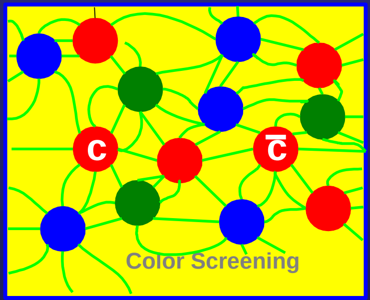
Heavy quarks: where do we stand ? What next?

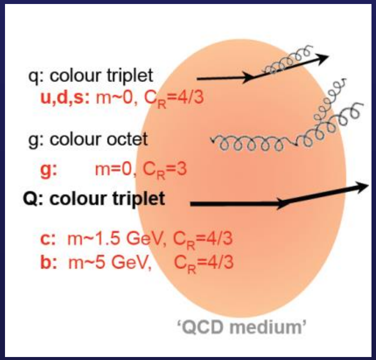
E. Scomparin (INFN-Torino)

XXIV QUARK MATTER
DARMSTADT 2014

Student Day, May 18, 2014

Quarkonia → Sensitive to the temperature of QGP



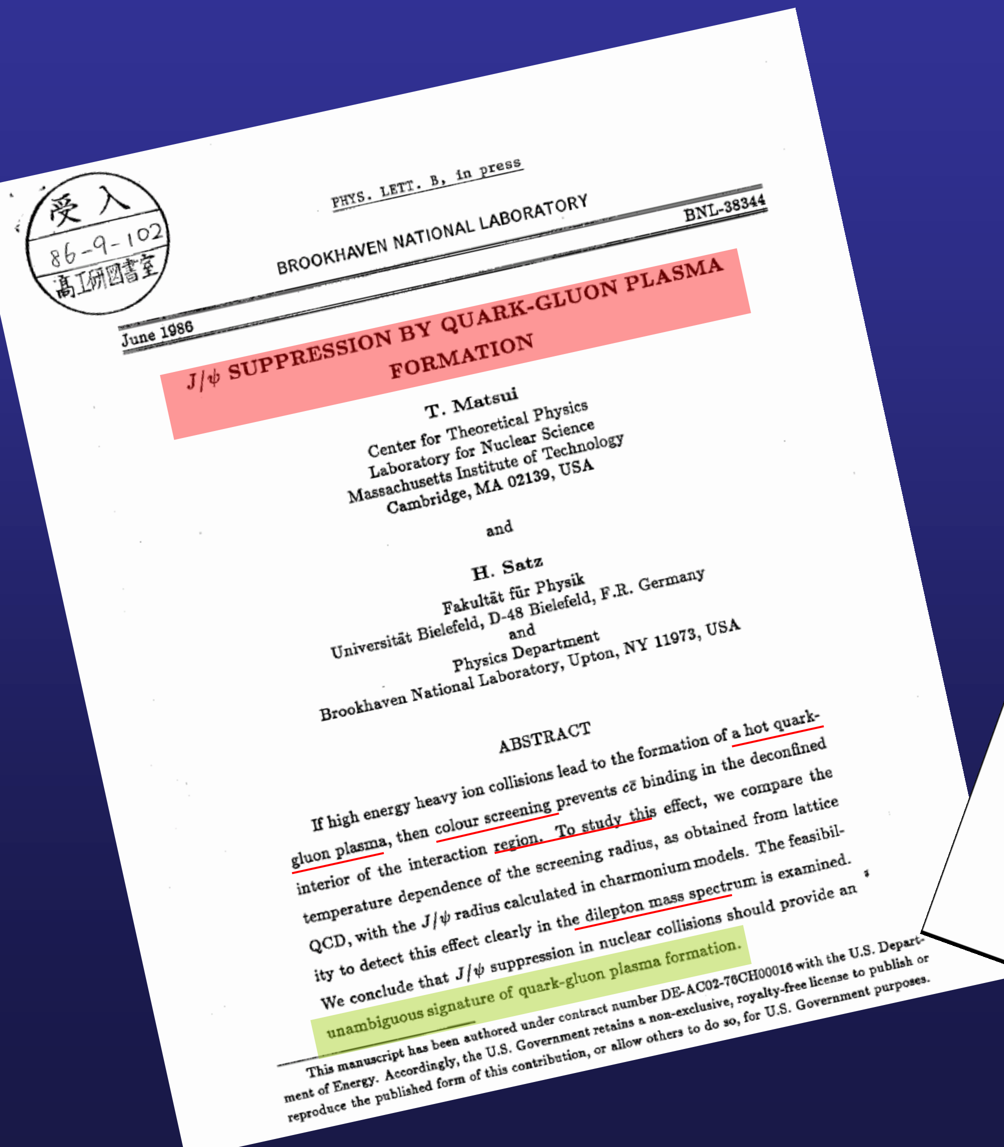


Probe the opacity of QGP ← Open heavy quarks

The beginning of the story…

…28 years after the prediction of J/ψ suppression by Matsui and Satz

… 18 years after the prediction of radiative energy loss by the BDMPS group


PHYS. LETT. B, in press

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June 1986

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J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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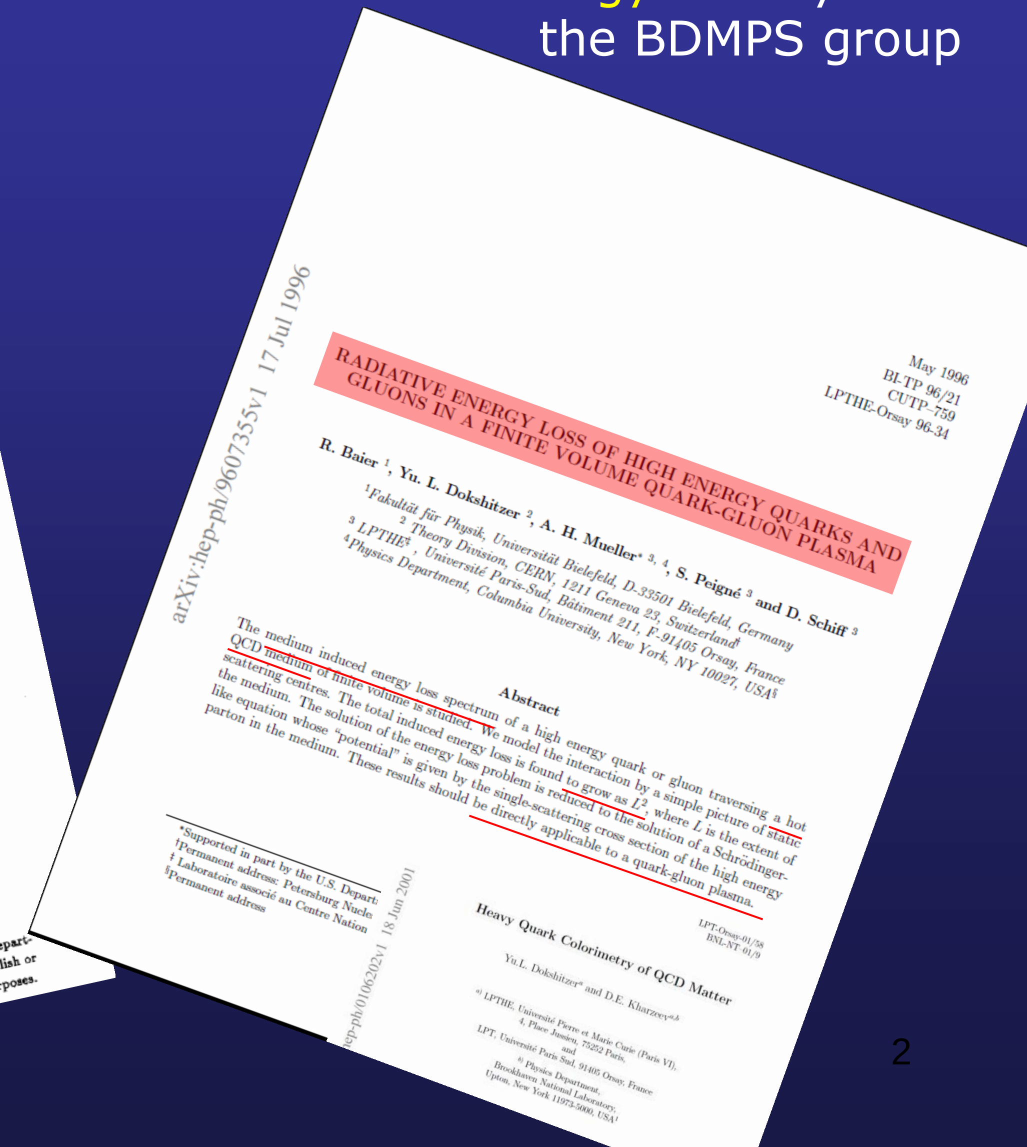
arXiv:hep-ph/9607355v1 17 Jul 1996

May 1996
BI-TP 96/21
CUTP-759
LPTHE-Orsay 96-34

RADIATIVE ENERGY LOSS OF HIGH ENERGY QUARKS AND GLUONS IN A FINITE VOLUME QUARK-GLUON PLASMA

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Abstract

The medium induced energy loss spectrum of a high energy quark or gluon traversing a hot QCD medium of finite volume is studied. We model the interaction by a simple picture of static scattering centres. The total induced energy loss is found to grow as L^2, where L is the extent of the medium. The solution of the energy loss problem is reduced to the solution of a Schrödinger-like equation whose "potential" is given by the single-scattering cross section of the high energy parton in the medium. These results should be directly applicable to a quark-gluon plasma.

*Supported in part by the U.S. Depart…
†Permanent address: Petersburg Nucle…
‡Laboratoire associé au Centre Nation…
§Permanent address

hep-ph/0106202v1 18 Jun 2001

LPT-Orsay-01/58
BNL-NT-01/9

Heavy Quark Colorimetry of QCD Matter

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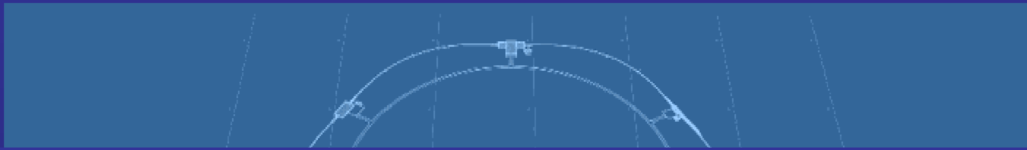
[b] Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

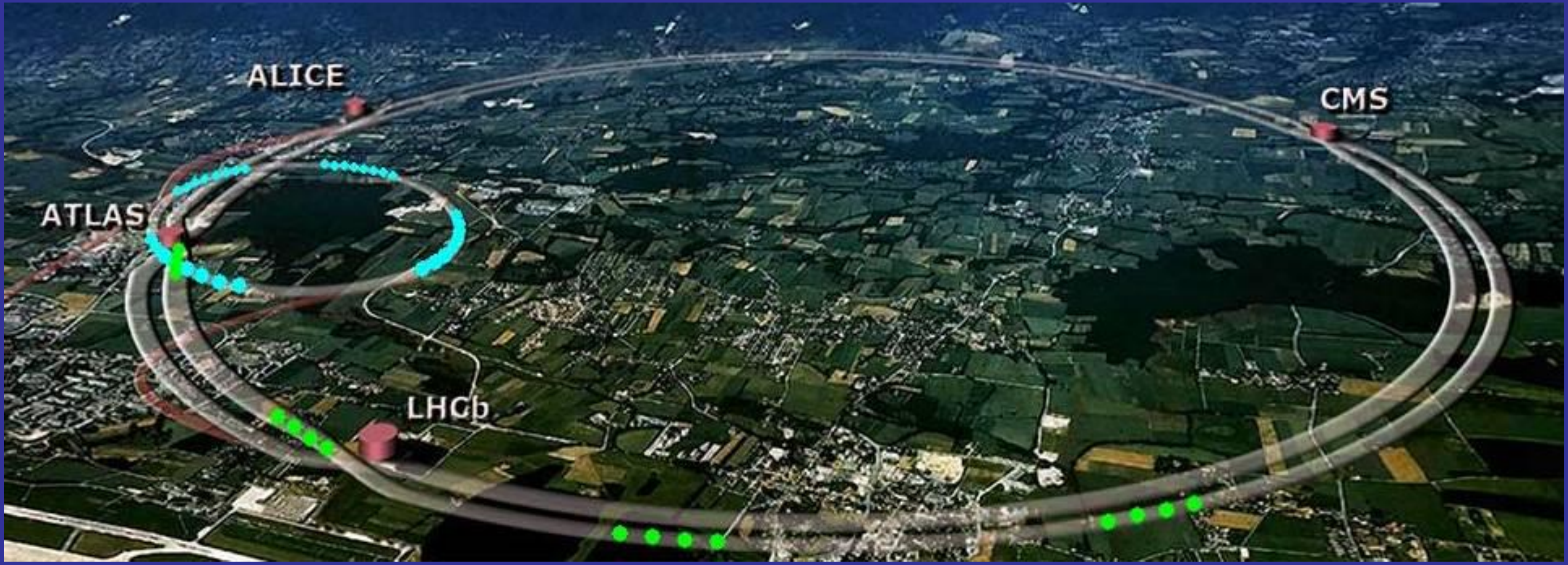
… and the story goes on

…28 years after O beams were first accelerated in the SPS

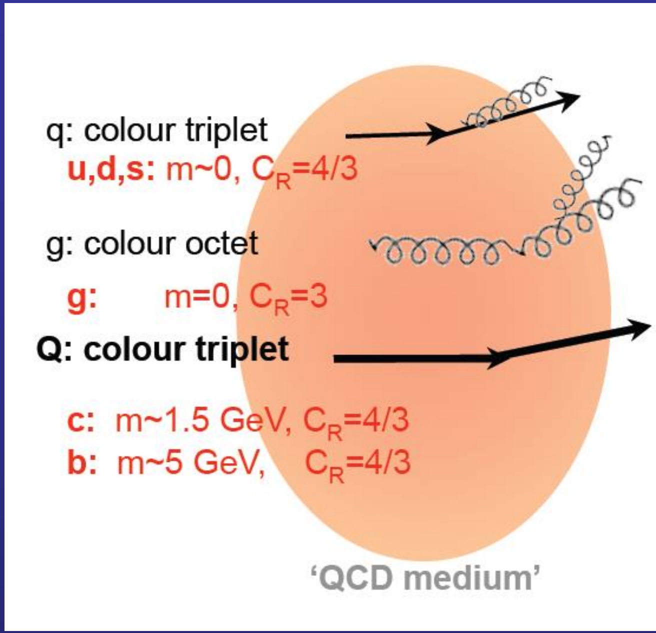
…14 years after Au beams were first accelerated at RHIC



… and barely 3.5 years (!!!) after Pb beams first circulated inside the LHC

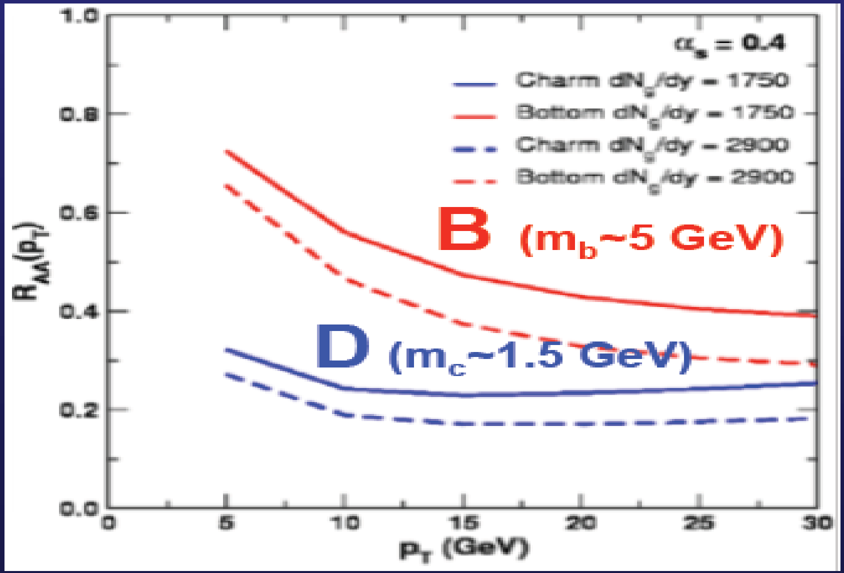


Heavy quark energy loss…



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

..but should critically depend on the properties of the parton
  - Casimir factor
  - Quark mass (dead cone effect)



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

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

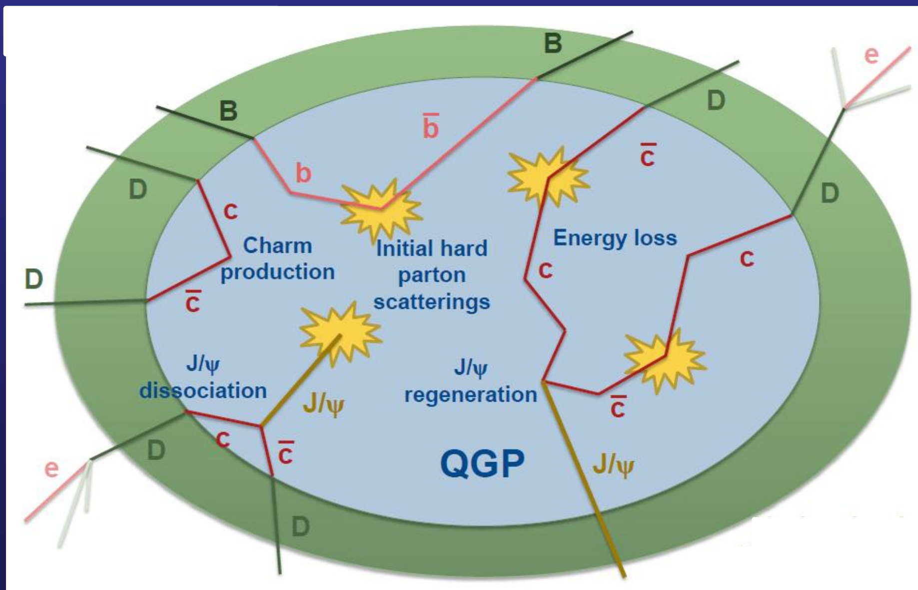
which should imply

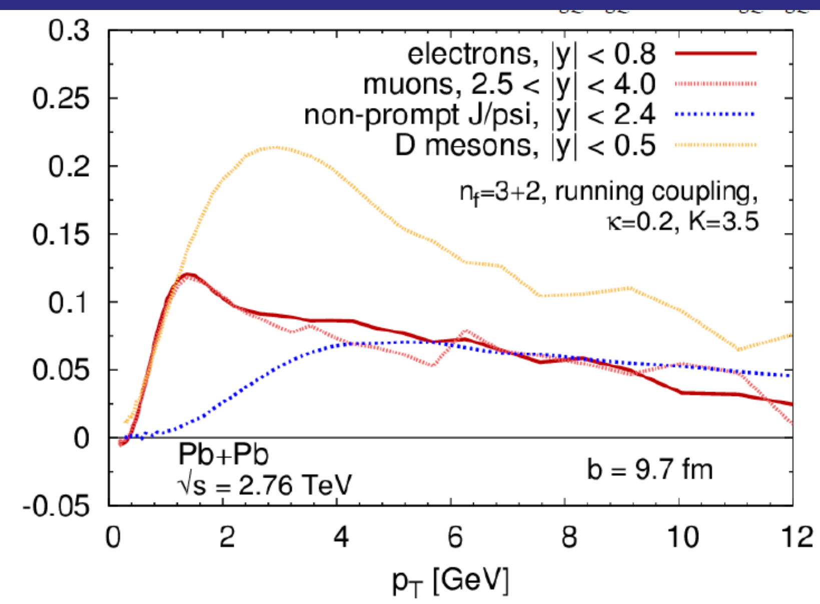
$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

… and v_2

- 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

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



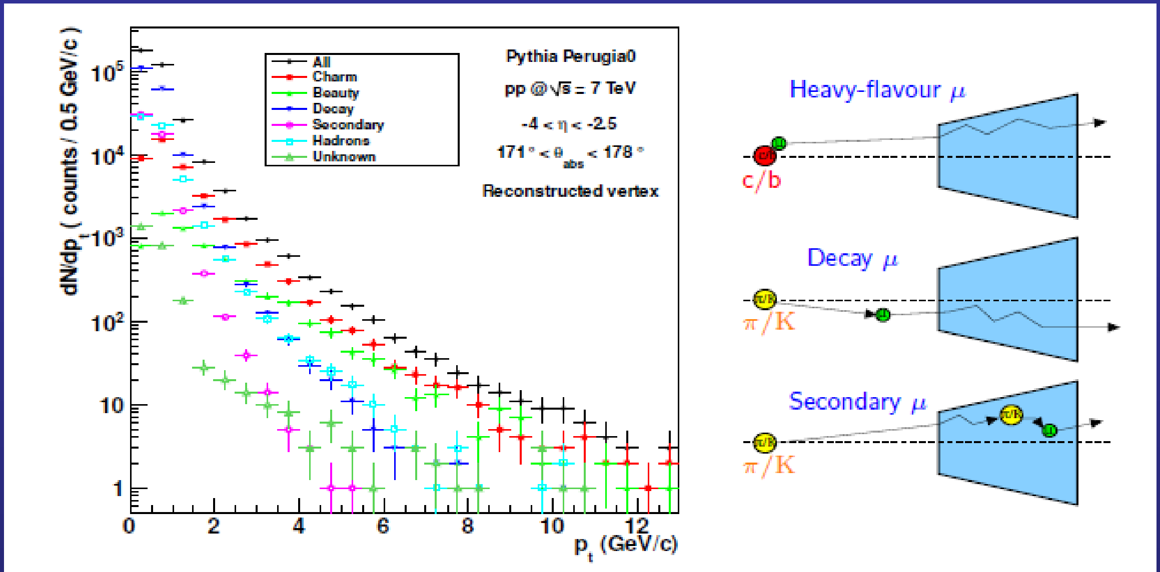


Can the unprecedented abundance of heavy quarks produced at the LHC bring to a (final ?) clarification of the picture ?

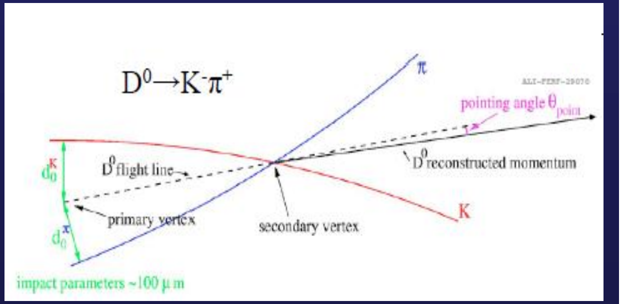
Experimental techinques: charm

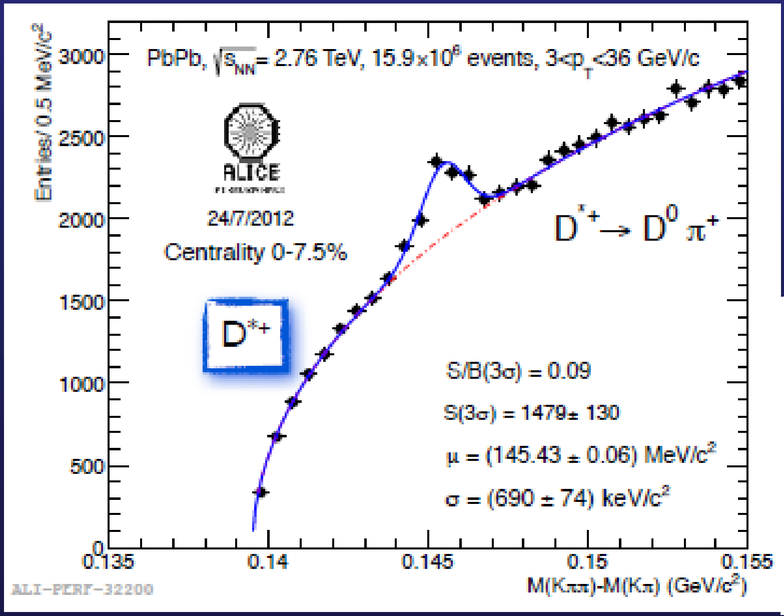
- ❑ Semi-leptonic decays
  → High-p_T single leptons
  (pioneered at RHIC)

  Non-negligible background issues



- ❑ Direct reconstruction of the decay products (D-mesons)





Needs
Vertexing resolution
Particle ID
Topological cuts

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

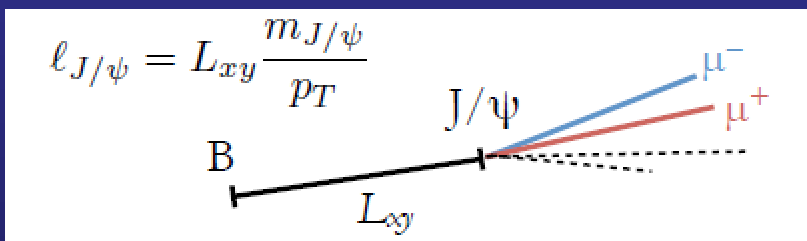
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$

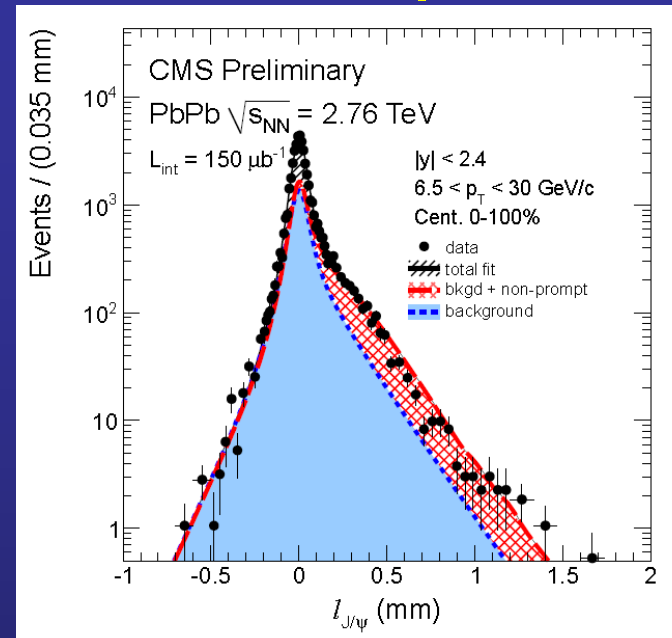
$D^+_s \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$

Experimental techniques: beauty

Non-prompt J/ψ

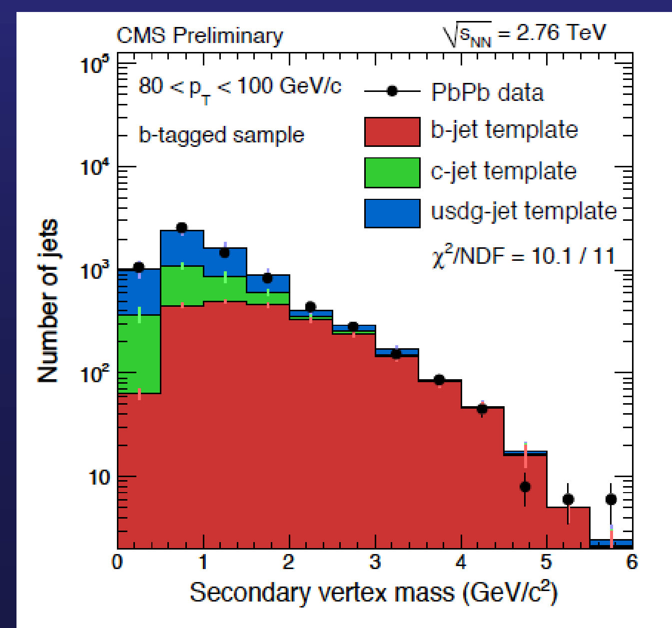
- Fraction of non-prompt J/ψ from simultaneous fit to $\mu^+\mu^-$ invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)
- Expected shapes from sidebands (background) +MC templates (signals)





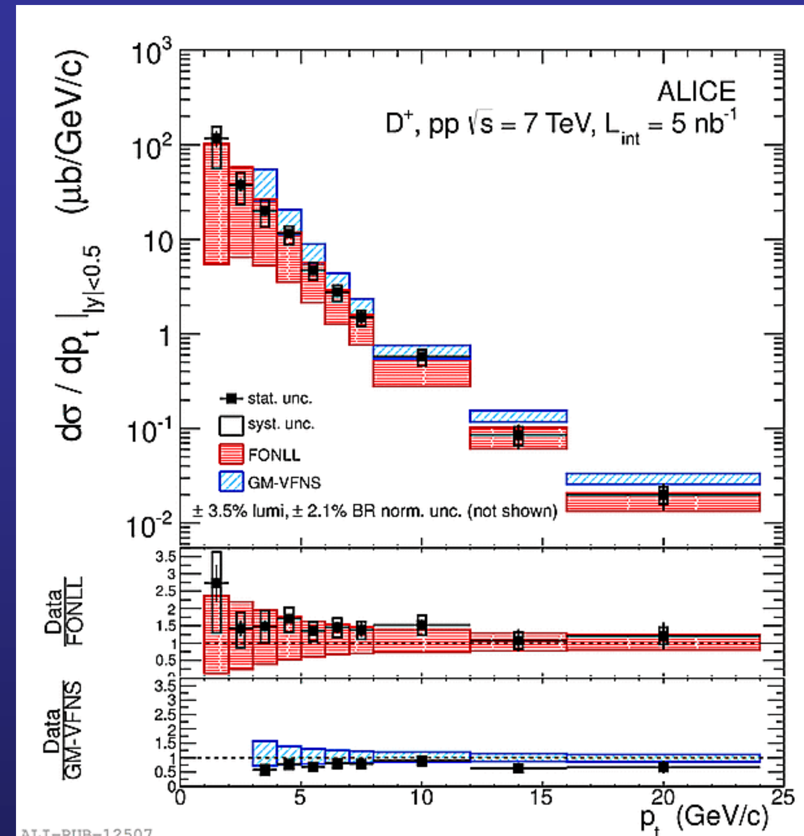
b-jet measurements

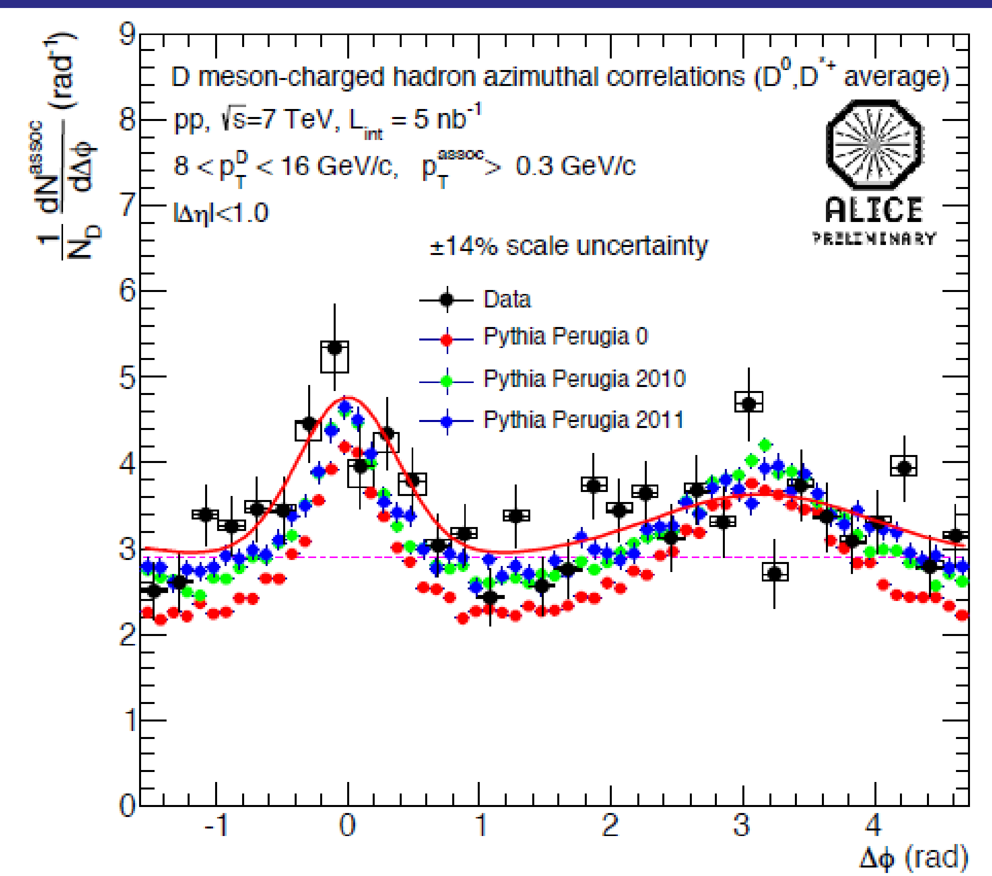
- Jets are tagged by cutting on discriminating variables based on the flight distance of the secondary vertex
  → enrich the sample with b-jets
- b-quark contribution extracted using template fits to secondary vertex inv. mass distributions



Selected charm pp results

- Excellent testing ground for QCD calculations
- Good agreement between data and models at BOTH √s=7 and 2.76 TeV
- Confirmed by single-lepton studies

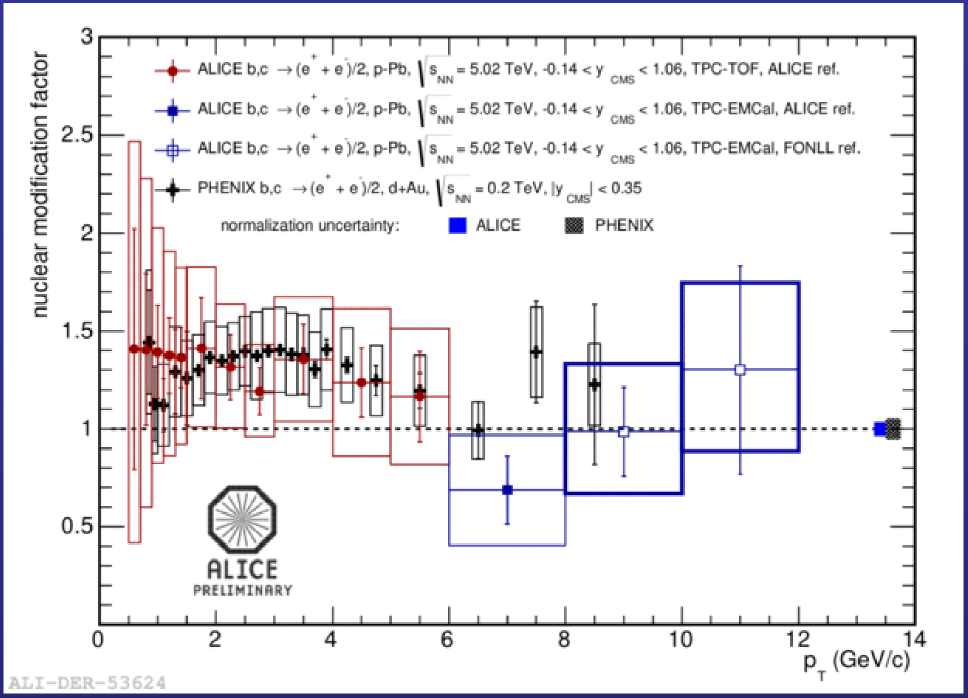




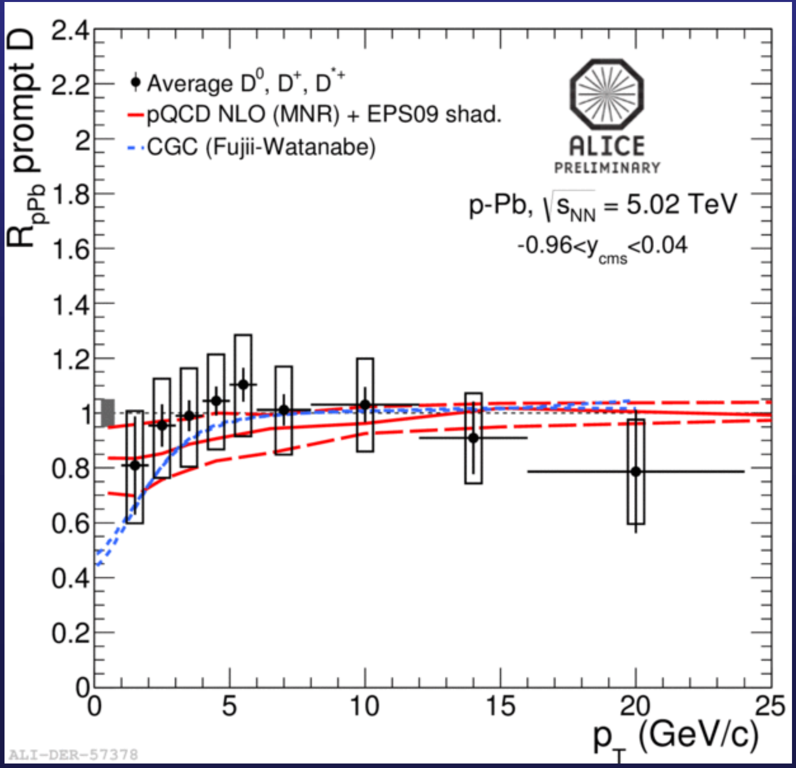
- D-hadron correlations
  - Promising tool to investigate production mechanisms
  - Gluon splitting → no away-side
  - LO (also NLO) → Back-to-back

p-Pb results: CNM

- ❑ R_{pPb} for HFE (mid-rapidity) compatible with 1
- ❑ HFM (forward rapidity) to be shown at QM2014

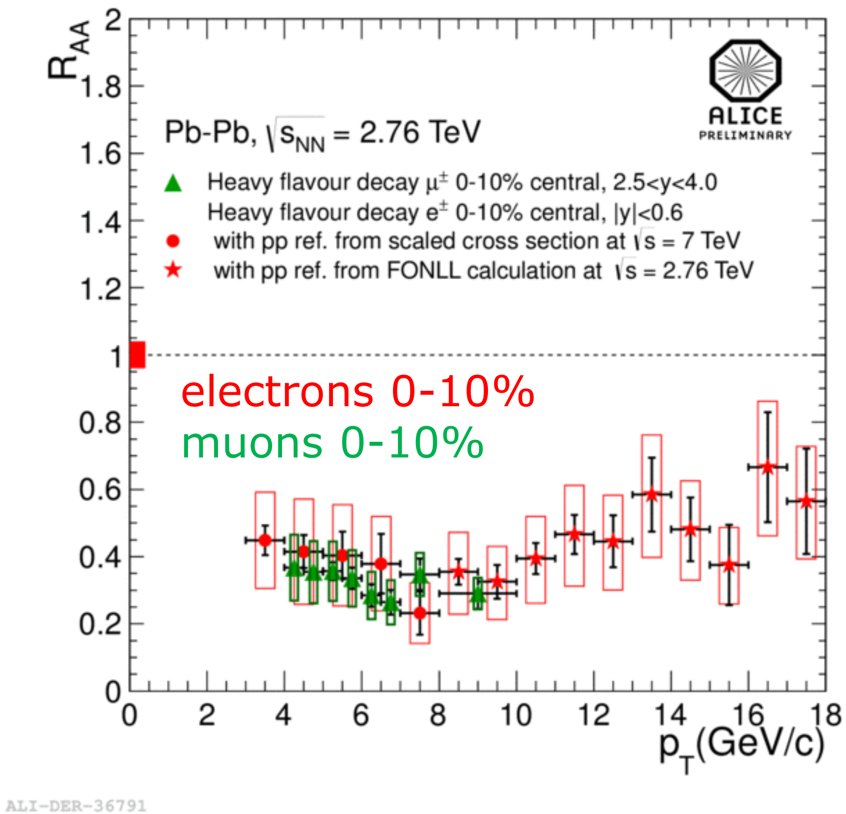


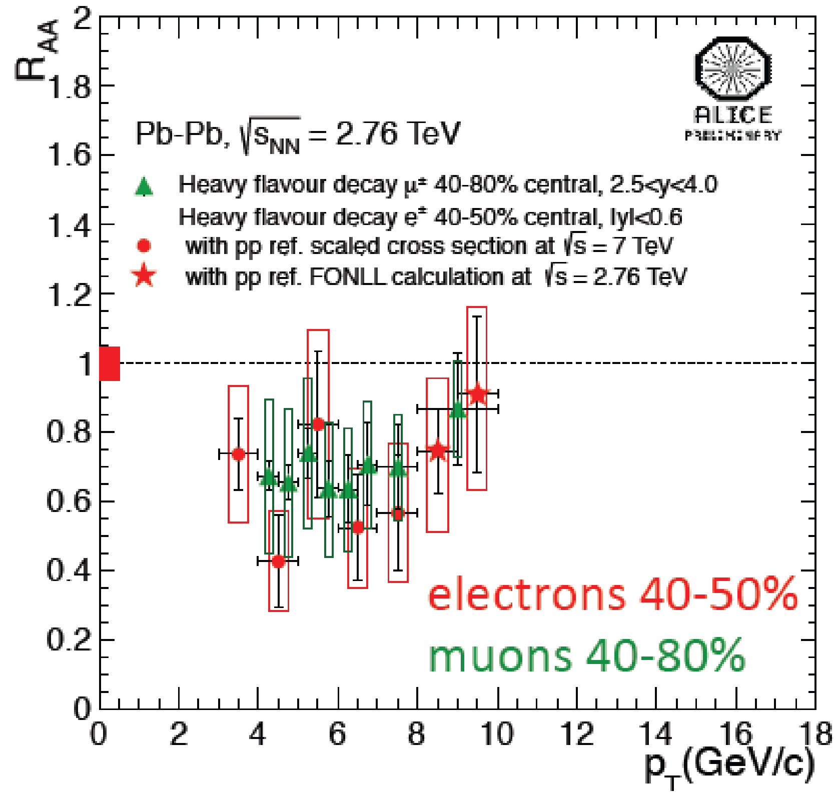
- ❑ Absence of significant CNM effects
- ❑ Similarity to PHENIX not really expected (different shadowing)



- ❑ Direct measurements confirm R_{pPb}~1 (with smaller uncertainties!)
- ❑ Compatible D-meson production ratios between pp and p-Pb for all the measured states (D^0,D^+,D_s^+,D^{*+})

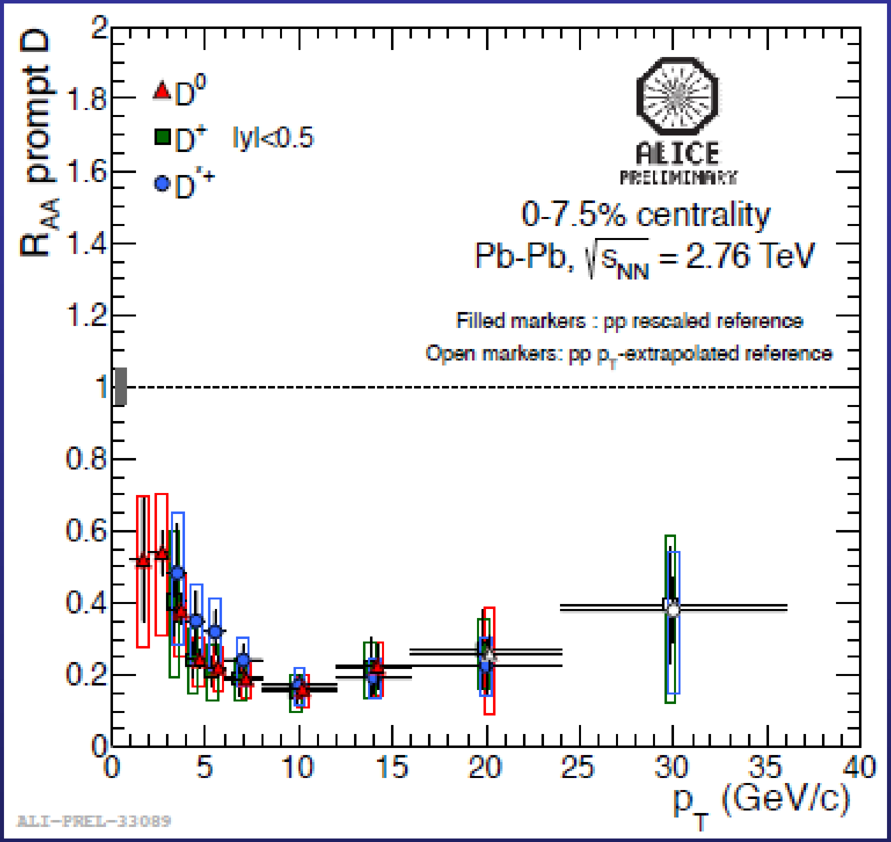
Pb-Pb results (semi-leptonic)

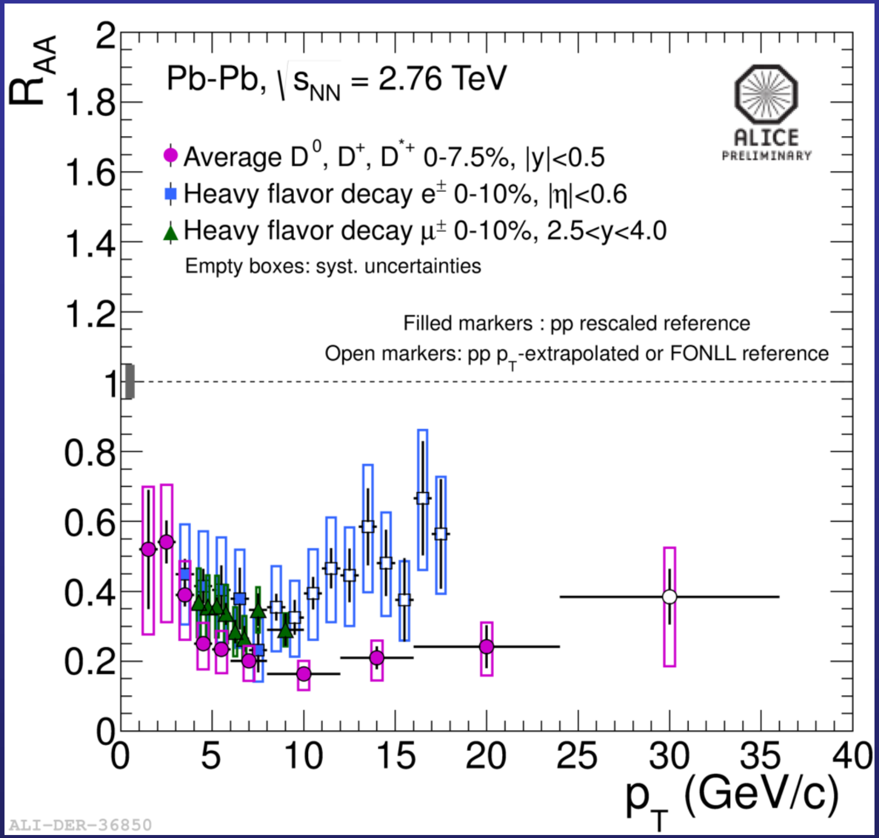




- ❑ Results available up to p_T=18 GeV/c (EMCAL)
- ❑ Clear suppression for central collisions in the studied p_T range
- ❑ Stronger suppression for central collisions (hint)
- ❑ Good compatibility between mid- and forward rapidity results
- ❑ No separation D vs B

Pb-Pb results (direct)





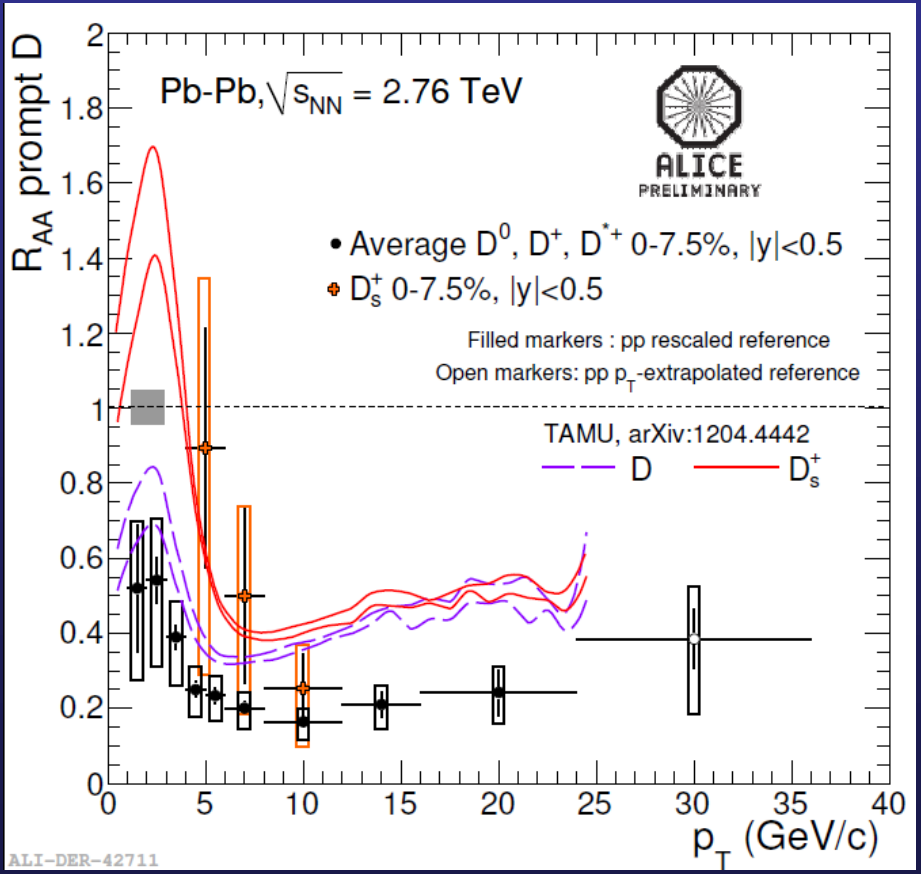
- D^0, D^+ and D^{*+} R_{AA} agree within uncertainties

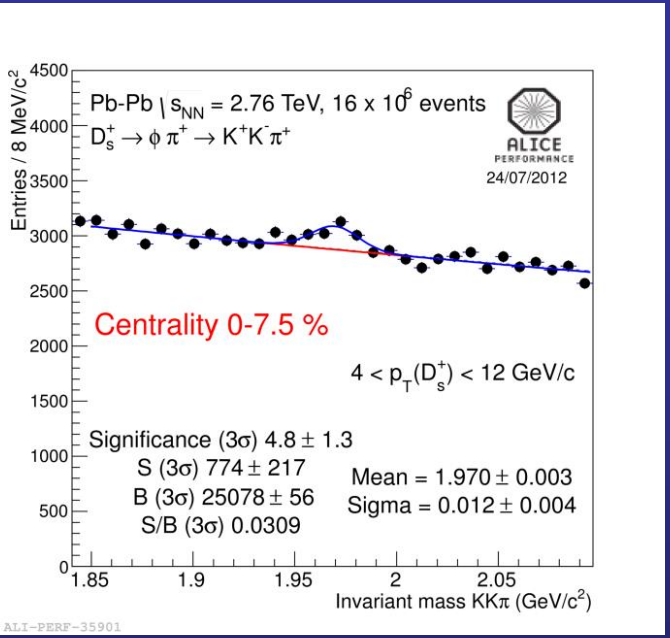
Strong suppression of prompt D mesons in central collisions
→ up to a factor of 5 for $p_T \approx 10$ GeV/c

- Comparison e, μ results vs direct D not straightforward (decay kinematics)
- High p_T : $p_T^e \approx 0.5 \cdot p_T^D$
- Larger suppression for D than for e? B component may have larger R_{AA}

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

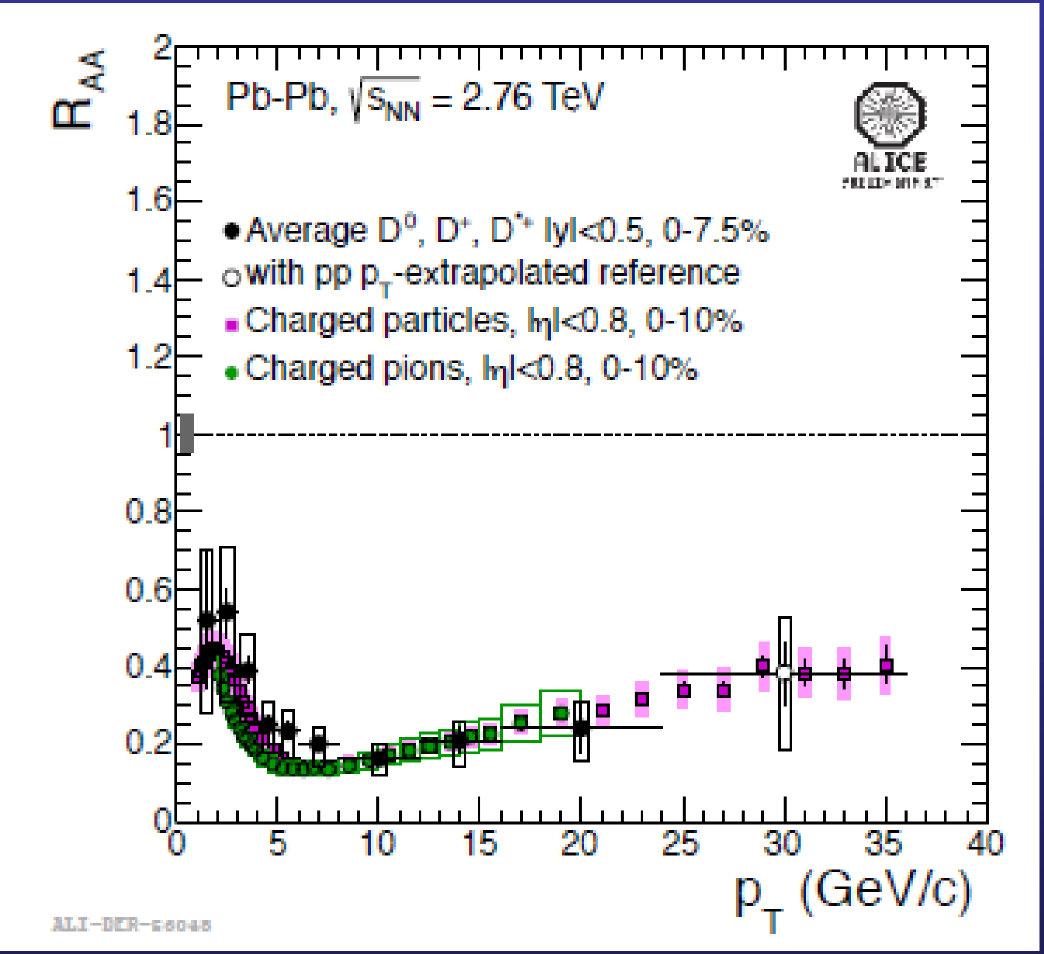
- First measurement of D_s^+ in AA collisions
- Expectation: enhancement of the strange/non-strange D meson yield at intermediate p_T if charm hadronizes via recombination in the medium





- Strong D_s^+ suppression (similar as D^0, D^+ and D^{*+}) for 8<p_T<12 GeV/c
- R_{AA} seems to increase at low p_T
- Current data do not allow a conclusive comparison to other D mesons within uncertainties

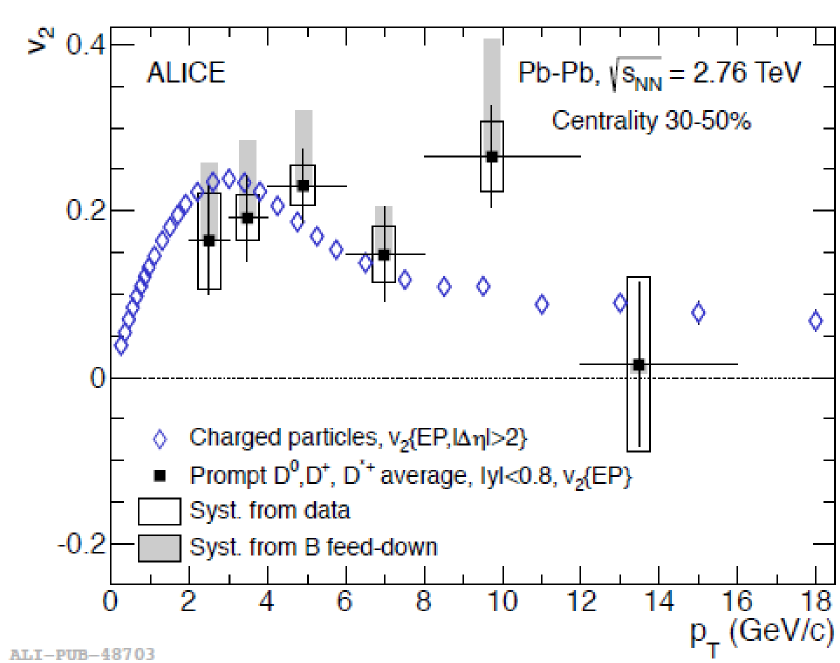
Comparison D vs π

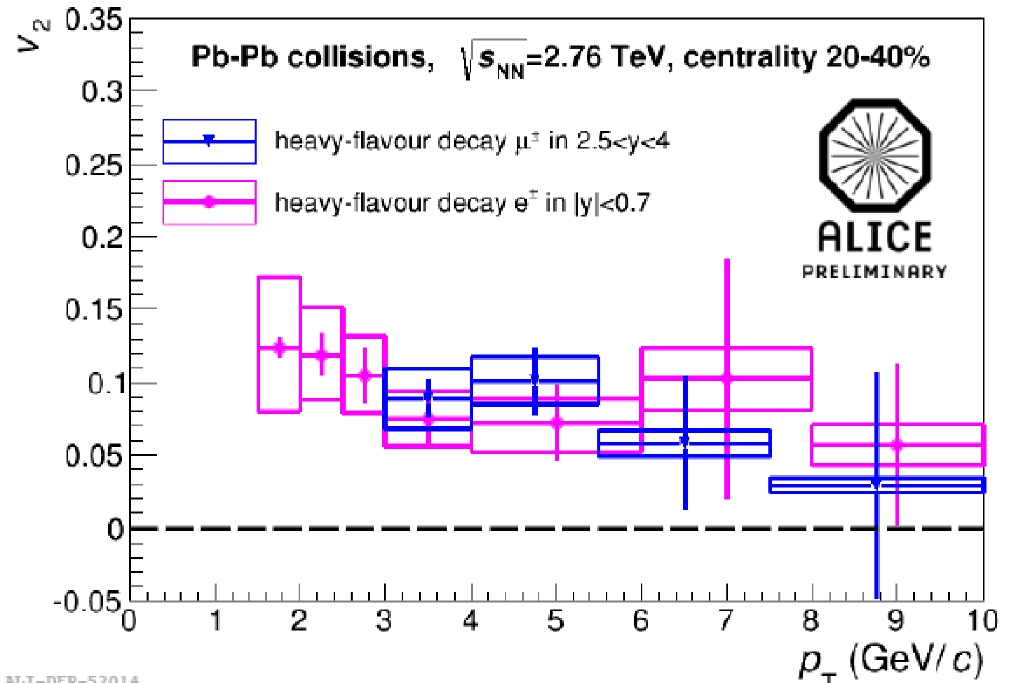


- ❑ Test the mass ordering of energy loss
- ❑ ΔE(q,g)>ΔE(c) ? → Not evident, but….
  - ❑ Different quark spectrum
  - ❑ D_s enhancement may bring down D
  - ❑ ….

D-meson and HFE/HFM v_2

- First measurements of charm anisotropy in heavy-ion collisions



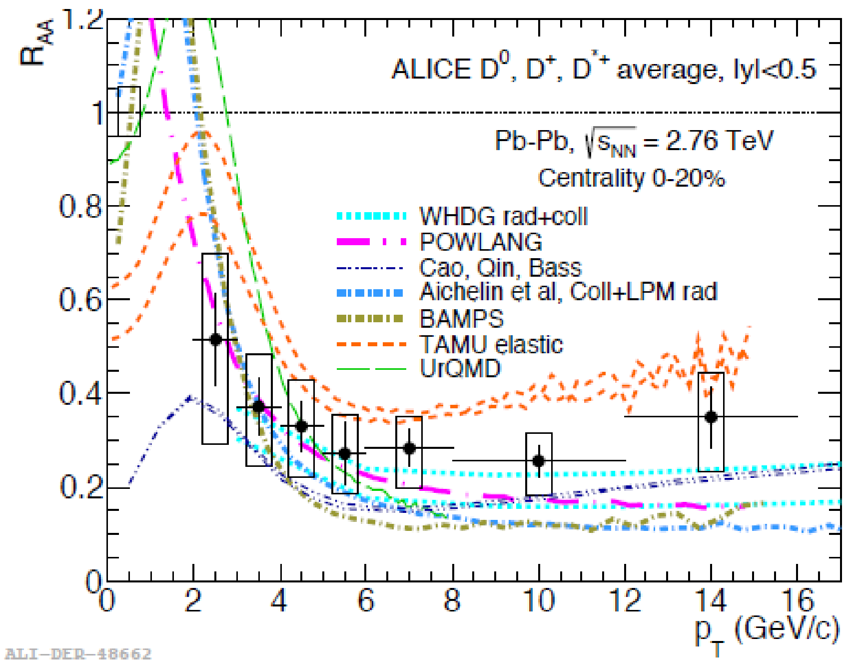


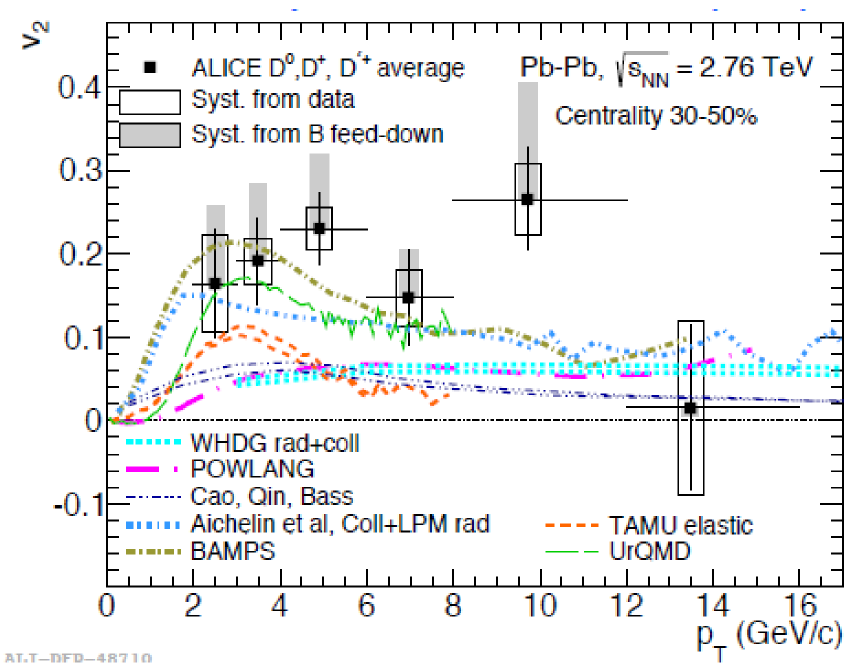
- Similar amount of v_2 for D-mesons and charged pions
- Similar v_2 values for HF decay muons and HF decay electrons (different y)
- All channels show positive v_2 (>3 σ effect)

Information on the initial azimuthal anisotropy transferred to charm quarks

Open charm: model comparisons

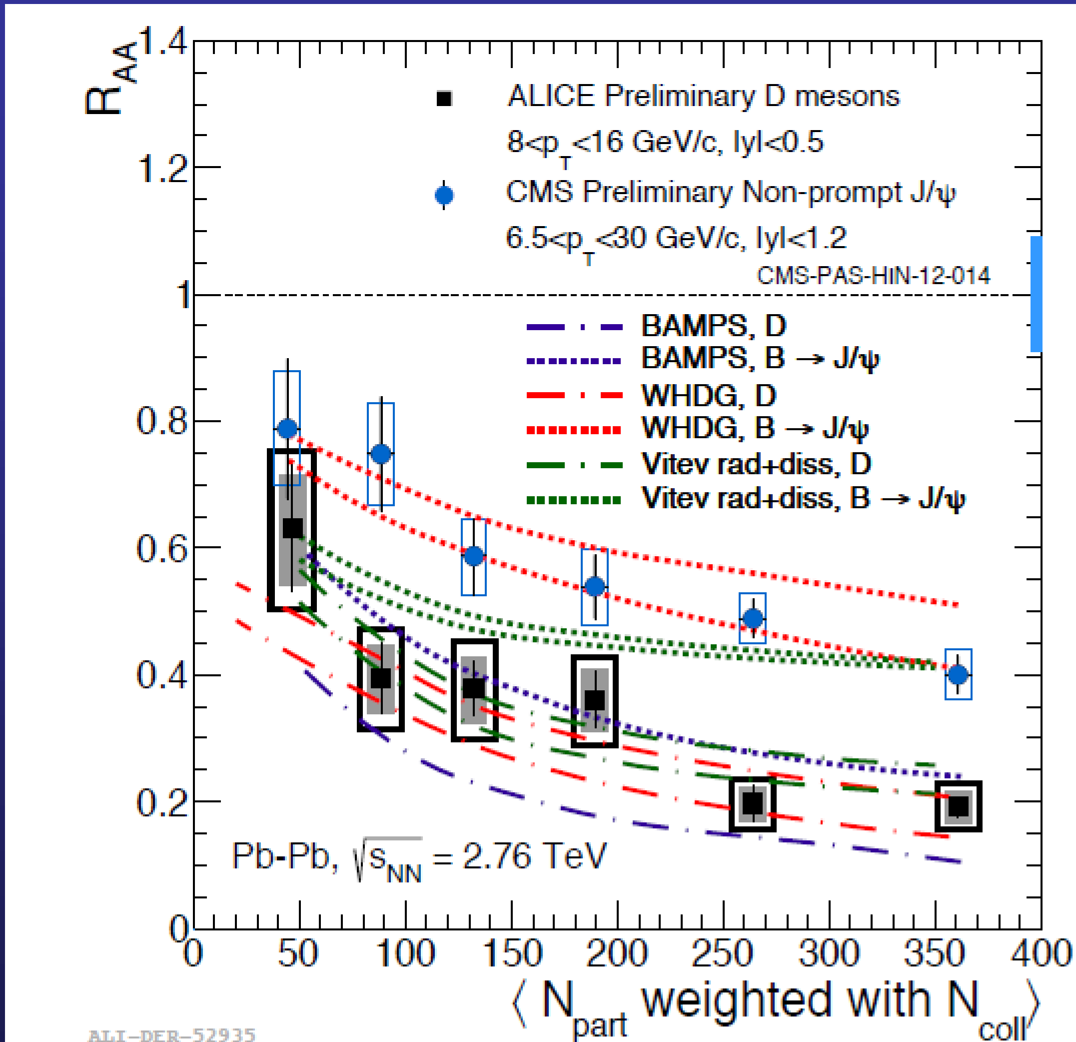
- Simultaneous measurement/description of v_2 and R_{AA}
  → Understanding heavy quark transport coefficient of the medium



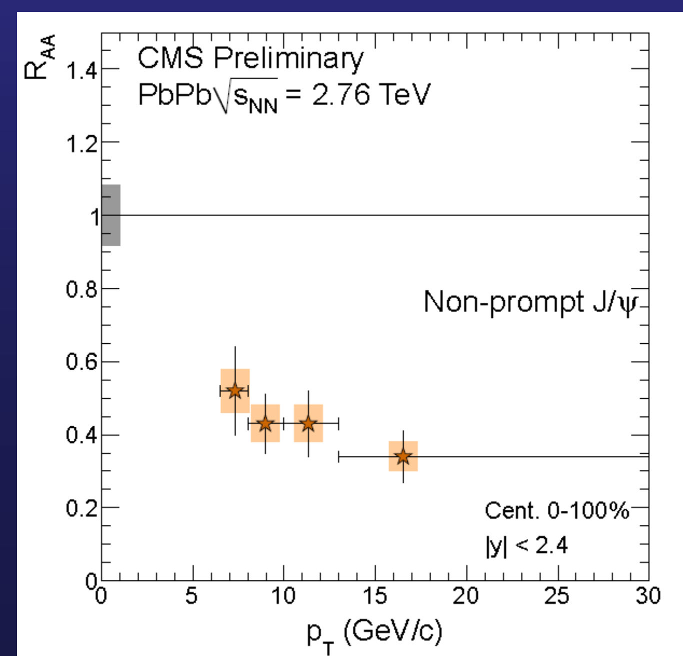


- Wealth of theory calculations
  - Main features correctly reproduced but….
  - In spite of the relatively large experimental uncertainties there are still difficulties in reproducing BOTH R_{AA} and v_2

Charm vs beauty

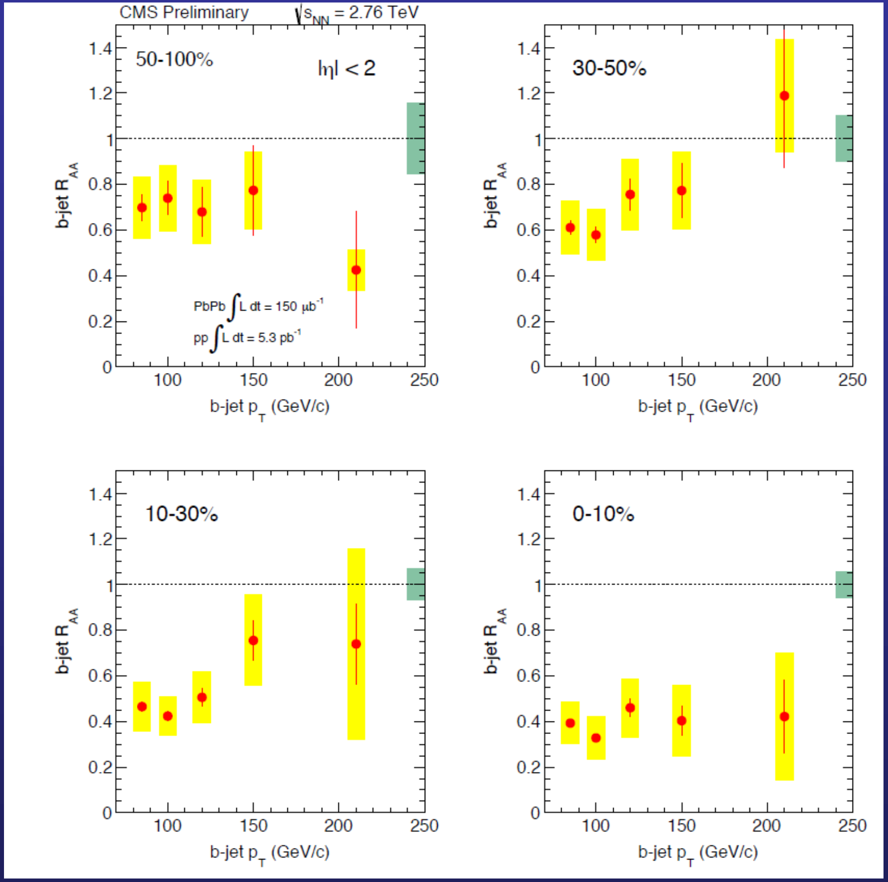


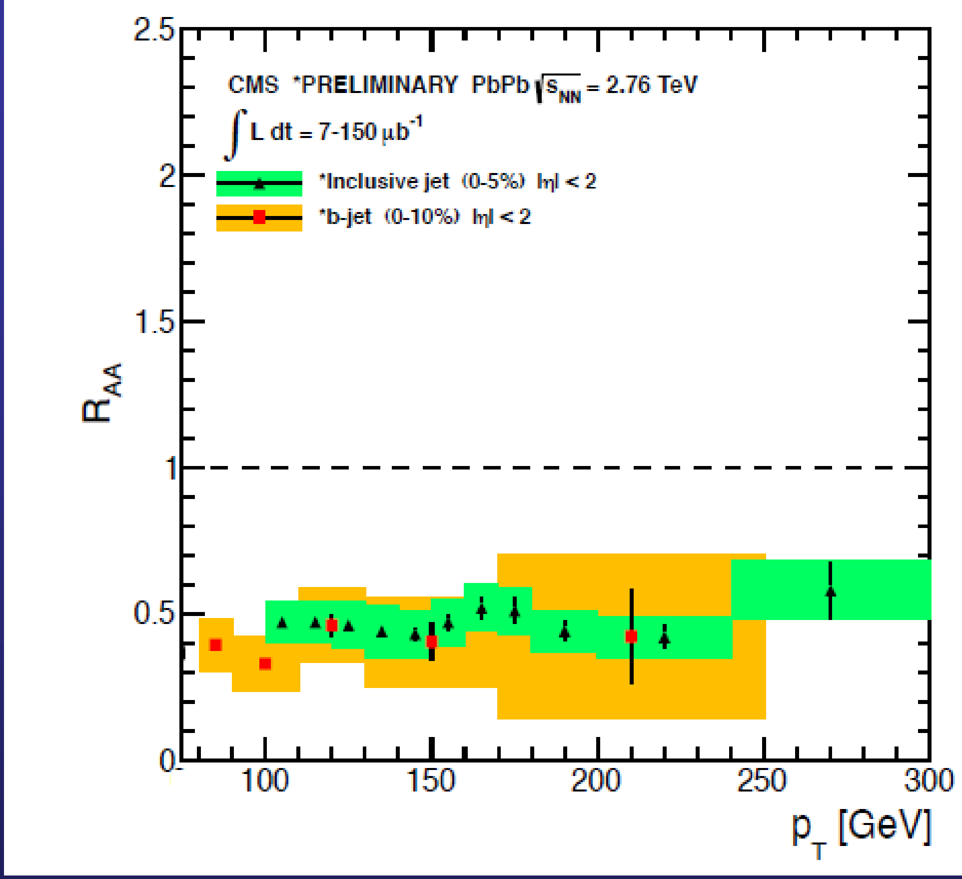
- Comparing direct D results with non-prompt J/ψ
- Similar kinematic range
- In agreement with expectations $R_{AA}(B)>R_{AA}(D)$
- Nice qualitative agreement with models



- B-suppression stronger at large p_T (still large uncertainties, though)

b-jet tagging



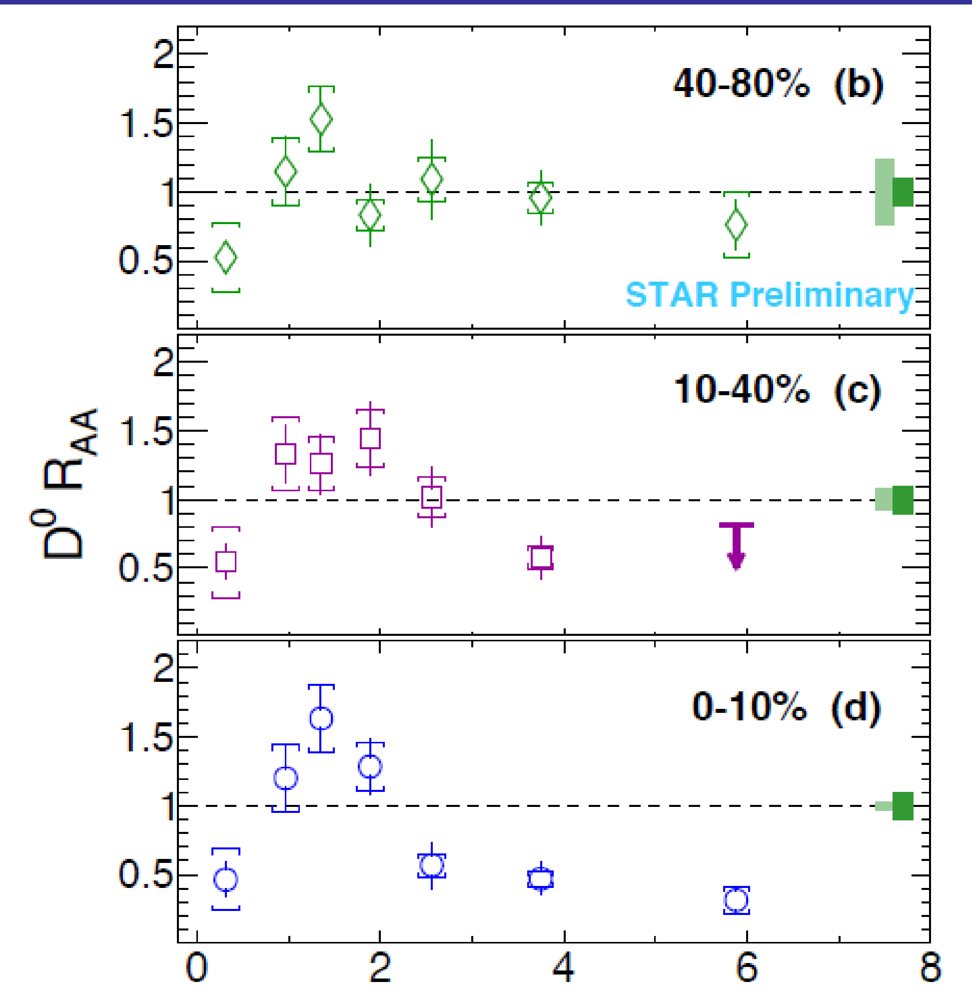


- ❑ Clear suppression of b-jets
- ❑ R_{AA} vs p_T shows suppression up to very large p_T
- ❑ Trend vs centrality well visible

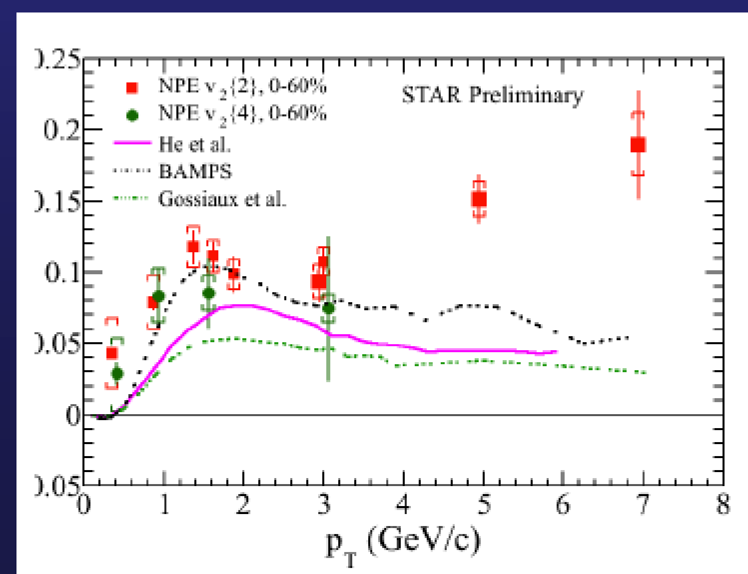
- ❑ Central b-jet suppression consistent with that in inclusive jets

At large p_T the effects related to quark mass become negligible

Some results from RHIC

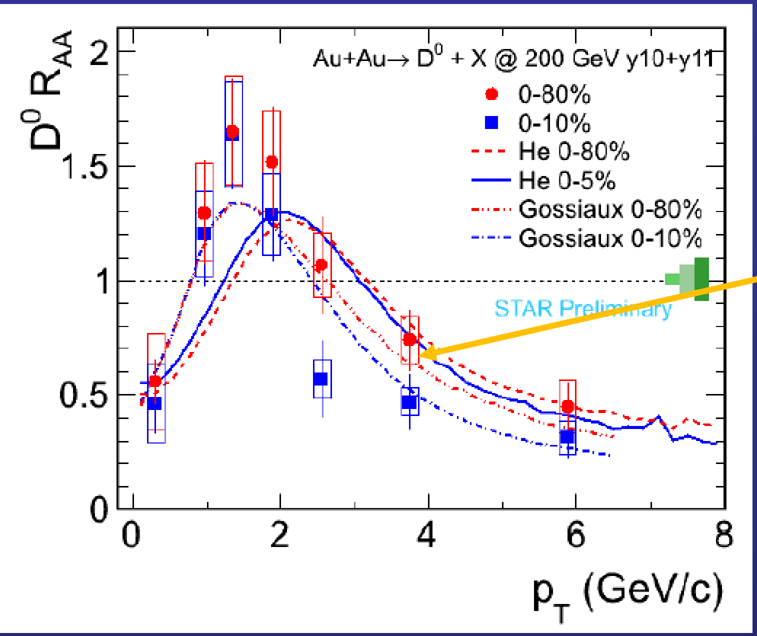


- Significant low-p_T enhancement (confirmed in U-U at 193 A GeV)
- Could be due to a combination of various effects
  - High p_T quenching
  - Effect of low p_T radial flow
  - Shadowing
- Significant NPE v_2 at low p_T
  - Coalescence with light quark?
  - Charm flow ?

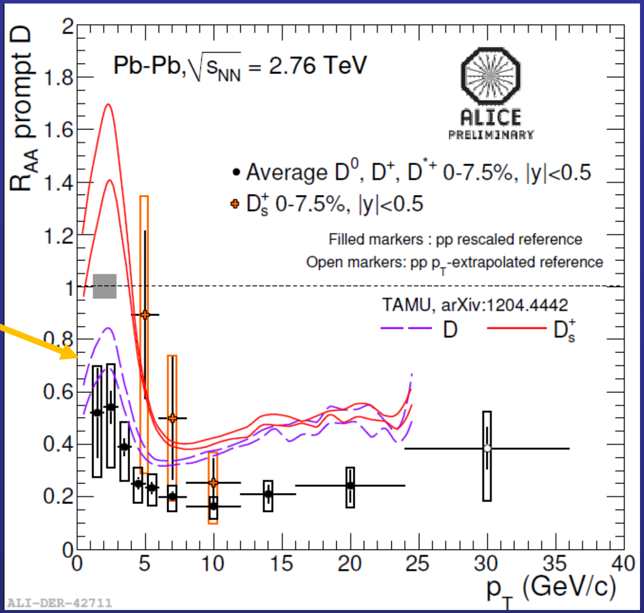


- Quite different low p_T behaviour for R_{AA} with respect to LHC energy

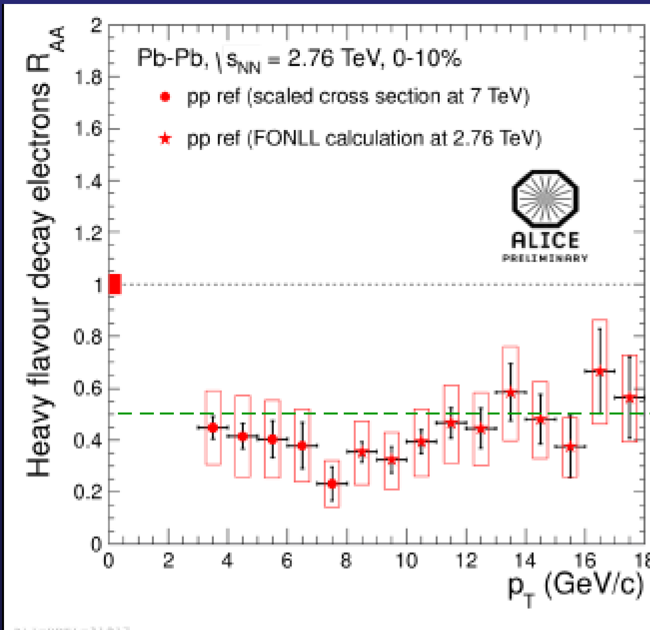
Comparisons LHC vs RHIC

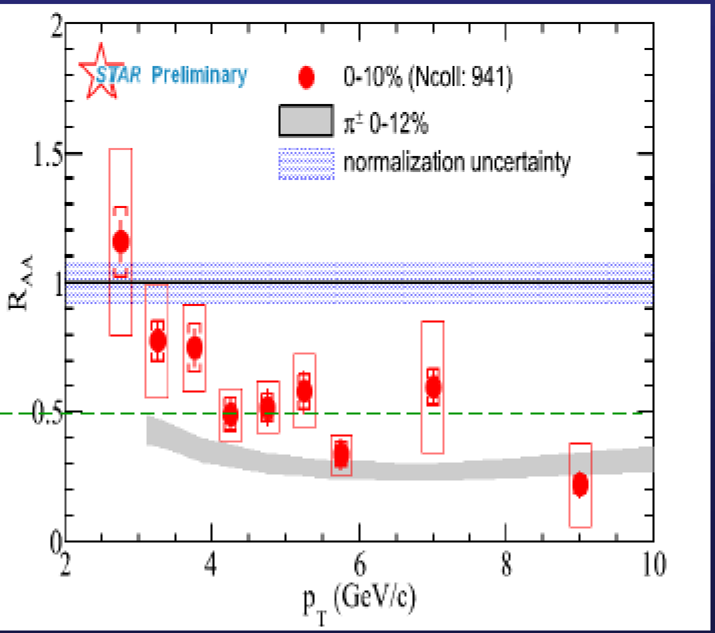


Same model can reproduce results at the two energies



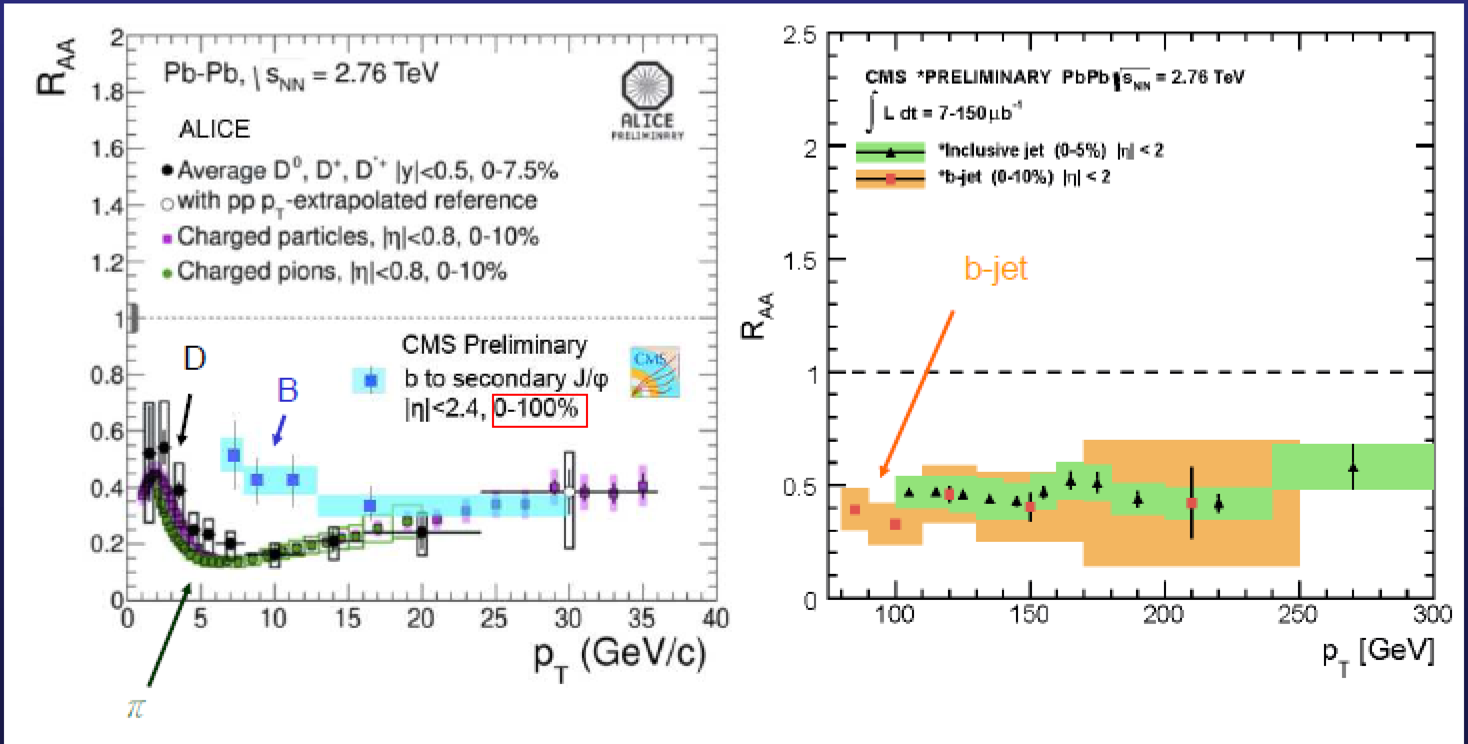
- Qualitative agreement also for HFE





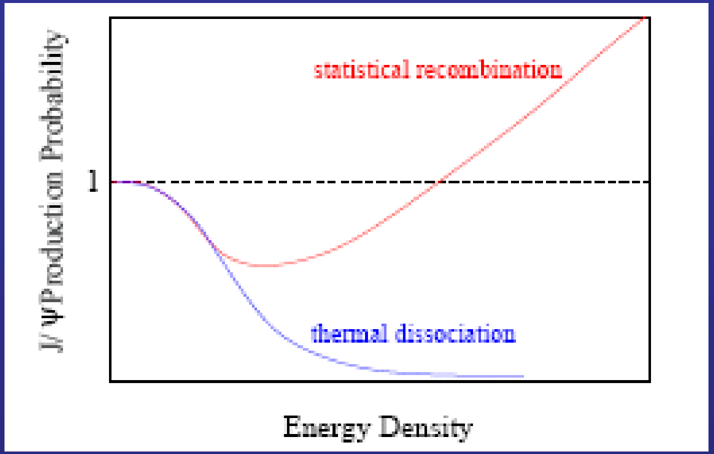
Open charm/beauty: short summary

- Abundant heavy flavour production at the LHC
  - Allow 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
- Hadrochemistry of D meson species: first intriguing result on D_s



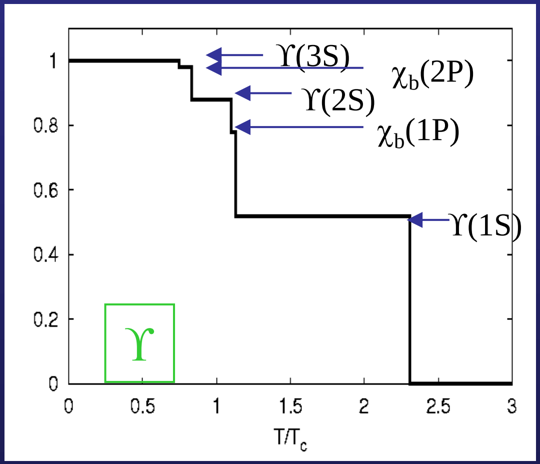
Charmonia/bottomonia

- ❑ Three main issues/problems

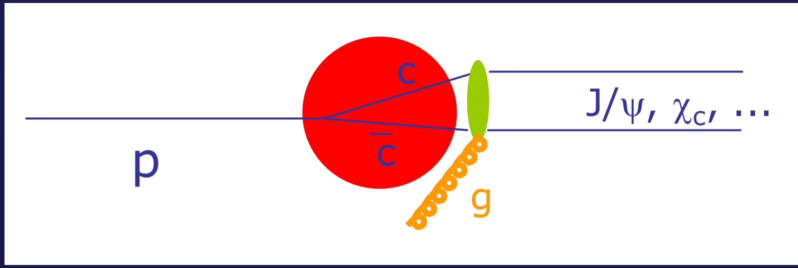


- ❑ Two competing mechanisms
  - ❑ Color screening → suppression
  - ❑ (Re)-combination → enhancement

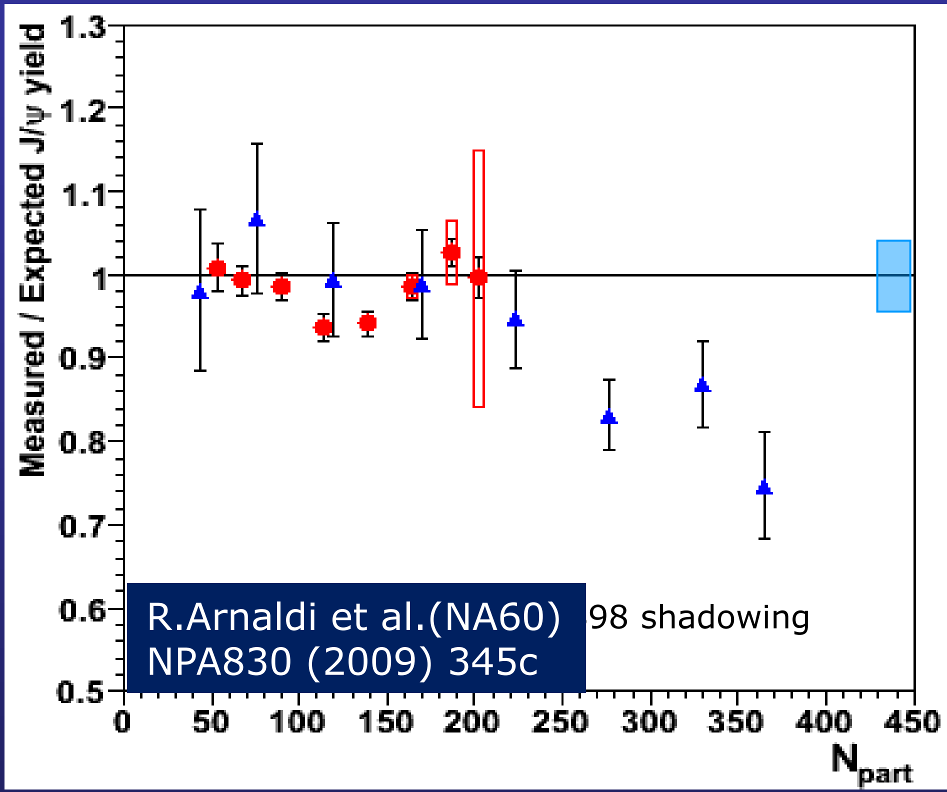
- ❑ Sequential suppression
  - ❑ Charmonium → J/ψ, χ_c, ψ(2S)
  - ❑ Bottomonium → Υ(1S), Υ(2S), Υ(3S), χ_b
  - ❑ Relying on theory for connection with temperature

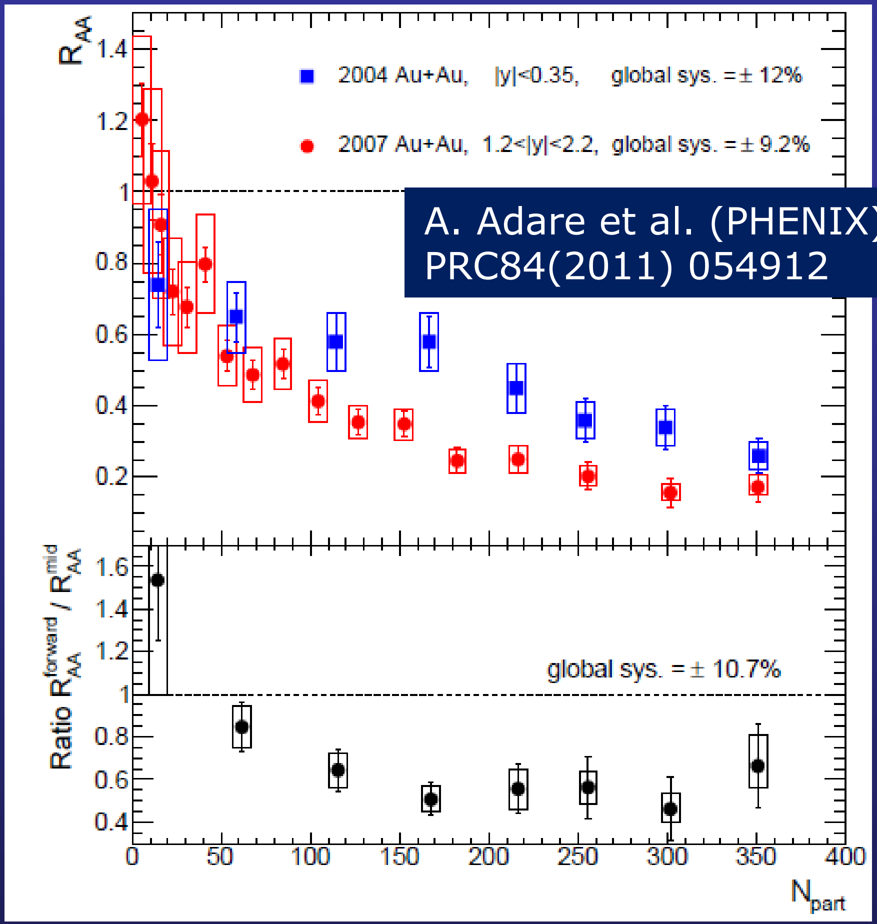


- ❑ Cold nuclear matter effects
  - ❑ Very effective at all energies
  - ❑ Description/understanding of underlying mechanisms difficult
  - ❑ Extrapolation pA → AA "model-"dependent



The legacy: SPS and RHIC





- SPS: first evidence of anomalous suppression (i.e., beyond CNM expectations) in Pb-Pb at √s= 17 GeV

- RHIC: suppression, strongly depending on rapidity, in Au-Au at √s= 200 GeV
- Weaker suppression at y=0: evidence for re-combination?

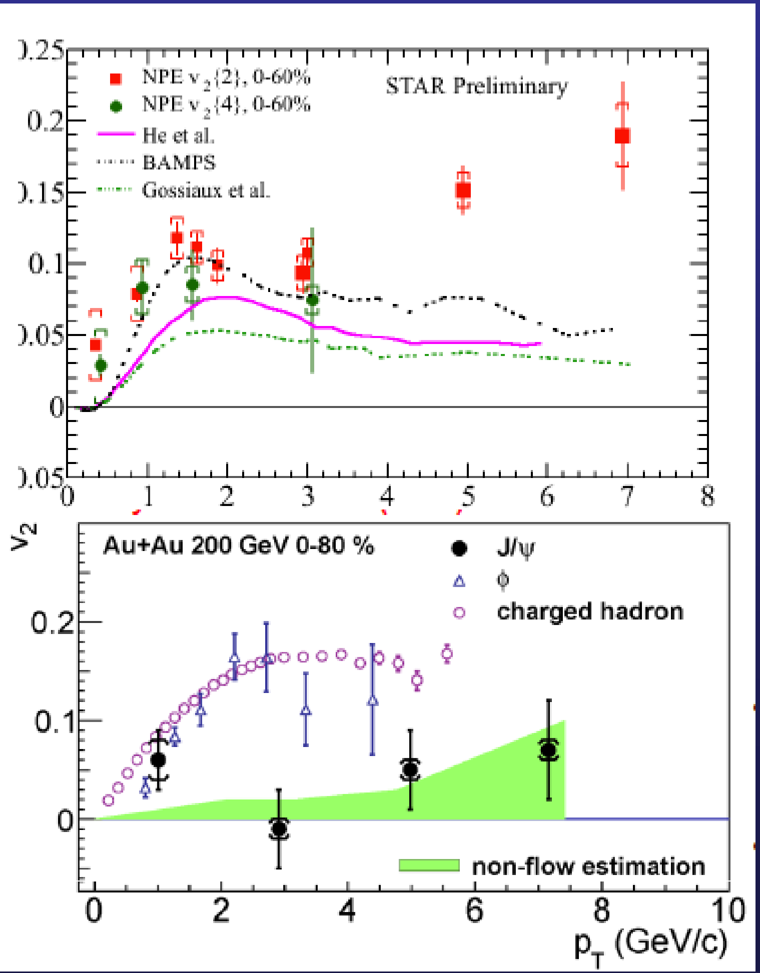
RHIC: suppression vs recombination

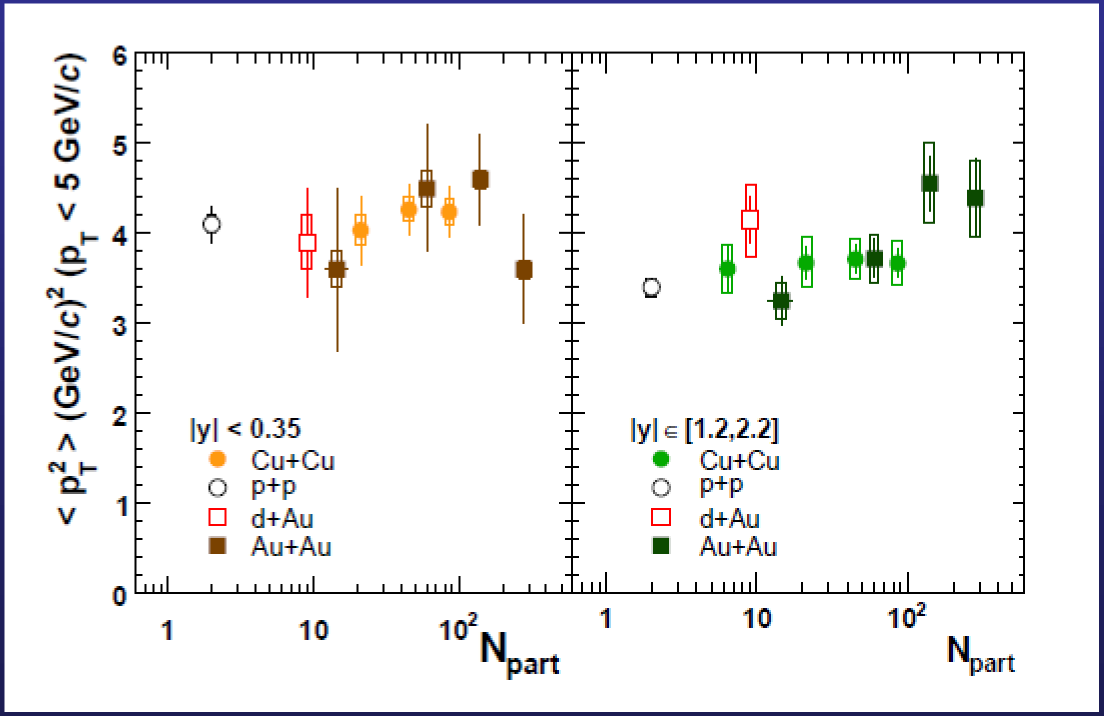
- ❑ Did we reach a consensus on the role played by recombination at RHIC ?

One should in principle observe

J/ψ elliptic flow
→ J/ψ should inherit the heavy quark flow

J/ψ p_T distribution
→ should be softer ($<p_T^2>$↓) wrt pp



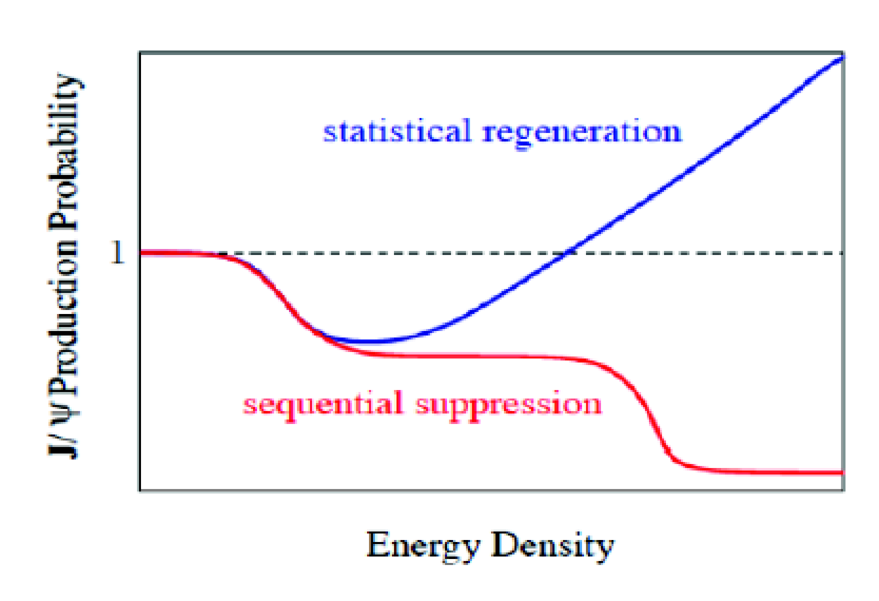


- ❑ Evidence not compelling
- ❑ Could weaker suppression at y=0 be due to other effects (CNM, for example)?

Questions for LHC

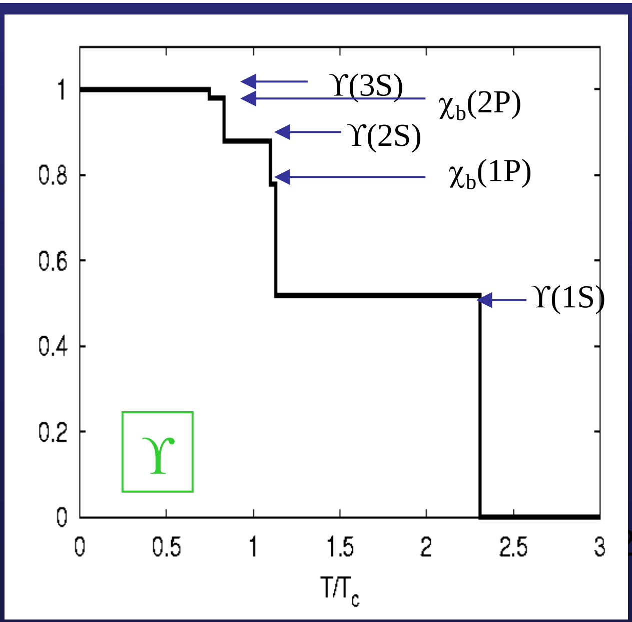
1) Evidence for charmonia (re)combination: now or never!

Do we see enhancement vs centrality ?
Do we see J/ψ flow?
Do we see softer p_T distributions?

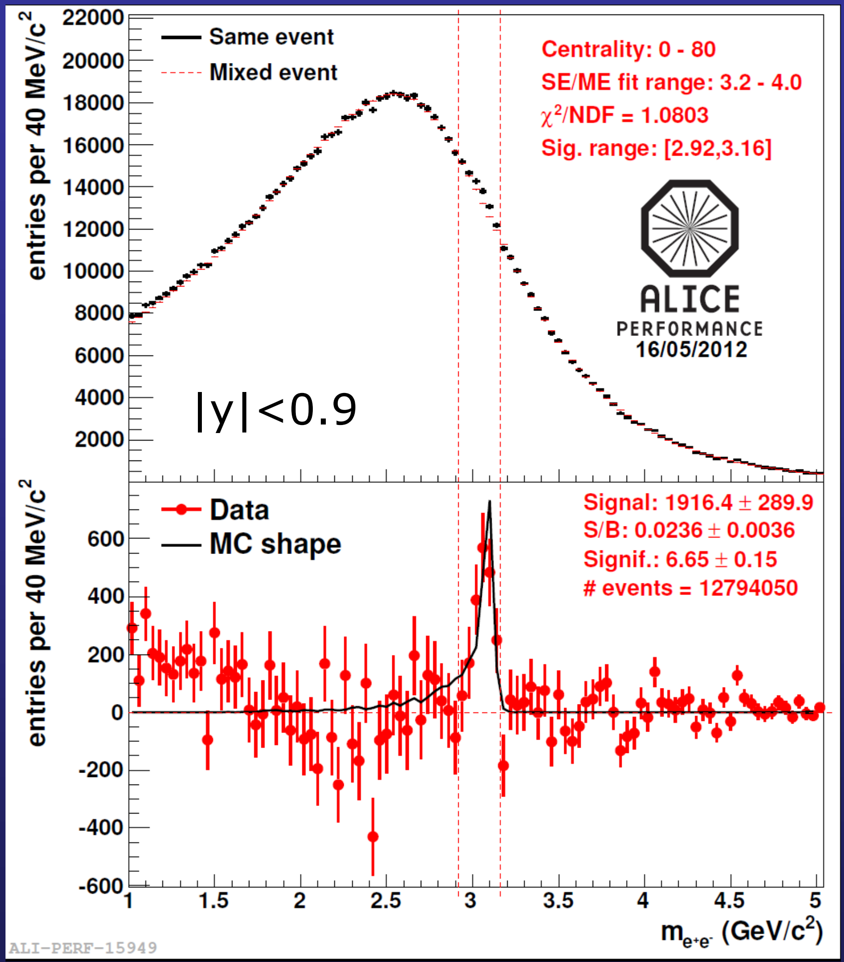


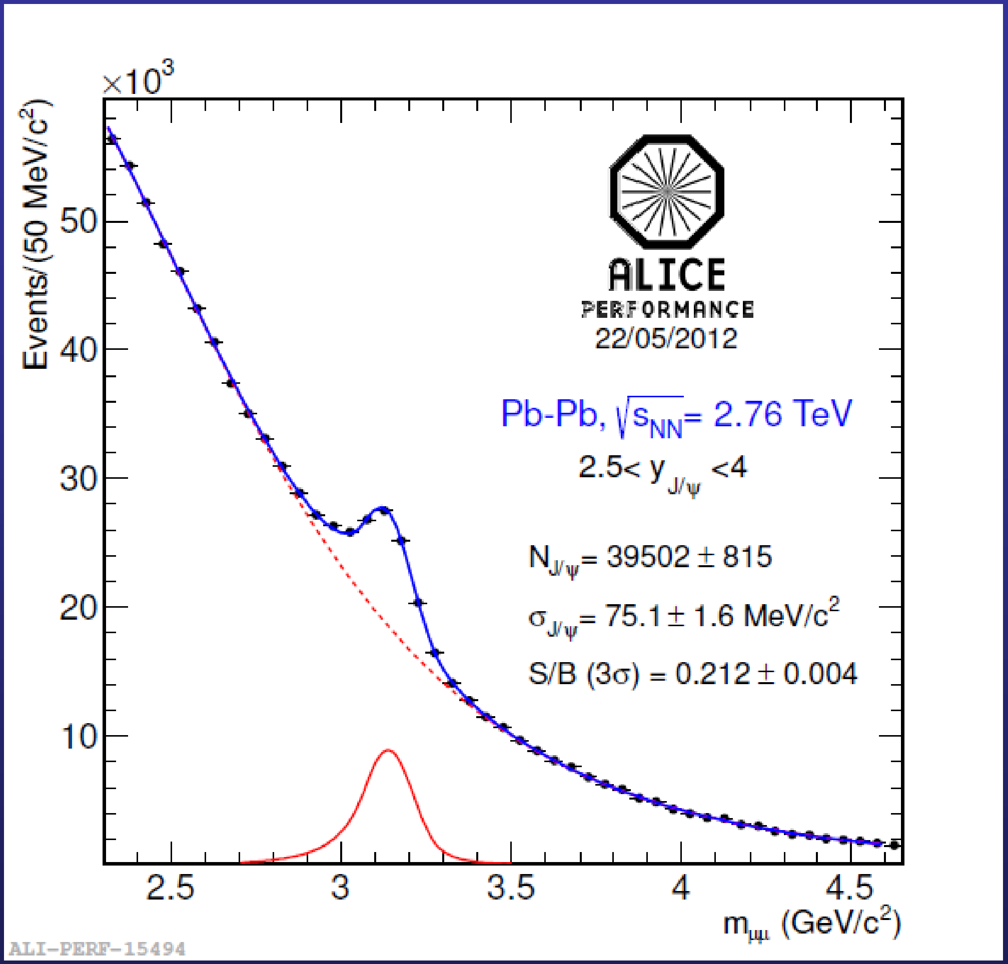
2) A detailed study of bottomonium suppression

Do we see sequential suppression ?
(as recombination does not play a role)



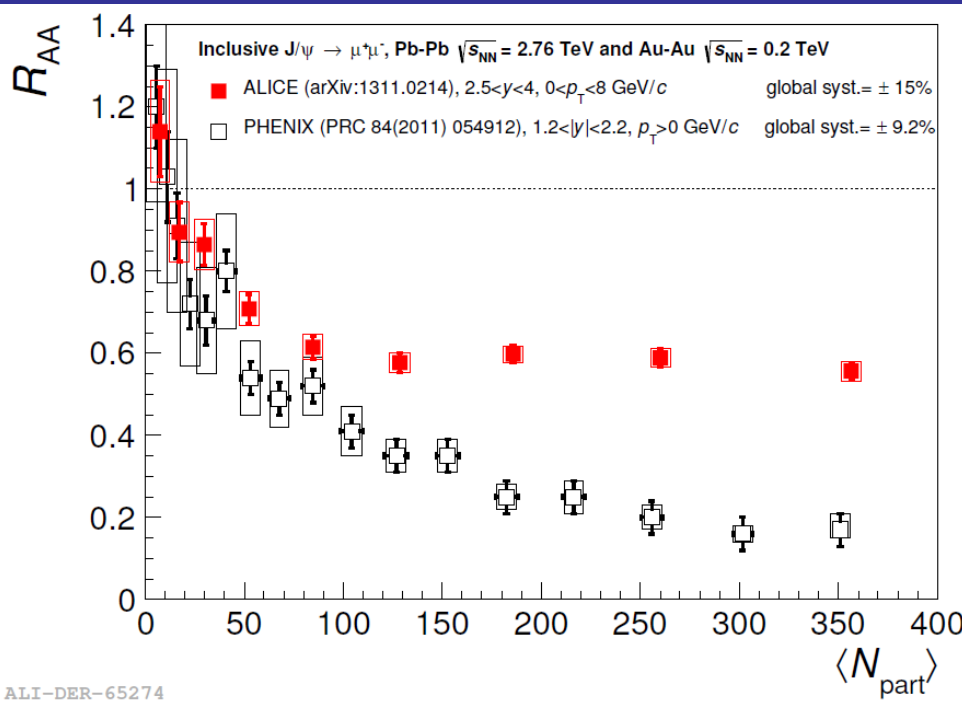
ALICE, focus on low-p_T J/ψ

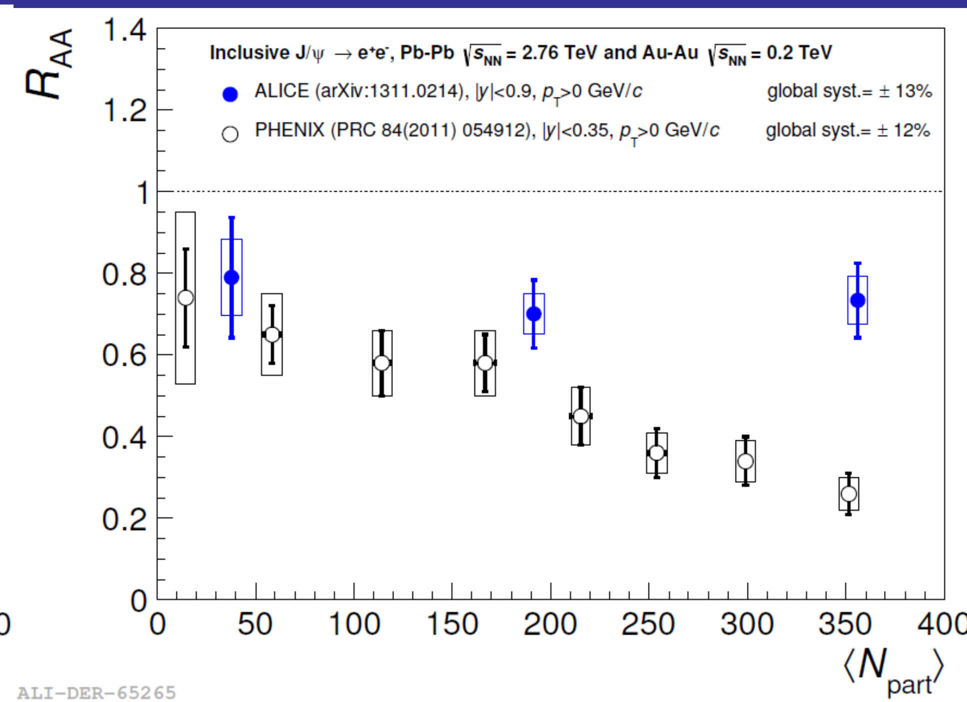




- Electron analysis: background subtracted with event mixing → Signal extraction by event counting
- Muon analysis: fit to the invariant mass spectra → signal extraction by integrating the Crystal Ball line shape

J/ψ, ALICE probes the low p_T

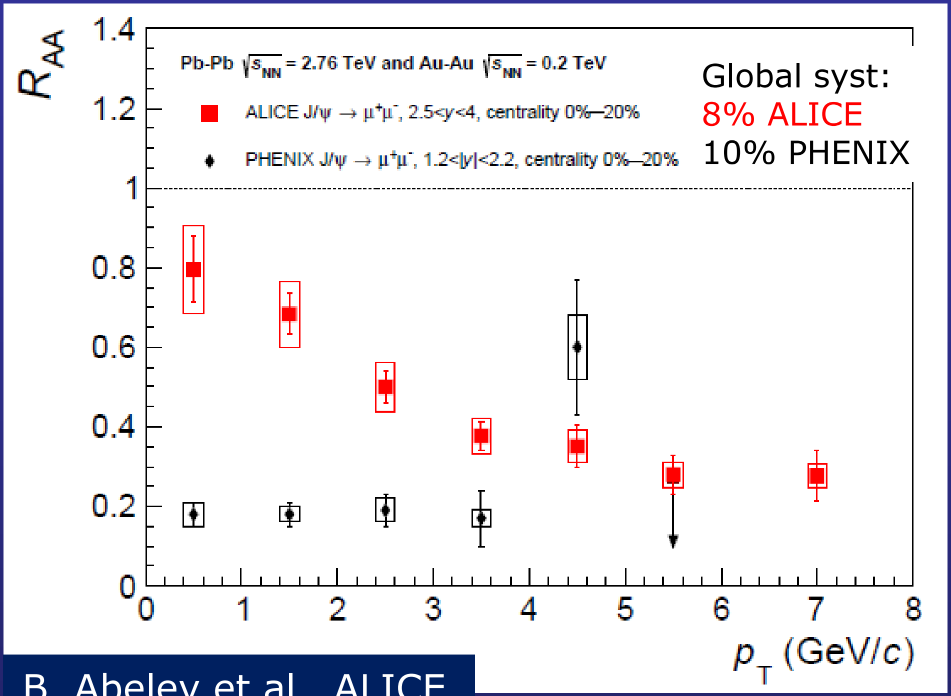




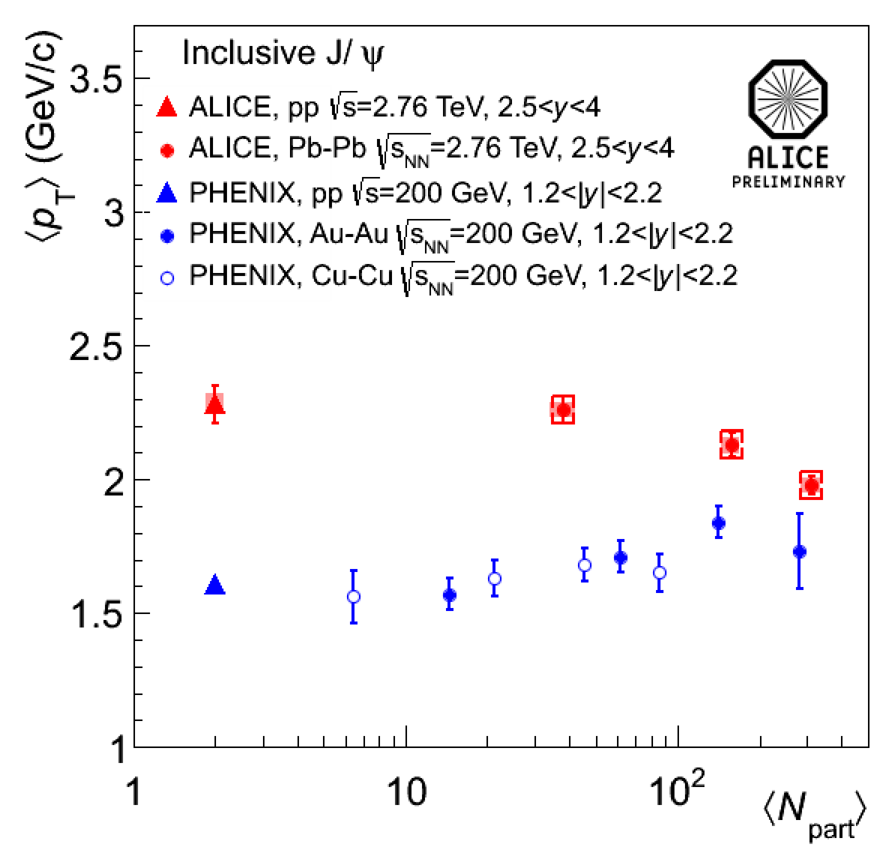
- Even at the LHC, NO rise of J/ψ yield for central events, but….
- Compare with PHENIX
  - Stronger centrality dependence at lower energy
  - Systematically larger R_{AA} values for central events in ALICE

Is this the expected signature for (re)combination ?

The p_T signature



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

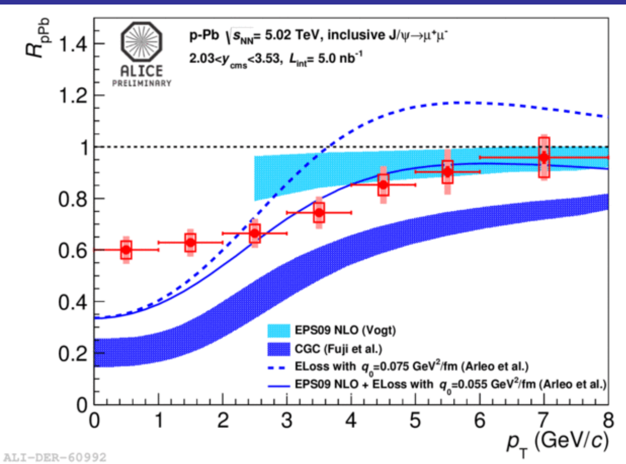


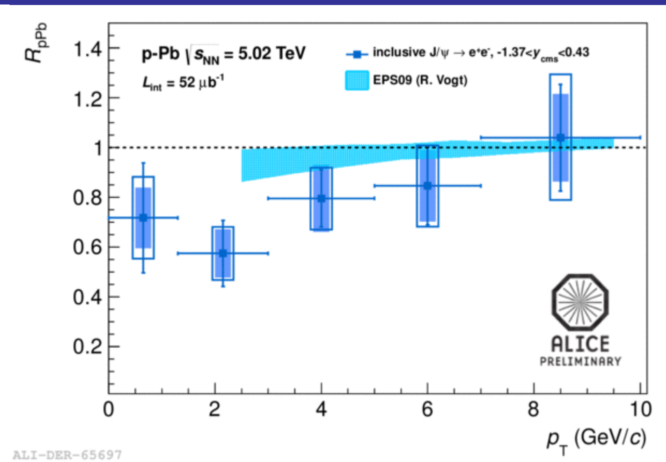
- Expect smaller suppression for low-p_T J/ψ → observed!

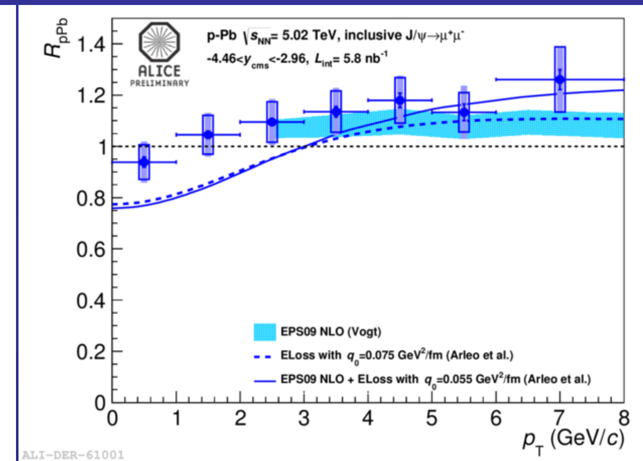
The trend is different wrt the one observed at lower energies, where an increase of the $<p_T>$ with centrality was obtained

- Fair agreement with transport models and statistical model

CNM effects are not negligible!

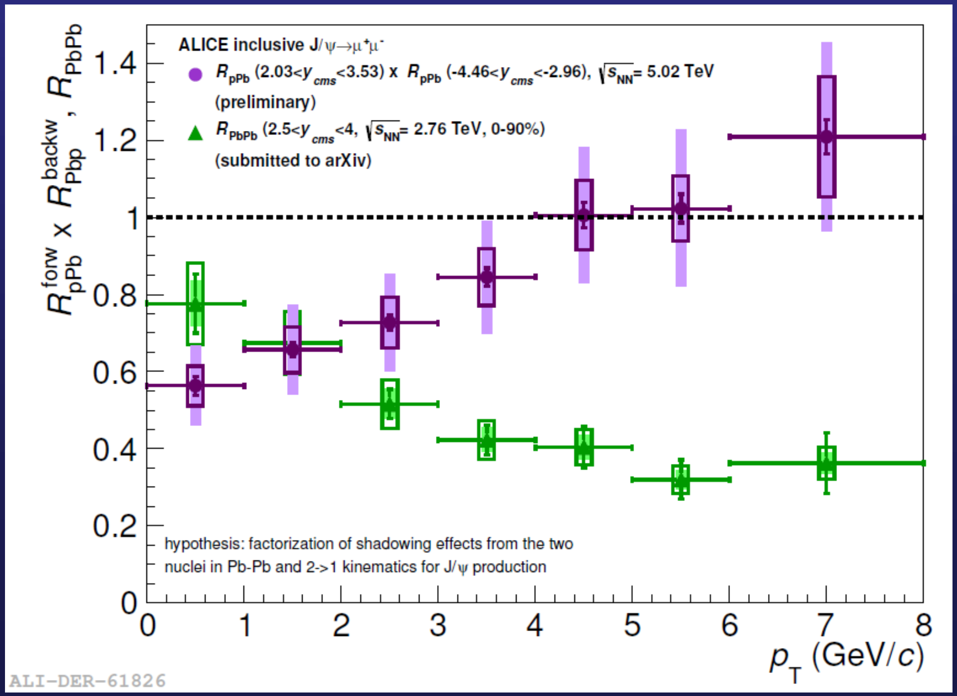




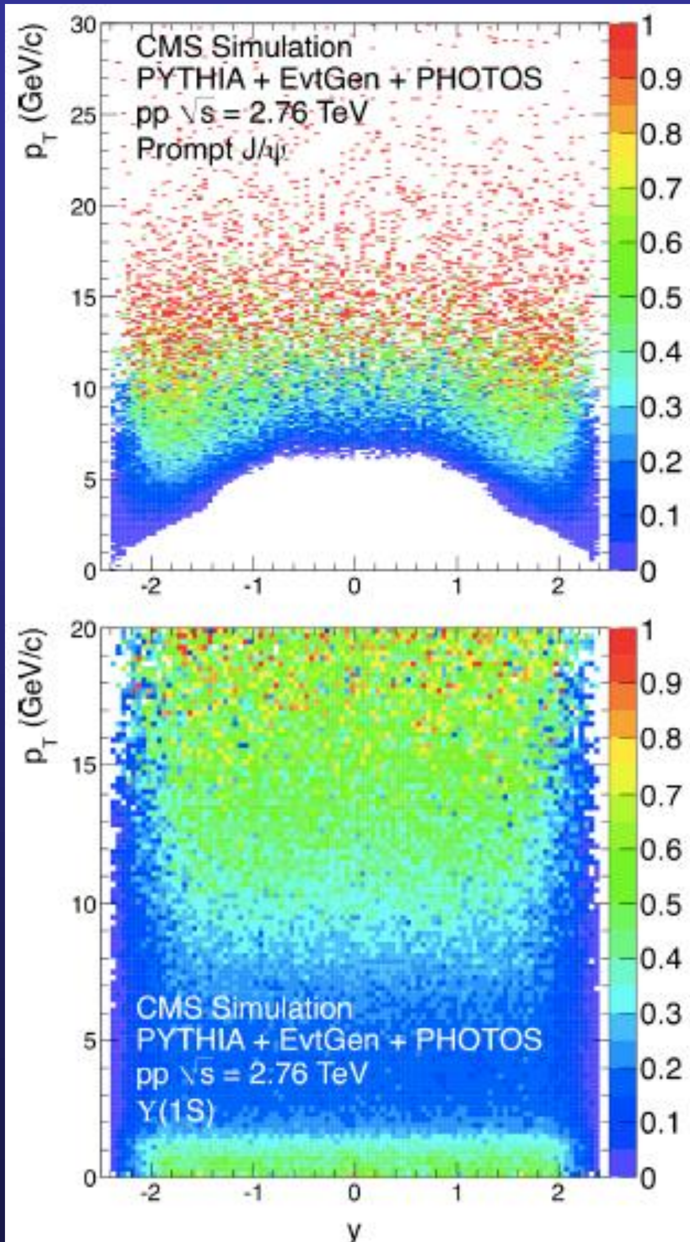


- ❑ Suppression at backward + central rapidity
- ❑ No suppression (enhancement?) at forward rapidity
- ❑ Fair agreement with models (shadowing + energy loss)

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

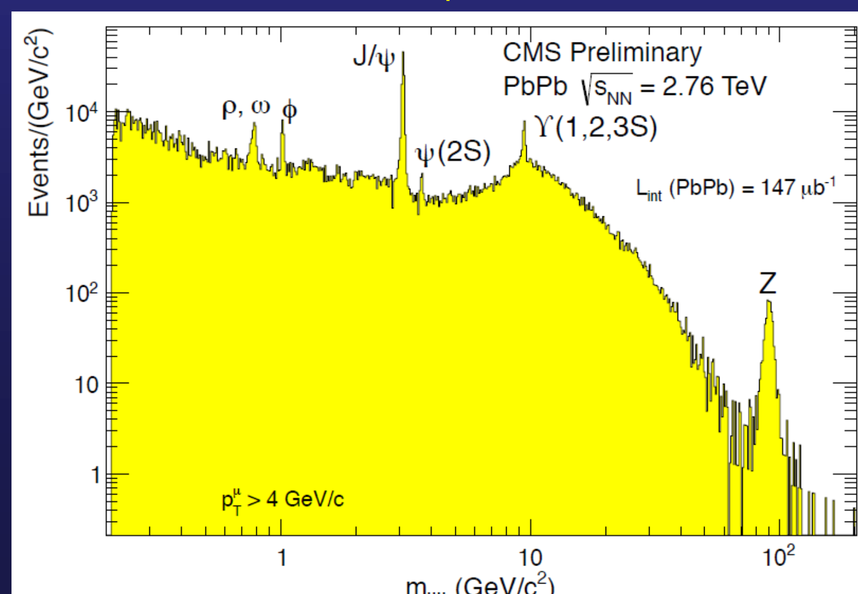


CMS, focus on high p_T

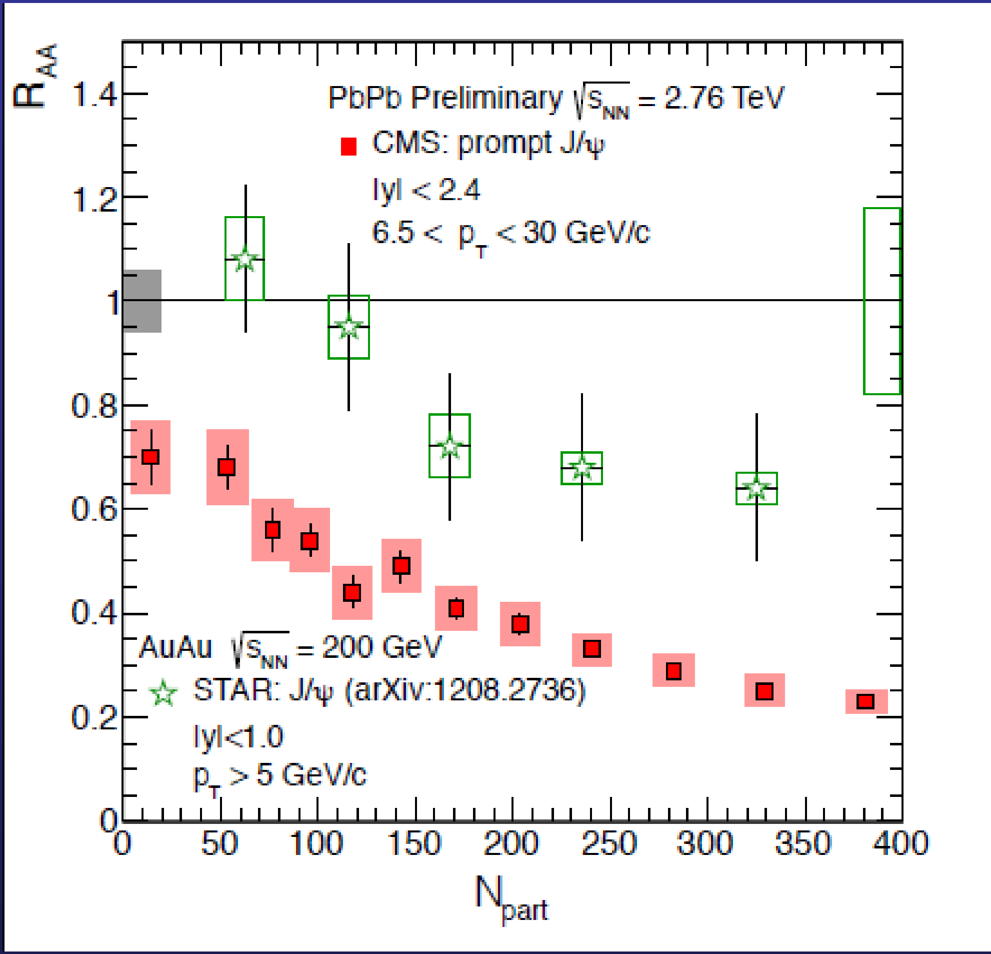


- Muons need to overcome the magnetic field and energy loss in the absorber
- Minimum total momentum p~3-5 GeV/c to reach the muon stations
- Limits J/ψ acceptance
  - Midrapidity: p_T>6.5 GeV/c
  - Forward rapidity: p_T>3 GeV/c

..but not the Υ one (p_T > 0 everywhere)



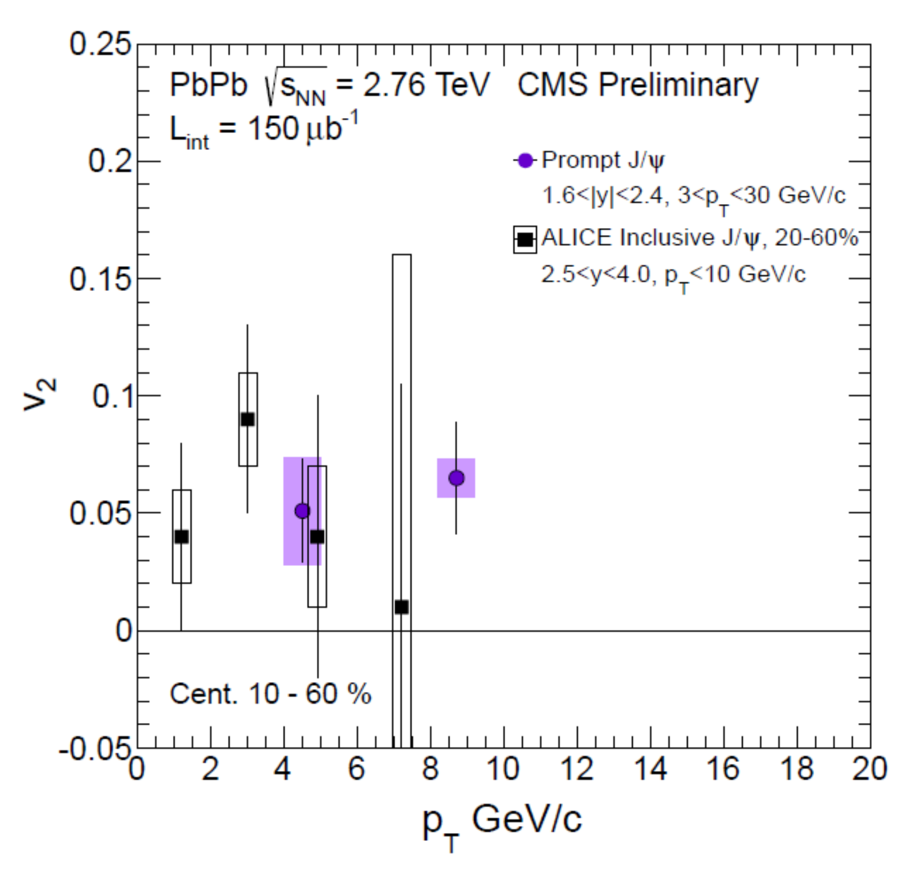
High p_T J/ψ: comparison CMS vs STAR



- ❑ Opposite behaviour when compared to low-p_T results
- ❑ Suppression is stronger at LHC energy (by a factor ~3 compared to RHIC for central events)

- ❑ Negligible (re)generation effects expected here
- ❑ Is the suppression for central events (R_{AA}~0.2) compatible with a full suppression of all charmonia (excluding corona) ?

Non-zero v_2 for J/ψ at the LHC



CMS HIN-2012-001

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 ? Expected for J/ψ ?
- In contrast to these observations STAR measures v_2=0

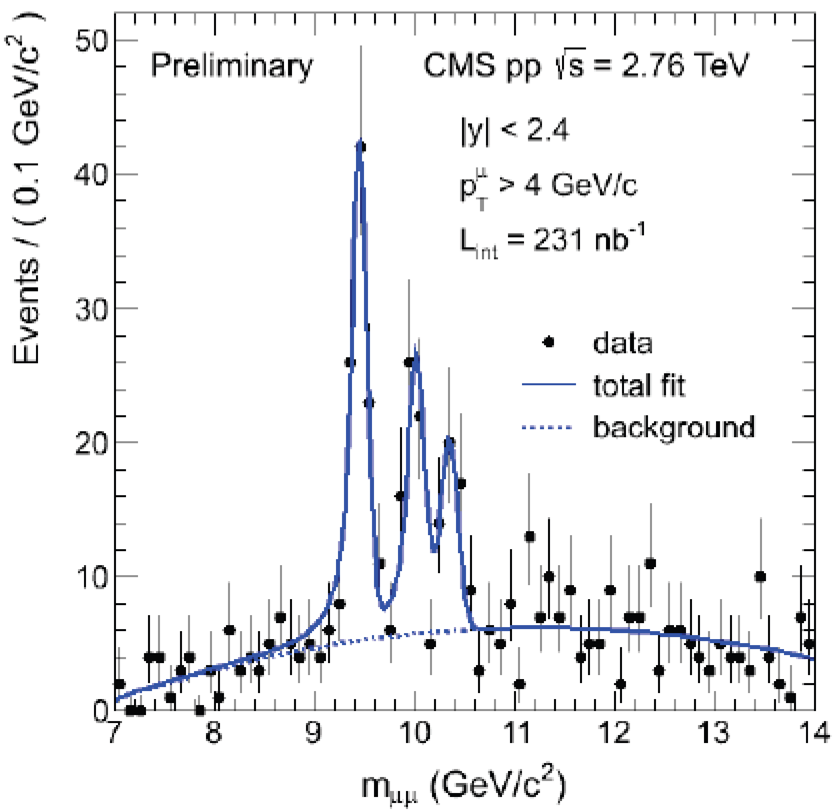
Finally, the Υ

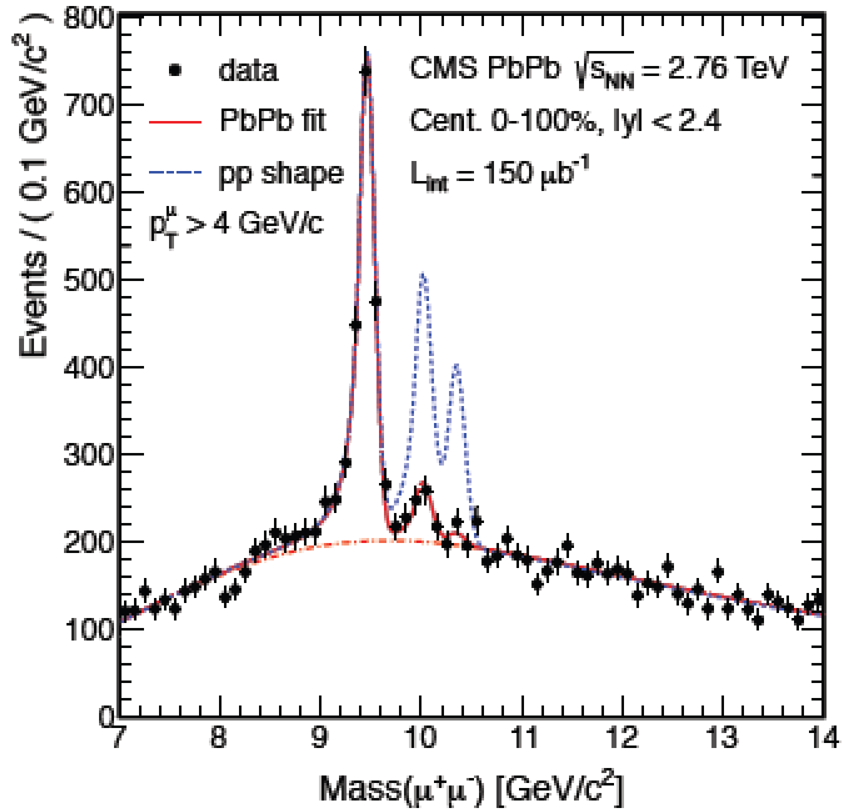
- LHC is really the machine for studying bottomonium in AA collisions (and CMS the best suited experiment to do that!)

pp

CMS-HIN-11-011

PbPb





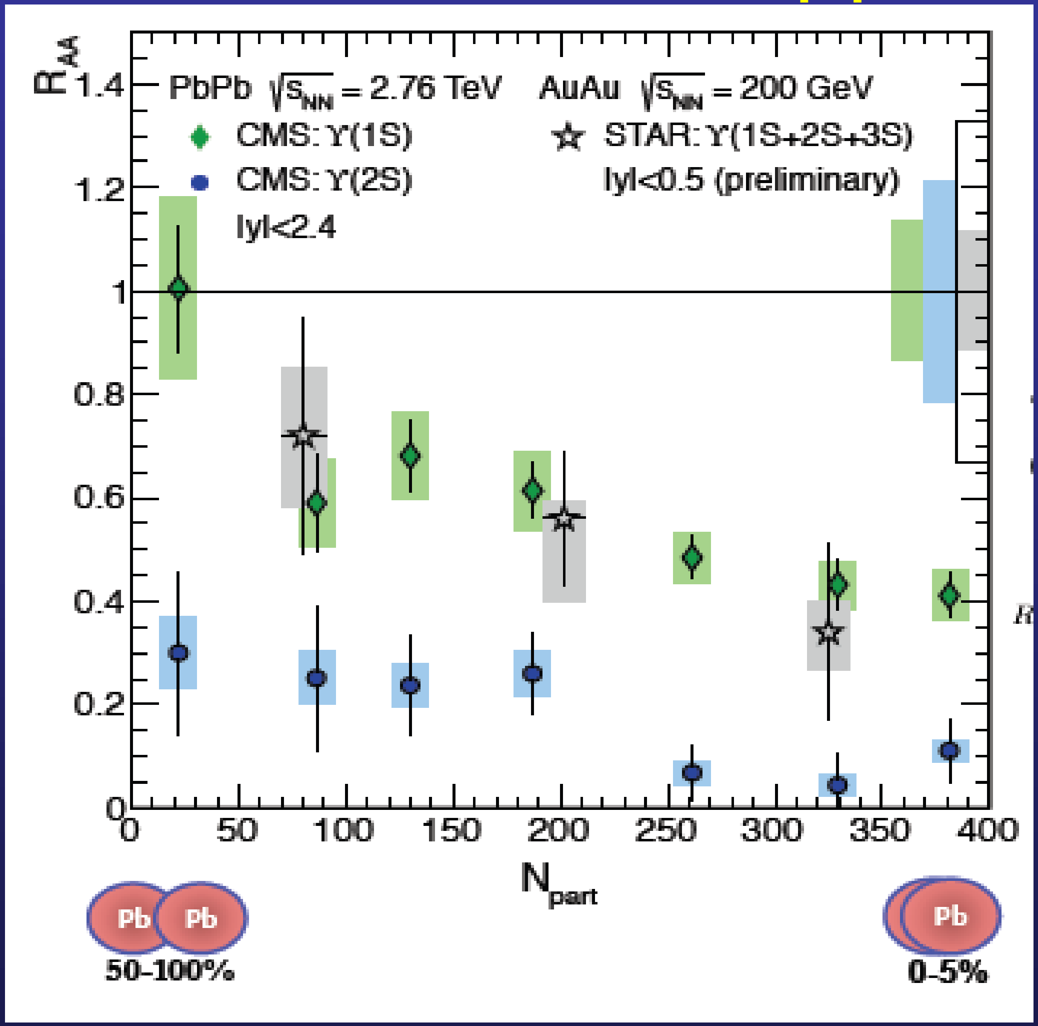
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

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

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

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

First accurate determination of ϒ suppression



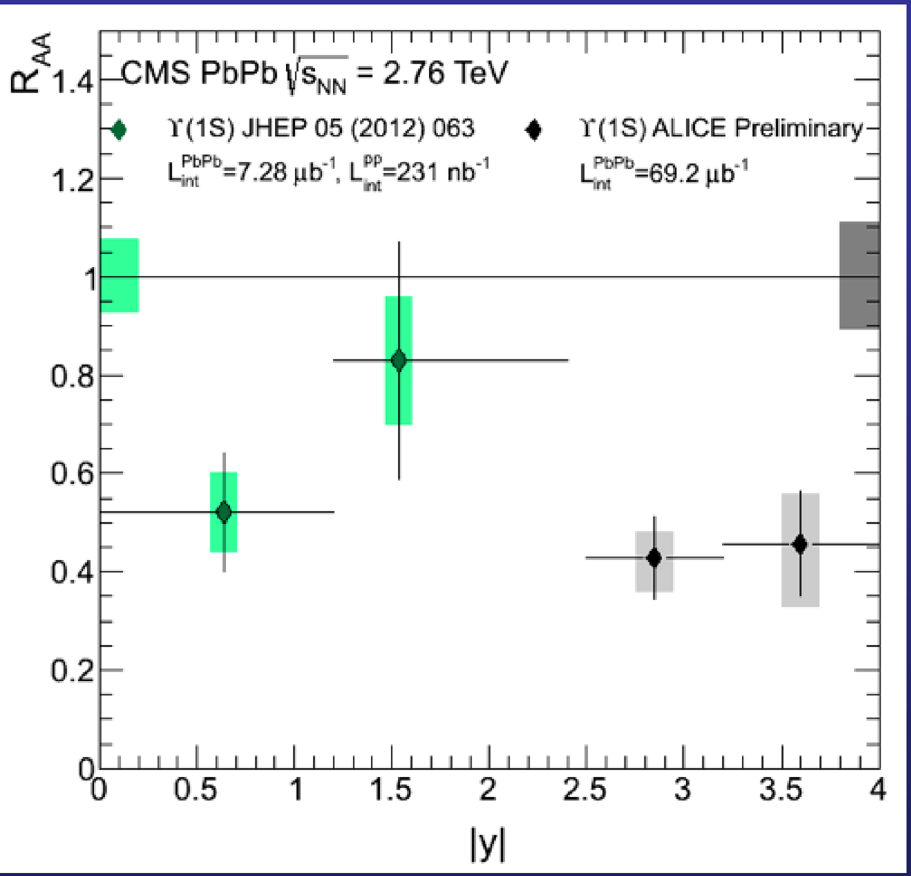
- Suppression increases with centrality
- First determination of ϒ(2S) R_{AA}: already suppressed in peripheral collisions
- ϒ(1S) (see also ALICE) compatible with only feed-down suppression ?

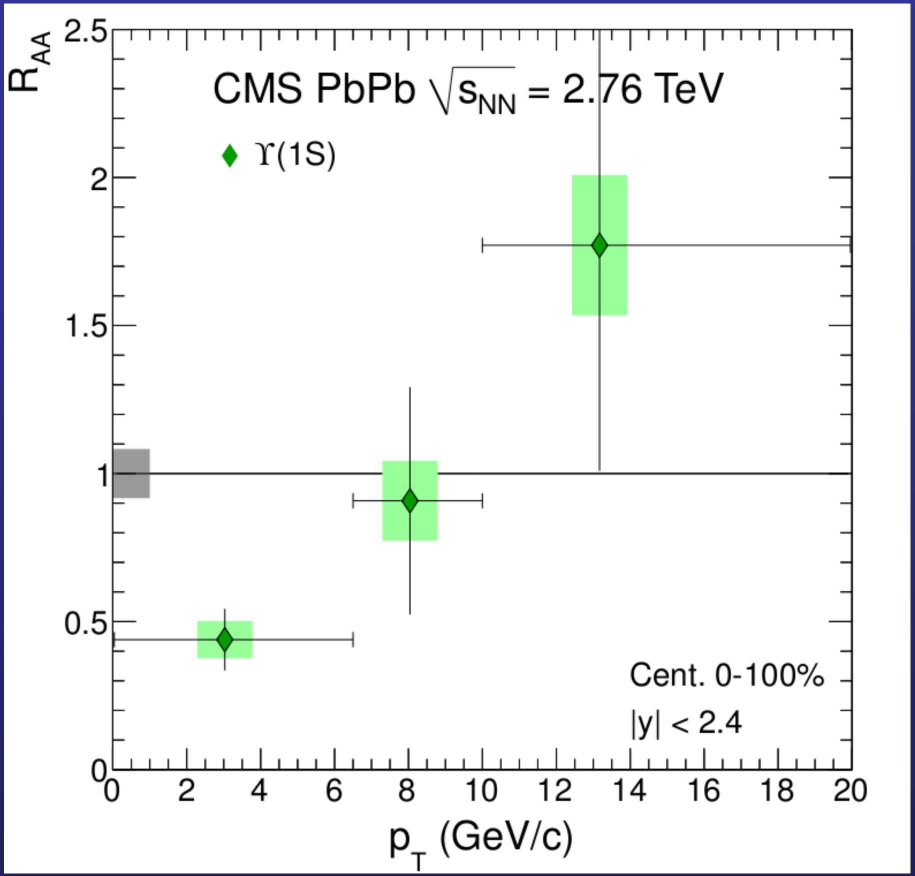
→ Probably yes, also taking into account the normalization uncertainty

Compatible with STAR (1S+2S+3S)(but large uncorrelated errors): expected ?

Is ϒ(1S) dissoc. threshold still beyond LHC reach ? → Full energy

Υ(1S) vs y and p_T from CMS+ALICE

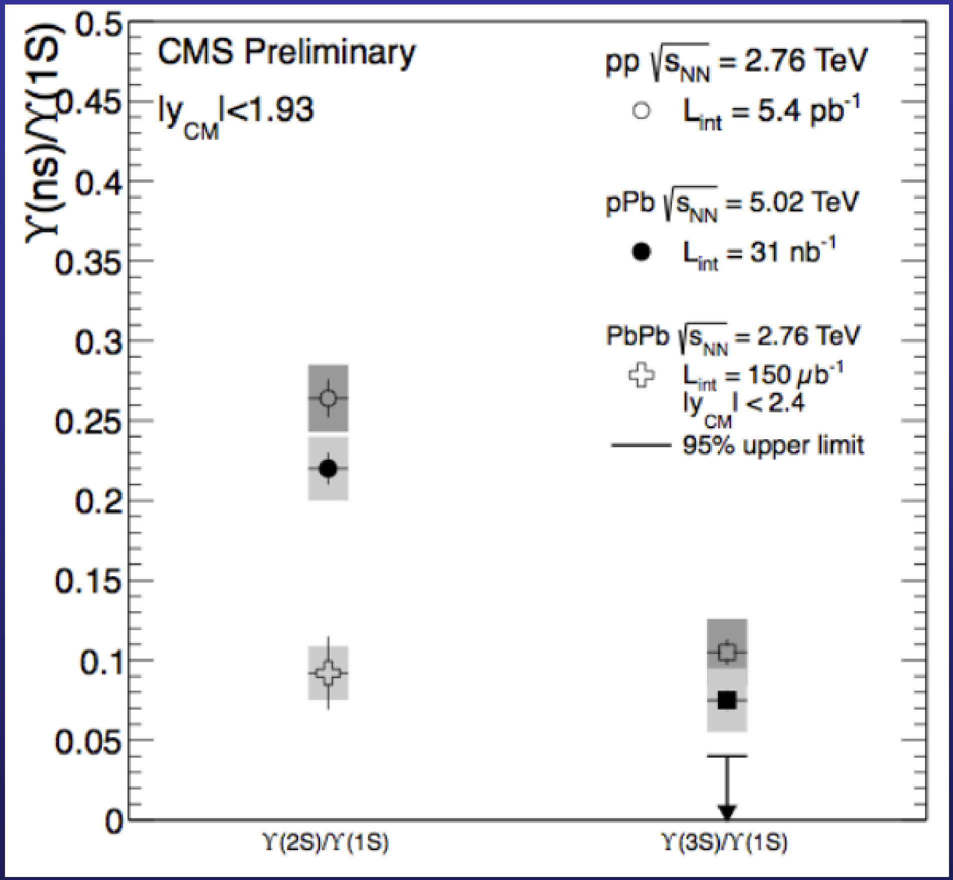


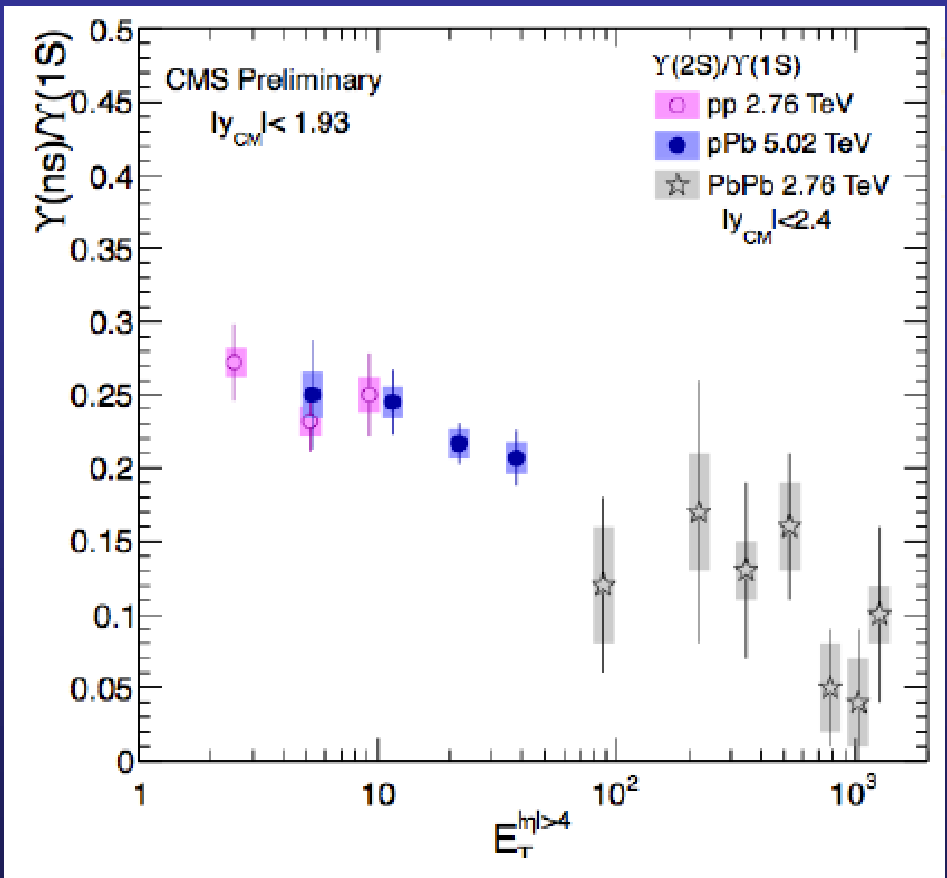


- Start to investigate the kinematic dependence of the suppression
- Suppression concentrated at low p_T (opposite than for J/ψ, no recombination here!)
- Suppression extends to large rapidity (puzzling y-dependence?)

Do not forget CNM…

- Also in the ϒ sector, the influence of CNM is not negligible

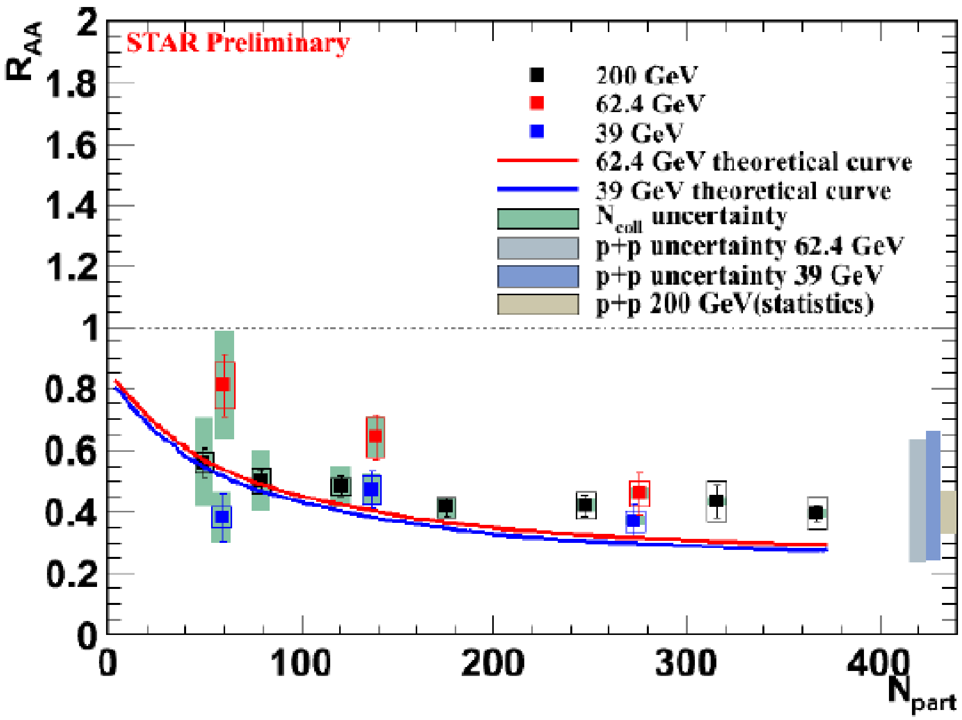


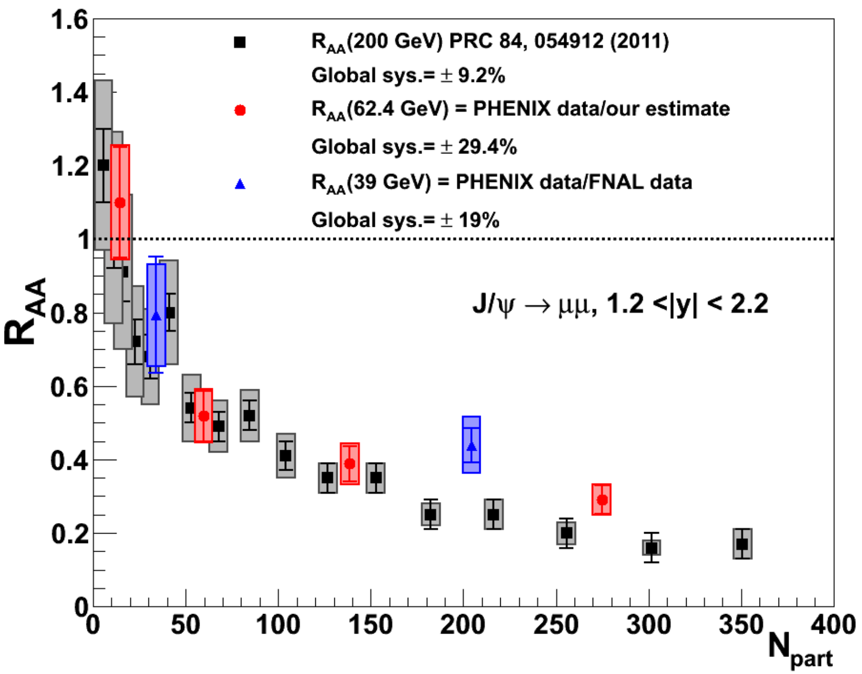


- With respect to 1S, the 2S and 3S states are more suppressed than in pp… but less than in Pb-Pb → confirm Pb-Pb suppression as hot matter effect
- As a function of event activity, loosely related to centrality in pPb (and surely not in pp!) "smooth" behaviour: to be understood!

RHIC: energy scan

- System size and energy dependence of R_{AA}





- No appreciable dependence on both energy and system size

- Not trivial! Requires
  - counterbalancing of suppression+regeneration effects over a large √s-region (note however large global systematics)
  - Warning: CNM effects (shadowing) expected to vary with √s

Quarkonia – where are we ?

- 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

- ALICE is fully exploiting the physics potential in the charmonium sector (optimal coverage at low p_T and reaching 8-10 GeV/c)

  - 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

- CMS is fully exploiting the physics potential in the bottomonium sector (excellent resolution, all p_T coverage)

  - 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

LHC: first round of observations EXTREMELY fruitful

- Many (most) of the heavy-quark/quarkonia related observables were investigated, no showstoppers, first physics extracted
- Many (most) of the heavy-quark/quarkonia related observables would benefit from more data to sharpen the conclusions
  → full energy run, 2015-2017
  → upgrades, 2018 onwards

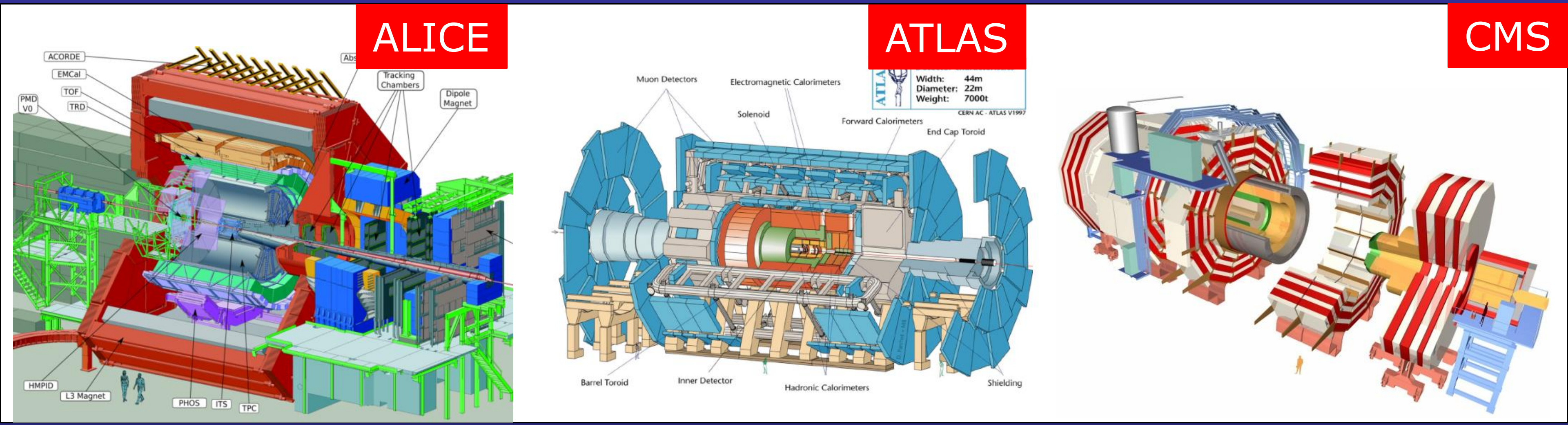
RHIC: still a main actor, with upgraded detectors

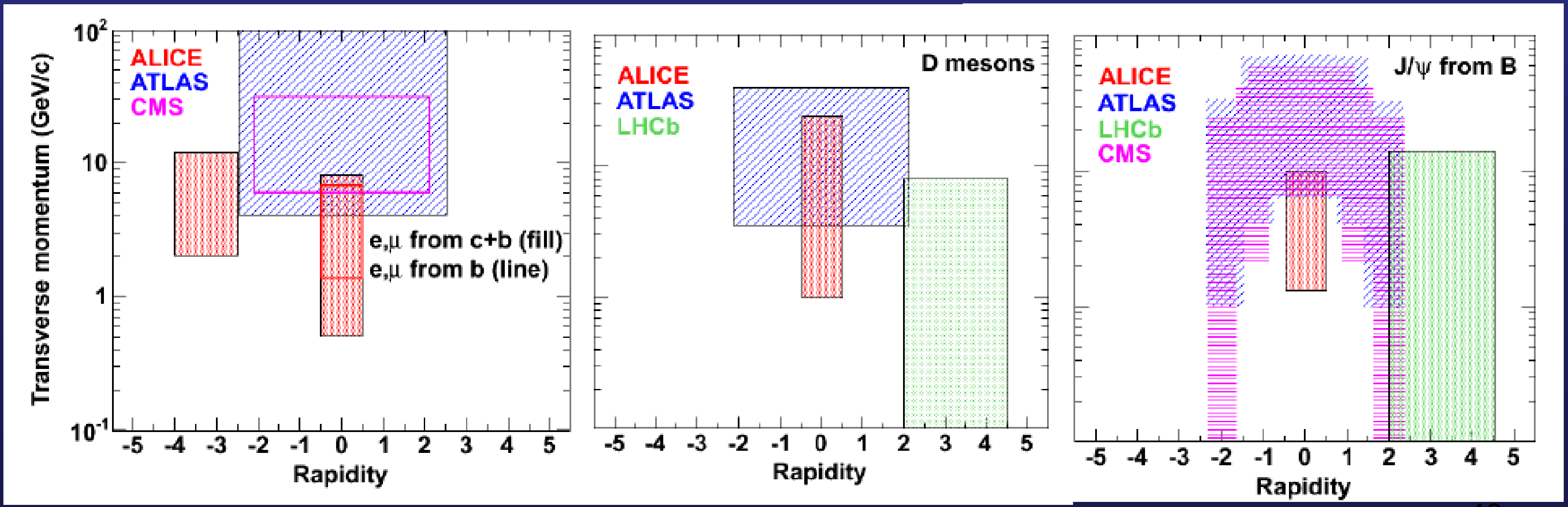
Lower energies: SPS, FAIR

- Serious experimental challenge
- High-μ_B region of the phase diagram unexplored for what concerns heavy quark/quarkonia below 158 GeV/c

Backup

LHC, 3 factories for heavy quark in Pb-Pb

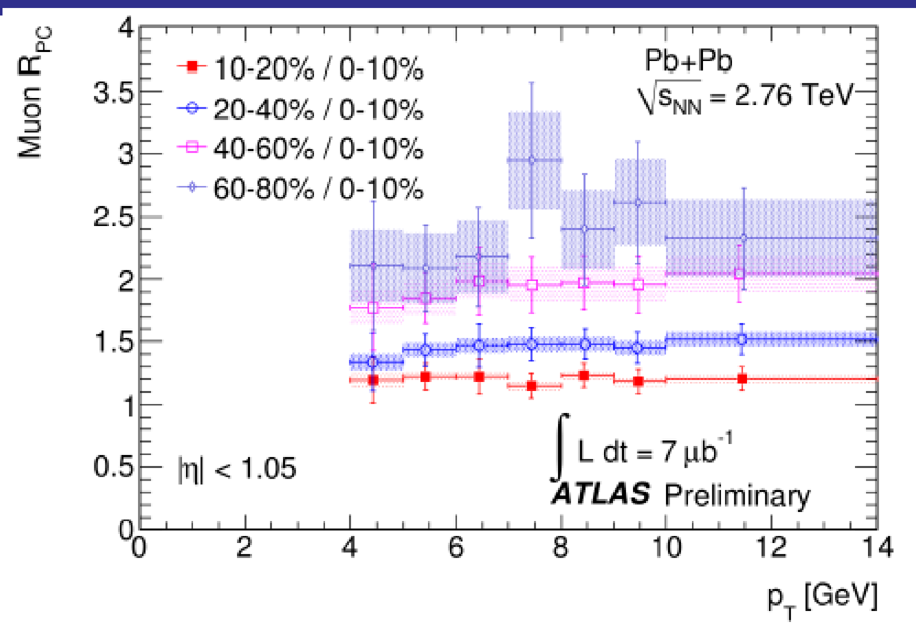




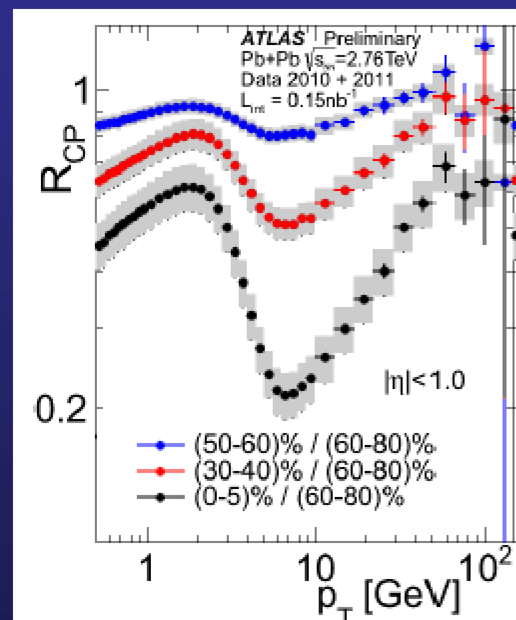
ATLAS open heavy flavours

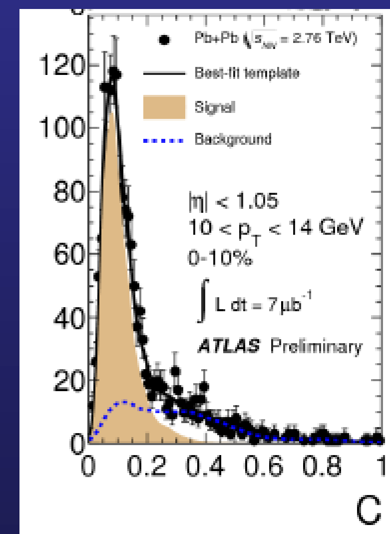
- ATLAS measures muons from HF in $|\eta|<1.05$, $4<p_T<14$ GeV/c
- No pp at 2.76 TeV reference available, use R_{CP} rather than R_{AA}

HF yield through fit of templates for discriminant variable C



Boxes: Fully correlated systematics
Error bars: uncorrelated combined statistical+systematic



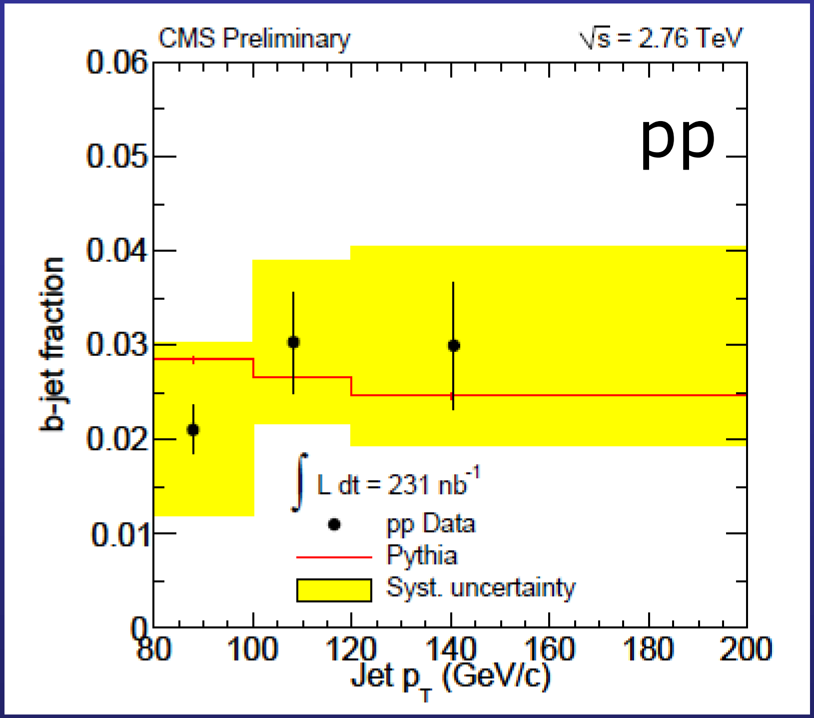


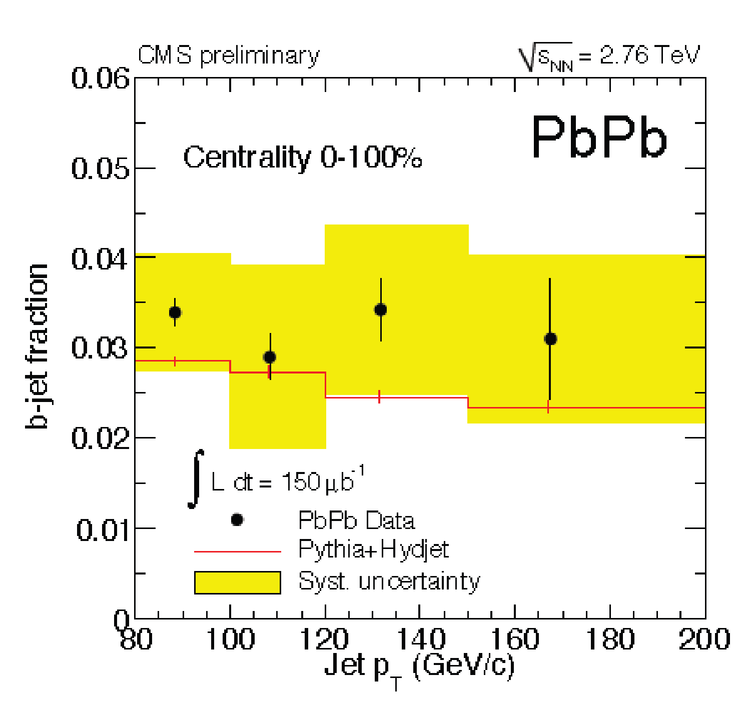
- R_{CP} subject to statistical fluctuations → use R_{PC} too!
- ~flat vs p_T up to 14 GeV/c, different from inclusive R_{CP}!

If ~no suppression for 60-80% → central ~ forward suppression

The new frontier: b-jet tagging

M. Nguyen

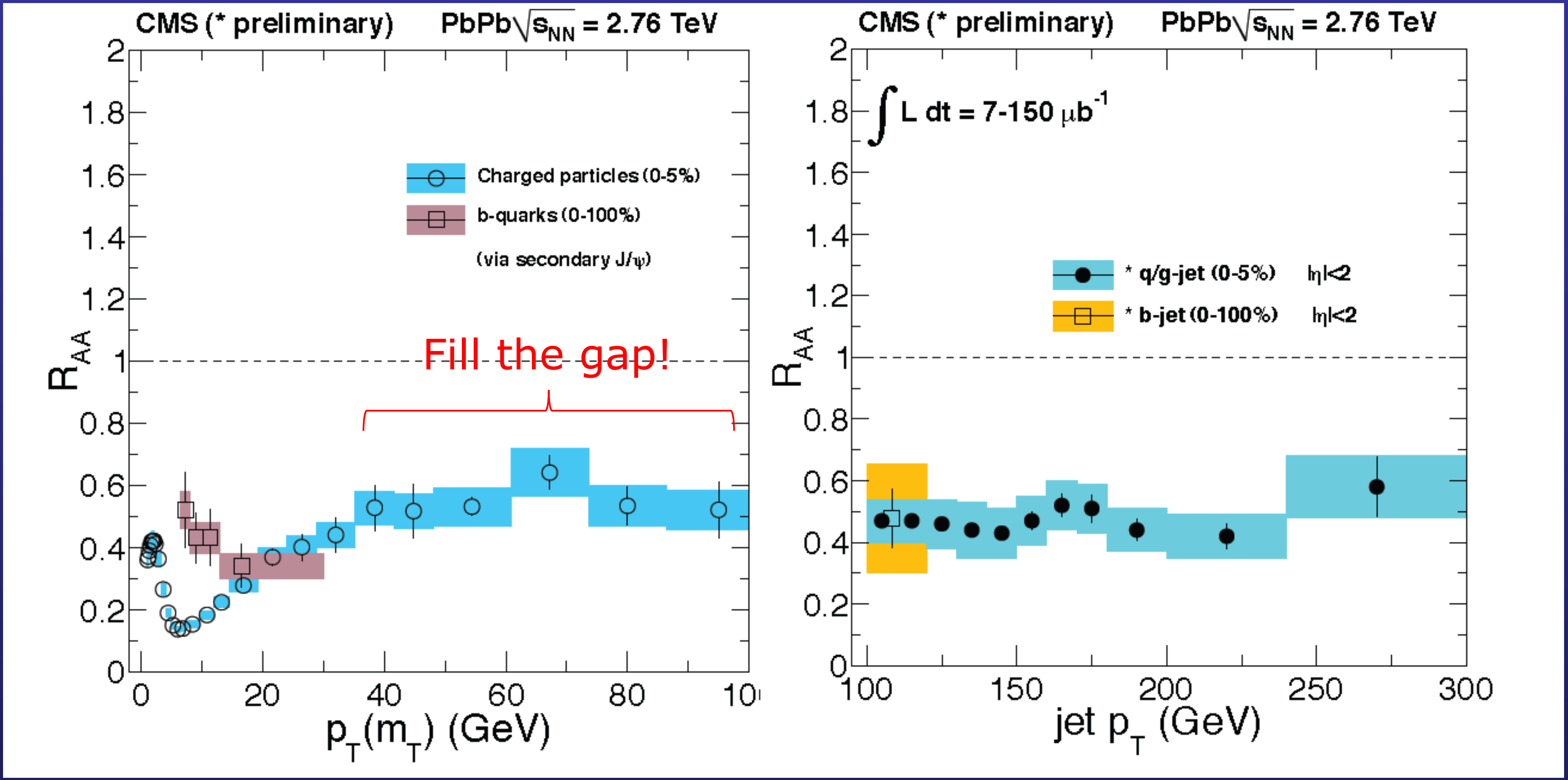




- Jets are tagged by cutting on discriminating variables based on the flight distance of the secondary vertex
  → enrich the sample with b-jets
- b-quark contribution extracted using template fits to secondary vertex invariant mass distributions

b-fraction ~constant vs both p_T and centrality

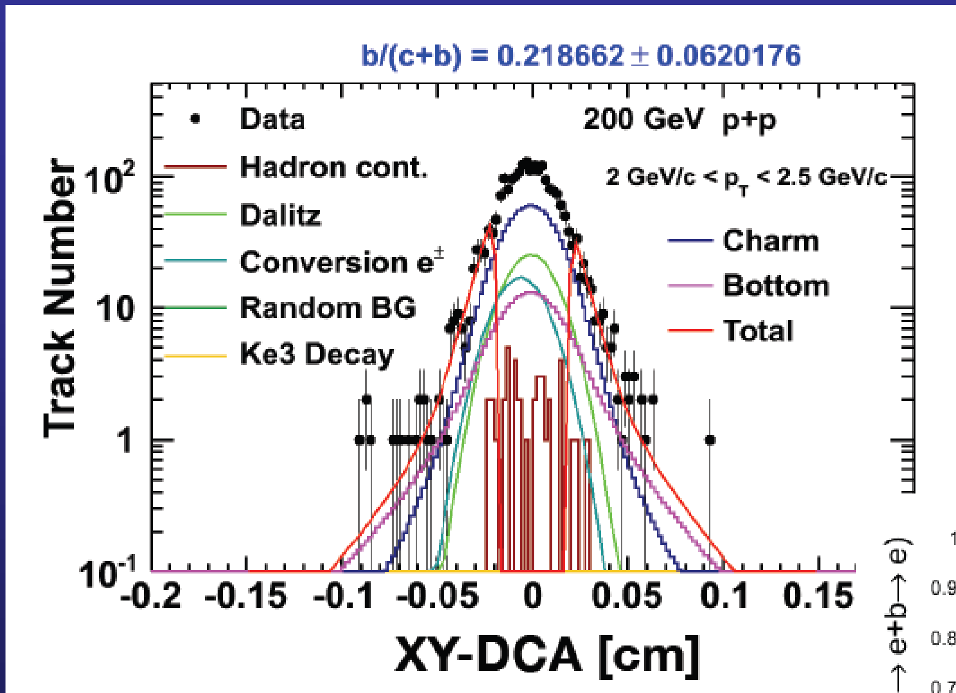
Beauty vs light: high vs low p_T

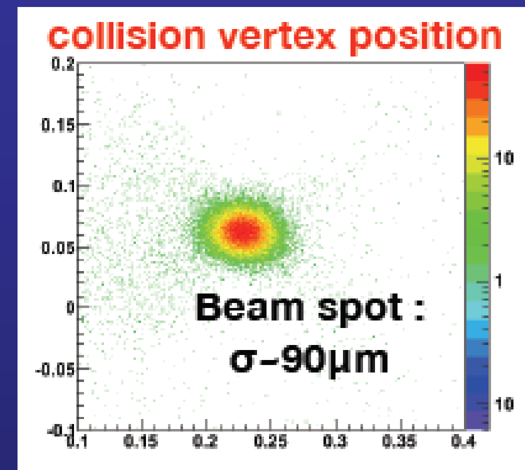


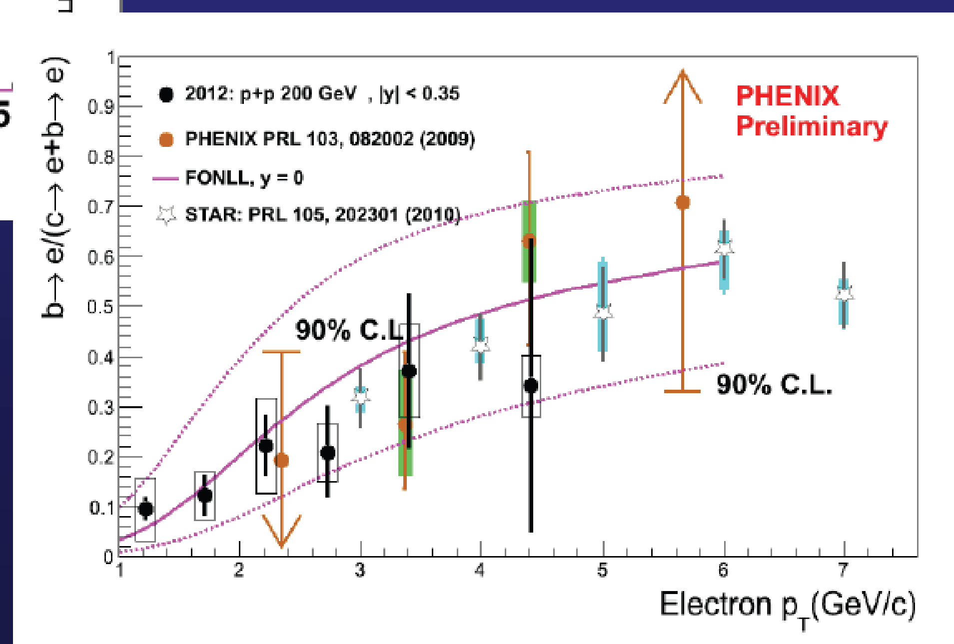
- ❑ Low p_T: different suppression for beauty and light flavours, but:
  - ❑ Different centrality
  - ❑ Decay kinematics
- ❑ High p_T: similar suppression for light flavour and b-tagged jets

PHENIX, b vs c

- Charm and bottom contributions in electron from heavy-quark decay is measured directly from the electron DCA distribution (VTX)



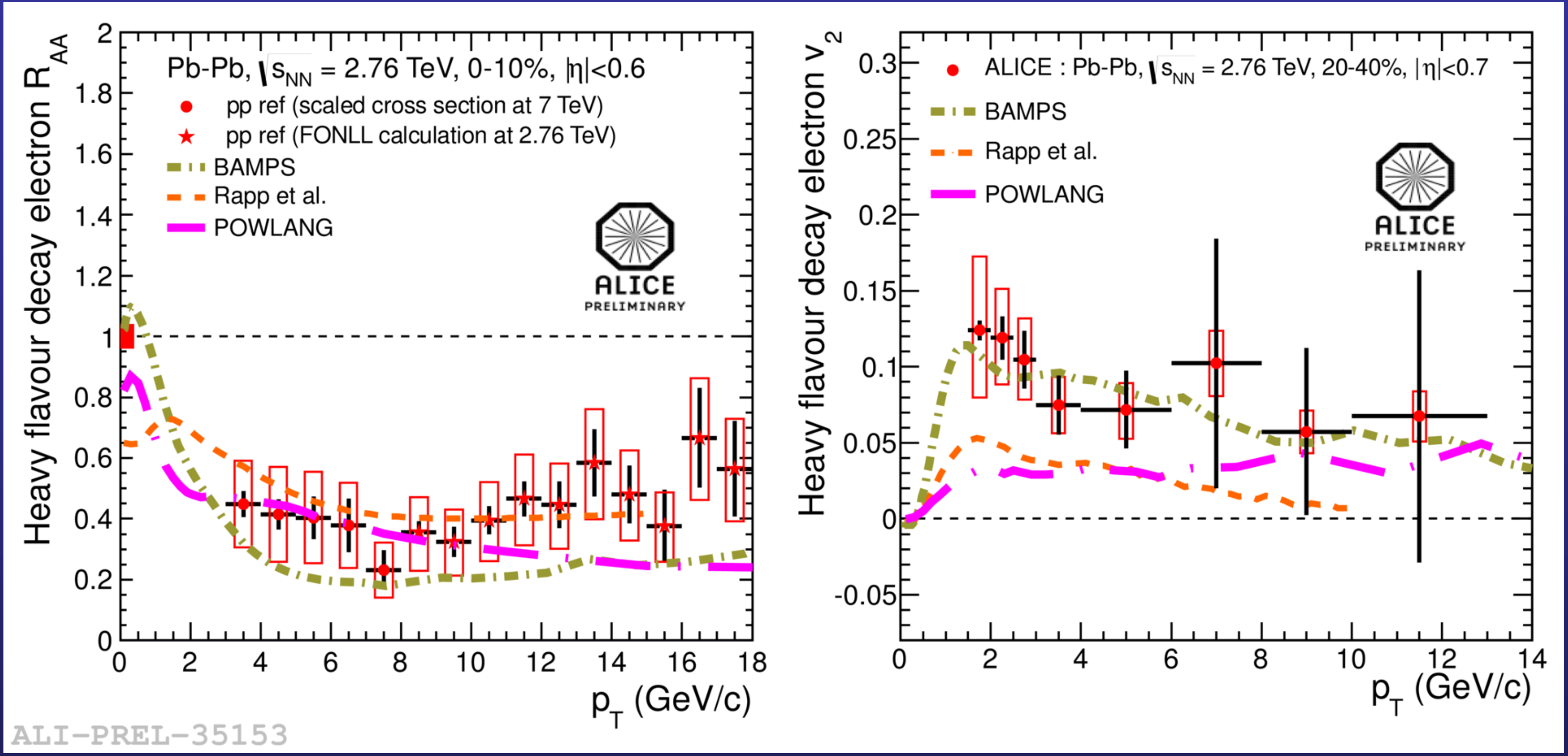




- Bottom fraction in pp consistent with published data (from e-h correlations) and with FONLL

Look forward to forthcoming Au-Au results!

Data vs models: HFE



Simultaneous description of heavy-flavor electrons R_{AA} and v_2

⬇

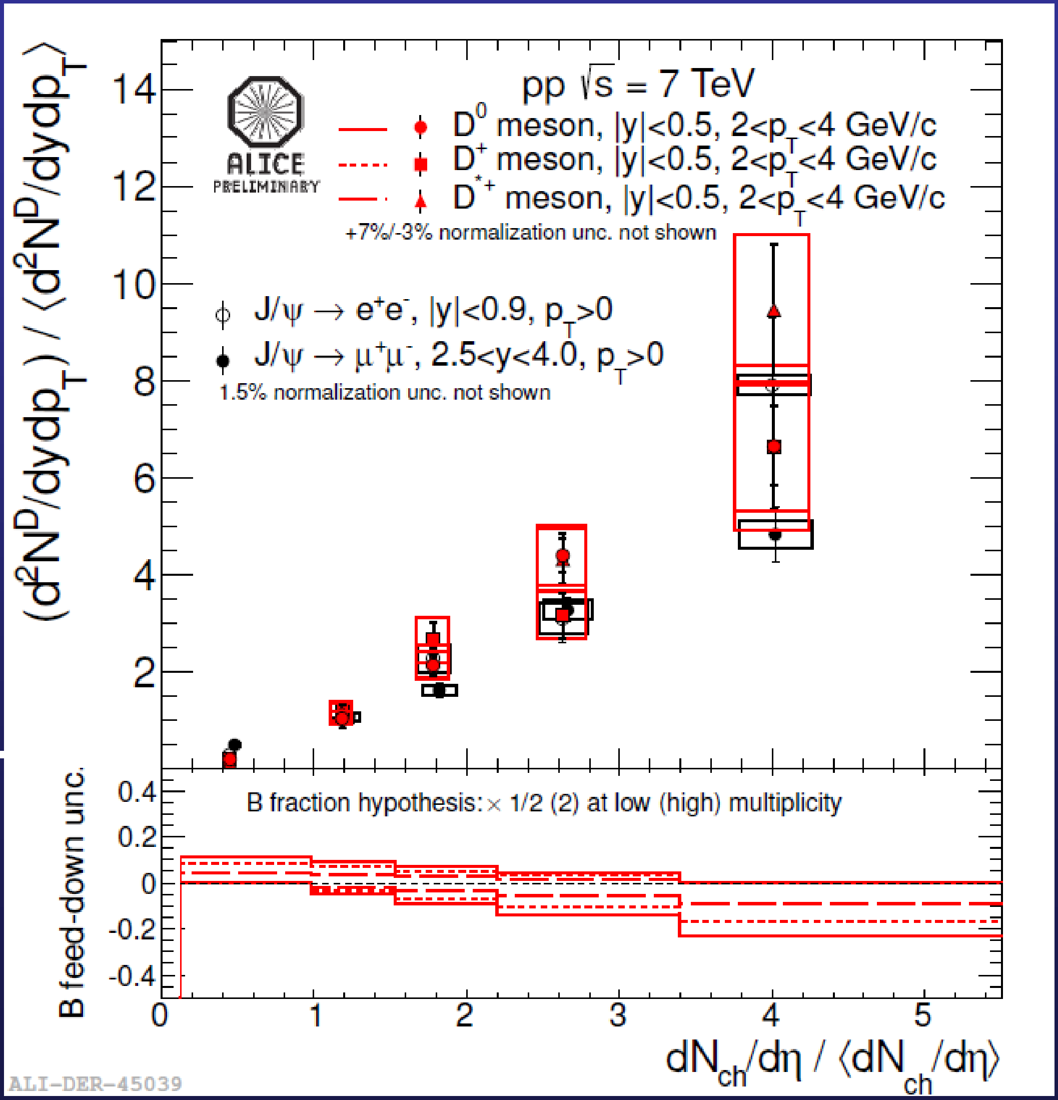
Challenge for theoretical models

Intermezzo: multiplicity dependence of D and J/ψ yields

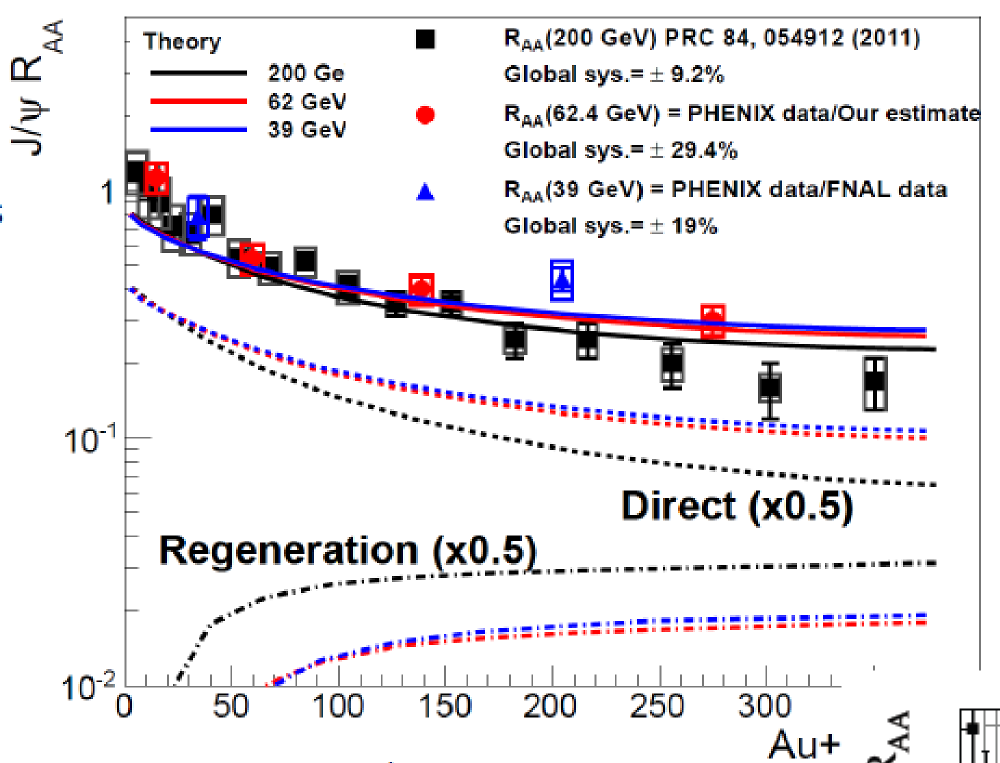
- Should help to explore the role of multi-parton interactions in pp collisions

- The ~linear increase of the yields with charged multiplicities and the similar behaviour for D and J/ψ are remarkable…..

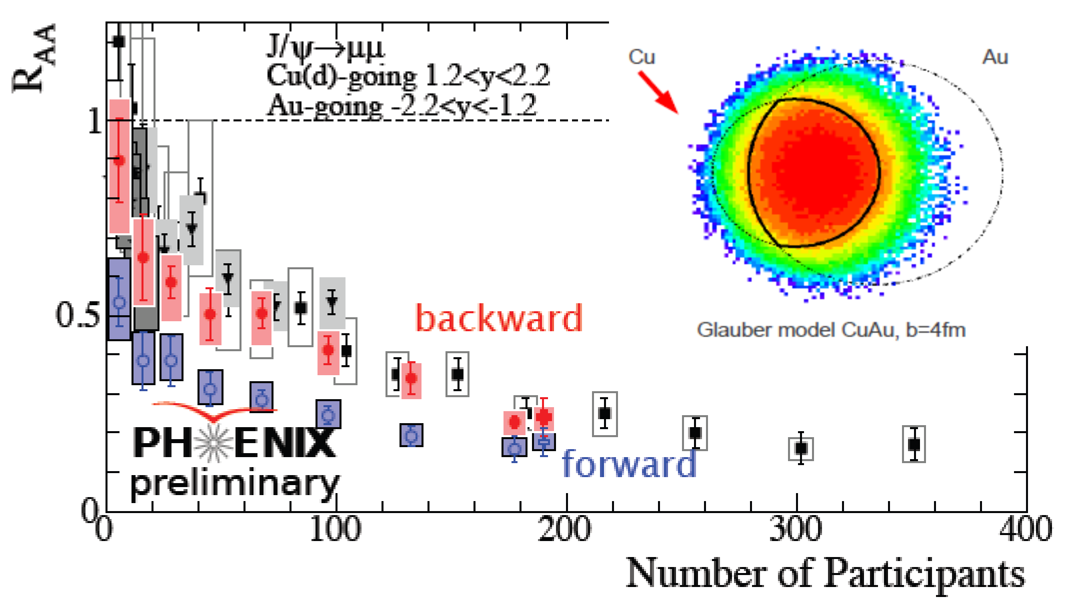
…but need to be explained!



PHENIX – new systems/energies

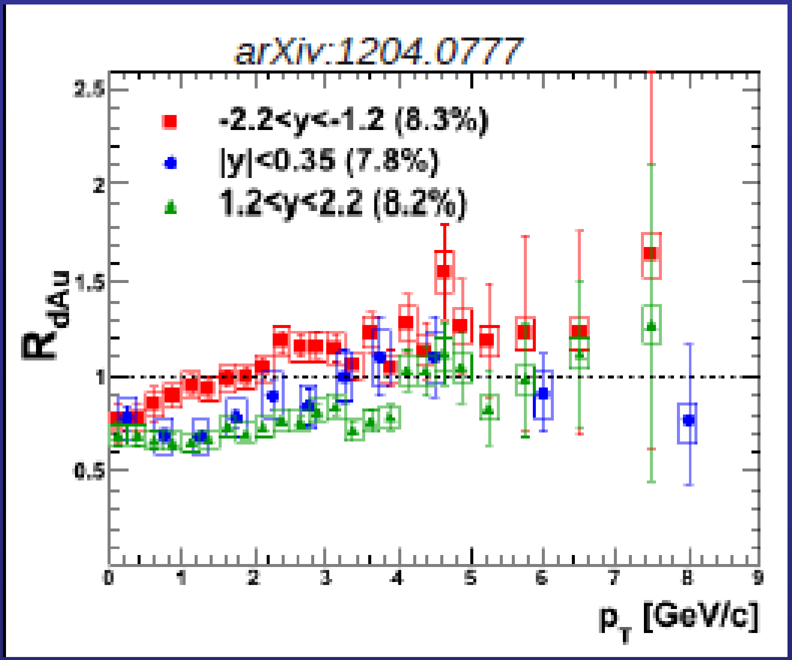


- New system (Cu-Au) at old energy: Cu-going finally different! (probably not a CNM effect)
- A challenge to theory
- SPS went the other way round (from S-U to Pb-Pb…)



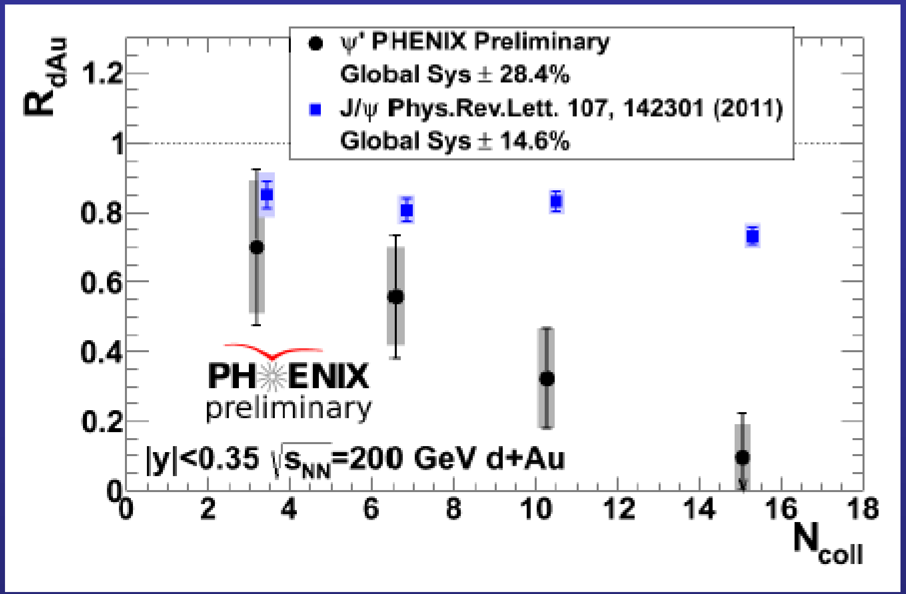
- Old system (Au-Au) at new energy: still a balancing of suppression and regeneration ?
- Theory seems to say so….

PHENIX – CNM

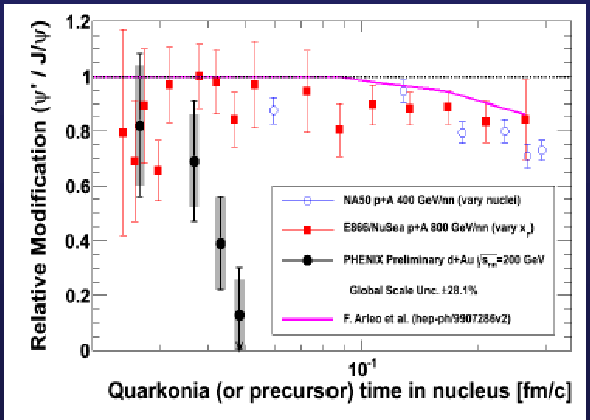


- p_T dependence of R_{dAu}
- Increase vs p_T at central/forward y
  → Reminds SPS observation
- But different behaviour at backward rapidity
- Not easy to reproduce in models!

Overall picture still not clear !



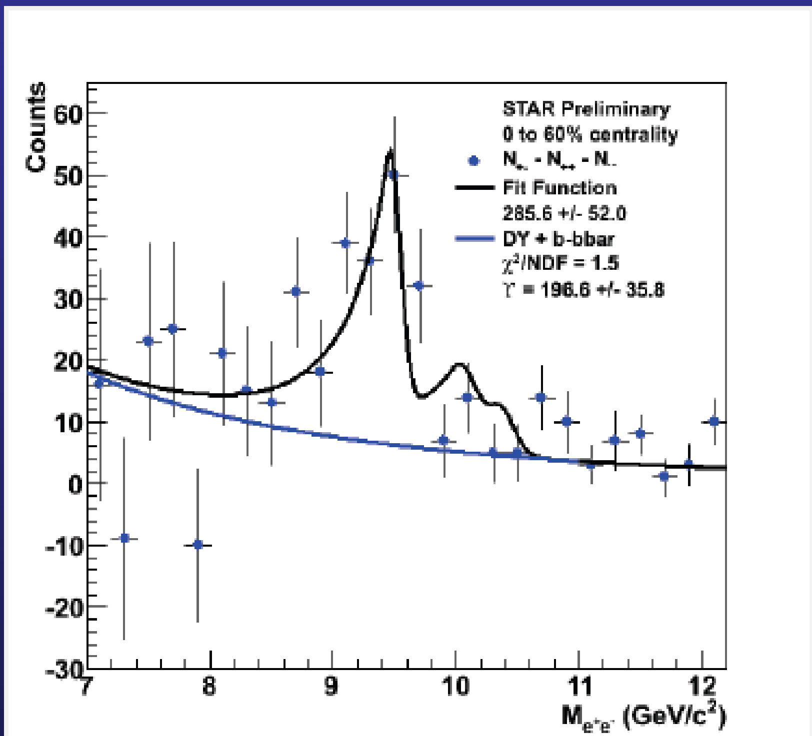
- First study of a charmonium excited state at collider energy
  → Seems contradicting our previous knowledge



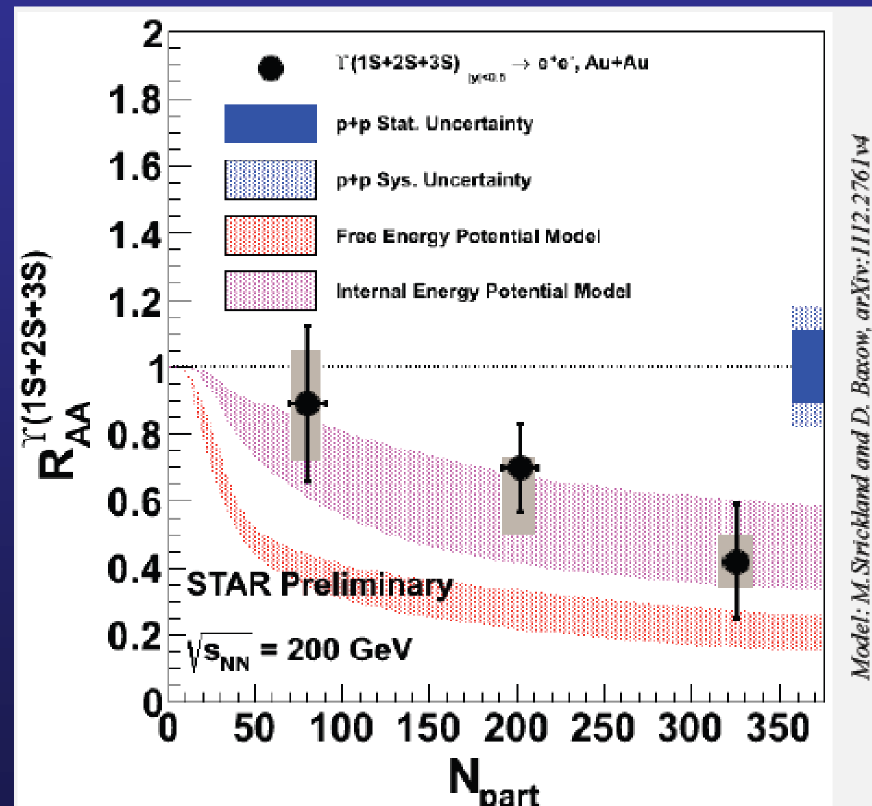
STAR - Υ

- Bottomonium: the "clean" probe
- 3 states with very different binding energies
- No complications from recombination

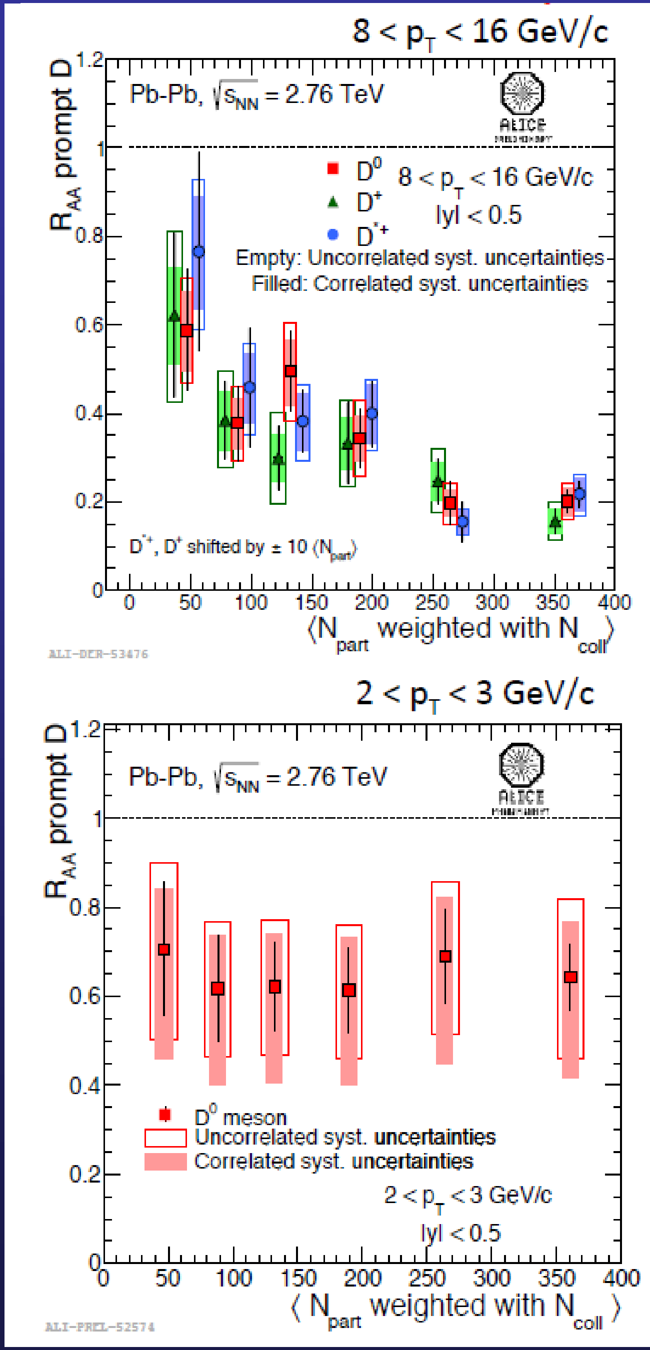
But not that easy at RHIC!



…and this has been split into 3 centrality bins….

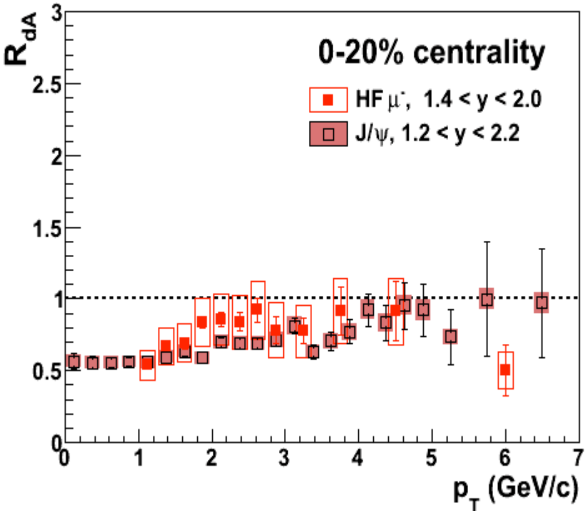


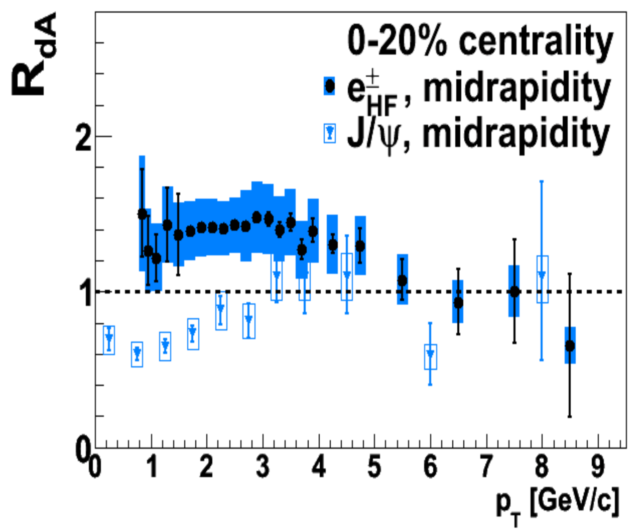
Compatible with 3S melting and 2S partial melting

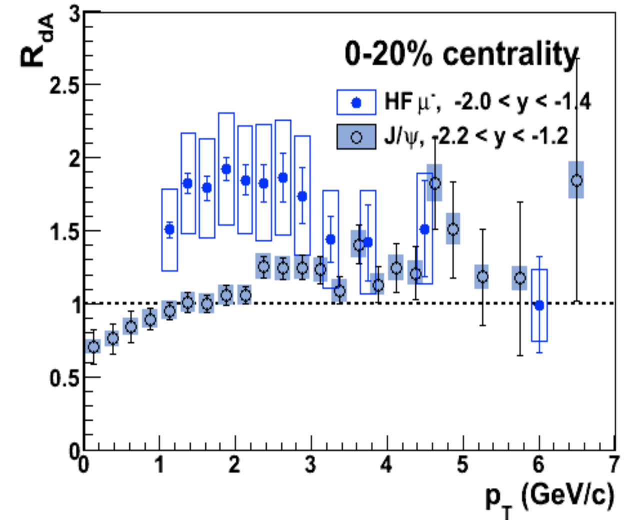


- Different centrality dependence high vs low p_T
  → might be due to D "pushed" from high p_T

PHENIX: dAu, open vs closed charm



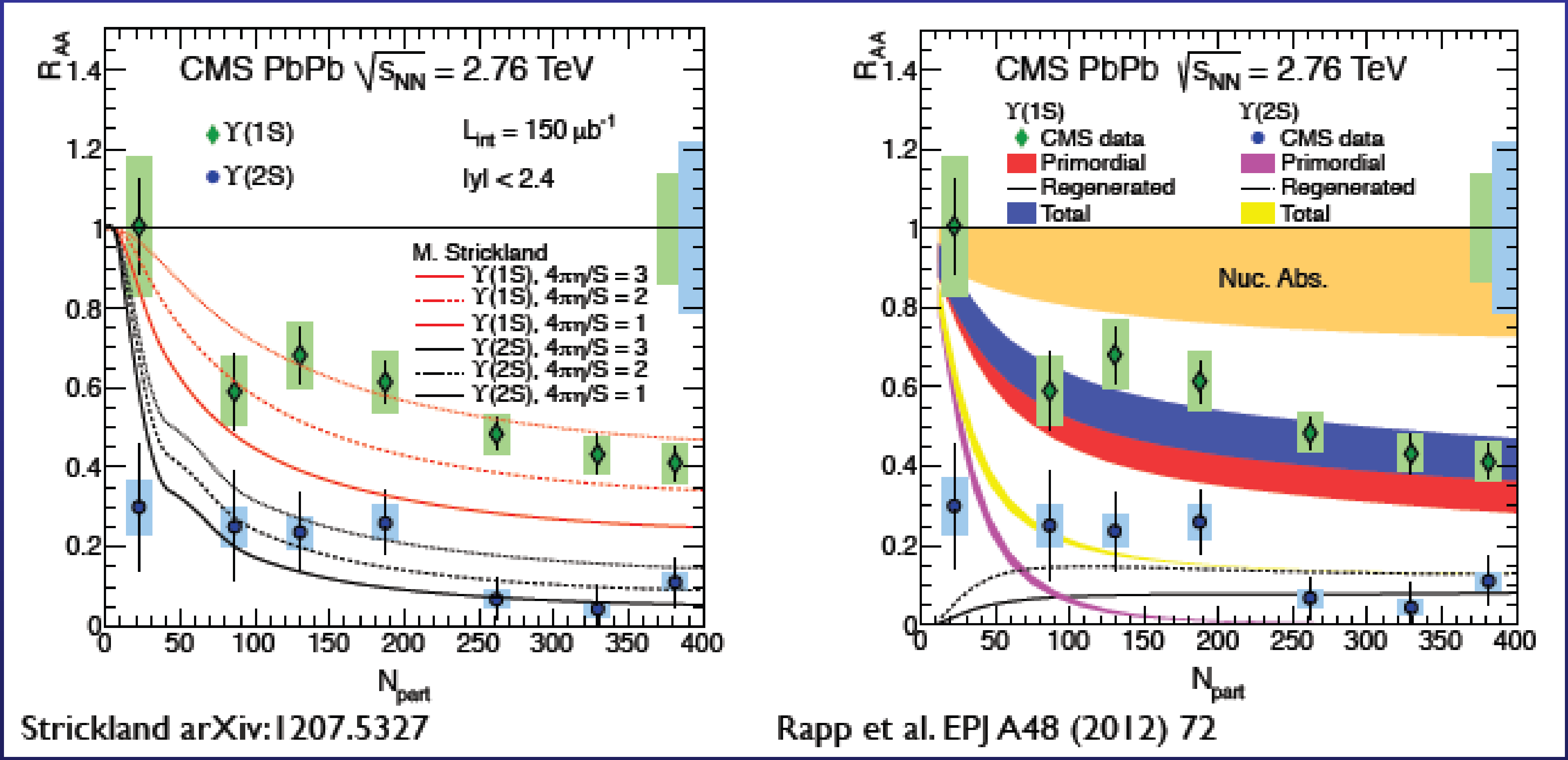




- ❑ Interesting effect as a function of rapidity
- ❑ Stronger suppression for J/ψ than for open charm at backward and central rapidity → where ccbar spends more time in CNM
- ❑ Evidence for J/ψ break-up ? Maybe, but
  - ❑ Backward rapidity open charm results not compatible with shadowing
  - ❑ Same p_T comparison between open and closed charm is questionable

- ❑ More generally: comparison open vs closed heavy quarks very interesting

Hints from theory

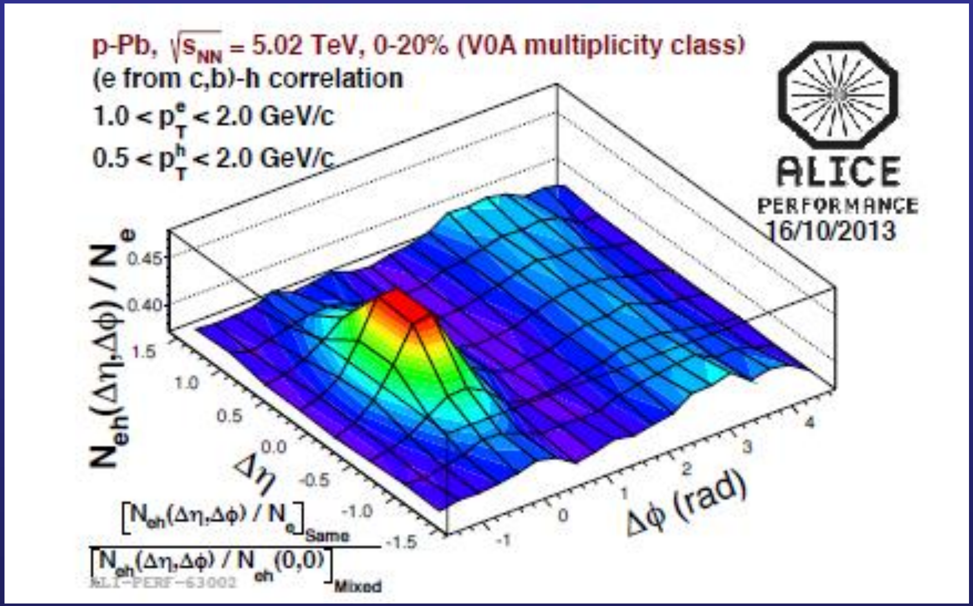


- ❑ Theory is on the data ! Fair agreement, but….
  - ❑ … one model has no CNM, no regeneration
  - ❑ …the other one has both CNM and regeneration
    (which would be responsible for all ϒ(2S) in central events)

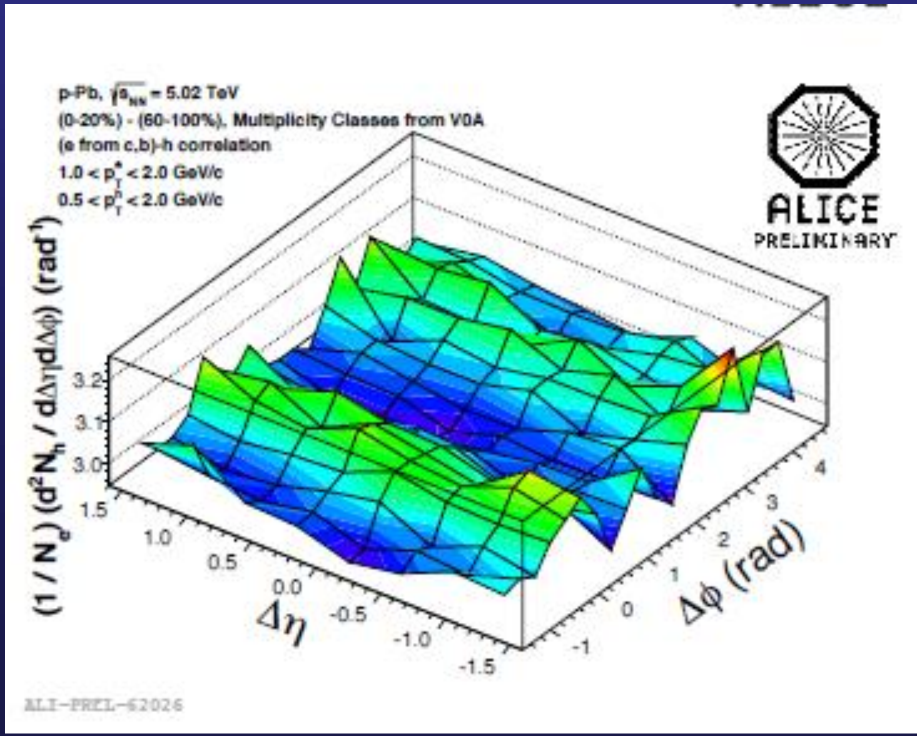
Still too early to claim a satisfactory understanding ?

p-Pb results: collective effects ?

- Study of the correlation function between trigger particles (electrons from heavy-flavour hadron decay) and associated particles (charged hadrons)

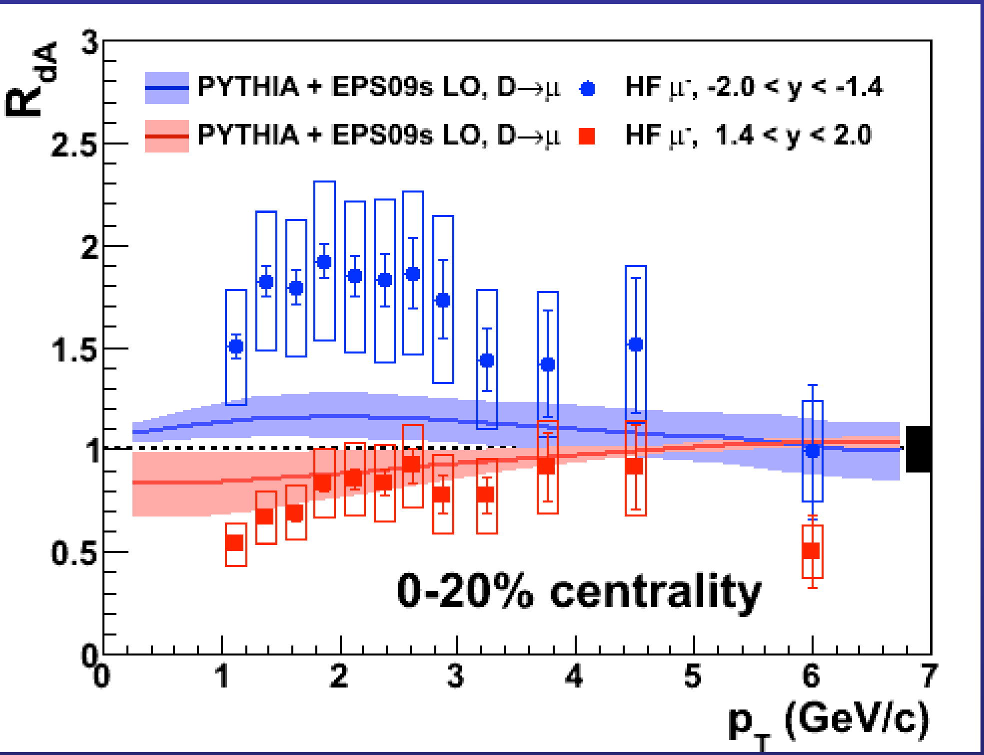


Difference of highest multiplicity event class (0-20% multiplicity) and lowest multiplicity event class (60-100%) (removes jet-like corr.)



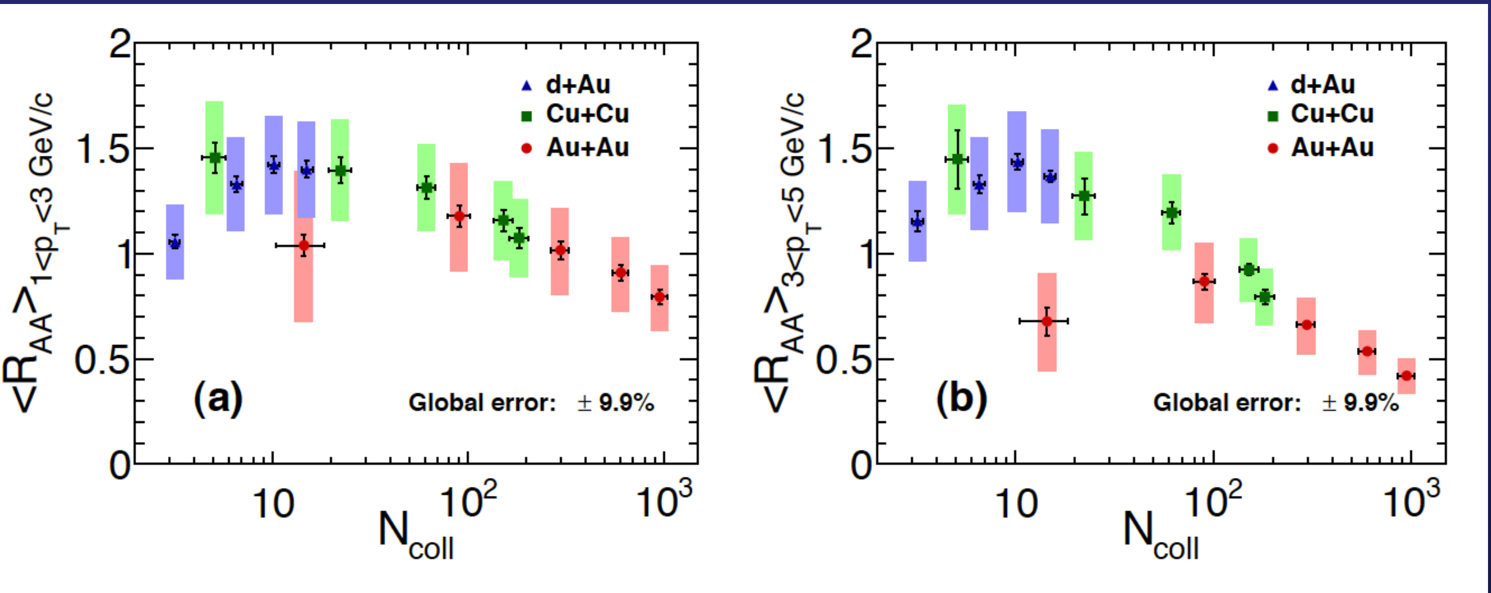
- Double ridge structure observed also for HF e-h correlation as in h-h correlations
- For h-h correlations it has been described in terms of hydro or CGC

Results from PHENIX



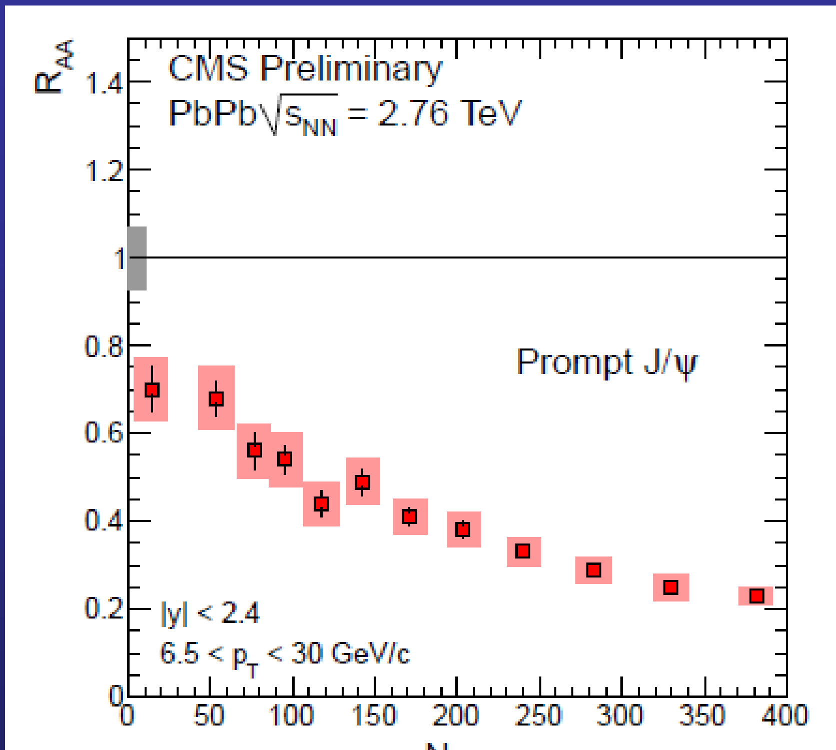
- Detailed study of HFM in dAu collisions
- Clear enhancement beyond shadowing effects at y<0 (Au-going direction)
- Compatible with unity at y>0 (and also at mid-rapidity)

...still waiting for an explanation

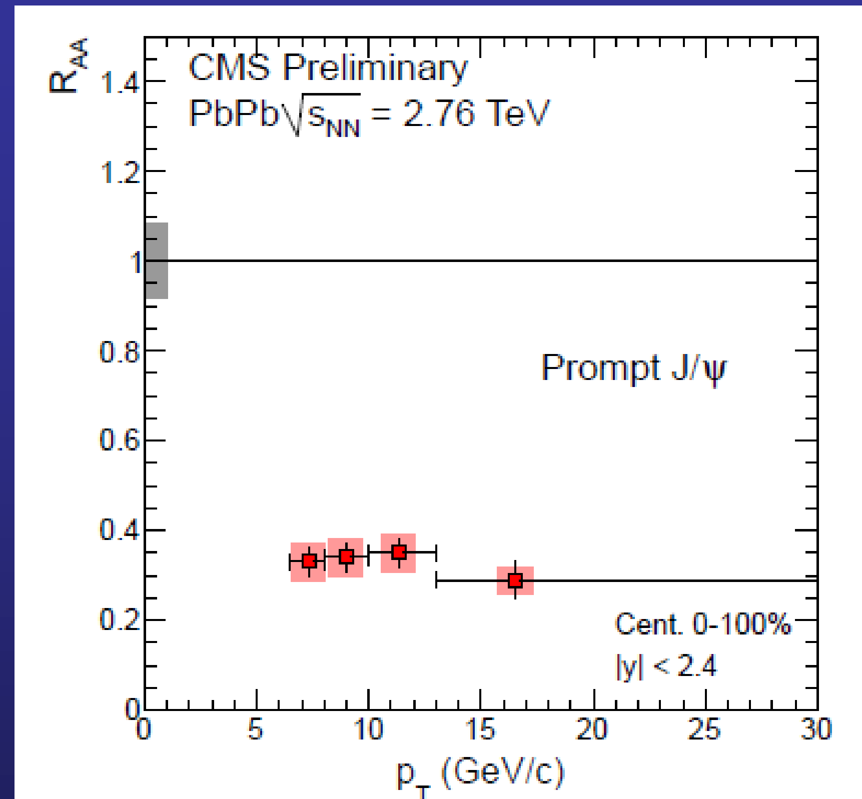


From enhancement to suppression with increasing reaction volume

CMS results: prompt J/ψ at high p_T

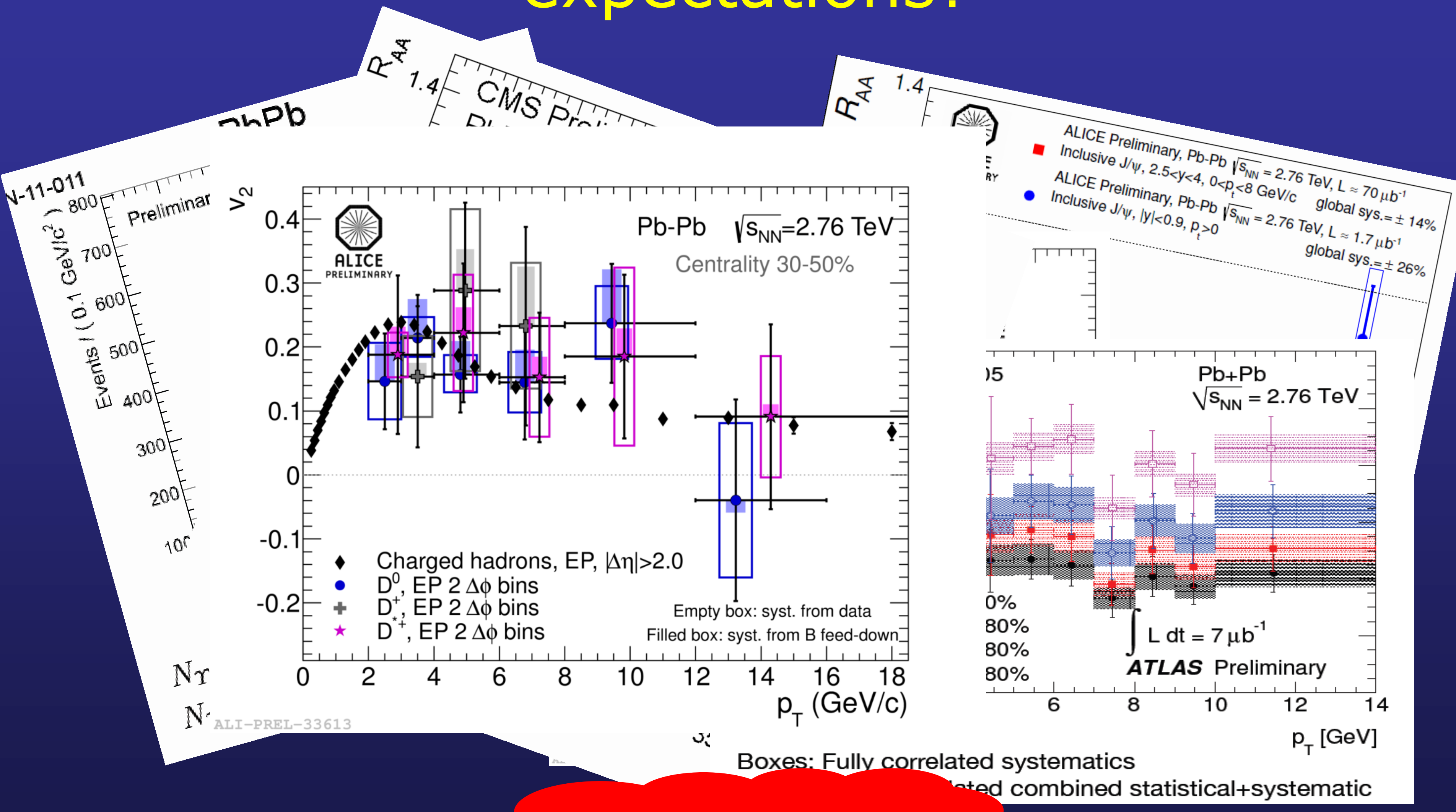


CMS PAS HIN-2012-014



- Striking difference with respect to ALICE
  - No saturation of the suppression vs centrality
  - Factor 5 suppression for central events
  - No significant p_T dependence from 6.5 GeV/c onwards
- (Re)generation processes expected to be negligible

Are LHC results matching our expectations?



Definitely yes !

..and RHIC is keeping pace