Charmonium production in PbPb collisions: a look at LHC results

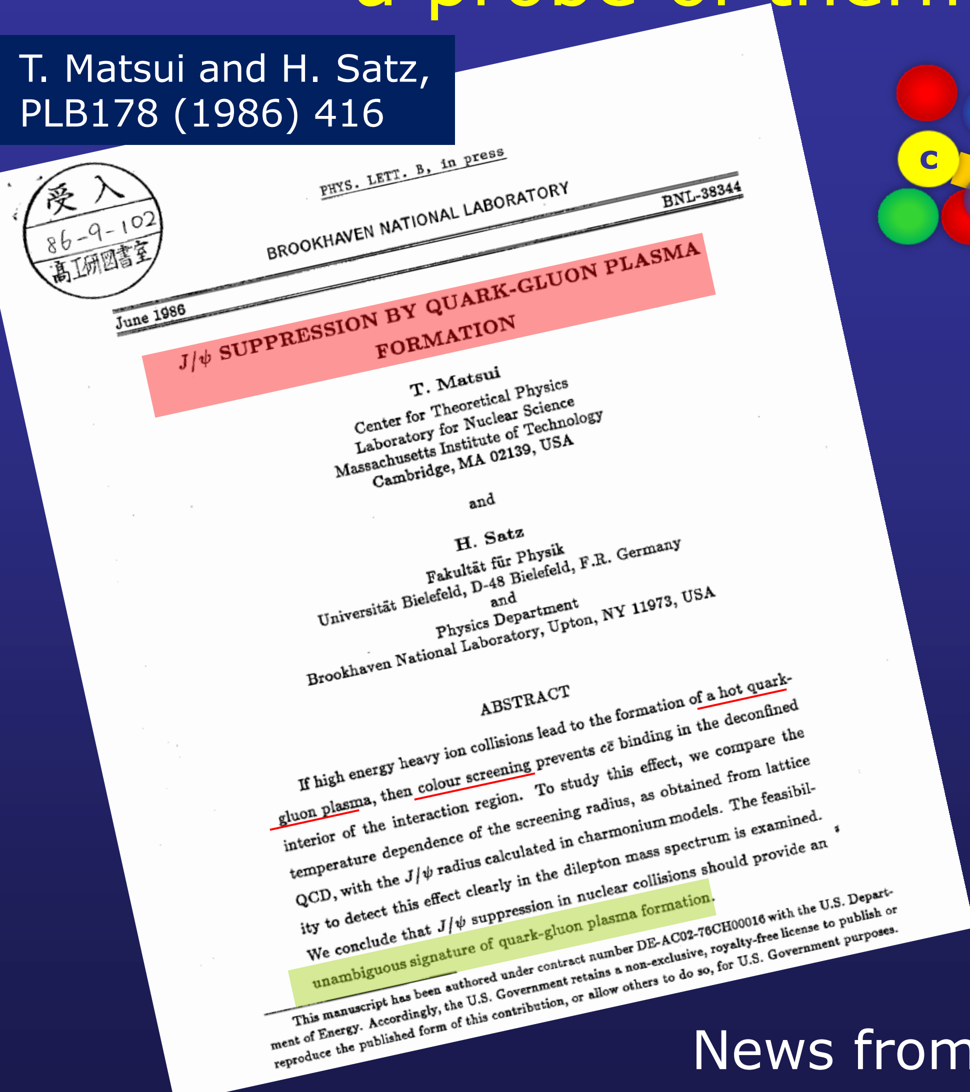
- Introduction: the SPS/RHIC legacy
- The J/ψ at LHC
  - Results from ALICE and CMS
  - Between suppression and (re)generation
- Other resonances: ψ(2S)

E. Scomparin
INFN Torino (Italy)

First Sapor(e)Gravis Workshop (SGW 2013)
December 2nd-5th 2013, Nantes, France

J/ψ: a QGP thermometer or a probe of thermal equilibrium ?

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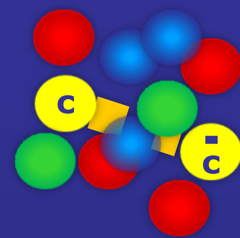
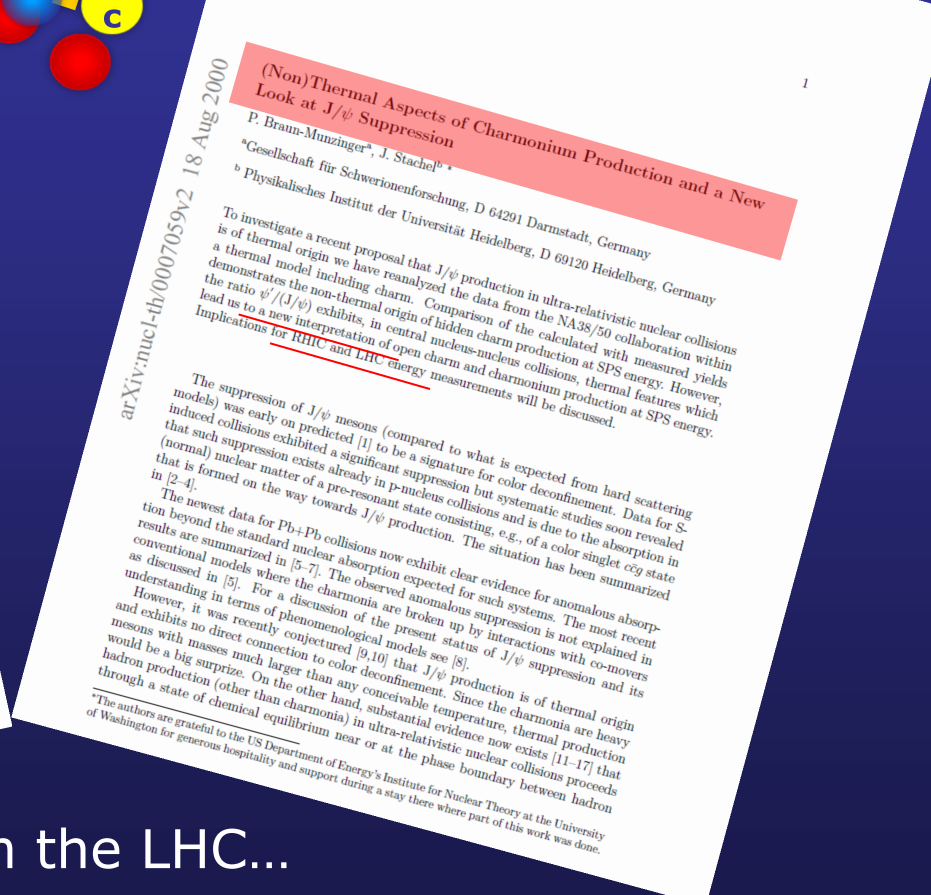


P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196



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(Non)Thermal Aspects of Charmonium Production and a New Look at J/ψ Suppression

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To investigate a recent proposal that J/ψ production in ultra-relativistic nuclear collisions is of thermal origin we have reanalyzed the data from the NA38/50 collaboration within a thermal model including charm. Comparison of the calculated with measured yields demonstrates the non-thermal origin of hidden charm production at SPS energy. However, the ratio ψ′/(J/ψ) exhibits, in central nucleus-nucleus collisions, thermal features which lead us to a new interpretation of open charm and charmonium production at SPS energy. Implications for RHIC and LHC energy measurements will be discussed.

The suppression of J/ψ mesons (compared to what is expected from hard scattering models) was early on predicted [1] to be a signature for color deconfinement. Data for S-induced collisions exhibited a significant suppression but systematic studies soon revealed that such suppression exists already in p-nucleus collisions and is due to the absorption in (normal) nuclear matter of a pre-resonant state consisting, e.g., of a color singlet $c\bar{c}g$ state that is formed on the way towards J/ψ production. The situation has been summarized in [2–4].

The newest data for Pb+Pb collisions now exhibit clear evidence for anomalous absorption beyond the standard nuclear absorption expected for such systems. The most recent results are summarized in [5–7]. The observed anomalous suppression is not explained in conventional models where the charmonia are broken up by interactions with co-movers as discussed in [5]. For a discussion of the present status of J/ψ suppression and its understanding in terms of phenomenological models see [8].

However, it was recently conjectured [9,10] that J/ψ production is of thermal origin and exhibits no direct connection to color deconfinement. Since the charmonia are heavy mesons with masses much larger than any conceivable temperature, thermal production would be a big surprise. On the other hand, substantial evidence now exists [11–17] that hadron production (other than charmonia) in ultra-relativistic nuclear collisions proceeds through a state of chemical equilibrium near or at the phase boundary between hadron

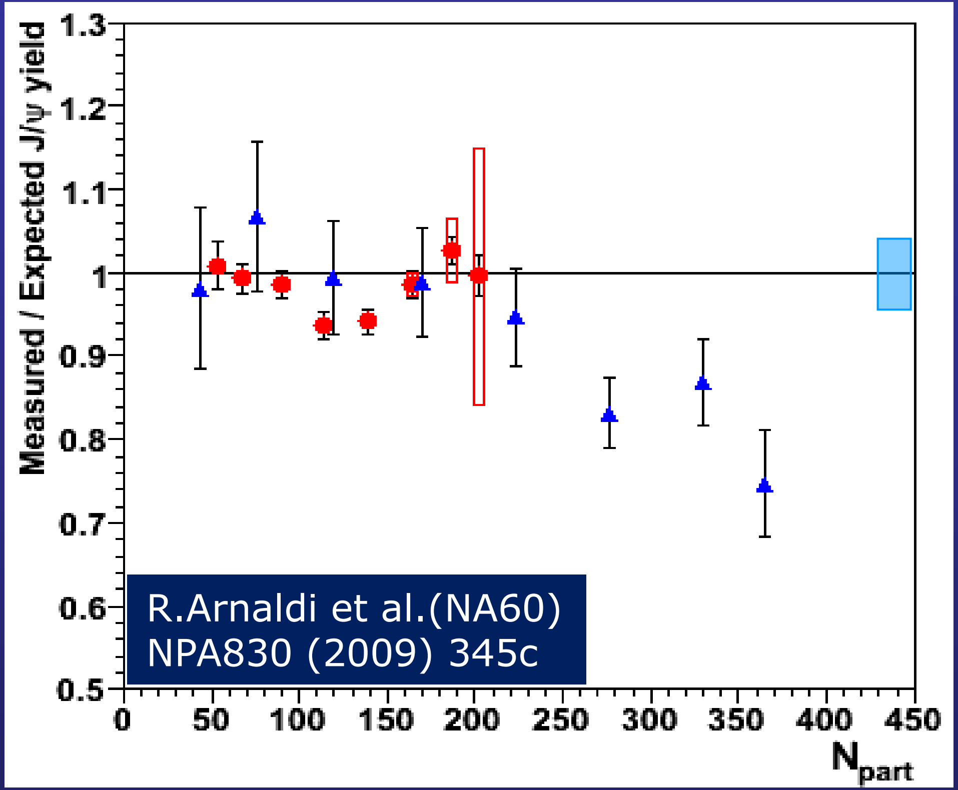
*The authors are grateful to the US Department of Energy's Institute for Nuclear Theory at the University of Washington for generous hospitality and support during a stay there where part of this work was done.

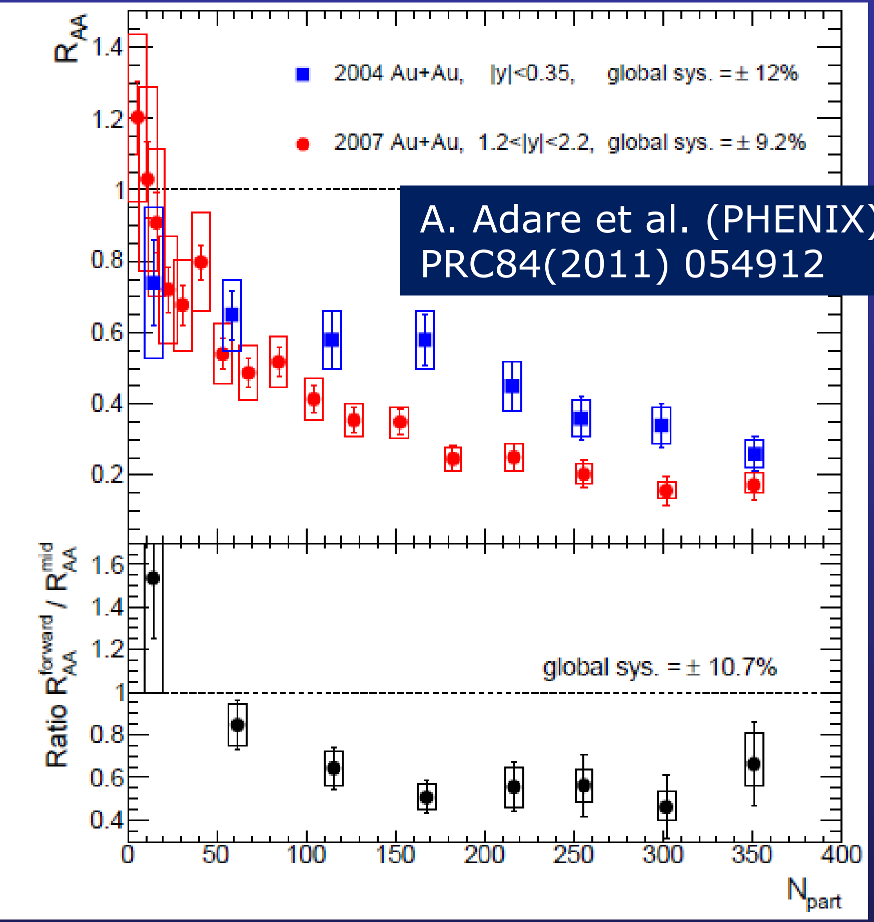
News from the LHC…

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

… ~13 years after the thermal hypothesis for J/ψ yields in AA by Braun-Munzinger and Stachel

The legacy: SPS and RHIC





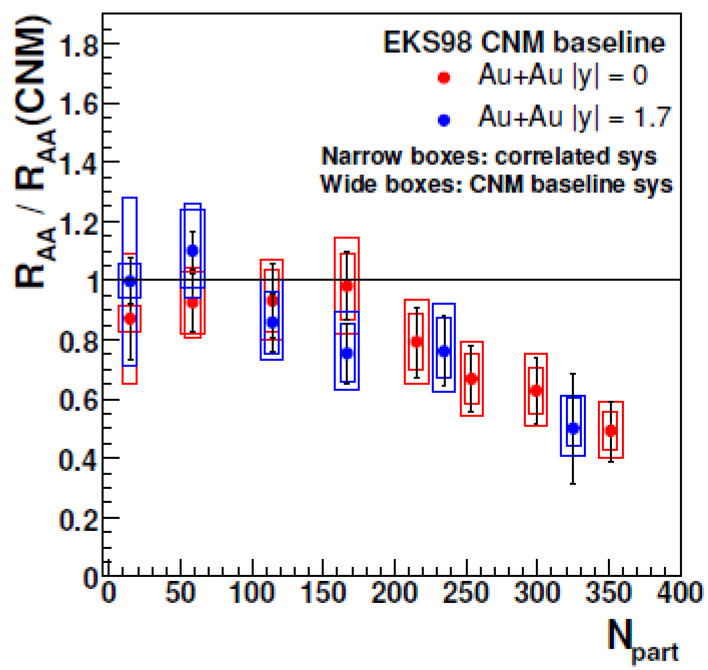
- SPS: first evidence of anomalous suppression (i.e., beyond CNM expectations) in Pb-Pb at √s= 17 GeV

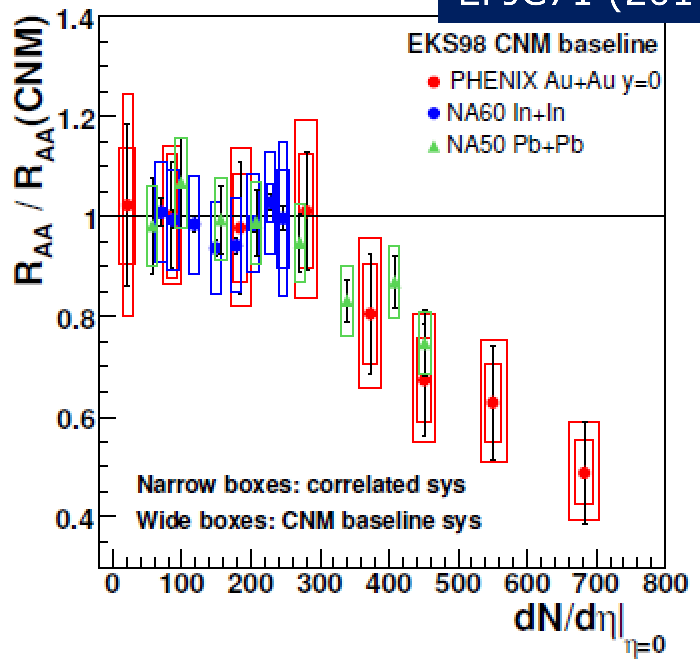
- RHIC: suppression, strongly depending on rapidity, in Au-Au at √s= 200 GeV

SPS vs RHIC

- Once cold nuclear matter effects are taken into account (model-dependent) a very good agreement between the suppression patterns is found

N.Brambilla et al. (QWG)
EPJC71 (2011) 1534

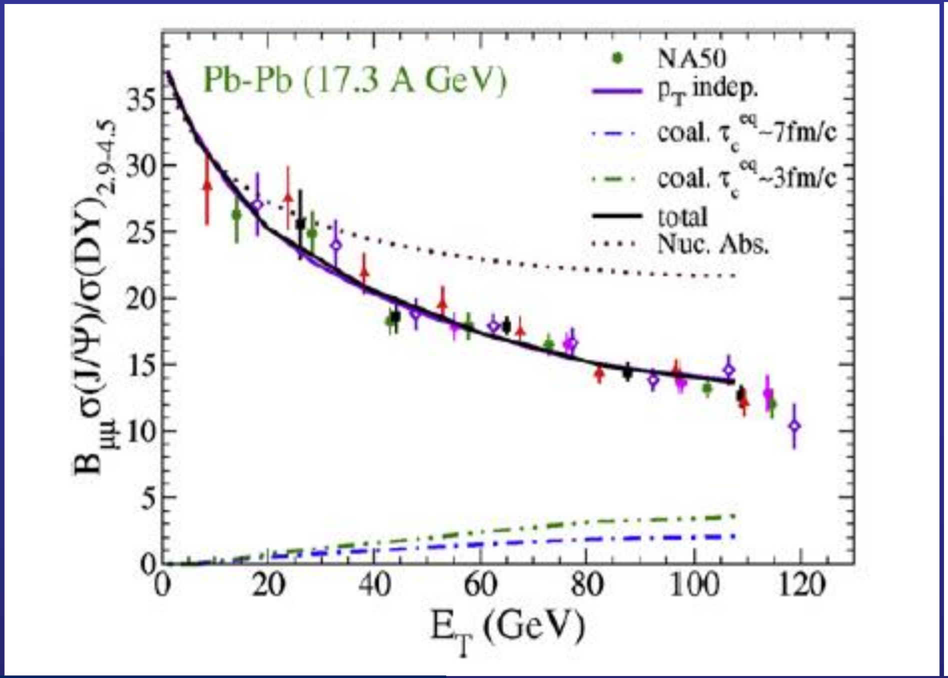


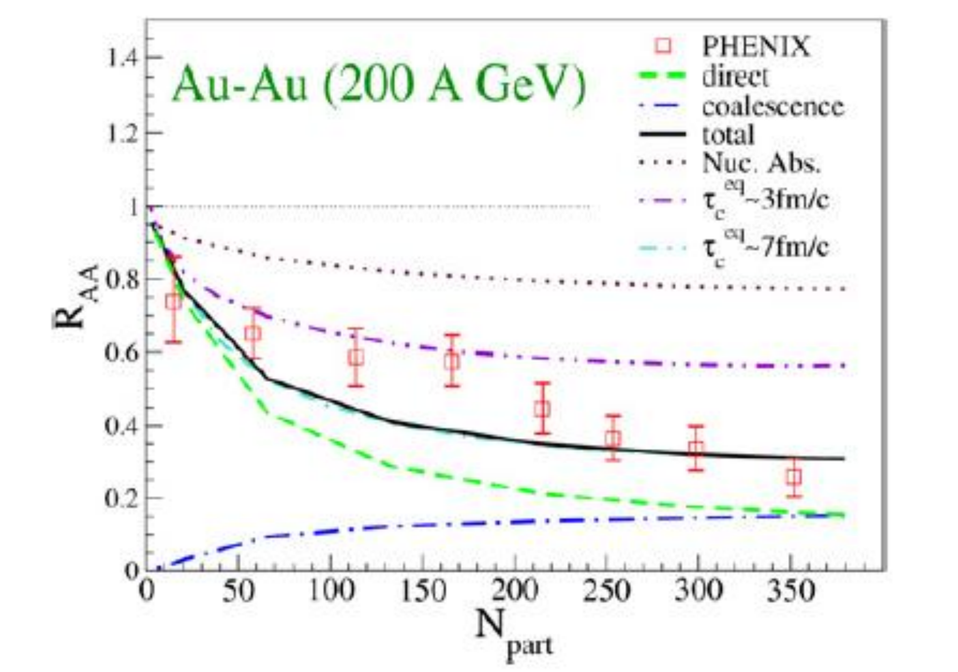


- Same physics (suppression of feed-down J/ψ) or compensation of suppression/enhancement ?
  → Intelligent design or miraculous accident ? (Jurgen, HP12)

- Understanding cold nuclear matter effects and feed-down is essential for a quantitative assessment of charmonium physics

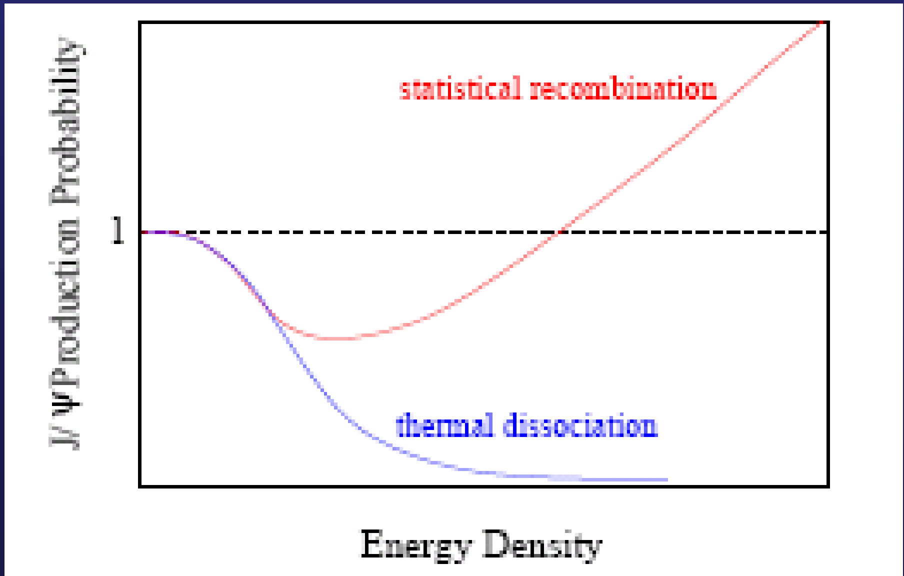
From SPS/RHIC to LHC





X. Zhao and R. Rapp, PLB 664 (2008) 253.

A decisive test of the various pictures

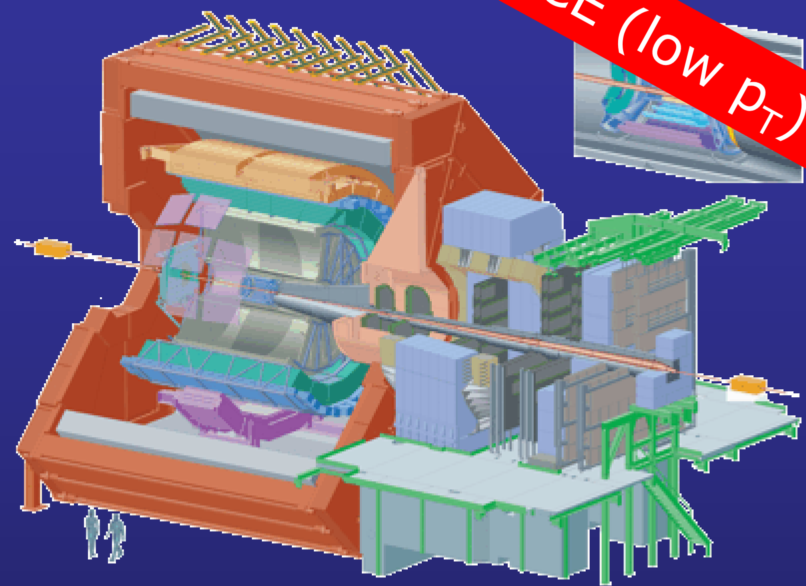


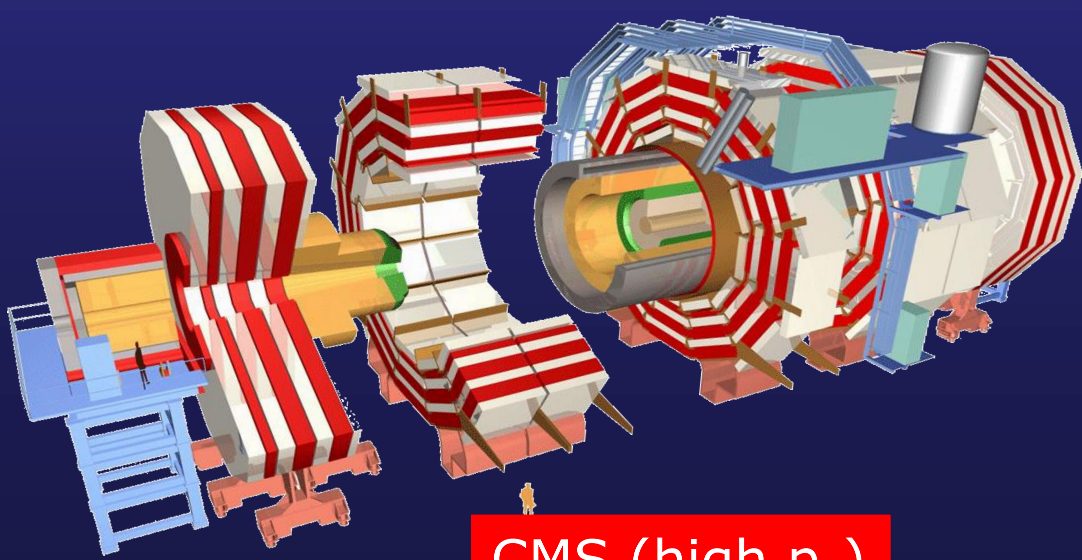
The ultimate goal: a quantitative understanding

The main actors

ALICE (low p_T)

- ALICE
  - Access mid- and forward-rapidity (e^+e^- and $\mu^+\mu^-$ respectively)
  - Good mass resolution for J/ψ (~70 MeV for muons, ~30 MeV for electrons)
  - Full p_T acceptance in the whole y-range
  - Prompt vs non-prompt at y=0



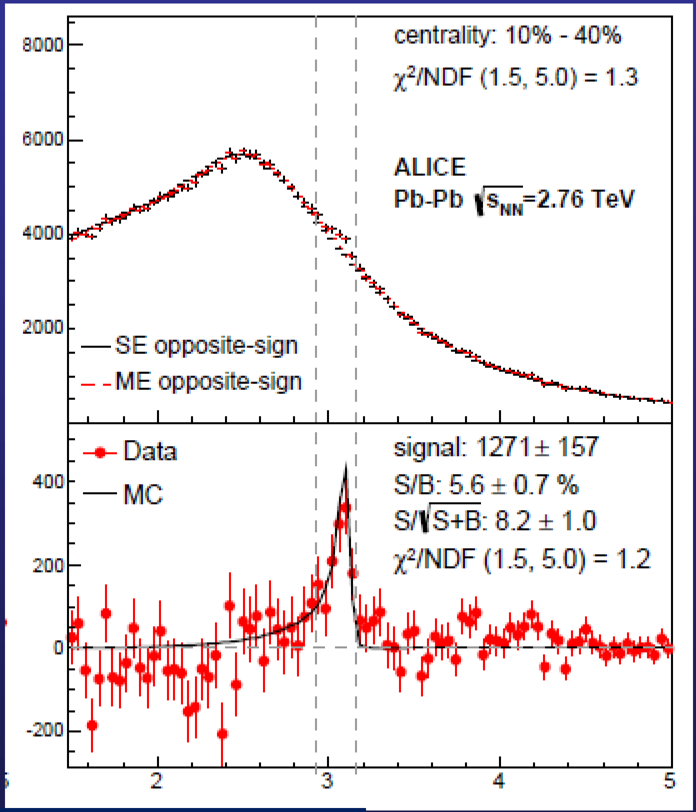


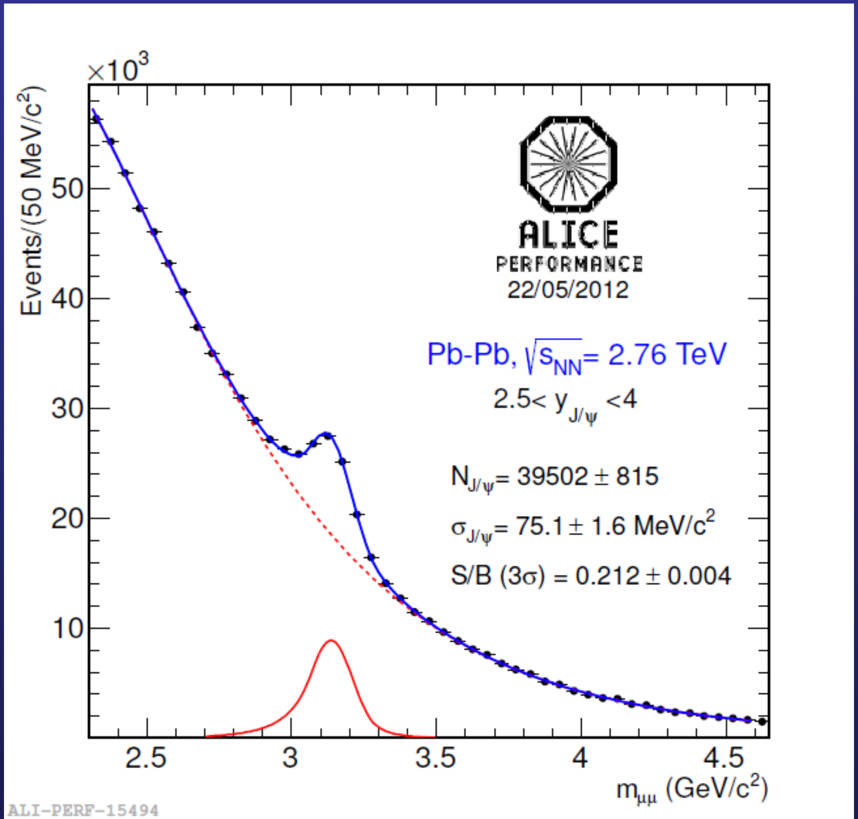
CMS (high p_T)

- CMS
  - Excellent mass resolution for muons(35 MeV for J/ψ)
  - Prompt vs non-prompt
  - Cut low-p_T charmonia (may reach in the future p_T=0 in Pb-Pb for 1.6<y<2.4 ??)

Charmonia – data samples

- ALICE
  - L_{int} (2011) = ~70 μb^{-1} (2.5<y<4), ~28 μb^{-1} (|y|<0.9)
  - Trigger: MB + 2 tracks in the muon trigger chambers (p_T> 1 GeV/c)



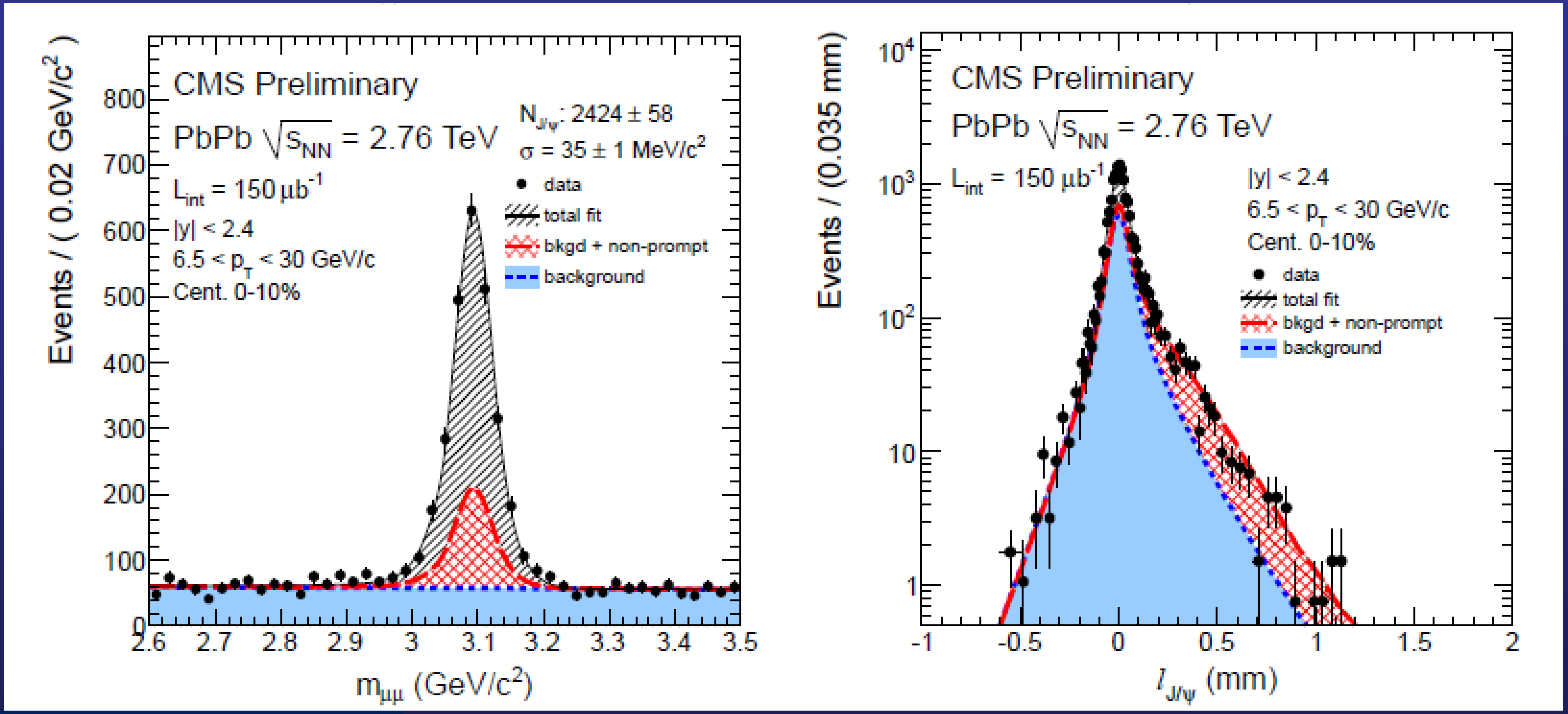


B. Abelev et al., ALICE arXiv:1311.0214.

Background subtraction via like-sign or mixed-event techniques

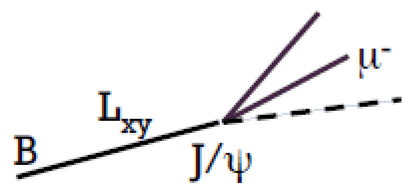
Charmonia – data samples

- CMS
  - L_{int} (2011) = ~150 μb^{-1} ($|y|<2.4$)
  - Trigger: dimuon events at L1 (no constraints on muon momentum)



CMS PAS HIN-2012-014

Use pseudo-proper decay length to estimate the b-hadron decay length

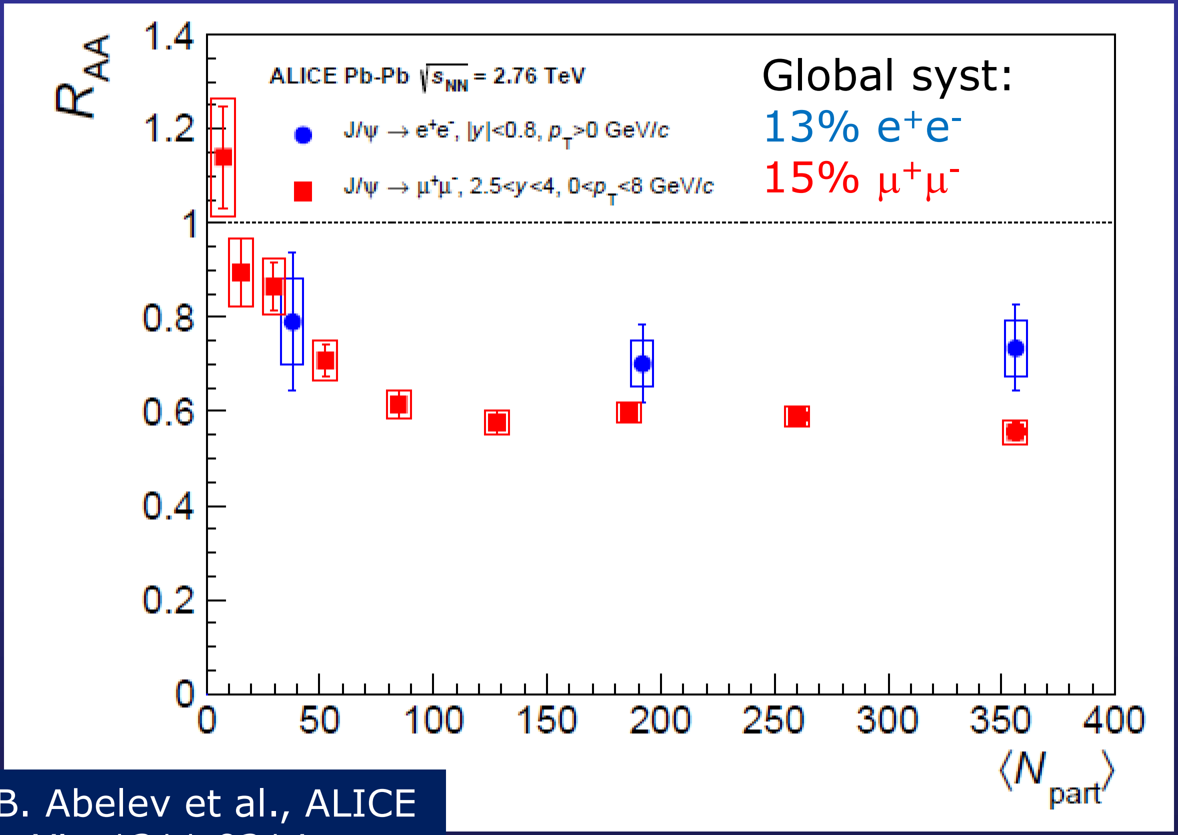


$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

N.B.: discuss only prompt production in this talk

The low p_T region: ALICE

- Centrality dependence of the nuclear modification factor studied at both central and forward rapidities



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

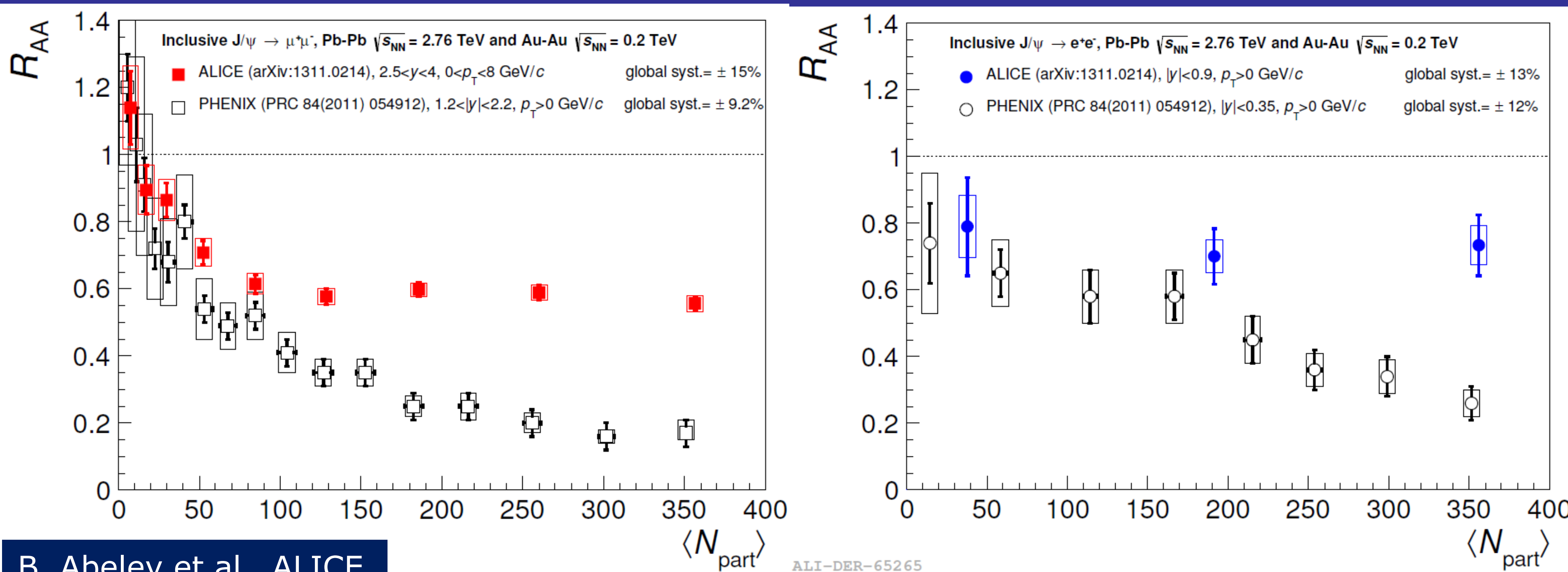
Inclusive J/ψ R_{AA}

Small effect of non-prompt contribution on the inclusive R_{AA}

Forward y:
No B suppression
$\rightarrow R_{AA}^{prompt} \sim 0.94 R_{AA}^{incl}$
Full B suppression
$\rightarrow R_{AA}^{prompt} \sim 1.07 R_{AA}^{incl}$
Central y:
No B suppression
$\rightarrow R_{AA}^{prompt} \sim 0.91 R_{AA}^{incl}$
Full B suppression
$\rightarrow R_{AA}^{prompt} \sim 1.17 R_{AA}^{incl}$

- At forward y, R_{AA} flattens for $N_{part} \geq 100$
- Central and forward rapidity suppressions compatible within uncertainties

Low p_T: comparison ALICE vs PHENIX



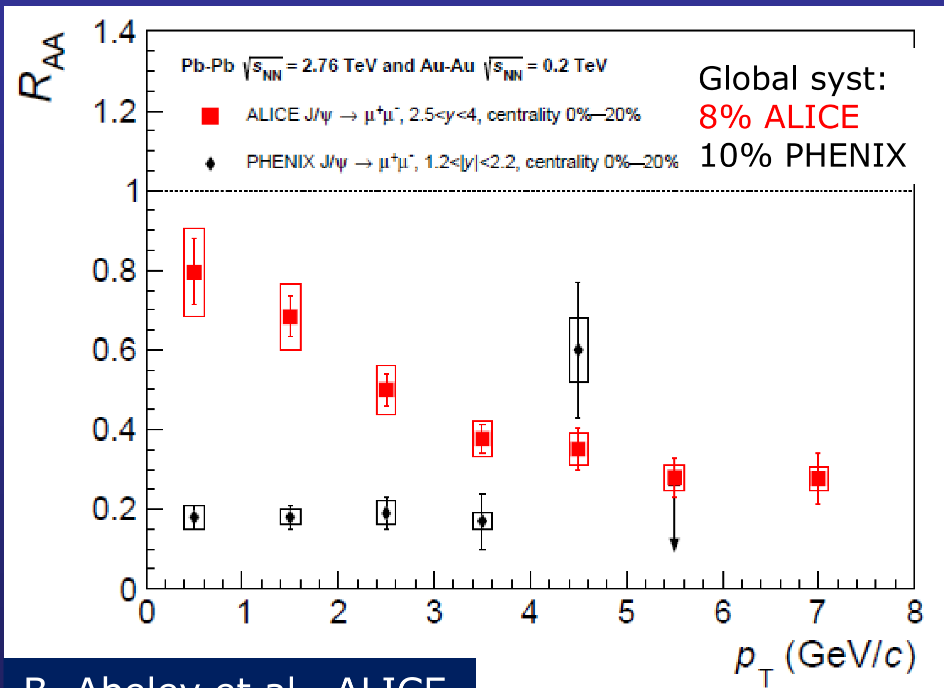
B. Abelev et al., ALICE arXiv:1311.0214.

- Comparison with PHENIX

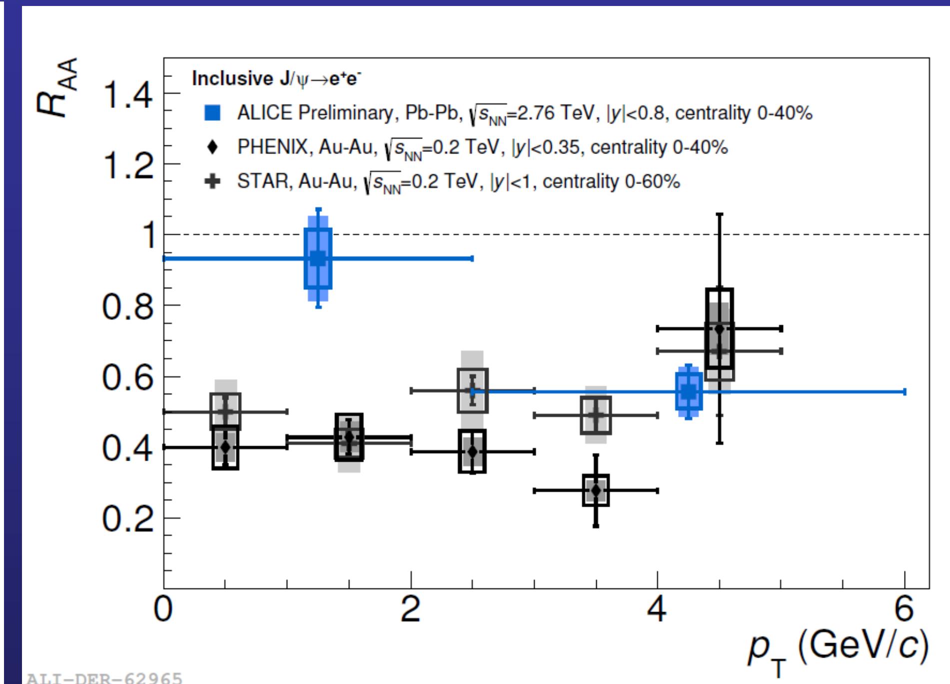
- Stronger centrality dependence at lower energy
- Systematically larger R_{AA} values for central events in ALICE

- Behaviour qualitatively expected in a (re)generation scenario
  → Look at the p_T dependence of the suppression

A (re)generation "signature": the p_T dependence of R_{AA}



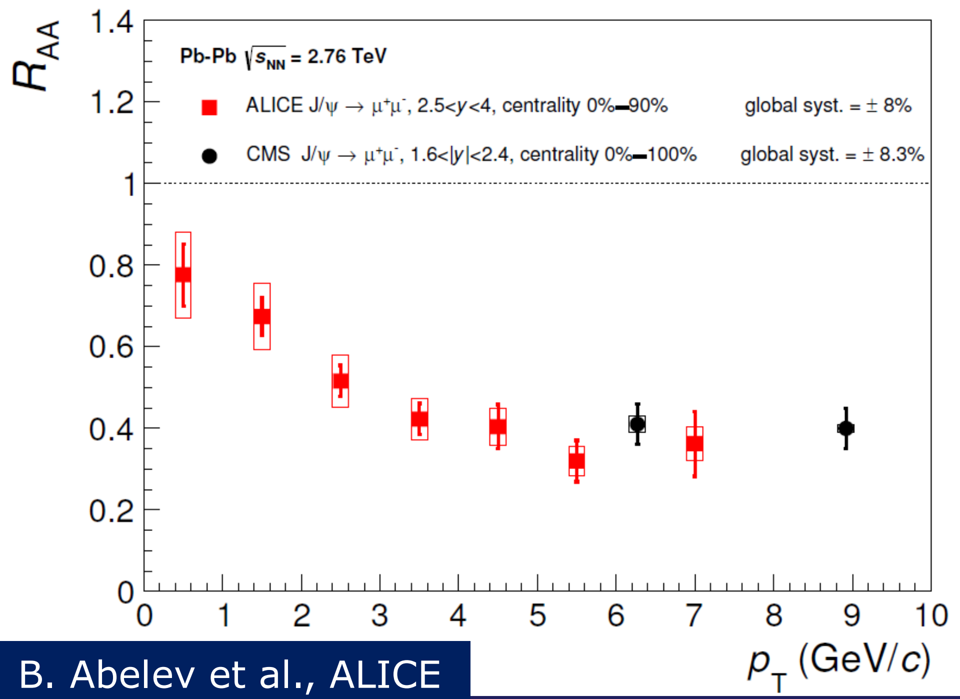
B. Abelev et al., ALICE arXiv:1311.0214.

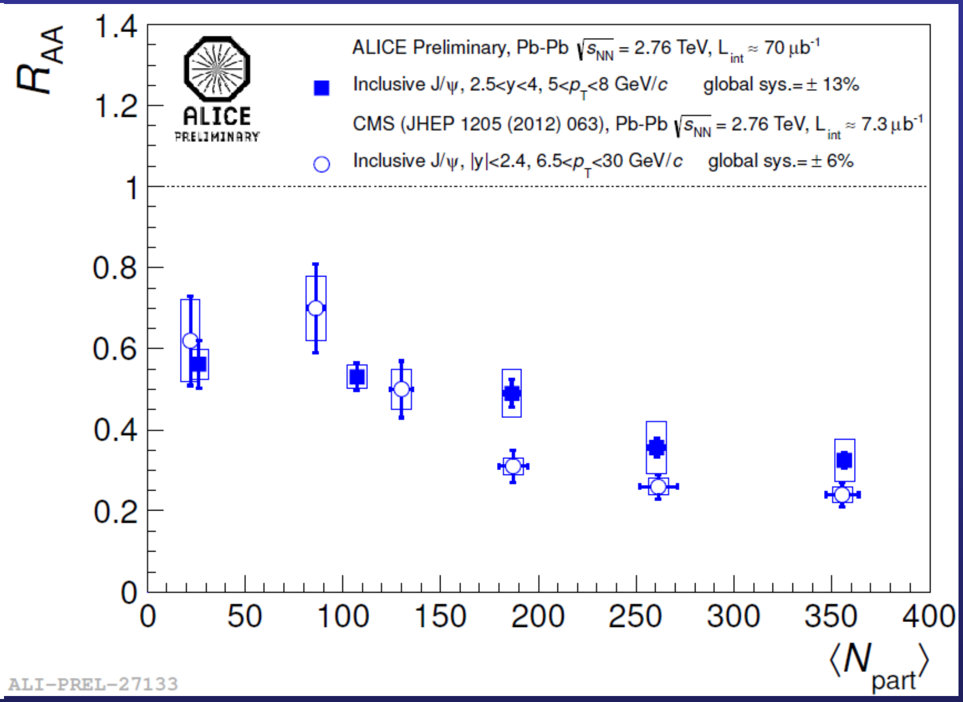


- At low p_T, for central events, the suppression is up to 4 times larger at PHENIX, compared to ALICE

→ Strong indication for (re)generation

Moving to higher p_T: compatibility checks CMS vs ALICE

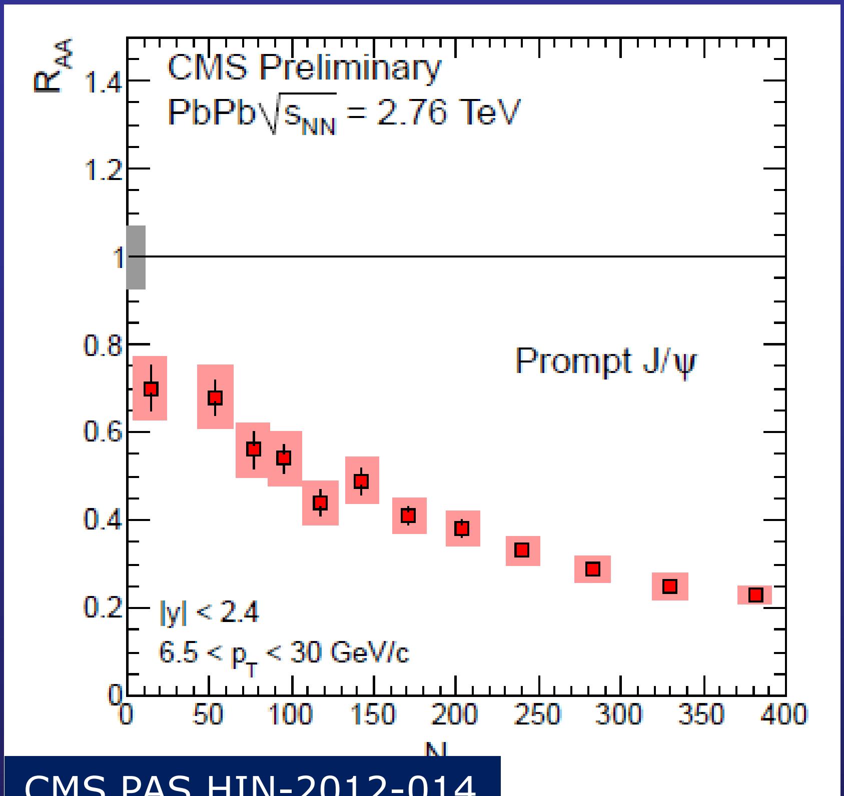




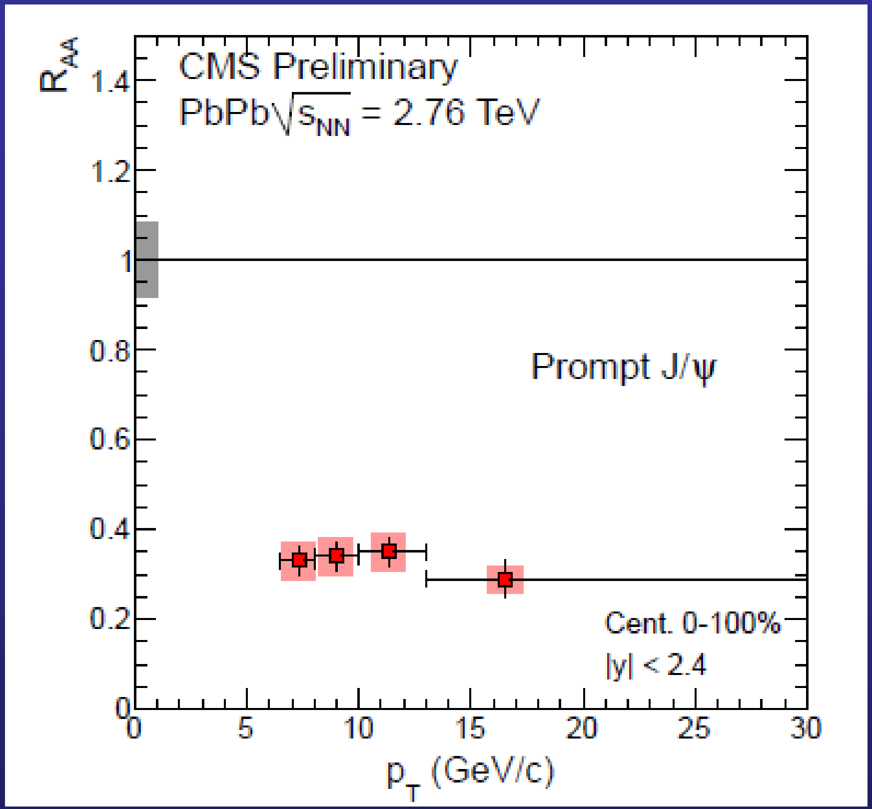
B. Abelev et al., ALICE arXiv:1311.0214.

- Complementary y-coverage: 2.5<y<4 (ALICE) vs
  1) 1.6<|y|<2.4 (CMS, left)
  2) |y|<2.4 (CMS, right)
- Qualitative agreement in the common p_T range

CMS results: prompt J/ψ at high p_T

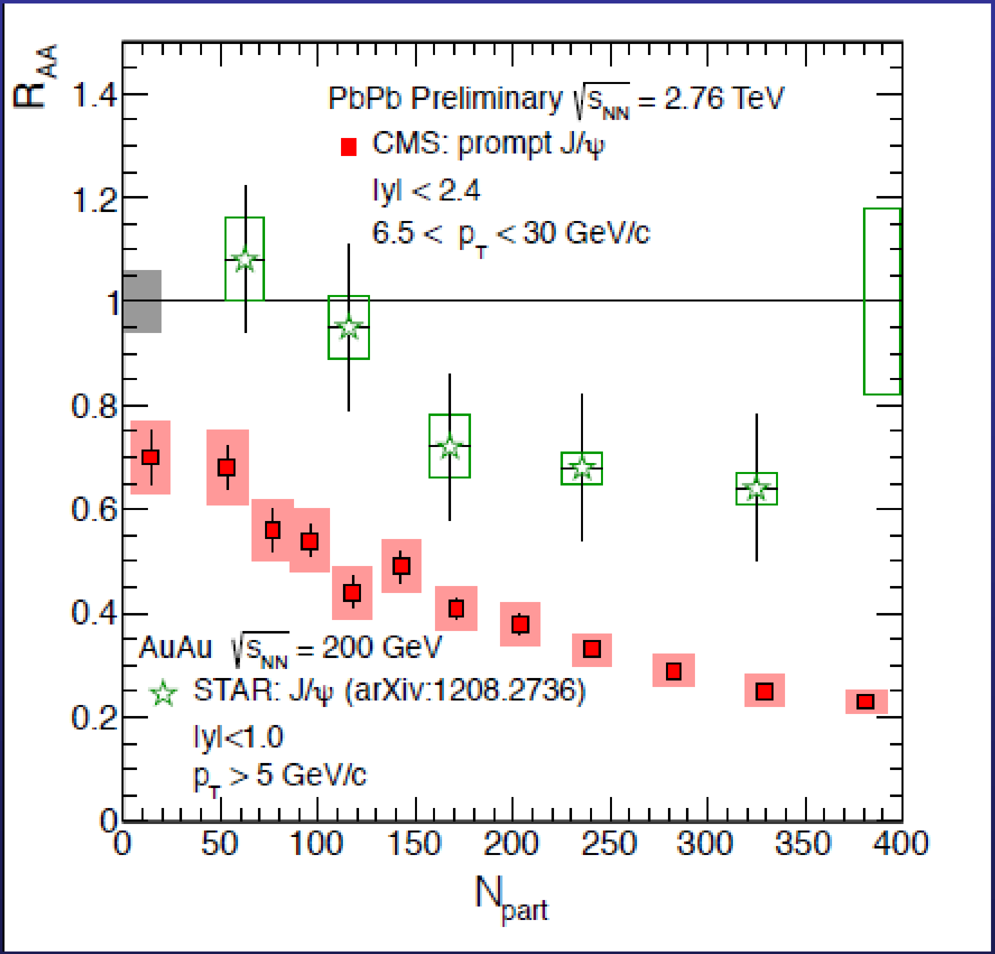


CMS PAS HIN-2012-014



- 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

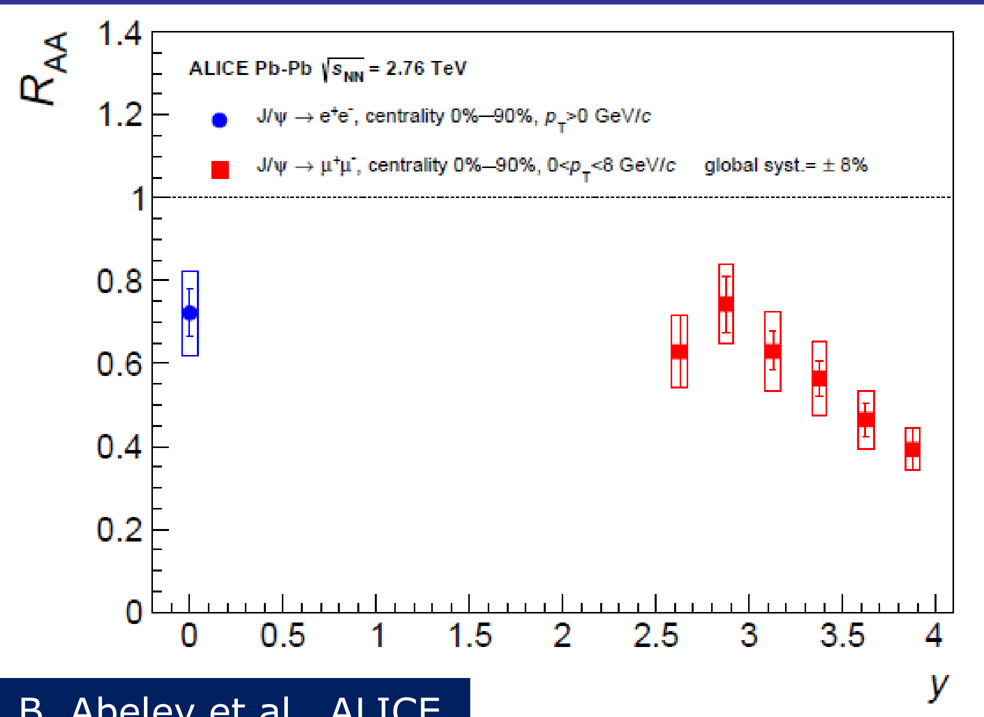
High p_T J/ψ: comparison CMS vs STAR



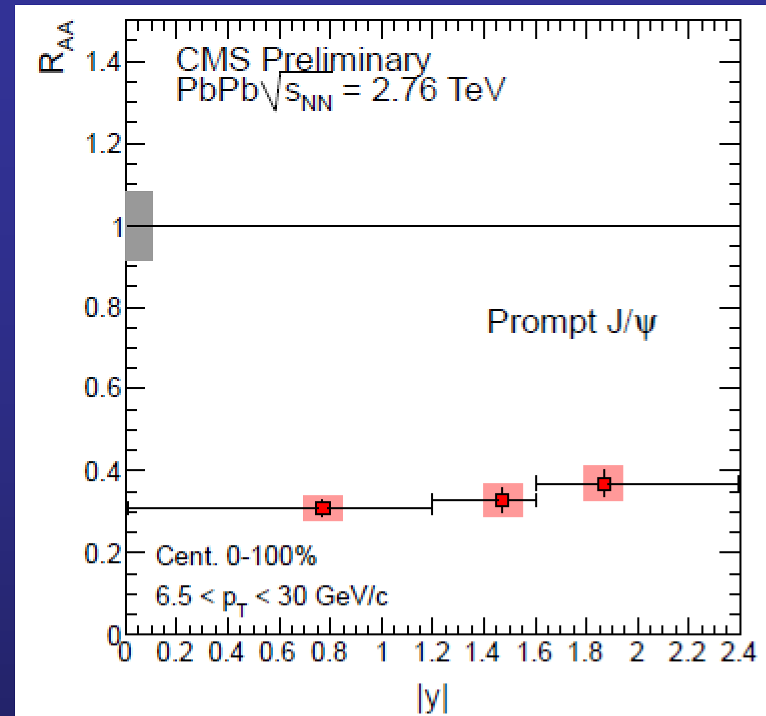
- ❑ Opposite behaviour when compared to low-p_T results
- ❑ Suppression is stronger at LHC energy (by a factor ~3 compared to RHIC for central events)

- ❑ 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) ?

Rapidity dependence of J/ψ R_{AA}



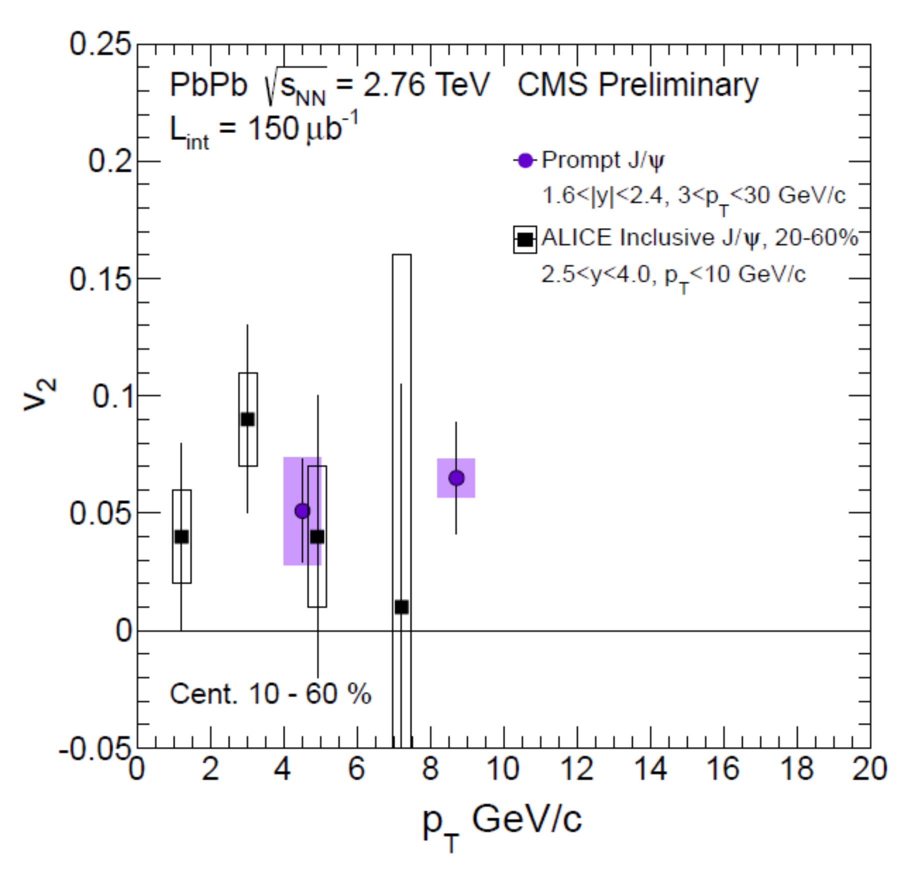
B. Abelev et al., ALICE arXiv:1311.0214.



CMS PAS HIN-2012-014

- Low p_T data: larger suppression at forward y (RHIC-like)
- Almost no effect in 0<|y|<2.4 at high p_T

A new actor: the J/ψ v_2



CMS HIN-2012-001

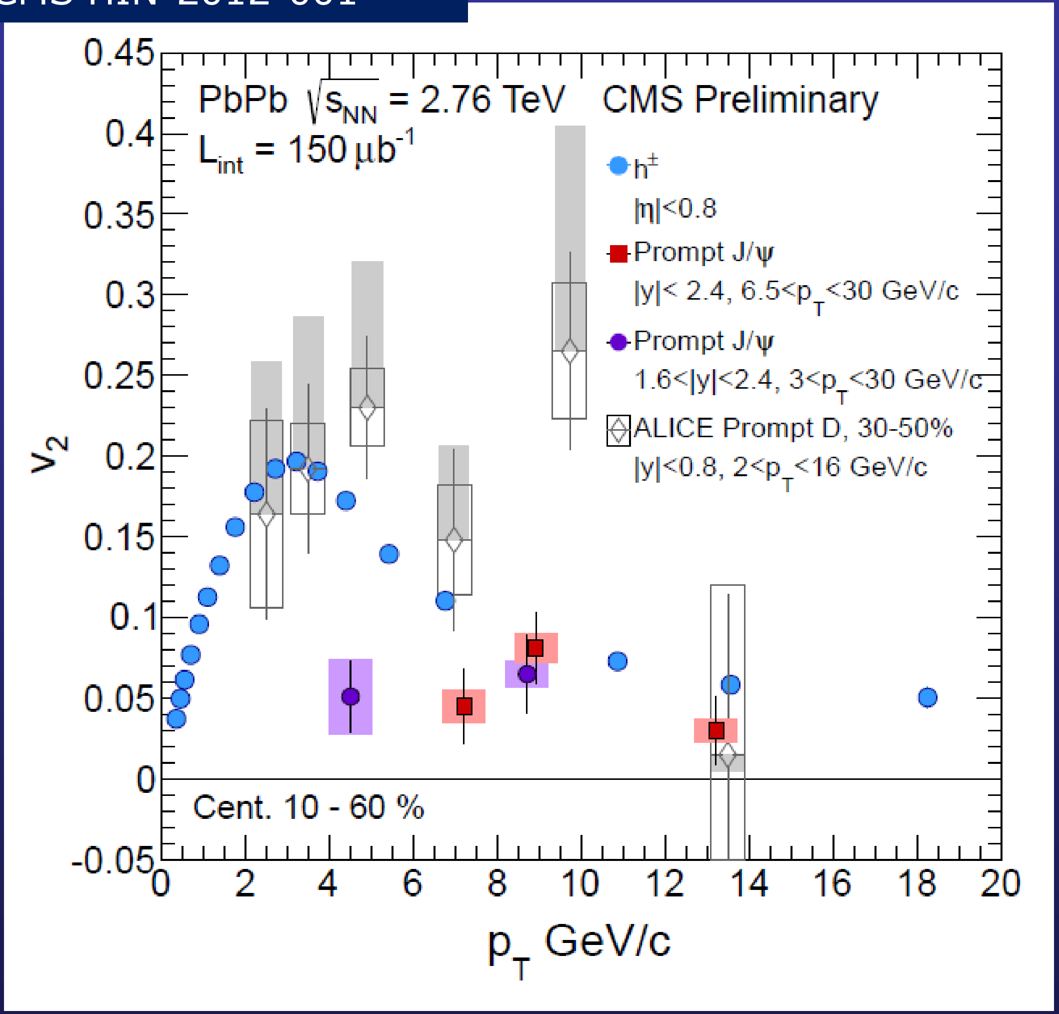
E.Abbas et al. (ALICE), PRL111(2013) 162301

- 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

J/ψ vs open HF v_2

CMS HIN-2012-001

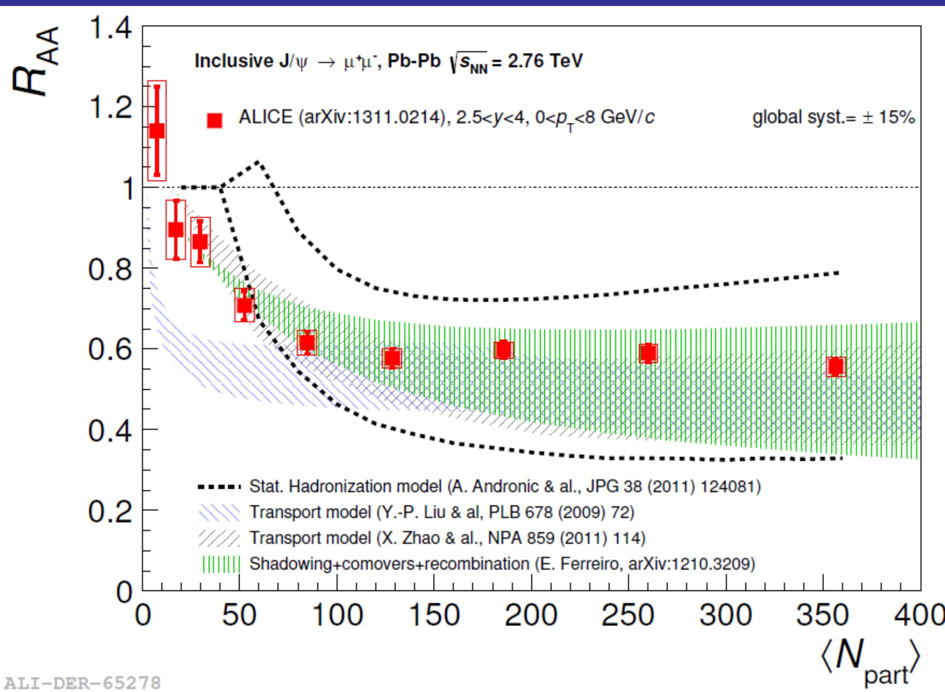


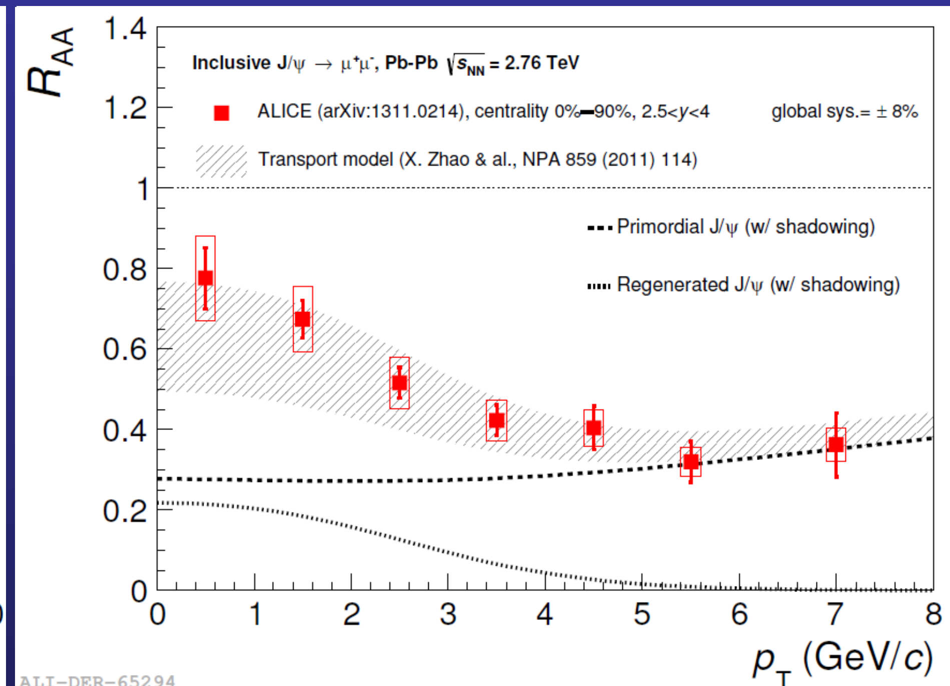
- J/ψ elliptic flow should be directly related to HF v_2
- Smaller values for J/ψ in the region where (re)generation should play a role
- Simply a reflection of the fraction of J/ψ due to (re)generation?

- Similar values at very high p_T (uncertainties!) for all particles

Towards a quantitative understanding?

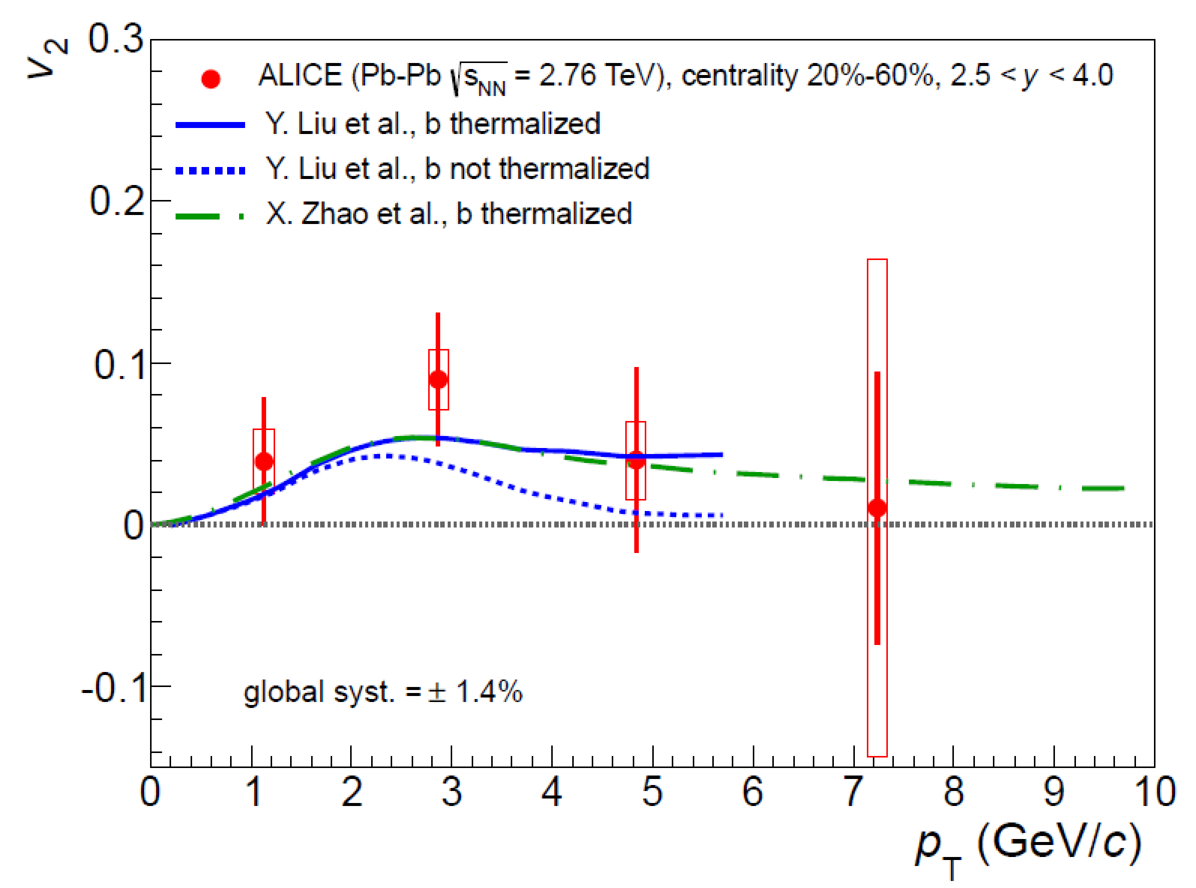
- Data shown in the previous slides were compared with theoretical models that implement suppression/(re)generation scenarii





- Good qualitative description of the results
- Theoretical uncertainties larger than experimental ones!
- Can the experiment help in fixing (some of) the theory inputs? (CNM, open charm?)

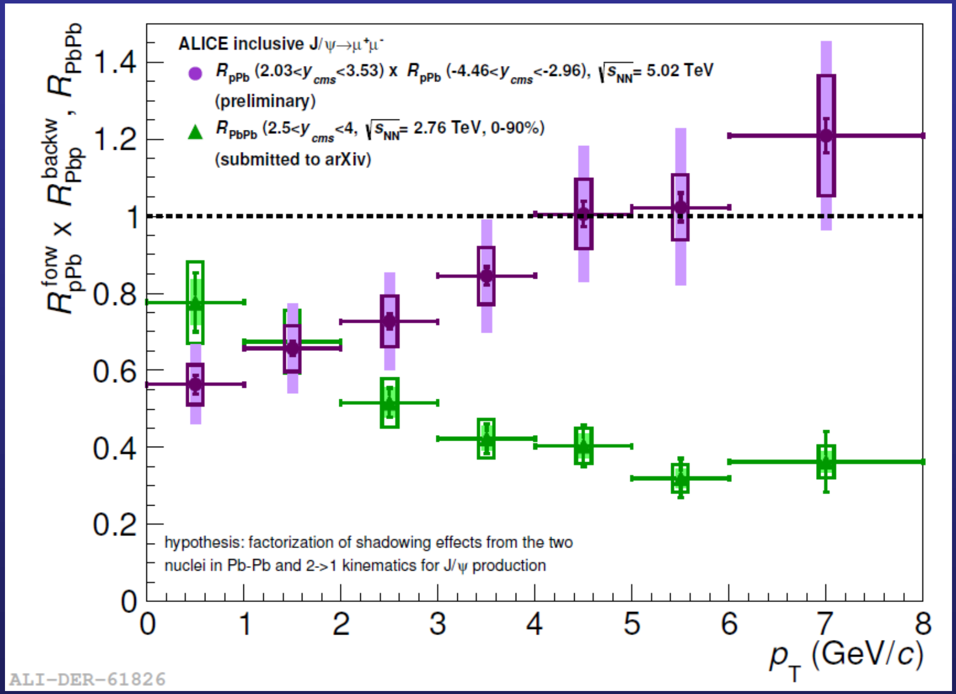
Flow: comparison to theory

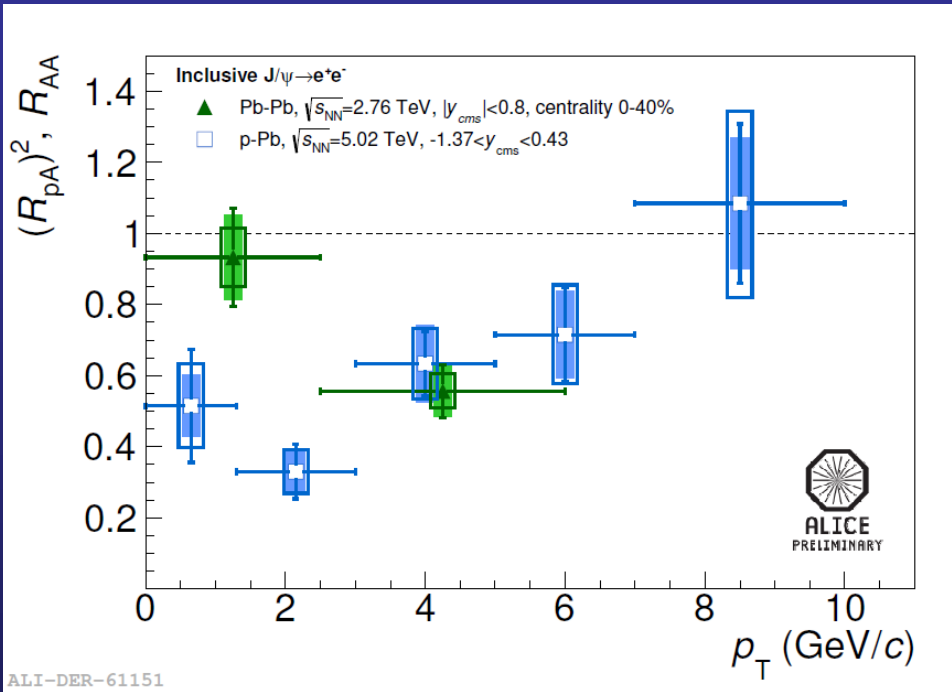


- Same transport model calculations used for R_{AA}
- Include a J/ψ regeneration component (30%) from deconfined medium
- Large positive v_2 from (re)generation at low p_T and smaller positive v_2 due to path-length dependence at high p_T → maximum at ~2.5 GeV/c
- B-quark thermalization could increase v_2 at large p_T

Role of CNM

- Proved to be extremely important in understanding SPS/RHIC results. First results on J/ψ in p-Pb at LHC energy are available





- Try the simplest possible comparison: pure shadowing, 2→1 production kinematics
- From enhancement to suppression when increasing p_T
- Is a "standard model" for CNM extrapolations within reach ?

Role of CNM

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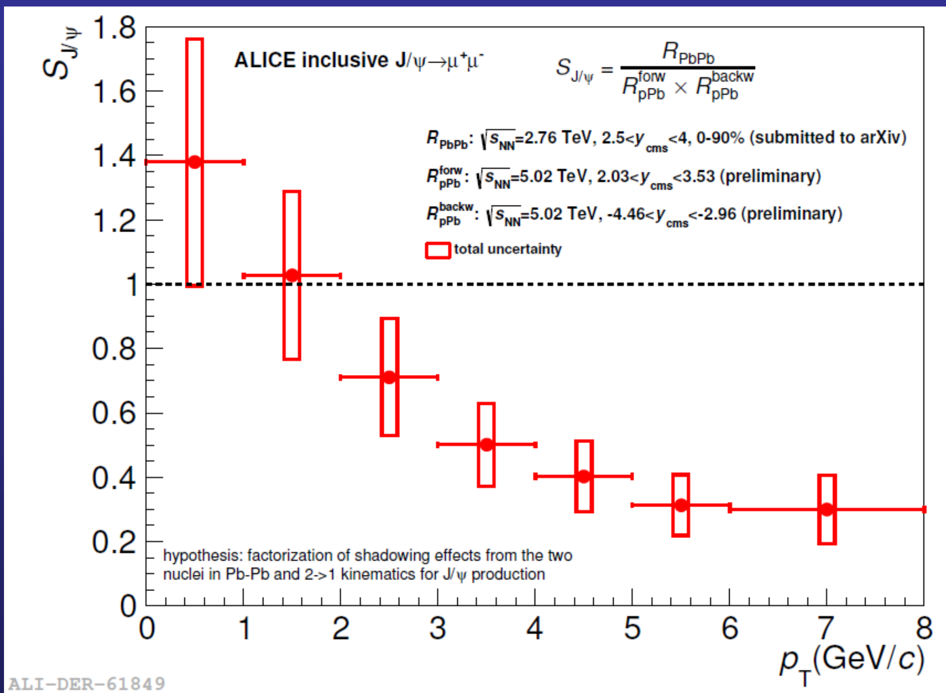
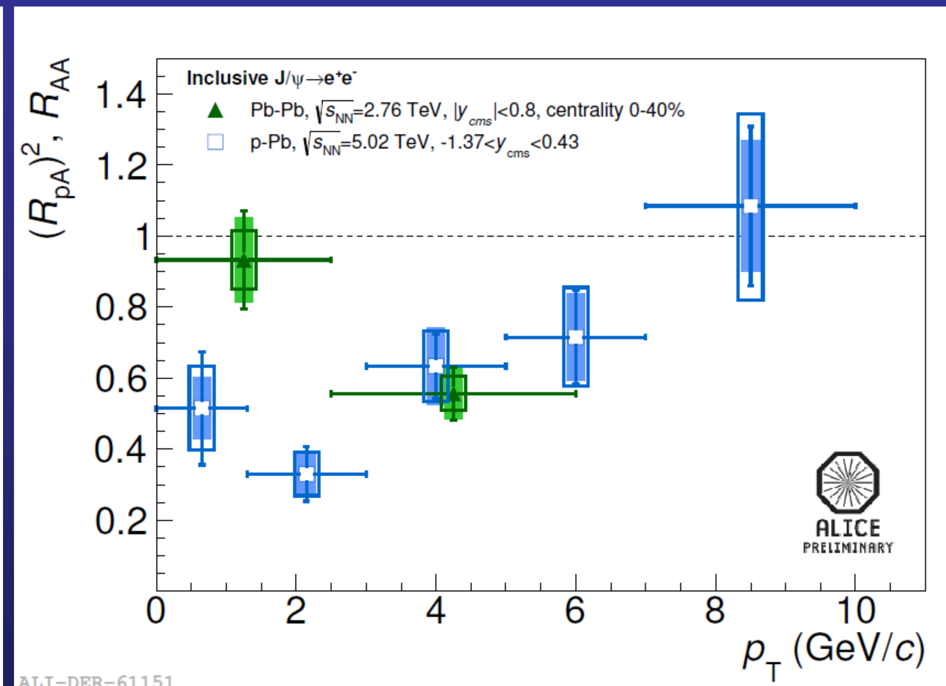


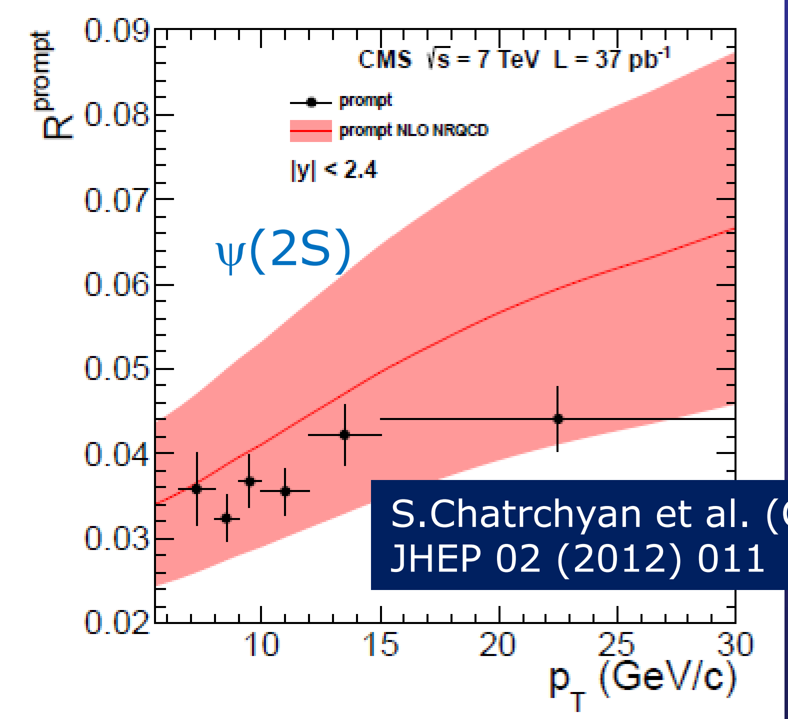


- ❑ Try the simplest possible comparison: pure shadowing, 2→1 production kinematics

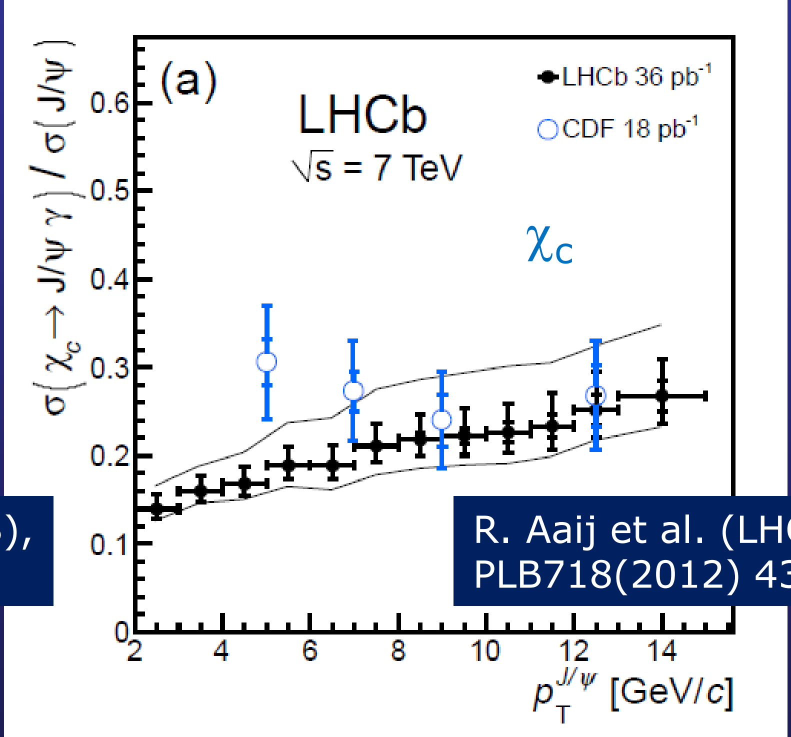
- ❑ From enhancement to suppression when increasing p_T
- ❑ Is a “standard model” for CNM extrapolations within reach ?

Role of feed-down

- The study of the sequential suppression of charmonium resonances requires a good knowledge of the feed-down fractions
- Accurate pp measurements exist on a wide p_T range



S.Chatrchyan et al. (CMS), JHEP 02 (2012) 011

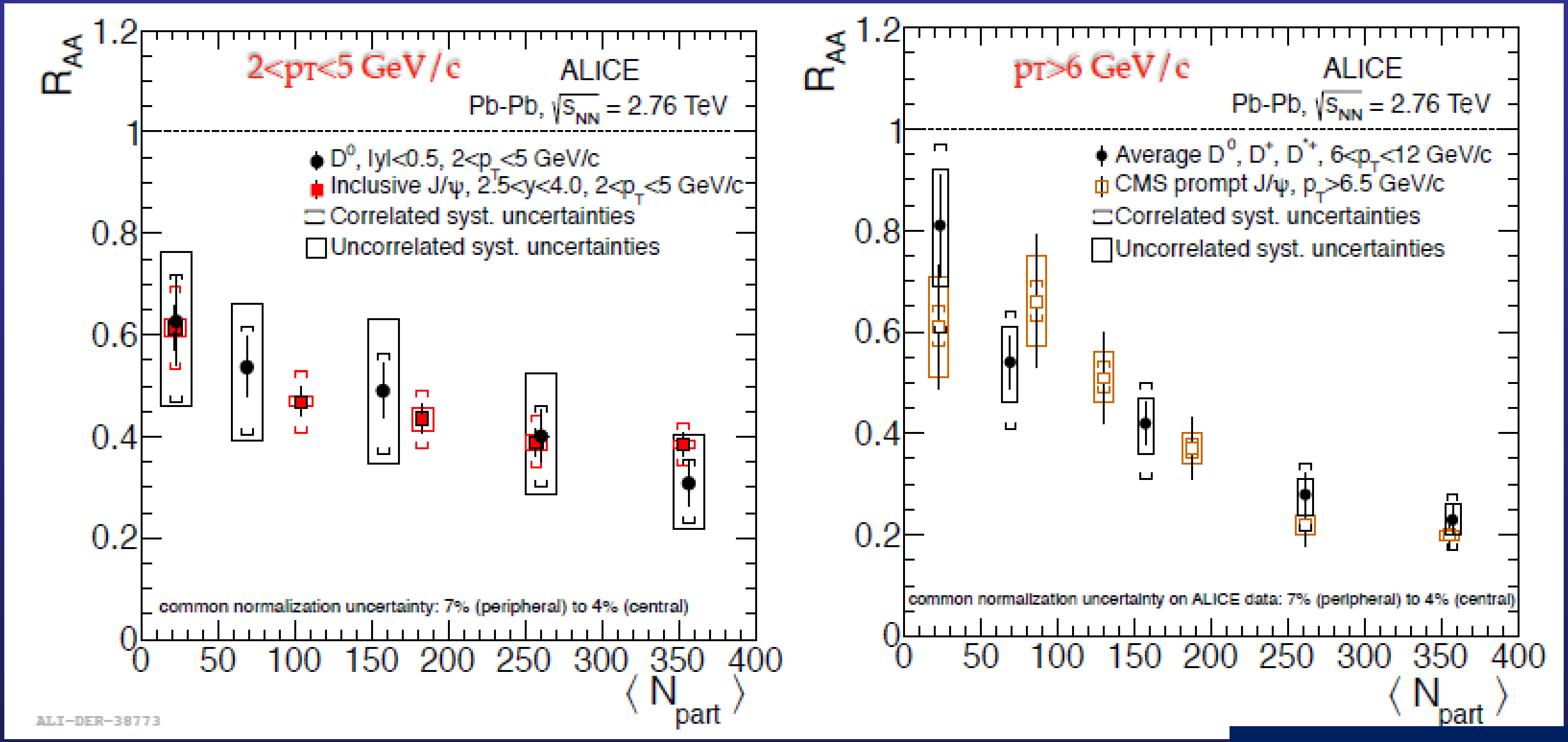


R. Aaij et al. (LHCb), PLB718(2012) 431

- Initial temperatures reached in central collisions at LHC possibly exceed dissociation temperatures even for direct J/ψ
- Can the threshold for direct J/ψ suppression be singled out (non-central collisions, high-p_T charmonia)?

Comparison D vs J/ψ

- Open charm is in principle a very good reference for the study of J/ψ suppression
  → Intriguing observation comparing ALICE Ds with CMS J/ψ



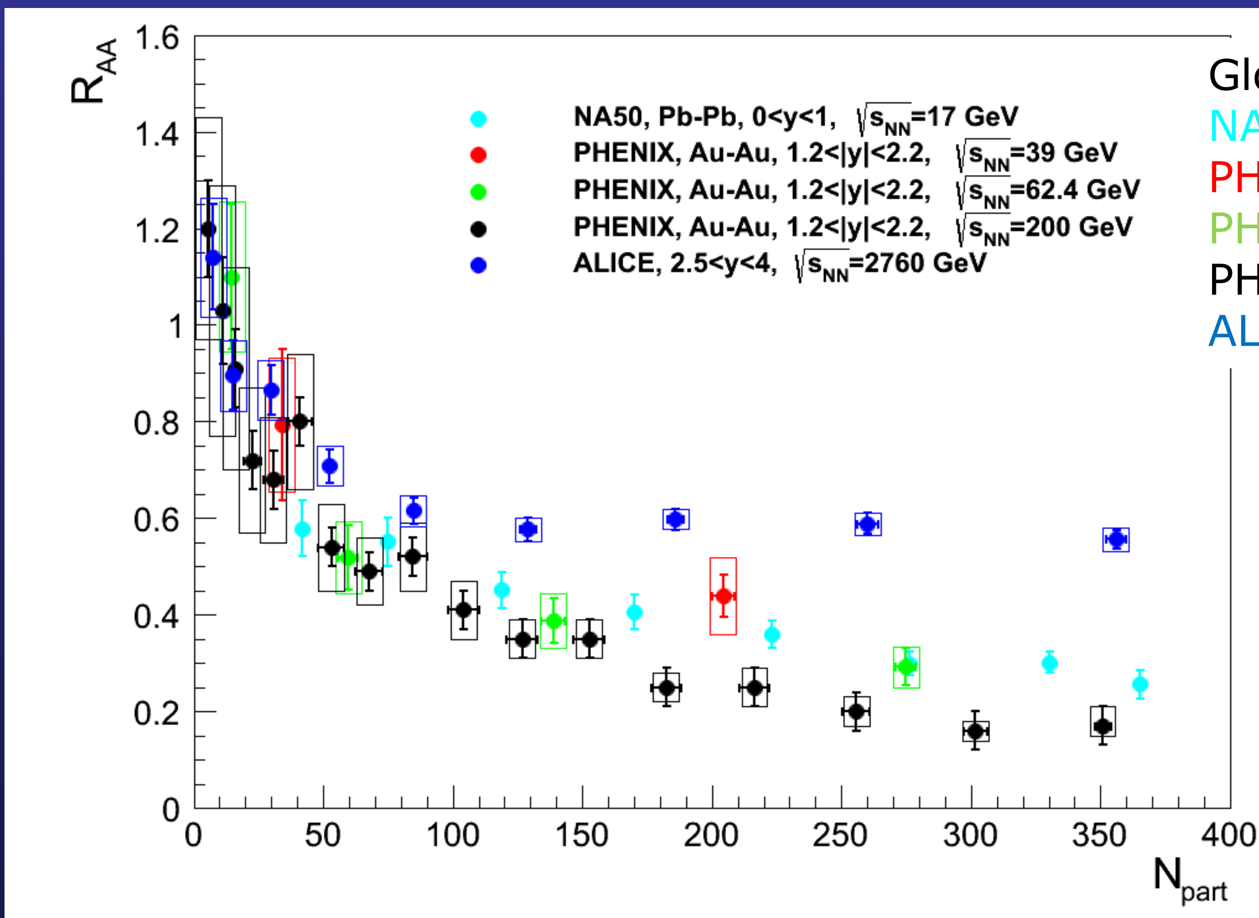
Z. Conesa (ALICE), Quark Matter 2012

- Caveat(s)
  - Comparison in restricted kinematic ranges is delicate
  - Prospects for extending D measurements to p_T=0 being defined

A challenge for the interpretation

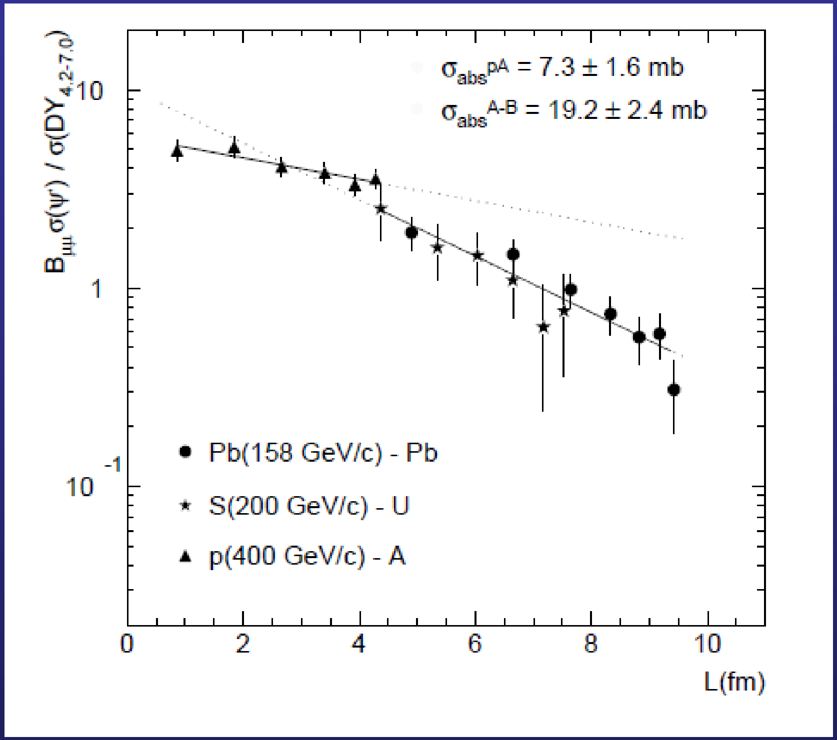
- We have by now a sort of "energy scan" over
  - ~2 orders of magnitude in $\sqrt{s}$
  - light vs heavy nuclei

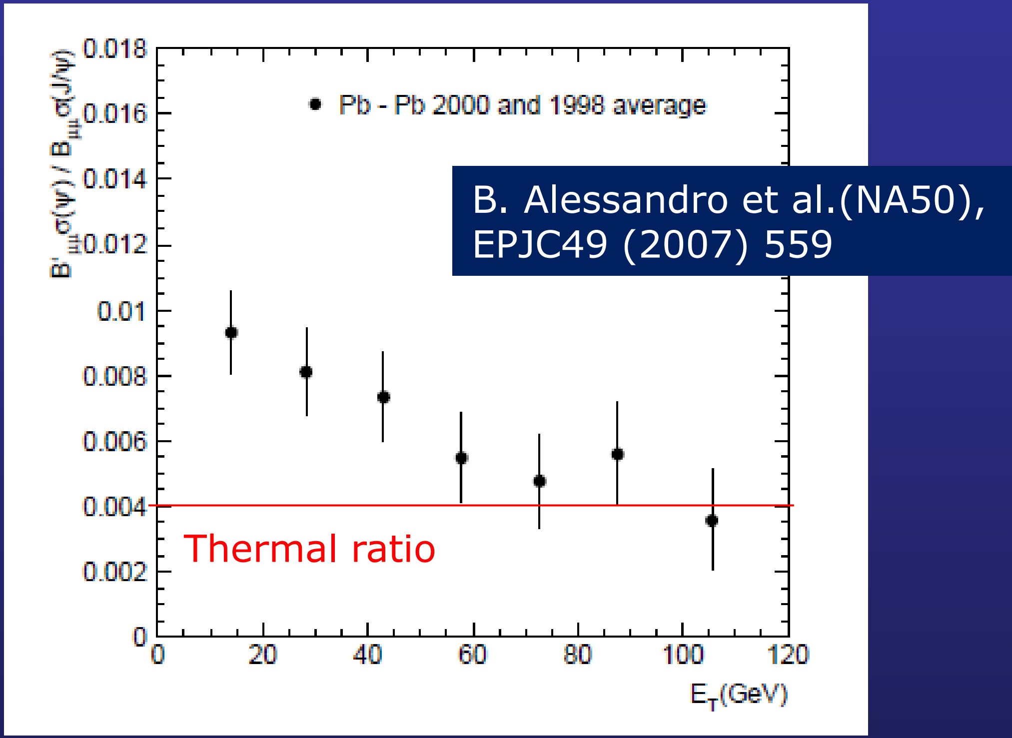
} powerful testing ground



Global systematics
NA50 ± 11%
PHENIX 39 GeV: ±19%
PHENIX 62.4 GeV: ±29.4%
PHENIX 200 GeV: ±9.2%
ALICE 2760 GeV: ±15%

ψ(2S): what did we learn at lower (SPS) energies ?





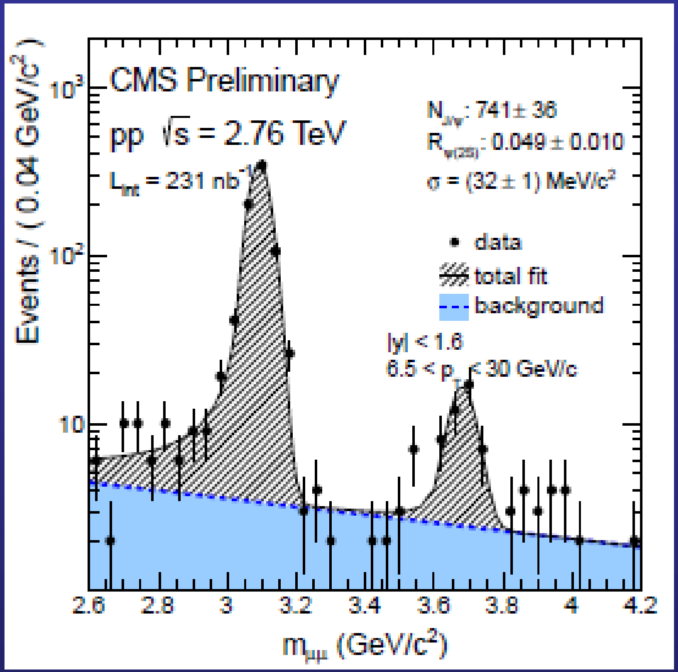
- ❑ Substantially different behaviour in p-A and A-A
- ❑ Stronger suppression already for peripheral events (compared to J/ψ, where the anomalous suppression sets in at higher N_{part})

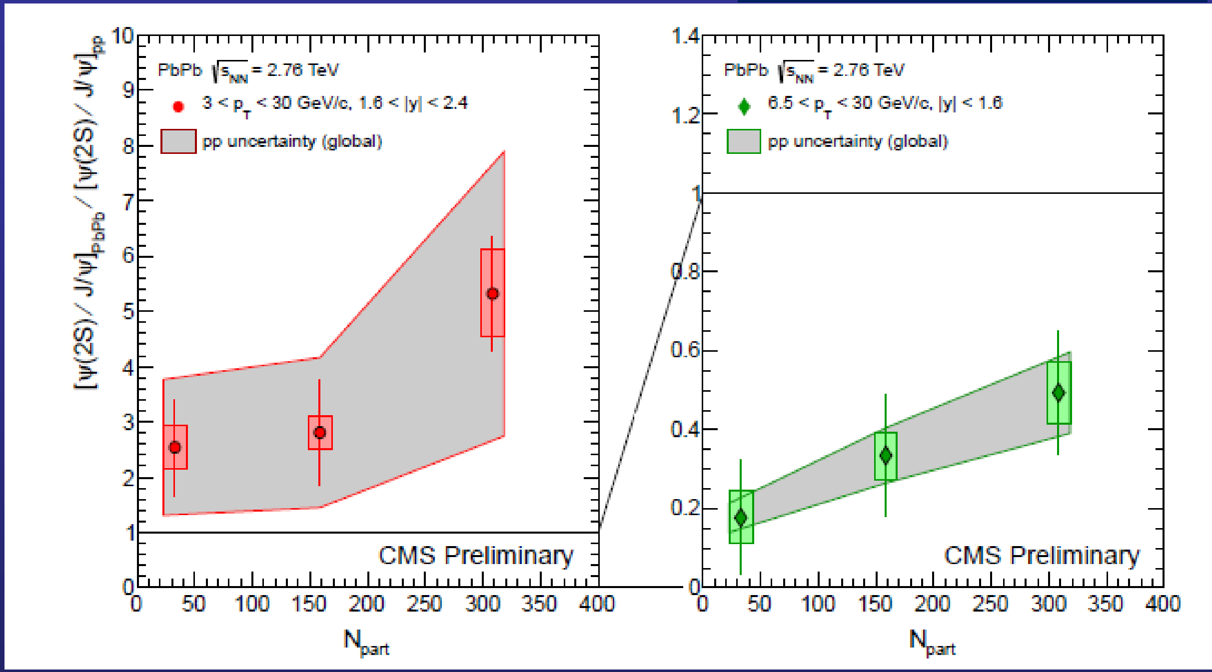
- ❑ Values of the ψ(2S)/(J/ψ) ratio approach thermal expectations for central collisions → one of the pillars of this approach

ψ(2S): CMS results

- Intriguing set of preliminary results

CMS PAS HIN-12-007

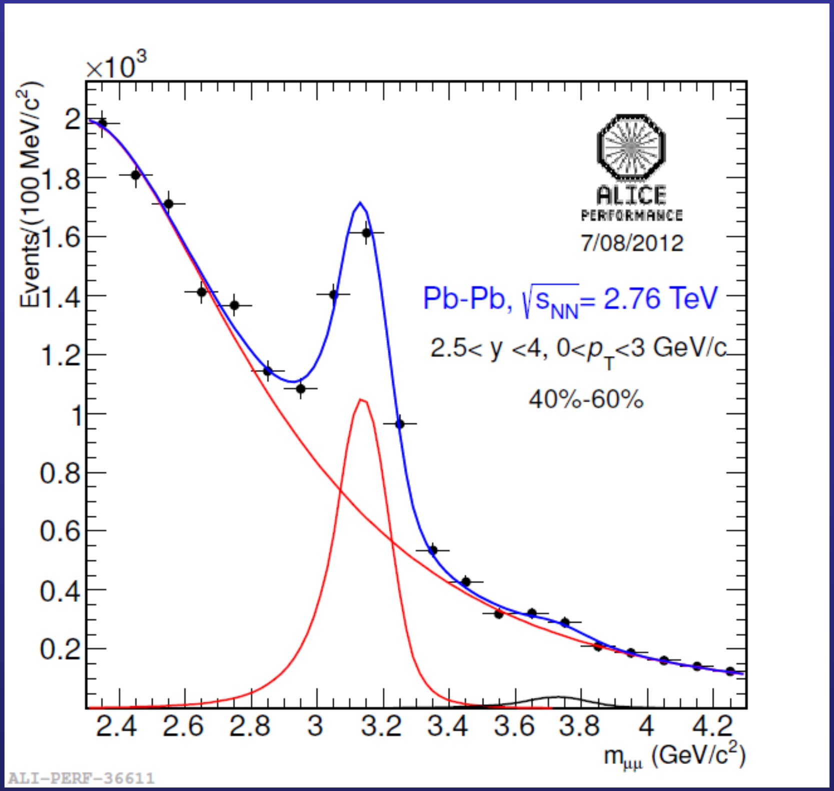


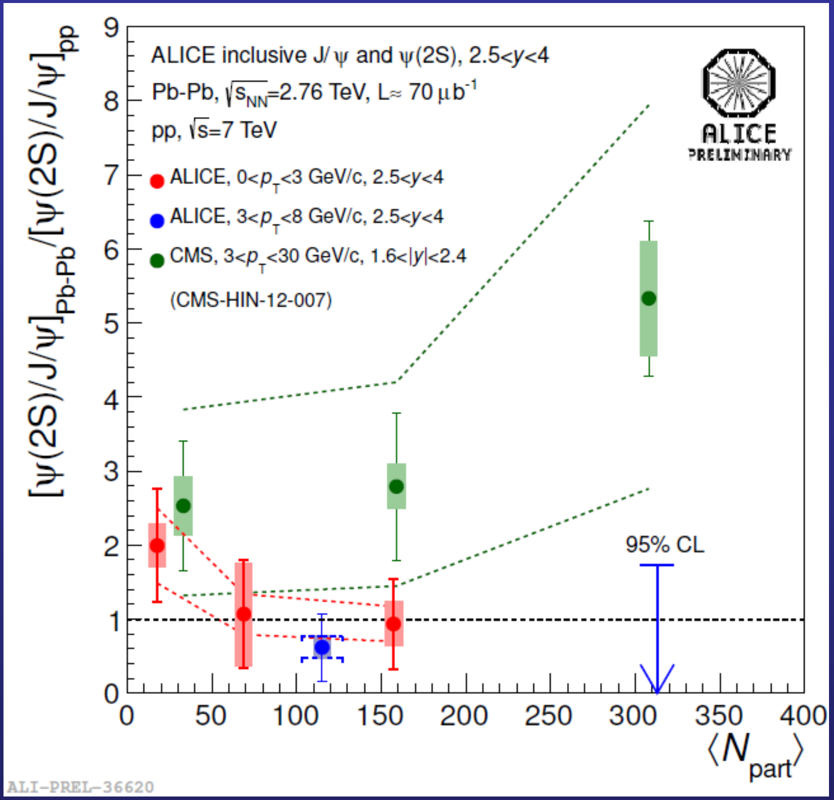


- ψ(2S) signal well visible in the invariant mass spectra
- $3<p_T<30$ GeV/c, $1.6<|y|<2.4$: enhancement 2S/1S ratio relative to pp
- $6.5<p_T<30$ GeV/c, $|y|<1.6$: suppression 2S/1S ratio relative to pp

- Room for reducing reference uncertainties (now major contribution)
- Intepretation not straightfoward

$\psi(2S)$: ALICE results





- Worse mass resolution wrt CMS but signal still visible
- Comparison ALICE vs CMS suggests some tension for central Pb-Pb collisions (no significant enhancement found)

- Double ratio at SPS energy → ~0.3
- Similar or smaller value expected at LHC, in either a sequential suppression or a thermal scenario

Conclusions

- First round of experimental observations on charmonium at LHC
- Extensive set of results from ALICE and CMS experiments

→ Very interesting observations, qualitative understanding of the main features

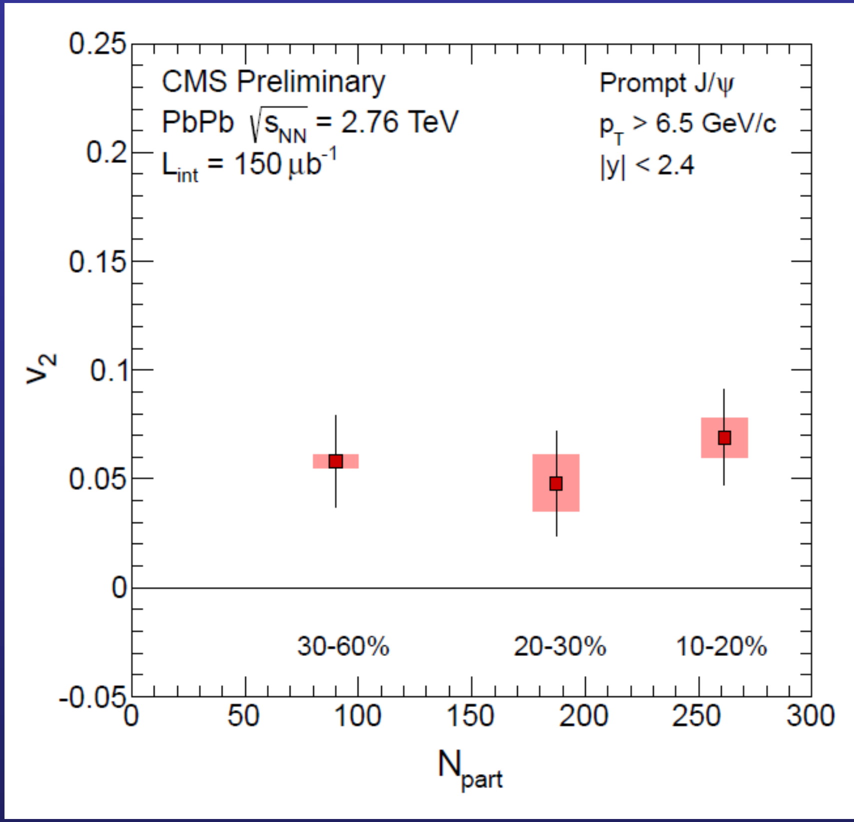
- J/ψ
  - Important role of (re)generation processes at low p_T
  - Very strong suppression for central events at high p_T

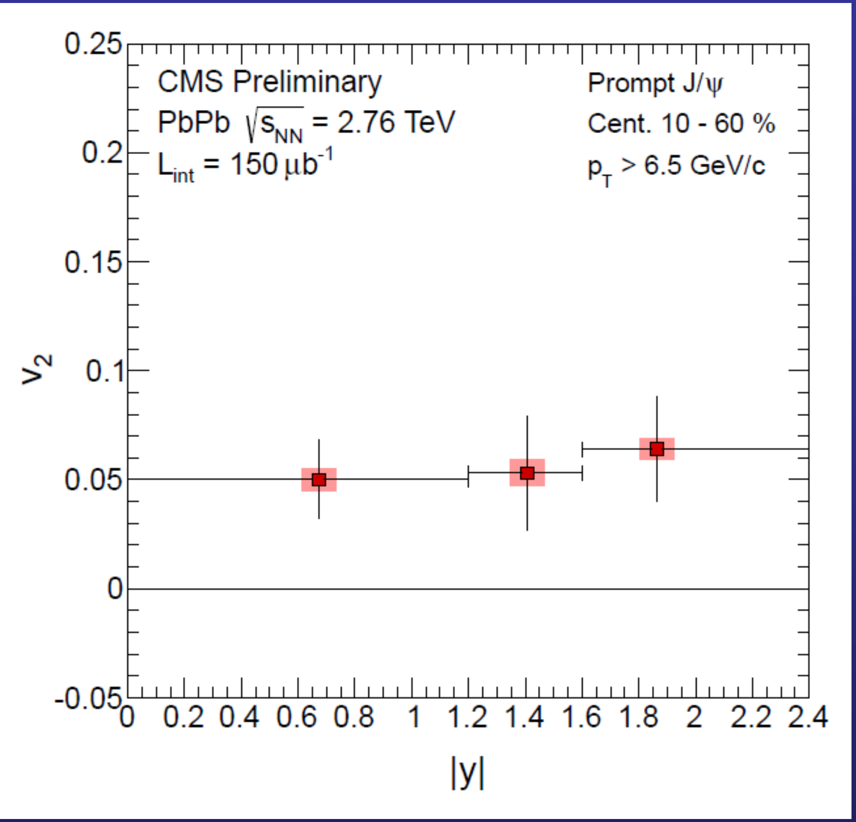
- $\psi(2S)$
  - Results need to be finalized, interpretation not straightforward

- Should now move towards a quantitative understanding
  - CNM measurements exist → recipe for extrapolation to AA?
  - Can we describe results over 2 orders of magnitude in $\sqrt{s}$?
  - Tuning the models (open charm multiplicity, initial temperature) in order to reproduce 2.76 TeV data, can precise predictions for top LHC energy be given?

Backup

Other flow results: CMS

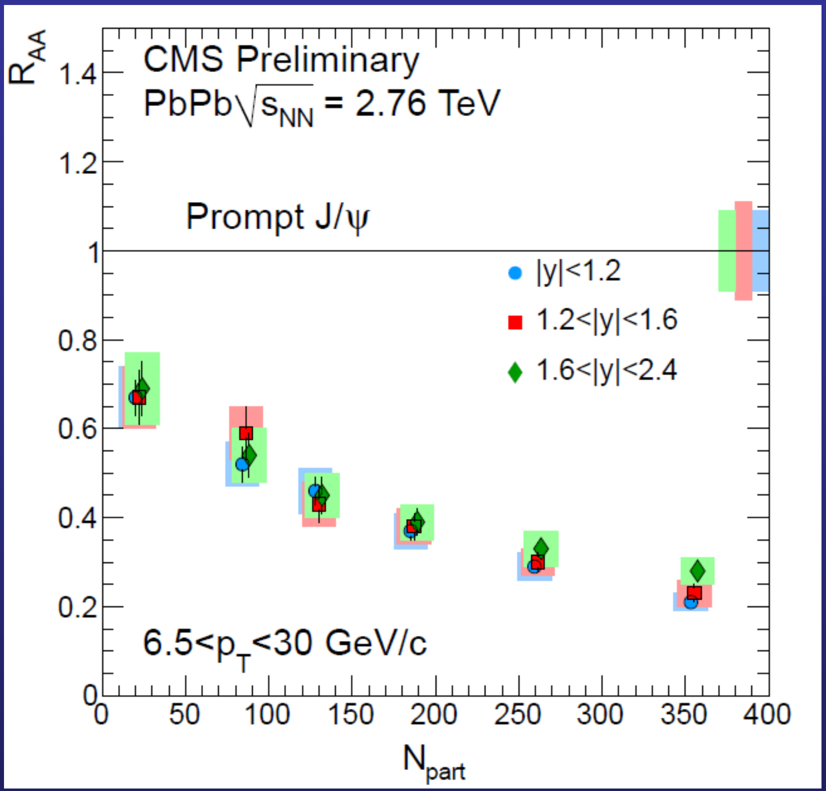


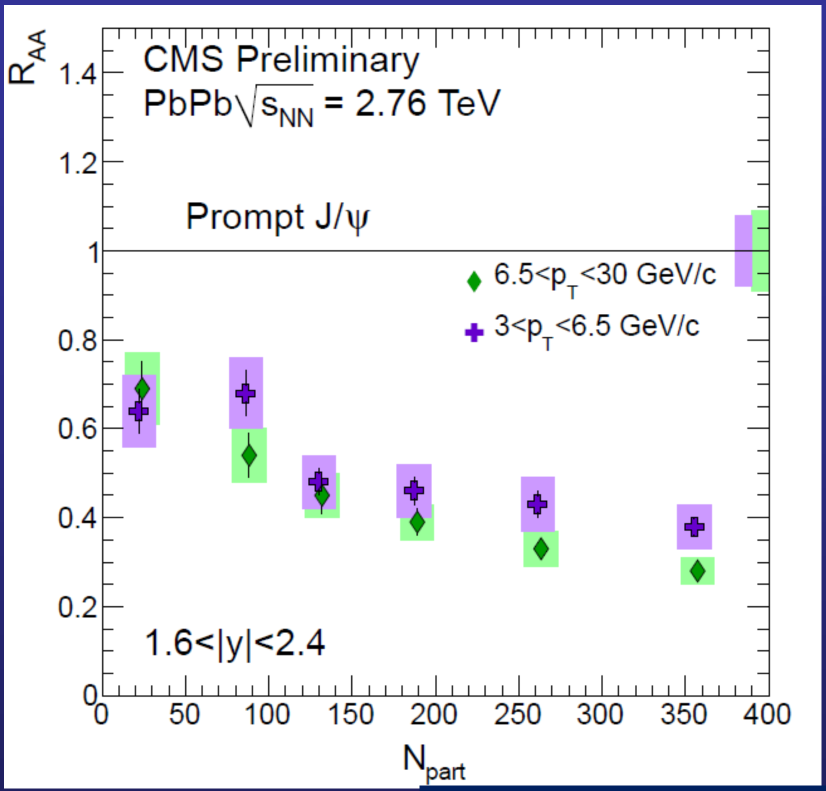


CMS PAS HIN-2012-001

- Non-zero v_2 for prompt J/ψ vs centrality and rapidity
- In (10-60%), $6.5<p_T<30$ GeV/c: $v_2=0.054 \pm 0.013 \pm 0.006$ (3.8 σ significance)

CMS: multidifferential J/ψ R_{AA}

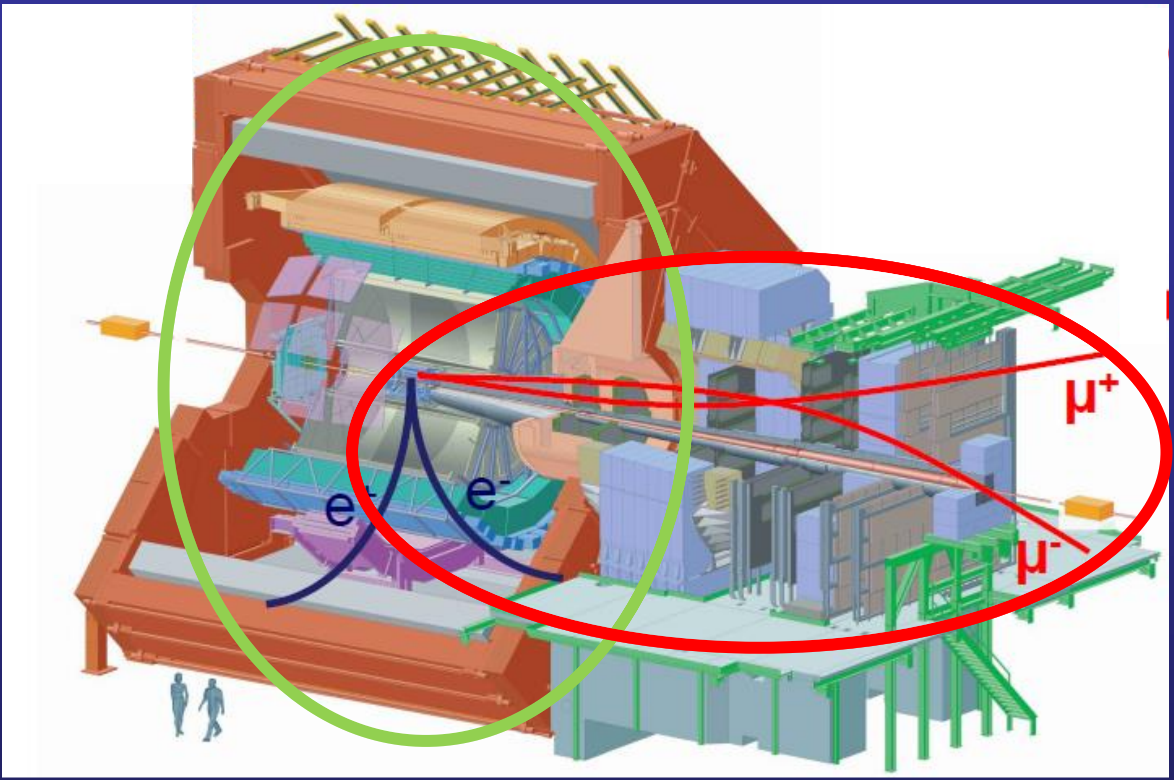




CMS PAS HIN-2012-014

- In the high p_T region, weak or no
  - rapidity dependence of R_{AA}
  - p_T dependence of R_{AA}

ALICE, experiment and data taking



Quarkonia detection

In the forward muon spectrometer ($2.5<y<4$) via $\mu^+\mu^-$ decays

In the central barrel ($|y|<0.9$) via e^+e^- decays

Acceptance extends down to $p_T=0$

- MB trigger based on
  - Forward scintillator arrays (VZERO)
  - Silicon pixel (SPD)
- In addition, trigger on muon (pairs) in the forward spectrometer (p_T ~ 1 GeV/c threshold for Pb-Pb 2011)

Integrated luminosity for quarkonia analysis

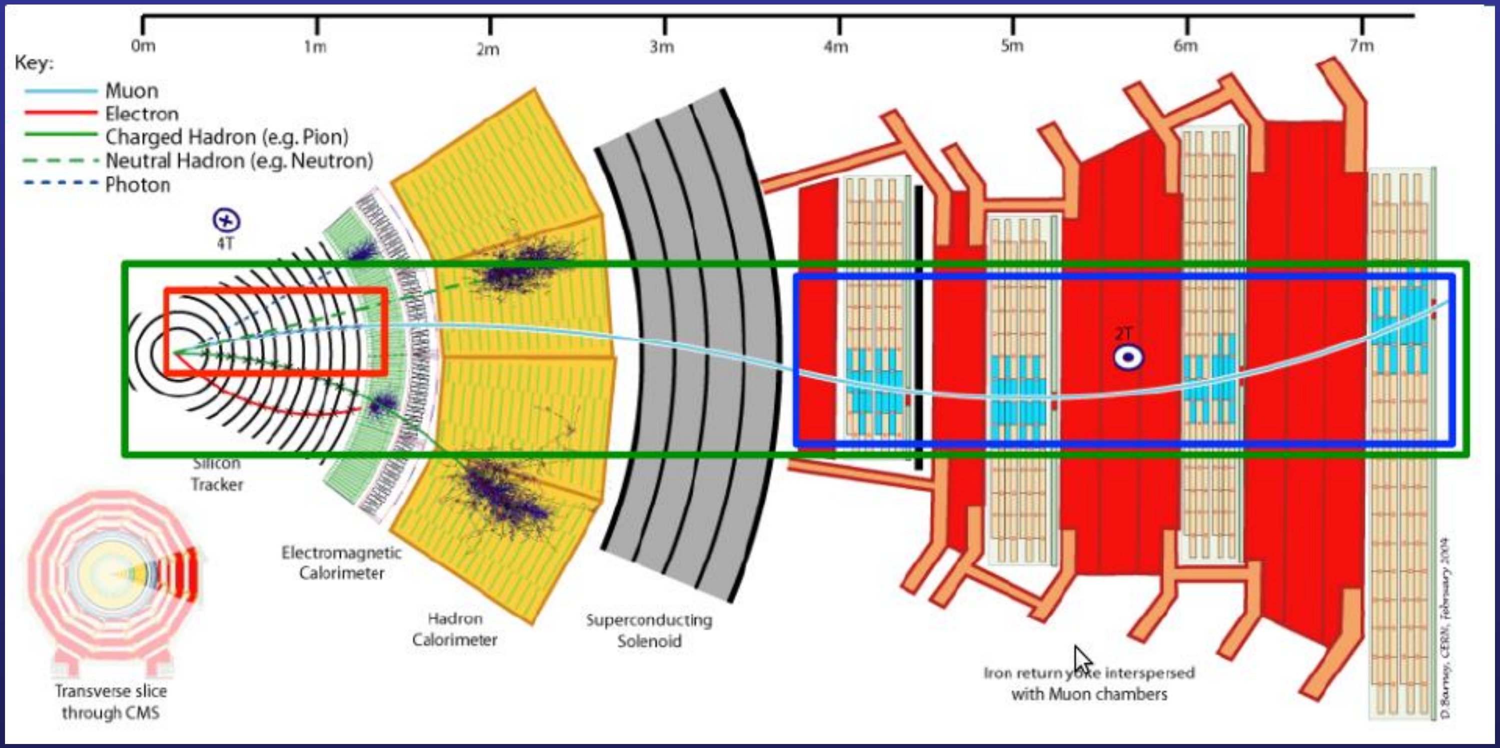
⇓

(up to) ~100 nb^{-1} for pp

~ 70 μb^{-1} for Pb-Pb

CMS experiment

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

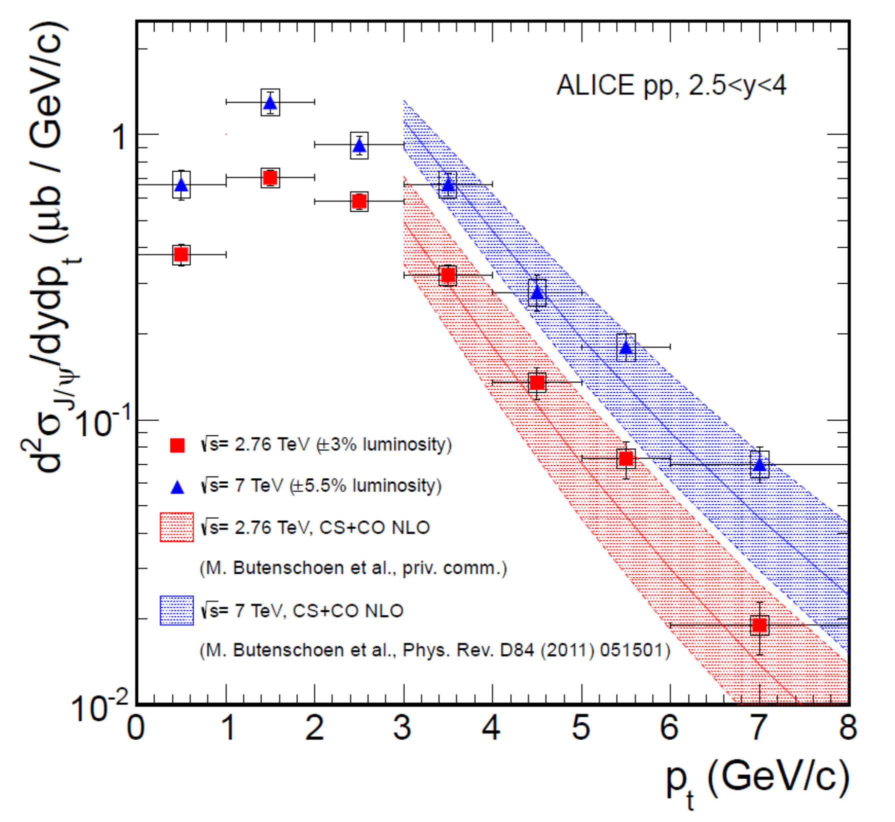


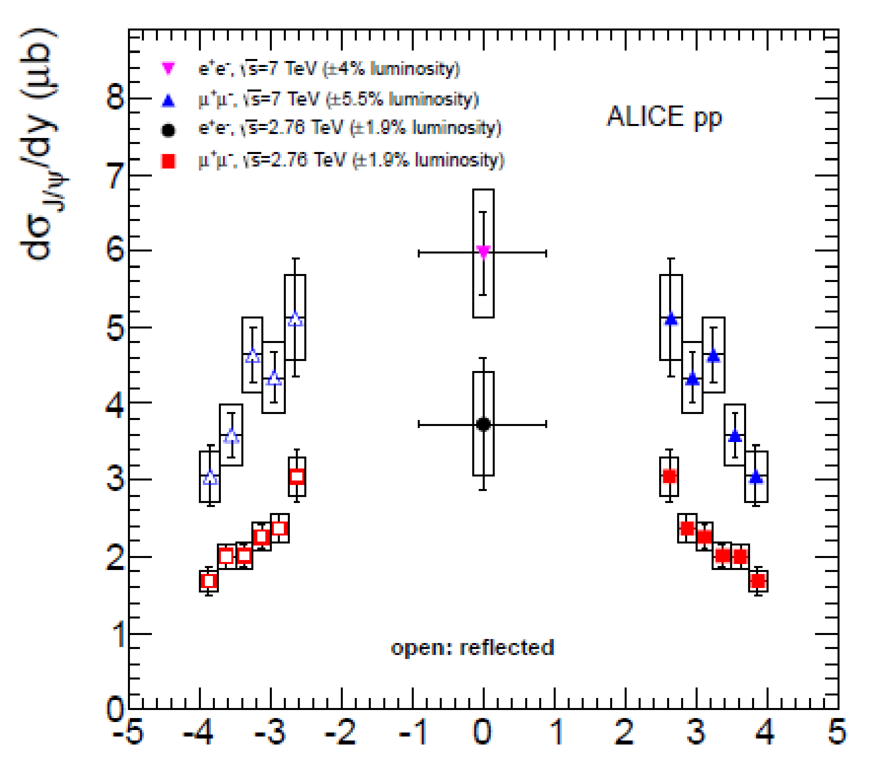
- "Global" muons reconstructed with information from inner tracker and muon stations
- Further muon ID based on track quality (χ^2, # hits,…)
- Magnetic field and material limit minimum momentum for muon detection → p_T cut for J/ψ

ALICE pp reference

- Data taking at $\sqrt{s}$=2.76 TeV essential to build the R_{AA} reference, result based on L_{int}^{e}=1.1 nb^{-1} and L_{int}^{μ}=19.9 nb^{-1}

$$\sigma_{J/\psi}(|y|<0.9) = 6.71 \pm 1.54(\text{stat.}) \pm 1.21(\text{syst.}) + 1.01(\lambda_{\text{HE}}=1) - 1.41(\lambda_{\text{HE}}=-1)\ \mu\text{b and}$$
$$\sigma_{J/\psi}(2.5<y<4) = 3.34 \pm 0.13(\text{stat.}) \pm 0.27(\text{syst.}) + 0.53(\lambda_{\text{CS}}=1) - 1.07(\lambda_{\text{CS}}=-1)\ \mu\text{b}.$$



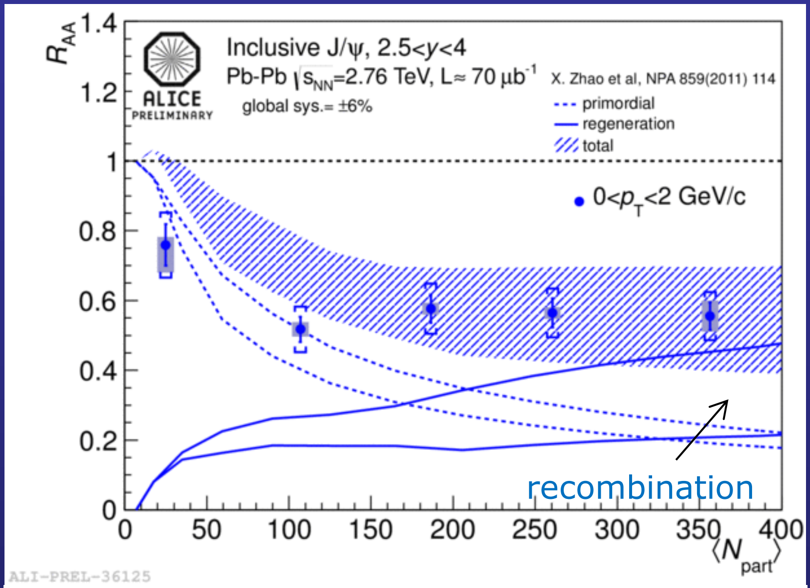


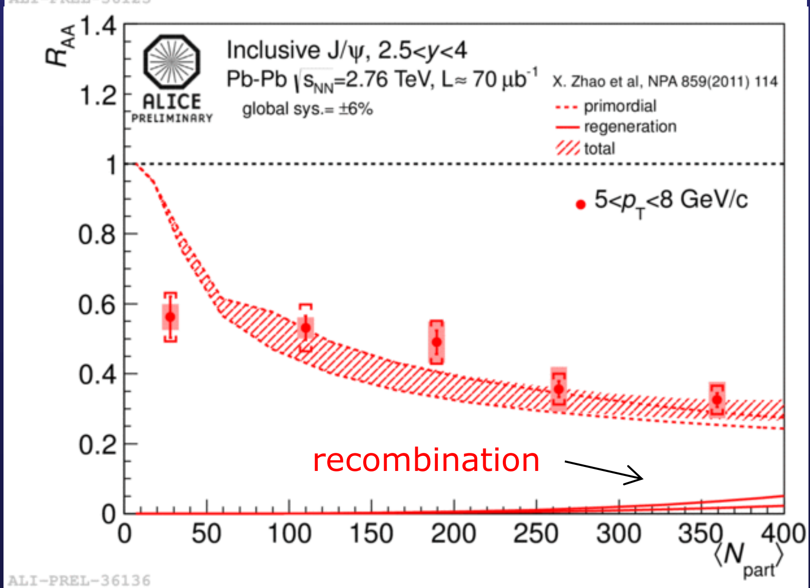
ALICE Coll., arXiv:1203.3641

- Results in agreement with NLO NRQCD calculations

ALICE R_{AA} vs $\langle N_{part} \rangle$ in p_T bins

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

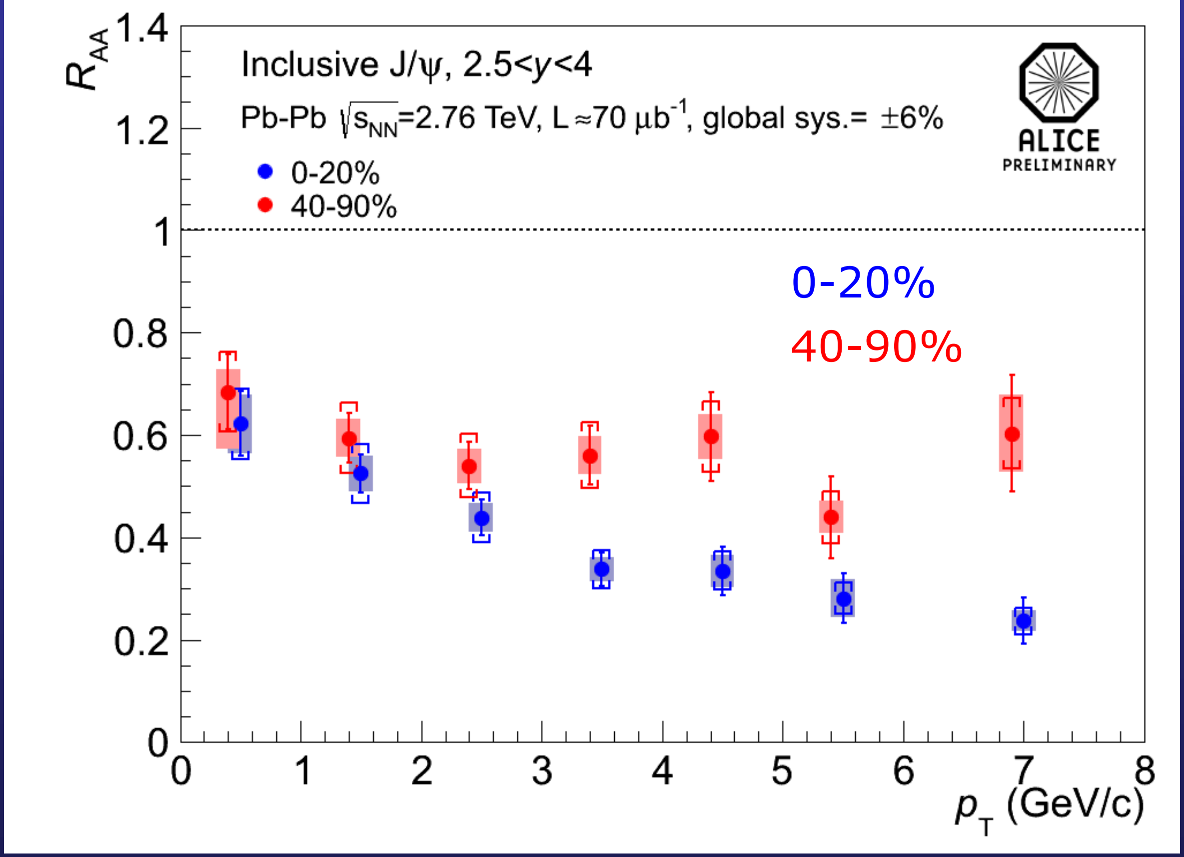




- Compare R_{AA} vs $\langle N_{part} \rangle$ for low-p_T ($0<p_T<2$ GeV/c) and high-p_T ($5<p_T<8$ GeV/c) J/ψ
- Different suppression pattern for low- and high-p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ
- In the models, ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution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

ALICE J/ψ R_{AA} vs p_T

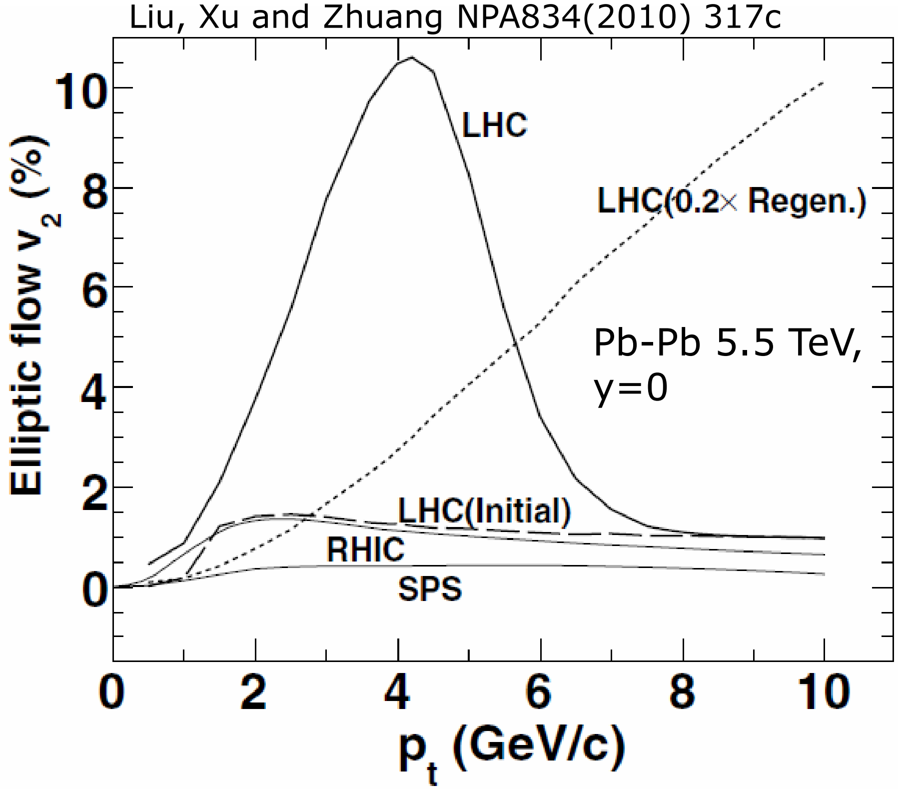
- As an alternative view, R_{AA} is shown as a function of the J/ψ p_T for various centrality bins

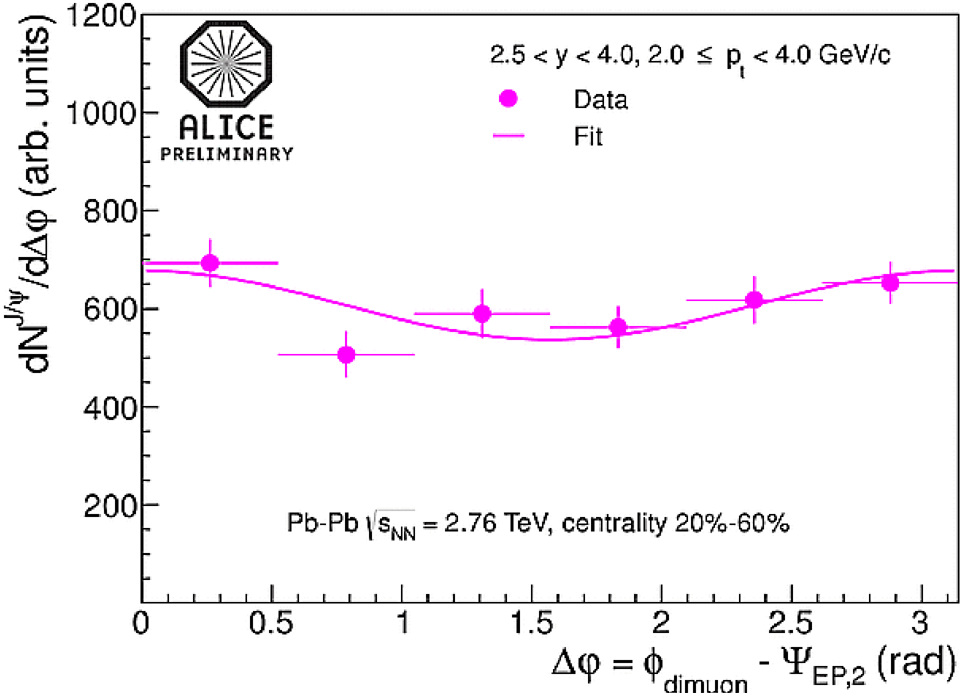


- Splitting in centrality bins we observe that the difference low- vs high-p_T suppression is more important for central collisions

ALICE J/ψ elliptic flow

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

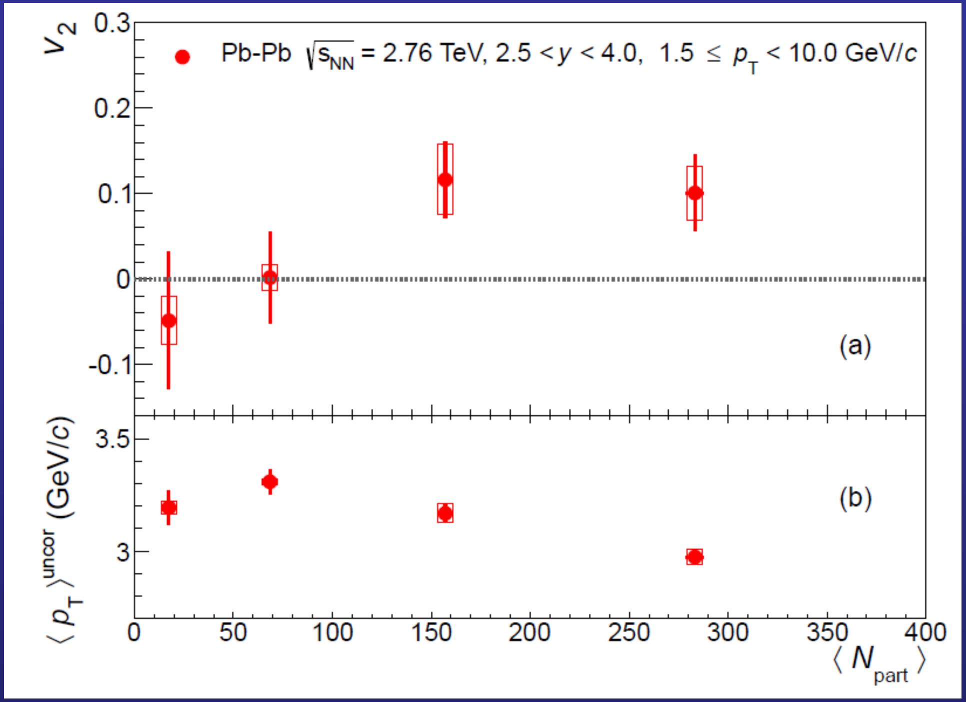




$$dN_{J/\psi} / d\Delta\varphi = A \times \left[1 + 2v_2^{obs}\cos(2\Delta\varphi)\right]$$

- Analysis performed with the EP approach (using VZERO-A)
- Correct v_2^{obs} by the event plane resolution, $v_2 = v_2^{obs}/\sigma_{EP}$ (σ_{EP} measured by 3 sub-events method)
- Checks with alternative methods performed

ALICE: more results on flow



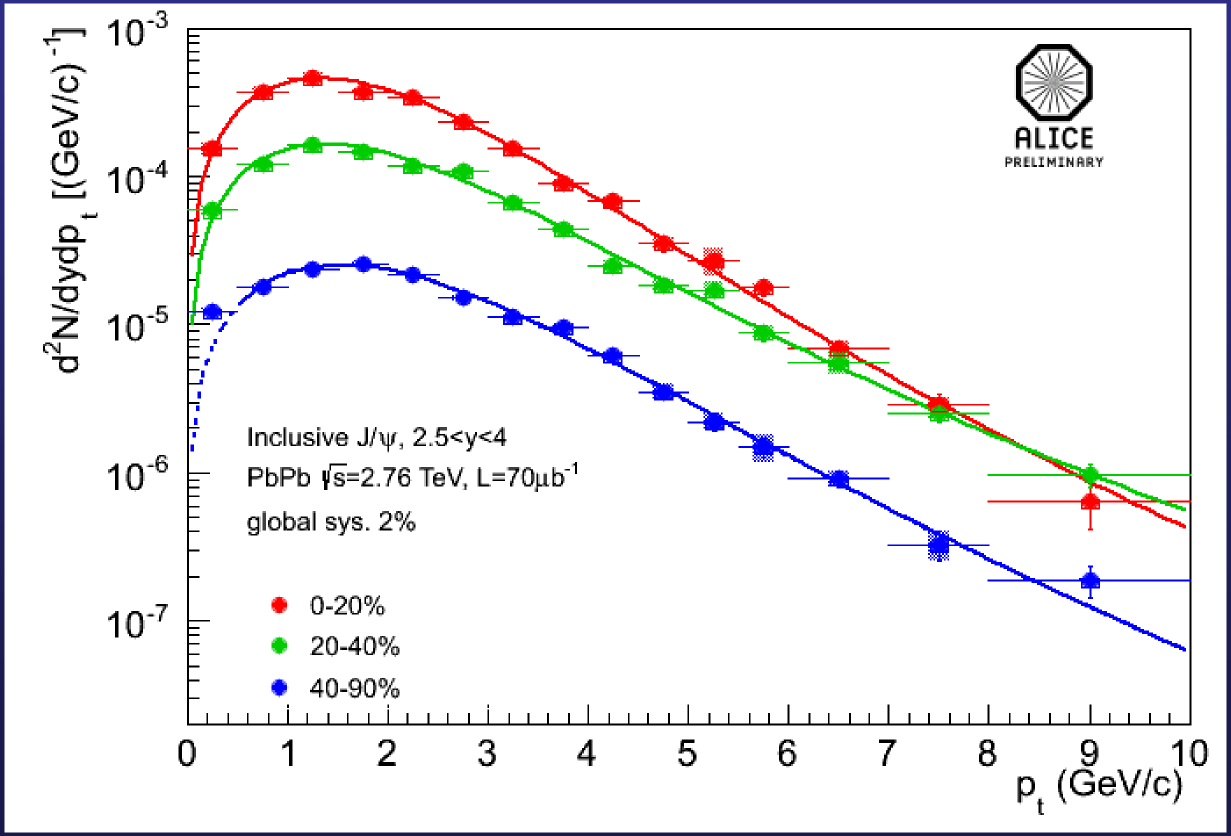
E.Abbas et al. (ALICE), PRL111(2013) 162301

- ❑ ALICE: hint for non-zero v_2 in both
  - ❑ 20-60% central events in 2<p_T<4 GeV/c
  - ❑ 5-20% and 20-40% central events for 1.5<p_T<10 GeV/c
- ❑ Combined significance for the two more central bins → 2.9 σ

ALICE J/ψ p_T spectra vs centrality

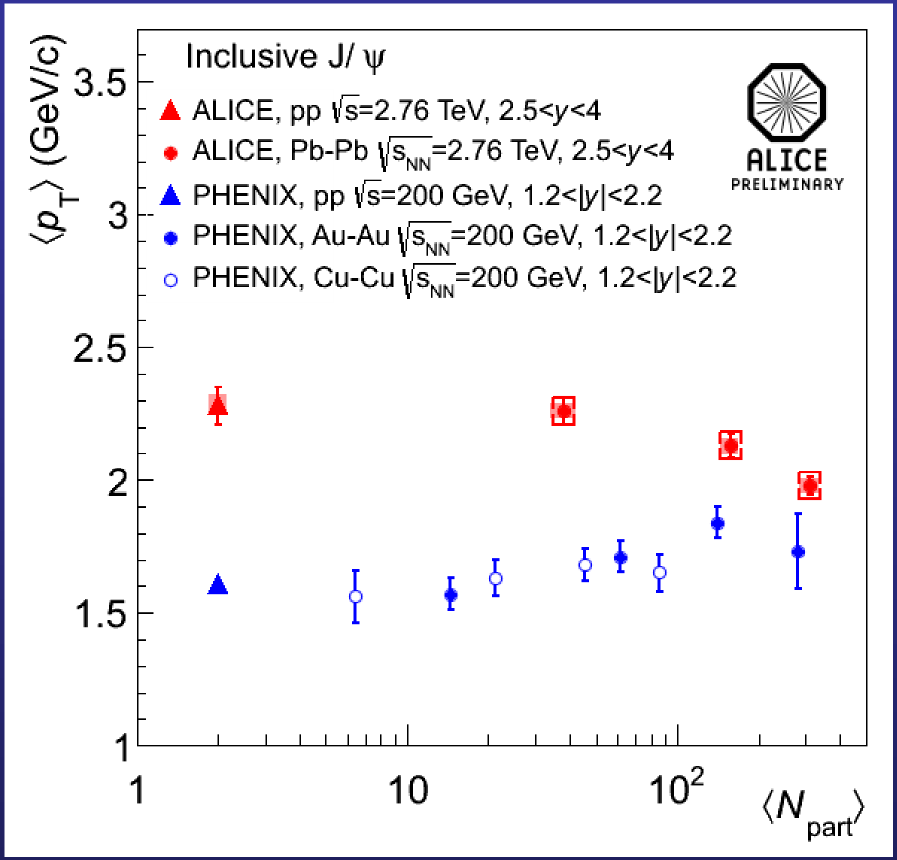
- Comparison with lower energy results can be carried out by studying $<p_T>$ and $<p_T^2>$ vs centrality
- J/ψ $<p_T>$ and $<p_T^2>$ values are extracted from fits to $d^2N/dydp_T$

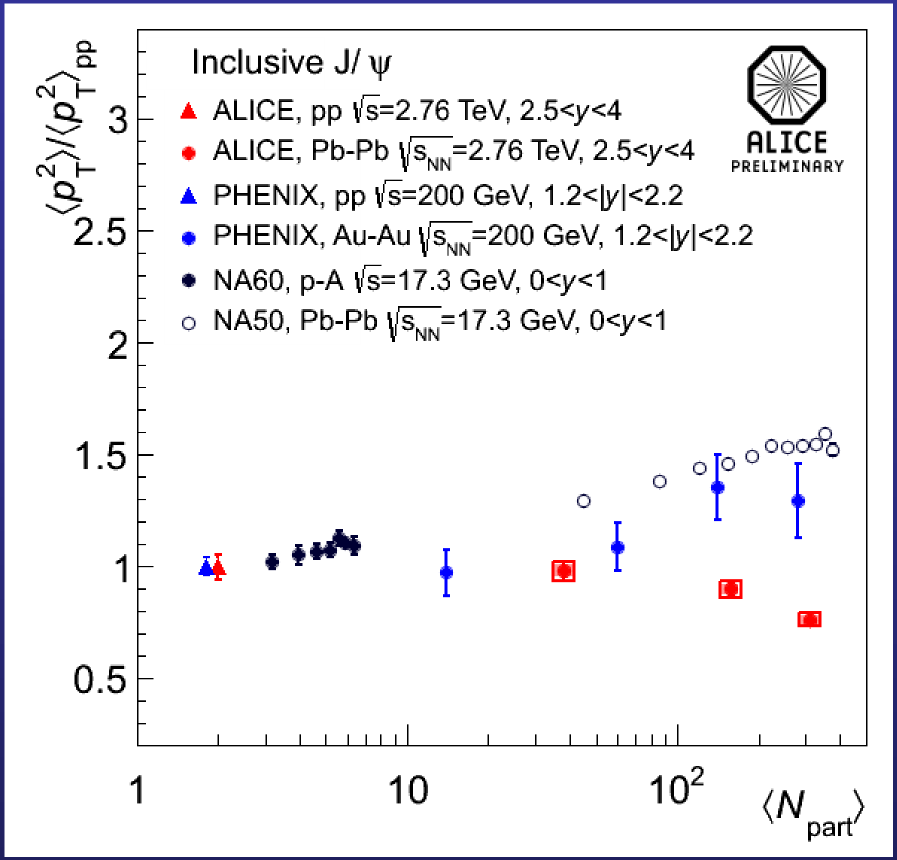
$$\frac{d^2N}{dydp_T} \propto \frac{p_T}{\left(1+\left(\frac{p_T}{p_0}\right)^2\right)^x}$$



- Relative shapes of spectra strictly related to R_{AA}
- Finer binning than in R_{AA} studies possible (not limited by pp statistics)

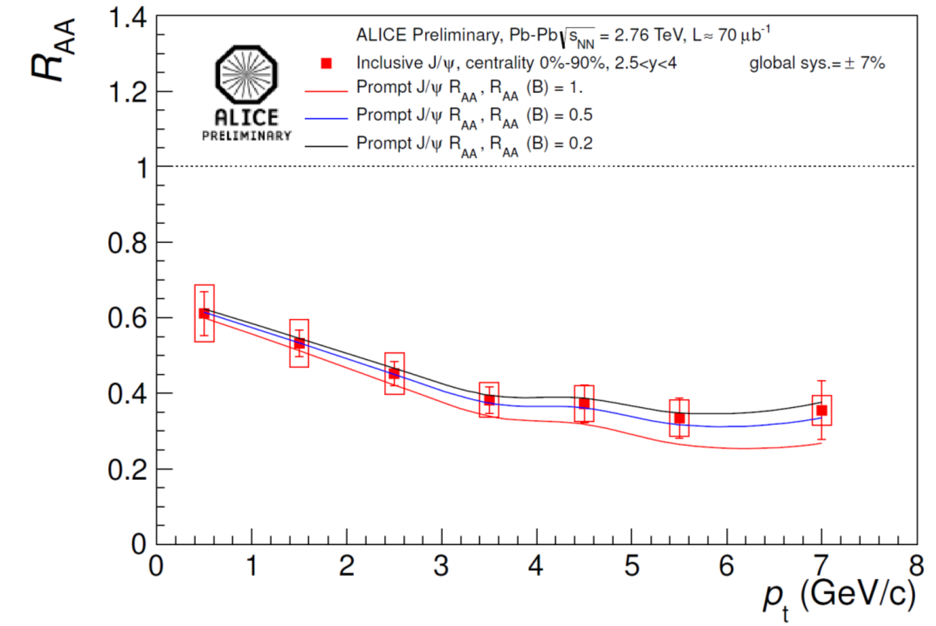
ALICE J/ψ $\langle p_T \rangle$ and $\langle p_T^2 \rangle$

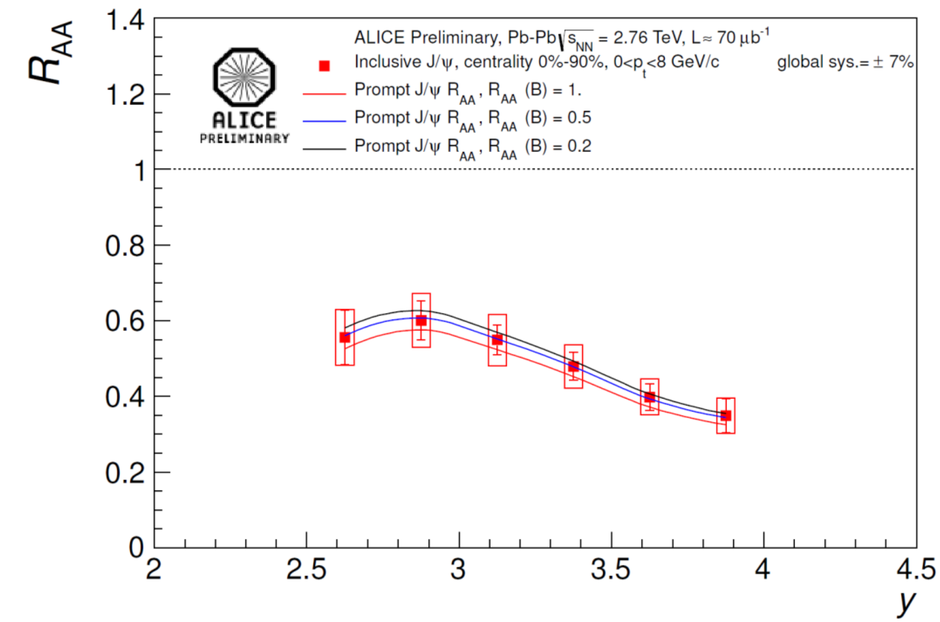




- The J/ψ $<p_T>$ and $<p_T^2>$ show a decreasing trend as a function of centrality, confirming the observation that low-p_T J/ψ are less suppressed in central collisions
- The trend is different wrt the one observed at lower energies, where an increase of the $<p_T>$ and $<p_T^2>$ with centrality was obtained

Effect of non-prompt J/ψ





Inclusive J/ψ measured in ALICE

Estimate of prompt J/ψ RAA using:

- b-fraction measured by CDF, CMS and LHCb
- Interpolation at √s= 2.76 TeV
- Different b-quenching hypothesis from R_{AA}(B)=0.2 to R_{AA}(B)=1

J/ψ from b-hadrons decays have a negligible influence on our measurements