Charmonia in A-A at the LHC

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Sapore Gravis Workshop

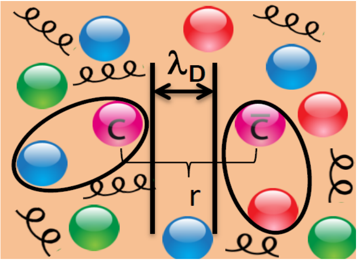
Padova, 9-12 December 2014

Charmonium suppression

Charmonium states are produced in the initial hard partonic collisions
- (τ ≃ 1/ mQ ≃ 0.05-0.15 fm/c)
- stable and tightly bound (Mccbar < 2 MD)

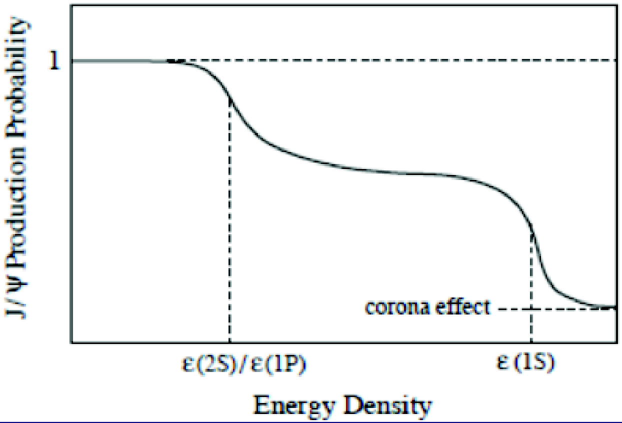
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

In ultra-relativistic heavy ion collisions, at T >> 0 , Debye screening induced by the high density of colour charges of the medium:



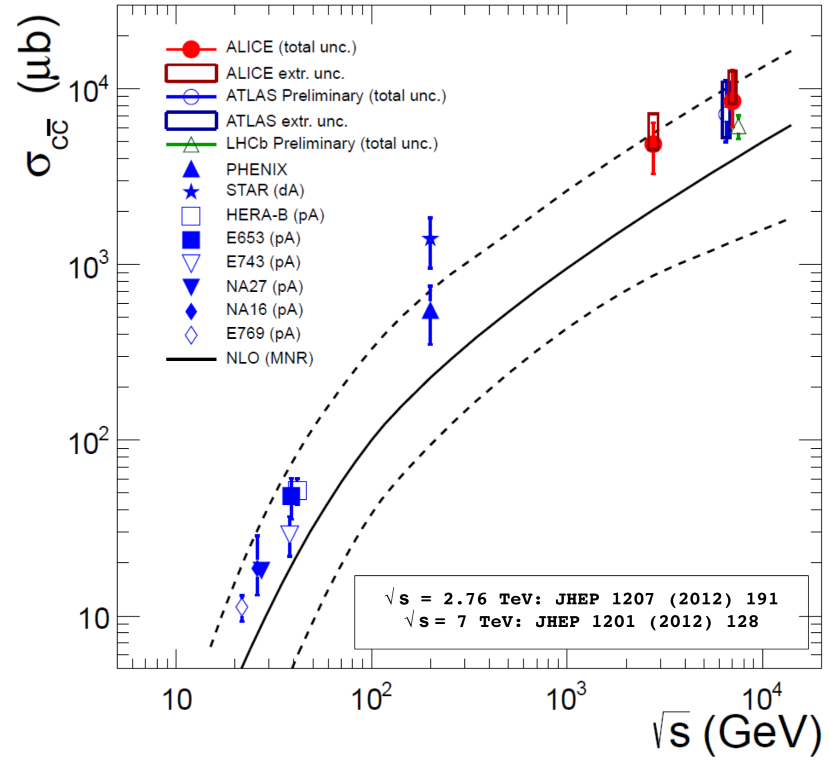
J/ψ suppression in heavy-ion collisions is a signature of deconfinement.
T. Matsui and H. Satz, J/ψ Suppression by Quark-Gluon Plasma Formation, Phys. Lett. B178, 416(1986)

Different binding energy would lead to a sequential suppression of quarkonium states
Digal et al. PRD64(2001)



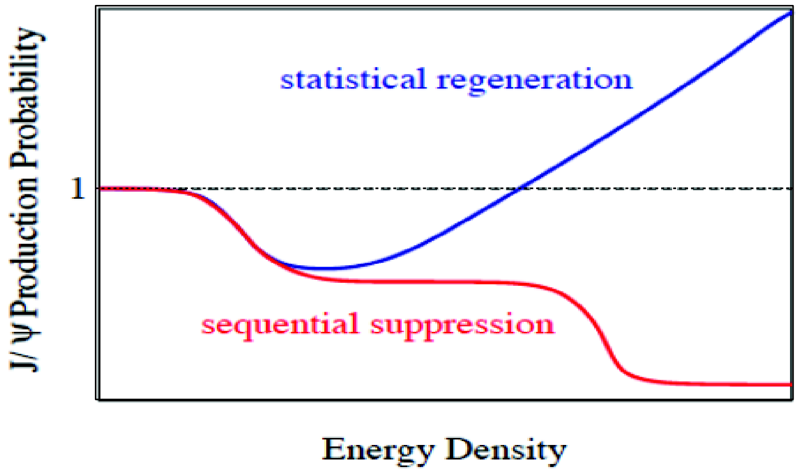
... to Charmonium enhancement.

Large number of charm quarks created in central Pb-Pb collisions at LHC:
→ recombination of c and $\bar{c}$
→ regeneration of charmonia
Braun-Munzinger, Stachel PLB490(2000)
Thews et al. PRC62(2000)



In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~110

[NB: shadowing effects may lower these numbers !
Factor ~ 1.6 (1.1) at LHC (RHIC)]



Implication of regeneration:
- enhancement of J/ψ (or less suppression)
- charmonium states not anymore a QGP thermometer
- **evidence of thermalization of charm quarks**
- **evidence of deconfinement**

… to Charmonium enhancement.

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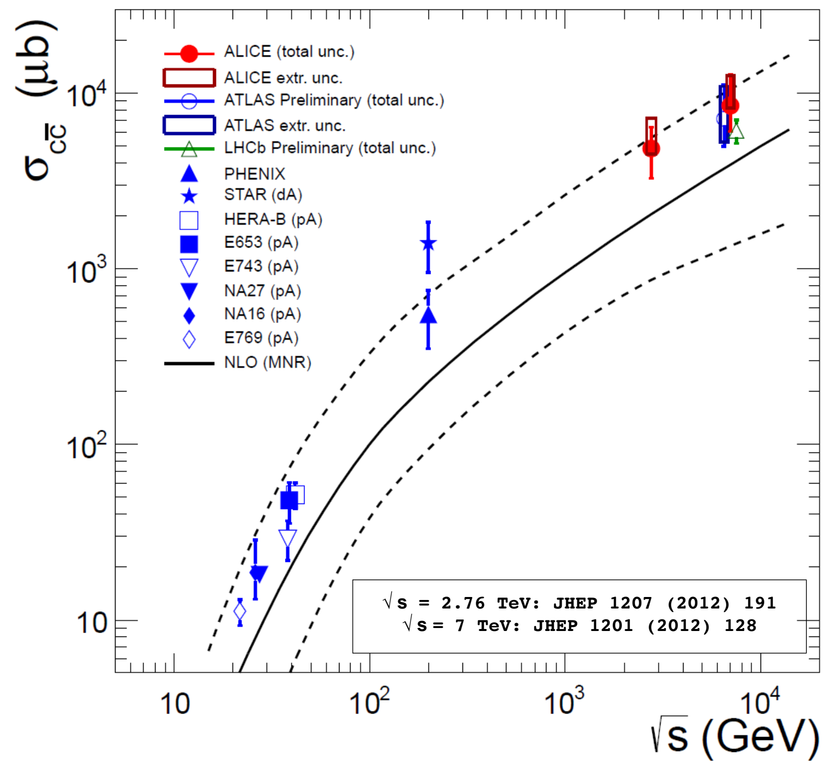

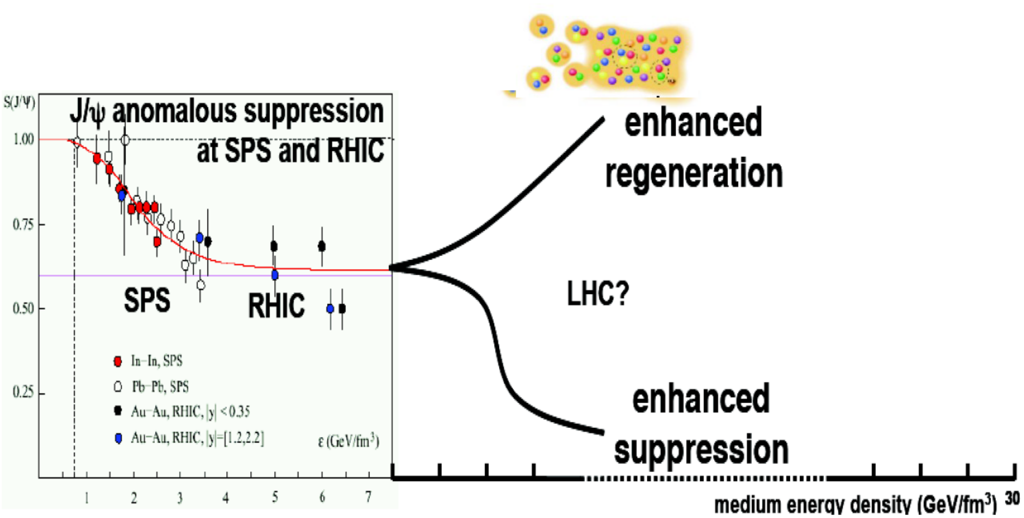

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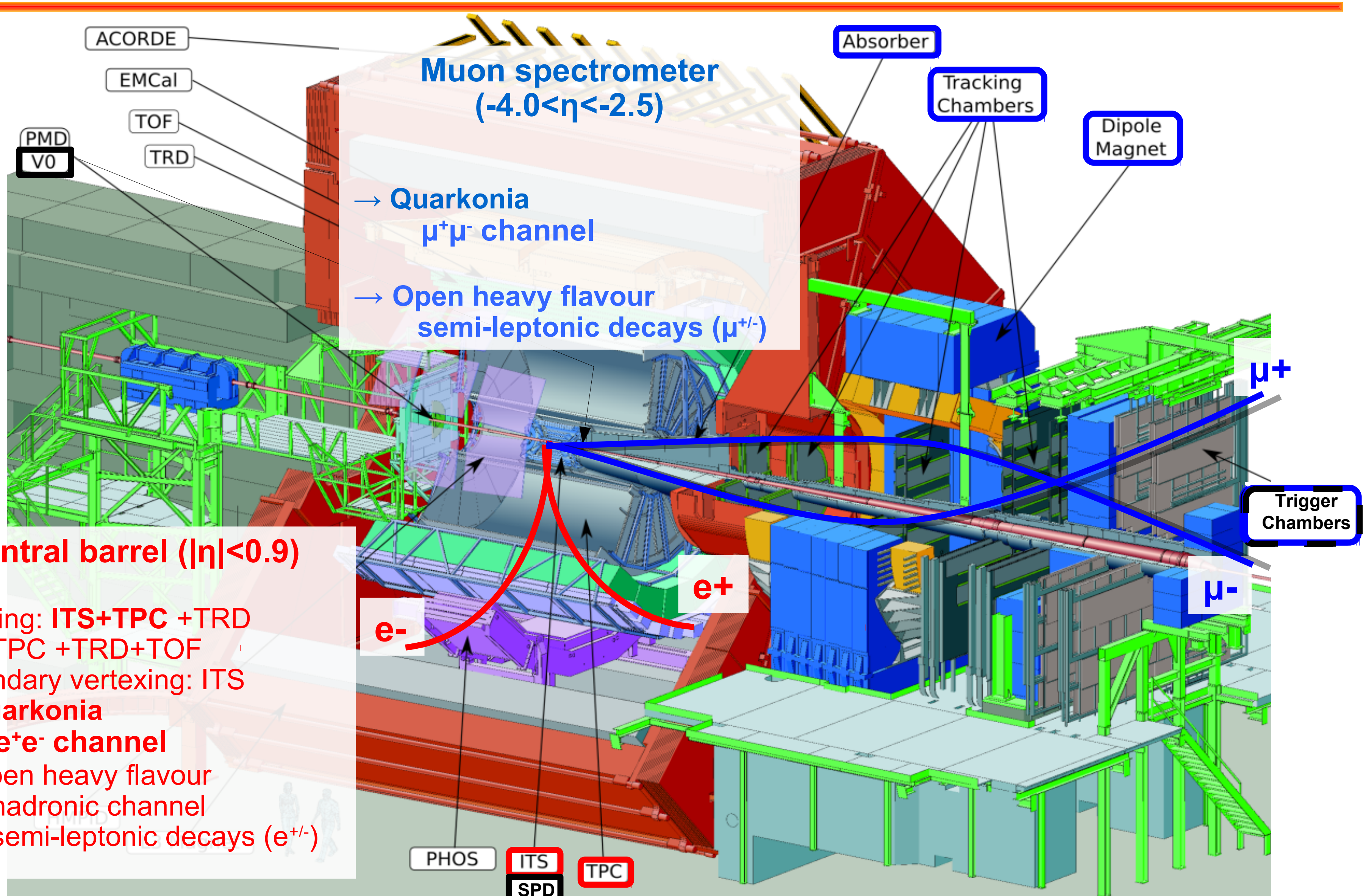
The ALICE detector



Muon spectrometer
(-4.0<η<-2.5)

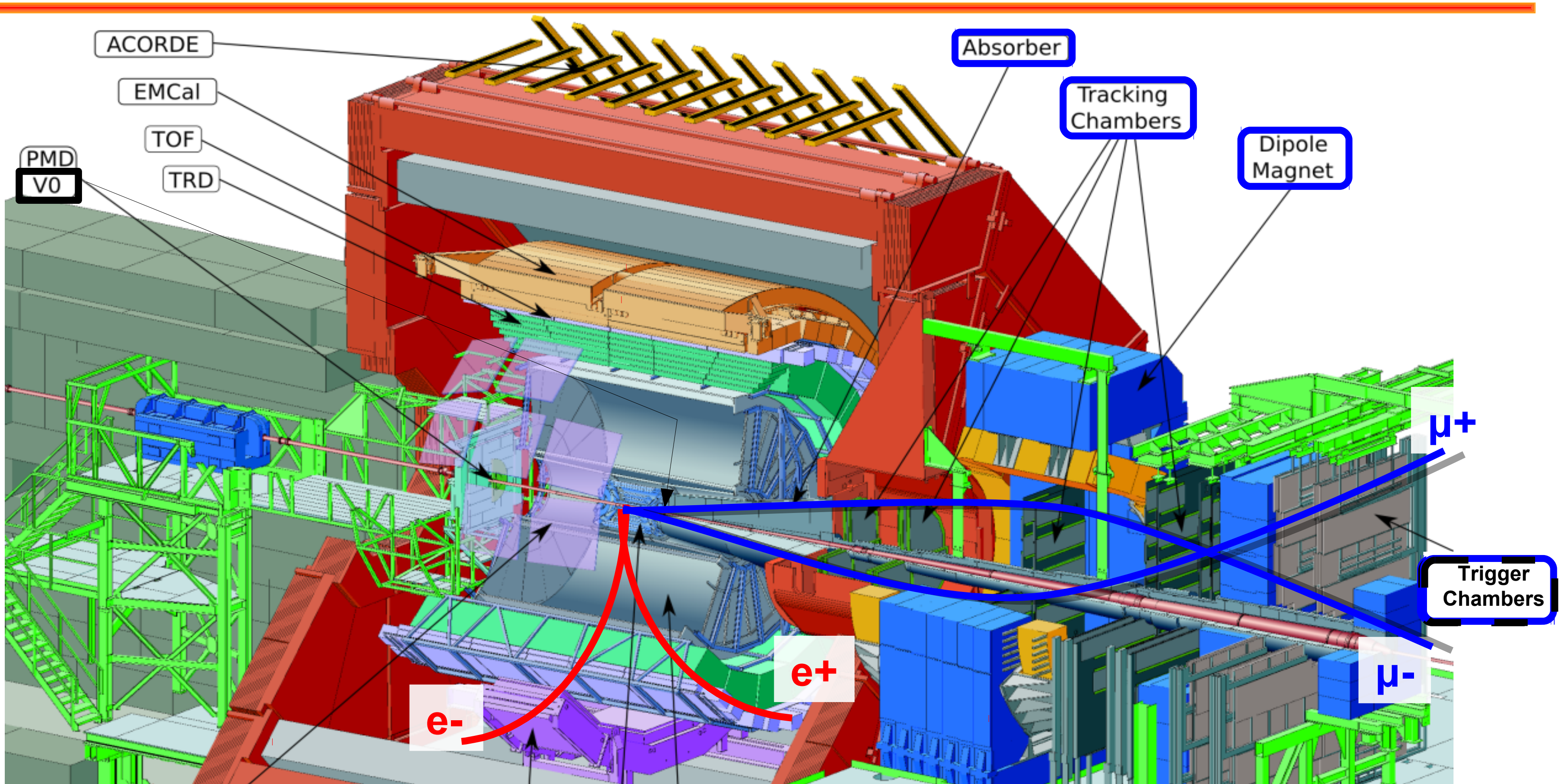
→ **Quarkonia**
$\mu^+\mu^-$ channel

→ **Open heavy flavour**
semi-leptonic decays ($\mu^{+/-}$)

Central barrel (|η|<0.9)

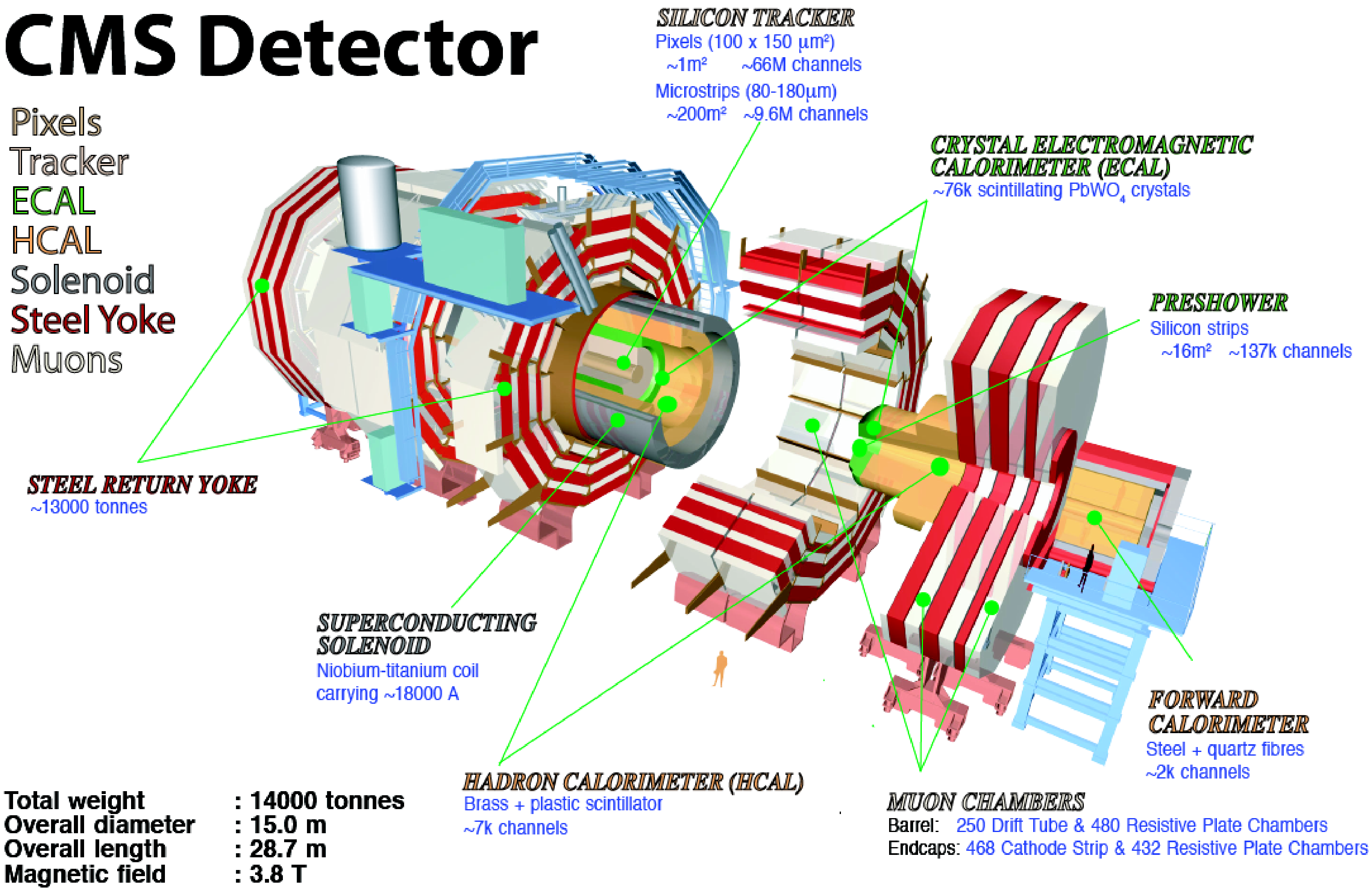
Tracking: **ITS+TPC** +TRD
PID: TPC +TRD+TOF
Secondary vertexing: ITS
→ **Quarkonia**
e^+e^- channel
→ Open heavy flavour
hadronic channel
semi-leptonic decays ($e^{+/-}$)

The ALICE detector



Charmonia analysis in 2 rapidity ranges, both with p_T down to 0 GeV/c
→ |y| < 0.9, prompt/non-prompt separation but no charmonia trigger
→ 2.5 < y < 4, dedicated charmonia trigger but inclusive measurements

The CMS detector



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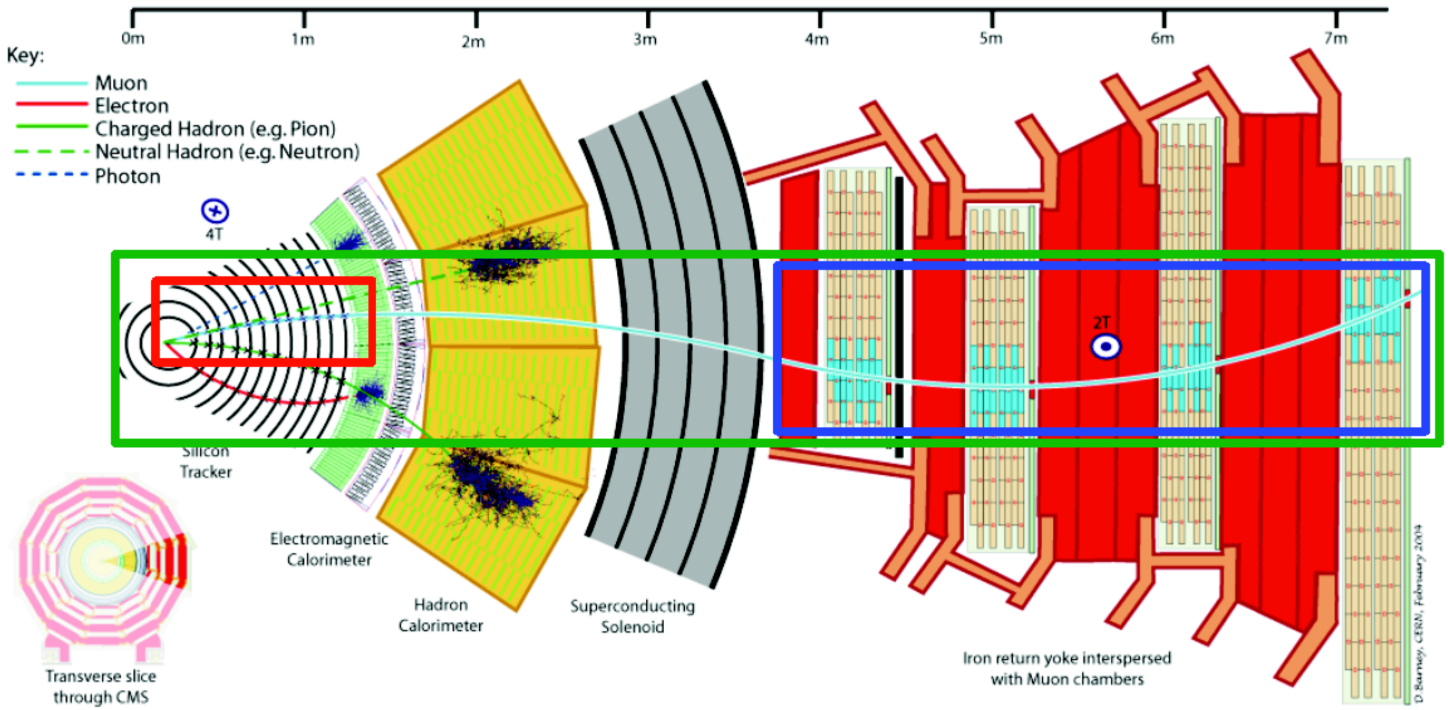
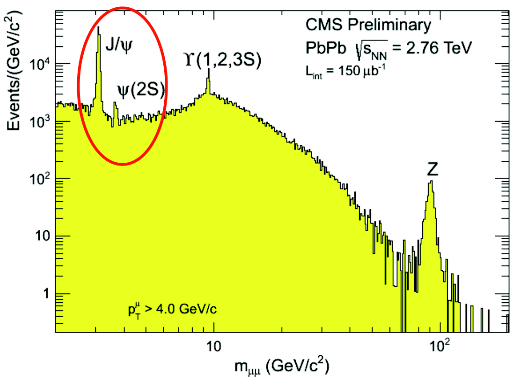
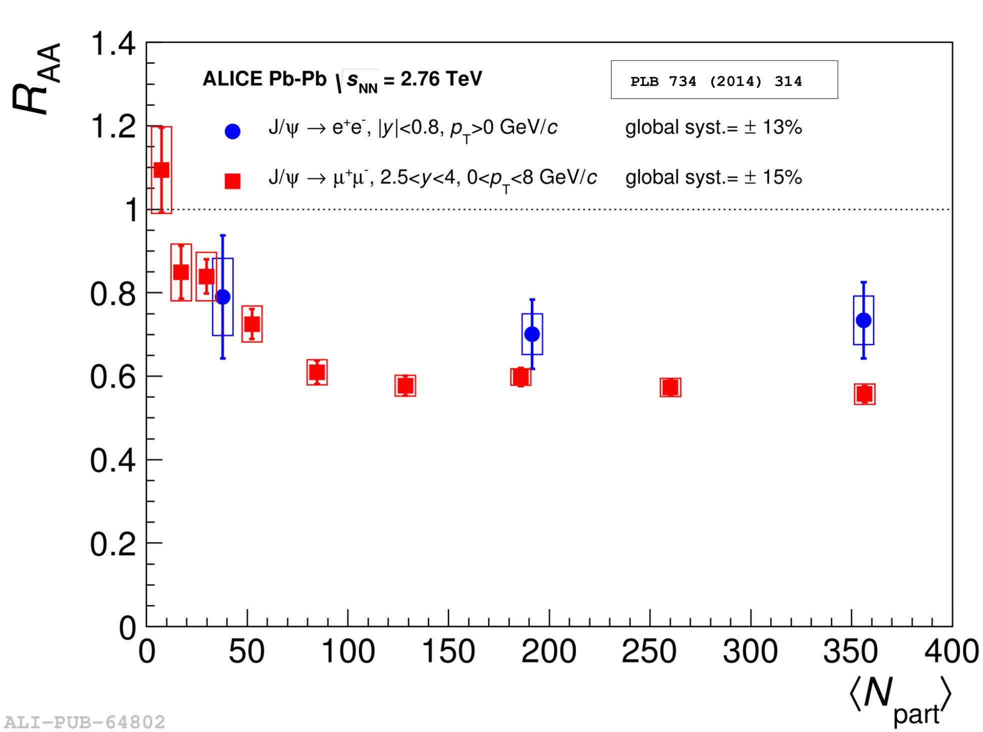
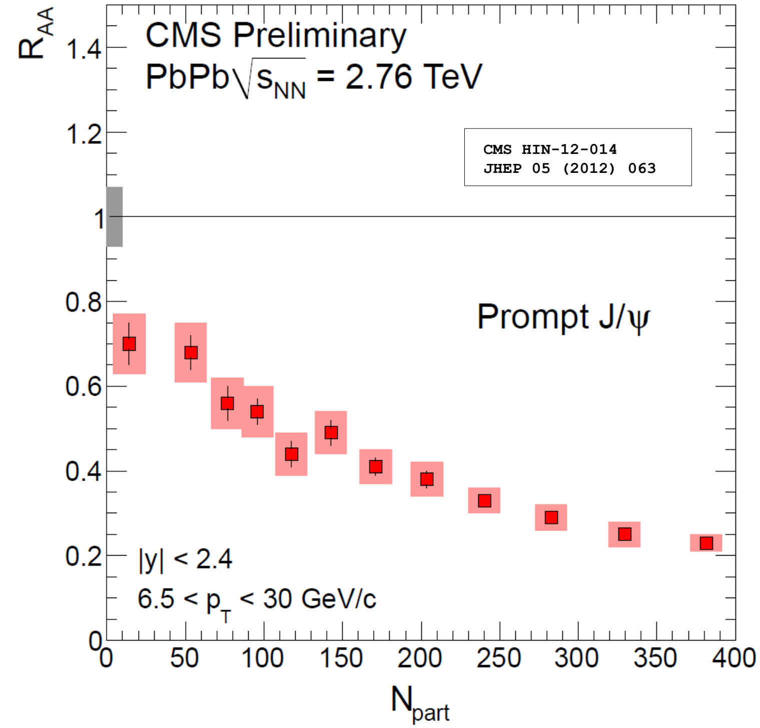


Global muons (inner tracker + muon station) analysis
→ very good mass resolution
→ large acceptance (|y| < 2.4)
→ prompt/non-prompt separation
but cannot access low-p_T charmonia (>3 or 6 GeV/c) in PbPb



J/ψ R_{AA} Pb-Pb collisions $\sqrt{s_{NN}}$ =2.76 TeV





At low-p_T (p_T > 0), ALICE shows J/Ψ (inclusive) suppression with almost no centrality dependence for Npart>100 for 2.5 < |y| < 4 and |y| < 0.8.

At high-p_T (p_T > 6.5), CMS shows strong suppression with a clear centrality dependence for |y| < 2.4.

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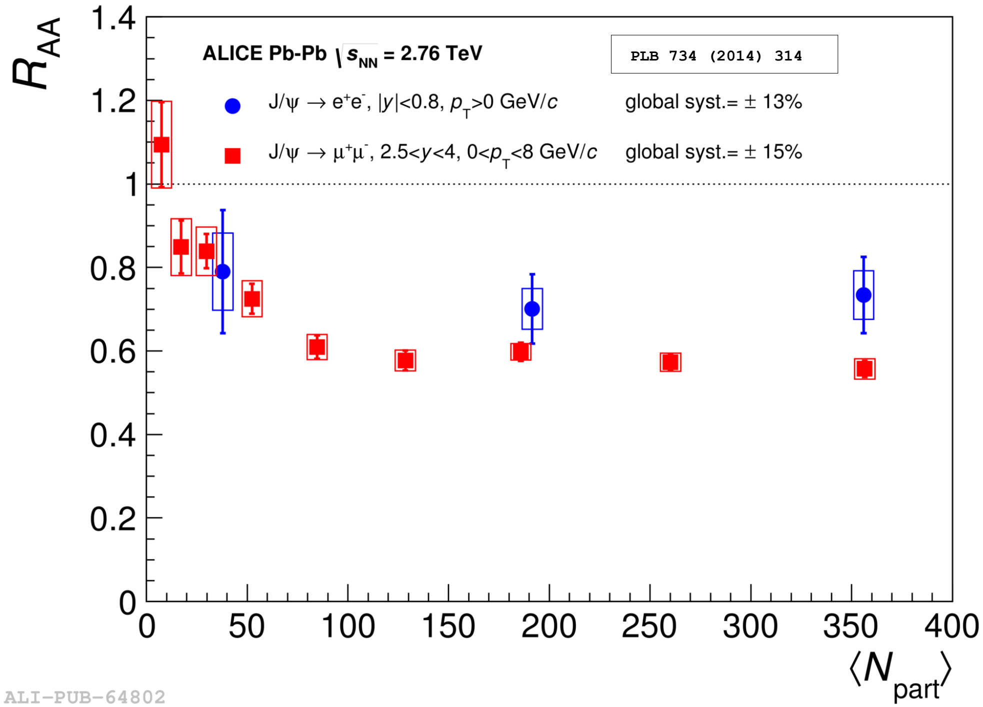

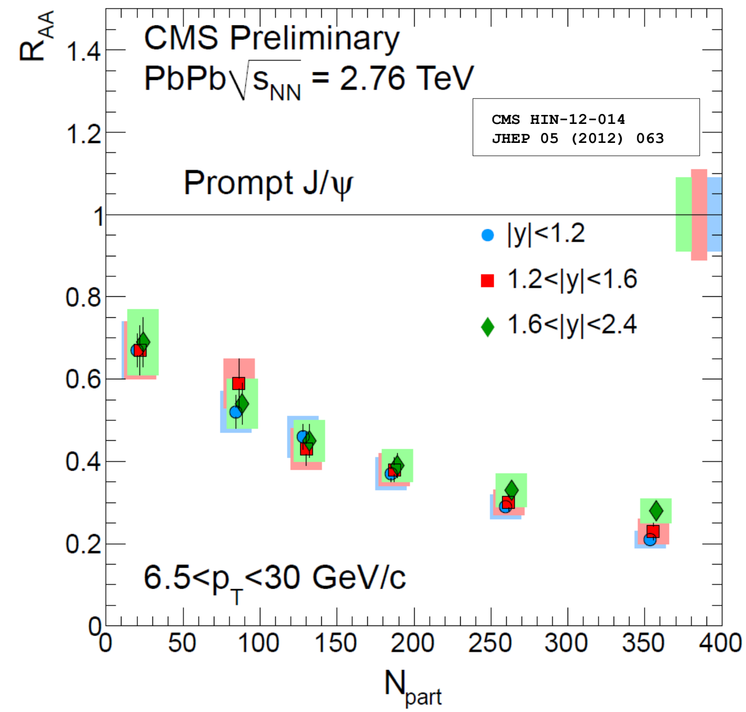

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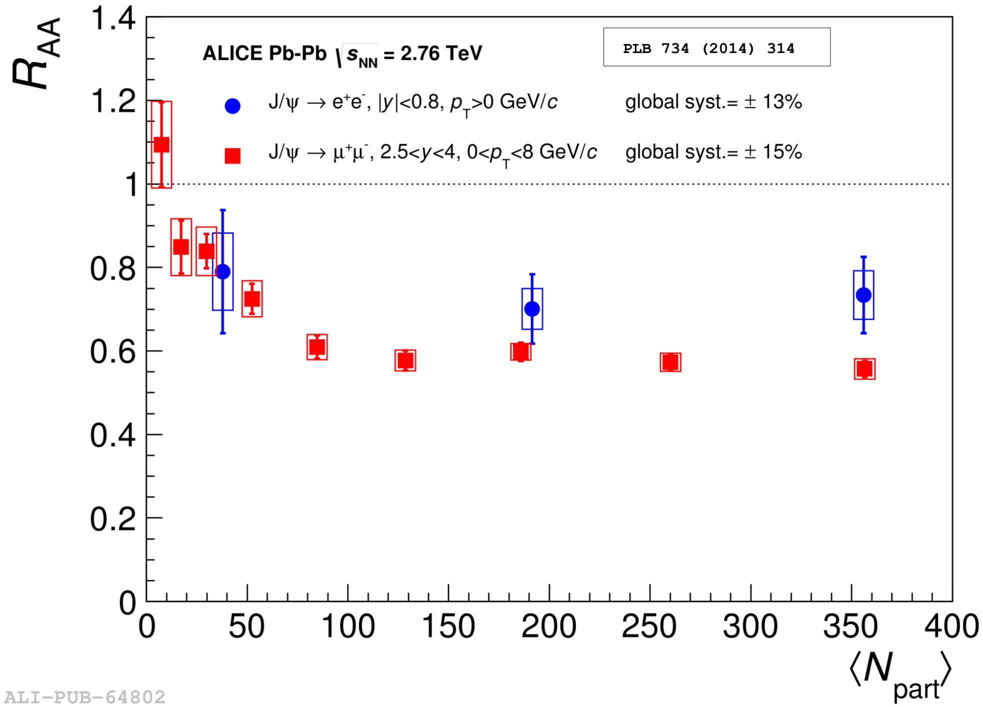
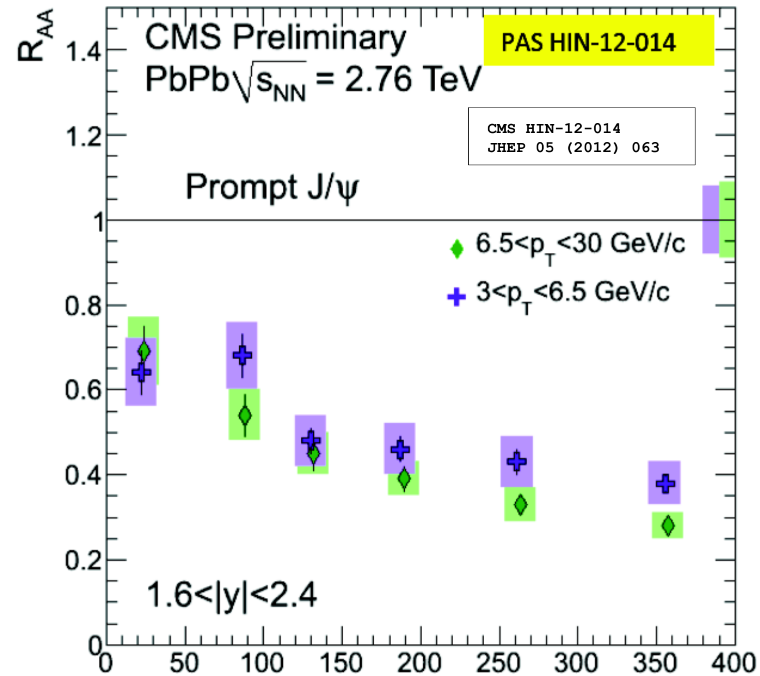
At high-p_T (p_T > 6.5), CMS shows strong suppression with a clear centrality dependence for |y| < 2.4.
→ no indication of rapidity dependence

Centrality dependence of J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV





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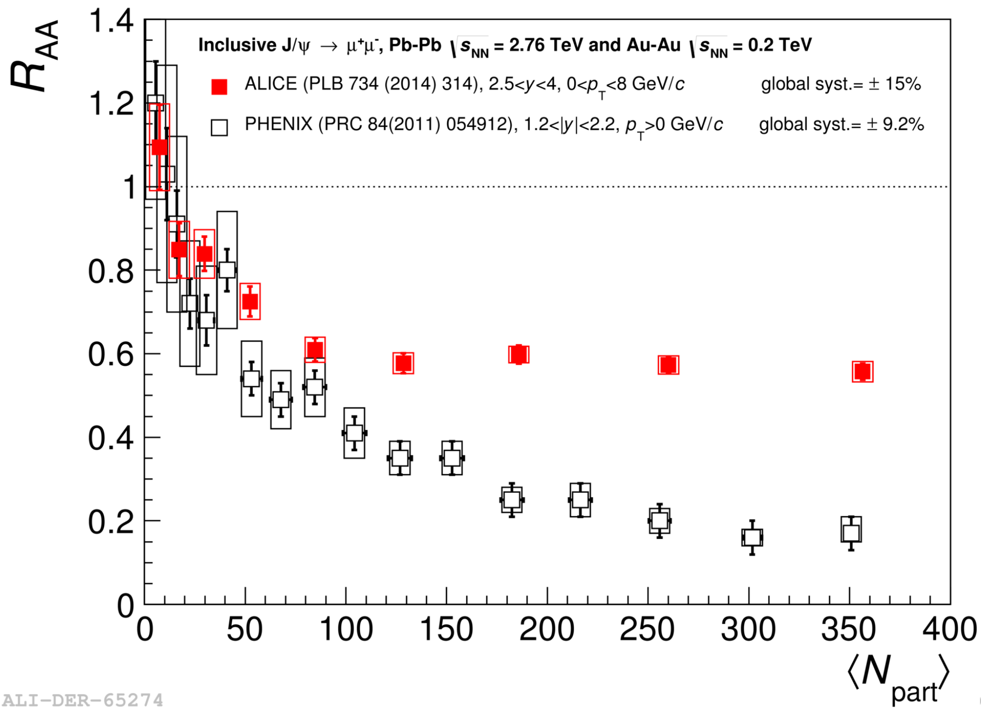
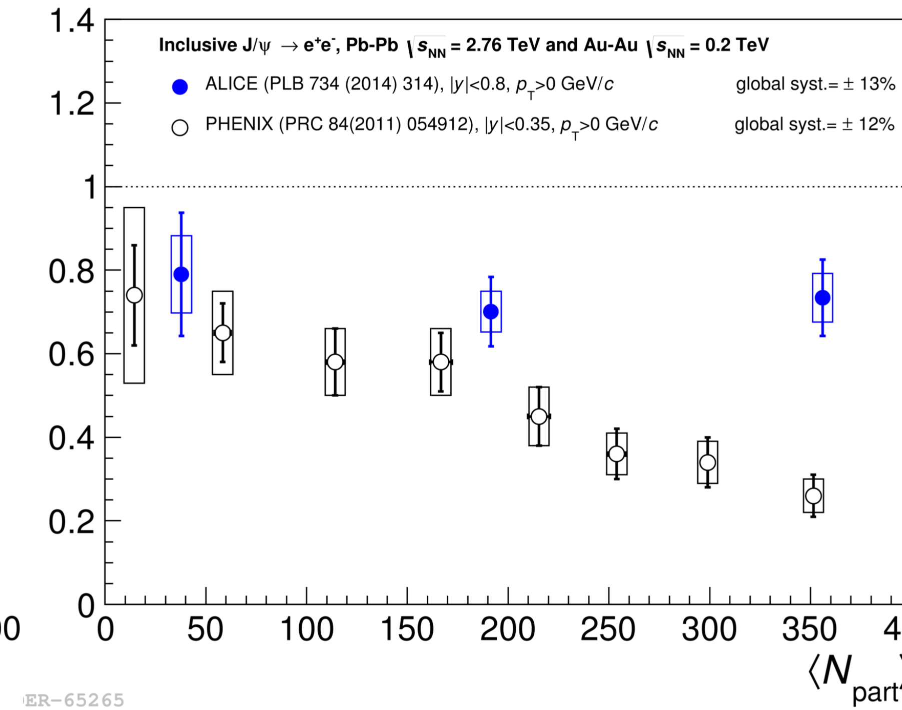
→ J/ψ may be less suppressed at lower p_T than higher p_T

Centrality dependence of J/ψ R_{AA}

Pb-Pb@$\sqrt{s_{NN}}$=2.76 TeV and Au-Au@$\sqrt{s_{NN}}$=2.76 TeV





At low-p_T (p_T > 0), large differences between PHENIX and ALICE:

i) R_{AA} larger in ALICE at both forward and mid-rapidity

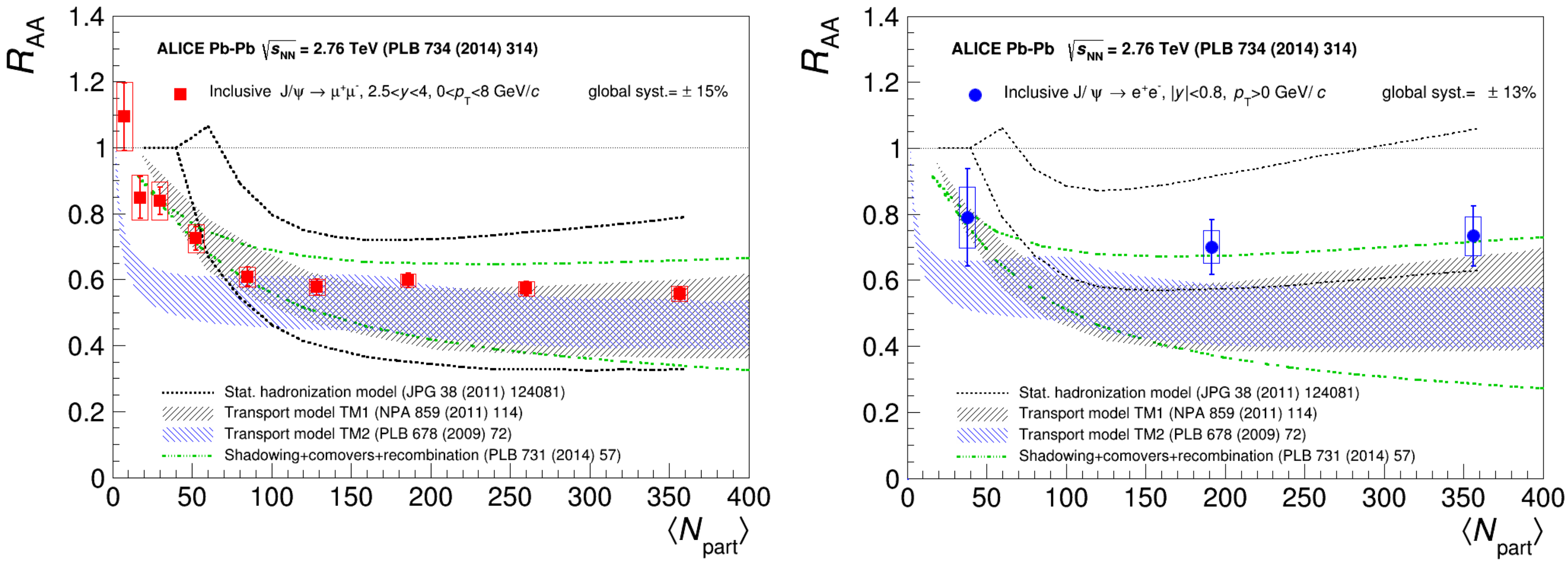
ii) weaker centrality dependence in ALICE

→ expected if regeneration mechanisms play a (big) role

[keep in mind that we have different size of CNM effects (RHIC/LHC)]

Centrality dependence of J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV

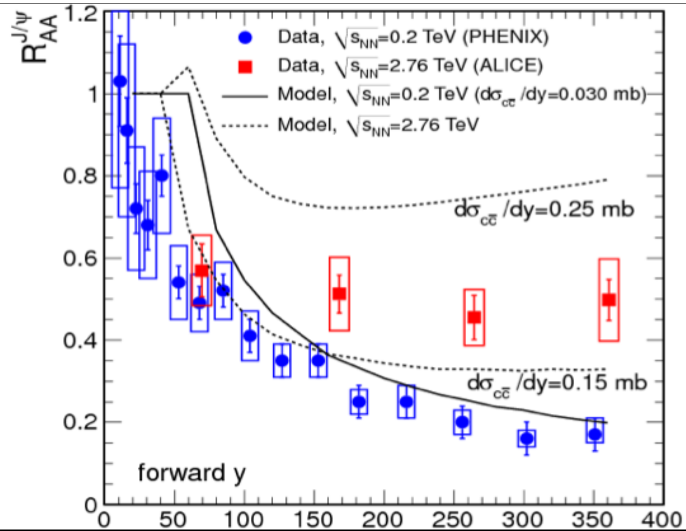


All models include J/ψ production via $c\bar{c}$ recombination and fairly reproduce the ALICE results but large uncertainties in the calculations.

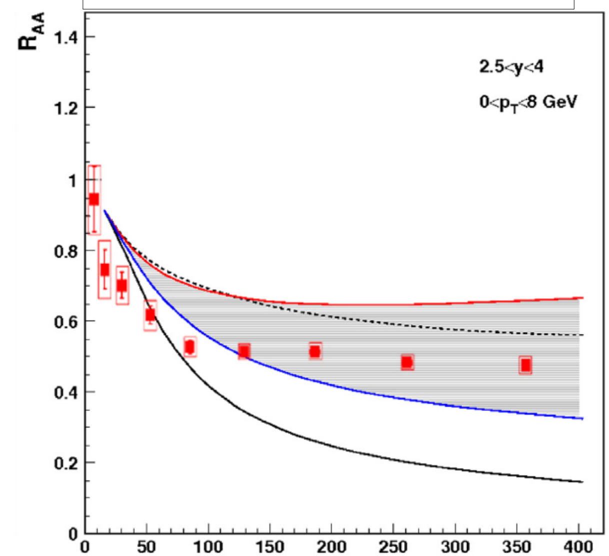
Some key ingredients need to be measured or better estimated
→ shadowing
→ $d\sigma_{c\bar{c}}/dy$
+ now would be the good time for LHC run-II Pb-Pb energy $\sqrt{s_{NN}}$ ≈ 5 TeV predictions

Models for J/ψ production

P. Braun-Münzinger & J. Stachel, PLB490 (2000) 196
A. Andronic @ QM2011, A. Andronic et al., PLB571 (2003) 36



E.G. Ferreiro, PLB731 (2014) 57-63
A.Capella et al. PLB 393(1997) 431

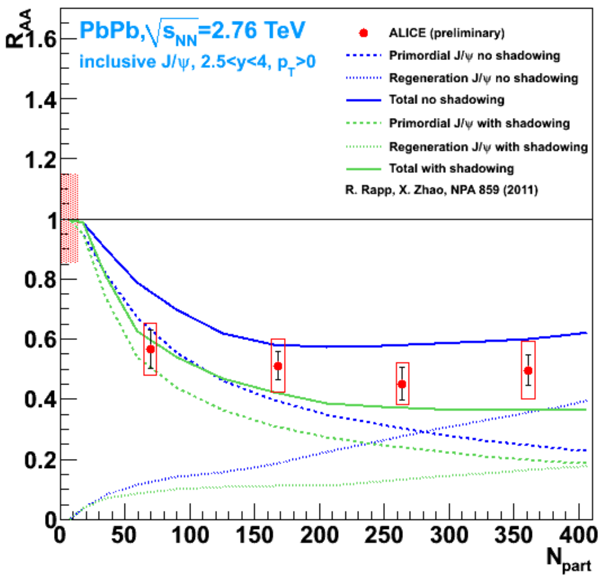


Statistical Hadronization Model (w/o update):
→ screening by QGP of **all** direct J/ψ's
→ charmonium production at phase boundary by statistical combination of uncorrelated charm quarks
→ no B feed-down
→ open charm cross-sections include CNM: 2.5<y<4, $d\sigma_{c\bar{c}}/dy$ [0.25;0.15]
|y|<0.9, $d\sigma_{c\bar{c}}/dy$ [0.3;0.4]

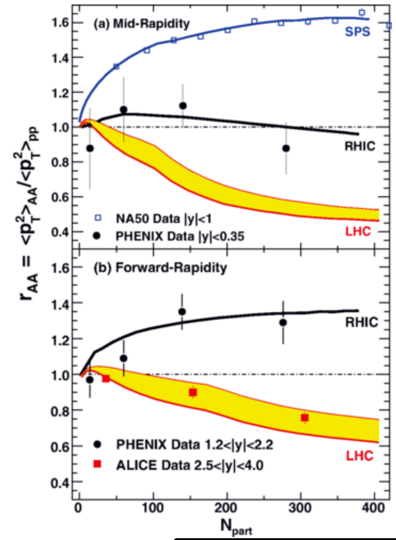
Comover Interaction Model:
→ Interaction with a co-moving medium causing J/ψ dissociation (σ_{CO} = 65mb)
→ Recombination effects prop. to σ_{CO}, n_c and $n_{\bar{c}}$
→ Shadowing similar to EKS98/nDSg
→ no B feed-down
→ 2.5<y<4, $d\sigma_{c\bar{c}}/dy$ [0.4;0.6]
→ |y|<0.9, $d\sigma_{c\bar{c}}/dy$ [0.6;0.8]

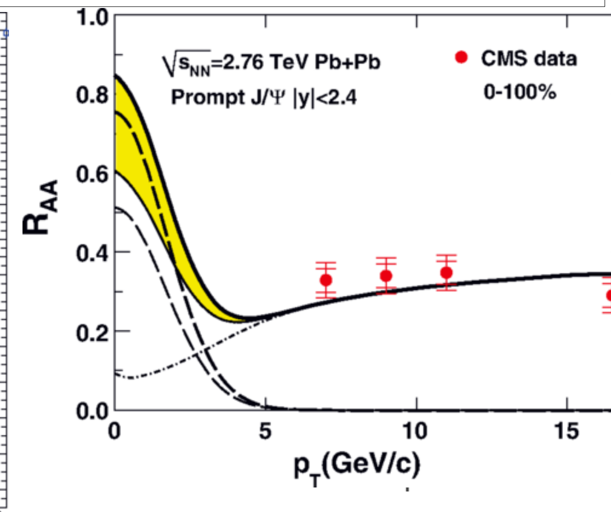
Models for J/ψ production

X. Zhao, R. Rapp, NPA859 (2011) 114-125
R. Rapp, private communication



X. Zhu, P. Zhuang, N. Xu, PLB607 (2005) 107
Y. Liu, Z. Qu, N. Xu, P. Zhuang, PLB678 (2009) 72
Zhou et al, PRC 89 (2014) 054911

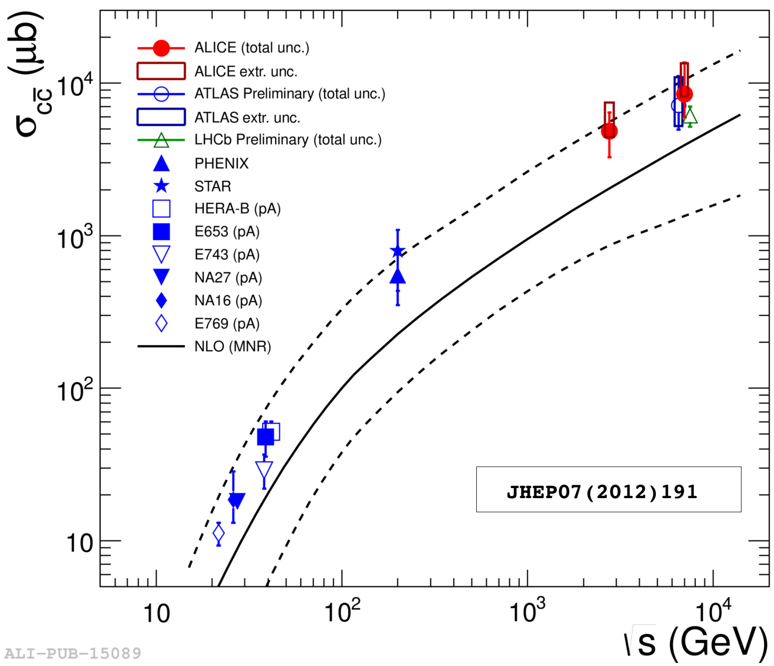




Transport model (prediction w/o update):
→ prompt J/ψ dissociation in the QGP
→ J/ψ regeneration by charm quark pair recombination
→ Feed-down contributions from B (10%, no quenching)
→ Shadowing effect "by hand" leading to 30% suppression in most central collisions
→ |y|<0.9, $d\sigma_{c\bar{c}}/dy$ ~ 0.75

Transport Model:
→ prompt J/ψ dissociation in QGP
→ J/ψ regeneration by charm quark pair recombination (detailed balance)
→ Shadowing and Cronin effect
→ Feed-down contributions from B (10%), quenching ~ 0.4 for p_T>5 GeV/c
→ 2.5<y<4, $d\sigma_{c\bar{c}}/dy$ [0.4;0.5]
→ |y|<0.9, $d\sigma_{c\bar{c}}/dy$ [0.65;0.8]

Models for J/ψ production
$\sqrt{s_{NN}}$=2.76 TeV



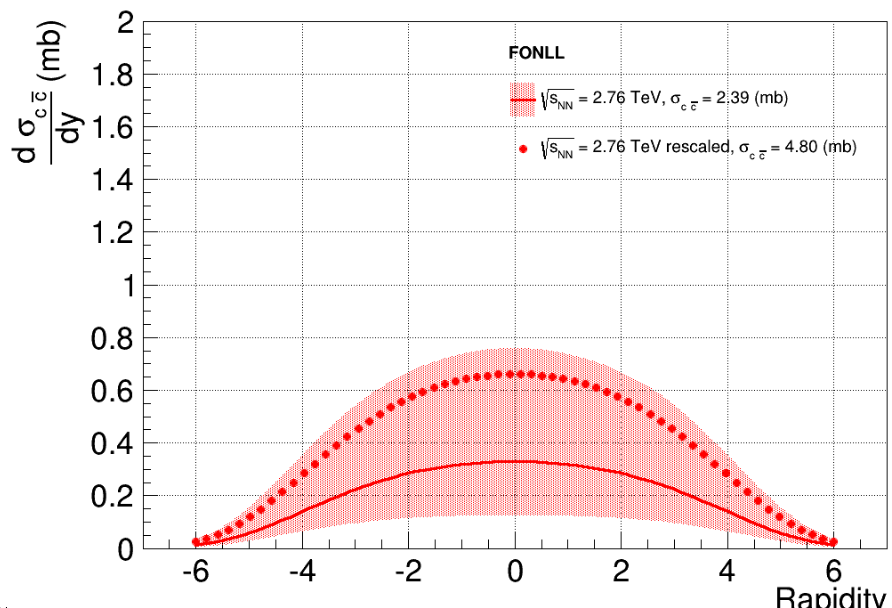
Measured charm cross-section at LHC lies at the upper-end of model calculation
→ $\sigma_{c\bar{c}}$ crucial input to models

What is used in models ?
→ |y|<0.9, $d\sigma_{c\bar{c}}/dy$ ~ [0.3;0.4]/shad, [0.6-0.8], 0.75, [0.65;0.8]
→ 2.5<y<4, $d\sigma_{c\bar{c}}/dy$ [0.25;0.15]/shad, [0.4;0.6], [0.4;0.5]

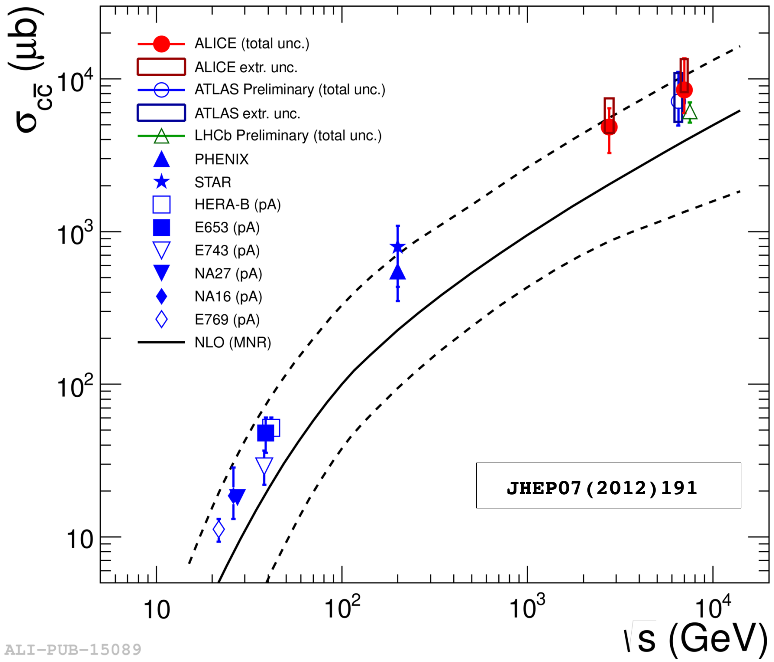
Simple calculations to rescale FONNL to ALICE results:

- $d\sigma_{c\bar{c}}/dy\,|_{y\approx0}$ ~ 0.7
- $d\sigma_{c\bar{c}}/dy\,|_{y\approx2.5}$ ~ 0.5
- $d\sigma_{c\bar{c}}/dy\,|_{y\approx4}$ ~ 0.3

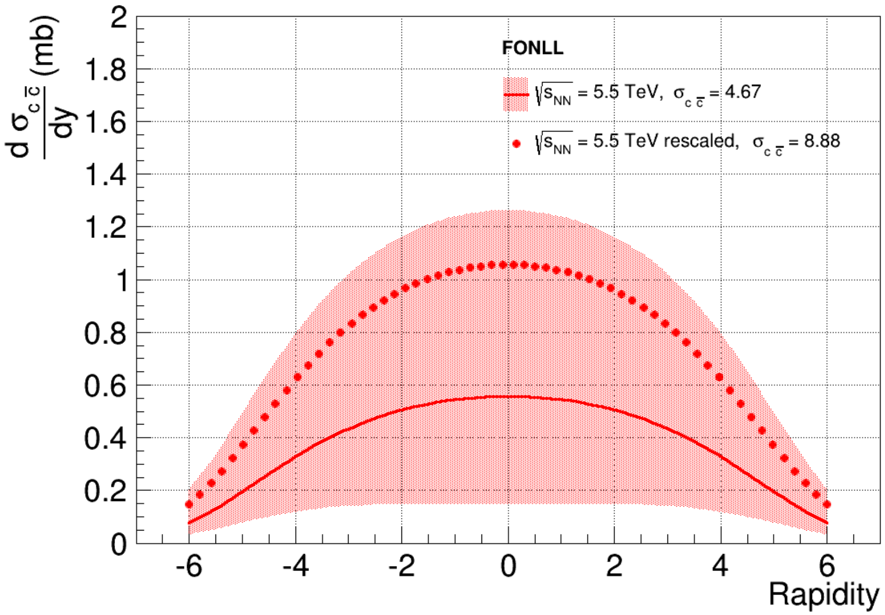
→ then proper shadowing should be added



Models for J/ψ production
$\sqrt{s_{NN}}$=5.5 TeV



No measurement of charm cross-section at 5.5 TeV. But according to the 2.76 TeV and the 7 TeV results, one could assume the same trend.



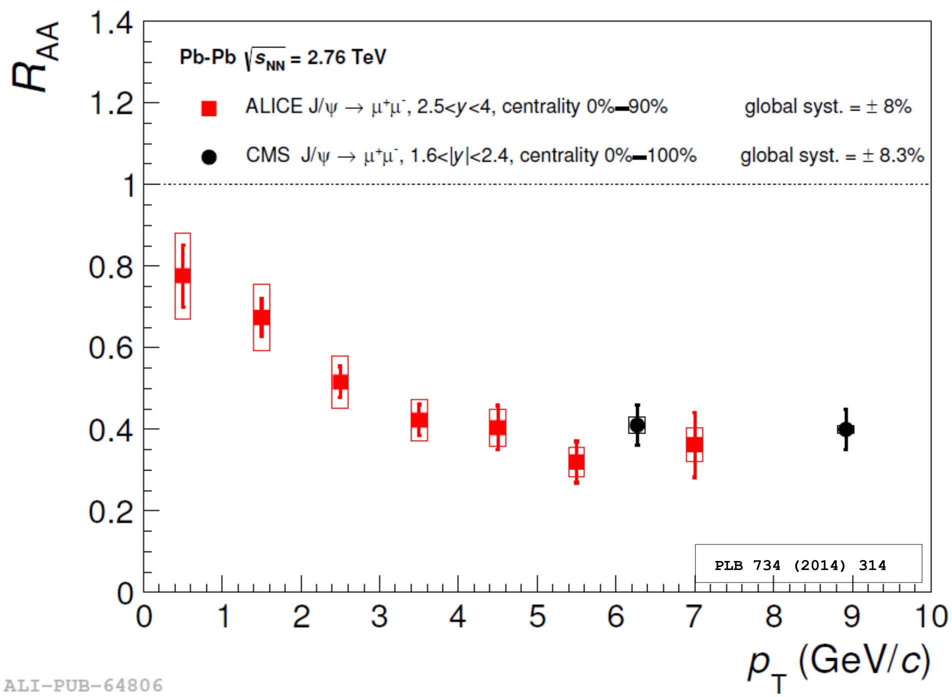
Simple calculations to rescale FONNL to ALICE results:

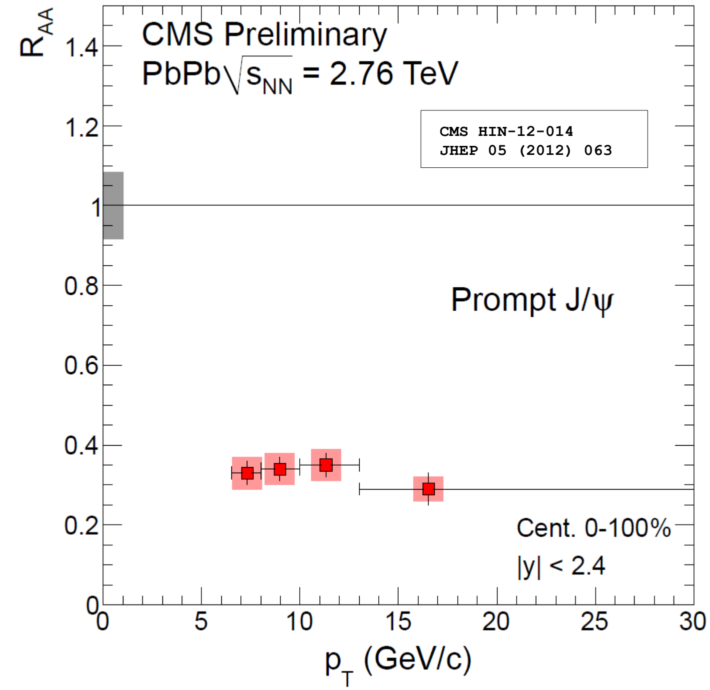
- $d\sigma_{c\bar{c}}/dy\ |_{y\approx 0}$ ~ 1.1
- $d\sigma_{c\bar{c}}/dy\ |_{y\approx 2.5}$ ~ 0.9
- $d\sigma_{c\bar{c}}/dy\ |_{y\approx 4}$ ~ 0.6

→ then proper shadowing should be added

Transverse momentum dependence of J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV





At LHC:

- higt-p_T (p_T > 5 GeV/c) J/Ψ are suppressed (|y| <4)
- low-p_T (p_T < 3GeV/c) J/Ψ are less suppressed with $p_T \rightarrow 0$

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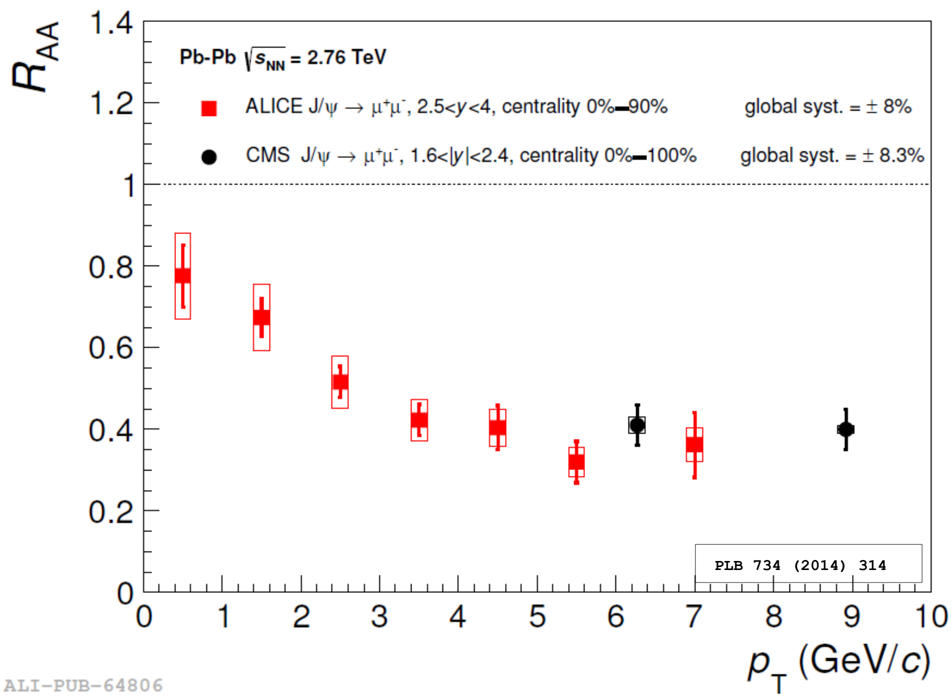

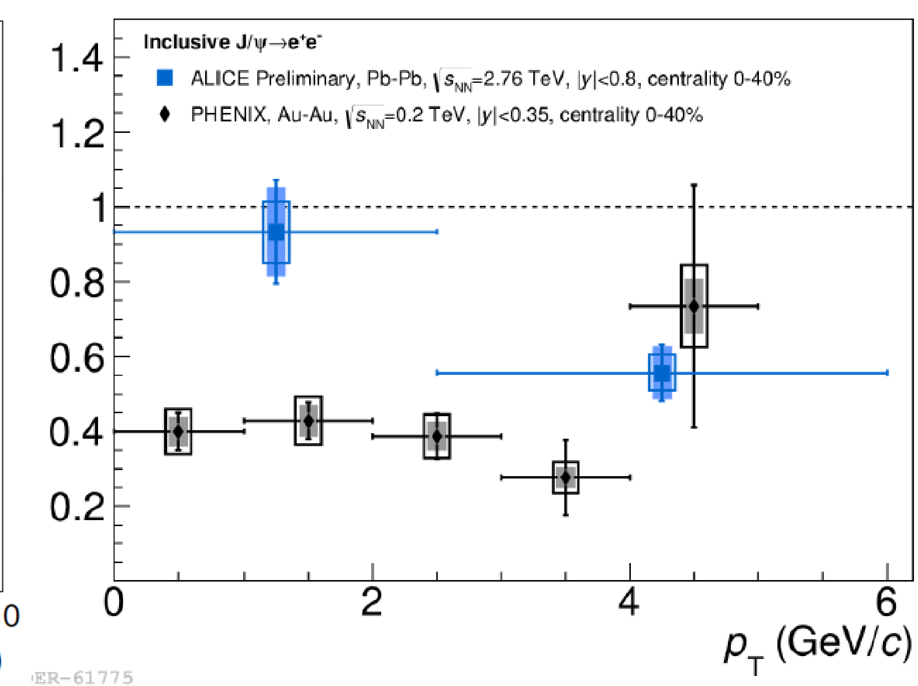

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  → true at forward and central y

Transverse momentum dependence of J/ψ R_{AA}

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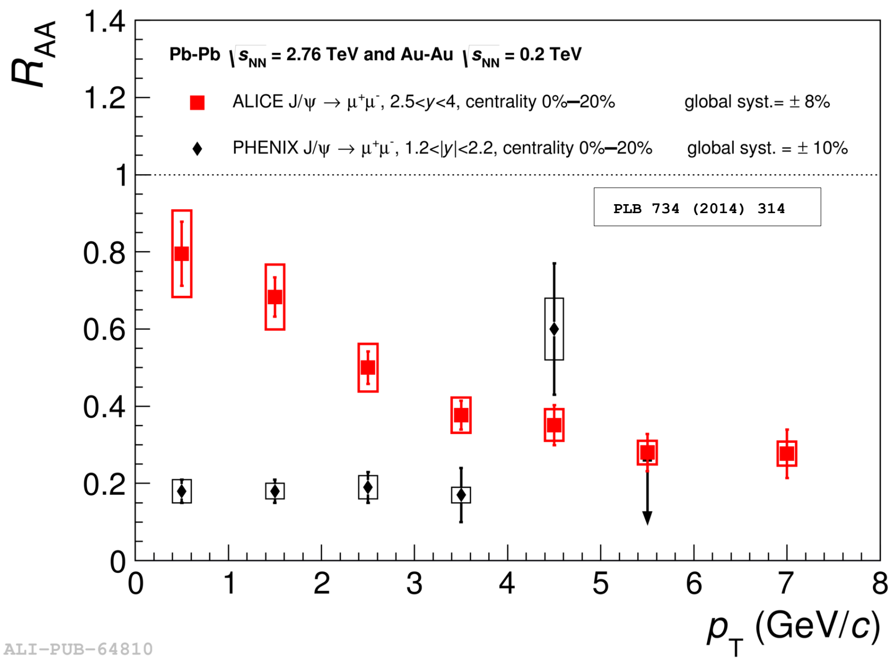
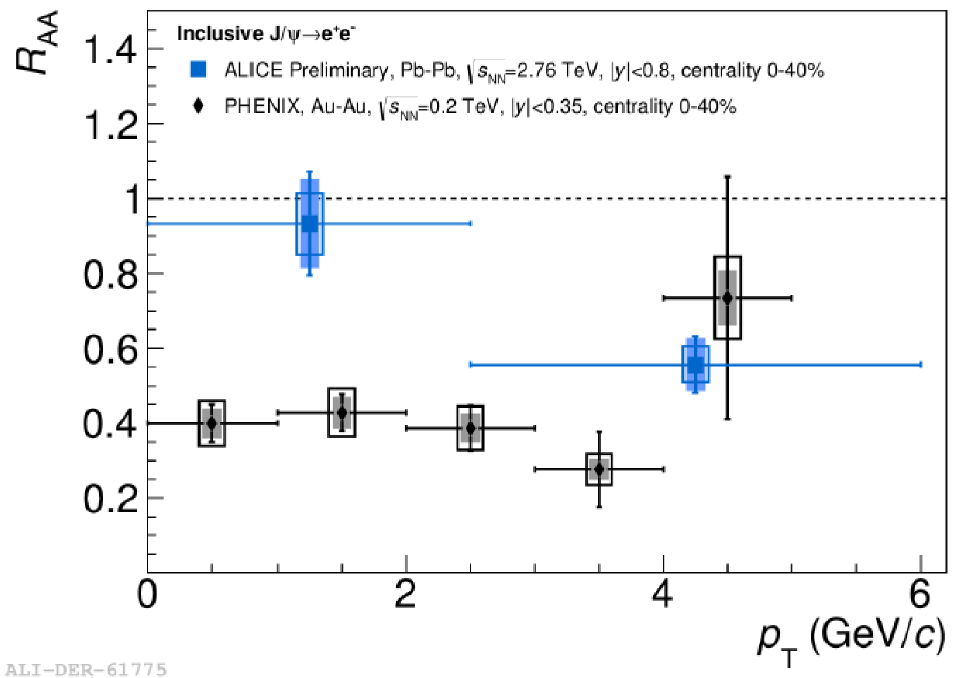


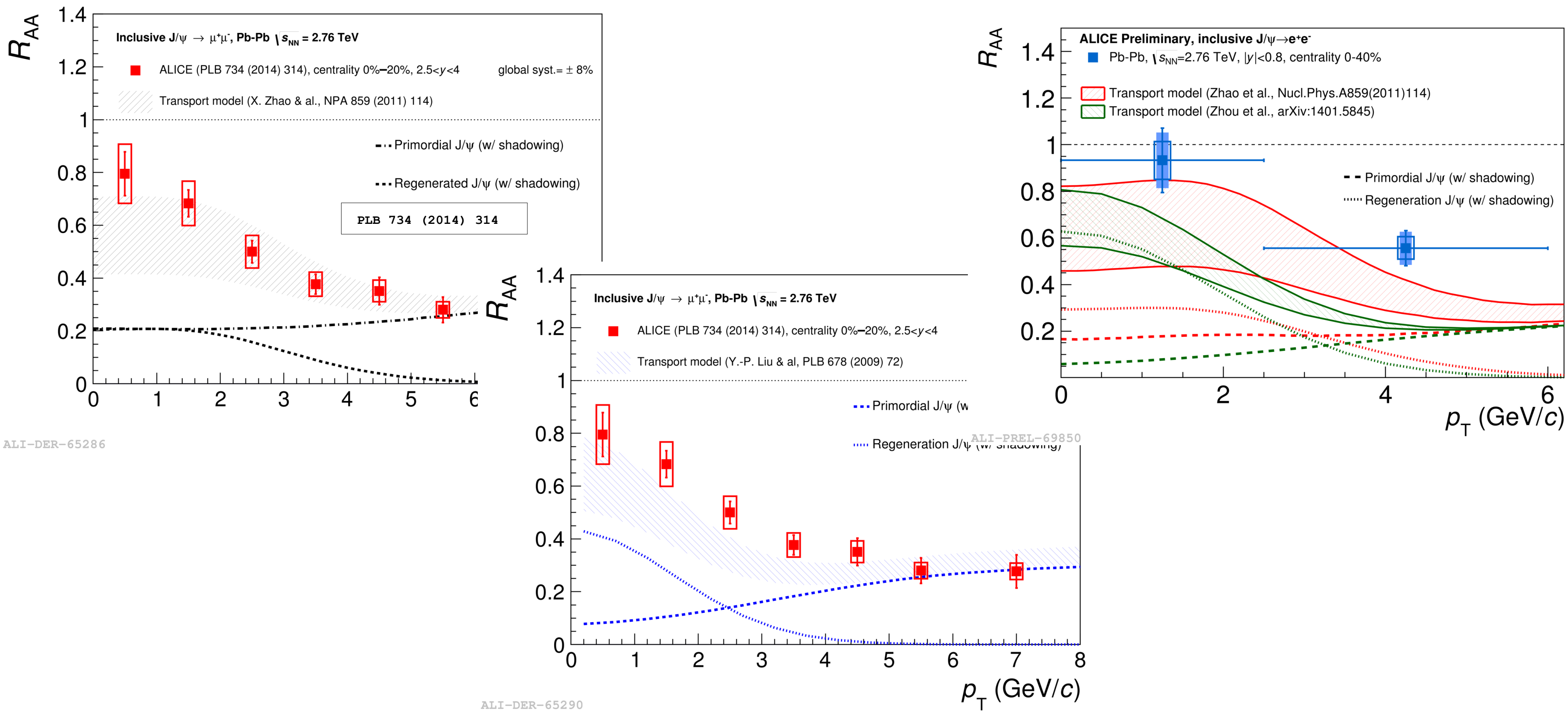


Very large difference in the J/Ψ R_{AA} p_T dependence between RHIC and LHC central and forward results.

→ Large J/Ψ R_{AA} at low-p_T fits well with a regeneration scenario

Transverse momentum dependence of J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV

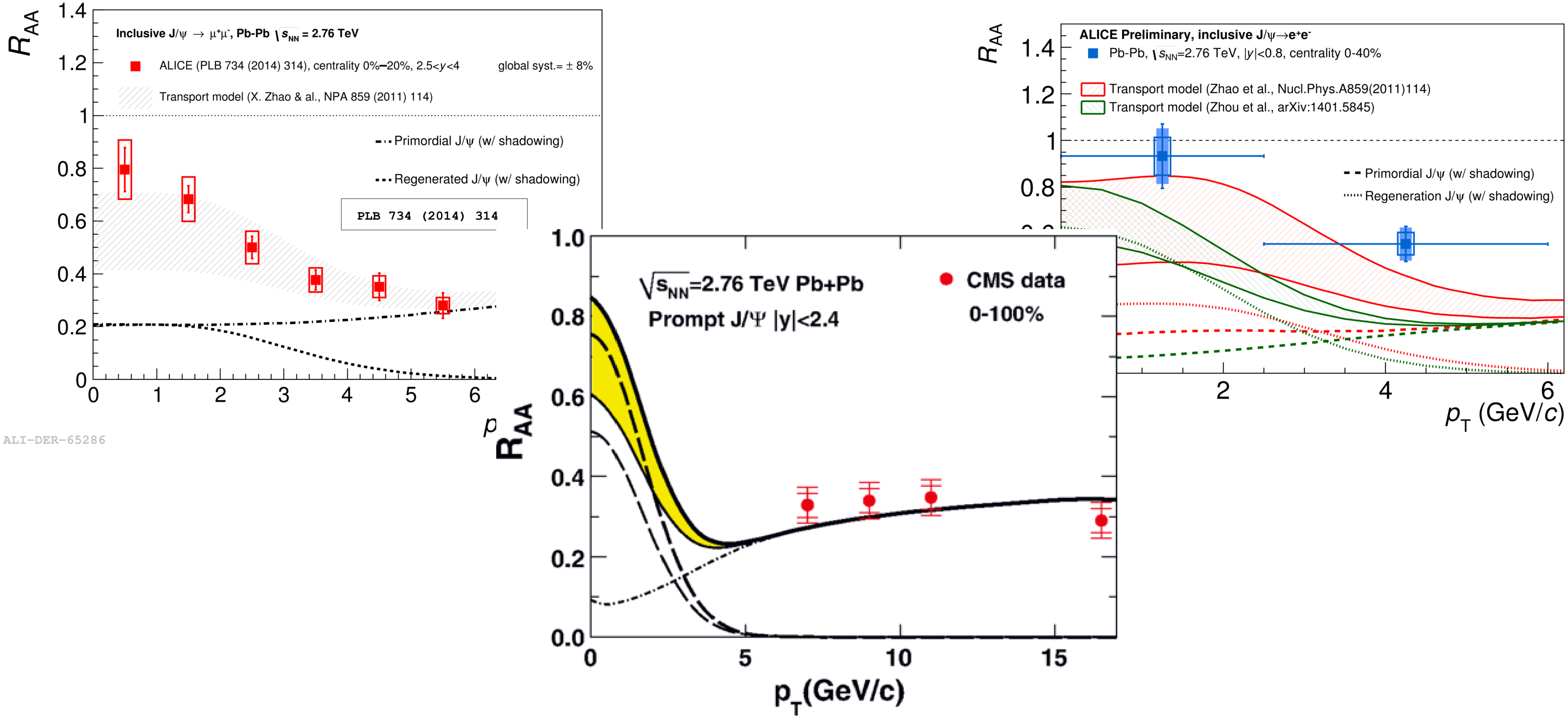


Models with large J/Ψ regeneration (important at low-p_T) reproduce fairly well the results

→ models slightly underestimate the measurements at low-p_T

Transverse momentum dependence of J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV



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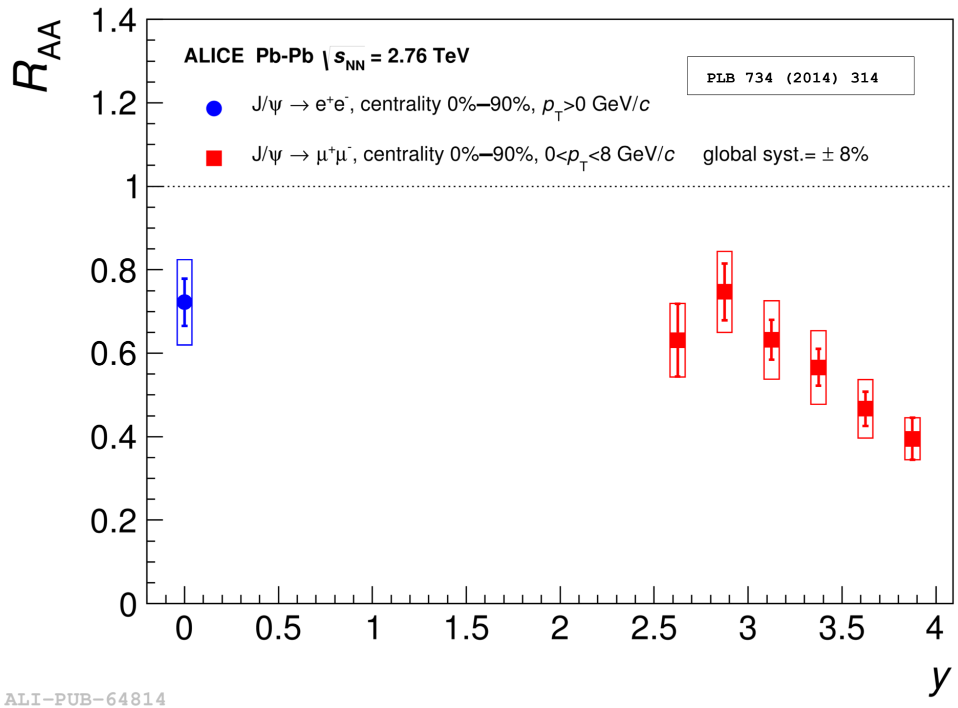
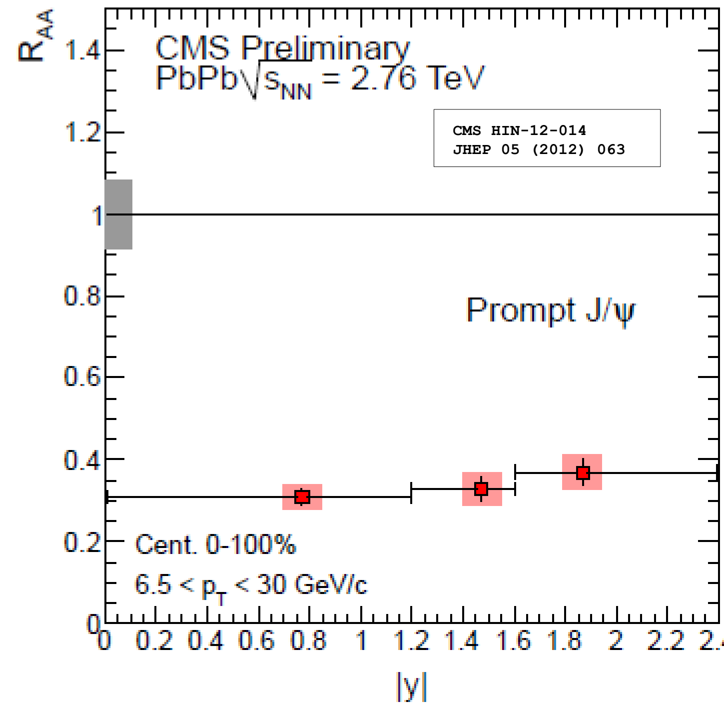
At high-p_T model inputs have lower uncertainties and match the results quite well.

Rapidity dependence of J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV





At low-p_T (p_T > 0), ALICE shows similar J/Ψ suppression at y ~ 0 and y ~ 3. Then a decreasing trend appears.
At high-p_T (p_T > 6.5), CMS shows strong J/Ψ suppression with almost no rapidity dependence for |y| < 2.4.

Rapidity dependence of J/ψ R_{AA}

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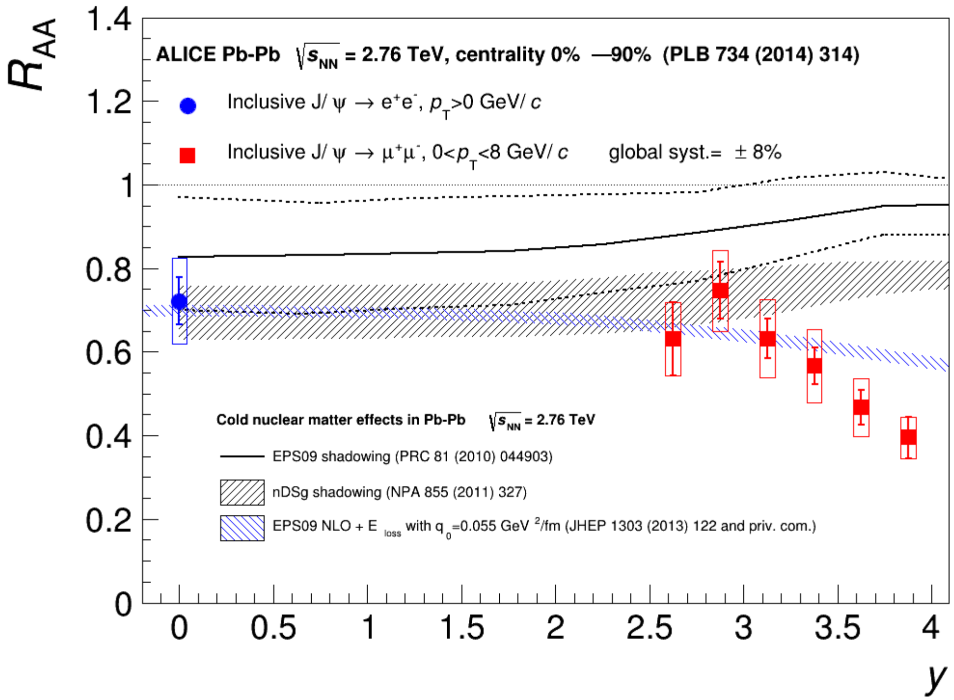
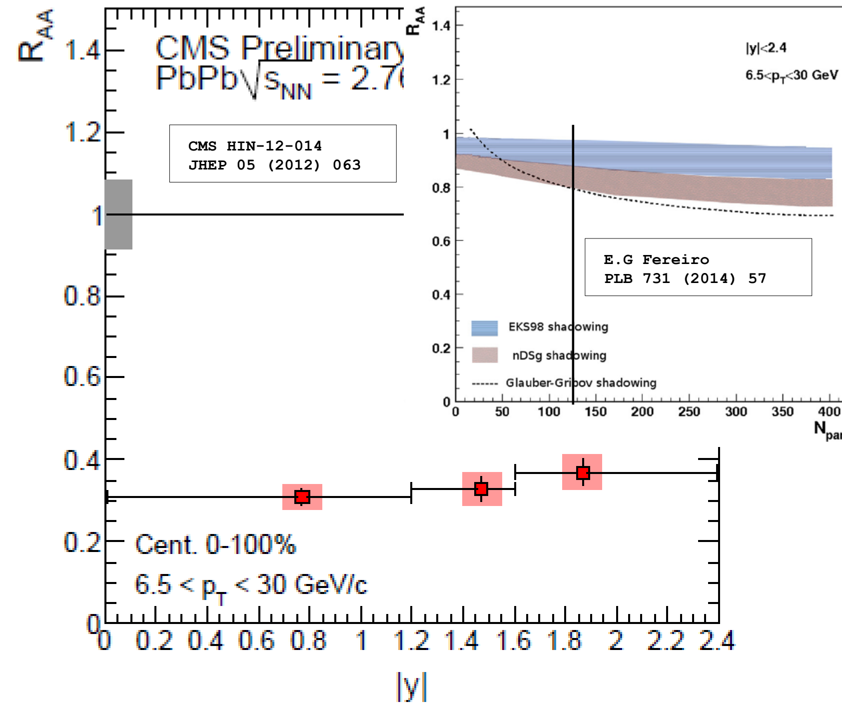
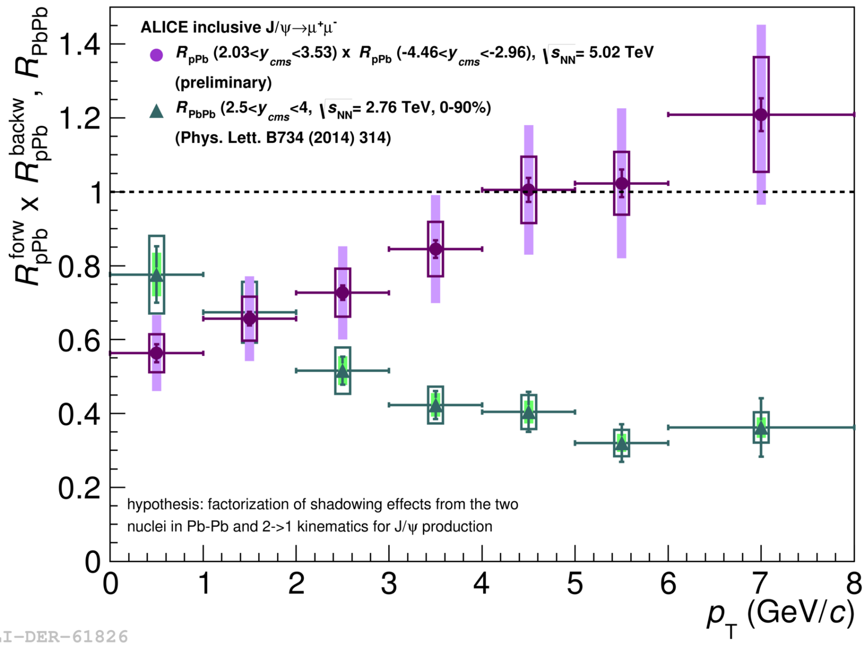


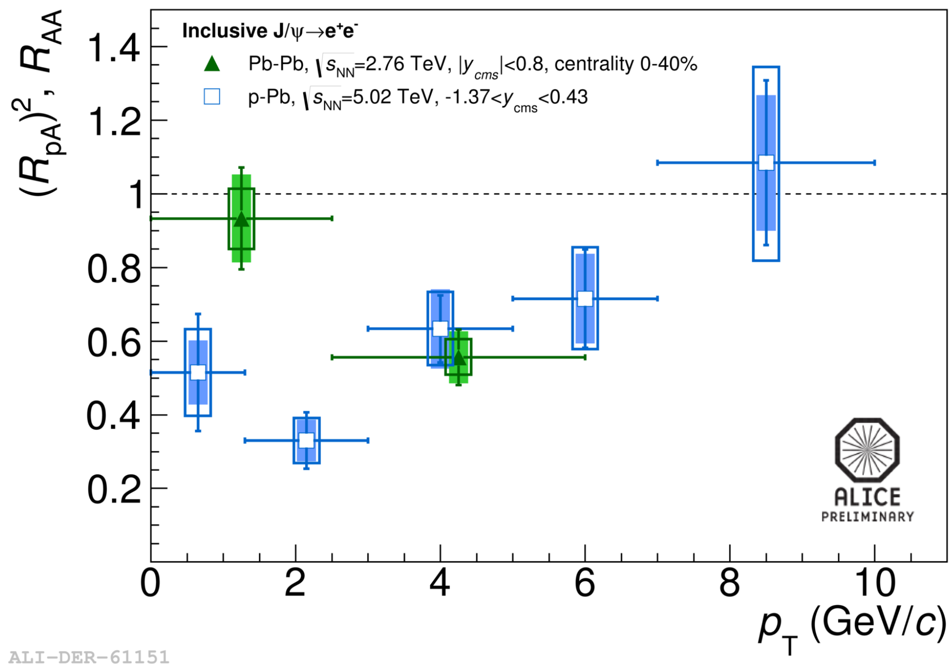


At low-p_T (p_T > 0), shadowing/energy loss effects are of the same order of magnitude as the measured J/Ψ suppression.
At high-p_T (p_T > 6.5), shadowing expected in the range [0.8-0.95], clearly above the CMS results.
→ At low-p_T, the J/Ψ suppression could be compensated by regeneration mechanisms that do not play a role at high-p_T.

Factorize out CNM effects in the J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV and pPb @ $\sqrt{s_{NN}}$ =5.02 TeV





Attempt made by ALICE assuming:

i) 2 → 1 kinematics for J/ψ production

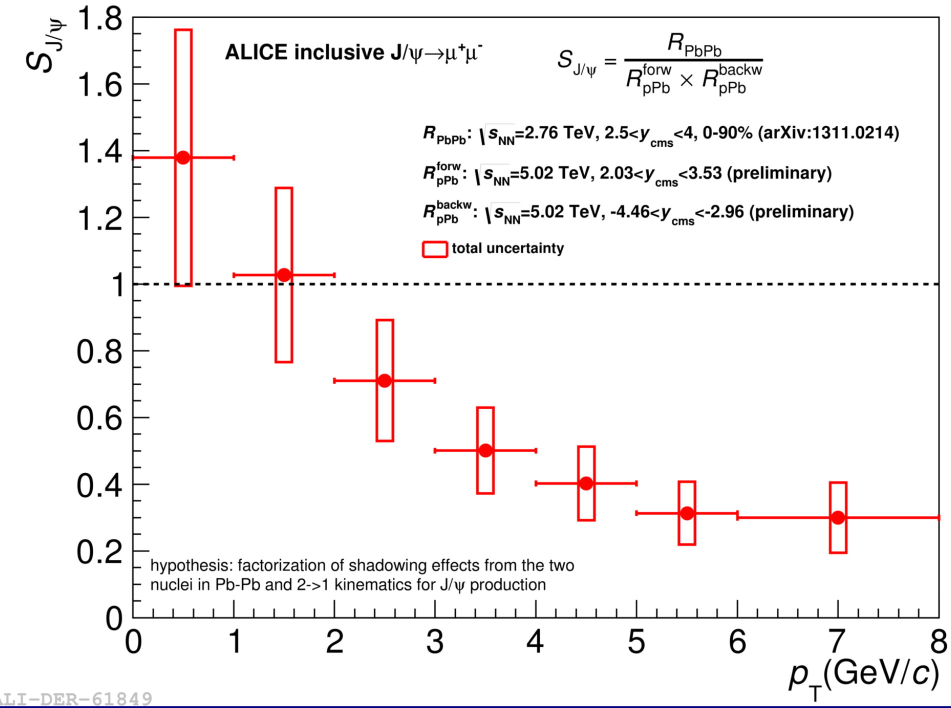
ii) CNM effects factorize in p-A and are dominated by shadowing

then CNM evaluated as R_{pPb} x $R_{Pb\text{-}p}$ (similar $x_{Bjorken}$ coverage as Pb-Pb)

→ Strong p_T dependence of the R_{AA} in Pb-Pb and pPb

Factorize out CNM effects in the J/ψ R_{AA}

Pb-Pb @ $\sqrt{s_{NN}}$ =2.76 TeV and pPb @ $\sqrt{s_{NN}}$ =5.02 TeV



Attempt made by ALICE assuming:

i) 2 → 1 kinematics for J/ψ production

ii) CNM effects factorize in p-A and are dominated by shadowing

then CNM evaluated as R_{pPb} x $R_{Pb\text{-}p}$ (similar $x_{Bjorken}$ coverage as Pb-Pb)

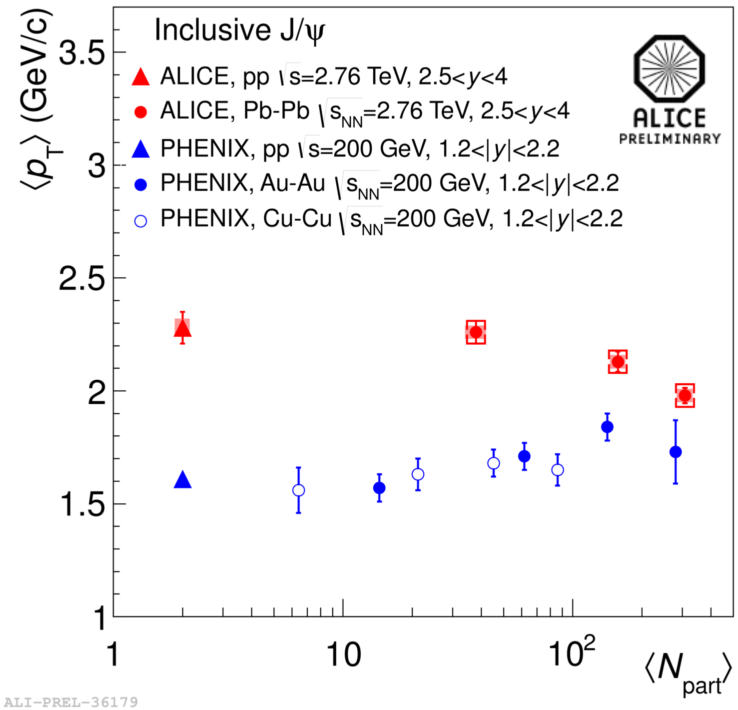
→ Strong p_T dependence of the R_{AA} in Pb-Pb and pPb

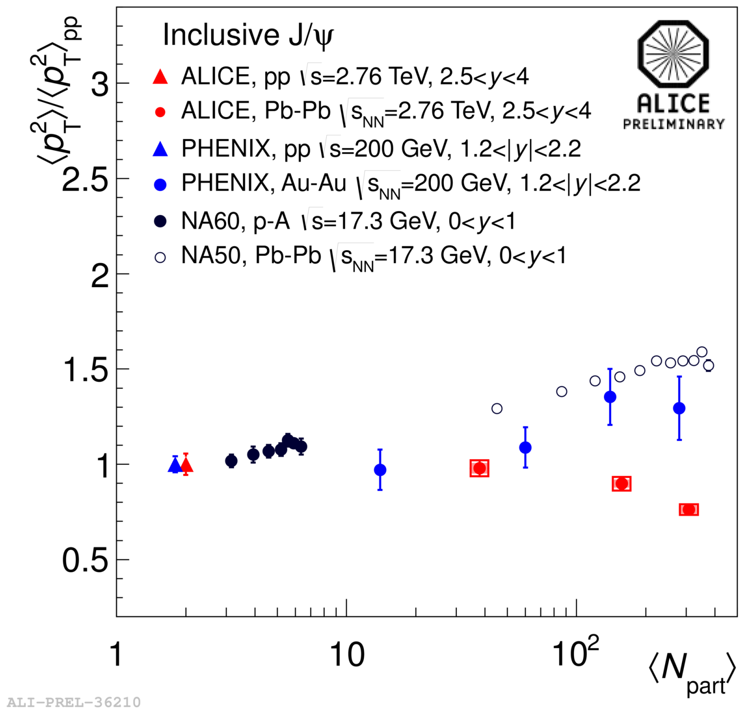
→ Matches a scenario of regeneration at low-p_T and suppression at high-p_T

BUT one must be careful, e.g. shadowing do not describe well the low-p_T p-Pb results

Looking at the J/ψ ⟨p_T⟩ and ⟨p_T^2⟩

pp,Pb-Pb, CuCu, AuAu@$\sqrt{s_{NN}}$=0.02,0.2 ,2.76 TeV



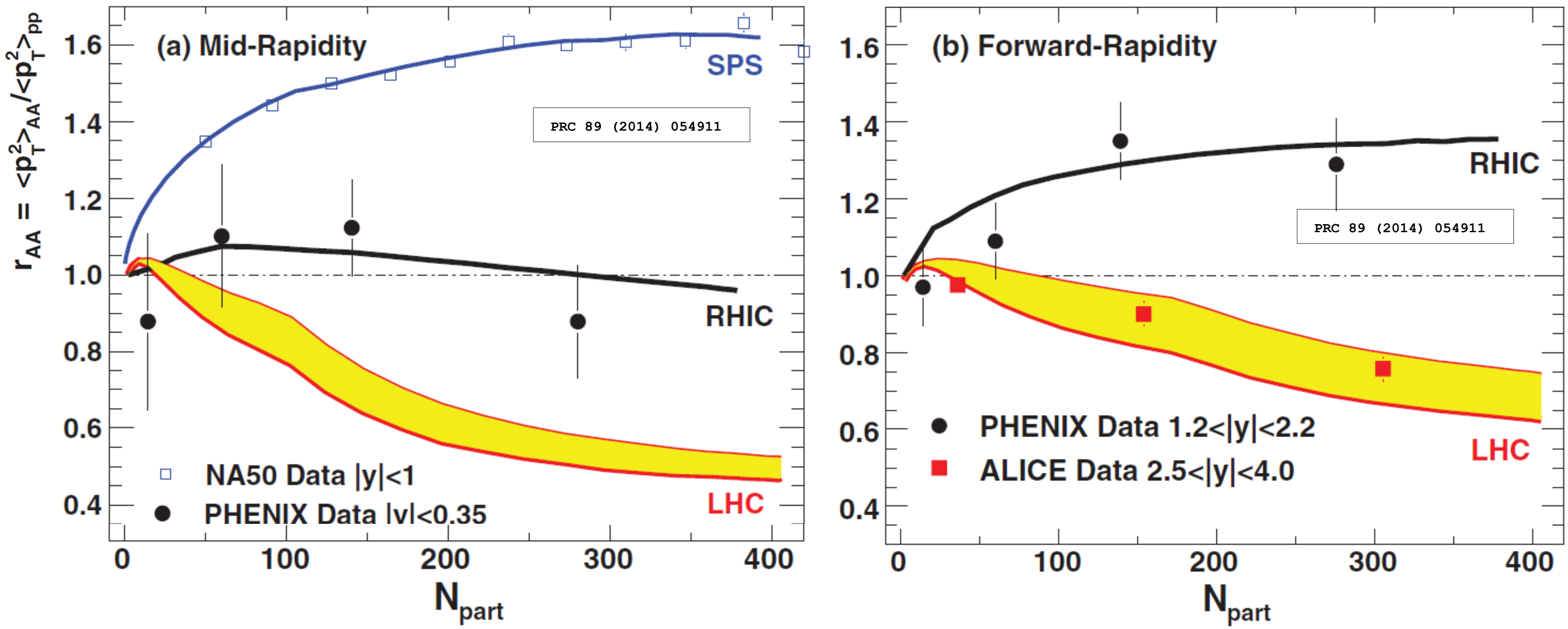


ALICE J/ψ ⟨p_T⟩ (and ⟨p_T^2⟩) shows a decreasing trend as a function of centrality
→ dominated by low-pT J/ψ in central Pb-Pb

Comparison to lower $\sqrt{s_{NN}}$ results from **NA50** and PHENIX for $\langle p_T^2\rangle_{A\text{-}A}/\langle p_T^2\rangle_{pp}$
→ clear differences in the centrality dependence

Looking at the J/ψ r_{AA}

pp,Pb-Pb, CuCu, AuAu@$\sqrt{s_{NN}}$=0.02,0.2 ,2.76 TeV

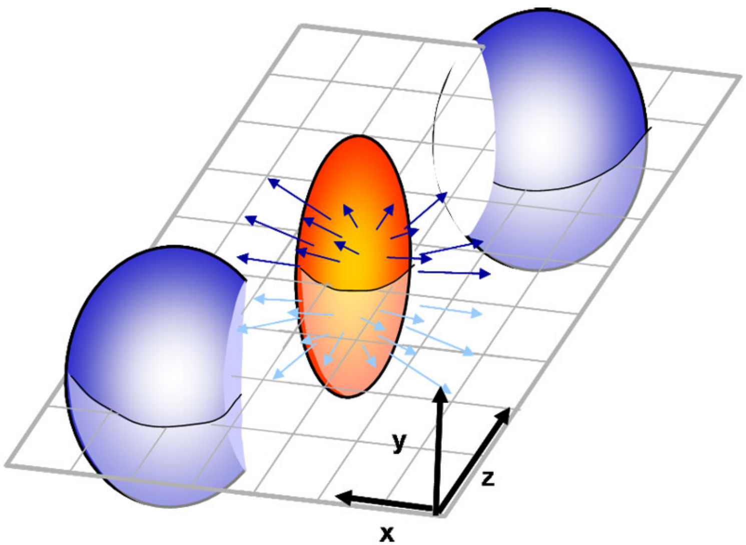


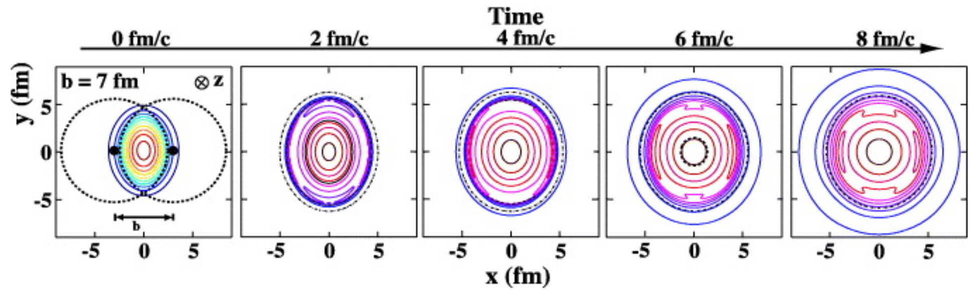
J/ψ r_{AA} centrality dependence well reproduced by a transport model (Zhou et al., PRC89, 054911 (2014)) over a wide $\sqrt{s_{NN}}$ range at SPS, RHIC and LHC.

→ J/ψ suppression and regeneration needed at LHC

J/ψ elliptic flow (v_2)

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV





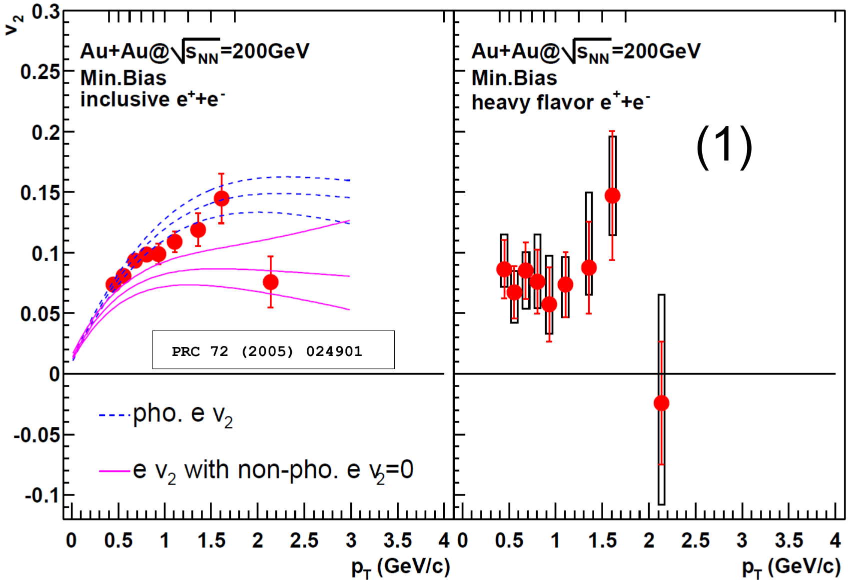
pressure gradients in a thermalized medium convert spatial anisotropy into momentum space

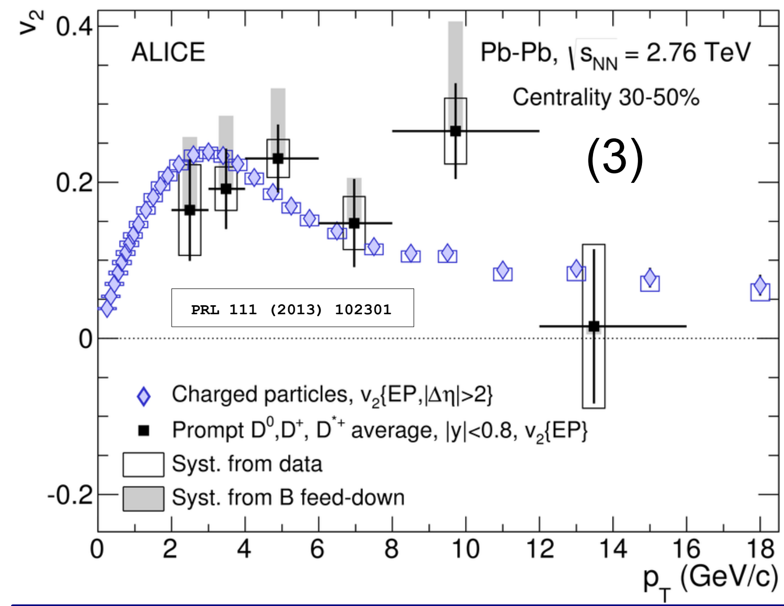
$$\frac{dN}{d\phi} = N\left(1 + 2v_2 \cos 2(\phi - \psi)\right)$$

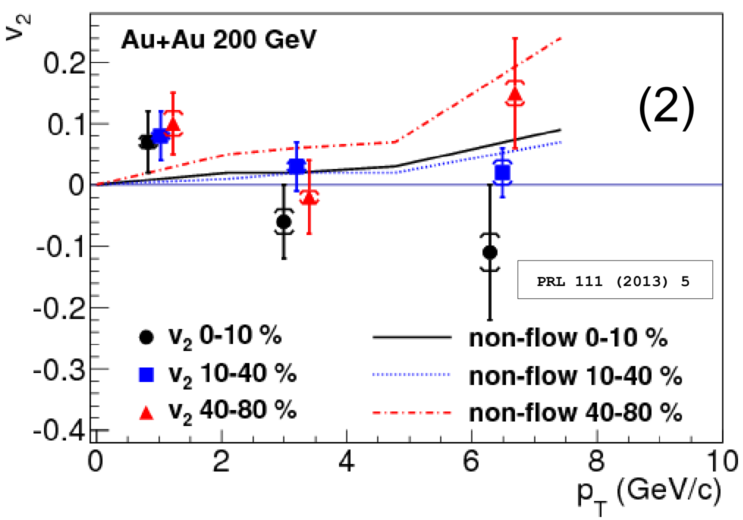
Initial spatial anisotropy is converted into momentum-space anisotropy
Strong elliptic flow observed for light particles and D mesons
→ does the J/ψ inherit any of the fireball collective flow via recombination?

J/ψ elliptic flow (v_2)

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV







At RHIC:

(1) Charm (non-photonic electrons) measured v_2 is ~ 8%

(2) J/Ψ v_2 is consistent with 0

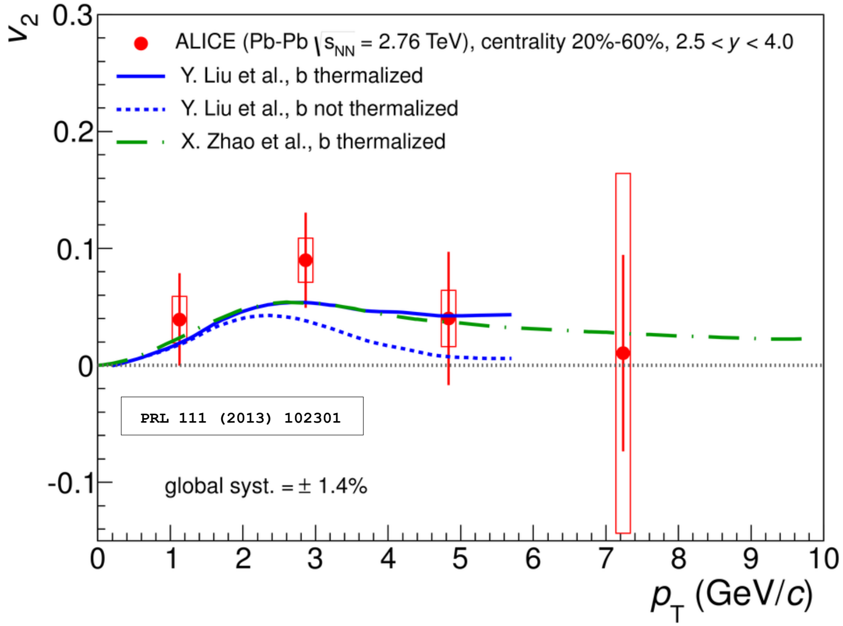
At LHC:

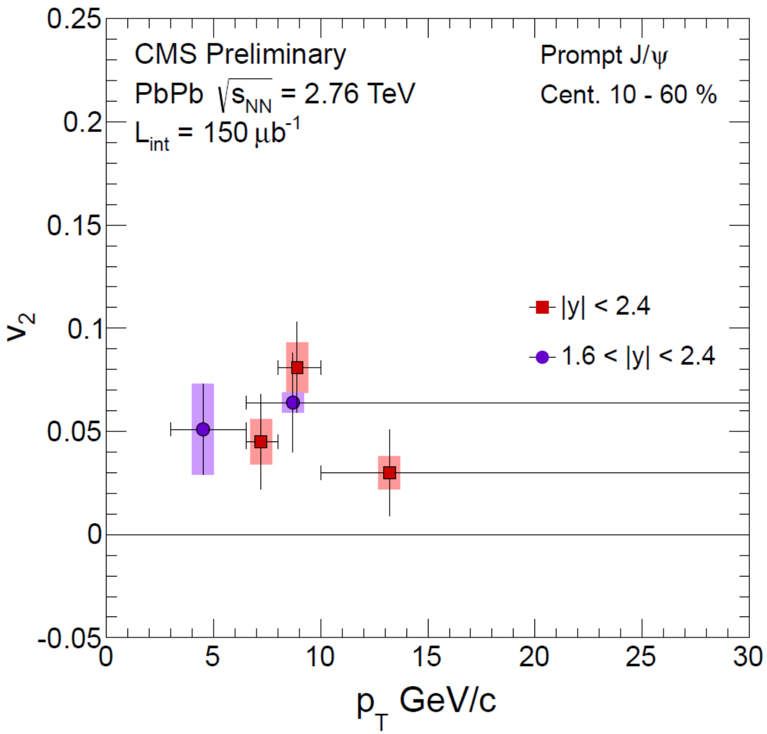
(3) v_2 from D^+ and D^0 mesons larger than 10%

Do J/Ψ exhibit elliptic flow at LHC ?

J/ψ elliptic flow (v_2)

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV





Significant v_2 signals observed by ALICE (low-p_T) and CMS (high-p_T)

→ at low/intermediate-p_T, the J/ψ v_2 signal is rather clear, in agreement with regeneration models

→ at high-p_T, the J/ψ v_2 signal is still present.

- path length dependence of energy loss ?
- check model expectations

ψ(2S) production
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

ψ(2S) state is less bound than the J/ψ.
→ statistical and transport models have rather different predictions for ψ(2S) prod.

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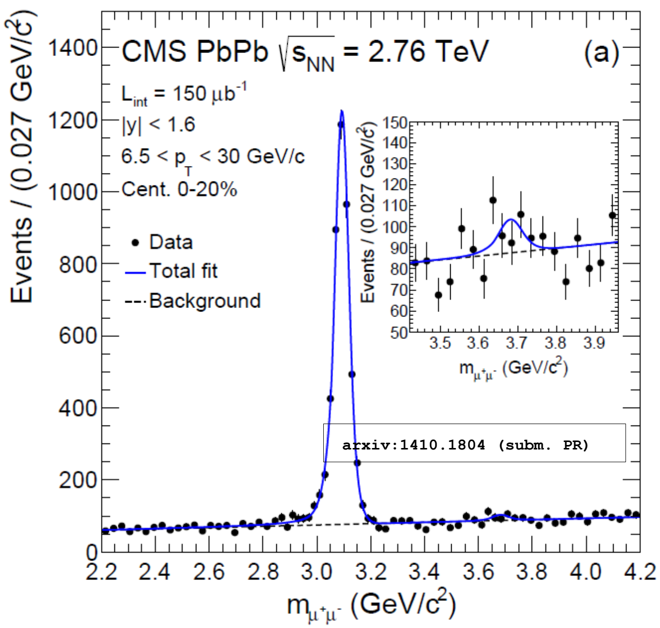
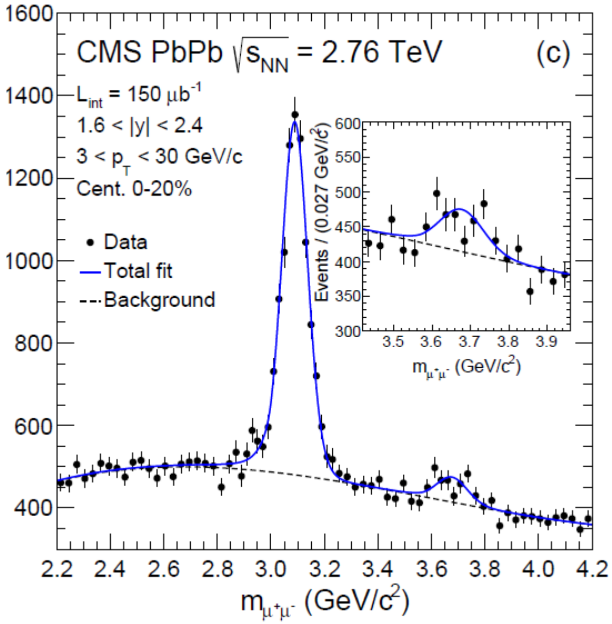
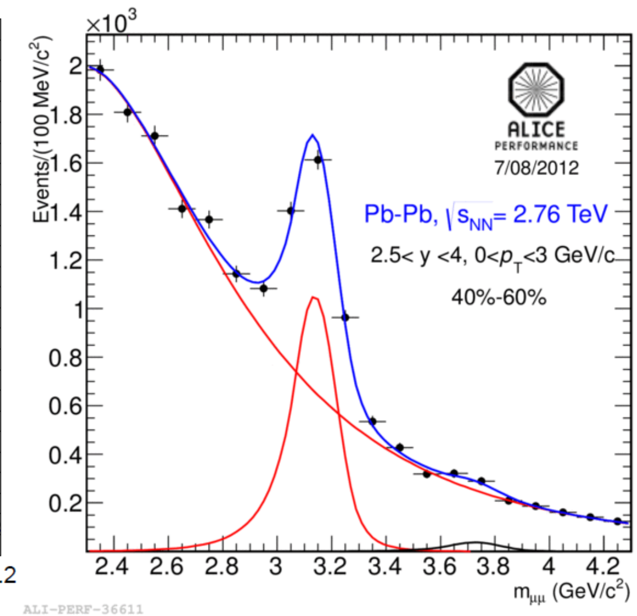


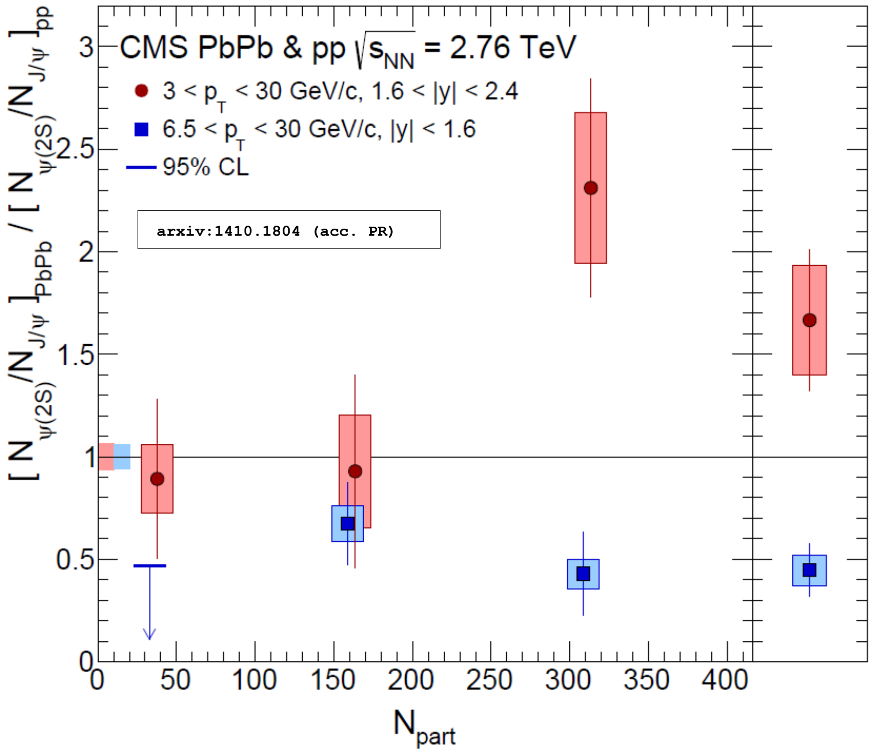


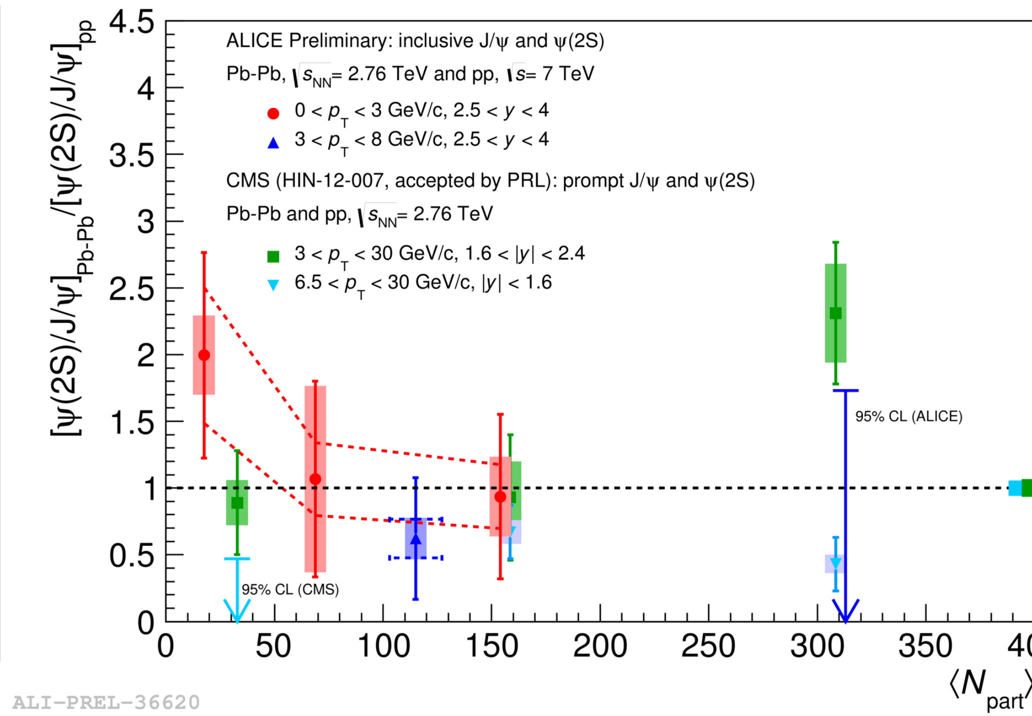


CMS ψ(2S) signal extraction in central Pb-Pb, especially at high-p_T,appears difficult.
At low-p_T, ALICE only succeeded to extract the ψ(2S) in peripheral collisions (confidence limit otherwise).

ψ(2S) production

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV





In most central Pb-Pb collisions, CMS measure a sizable enhancement in the range [3<p_T<30 GeV/c and 1.6 < |y| < 2.4] w.r.t. [6.5<p_T<30 GeV/c and |y| < 1.6]

→ interpretation of such effect still unclear.

ALICE/**CMS** comparison (3<p_T<8/30 GeV/c) in most central collisions

→ so far, no clear discrepancy/tension (may come with run-II...)

Conclusions and outlook

- Charmonia Physic at LHC is very interesting

  → suppression and regeneration mechanisms are both needed to explain the LHC run-I results

- LHC run-II will allow deeper investigation of charmonia production
  - larger statistics for
    - J/ψ v_2 and R_{AA}
    - ψ(2S)
    - ratio J/ψ over Dmesons
  - need of a proper pp reference @ $\sqrt{s}$ = 5 TeV → lower uncertainties
    - final word on the recombination ?
    - more constraint on models
  - model calculations
    - several observables (R_{AA} and r_{AA} and v_2)
    - room for improvement in the uncertainties from CNM and $d\sigma_{c\bar{c}}/dy$?

      → double ratios [5.TeV/2.76TeV]