INT Workshop

September 29th – October 1st 2014

Seattle

Quarkonium production in Pb-Pb collisions at the LHC

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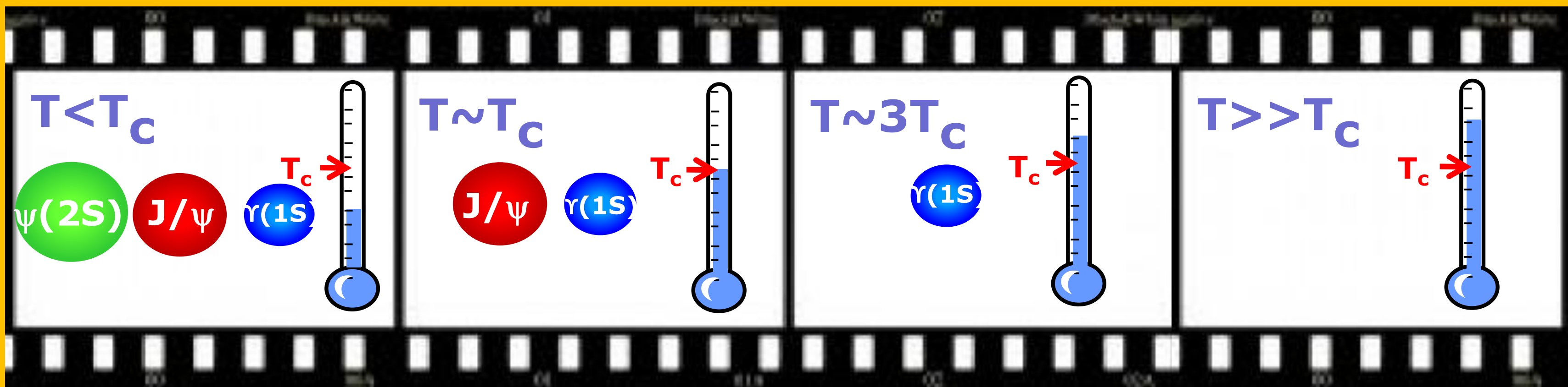
focusing on the most recent ALICE Pb-Pb (Run-I) results on

- **Charmonium: J/ψ and ψ(2S)**
- **Bottomonium: Υ(1S)**

FROM SUPPRESSION TO RECOMBINATION IN 1 SLIDE!

Sequential melting

depending on the binding energies of the quarkonium states



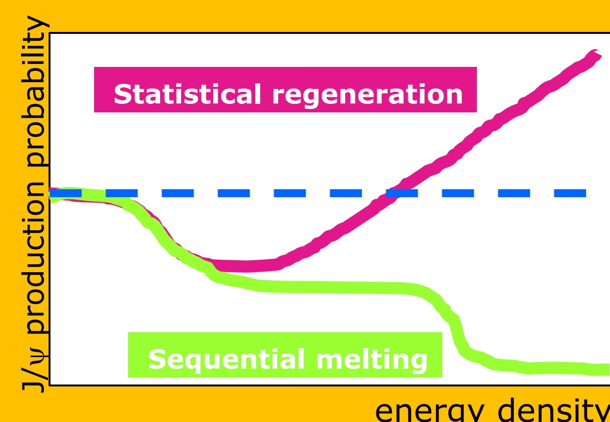
Digal,Petrecki,Satz PRD 64(2001) 0940150

(Re)combination

Increasing the collision energy the cc pair multiplicity increases

Most central AA collisions	SPS 20 GeV	RHIC 200GeV	LHC 2.76TeV
N_{ccbar}/event	~0.2	~10	~75

→ enhanced quarkonia production via (re)combination at hadronization or during QGP stage



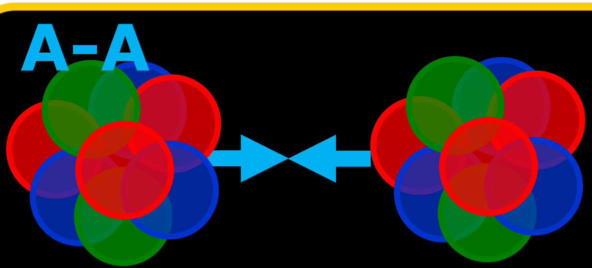
P. Braun-Muzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)

OTHER EFFECTS

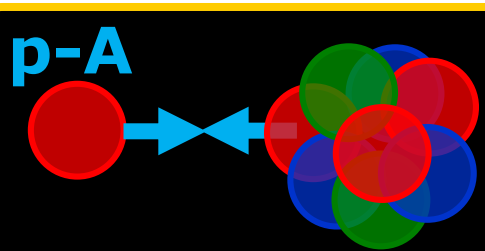
- On top of these mechanisms related to hot matter effects, other effects have to be taken into account to interpret quarkonium A-A results:
  - Role of feed-down from higher states
  - Role of cold matter effects (CNM)
    - Nuclear parton shadowing
    - energy loss
    - $c\bar{c}$ in medium break-up

  investigated through pA collisions

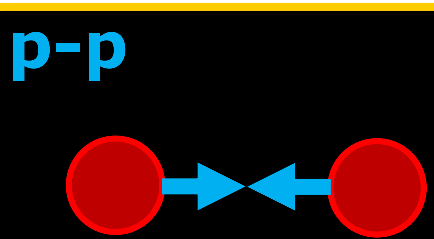
QUARKONIUM STUDIES IN HEAVY-ION COLLISIONS



- Quarkonium as a probe of the hot medium created in the collision (QGP)
- Suppression vs regeneration



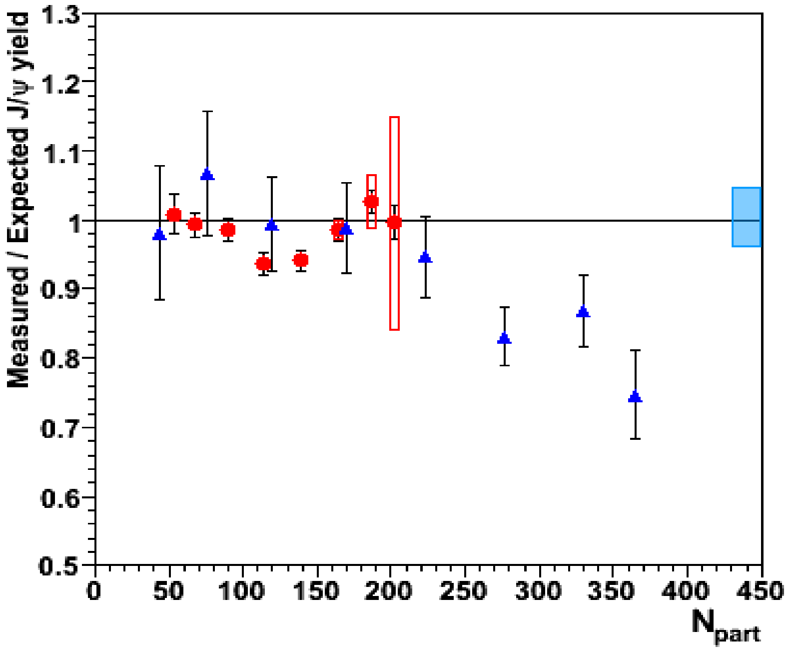
- Investigation of cold nuclear matter effects (shadowing, energy loss…)
- Crucial tool to disentangle genuine QGP effect is AA collisions



- Reference process to understand behaviour in pA, AA collisions
- Useful to investigate production mechanisms (NRQCD, CEM models...)

LOW ENERGY RESULTS: J/ψ FROM SPS & RHIC

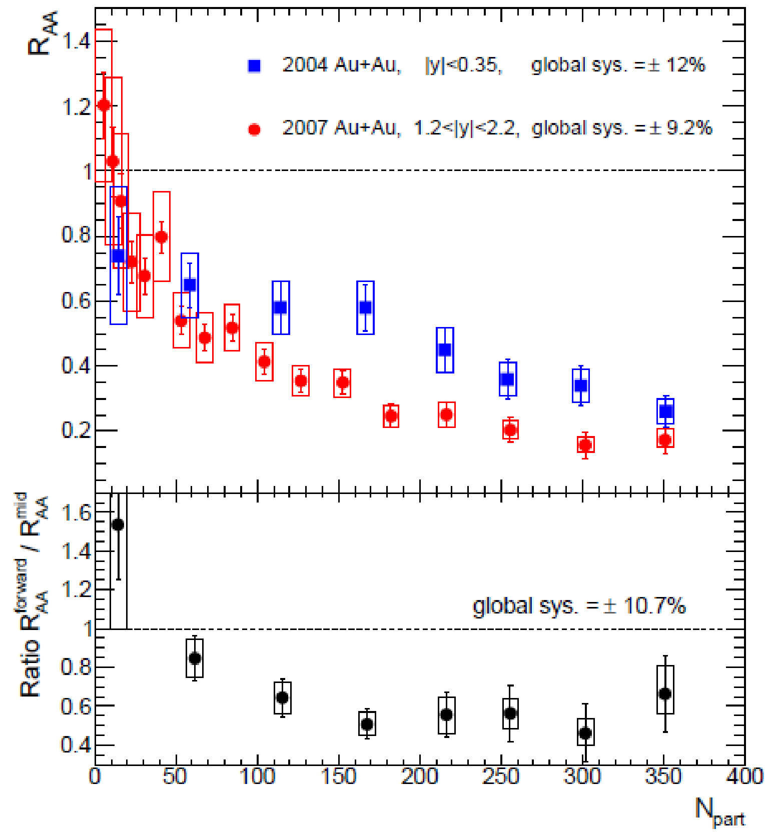
SPS (NA38, NA50, NA60)
$\sqrt{s_{NN}}$ = 17 GeV



- first evidence of anomalous suppression (i.e. beyond CNM expectations) in Pb-Pb collisions

  ~30% suppression compatible with ψ(2S) and χ_c decays

RHIC (PHENIX, STAR)
$\sqrt{s_{NN}}$ = 39, 62.4, 200 GeV

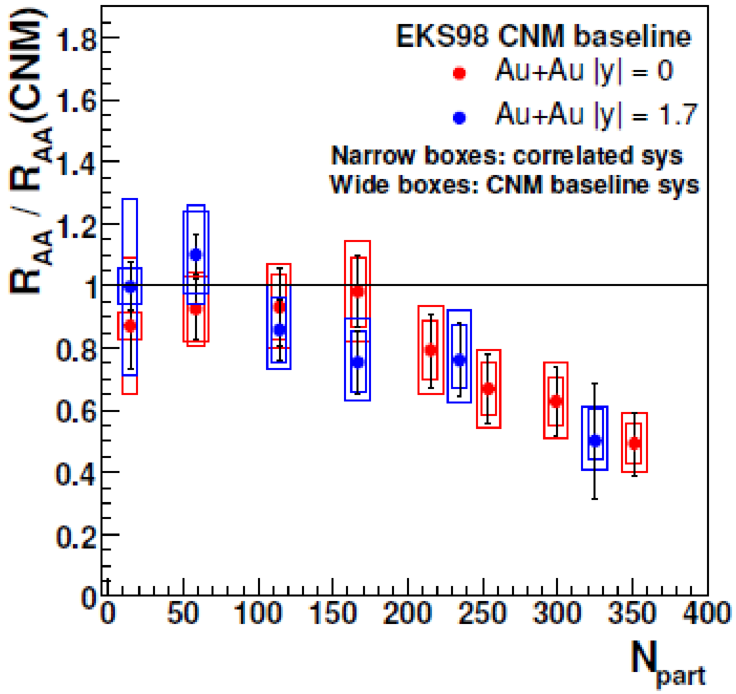


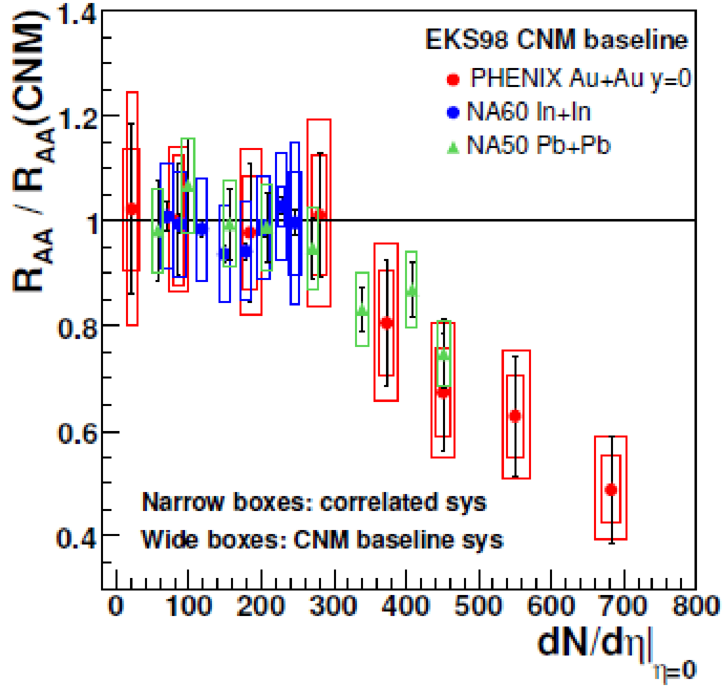
- suppression, strongly rapidity dependent, in Au-Au at $\sqrt{s}$= 200 GeV

LOW ENERGY RESULTS: J/ψ FROM SPS & RHIC

Comparison of SPS and RHIC results

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





- Good agreement between SPS and RHIC patters if cold nuclear matter effects are taken into account

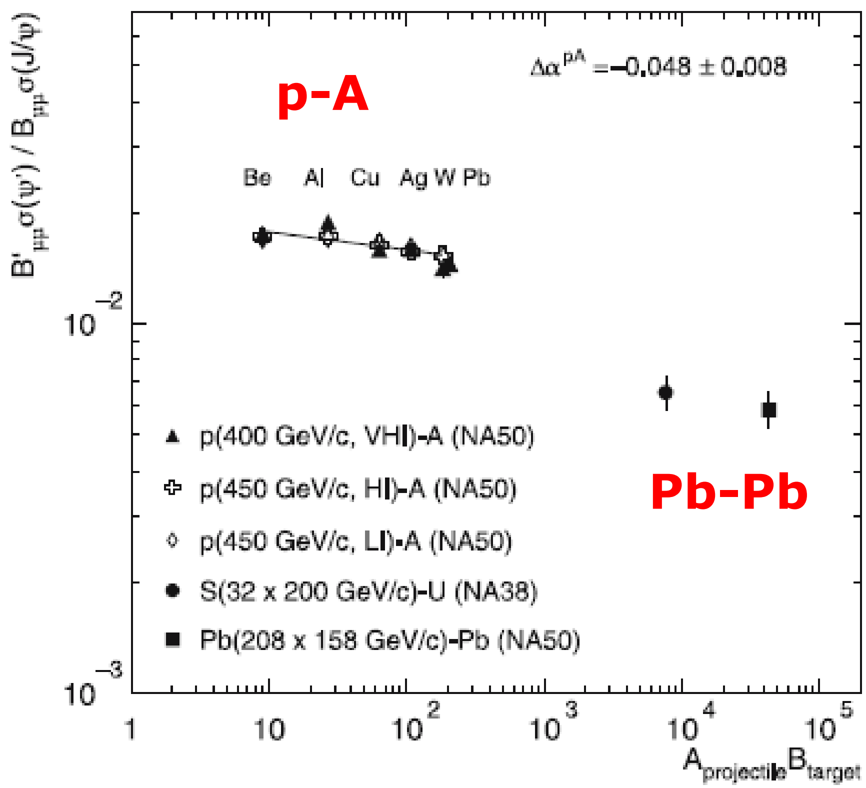
  → Compensation of suppression/recombination effects?

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

LOW ENERGY RESULTS: ψ(2S) FROM SPS & RHIC

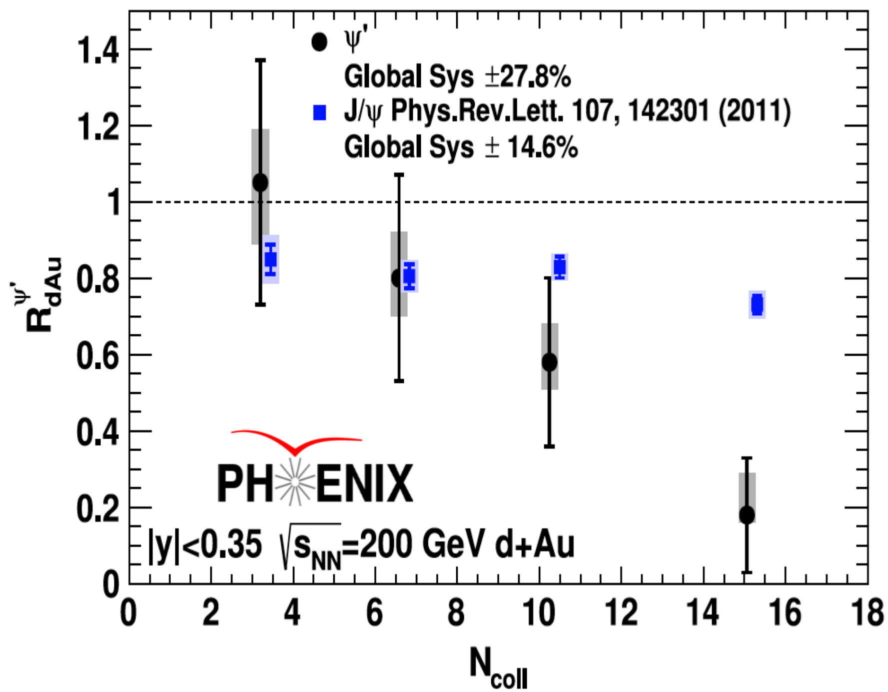
SPS (NA50) pA, AA @ $\sqrt{s_{NN}}$ = 17 GeV

Eur. Phys. J. C 49, 559 (2007)



RHIC (PHENIX)
d-Au @$\sqrt{s_{NN}}$ = 200 GeV

PRL 111, 202301 (2013)

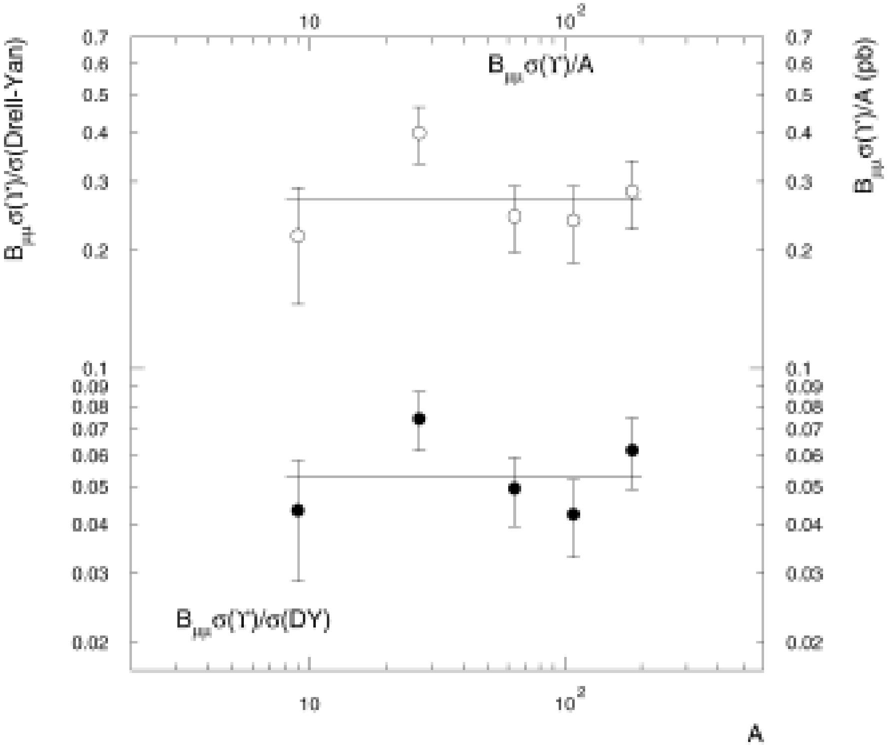


- ψ(2S) is more suppressed than J/ψ already in pA collisions and the suppression increases in Pb-Pb

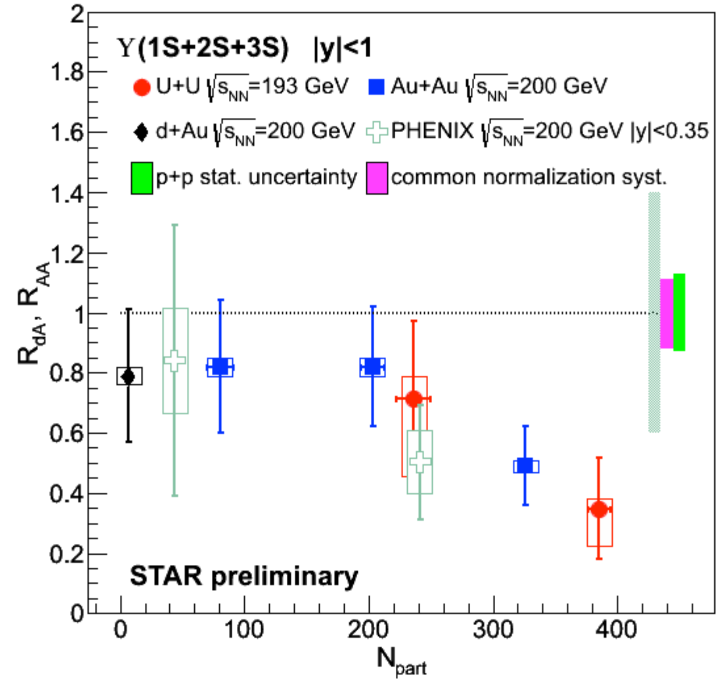
- unexpected ψ(2S) suppression, stronger than the J/ψ one in d-Au

LOW ENERGY RESULTS: Υ FROM SPS & RHIC

SPS (NA50) pA, $\sqrt{s_{NN}}$=29 GeV



RHIC (PHENIX, STAR) dAu, Au-Au $\sqrt{s_{NN}}$ = 200 GeV



- First Υ measurement at SPS energies.
  Hint for no strong medium effects on Υ(1S+2S+3S) in pA

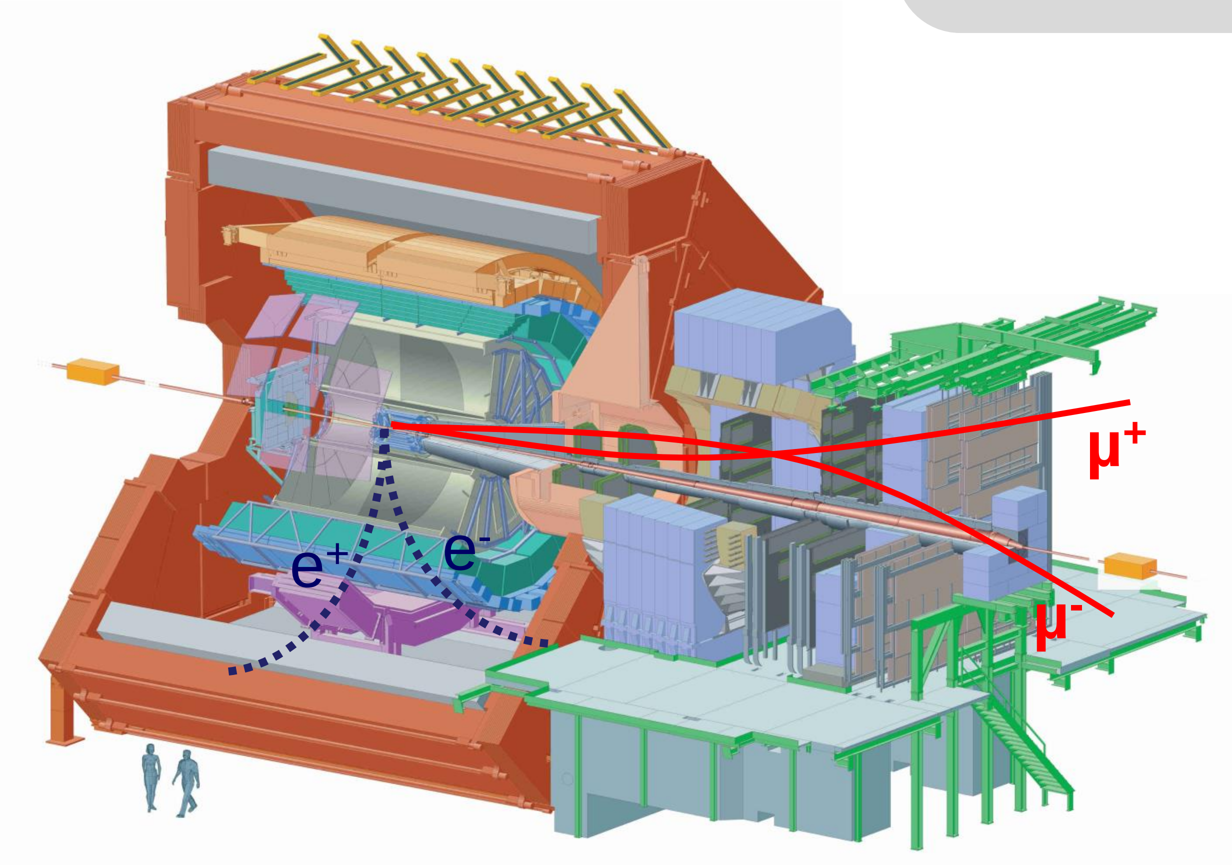
- Υ R_{AA} compatible with suppression of excited states but large uncertainties prevents further insights

B. Alessandro (NA50 Coll), PLB 635(2006) 260

A. Adare (PHENIX Coll.), 1404.2246
L. Adamcz (STAR Coll.) PLB 735 (2014) 127

QUARKONIUM IN ALICE

- Quarkonium (J/ψ, $\psi(2S)$ and Υ) has been measured in ALICE in:
  - pp @ $\sqrt{s}$= 2.76, 7 and 8TeV
  - Pb-Pb @ $\sqrt{s_{NN}}$= 2.76TeV
  - p-Pb @ $\sqrt{s_{NN}}$= 5.02TeV



QUARKONIUM IN ALICE

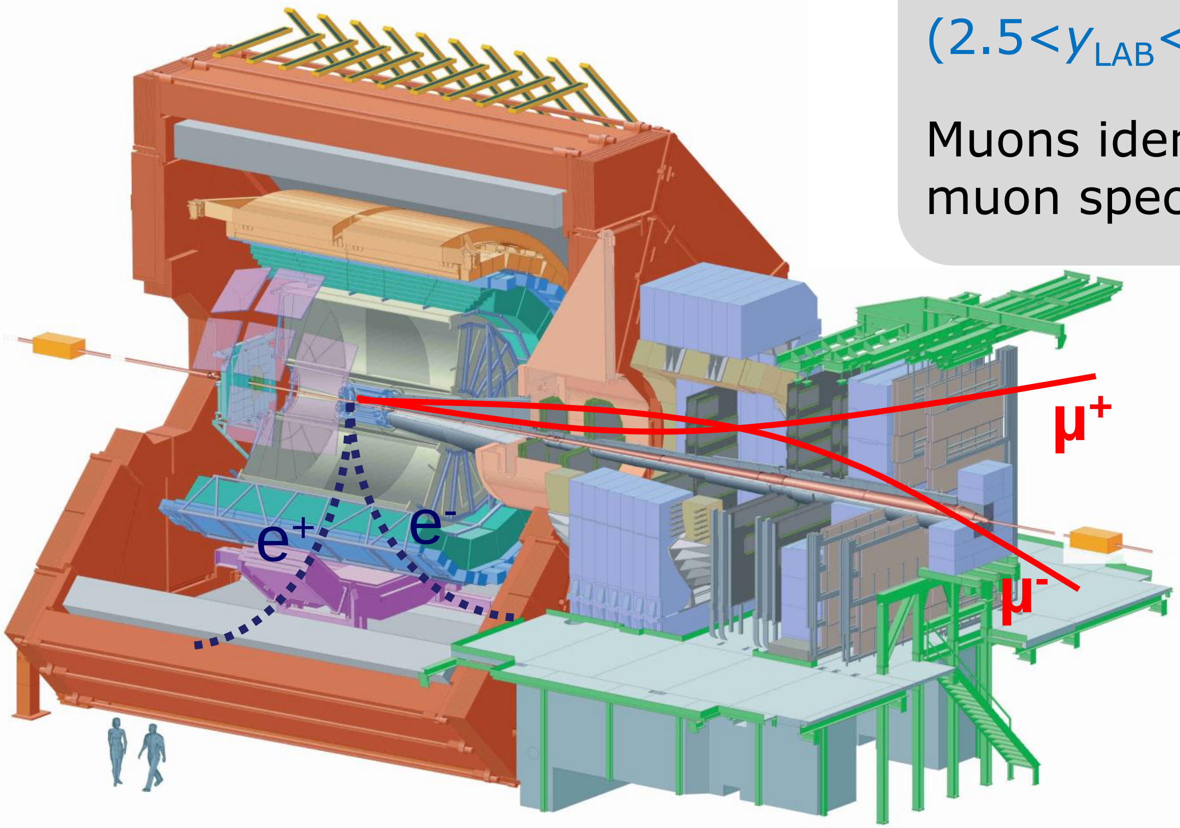
- Quarkonium in ALICE can be measured in two ways:

Central Barrel **$J/\psi \rightarrow e^+e^-$**
($|y_{LAB}|<0.9$)

Electrons tracked using ITS and TPC
Particle identification: TPC, TOF, TRD

Forward muon arm **$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$**
$\Upsilon \rightarrow \mu^+\mu^-$
($2.5<y_{LAB}<4$)

Muons identified and tracked in the muon spectrometer



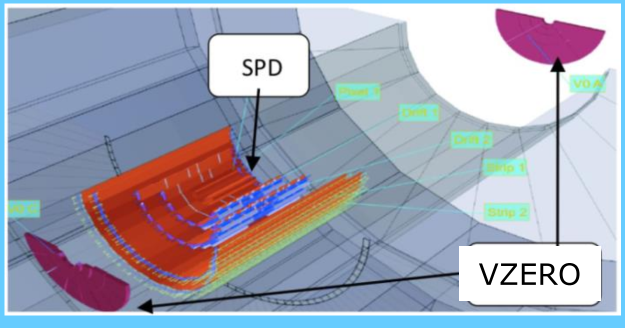
- Acceptance coverage in both y regions down to zero p_T
- ALICE measures inclusive J/ψ at mid and forward-y and prompt J/ψ at mid-y

EVENT AND TRACK SELECTION

Event and track selection details are specific to the various analyses, but general features are:

Event selection:

- Rejection of beam gas and EM interactions (VZERO and ZDC)
- SPD for vertex determination



Trigger:

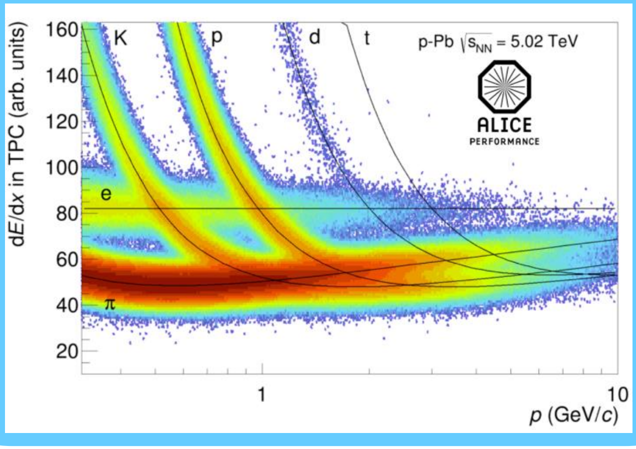
- Electron analysis: MB trigger
- Muon analysis: dimuon trigger, i.e. coincidence of MB with two μ^+, μ^- tracks in the Muon Spectrometer trigger chambers

Centrality:

- VZERO classes for PbPb

Electron track selection:

- $|\eta_e|<0.9$, $p_T>1$GeV/c
- Rejection of tracks from photon conversion



Muon track selection:

- Muon tracking-trigger matching
- $-4<\eta_\mu<-2.5$, $2.5<y^{\mu\mu}_{LAB}<4$
- $17.6<R_{abs}<89$ cm (R_{abs}= track radial position at the absorber end)

QUARKONIUM NUCLEAR MODIFICATION FACTOR

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle \, \sigma_{pp}^{J/\psi}}$$

The J/ψ ϒ, production in b-Pb, with respect to binary scaled pp yield, is quantified with the nuclear modification factor

(nuclear overlap T_{AA} from Glauber model)

J/ψ R_{AA}:

pp reference at √s = 2.76TeV

J/ψ→μ⁺μ⁻

ALICE pp data at √s=2.76TeV

ALICE, Phys. Lett. B718, 295 (2012)

J/ψ→e⁺e⁻

Interpolation of measured inclusive J/ψ mid-*y* cross sections (PHENIX, CDF and ALICE)

Phenix, Phys. Rev. D85, 092004 (2012)
CDF, Phys. Rev. D71, 032001 (2005)
ALICE, Phys. Lett. B718, 295&692 (2012)

ϒ R_{AA}:

pp reference at √s = 2.76TeV

ϒ→μ⁺μ⁻

LHCb pp data at √s=2.76TeV

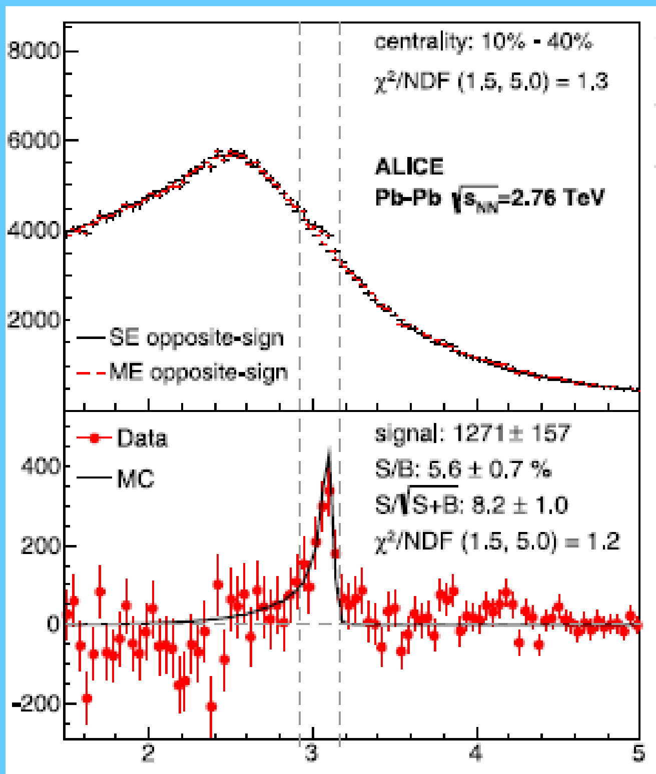
LHCb, Eur. Phys. J. C74(2014) 2835

(for y-differential results, a *y*-interpolation has been performed)

J/ψ in Pb-Pb collisions

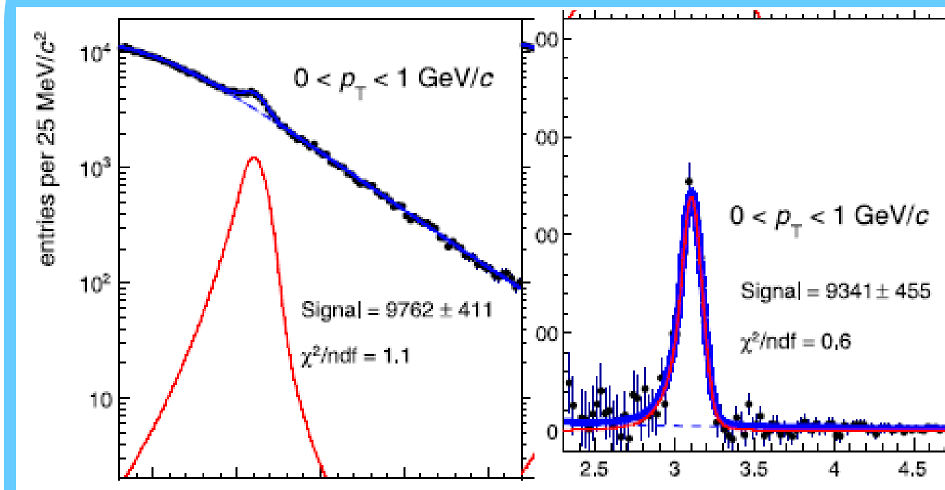
J/ψ SIGNAL EXTRACTION

Dielectron analysis:



Charmonium yields extracted with a counting technique, after subtraction of the combinatorial background (via mixed events technique)

Dimuon analysis:

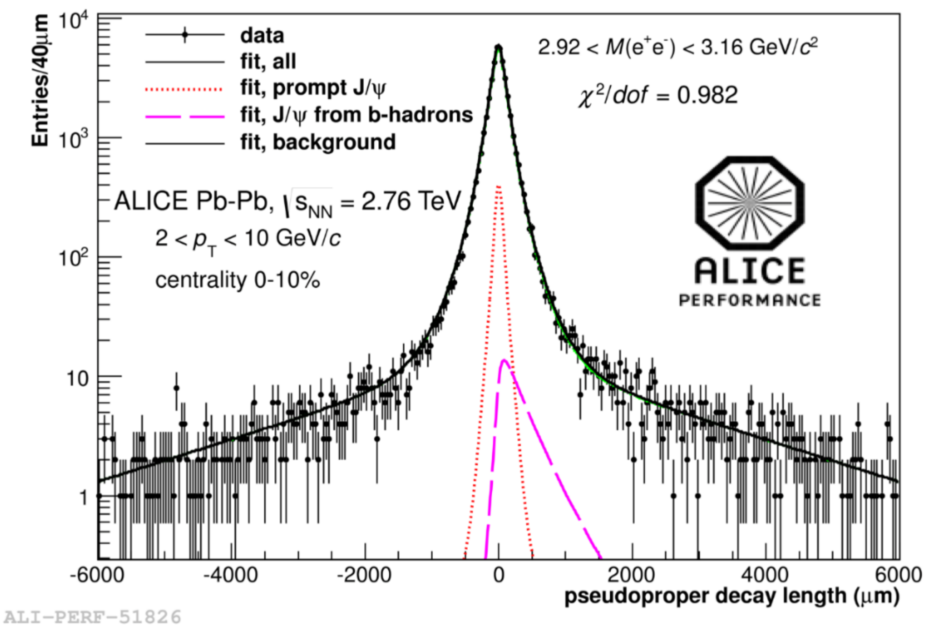


Charmonium yields extracted fitting the opposite sign dimuon invariant mass spectrum

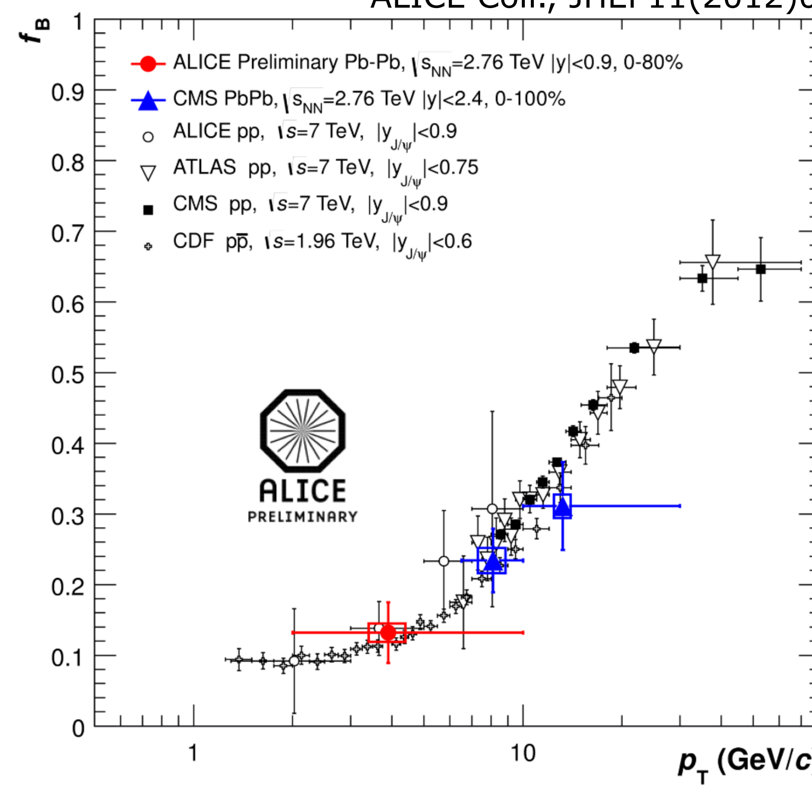
Signal: extended Crystal Ball function
Background: background evaluated through fitting or via mixed-event technique

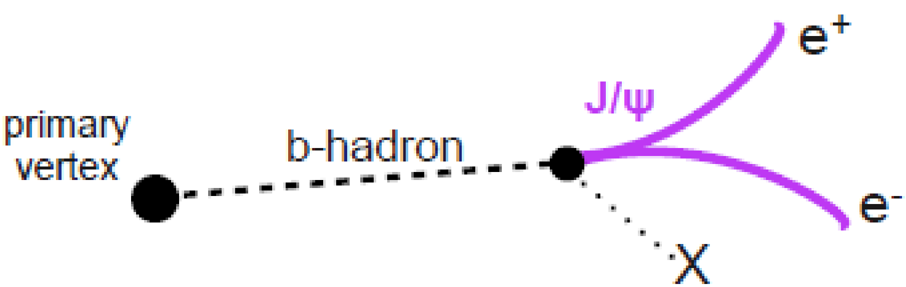
PROMPT AND NON-PROMPT J/ψ

- Separation via secondary vertex identification exploiting the ALICE ITS capabilities



ALICE Coll., JHEP11(2012)065



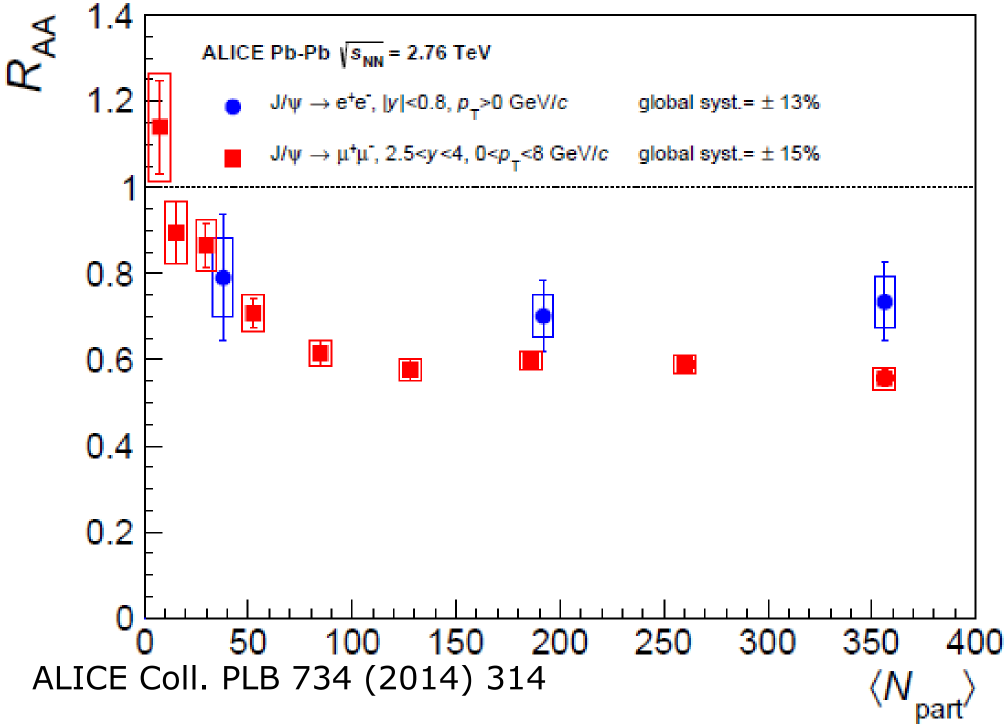


Fraction of b-hadron decays obtained down to $p_{T,J/\psi}$= 2GeV/c

…but for the moment ALICE R_{AA} results are for inclusive J/ψ

J/ψ R_{AA} VS CENTRALITY

- Centrality dependence of the J/ψ inclusive R_{AA} studied in both central and forward rapidities



ALICE Coll. PLB 734 (2014) 314

ALICE results:

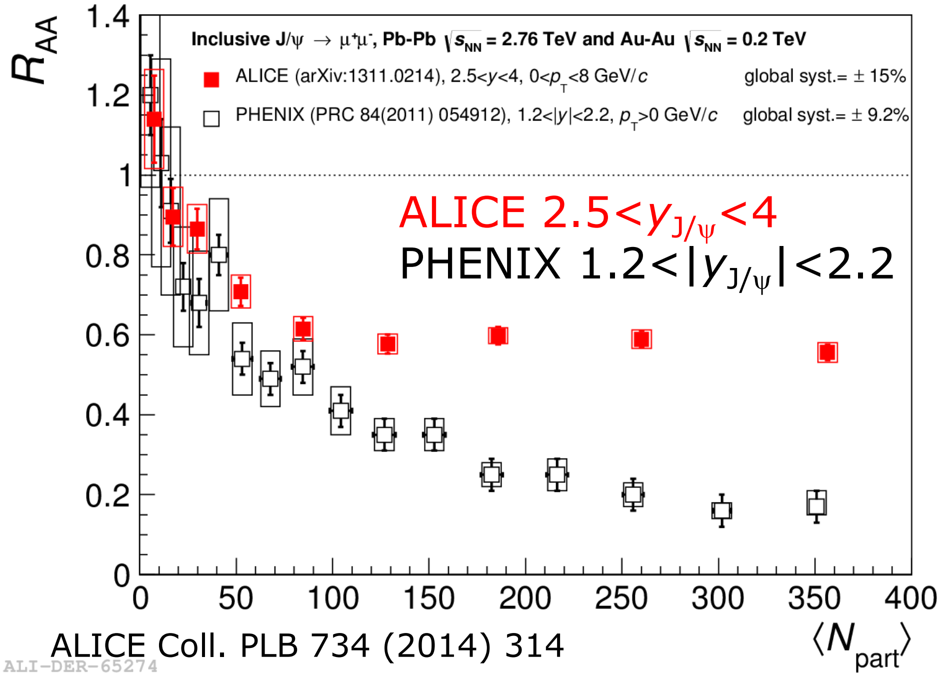
- Clear J/ψ suppression with almost no centrality dependence for N_{part}>100
- Less J/ψ suppression at mid-*y* wrt forward *y* for central events

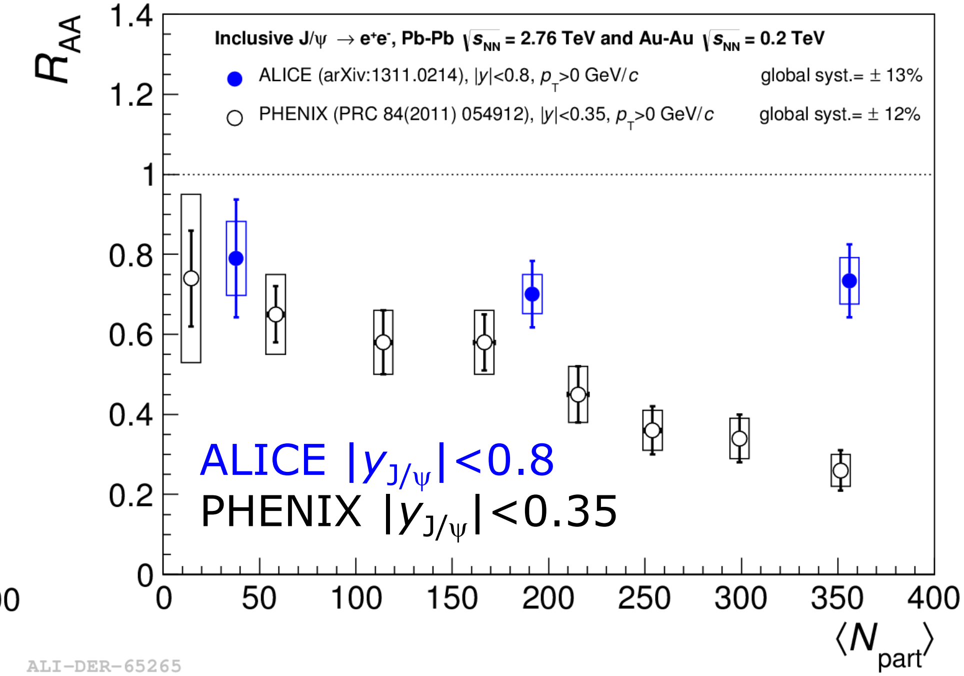
- Small effect of non-prompt contribution on the inclusive R_{AA}

Forward y:
no B suppression → $R_{AA}^{prompt} \sim 0.94 R_{AA}^{incl}$
full B suppression → $R_{AA}^{prompt} \sim 1.07 R_{AA}^{incl}$

Mid-y:
no B suppression → $R_{AA}^{prompt} \sim 0.93 R_{AA}^{incl}$
full B suppression → $R_{AA}^{prompt} \sim 1.17 R_{AA}^{incl}$

J/ψ R_{AA} vs centrality: comparison with PHENIX

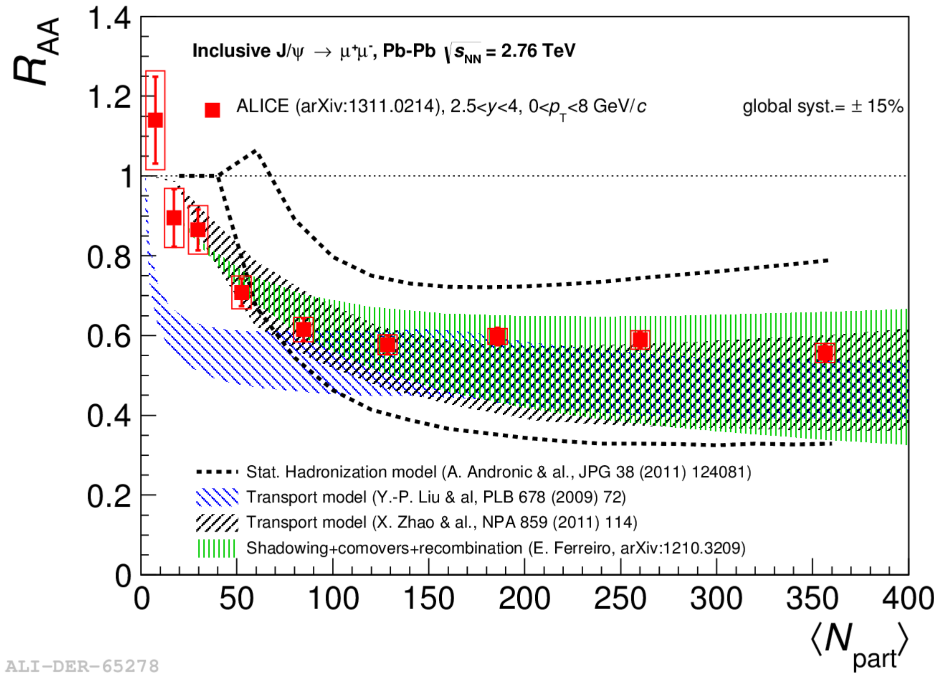


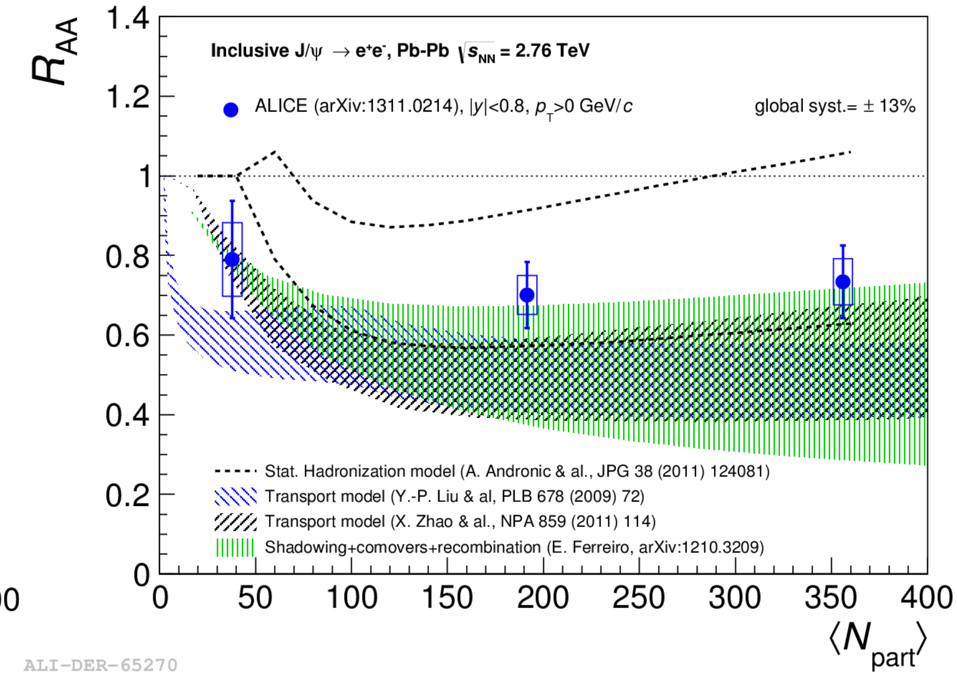


Comparison with PHENIX:
ALICE results show weaker centrality dependence and smaller suppression for central events

➡ Behaviour expected in a (re)combination scenario

J/ψ R_{AA} vs centrality: theory comparison



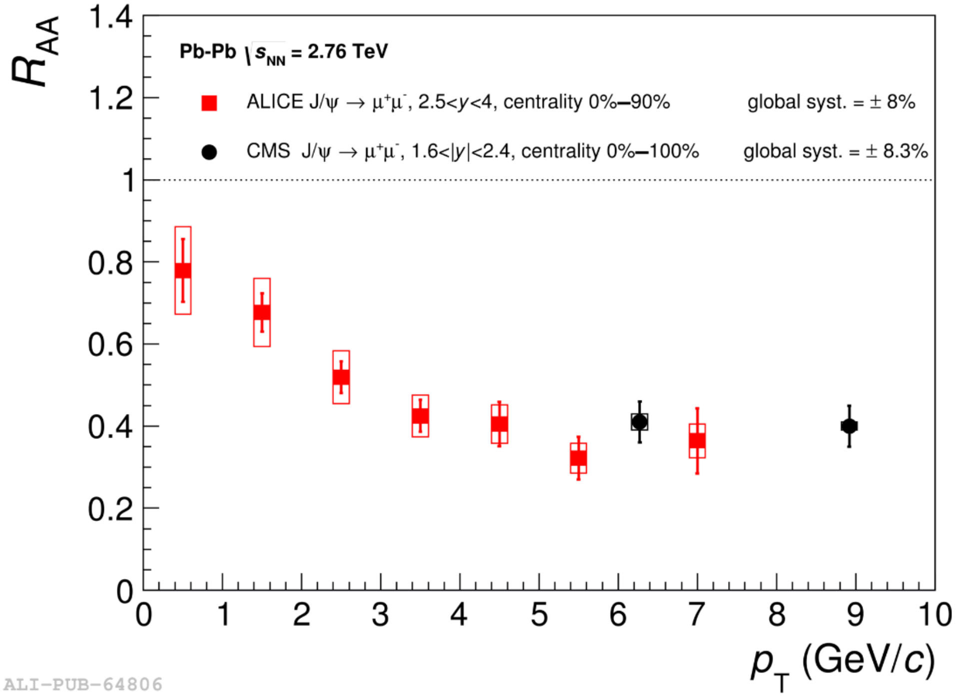


Comparison to theory calculations:

- Models including a large fraction (> 50% in central collisions) of J/ψ produced from (re)combination or models with all J/ψ produced at hadronization provide a reasonable description of ALICE results
- Still rather large theory uncertainties: models will benefit from a precise measurement of σ_{cc} and from cold nuclear matter evaluation

J/ψ R_{AA} VS TRANSVERSE MOMENTUM

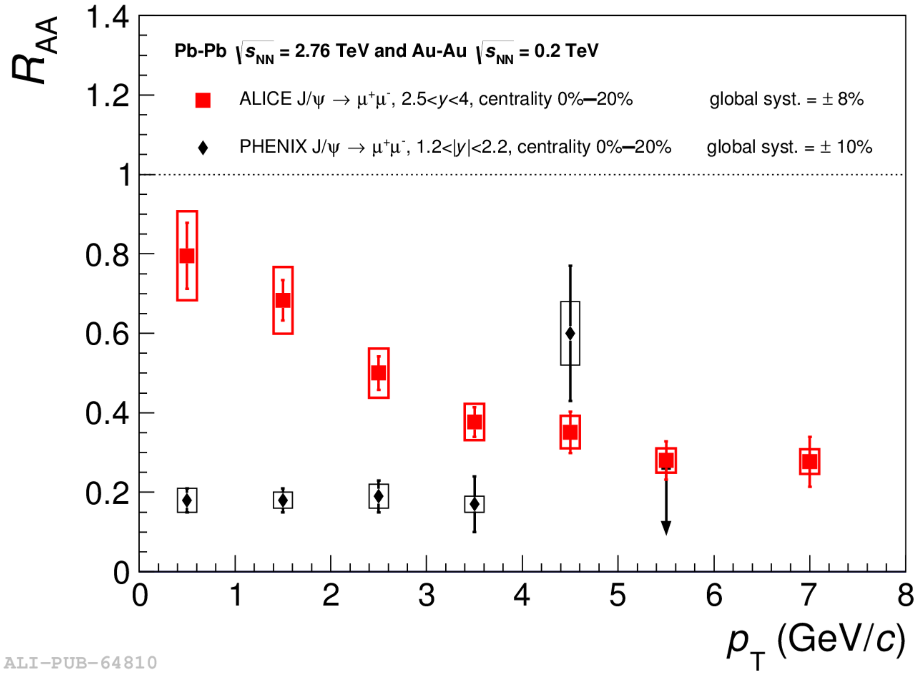
- J/ψ production via (re)combination should be more important at low transverse momentum → p_T region accessible by ALICE

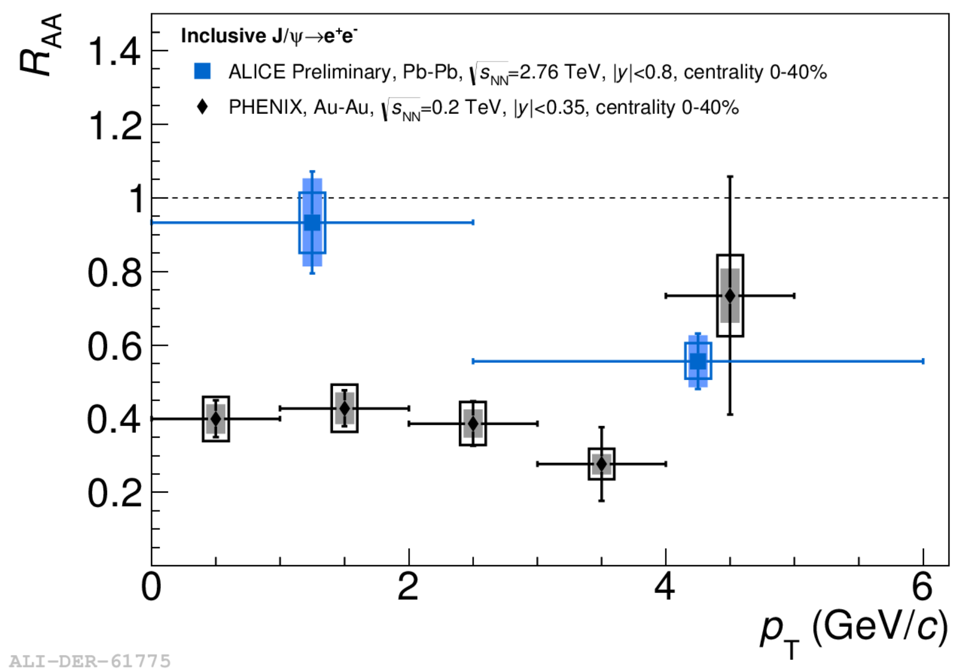


- Different suppression for low and high p_T J/ψ
  → smaller R_{AA} for high p_T J/ψ in both rapidity ranges
- High p_T J/ψ in agreement with CMS results (but different *y* range, CMS 1.6<|y|<2.4)

J/ψ R_{AA} VS TRANSVERSE MOMENTUM

- J/ψ production via (re)combination should be more important at low transverse momentum
- p_T region accessible by ALICE

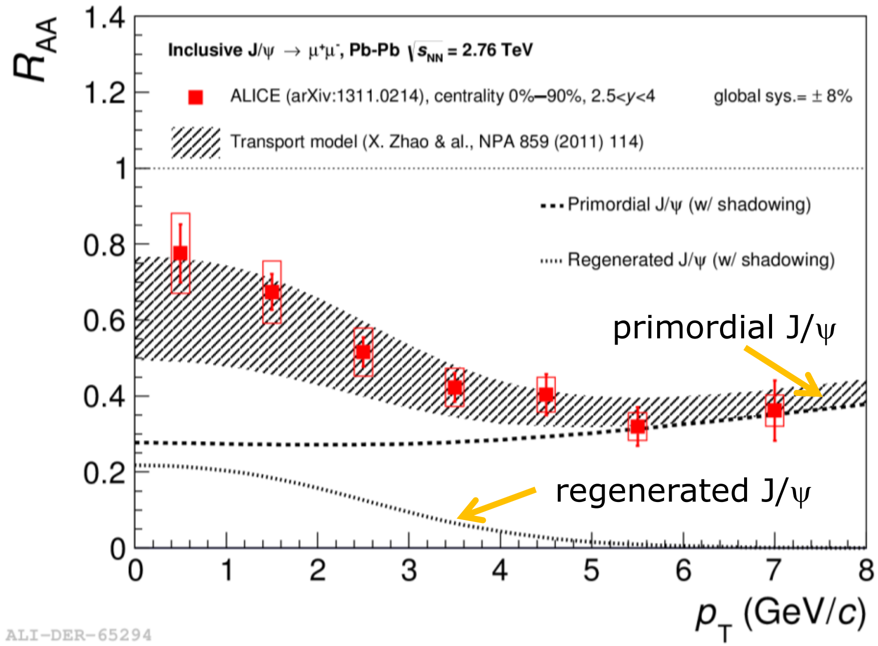


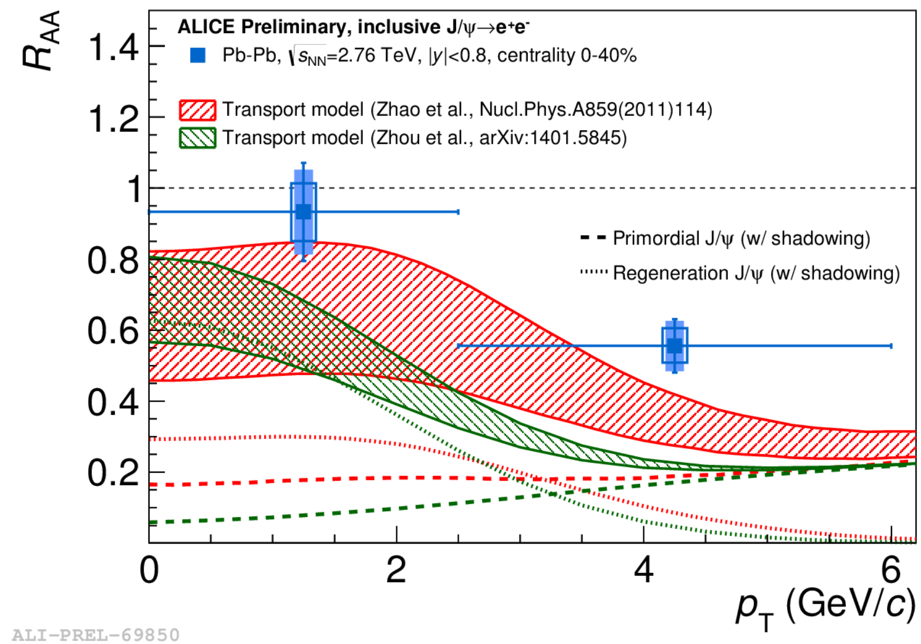


- Different suppression for low and high p_T J/ψ
  → smaller R_{AA} for high p_T J/ψ in both rapidity ranges
- Striking difference between the PHENIX and ALICE patterns, in particular at low p_T and central collisions (where PHENIX suppression is 4 times larger)

J/ψ R_{AA} VS TRANSVERSE MOMENTUM

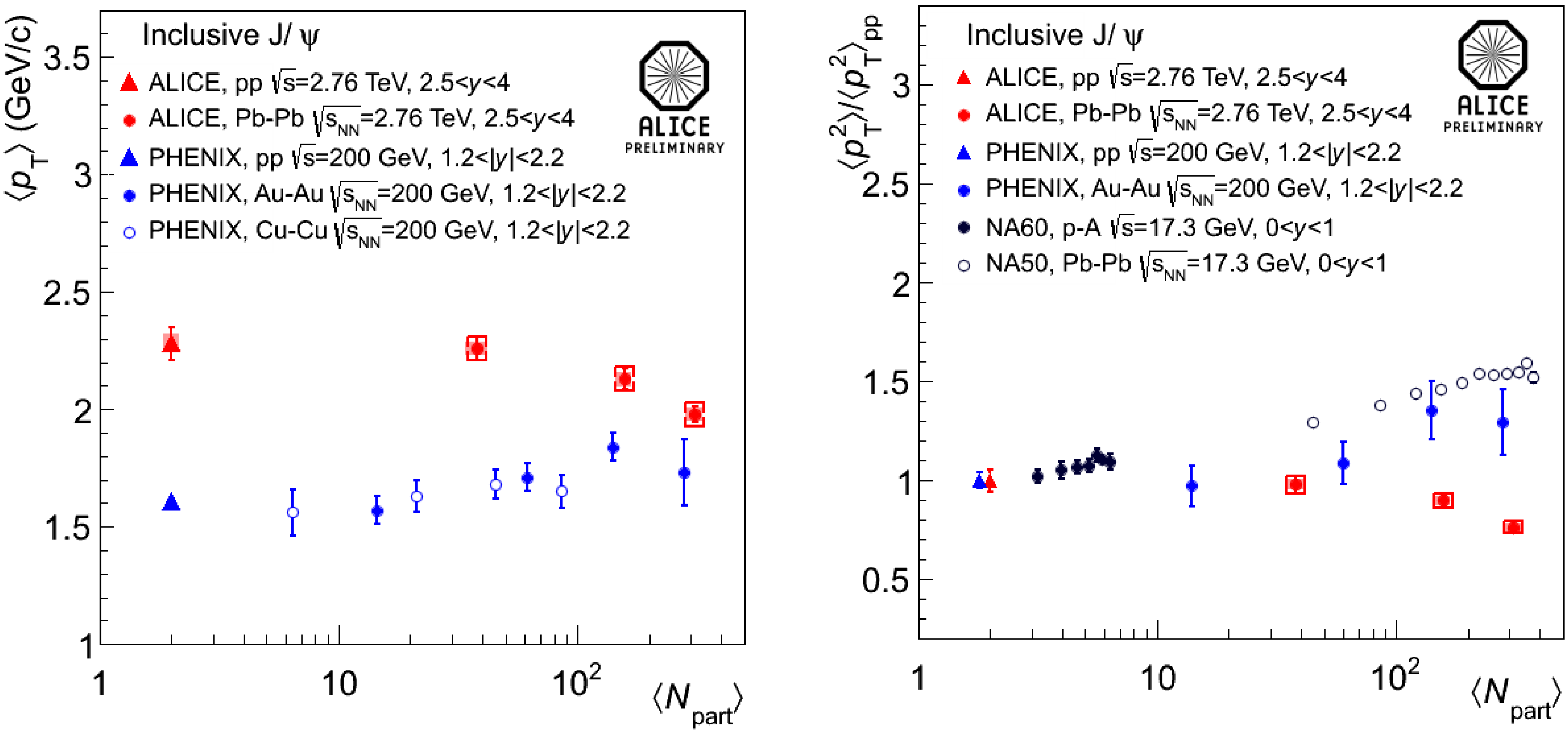
- J/ψ production via (re)combination should be more important at low transverse momentum ➡ p_T region accessible by ALICE





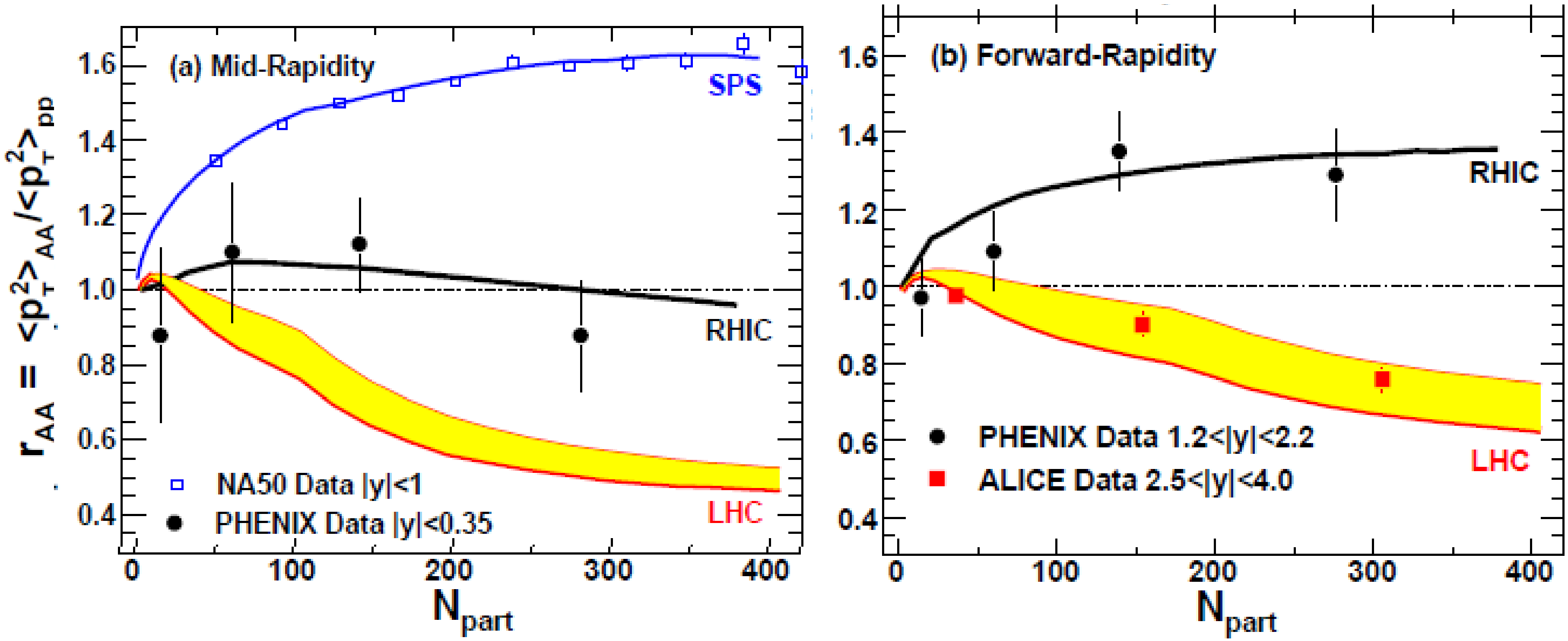
- Models with a large regeneration component (at low p_T) are in fair agreement with the data
- Multi-differential studies show that the difference low vs high p_T suppression is even more important for central collisions

J/ψ $\langle P_T \rangle$ AND $\langle P_T^2 \rangle$



- The J/ψ $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ 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 measured at lower energies, where an increase of the $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ with centrality was observed

J/ψ $\langle P_T \rangle$ AND $\langle P_T^2 \rangle$



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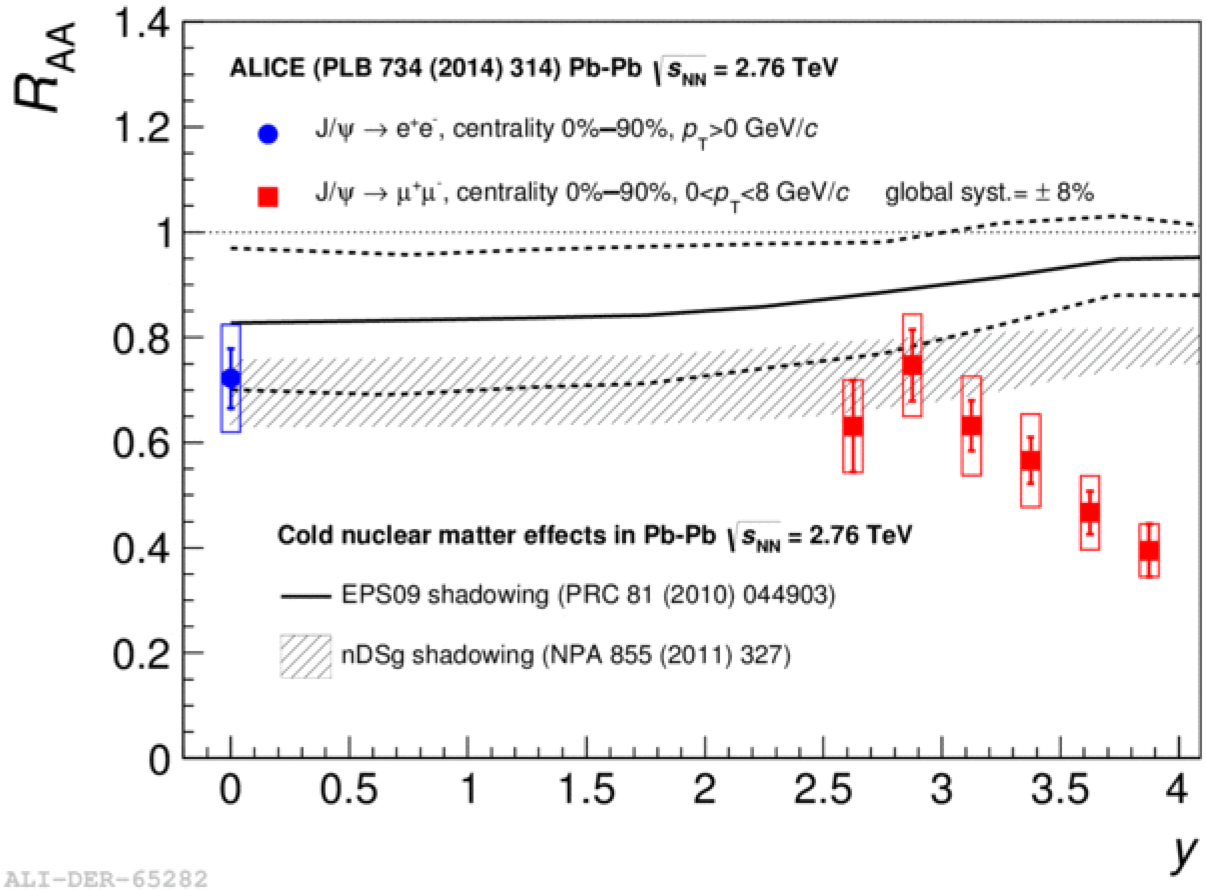
- The trend is different wrt the one measured at lower energies, where an increase of the $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ with centrality was observed
- Patterns described in transport models including J/ψ suppression and regeneration

Tang et al. arXiv:1409.5559

J/ψ R_{AA} VS RAPIDITY



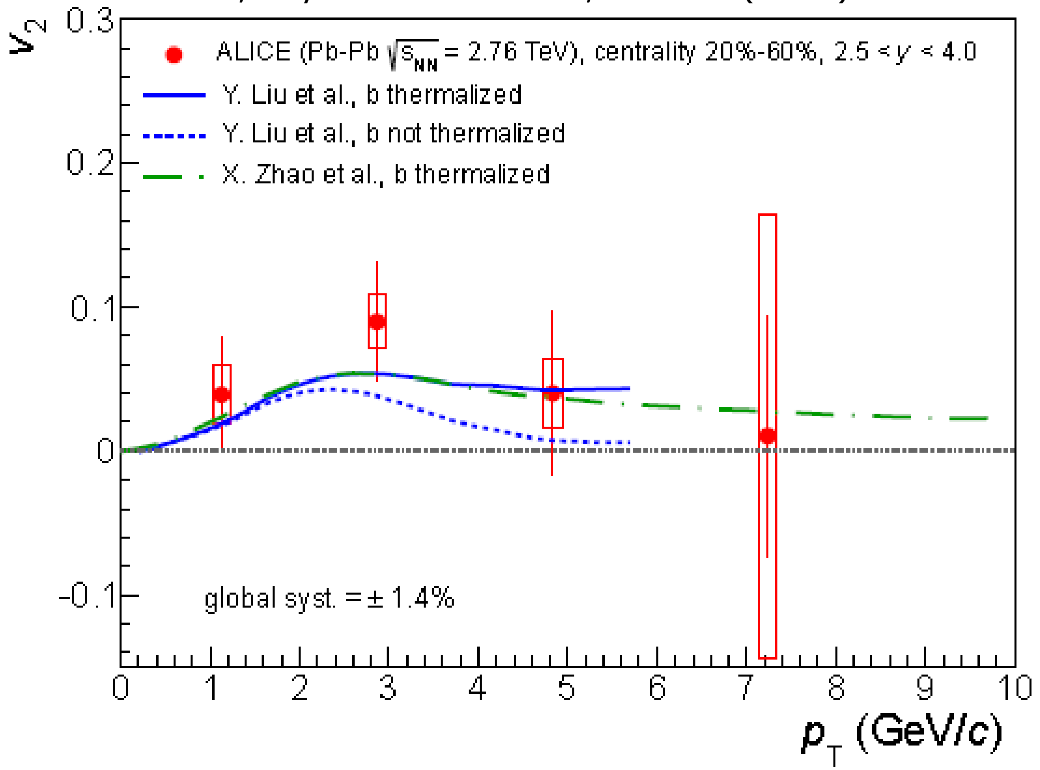
- Up to 40% more suppression at forward-*y*

- Shadowing calculations are rather flat vs rapidity → consistent with R_{AA} only within $|y|<3$

J/ψ FLOW

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

ALICE, Phys. Rev. Lett. 111, 162301 (2013)



- Hint for J/ψ flow at forward *y* and semi-central collisions (contrary to v_2~0 observed at RHIC!)

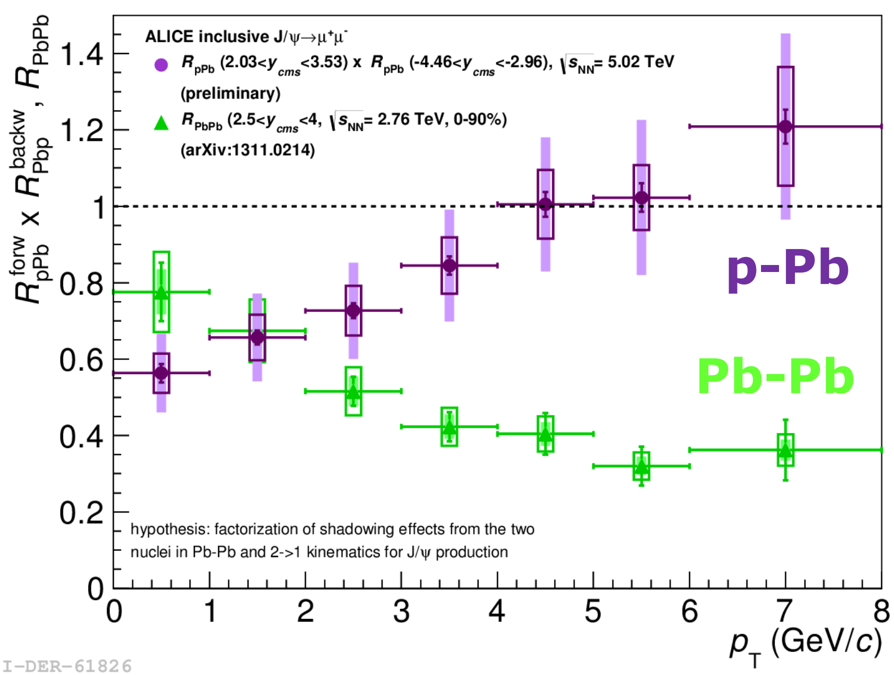
- Significance up to 3σ for chosen kinematic/centrality selections
- Qualitative agreement with transport models including regeneration (same as R_{AA})

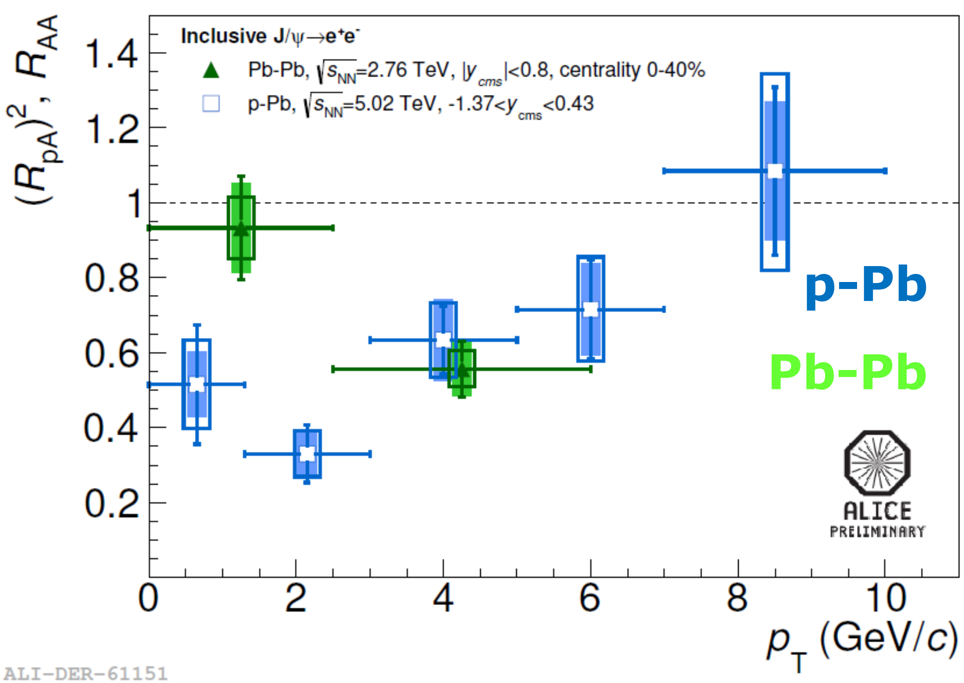
ROLE OF CNM EFFECTS

CNM effects evaluated from pA data

Hypothesis:

- 2→1 kinematics for J/ψ production
- CNM effects factorize in p-A and are dominated by shadowing
- CNM evaluated as R_{pA} x R_{Ap} (similar x coverage as Pb-Pb)





Sizeable p_T dependent suppression still visible
→ CNM effects not enough to explain AA data at high p_T

ROLE OF CNM EFFECTS

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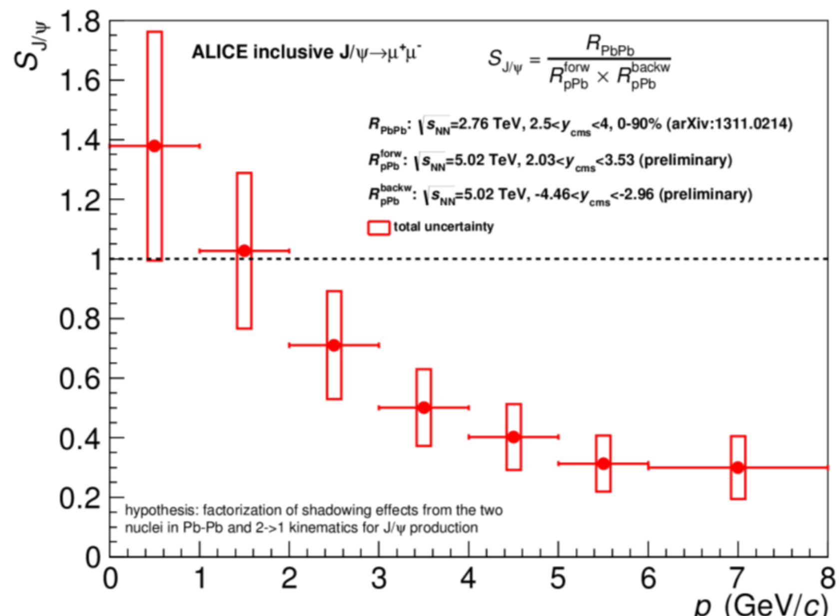
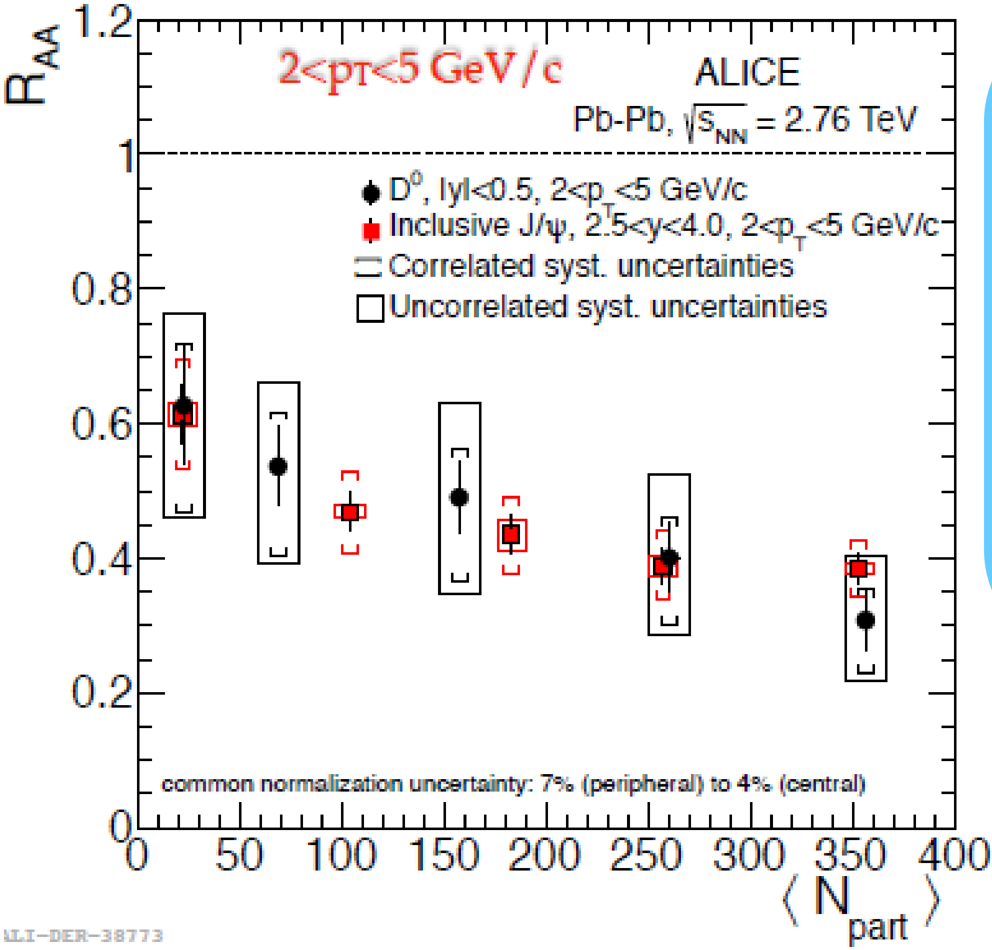


- Sizeable p_T dependent suppression still visible → CNM effects not enough to explain AA data at high p_T
- From enhancement to suppression increasing p_T → hint for recombination?

COMPARISON D VS J/ψ

- Open charm should be a very good reference to study J/ψ suppression (a' la Satz)



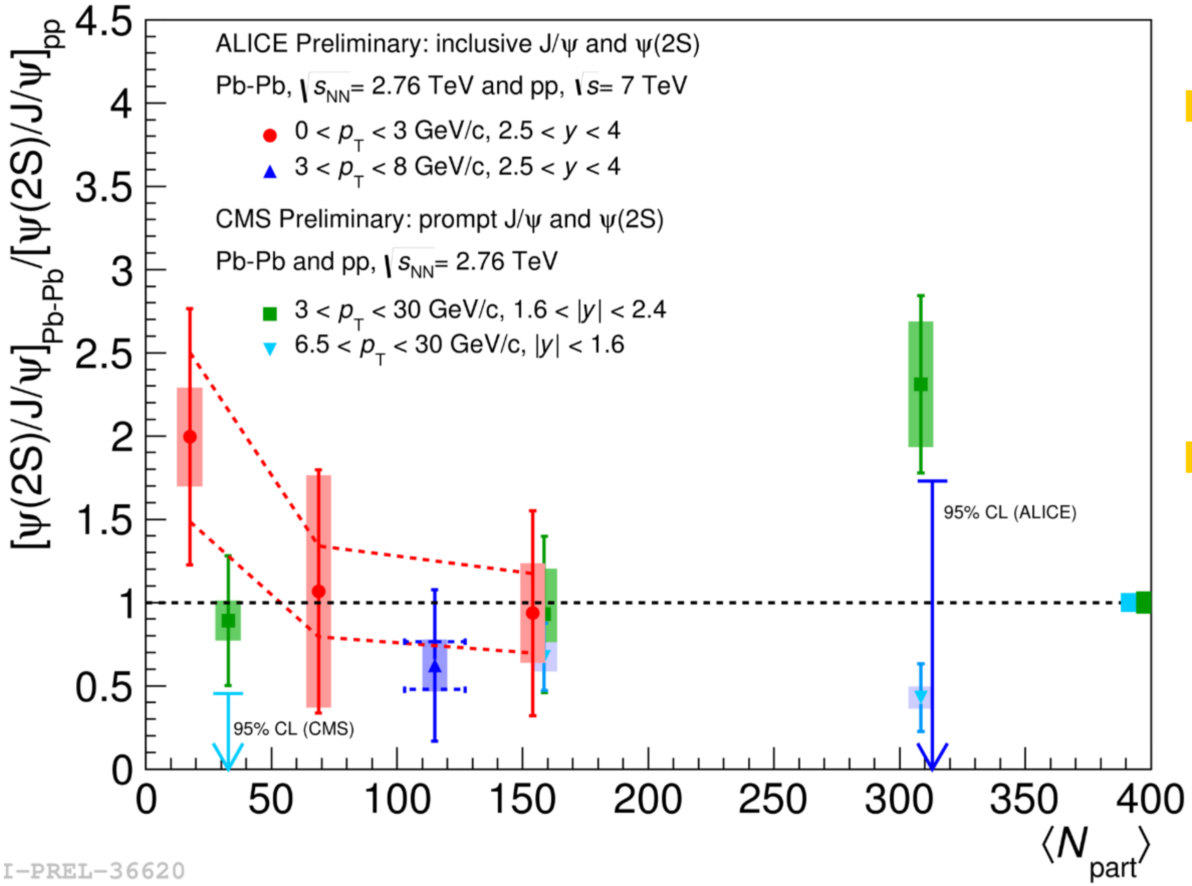
- Interesting comparison between ALICE and CMS J/ψ compared to D

Caveat:
complicate to compare J/ψ and D R_{AA} at LHC because of restricted kinematic regions. Low p_T D not accessible for the moment

$\psi(2S)$ in Pb-Pb collisions

ψ(2S)/J/ψ VS CENTRALITY

- The ψ(2S) yield is compared to the J/ψ one in Pb-Pb and in pp



I-PREL-36620

CMS-HIN-12-007

- Reference: pp@√s=7TeV (small √s- and y-dependence from $[\psi(2S)/J/\psi]_{pp}$ results by CDF, LHCb and CMS taken into account in the syst. uncertainty)
- Main systematic uncertainties (some sources cancel out in the double ratio) are the signal extraction and the choice of the MC inputs for acc. calculation

- Improved agreement between ALICE and CMS data (new pp CMS reference)
- Large statistics and systematic uncertainties prevent a firm conclusion on the ψ(2S) trend vs centrality

Υ in Pb-Pb collisions

Υ(1S) production in Pb-Pb collisions

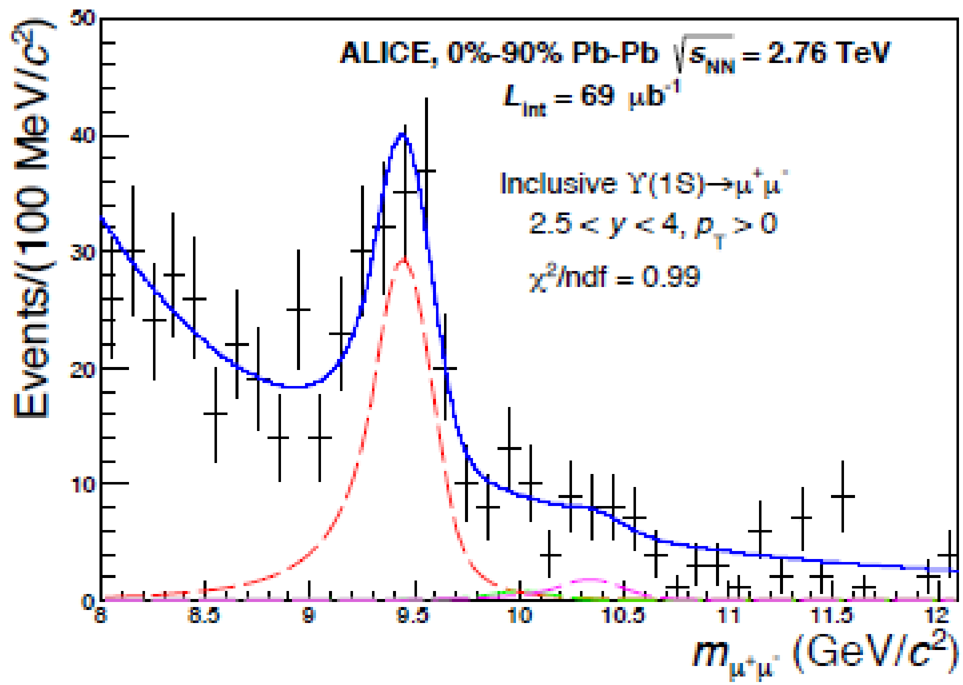
➡ LHC is the machine for studying bottomonium in AA collisions

arXiv:1405.4493

Main features of bottomonium production wrt charmonia:

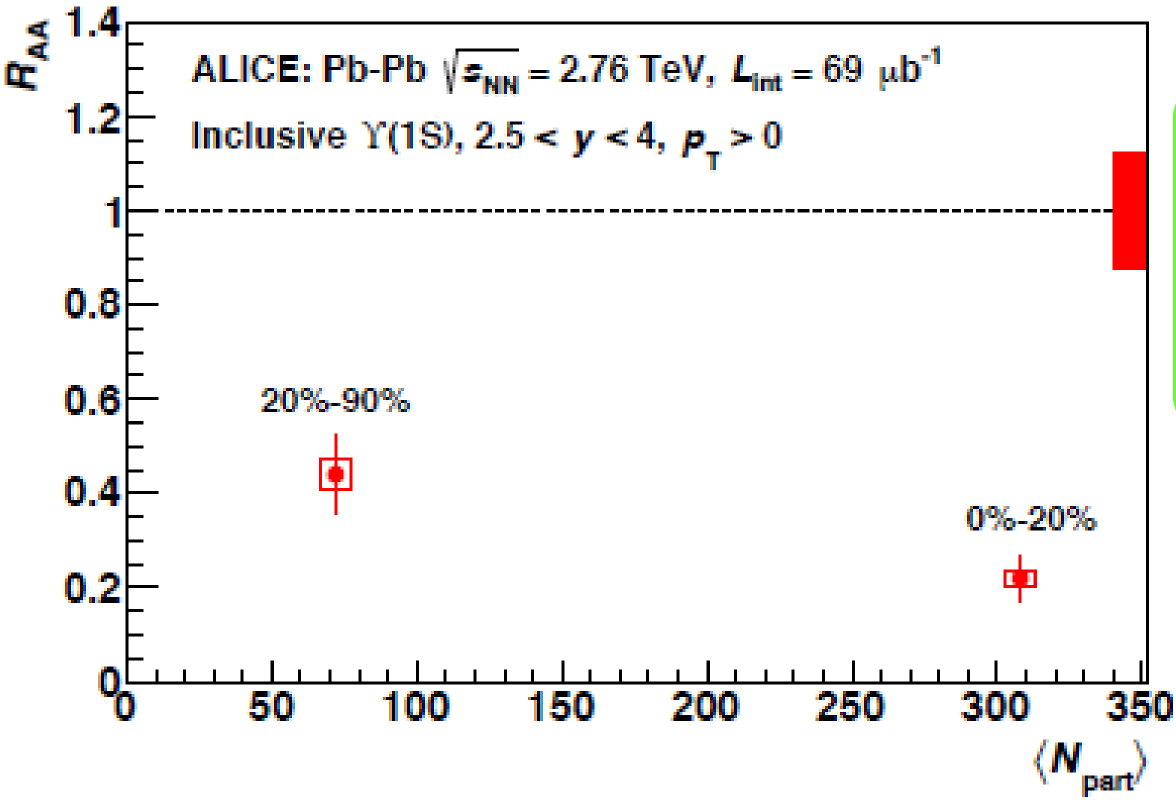
- no B hadron feed-down
- gluon shadowing effect are smaller
- (re)combination expected to be smaller
- theoretical predictions more robust due to the higher mass of b quark

with a drawback…smaller production cross-section



➡ ALICE measures inclusive Υ(1S) in Pb-Pb

ϒ(1S) production in Pb-Pb collisions



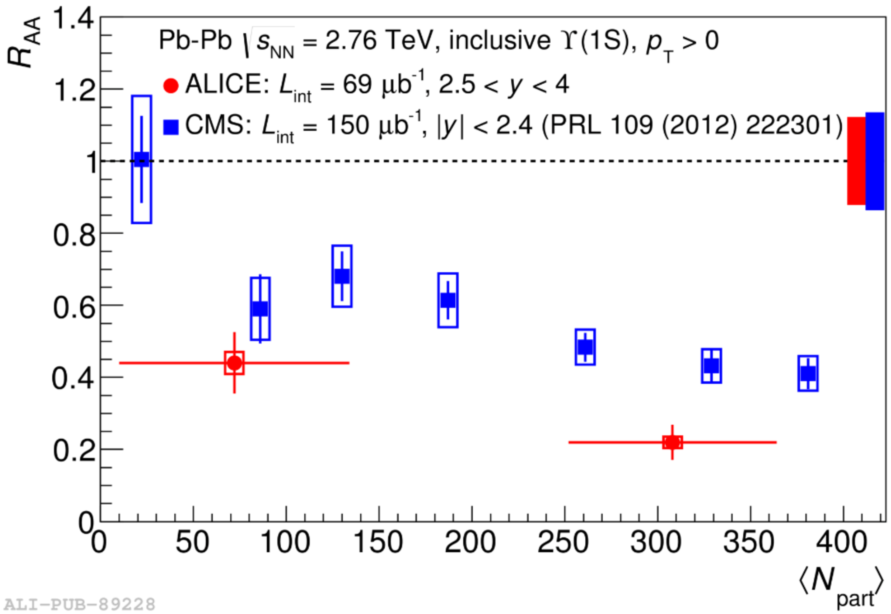
- Strong inclusive ϒ(1S) suppression:

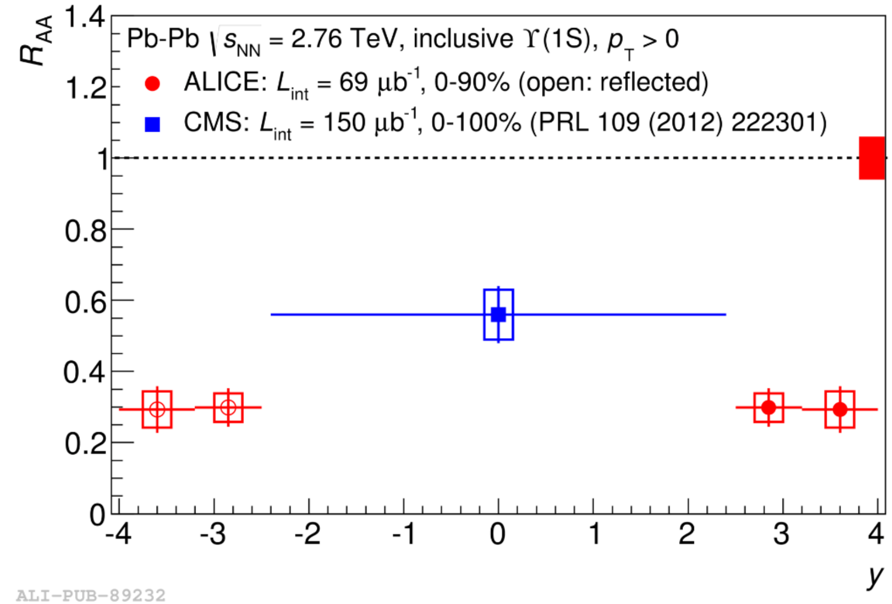
R_{AA} = 0.304±0.047(stat)±0.042(syst) (integrated over centrality)

- Suppression increases towards most central collisions and it is compatible with the in-medium dissociation of higher mass bottomonia
  - Estimate of CNM effects and precise measurement of feed-down from higher mass bottomonia needed

COMPARISON WITH CMS RESULTS

- Comparison with CMS mid-rapidity results (PRL 109 (2012) 222301)

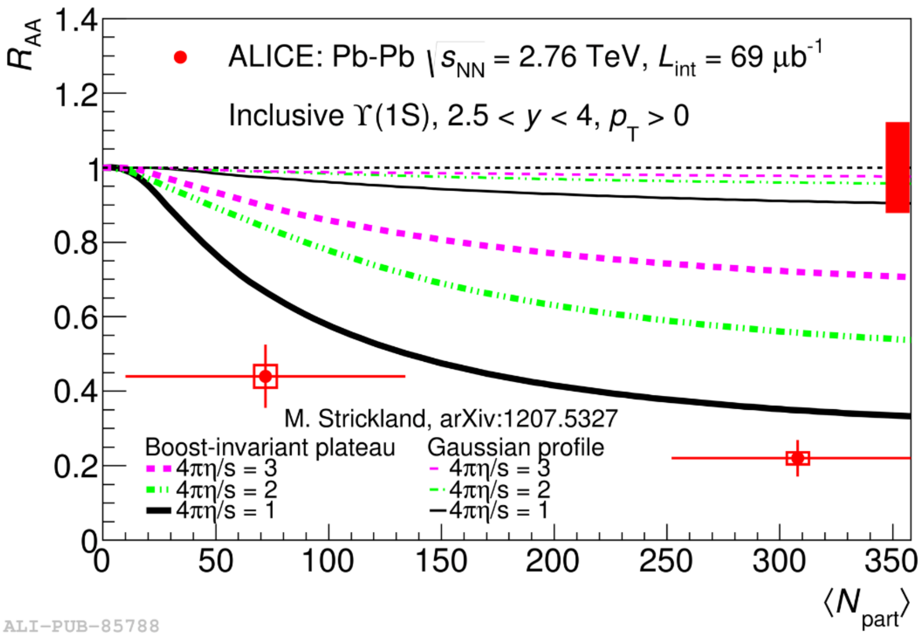


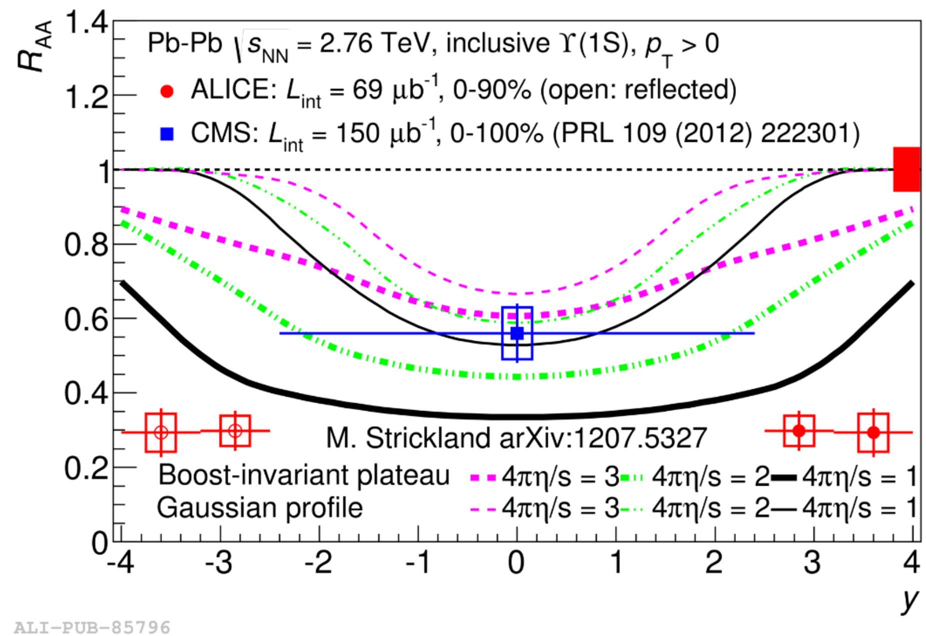


- In most central collisions suppression seems stronger at forward rapidities

- Stronger suppression at forward rapidity than at mid-rapidity

COMPARISON WITH THEORY



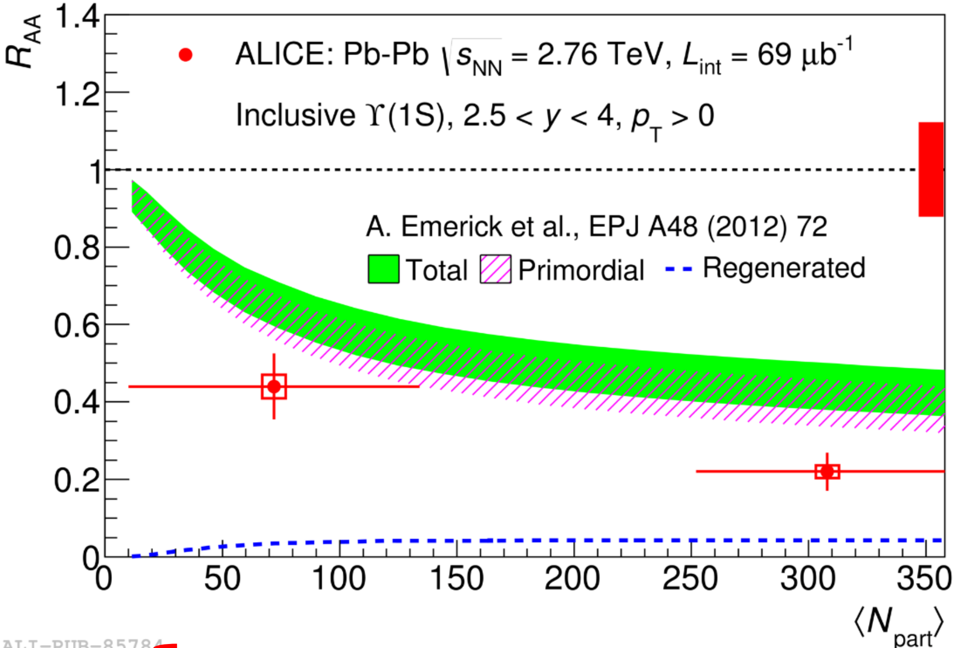


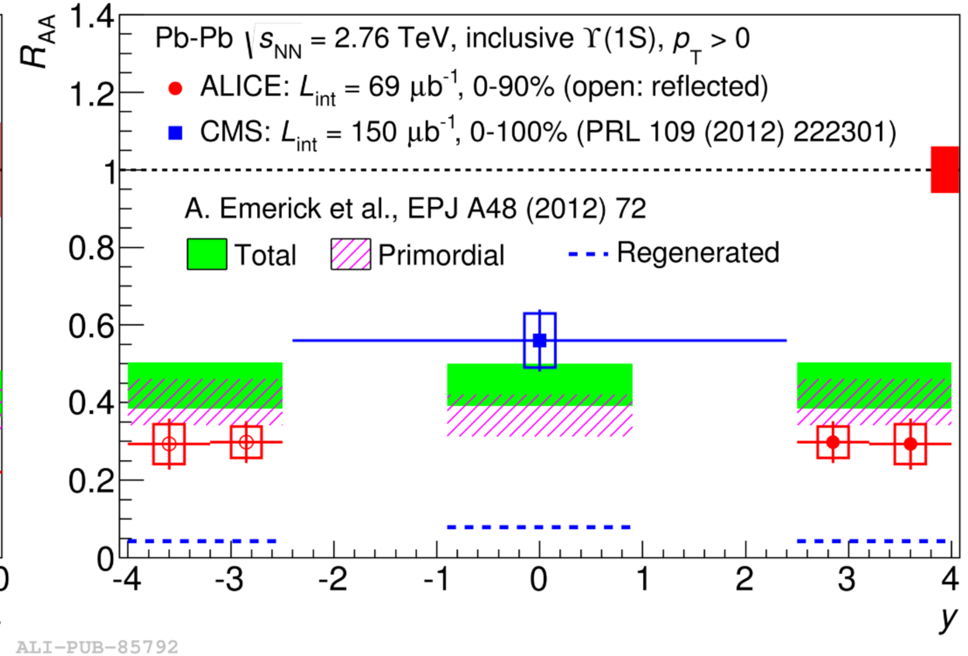
MODEL

- Evolving QGP described via a dynamical model including suppression of bottomonium states, but not CNM nor recombination
- Two different initial temperature rapidity profiles: boost invariant or Gaussian (three tested shear viscosity)

➡ In all cases, the model underestimates the measured ϒ(1S) suppression at forward-*y*

COMPARISON WITH THEORY





MODEL

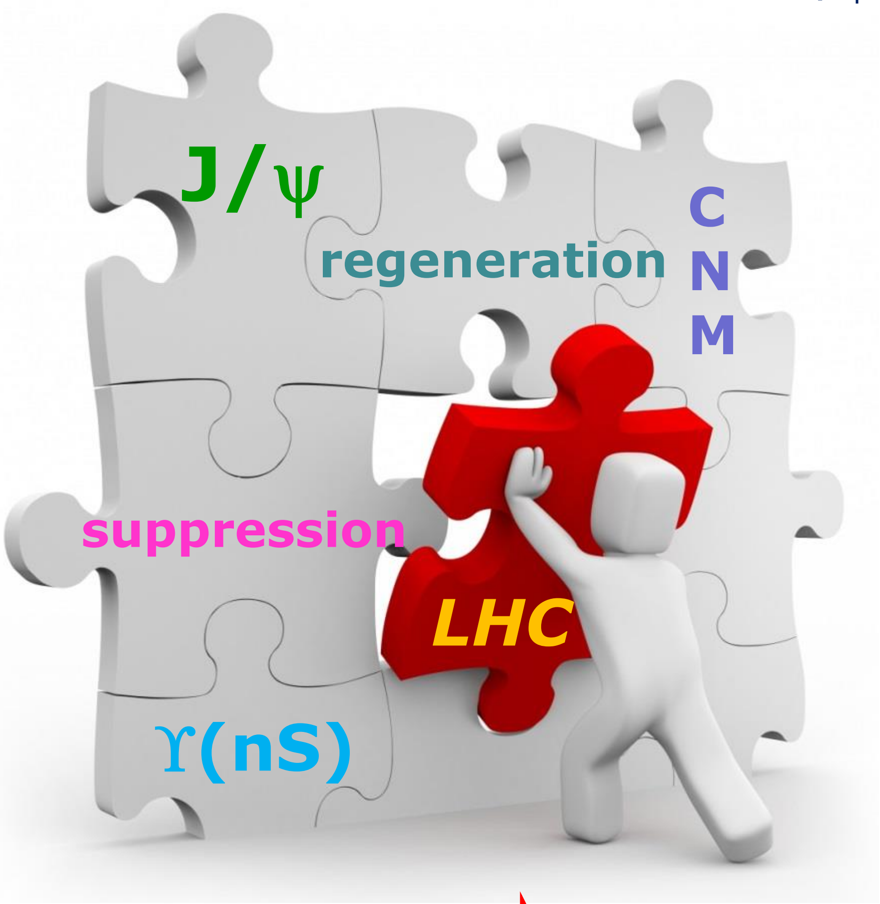
- Transport model accounting for both regeneration and suppression
- CNM effects included via an effective absorption cross section (0-2 mb)

➡ The measured R_{AA} vs centrality is slightly overestimated by the model (even if the decreasing trend is reproduced)
Constant R_{AA} behavior vs *y* is not supported by the data

CONCLUSIONS

- First round of quarkonium experimental observations at LHC! Results now complementing the large wealth of data from SPS, RHIC!

- Very interesting observations, qualitative understanding of the main J/ψ and ϒ features:



- important role of charmonium (re)generation processes at low p_T
- strong charmonium suppression for central events at high p_T
- strong y-dependent ϒ(1S) suppression

…however the picture is complicate because of the interplay of many mechanisms!

- now move towards a quantitative understanding, addressing CNM influence, results description over 2 order of magnitude in √s, behaviour of all quarkonium states…

- Results from LHC Run2 eagerly awaited!

BACKUP SLIDES

ALICE PAST & FUTURE

Heavy-ion data from RUN1:

System	$\sqrt{s_{NN}}$ (TeV)	Year	Integrated luminosity
Pb-Pb	2.76	2010	~10 μb^{-1}
		2011	~100 μb^{-1}
p-Pb	5.02	2013	~30nb^{-1}

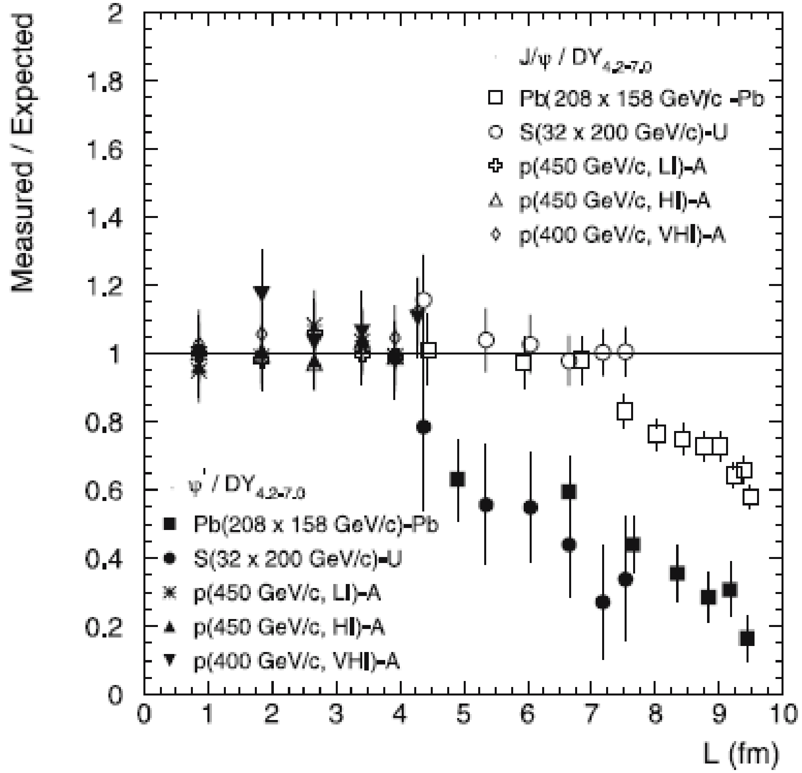
Future:

➡ RUN2 (2015-2017): complete the heavy-ion program:

- improved detectors, readout and trigger
- higher LHC energy ($\sqrt{s}$ = 13TeV for pp, 5.1TeV for PbPb)
- pp, p-Pb, Pb-Pb runs with much larger statistics!

➡ RUN3+4 (~2020): major detectors upgrade

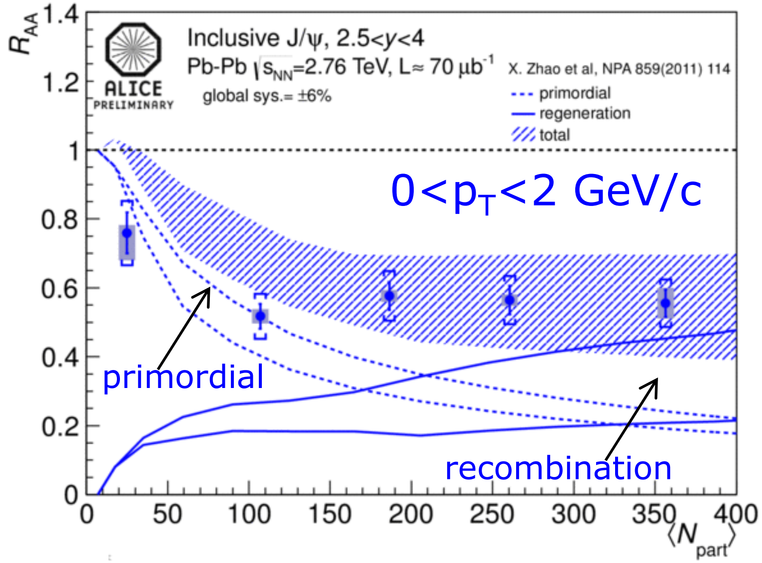
- operate ALICE at high rate (increased by a factor 100!), preserving unique tracking and PID
- improvements in vertexing capability and low p_T tracking (new ITS and TPC readout)
- focus on rare probes (heavy flavor,quarkonia,low-mass dileptons,jets…)

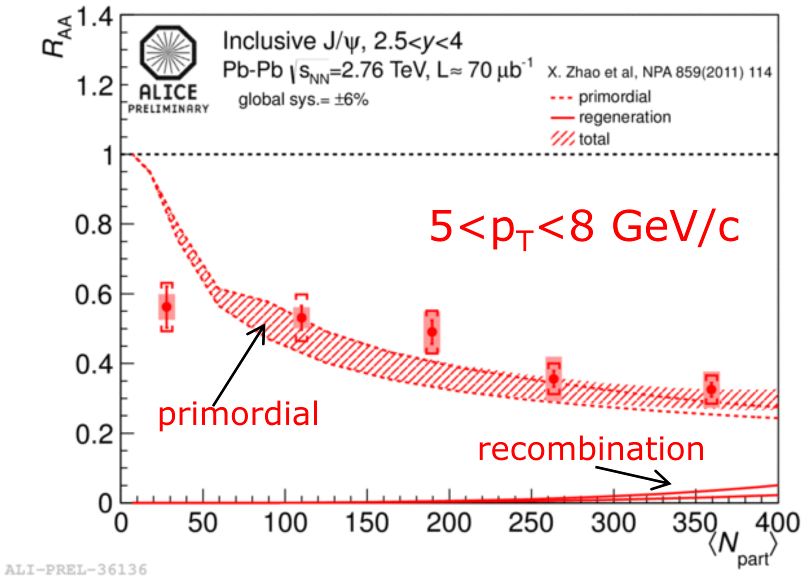


Measured / Expected
L (fm)
J/ψ / DY4.2-7.0
Pb(208 x 158 GeV/c -Pb
S(32 x 200 GeV/c)-U
p(450 GeV/c, LI)-A
p(450 GeV/c, HI)-A
p(400 GeV/c, VHI)-A
ψ' / DY4.2-7.0
Pb(208 x 158 GeV/c)-Pb
S(32 x 200 GeV/c)-U
p(450 GeV/c, LI)-A
p(450 GeV/c, HI)-A
p(400 GeV/c, VHI)-A

J/ψ R_{AA} vs. centrality in p_T bins

➡ J/ψ production via (re)combination should be important at low p_T

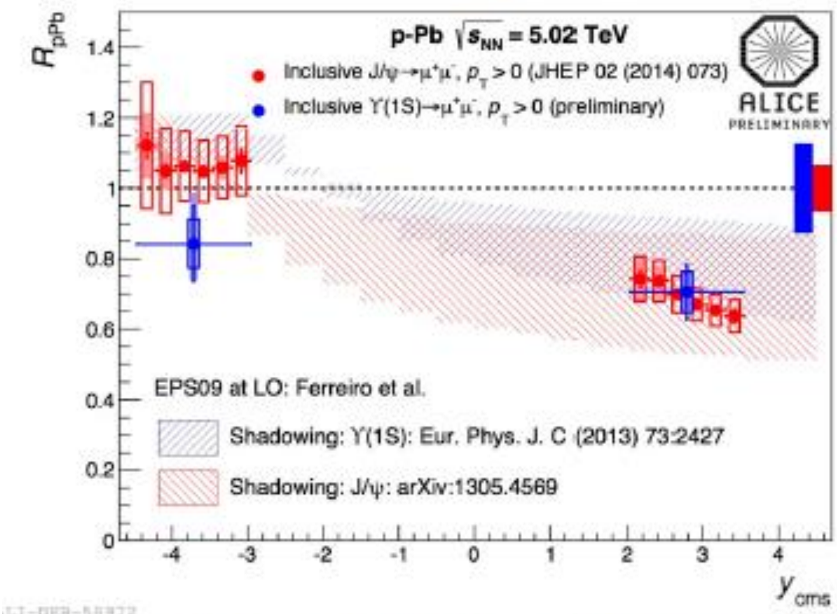


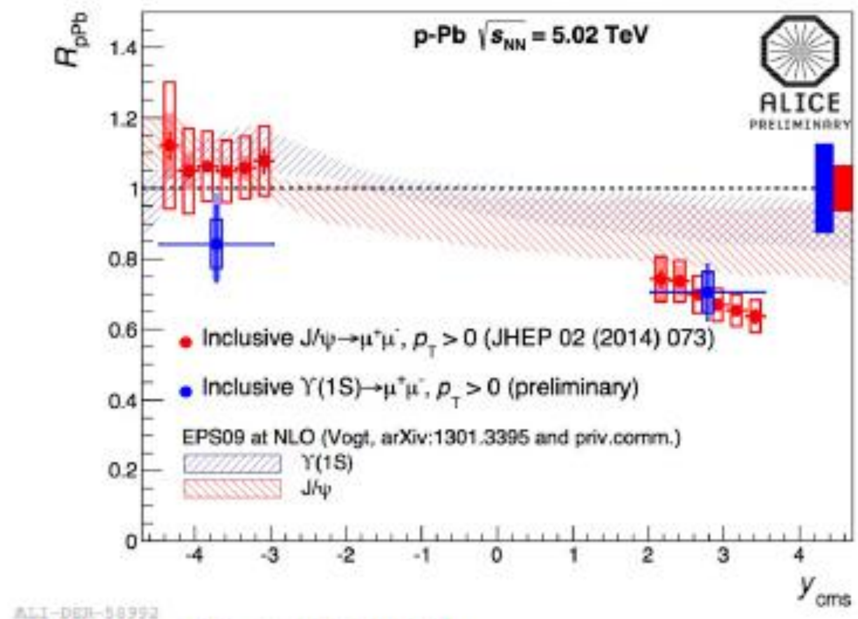


Comparison of the R_{AA} centrality dependence of low (0<p_T<2 GeV/c) and high (5<p_T<8 GeV/c) p_T J/ψ

- Different suppression for low and high p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ

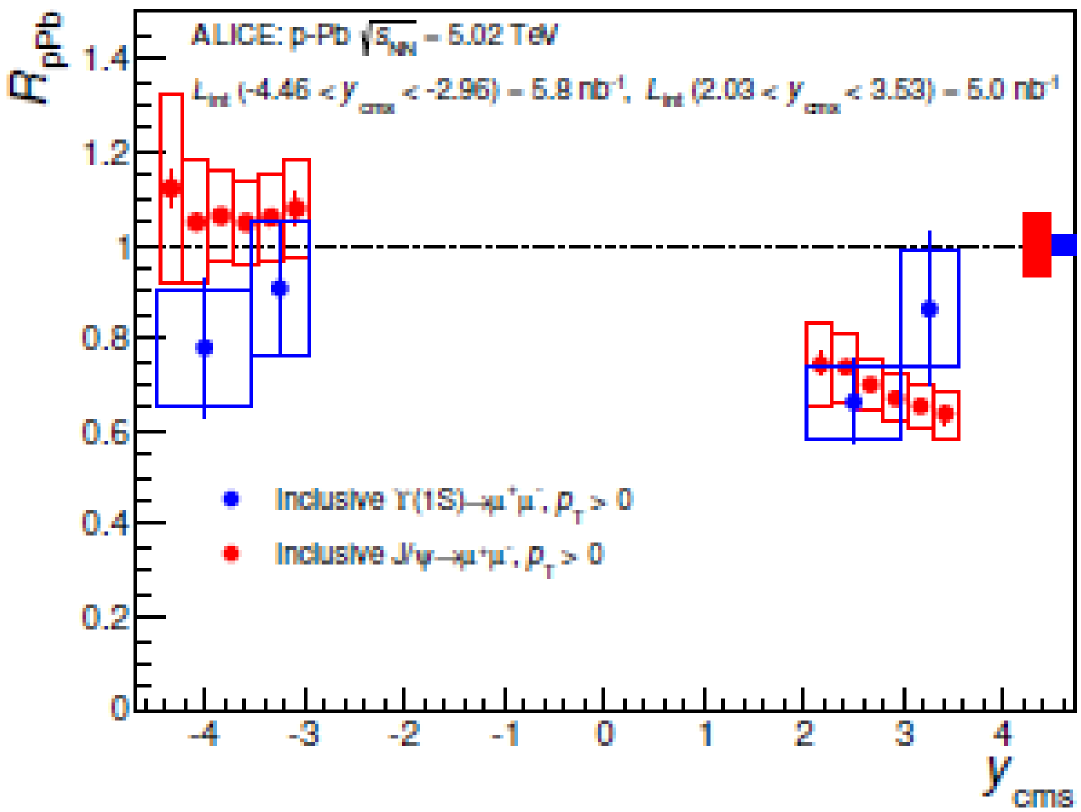
- In central collisions, these models (X. Zhao et al, Y.P. Liu et al, E. Ferreiro) predict ~50% of low p_T J/ψ to be produced via (re)combination, while at high p_T the contribution is negligible



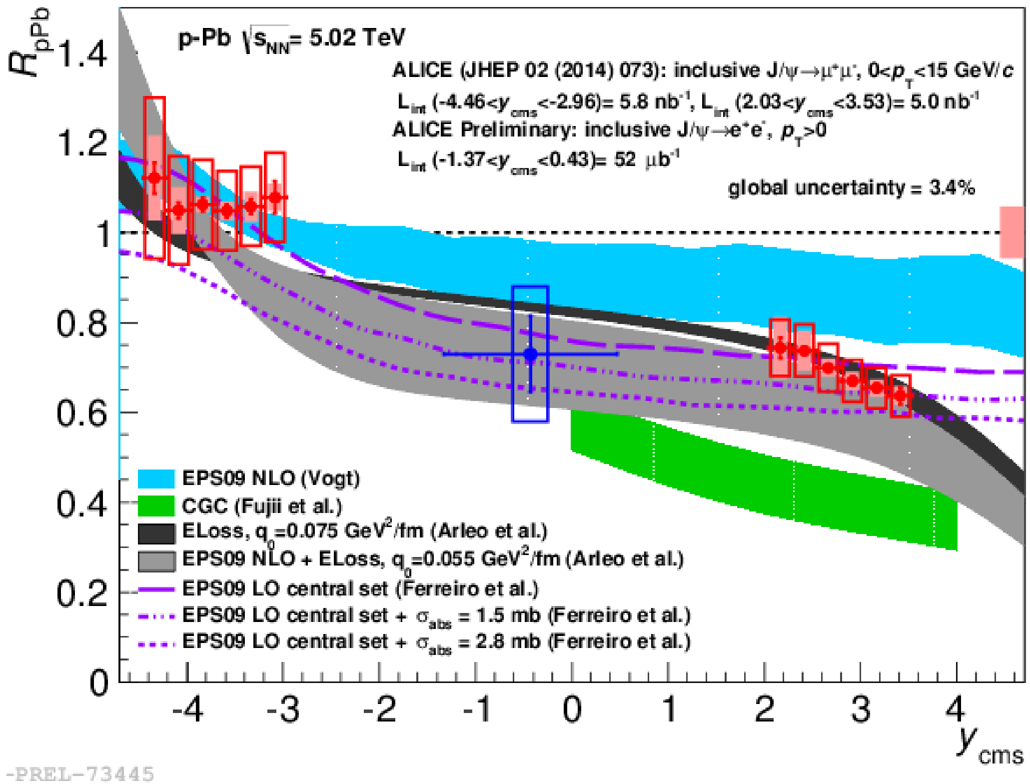


- Ferreiro et al. [EPJC 73 (2013) 2427]
  - Generic 2→2 production model at LO
  - EPS09 shadowing parameterization at LO
  - Fair agreement with measured R_{pPb}
    - Although slightly overestimates it in the antishadowing region

- Vogt [arXiv:1301.3395]
  - CEM production model at NLO
  - EPS09 shadowing parameterization at NLO
  - Fair agreement with measured R_{pPb} within uncertainties
    - Although slightly overestimates it

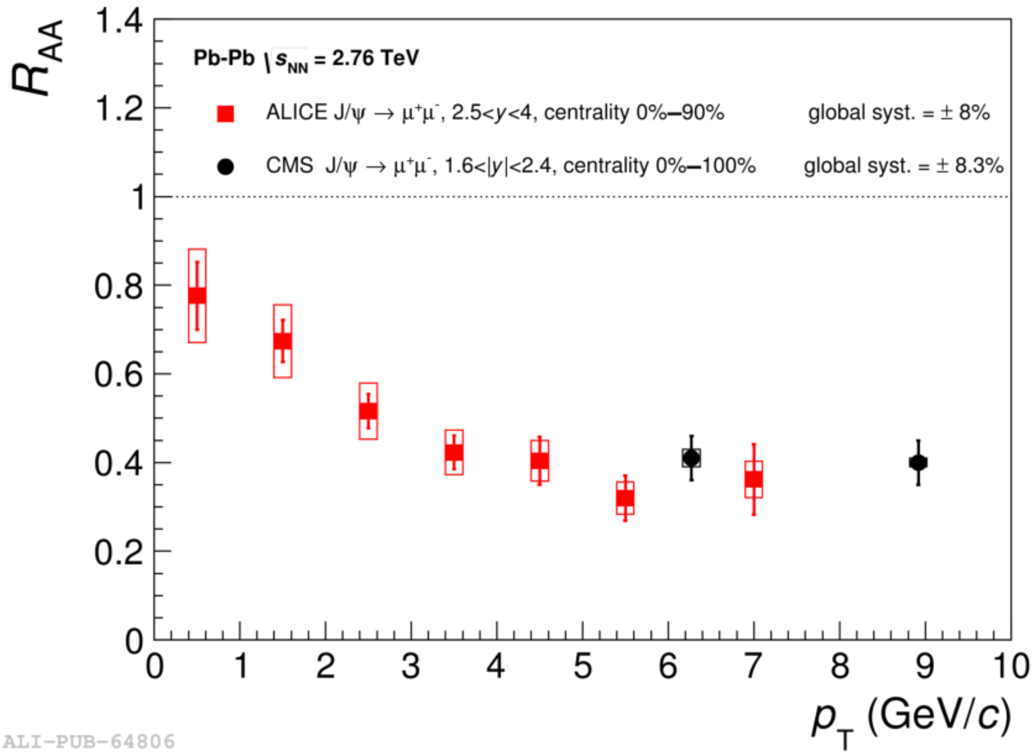


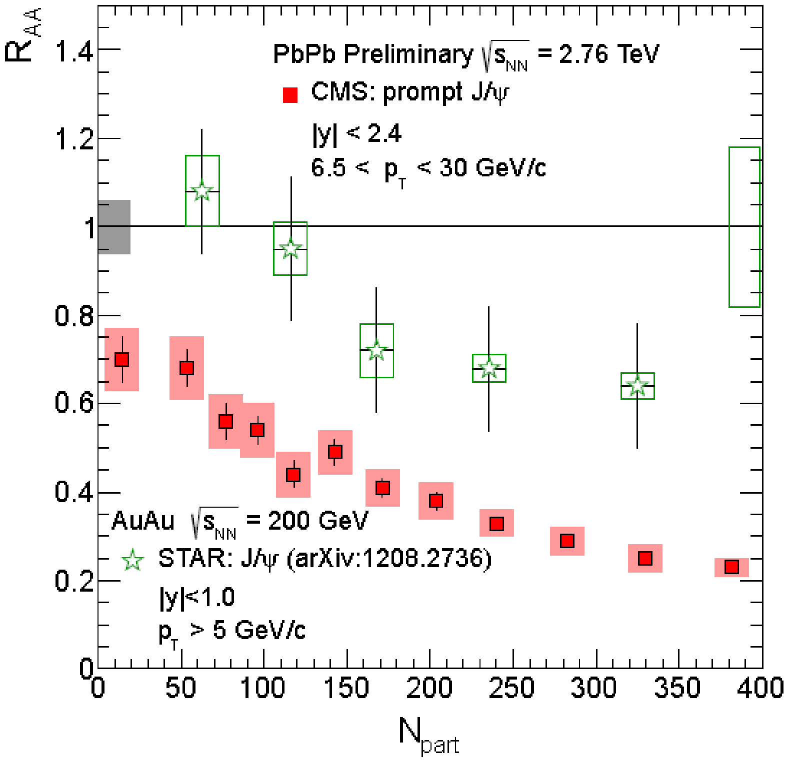
ALICE: p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
L_{int} ($-4.46 < y_{cms} < -2.96$) = 5.8 nb^{-1}, L_{int} ($2.03 < y_{cms} < 3.53$) = 5.0 nb^{-1}
Inclusive $\Upsilon(1S)\rightarrow\mu^+\mu^-$, $p_T > 0$
Inclusive $J/\psi\rightarrow\mu^+\mu^-$, $p_T > 0$
R_{pPb}
y_{cms}


p-Pb √sNN = 5.02 TeV
ALICE (JHEP 02 (2014) 073): inclusive J/ψ→μ+μ-, 0<pT<15 GeV/c
Lint (-4.46<ycms<-2.96)= 5.8 nb-1, Lint (2.03<ycms<3.53)= 5.0 nb-1
ALICE Preliminary: inclusive J/ψ→e+e-, pT>0
Lint (-1.37<ycms<0.43)= 52 μb-1
global uncertainty = 3.4%
EPS09 NLO (Vogt)
CGC (Fujii et al.)
ELoss, q0=0.075 GeV2/fm (Arleo et al.)
EPS09 NLO + ELoss, q0=0.055 GeV2/fm (Arleo et al.)
EPS09 LO central set (Ferreiro et al.)
EPS09 LO central set + σabs = 1.5 mb (Ferreiro et al.)
EPS09 LO central set + σabs = 2.8 mb (Ferreiro et al.)
RpPb
ycms
-PREL-73445

CMS: high p_T J/ψ

- The high p_T region can be investigated by CMS!



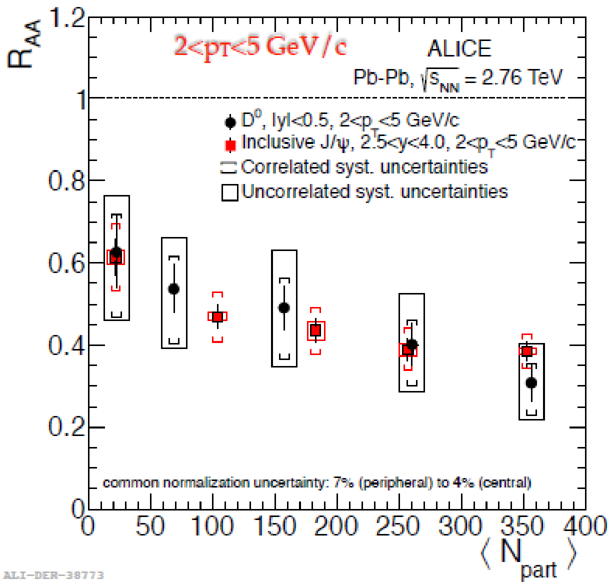


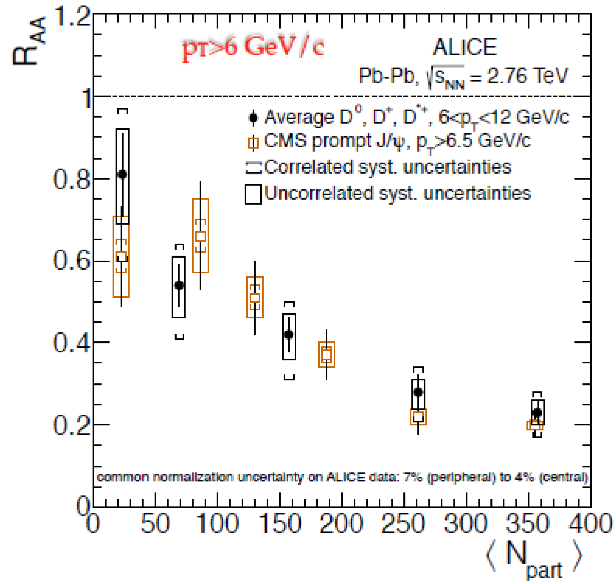
- Good agreement with ALICE (at high p_T) in spite of the different rapidity range

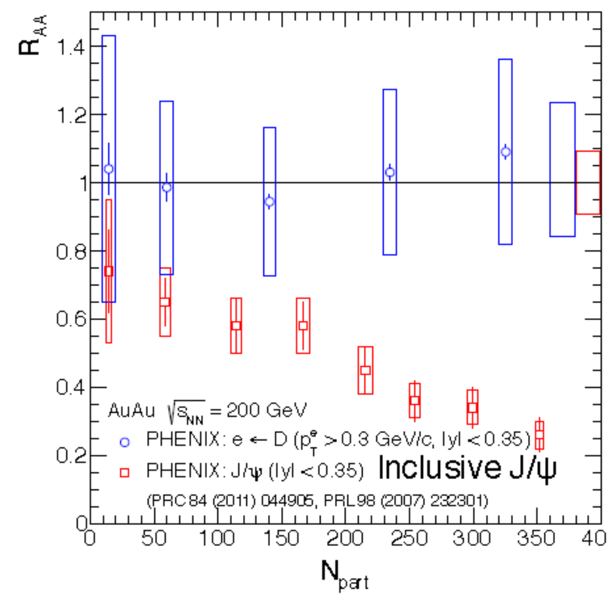
- High p_T: stronger J/ψ suppression at LHC wrt to RHIC (re-combination should not play a role)

J/ψ vs D in AA collisions

- Open charm should be a very good reference to study J/ψ suppression (a` la Satz)







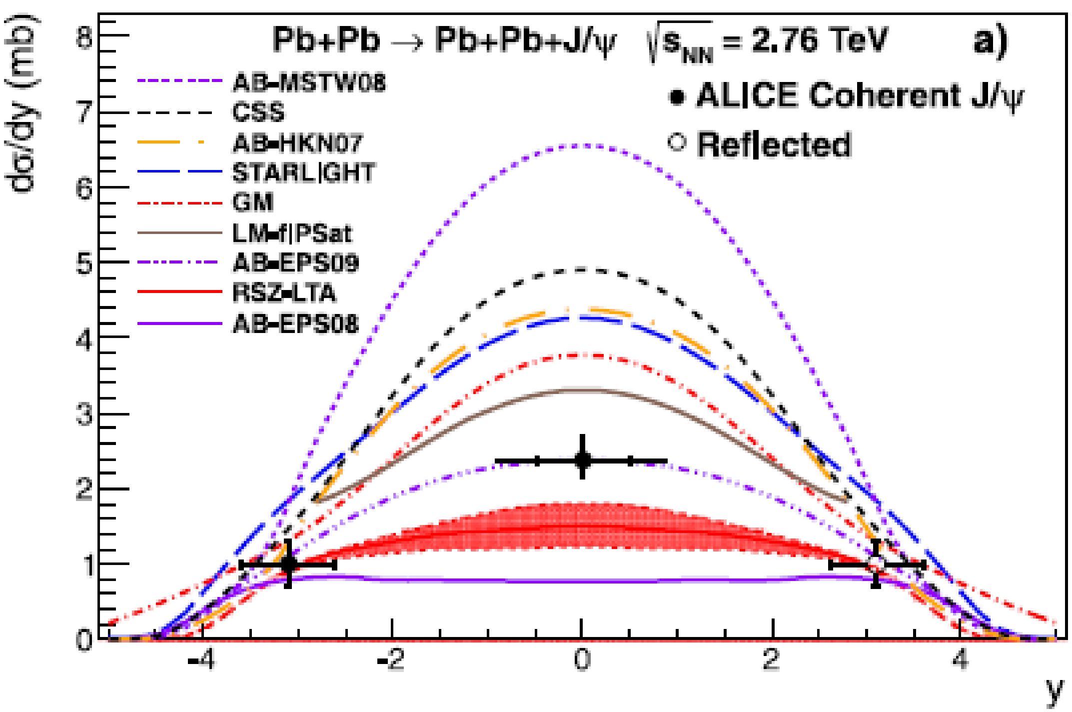
- Interesting comparison between ALICE and CMS J/ψ compared to D

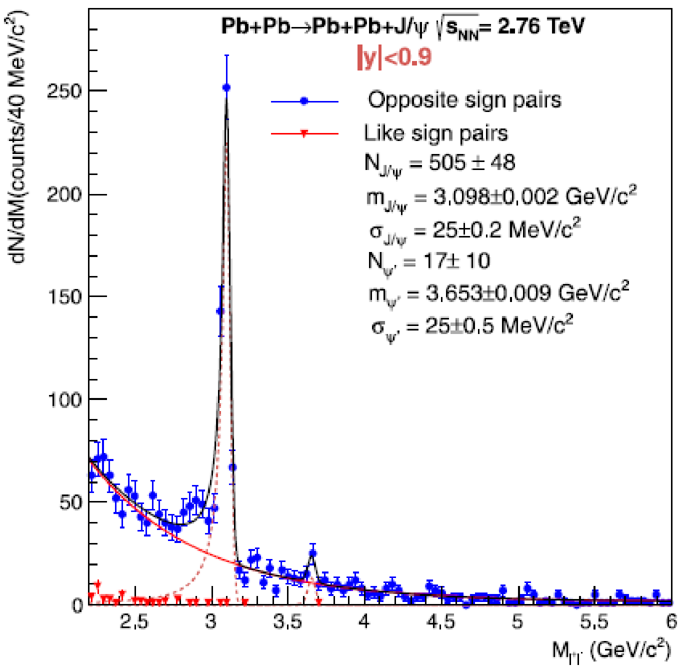
Caveat:
complicate to compare J/ψ and D R_{AA} at LHC because of restricted kinematic regions.
Low p_T D not accessible for the moment

- Different trend observed at low p_T at RHIC.
At high p_T trend is similar to the LHC one

COHERENT J/ψ PHOTO-PRODUCTIONS

- Studied in ultraperipheral PbPb collisions





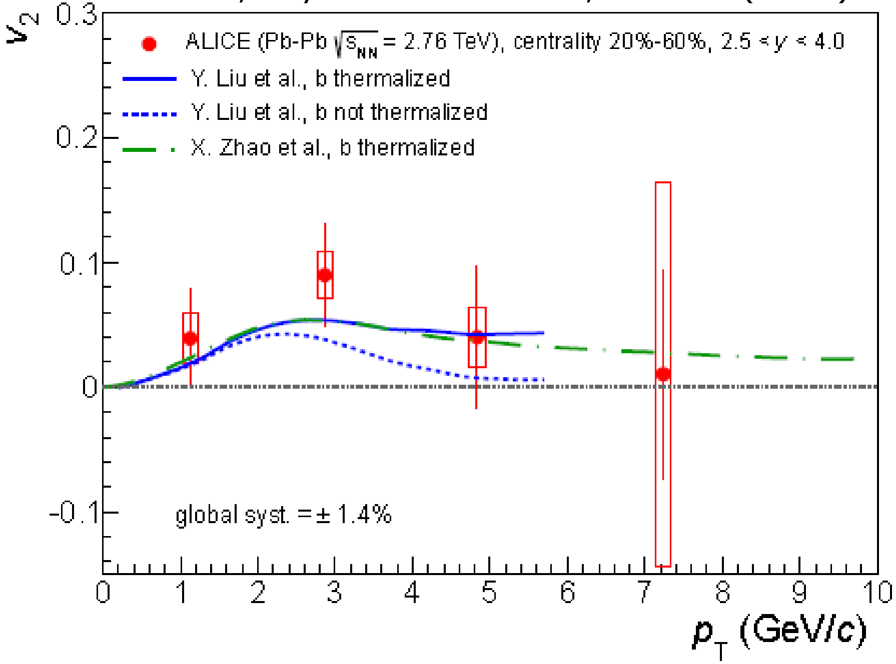
- Tool to constrain gluon shadowing distributions

ALICE Coll., Phys. Lett. B 718 (2013) 1273
ALICE Coll., Eur. Phys. J C (2013) 73

J/ψ FLOW

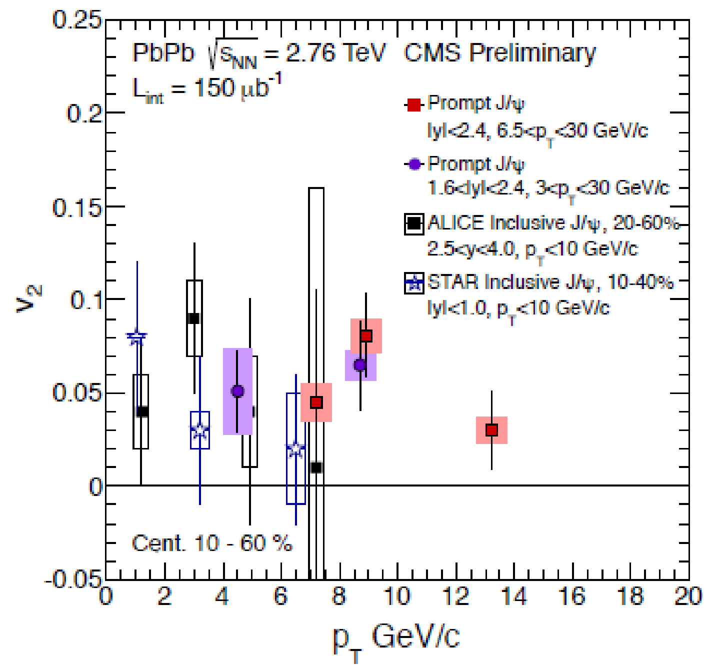
- The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy

ALICE, Phys. Rev. Lett. 111, 162301 (2013)



- Hint for J/ψ flow at forward *y* and semi-central collisions (contrary to v_2~0 observed at RHIC!)

CMS-PAS-HIN-12-001



- Significance up to 3σ for chosen kinematic/centrality selections
- Qualitative agreement with transport models including regeneration (same as R_{AA})

Non-zero v_2 observed also by CMS→ path length dependence of energy loss?