LHC results on open heavy quarks and quarkonia

Heavy quarks and quarkonia in thermal QCD

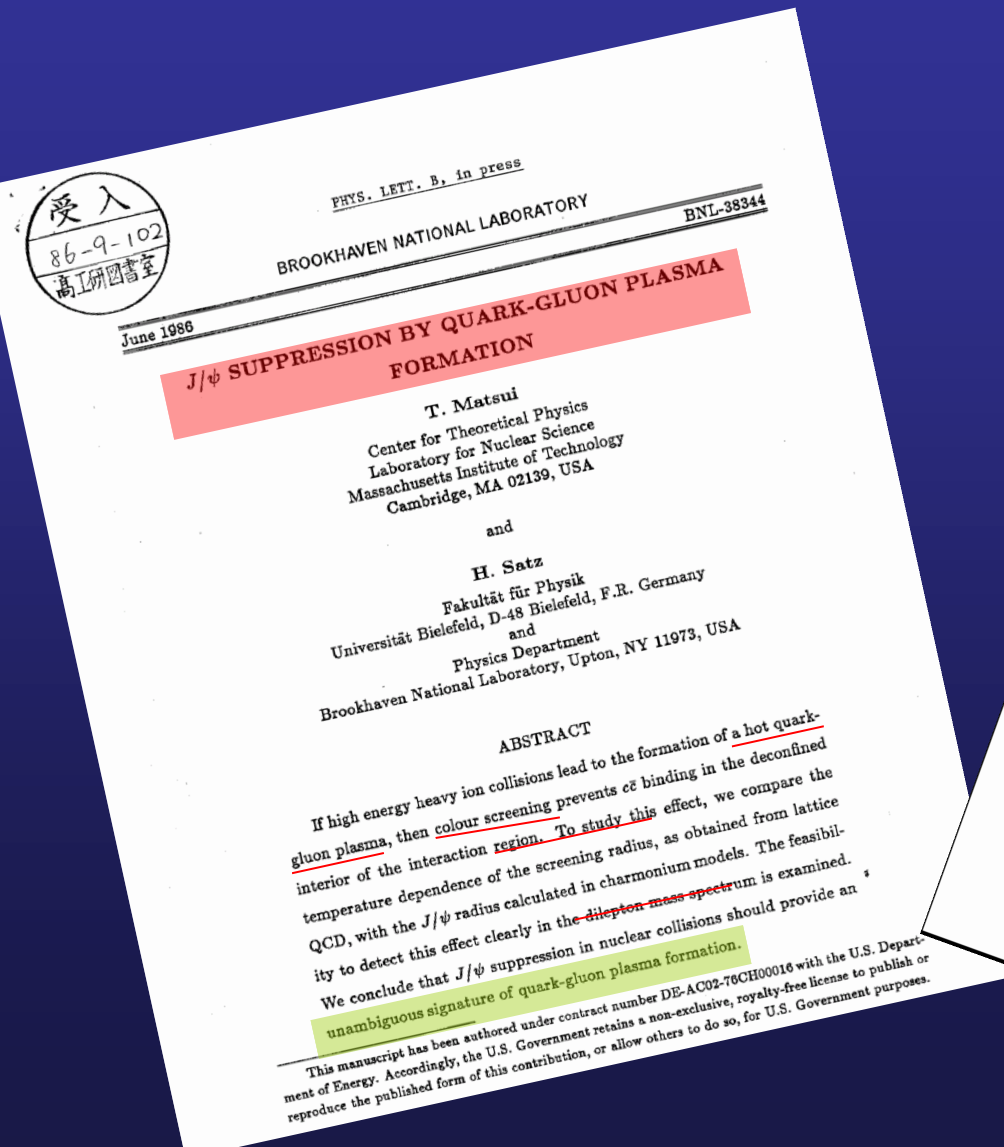
Trento, 2-5 April 2013

E. Scomparin (INFN-Torino)

ECT* European Centre for Theoretical Studies in Nuclear Physics and Related Areas

A new episode of a long story….

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


PHYS. LETT. B, in press

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June 1986

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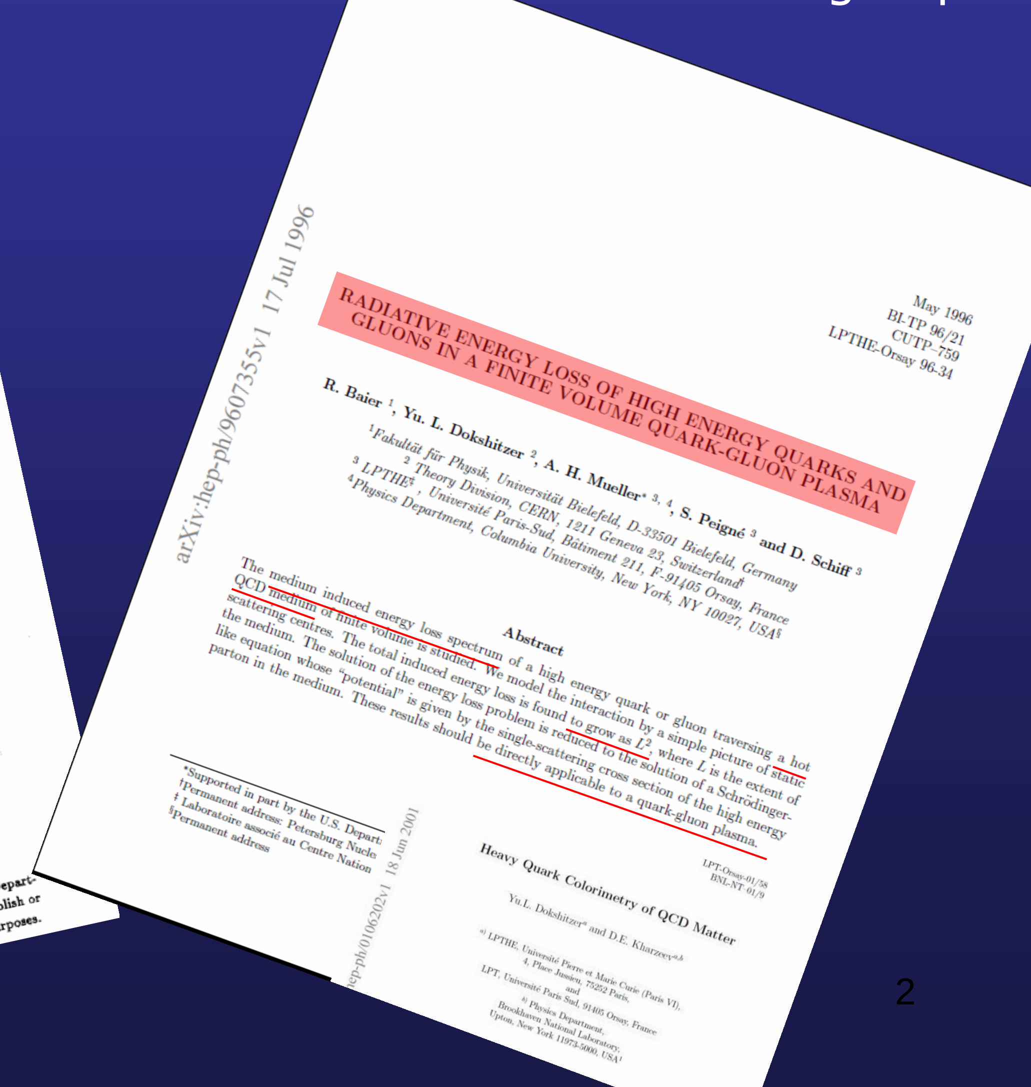
… 17 years after the prediction of radiative energy loss by the BDMPS group


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

arXiv:hep-ph/9607355v1 17 Jul 1996

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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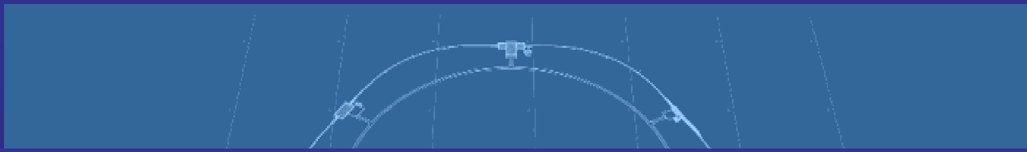
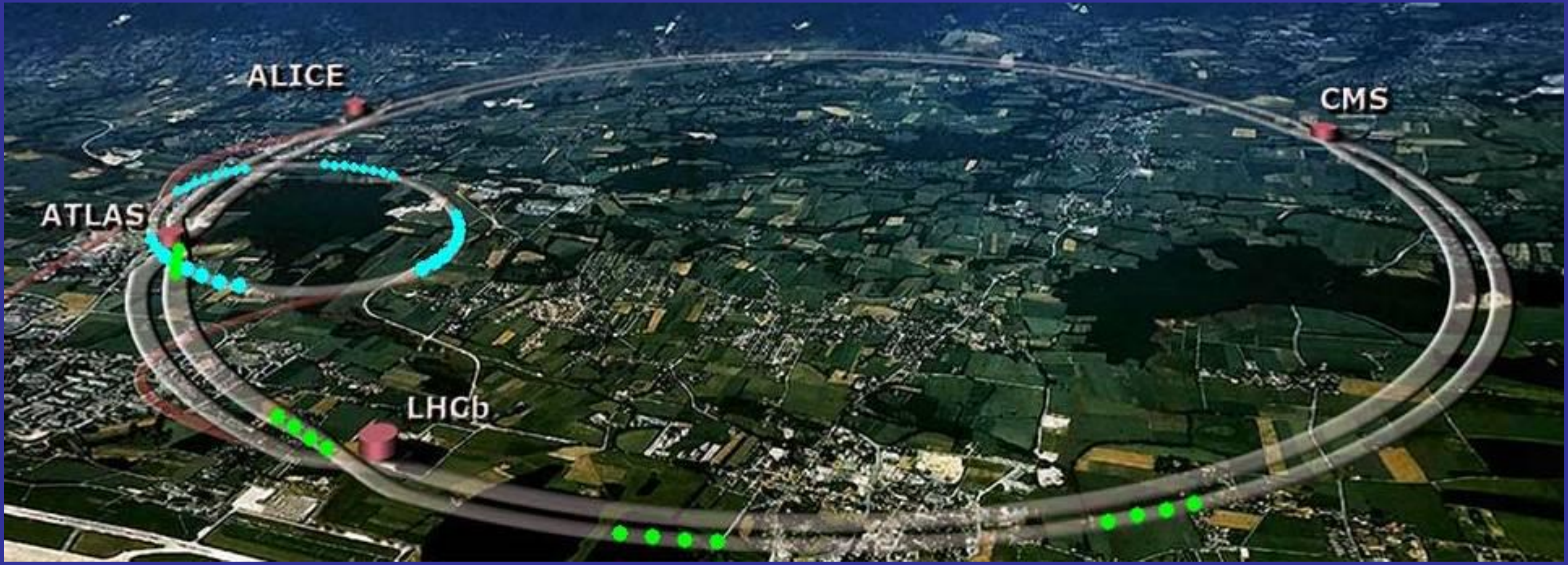
A new episode of a long story….

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

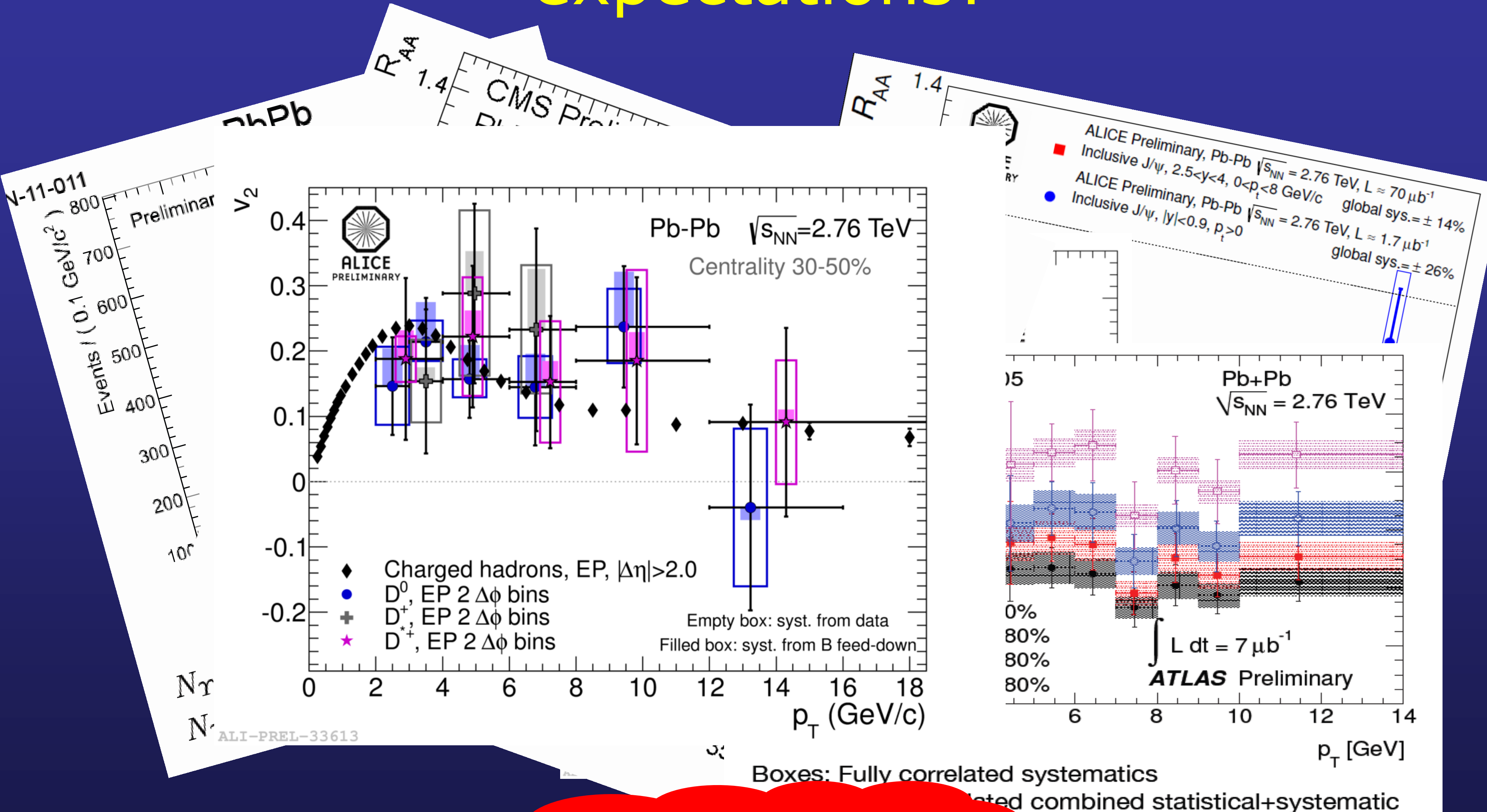
…13 years after Au beams were first accelerated at RHIC



… and barely 2.5 years (!!!) after Pb beams first circulated inside the LHC

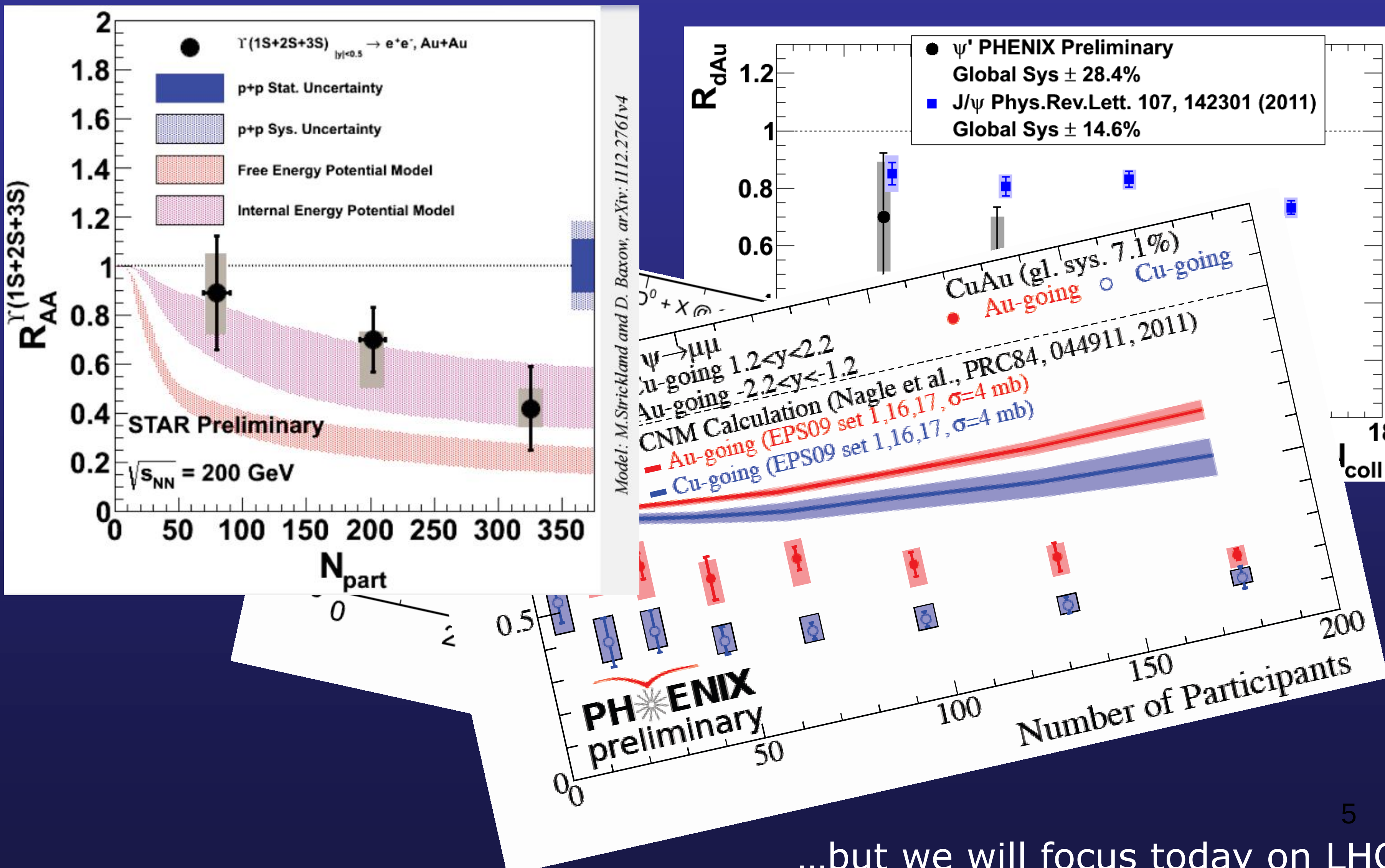


Are LHC results matching our expectations?



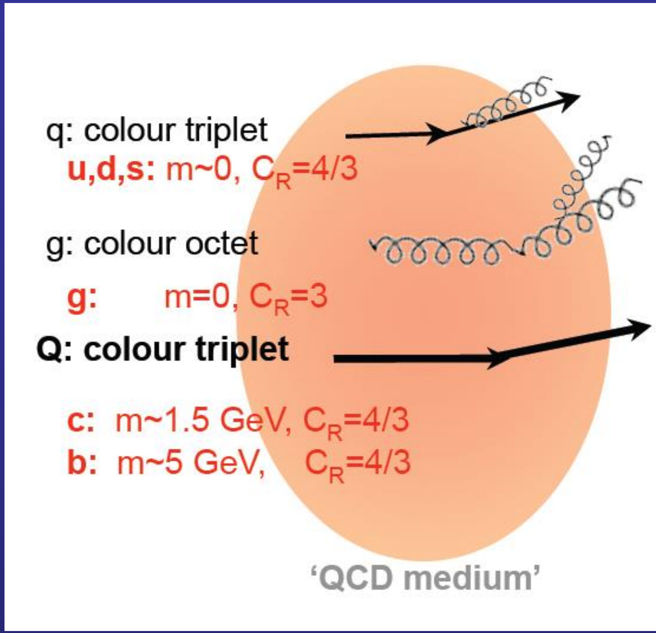
Definitely yes !

..and RHIC is keeping pace



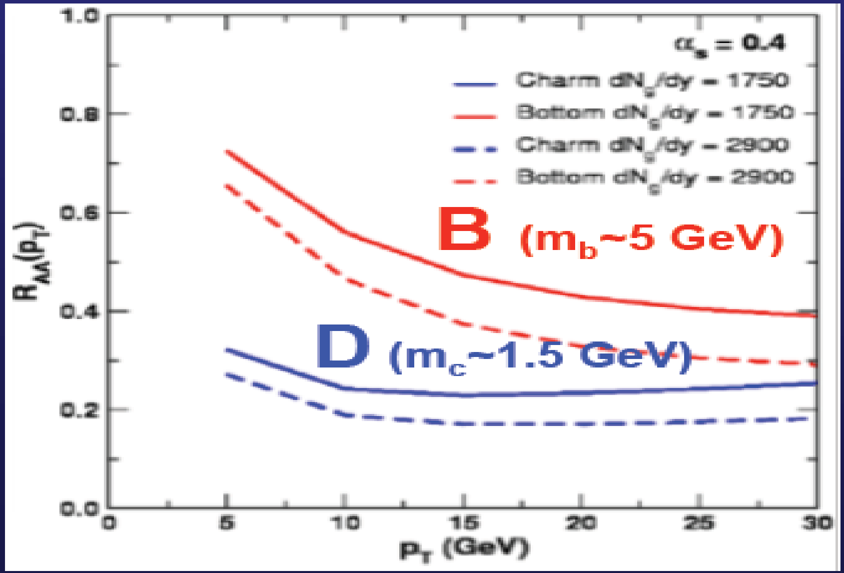
…but we will focus today on LHC

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

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

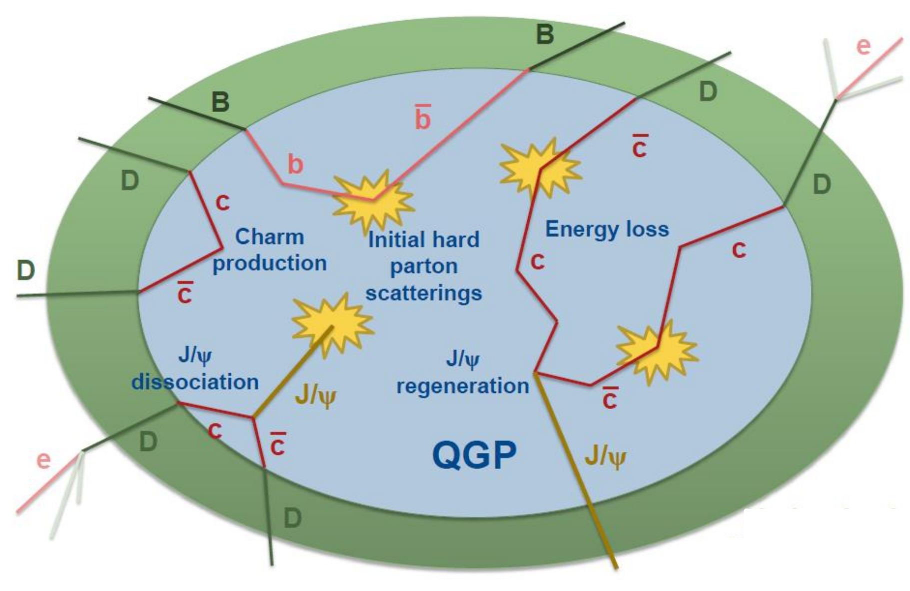
which should imply

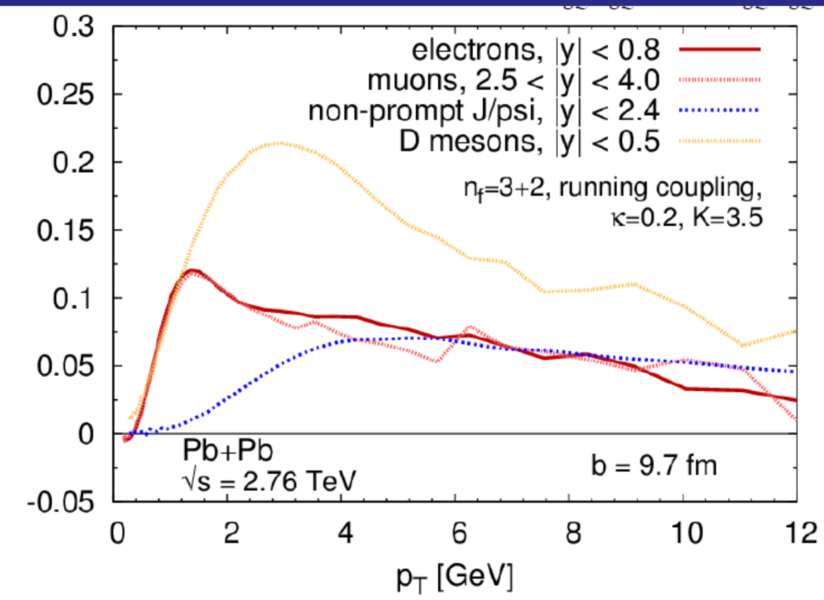
$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

… 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

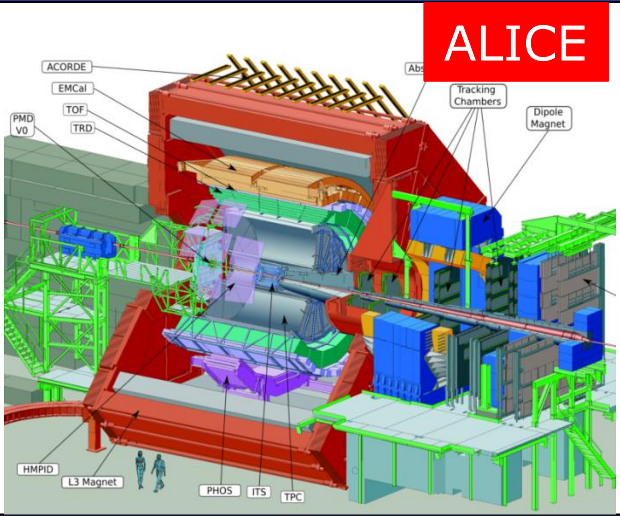




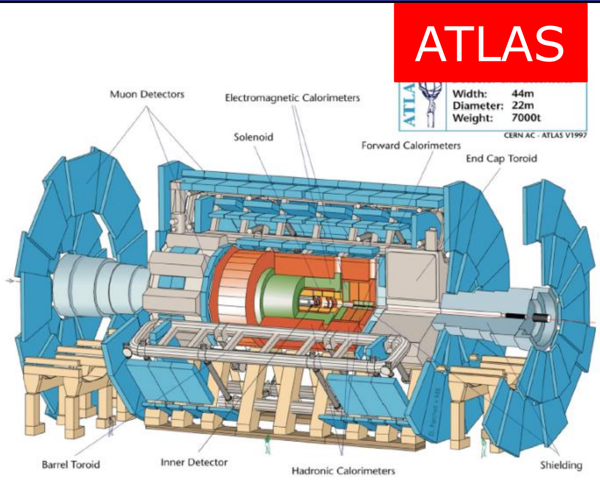
Can the unprecedented abundance of heavy quarks produced at the LHC bring to a (final ?) clarification of the picture ?

LHC, 3 factories for heavy quark in Pb-Pb

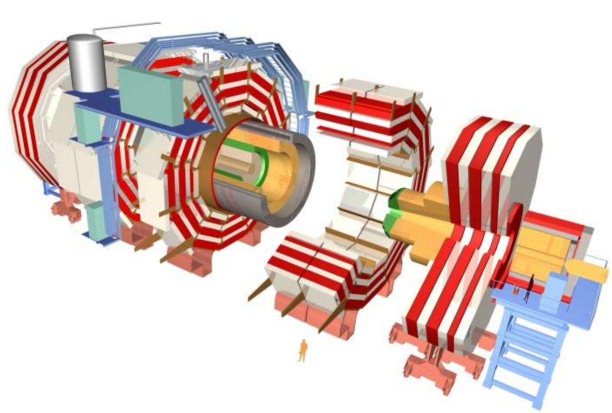
ALICE

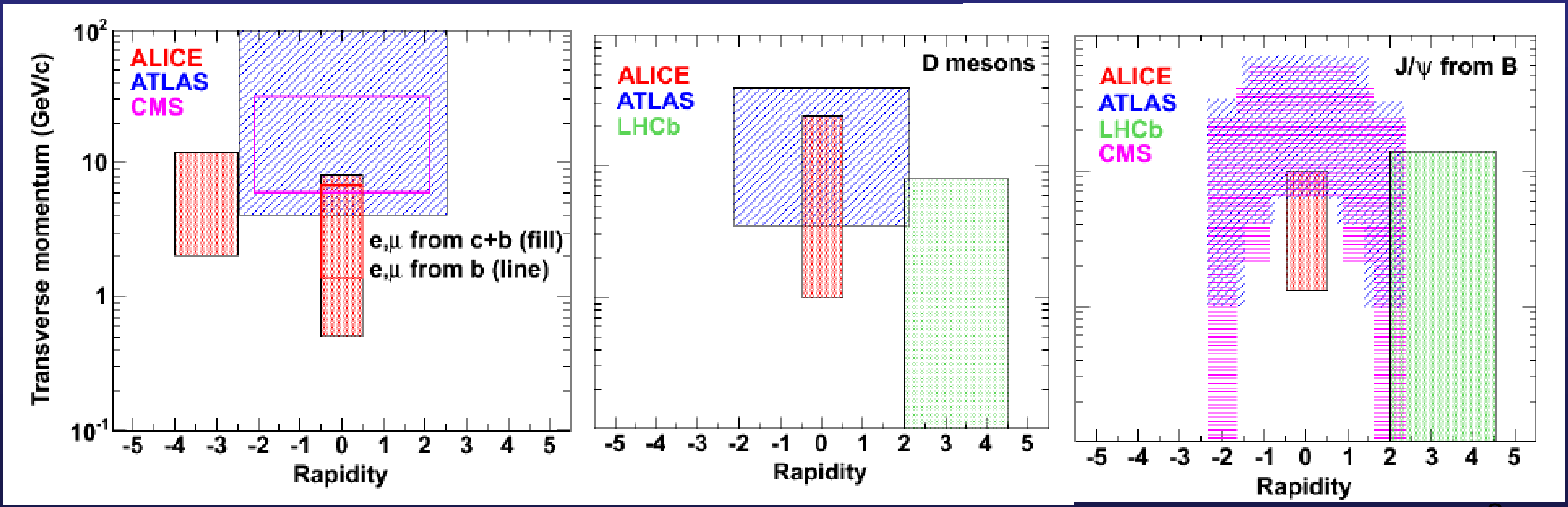


ATLAS



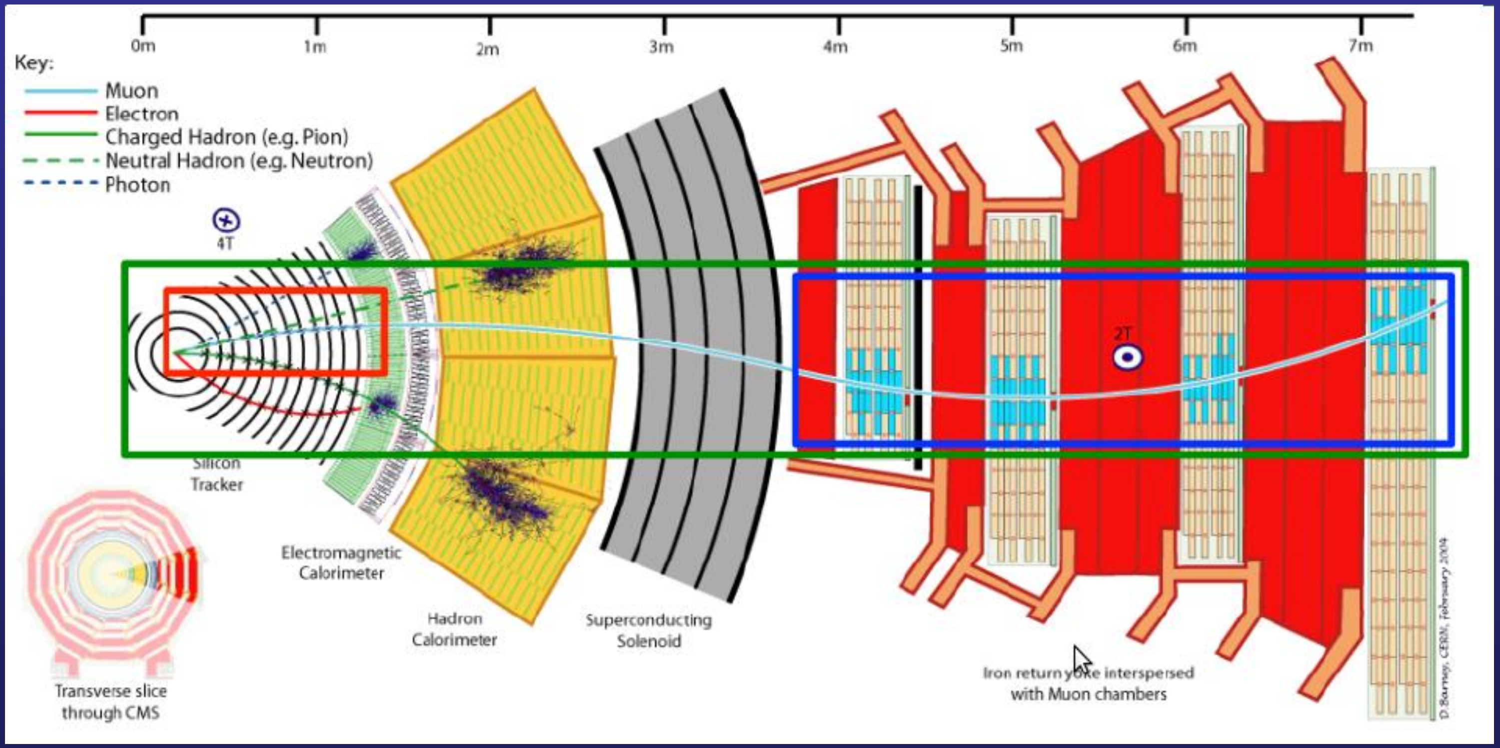
CMS





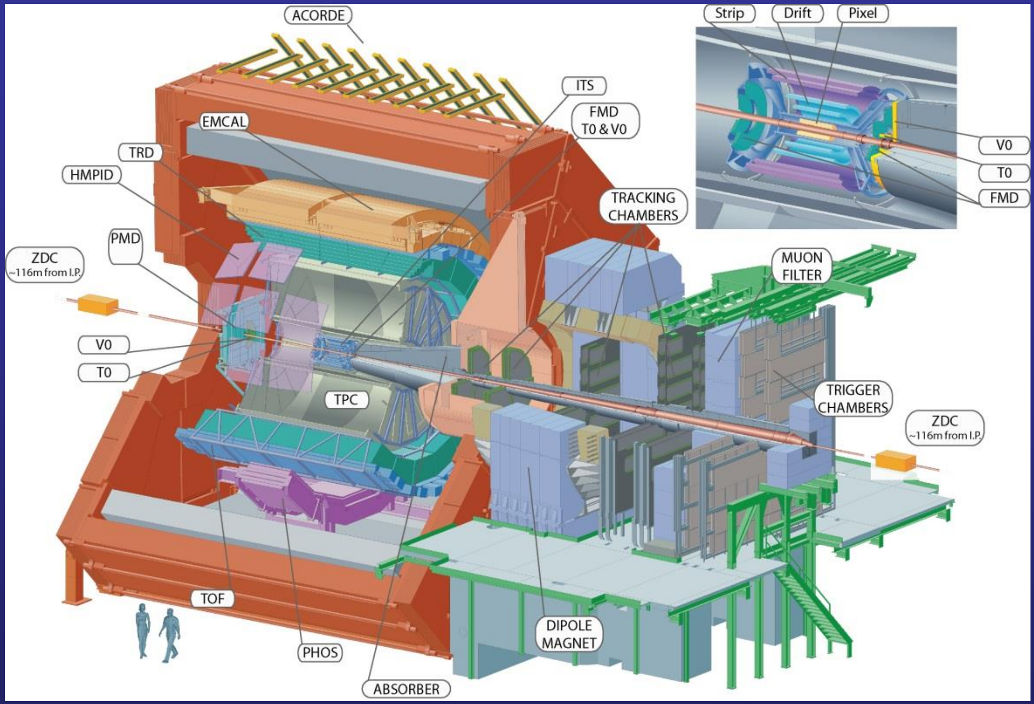
A (slightly) closer look to experiments: CMS

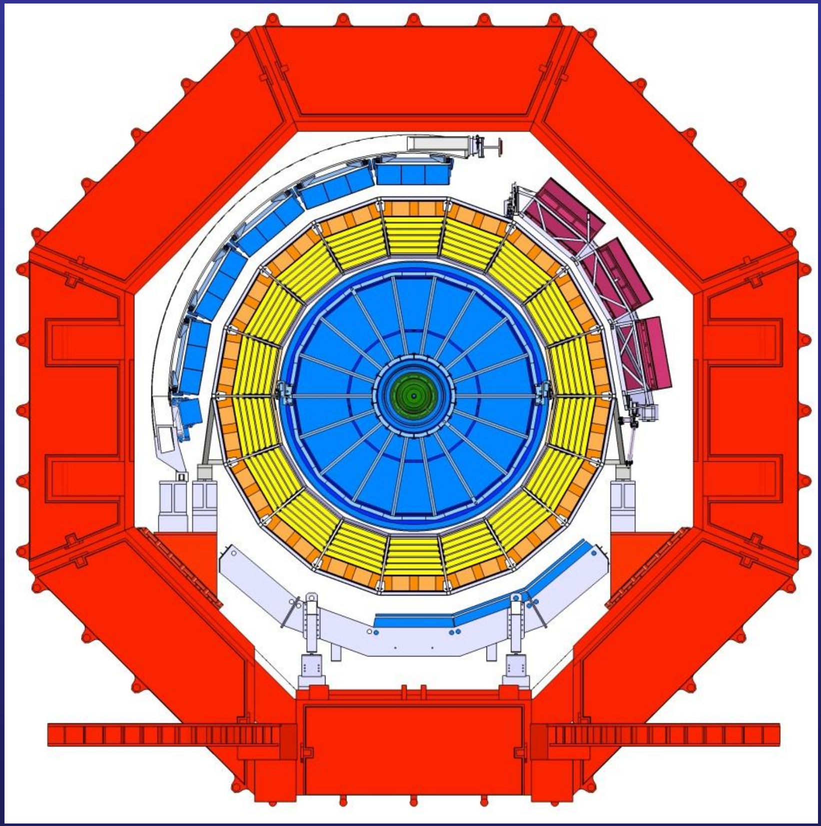
- Tracker p_T resolution: 1-2% up to p_T~100 GeV/c
- Separation of quarkonium states
- Displaced tracks for heavy-flavour measurements



- "Global" muons reconstructed with information from inner tracker and muon stations
- Further muon ID based on track quality (χ2, # hits,...)
- Magnetic field and material limit minimum momentum for muon detection → p_T cut for J/ψ

A (slightly) closer look to experiments: ALICE





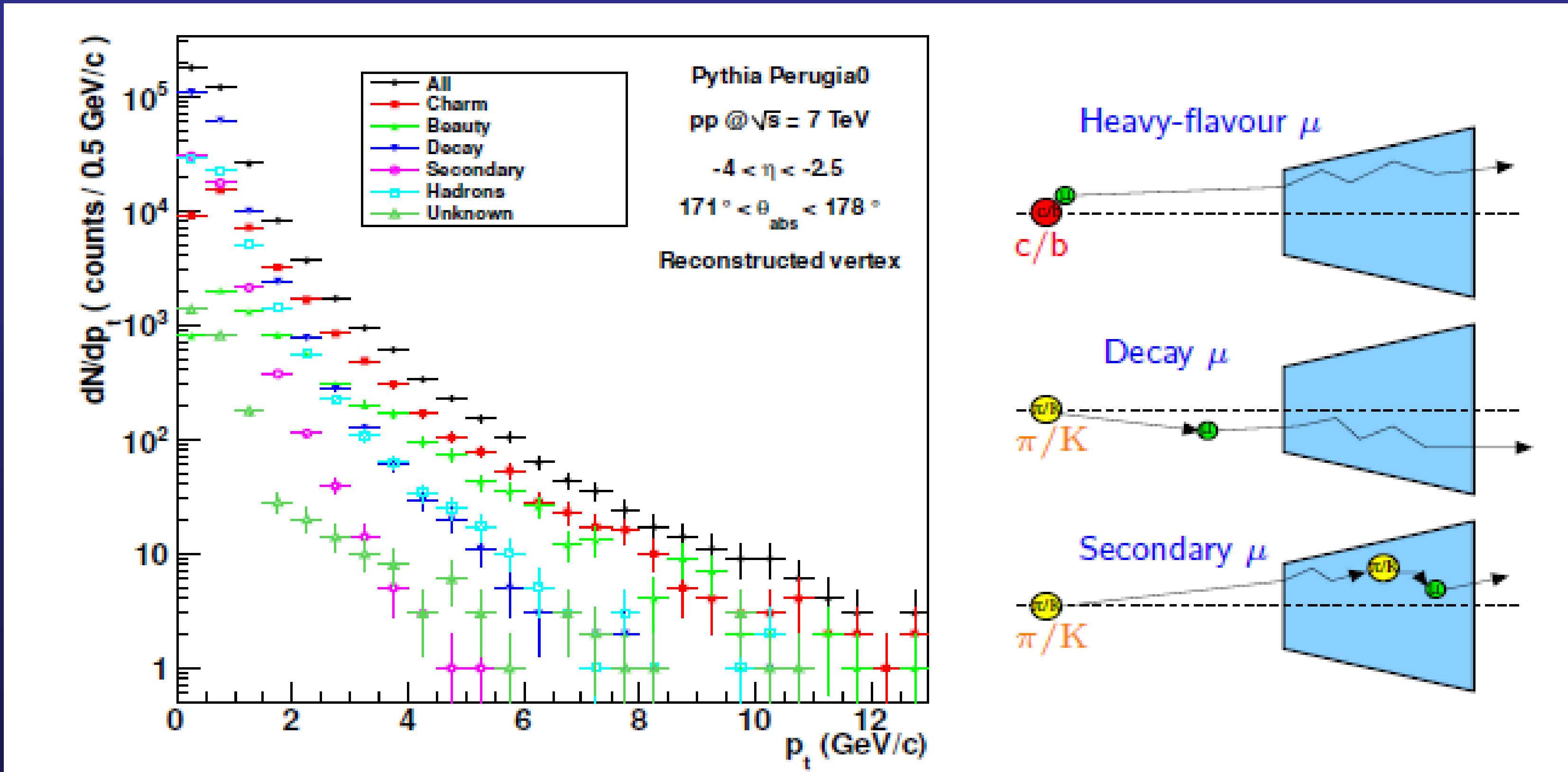
- Main difference with respect to CMS: PID over a large p_T range, down to low p_T (~0.1 GeV/c)
- TPC as main tracker → slower detector, lower luminosity

- "Intermediate" situation for the forward muon arm
- Faster detectors, can stand higher luminosity

“Indirect” measurements

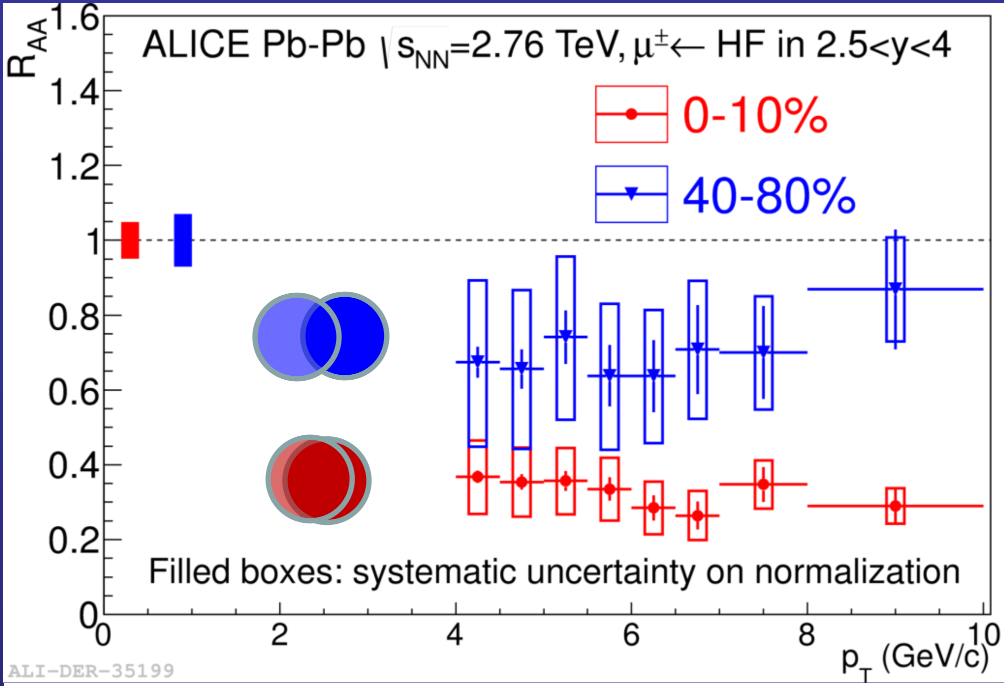
- Semileptonic decays, the shortcut to heavy quark production (pioneered by RHIC and also SPS!)

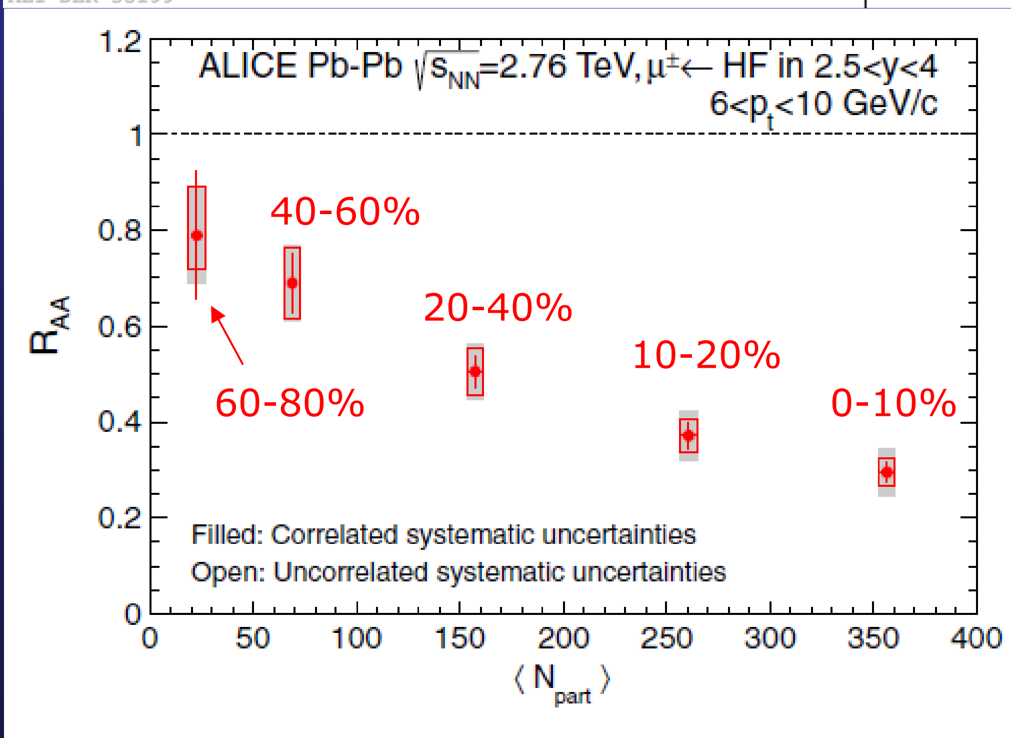
- ALICE: HF muons at forward rapidity ($-4<\eta<-2.5$)
- Non-negligible background issues



- Remove hadrons and low-p_t secondary μ → matching tracks with trigger
- Remove decay μ → vertex displacement, high-p_t data, models

Results





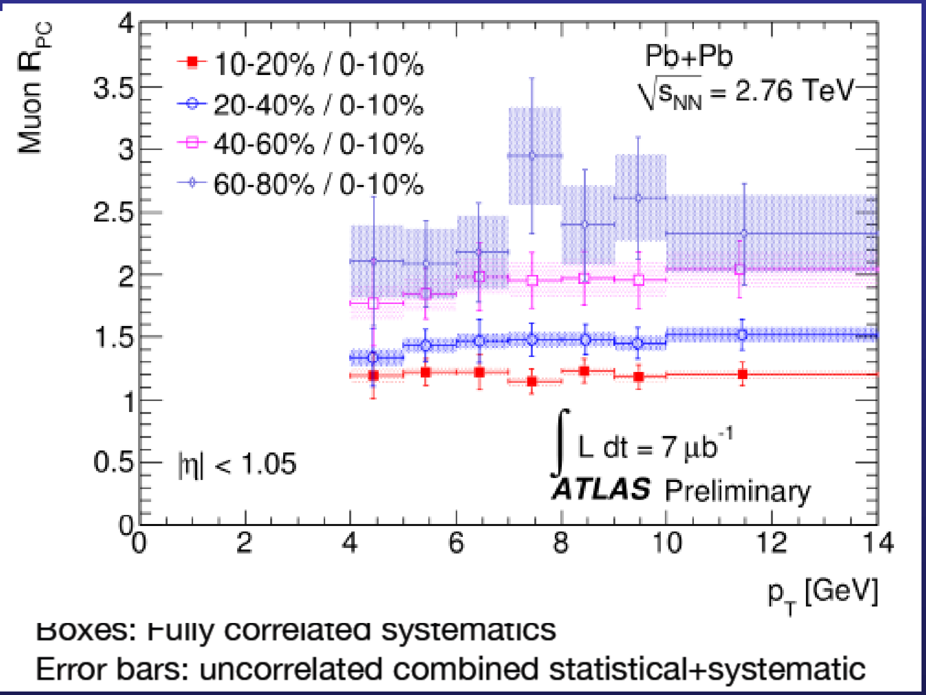
Forward muon spectrometer

- 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

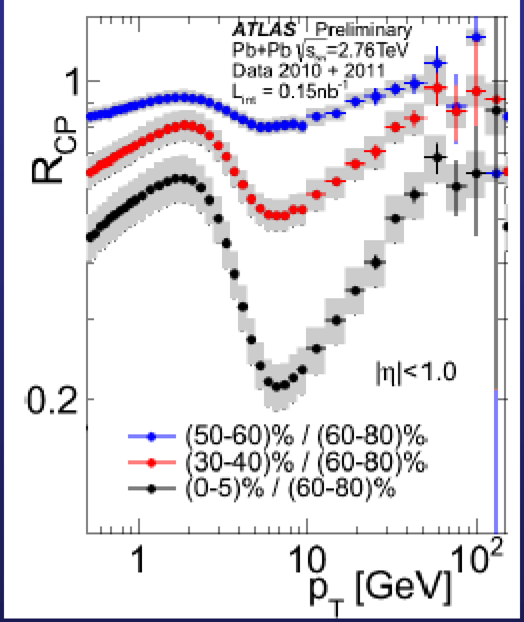
→ Factor ~3-4 suppression for central events, weak p_T-dependence

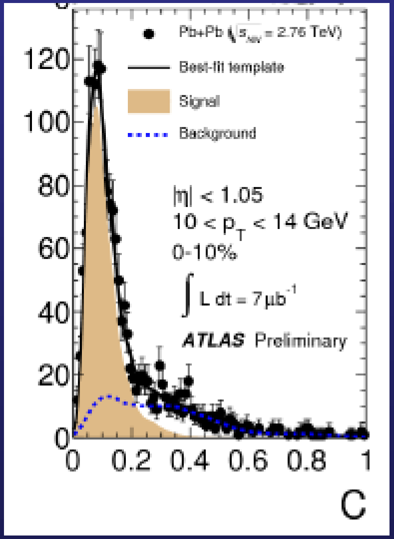
What about central rapidity ?

- 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



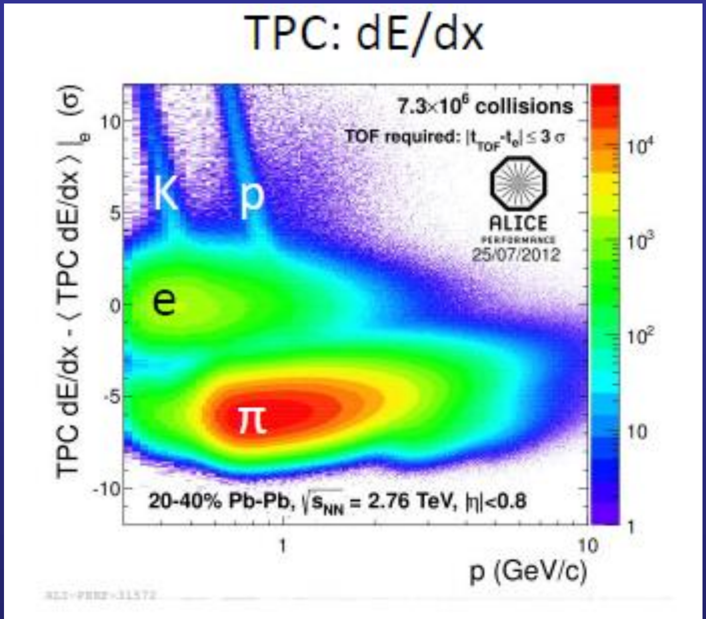


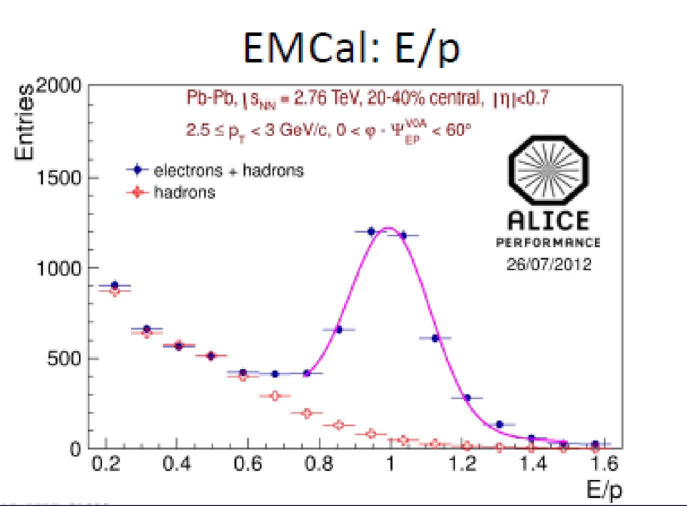
- R_{CP} subject to statistical fluctuations → use R_{PC} too!
- ~flat vs p_T up to 14 GeV/c, different from inclusive R_{CP}!

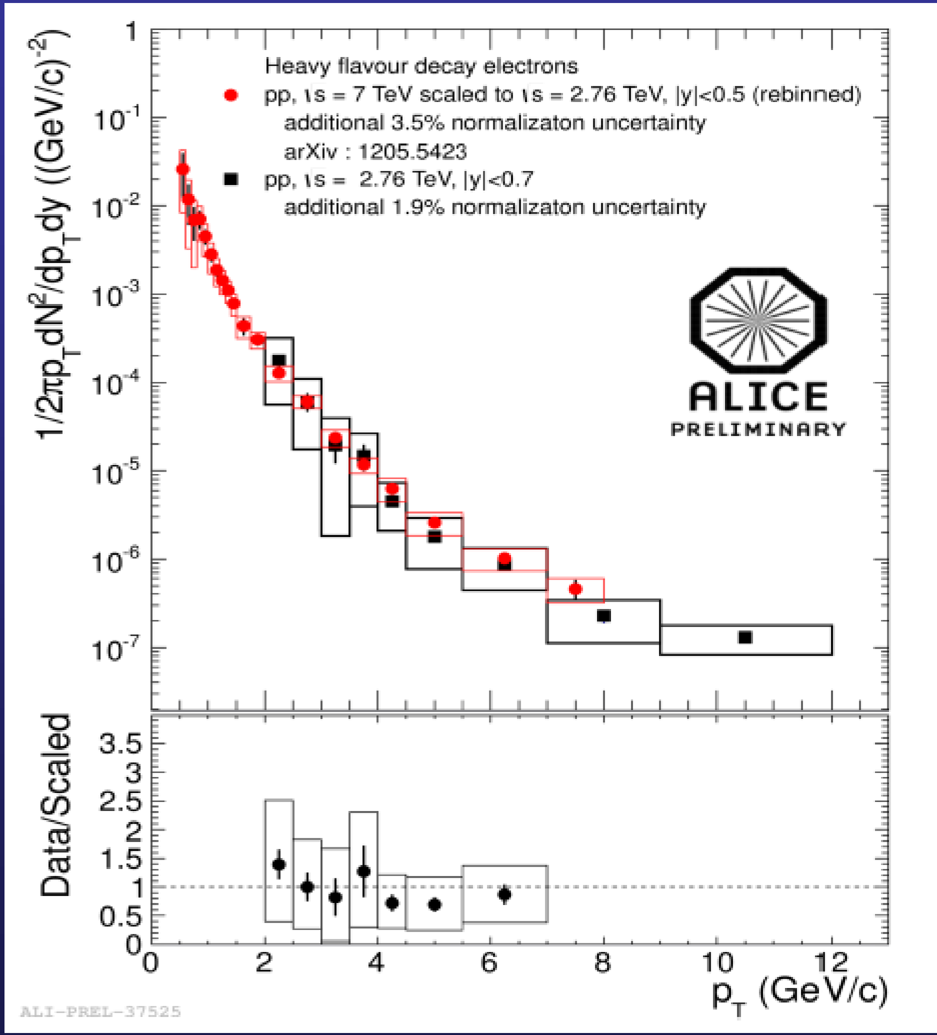
If ~no suppression for 60-80% → central ~ forward suppression

Electron ID in ALICE

- Low-p_T electrons identified mainly via dE/dx in the TPC for MB events
- High-p_T electrons: EMCal becomes essential (in addition to TPC)



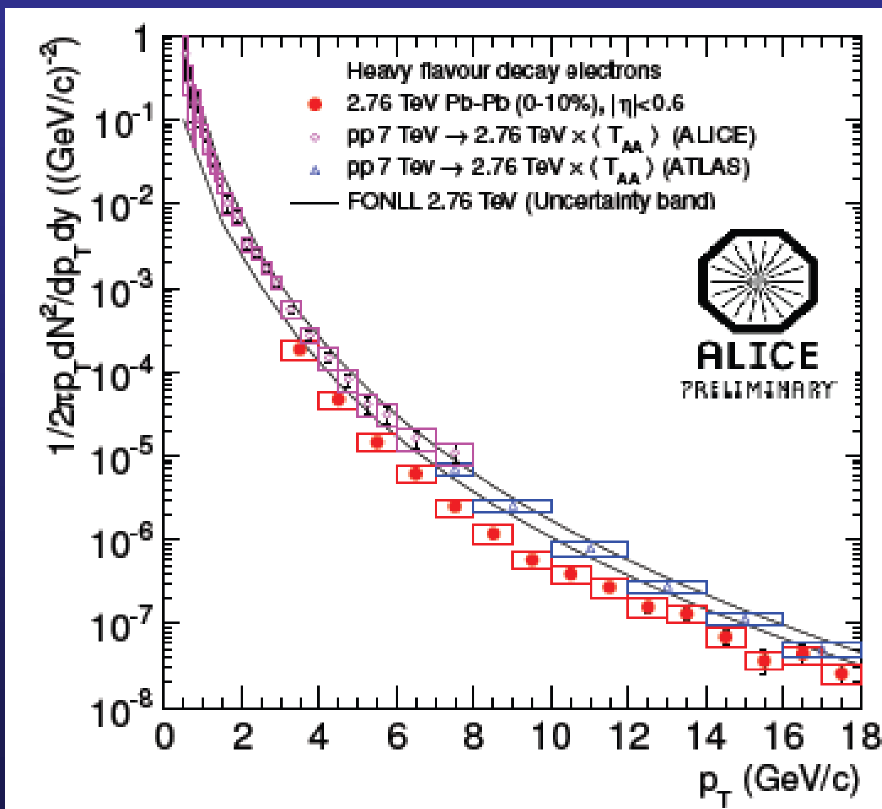


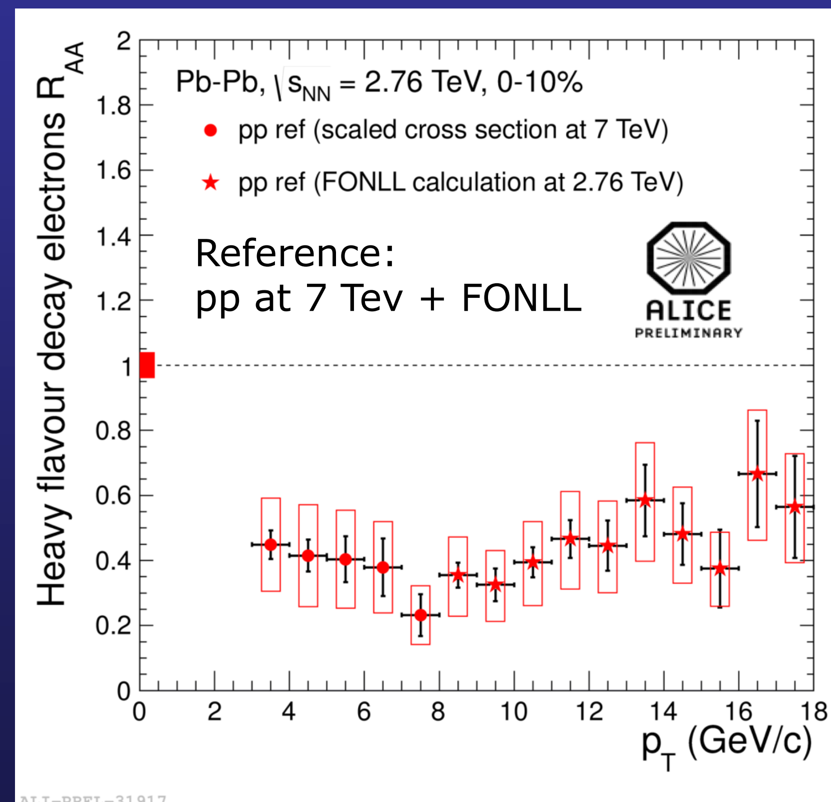


- Check matching of the distributions in the common p_T region

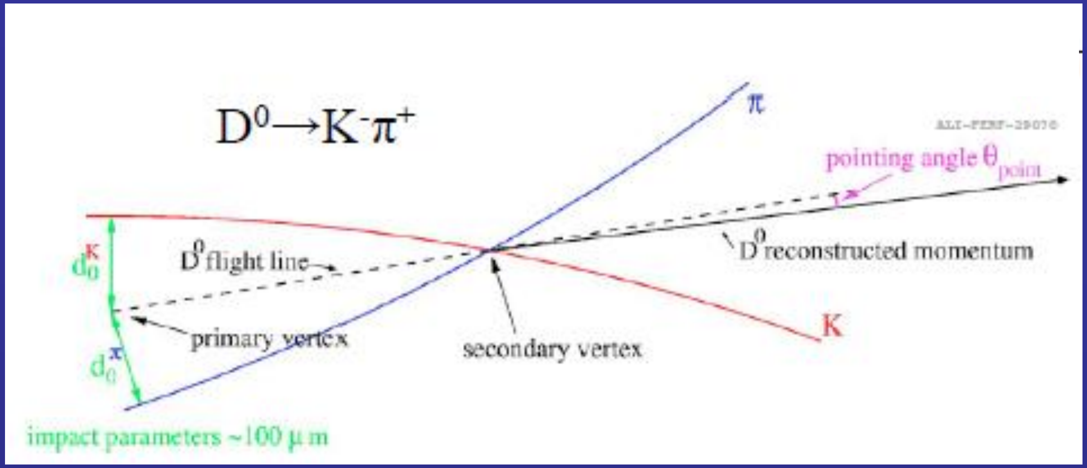
Electrons at midrapidity

- ALICE measures inclusive electron production at midrapidity
- "Photonic" background subtraction through invariant mass reconstruction (pair candidate with other e and reject low masses)
- Contribution from $J/\psi \rightarrow ee$ also subtracted





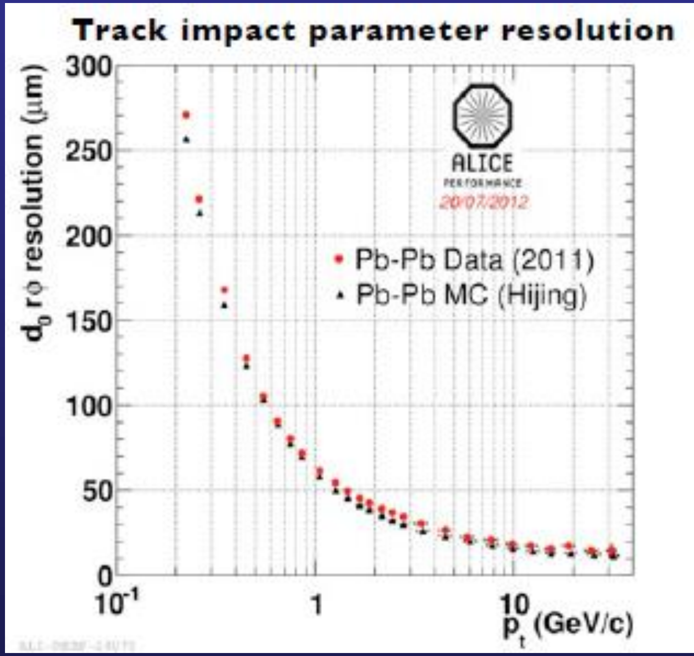
Suppression in $3<p_T<18$ GeV/c (factor up to ~3)
Hints for less suppession at high p_T ?

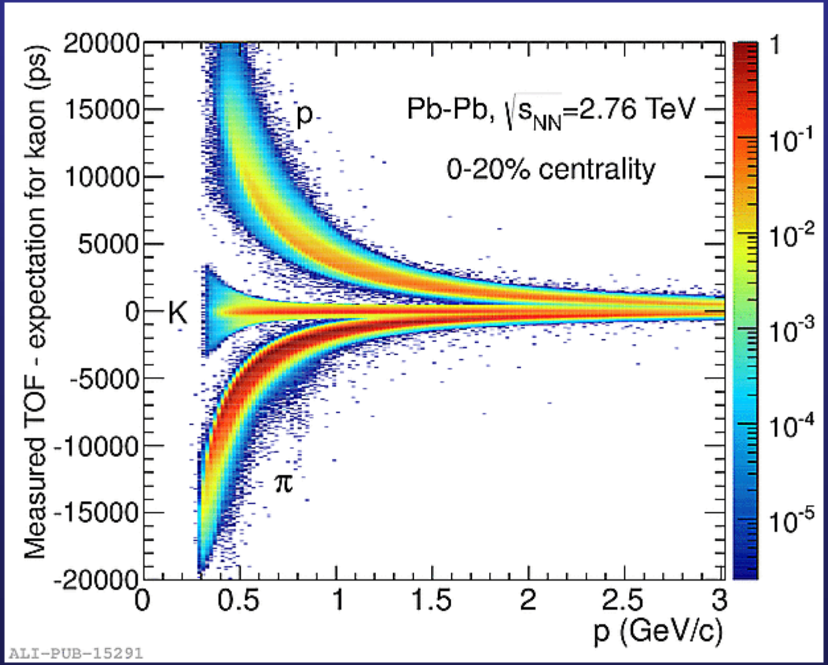


Reconstructing D-decay topology

$D^0 \rightarrow K^-\pi^+$	$c\tau \sim 120\ \mu m$
$D^+ \rightarrow K^-\pi^+\pi^+$	$c\tau \sim 300\ \mu m$

- ALICE: good vertexing resolution + PID → study D-decay topology



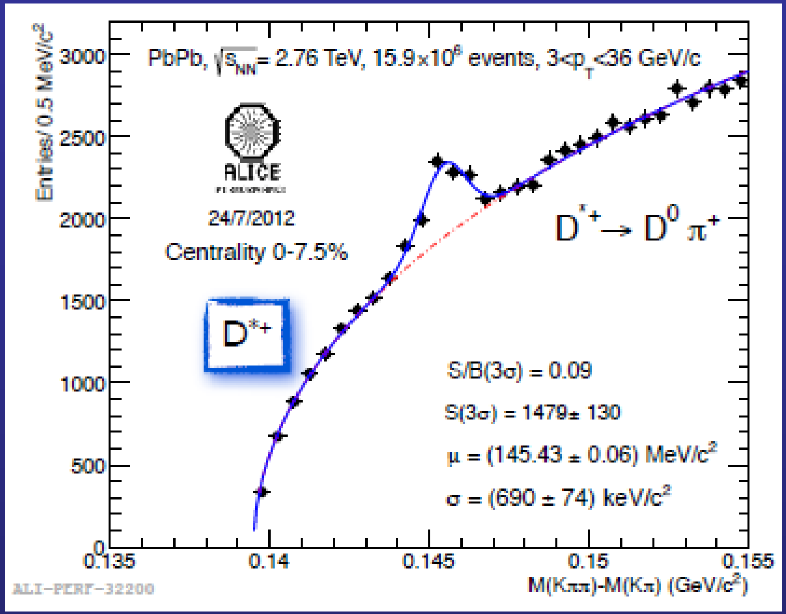


- Topology of the decay resolved via the reconstruction of secondary vertex
- Combinatorial background reduced via topological selections (e.g. $\cos\theta_{point}$)
- PID using TOF and TPC to further suppress background
- Invariant mass analysis

More complex topologies

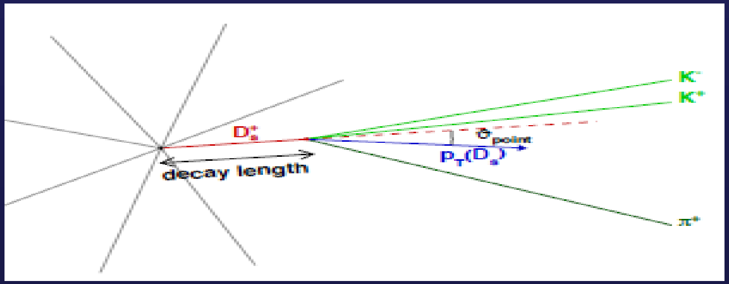
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$

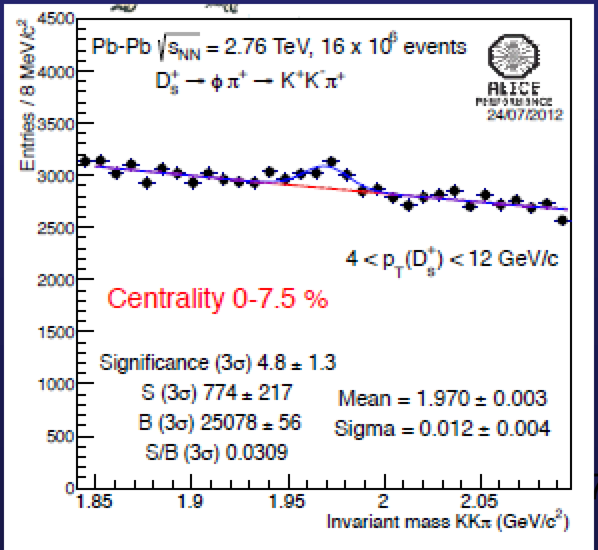
$D^+_s \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$



- D*: look for soft pion from primary vertex (strong decay)
  - 100-200 MeV momentum, detection in the ITS (no PID)
  - Small Q-value, signal at the beginning of Δm plot, background not too large

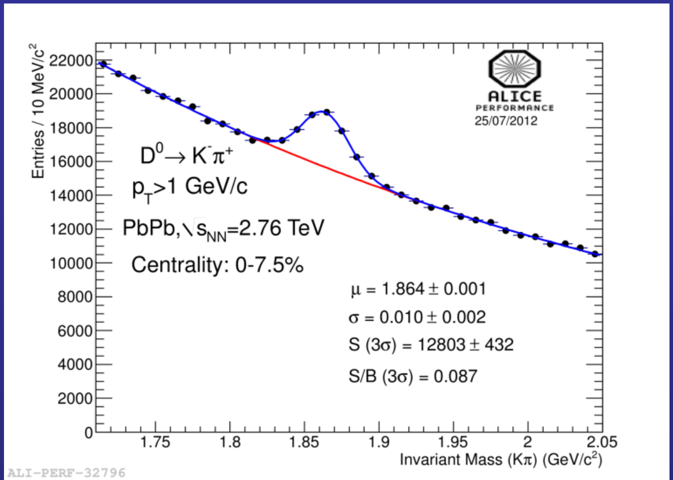
- D_s: small $c\tau$ factor wrt D^+
  - 2K PID helps removing background, but not enough
  - Selection around ϕ-mass

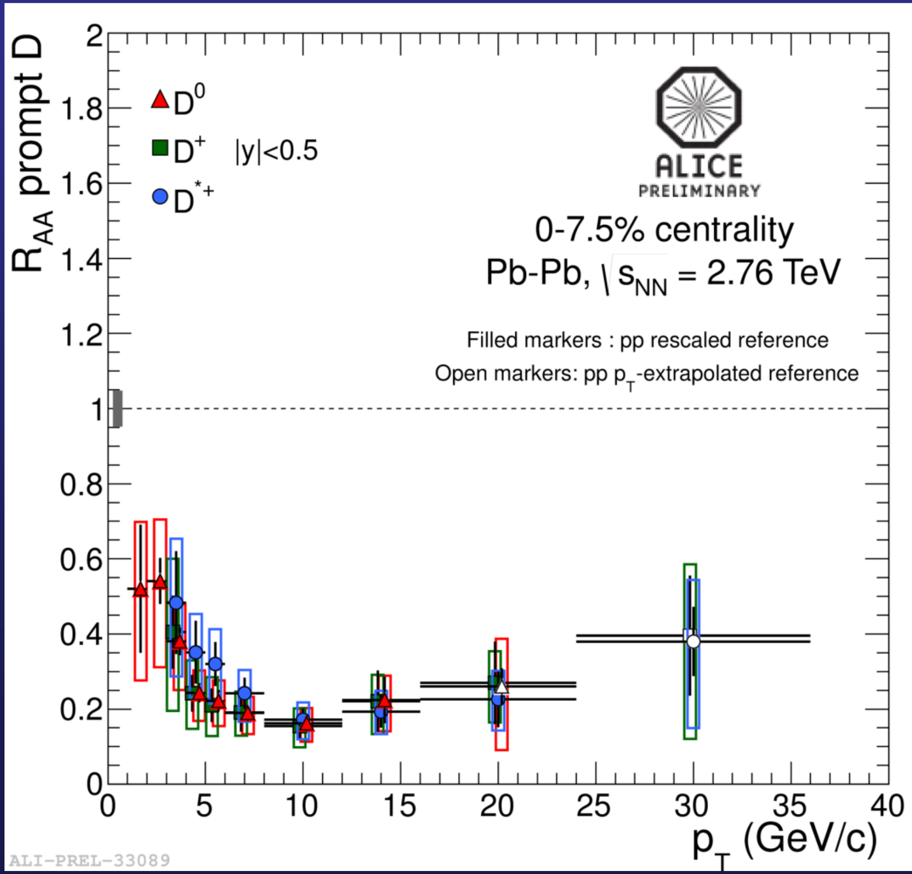




D-meson R_{AA}

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



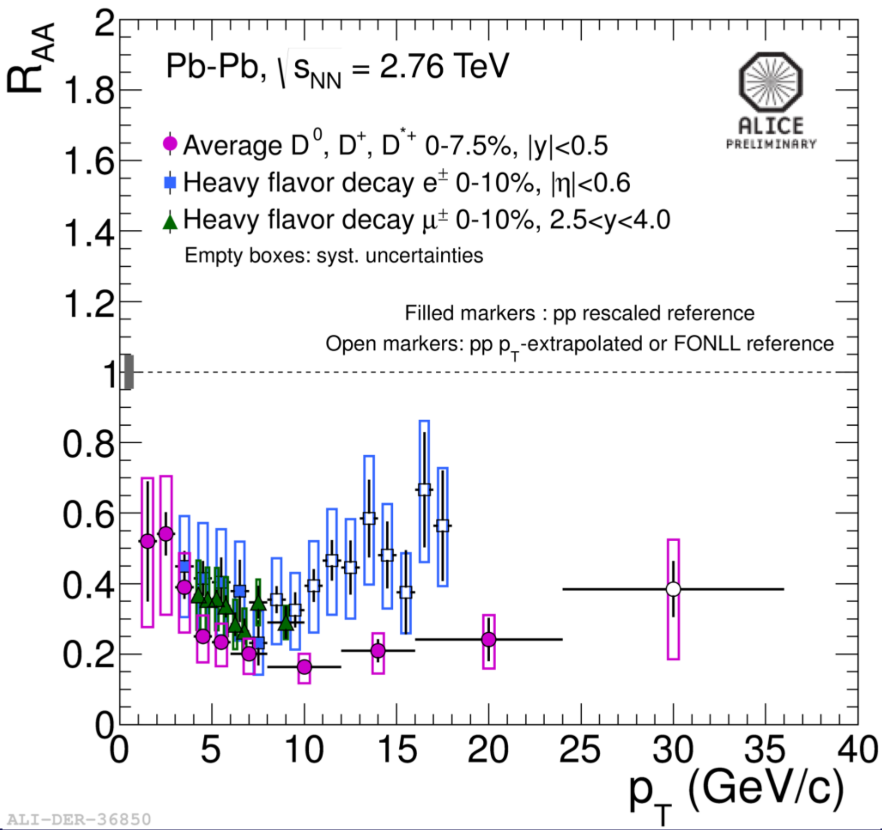


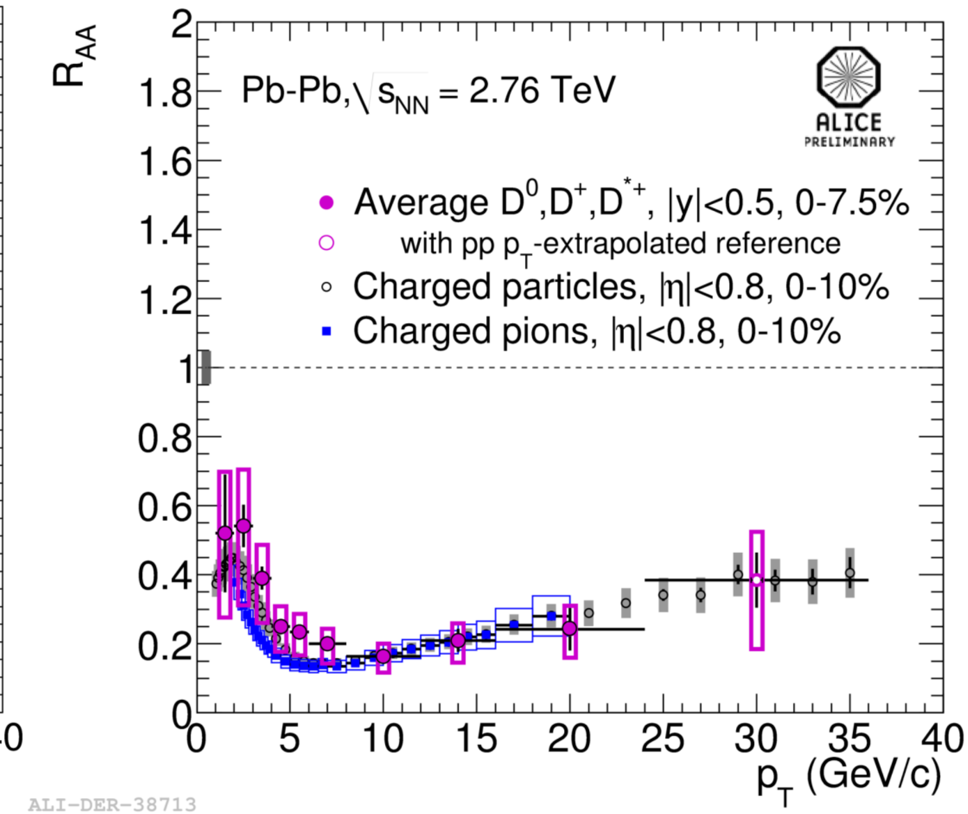
- ❑ Reference
  - ❑ 7 TeV scaled to 2.76 with FONLL
  - ❑ Use FONLL shape if no pp

- ❑ 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≈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)

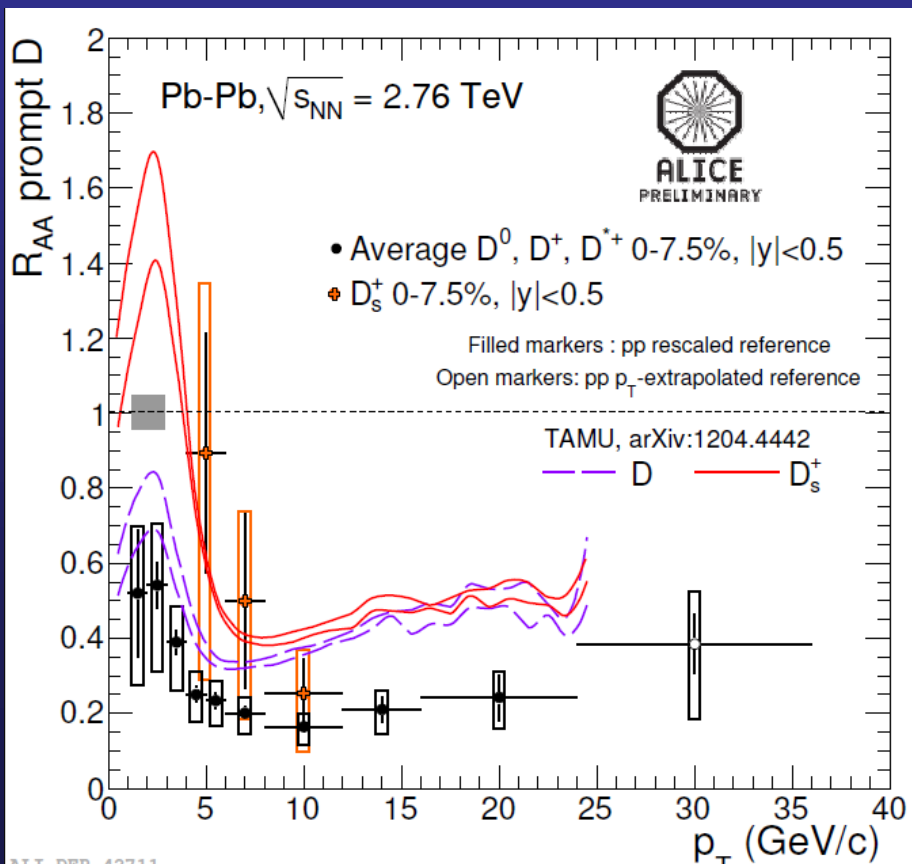
- Similar trend vs. p_T for D, charged particles and $\pi^{\pm}$

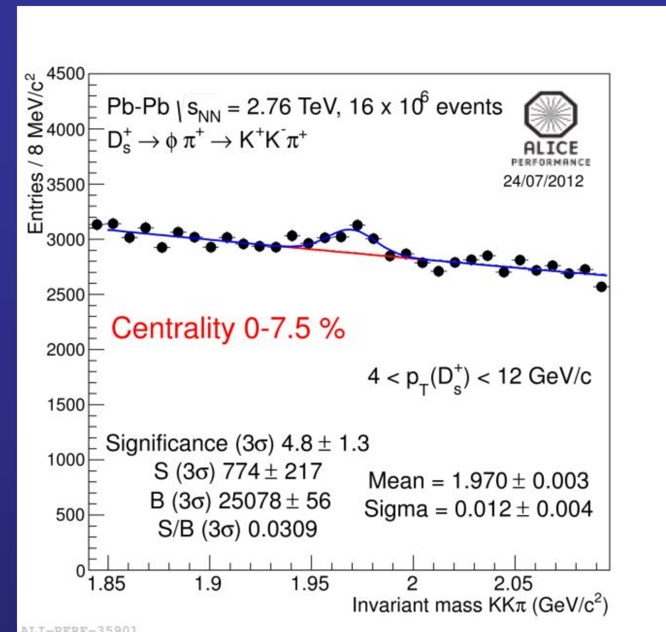
Hint of $R_{AA}^D > R_{AA}^{\pi}$ at low p_T ?

→ Look at beauty

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

- 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

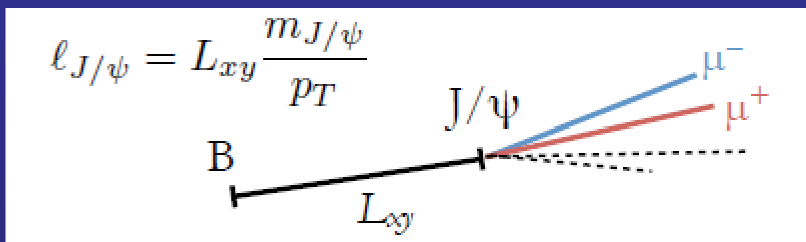


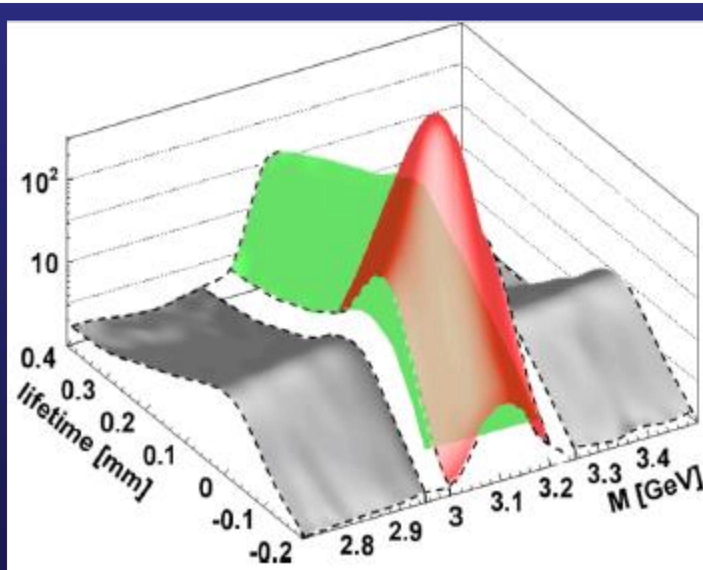


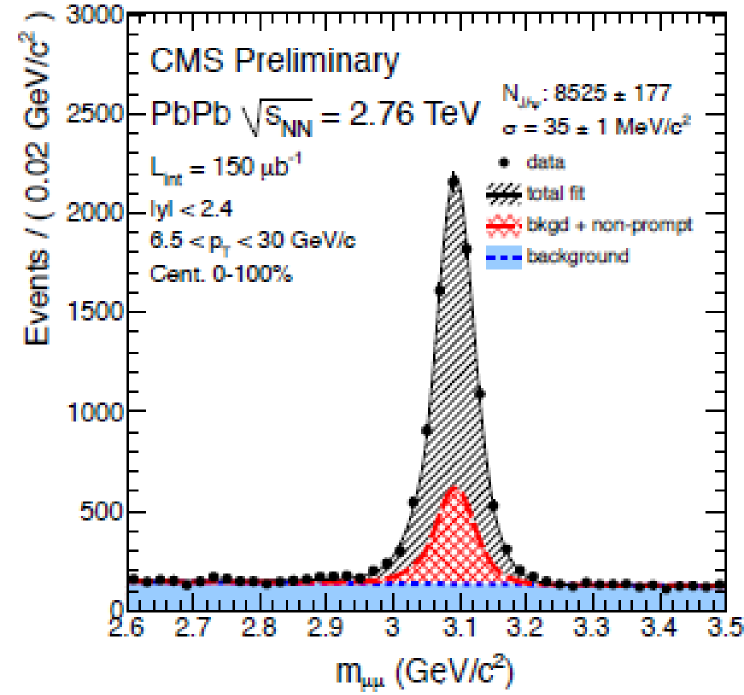
- Strong D_s^+ suppression (similar as D^0, D^+ and D^{*+}) for $8<p_T<12$ GeV/c
- R_{AA} seems to increase at low p_T
- Current data do not allow a conclusive comparison to other D mesons within uncertainties

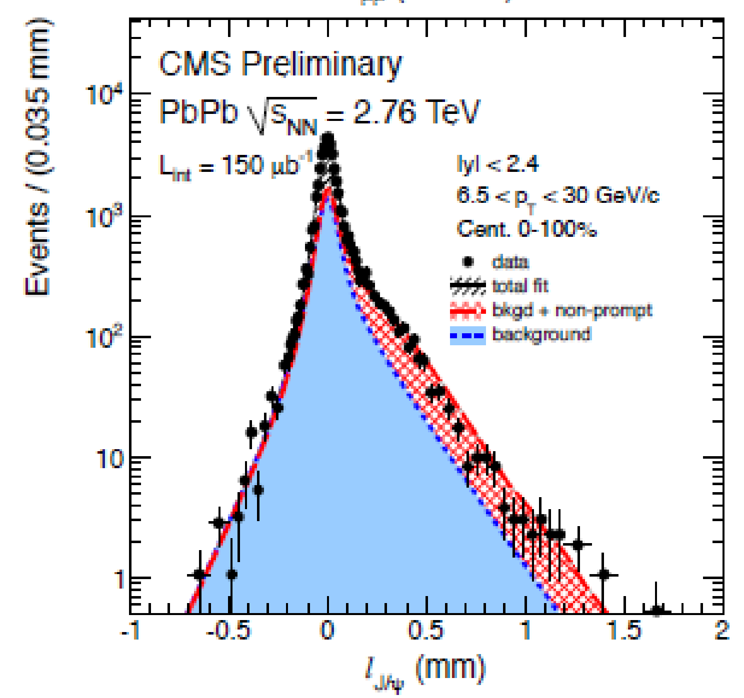
Beauty via displaced J/ψ

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





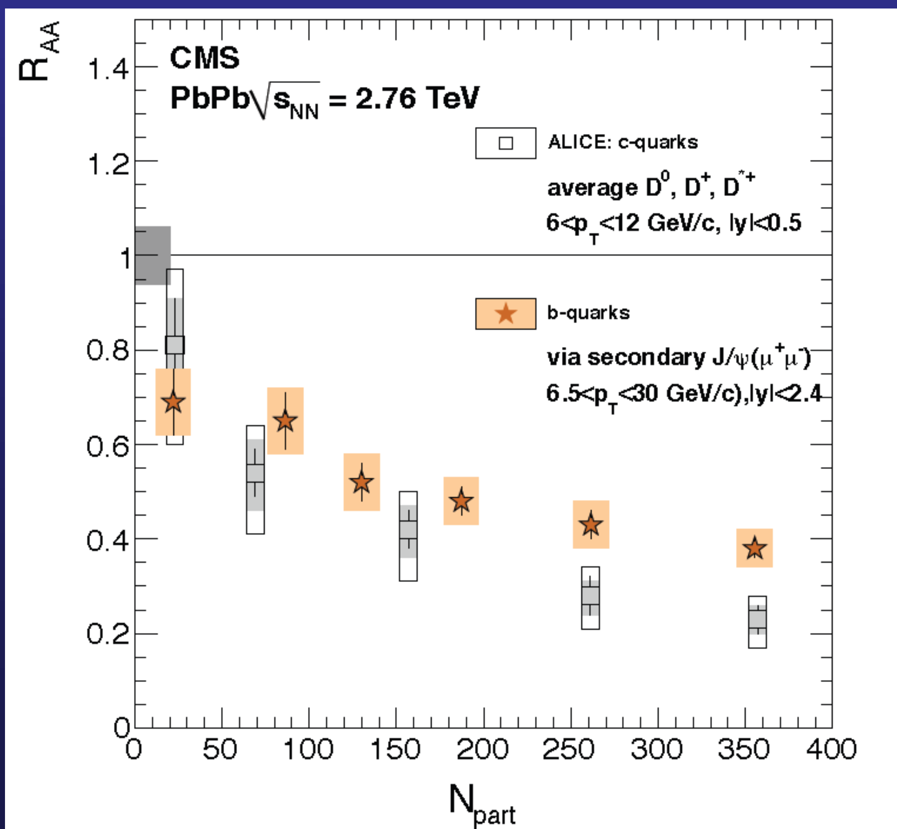




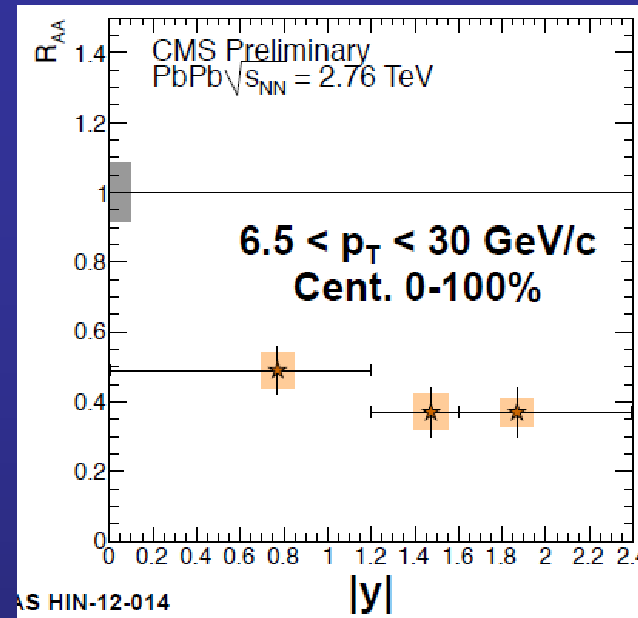
- Background from sideways (sum of 3 exp.)
- Signal and prompt from MC template

Non-prompt J/ψ

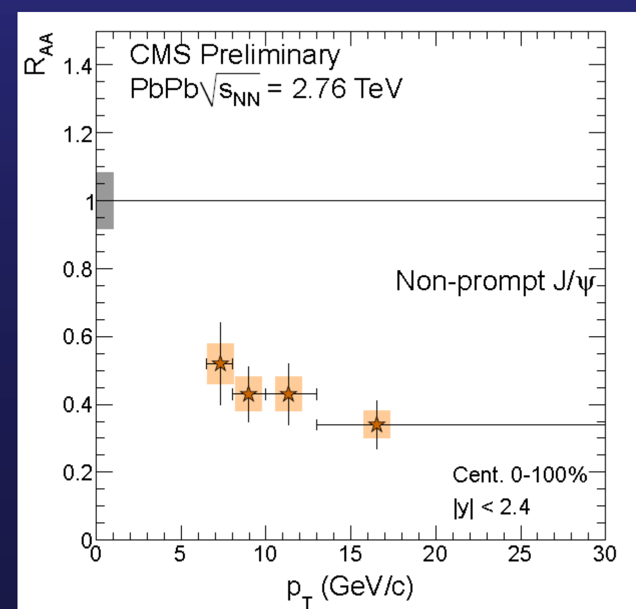
Suppression hierarchy (b vs c) observed, at least for central collisions (note different y range)



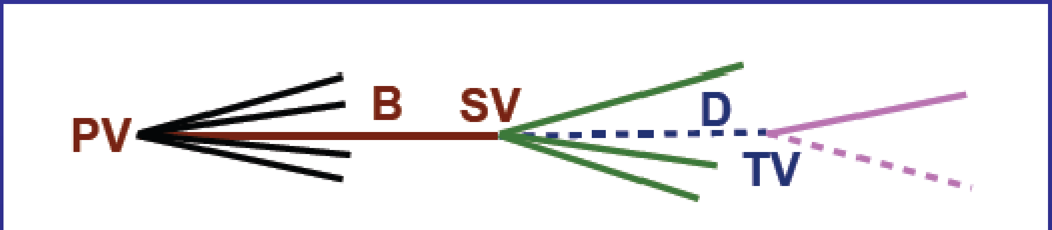
(Slightly) larger forward suppression



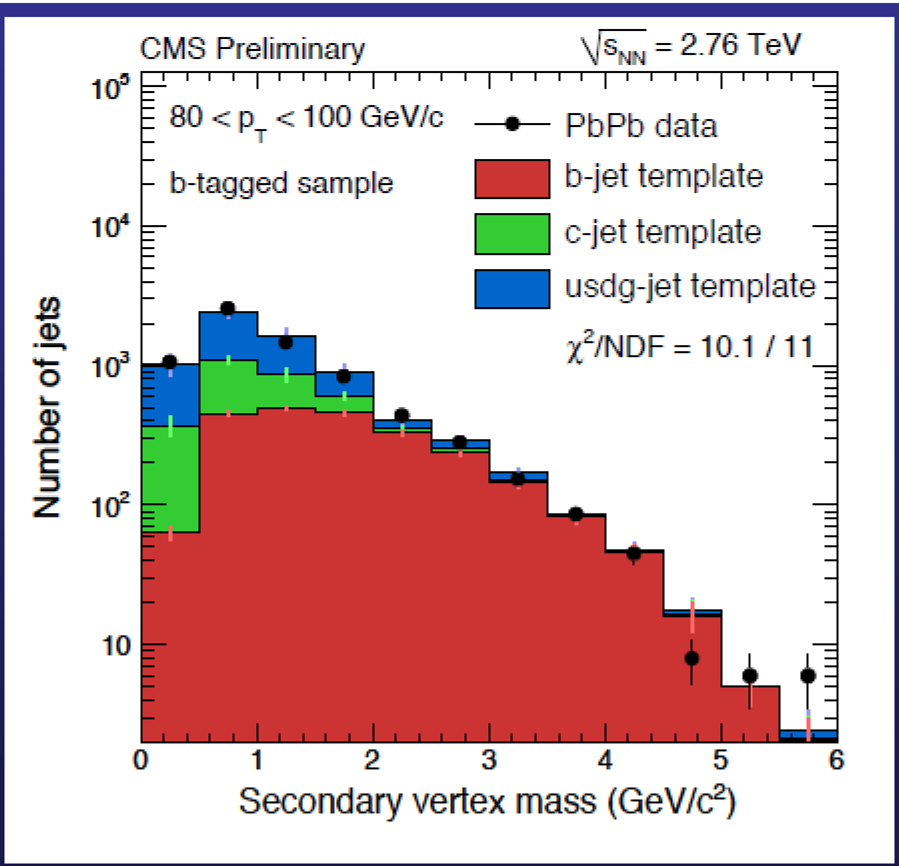
Larger suppression at high p_T ?

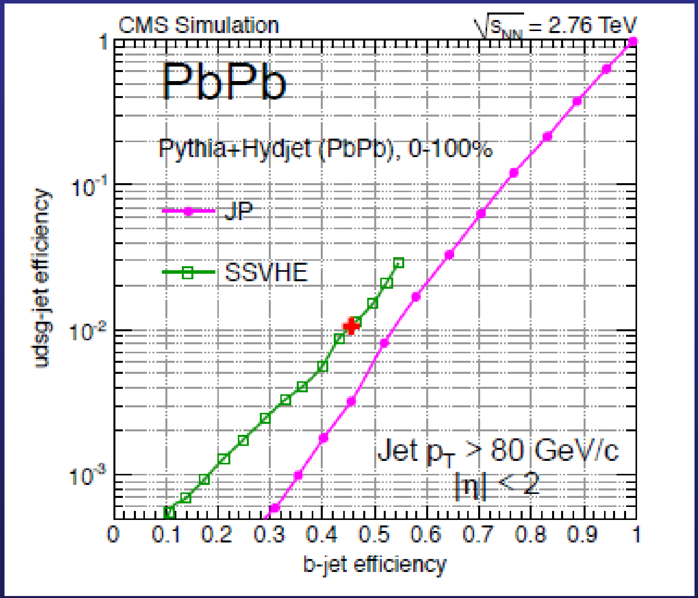


The new frontier: b-jet tagging



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

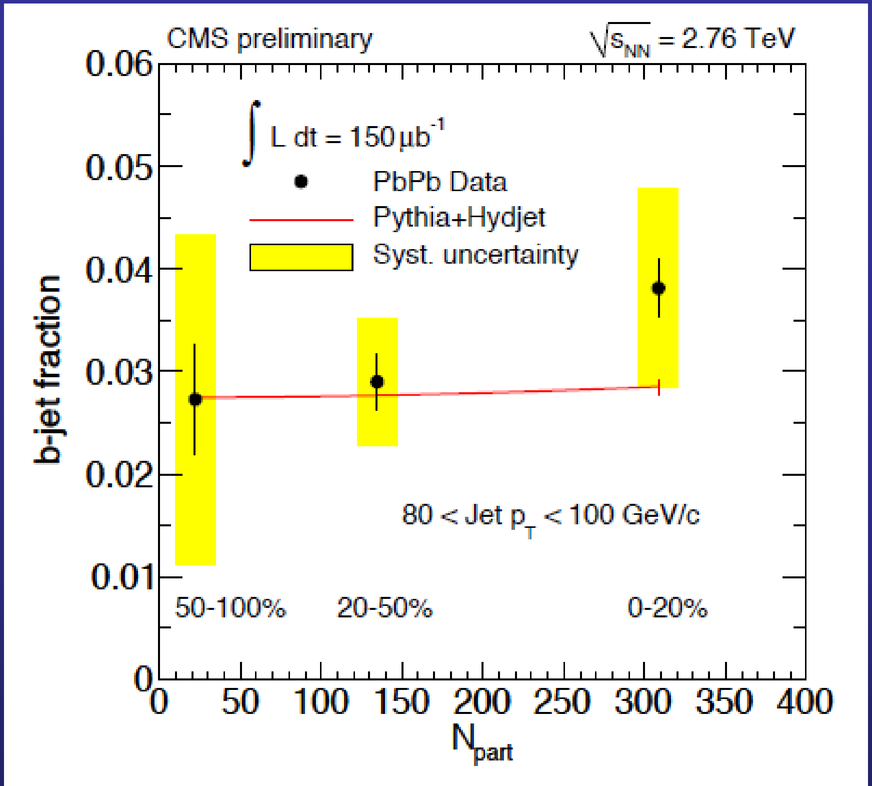


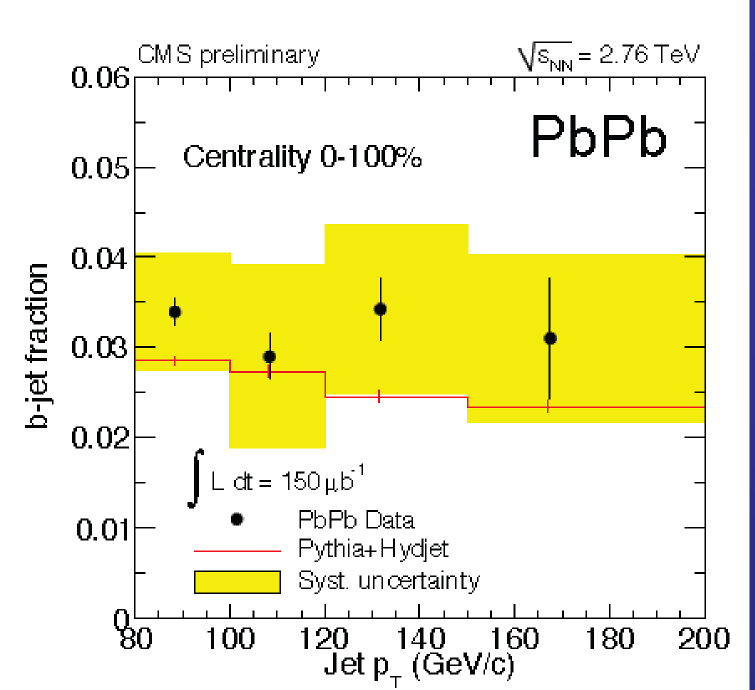


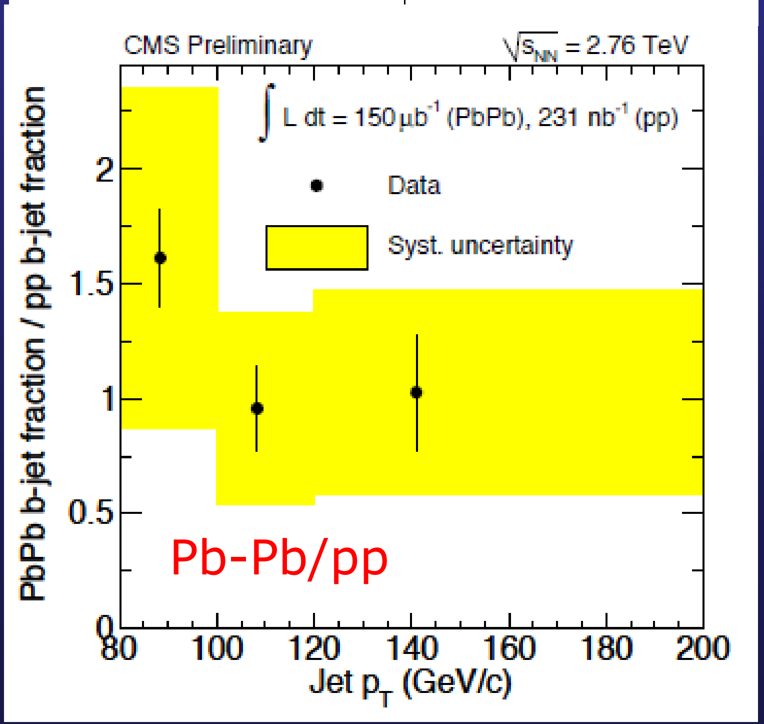
Factor 100 light-jet rejection for 45% b-jet efficiency

- b-quark contribution extracted using template fits to secondary vertex invariant mass distributions

b-jet vs centrality/p_T

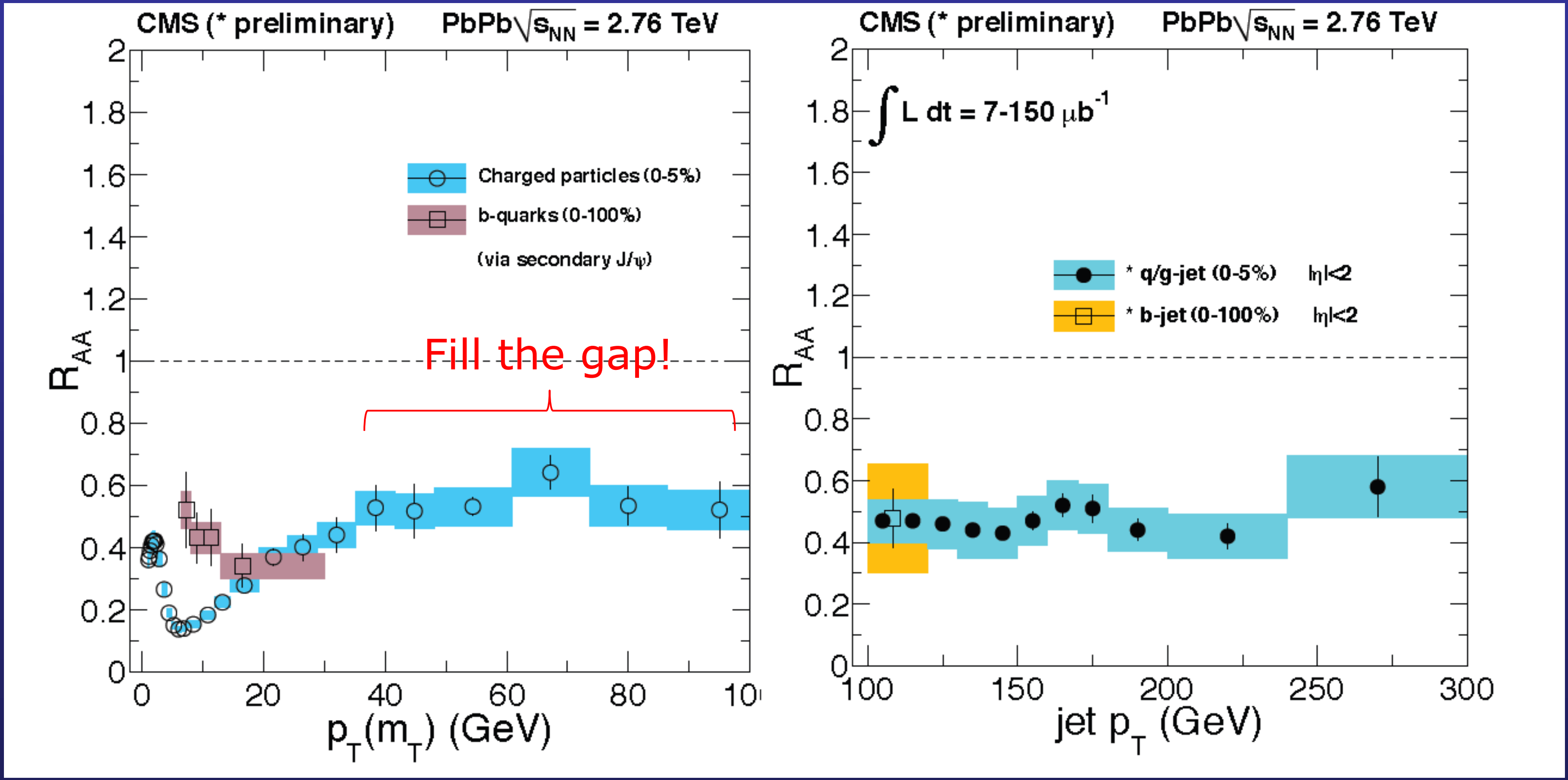






- b-fraction ~constant vs both p_T and centrality
- b-fraction similar (within errors) in p-p and Pb-Pb

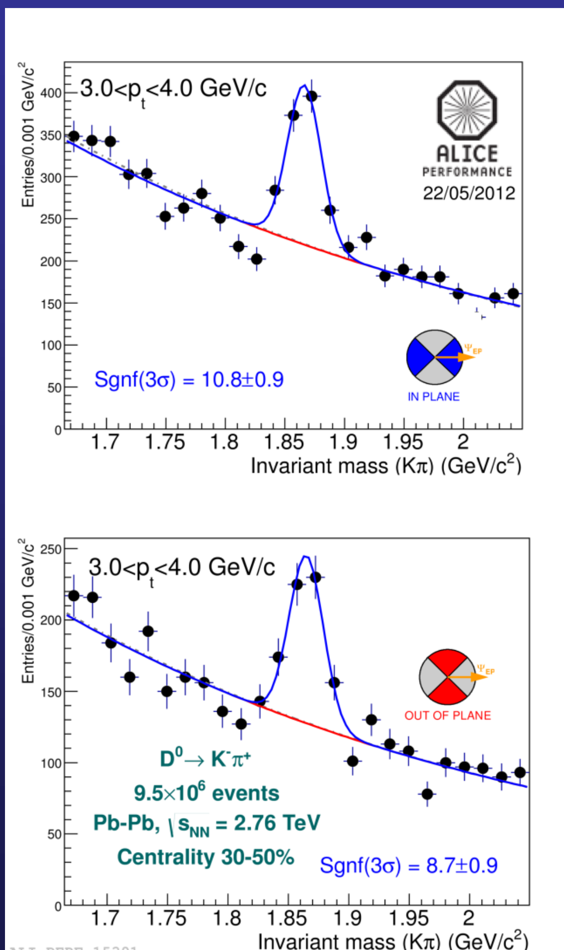
Beauty vs light: high vs low p_T



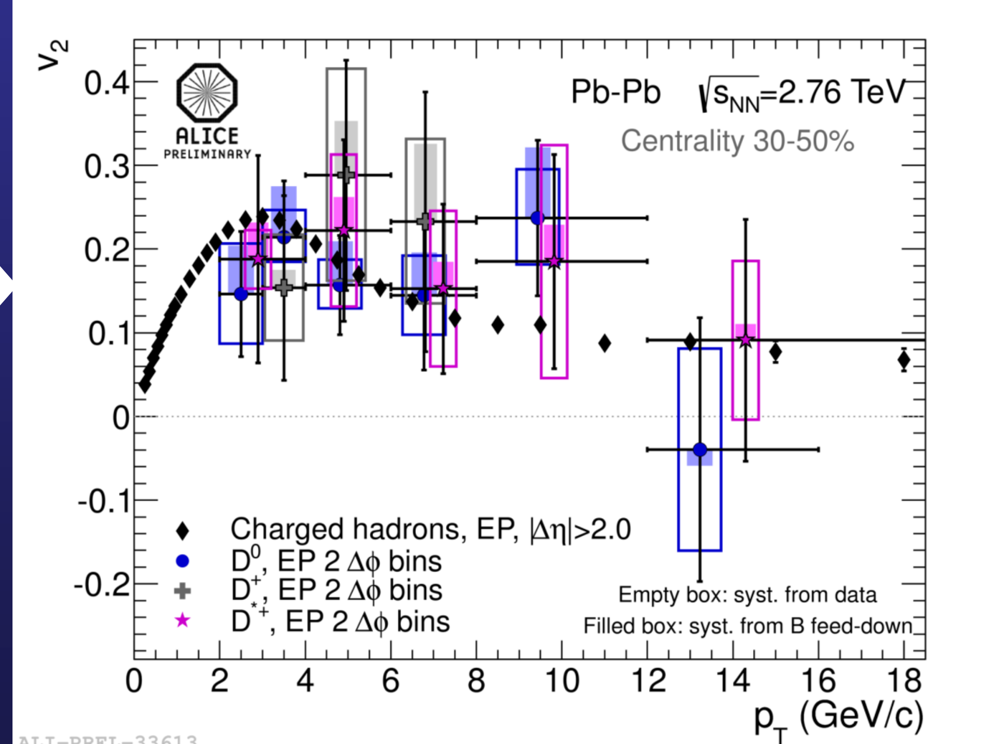
- ❑ Low p_T: different suppression for beauty and light flavours, but:
  - ❑ Different centrality
  - ❑ Decay kinematics
- ❑ High p_T: similar suppression for light flavour and b-tagged jets

HQ v_2 at the LHC

- 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



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

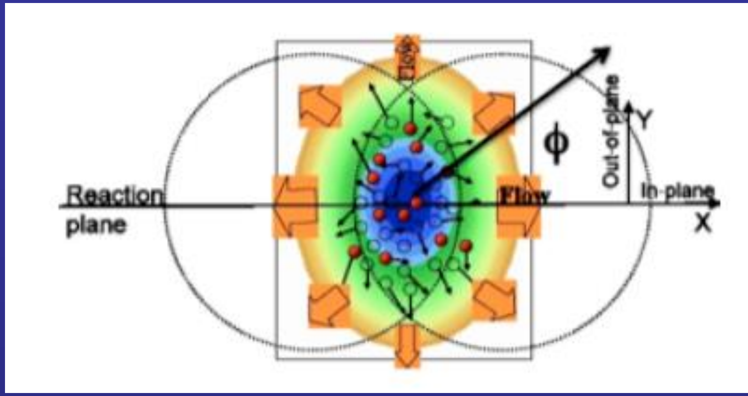


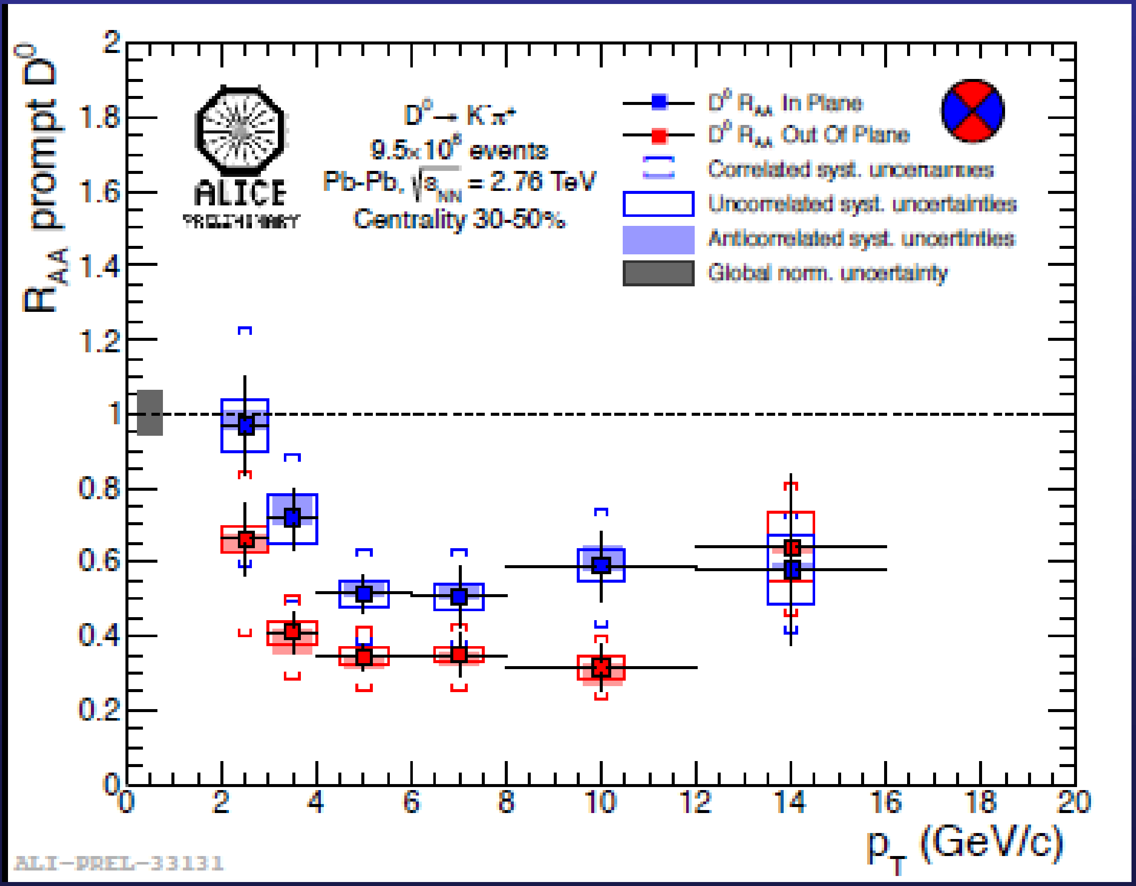
Indication of non-zero D meson v_2 (3σ effect) in $2<p_T<6$ GeV/c

26

EP dependence of R_{AA} (30-50%)

- ❑ Raw yield in and out of plane in 30-50%
- ❑ Efficiencies from MC simulations
- ❑ Feed-down subtraction with FONLL
- ❑ Reference: 7TeV pp data scaled to 2.76 TeV

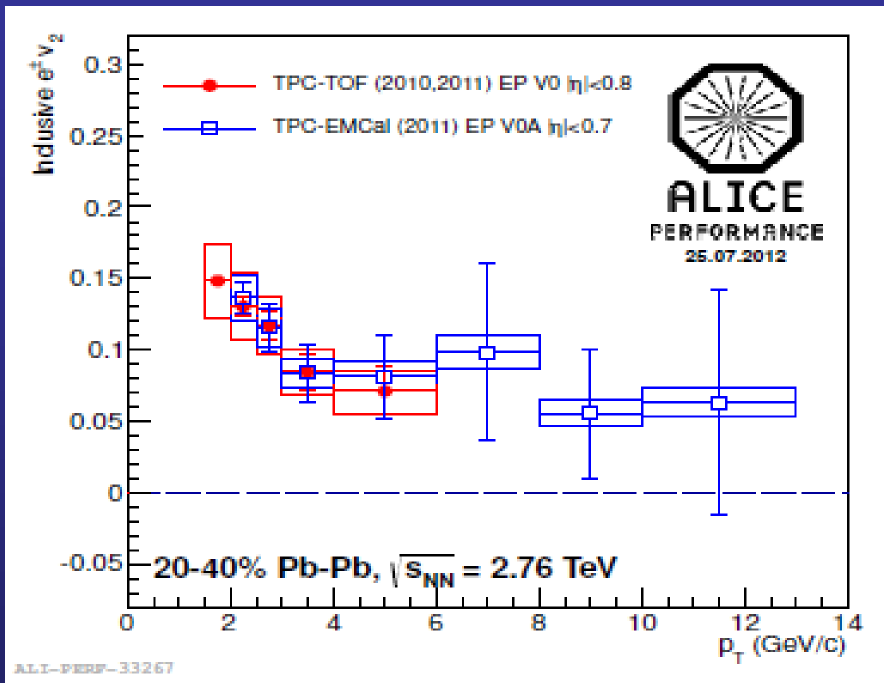




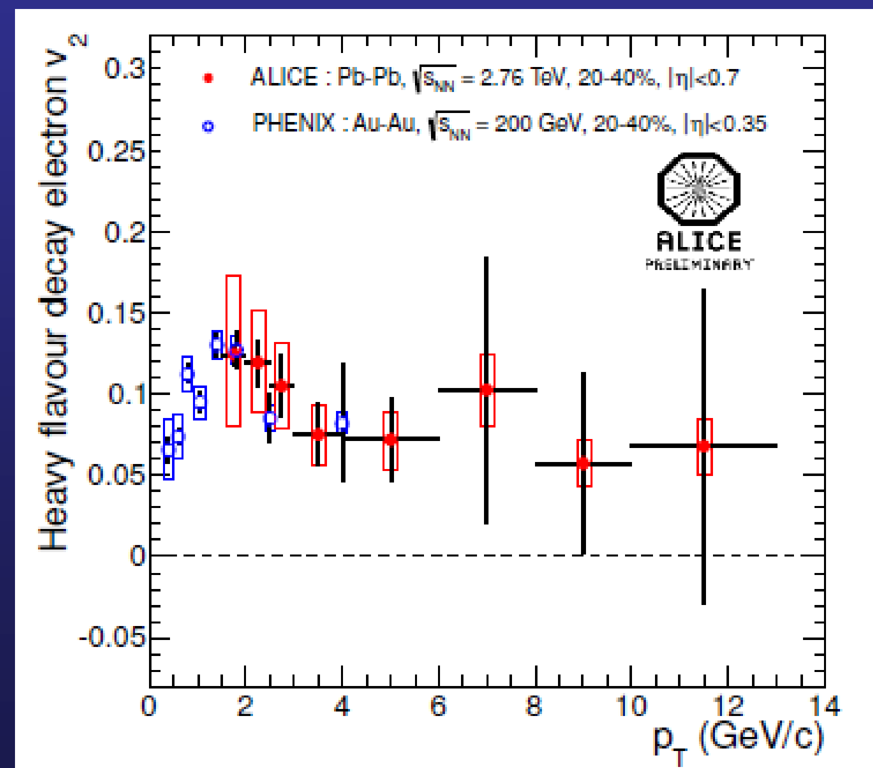
More suppression
out of plane
with respect to
in plane:
longer path length
at high p_T,
elliptic flow at low p_T

Electron v_2

- As for single-electron R_{AA}, different detection techniques according to p_T

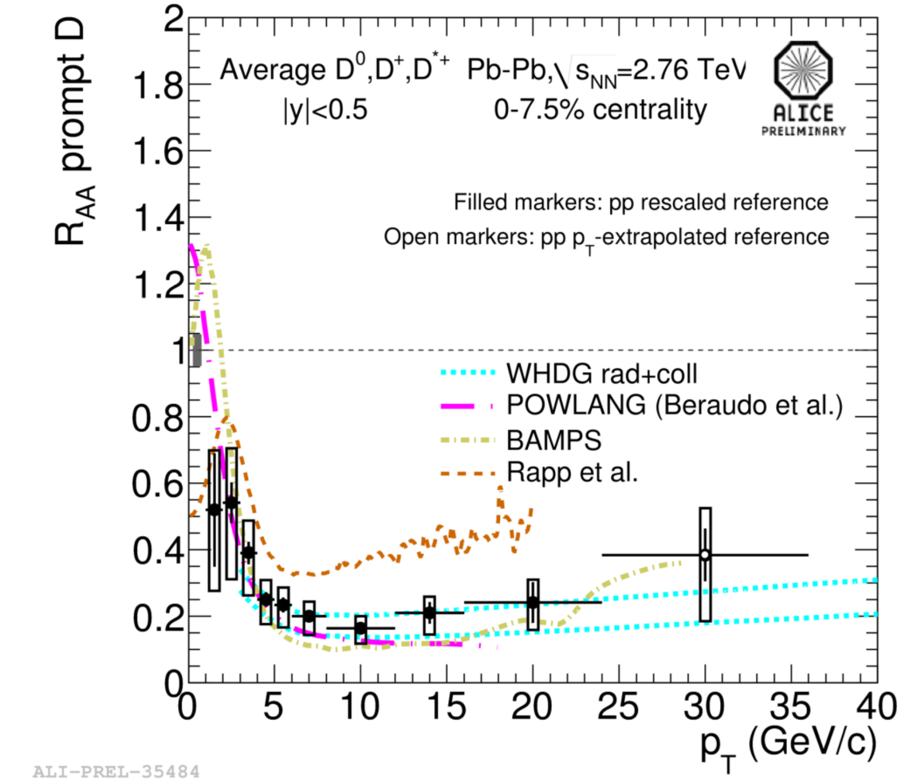


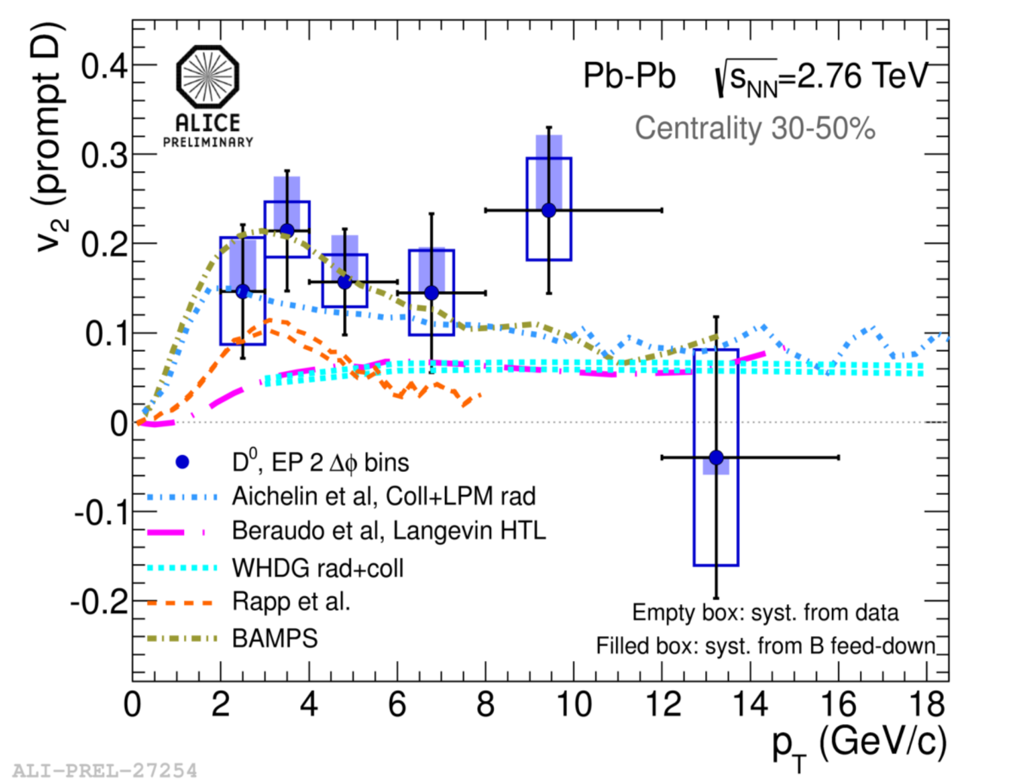
$$v_2^{HFE} = \frac{(1+R)v_2^{inclusive} - v_2^{background}}{R}, \quad R = \frac{N_{HFE}}{N_{background}}$$



- HFE $v_2>0$ observed in 20-40% $>3\sigma$ in $2<p_T<3$ GeV/c
- Suggests strong re-interaction with the medium
- Magnitude of v_2 comparable at RHIC/LHC in the common p_T range

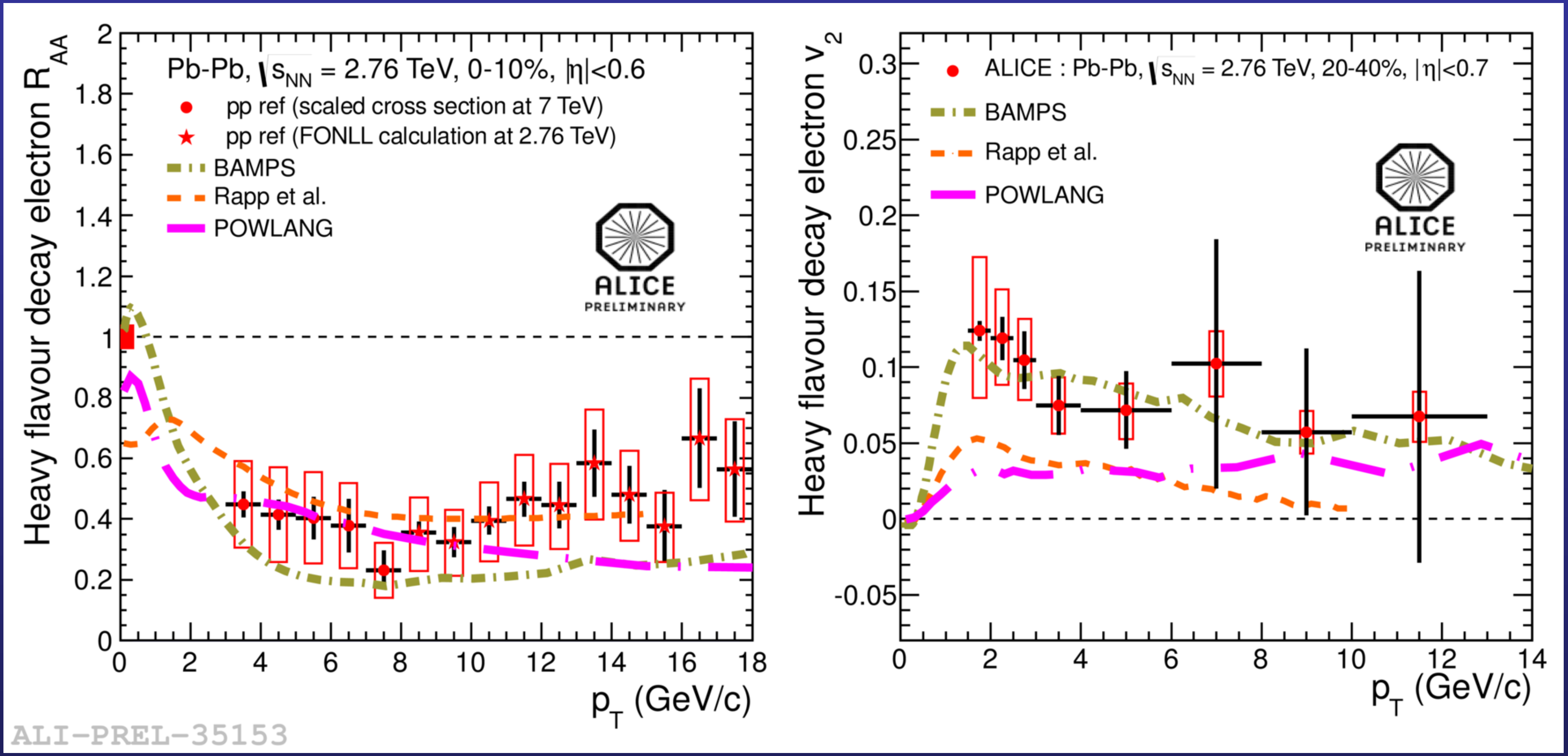
Data vs models: D-mesons





Consistent description of charm R_{AA} and v_2
very challenging for models,
can bring insight on the medium transport properties,
also with more precise data from future LHC runs

Data vs models: HFE



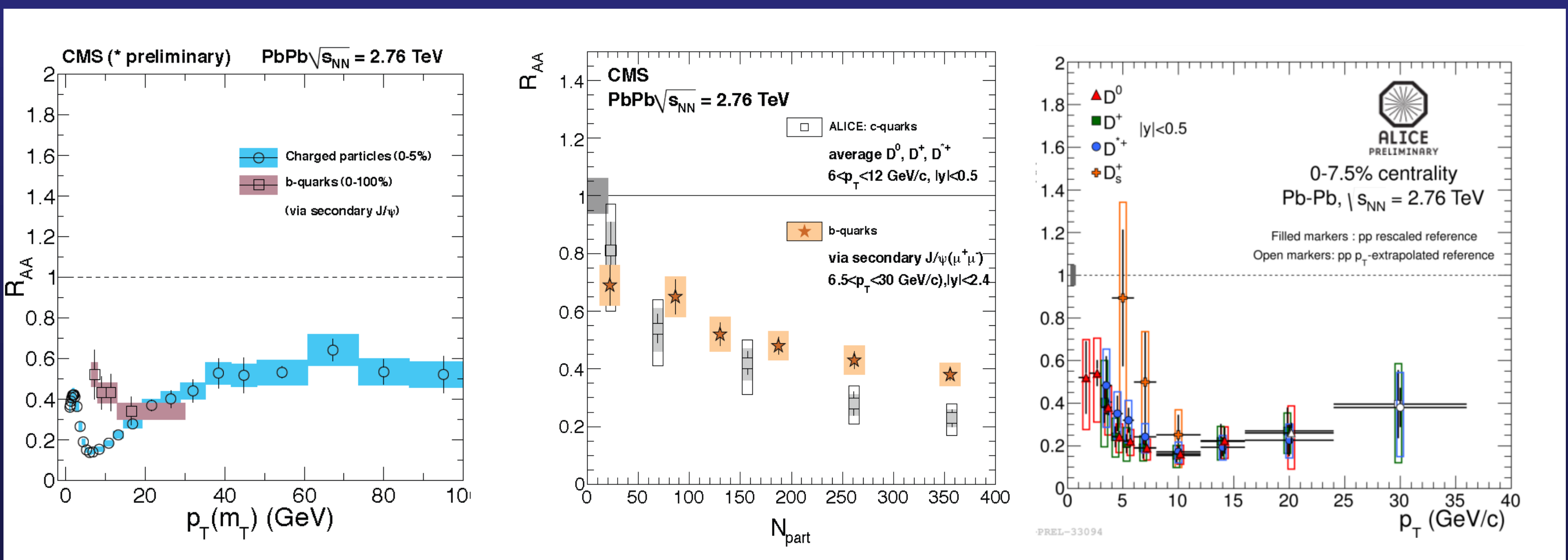
Simultaneous description of heavy-flavor electrons R_{AA} and v_2

⇓

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

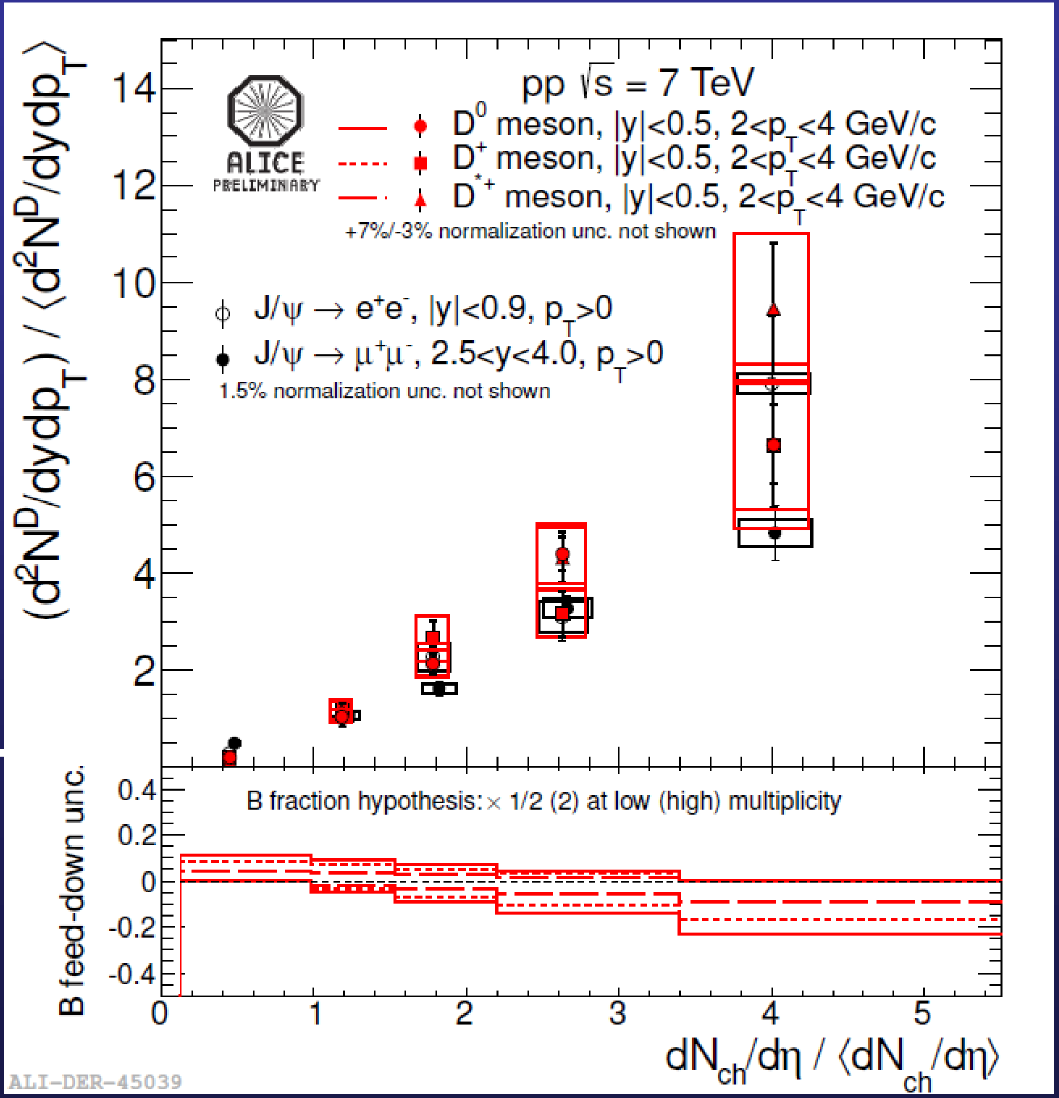


Intermezzo: multiplicity dependence of D and J/ψ yields

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

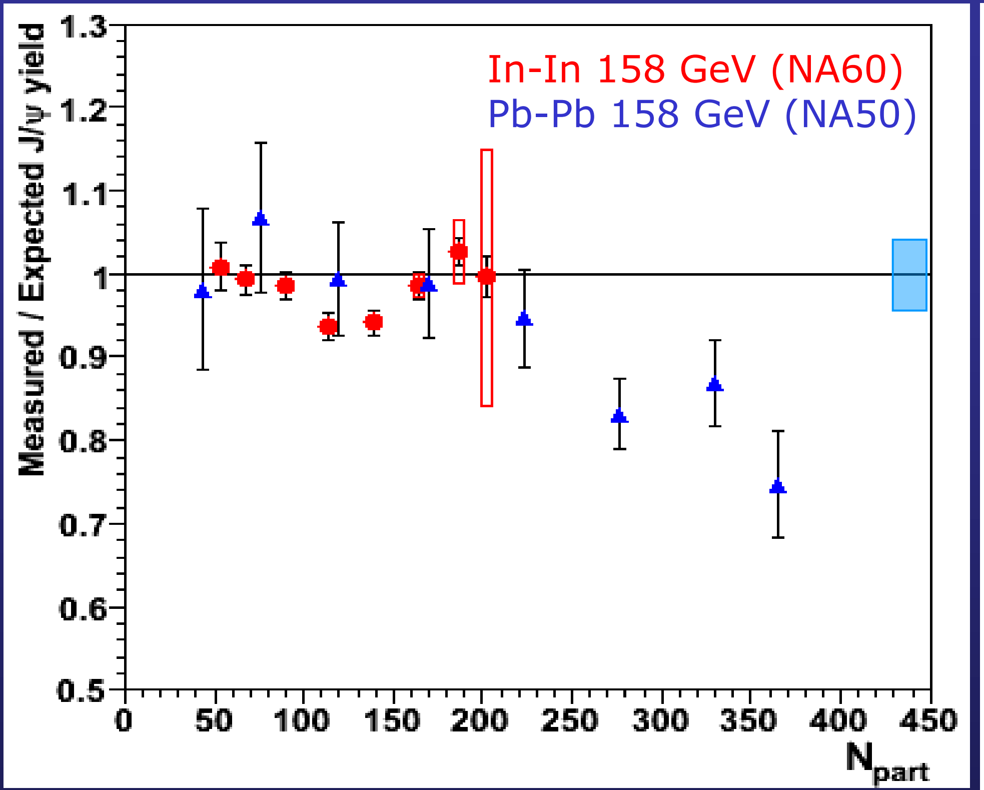
- The ~linear increase of the yields with charged multiplicities and the similar behaviour for D and J/ψ are remarkable…..

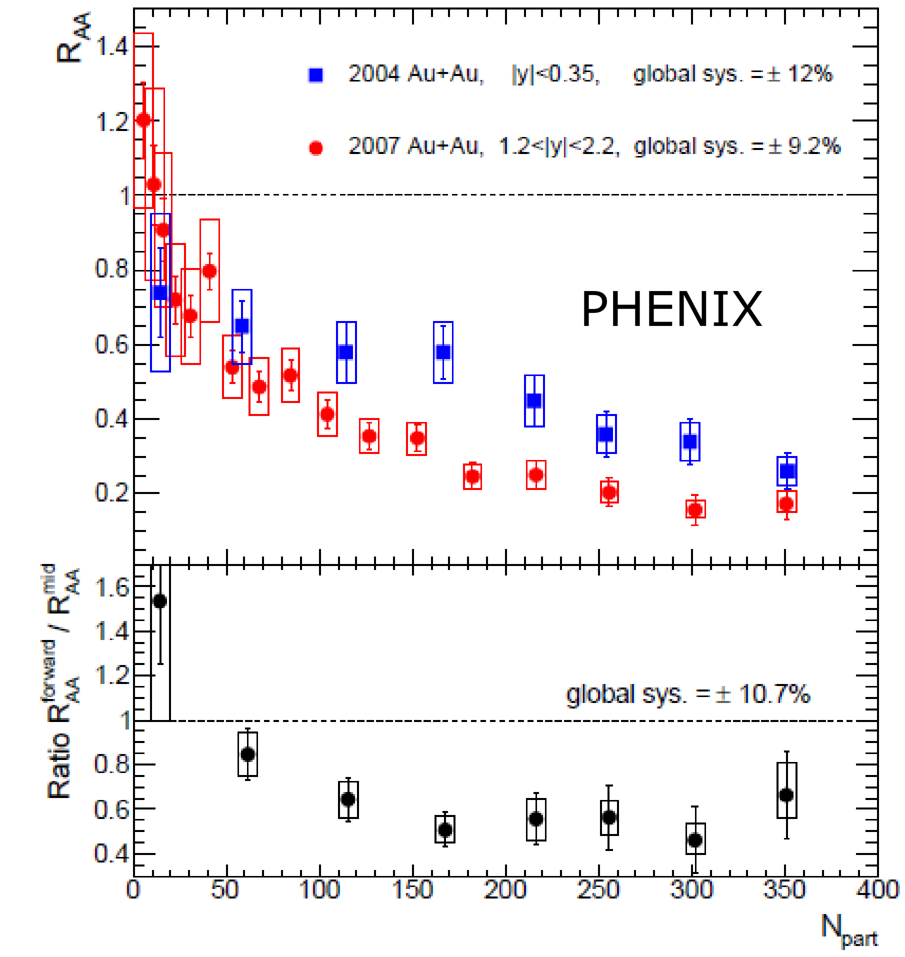
…but need to be explained!



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 !

Great expectations for LHC

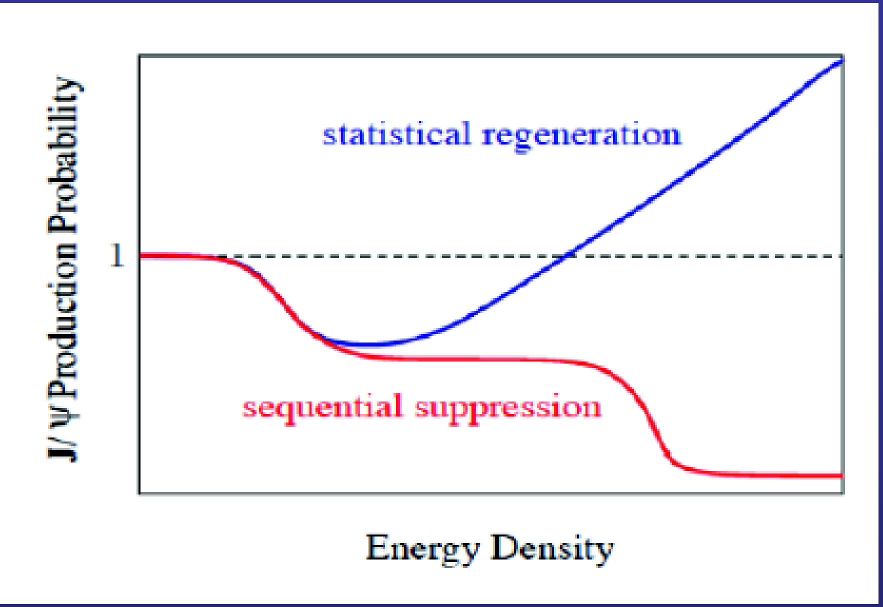
…along two main lines

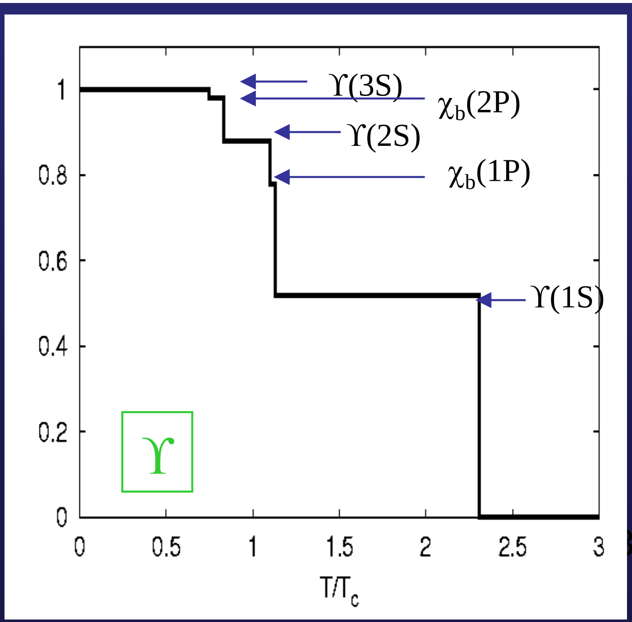
1) Evidence for charmonia (re)combination: now or never!

2) A detailed study of bottomonium suppression

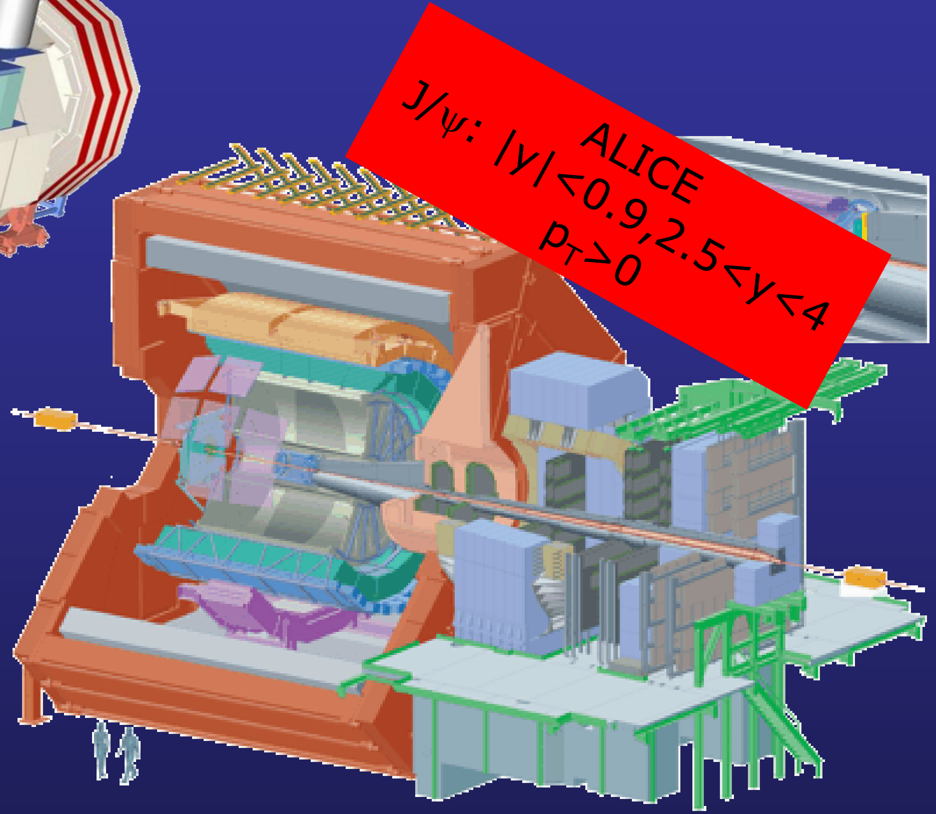
❑ Finally a clean probe, as J/ψ at SPS

Yes, we can!





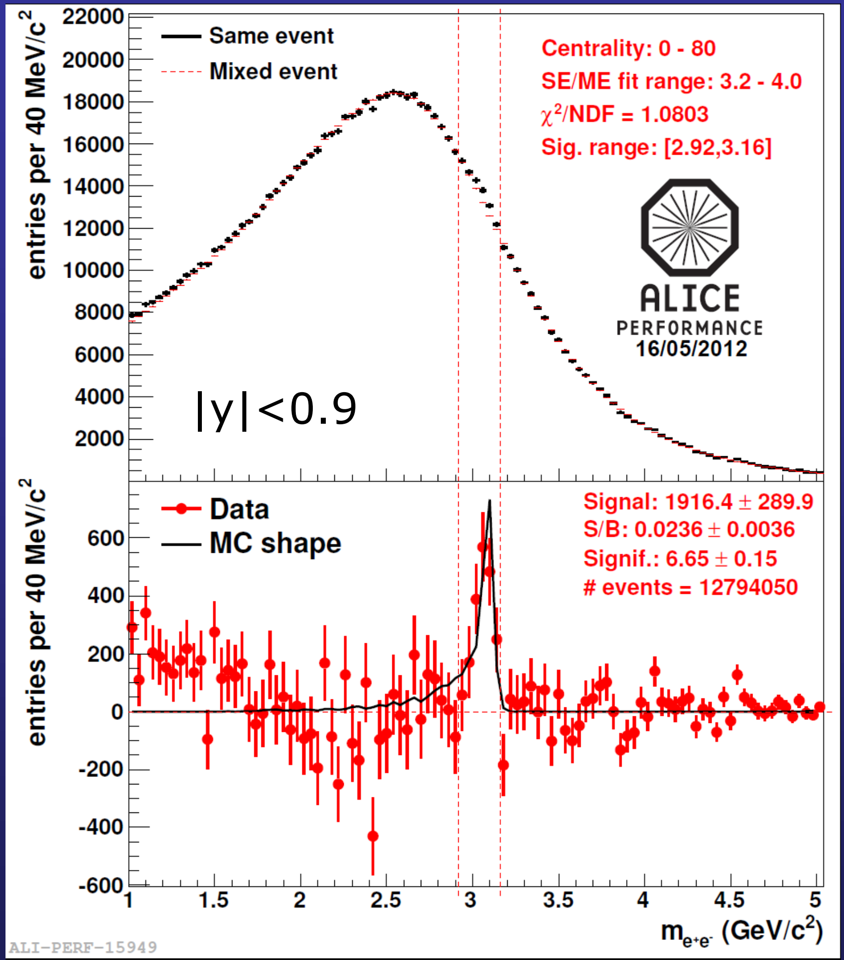
Once again, the main actors

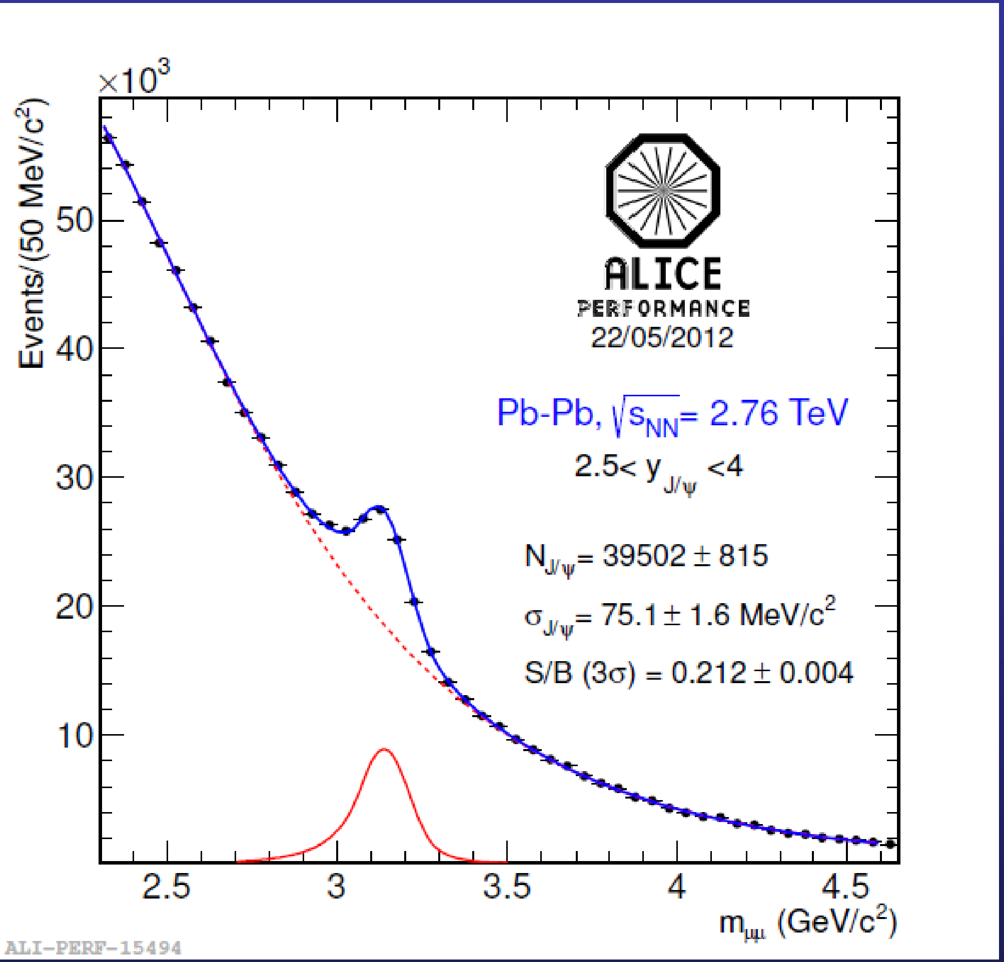


Complementary kinematic coverage!

Will LHCb join the club ?

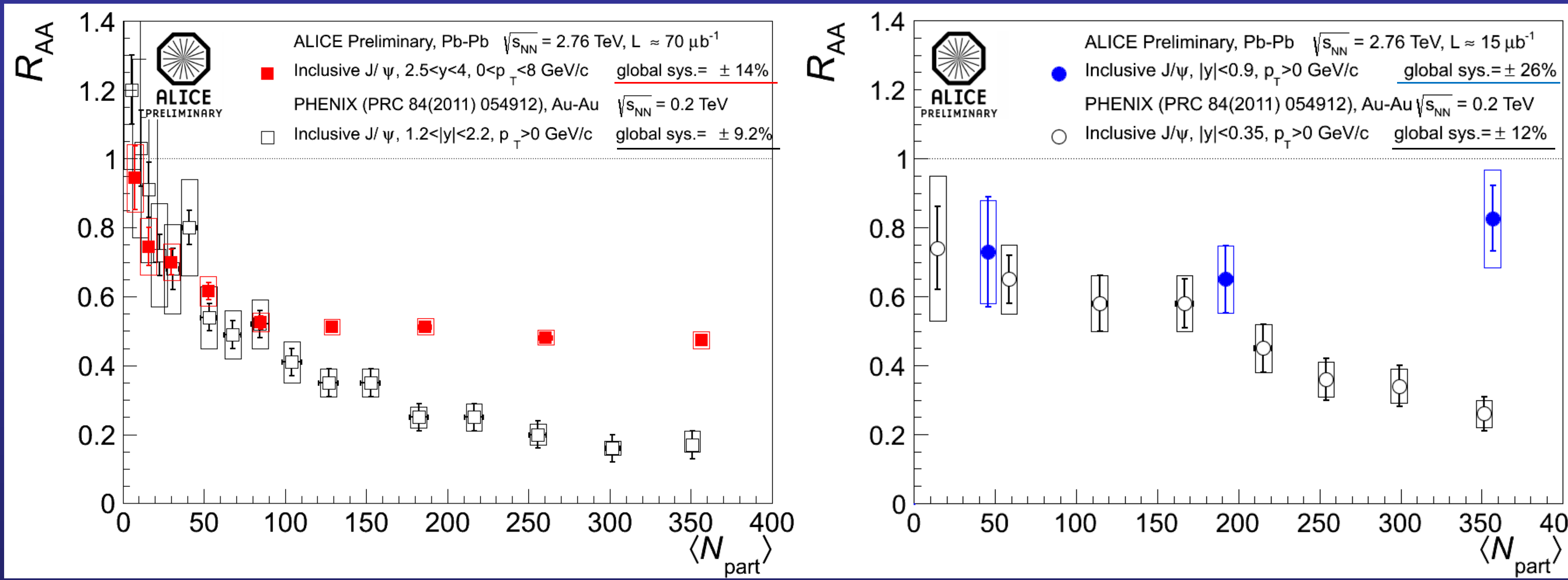
ALICE, focus on low-p_T J/ψ





- 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 vs PHENIX

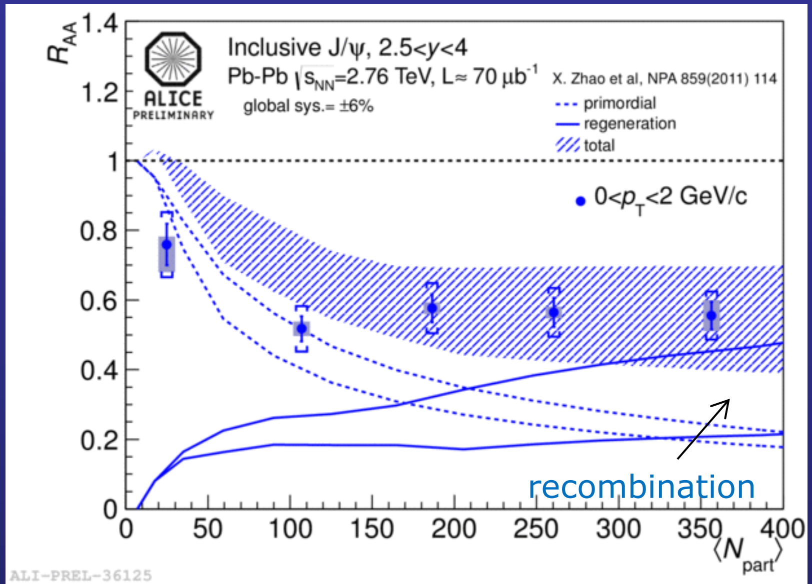


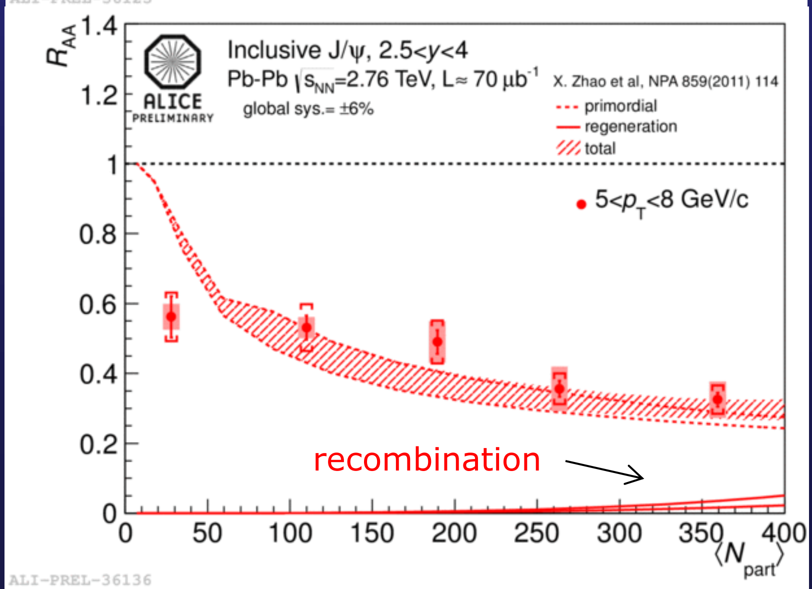
- Even at the LHC, NO rise of J/ψ yield for central events, but….
- Compare with PHENIX
  - Stronger centrality dependence at lower energy
  - Systematically larger R_{AA} values for central events in ALICE

Is this the expected signature for (re)combination ?

R_{AA} vs ⟨N_{part}⟩ in p_T bins

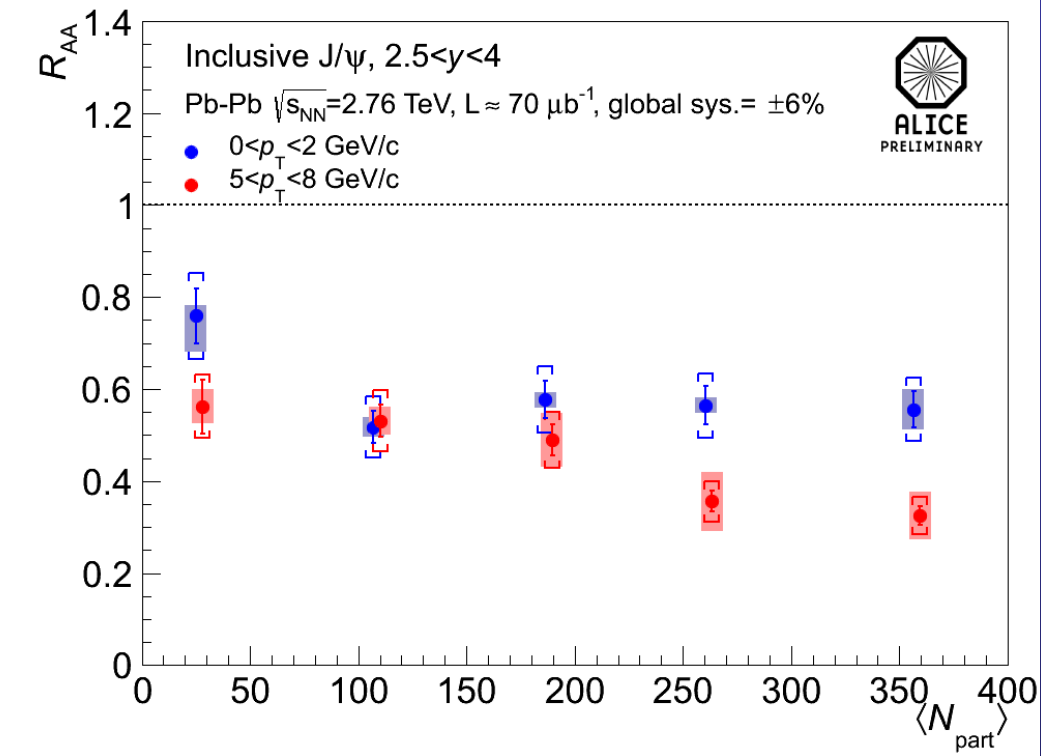
- J/ψ production via (re)combination should be more important at low transverse momentum

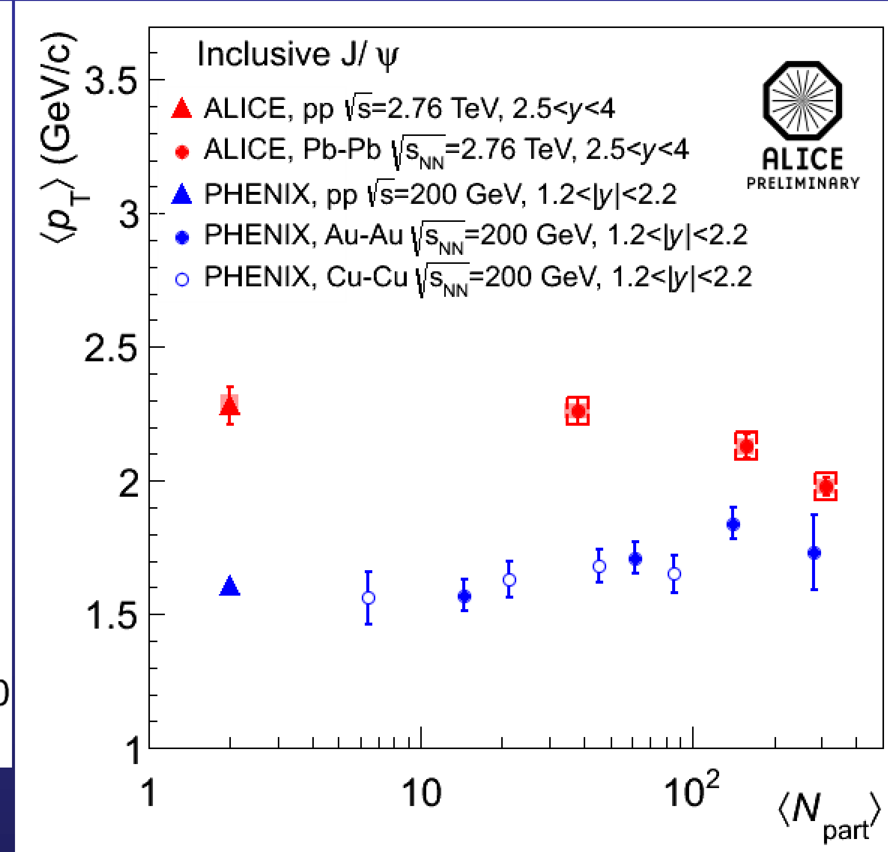




- Compare R_{AA} vs ⟨N_{part}⟩ for low-p_T (0<p_T<2 GeV/c) and high-p_T (5<p_T<8 GeV/c) J/ψ
- Different suppression pattern for low- and high-p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ
- In the models, ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible → fair agreement from N_{part}~100 onwards

R_{AA} vs p_T



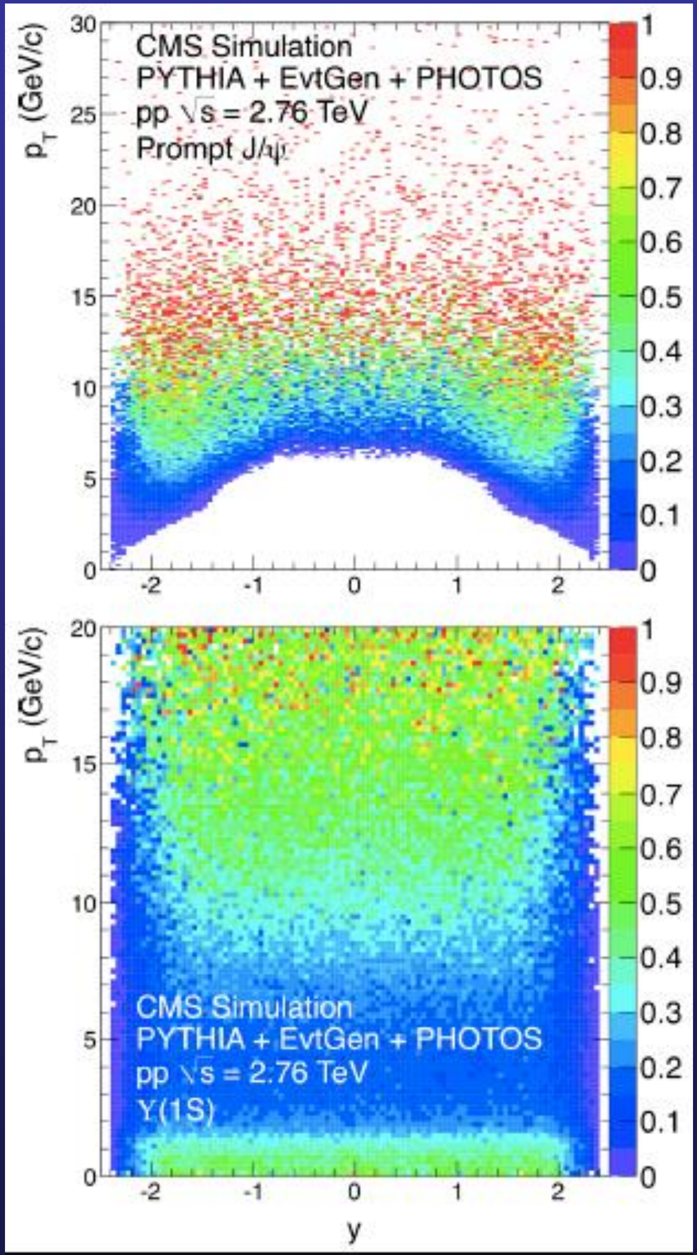


- Expect smaller suppression for low-p_T J/ψ → observed!

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

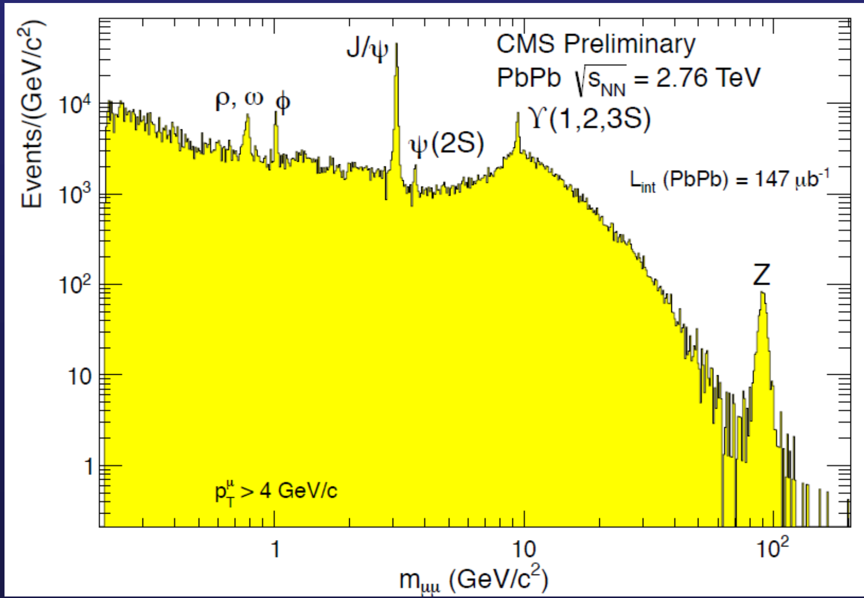
- Fair agreement with transport models and statistical model

CMS, focus on high p_T

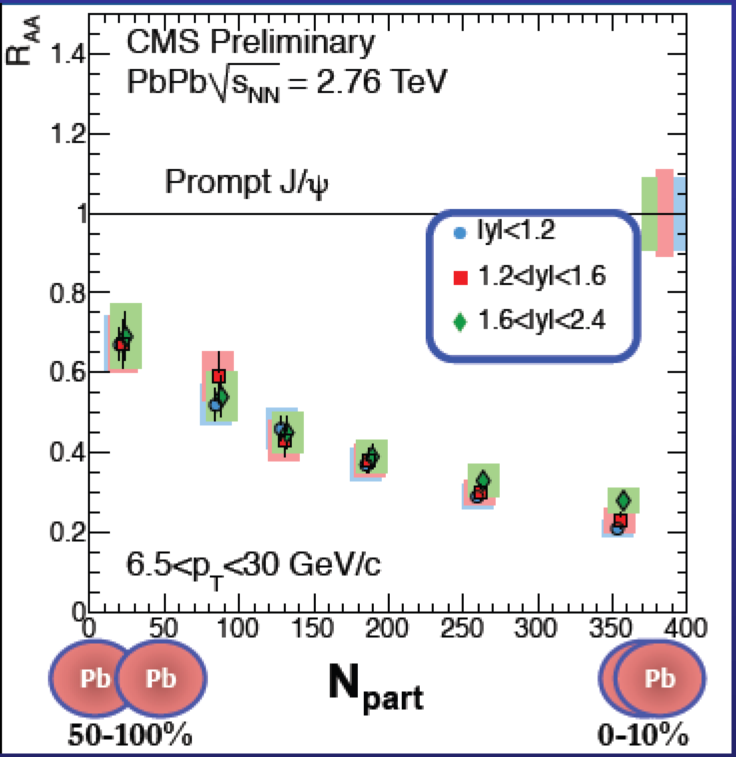


- Muons need to overcome the magnetic field and energy loss in the absorber
- Minimum total momentum p~3-5 GeV/c to reach the muon stations
- Limits J/ψ acceptance
  - Midrapidity: p_T>6.5 GeV/c
  - Forward rapidity: p_T>3 GeV/c

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



CMS explores the high p_T region

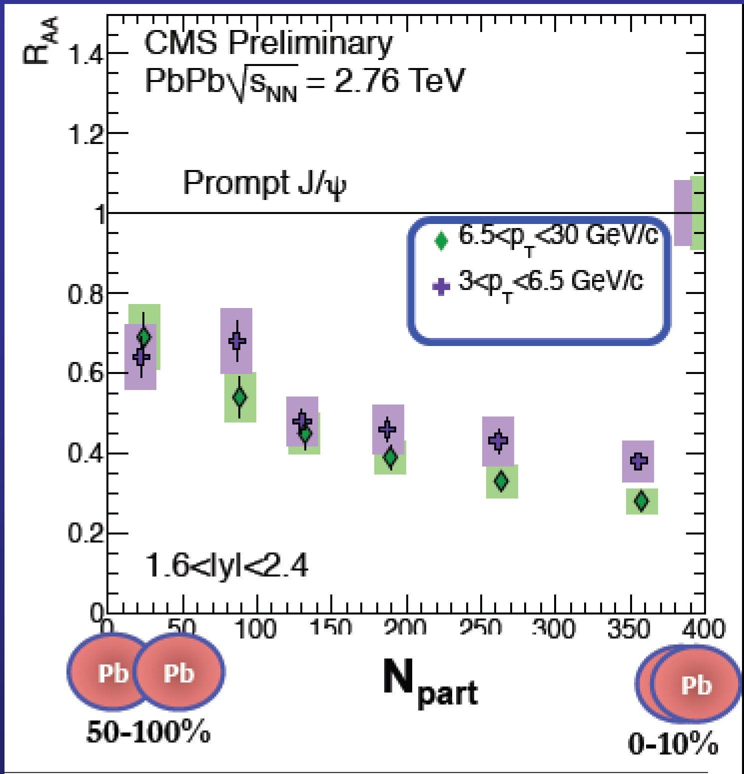


Centrality dep. in

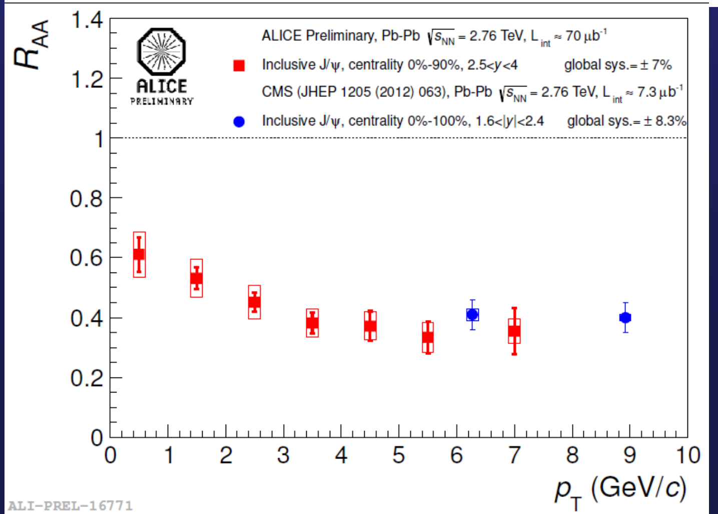
p_T →

← y

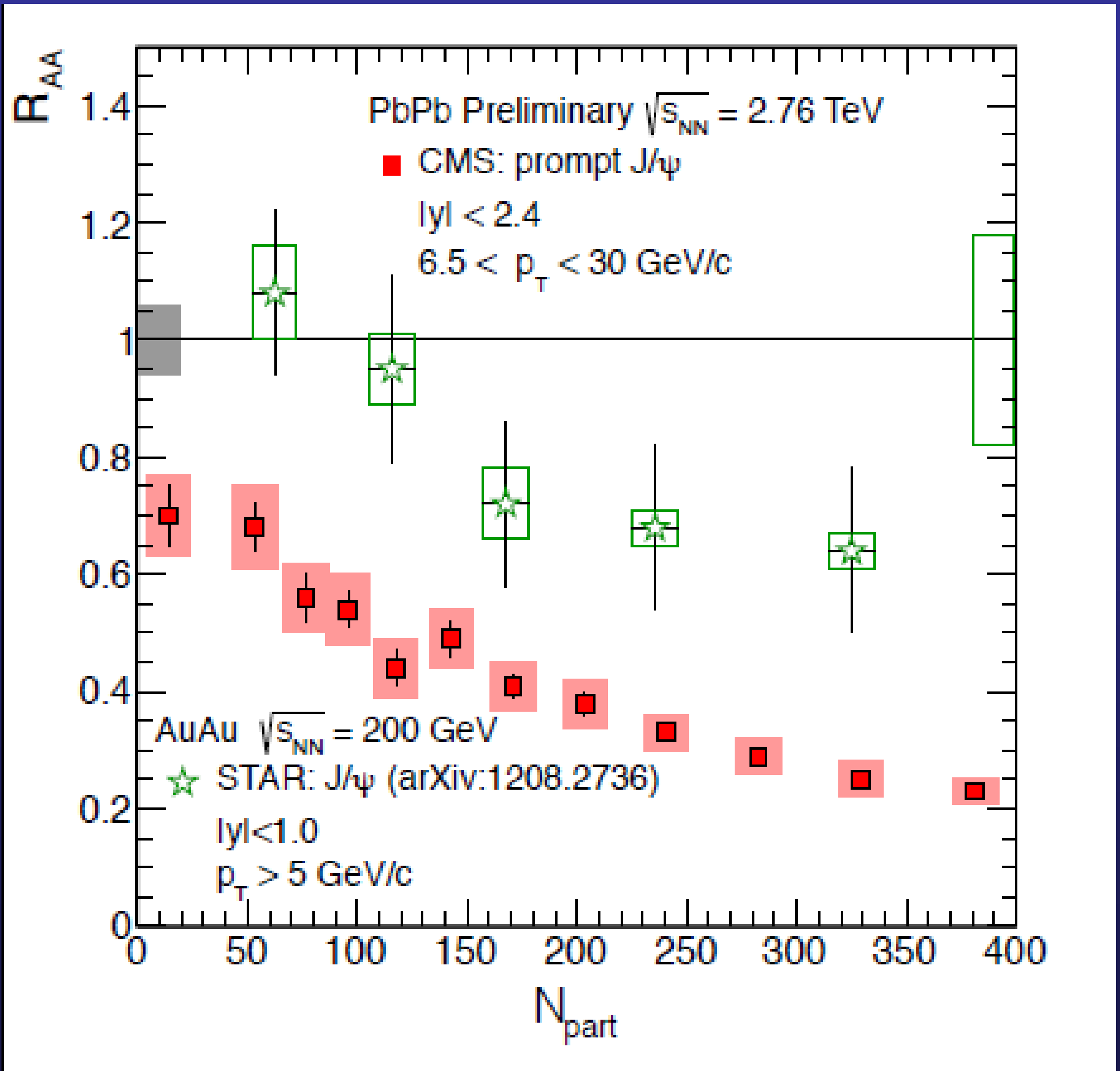
bins



- (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)



CMS vs STAR high-p_T suppression



- (Re)combination effects should be negligible

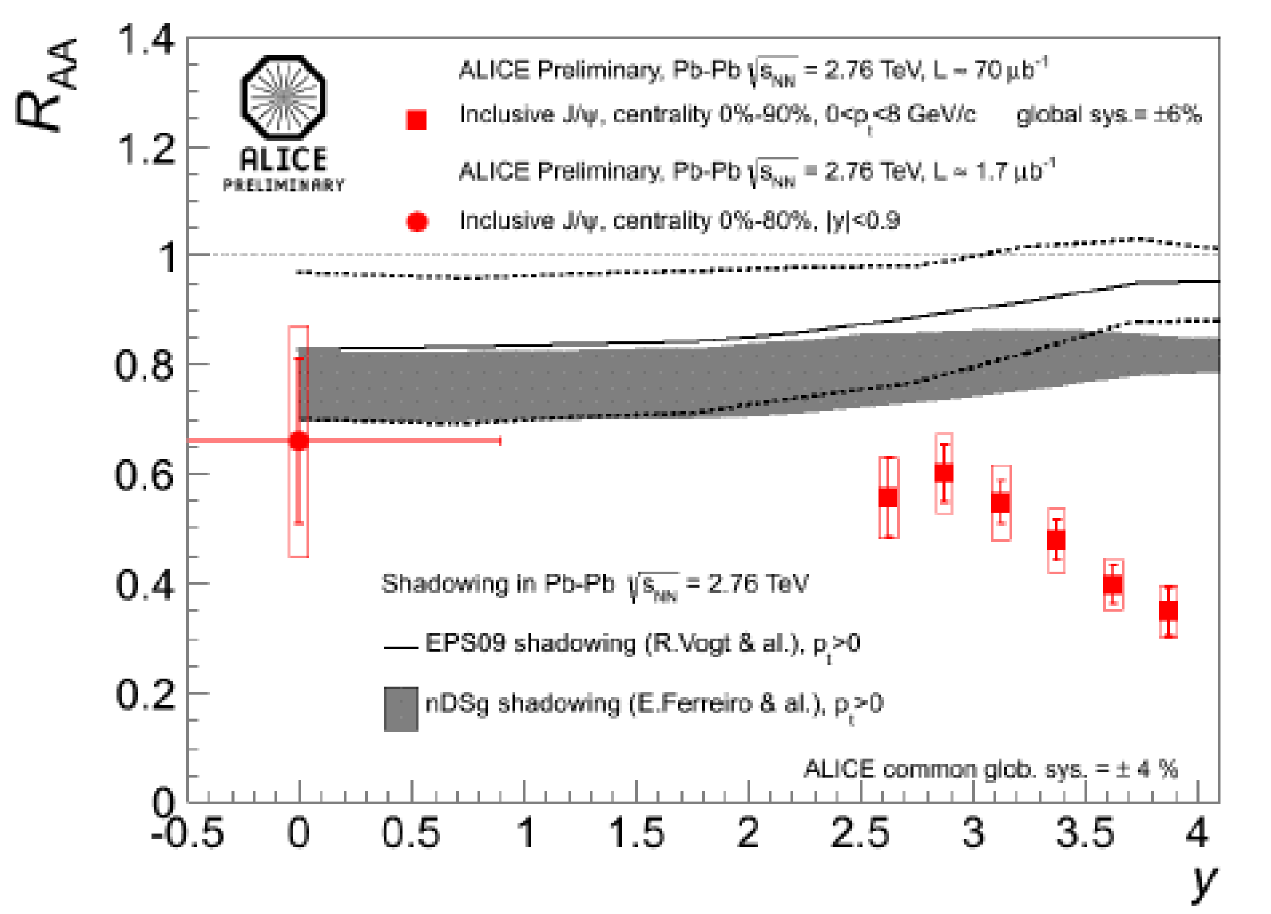
- CMS: prompt J/ψ
  p_T > 6.5 GeV/c , |y|<2.4
  0-5%
  → factor 5 suppression
  60-100%
  → factor 1.4 suppression

- STAR: inclusive J/ψ
  p_T>5 GeV/c , |y|<1

High p_T: less suppression at RHIC than at LHC

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 slides)
- PHENIX-like ??



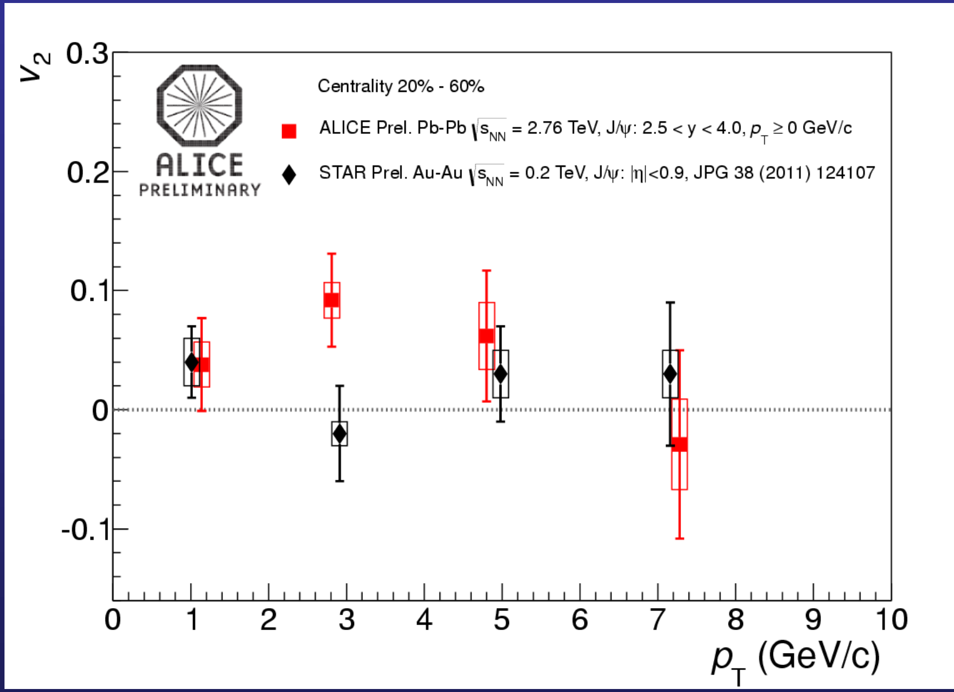
Shadowing estimate (EPS09, nDSg)

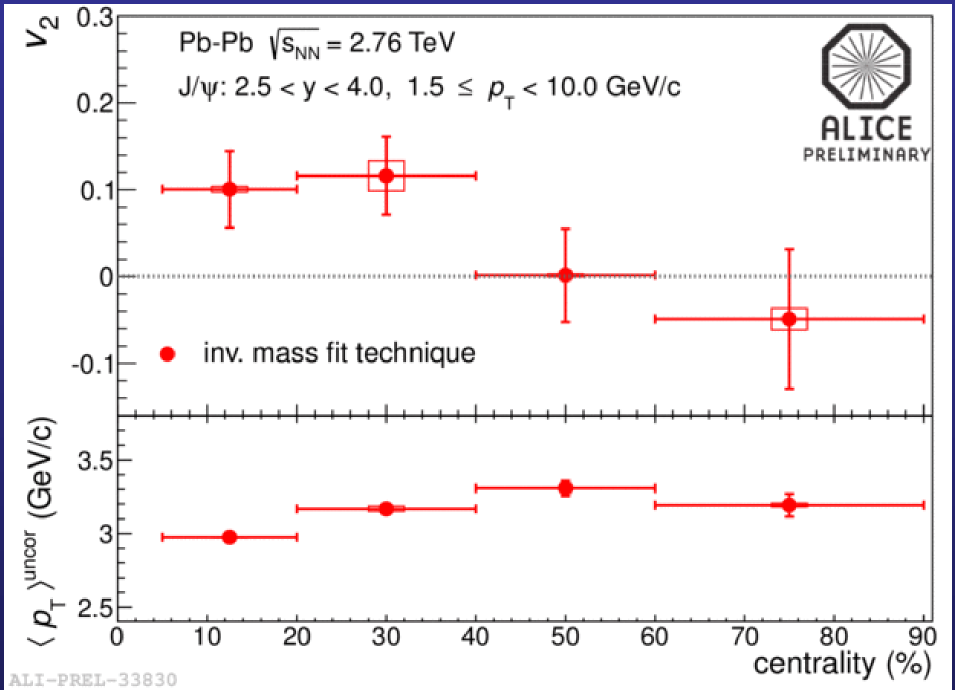
Compatible with central, NOT with forward y

More general CNM issue

Does the J/ψ finally flow ?

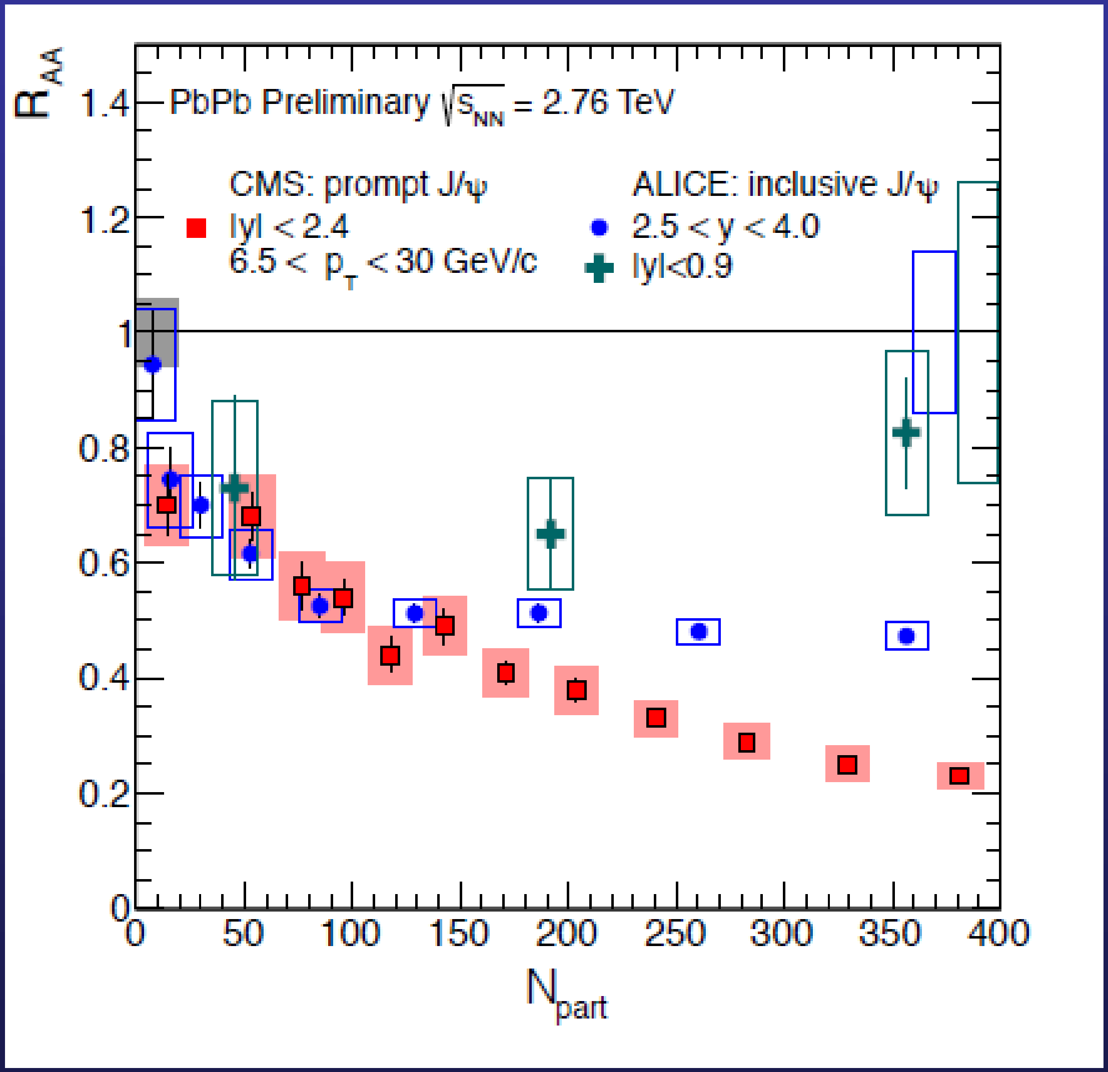
- The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy



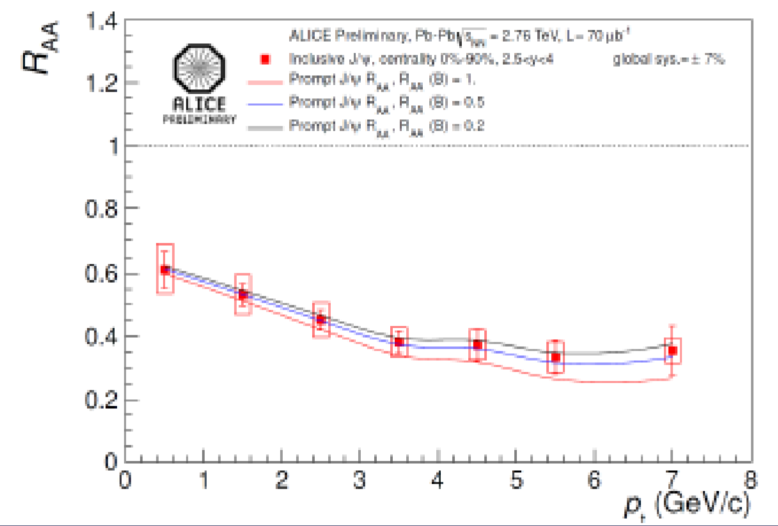


- First hint for J/ψ flow in heavy-ion collisions (ALICE, forward y) !
- Significance up to 3.5 σ for chosen kinematic/centrality selections
- Qualitative agreement with transport models including regeneration

J/ψ at the LHC: a "summary" plot

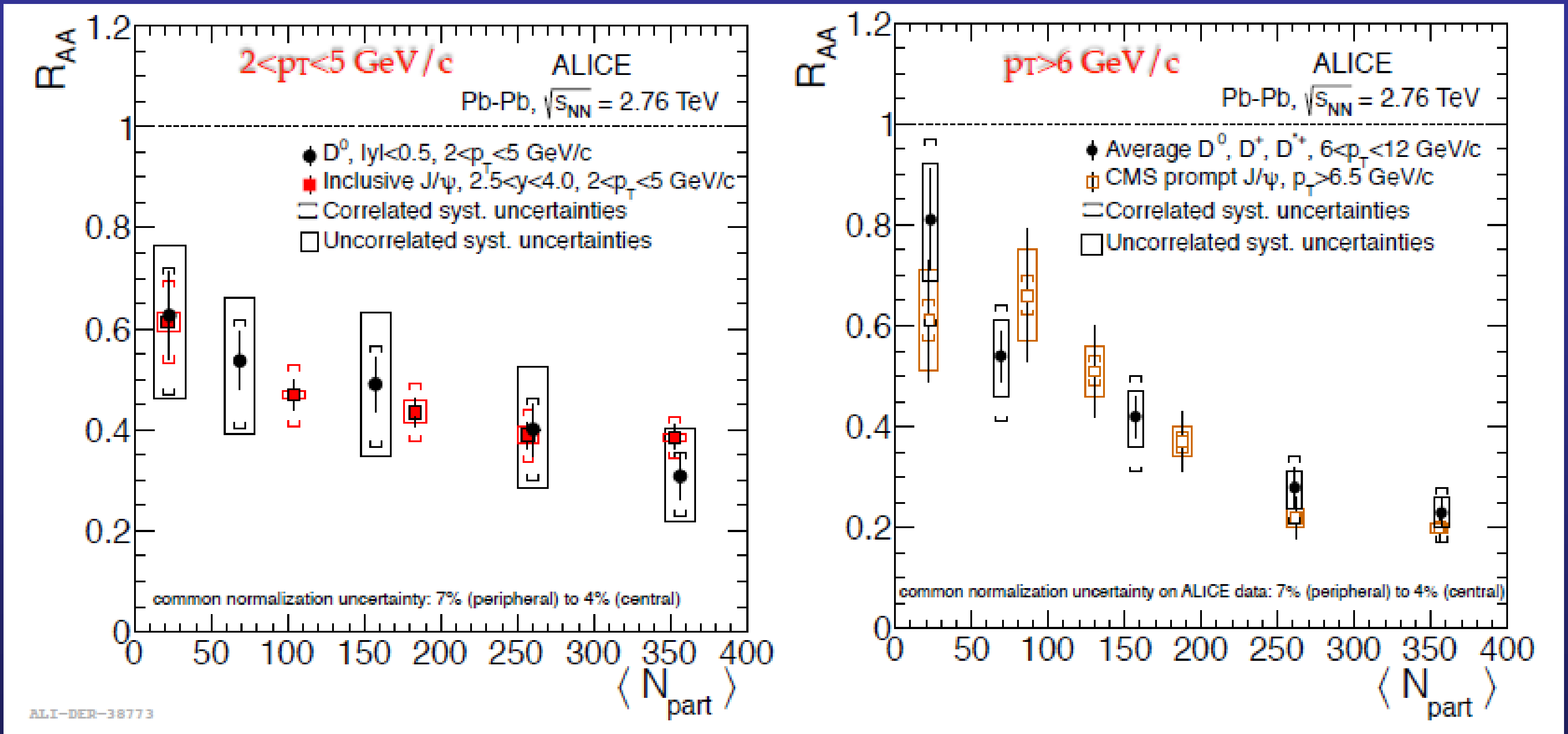


- Main "qualitative" features now explored
- Precise theory calculations are now needed!
- Effect of "inclusive" (ALICE) vs "prompt" (CMS) expected to be small



"Onset" of regeneration at small y, p_T ?

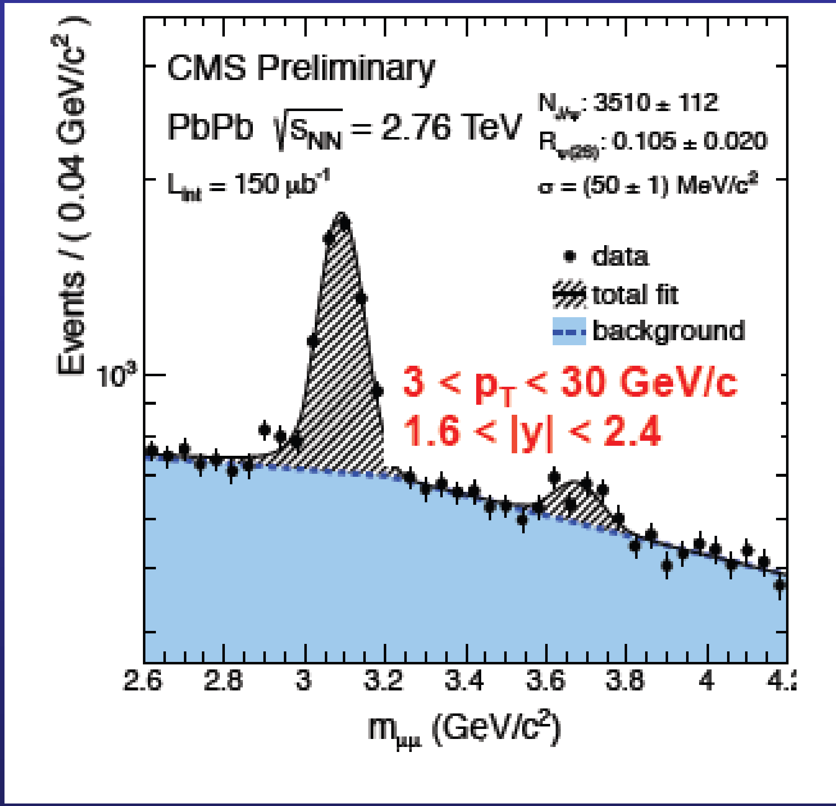
J/ψ and open charm, more questions

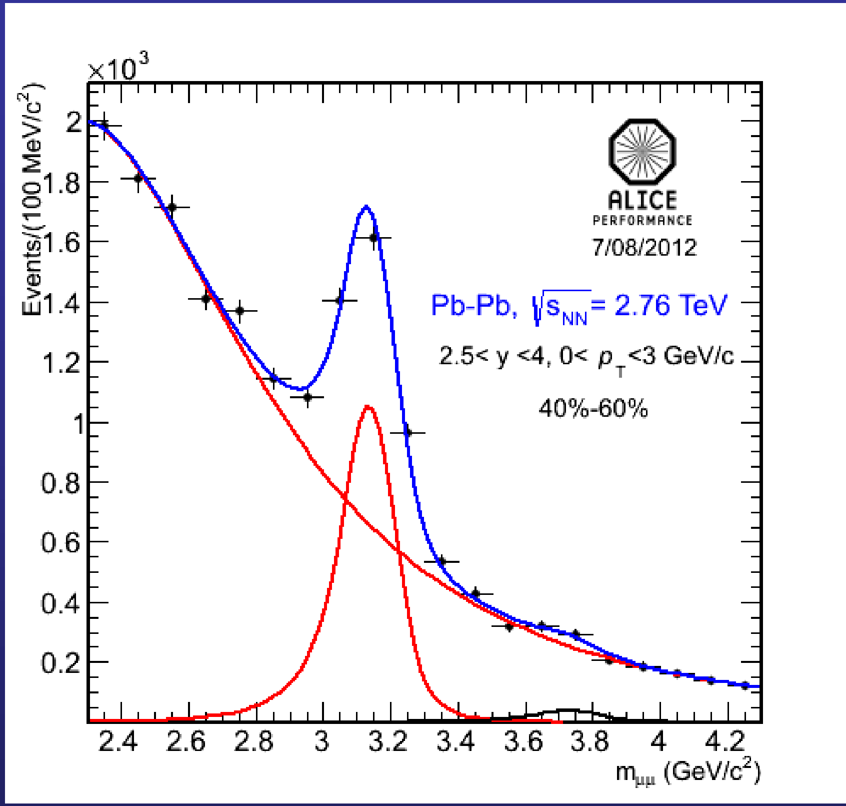


[ALICE Coll. arXiv:1203.2160 (2012)] [CMS Coll., JHEP 05 (2012) 063]

- Is the apparent similarity of D and J/ψ R_{AA} telling us something ?
- In principle suppression mechanisms are different (en. loss vs suppression) but….

ψ(2S): CMS vs ALICE

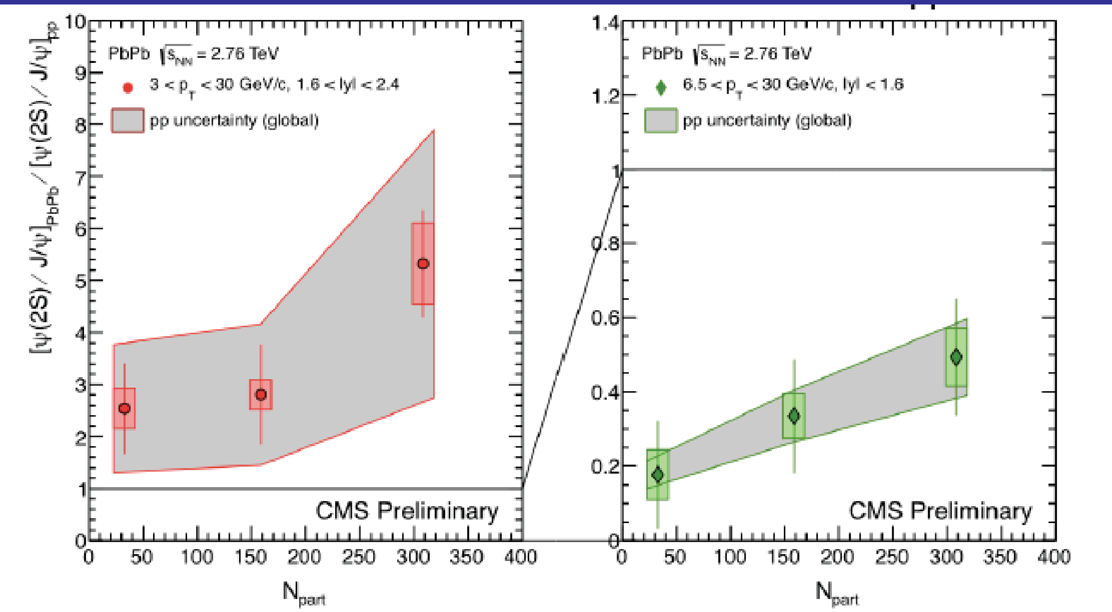


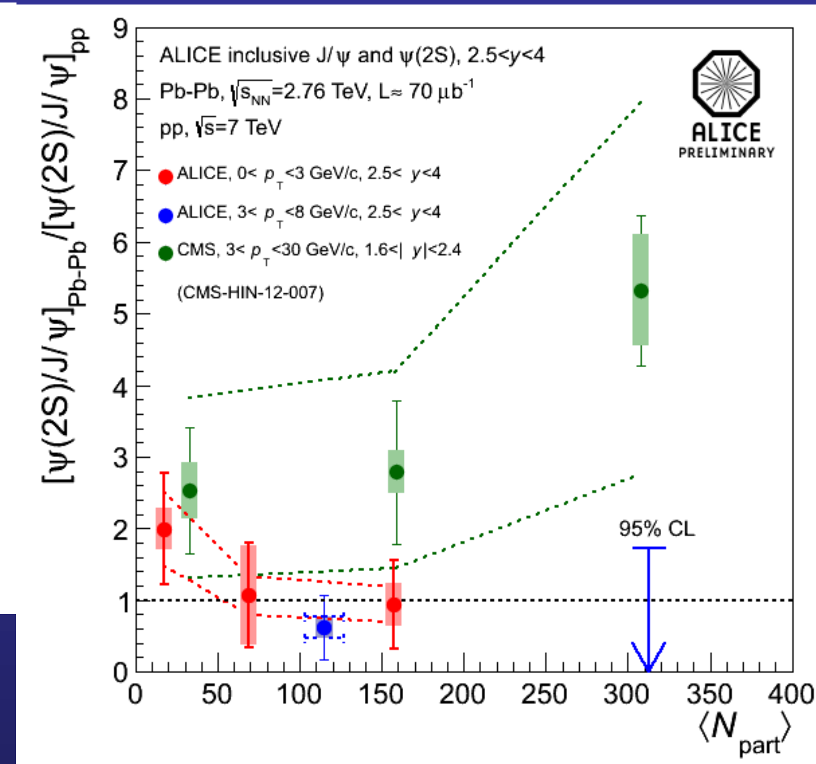


- ψ(2S) much less bound than J/ψ
- Results from the SPS showed a larger suppression than for J/ψ (saturating towards central events ? One of the landmarks of stat. model)
- No results from RHIC in Au-Au
- Seen by both CMS (much better resolution!) and ALICE, different kinem.

Expectations for LHC ?

Enhancement/suppression ?





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

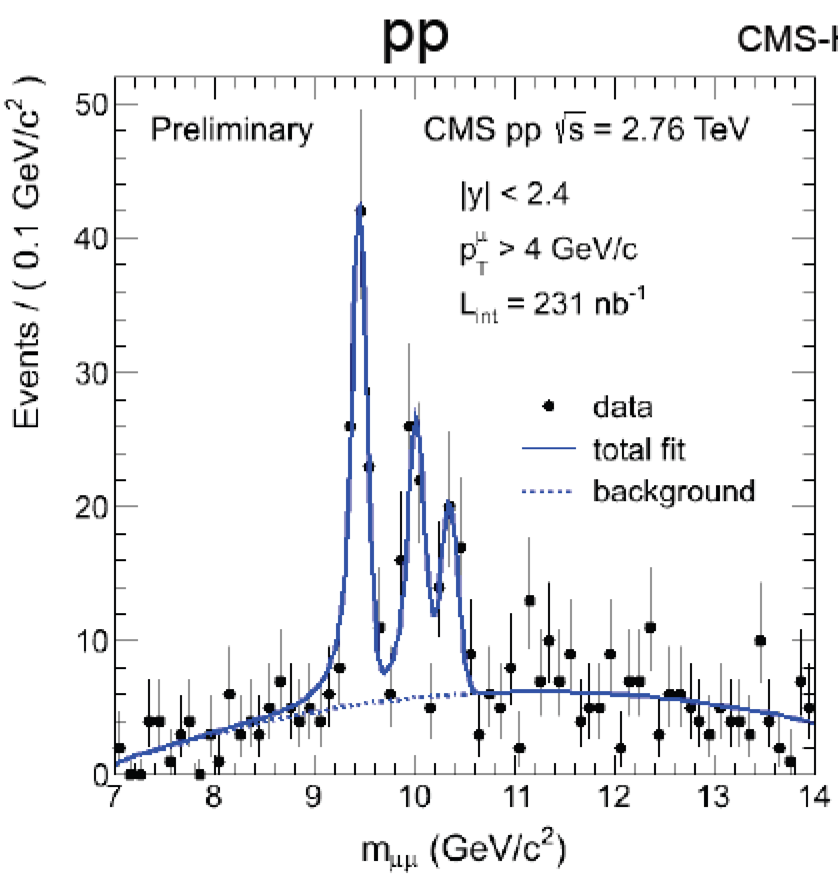
ALICE excludes a large enhancement

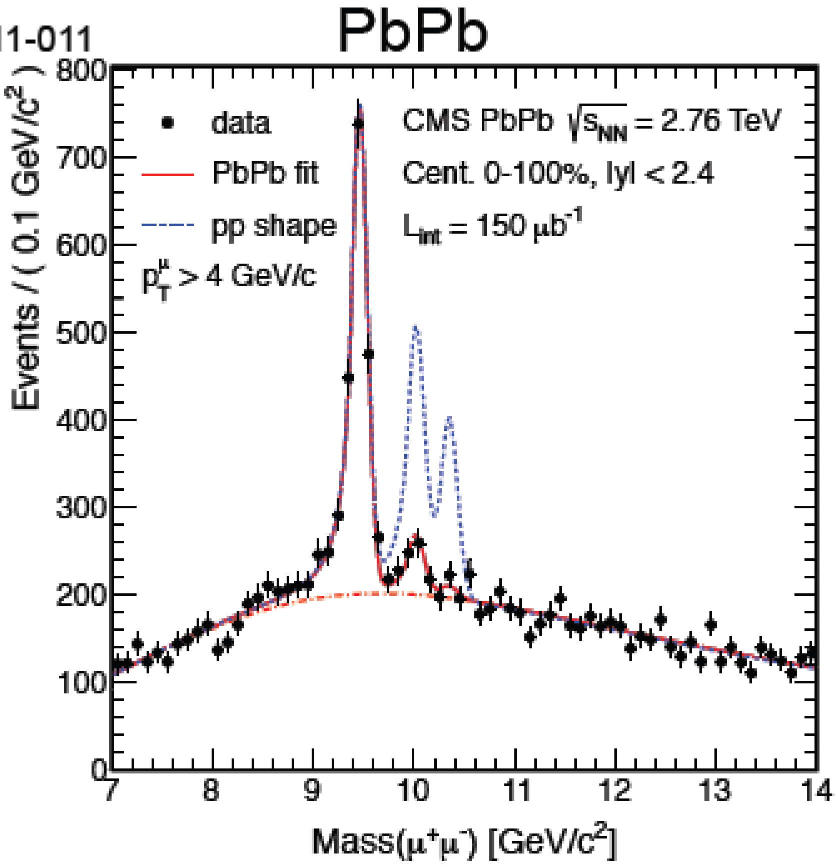
- At SPS, the suppression increased with centrality (the opposite for CMS)
- Overall interpretation is challenging
- ALICE vs CMS: should we worry? Probably not, seen the size of the errors
- Large uncertainties: signal extraction, pp reference
- Work needed to reduce systematics

Finally, the Υ

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

CMS-HIN-11-011





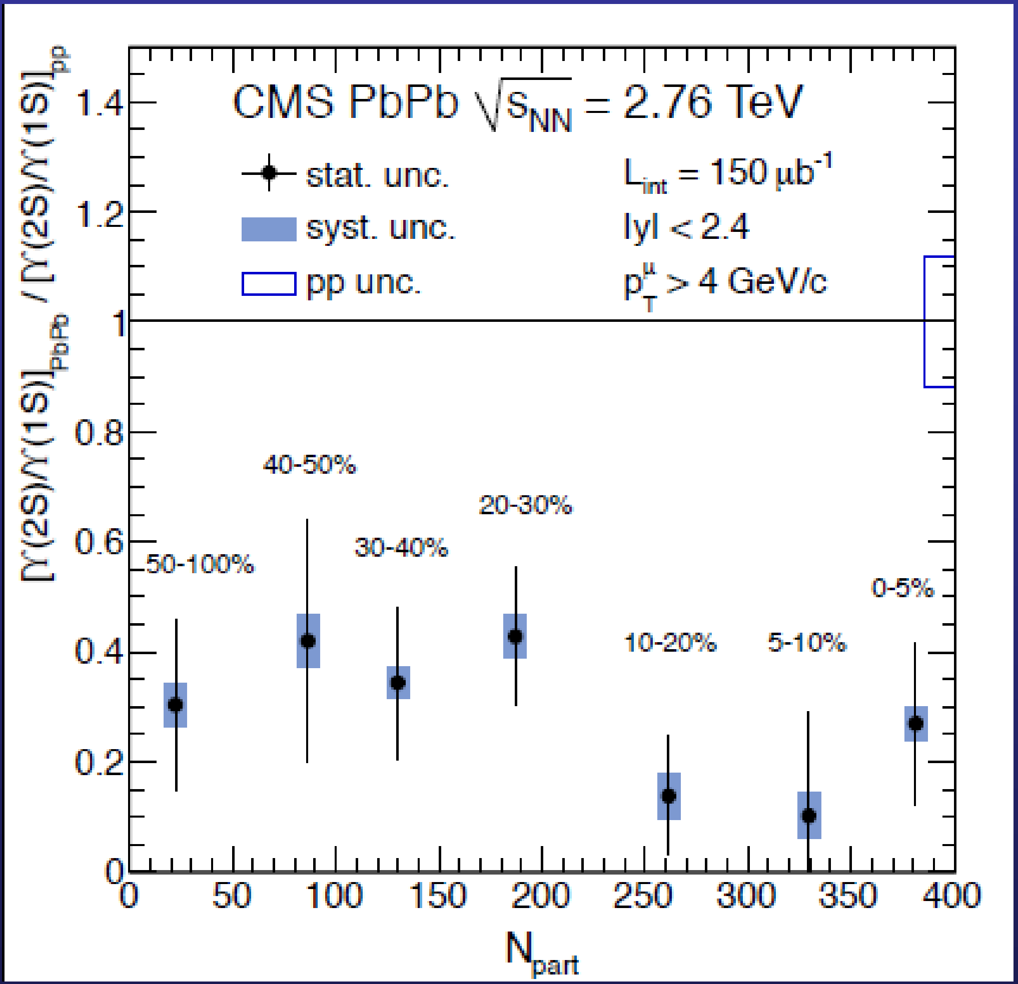
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\rm pp} = 0.56 \pm 0.13 \pm 0.01$$

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

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

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

Strong suppression of Υ(2S), wrt to Υ(1S)

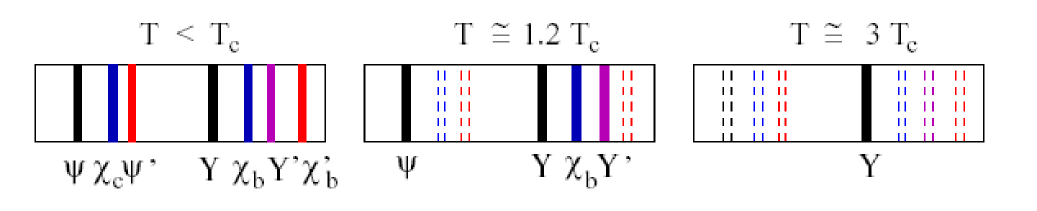


- Separated Υ(2S) and Υ(3S)
- Measured Υ(2S)/Υ(1S)double ratio vs. centrality
  - centrality integrated

$$\frac{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

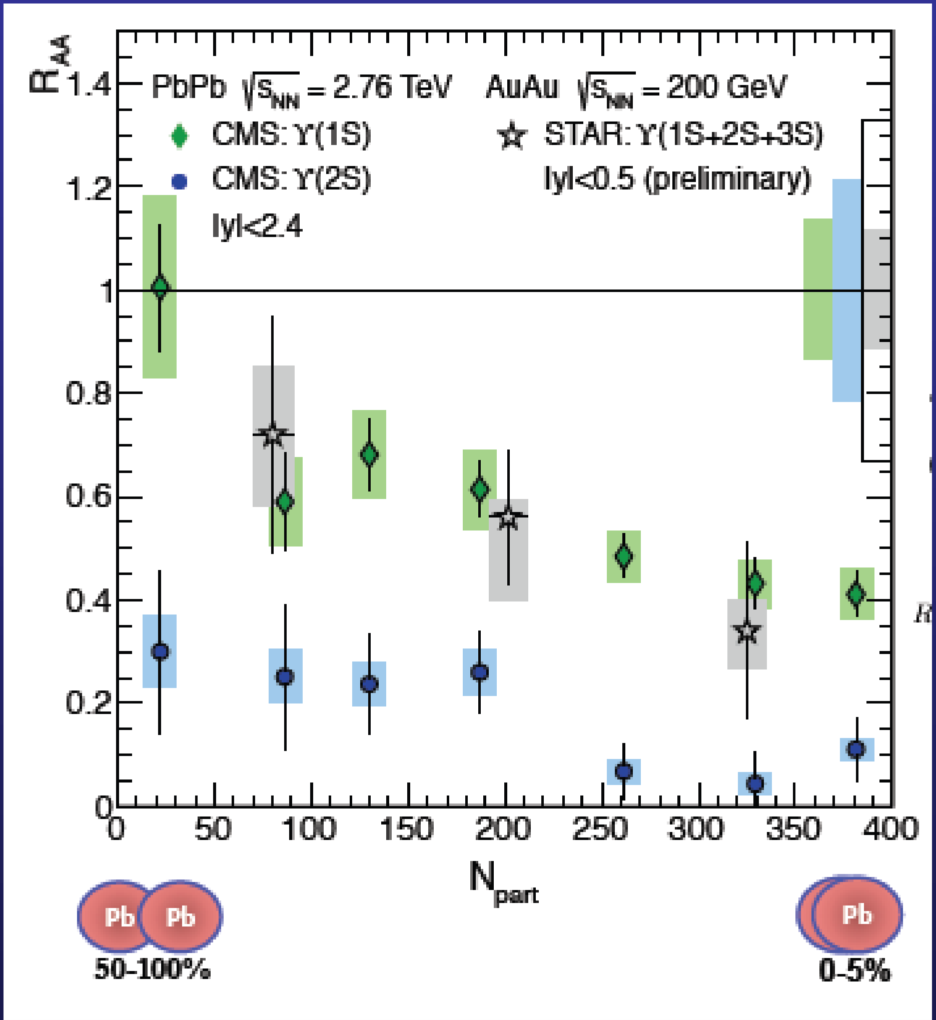
  - no strong centrality dependence
- Upper limit on Υ(3S)
  - centrality integrated

$$\frac{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp}} < 0.17 \text{ (95\% C.L.)}$$



One of the long-awaited signatures ?

First accurate determination of ϒ suppression

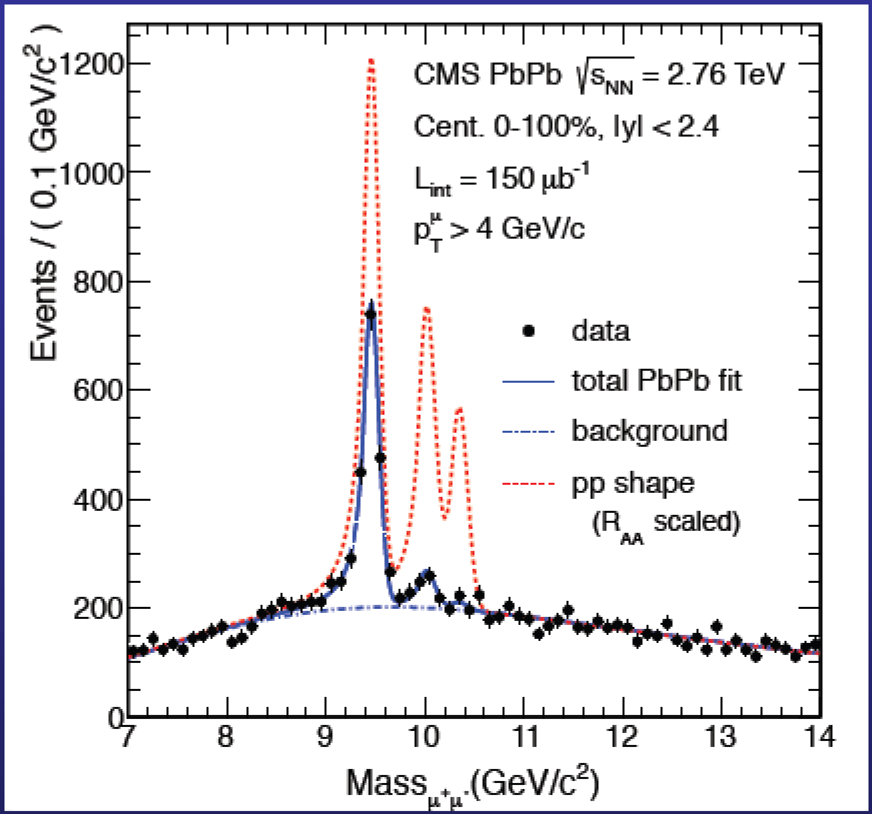


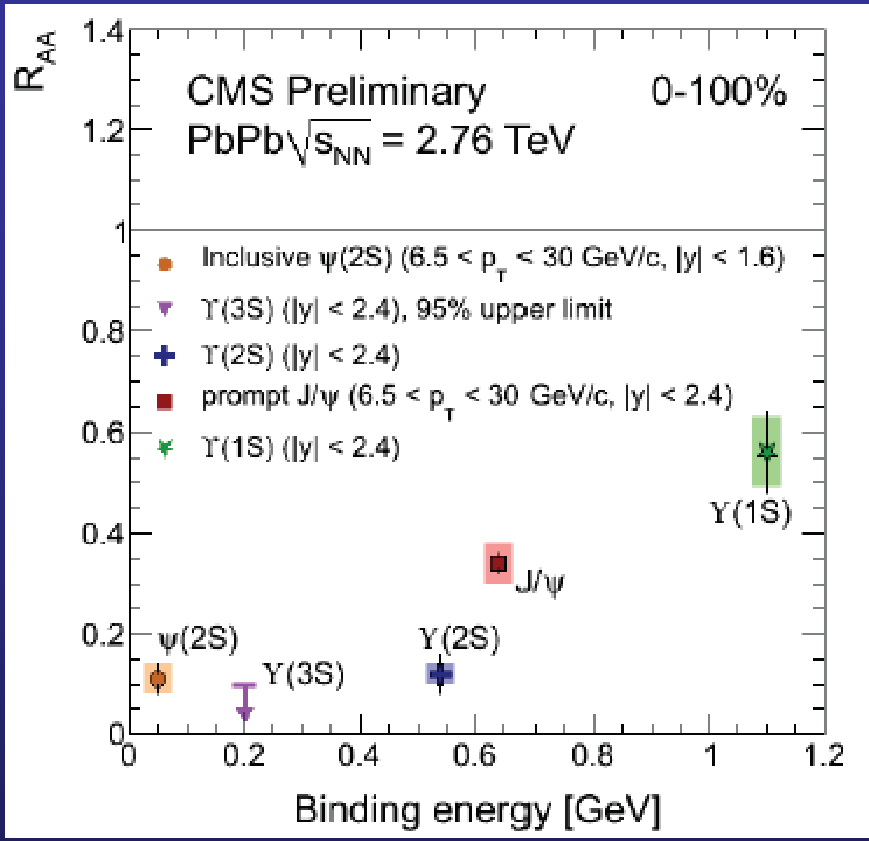
- Suppression increases with centrality
- First determination of ϒ(2S) R_{AA}: already suppressed in peripheral collisions
- ϒ(1S) compatible with only feed-down suppression ?

→ 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 ?

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

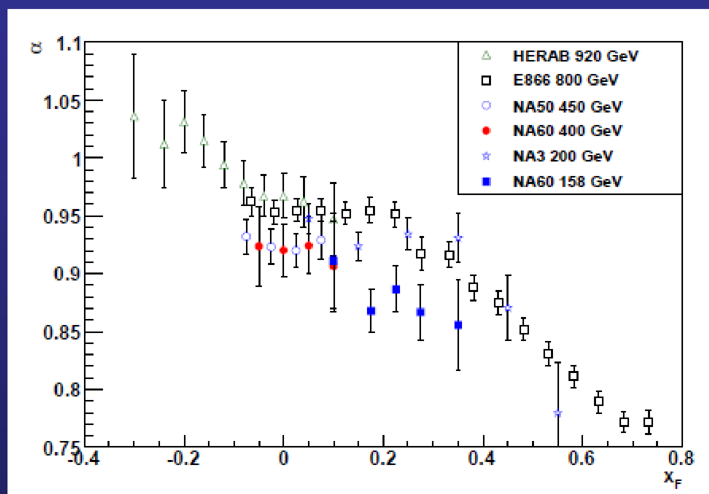
- ALICE is fully exploiting the physics potential in the charmonium sector (optimal coverage at low p_T and reaching 8-10 GeV/c)
  - R_{AA} → weak centrality dependence at all *y*, larger than at RHIC
  - Less suppression at low p_T with respect to high p_T

- 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
  - ϒ(1S) suppression consistent with excited state suppression (50% feed-down)

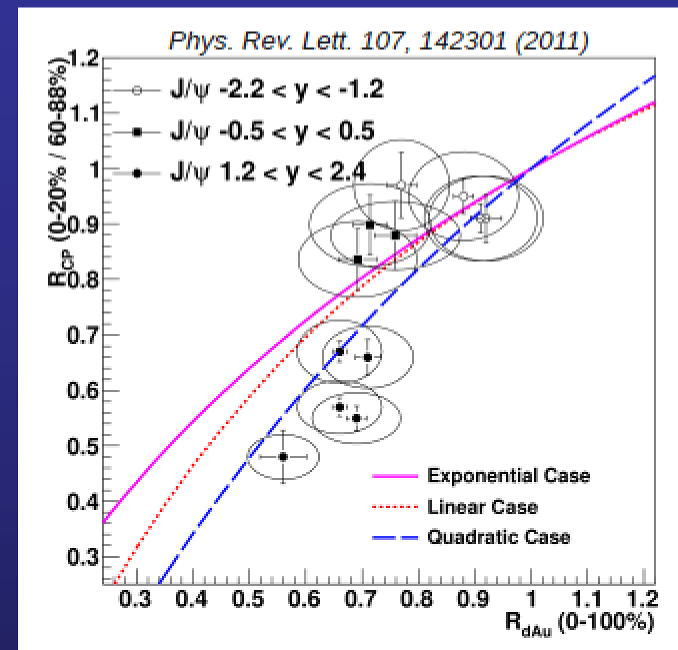
CNM: will pA help ?

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

SPS

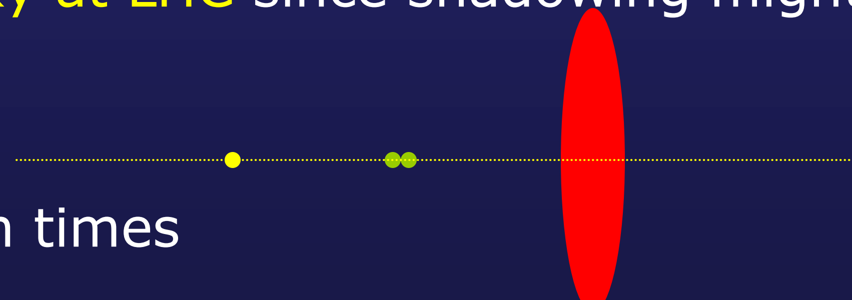


RHIC

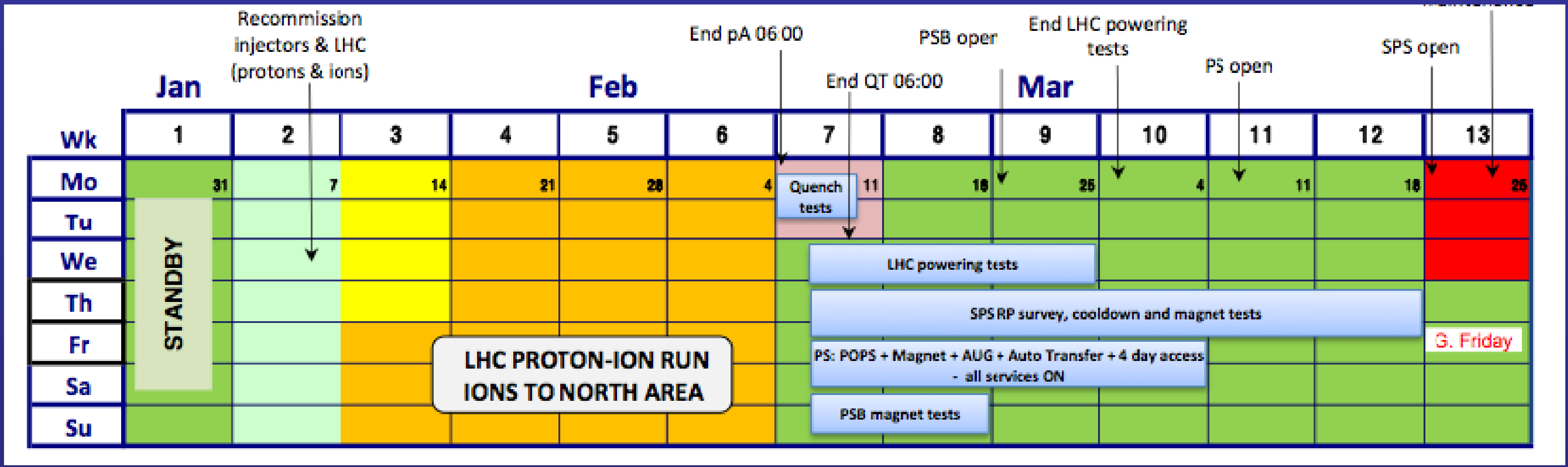


- We might be a bit more lucky at LHC since shadowing might become the only CNM effect

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



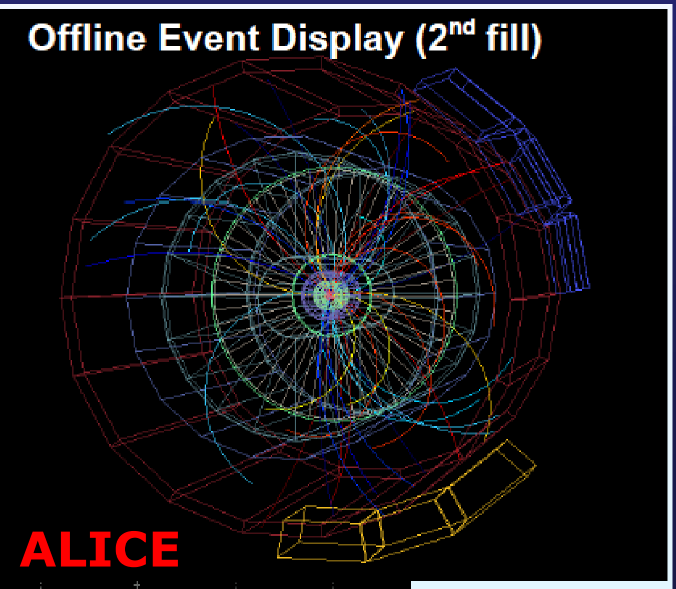
News from pA run



Goal: 30 nb^{-1} integrated luminosity → reached

Data taken for p-Pb AND Pb-p: maximum forward rapidity coverage

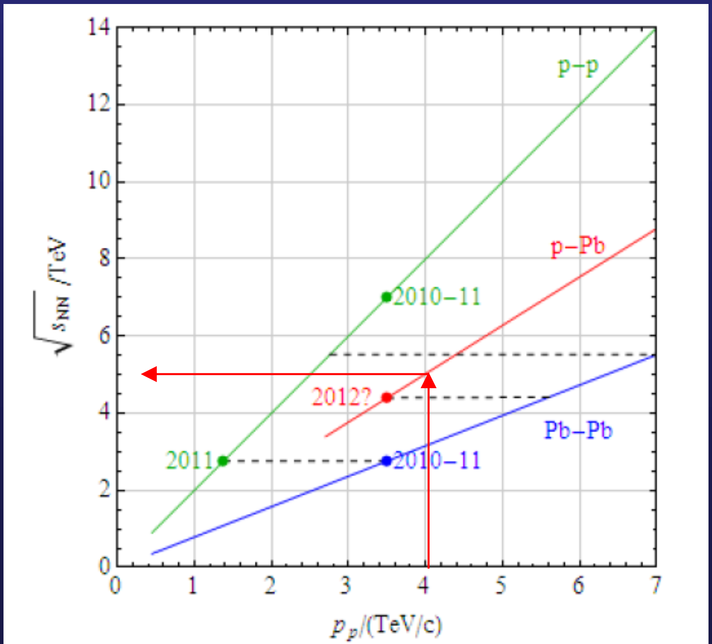
p-Pb peak luminosity > 10^{29} $cm^{-2}s^{-1}$



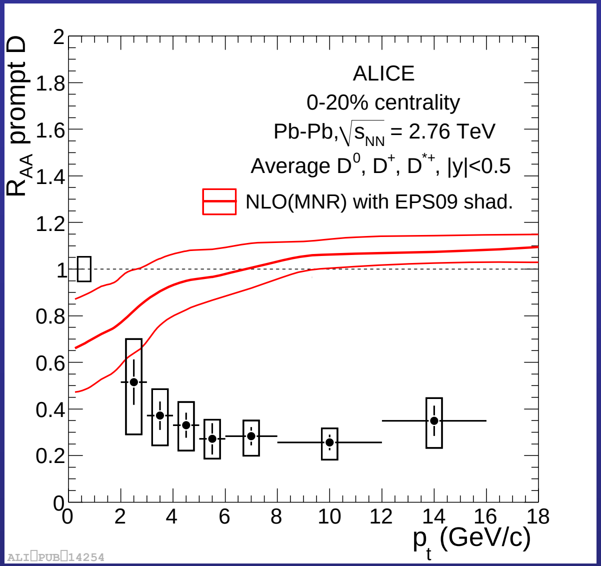
Asymmetric energy of the two beams

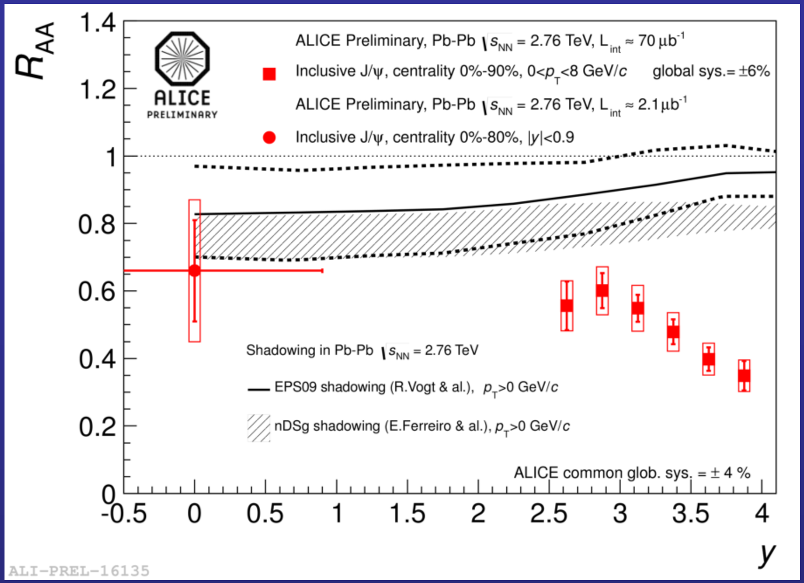
$\sqrt{s}$=5.023 TeV

Δy=0.465

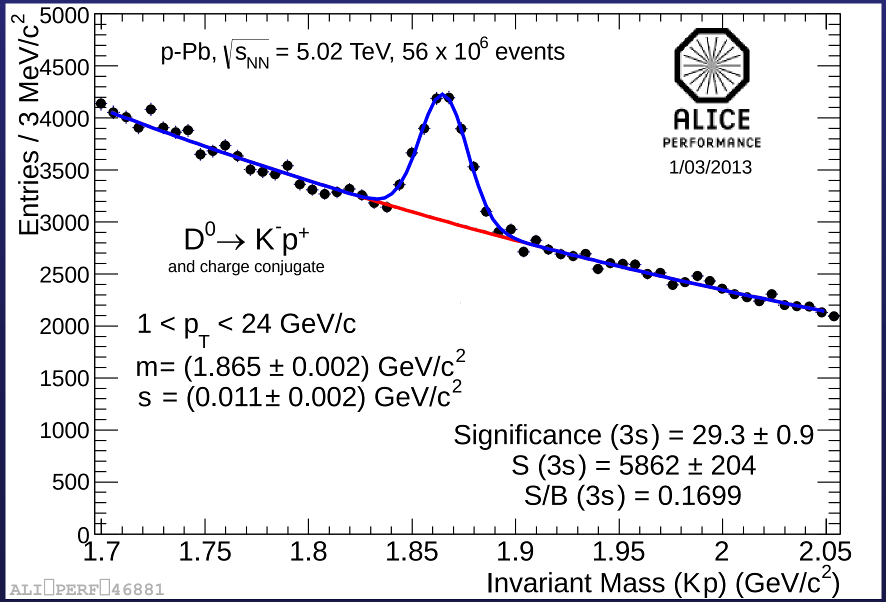


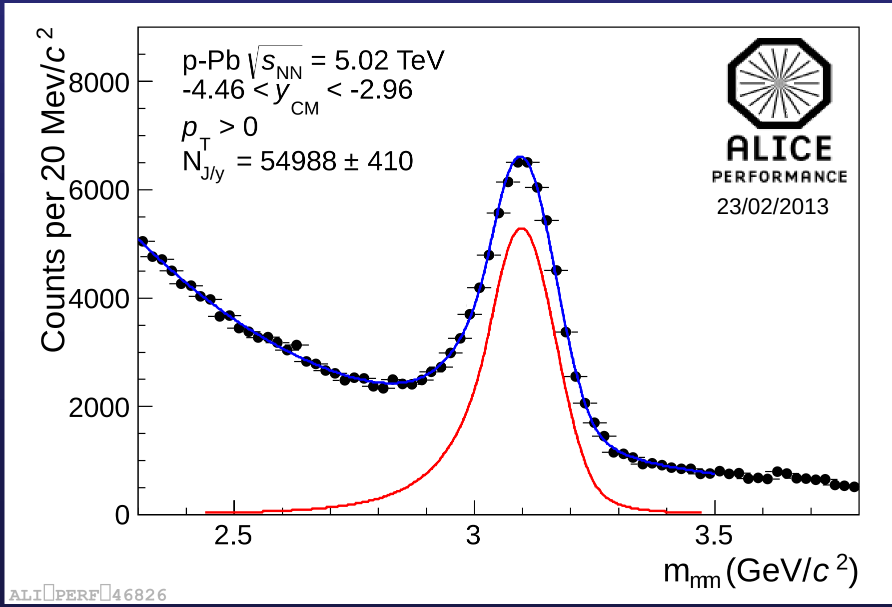
A taste of what's coming





Calibrate CNM effects → within reach for both HF and quarkonia!





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

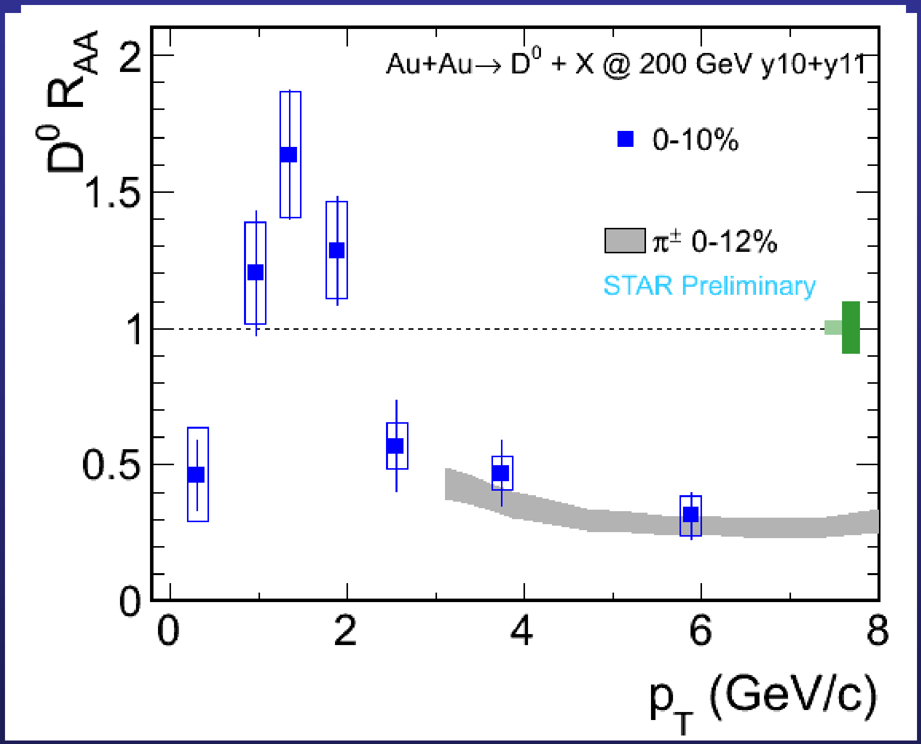
Lower energies: SPS, FAIR

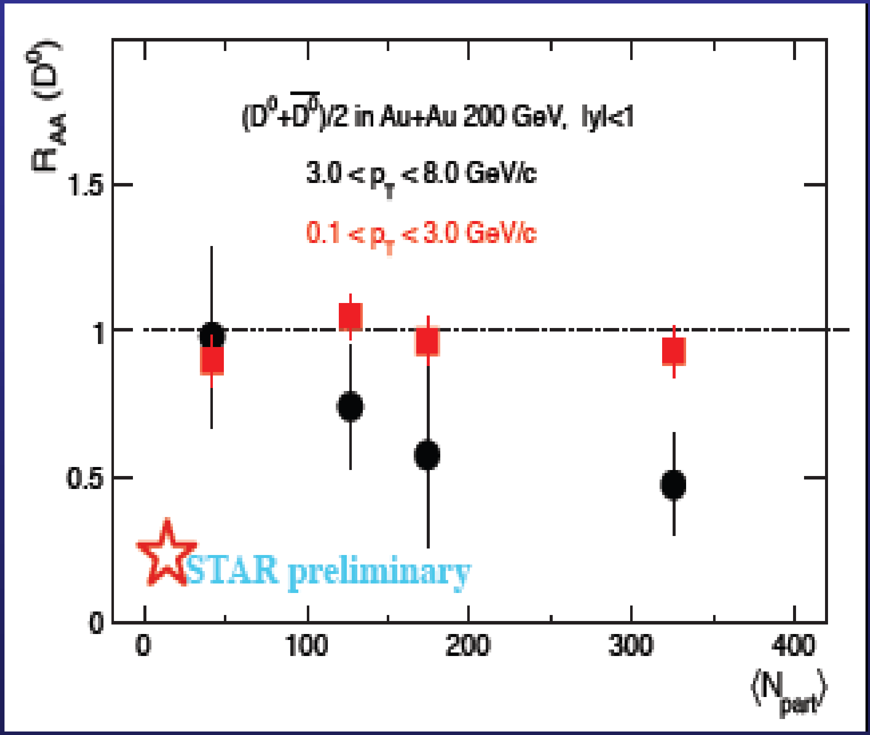
- Serious experimental challenge
- High-μ_B region of the phase diagram unexplored for what concerns heavy quark/quarkonia below 158 GeV/c

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)

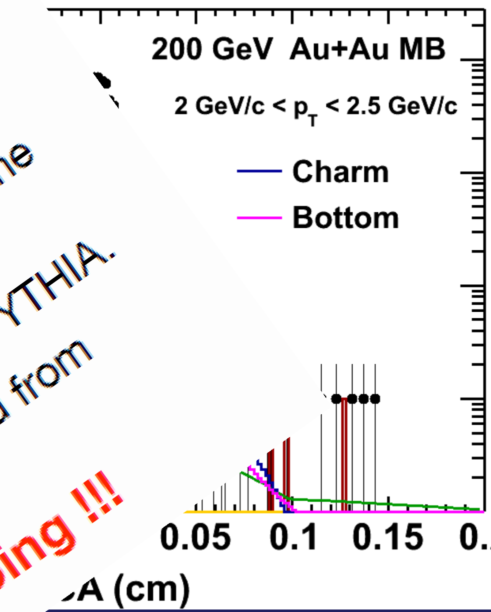
PHEN... c

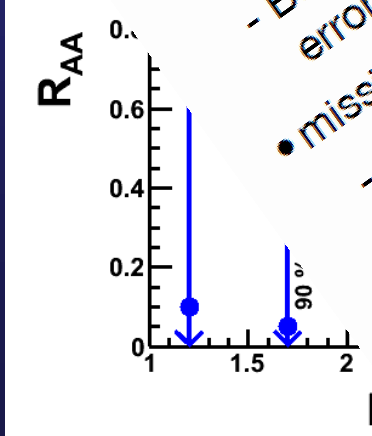
R. Akimoto

TO BE BETTER UNDERSTOOD !

PHENIX VTX tracker

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





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 !!!

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

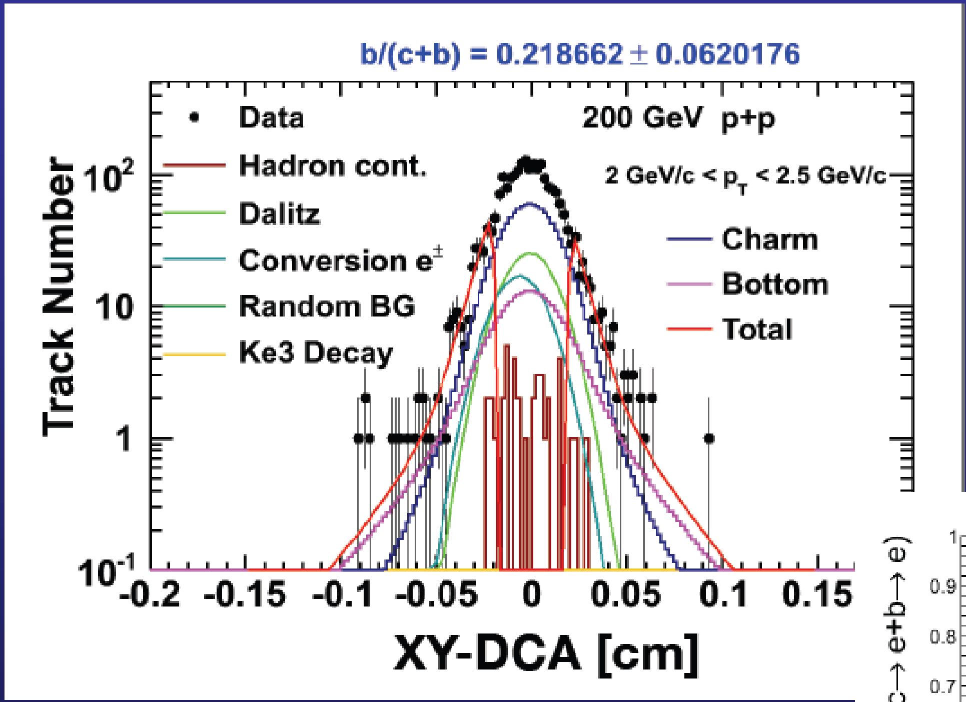
...arger suppression for beauty
→ Challenging result !

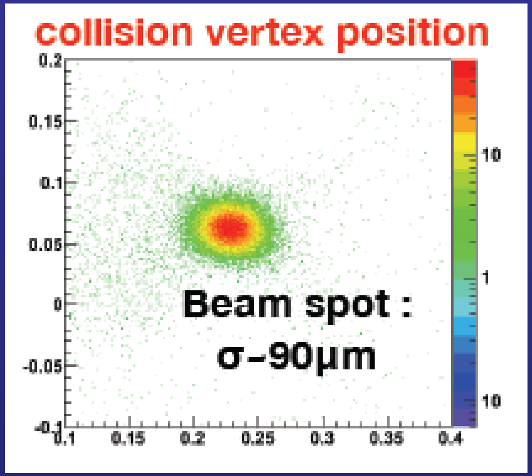
TO BE UNDERSTOOD

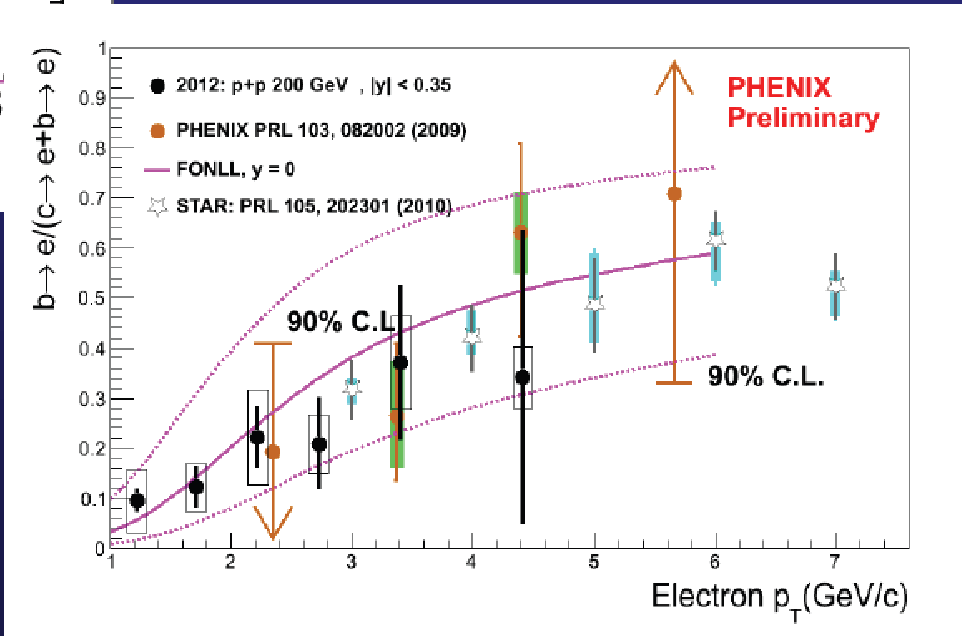
PHENIX, b vs c

R. Akimoto

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







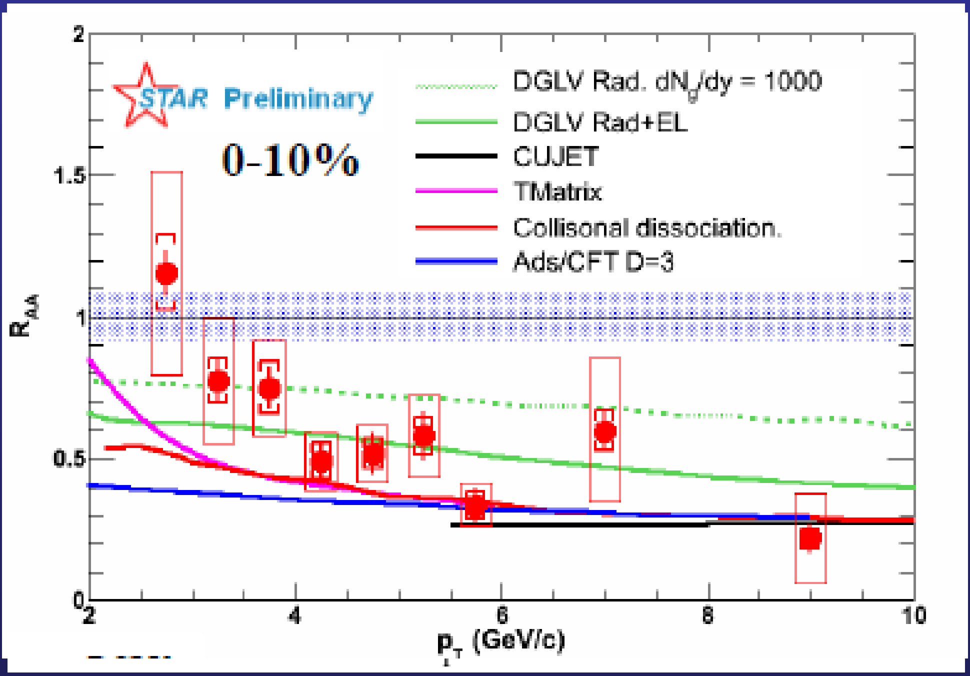
- Bottom fraction in pp consistent with published data (from e-h correlations) and with FONLL

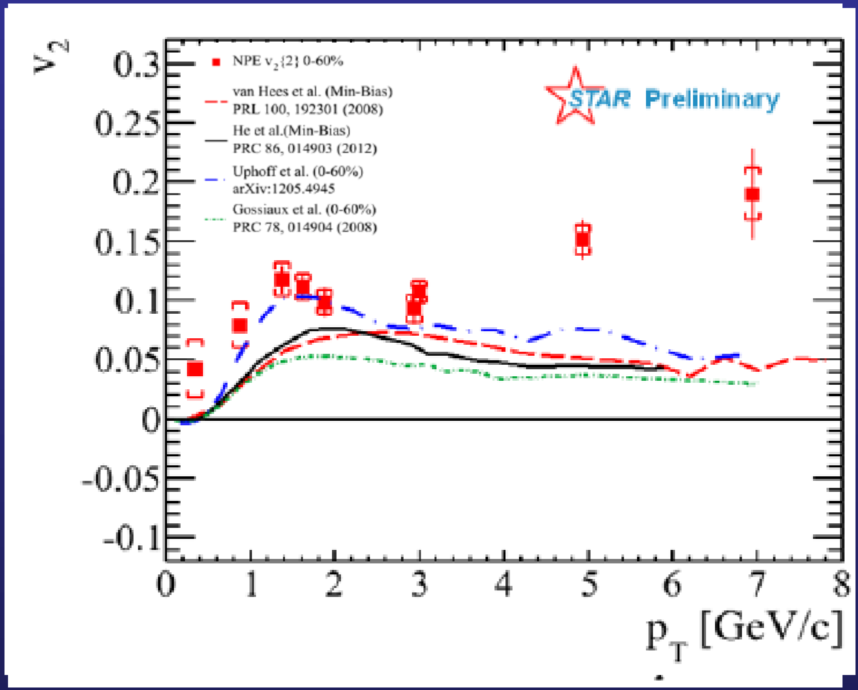
Look forward to forthcoming Au-Au results!

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

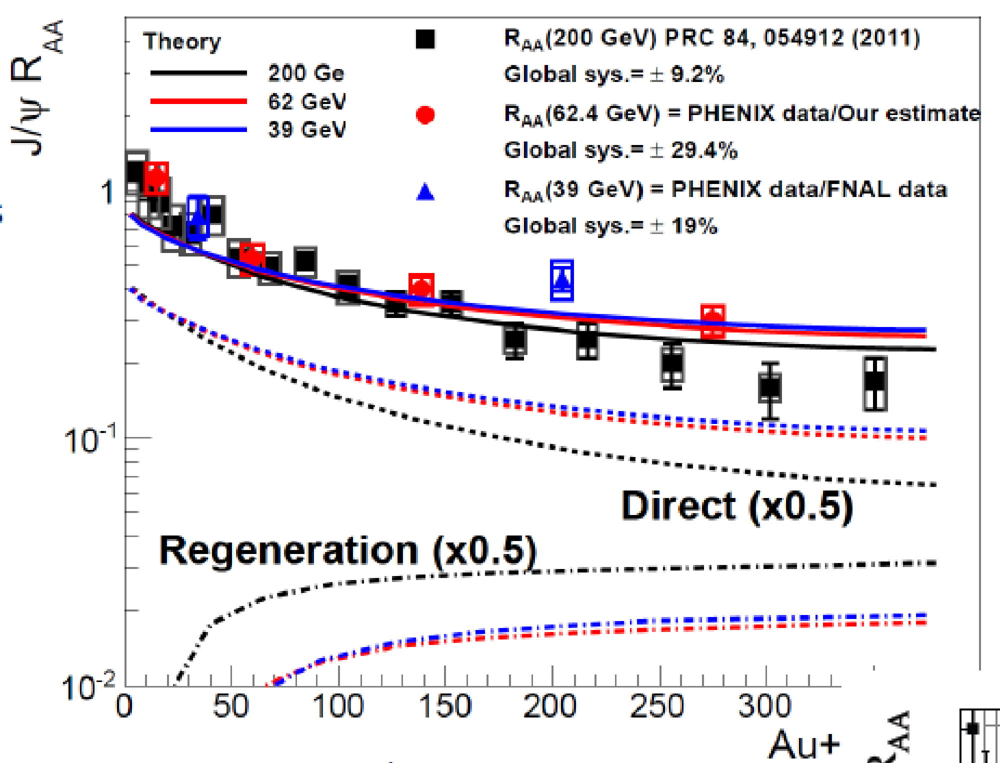




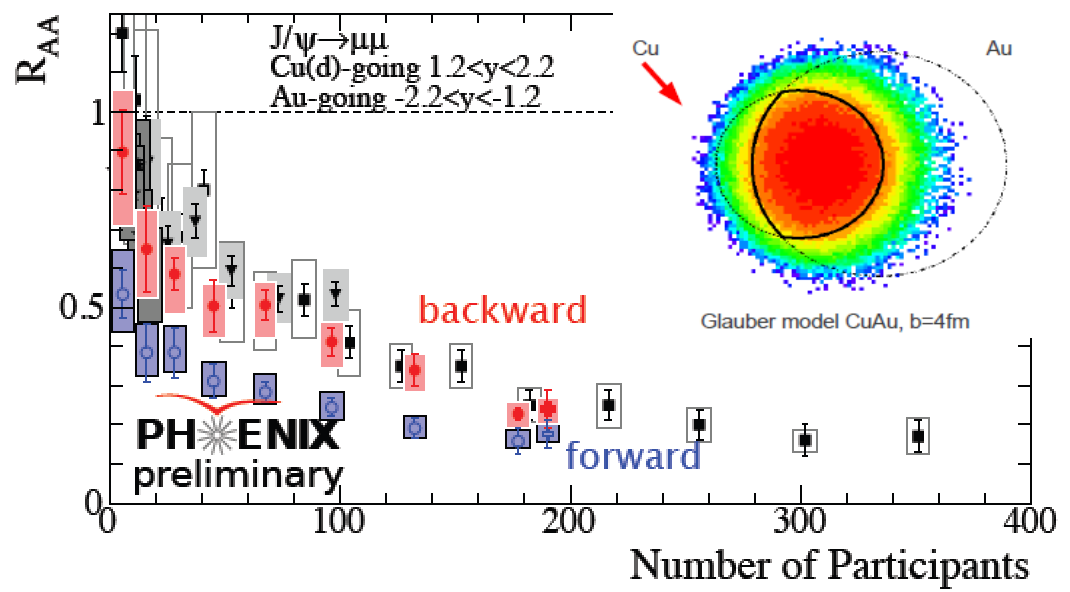
- Strong suppression of HQ (consistent with D), pure energy loss disfavoured
- Finite v_2 at low p_T, increase at high p_T (jet corr., path length dependence)
- Simultaneous description of R_{AA} and v_2 → challenge for models
- v_2 tends to zero at low $\sqrt{s}$ → lighter charm-medium interactions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

PHENIX – new systems/energies

M. Durham

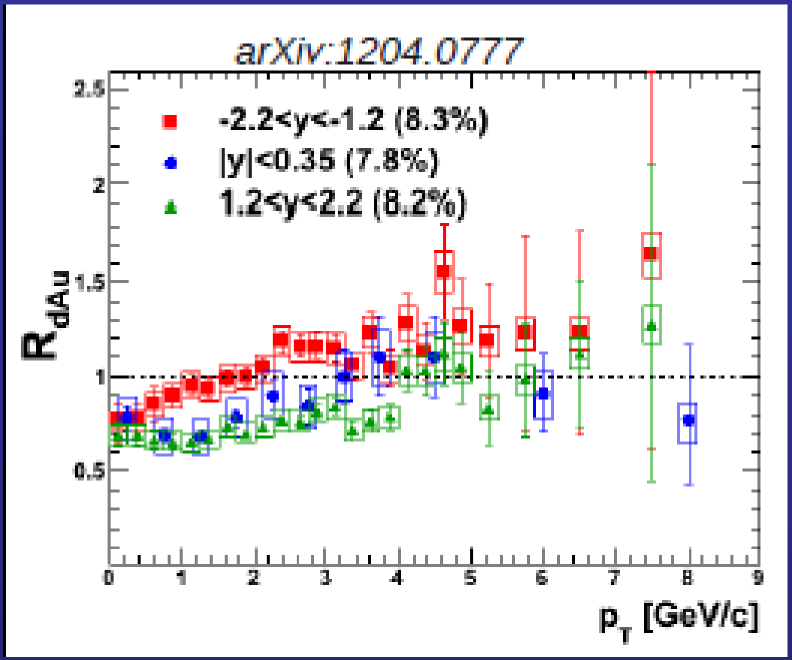


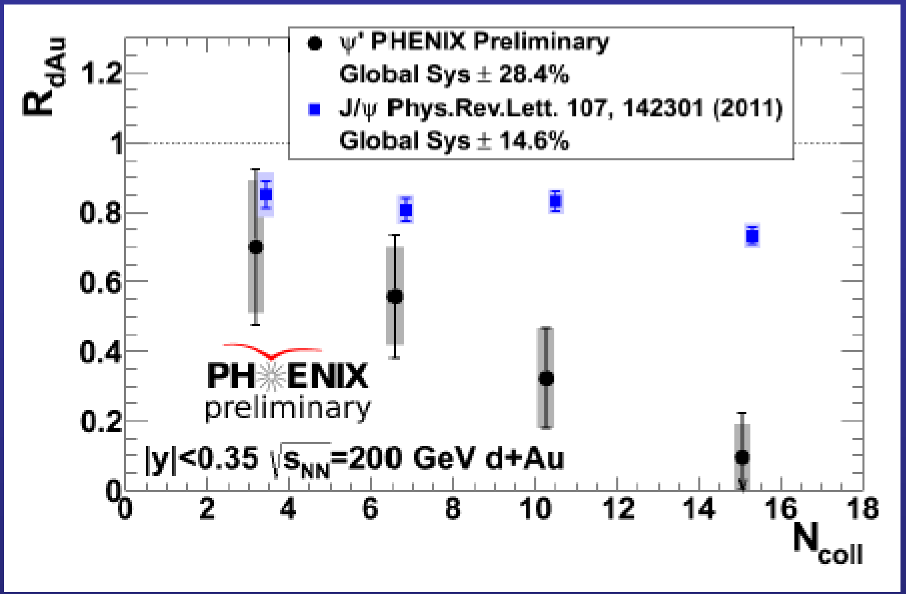
- New system (Cu-Au) at old energy: Cu-going finally different! (probably not a CNM effect)
- A challenge to theory
- SPS went the other way round (from S-U to Pb-Pb...)



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

PHENIX – CNM

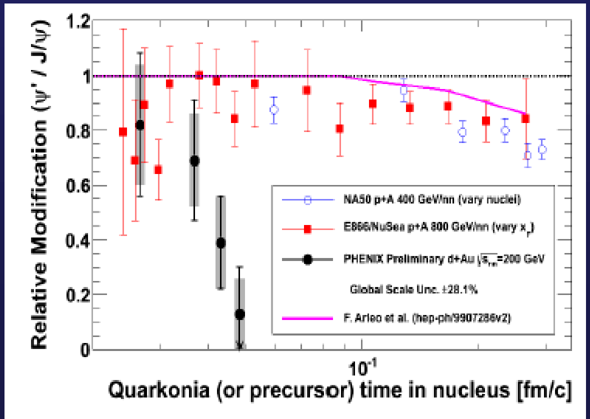




- p_T dependence of R_{dAu}
- Increase vs p_T at central/forward y
  → Reminds SPS observation
- But different behaviour at backward rapidity
- Not easy to reproduce in models!

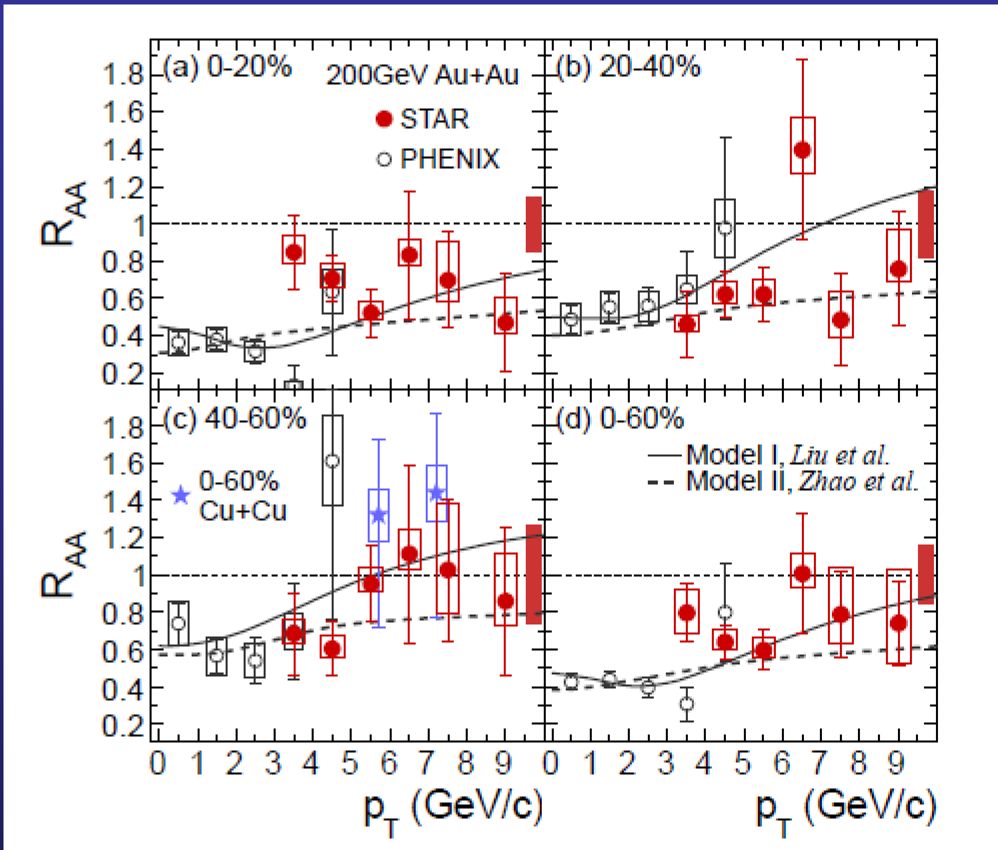
Overall picture still not clear !

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



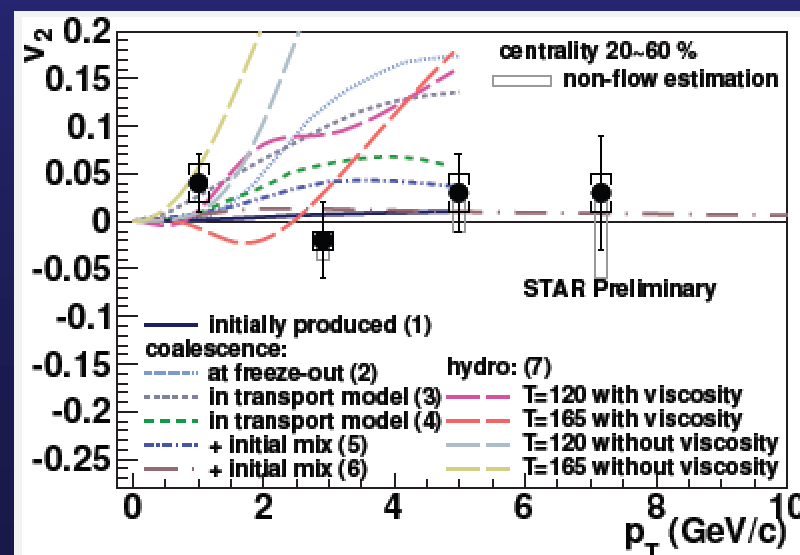
STAR – J/ψ

B. Trzeciak



- 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 ?

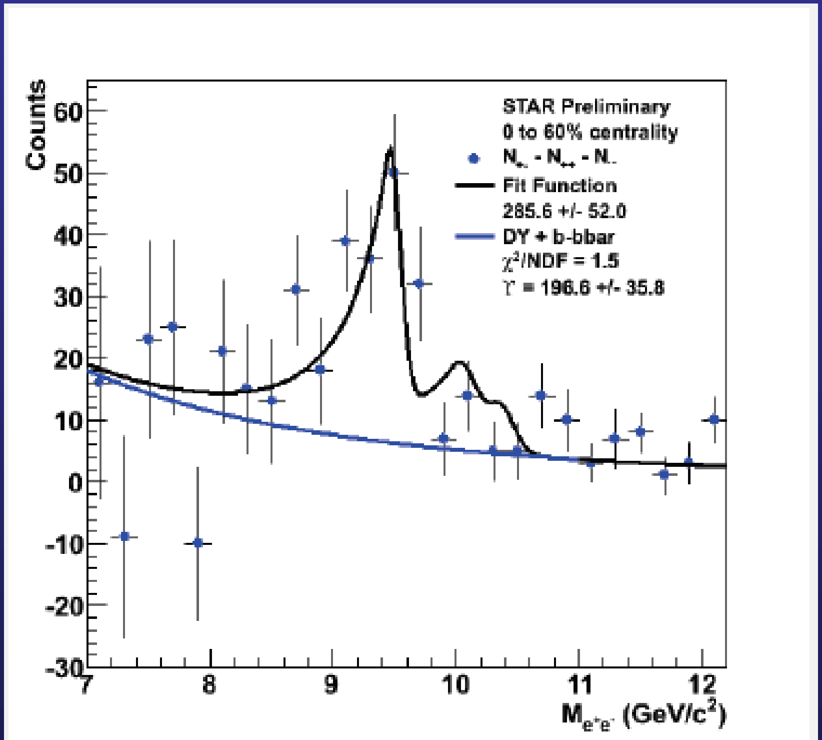


STAR - Υ

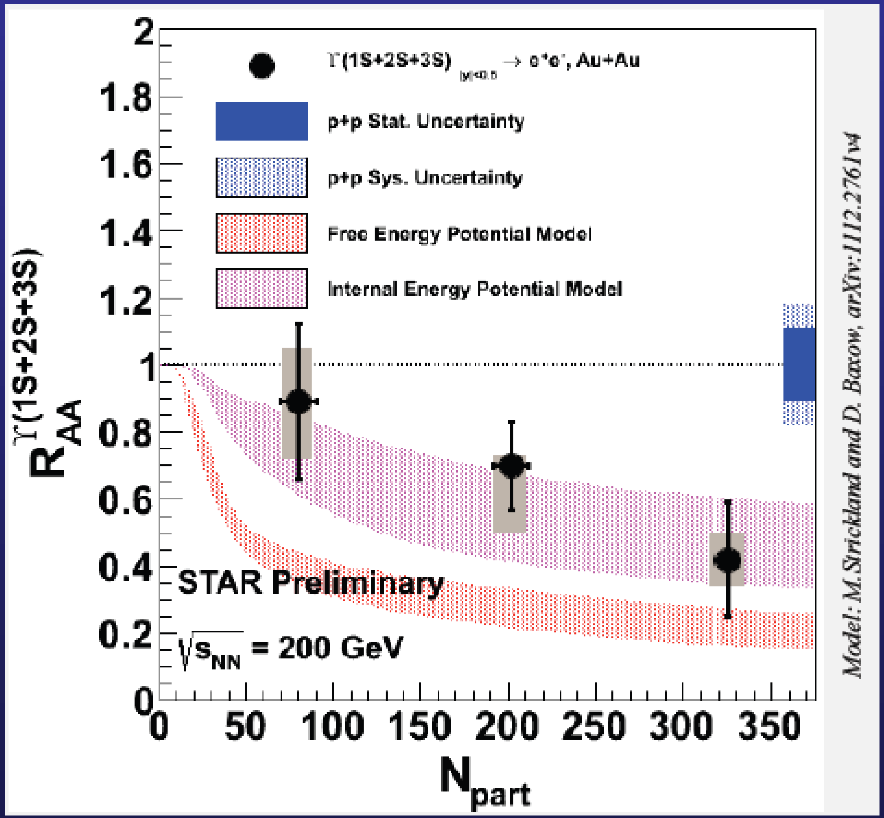
- Bottomonium: the "clean" probe
- 3 states with very different binding energies
- No complications from recombination

But not that easy at RHIC!

M. Calderon

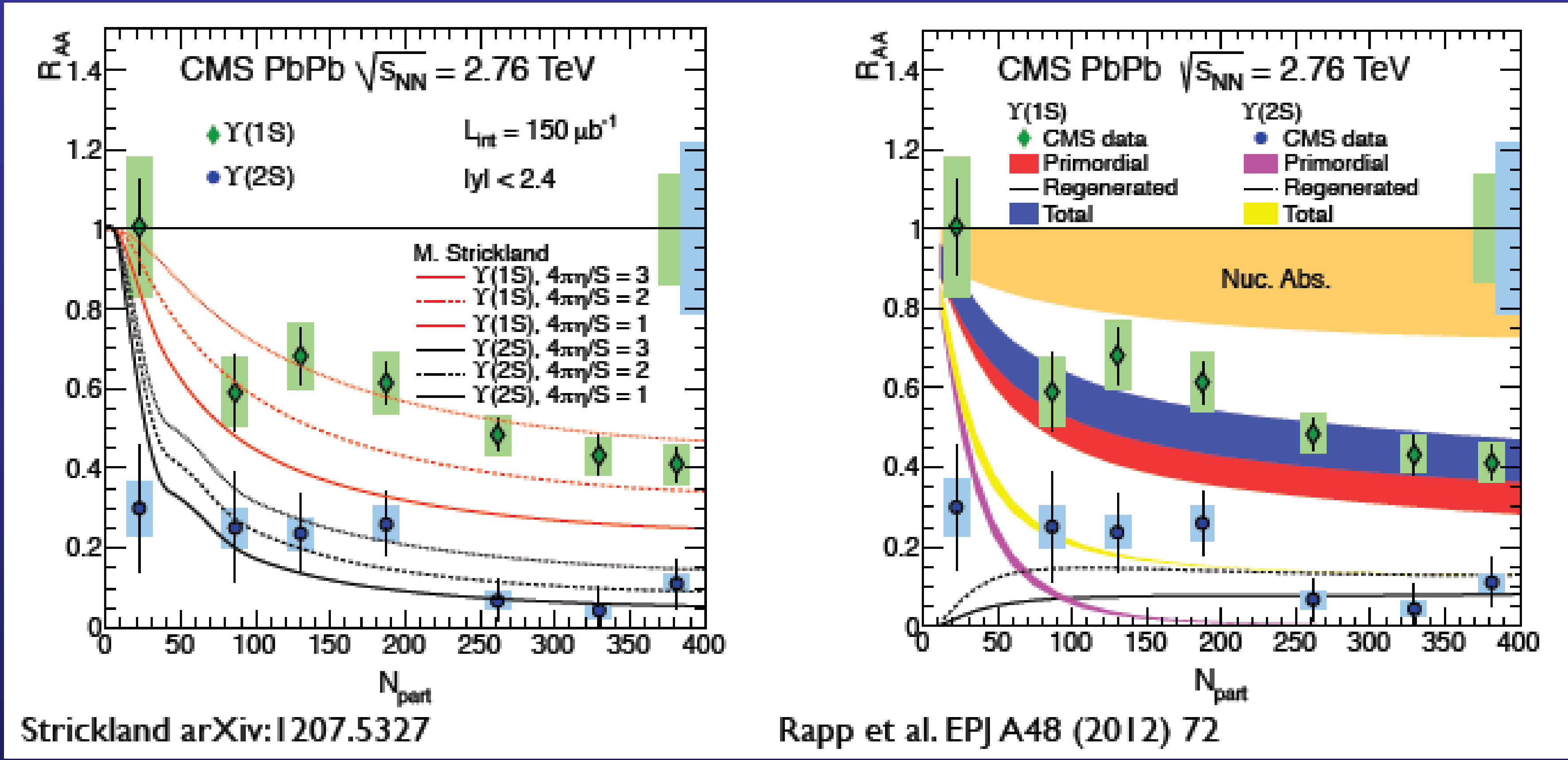


...and this has been split into 3 centrality bins....



Compatible with 3S melting and 2S partial melting

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

Still too early to claim a satisfactory understanding ?