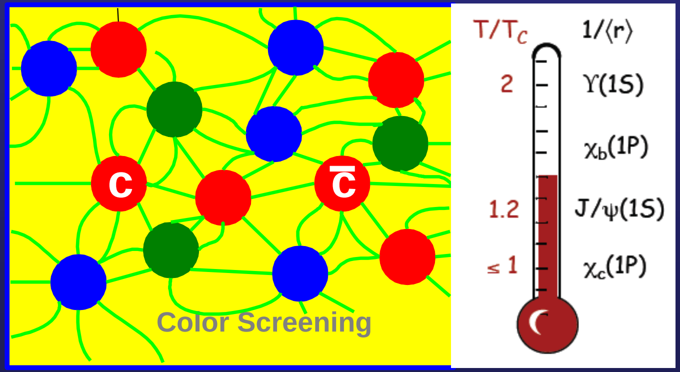
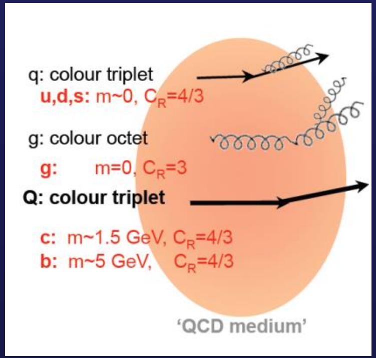
Quarkonia and heavy flavors: where do we stand ? What next?

E. Scomparin (INFN-Torino)

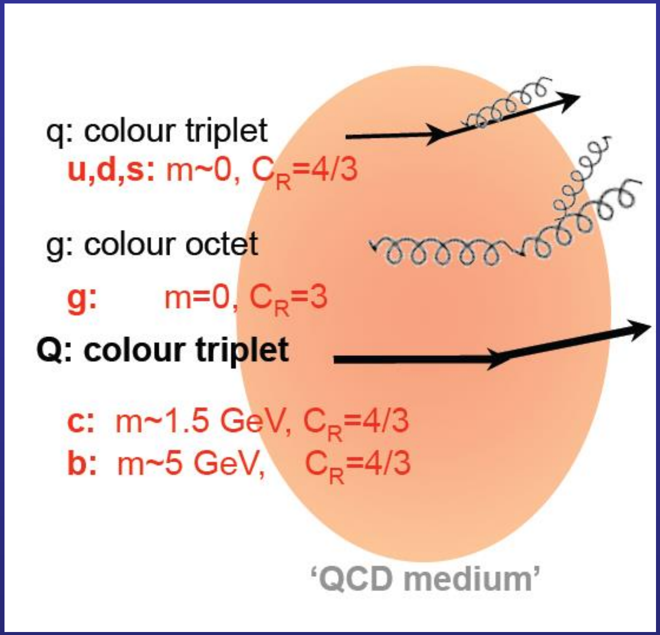
Quarkonia → Sensitive to the temperature of QGP





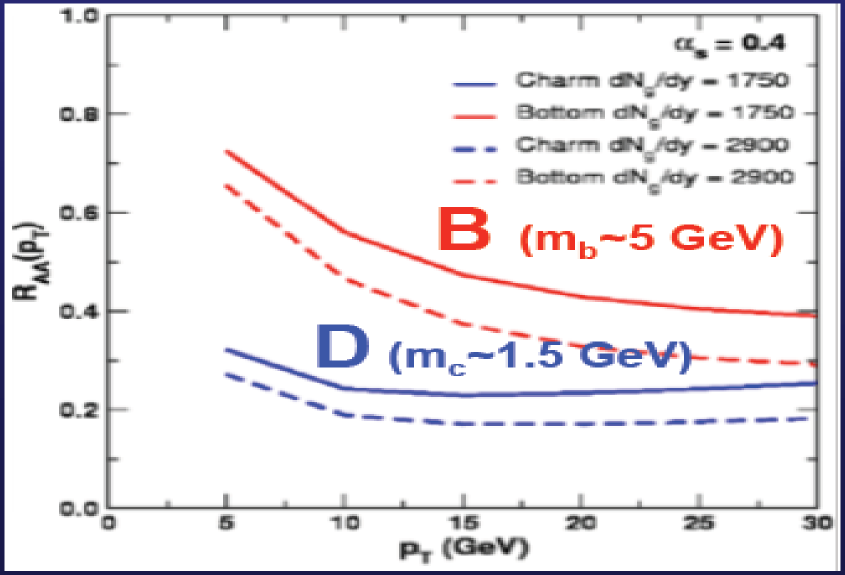
Probe the opacity of QGP ← Open heavy quarks

Heavy quark energy loss…



- Fundamental test of our understanding of the energy loss mechanism, since ΔE depends on
  - Properties of the medium
  - Path length

…but should also critically depend on the properties of the parton
  - Casimir factor ($C_R^g = 3$, $C_R^q = 4/3$)
  - Quark mass (dead cone effect)



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

which should imply

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

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

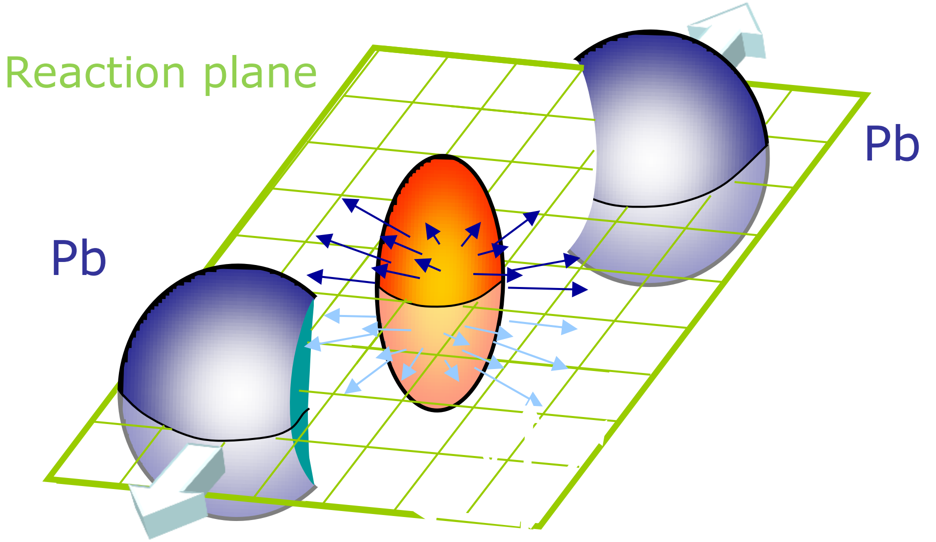
S. Wicks, M. Gyulassy, JPG35 (2008) 054001

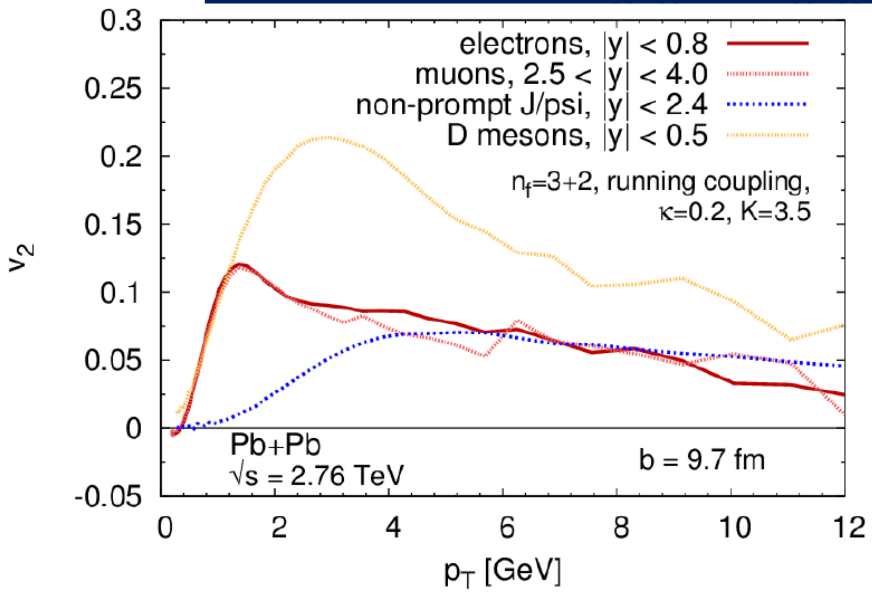
… and elliptic flow

- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium → $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium → Transported through the full system evolution

- Low/intermediate p_T: collective motion, thermalization
- High p_T: path-length dependence of heavy-quark energy loss

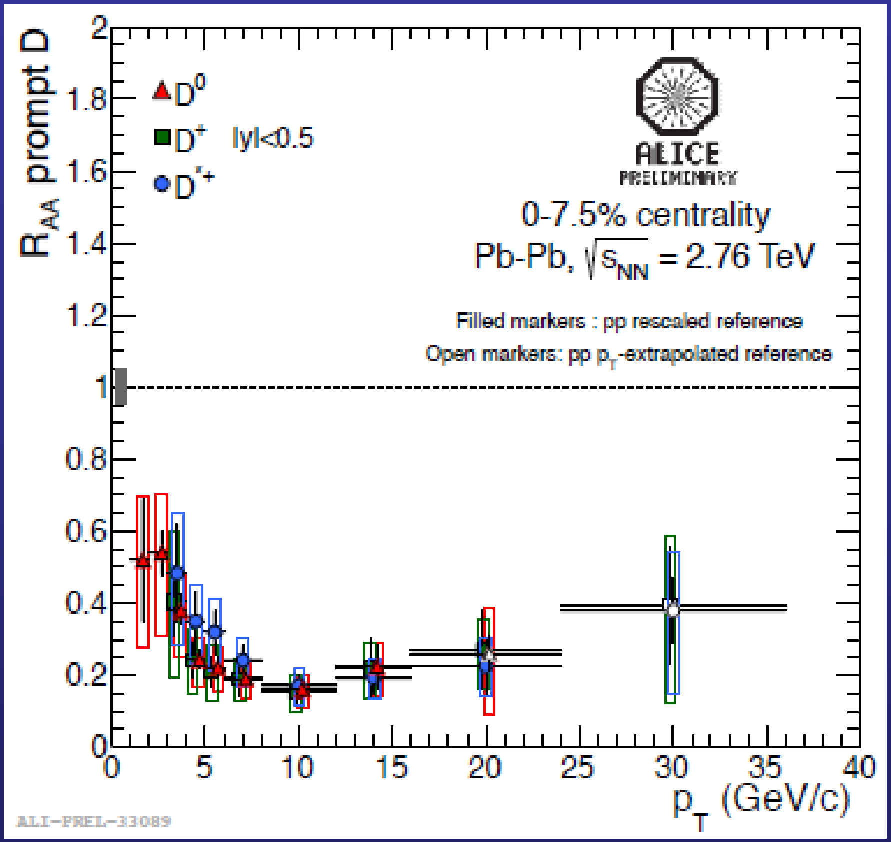
J. Uphoff et al., PLB 717 (2012), 430

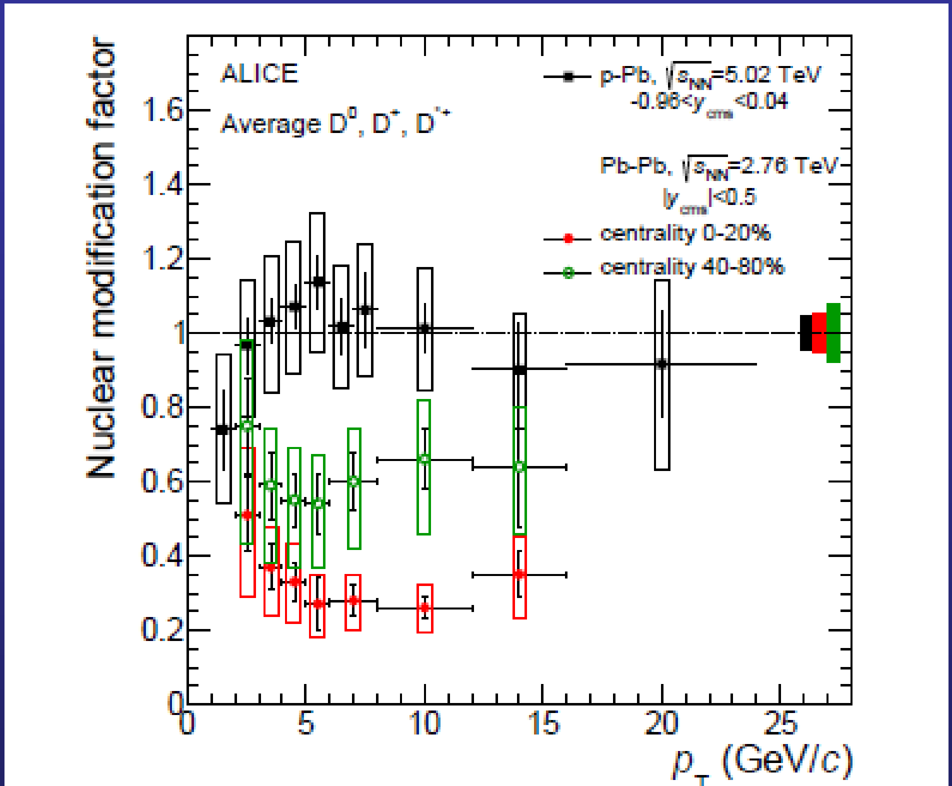




LHC: unprecedented abundance of heavy quarks
Opportunity for a deeper understanding of the underlying physics

Pb-Pb and p-Pb: results on D-mesons





B. Abelev et al. (ALICE), arXiv:1405.3452

- D^0, D^+ and D^{*+} R_{AA} agree within uncertainties

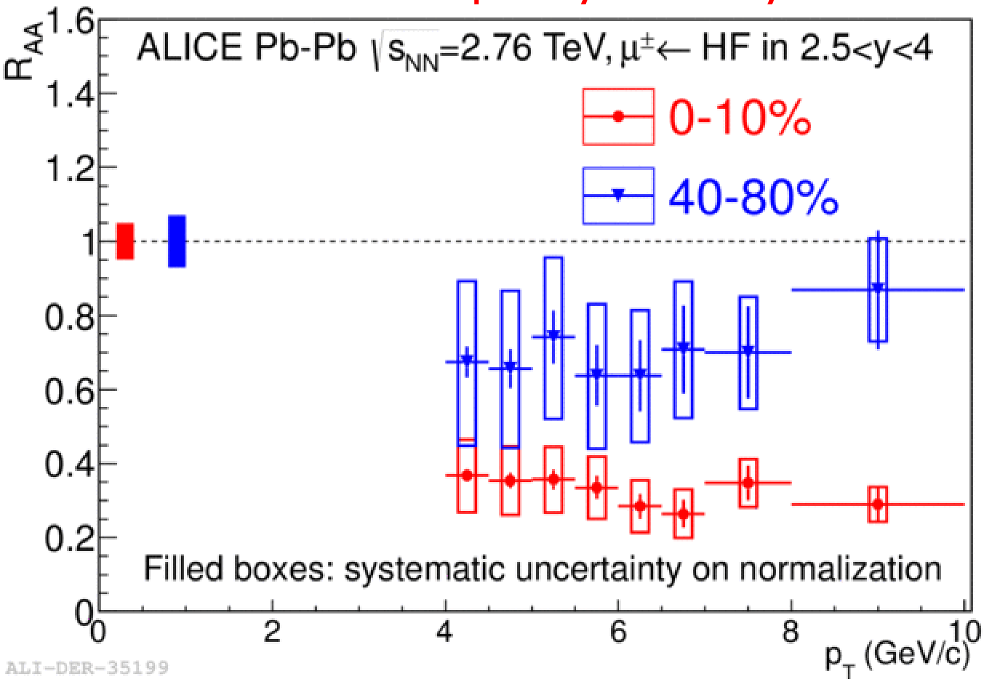
Strong suppression of prompt D mesons in central collisions
→ up to a factor of 5 for p_T≈10 GeV/c

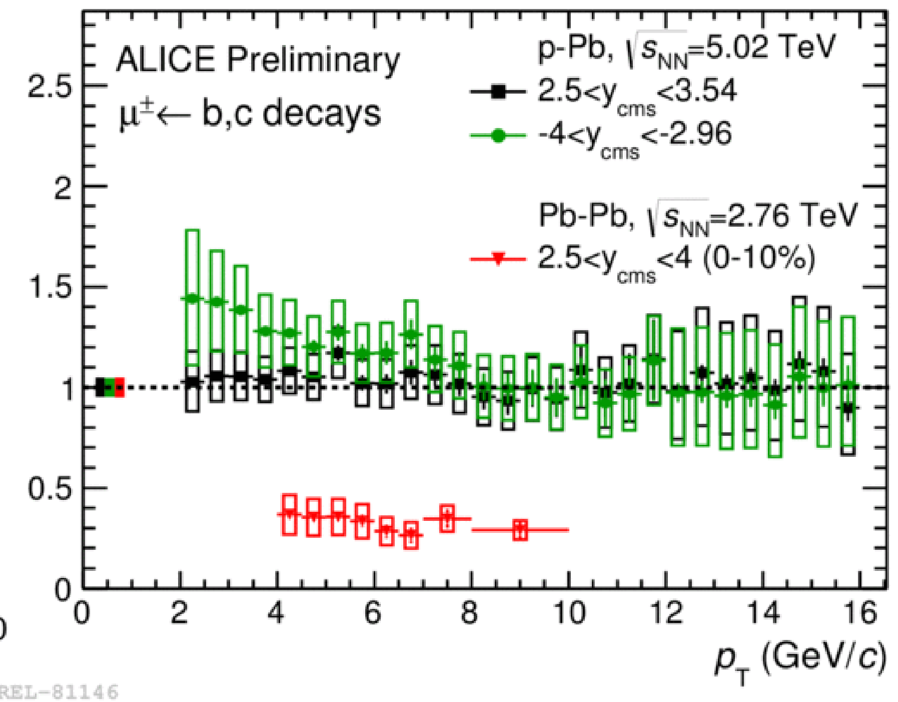
- Comparison with corresponding results for p-Pb collisions

Effect observed in central Pb-Pb due to strong final state effects induced by hot partonic matter

Pb-Pb and pPb: results on B,D→ muons

Forward rapidity: 2.5<y<4



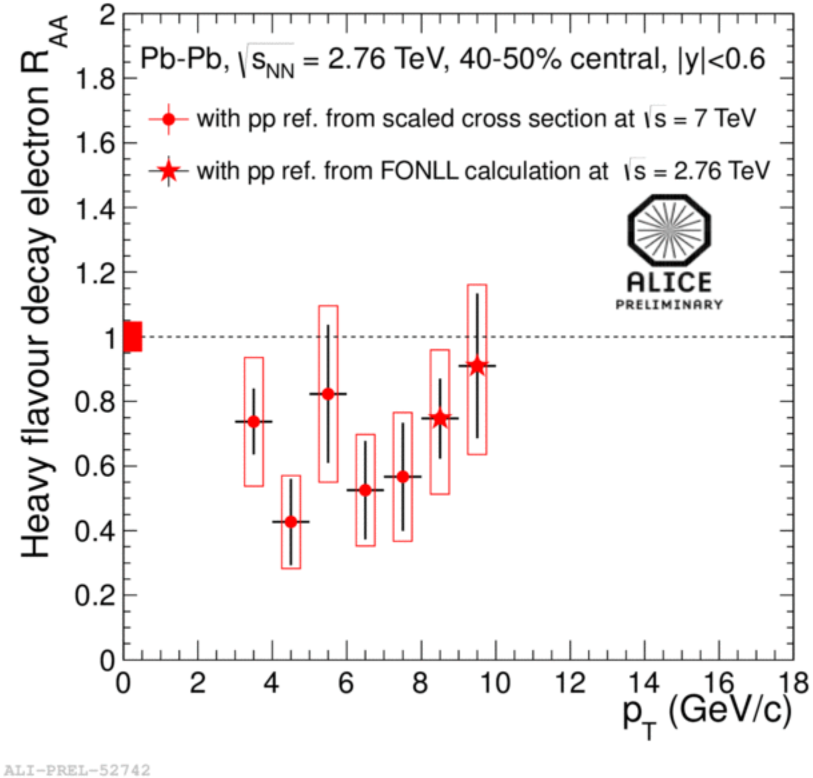


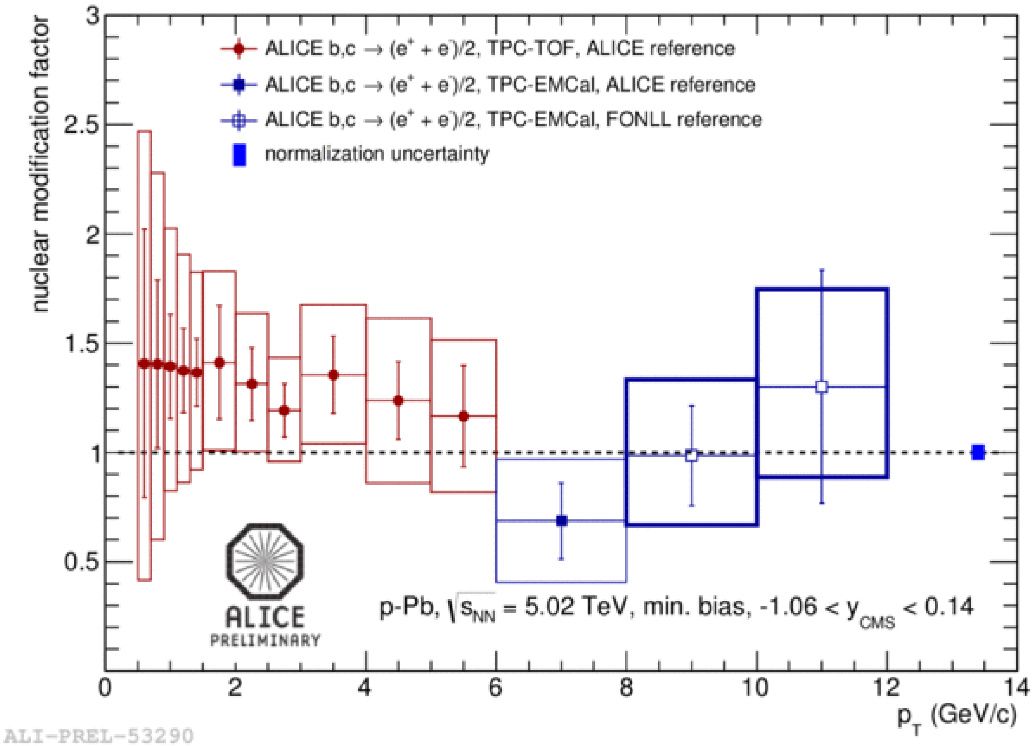
B. Abelev et al. (ALICE), PRL109 (2012) 112301

- Larger suppression (factor 3-4) in the 10% most central collisions with respect to 40-80% centrality class
- Suppression in the 10% most central Pb-Pb collisions due to a hot matter effect
- No separation of B/D decays

Pb-Pb and pPb: results on B,D→ electrons

Central rapidity: |y|<0.6





- ❑ Results available up to p_T=18 GeV/c for central events (EMCAL)
- ❑ Clear suppression for central collisions in the studied p_T range
- ❑ Stronger suppression for central collisions (hint)
- ❑ R_{pPb} compatible with unity within uncertainties
  → Pb-Pb suppression due to final state effects
- ❑ No separation D vs B (possible, based on electron impact parameter, but with rather large uncertainties)

Pb-Pb and pPb: results on B,D→ electrons

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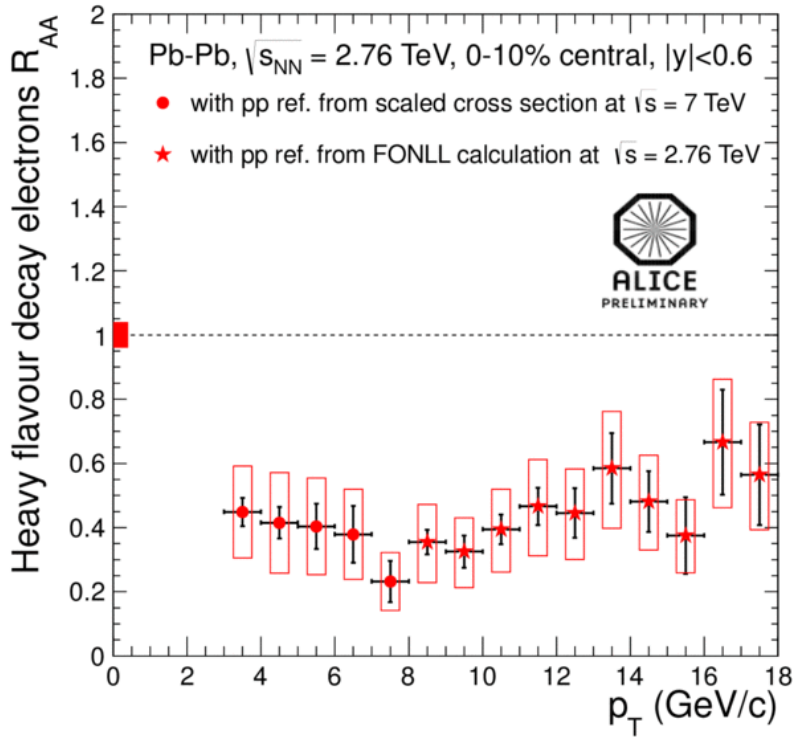

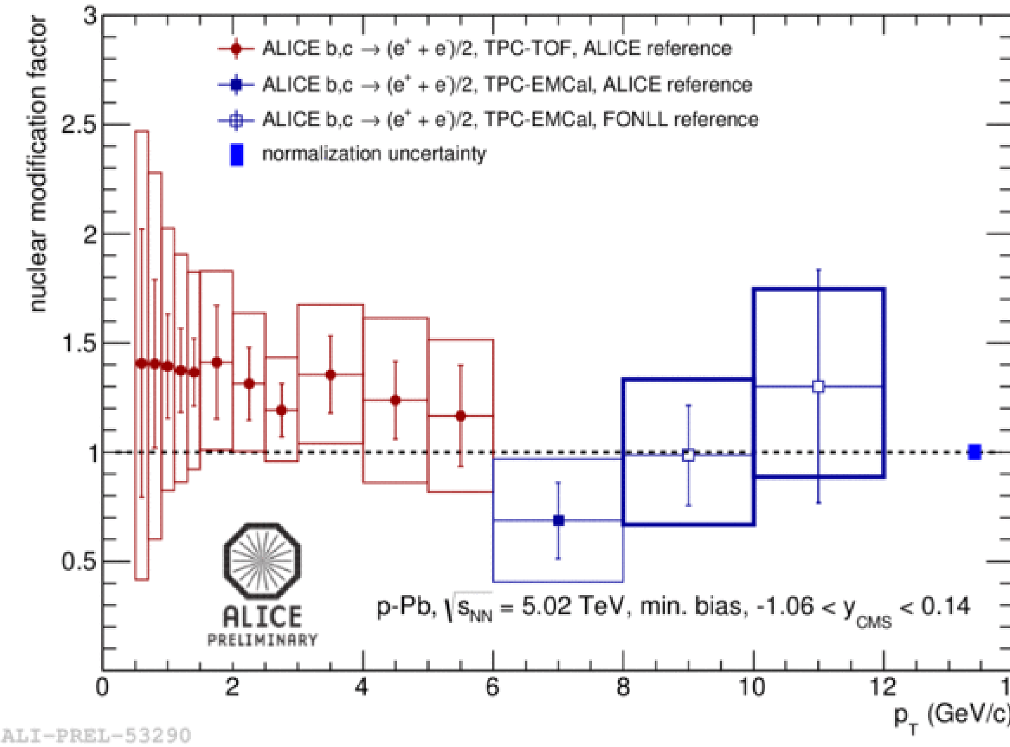

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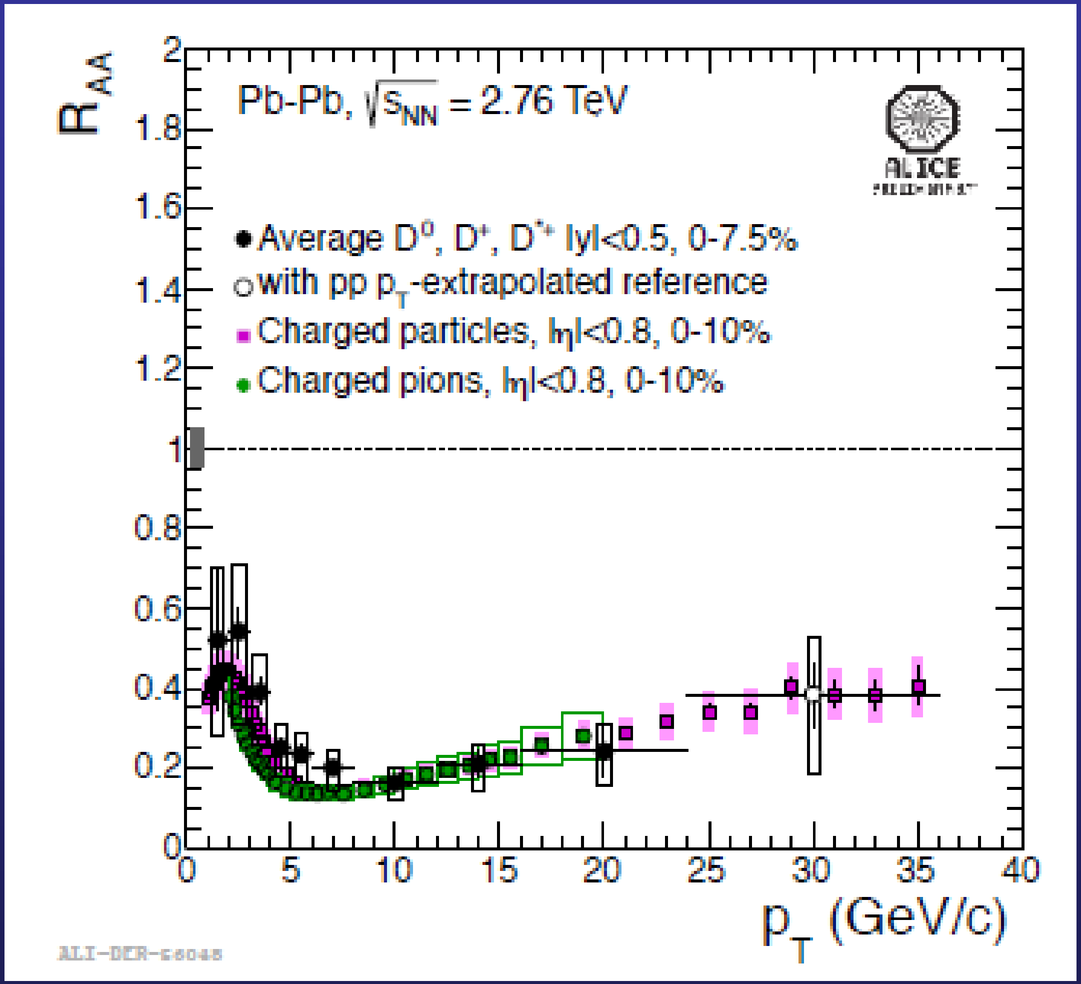
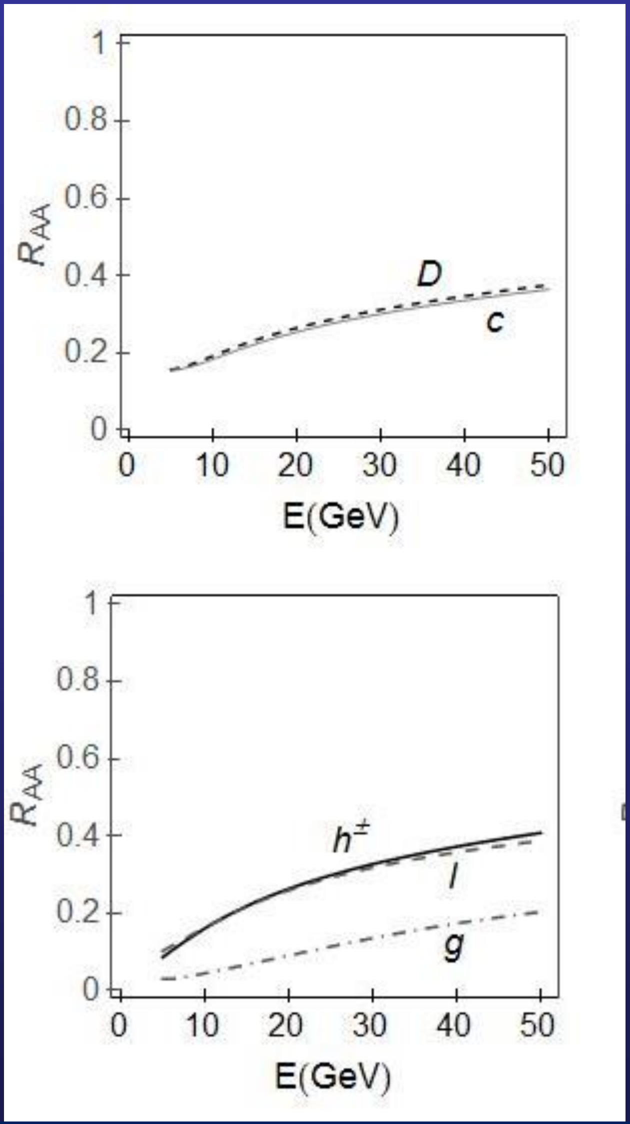
Comparison D vs $\pi/h^{\pm}$

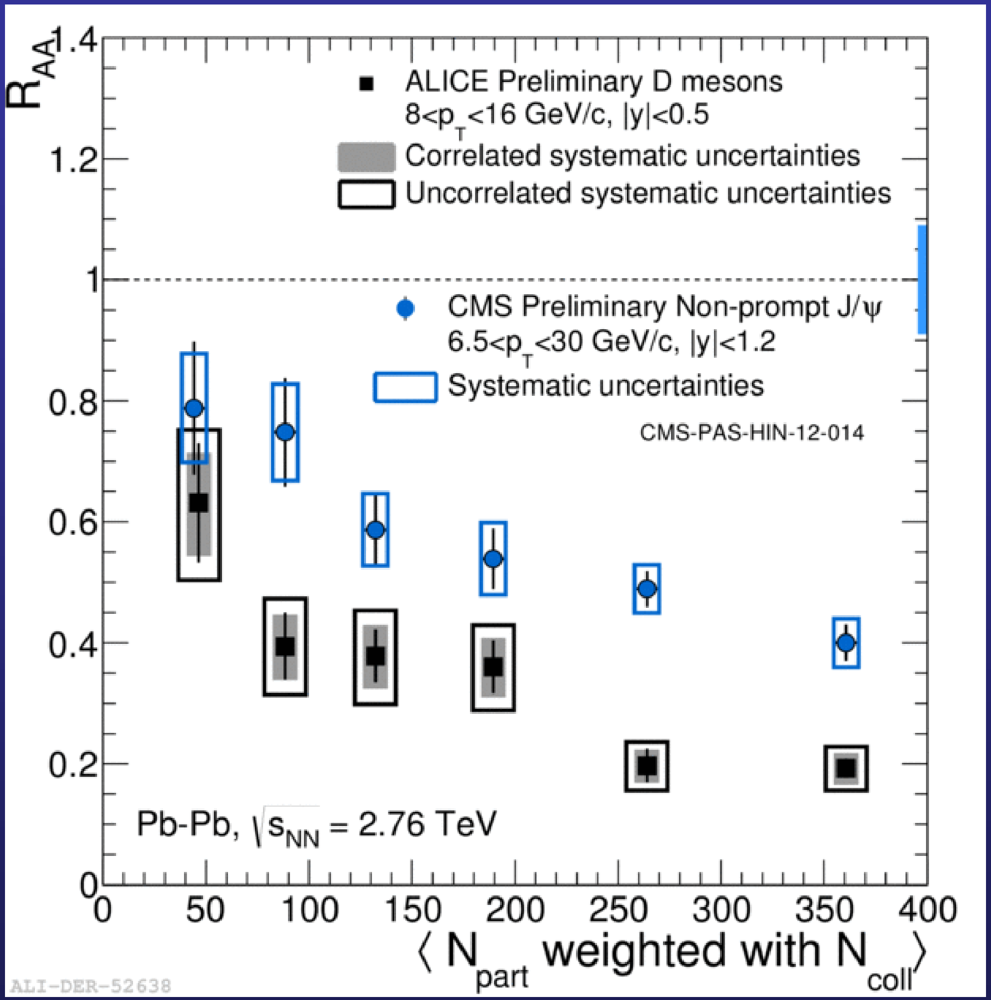




- ❑ Test the mass ordering of energy loss
- ❑ ΔE(q,g)>ΔE(c) ? → Not evident, but….
  - ❑ Different quark spectrum
  - ❑ Fragmentation effect

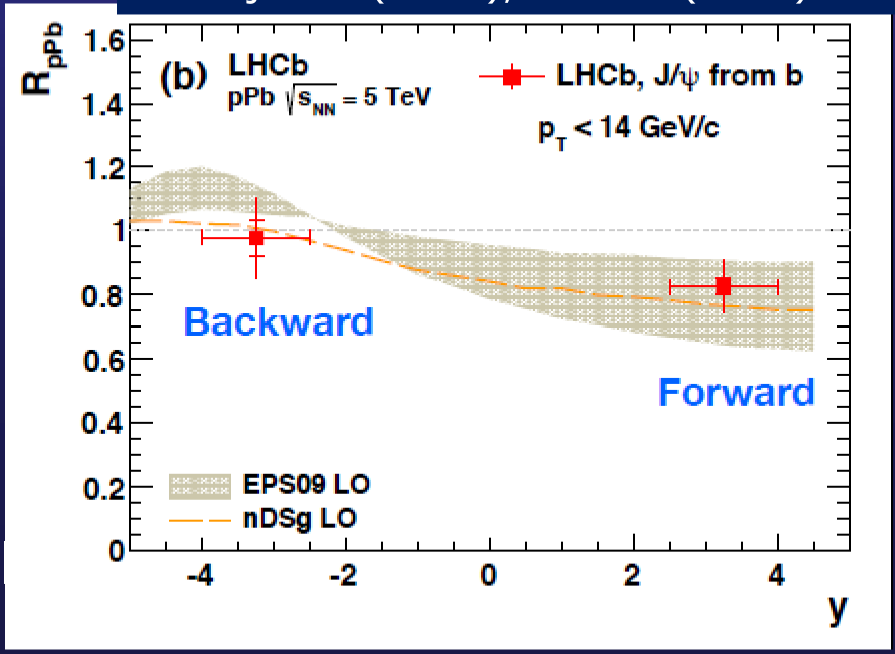
M.Djordjevic, PRL112, 042302 (2014)

Charm vs beauty



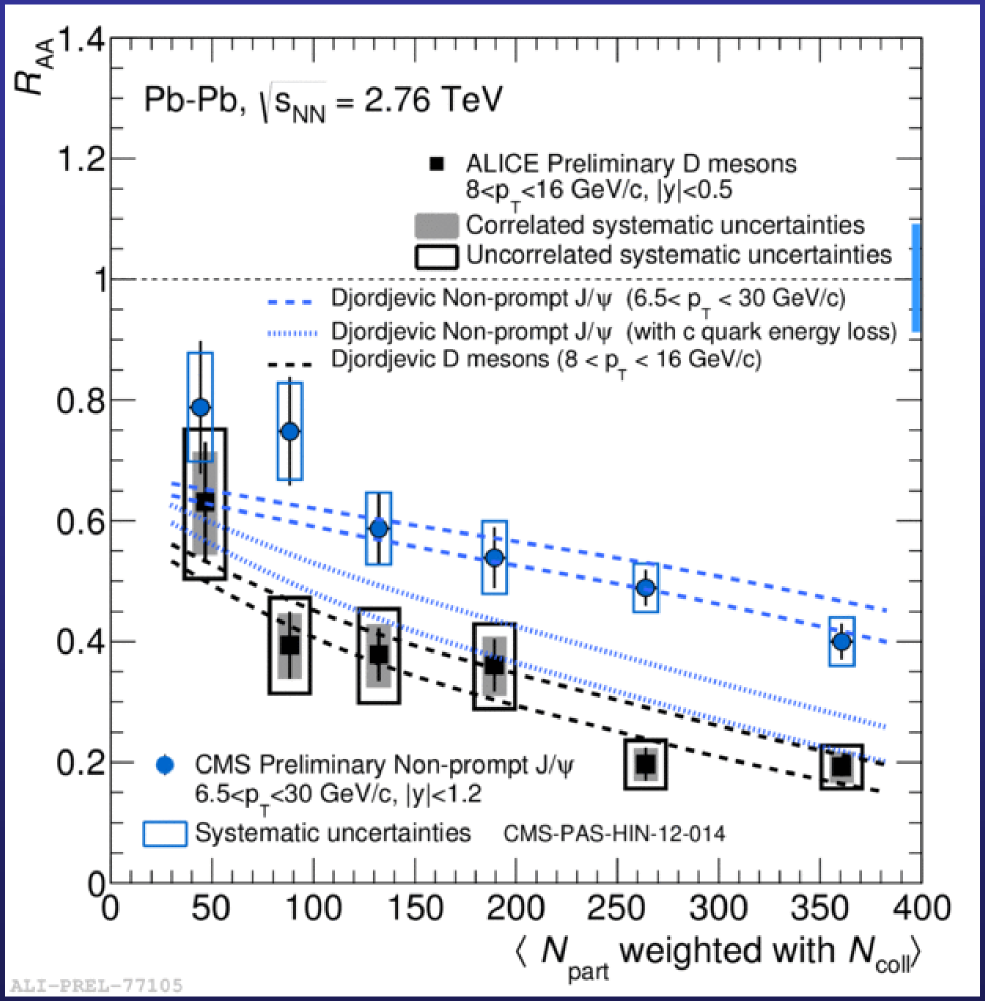
- Comparing **direct D** results with **non-prompt J/ψ**
- Similar kinematic range ($\langle p_T \rangle \sim 10$ GeV/c)
- In agreement with expectations $R_{AA}(B) > R_{AA}(D)$
- **Comparison with** models → mass-related effect

R. Aaij et al.(LHCb), JHEP 02(2014) 072



- p-Pb results on b → small or no effect at backward and forward y
- What about mid-y ?

Charm vs beauty



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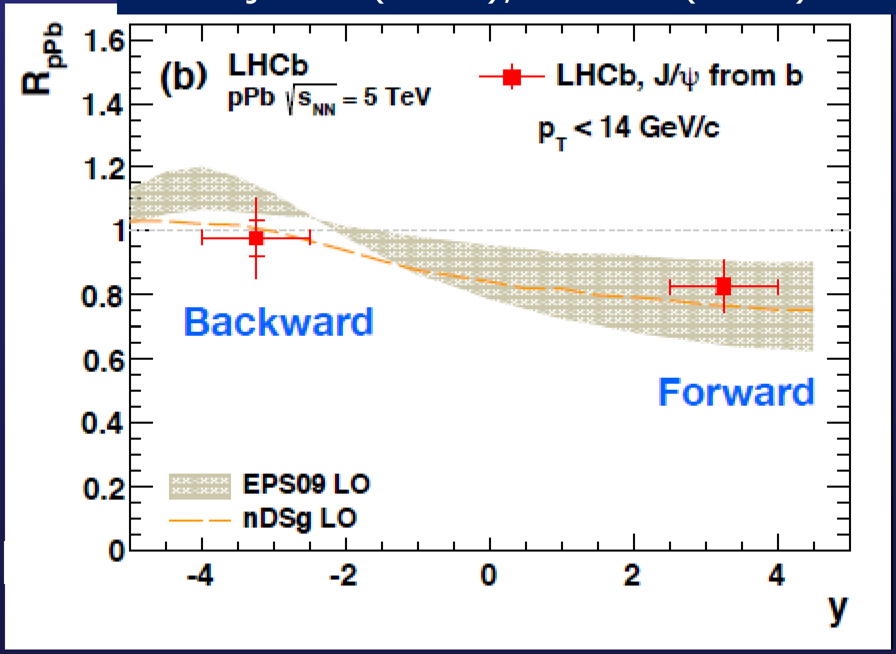
R. Aaij et al.(LHCb), JHEP 02(2014) 072



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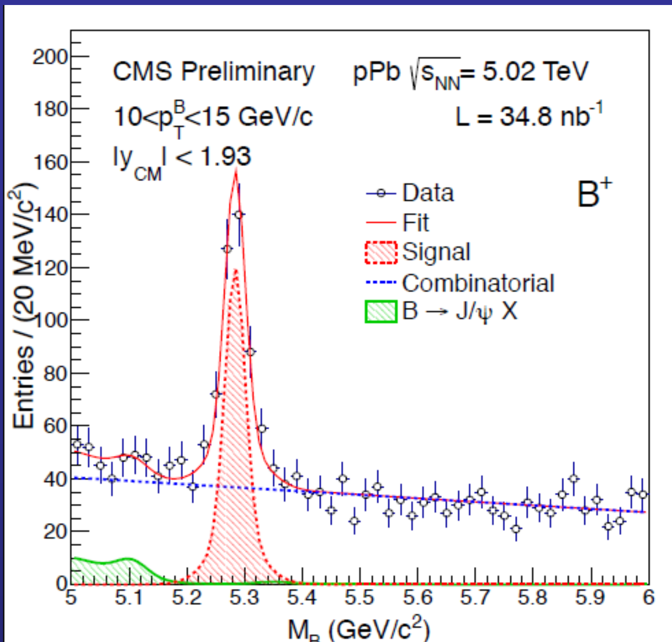
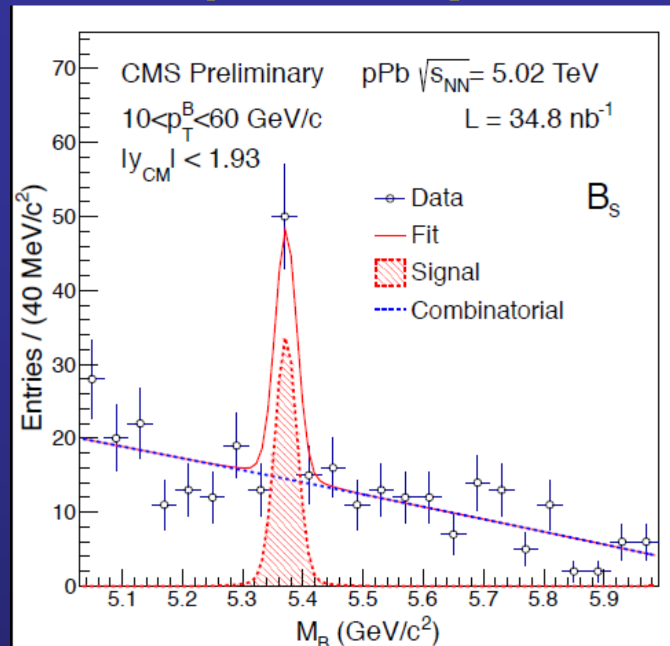
- What about mid-y ?

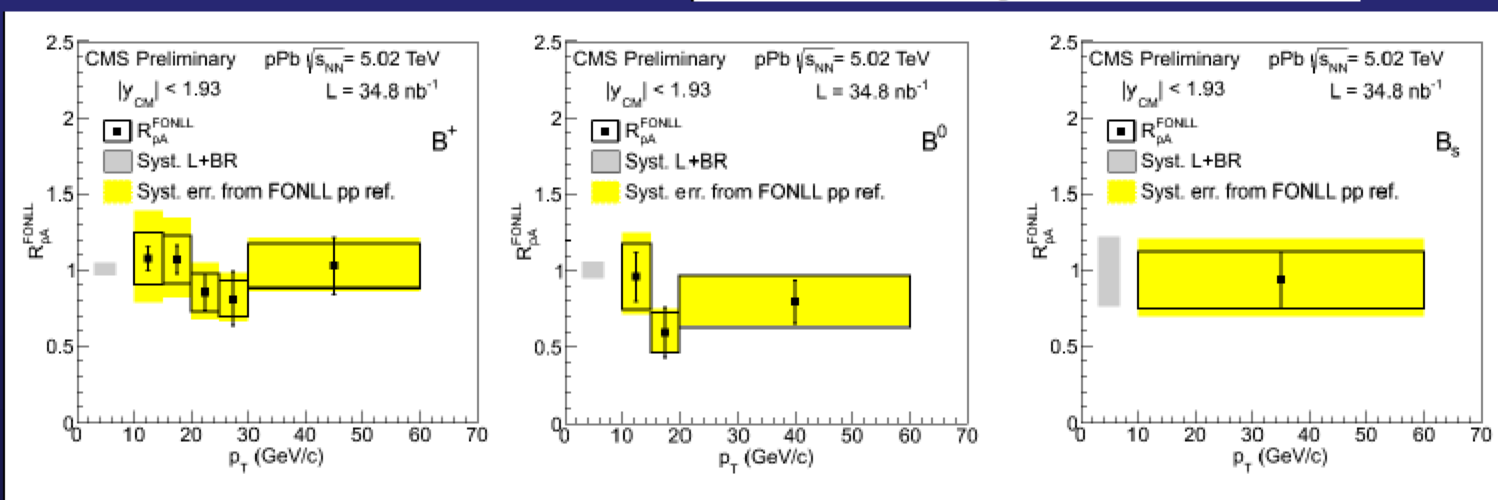
Direct B in p-Pb (mid-y)





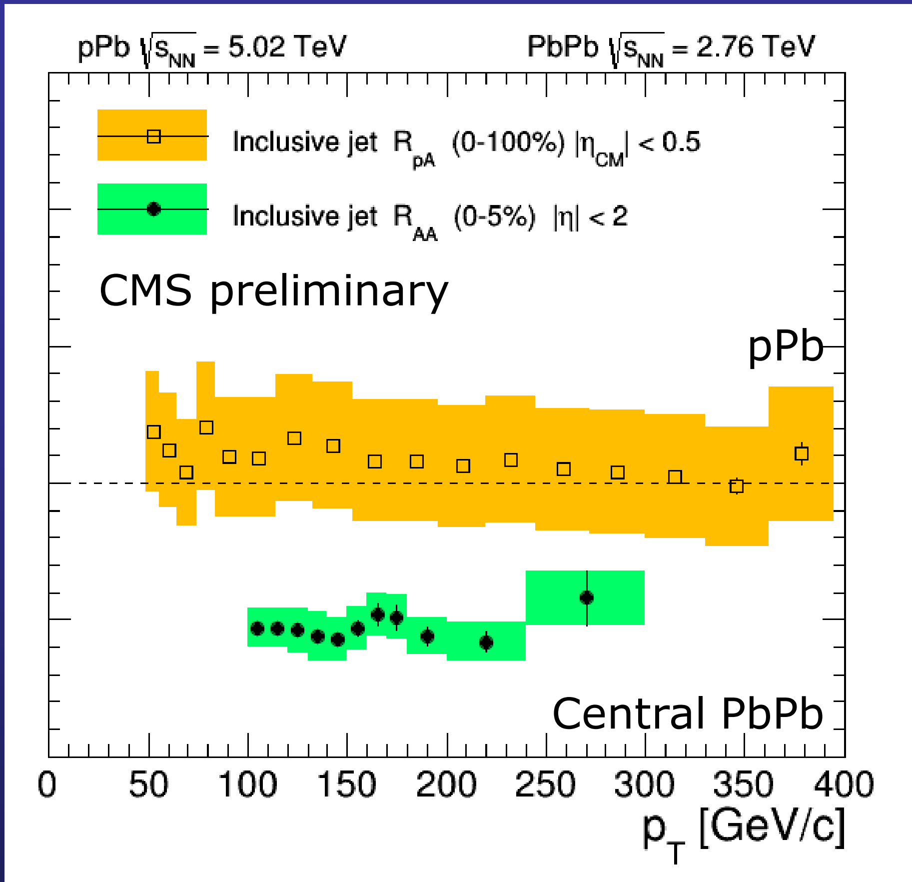
$B^+ \rightarrow J/\psi\ K^+$
$B^0 \rightarrow J/\psi\ K^*$
$B_S \rightarrow J/\psi\ \varphi$

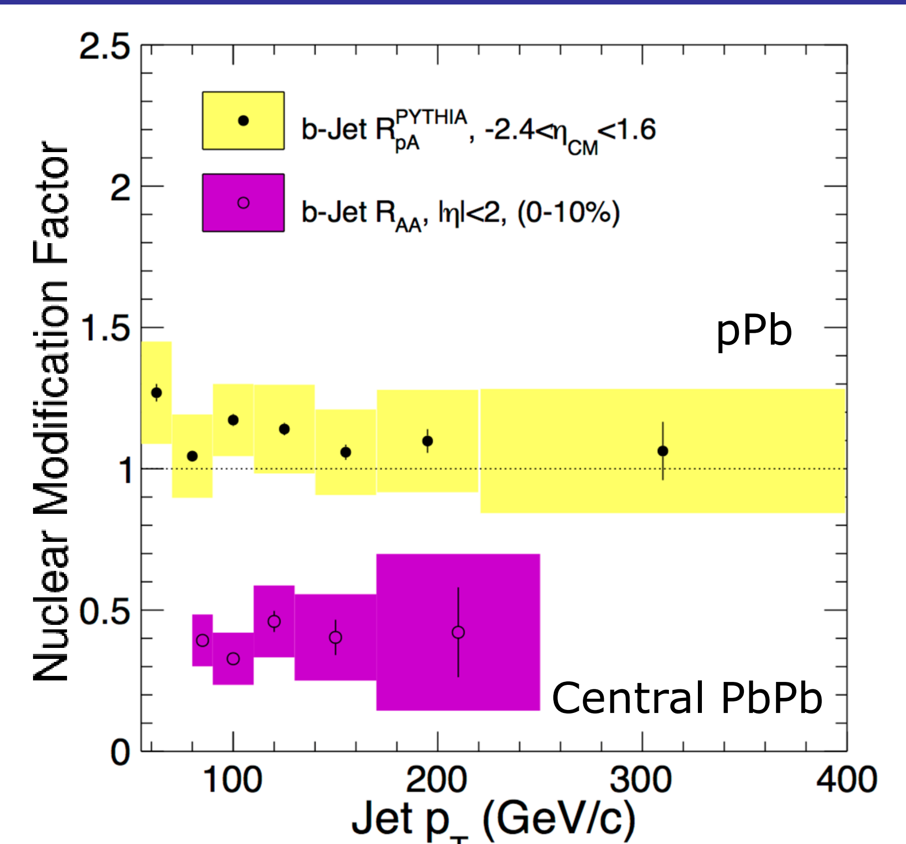
$\langle p_T \rangle > 10$ GeV/c



- ❑ Use FONLL for pp reference cross section
- ❑ R_{pA}^{FONLL} is compatible with unity for all three B-mesons

R_{pPb} & R_{AA} for jets and b jets





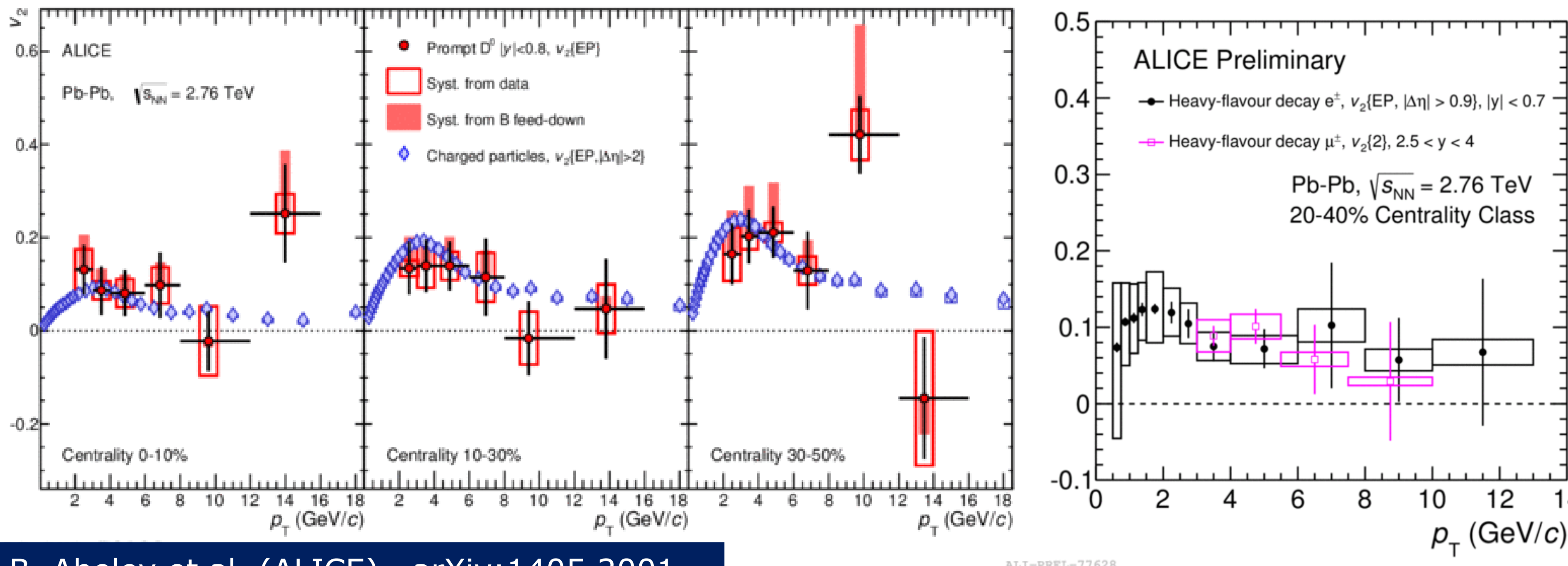
S. Chatrchyan et al. (CMS), arXiv:1312.4198

- ❑ Discriminating variable → Flight distance of the secondary vertex
- ❑ b-jet fraction → template fits to secondary vertex inv. mass distributions

- ❑ b-jet R_{AA} is much smaller than R_{pPb} → strong in-medium effects
- ❑ No jet modification in p-Pb collisions
- ❑ No flavour dependence of the effect

D-meson and HFE/HFM v_2

- First measurements of charm anisotropy in heavy-ion collisions



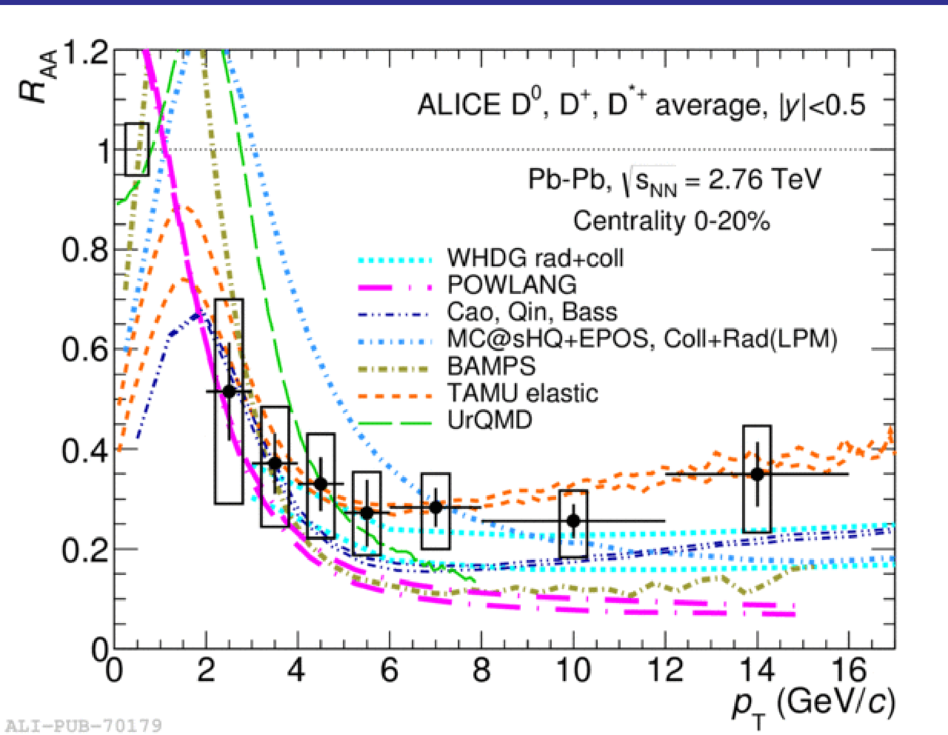
B. Abelev et al. (ALICE), arXiv:1405.2001

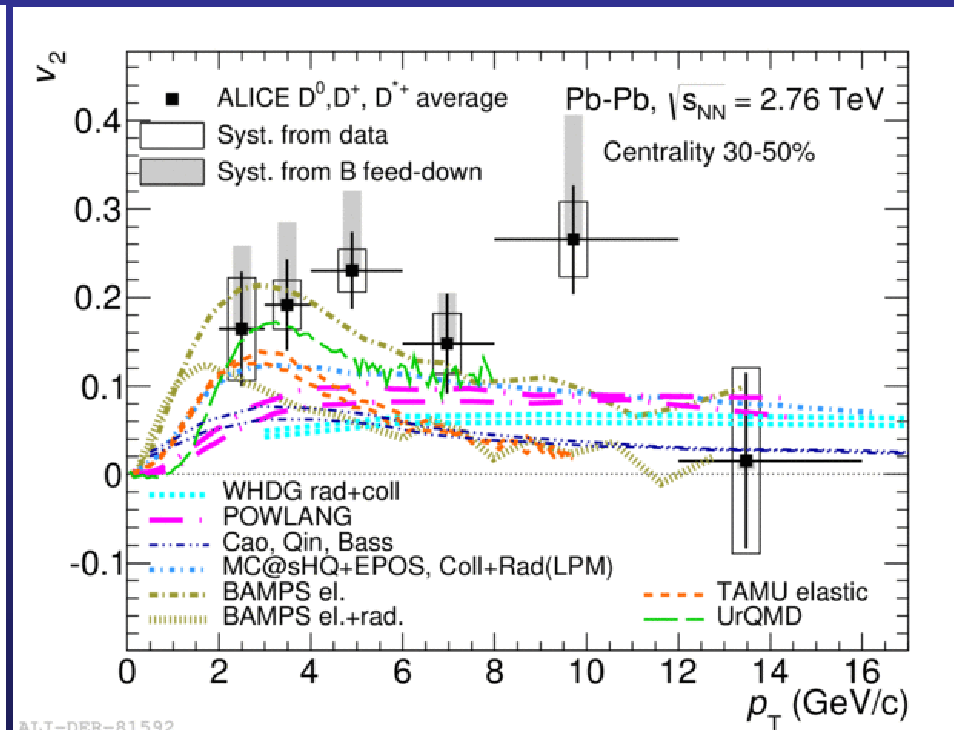
- Similar amount of v_2 for D-mesons and charged pions
- Similar v_2 values for HF decay muons and HF decay electrons (different y)
- All channels show positive v_2 (>3 σ effect)

Information on the initial azimuthal anisotropy transferred to charm quarks

Open charm: model comparisons

- Simultaneous measurement/description of v_2 and R_{AA}
  → Understanding heavy quark transport coefficient of the medium



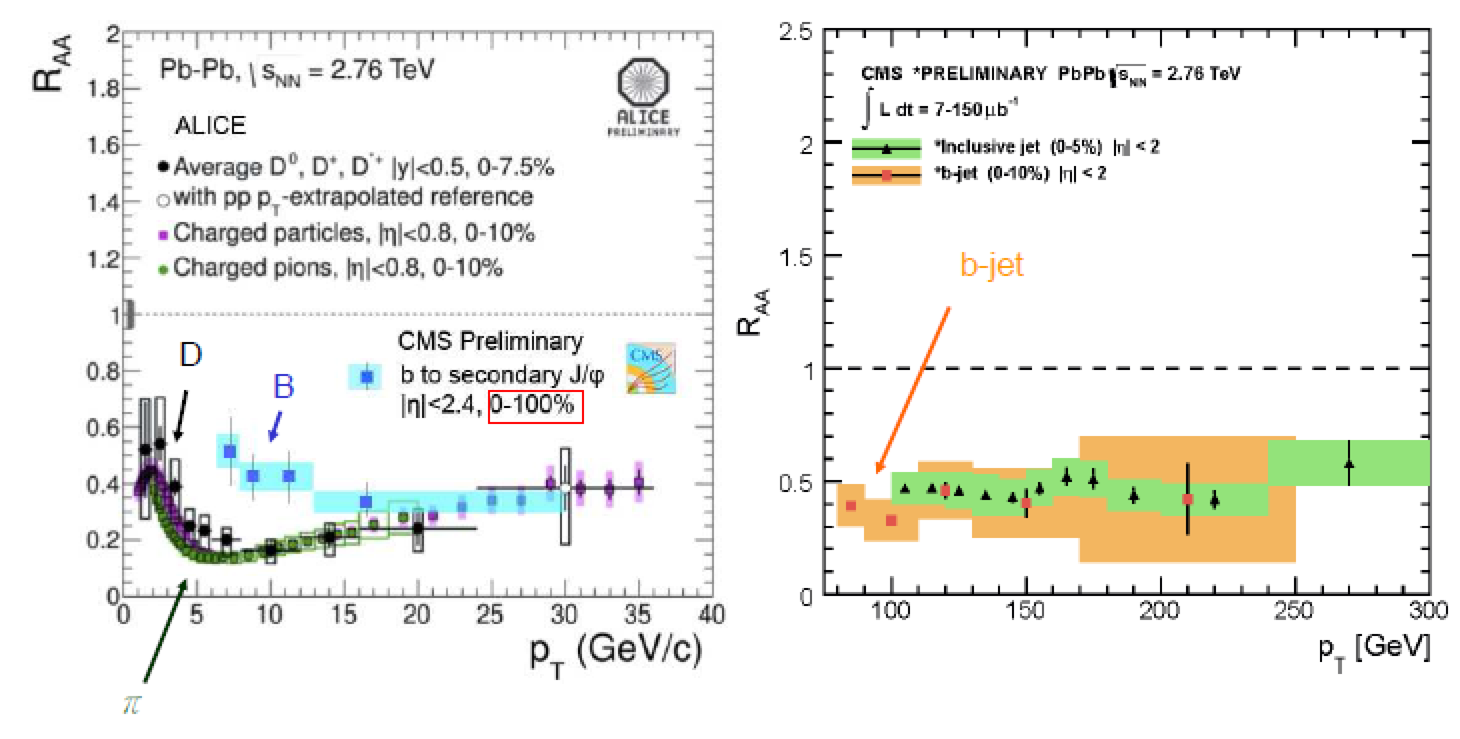


B. Abelev et al. (ALICE), arXiv:1405.2001

- Wealth of theory calculations
  - Main features correctly reproduced
  - Simultaneous comparison with v_2 and R_{AA} gives strong constraint to the models → still challenging!

Open charm/beauty: short summary

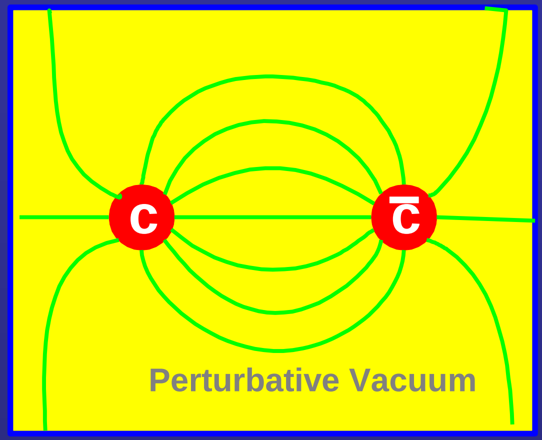
- Abundant heavy flavour production at the LHC
  - Allows for precision measurements
- Can separate charm and beauty (vertex detectors!)
  - Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
  - $R_{AA}^{beauty} > R_{AA}^{light}$ at low p_T, effect vanishing at very high p_T
  - R_{AA}^{charm} vs. R_{AA}^{light} comparison more delicate
- Indication (3σ) for non-zero charm elliptic flow at low p_T

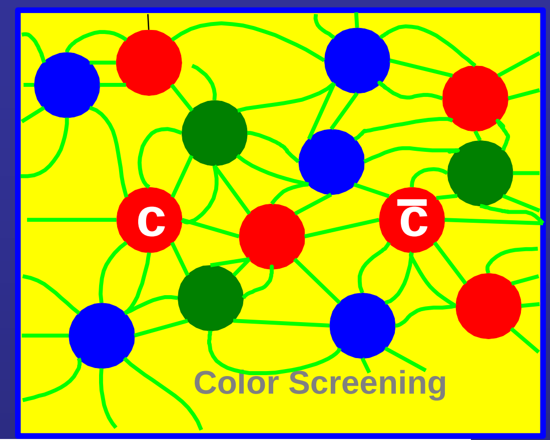


Quarkonia: from color screening…

Screening of strong interactions in a QGP

T. Matsui and H. Satz, PLB178 (1986) 416

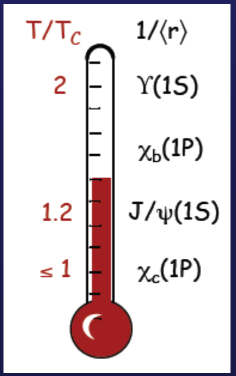


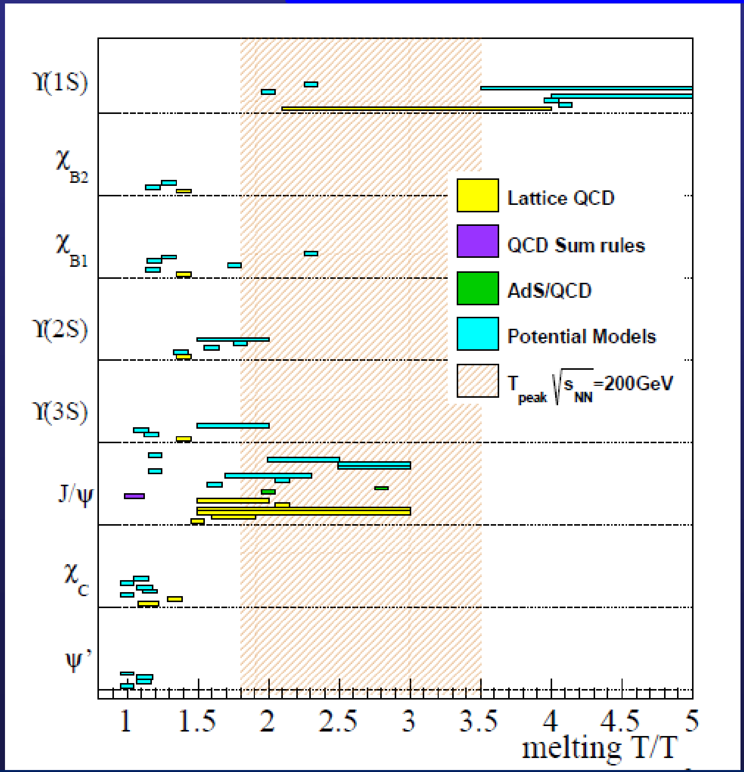


- Screening stronger at high T
- λ_D → maximum size of a bound state, decreases when T increases
- Different states, different sizes

Resonance melting

QGP thermometer



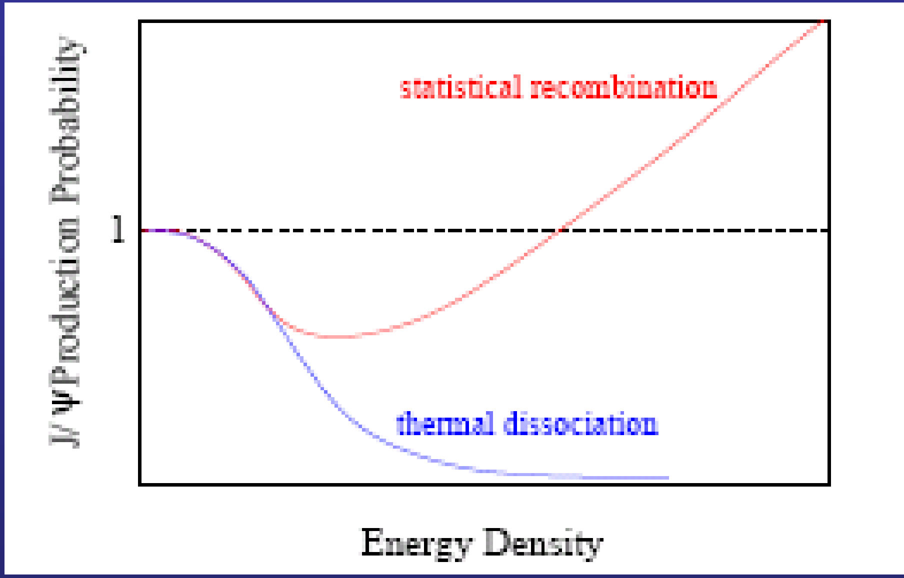


A. Adare et al. (PHENIX), arXiv:1404.2246

...to regeneration (for charmonium!)

At sufficiently high energy, the cc pair multiplicity becomes large

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



P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196

Statistical approach:

- ❑ Charmonium fully melted in QGP
- ❑ Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

Kinetic recombination:

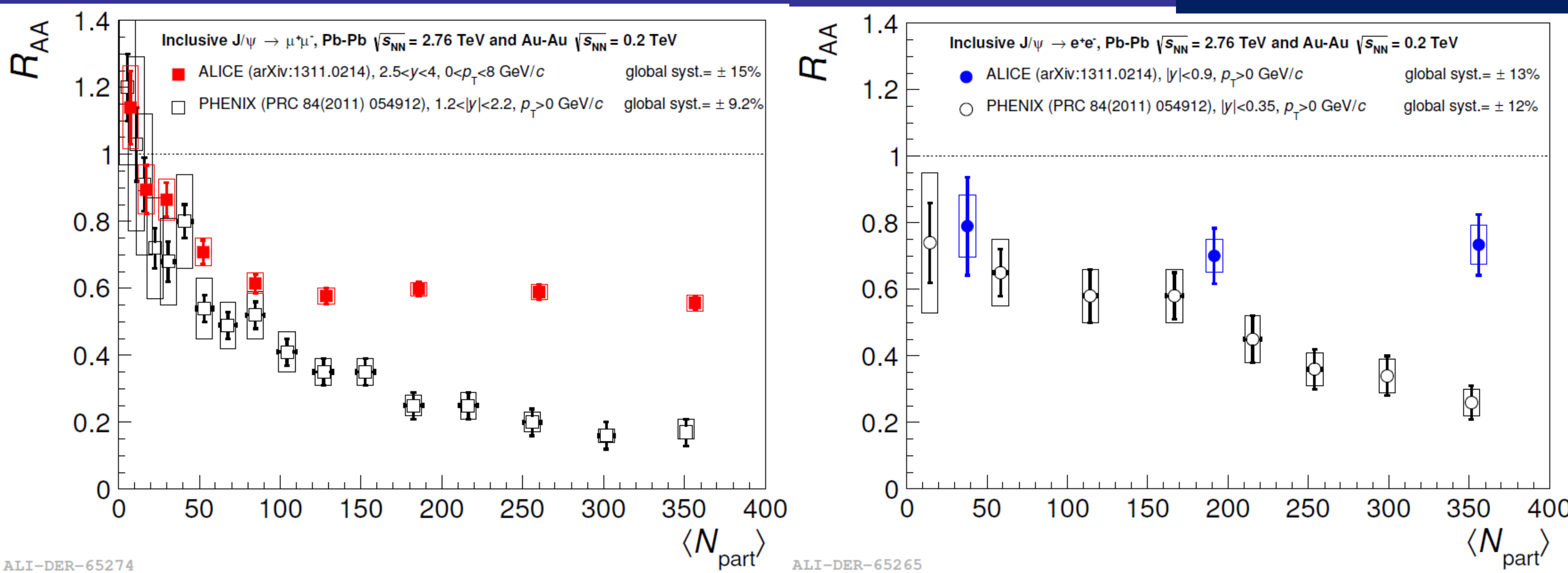
- ❑ Continuous dissociation/regeneration over QGP lifetime

Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

if supported by data, charmonium looses status as "thermometer" of QGP
...and gains status as a powerful observable for the phase boundary

Low p_T J/ψ: ALICE

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

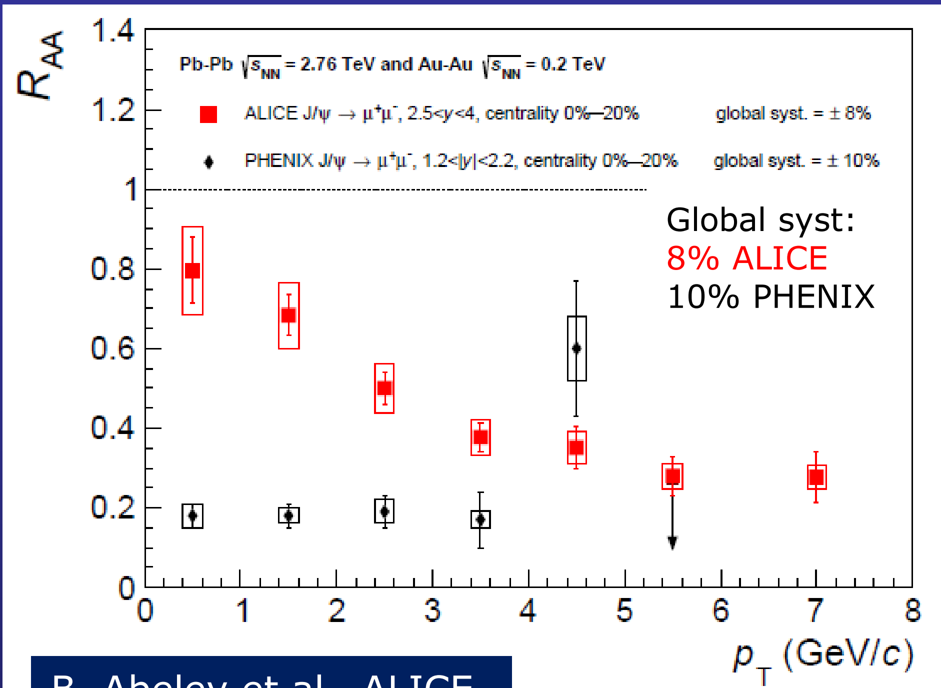


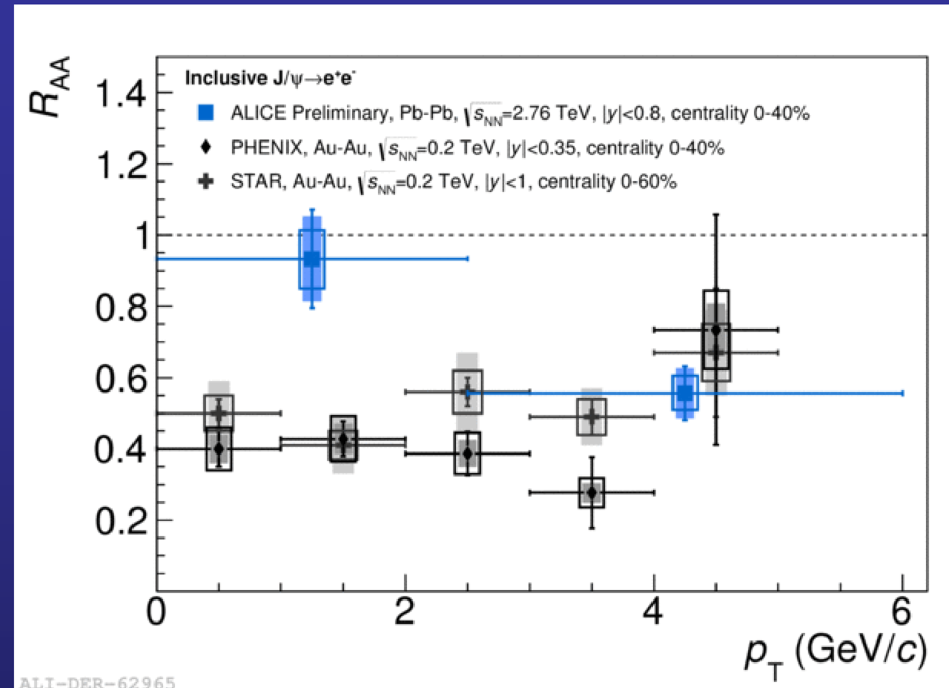
- Compare J/ψ suppression, RHIC ($\sqrt{s_{NN}}$=0.2 TeV) vs LHC ($\sqrt{s_{NN}}$=2.76 TeV)
- Results dominated by low-p_T J/ψ
  - Stronger centrality dependence at lower energy
  - Systematically larger R_{AA} values for central events in ALICE

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

How can this picture be validated?

R_{AA} vs p_T





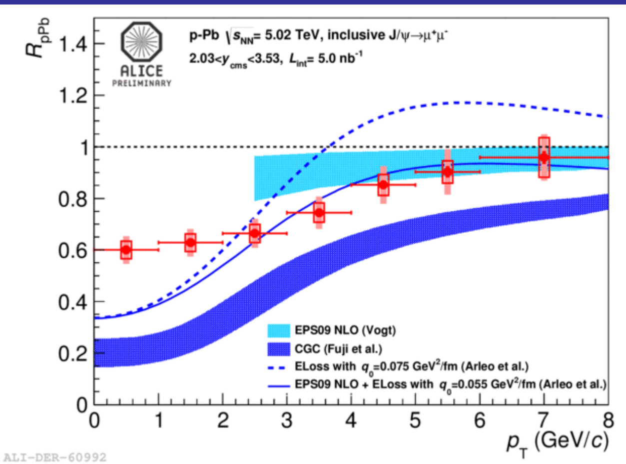
B. Abelev et al., ALICE arXiv:1311.0214.

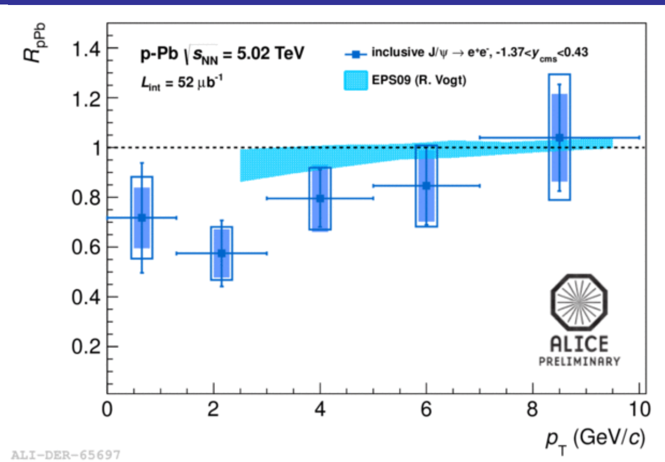
- ❑ Charm-quark transverse momentum spectrum peaked at low-p_T
- ❑ Recombination processes expect to mainly enhance low-p_T J/ψ
  → Expect smaller suppression for low-p_T J/ψ → observed!

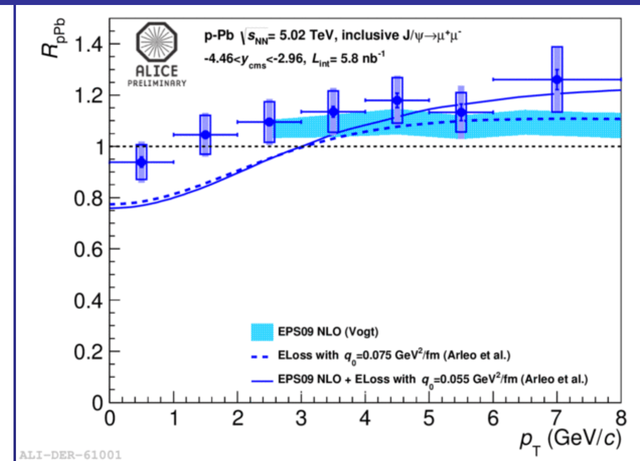
- ❑ Opposite trend with respect to lower energy experiments
- ❑ Fair agreement with transport and statistical models (not shown)

- ❑ Other strong hint for recombination: non-zero v_2 for J/ψ (ALICE+CMS)

CNM effects are not negligible!

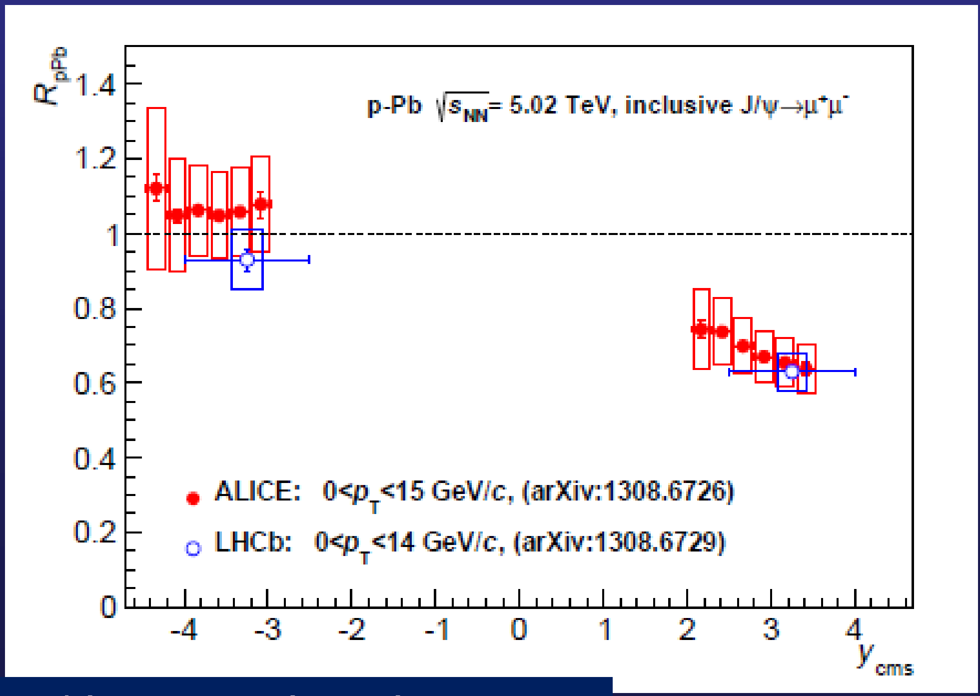






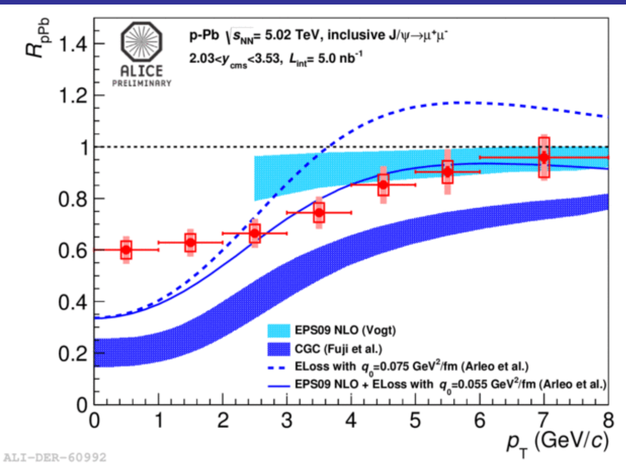
- Suppression at backward + central rapidity
- No suppression (enhancement?) at forward rapidity
- Fair agreement with models (shadowing + energy loss)

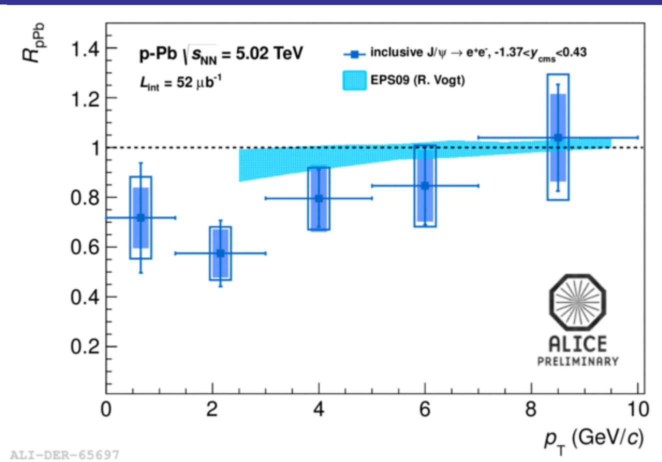
- (Rough) extrapolation of CNM effects to Pb-Pb → evidence for hot matter effects!

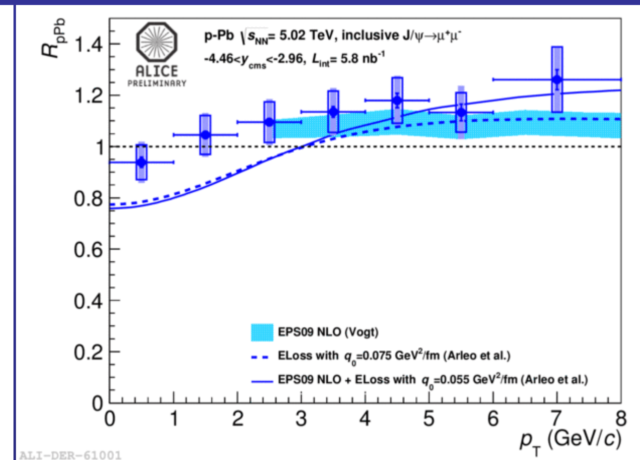


R. Aaij et al.(LHCb), JHEP 02(2014) 072
B. Abelev et al. (ALICE), JHEP 02(2014) 073

CNM effects are not negligible!







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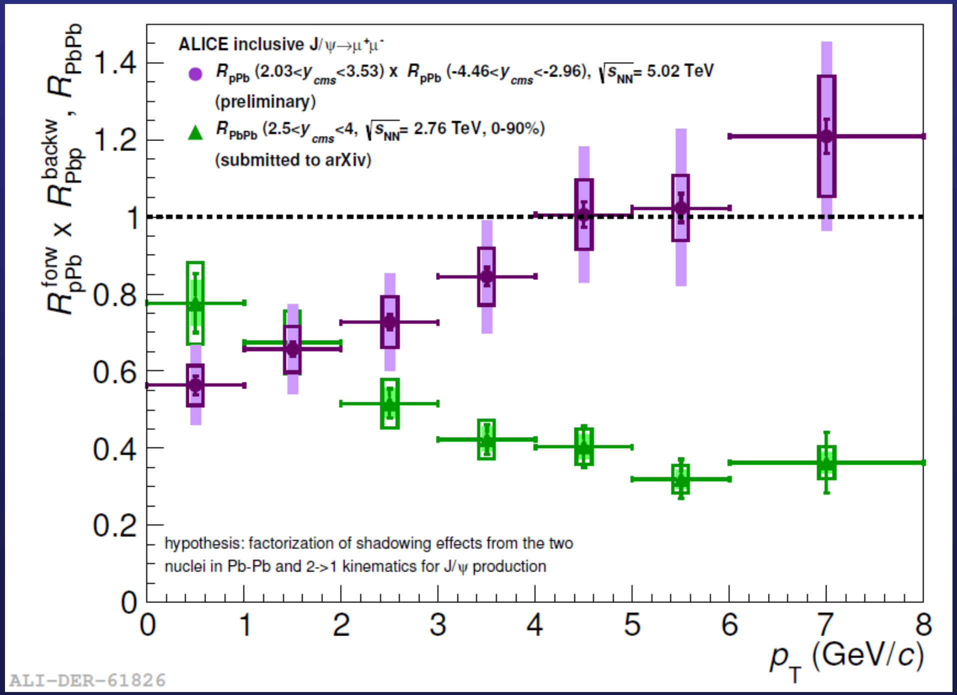
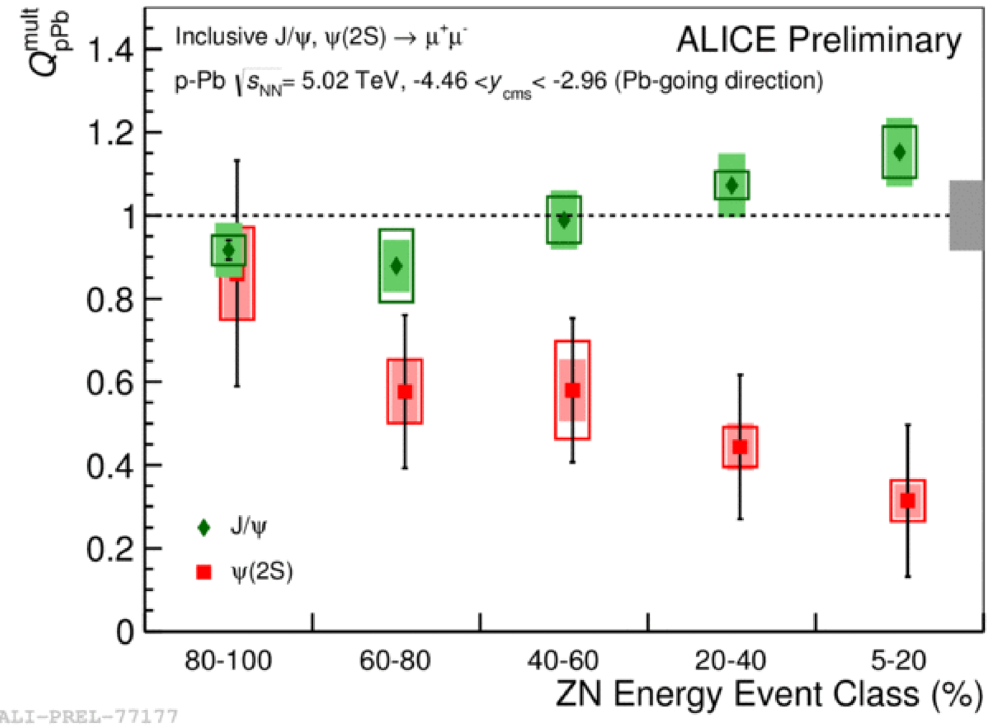
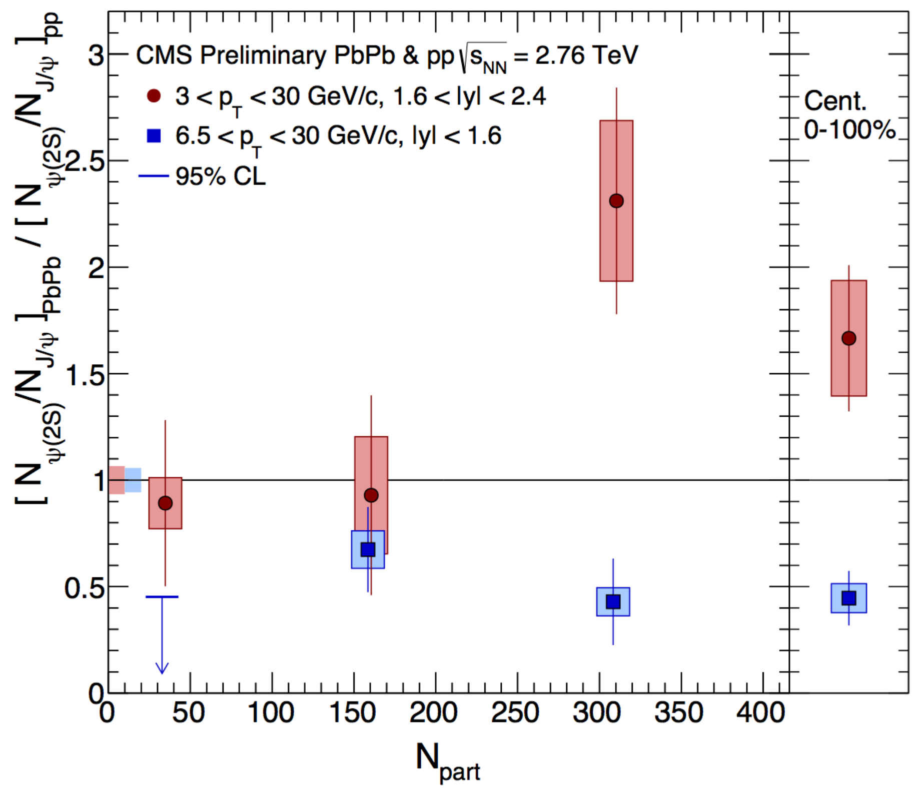


Weakly bound charmonia: $\psi(2S)$



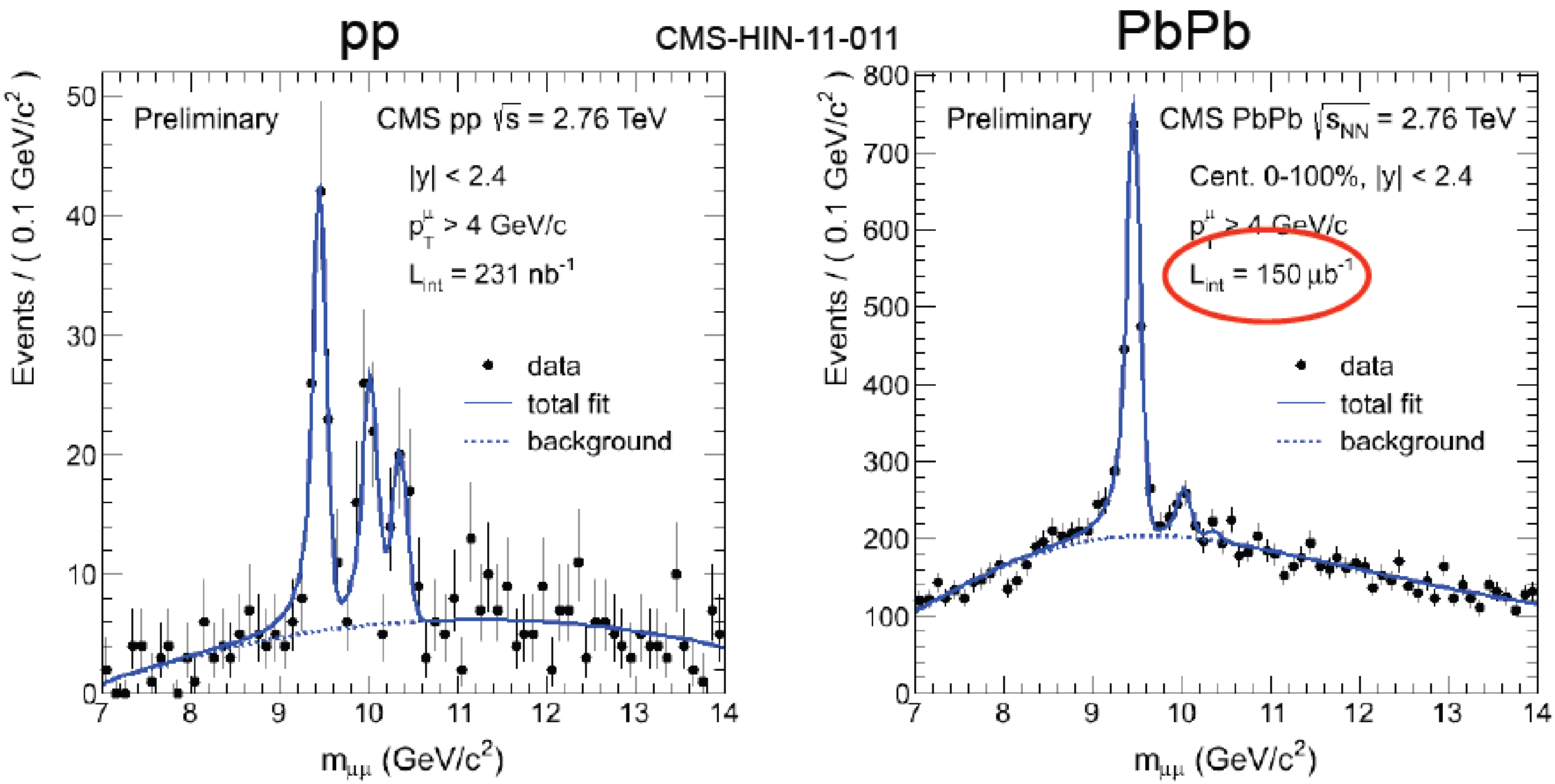


ALICE: evidence for strong suppression effects in p_T-integrated p-Pb collisions (compared to J/ψ), increasing with the event activity

CMS: from enhancement to strong suppression moving from intermediate (p_T >3 GeV/c) to large (p_T >6.5 GeV/c) transverse momentum

How can these observations be reconciled ?

ϒ suppression: CMS results



$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{pp}} = 0.56 \pm 0.13 \pm 0.01$

$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\mathrm{pp}} = 0.21 \pm 0.11 \pm 0.02$

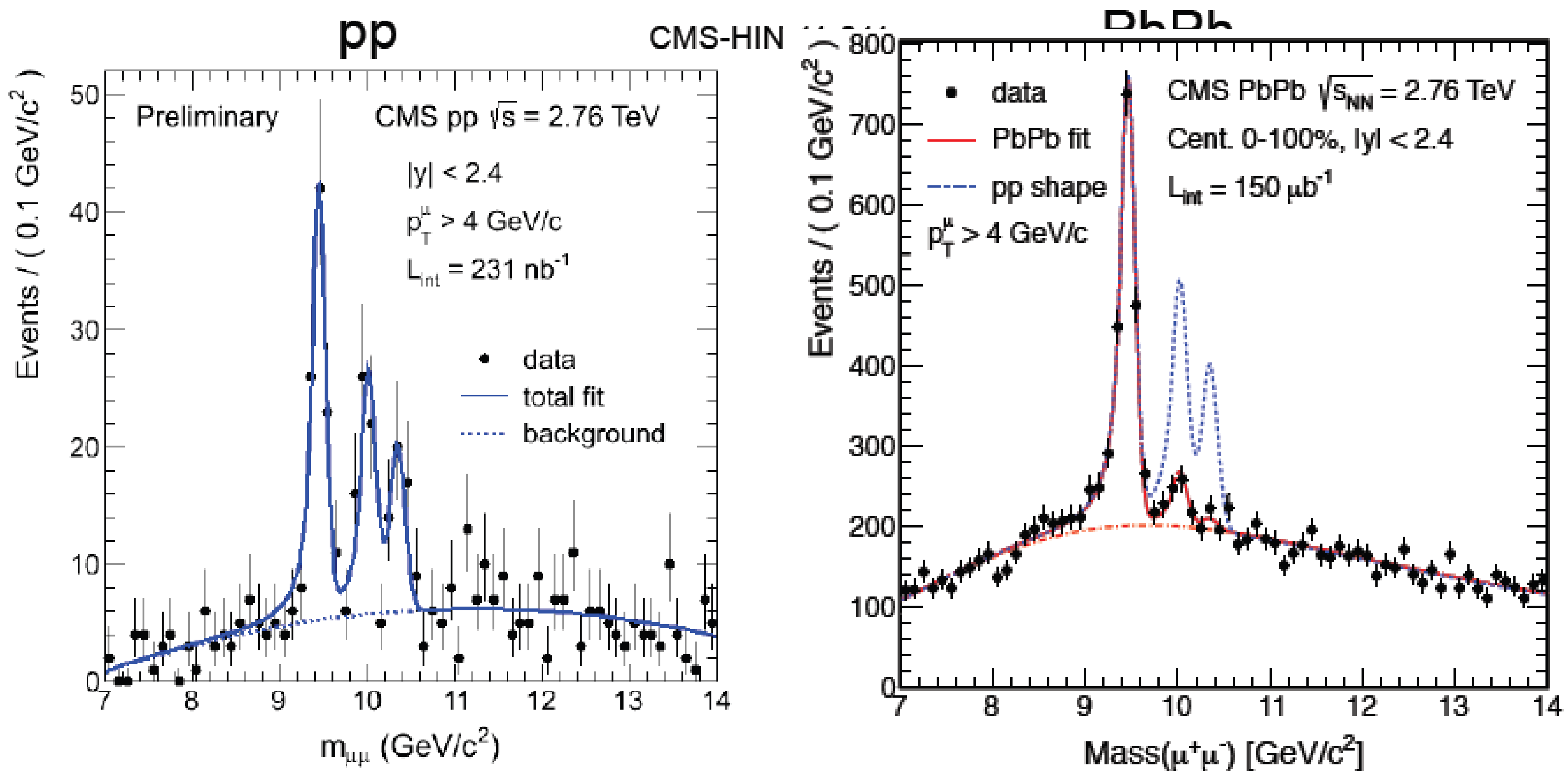
$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} = 0.12 \pm 0.03 \pm 0.01$

$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} < 0.07$

S. Chatrchyan et al.(CMS), PRL 109 (2012) 222301

- More weakly bound states (ϒ(2S), ϒ(3S)) show strong suppression in Pb-Pb, compared to ϒ(1S)
- Expected signature for QGP-related suppression
- Regeneration effects expected to be negligible for bottomonia

Υ suppression: CMS results



$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{pp}} = 0.56 \pm 0.13 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\mathrm{pp}} = 0.21 \pm 0.11 \pm 0.02$$

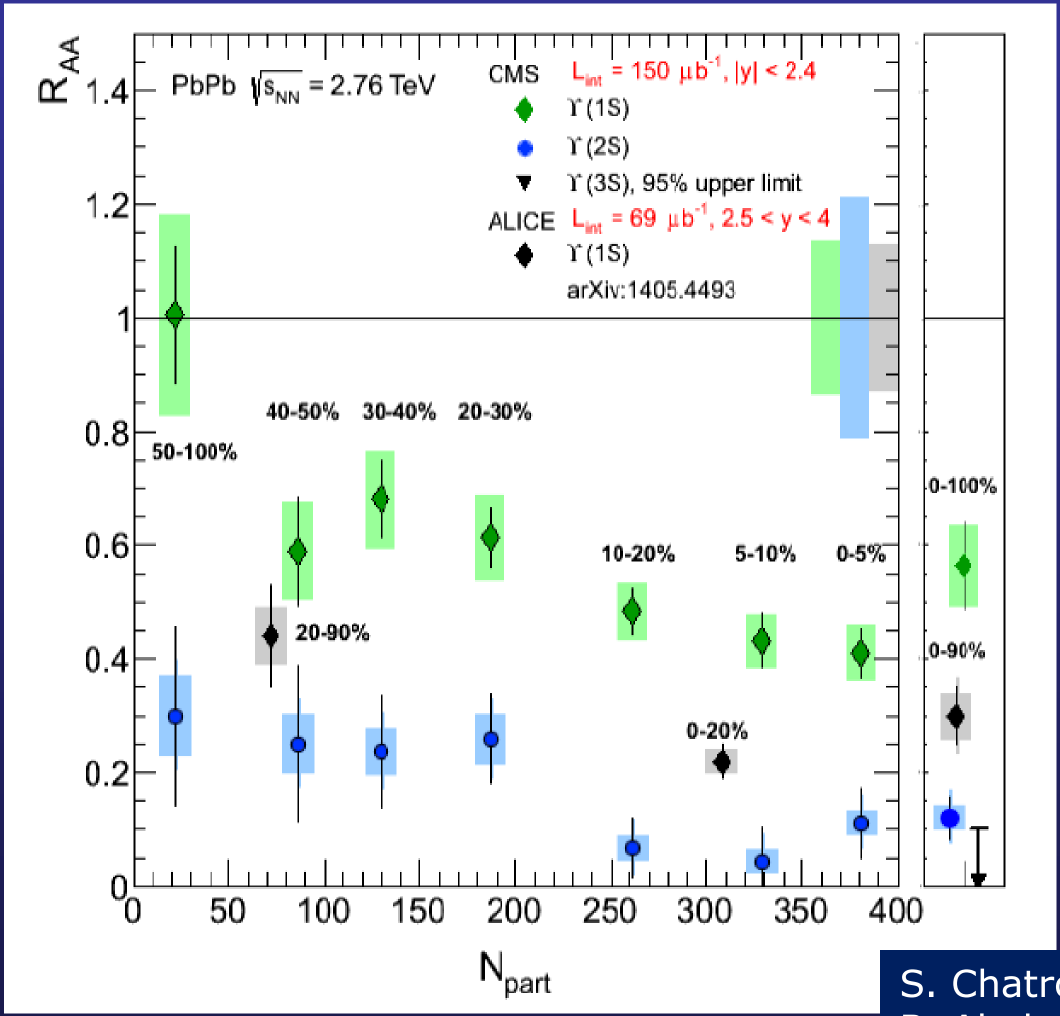
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} = 0.12 \pm 0.03 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} < 0.07$$

S. Chatrchyan et al.(CMS), PRL 109 (2012) 222301

- More weakly bound states (Υ(2S), Υ(3S)) show strong suppression in Pb-Pb, compared to Υ(1S)
- Expected signature for QGP-related suppression
- Regeneration effects expected to be negligible for bottomonia

First accurate determination of Υ suppression



- Suppression increases with centrality
- First determination of Υ(2S) R_{AA}: already suppressed in peripheral collisions
- Υ(1S) (see also ALICE) compatible with suppression of bottomonium states decaying to Υ(1S)

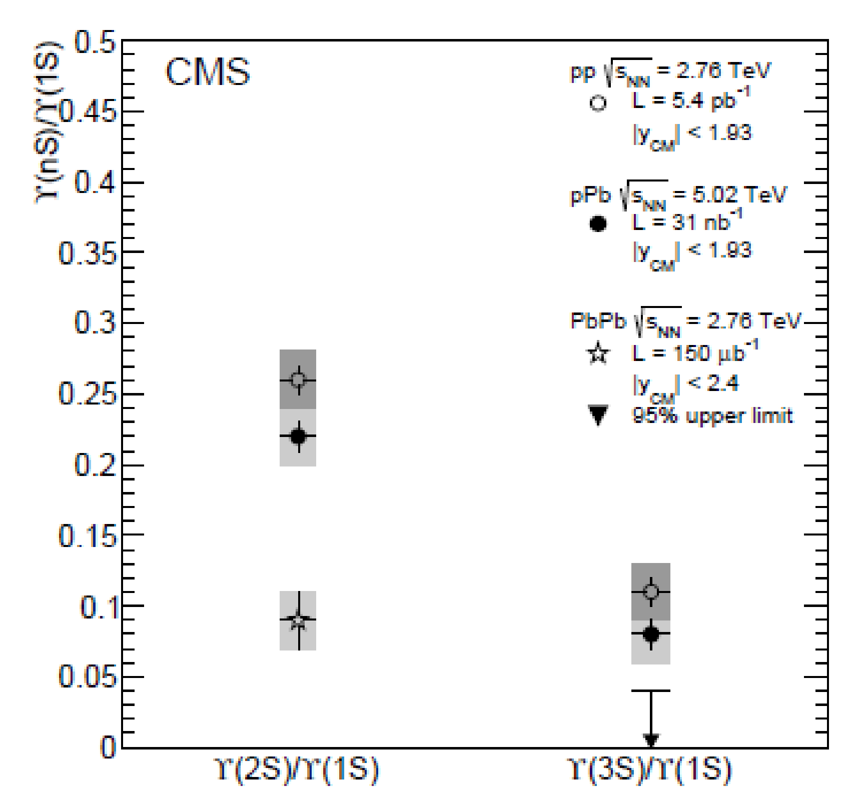
→ Probably yes, also taking into account the normalization uncertainty

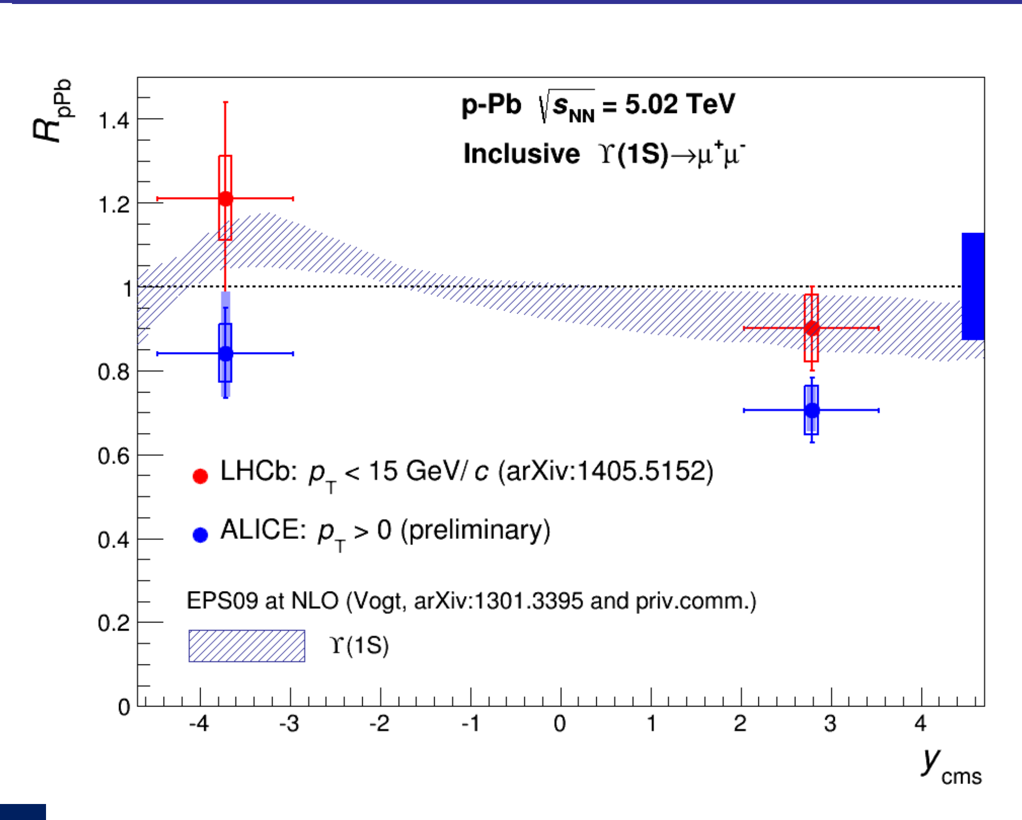
S. Chatrchyan et al.(CMS), PRL 109 (2012) 222301
B. Abelev et al. (ALICE), arXiv:1405.4493

Is Υ(1S) dissoc. threshold still beyond LHC reach ? → Run-II

Do not forget CNM…

- In the ϒ sector, the influence of CNM effects is small

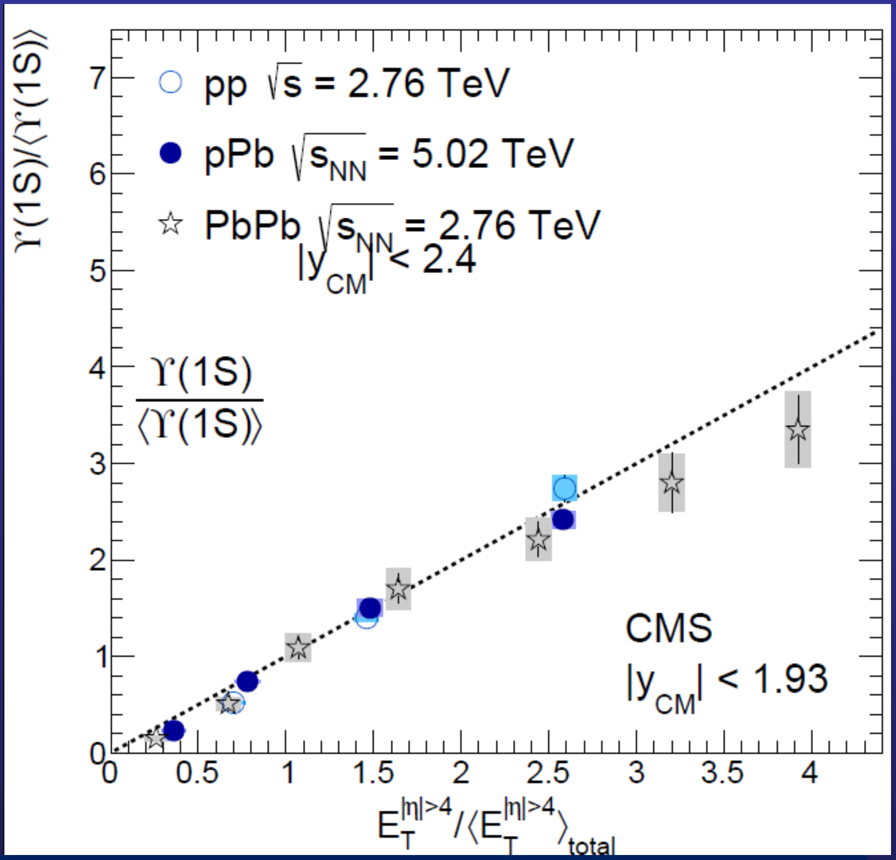


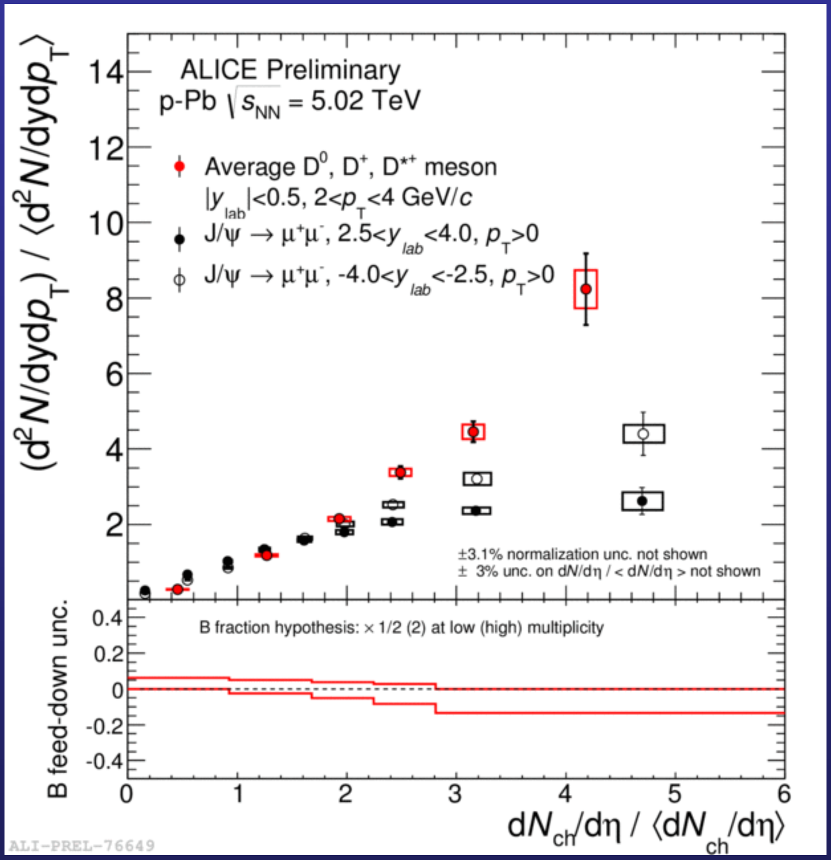


S. Chatrchyan et al.(CMS), JHEP 04(2014) 103

- Hints for suppression of ϒ(1S) at forward rapidity?
- (Small) relative suppression of ϒ(2S) and ϒ(3S) wrt ϒ(1S) at mid-rapidity
- Qualitative agreement with models within uncertainties
- CNM cannot account for all of the effect observed in Pb-Pb

Evolution of relative yields: pp, p-Pb, Pb-Pb





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

- Strong correlation of charmonia/bottomonia/open charm relative yields as a function of quantities related to the hadronic activity in the event
- Observation related to the role of MPI in pp also in the hard sector ?

Charmonia/bottomonia: short summary

- Two main mechanisms at play
  1) Suppression in a deconfined medium
  2) Re-generation (for charmonium only!) at high $\sqrt{s}$

  can qualitatively explain the main features of the results

- In the charmonium sector
  - R_{AA} → weak centrality dependence at all y, larger than at RHIC
  - Less suppression at low p_T with respect to high p_T
  - CNM effects non-negligible but cannot explain Pb-Pb observations

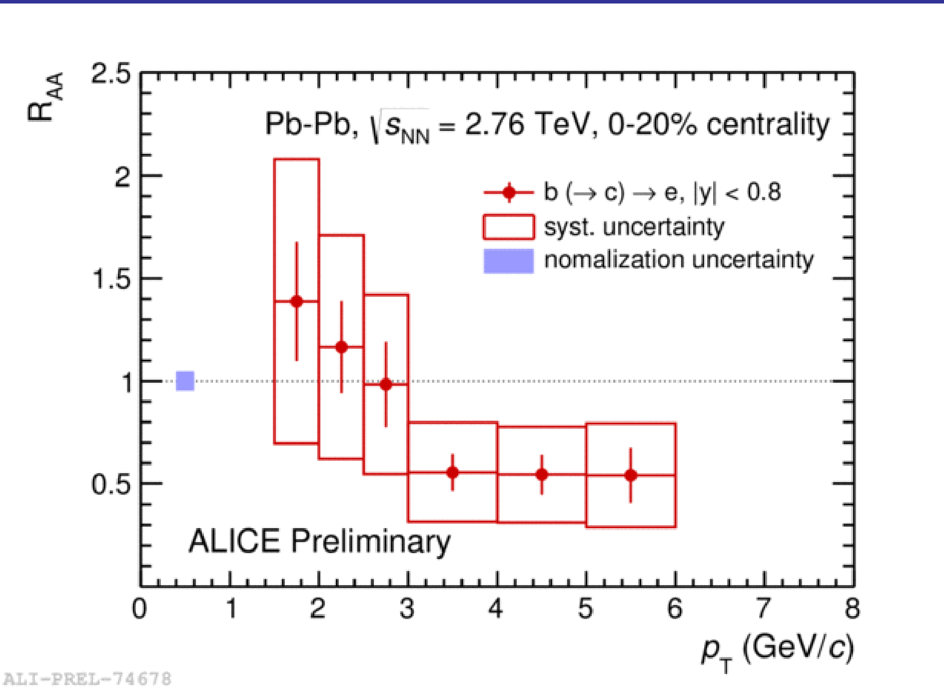
- In the bottomonium sector
  - Clear ordering of the suppression of the three Υ states with their binding energy → as expected from sequential melting
  - $\Upsilon(1S)$ suppression consistent with excited state suppression (50% feed-down)

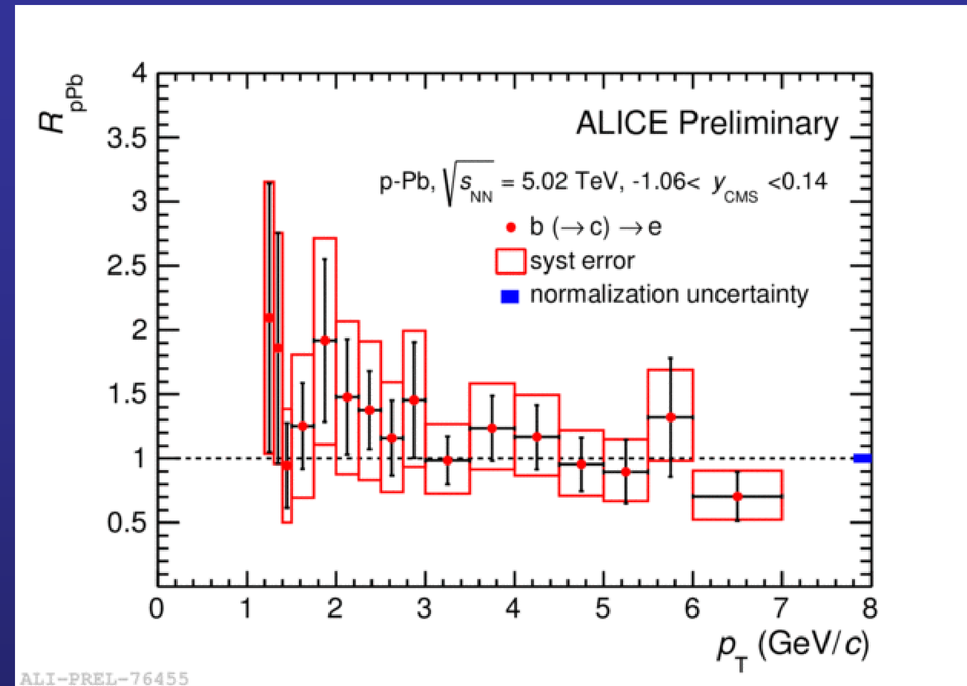
Conclusions

- Complete set of results from run-I is now available
  - Confirm the role of heavy quarks/quarkonia as privileged probes for the study of Quark-Gluon Plasma
    - Open charm/beauty mesons are strongly affected by the medium
      - Energy loss pattern, including mass-related effects, in agreement with calculations
      - Significant v_2 confirms the presence of collective effects (low p_T) as well as path-length dependence of energy loss (high p_T)
    - Charmonia/bottomonia are suppressed in the QGP according to their binding energy
      - Charmonium results show clear 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 at $\sqrt{s_{NN}}$~5.1 TeV , 2015-2017
  - Experiment upgrades, 2018 onwards

Backup

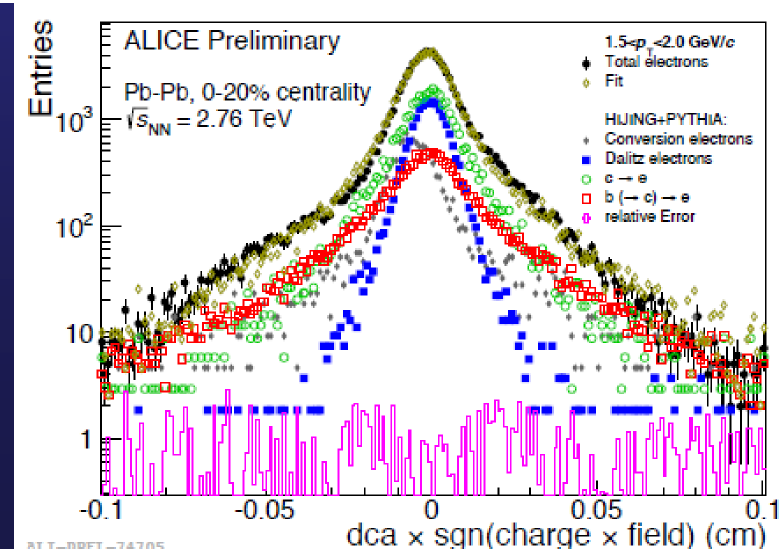
First B→e measurement in Pb-Pb



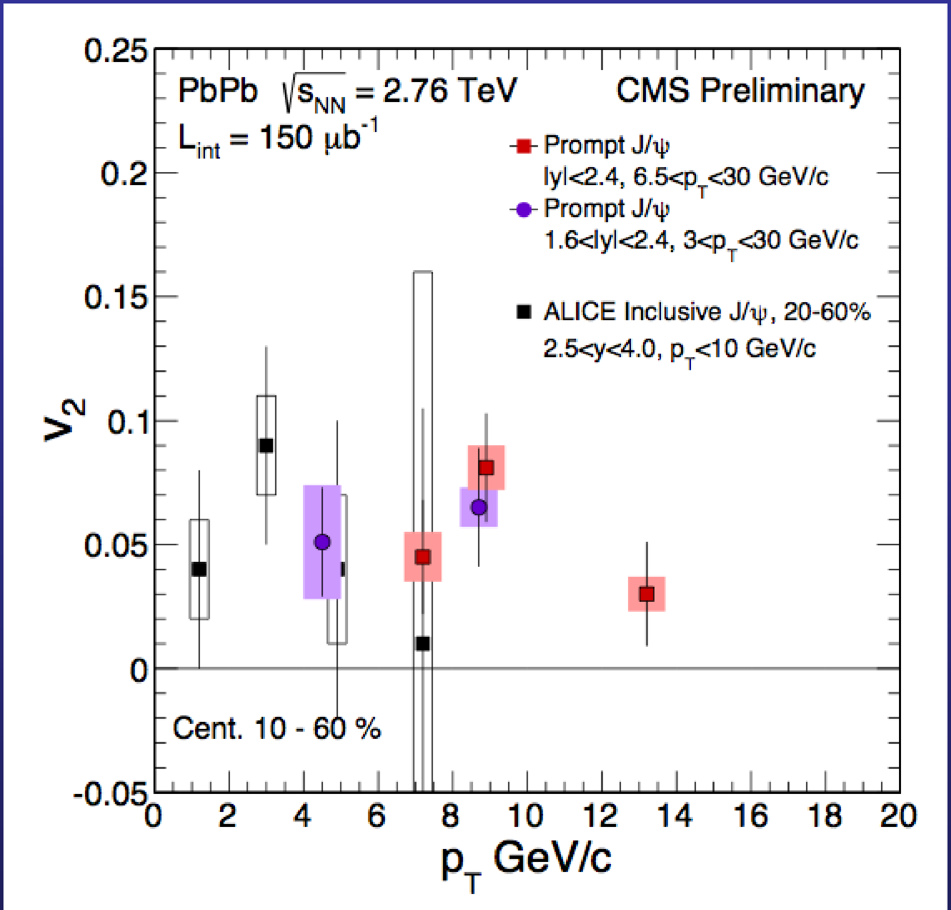


- Analysis based on the study of the electron impact parameter distribution

- Indicates $R_{AA}<1$ for $p_T>3$ GeV/c
- R_{pPb} (b→e) compatible with unity: b-quark affected by the interaction with the hot medium



Non-zero v_2 for J/ψ at the LHC



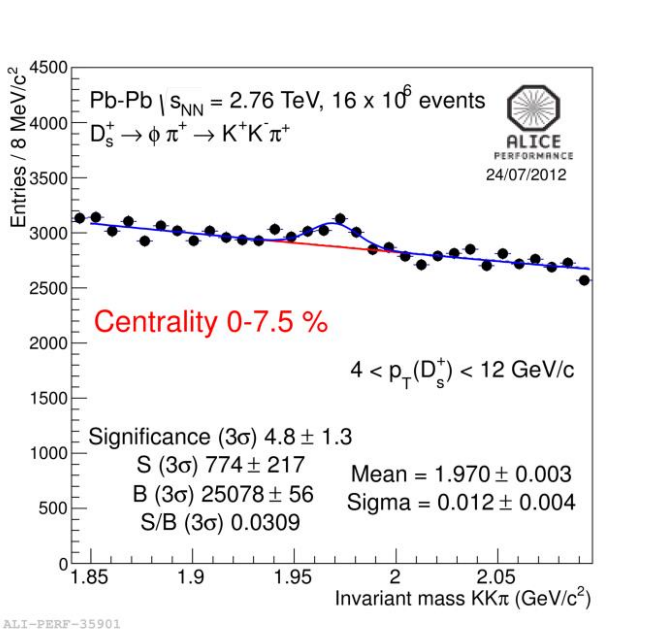
E.Abbas et al. (ALICE), PRL111(2013) 162301

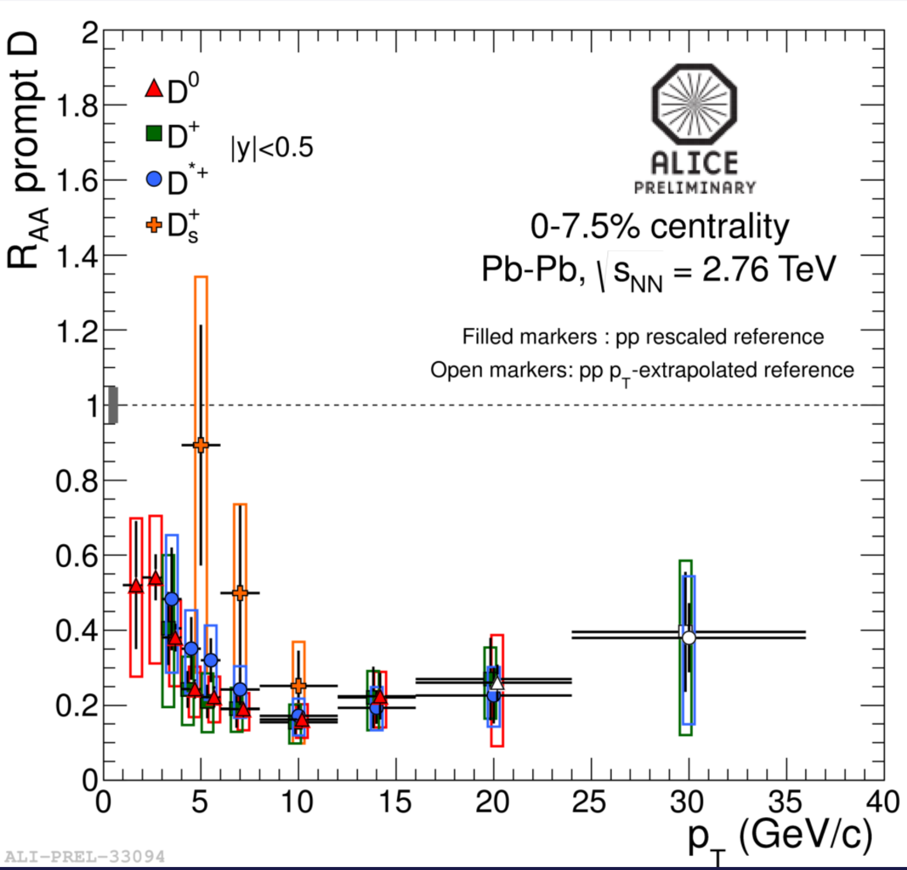
- The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy

- A significant v_2 signal is observed by BOTH ALICE and CMS
- The signal remains visible even in the region where the contribution of (re)generation should be negligible
- Due to path length dependence of energy loss ?
- In contrast to these observations STAR measures v_2=0

Charm(ed) and strange: D_S R_{AA}

- First measurement of D_s^+ in AA collisions
- Expectation: enhancement of the strange/non-strange D meson yield at intermediate p_T if charm hadronizes via recombination in the medium





- Strong D_s^+ suppression (similar as D^0, D^+ and D^{*+}) for $8<p_T<12$ GeV/c
- More statistics needed to conclude about the low-p_T region

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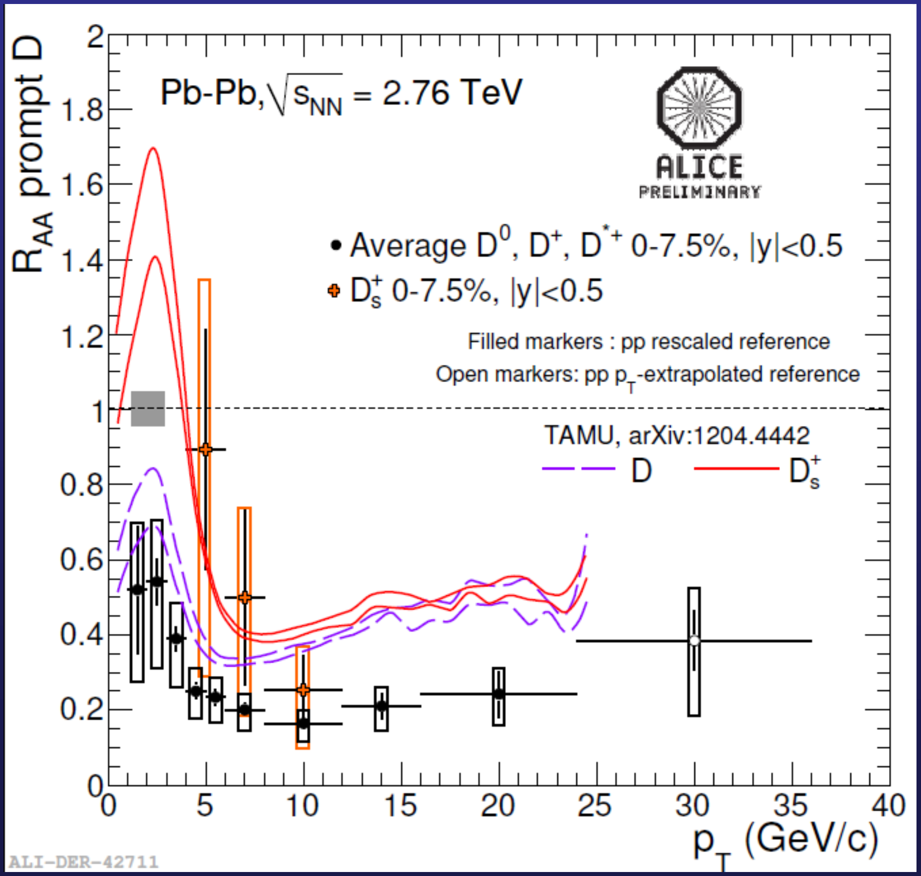

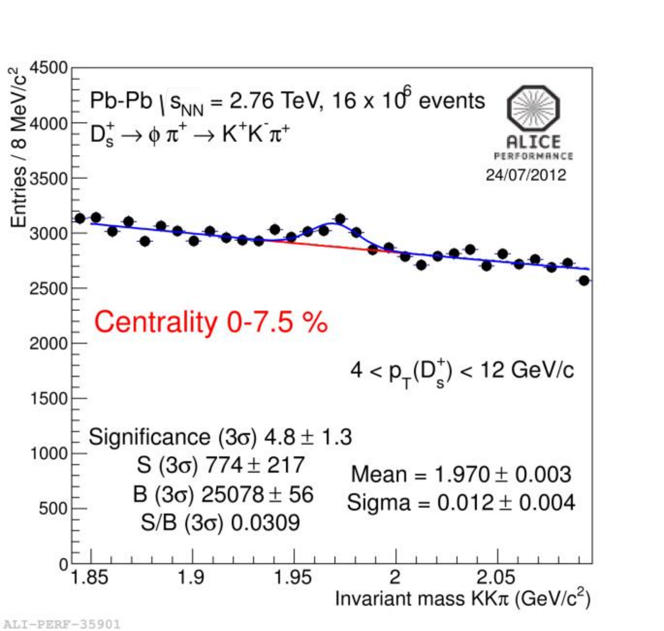

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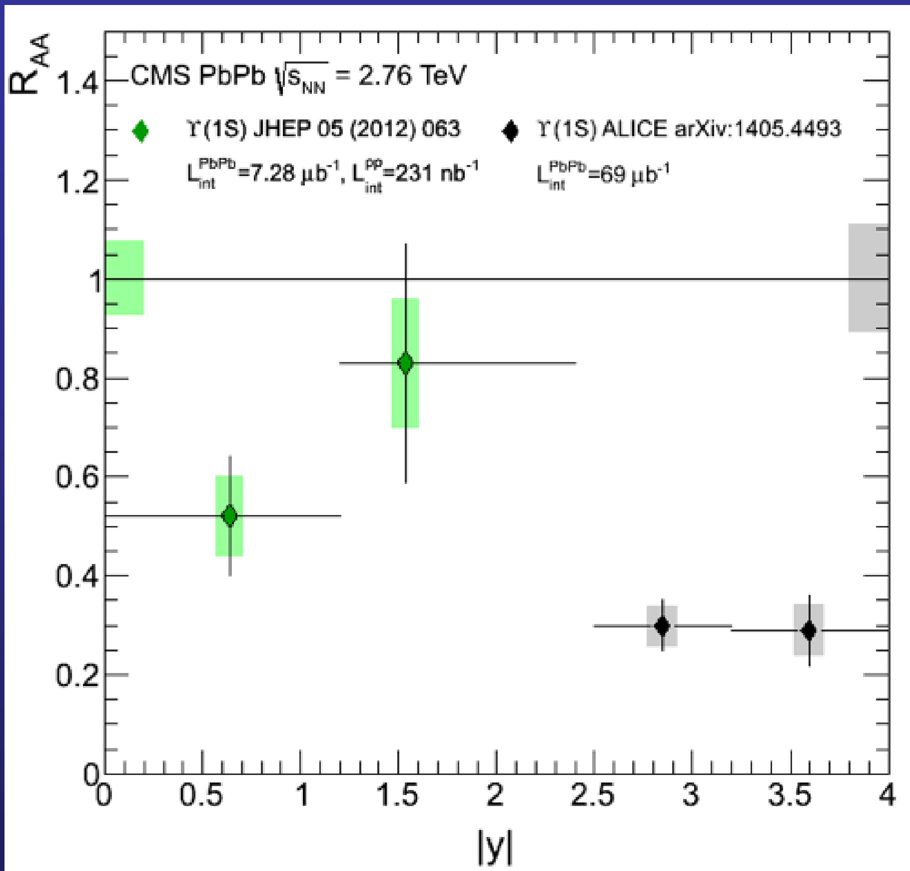
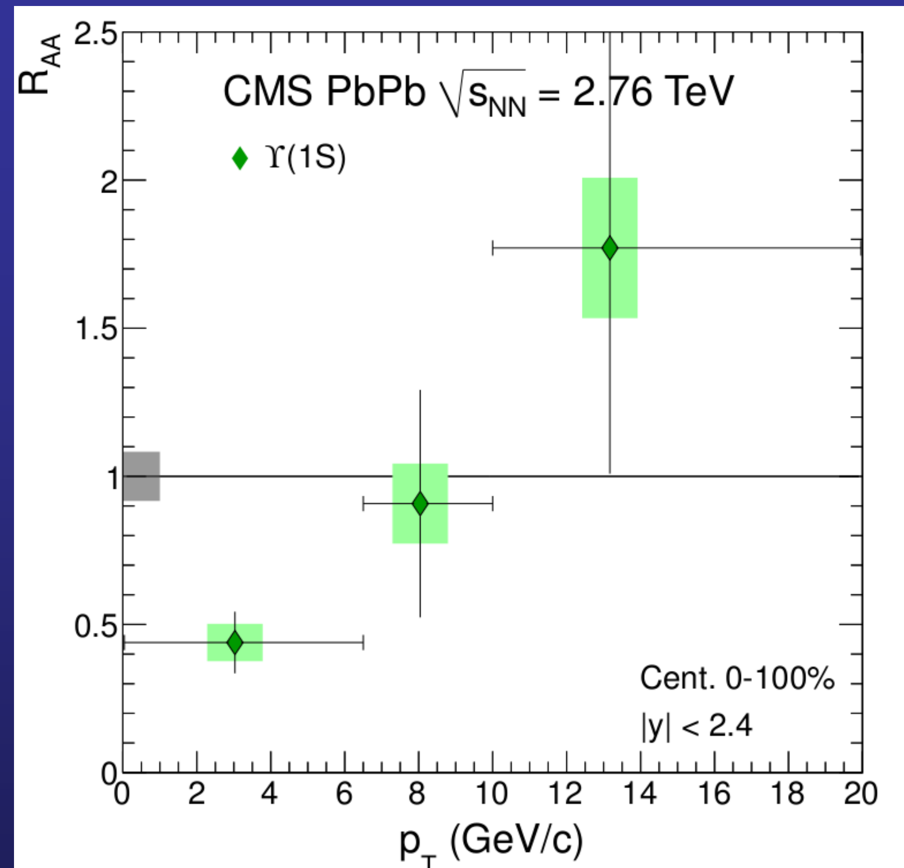
ϒ(1S) vs y and p_T from CMS+ALICE

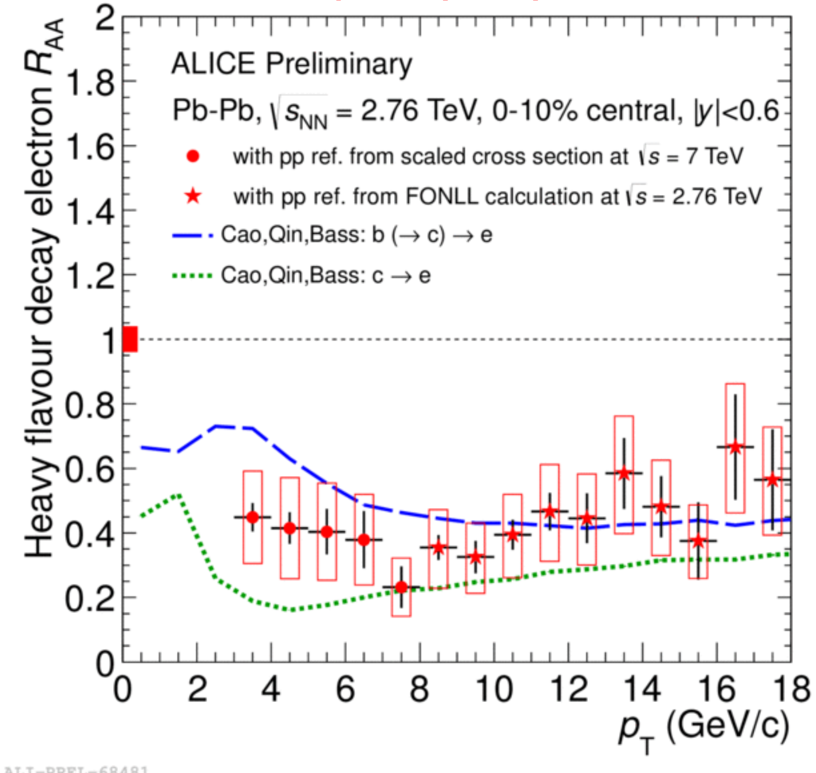


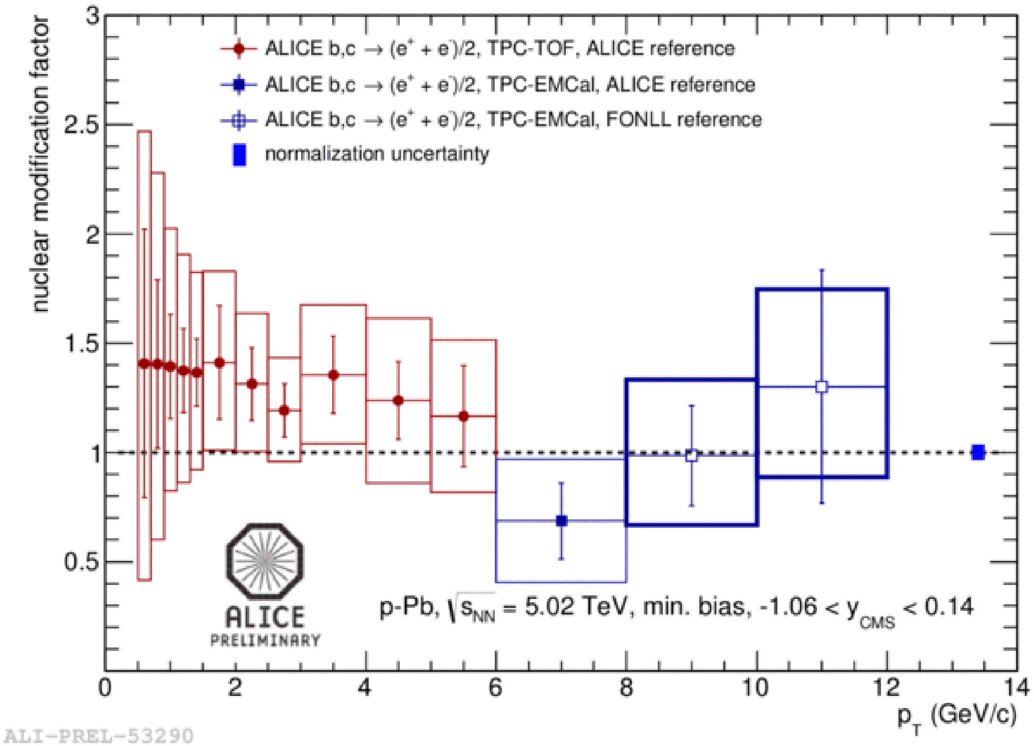


- ❑ Start to investigate the kinematic dependence of the suppression
- ❑ Suppression concentrated at low p_T (opposite than for J/ψ, no recombination here!)
- ❑ Suppression extends to large rapidity (puzzling y-dependence?)

Pb-Pb and pPb: results on B,D→ electrons

Central rapidity: |y|<0.6





- Results available up to p_T=18 GeV/c for central events (EMCAL)
- Clear suppression for central collisions in the studied p_T range
- Stronger suppression for central collisions (hint)
- R_{pPb} compatible with unity within uncertainties
  → Pb-Pb suppression due to final state effects
- No separation D vs B (possible, based on electron impact parameter, but with rather large uncertainties)