Open heavy-flavor and quarkonium measurements in heavy-ion collisions at the LHC

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Motivations

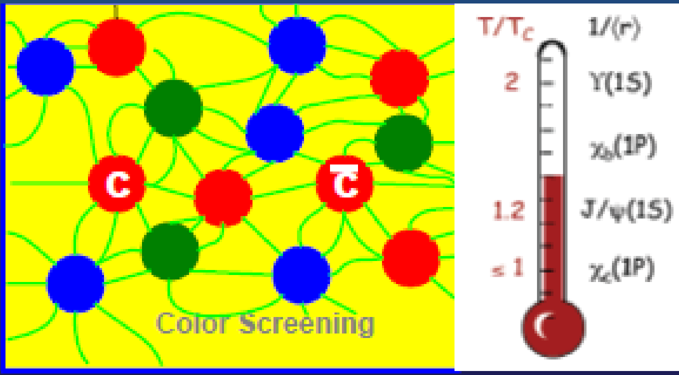
Why to study heavy-flavor production in heavy-ion collisions?

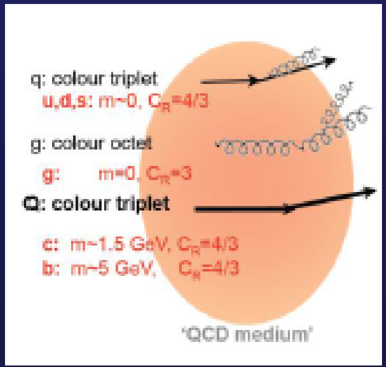
→ Due to their large mass, heavy quarks (c and b) are produced at the initial stage of the collision, with typical times $\tau_p \sim 1/m_Q \sim 0.05\text{-}0.15$ fm/c, shorter than the QGP one.

→ Flavor is conserved in strong interactions, so heavy quarks are transported through (and are sensitive to) the full system evolution

Complementarity between open heavy flavors and quarkonia:

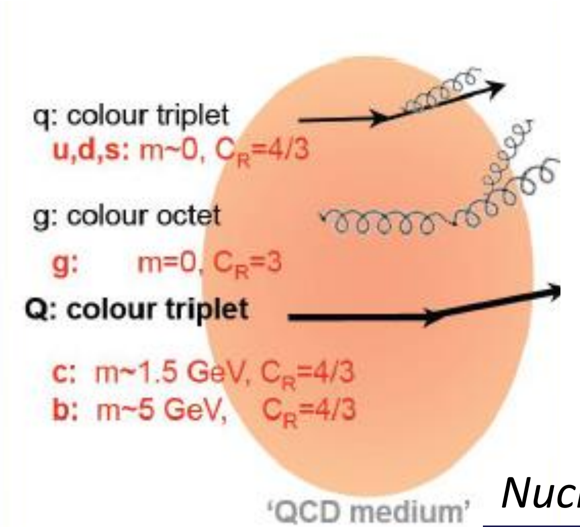
Quarkonia → Sensitive to the temperature of QGP





Probe the opacity of QGP ← Open heavy quarks

Open Heavy Flavors: energy loss and elliptic flow



Heavy quark energy loss:

Relevant for understanding general properties of energy loss since this is expected to depend (also) on:

- Casimir Factor
- Quark mass

$\Delta E_{quark} < \Delta E_{gluon}$

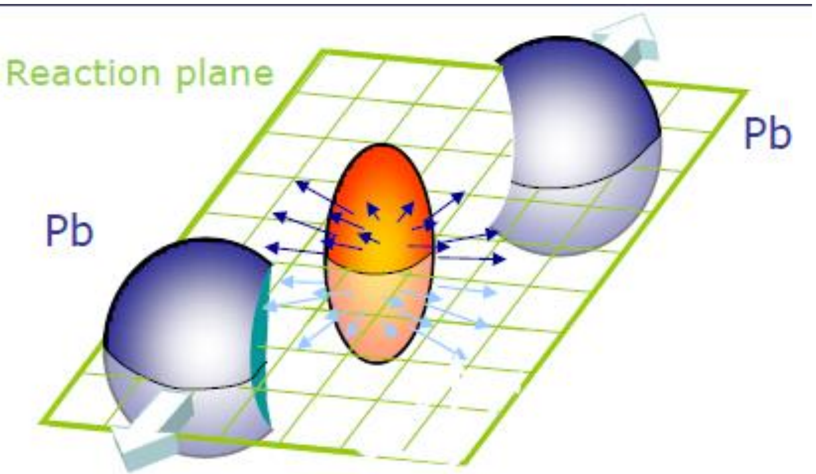
$\Delta E_b < \Delta E_c < \Delta E_{light\ q}$

which should imply

$R_{AA}^{B} > R_{AA}^{D} > R_{AA}^{\pi}$

Nuclear Modification Factor

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



Heavy quark elliptic flow:

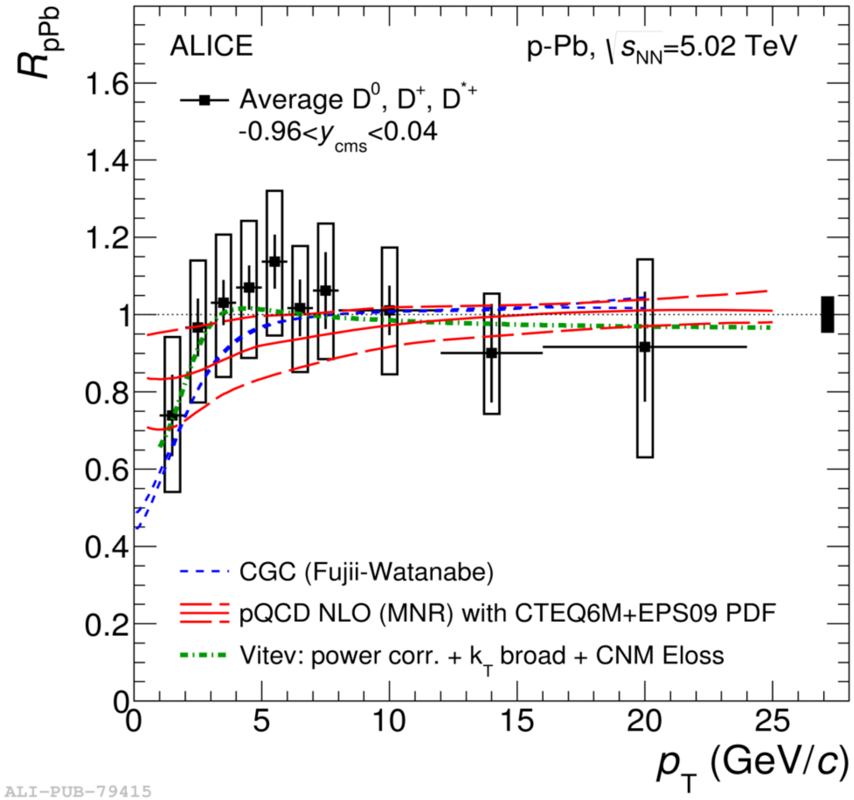
Due to their large mass, c and b quarks are expected to take a longer time (i.e. more re-scatterings) to be influenced by the collective expansion.

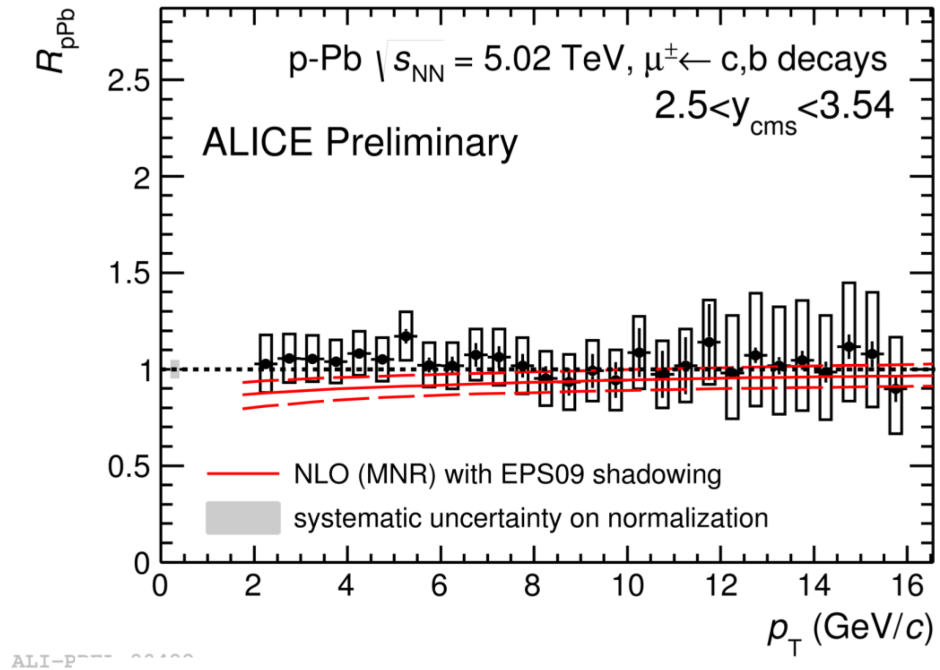
- Low p_T : v_2 sensitive to collective motion and thermalization
- High p_T: v_2 sensitive to path-length dependence of energy loss

Open Heavy Flavor Results

- Focus on:
  - Pb-Pb results at $\sqrt{s_{NN}}$ = 2.76 TeV
  - p-Pb results at $\sqrt{s_{NN}}$ = 5.02 TeV

Nuclear Modification Factor in p-Pb



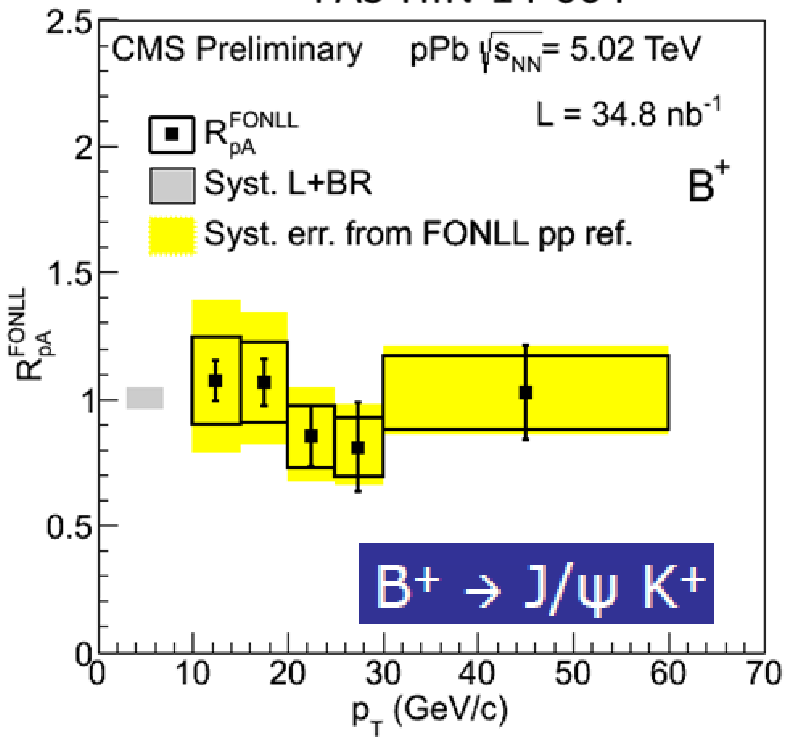


[M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B 373 (1992) 295;
K. Eskola, H. Paukkunen and C. Salgado, JHEP 04467 (2009) 065.;
H. Fujii and K. Watanabe, arXiv:1308.1258.
R. Sharma, I. Vitev and B. -W. Zhang, Phys. Rev. C 80461 (2009) 054902.]

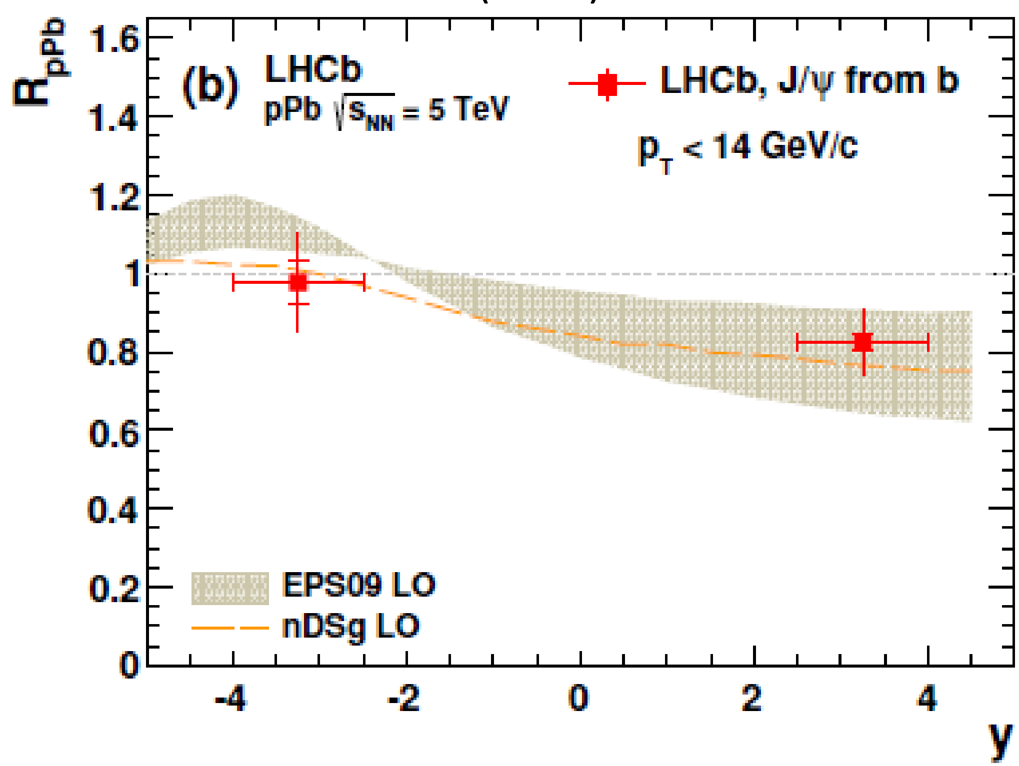
- D mesons and e/μ from HF decays
  - Nuclear Modification Factor close to unity at intermediate and high p_T
  - Reasonably good agreement with calculations including initial-state effects
- Data confirm the expectation that Nuclear Matter effects are small at large transverse momenta

Nuclear Modification Factor in p-Pb

PAS-HIN-14-004

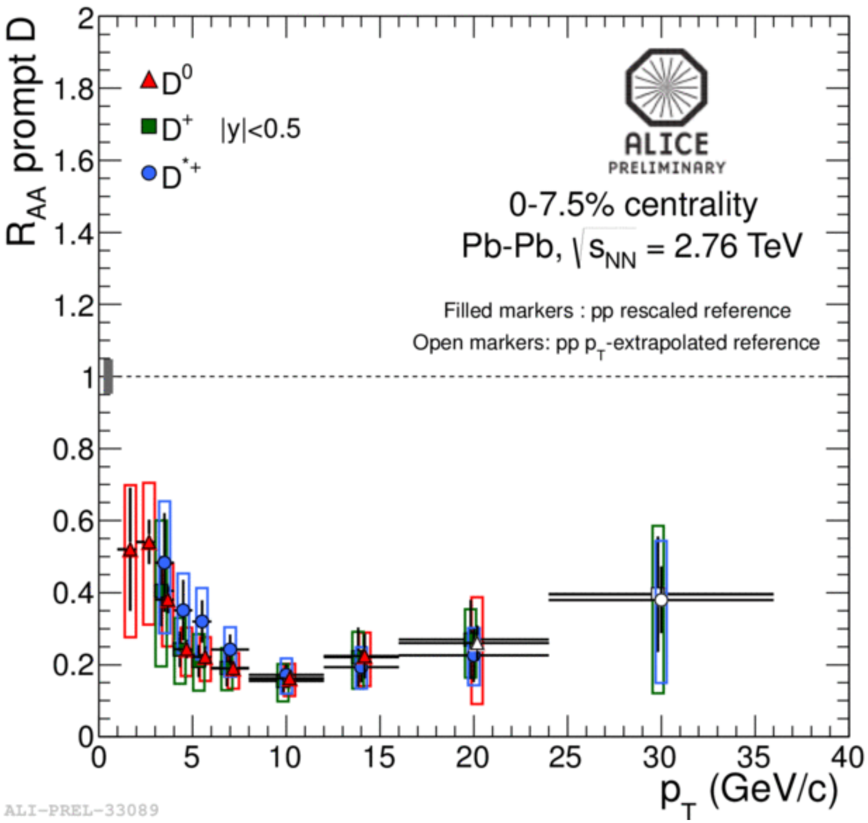


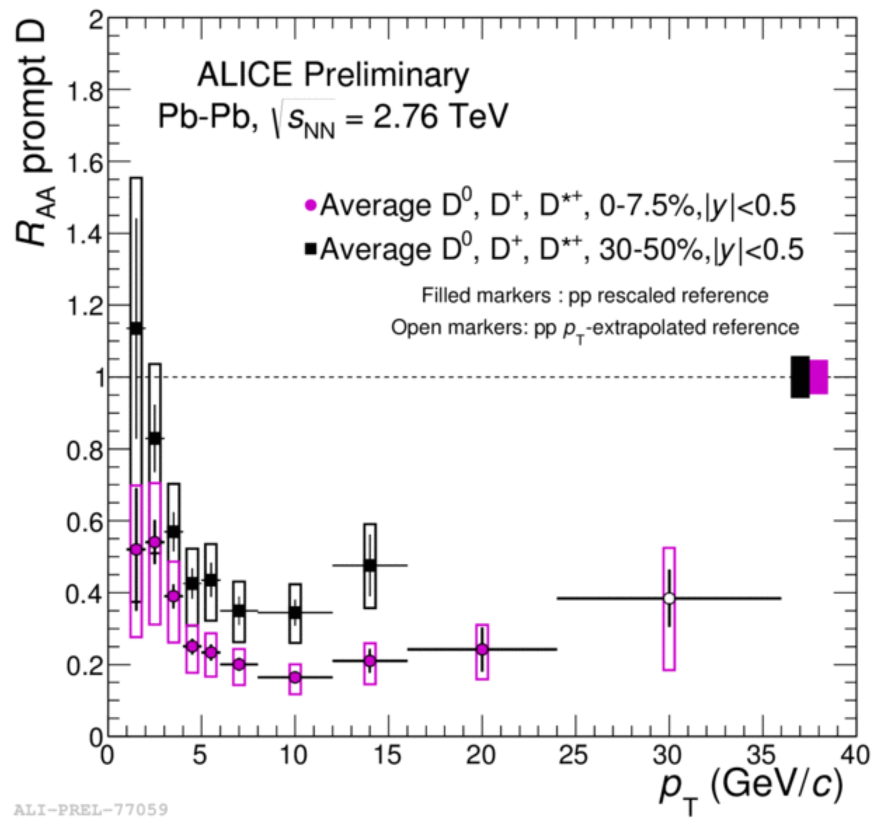
JHEP 02 (2014) 072



- B mesons and non-prompt J/ψ
  - B mesons: R_{pPb} close to unity (with FONLL used for pp reference)
  - J/ψ from b: small or no nuclear matter effect at forward and backward rapidity

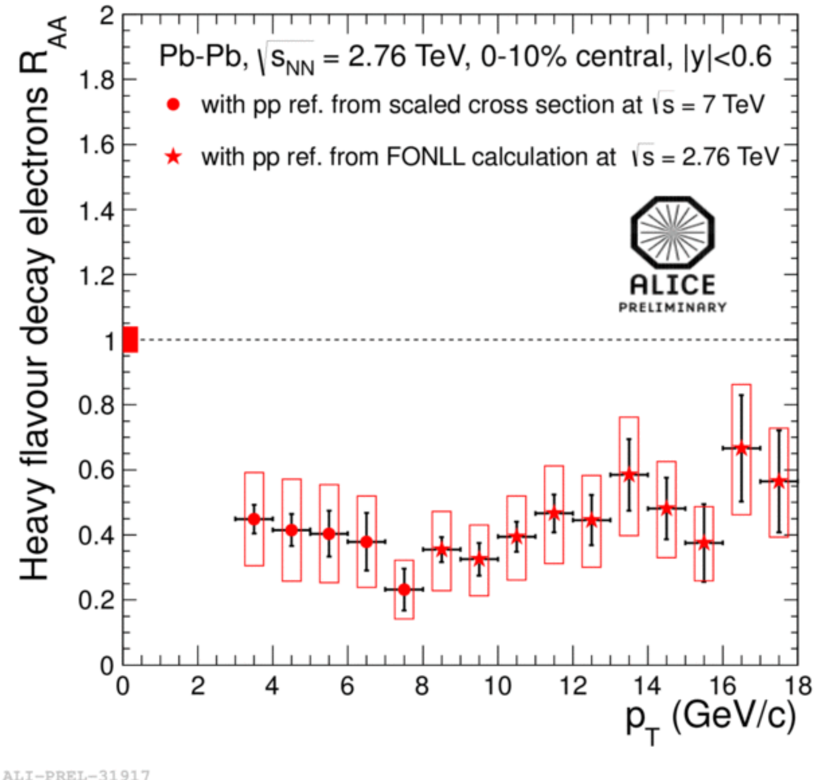
Nuclear Modification Factor in Pb-Pb: D-mesons

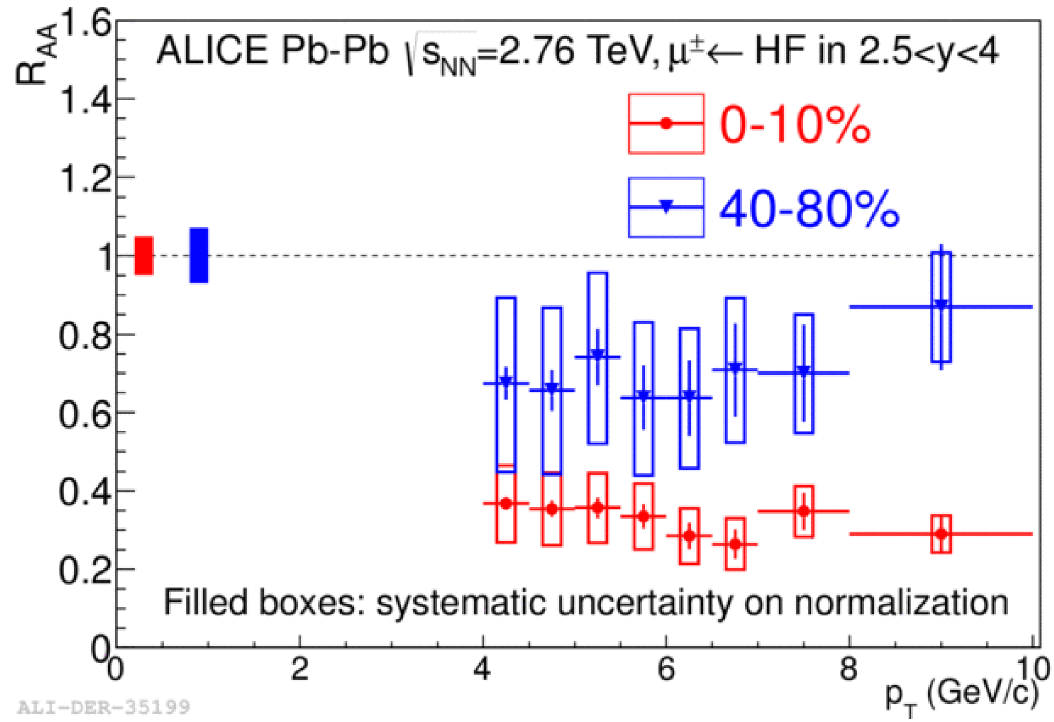




- Strong suppression of prompt D mesons in central Pb-Pb collisions (up to a factor of ~ 5 for p_T ~ 10 GeV/c)
- Comparison to corresponding p-Pb results suggests that the observed suppression in Pb-Pb is due to final state effects induced by hot and dense partonic matter

R_{AA} in Pb-Pb: HF decay leptons

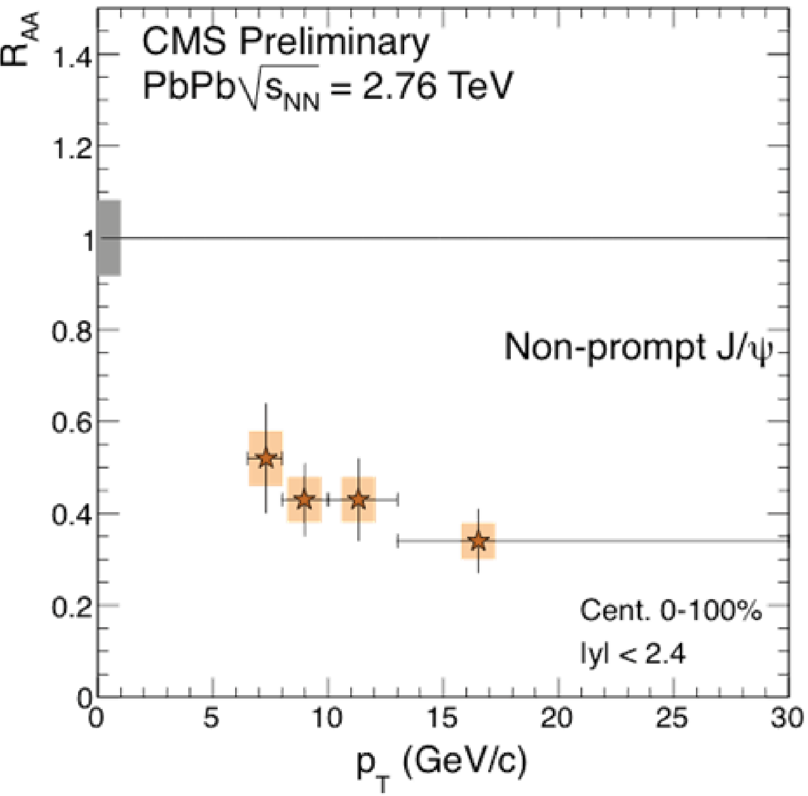


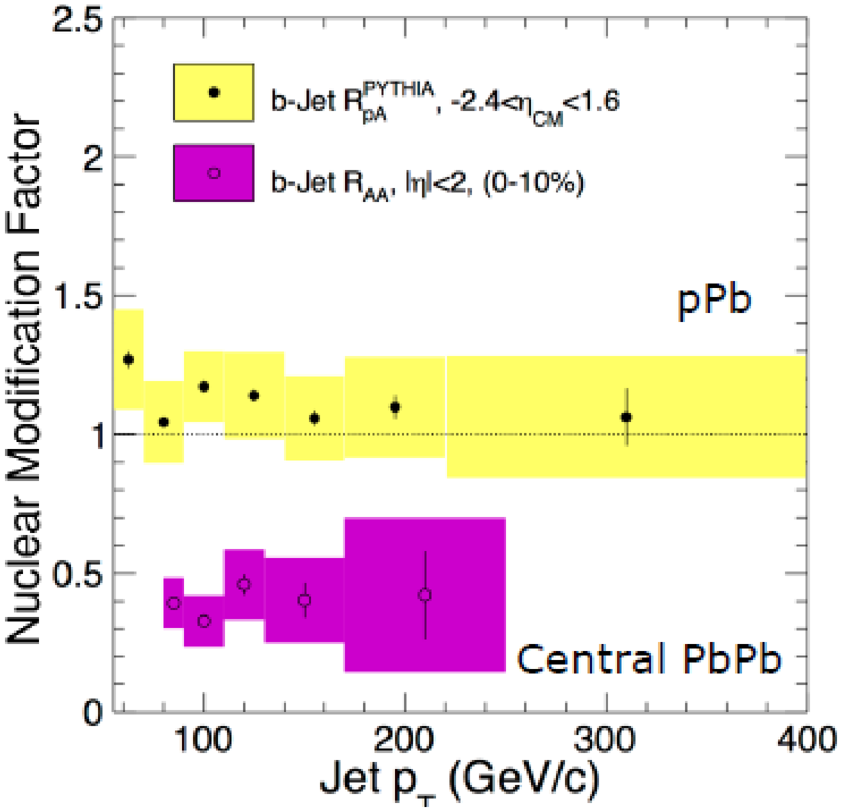


- Similar R_{AA} for HF decay muons and electrons
- Compatible with D meson R_{AA} considering the decay kinematics
  (in average at high p_T electrons carry about ½ of the mother particle p_T)
- Picture arising from D meson data confirmed; suppression at large p_T suggests a sizeable energy loss of b quarks.

Nuclear Modification Factor in Pb-Pb: non-prompt J/ψ and b-Jets

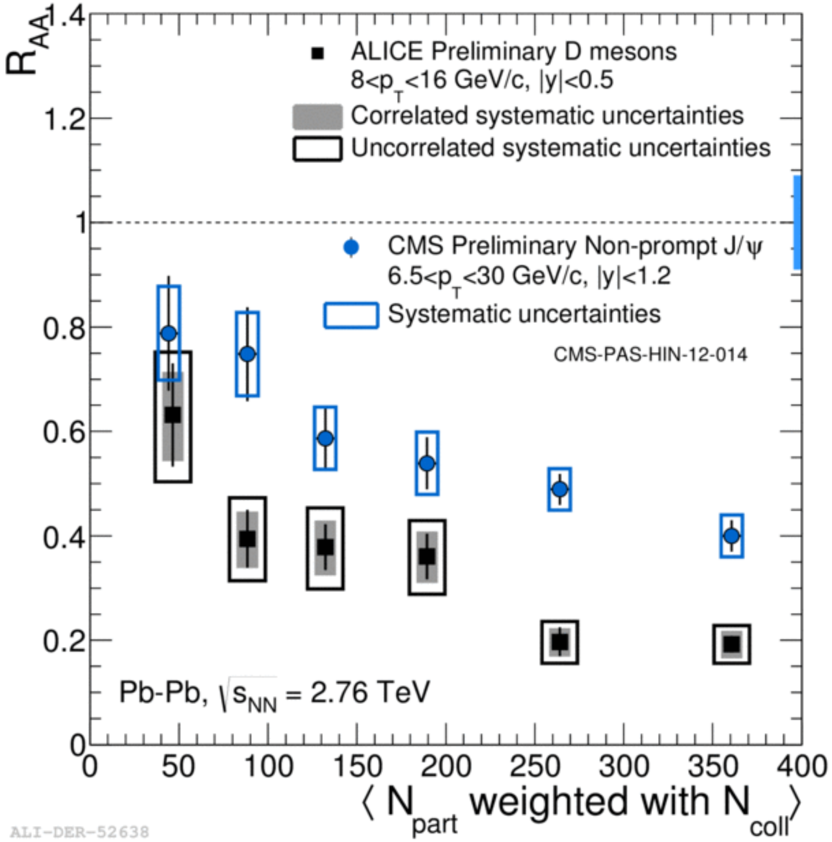
S. Chatrchyan et al. (CMS), arXiv:1312.4198

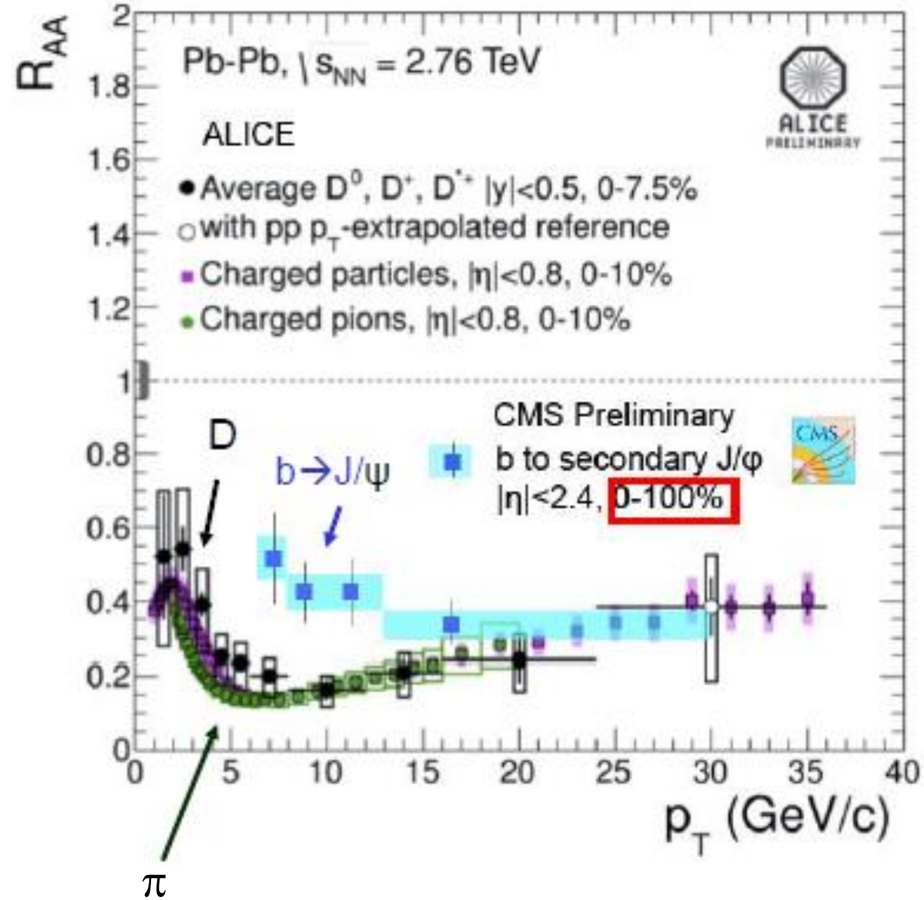




- Energy loss of b quarks confirmed by the measurements of R_{AA} for non-prompt J/ψ and b-jets

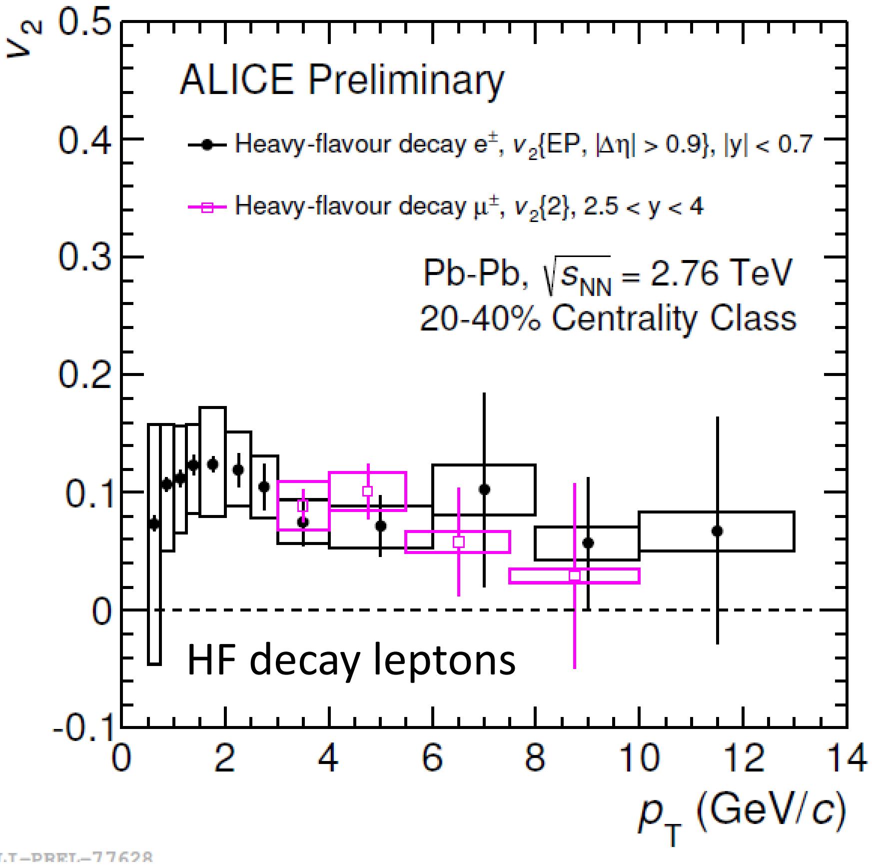
Charm, Beauty and light hadrons: a comparison

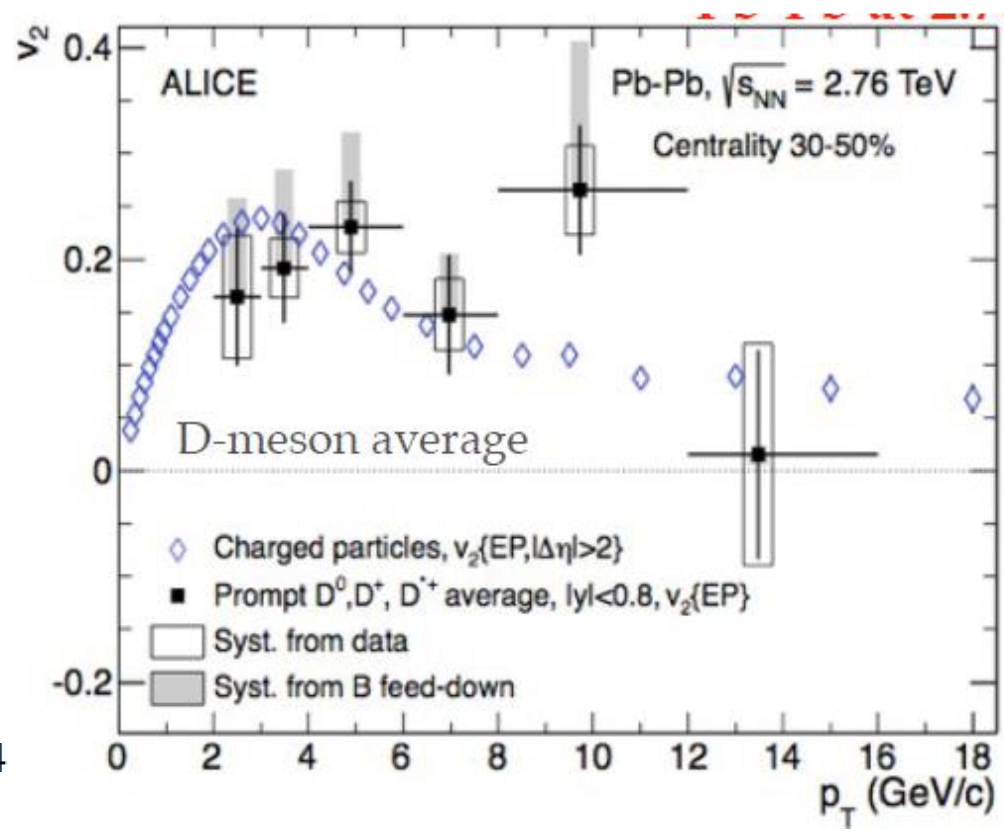




- Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
- $R_{AA}^{beauty} > R_{AA}^{light}$ at low p_T, effect vanishing at very high p_T
- R_{AA}^{charm} vs. R_{AA}^{light} comparison more delicate

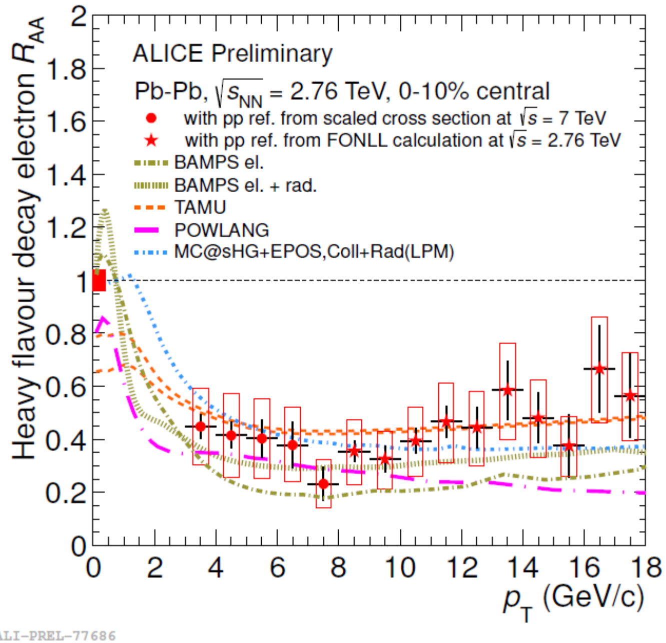
Heavy Flavor Elliptic Flow in Pb-Pb

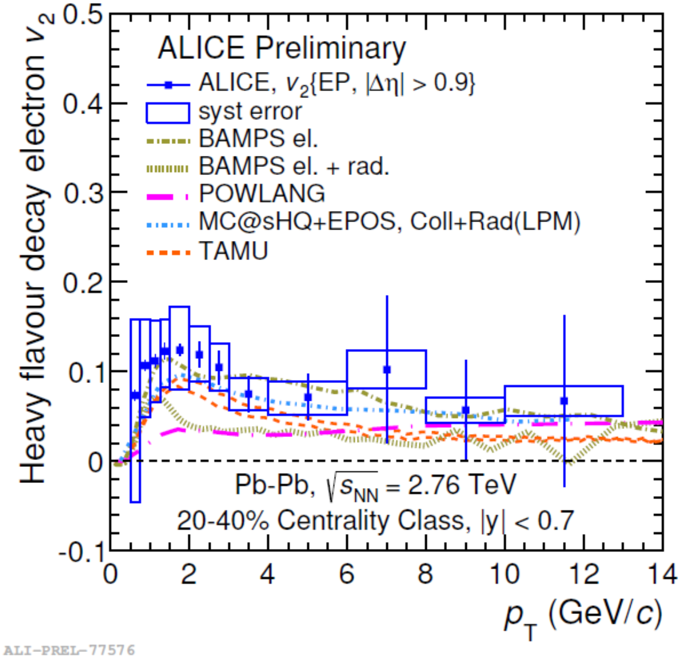




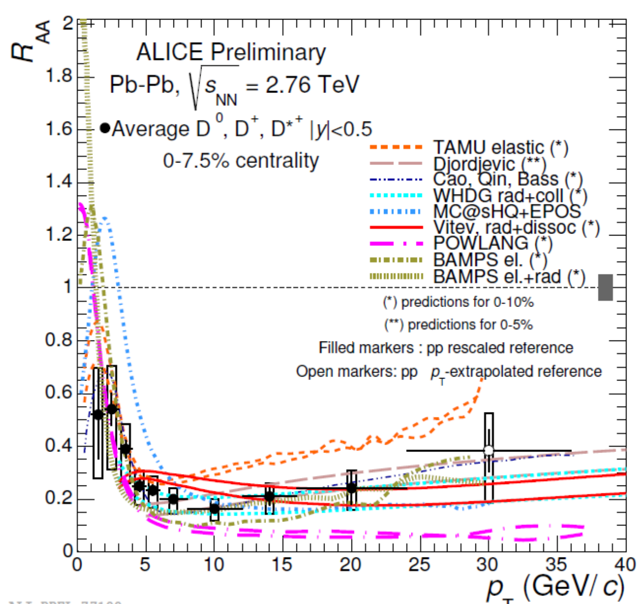
- Similar v_2 values for D mesons and charged particles
- Similar v_2 values for HF decay muons and HF decay electrons (different y)
- All channels show positive v_2 (>3 σ effect)
- **Information on the initial azimuthal anisotropy transferred to charm quarks**

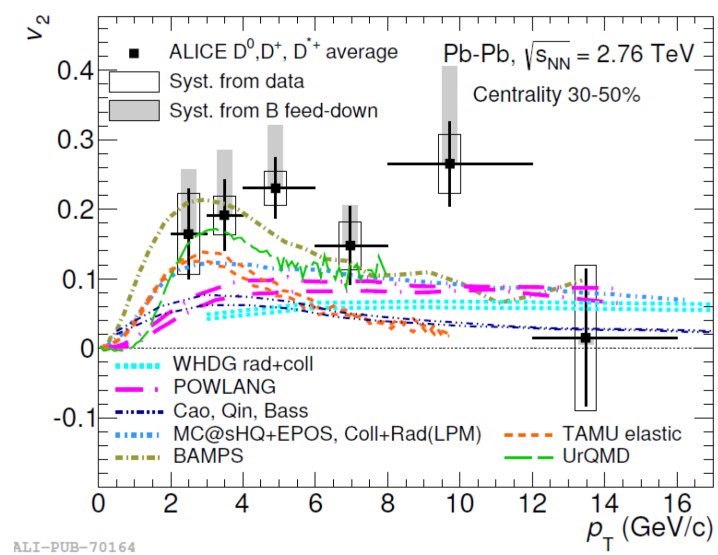
Open Heavy Flavor in Pb-Pb: R_{AA} & V_2





Simultaneous description of v_2 and R_{AA}: benchmark for models





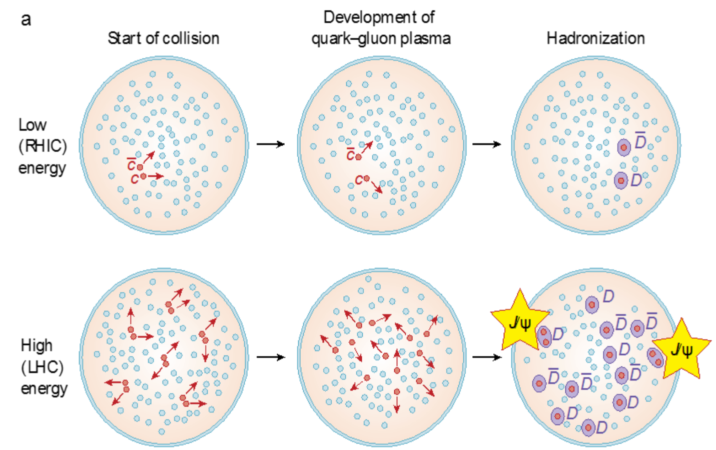
[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
POWLANG: Eur. Phys. J C 71 (2011)1666]
[M. He, R. J. Fries and R. Rapp, Phys. Rev. C86 014903; Phys. Rev. Lett.110.112301]

Open heavy flavors: a short summary

- Abundant heavy quark production at the LHC allows for detailed measurements
- R_{AA} measurements:
  - Heavy flavor production is significantly suppressed (at intermediate to high p_T) in central Pb-Pb collisions with respect to binar-scaled pp collisions.
  - Comparison to p-Pb results (R_{pPb} close to unity) points to final state effect related to the quark energy loss in the dense and hot partonic medium.
  - First experimental indications (charm more suppressed than beauty) about mass hierarchy in the energy loss.
- V_2 mesurements:
  - Indications for positive values D mesons and HF leptons (3σ at low p_T).
  - Suggests that (low-p_T) charm quarks take part in the collective motion of the system.
  - At higher p_T, (more precise) v_2 measurements may be useful to shed light on the path-length dependence of the energy loss.

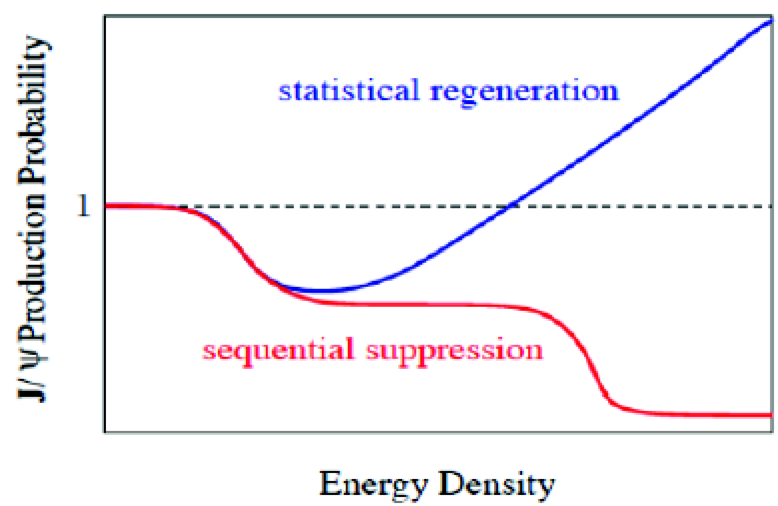
Quarkonia: suppression … and (re)-generation

- Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature
  (Digal,Petrecki,Satz PRD 64(2001) 0940150)
  → thermometer of the initial QGP temperature



- Increasing the energy of the collision the $c\bar{c}$ pair multiplicity increases and may led to charmonium production via recombination

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60



Charmonoum production **may be enhanced via (re)combination of cc pairs** at hadronization (statistical approach) or during QGP stage (kinetic recombination approach)

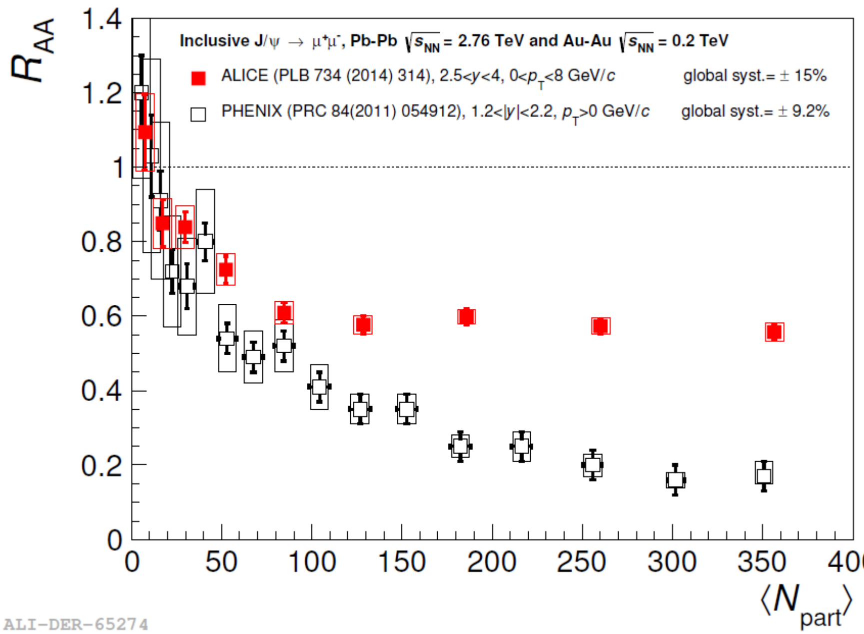
P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196, R. Thews et al, Phys.ReV.C63:054905(2001)

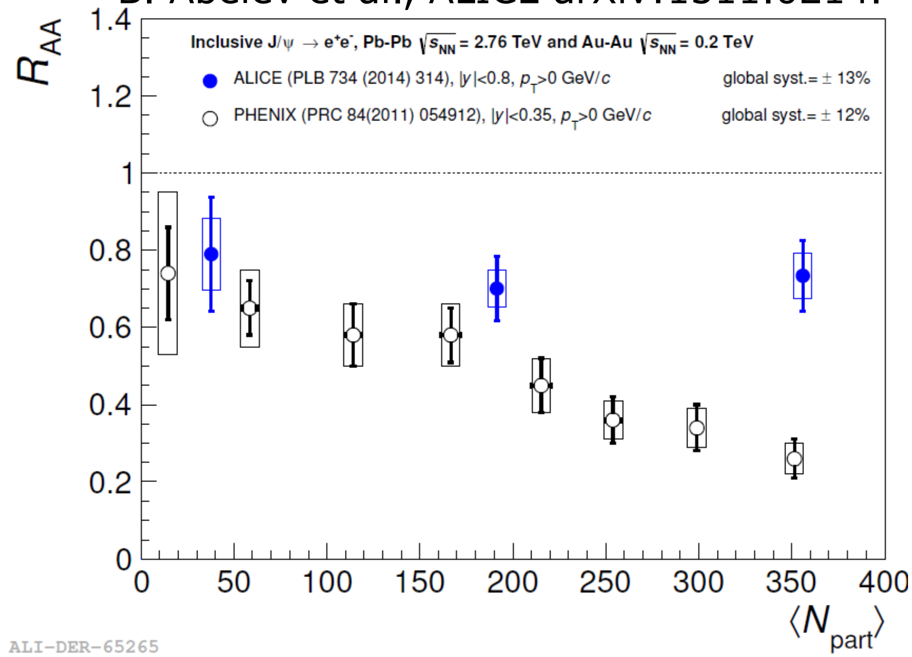
Quarkonium Results

- Focus on:
  - Pb-Pb results at $\sqrt{s_{NN}} = 2.76$ TeV
  - p-Pb results at $\sqrt{s_{NN}} = 5.02$ TeV

J/ψ R_{AA} in Pb-Pb: low p_T

B. Abelev et al., ALICE arXiv:1311.0214.



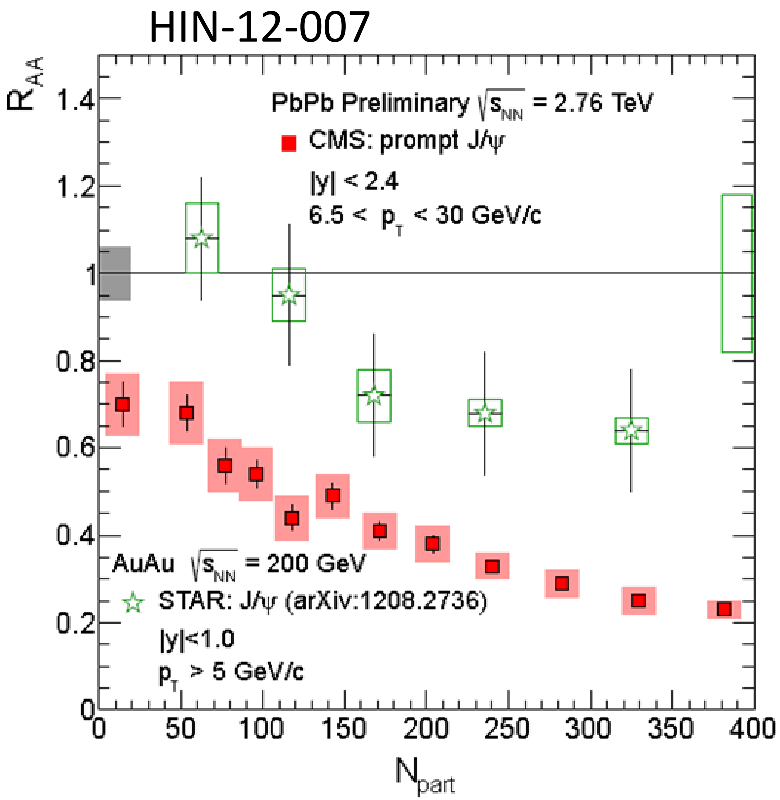


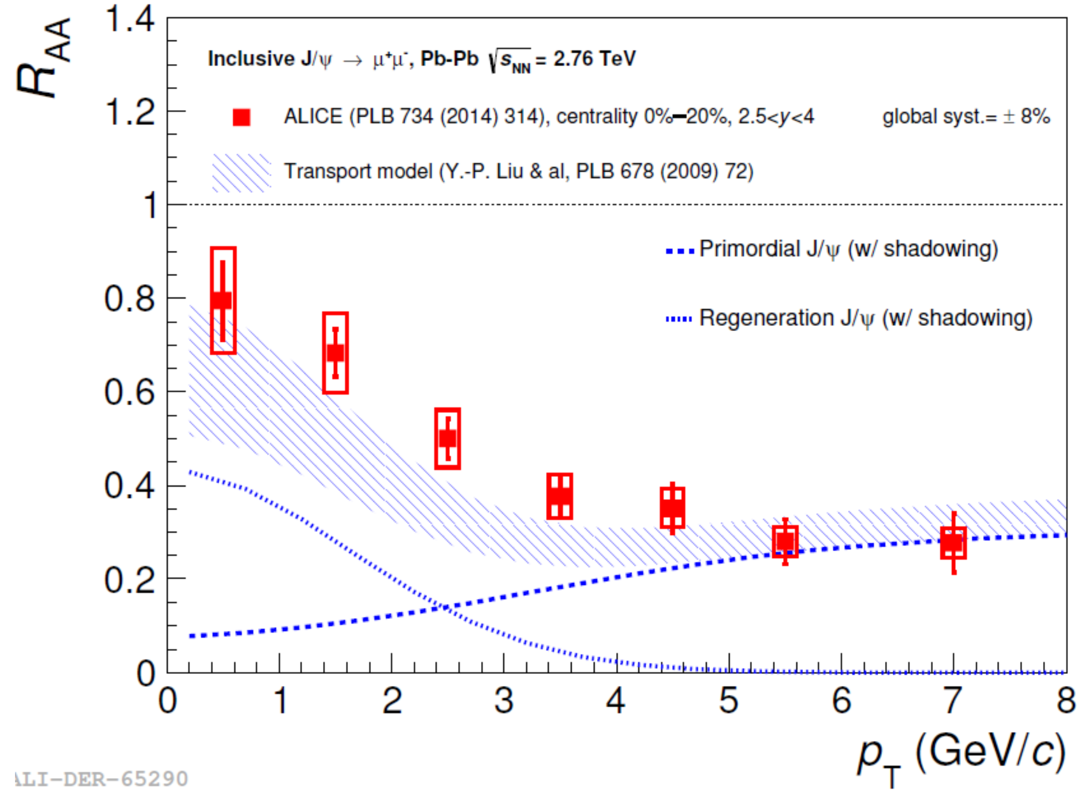
- ❑ Compare J/ψ suppression, RHIC ($\sqrt{s_{NN}}$=0.2 TeV) vs LHC ($\sqrt{s_{NN}}$=2.76 TeV)
- ❑ Results dominated by low-p_T J/ψ
  - ❑ Stronger centrality dependence at lower energy
  - ❑ Systematically larger R_{AA} values for central events in ALICE

Possible interpretation:
- RHIC energy → suppression effects dominate
- LHC energy → suppression + regeneration

How can this picture be validated?

J/ψ R_{AA} in Pb-Pb at higher p_T



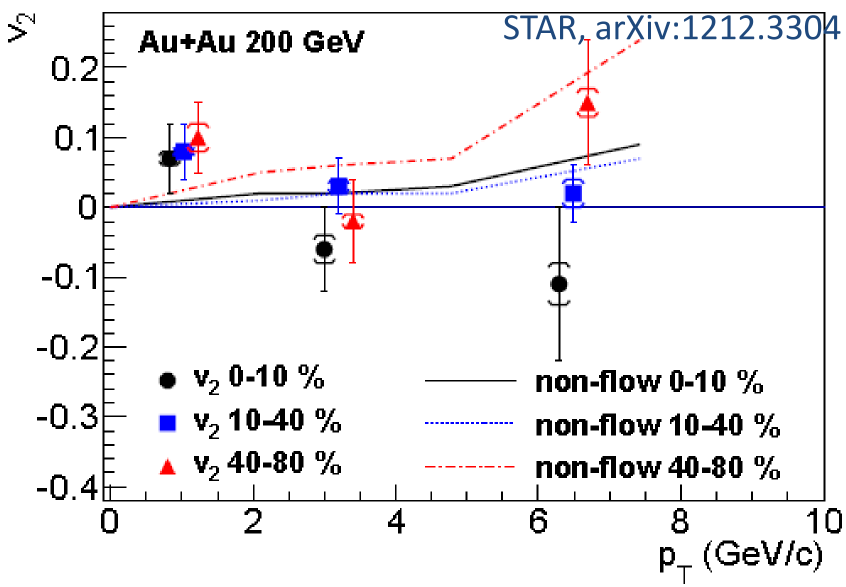


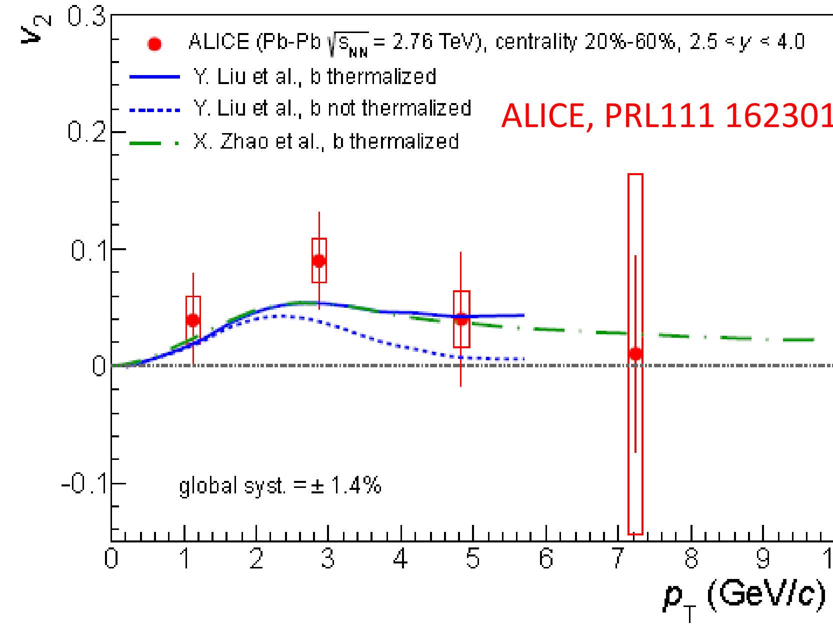
The observed suppression increases with p_T and becomes larger than the one observed at RHIC in similar (high) p_T ranges.

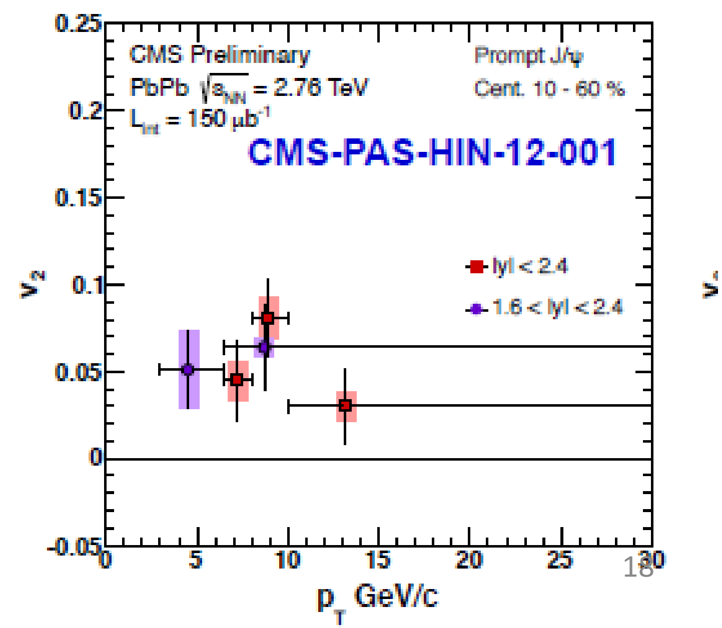
→ in line with recombination, which is expected to enhance mainly low-p_T J/ψ , as the charm quarks transverse momentum distribution is peaked at low p_T

J/ψ anisotropic flow in Pb-Pb

The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy ….



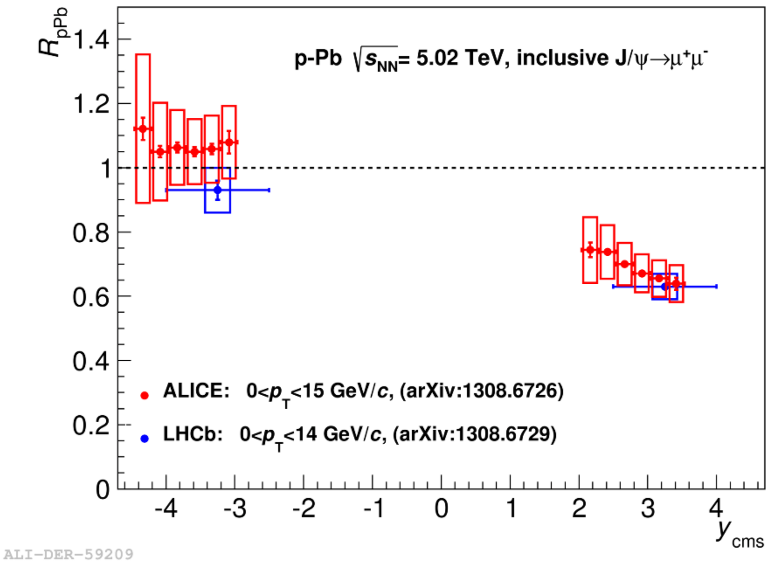




First hint for J/ψ positive v_2 in heavy-ion collisions, contrary to v_2~0 observed at RHIC!
Supports the picture that new mechanisms are at play at LHC energies

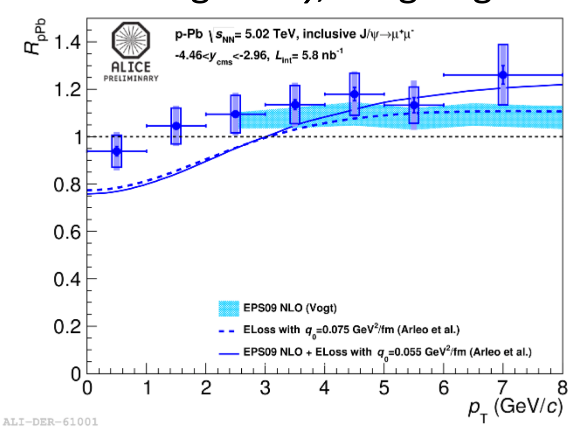
J/ψ p-Pb results

- Cold Nuclear matter effects are not negligible!

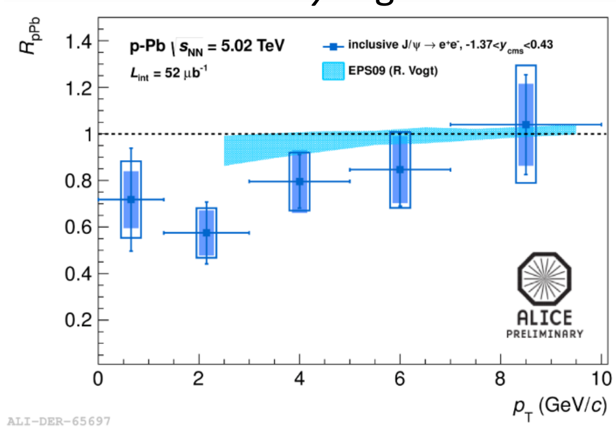


- Suppression at positive *y* (p-going, low-x in Pb nucleus) and in central rapidity region at low p_T
- No suppression (enhacement?) at negative *y*
- Fair agreement with models (shadowing + energy loss)

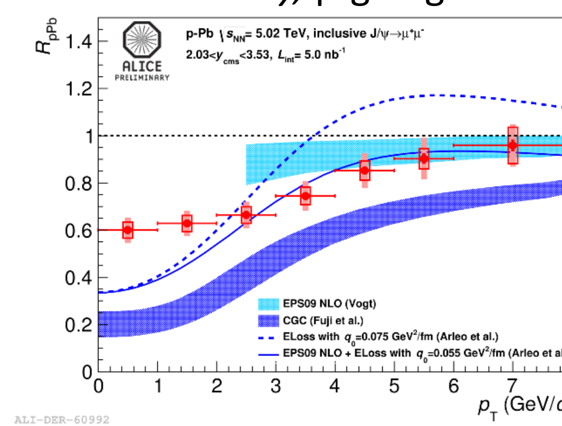
Negative *y*, Pb-going



Central *y* region

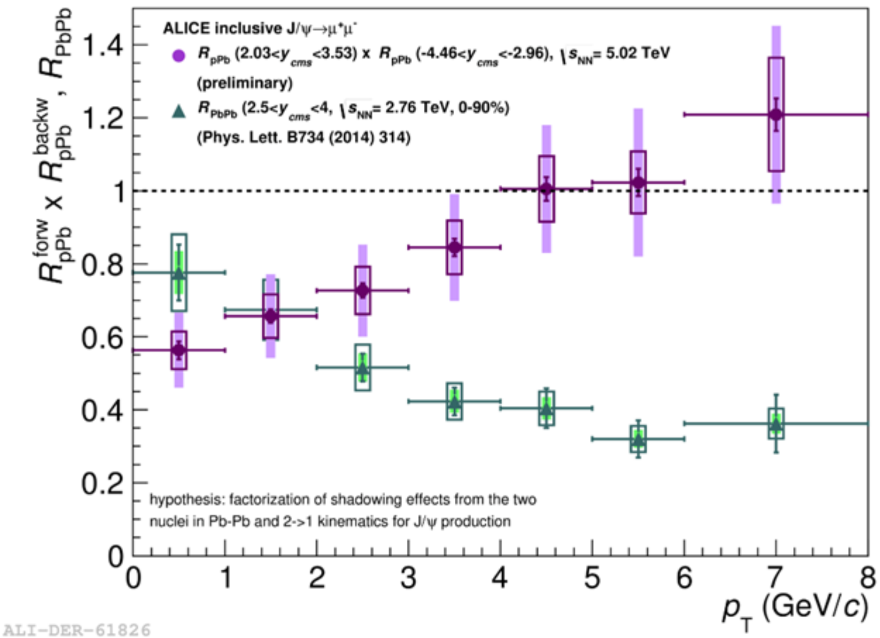


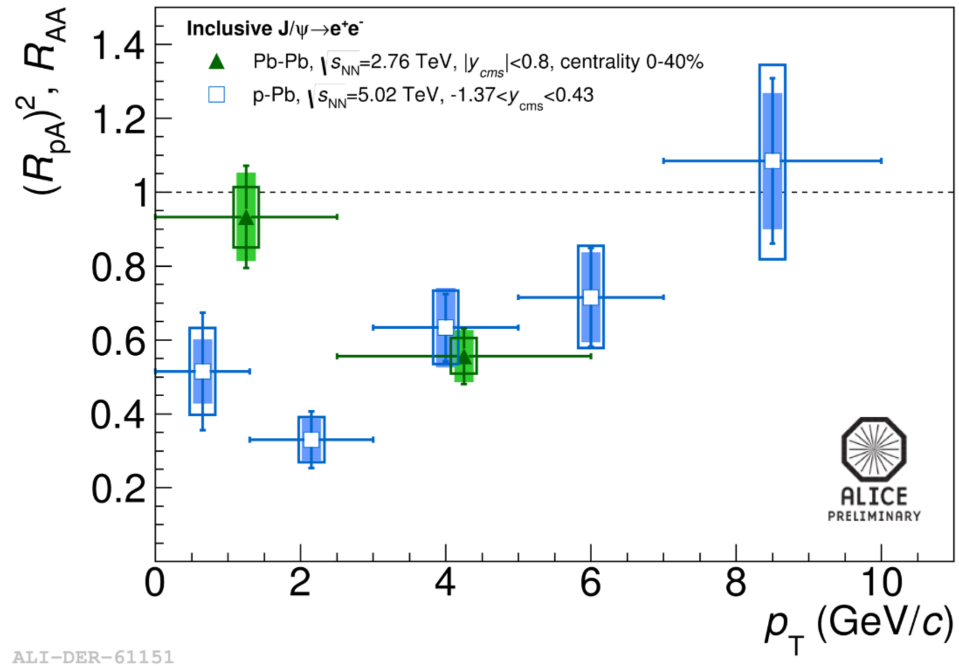
Positive *y*, p-going



J/ψ p-Pb results

- Rough extrapolation of CNM effects from p-Pb results to Pb-Pb, under the assumption that CNM effects factorize and 2→1 kinematics for J/ψ production

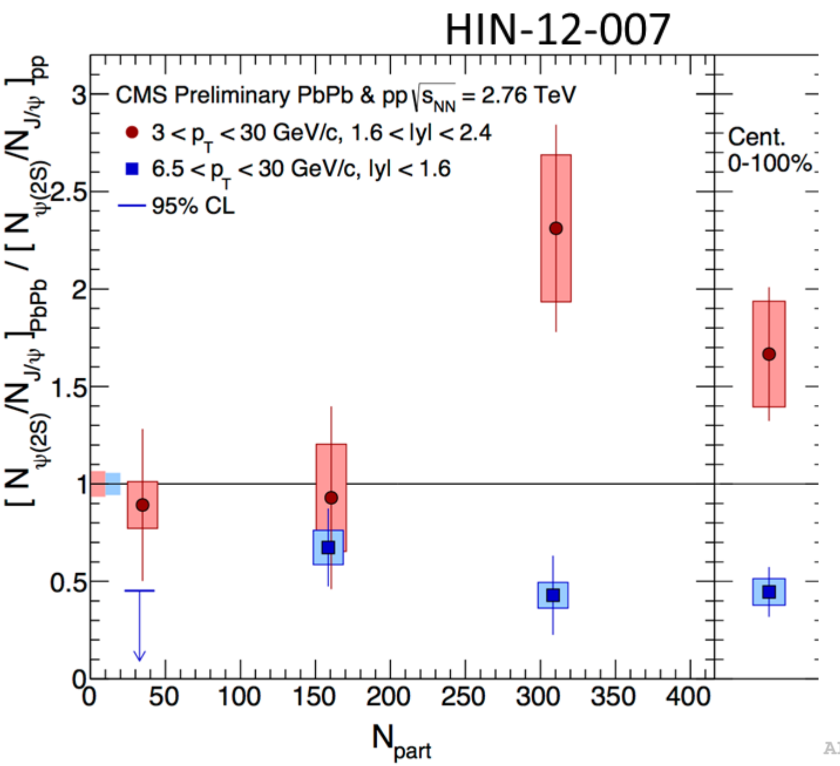


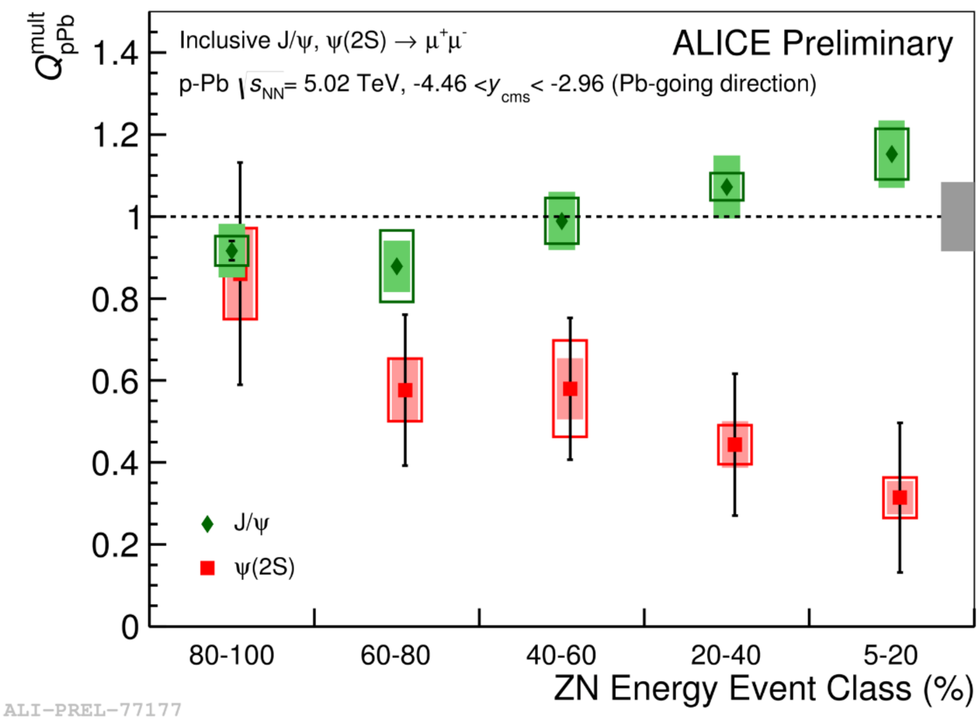


- hints of an excess of J/ψ above CNM at low p_T.
- strong suppression at high p_T.

→ These observations tend to favor the recombination scenario

ψ(2s): Pb-Pb and p-Pb Nuclear Modification Factors





Pb-Pb

- CMS: from enhancement to strong suppression moving from intermediate (p_T >3 GeV/c) to large (p_T >6.5 GeV/c) transverse momentum
- ALICE: excludes a large enhancement (not shown)

p-Pb

- ALICE: evidence for strong suppression of p_T-integrated ψ(2s) in p-Pb collisions (compared to J/ψ), increasing with the event activity

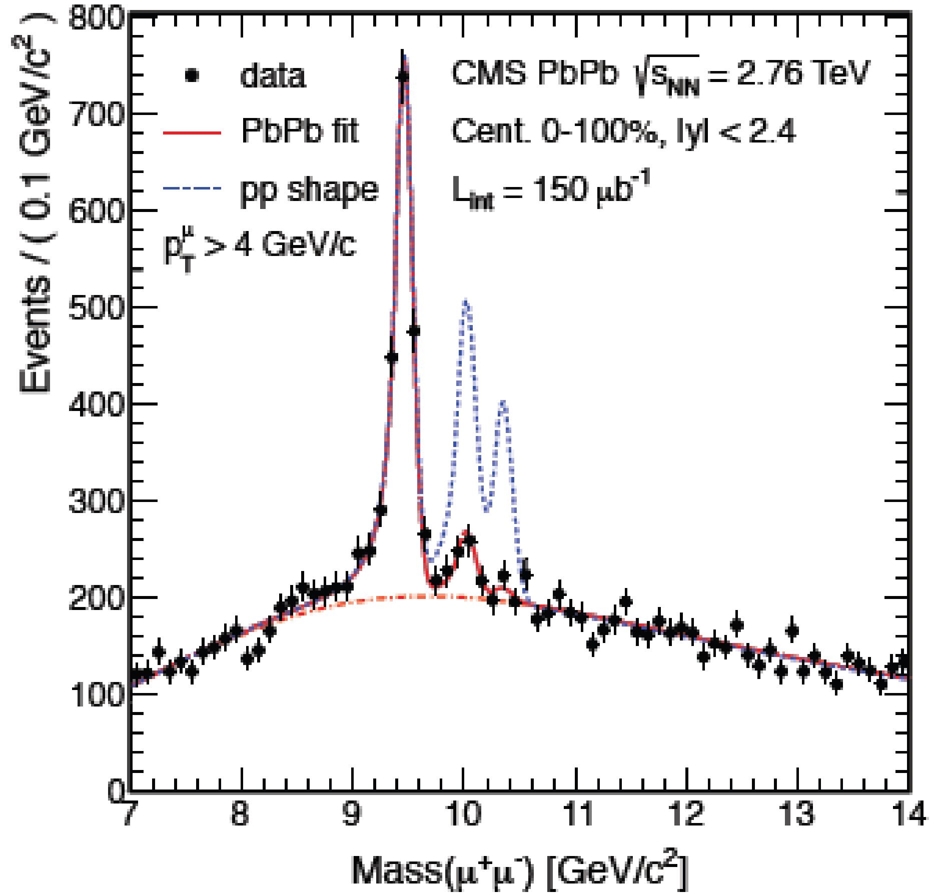
→ *How to reconcile these observations?*

The ϒ family: Pb-Pb results

➡ LHC is an ideal machine for studying bottomonium in AA collisions

Main features of bottomonium production:

- no B hadron feed-down
- gluon shadowing effects are smaller
- (re)combination expected to be less important

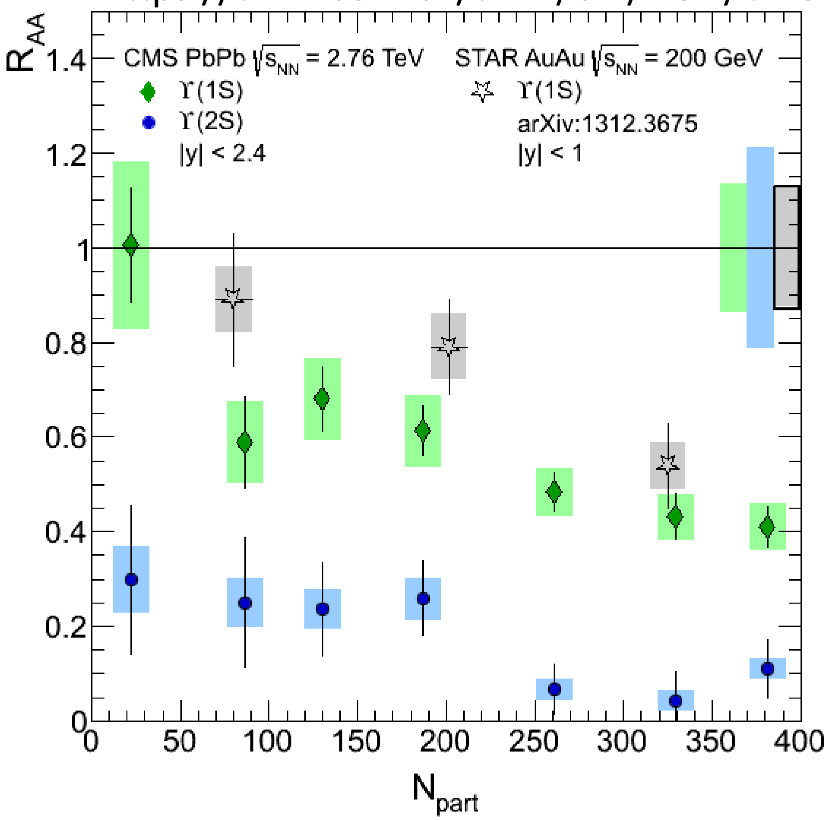


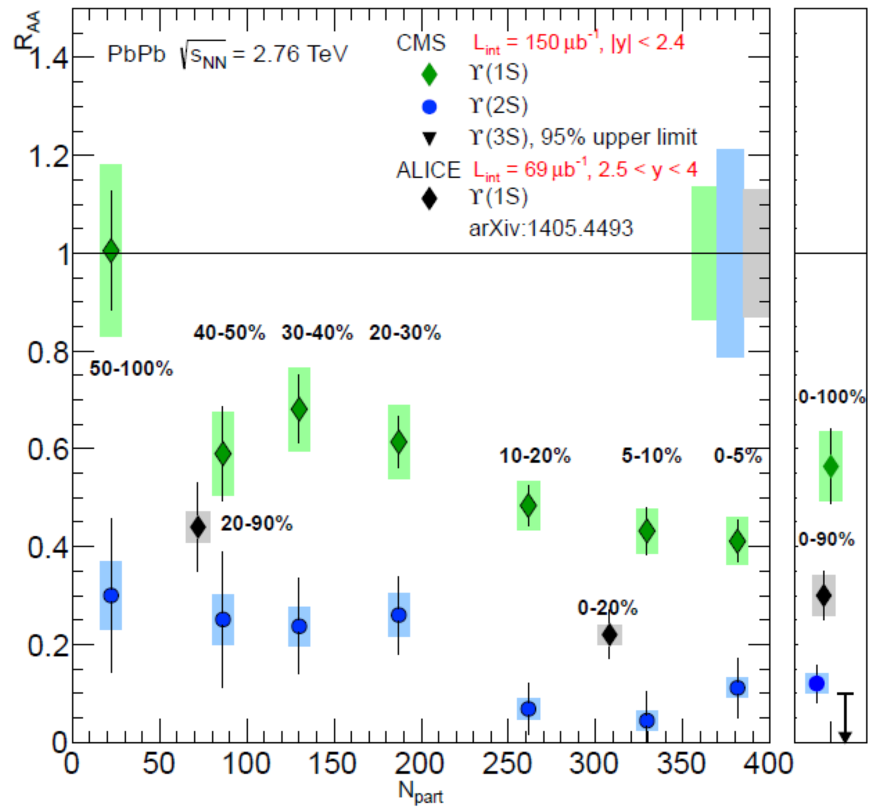
Clear suppression of ϒ(nS) in Pb-Pb wrt pp collisions

PRL 109, 222301 (2012)

Υ(nS): R_{AA} in Pb-Pb collisions

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011





- More suppression at the LHC than at RHIC?

STAR: $R_{AA}\,\Upsilon(1S) = 0.71 \pm 0.06\ (\text{stat}) \pm 0.06\ (\text{syst})$

CMS: $R_{AA}\,\Upsilon(1S) = 0.56 \pm 0.08\ (\text{stat}) \pm 0.07\ (\text{syst})$

- More suppression at forward rapidity ? (ALICE data)

- Sequential suppression of Υ states $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$

- Υ(1S) suppression might be compatible with excited state suppression (~50% feed-down)?

Υ(nS): R_{AA} in p-Pb collisions

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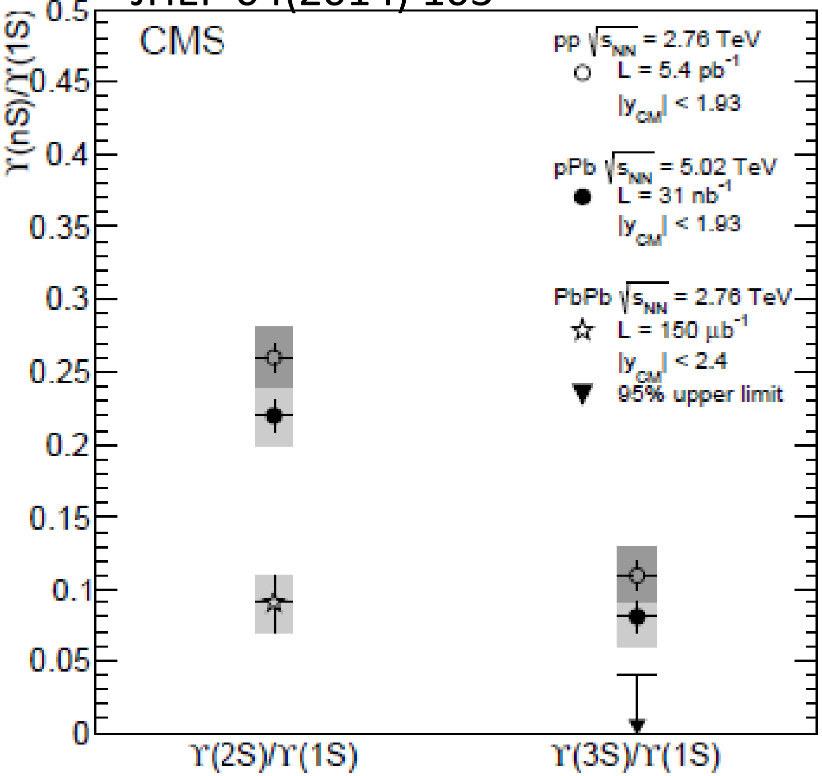
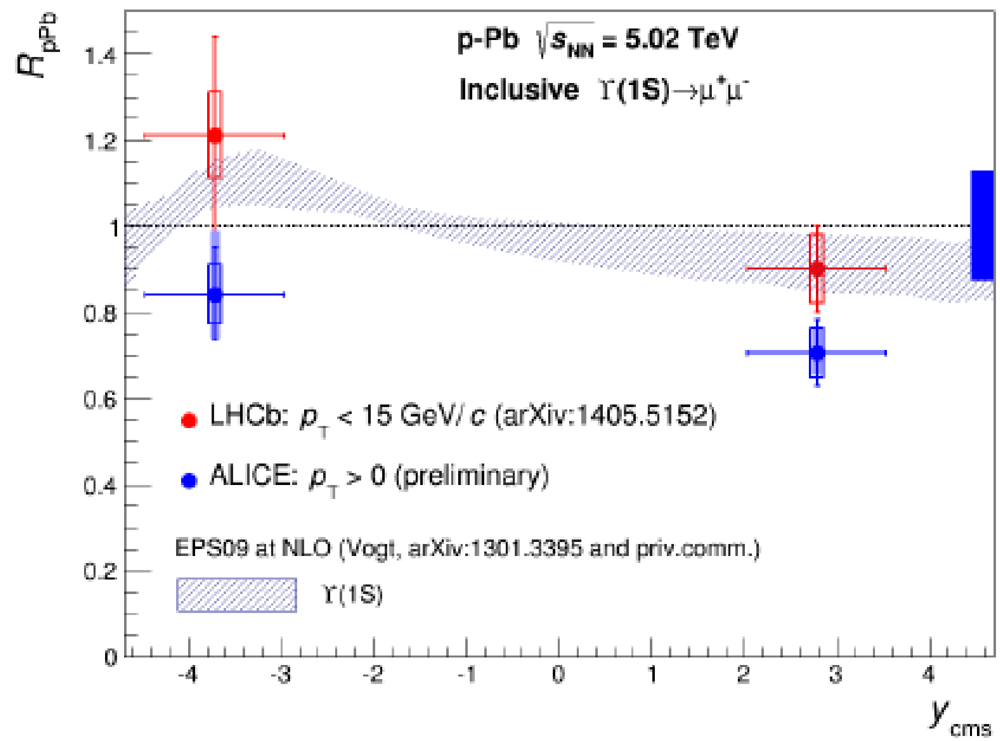




- (small) relative suppression of Υ(2S) and Υ(3S) w.r.t. Υ(1S) at mid rapidity.
- Hint for (small) suppression of Υ(1S) at forward rapidity (in qualitative agreement with models)
- CNM effects are small and cannot account for all the effects observed in Pb-Pb

Quarkonia: a short summary

- Two main mechanisms expected to play a role in heavy-ion collisions at LHC energies:
  - Suppression in a deconfined medium
  - (re)-generation of charmonium via charm quark (re)-combination

  → Run I data in qualitative agreement with such a picture

- About J/ψ
  - ✓ R_{AA} larger than at RHIC (at any rapidity), weak centrality dependence
  - ✓ R_{AA} depends on p_T and becomes smaller at large transverse momenta
  - ✓ CNM effects are sizeable, but cannot account for the effects observed in Pb-Pb

- About bottomonia
  - ✓ Ordering in the suppressions of the three Upsilon states with their binding energy clearly observed → in line with sequential melting
  - ✓ Suppression of $\Upsilon(1S)$ comparable with the one expected as a consequencce of the suppression of higher states → is $\Upsilon(1S)$ melting temperature still above the LHC - Run I reach ?

Conclusions

- Complete set of results from run-I is now available
  - Confirms the role of heavy quarks/quarkonia as privileged probes for the study of Quark-Gluon Plasma

- Open charm/beauty strongly affected by the medium
  - Energy loss pattern in agreement with calculations
  - Energy loss mass dependence observed
  - Significant v_2 confirms the presence of collective effects (low pT) opens to the study of path-length dependence of energy loss (high pT)

- Charmonia/bottomonia
  - Bottomonia sequential suppression according to their binding energy
  - J/ψ results show effects of re-generation during the QGP-phase and/or at phase boundary

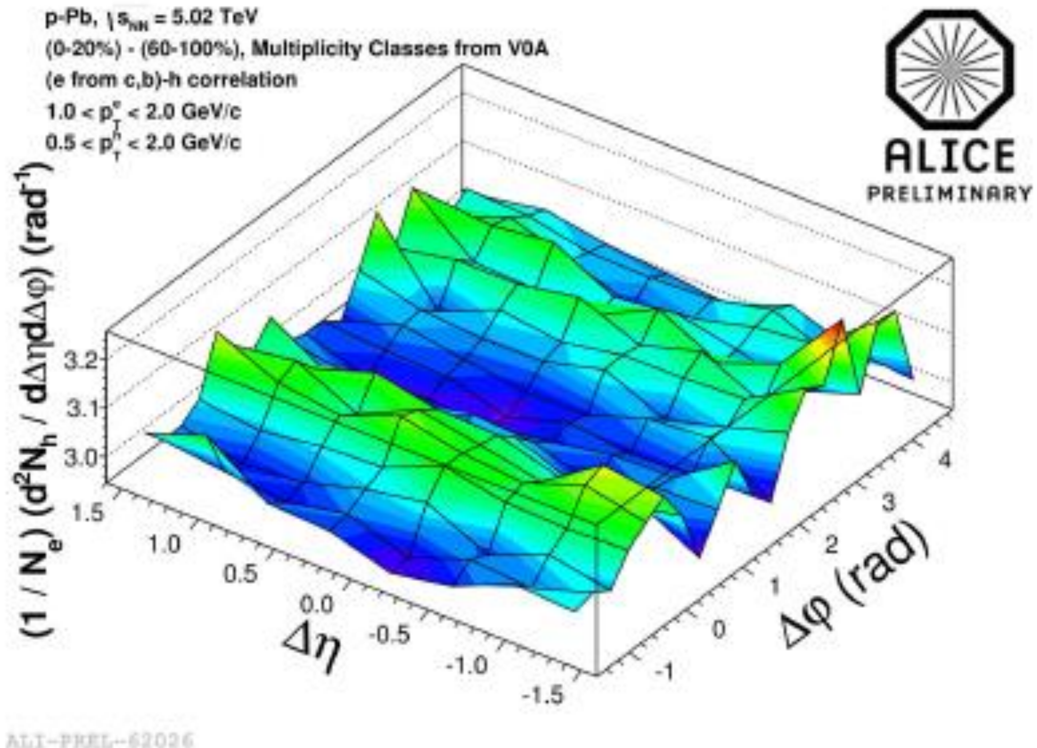
- Many (most) of the heavy-quark/quarkonia - related observables would benefit from more data to sharpen the conclusions

  → Run-II , with increased beam energy

  → Experiment upgrades, 2018 onwards

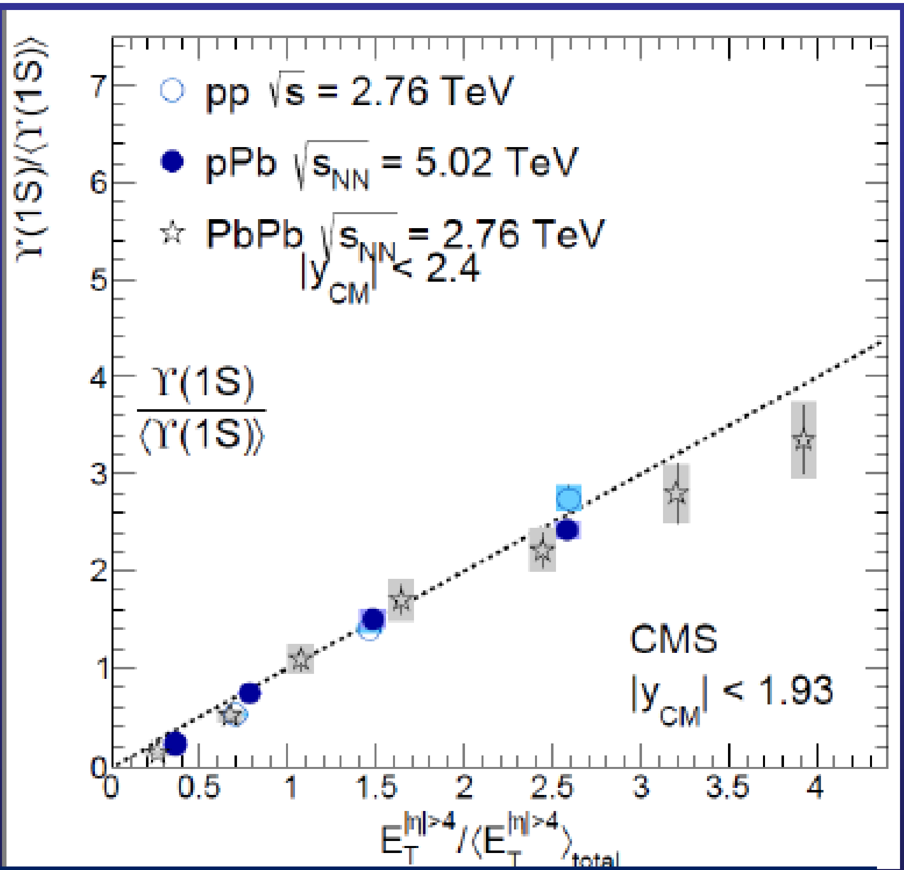
Backup

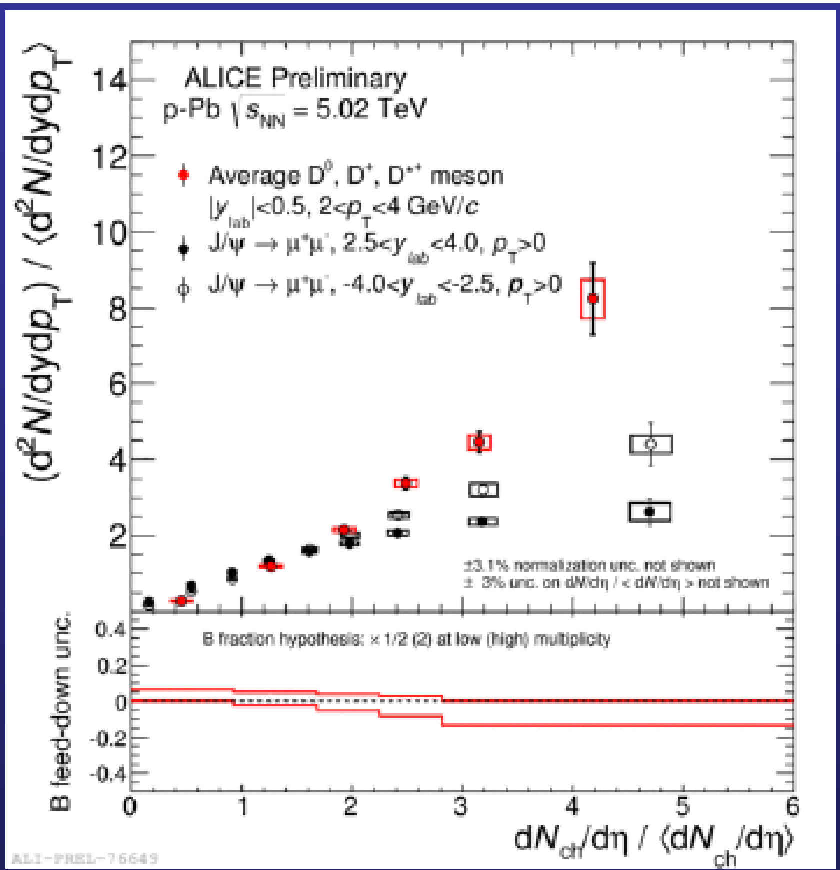
$e \leftarrow HF$-hadron azimuthal correlations in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV



- Removal of jet peak via subtraction of multiplicity classes: (0-20%) - (60-100%)
- Long range correlation featuring a double ridge structure observed for $1 < p_{\mathrm{T}}^{e} < 2$ GeV/c and $0.5 < p_{\mathrm{T}}^{h} < 2$ GeV/c
- The double ridge observed in light hadrons (Phys.Lett. B719 (2013) 29-41) is also observed in heavy-flavour sector. The mechanism (CGC? Hydro?) that generates it affects also heavy flavours

Evolution of the yields in pp, p-Pb and Pb-Pb

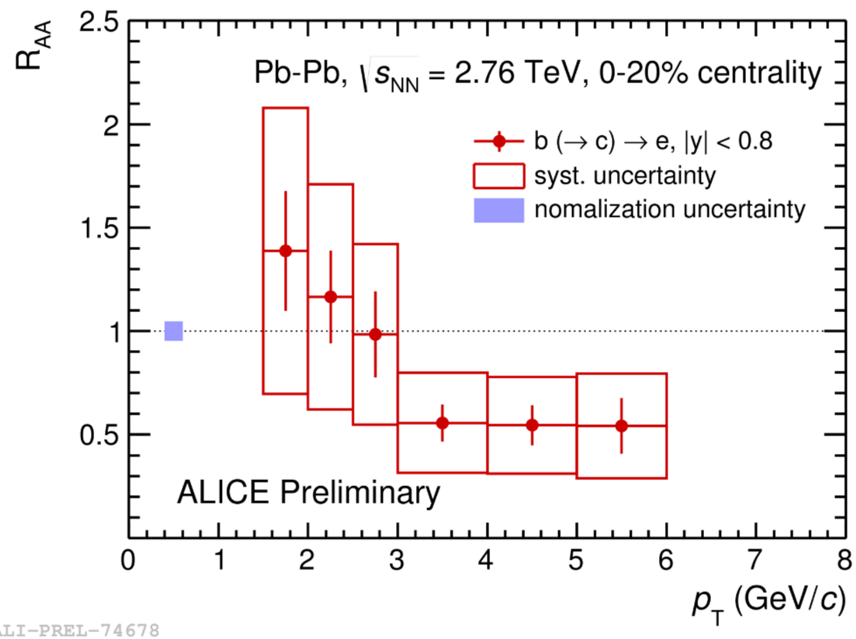


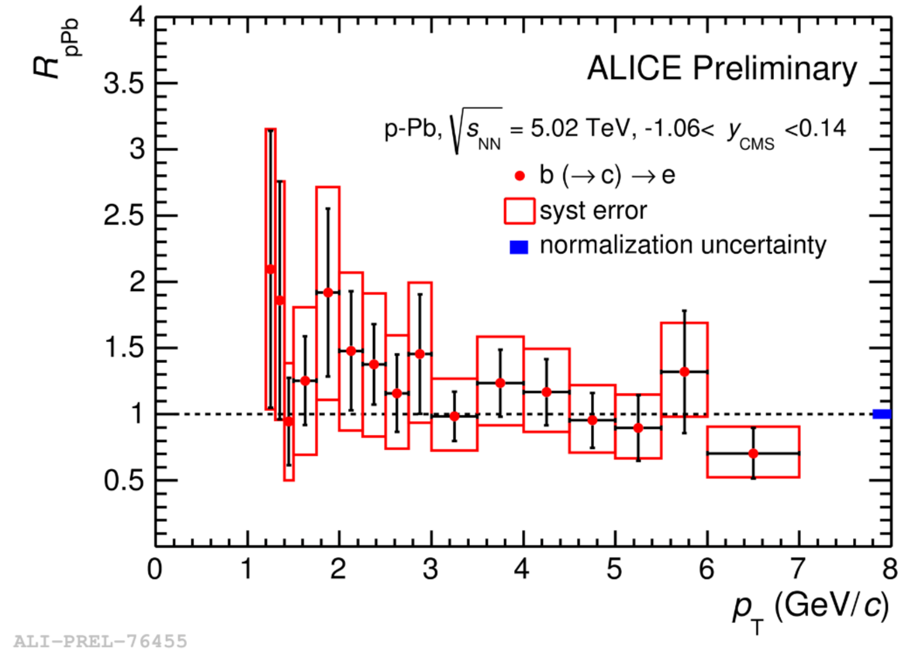


S. Chatrchyan et al.(CMS), JHEP 04(2014) 103

- charmonia/bottomonia/open charm *relative yields* show similar increasing trend as a function of the event activity
- Role of MPI in the hard sector?

Electrons from B decay in Pb-Pb





- Analysis based on the electron impact parameter distribution
- Pb-Pb: indication for R_{AA}<1 at p_T larger than 3 GeV/c
- p-Pb: R_{AA}compatible with unity

→ b-quark affected by interection with hot and dense medium