Experimental summary

5th International Workshop on Heavy Quark Production in heavy-ion collisions

Utrecht, 14-17 November 2012

E. Scomparin (INFN-Torino)

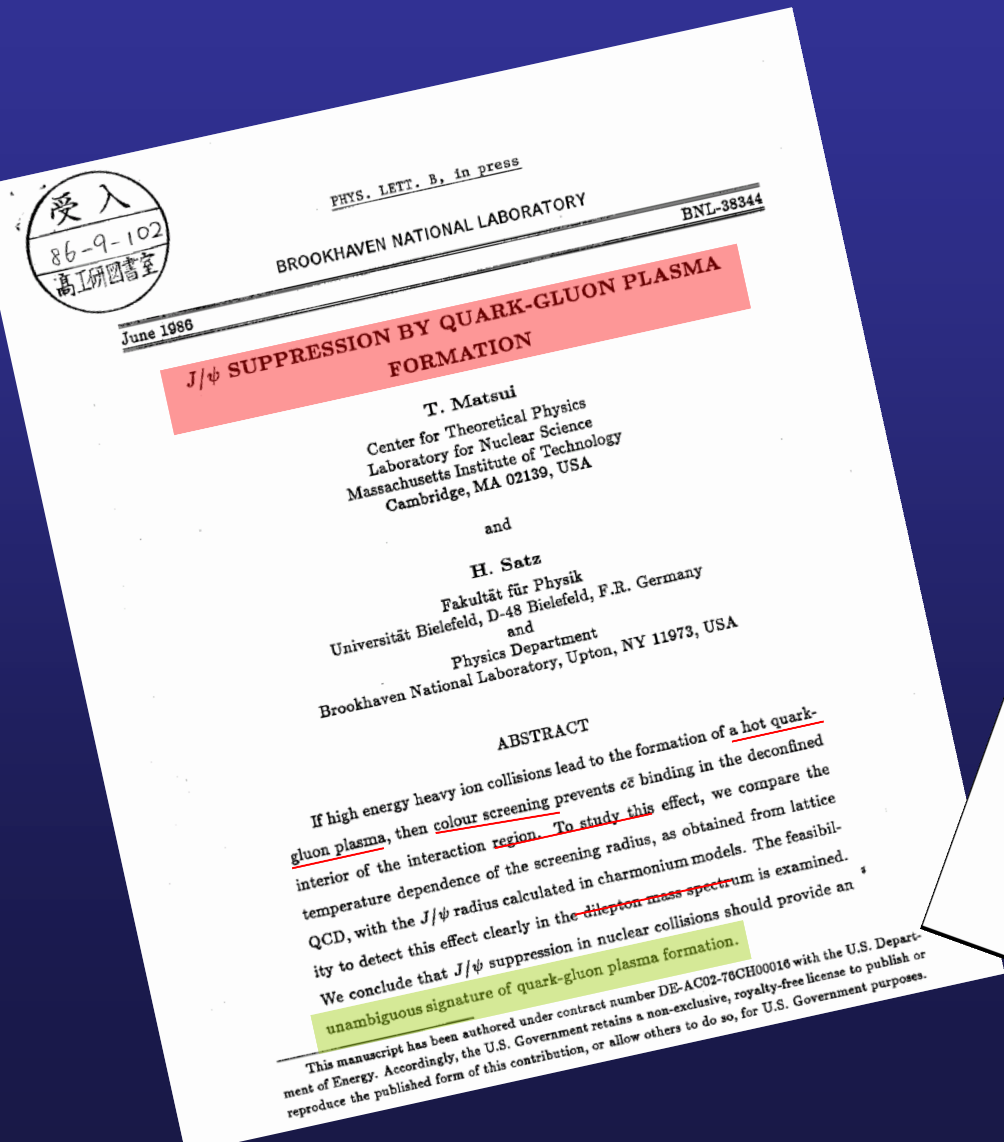
Thanks to

- the organizers, for the warm atmosphere and the perfect organization!
- all the speakers, for an exceptionally good coverage of all the physics items!

Here we are……

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

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



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

BNL-38344

June 1986

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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and

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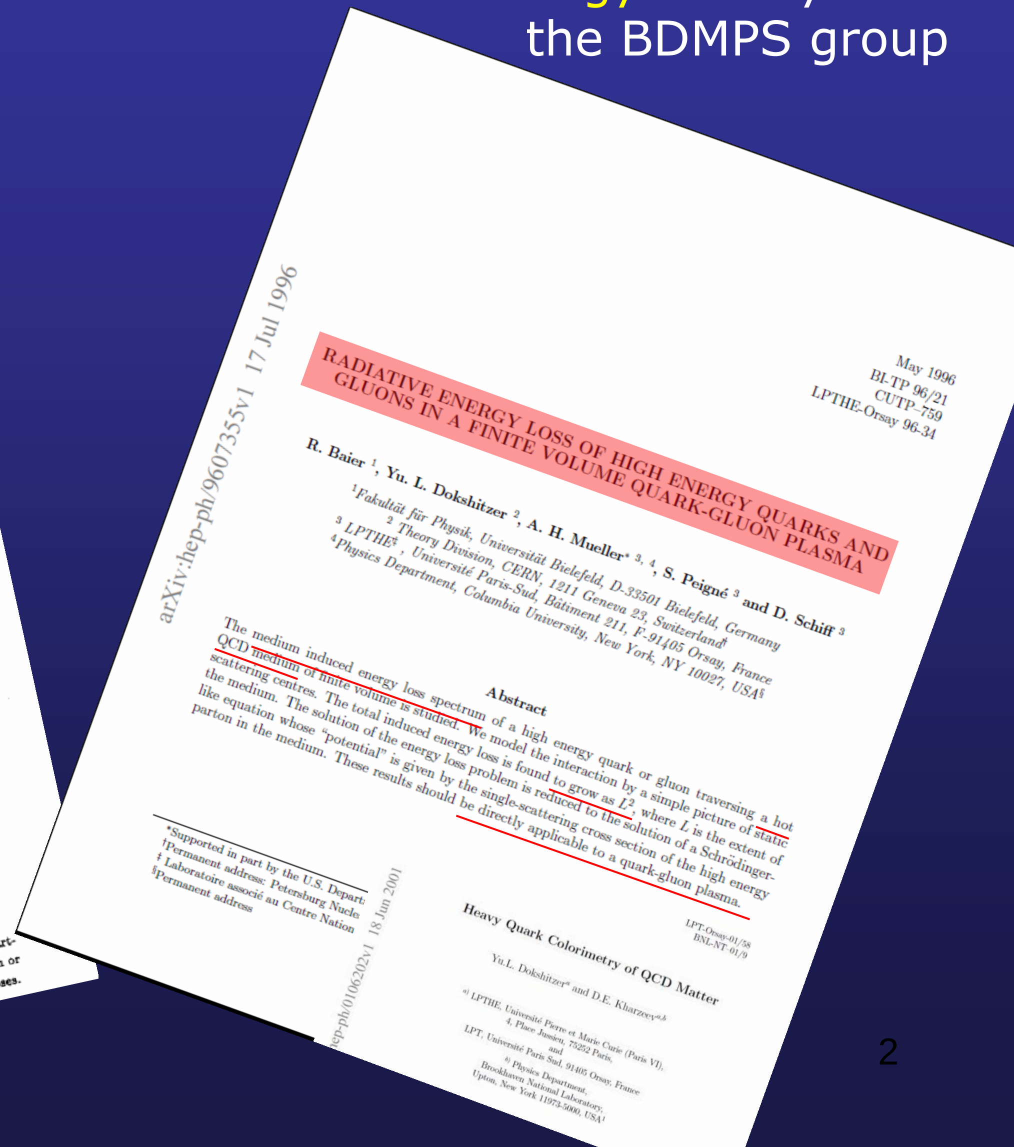
May 1996
BI-TP 96/21
CUTP-759
LPTHE-Orsay 96-34

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

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

Heavy Quark Colorimetry of QCD Matter

Yu.L. Dokshitzer[a] and D.E. Kharzeev[b]
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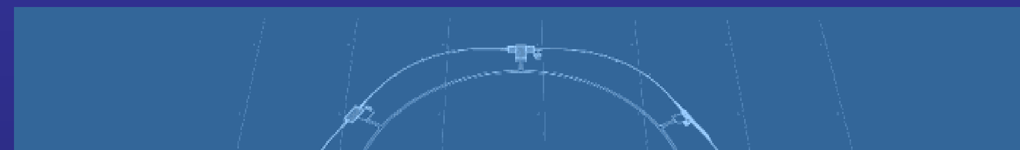
b) Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

Where are we ?

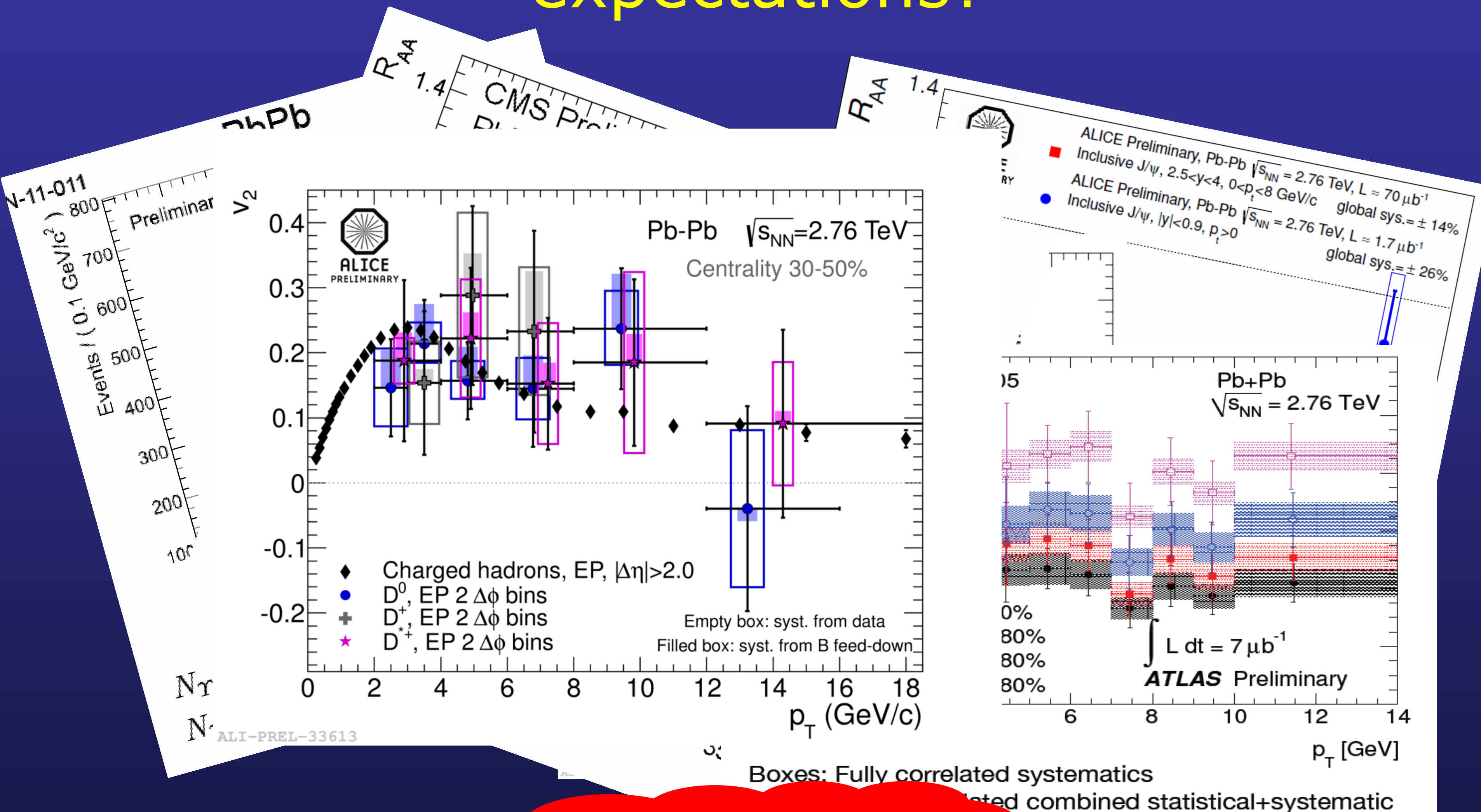
…26 years after O beams
were first accelerated in the SPS

…12 years after Au beams
were first accelerated at RHIC



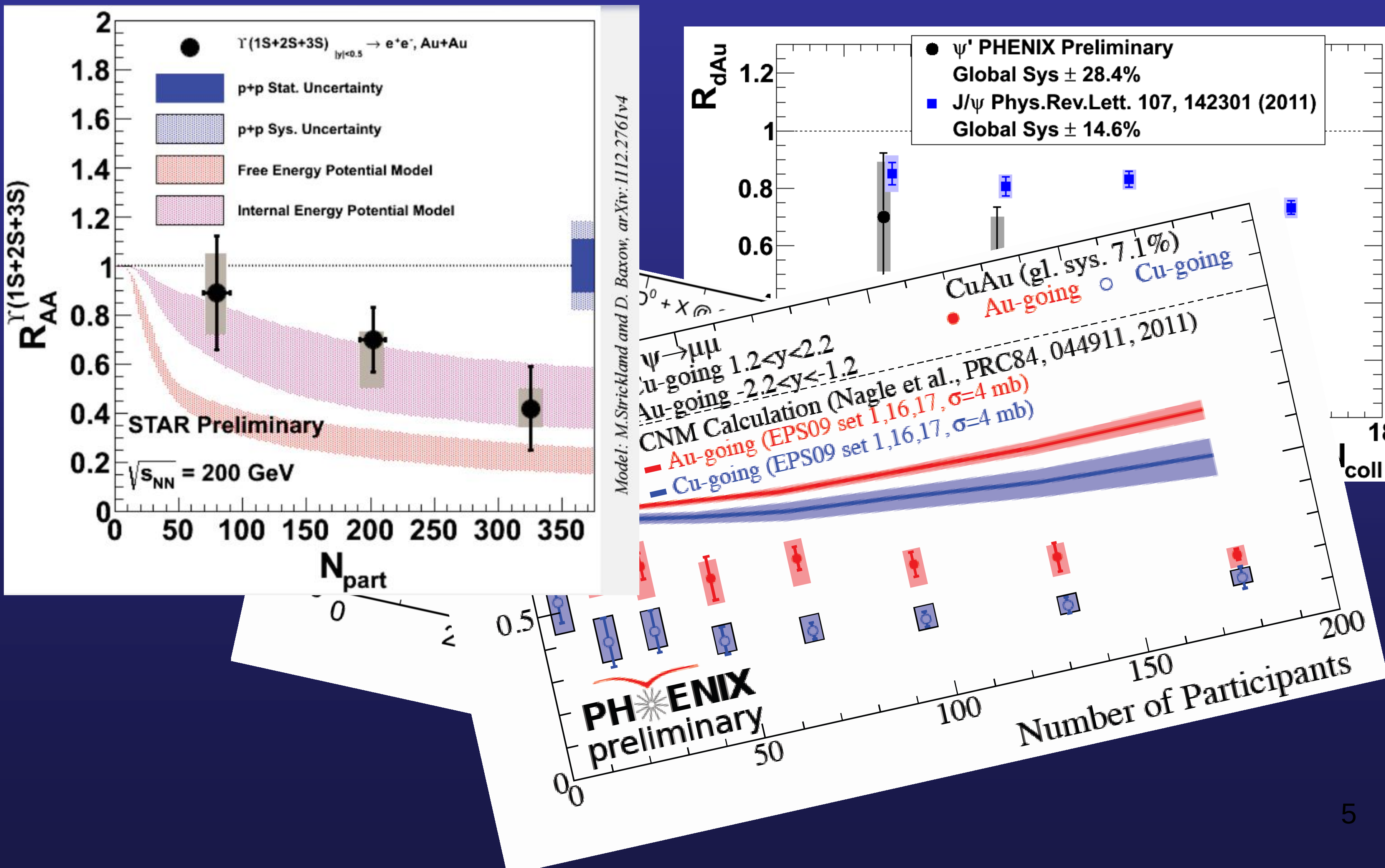
… and barely 2 years (!!!) after Pb beams first circulated inside the LHC

Are LHC results matching our expectations?

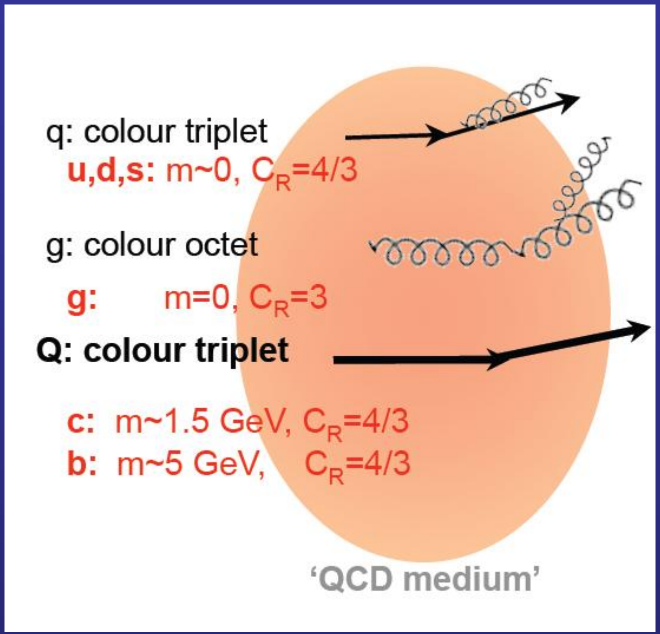


Definitely yes !

..and RHIC is keeping pace

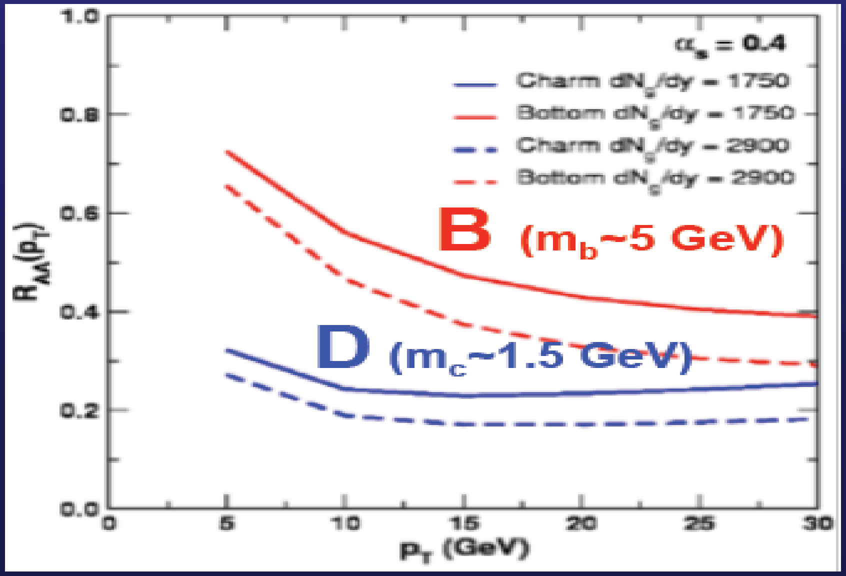


Heavy quark energy loss…



- **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

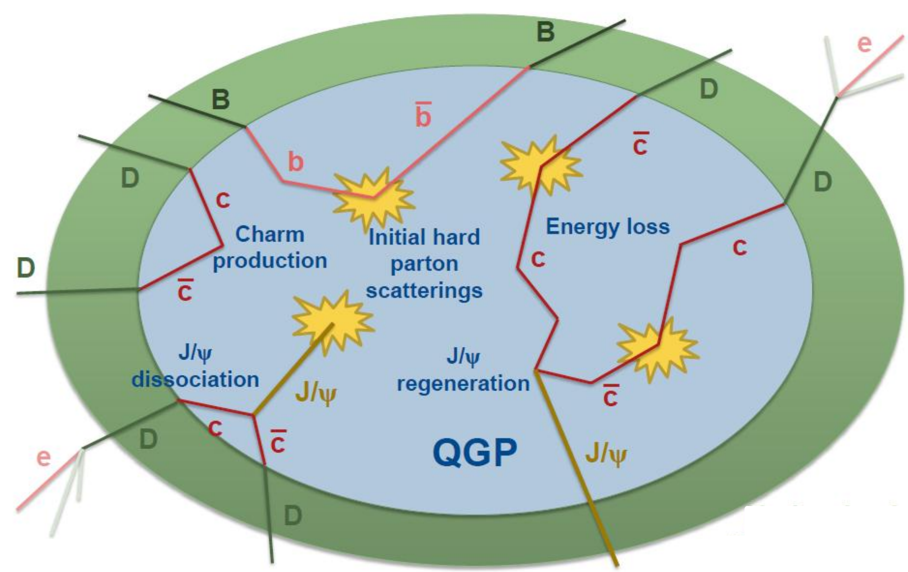
$$\Delta E_{quark} < \Delta E_{gluon}$$
$$\Delta E_b < \Delta E_c < \Delta E_{light\ q}$$

which should imply

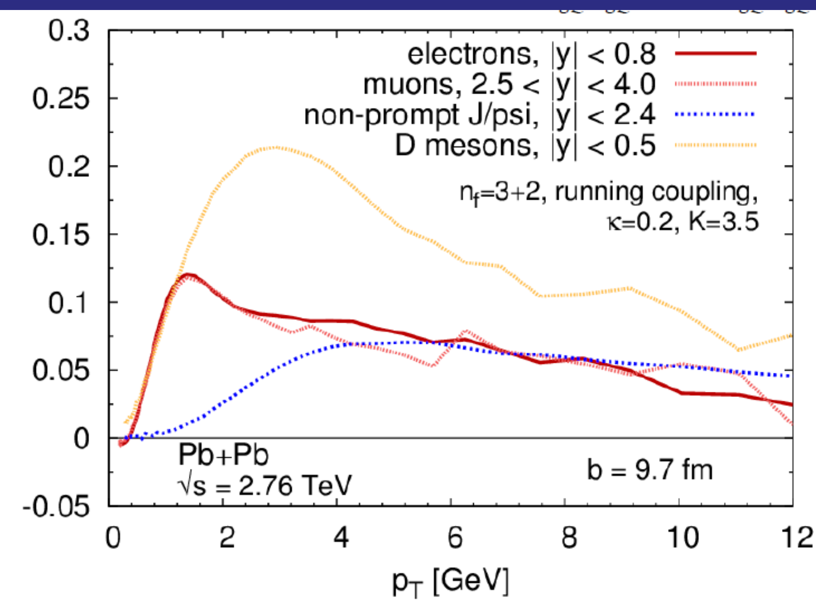
$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

… 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

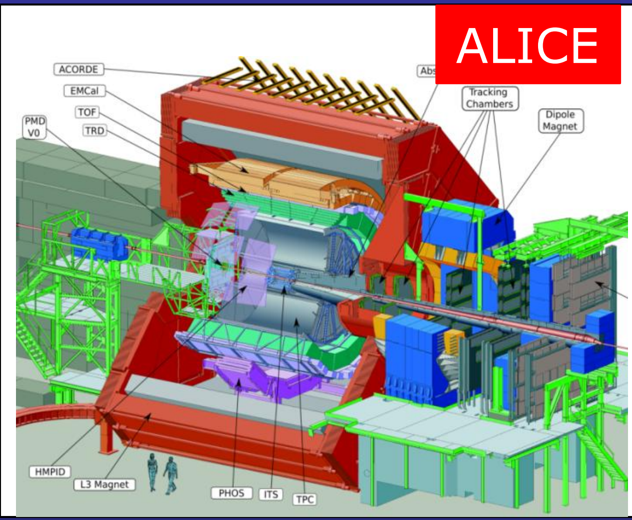


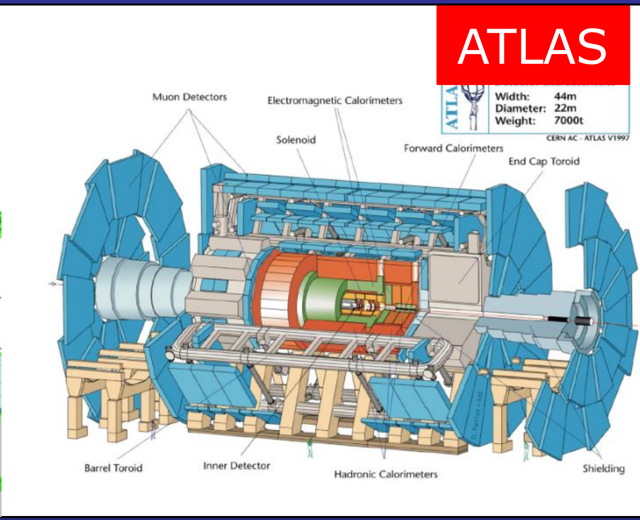
J. Uphoff et al., PLB 717 (2012), 430

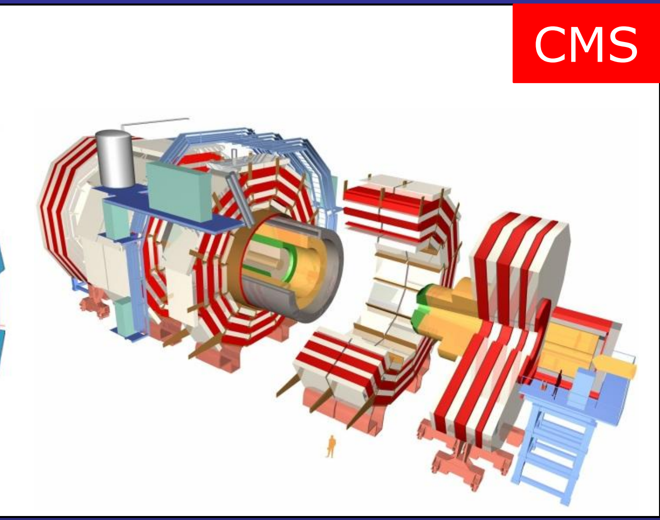


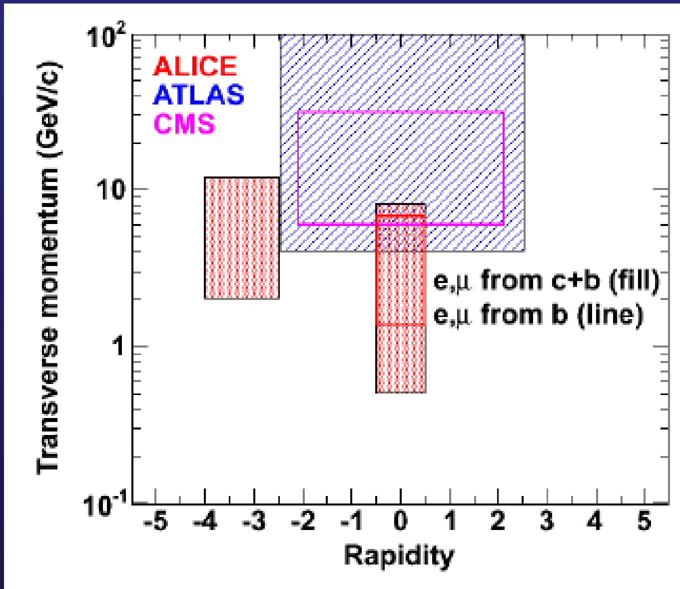
Can the unprecedented abundance of heavy quarks produced at the LHC bring to a (final ?) clarification of the picture ?

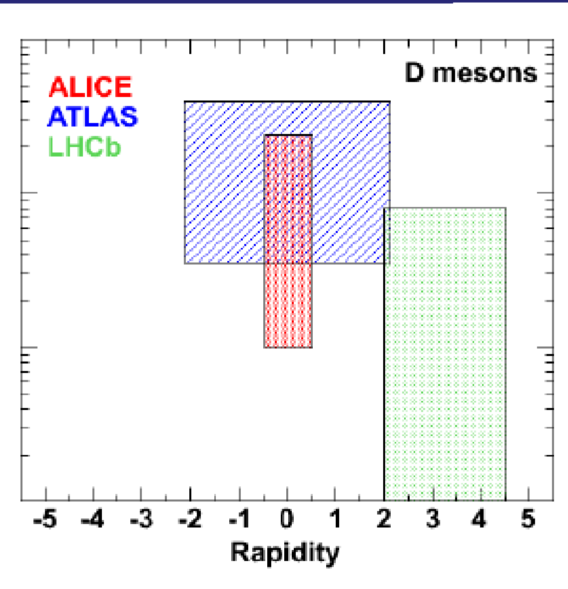
LHC, 3 factories for heavy quark in Pb-Pb

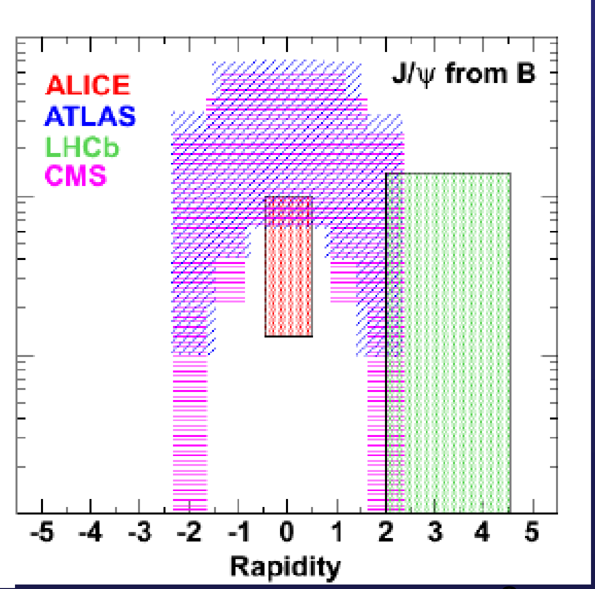








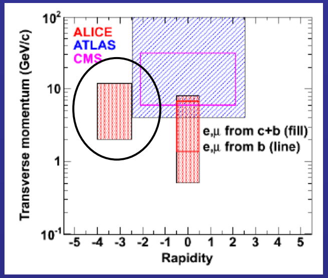




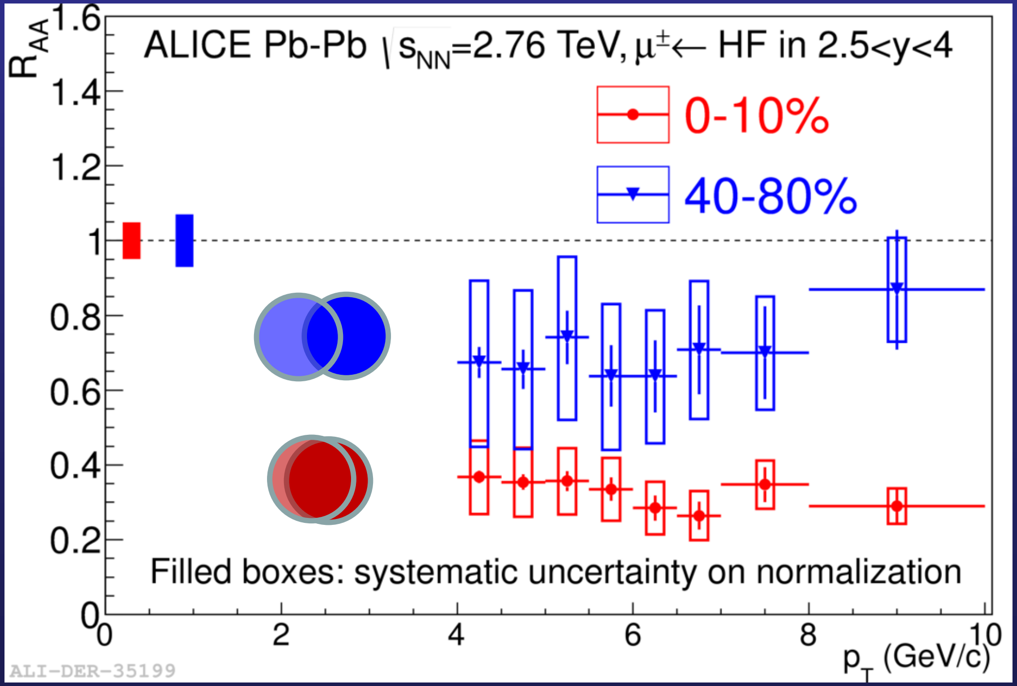
“Indirect” measurements

P.Pillot

- ❑ Semileptonic decays, the shortcut to heavy quark production (pioneered by RHIC and also SPS!)



ALICE: HF muons at forward rapidity ($-4<\eta<-2.5$)



Forward muon spectrometer

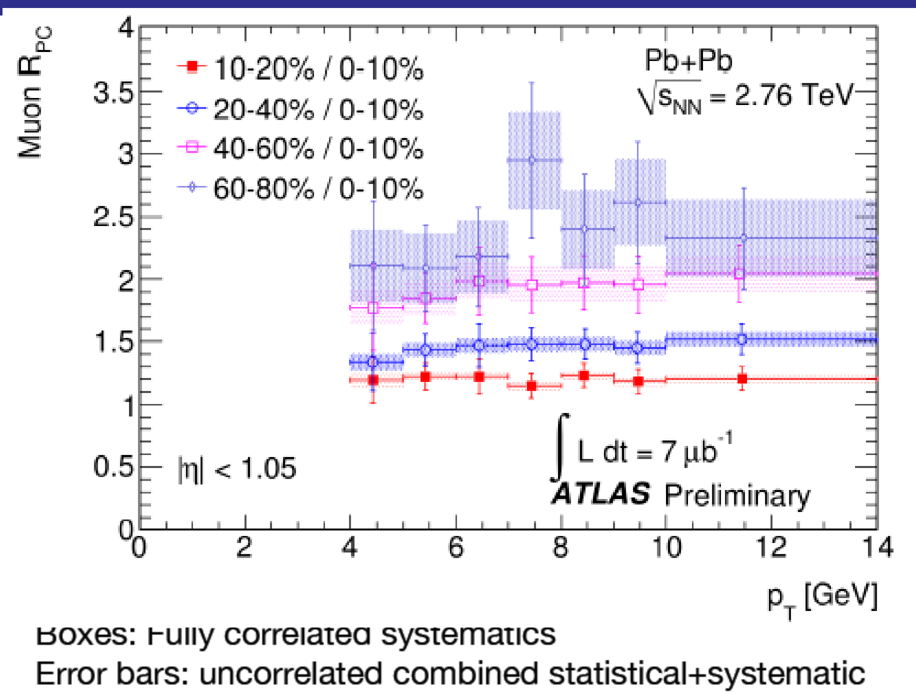
- ❑ Muon ID: matching track/trigger, rejects hadronic punch-through
- ❑ Background from π/K extrapolated from mid-y (assuming y-dep. of R_{AA})
- ❑ Reference: pp at 2.76 TeV

→ Factor ~3-4 suppression for central events, weak p_T-dependence

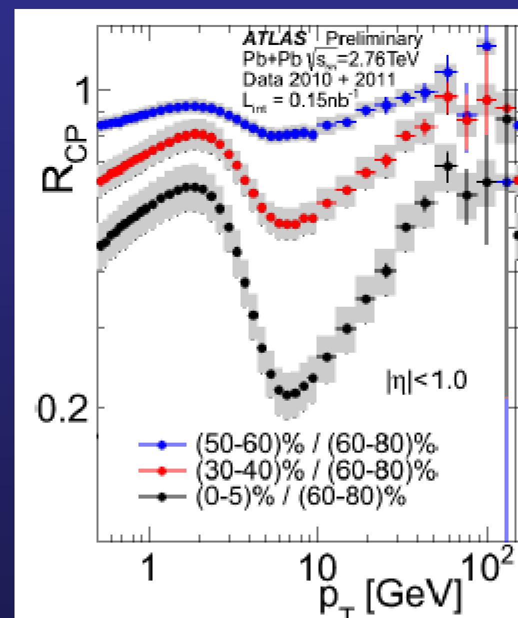
What about central rapidity ?

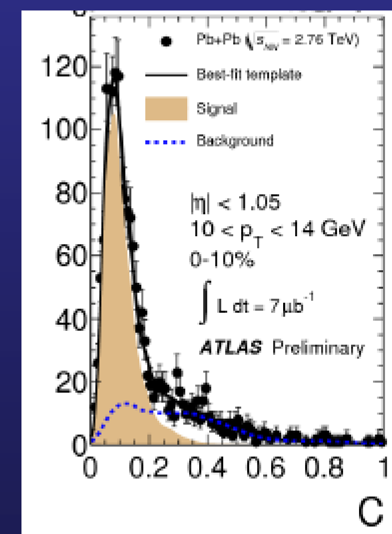
M.Przbycien

- 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





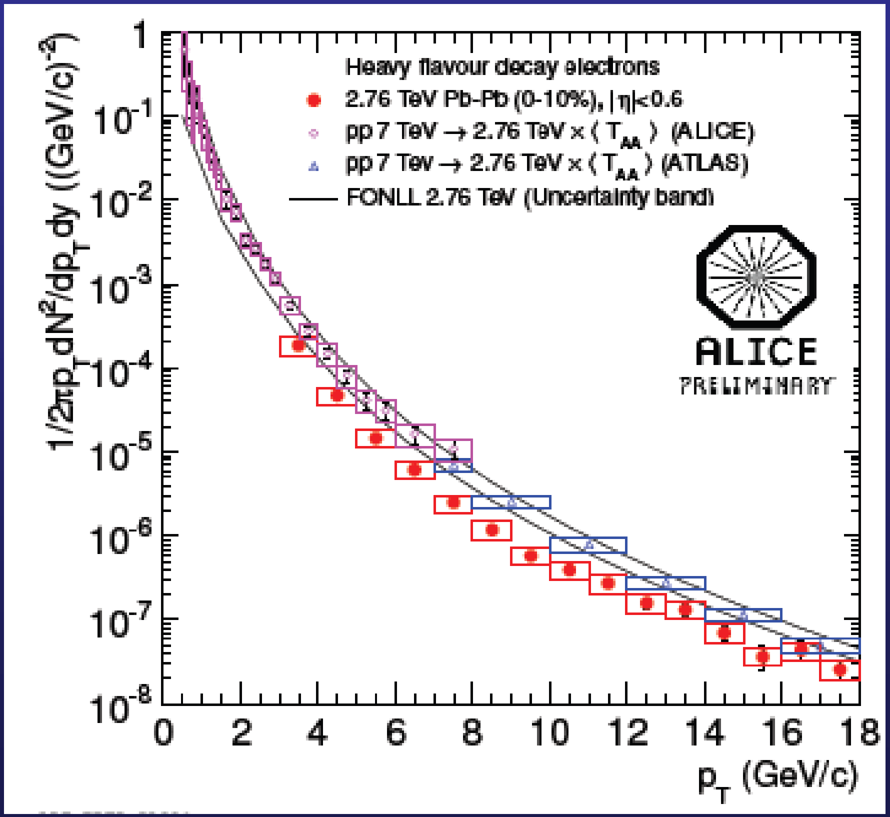
- R_{CP} subject to statistical fluctuations → use R_{PC} too!
- ~flat vs p_T up to 14 GeV/c, different from inclusive R_{CP}!

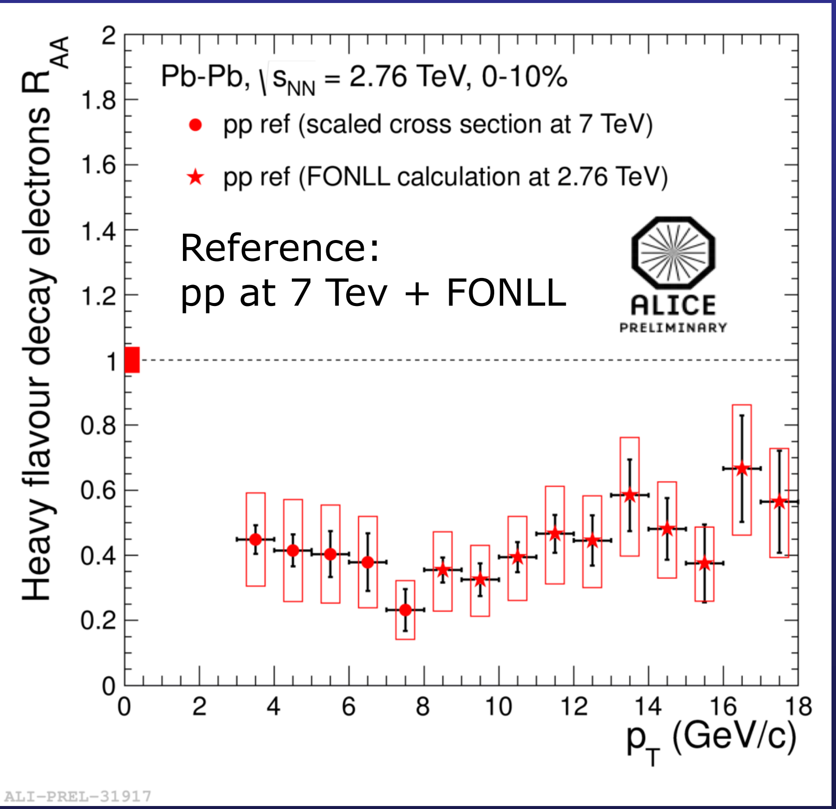
If ~no suppression for 60-80% → central ~ forward suppression

Electrons at midrapidity

B. Rascanu

- ALICE measures inclusive electron production at midrapidity
- "Photonic" background subtraction through invariant mass reconstruction
- Contribution from J/ψ → ee also subtracted



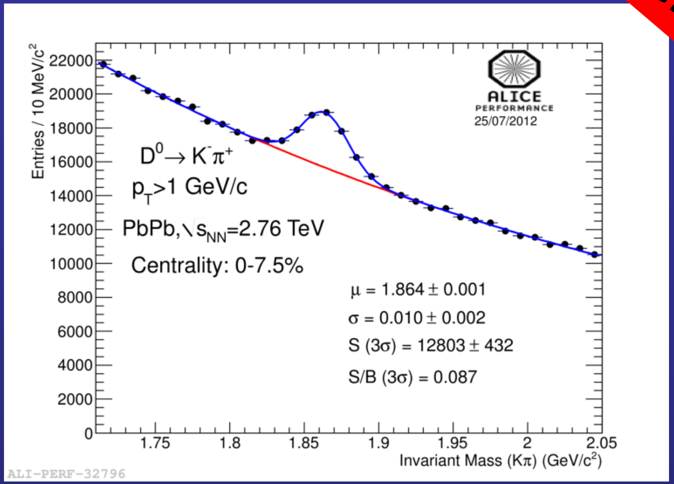


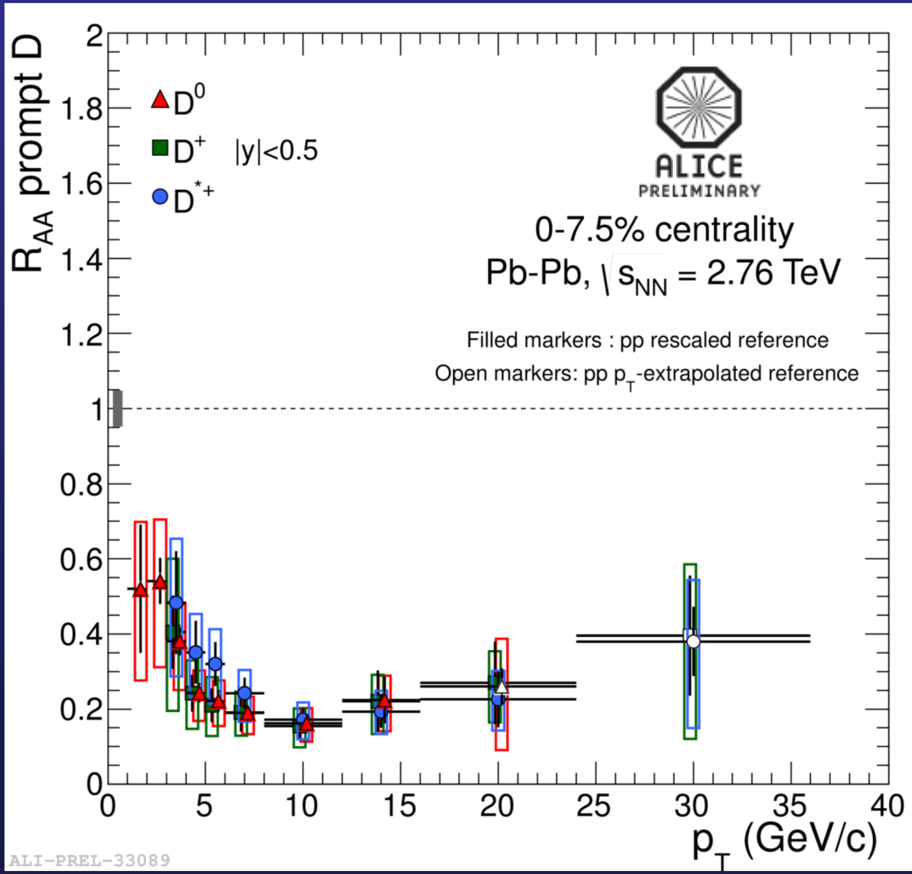
Suppression in $3<p_T<18$ GeV/c (factor up to ~3)
Hints for less suppession at high p_T ?

"Direct" measurements: D

A. Grelli

- ALICE: D-mesons at central rapidity
- Invariant mass analysis of fully reconstructed decay topologies displaced from the primary vertex

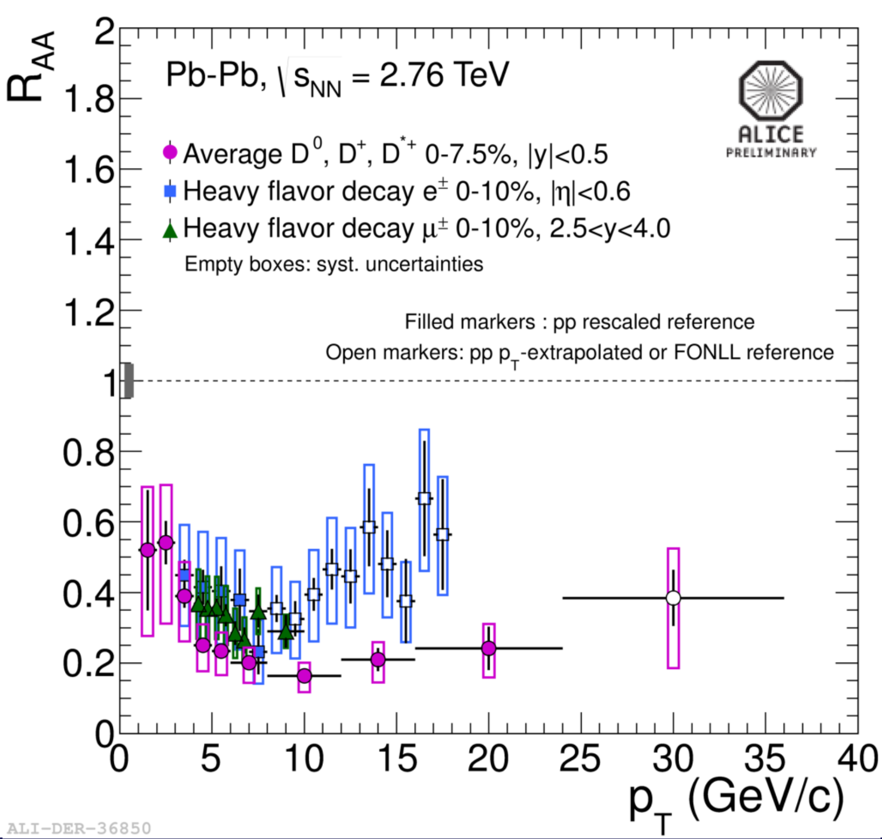


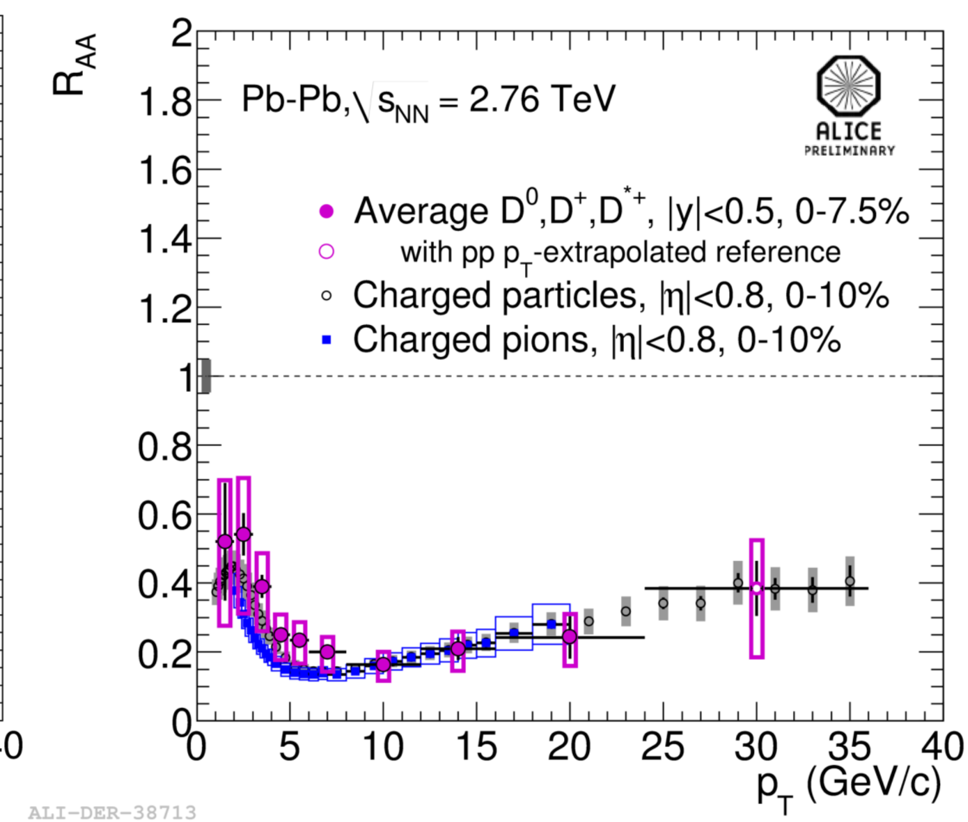


- Reference
  - 7 TeV scaled to 2.76 with FONLL
  - Use FONLL shape if no pp
- D^0, D^+ and D^{*+} R_{AA} agree within uncertainties

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

Comparisons: what do we learn?





- ❑ To properly compare D and leptons the decay kinematics should be considered ($p_T^e \approx 0.5 \cdot p_T^B$ at high p_T^e)

- ❑ Similar trend vs. p_T for D, charged particles and $\pi^\pm$

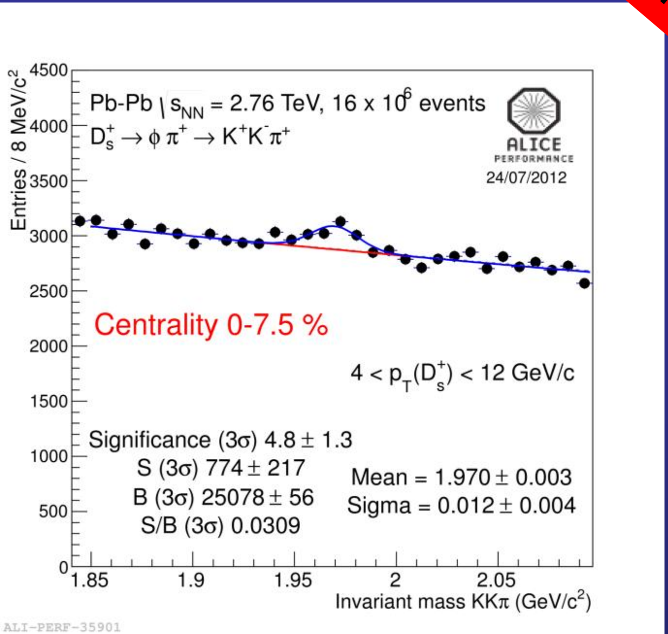
Hint of $R_{AA}^D > R_{AA}^\pi$ at low p_T ?

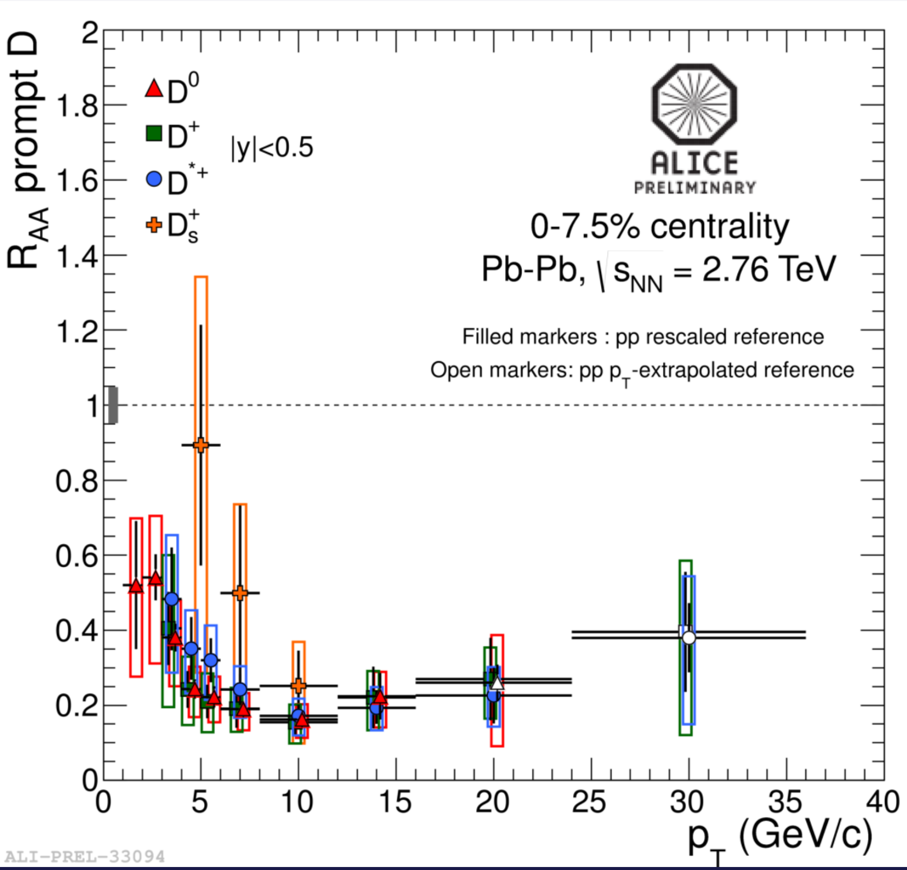
→ Look at beauty

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

A. Grelli

- 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

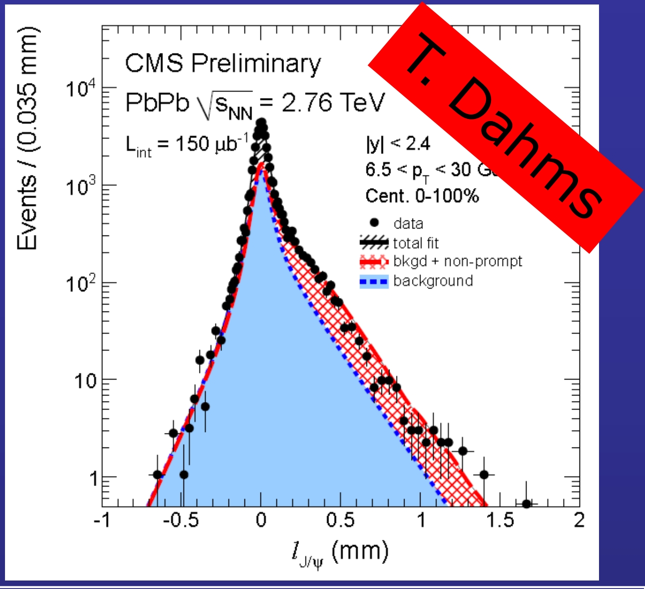


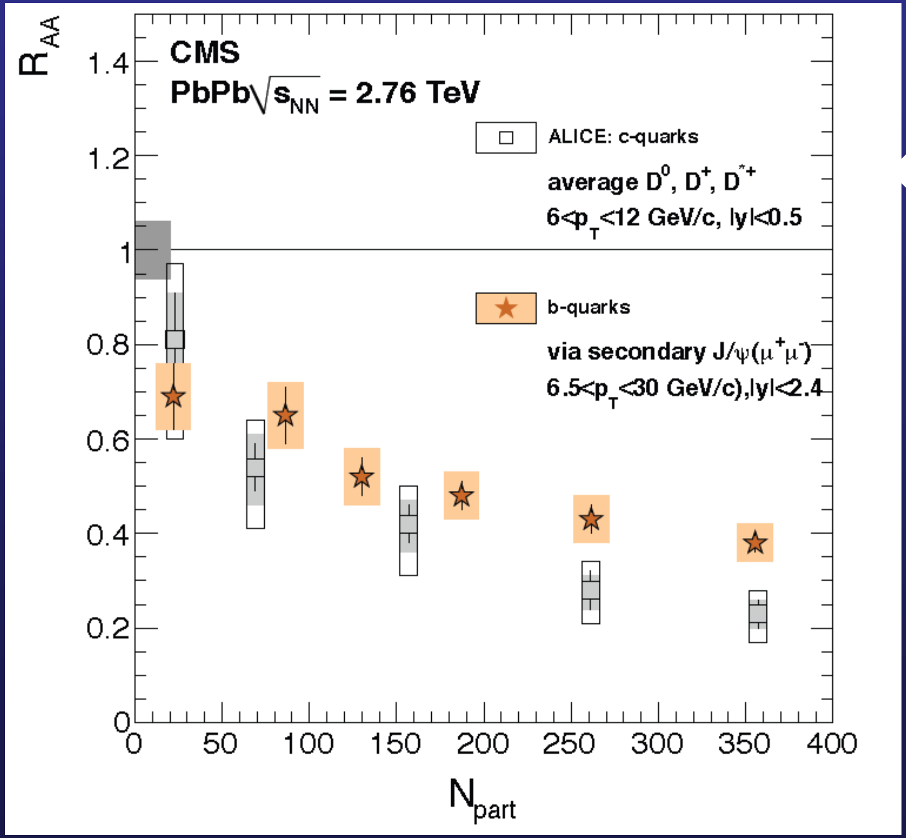


- Strong D_s^+ suppression (similar as D^0, D^+ and D^{*+}) for $8<p_T<12$ GeV/c
- R_{AA} seems to increase at low p_T
- Current data do not allow a conclusive comparison to other D mesons within uncertainties

Non-prompt J/ψ

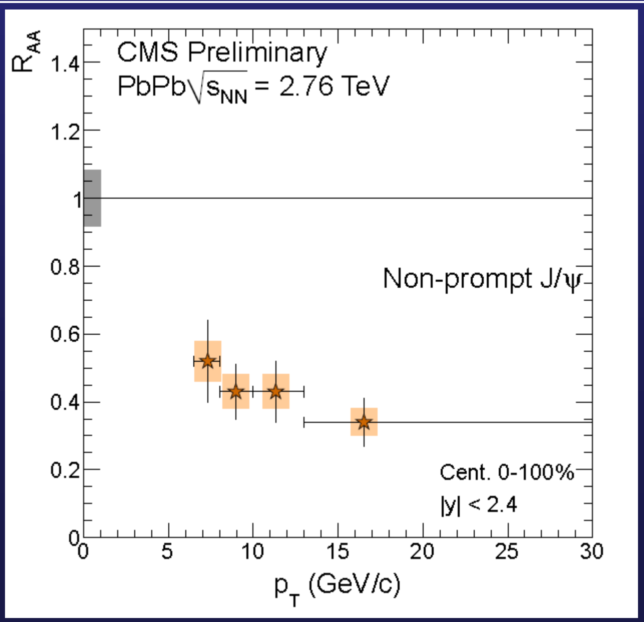
- Fraction of non-prompt J/ψ from simultaneous fit to $\mu^+\mu^-$ invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)





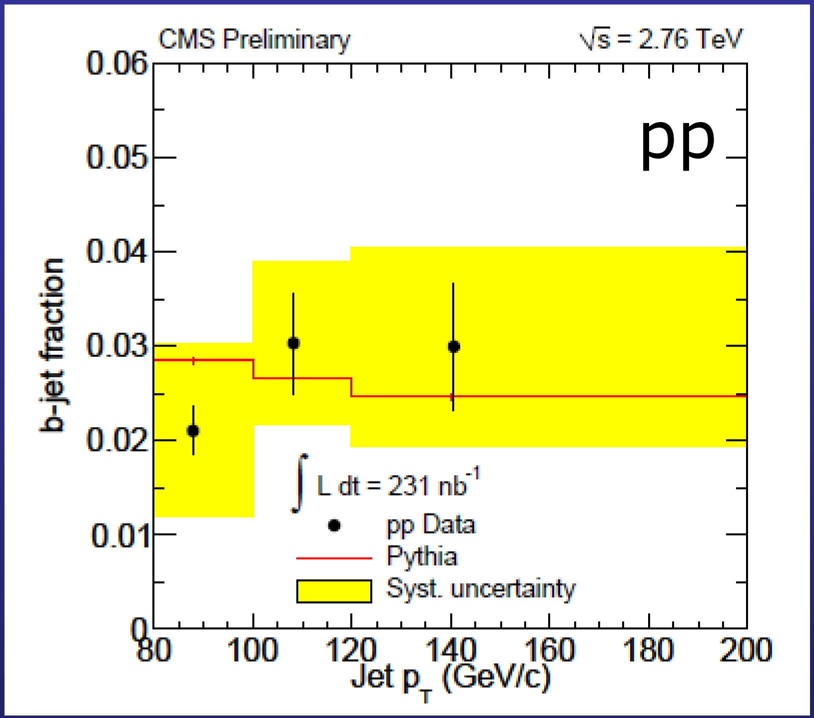
Suppression hierarchy (b vs c) observed, at least for central collisions (note different y range)

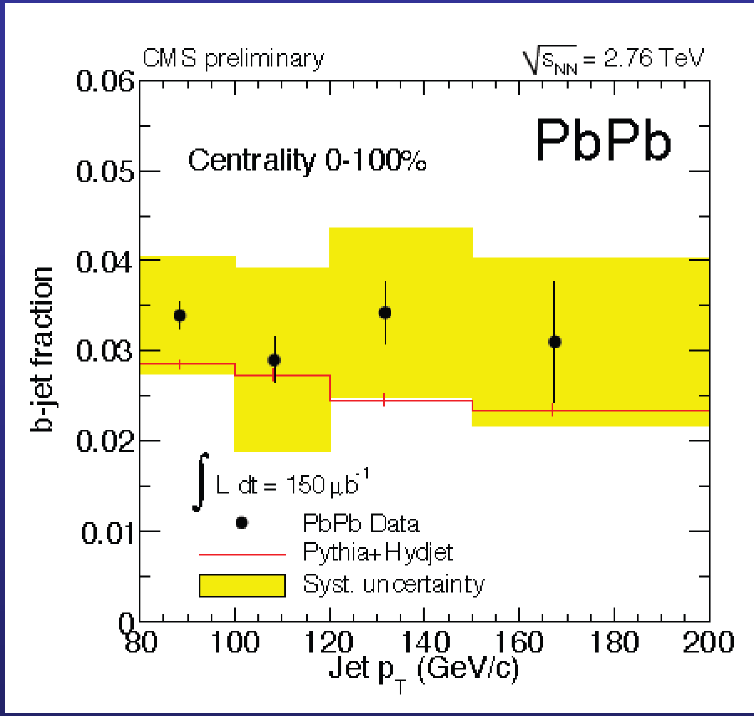
Larger suppression at high p_T ?



The new frontier: b-jet tagging

M. Nguyen



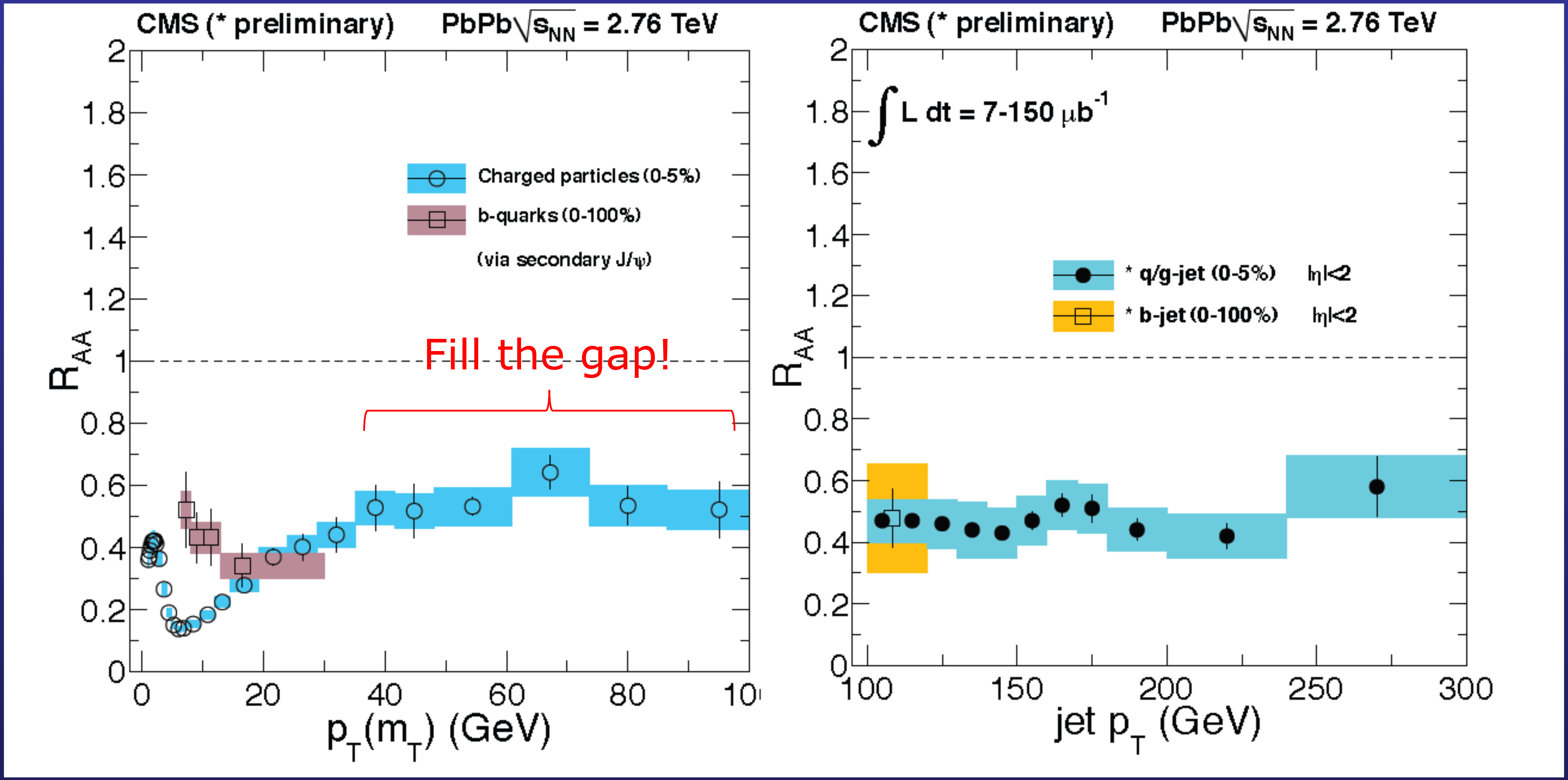


- Jets are tagged by cutting on discriminating variables based on the flight distance of the secondary vertex
  → enrich the sample with b-jets

- 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

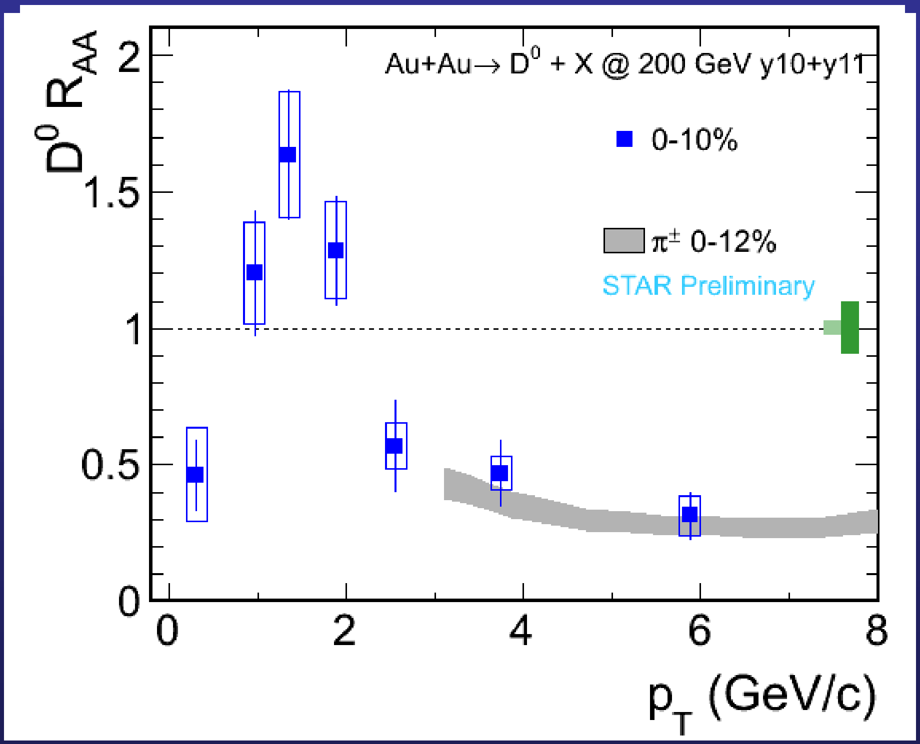


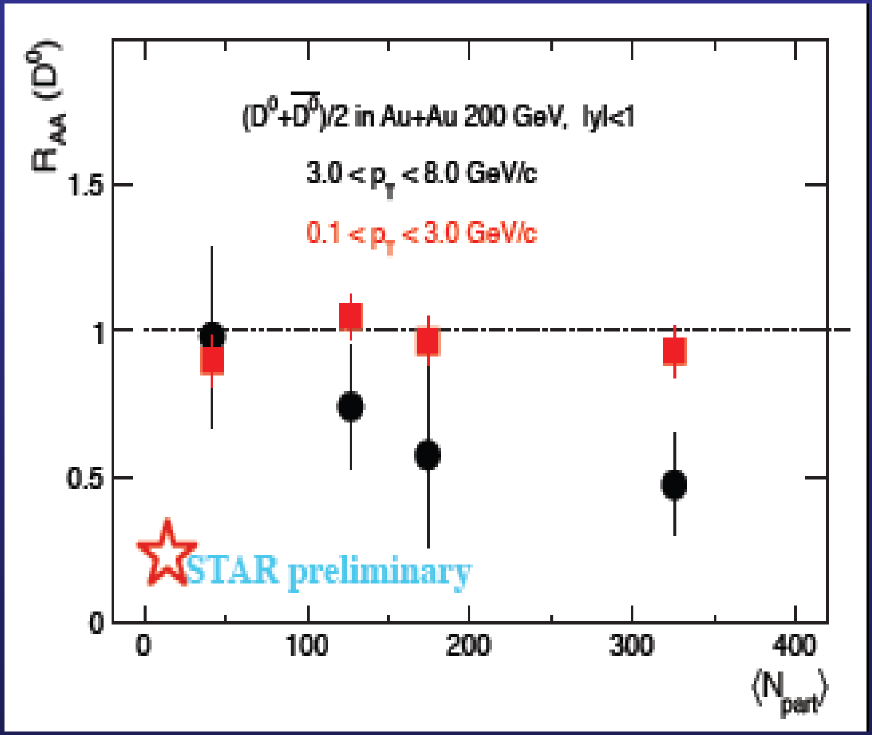
- Low p_T: different suppression for beauty and light flavours, but:
  - Different centrality
  - Decay kinematics
- High p_T: similar suppression for light flavour and b-tagged jets

Recent news from RHIC

J. Bielcik

- STAR: direct charm measurement vs p_T, in bins of centrality
- pp reference consistent with FONLL upper limit





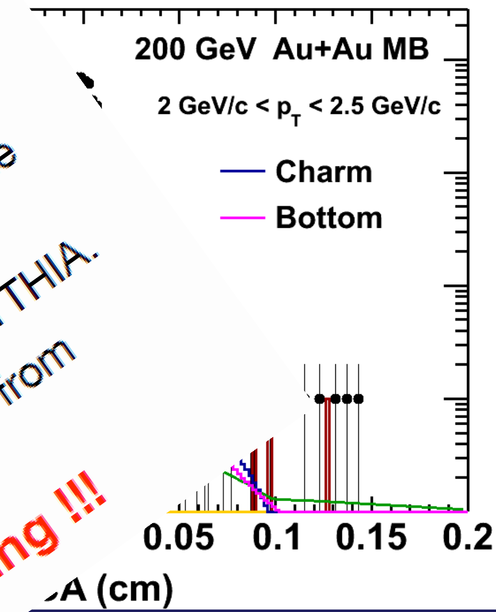
Suppression at high-p_T in central and mid-central collisions
Enhancement at "intermediate" p_T

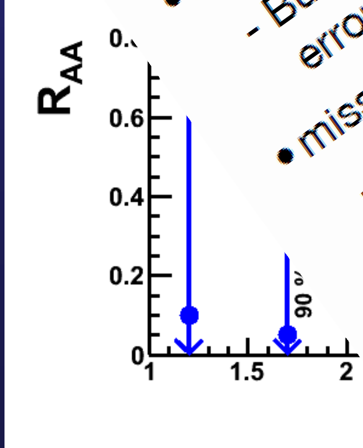
(consistent with resonance re-combination model)

PHENIX ... c

PHENIX VTX tracker

... is obtained from the ... f measured electrons





... ement with previous ... ults and with pp b/c ratios

Larger suppression for beauty
→ Challenging result !

TO BE UNDERSTOOD

TO BE BETTER UNDERSTOOD !

bottom fraction in Au+Au

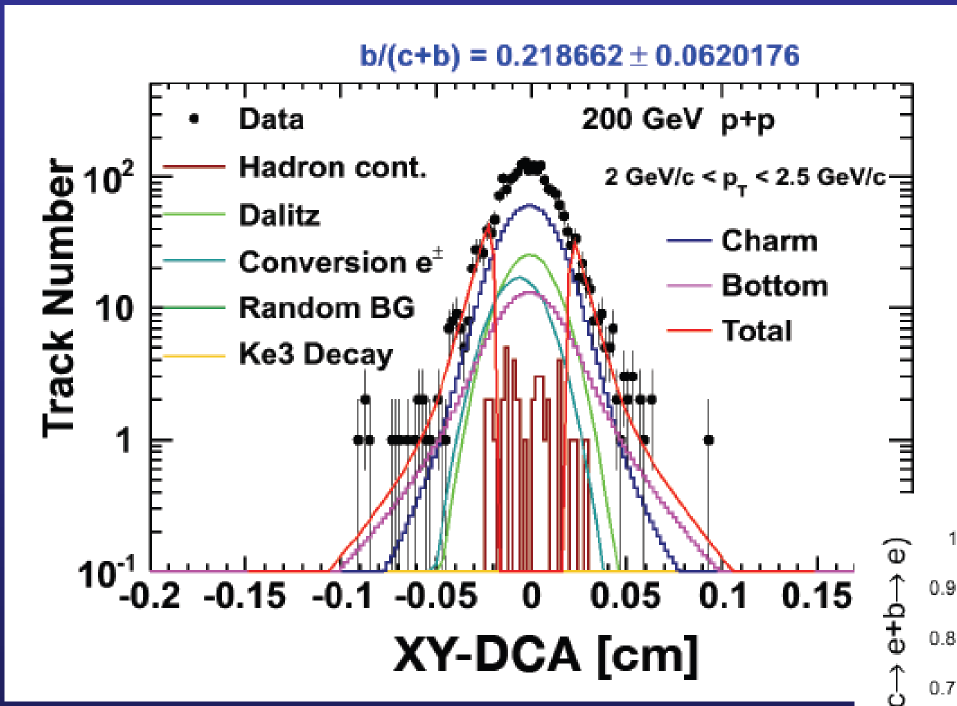
- Bottom fraction in Au+Au data is also evaluated.
  - But a missing item is found to be evaluated as a systematic error.
- missing item
  - If p_T distributions of heavy flavor hadrons are significantly modified, DCA templates are also modified.
  - √ p_T distribution in PYTHIA with default setup is used in the decomposition analysis.
  - For p+p data, p_T distribution is not so different from PYTHIA.
  - But for Au+Au data, p_T distribution can be changed from PYTHIA.

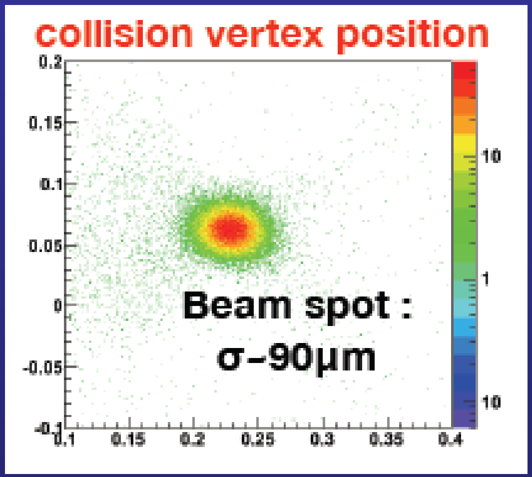
Evaluation of this item is ongoing !!!

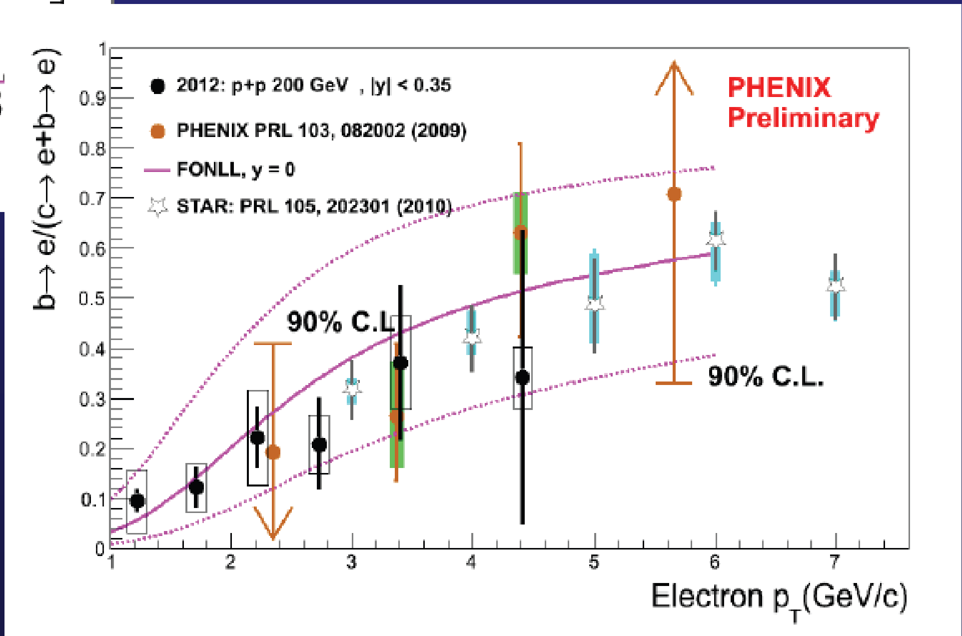
PHENIX, b vs c

R. Akimoto

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







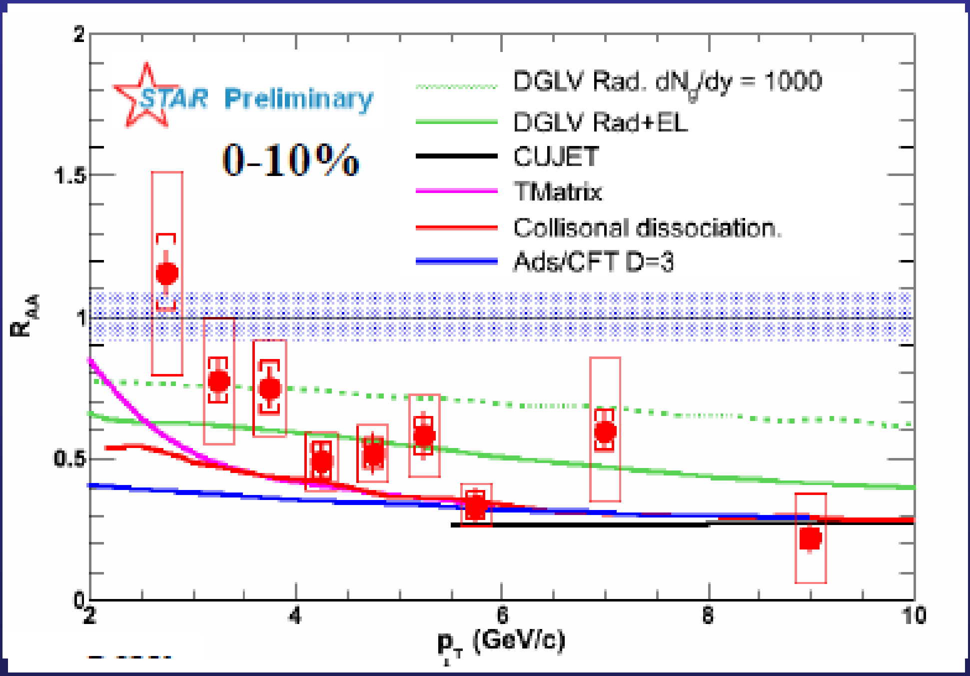
- ❑ Bottom fraction in pp consistent with published data (from e-h correlations) and with FONLL

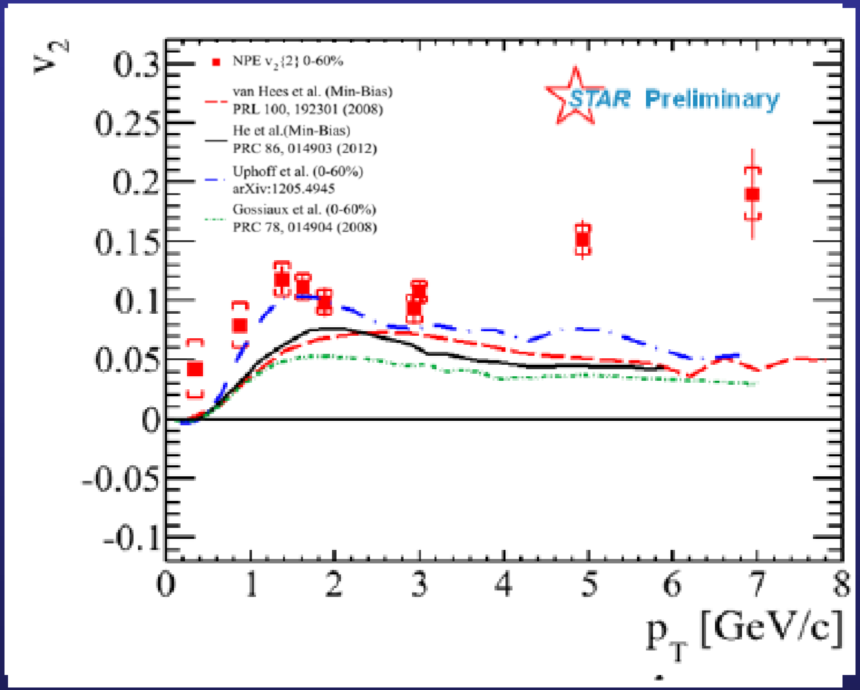
Look forward to forthcoming Au-Au results!

STAR, on R_{AA} and v_2

M. Mustafa

- 1 nb^{-1} sampled luminosity (Run2010) → new measurement of NPE with a highly improved result at high p_T



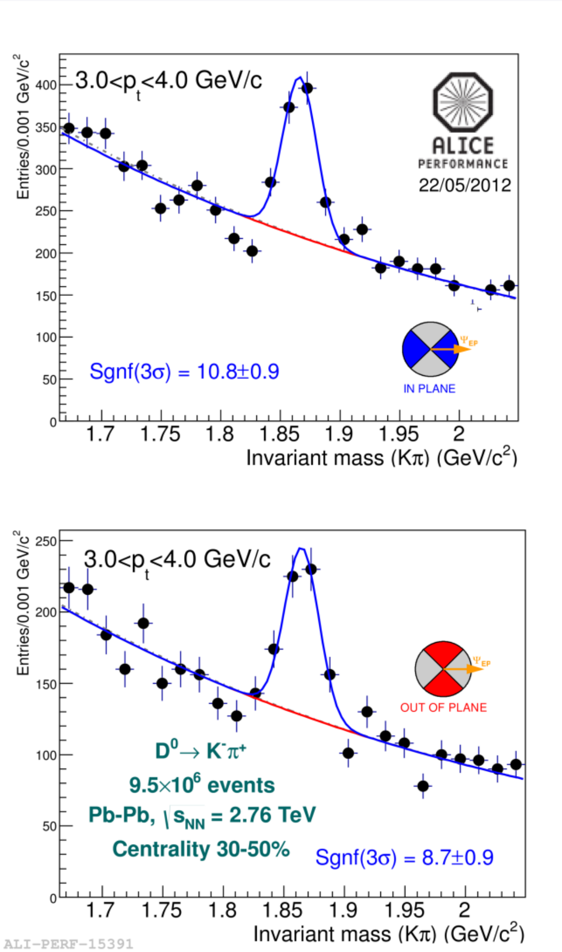


- Strong suppression of HQ (consistent with D), pure energy loss disfavoured
- Finite v_2 at low p_T, increase at high p_T (jet corr., path length dependence)
- Simultaneous description of R_{AA} and v_2 → challenge for models
- v_2 tends to zero at low $\sqrt{s}$ → lighter charm-medium interactions ?

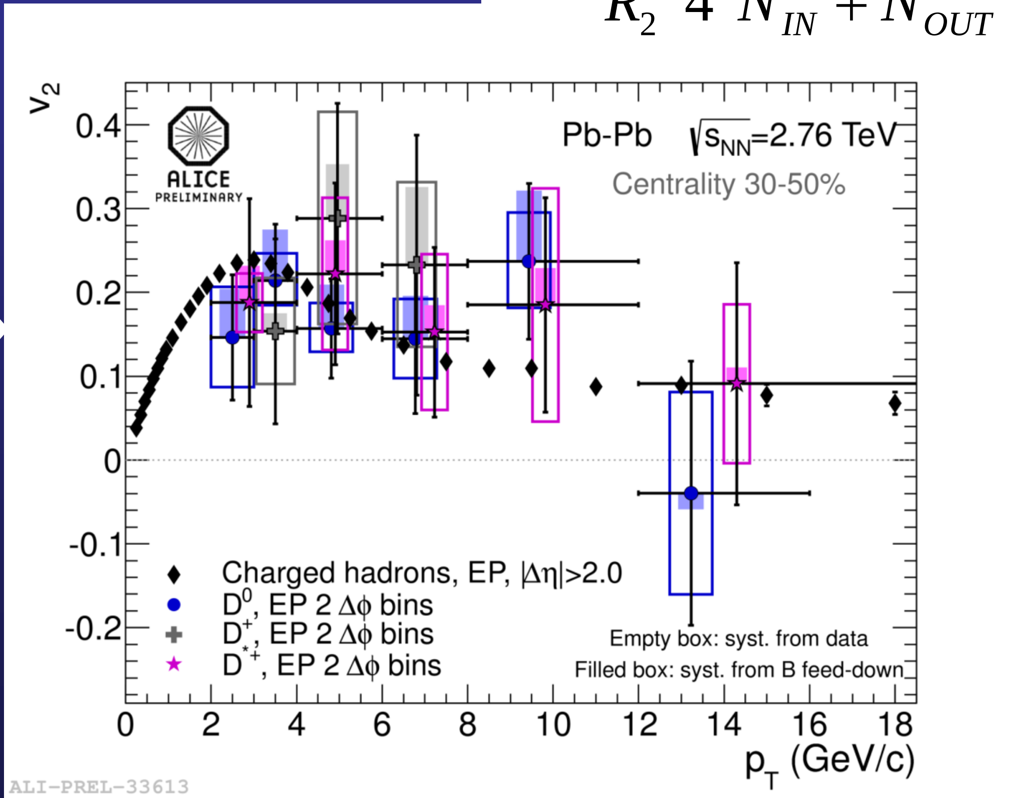
HQ v_2 at the LHC

A. Festanti

- First direct measurement of D anisotropy in heavy-ion collisions
- Yield extracted from invariant mass spectra of $K\pi$ candidates in 2 bins of azimuthal angle relative to the event plane

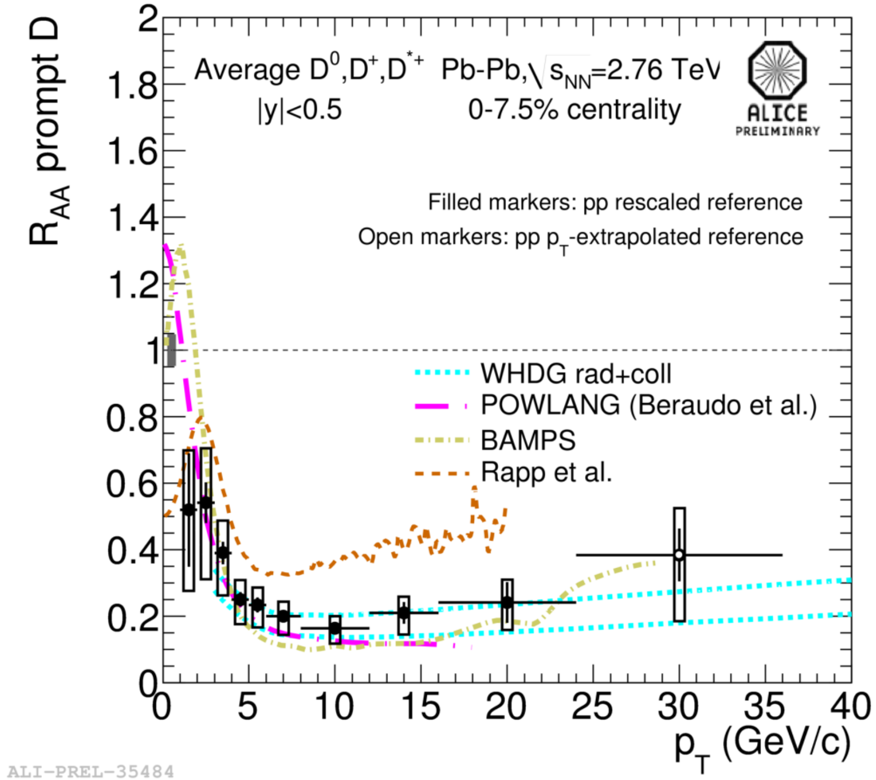


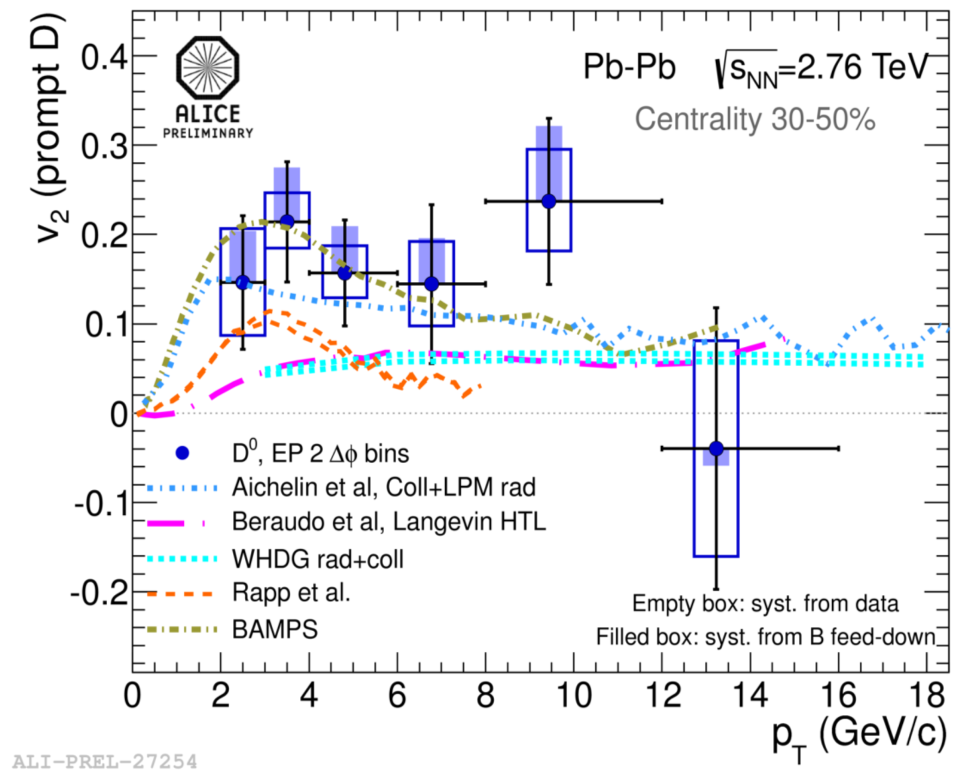
$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$



Indication of non-zero D meson v_2 (3σ effect) in $2<p_T<6$ GeV/c

Data vs models: D-mesons



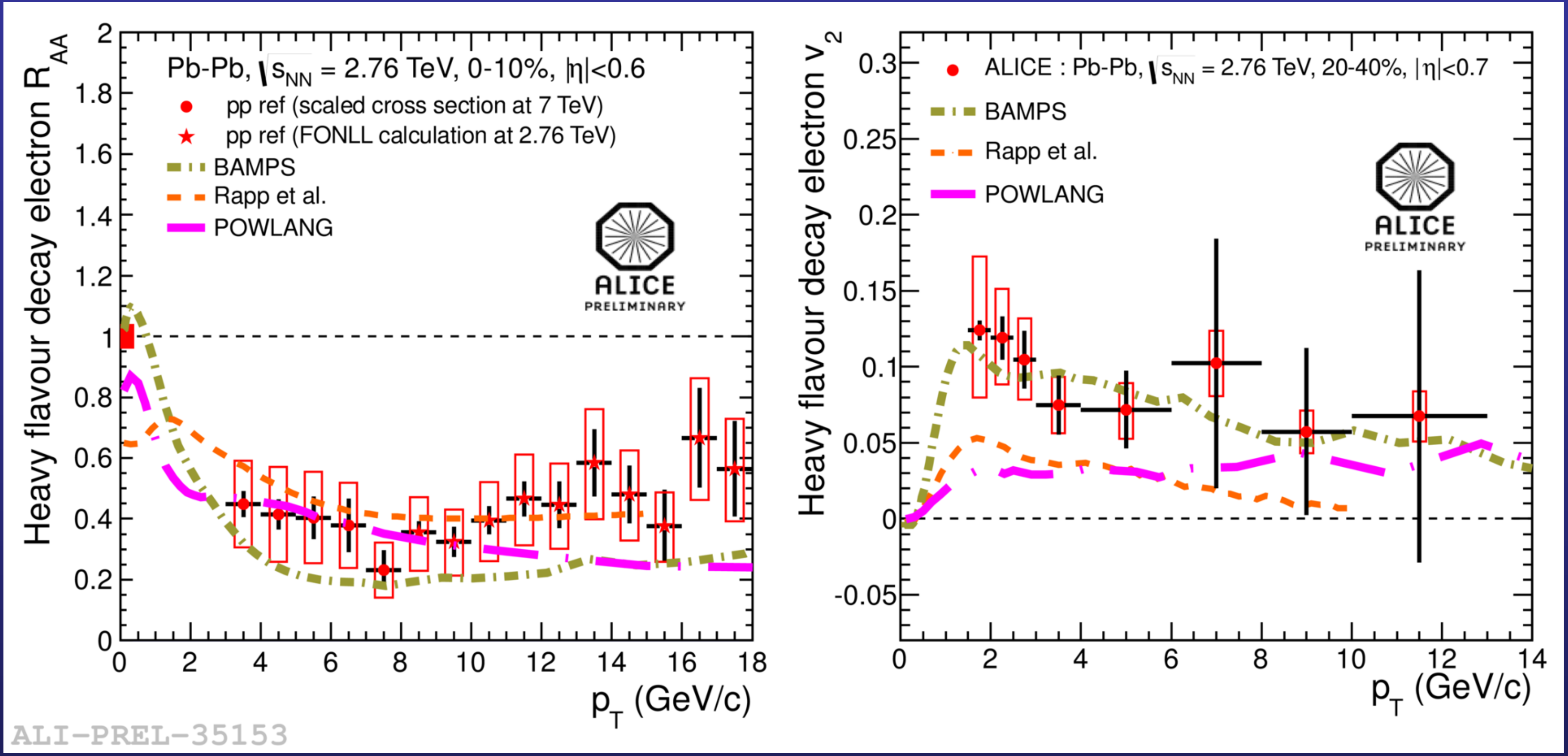


Simultaneous description of D meson R_{AA} and v_2

⬇

Challenge for theoretical models

Data vs models: HFE

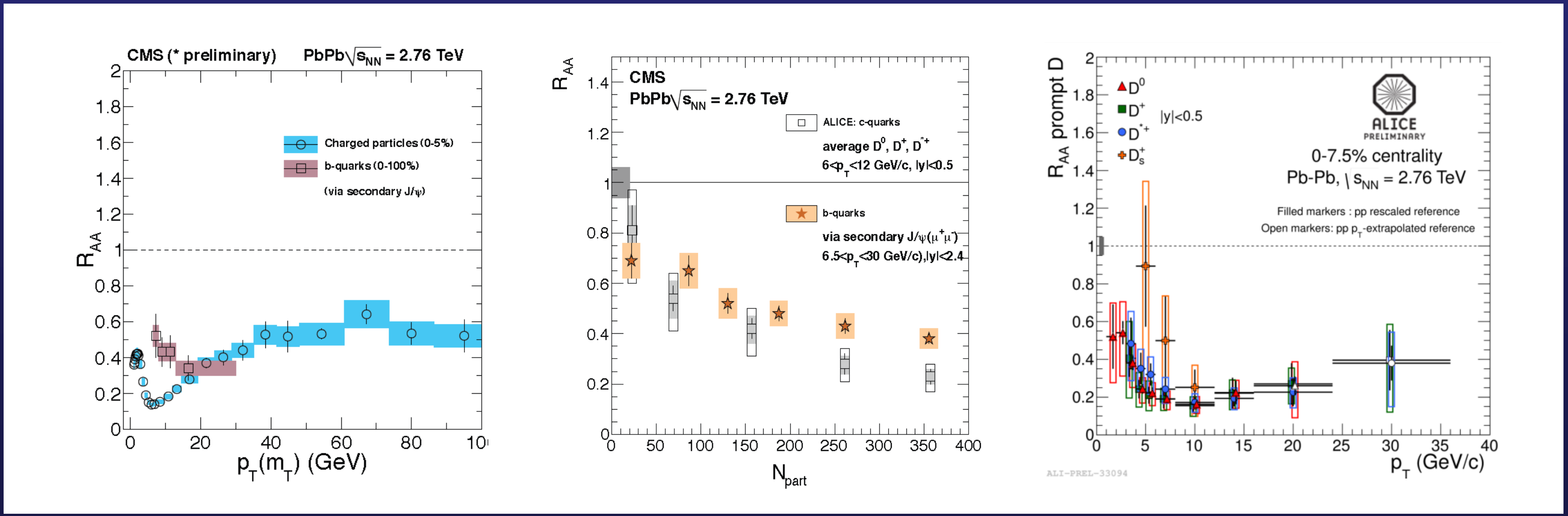


Simultaneous description of heavy-flavor electrons R_{AA} and v_2

Challenge for theoretical models

Heavy quark – where are we ?

- Abundant heavy flavour production at the LHC
  - Allow for precision measurements
- Can separate charm and beauty (vertex detectors!)
  - Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$ and $R_{AA}^{beauty} > R_{AA}^{light}$
  - More statistics needed to conclude on R_{AA}^{charm} vs. R_{AA}^{light}
- Indication (3σ) for non-zero charm elliptic flow at low p_T
- Hadrochemistry of D meson species :first intriguing result on D_s
- We need b/c in Au-Au at RHIC!



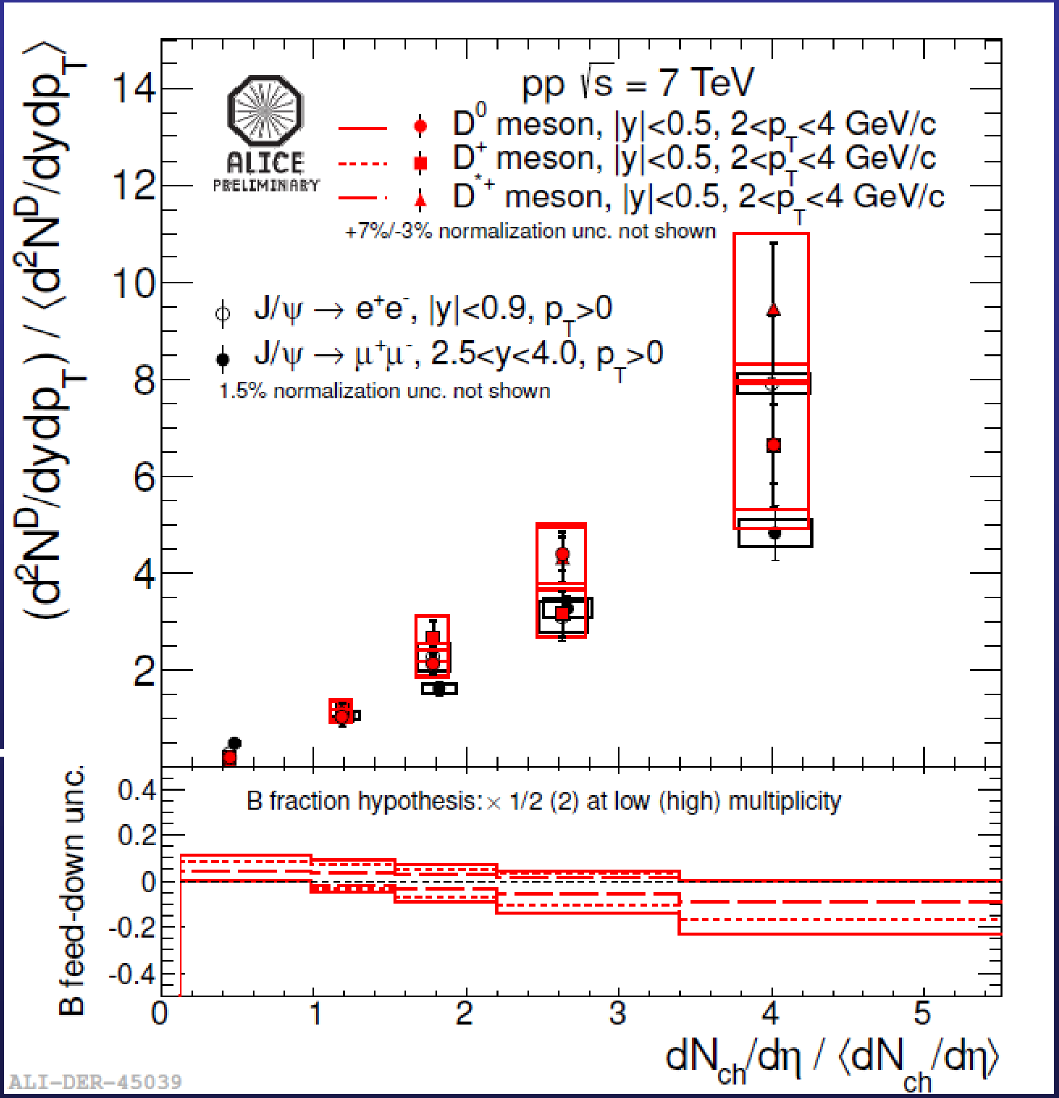
Intermezzo: multiplicity dependence of D and J/ψ yields

A. Grelli

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

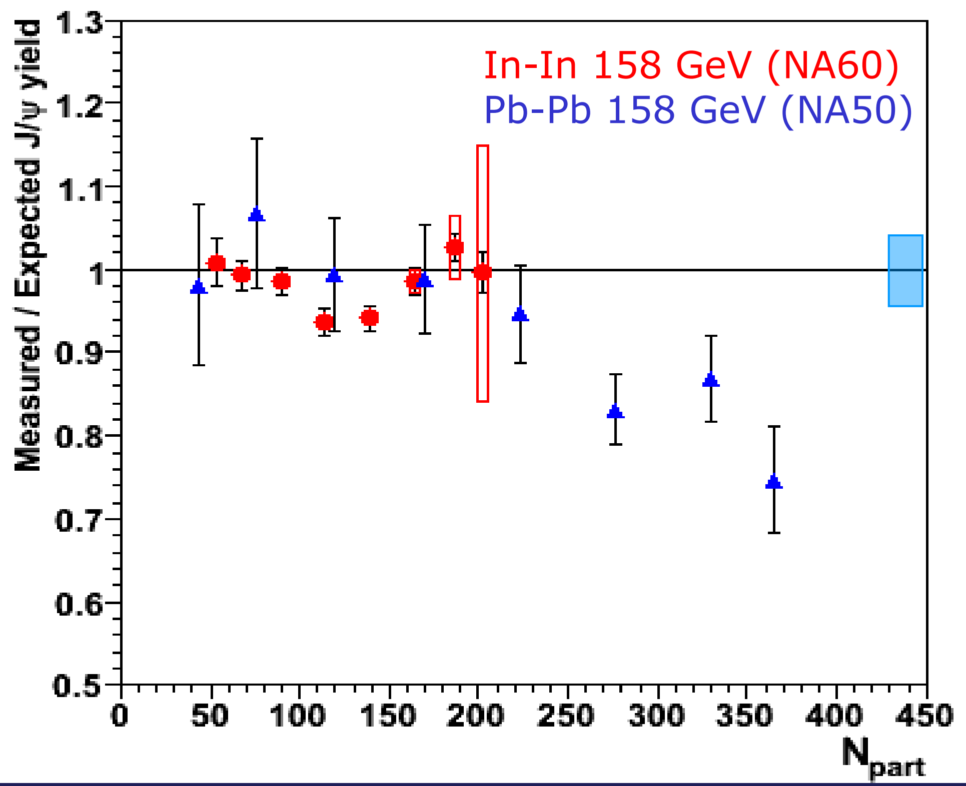
- The ~linear increase of the yields with charged multiplicities and the similar behaviour for D and J/ψ are remarkable…..

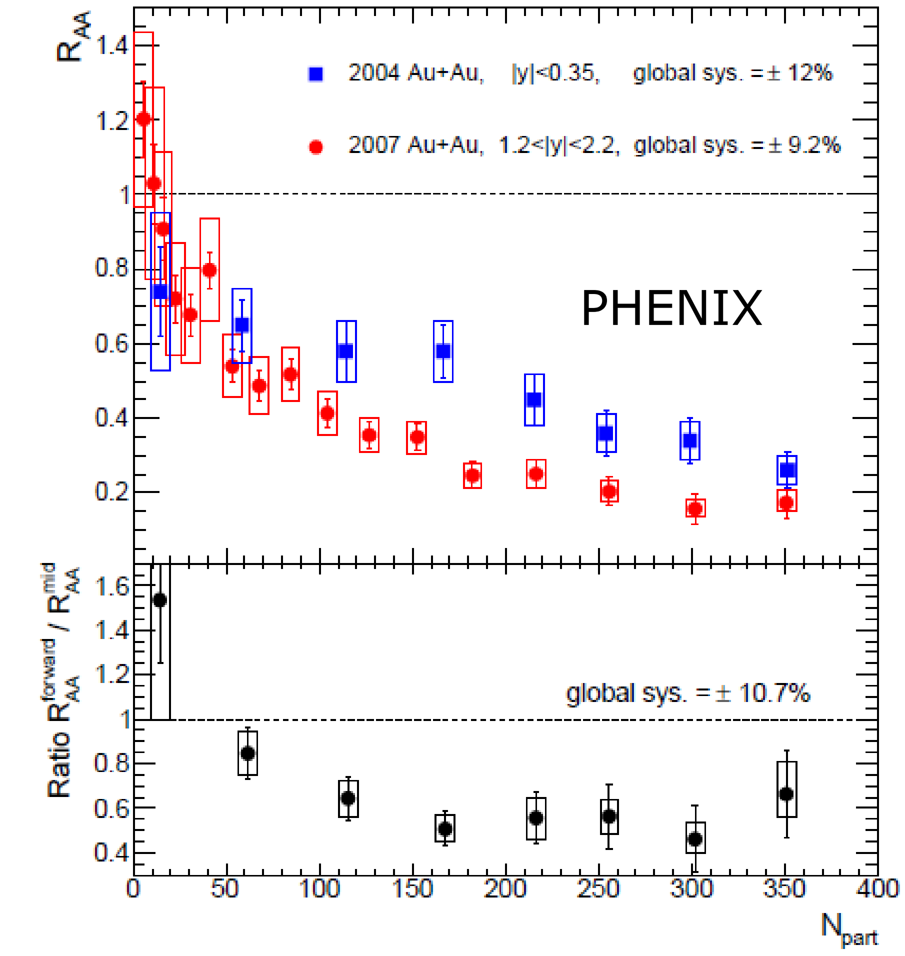
…but need to be explained!



Charmonia – the legacy

- ❑ The first "hard probe" to be extensively studied
- ❑ Several years of investigation at SPS and RHIC energies



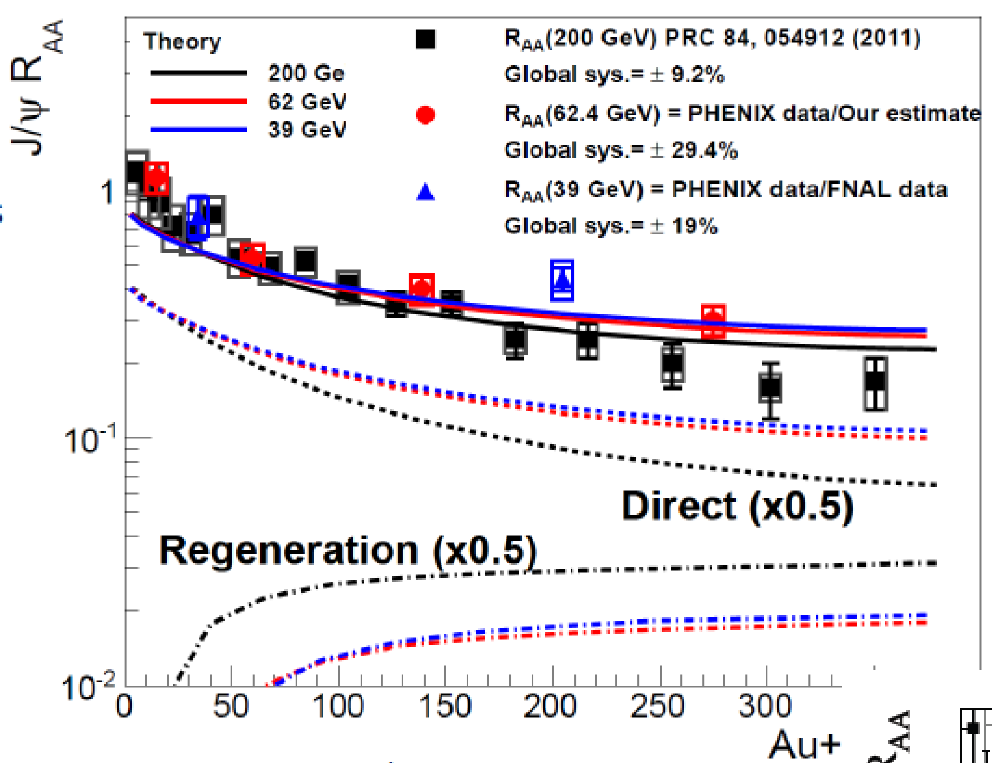


- ❑ Suppression beyond cold nuclear matter effects (firmly) established
- ❑ Role of (re)generation still under debate

Still producing new results !

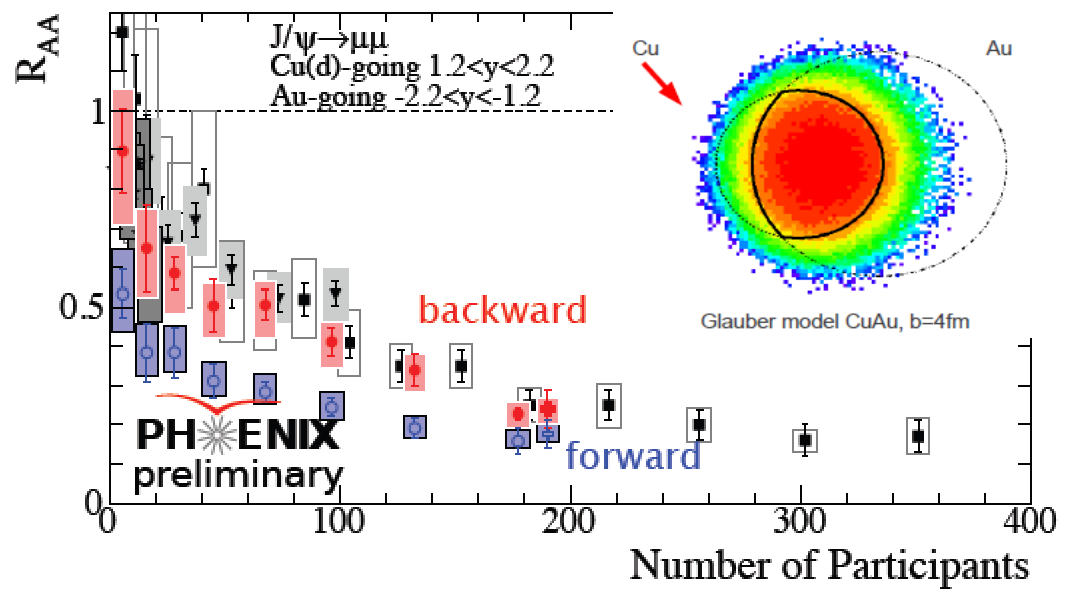
PHENIX – new systems/energies

M. Durham

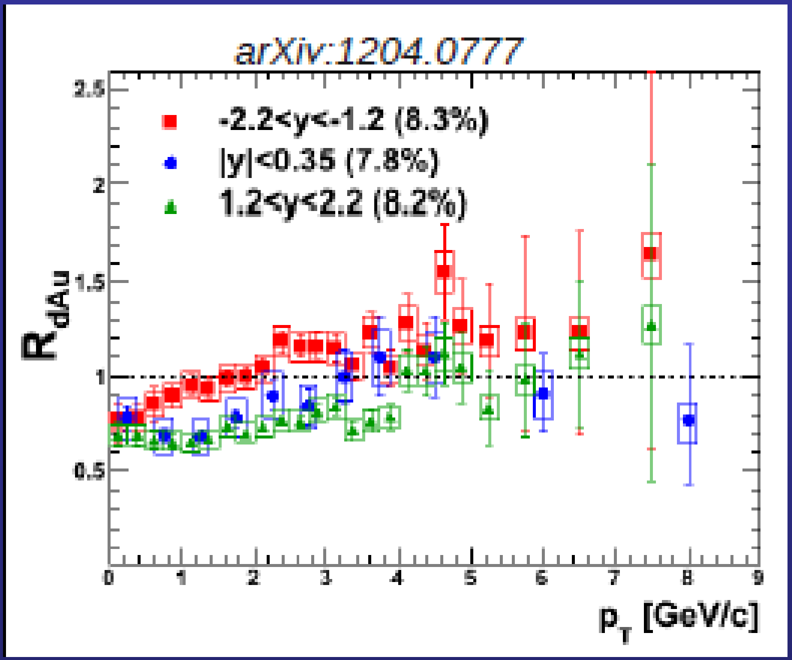


- New system (Cu-Au) at old energy: Cu-going finally different! (probably not a CNM effect)
- A challenge to theory
- SPS went the other way round (from S-U to Pb-Pb…)

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

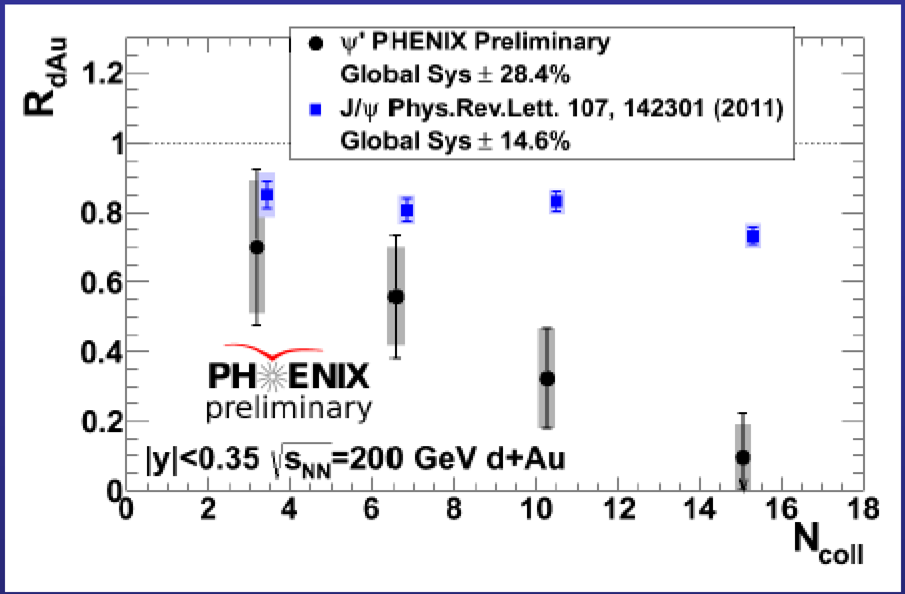


PHENIX – CNM

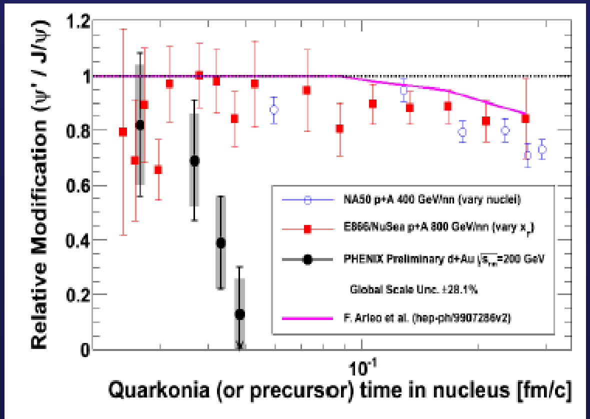


- p_T dependence of R_{dAu}
- Increase vs p_T at central/forward y
  → Reminds SPS observation
- But different behaviour at backward rapidity
- Not easy to reproduce in models!

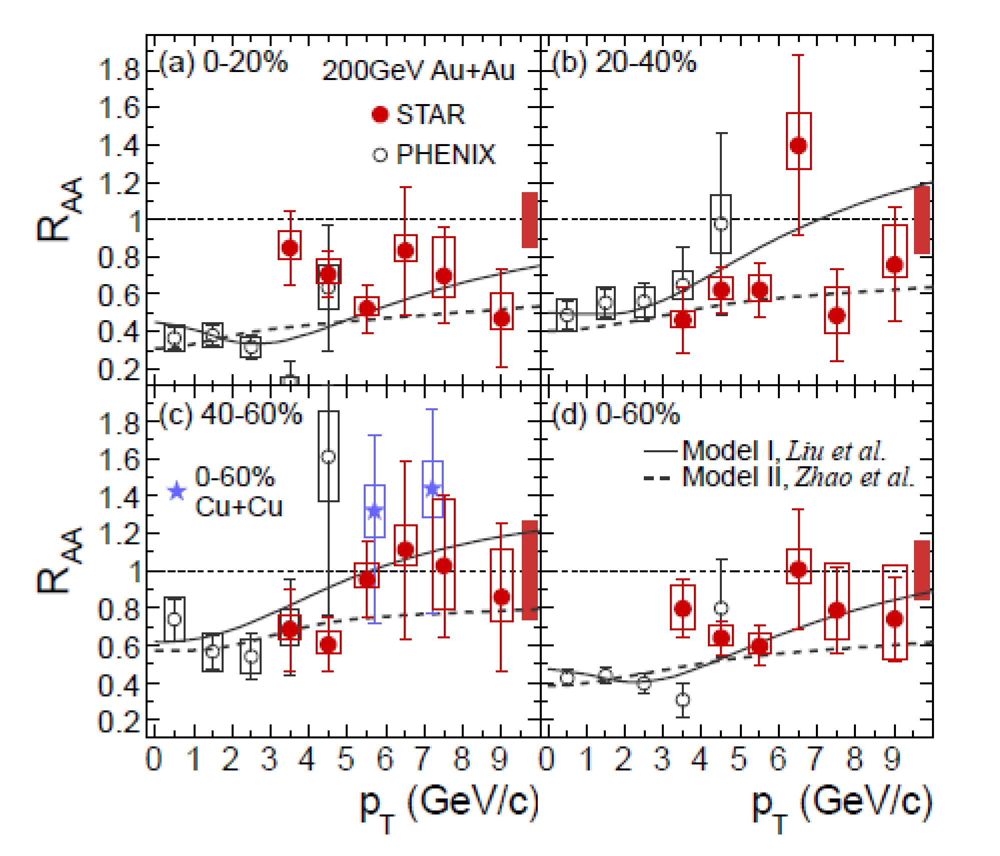
Overall picture still not clear !



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

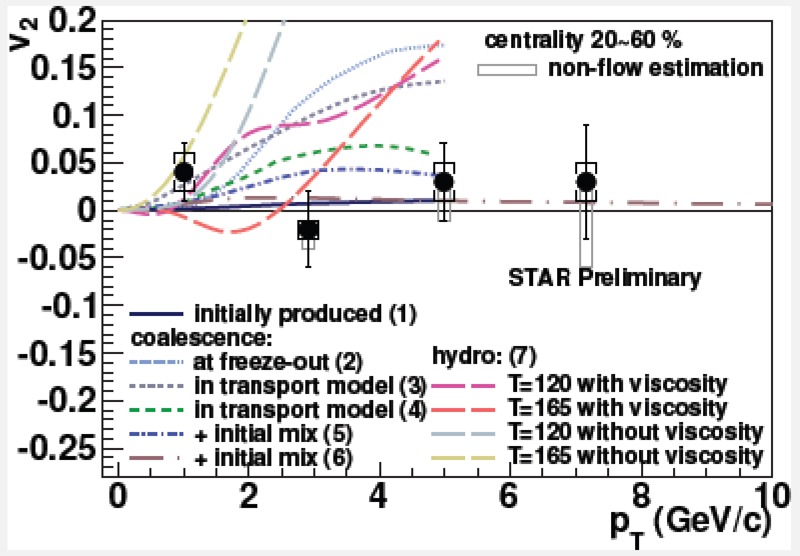


STAR – J/ψ



- STAR measures high-p_T J/ψ up to 10 GeV/c
- Fair agreement with models including color screening and recombination (the latter becomes negligible at low p_T)

- First measurement of J/ψ v_2 (will become final ?)
- Compatible with zero everywhere
- In contrast with recombination picture ?

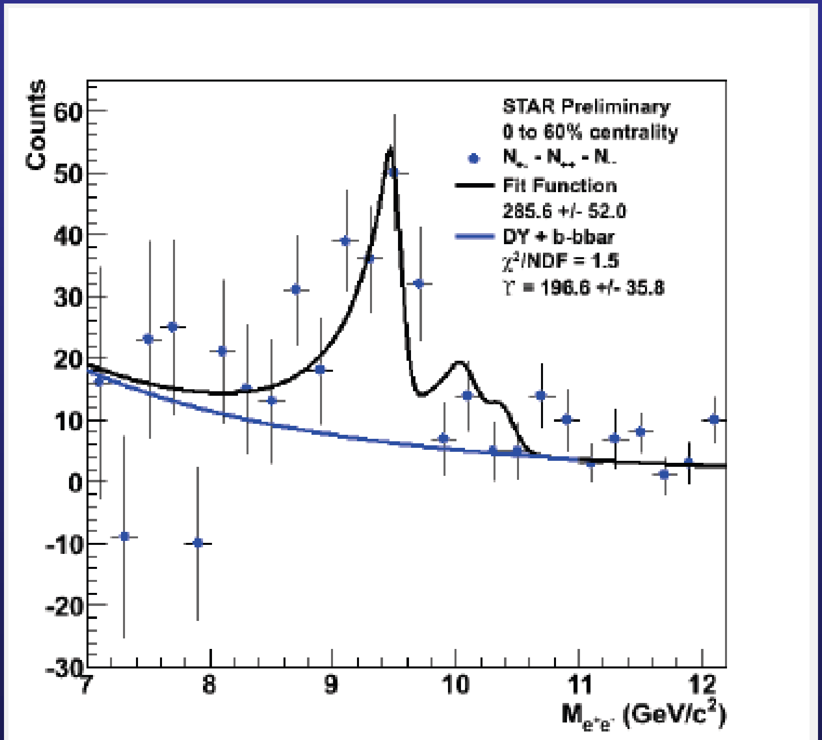


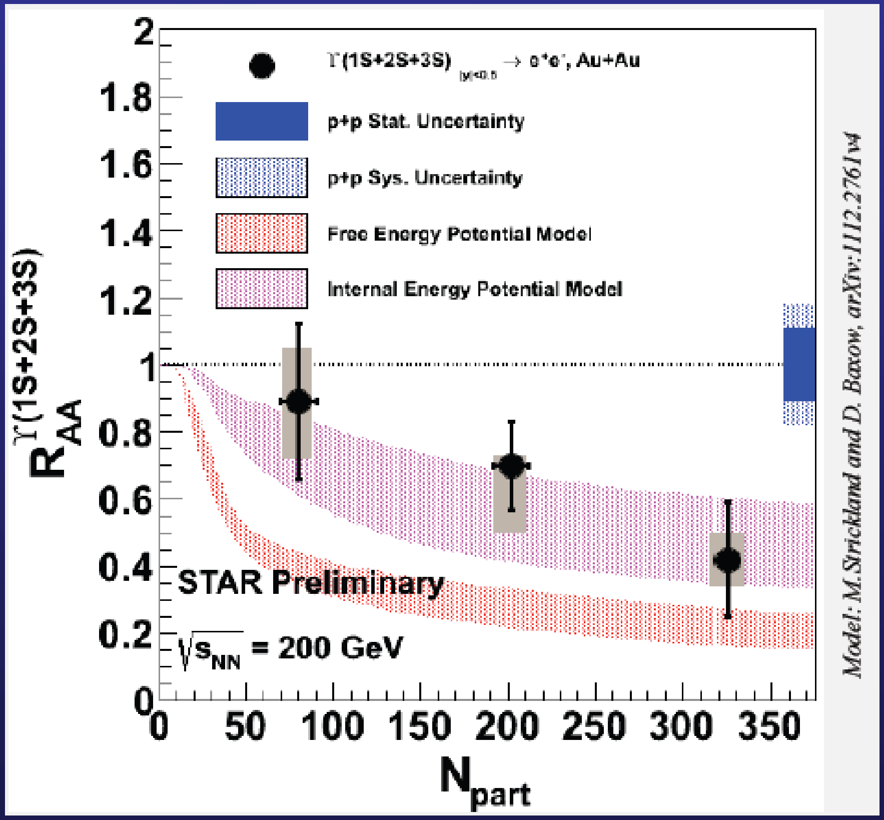
STAR - Υ

M. Calderon

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

But not that easy at RHIC!





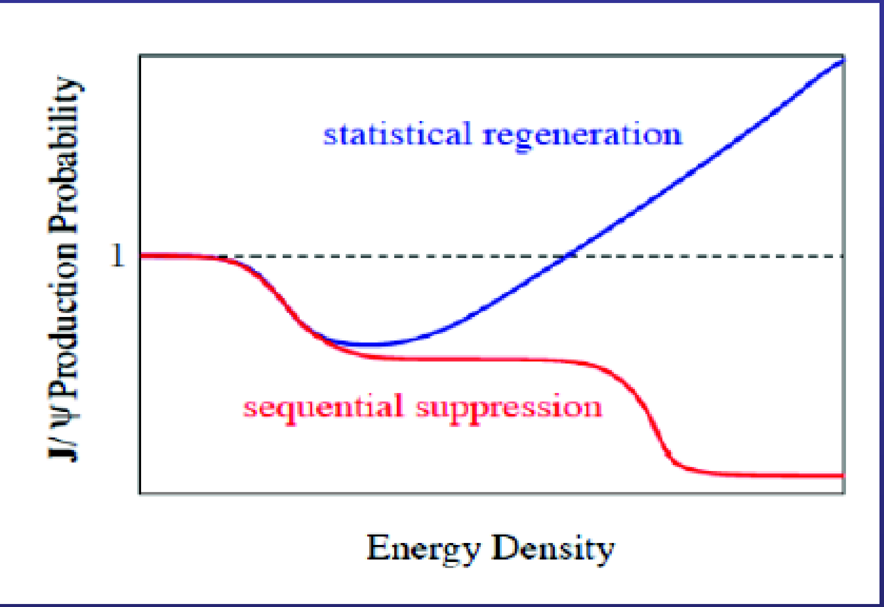
…and this has been split into 3 centrality bins….

Compatible with 3S melting and 2S partial melting

Great expectations for LHC

…along two main lines

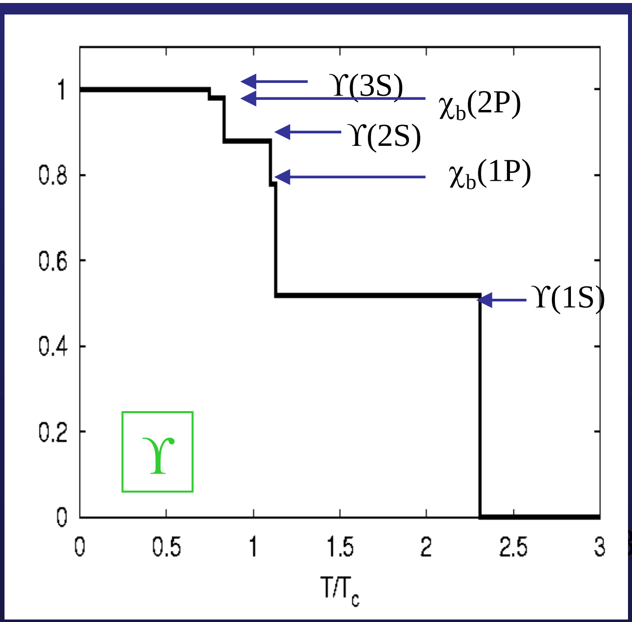
1) Evidence for charmonia (re)combination: now or never!



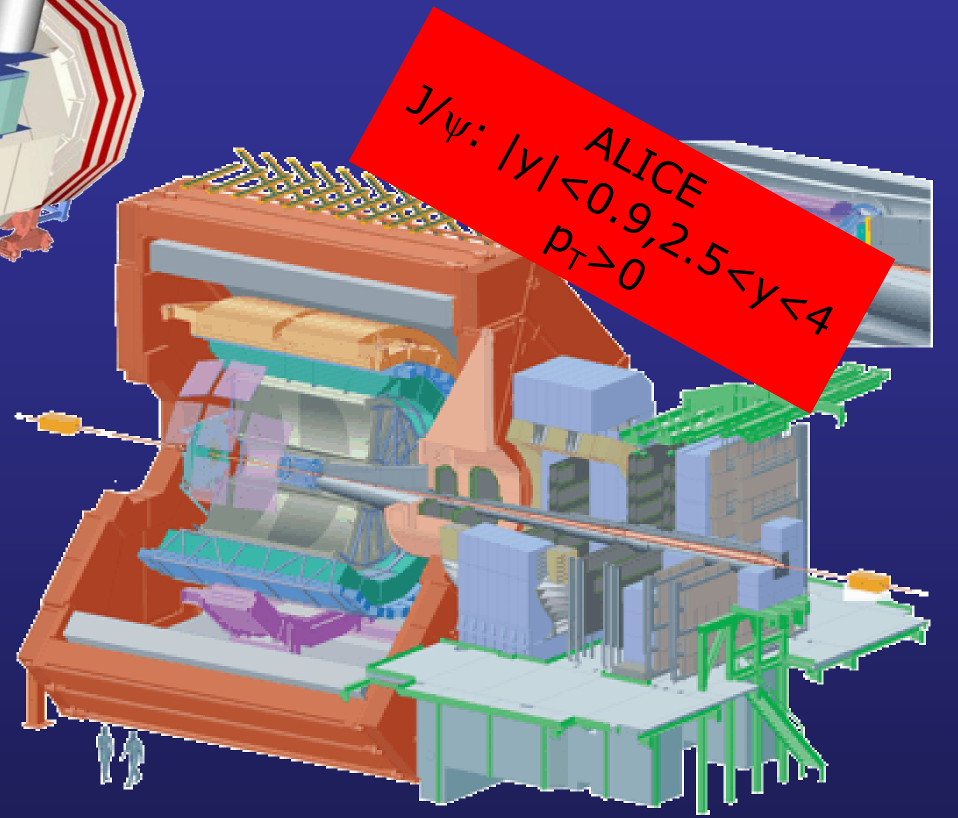
2) A detailed study of bottomonium suppression

- Finally a clean probe, as J/ψ at SPS

Yes, we can!



Once again, the main actors

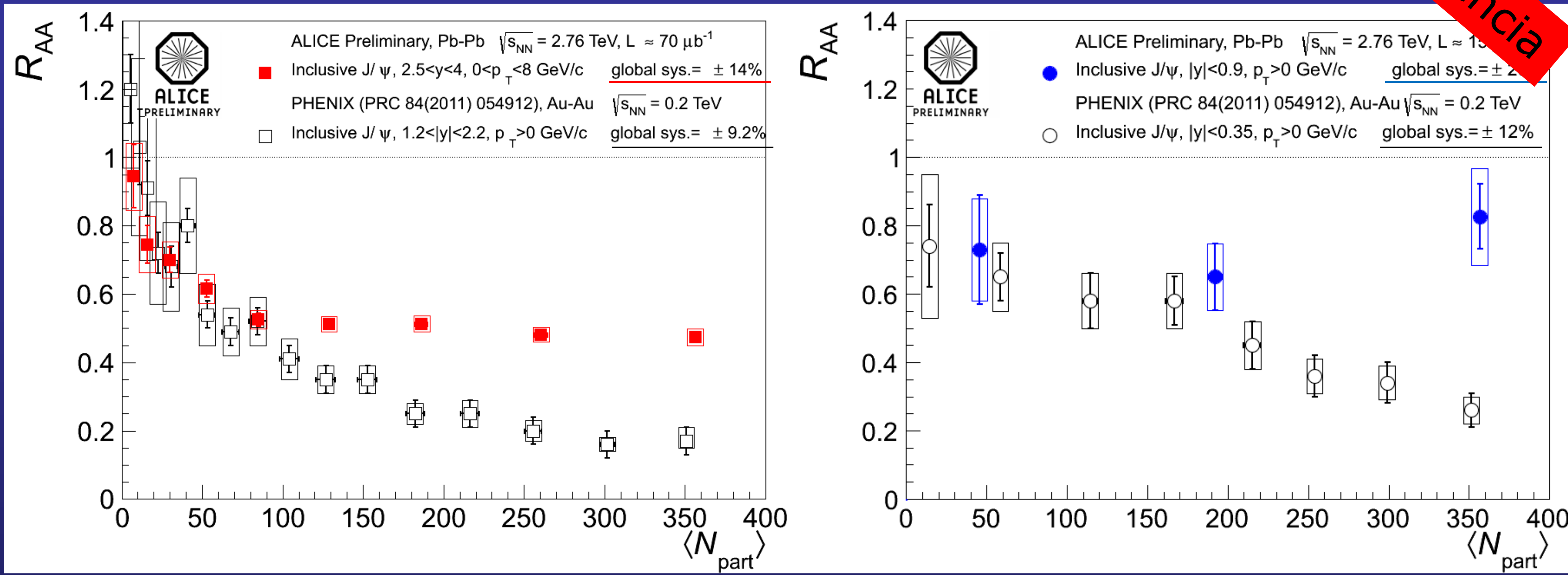


Complementary kinematic coverage!

Will LHCb join the club ?

J/ψ, ALICE probes the low p_T

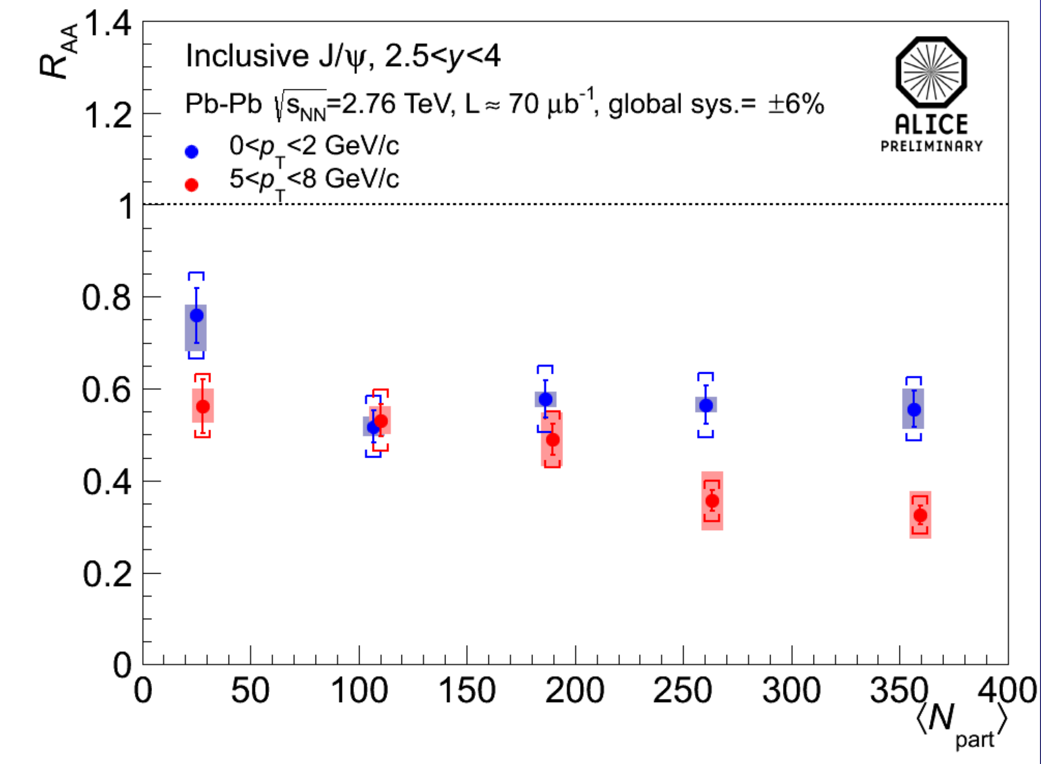
L. Valencia

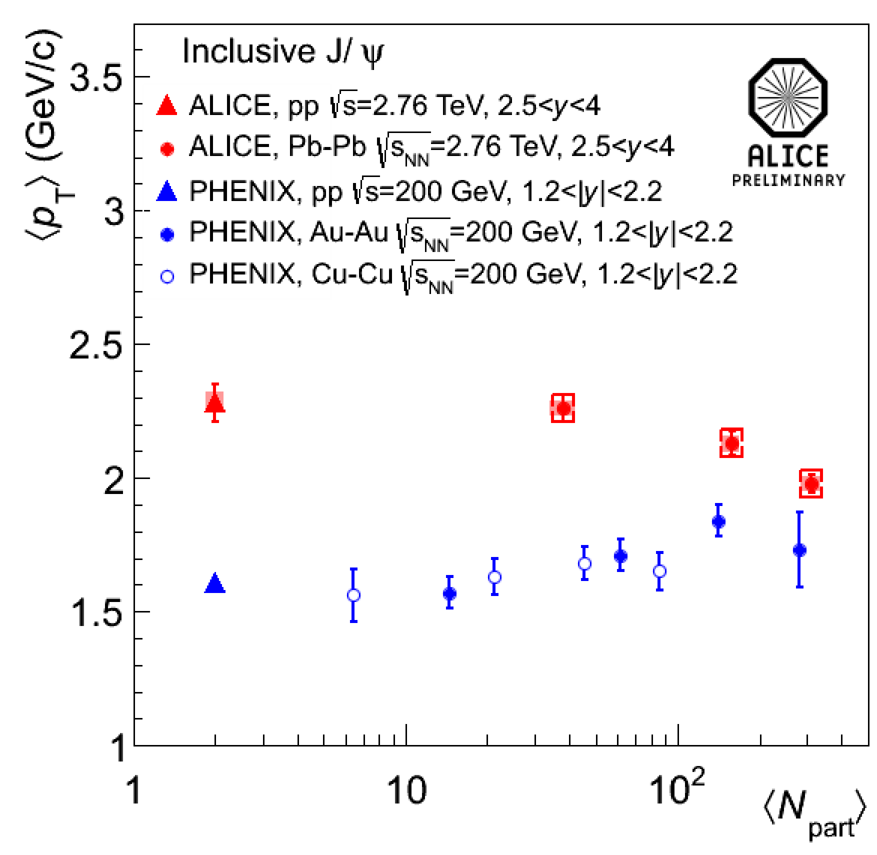


- Even at the LHC, NO rise of J/ψ yield for central events, but….
- Compare with PHENIX
  - Stronger centrality dependence at lower energy
  - Systematically larger R_{AA} values for central events in ALICE

Is this the expected signature for (re)combination ?

The p_T signature





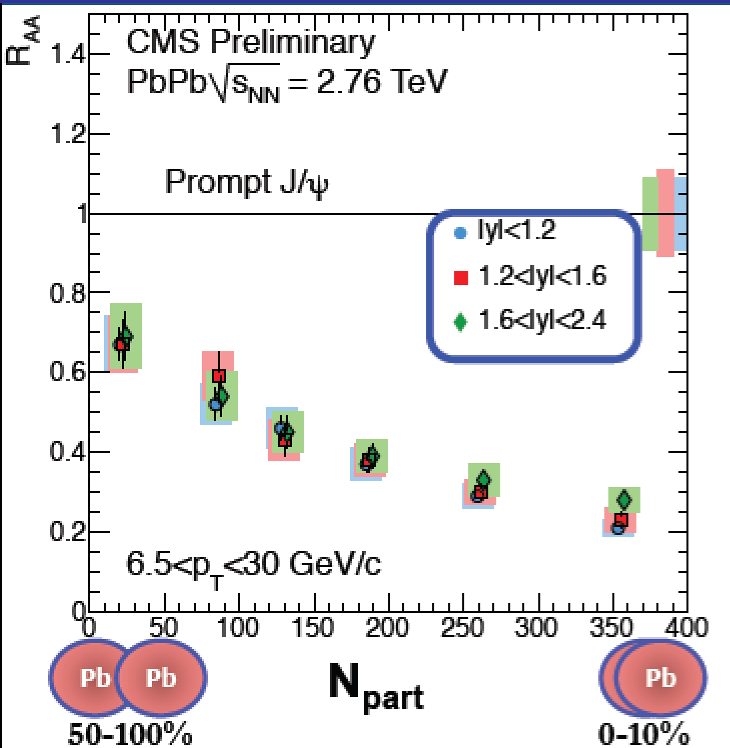
- ❑ Expect smaller suppression for low-p_T J/ψ → observed!

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

CMS explores the high p_T region

T. Dahms

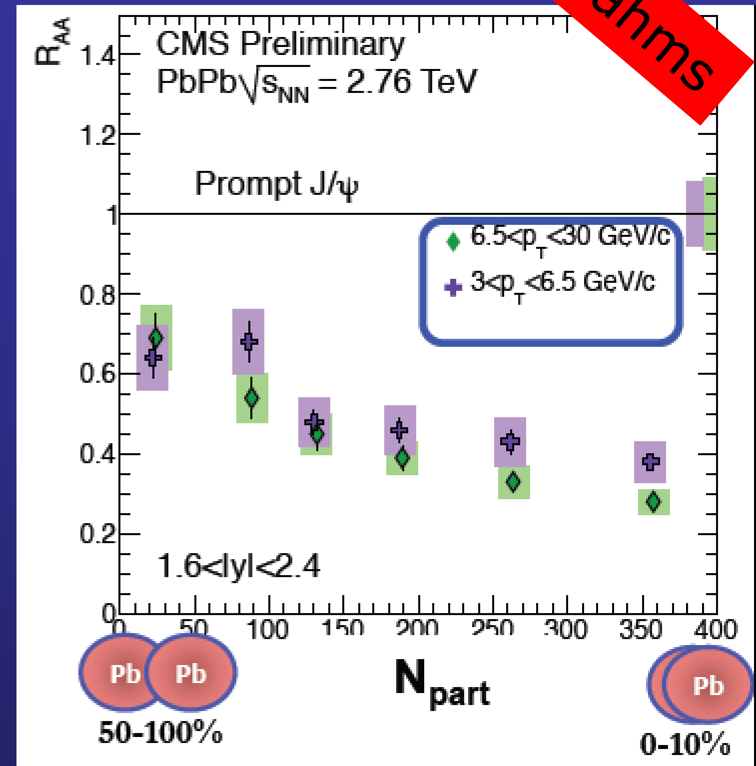


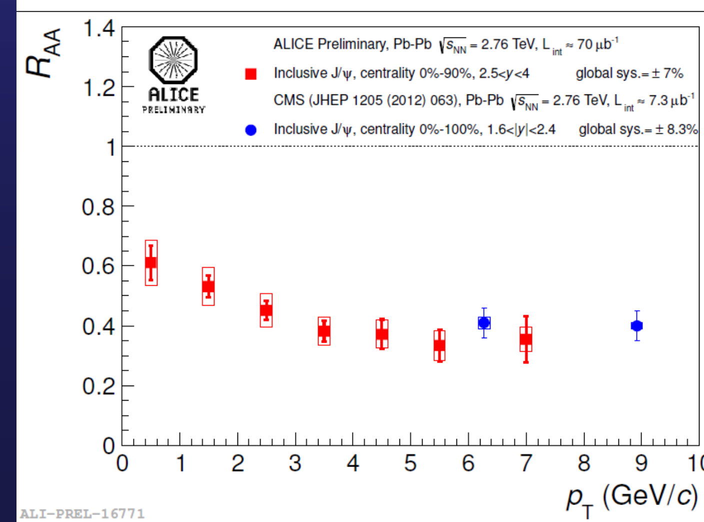
Centrality dep. in

p_T

y

bins

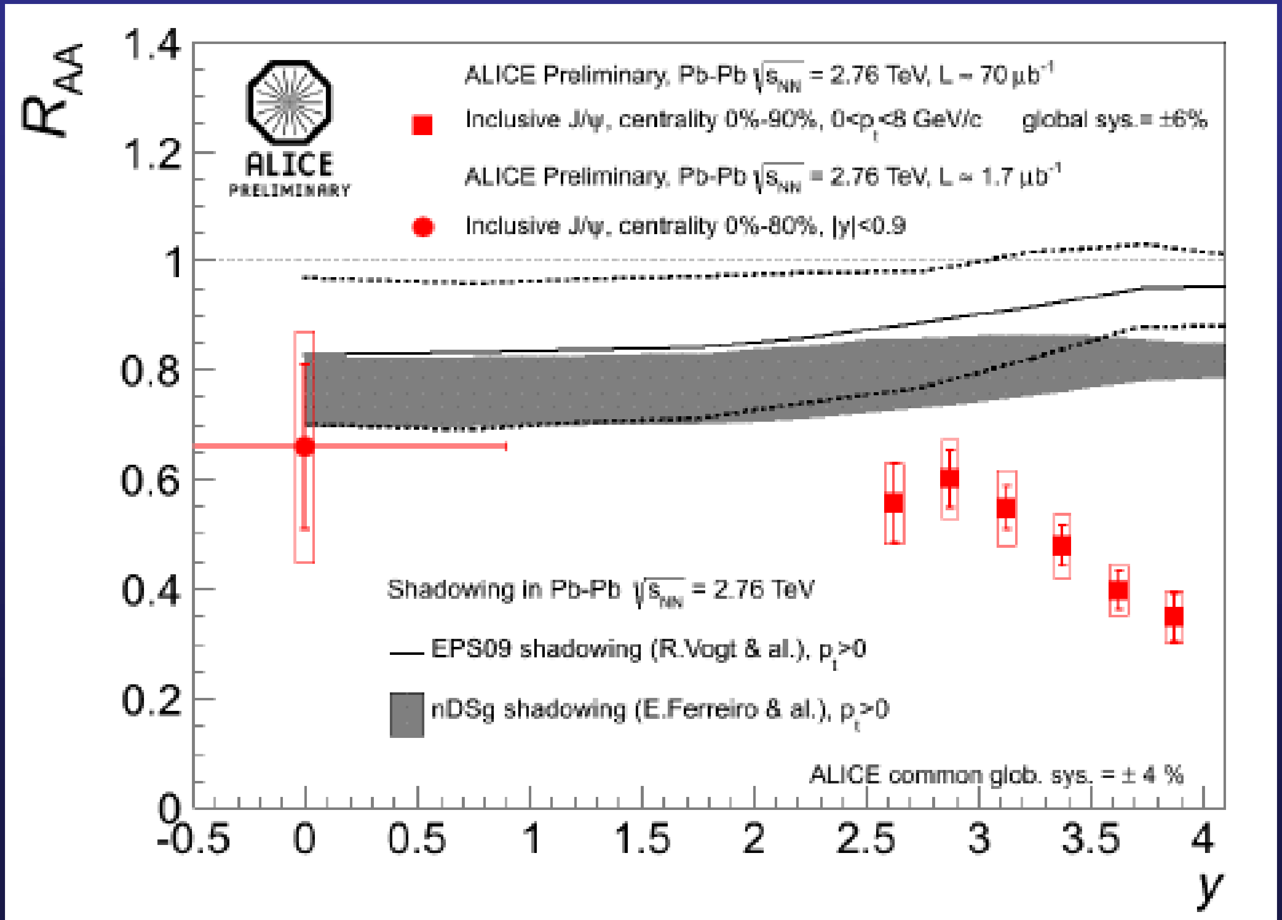




- (Maybe) we still see a hint of p_T dependence of the suppression even in the p_T range explored by CMS
- Good agreement with ALICE in spite of the different rapidity range (which anyway seems not to play a major role at high p_T)

Rapidity dependence

- Rather pronounced in ALICE, and evident in the forward region ($\sim$40% decrease in R_{AA} in $2.5<y<4$)
- More difficult to conclude between mid- and forward-rapidity
- Not so pronounced at high p_T (see CMS, previous slide)
- PHENIX-like ??



Shadowing estimate (EPS09, nDSg)

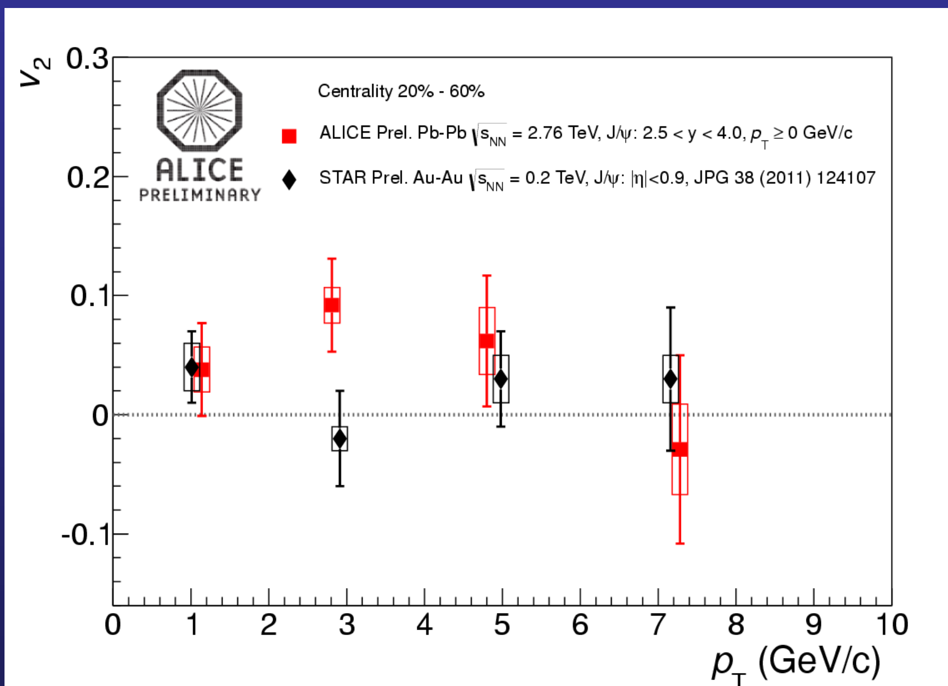
Compatible with central, NOT with forward y

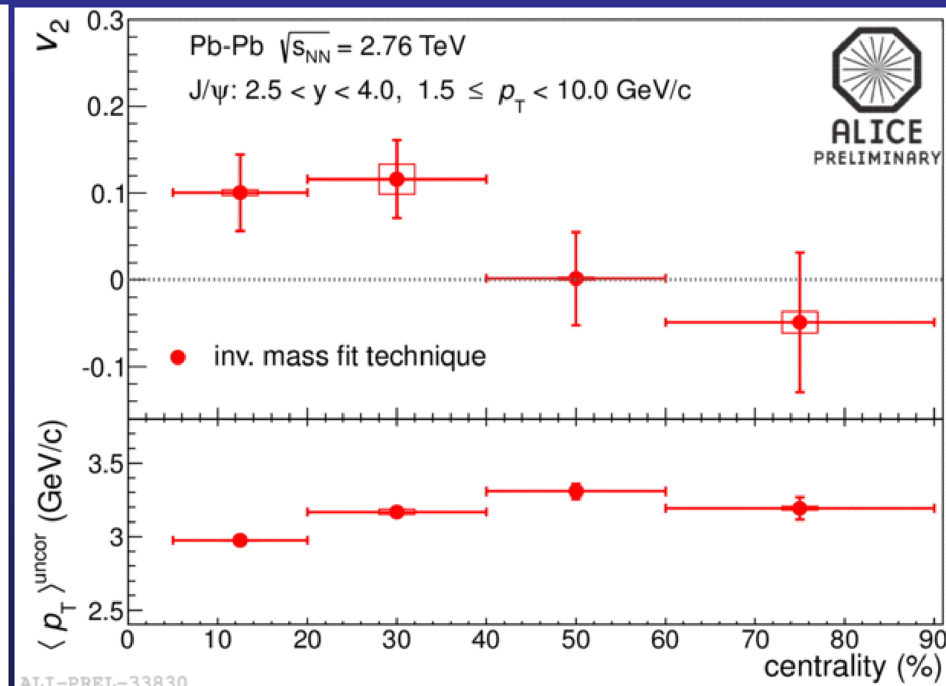
More general CNM issue

Does the J/ψ finally flow ?

I. Das

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

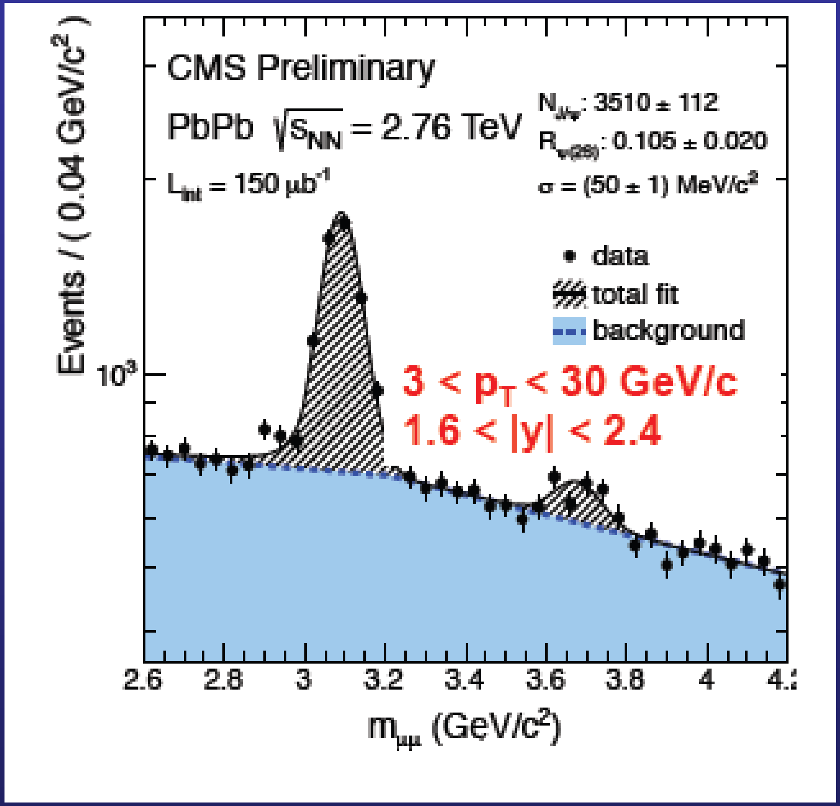


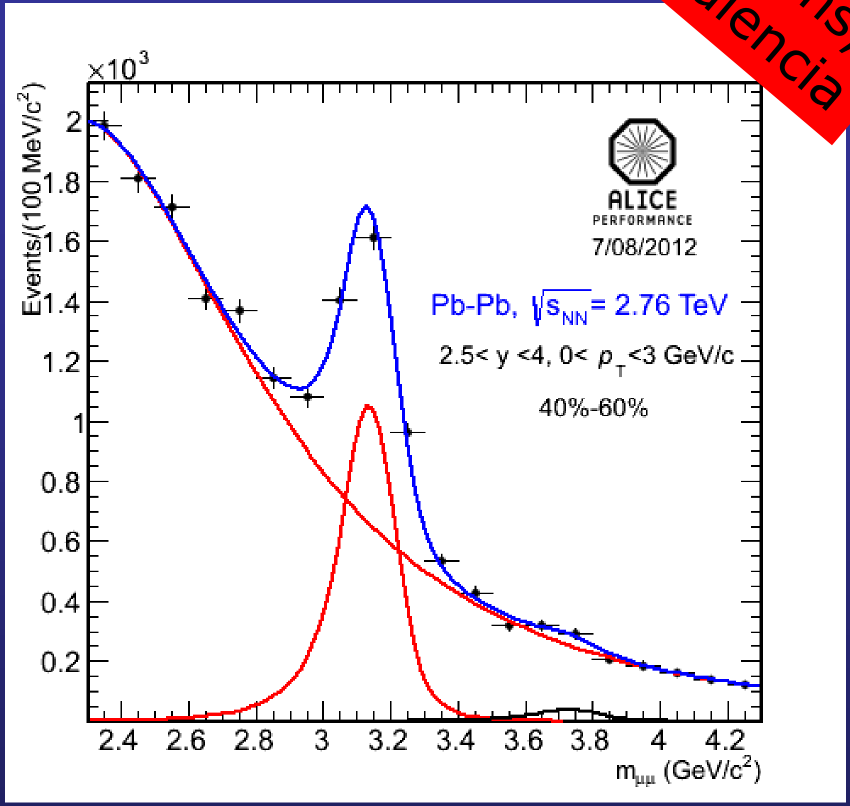


- First hint for J/ψ flow in heavy-ion collisions (ALICE, forward y) !
- Significance up to 3.5 σ for chosen kinematic/centrality selections
- Qualitative agreement with transport models including regeneration
- Note new result from PHENIX: hint for non-zero at p_T~3.5 GeV/c ?

ψ(2S): CMS vs ALICE

T. Dahms,
L. Valencia

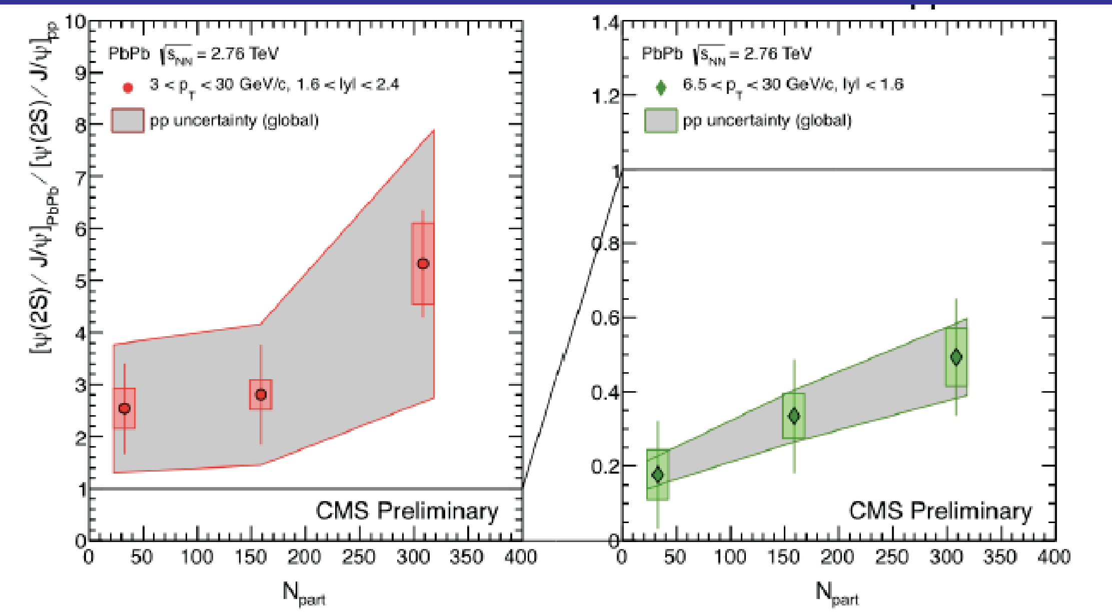


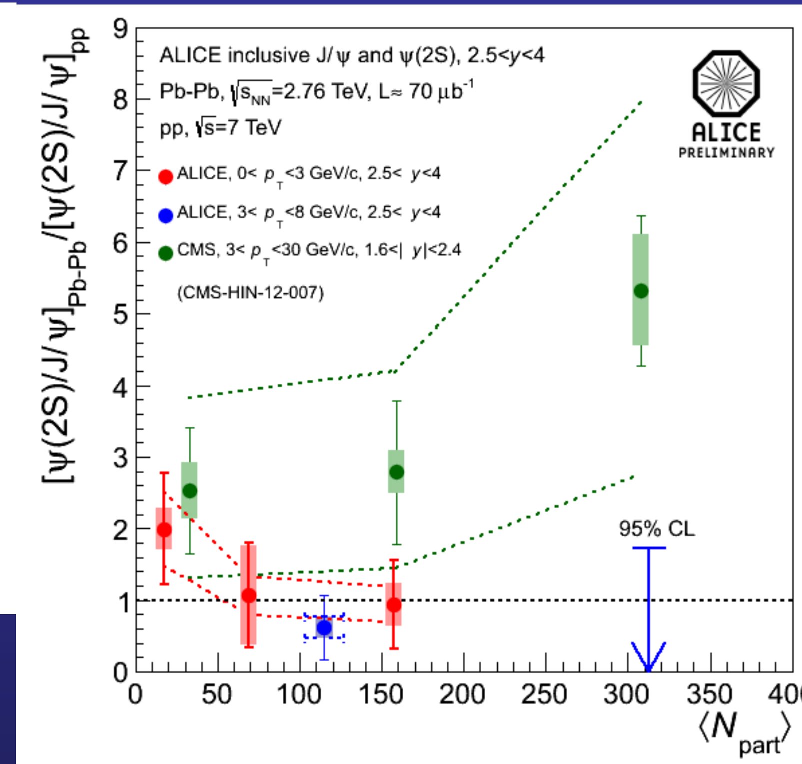


- ψ(2S) much less bound than J/ψ
- Results from the SPS showed a larger suppression than for J/ψ (saturating towards central events ? One of the landmarks of stat. model)
- No results from RHIC in Au-Au
- Seen by both CMS (much better resolution!) and ALICE, different kinem.

Expectations for LHC ?

Enhancement/suppression ?





- ❑ CMS: transition from strong (relative) enhancement to suppression in a relatively narrow p_T range

ALICE excludes a large enhancement

- ❑ At SPS, the suppression increased with centrality (the opposite for CMS)
- ❑ Overall interpretation is challenging
- ❑ ALICE vs CMS: should we worry? Probably not, seen the size of the errors
- ❑ Large uncertainties: signal extraction, pp reference
- ❑ Work needed to reduce systematics

Finally, the Υ

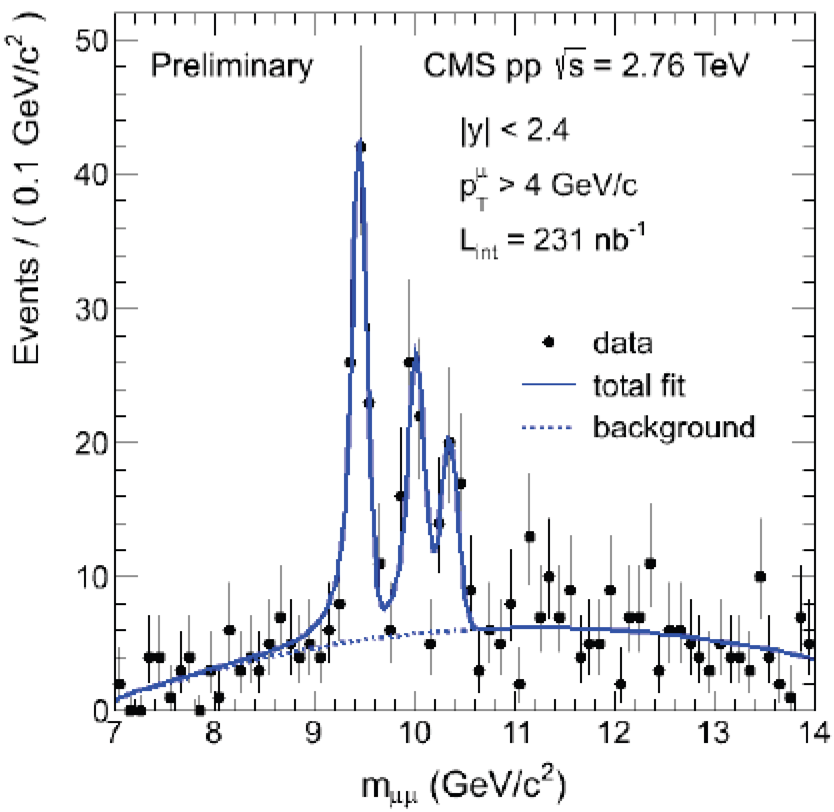
T. Dahms

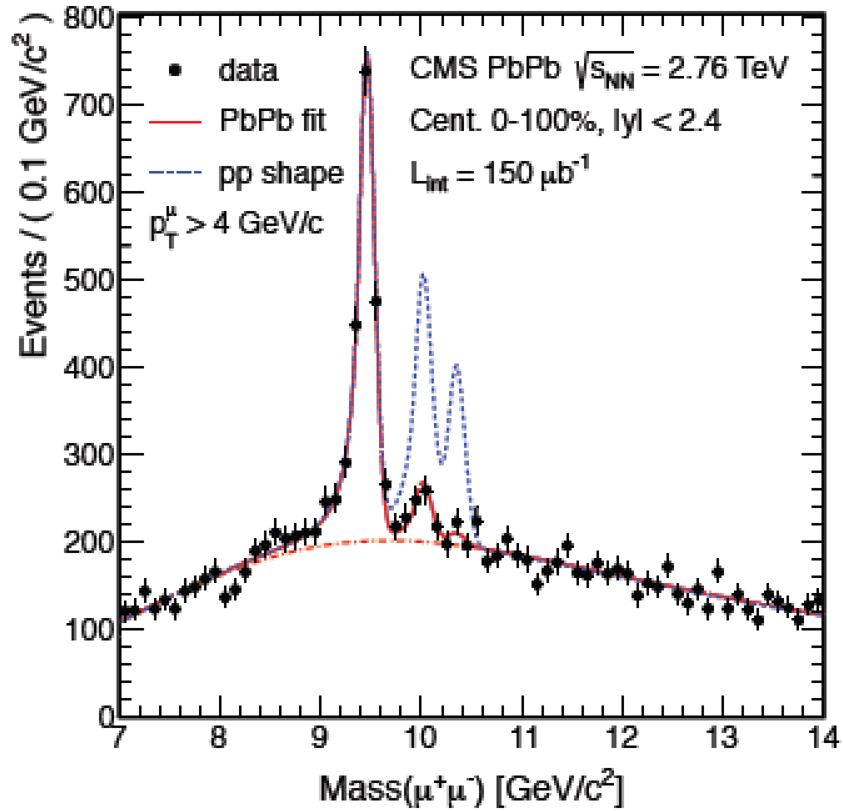
- LHC is really the machine for studying bottomonium in AA collisions (and CMS the best suited experiment to do that!)

pp

CMS-HIN-11-011

PbPb





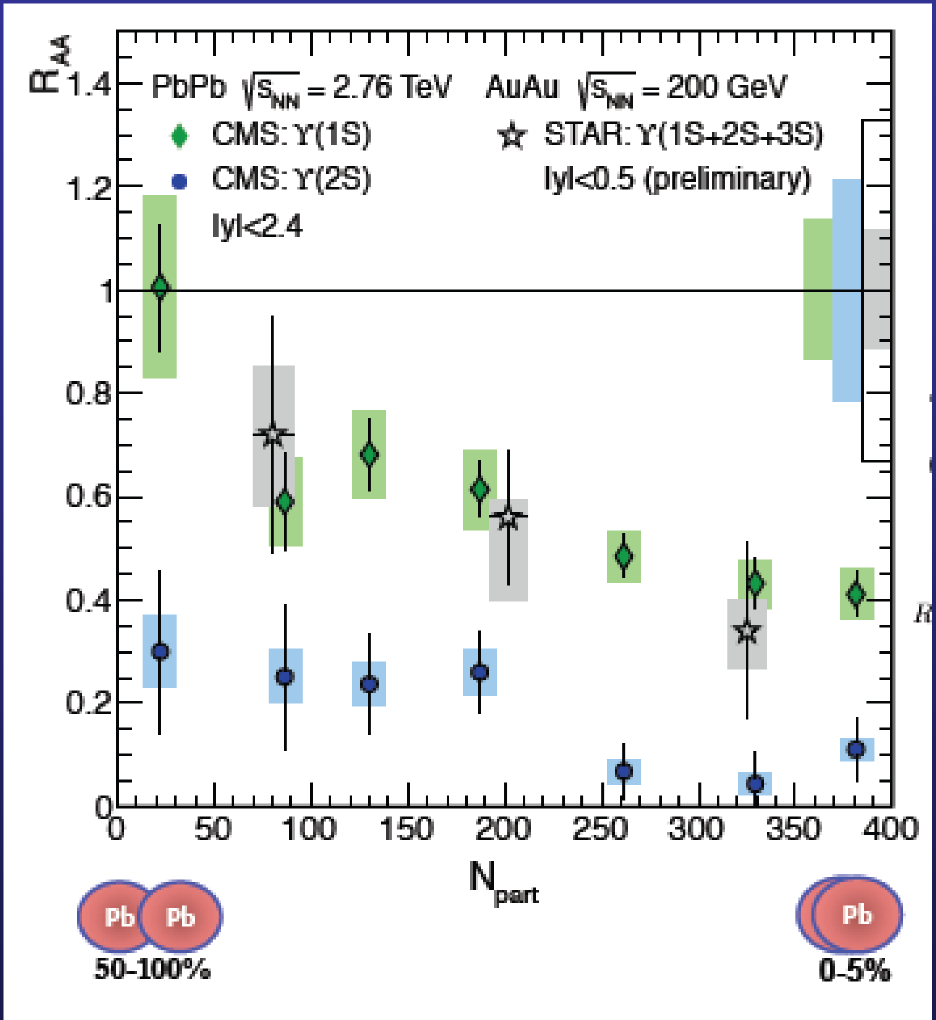
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

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

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

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

First accurate determination of Υ suppression

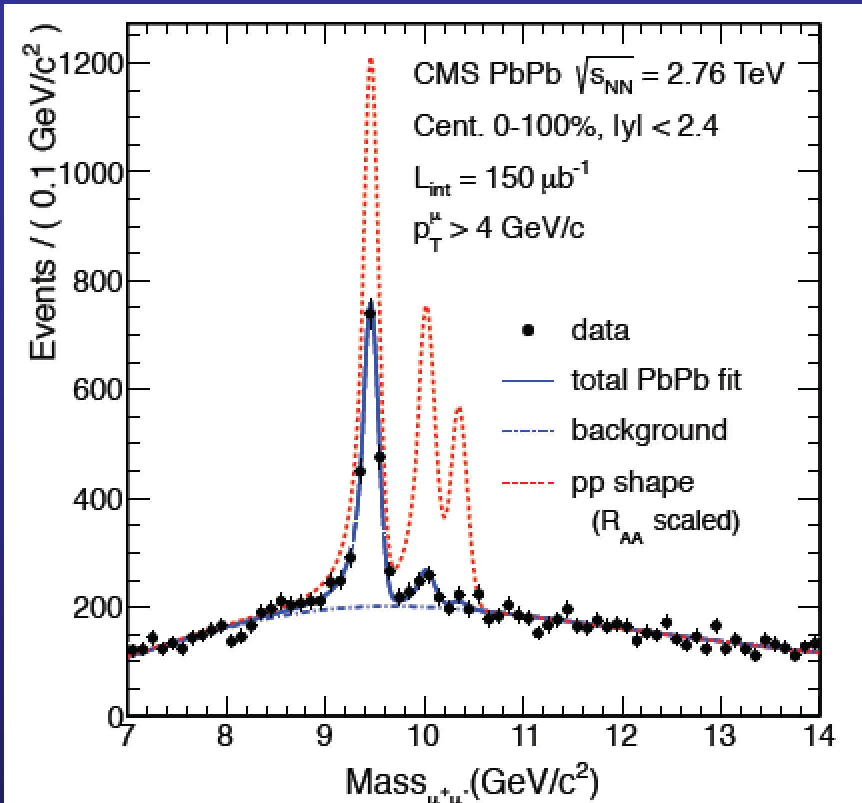


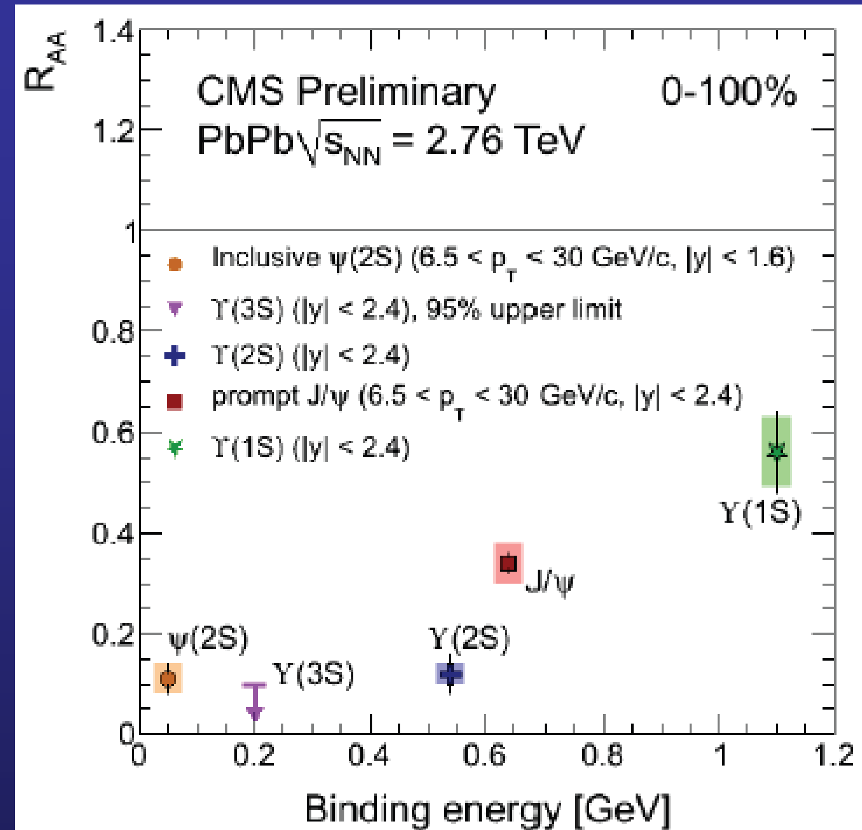
- Suppression increases with centrality
- First determination of Υ(2S) R_{AA}: already suppressed in peripheral collisions
- Υ(1S) compatible with only feed-down suppression ?

→ Probably yes, also taking into account the normalization uncertainty

Compatible with STAR (but large uncorrelated errors): expected ?
Is Υ(1S) dissoc. threshold still beyond LHC reach ? → Full energy

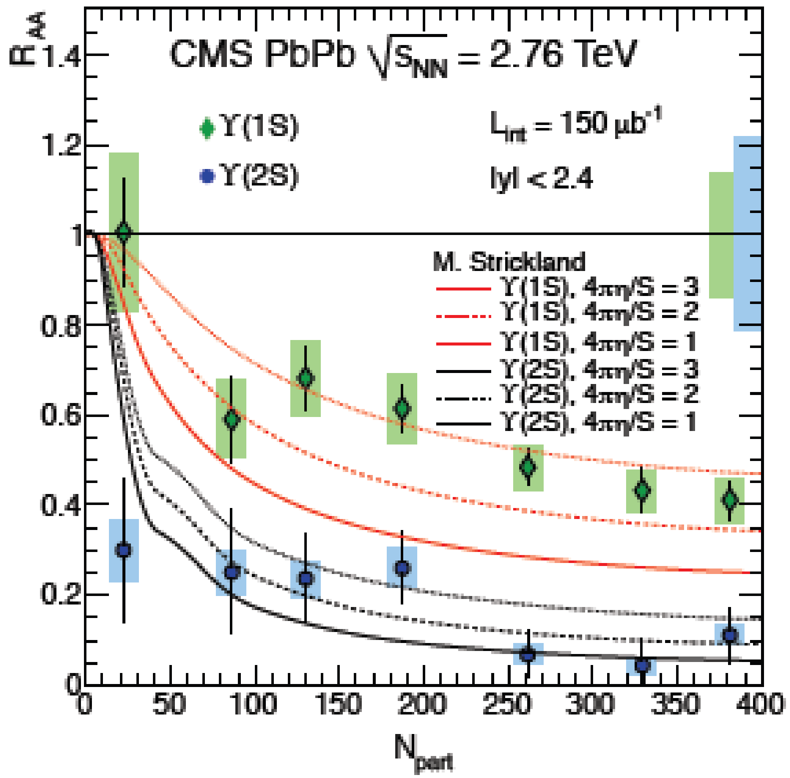
What did we learn ?



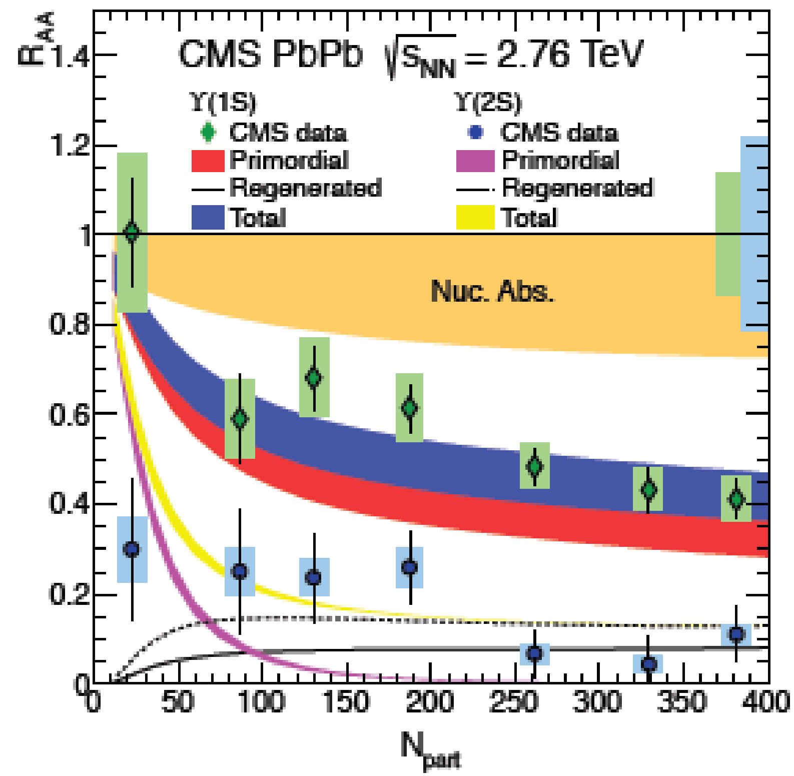


- 26 years after first suppression prediction, this is observed also in the bottomonium sector with a very good accuracy
- R_{AA} vs binding energy qualitatively interesting: can different p_T coverage be seen as a way to “kill” recombination ?

Hints from theory



Strickland arXiv:1207.5327



Rapp et al. EPJ A48 (2012) 72

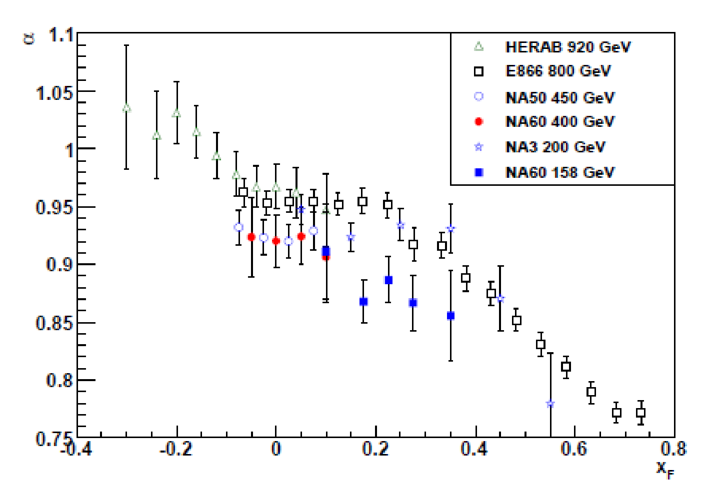
- Theory is on the data ! Fair agreement, but….
  - … one model has no CNM, no regeneration
  - …the other one has both CNM and regeneration

Still too early to claim a satisfactory understanding ?

CNM: will pA help ?

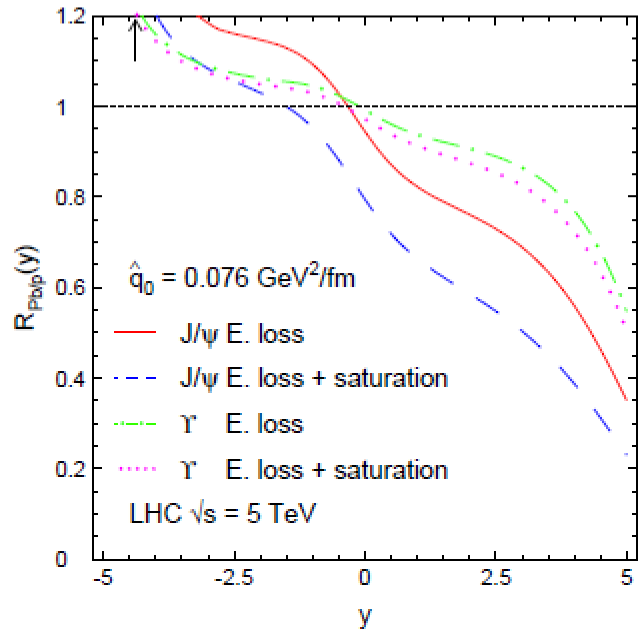
- ❑ In principle, yes !
- ❑ In practice, it is often difficult to
  - ❑ Understand the results
  - ❑ Use them to calculate CNM for AA

SPS



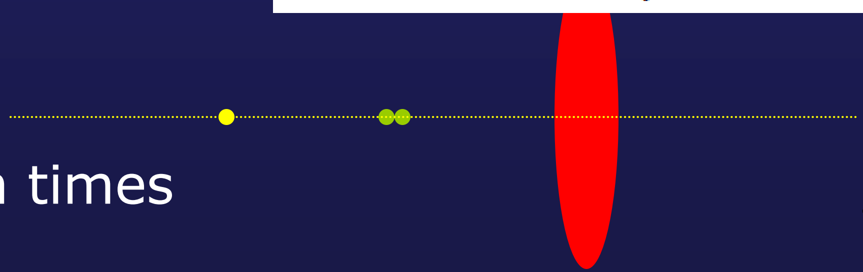
RHIC

- ❑ Do not forget alternative pictures (S. Peigne)! Might be proved/disproved in a few months!



- ❑ We might be a bit more lucky at LHC s become the only CNM effect

- ❑ Crossing times ~10^{-3} fm/c
- ❑ Much smaller than formation times



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

- 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 need 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

See you…

..in a few months from now at the "in media" session of the QWG workshop !
Beijing, April 22-26, 2013

We will extend the topics to include open charm/beauty results in media

Thank you !!!