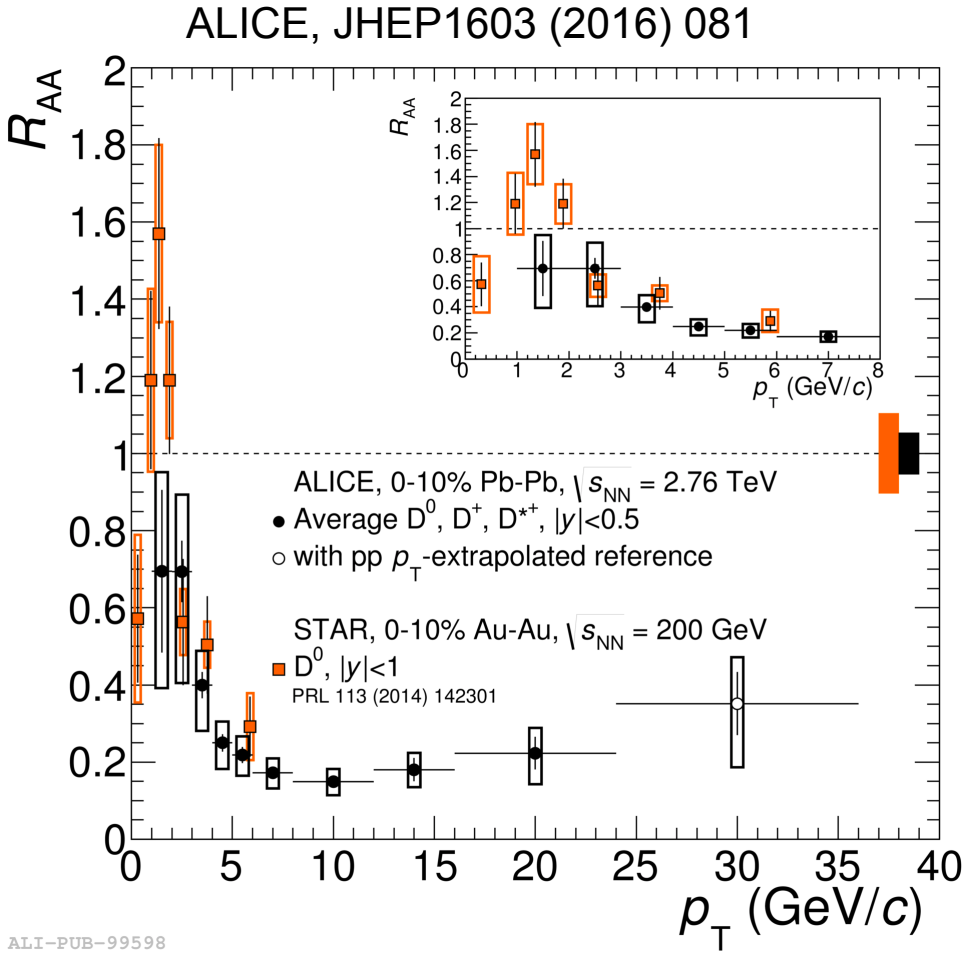
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{pp}/dp_T d\eta}$$



- **Energy loss depends on:**
  - **Colour charge $\Delta E_g > \Delta E_{u,d,s}$**
  - **Parton mass $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$**

See e.g. Dokshitzer and Kharzeev, PLB 519 (2001) 199

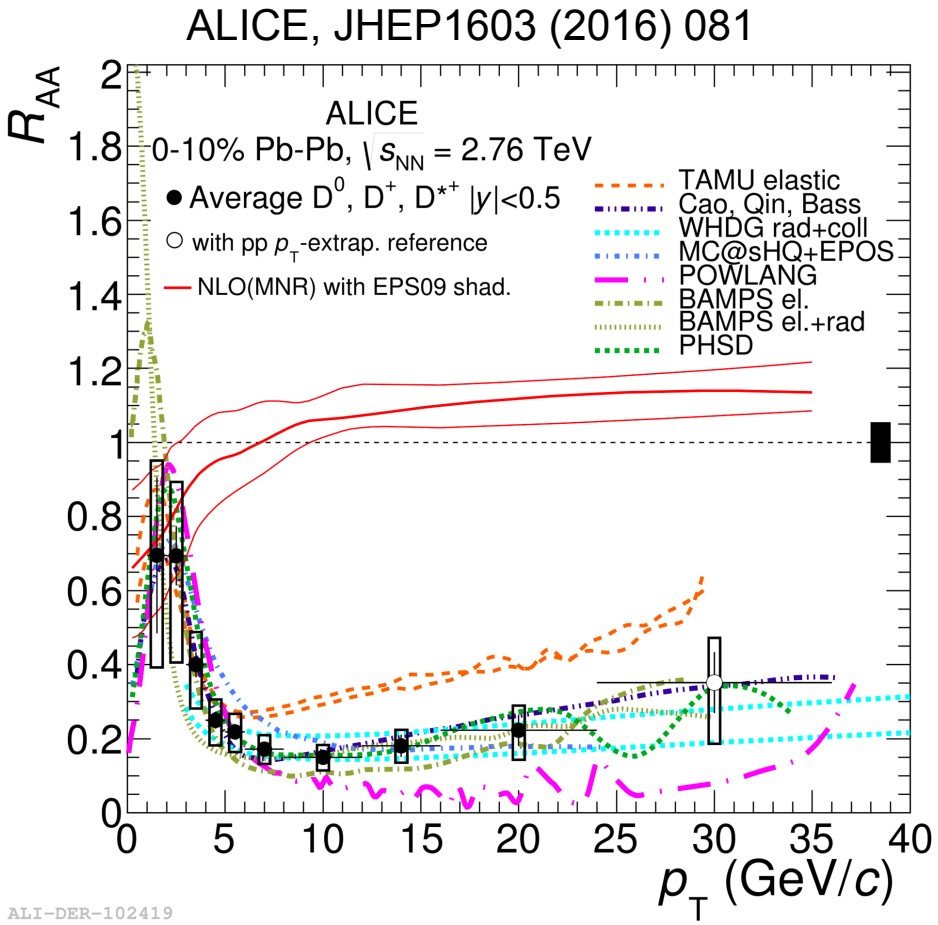
Open heavy-flavour R_{AA}



- **Strong suppression of D-mesons yields in the most central Pb-Pb collisions at mid-rapidity**
  - up to a factor 5 at $p_T \approx 10$ GeV/c

- **STAR results at $\sqrt{s_{NN}}$=200 GeV indicate that $R_{AA}>1$ at low p_T**

D-meson suppression in Pb-Pb collisions

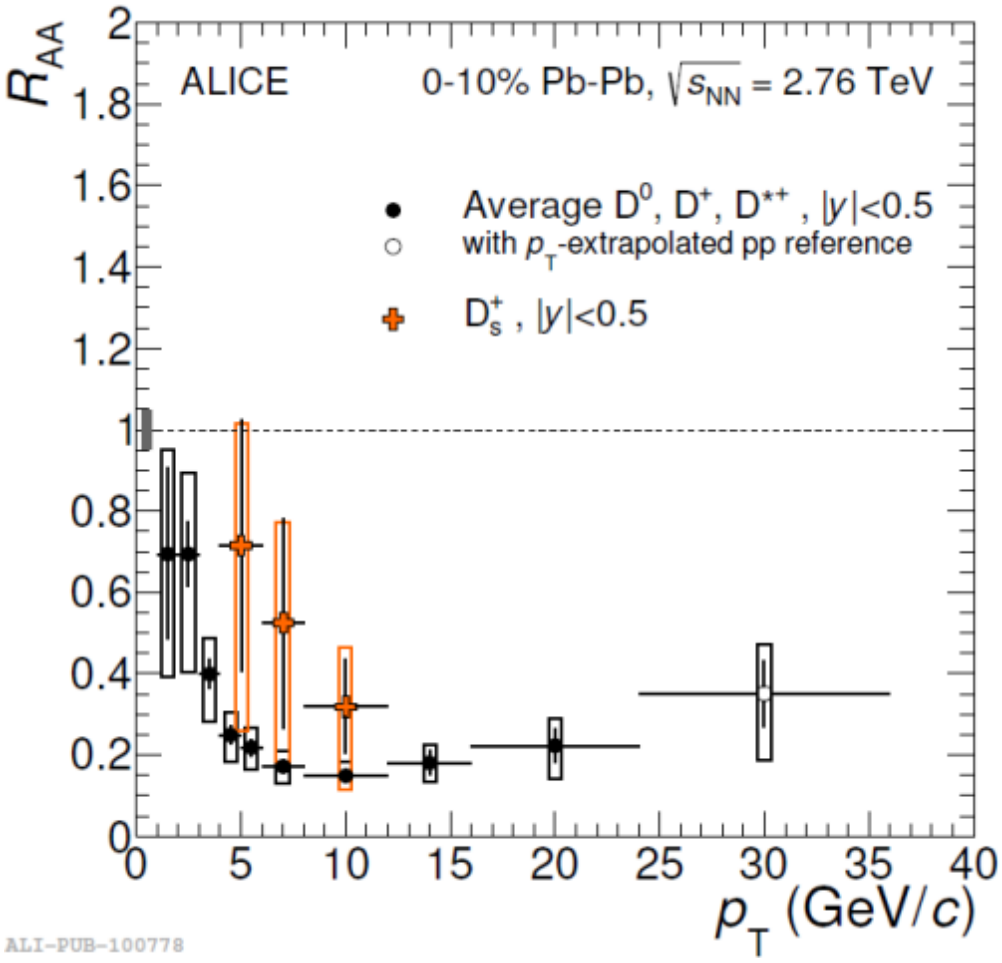


- **Strong final-state interactions of the charm quarks with the medium suggested by model calculations**
- **Main mechanism at play: energy loss via collisional and radiative processes**
- **A pQCD calculation implementing only shadowing indicates mild Cold Nuclear Matter (CNM) effects**

ALICE

Mass dependence of open heavy-flavour R_{AA} (I)

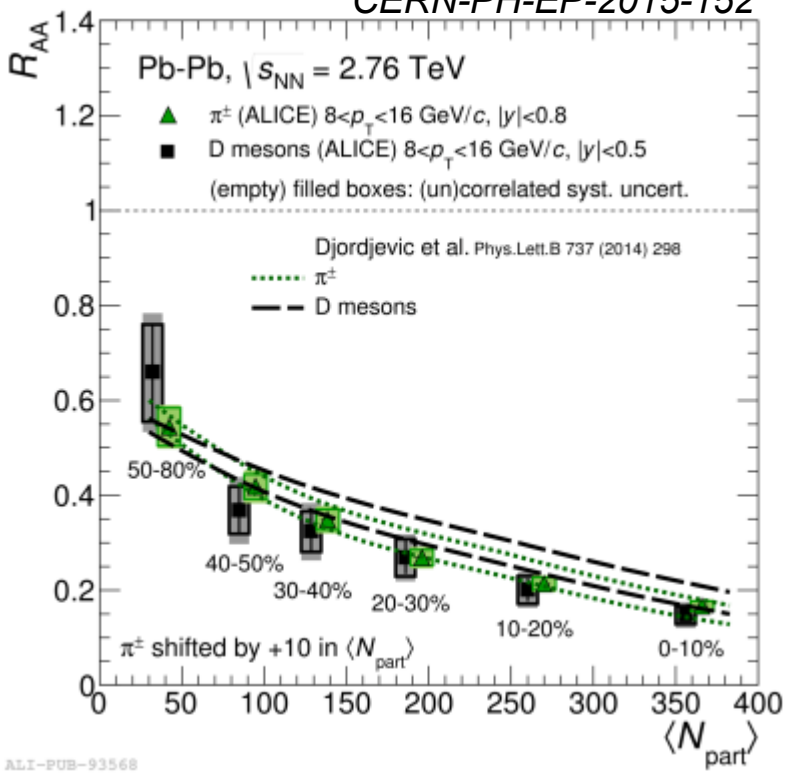
JHEP 03 (2016) 082

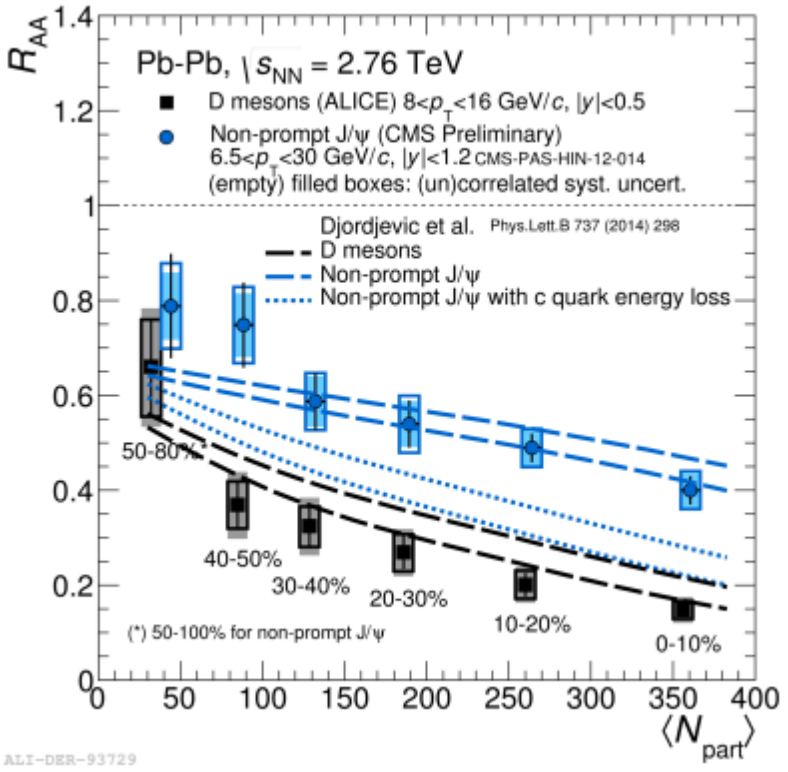


- **Comparison of D-meson and prompt D_S-meson (charmed, strange meson) R_{AA}**
  - **the values of the strange D_S-meson R_{AA} are higher than those of non-strange D-mesons**
  - **effect of hadronisation via quark recombination in the partonic medium?**

Mass dependence of open heavy-flavour R_{AA} (II)

CERN-PH-EP-2015-152





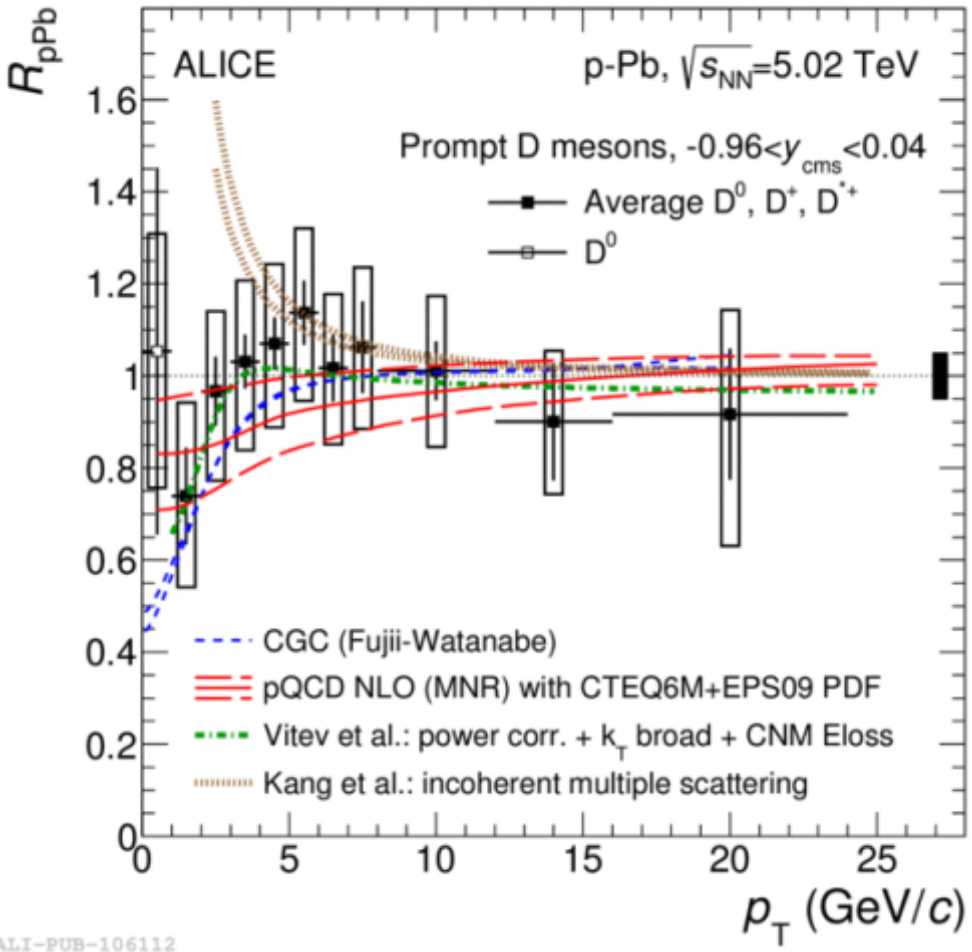
Comparison of pions, D mesons and non-prompt J/ψ R_{AA}

- R_{AA}(D) ~ R_{AA}(pions)
- R_{AA}(D) < R_{AA}(B→J/ψ)
  - hint of mass hierarchy of the R_{AA}
  - described by a model including mass-dependent radiative and collisional energy loss

ALICE, JHEP 1511 (2015) 205
CMS, PAS-HIN-12-014
(non-prompt J/ψ)

Open heavy-flavour production in p-Pb collisions

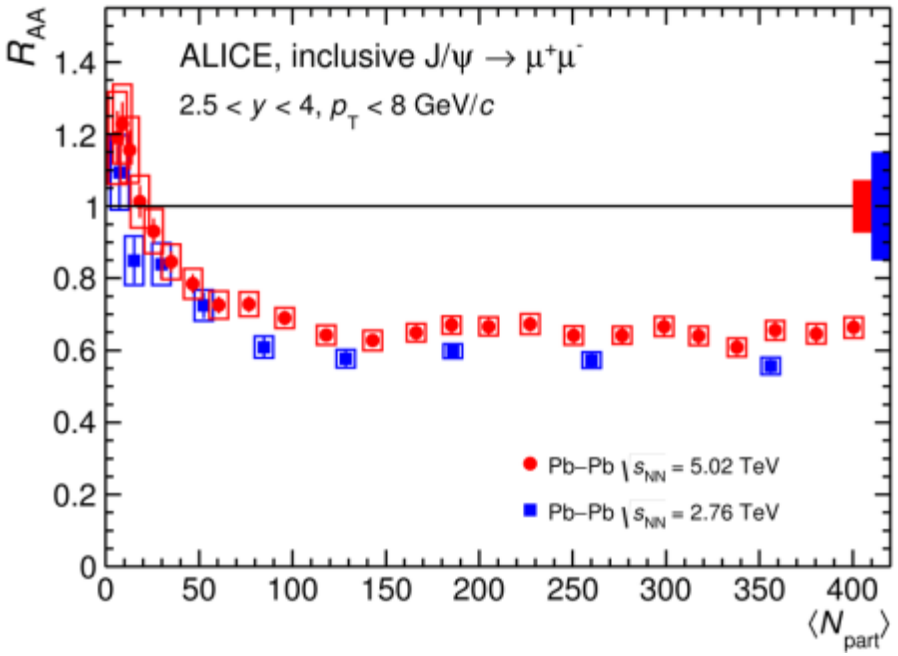
ALICE, PRL113 (2014), 232301, arXiv:1605.07569

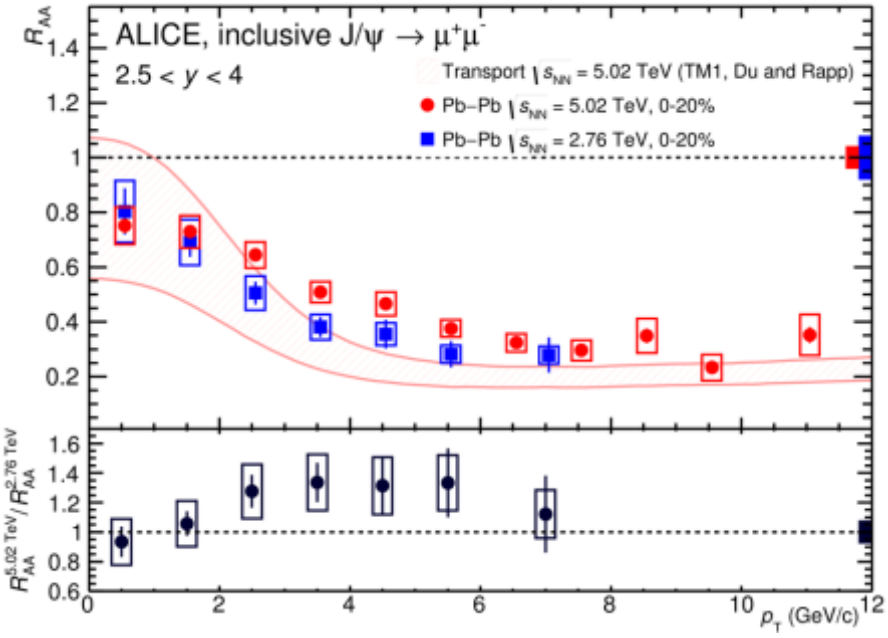


- R_{pPb} of D-mesons consistent with unity
- no indication for suppression larger than 15-20% at intermediate/high p_T
- R_{pPb} described within uncertainties by models including initial- or final-state effects

Inclusive J/ψ suppression in Pb-Pb collisions at 5.02 TeV

CERN-EP-2016-162, arXiv:1606.08197





- **Similar suppression pattern at both 5.02 and 2.76 TeV with nearly no centrality dependence for $N_{part} > 100$; R_{AA} at 5.02 TeV is ~15% higher than the one at 2.76 TeV**
- **Hint of a mild (~10%) increase of R_{AA} at 5 TeV for $2 < p_T < 6$ GeV/c**

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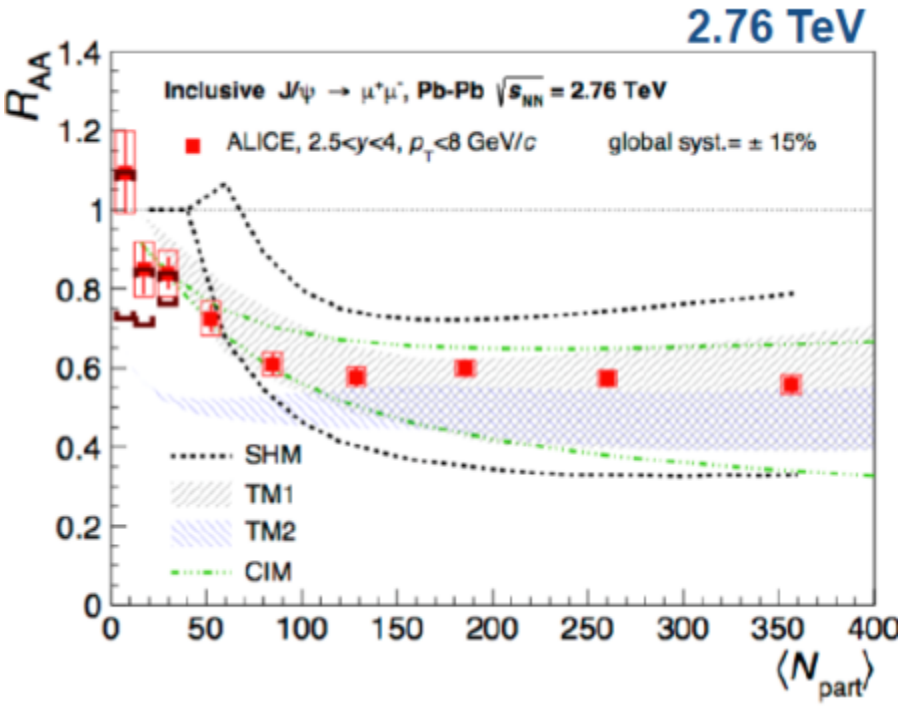
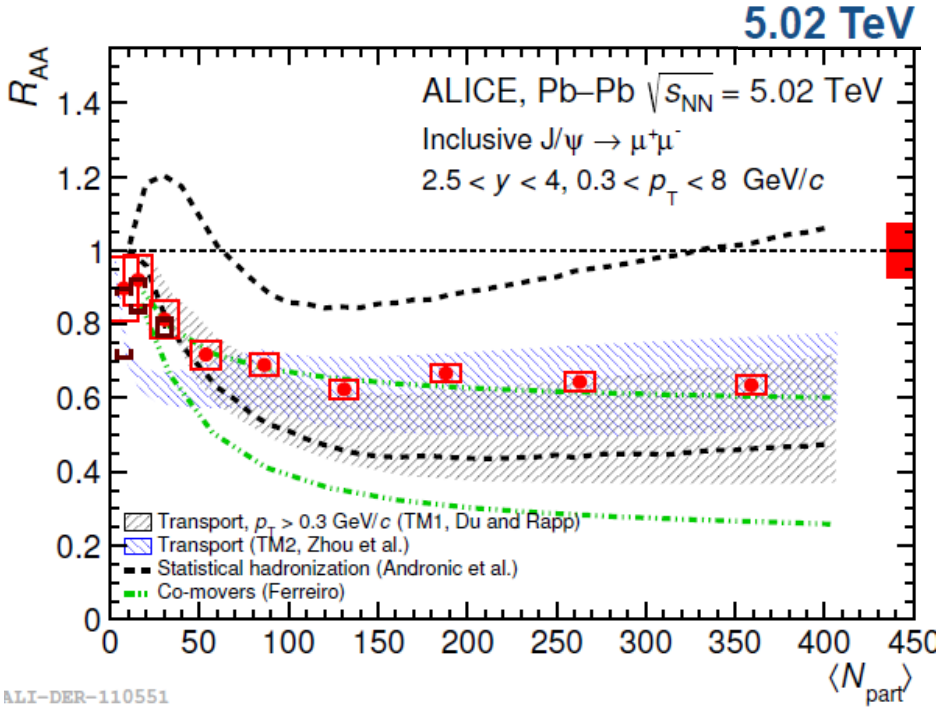
J/ψ suppression vs re-generation: comparison to models

- J/ψ R_{AA} vs centrality at 2.76 and 5.02 TeV

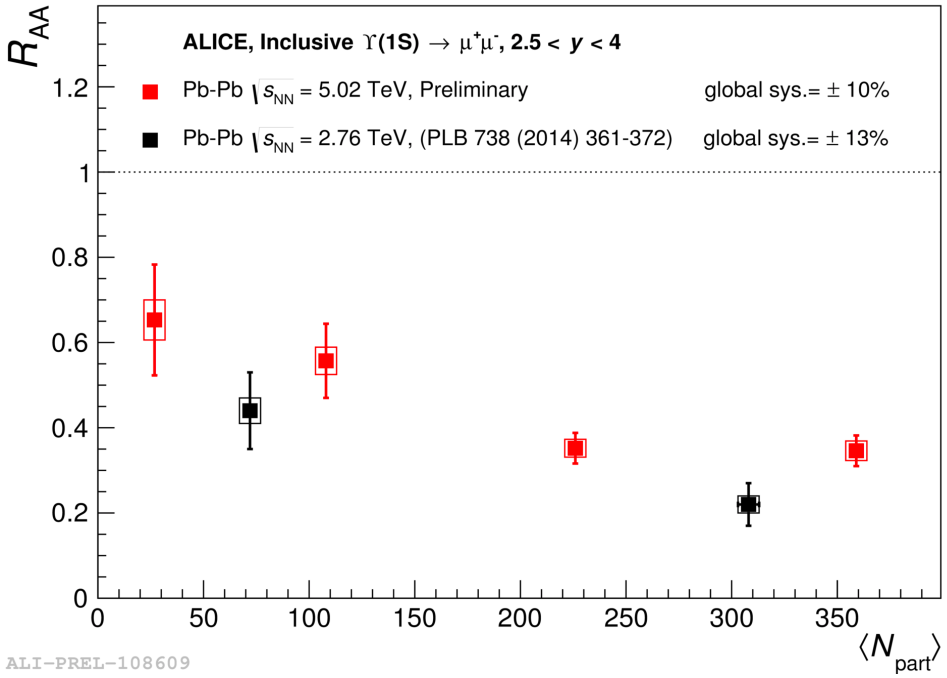
JHEP 1605 (2016) 179

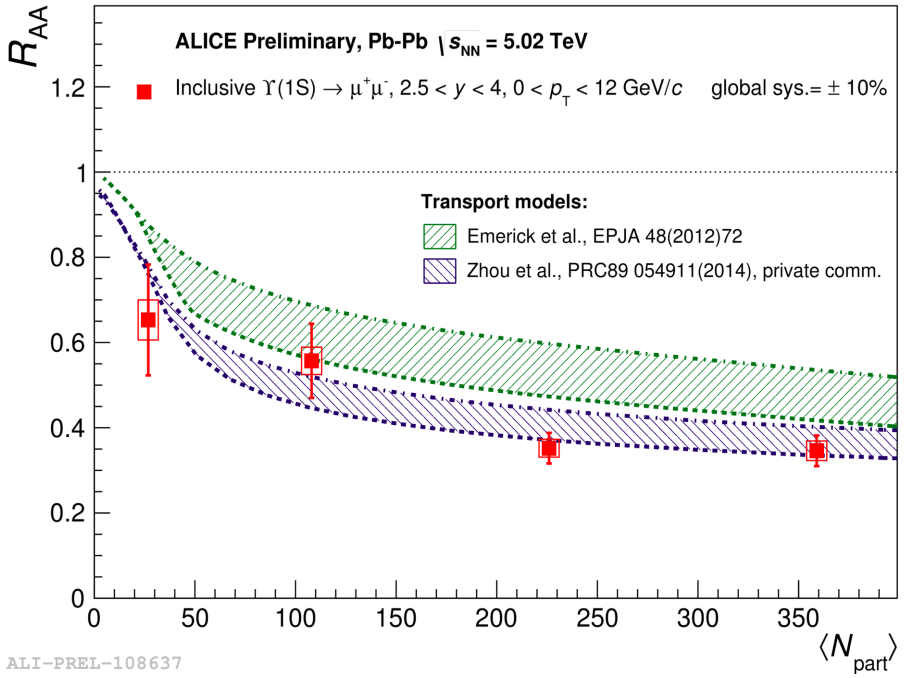




- Comparison to the same models at both energies
  - SHM (Andronic et al.): all J/ψ produced by statistical hadronisation at the QGP phase boundary
  - TM (Du et al. and Zhou et al.): rate equation of suppression and regeneration by/in the QGP
  - CIM (Ferreiro): suppression by the co-moving partonic medium and regeneration

Υ(1S) R_{AA} in Pb-Pb collisions at 5.02 TeV



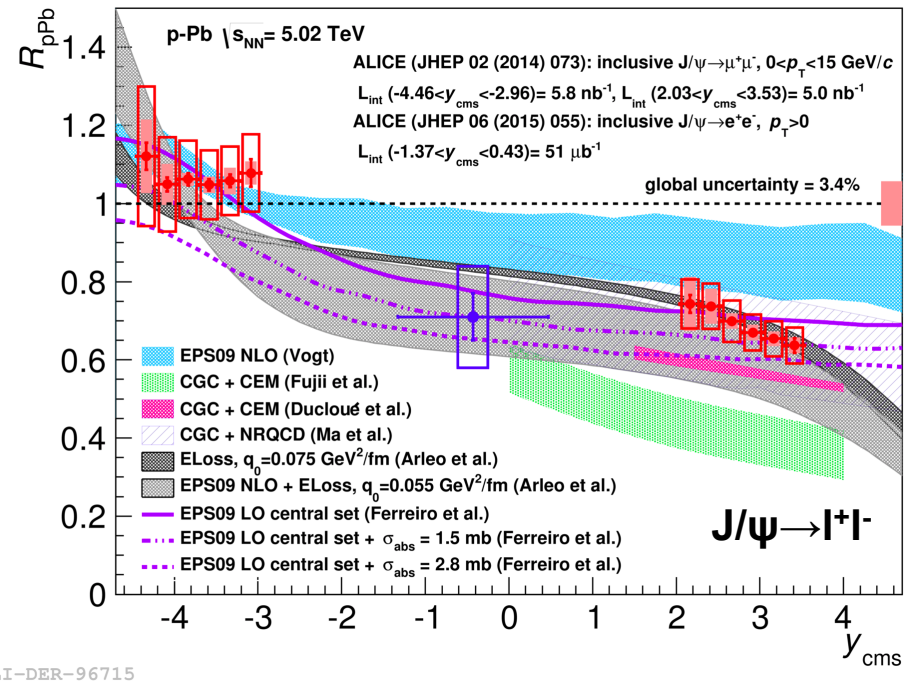


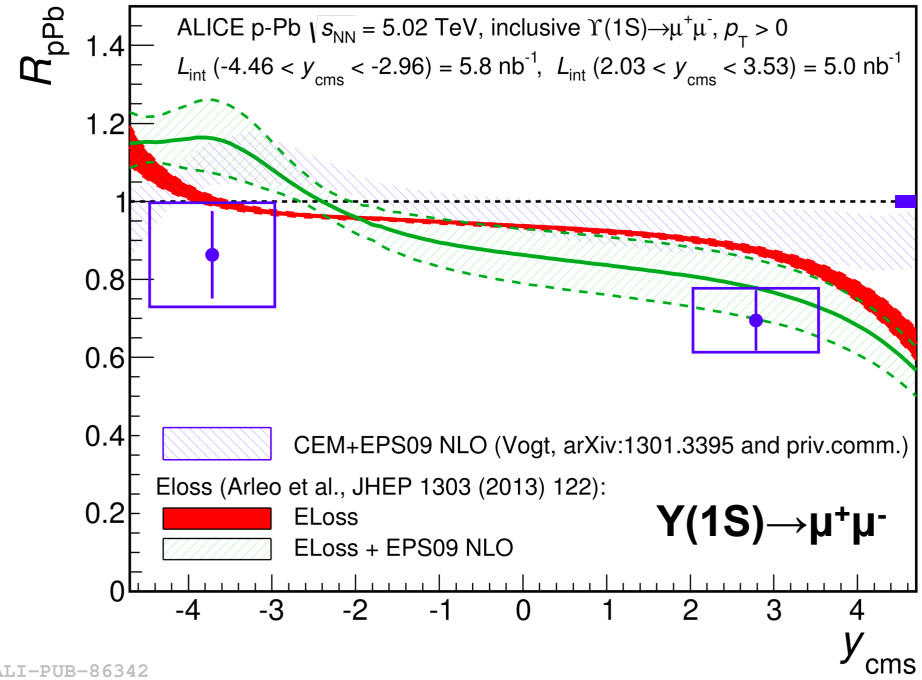
- **Bottomonium is much less affected by regeneration effects → cleaner probe for the medium properties**
- **Slightly less suppression at higher collision energy**
- **The suppression trend is reasonably described by transport model calculations with (Emerick et al.) or without (Zhou et al.) regeneration**

Quarkonia in p-Pb collisions at 5.02 TeV

JHEP02 (2014) 073, JHEP06 (2015) 055

PLB740 (2015) 105





- **J/ψ and Υ(1S) are suppressed at forward rapidity**
- **At backward rapidity both states are compatible with no suppression**
- **Data are consistent with expectations from shadowing and energy loss models**

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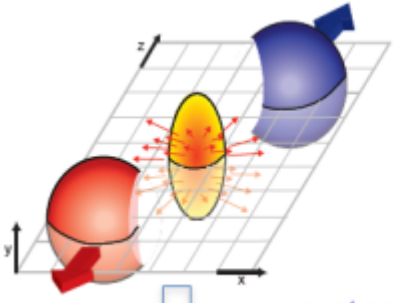
Nuclear geometry and hydrodynamic flow

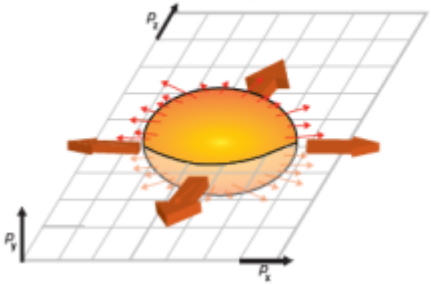
- **Interactions transfer the initial spatial geometry of matter into a momentum anisotropy of final-state particles**



system expansion

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi\rangle^2 + \langle r^n \sin n\varphi\rangle^2}}{\langle r^n\rangle}$$

coordinate space Anisotropy



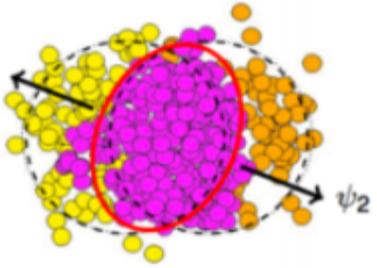
$$v_n = \langle \cos n(\varphi - \Psi_n)\rangle$$

momentum space Anisotropic Flow

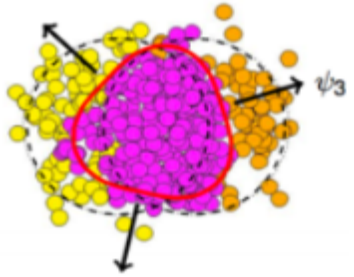
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

Ψ_n: symmetry planes

n = 2: elliptic flow



n = 3: triangular flow



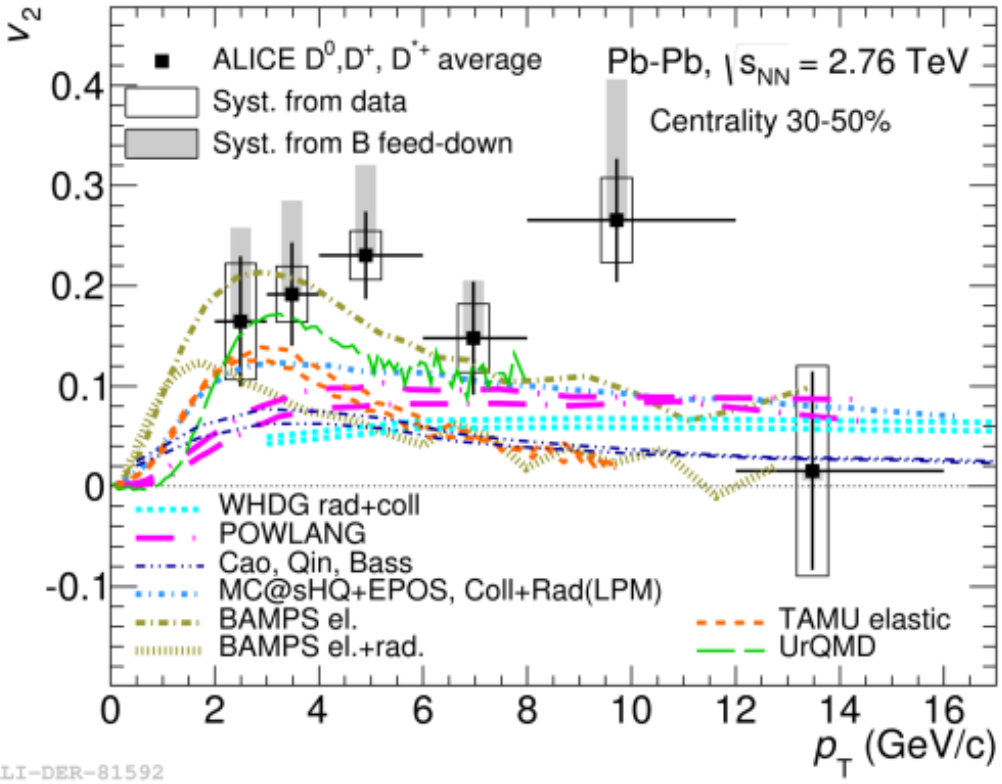
Transfer depends on the strength of collective phenomena

- **Large mean free path**
  - **particles stream out isotropically, no memory of the asymmetry**
  - **extreme: ideal gas (infinite mean free path)**
- **Small mean free path**
  - **larger density gradient → larger pressure gradient → larger momentum**
  - **extreme: ideal liquid (zero mean free path, hydrodynamic limit)**

Open heavy-flavour elliptic flow in Pb-Pb collisions

ALICE, PRC 90 (2014) 3, 034904

Phys.Rev.C90(2014)034904



- **Significant positive v_2 in $2<p_T<6$ GeV/c (with 5.7σ) for collision centrality 30-50%**
- **Heavy quarks at low p_T participate in the collective motion of the system**

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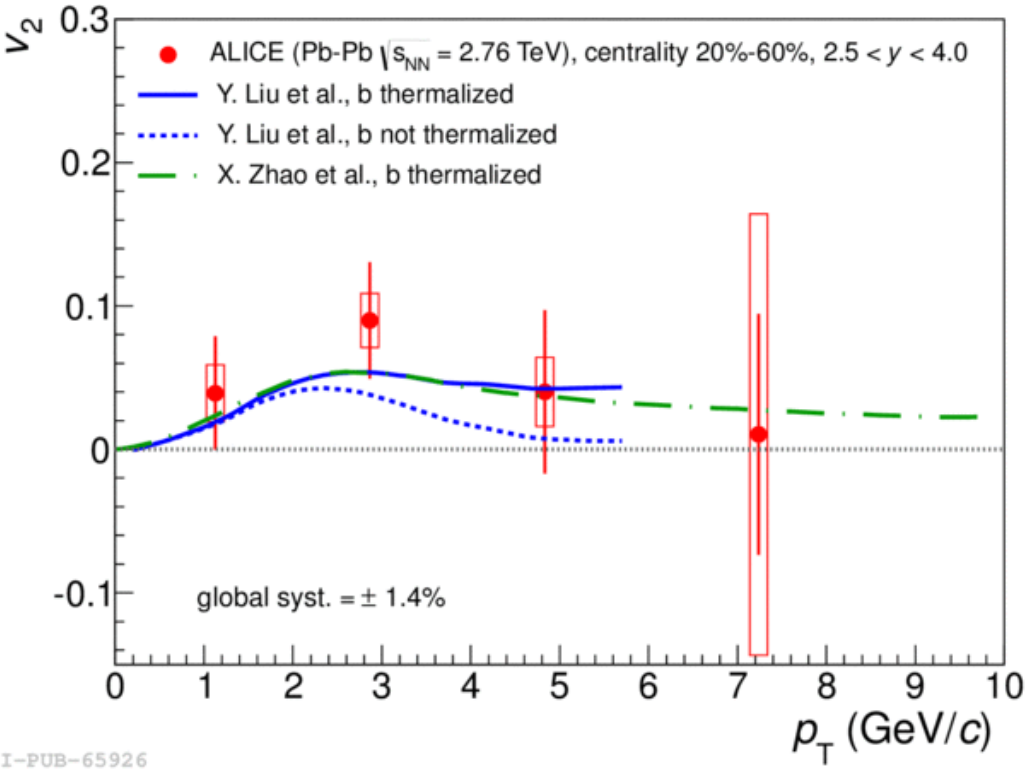
Inclusive J/ψ elliptic flow in Pb-Pb

PRL 111 (2013) 162301



- **Indication of non-zero J/ψ v_2 at intermediate p_T for semi-central collisions**
- **If c quarks participate in the collective motion of the QGP, then they will acquire some elliptic flow**
- **Regenerated J/ψ will inherit the elliptic flow of the c quarks**
- **Qualitatively described by models including regeneration**

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Conclusion

- **Open heavy-flavours**
  - Strong modification of the charm and beauty kinematics in Pb-Pb collisions w.r.t. pp collisions, with a significant centrality dependence
  - Indication of a stronger suppression of D-mesons w.r.t. non-prompt J/ψ at intermediate/high p_T
    → quark-mass dependent energy loss
  - Significant D-meson elliptic flow
  - No large CNM effects supported by the p-Pb data
    → the strong suppression in central Pb-Pb collisions is largely a hot medium effect

- **Quarkonia**
  - New results on J/ψ suppression in Pb-Pb collisions at 5.02 TeV indicate similar suppression level as the 2.76 TeV data
  - The p_T dependence of the J/ψ suppression suggests an important contribution from regeneration
  - The new Υ(1S) results at 5.02 TeV confirm the strong suppression observed in central Pb-Pb collisions at 2.76 TeV

Outlook

- **Run-2 data taking ongoing**
  - **Improve statistical and systematic uncertainties**
  - **Extend the measured p_T range to further constrain theory**
  - **Understand and disentangle Cold Nuclear Matter effects**
  - **High statistics open heavy-flavour and J/ψ elliptic flow measurements**

- **Detector upgrade will improve heavy-flavour capabilities (2019-2020)**

This is the end

Rephrasing it ...

Habe nun, ach! Philosophie, Juristerei und Medizin,
Und leider auch Theologie
Durchaus studiert, mit heißem Bemühn.
Da steh ich nun, ich armer Tor!
Und bin so klug als wie zuvor;
[...]
Drum hab ich mich der Magie ergeben,
[...]
Daß ich erkenne, was die Welt
Im Innersten zusammenhält, ...

Goethe, Faust I, Vers 382 f.

Ah! Now I've done Philosophy,
I've finished Law and Medicine,
And sadly even Theology:
Taken fierce pains, from end to end.
Now here I am, a fool for sure!
No wiser than I was before:
[…]
So I've given myself to Magic art,
[…]
That I may understand whatever
Binds the world's innermost core together, ...