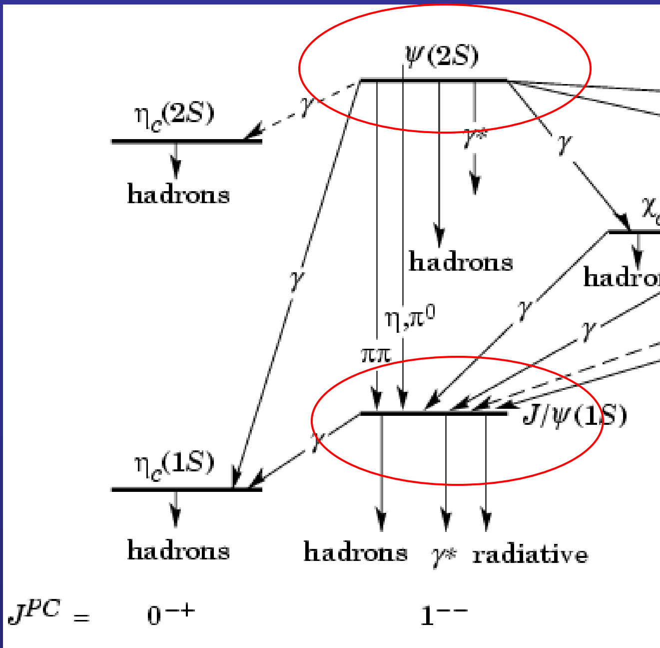
Charmonium production in Pb-Pb collisions at ALICE: from suppression to regeneration ?

E. Scomparin – INFN Torino (Italy)
for the ALICE Collaboration

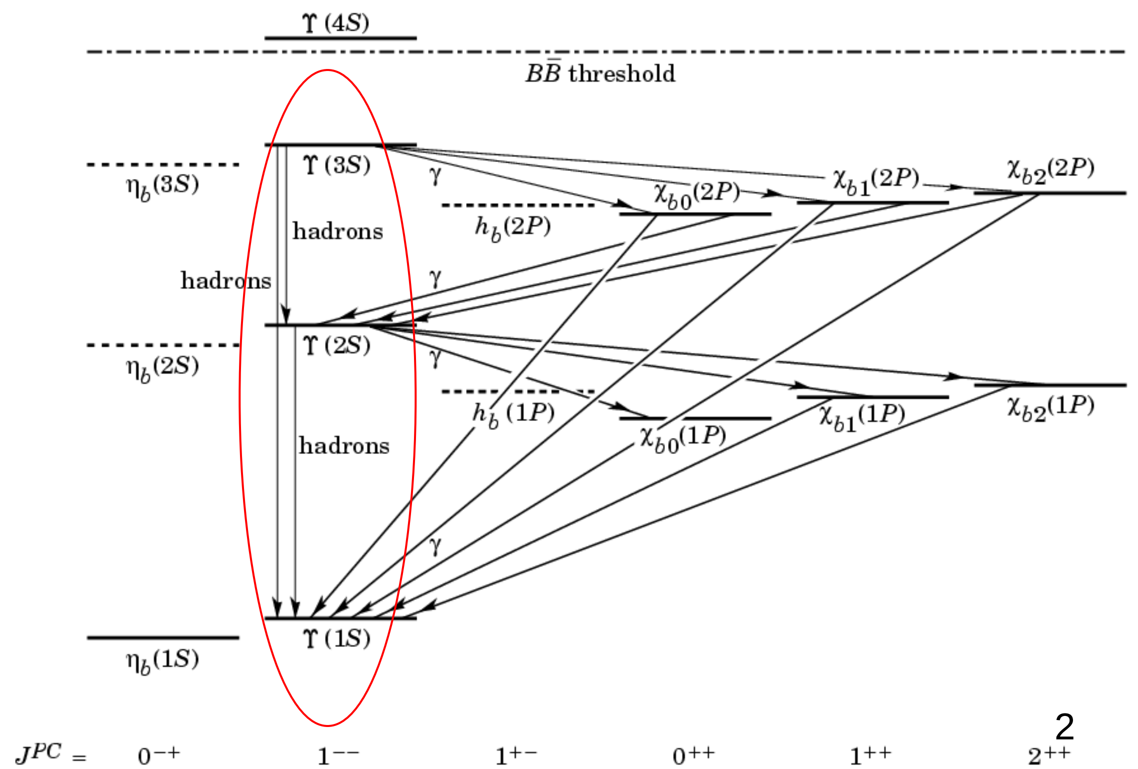
- Introduction: why quarkonia in heavy-ion collisions ?
- A bit of history: from the early days to RHIC
- ALICE measurements in Pb-Pb collisions
- Comparisons, models, interpretation
- Conclusions, what next

CERN
6 November 2012

Heavy quarkonia states



Almost 40 years of physics!

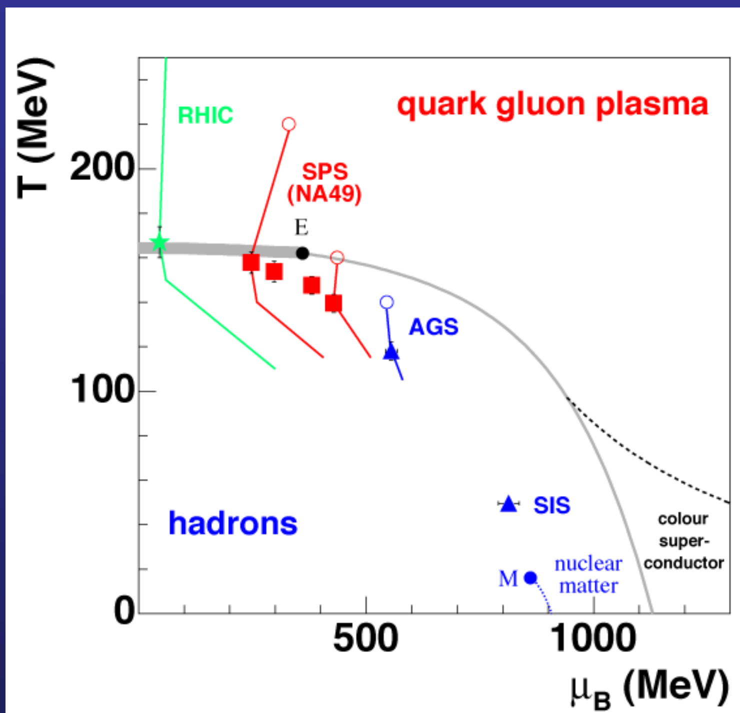


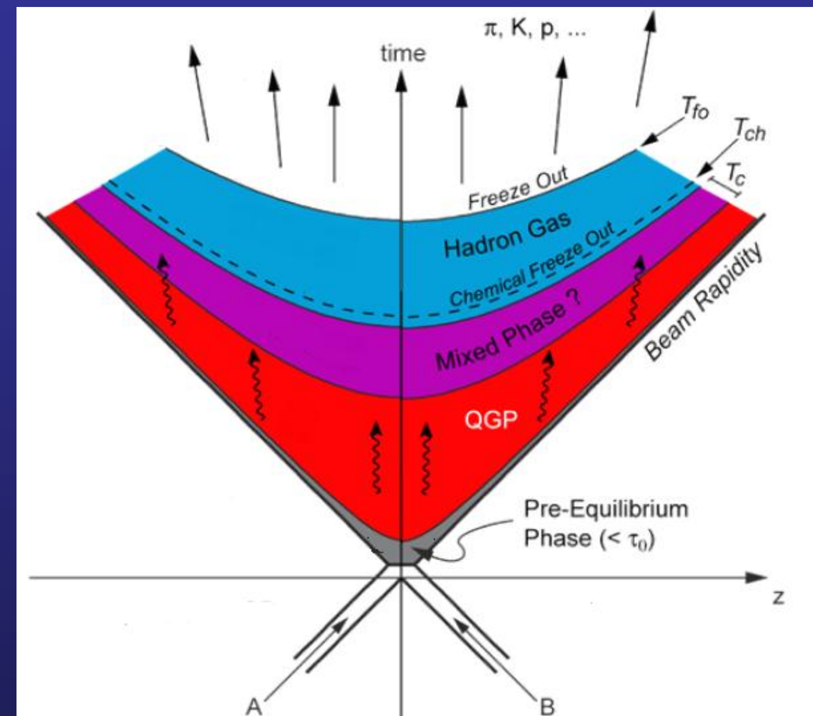
- Spectroscopy
- Decay
- Production
- In media

See 182 pages review
On arXiv:1010.5827

Which medium ?

- We want to study the phase diagram of strongly interacting matter; is it possible to deconfine quarks/gluons and create a Quark-Gluon Plasma (QGP) ?



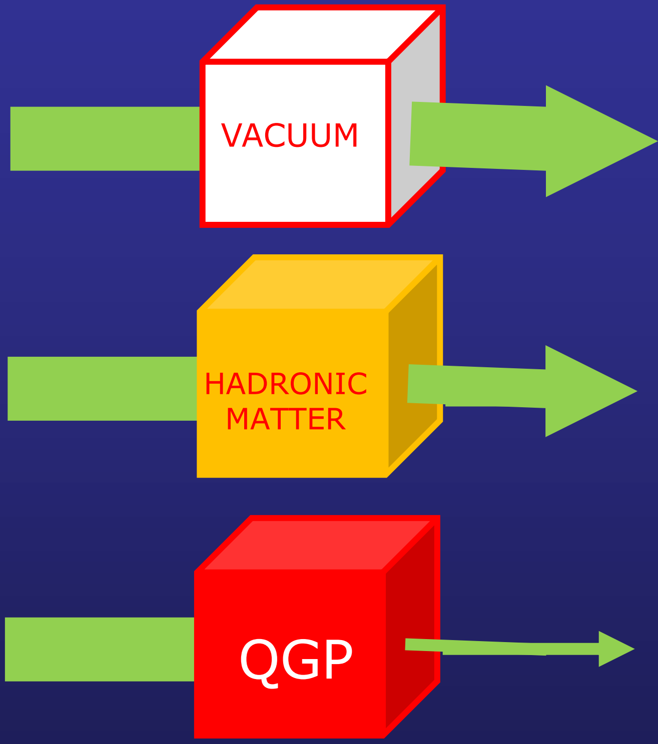


- Only way to do that in the lab → ultrarelativistic HI collisions
- Problems !
  - Quark-Gluon Plasma is short-lived !
  - Only final state hadrons/leptons are observed in our detectors (indirect observation)

Probing the QGP

- One of the best way to study QGP is via probes, created early in the history of the collision, which are sensitive to the short-lived QGP phase

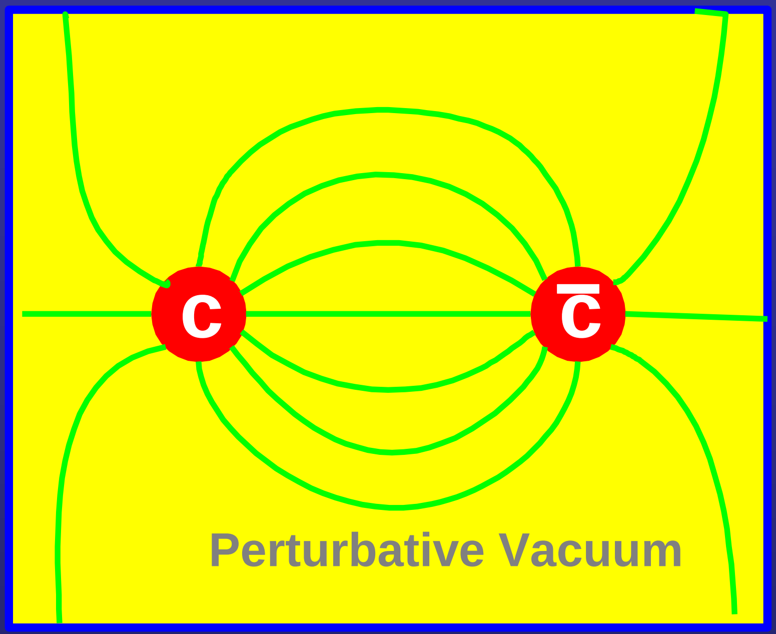
- Ideal properties of a QGP probe
  - Production in elementary NN collisions under control
  - Not (or slightly) sensitive to the final-state hadronic phase
  - High sensitivity to the properties of the QGP phase

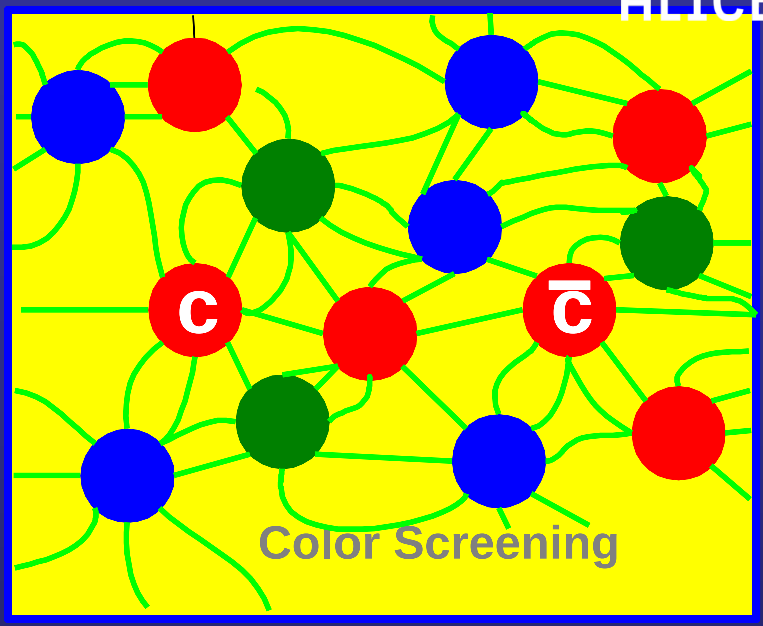


- None of the probes proposed up to now (including heavy quarkonia!) actually satisfies all of the aforementioned criteria

So what makes heavy quarkonia so attractive ?

Screening and initial temperature





- Screening of strong interactions in a QGP → no bound states
- Stronger at high T
- Larger states (less bound) are more easily dissociated
- λ_D → maximum size of a bound state in a QGP at a temperature T, decreases when T increases (Debye length)

T. Matsui and H. Satz, Phys.Lett. B178 (1986) 416

Sequential suppression

➡ The various quarkonium states are characterized by different

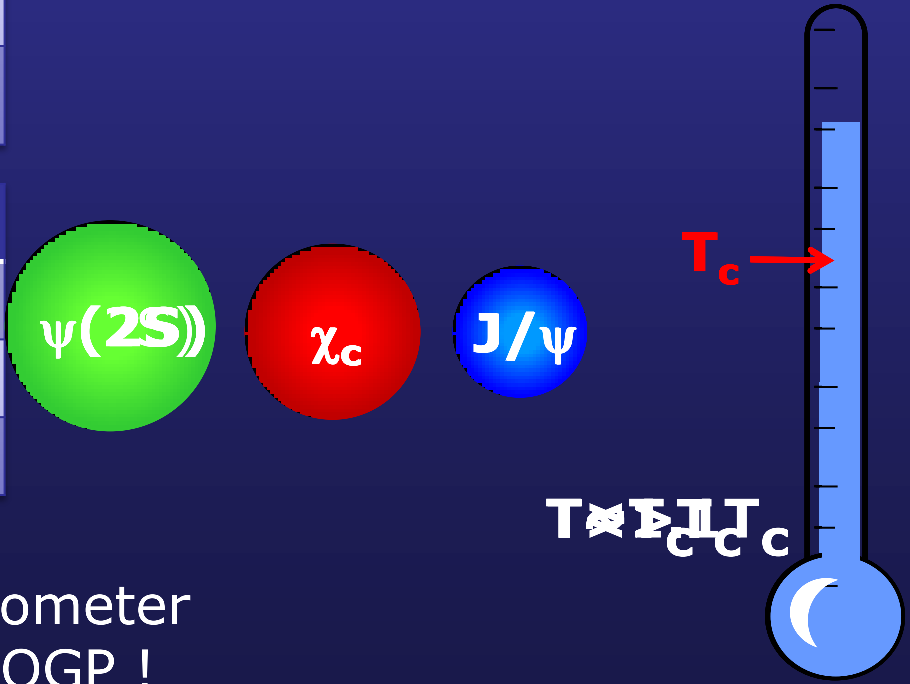
- binding energy
- radius

state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_o(fm)	0.25	0.36	0.45

state	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

More bound states → smaller size

Debye screening condition $r_0 > \lambda_D$ will occur at different T

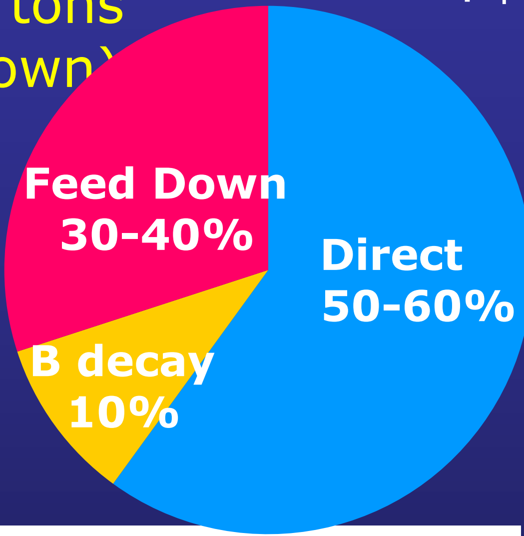


Sequential suppression of the resonances ➡ Thermometer of the QGP !

Sources of heavy quarkonia

- Quarkonium production can proceed:
  - directly in the interaction of the initial partons
  - via the decay of heavier hadrons (feed-down)

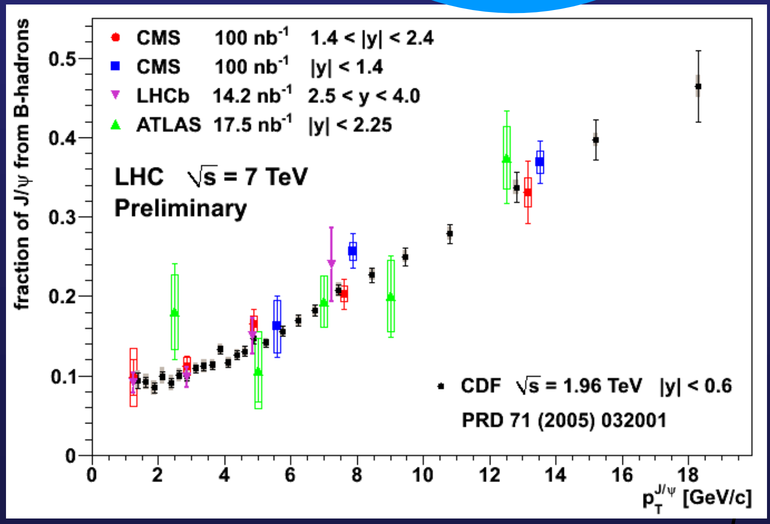
Low p_T



- For J/ψ (at CDF/LHC energies) the contributing mechanisms are:

Prompt
- Direct production
- Feed-down from higher charmonium states:
  ~ 8% from $\psi(2S)$,
  ~20-30% from χ_c

Non-prompt
- B decay
  contribution is p_T dependent
  ~10% at p_T~1.5GeV/c

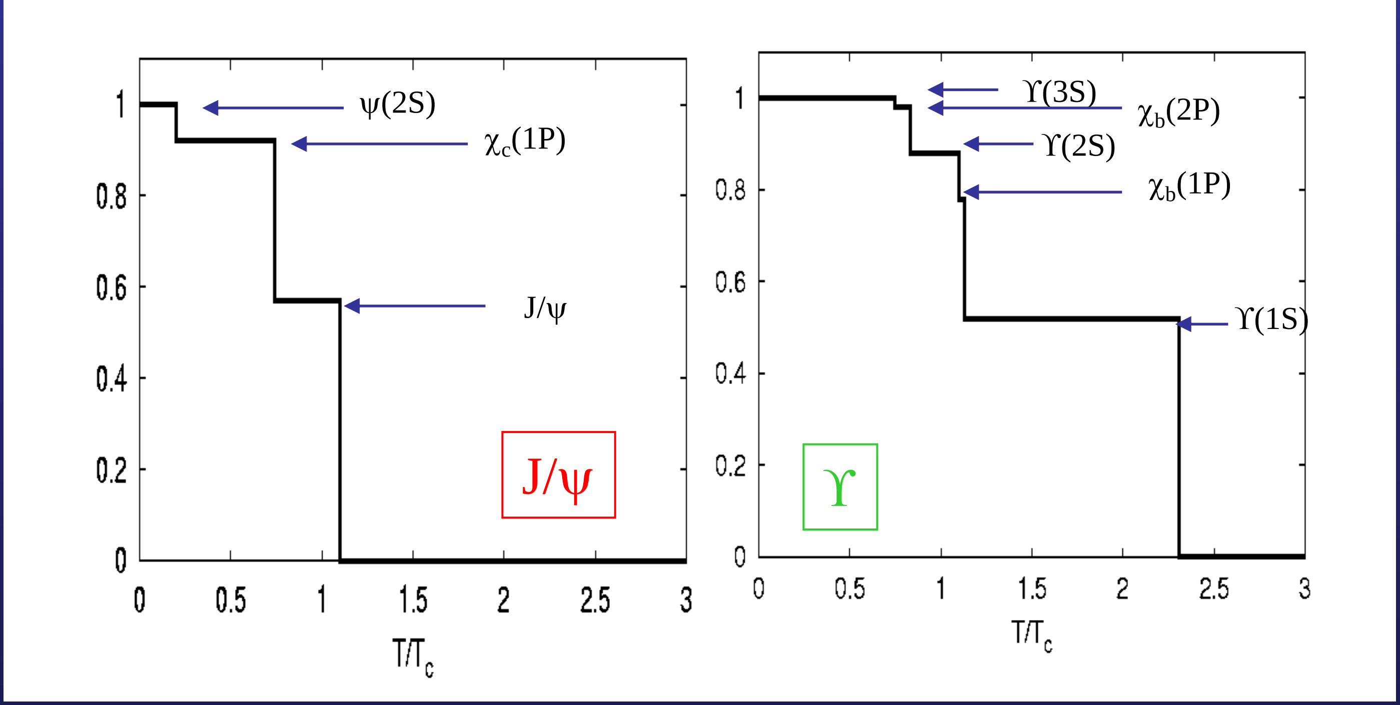


- B-decay component "easier" to separate → displaced production

from H. Woehri, Hard Probes 2010

Suppression pattern

- Since each resonance should have a typical dissociation temperature, one should observe «steps» in the suppression pattern of the measured J/ψ when increasing T



Digal et al., Phys.Rev. D64(2001) 094015

- Ideally, one could vary T
  - by studying the same system (e.g. Pb-Pb) at various √s
  - by studying the same system for various centrality classes

Quantifying the suppression

- Low energy (SPS)
  - Normalize the charmonia yield to the Drell-Yan dileptons
  - Advantages
    - Same final state, DY is insensitive to QGP
    - Cancellation of syst. uncertainties
  - Drawbacks
    - Different initial state (quark vs gluons)
    - Statistics is usually low

- At RHIC, LHC Drell-Yan is no more “visible” in the dilepton mass spectrum → overwhelmed by semi-leptonic decays of charm/beauty pairs. Normalize to pp via R_{AA}

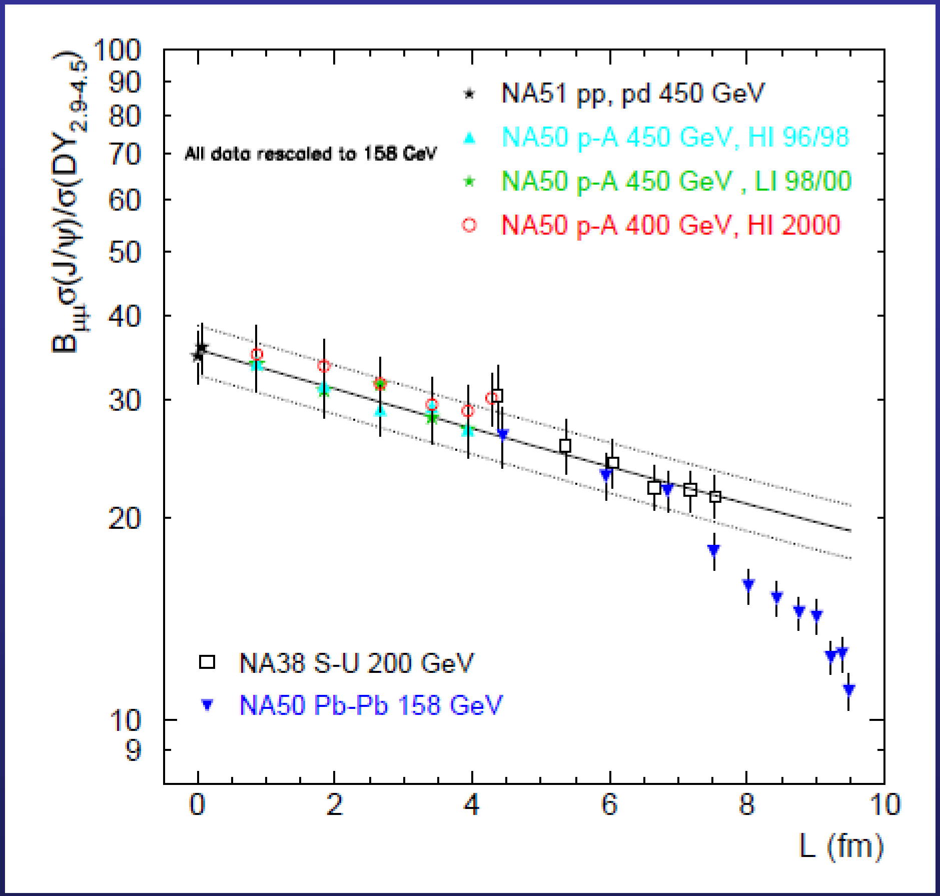
$$R_{AA} = \frac{dN^{P}{}_{AA}}{\langle N_{Coll} \rangle \, dN^{P}{}_{NN}}$$

$R_{AA}<1$ suppression
$R_{AA}>1$ enhancement

  - Advantages
    - same process in nuclear environment and in vacuum
  - Drawbacks
    - Full treatment of systematics needed

An ideal normalization would be the charm production cross section; however, this is not straightforward

PbPb results at $\sqrt{s_{NN}}$ =17.2 GeV (SPS)



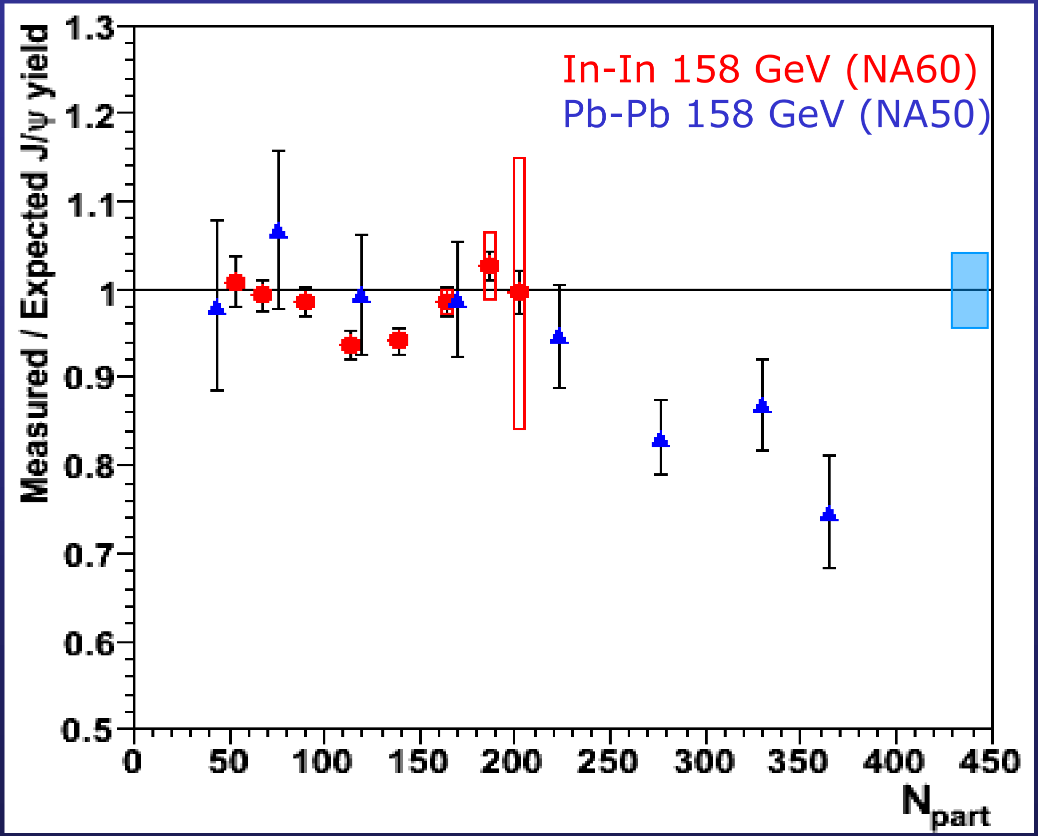
B. Alessandro et al. (NA50), EPJC 39(2005) 335

- NA50 and the discovery (2000) of the anomalous J/ψ suppression
- Use L as independent variable (thickness of nuclear matter seen by the J/ψ in its way through projectile/target)
- Suppression effects visible already in pA collisions

"Cold nuclear matter" effects represent an important issue in the interpretation of the suppression results

SPS "summary" plot

NA50 (Pb-Pb) and NA60 (In-In) results:



B. Alessandro et al. (NA50), EPJC39 (2005) 335
R. Arnaldi et al. (NA60), Nucl. Phys. A (2009) 345

- Anomalous suppression for central Pb-Pb collisions
- Agreement between Pb-Pb and In-In in the common N_{part} region
- Pb-Pb data not precise enough to clarify the details of the pattern!

Anomalous suppression up to ~30%, compatible with ψ(2S) and χ_c melting, i.e. with a sequential suppression scenario!

Moving to RHIC: expectations

❑ Two main lines of thought

1) We gain one order of magnitude in $\sqrt{s}$. In the "color screening" scenario we have then two possibilities

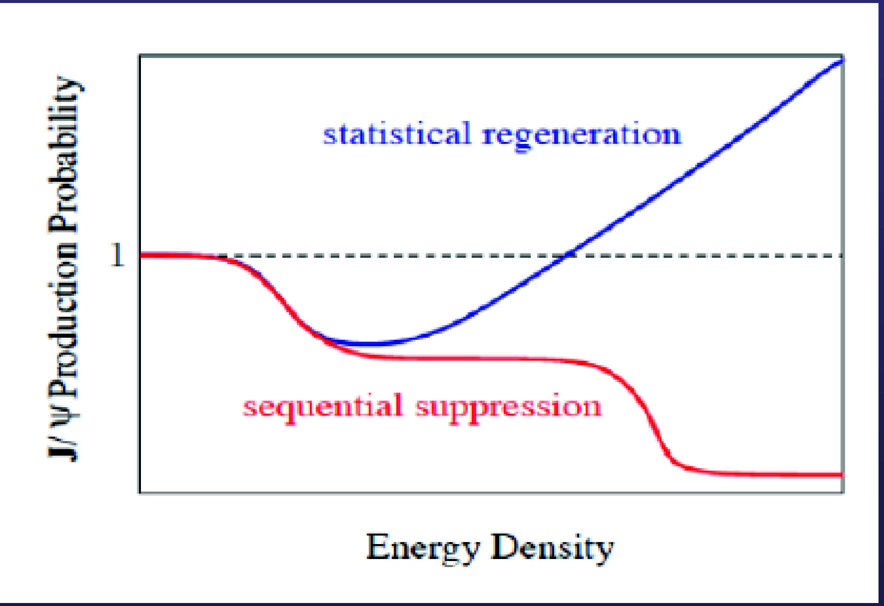
a) We reach $T>T_{diss}^{J/\psi}$ → suppression becomes stronger than at SPS

b) We do not reach $T>T_{diss}^{J/\psi}$ → suppression remains the same

2) Moving to higher energy, the cc pair multiplicity increases

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60

A (re)combination of ccbar pairs to produce quarkonia may take place at the hadronization
→ J/ψ enhancement ?!

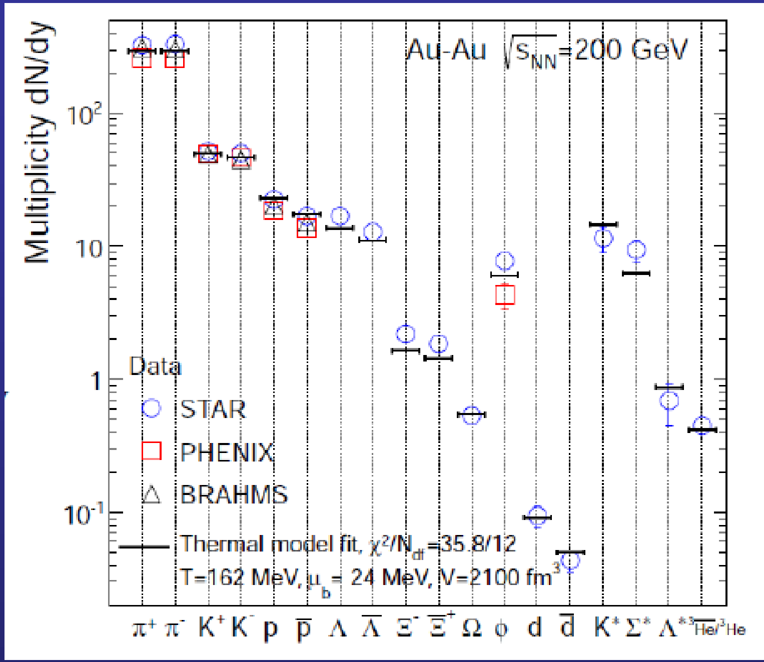


P. Braun-Munzinger and J. Stachel, Phys. Lett. B490(2000) 196

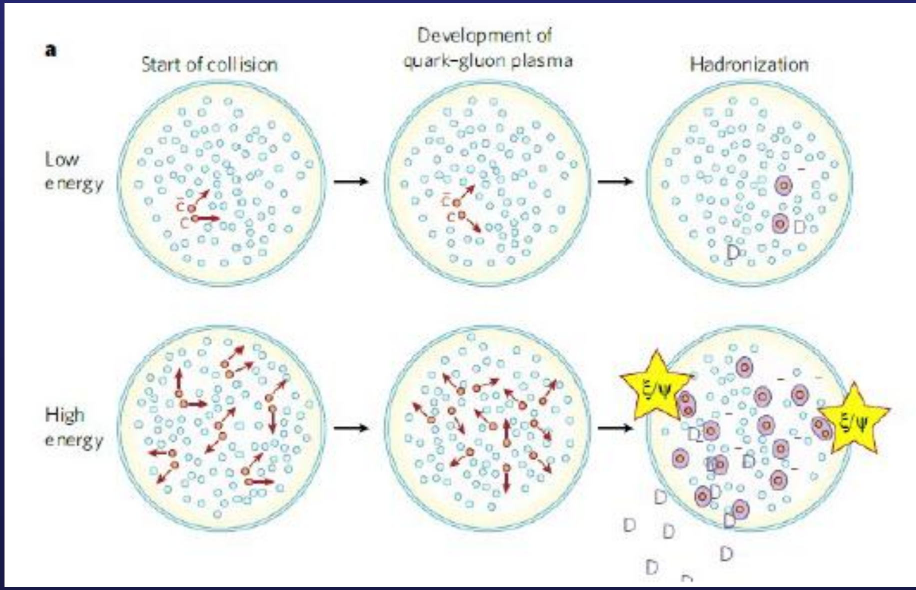
J/ψ and the statistical model

- Reproduces RHIC (and LHC too…) particle yields for light and strange quarks quite well

RHIC fit values
(combining experiments)
T=162 MeV
μ_B = 24 MeV



- Assumptions
  - All charm quarks produced in hard collisions, N_C const in QGP
  - All charmonia dissolved in QGP
  - Charmonia production at the phase boundary with statistical weights



A. Andronic et al.,arXiv:1210.7724
P. Braun-Munzinger et al., Nature 448 (2007) 302

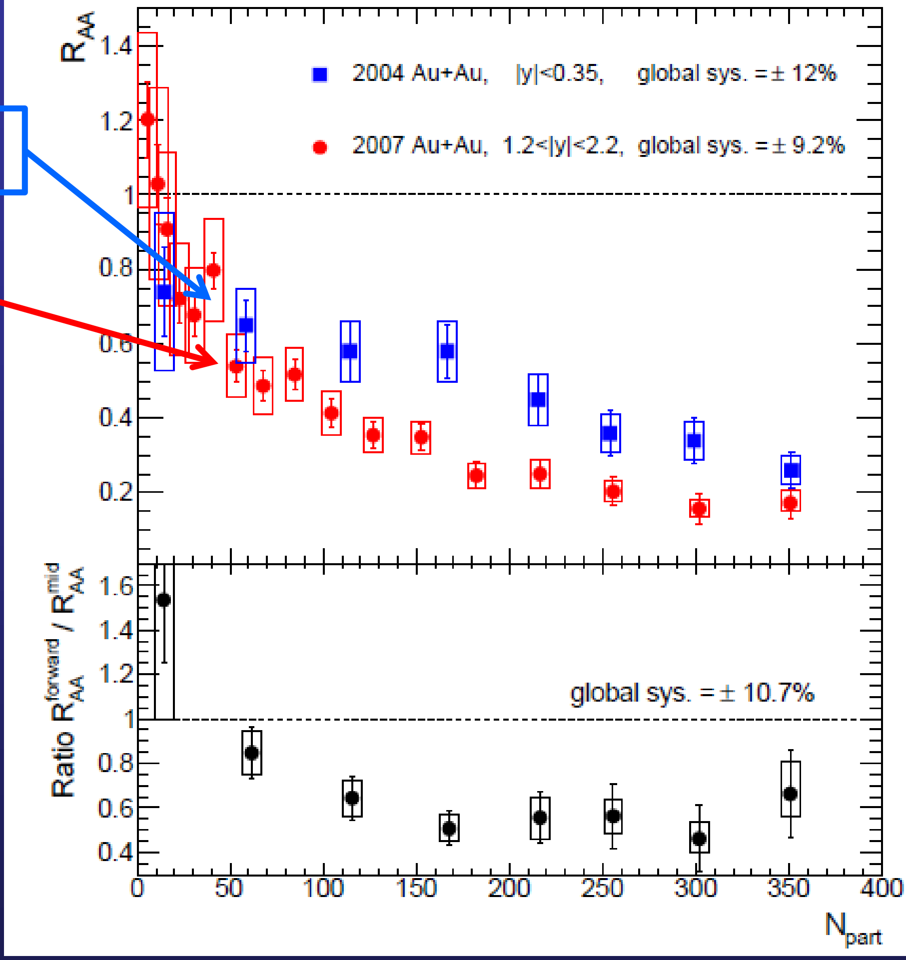
RHIC: forward vs central y

- Comparison of R_{AA} results obtained at different rapidities

Mid-rapidity

Forward-rapidity

- Stronger suppression at forward rapidities



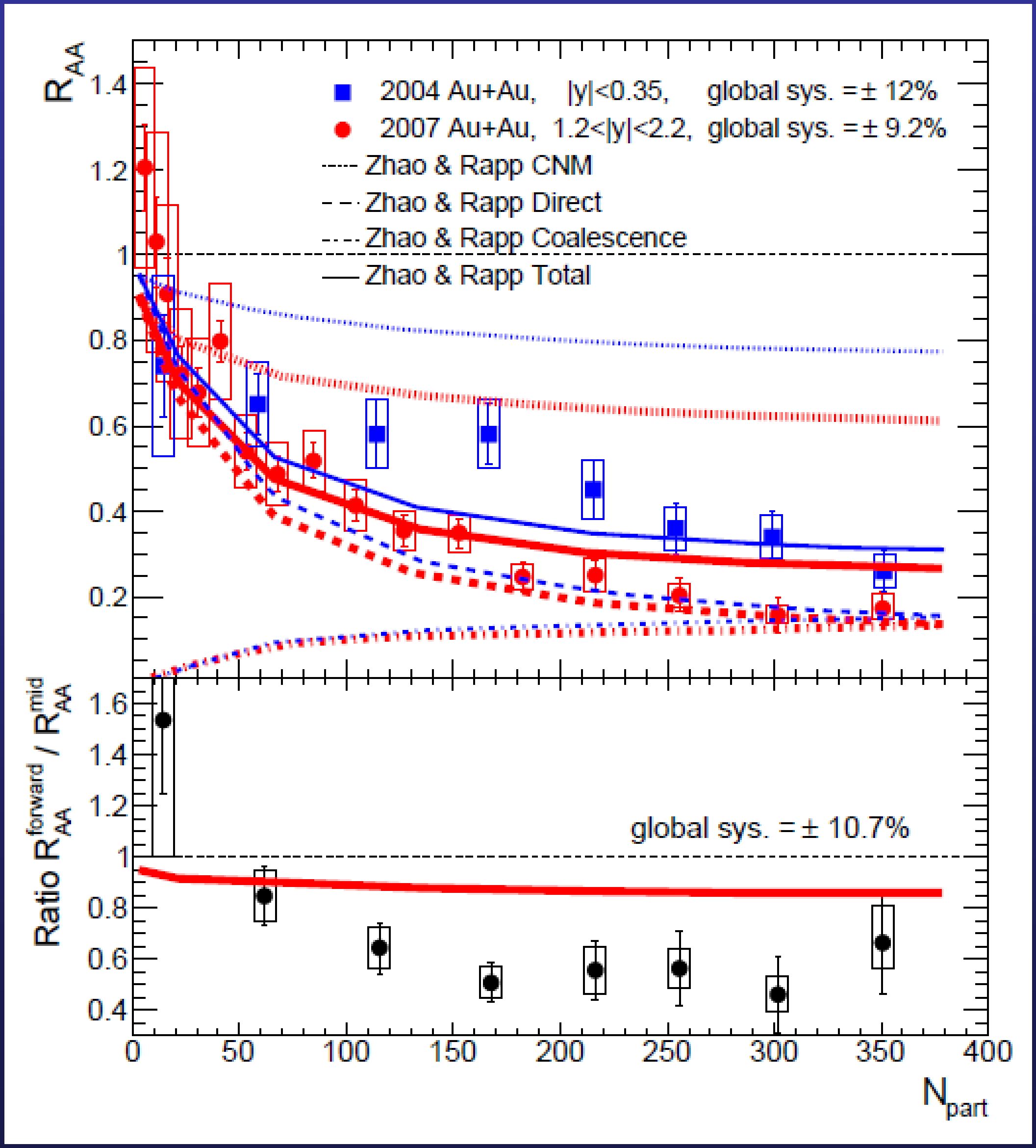
A.Adare et al. (PHENIX), PRC84 (2011) 054912

- Not expected if suppression increases with energy density (which should be larger at central rapidity)

- Are we seeing a hint of (re)generation, since there are more pairs at y=0?

- Or may other effects (e.g. cold nuclear matter effects) explain this feature ?

Comparisons with models



- Models can catch the main features of J/ψ suppression at RHIC, but no quantitative understanding

- In particular, no clear conclusion on

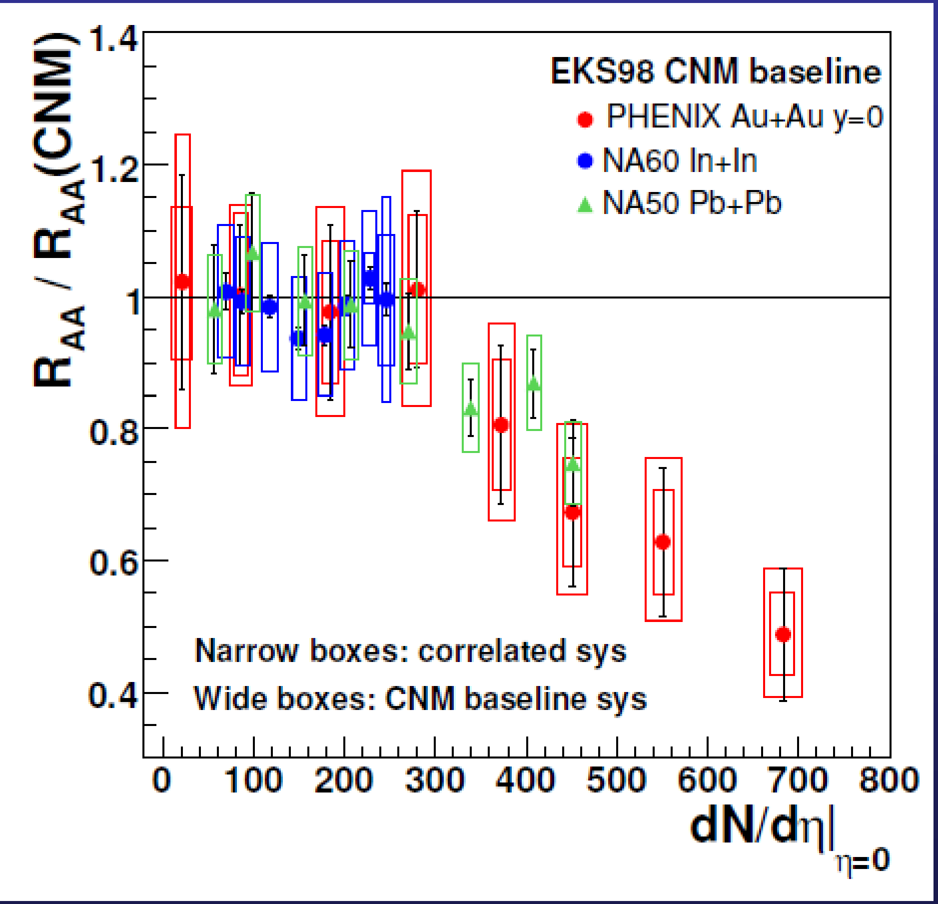
ψ(2S) and χ_c only suppression

vs

All charmonia suppressed + (re)generation

J/ψ suppression: SPS vs RHIC

- Let's compare the J/ψ suppression at SPS and RHIC, after having accounted for cold nuclear matter effects (not trivial, still matter of debate!)



Nice "universal" behavior

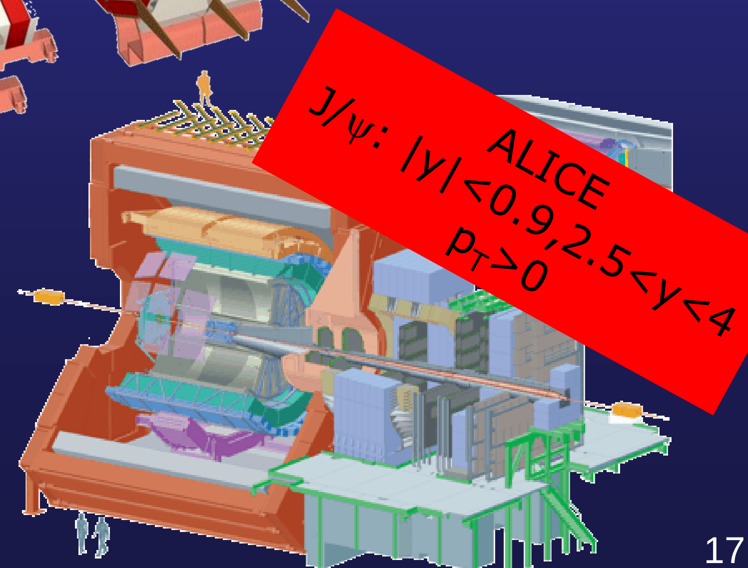
Note that
1) charged multiplicity is proportional to the energy density in the collision
2) Maximum suppression ~40-50% (still compatible with only ψ(2S) and χ_c melting)

Go to the LHC and get more data!

N.Brambilla et al., EPJ C71(2011) 1534

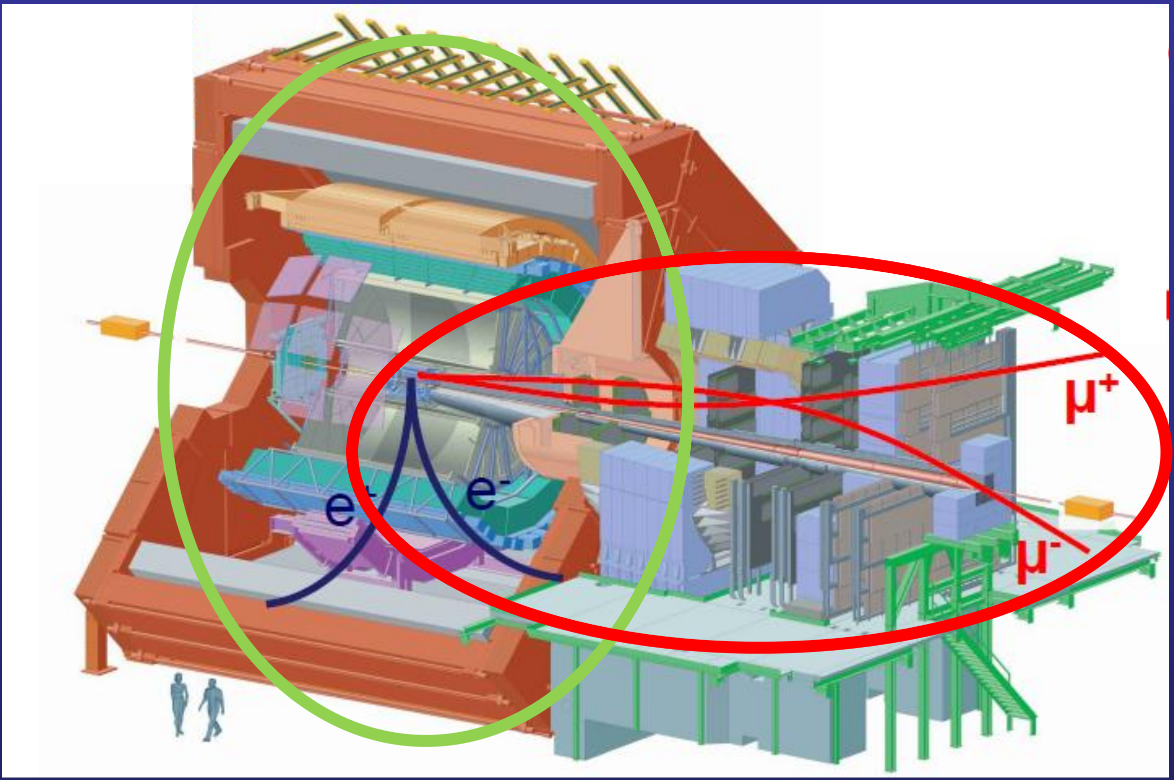
Moving to LHC

- The debate between suppression and regeneration scenarios could not be finally settled at lower energies
- Many hopes/expectations for LHC, and in particular
  - Clarify mechanisms affecting J/ψ production in HI collisions
  - Investigate Υ production (no regeneration)



- Complementary results from the LHC experiments

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 ($p_T \sim 1$ GeV/c threshold for Pb-Pb 2011)

Integrated luminosity for quarkonia analysis

⬇

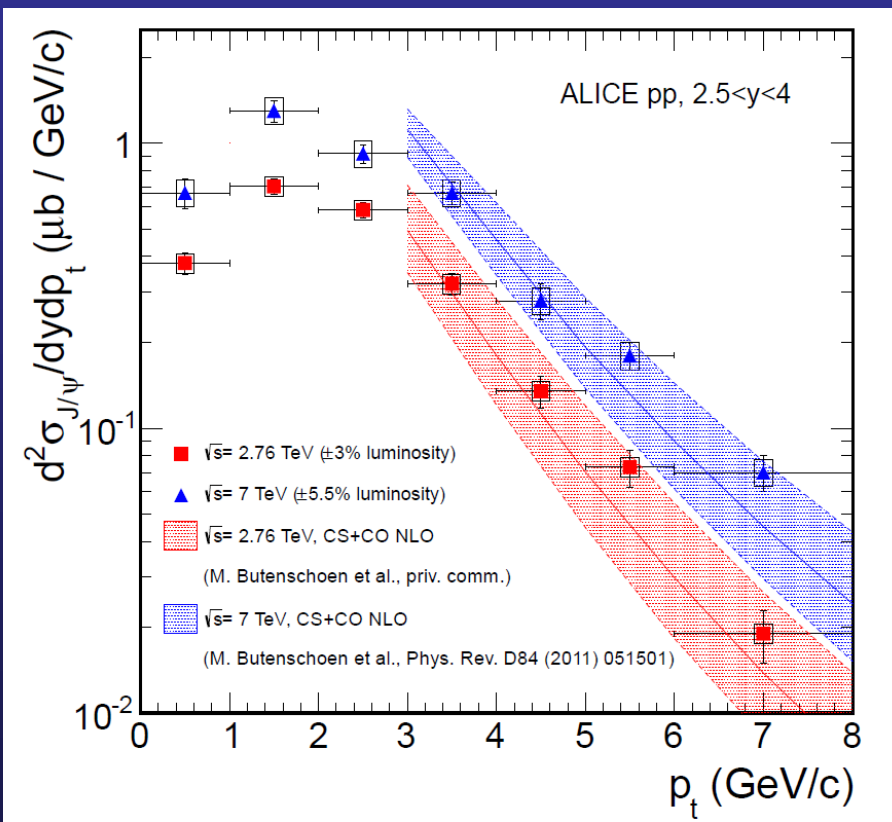
(up to) ~100 nb^{-1} for pp
~ 70 μb^{-1} for Pb-Pb

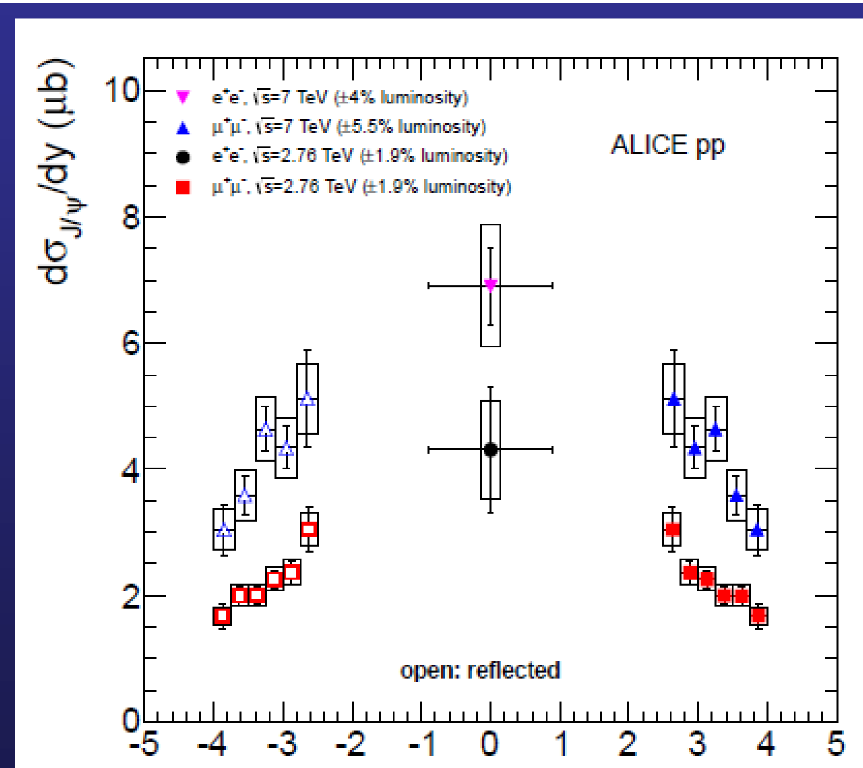
pp: the reference

ALICE

- 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}

$$\sigma_{J/\psi}(|y| < 0.9) = 7.75 \pm 1.78(\text{stat.}) \pm 1.39(\text{syst.}) + 1.16(\lambda_{HE} = 1) - 1.63(\lambda_{HE} = -1)\ \mu\text{b and}$$
$$\sigma_{J/\psi}(2.5 < y < 4) = 3.34 \pm 0.13(\text{stat.}) \pm 0.27(\text{syst.}) + 0.53(\lambda_{CS} = 1) - 1.07(\lambda_{CS} = -1)\ \mu\text{b.}$$





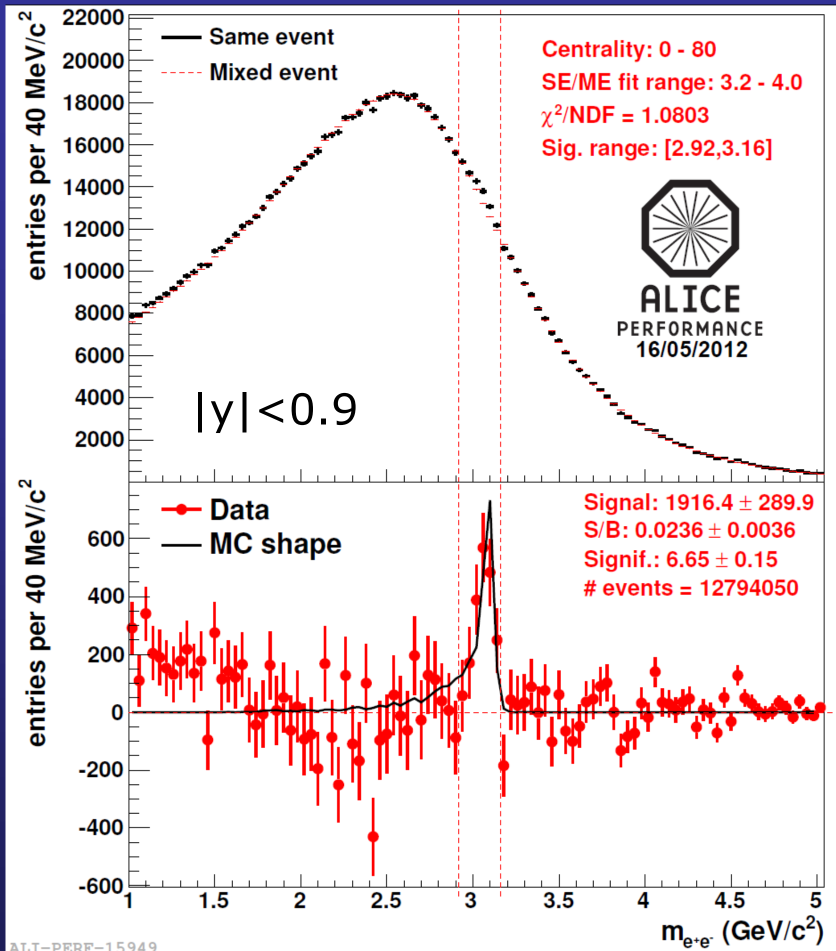
ALICE Coll., arXiv:1203.3641

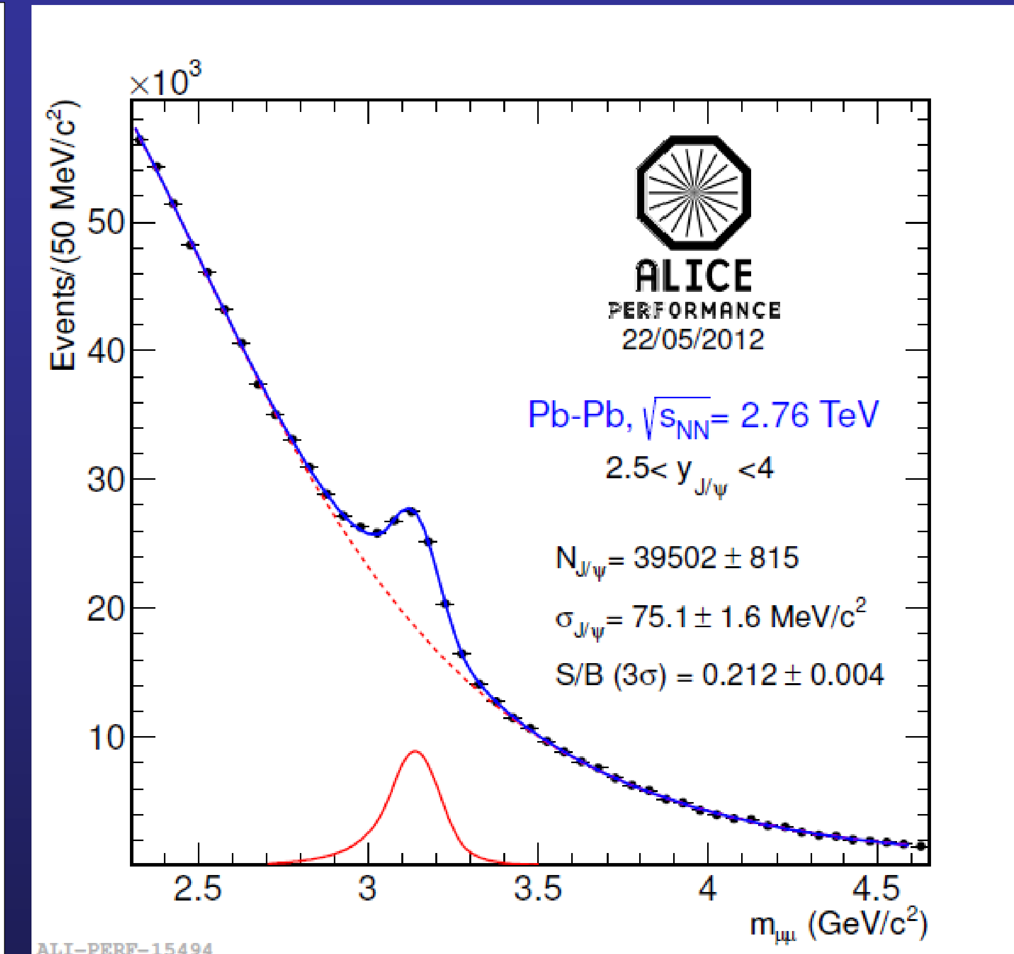
- Results in agreement with NLO NRQCD calculations

Pb-Pb collision results

- Lots of results available, most of them released only a few months ago!
  - R_{AA} vs $\langle N_{part} \rangle$
    - Forward rapidity
    - Mid-rapidity
    - Forward rapidity in p_T bins
  - R_{AA} vs p_T
    - Forward rapidity (HP '12)
    - Forward rapidity in centrality bins
    - J/ψ $\langle p_T \rangle$ and $\langle p_T^2 \rangle$
  - R_{AA} vs y
  - J/ψ elliptic flow
    - Intermediate centrality vs p_T (HP '12)
    - v_2 vs centrality
  - ψ(2S)/J/ψ ratio: Pb-Pb vs pp

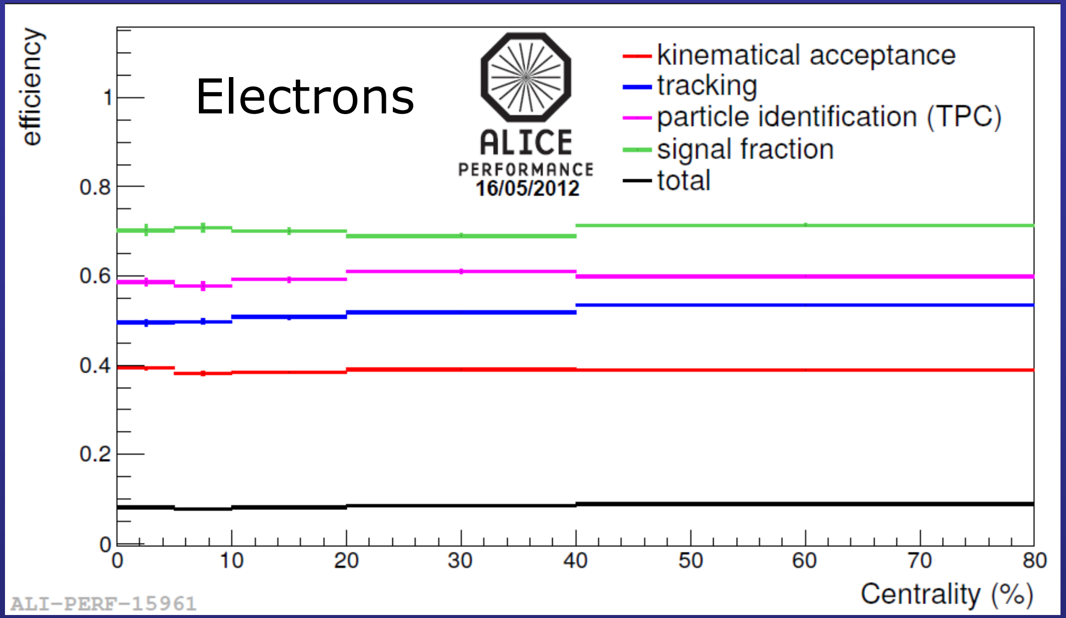
Charmonia detection (Pb-Pb) in ALICE

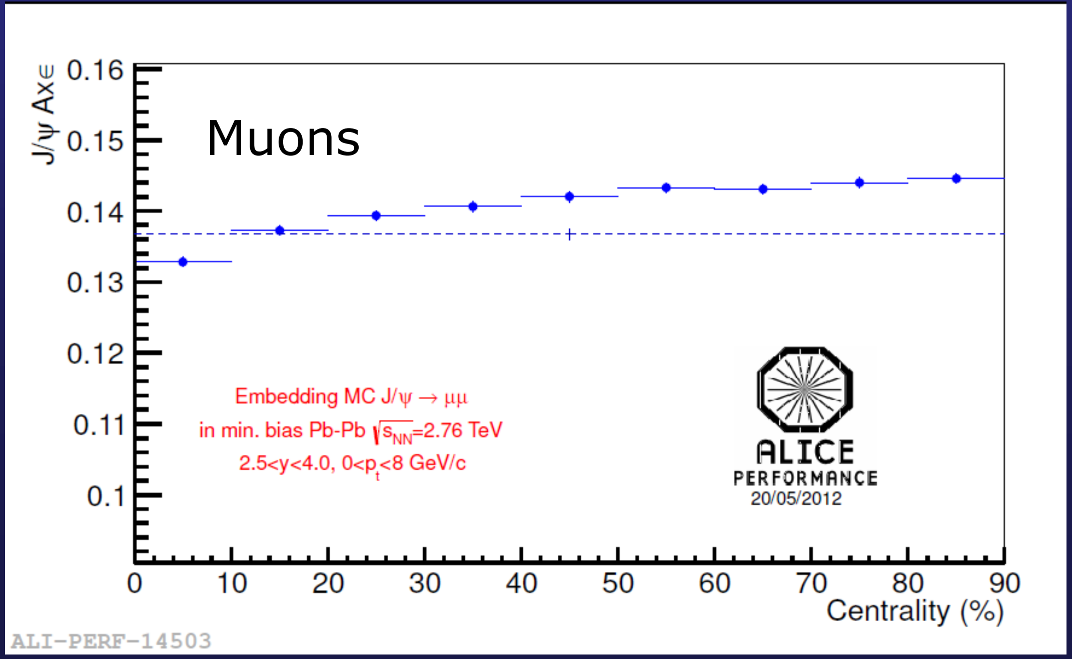




- Electron analysis: background subtracted with event mixing → Signal extraction by bin counting
- Muon analysis: fit to the invariant mass spectra → signal extraction by integrating the Crystal Ball line shape

Acceptance × efficiency

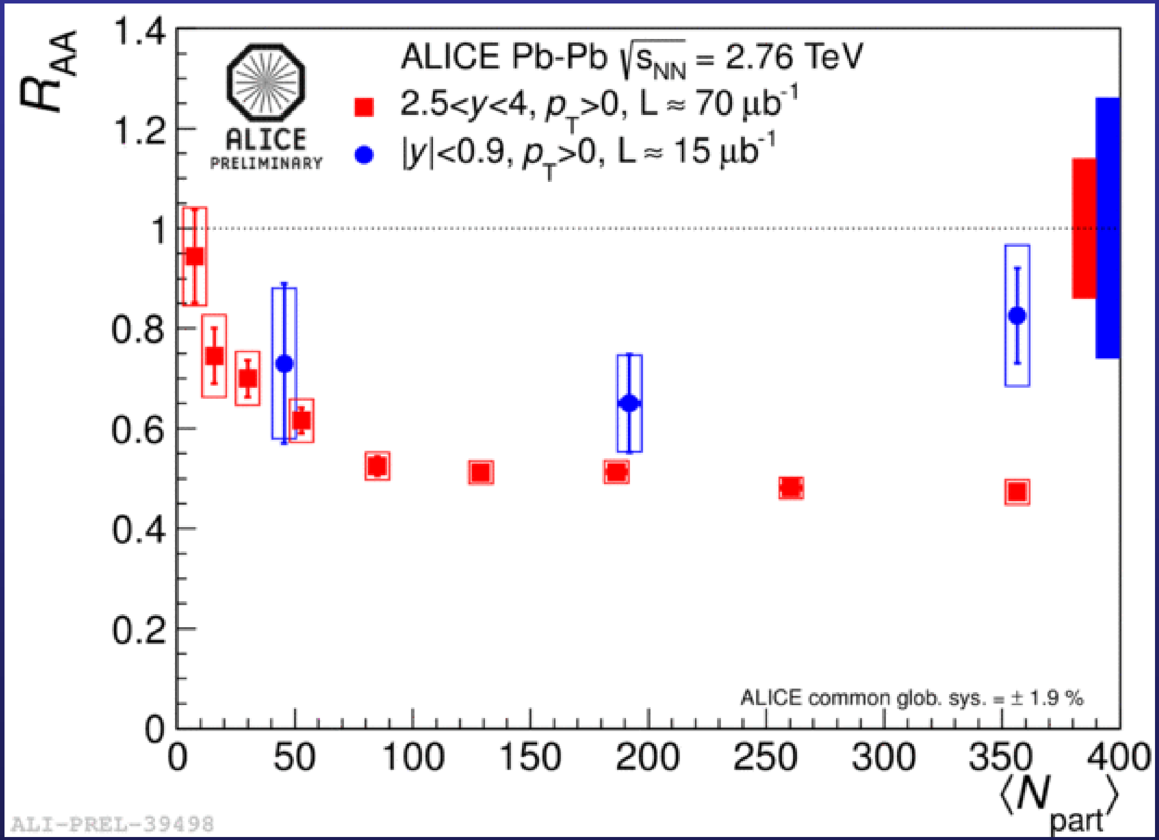




- For di-electron efficiency
  → HIJING enriched with J/ψ
- For di-muon efficiency
  → real Pb-Pb events enriched with MC J/ψ
- Only weak dependence on centrality
- Kinematic parameterization based on interpolation from RHIC to full LHC energy
- Shadowing
- No polarisation

Pb-Pb collisions: R_{AA} vs $\langle N_{part} \rangle$

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



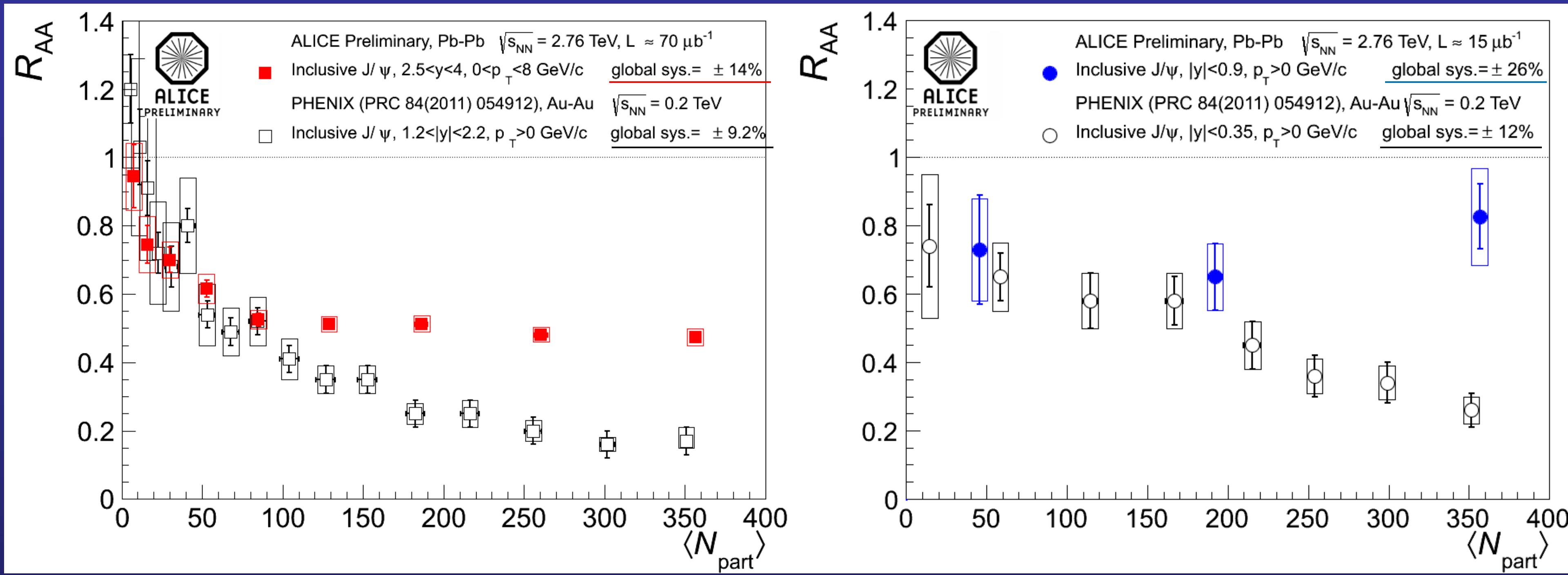
Inclusive J/ψ R_{AA}

Negligible effect of non-prompt contribution on the measured R_{AA}

B. Abelev et al. (ALICE), PRL 109(2012), 072301
R. Arnaldi, I. Arsene, E.S.. QM2012 (also for next slides)

- At forward y, R_{AA} flattens for $N_{part} \geq 100$
- Large uncertainty on the (midrapidity) pp reference prevents a final conclusion on a different behaviour for central events at mid- and forward rapidity

Pb-Pb collisions: R_{AA} vs $\langle N_{part} \rangle$

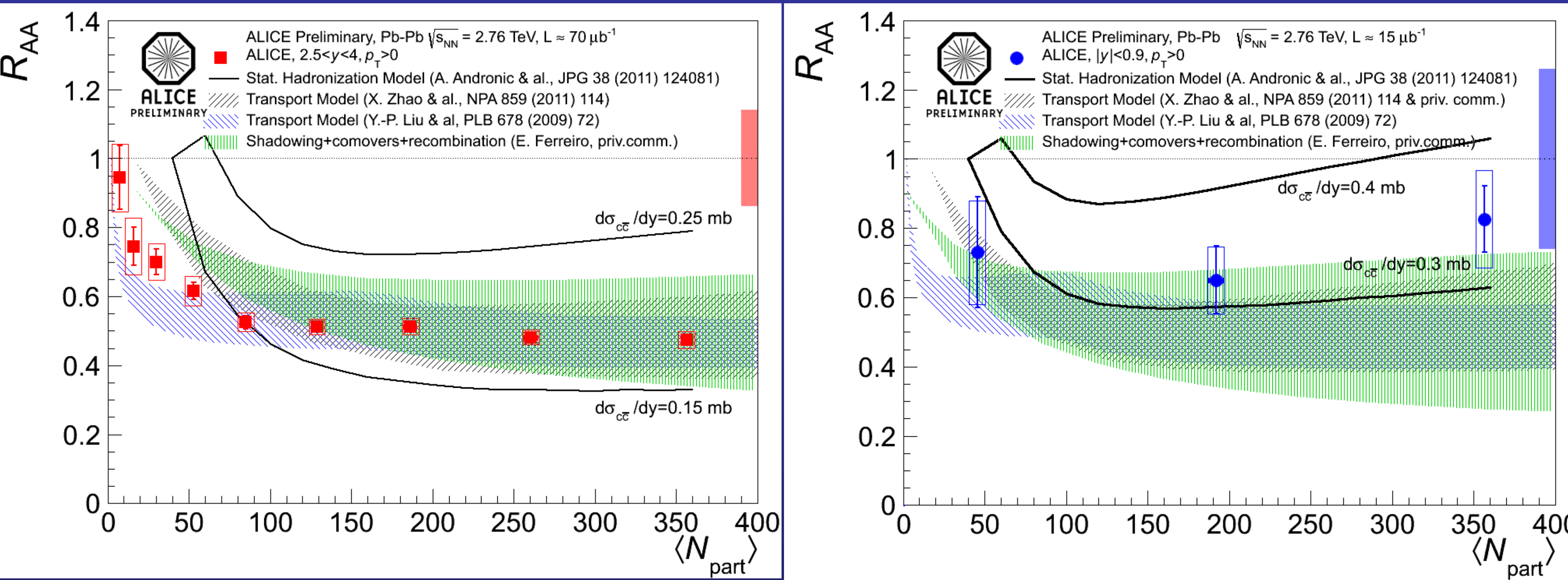


- Comparison with PHENIX

- 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 theoretical models

Pb-Pb collisions: R_{AA} vs $\langle N_{part} \rangle$

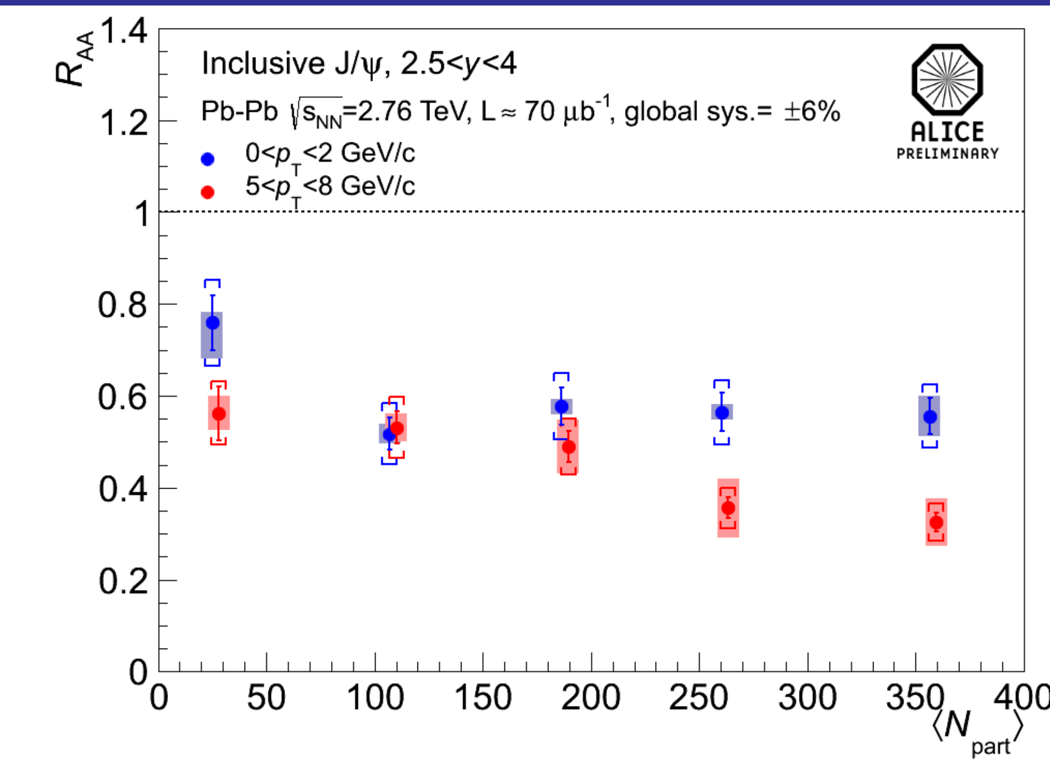


- Comparison with models
  - X.Zhao and R.Rapp, Nucl. Phys. A859(2011) 114
  - Y.Liu, Z. Qiu, N. Xu and P. Zhuang, Phys. Lett. B678(2009) 72
  - A. Capella et al., Eur. Phys. J. C58(2008) 437 and E. Ferreiro, priv. com
  - A.Andronic et al., arXiv:1210.7724

- 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 can describe ALICE results for central collisions in both rapidity ranges

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

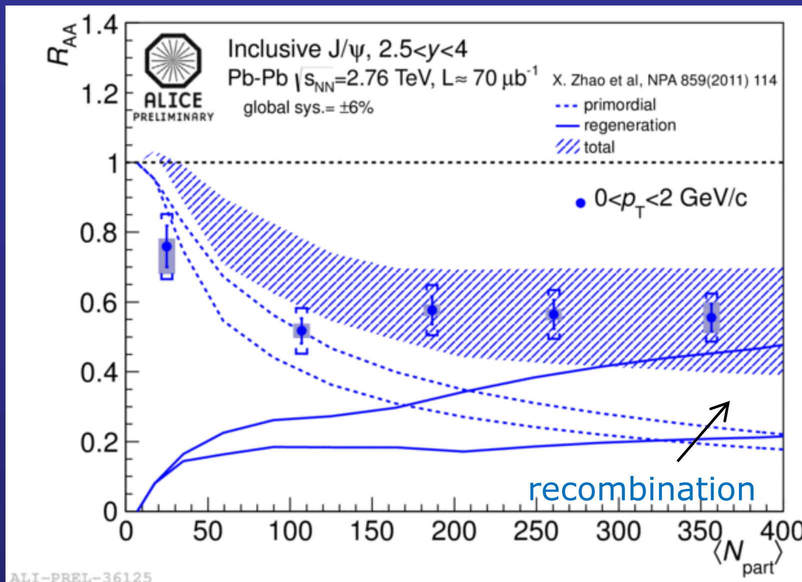
- Smaller R_{AA} for high p_T J/ψ

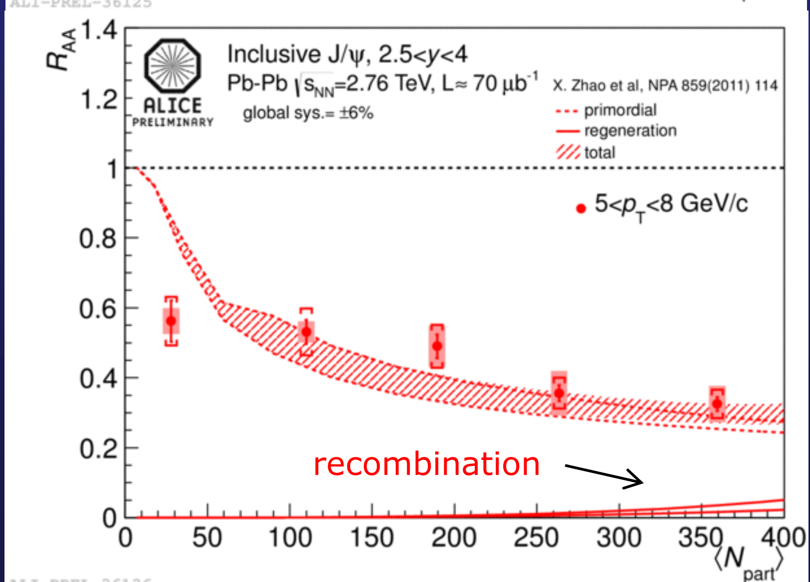
Uncertainties
uncorrelated (box around points)
partially correlated within and between sets ([])
100% correlated within a set and between sets (text)

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

ALICE

- 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

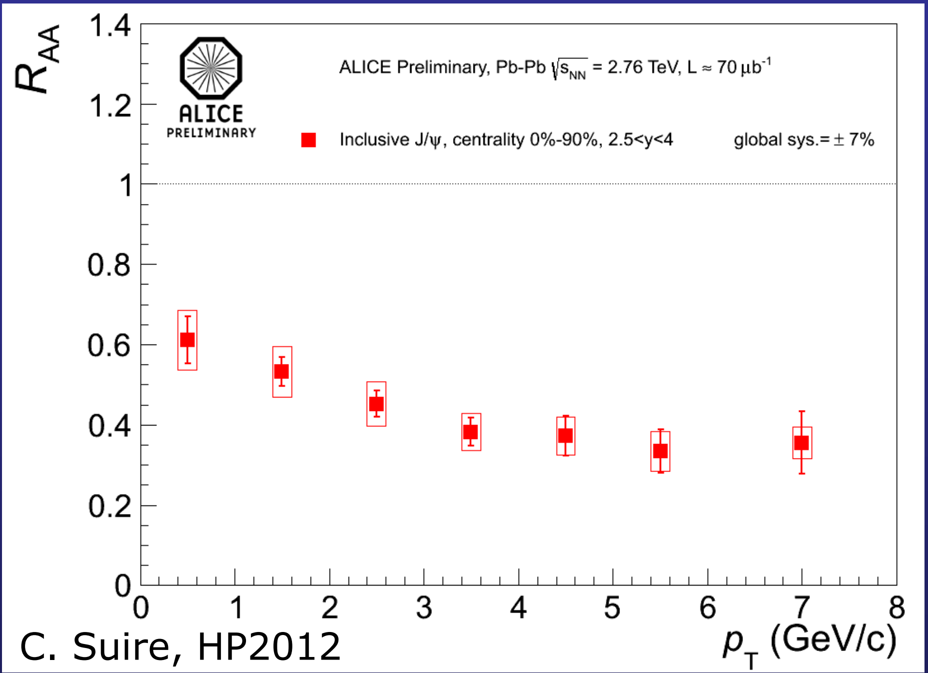
- Smaller R_{AA} for high p_T J/ψ

- 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

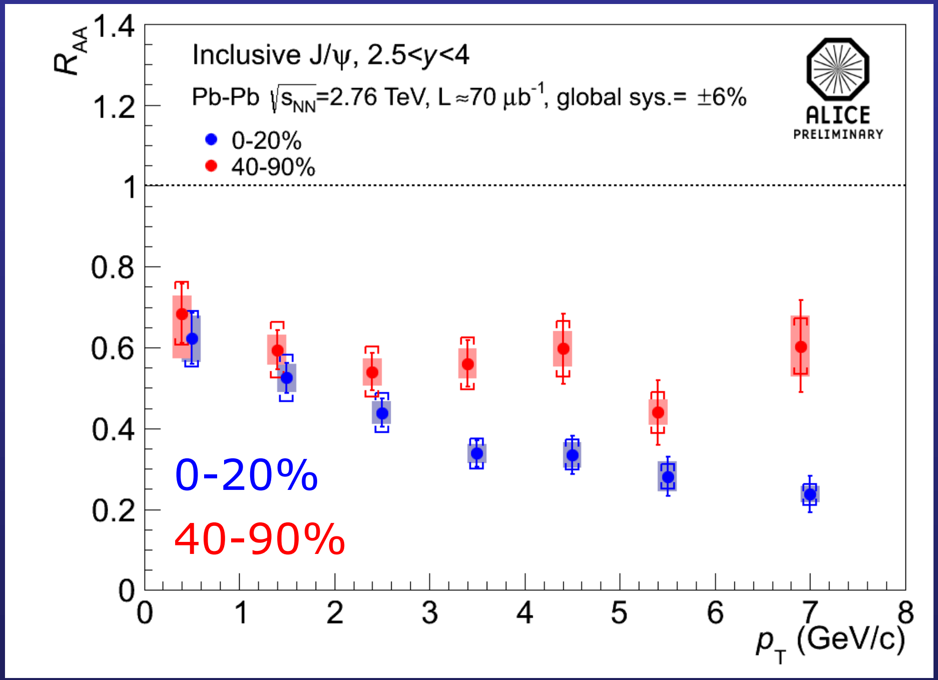
J/ψ R_{AA} vs p_T

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

0-90%



0-20% vs 40-90%



- Suppression is stronger for high-p_T J/ψ (R_{AA}~0.6 at low p_T and ~0.35 at high p_T)

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

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

ALICE

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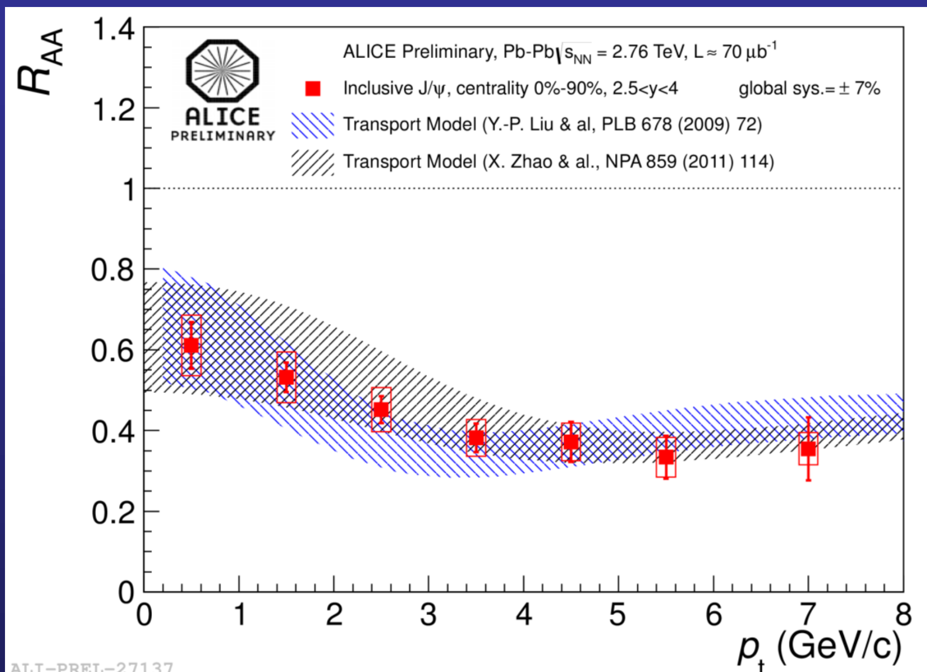

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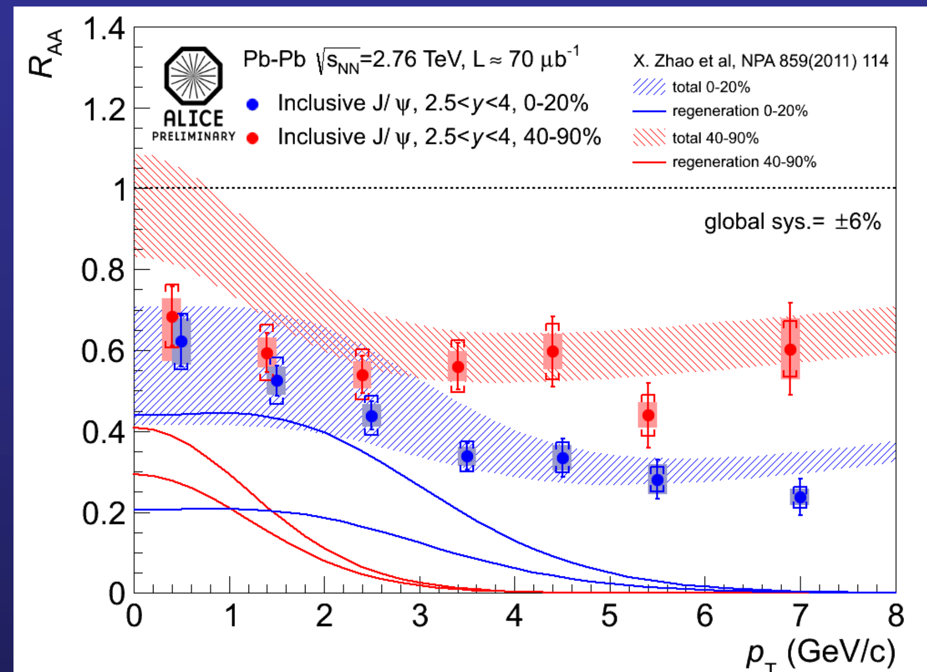

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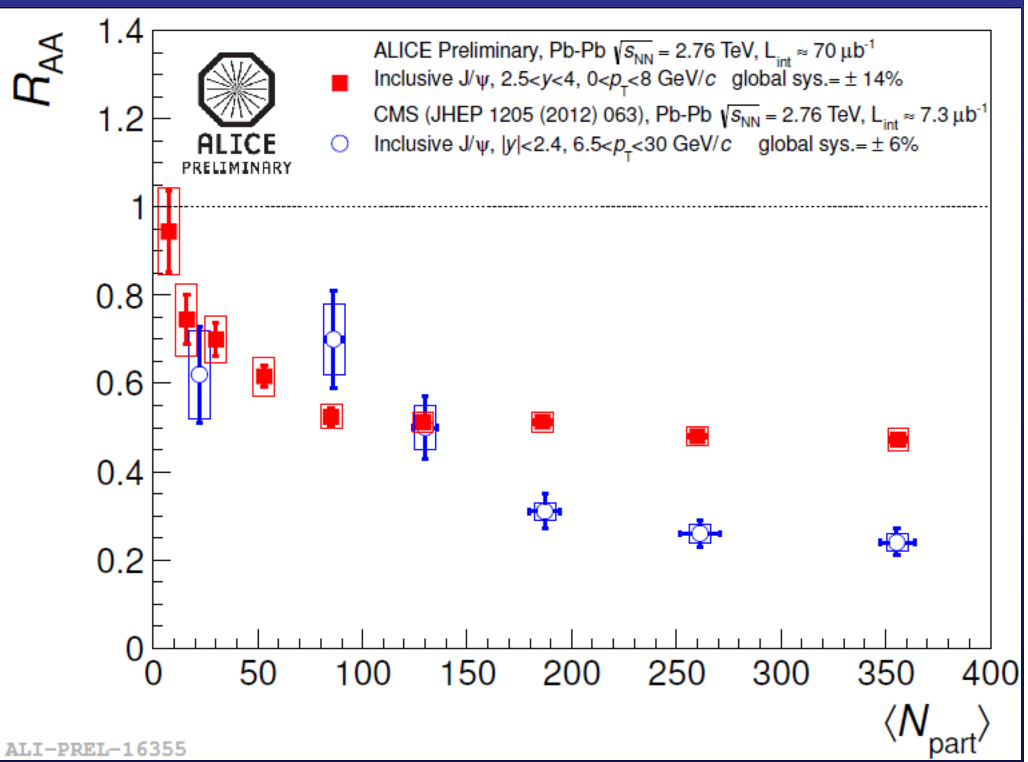
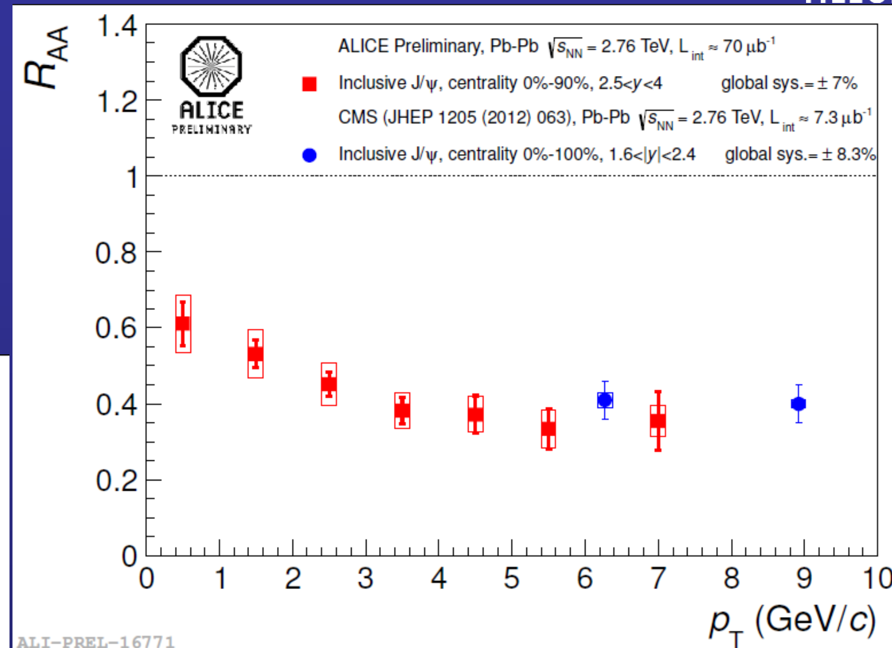
- Splitting in centrality bins we observe that the difference low vs high-p_T suppression is more important for central collisions

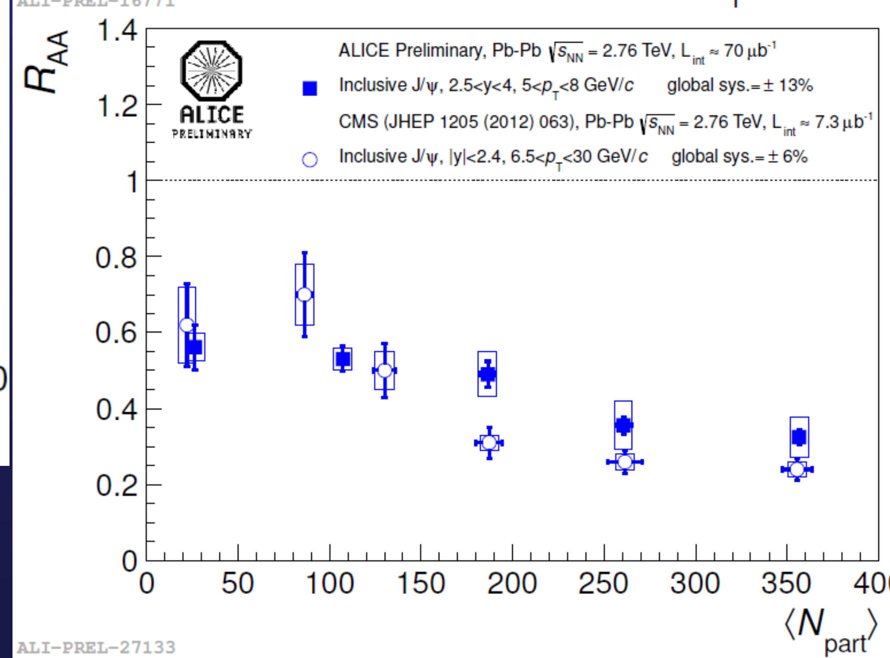
- Fair agreement data vs models with large contribution from (re)combination (slightly worse for peripheral events at low p_T)

What do other LHC experiments tell us ? ALICE vs CMS

- A complementary p_T range is explored by CMS, at $|y|<2.4$
  S. Chatrchyan (CMS) ,JHEP 05(2012) 063

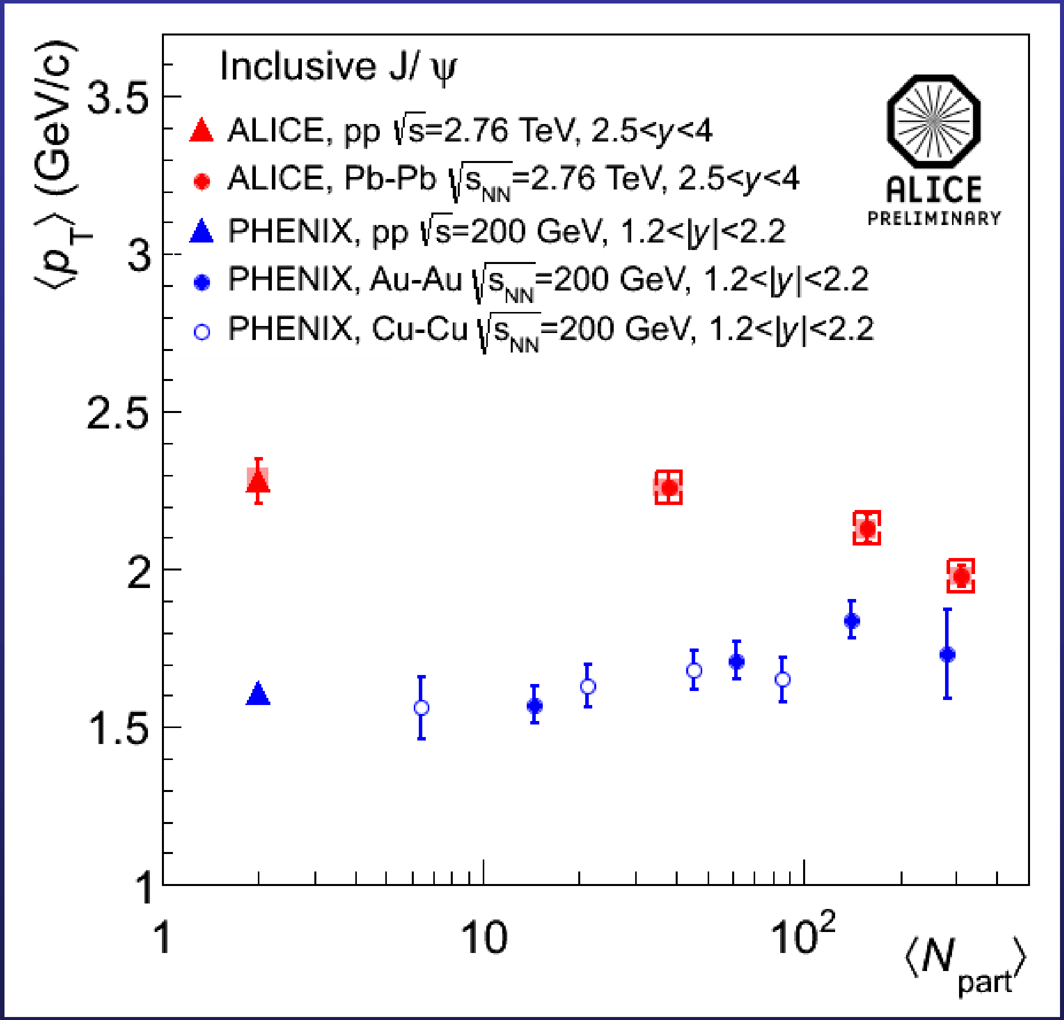






Larger suppression at high p_T, in particular for central events

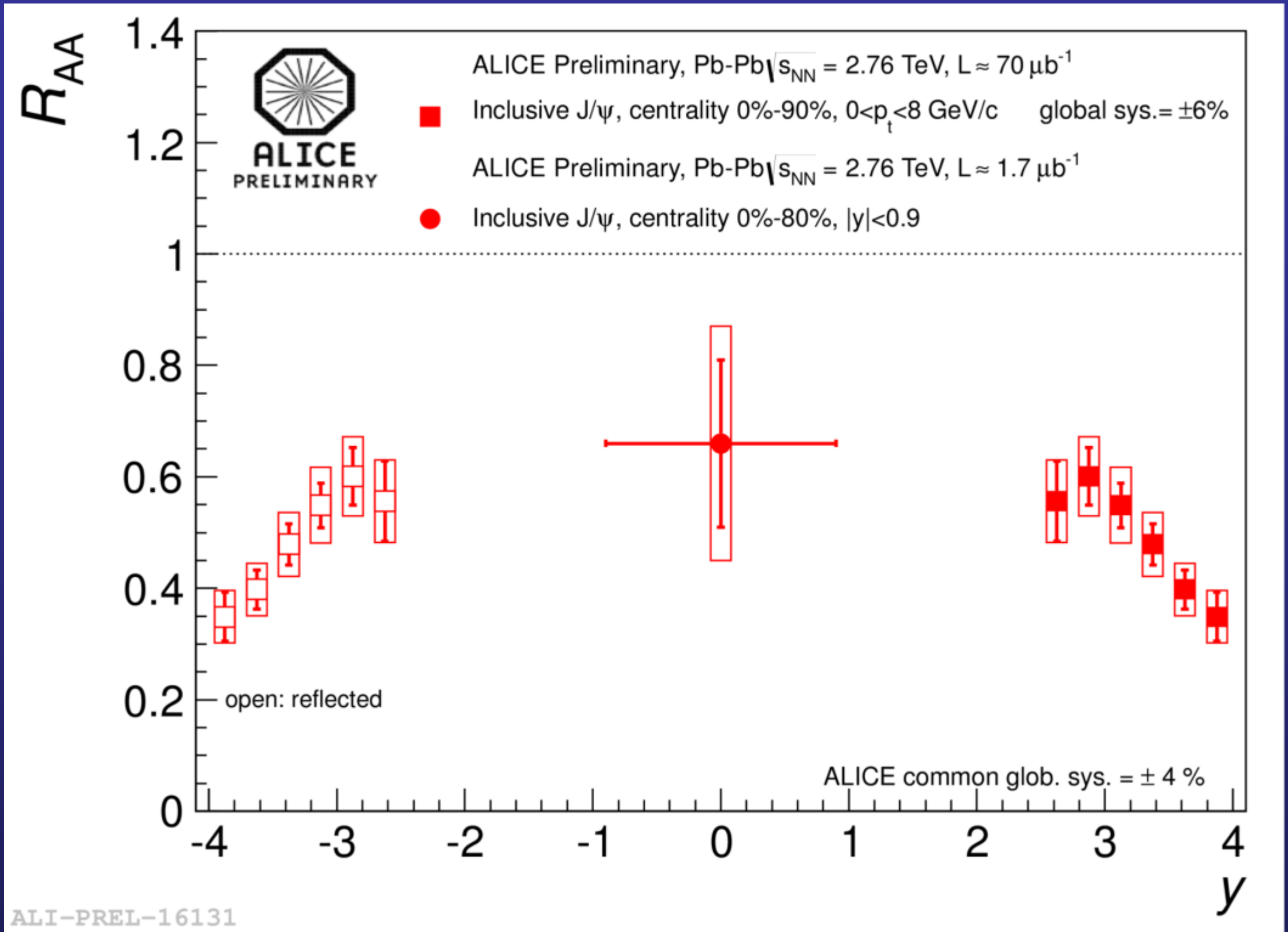
J/ψ ⟨p_T⟩



- The J/ψ <p_T> shows a decreasing trend as a function of centrality, confirming the observation that low-p_T J/ψ are less suppressed in central collisions

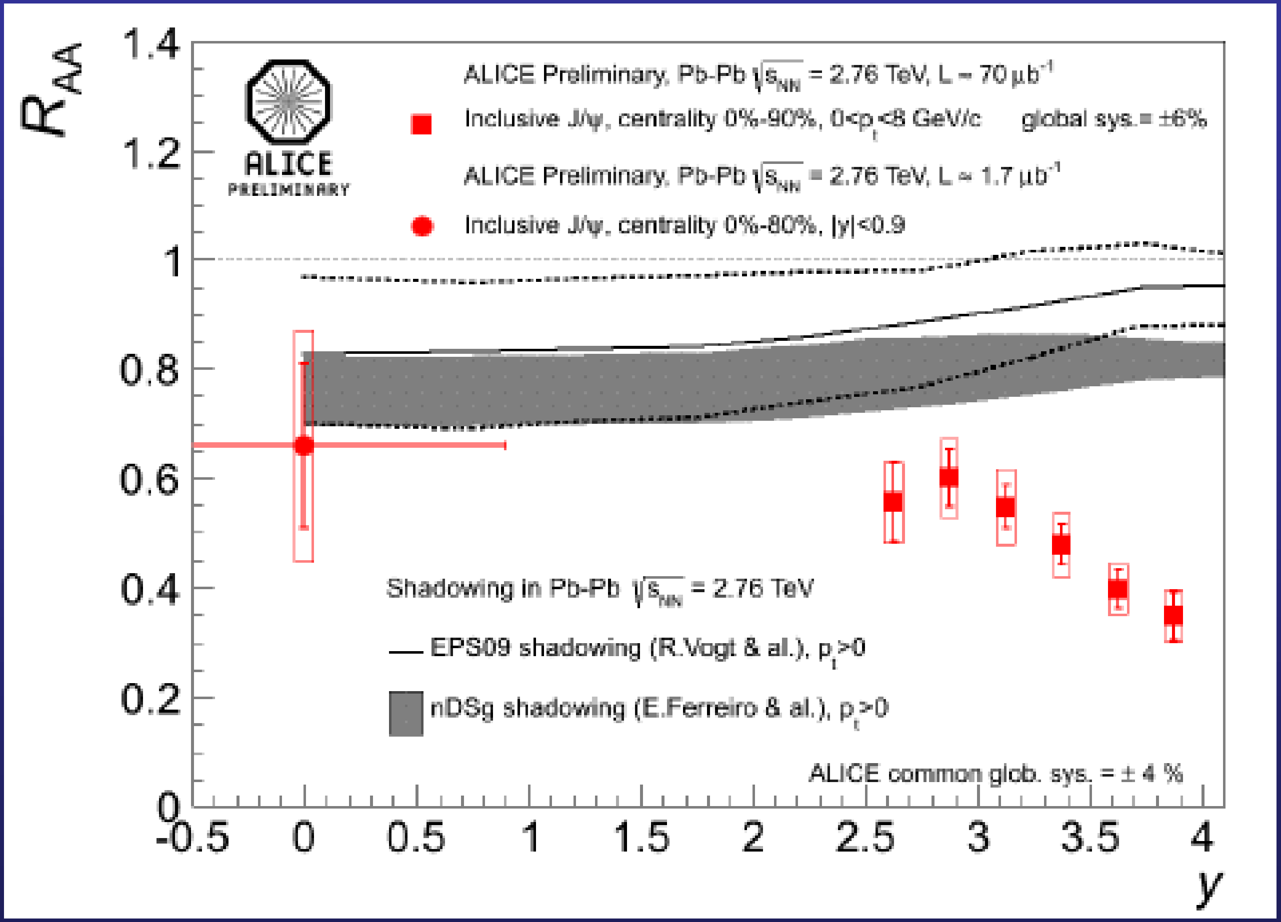
- The trend is different wrt the one observed at lower energies, where an increase of the <p_T> and <p_T^2> with centrality was obtained

J/ψ R_{AA} vs rapidity



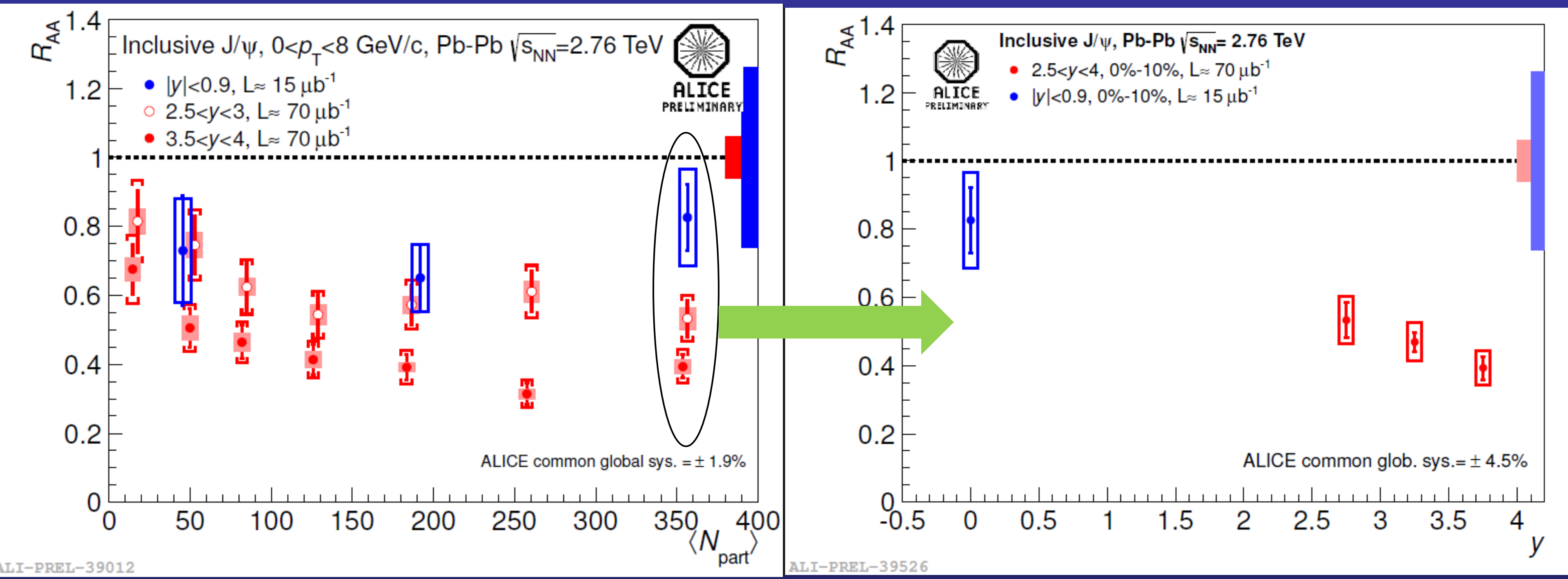
- Inclusive J/ψ measured also as a function of rapidity: R_{AA} decreases by 40% from y=2.5 to y=4

J/ψ R_{AA} vs rapidity



- Inclusive J/ψ measured also as a function of rapidity:
  R_{AA} decreases by 40% from y=2.5 to y=4
- Suppression beyond the current shadowing estimates.
  Important to measure cold nuclear matter effects (incoming pA data taking)

R_{AA} in rapidity bins: "summary"

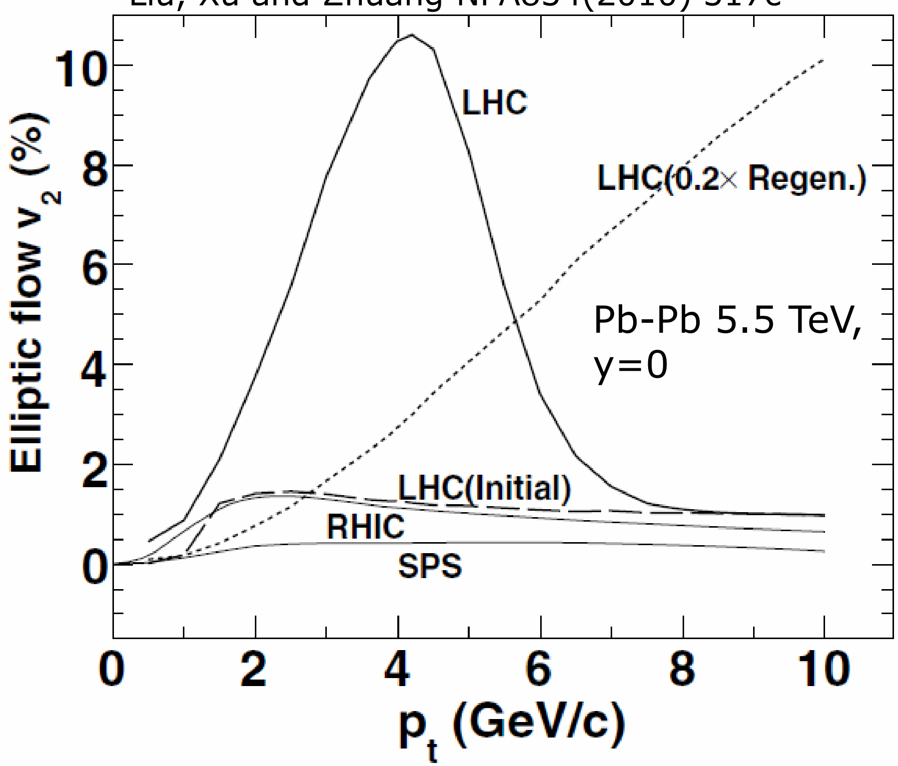


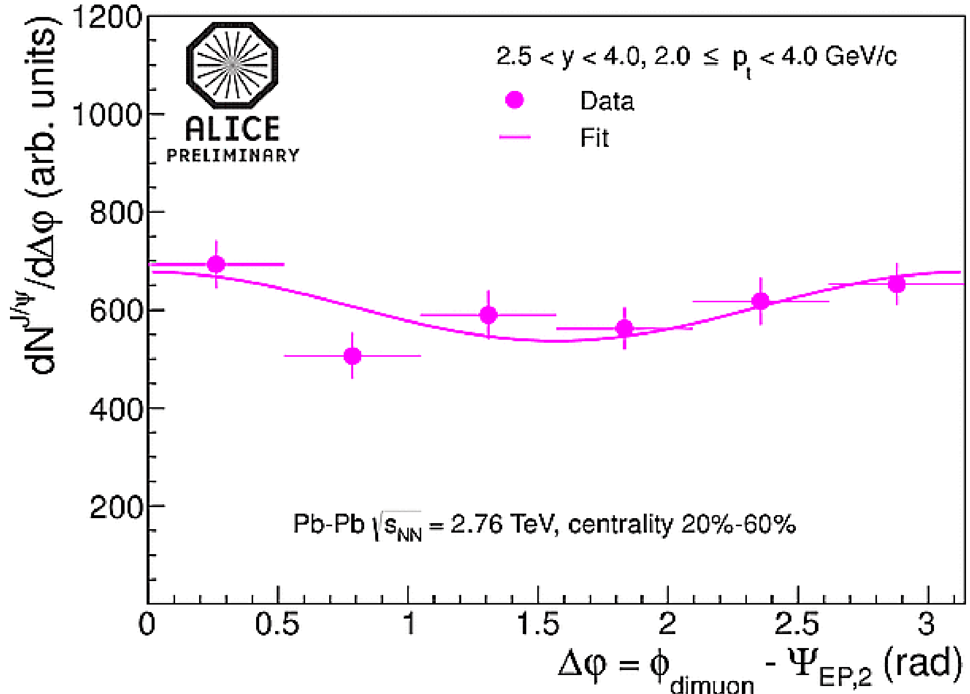
- Hierarchy of suppression (larger at larger y) for central events ?
- A larger statistics in our reference pp data would be essential to sharpen our conclusions!

J/ψ elliptic flow

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

Liu, Xu and Zhuang NPA834(2010) 317c

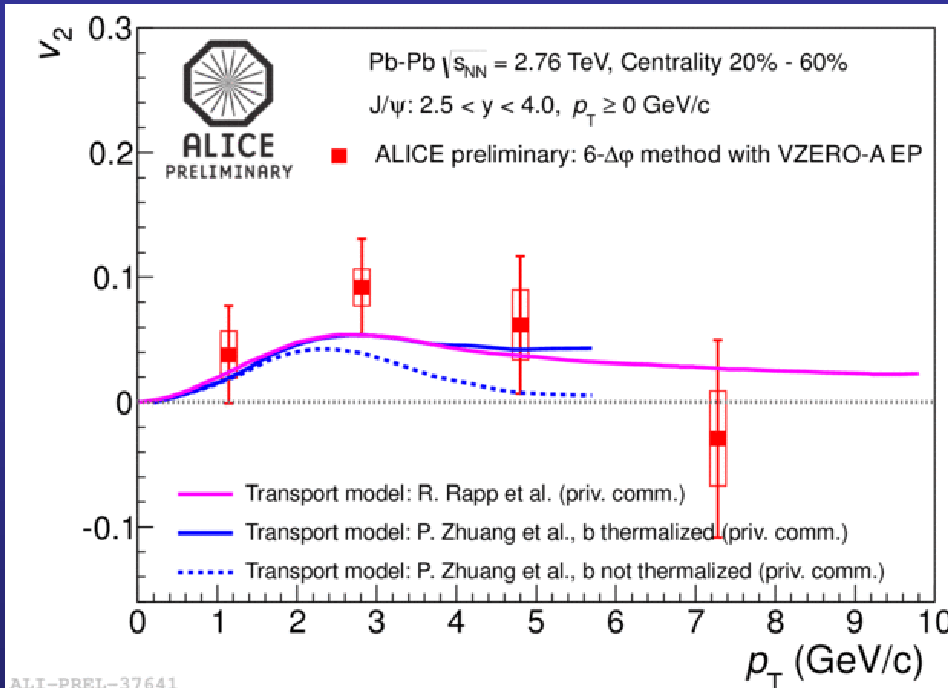


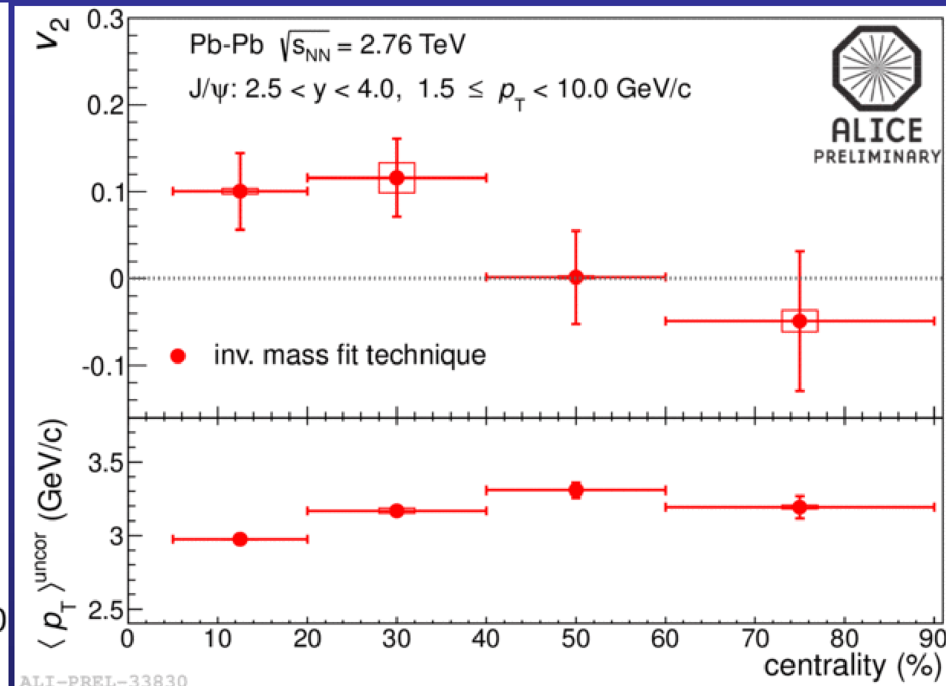


$$dN_{J/\psi}/d\Delta\varphi = A\times\left[1+2v_2^{obs}\cos(2\Delta\varphi)\right]$$

- 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

Non-zero J/ψ elliptic flow at the LHC





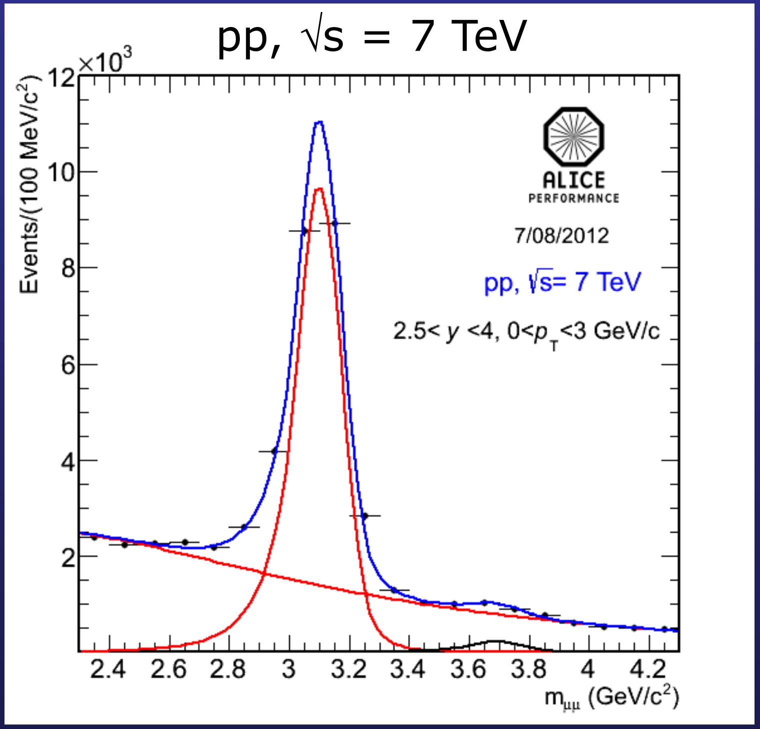
H. Yang et al. (ALICE), QM2012

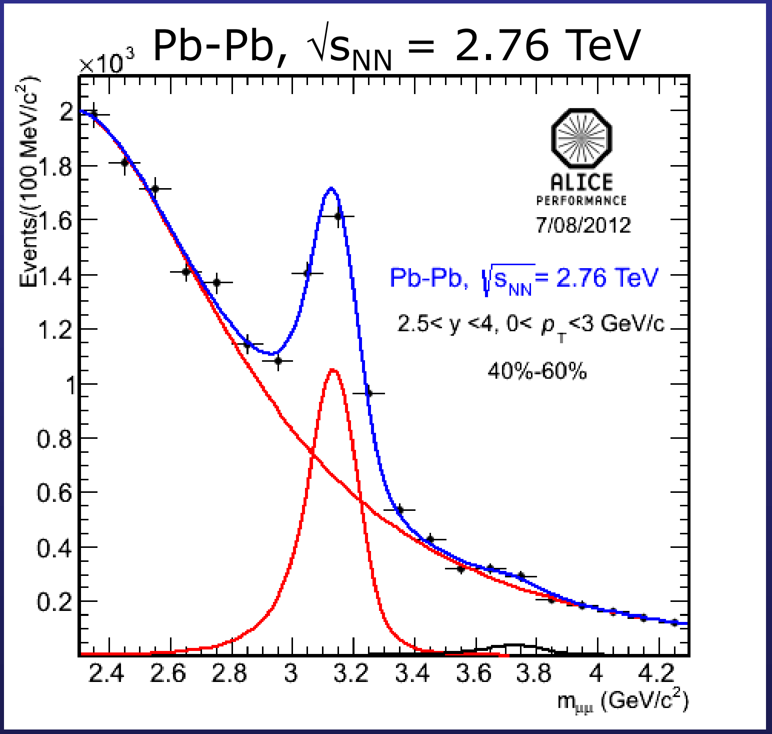
- STAR: v_2 compatible with zero everywhere
- ALICE: hint for non-zero v_2 in both
  - 20-60% central events in $2<p_T<4$ GeV/c
  - 5-20% and 20-40% central events for $1.5<p_T<10$ GeV/c
- Significance up to 3.5 σ for chosen kinematic/centrality selections

- Qualitative agreement with transport models including regeneration
- Complements indications obtained from R_{AA} studies

ψ(2S)

- Study the ψ(2S) yield normalized to the J/ψ one in Pb-Pb and in pp
- Charmonia yields are extracted fitting the invariant mass spectra in two p_T bins: $0<p_T<3$ and $3<p_T<8$ GeV/c and, for Pb-Pb, also as a function of centrality



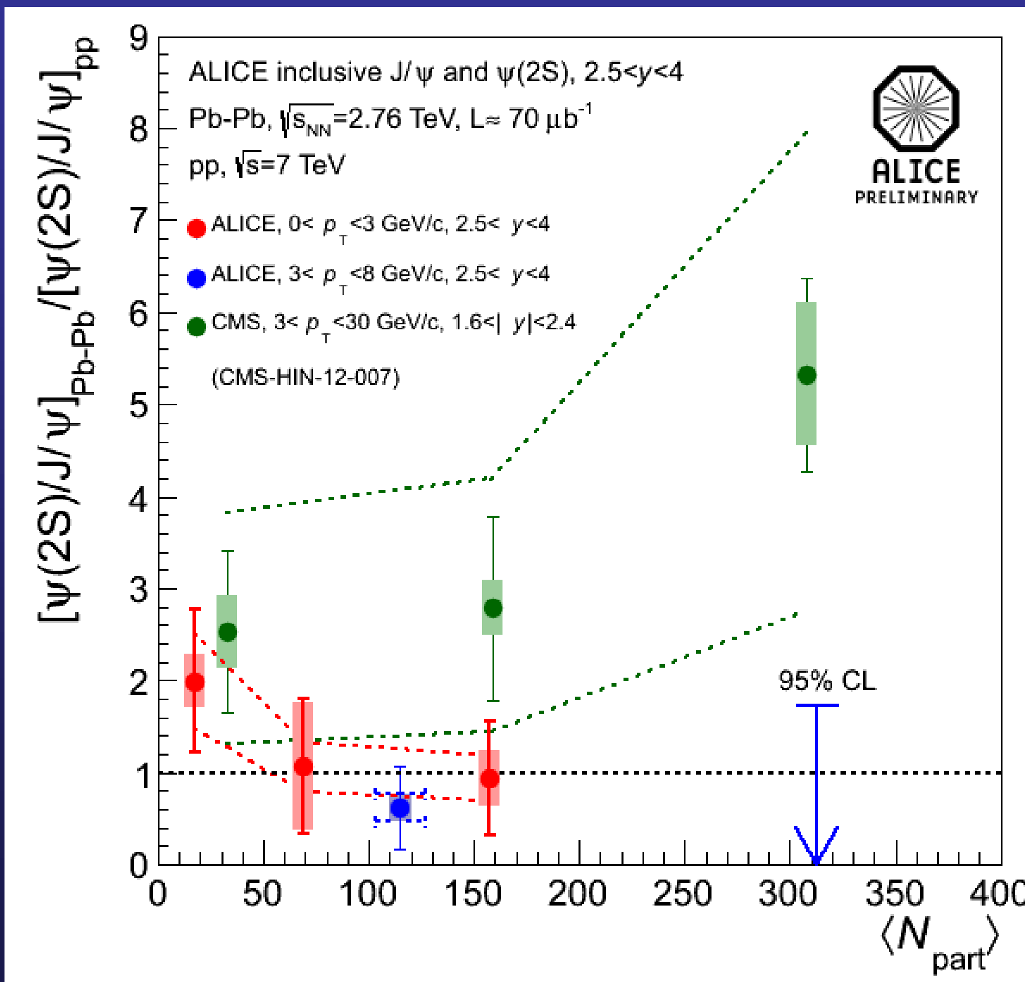


- Pb-Pb: S/B (at 3 σ around the ψ(2S)) varies between 0.01 and 0.3 from central to peripheral collisions

ψ(2S)/J/ψ double ratio

ALICE

- $[\psi(2S)/J/\psi]_{Pb\text{-}Pb}$ / $[\psi(2S)/J/\psi]_{pp}$
  - Use $\sqrt{s}$ = 7 TeV pp data as a reference (small $\sqrt{s}$- and *y*-dependence → accounted for in the syst.uncert.)



- Main systematic uncertainties (some sources cancel)
  - Signal extraction
  - MC inputs for acceptance calculation
- Large statistics and systematic errors prevent a firm conclusion on the ψ(2S) enhancement or suppression versus centrality
- Exclude large enhancement in central collisions

(uncertainty on the reference shown as colored dashed lines in the plot)

C. Mironov (CMS) QM2012, CMS-PAS-HIN-12-007
R. Arnaldi (ALICE) QM2012

Conclusions (1)

- Heavy quarkonia and QGP: after >25 years still a very lively field of investigation, with surprises still possible

- Very strong sensitivity of quarkonium states to the medium created in heavy-ion collisions: interpretation not always easy

- Two main mechanisms at play
  1) Suppression by color screening
  2) Re-generation (for charmonium only!) at high $\sqrt{s}$

  can qualitatively explain the main features of the results

- At the LHC, ALICE has studied J/ψ production in Pb-Pb collisions down to zero p_T

- Measurements complementary to those of the other LHC experiments
  - CMS/ATLAS: J/ψ production at high p_T
  - CMS: study of bottomonium production
    - Extremely relevant, not covered here: first ALICE results expected soon

Conclusions (2)

- Main findings from ALICE
  - R_{AA} exhibits a weak centrality dependence at all y and is larger than at RHIC
  - Less suppression at low p_T with respect to high p_T , with stronger p_T dependence for central events
  - Lower energy experiments show an opposite behaviour (see $\langle p_T \rangle$ vs $\langle N_{part} \rangle$)
  - Stronger suppression when rapidity increases
  - First measurement of J/ψ elliptic flow at the LHC, indications of non-zero v_2
  - First look at low-p_T ψ(2S) in Pb-Pb at the LHC
- Models including J/ψ production via (re)combination describe ALICE results on R_{AA} and v_2
- Future of quarkonia studies at the LHC
  - multi-differential suppression studies (already started)
  - cold nuclear matter at LHC
  - full LHC energy (and increased luminosity)
  - complete characterization of excited states in the QGP

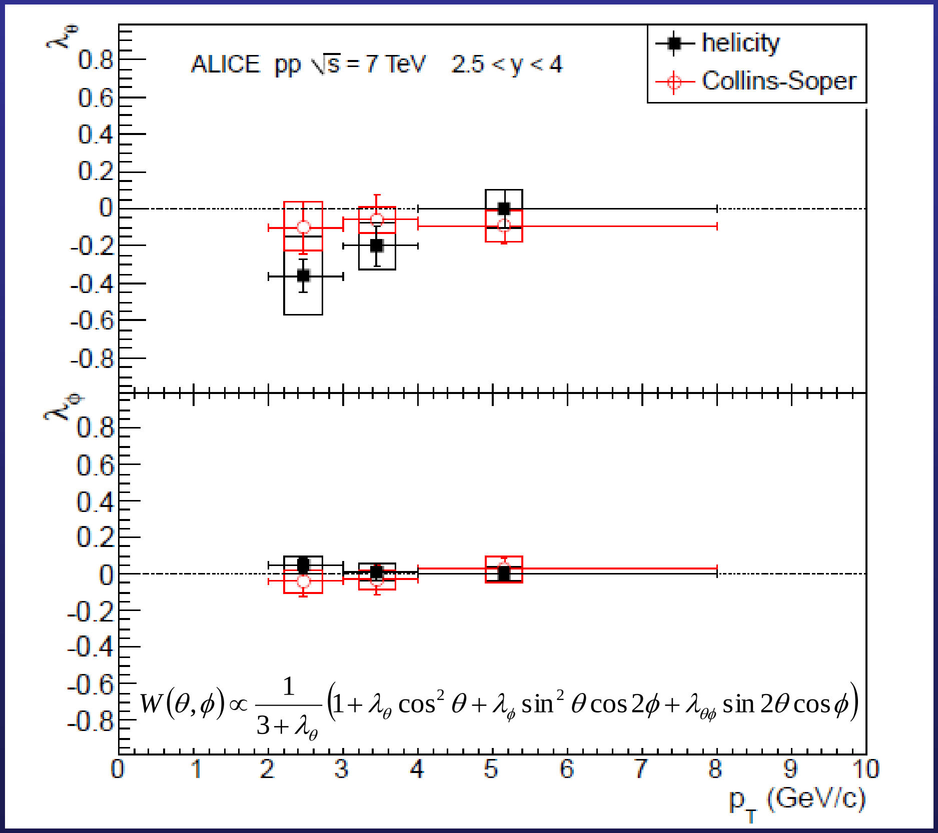
BACKUP

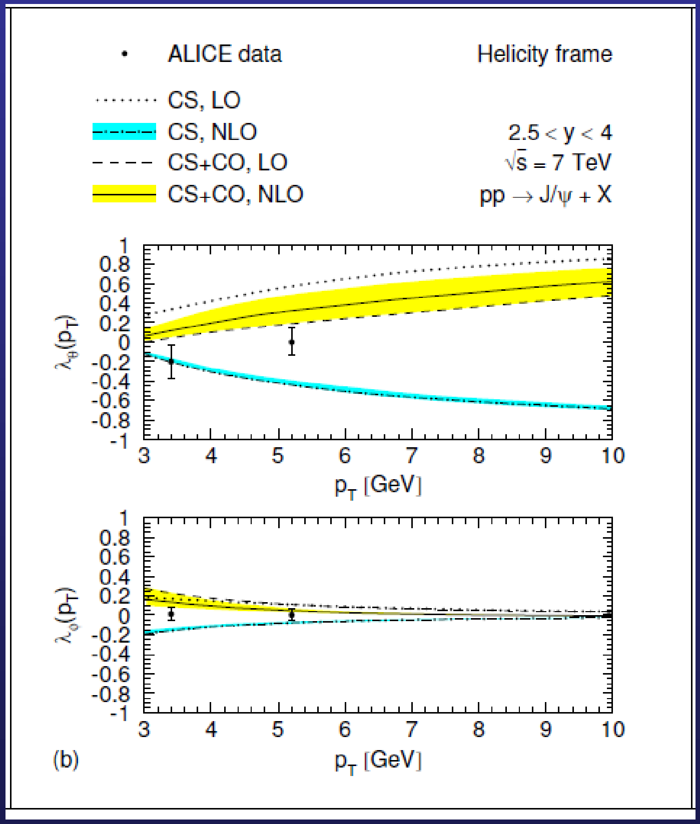
J/ψ polarization results

- Discriminate among the different theoretical models of J/ψ production
- Long-standing puzzle with CDF results

ALICE Coll., PRL 108(2012) 082001

M.Butenschoen, A.Kniehl, PRL. 108(2012), 172002



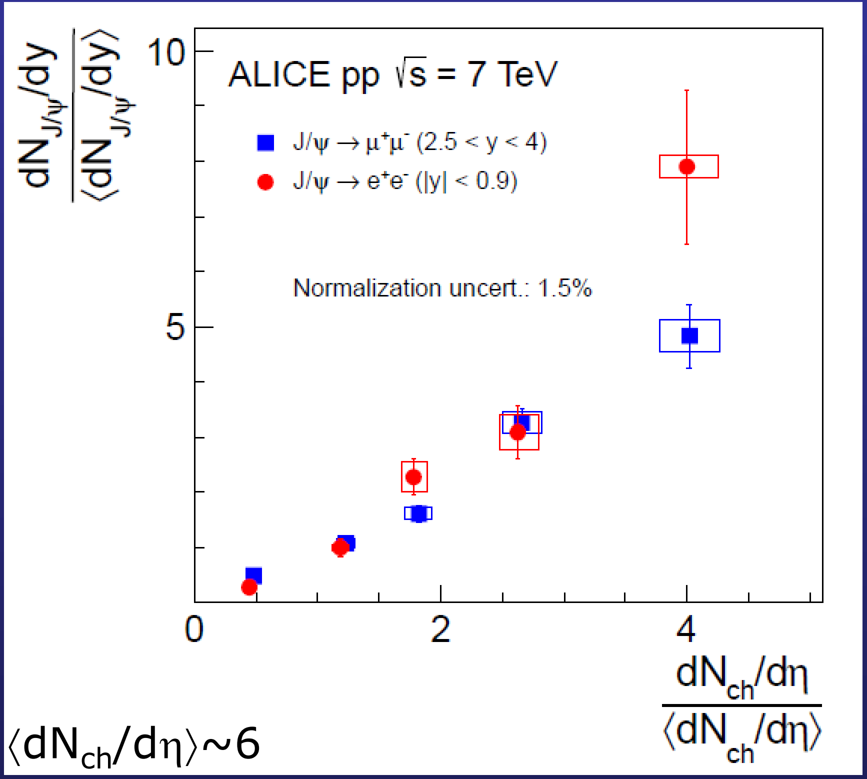


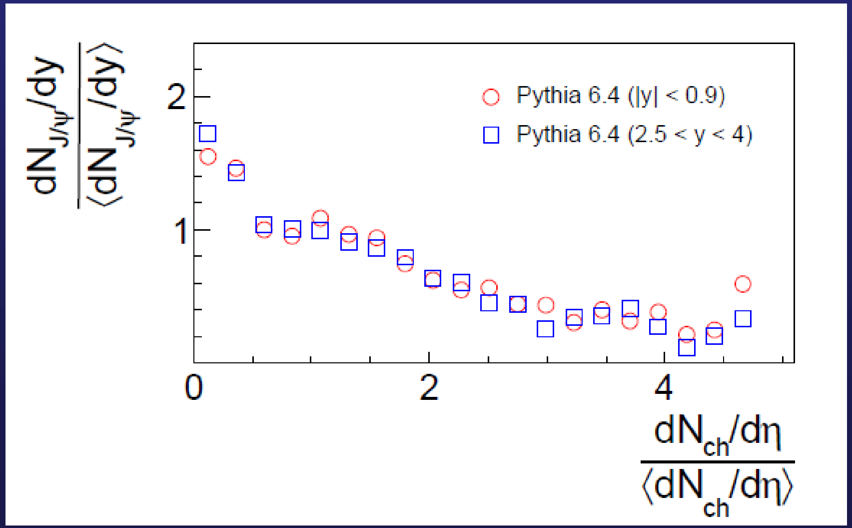
- First result at LHC energy: almost no polarization for the J/ψ
- First theoretical calculation (NLO NRQCD) compared to data: promising result, reasonable agreement with theory

Multiplicity dependence in pp

- Highest charged particle multiplicity ($dN_{ch}/d\eta$ ~30) in this analysis comparable with Cu-Cu collisions (50-55%) at RHIC

- Relative J/ψ yield increases linearly with the relative multiplicity
- Help to understand the interplay between hard and soft interactions in the context of multi-partonic interactions (MPI), and/or underlying event

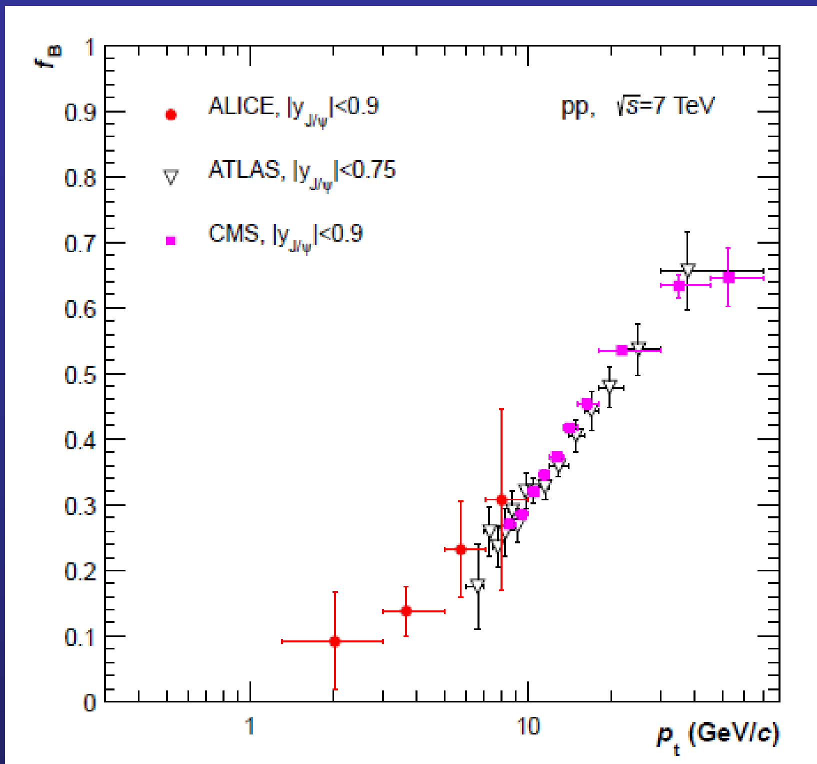


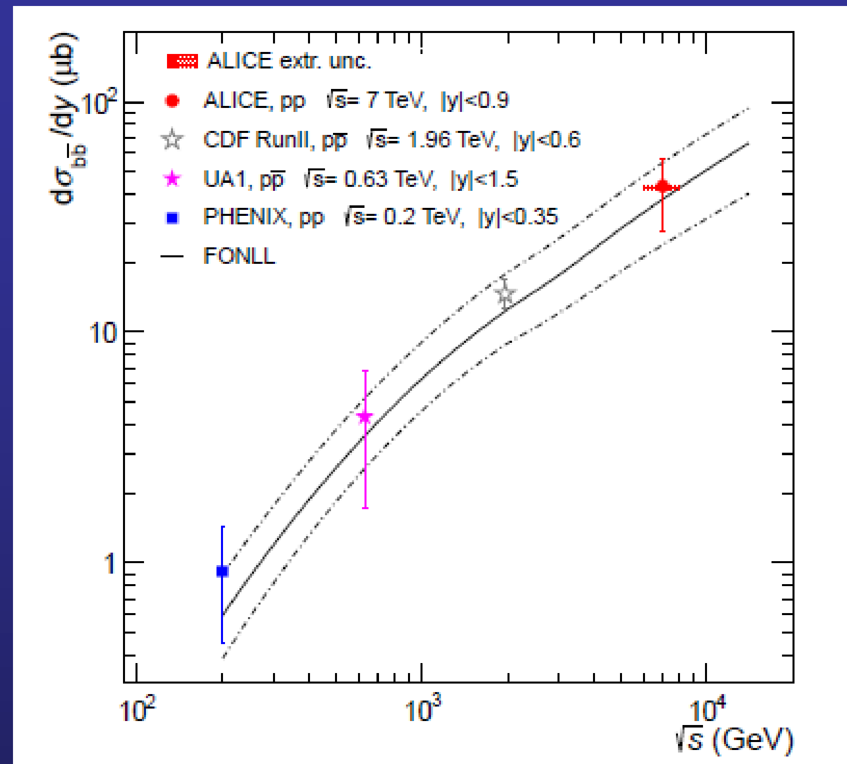


- Model predictions (PYTHIA) do not reproduce data
- Study ongoing with other particles, e.g. D-mesons

B. Abelev et al., ALICE Coll., Phys. Lett. B712(2012) 165

Prompt J/ψ and beauty cross section



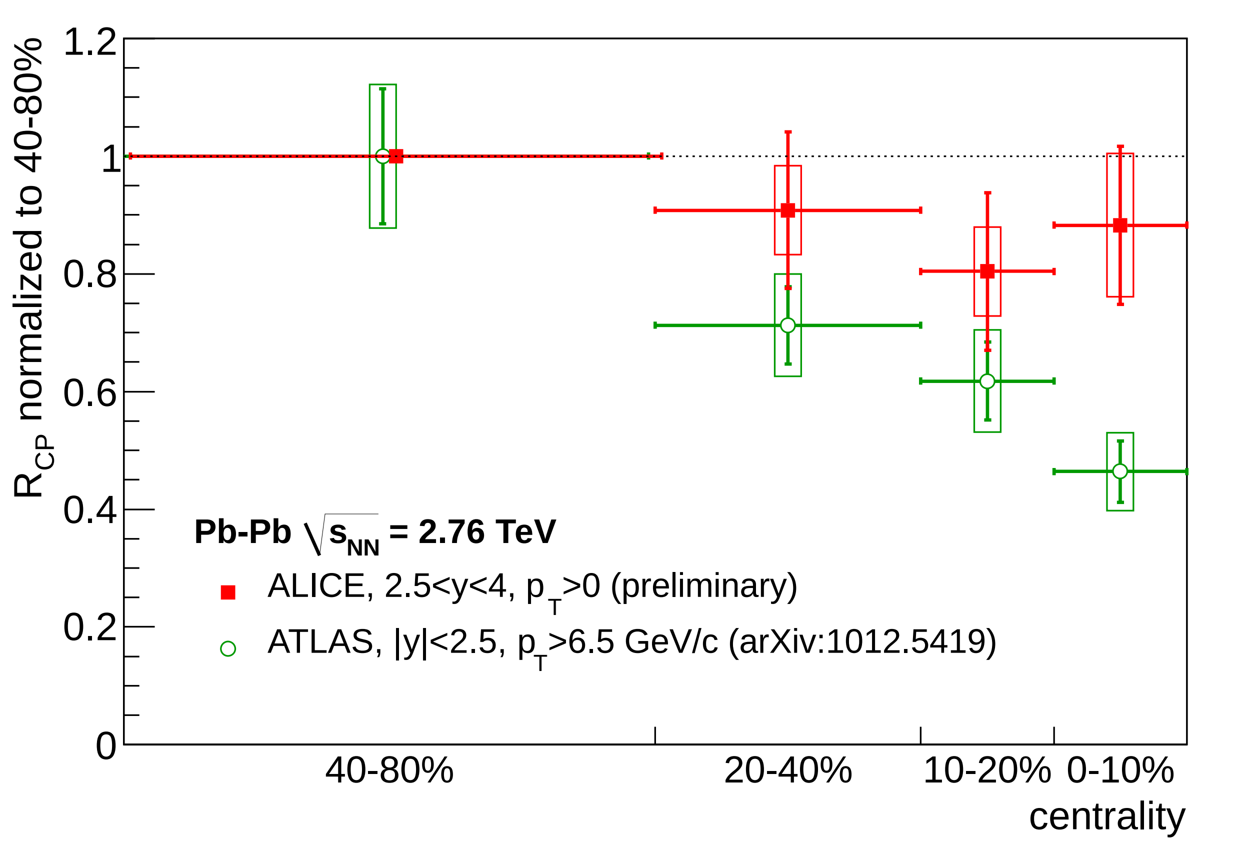


B. Abelev et al. (ALICE),arXiv:1205.5880

- Fraction of J/ψ yield from b-decays , by studying pseudo-proper decay length distribution
- ALICE: p_T>1.3 GeV/c, |y|<0.9 (complementary to other LHC exp.)
- Total beauty cross section (in agreement with LHCb results)

$$\sigma(pp \rightarrow bb + X) = 282 \pm 74\,(\text{stat.})\,^{+58}_{-68}\,(\text{syst.})\,^{+8}_{-7}\,(\text{extr.})\;\mu b$$

What do other LHC experiments tell us ? ALICE vs ATLAS



$$R^i_{CP} = \frac{Y^i_{J/\psi} \times < T^{40-80\%}_{AA} >}{< T^i_{AA} > \times Y^{40-80\%}_{J/\psi}}$$

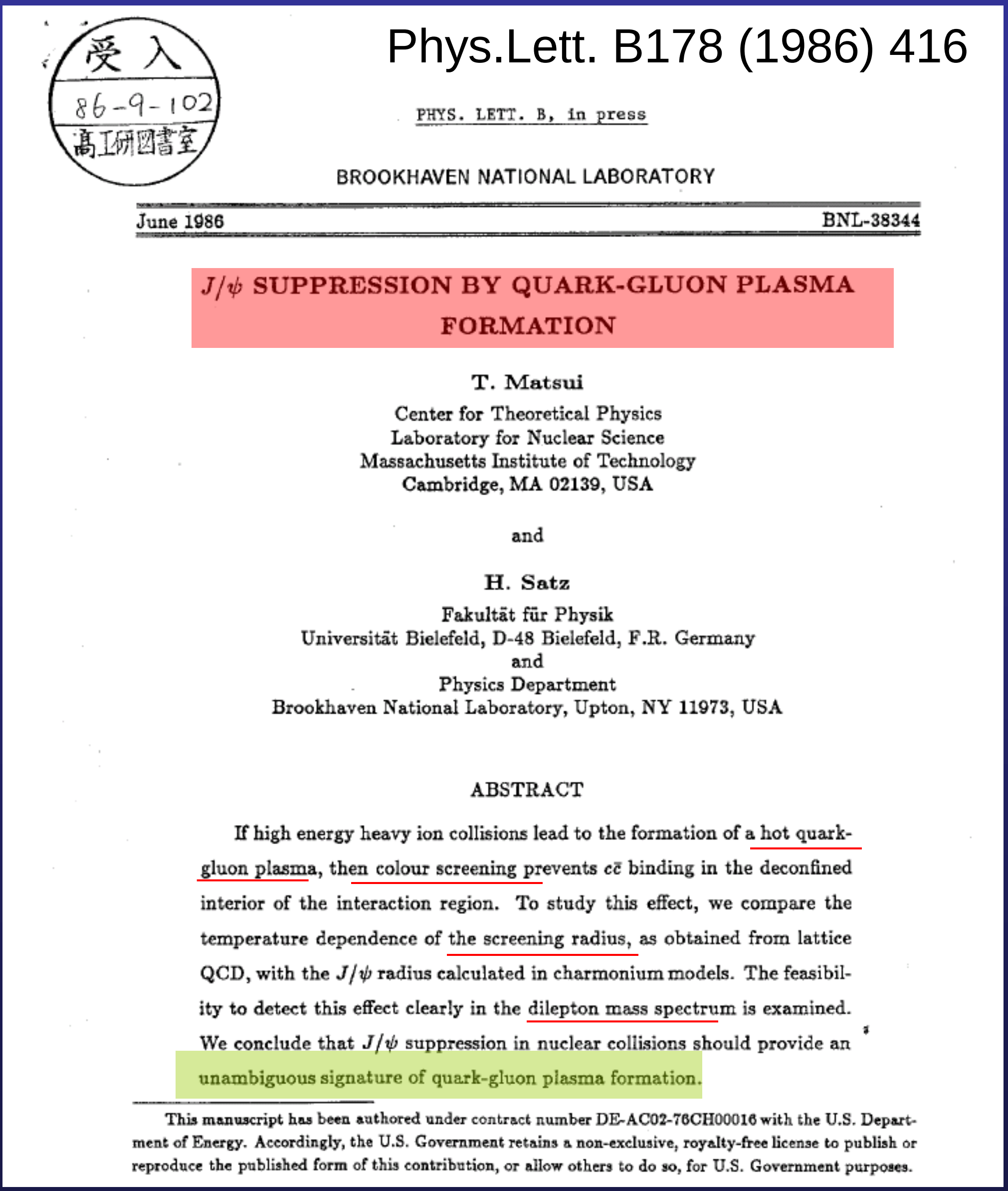
ALICE:
- 2.5<y<4
- p_T > 0

ATLAS:
- |y|<2.5
- 80% of J/ψ with p_T > 6.5 GeV/c

P. Pillot (ALICE), QM2011
G. Aad eta l. (ATLAS), PLB697 (2011) 294

- J/ψ R_{CP} larger for ALICE than for ATLAS in the most central collisions… but, as for CMS, p_T coverage is different (and y too)

How the whole story began…



Phys.Lett. B178 (1986) 416

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui
Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

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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First paper on the topic
→ 1986, Matsui and Satz

The most famous paper in our field (1570 citations!)

Keywords

1) Hot quark-gluon plasma
2) Colour screening
3) Screening radius
4) Dilepton mass spectrum

Unambiguous signature of QGP formation