Challenges in quarkonium suppression studies at LHC

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Quarkonium production: Probing QCD at LHC,
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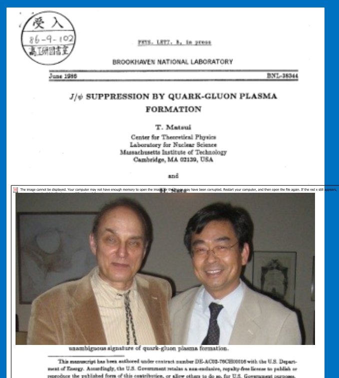
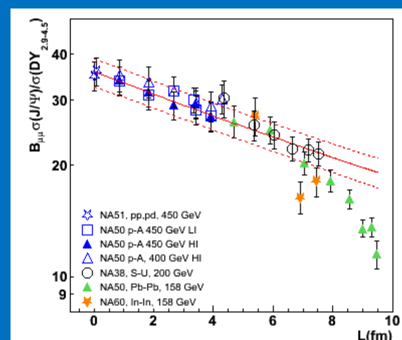
Quarkonium suppression in AA collisions

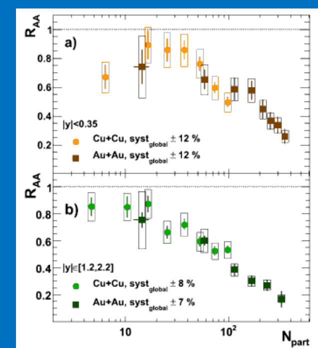
- Quarkonium suppression is considered since a long time as one of the most striking signatures for the QGP formation



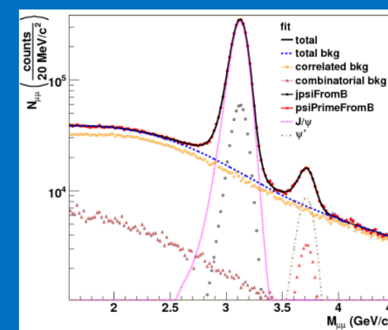
SPS



RHIC



LHC



√s — 17 GeV/c — 200 GeV/c — 2.76 TeV/c →

years — 1990 — ~2000 — 2010 →

- Quarkonium study in AA collisions is already a 25 years long story. Many results were provided by SPS and RHIC experiments, but the picture is yet not clear!
  - Can the LHC play a leading role in quarkonium suppression studies, providing an answer to the open questions?

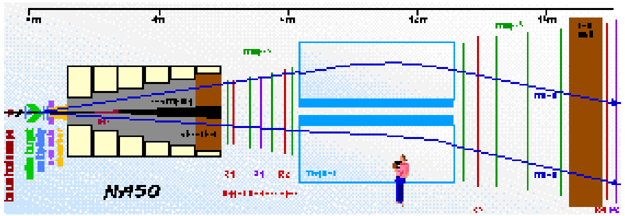
SPS heavy ion experiments

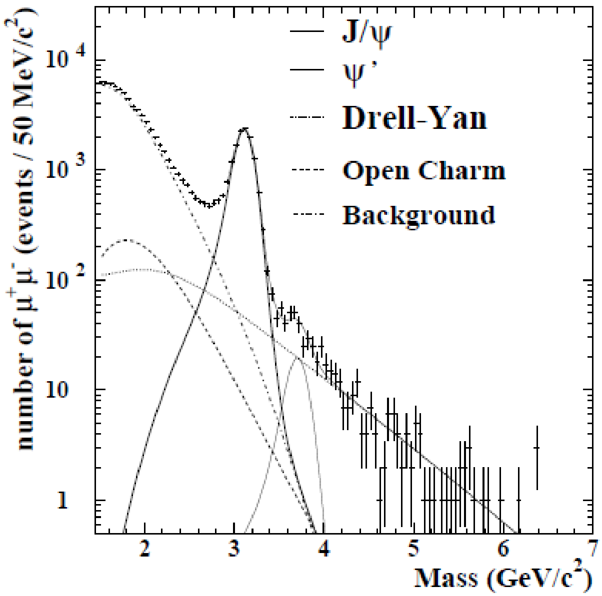
- A long heavy-ion program has been carried out at SPS and several experiments (NA38, NA50, NA60) were focused on charmonia study

NA50

Several years of data taking (1996-2000)

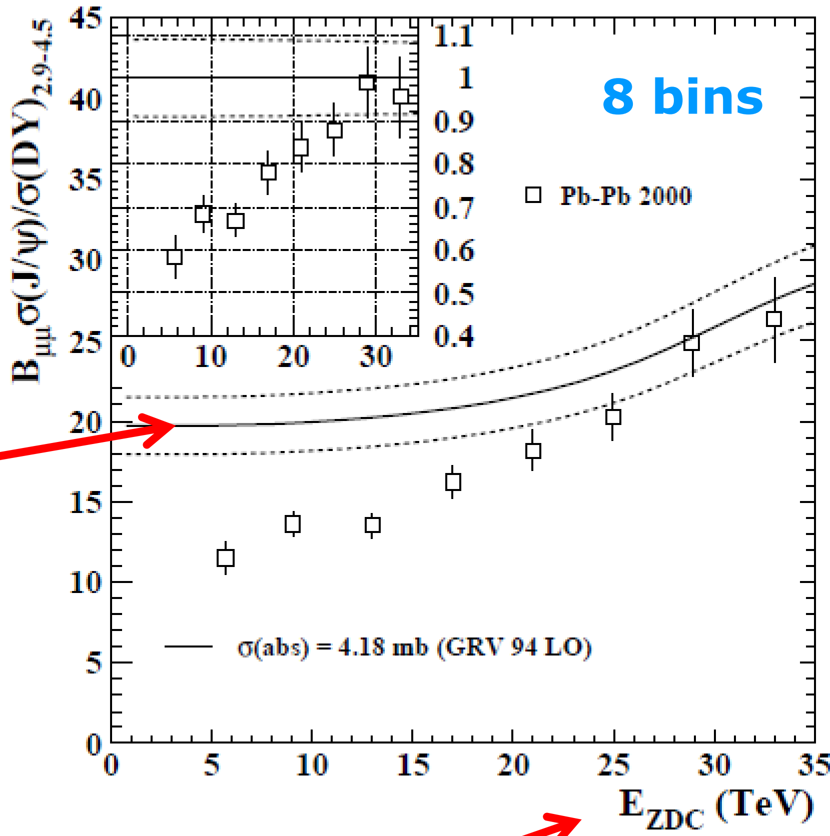
- PbPb collisions @ 158 GeV
- Number of collected J/ψ
  - 1995 → ~ 50000
  - 1996 → ~ 190000
  - 1998 → ~ 40000
  - 2000 → ~ 100000
- J/ψ width ~ 100 MeV/c^2





How NA50 studied J/ψ suppression?

- J/ψ suppression studied comparing J/ψ yield to the Drell-Yan one
  - Advantage: DY insensitive to the medium, efficiency and luminosity terms cancel out in the ratio
  - Drawback: the small Drell-Yan statistics limits the number of centrality bins



- Reference for the "anomalous" suppression is the J/ψ behaviour in cold nuclear matter, extracted from pA data

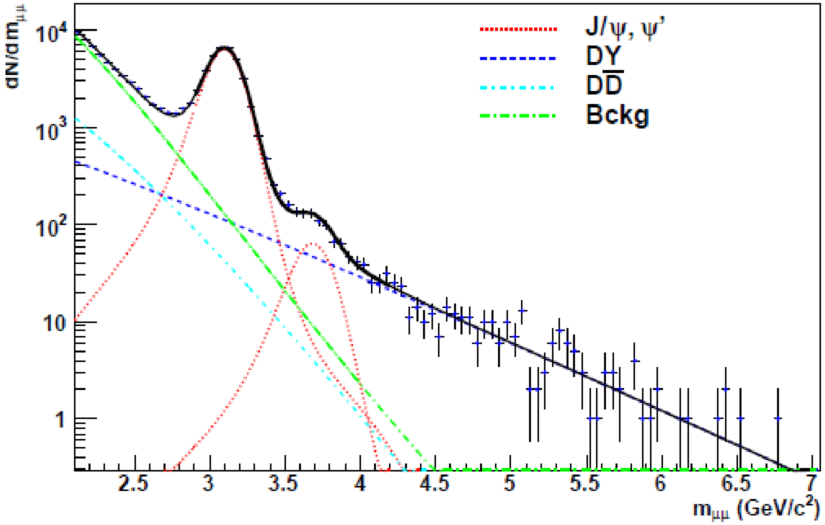
- Results presented as a function of several centrality estimators
  - Idea was to understand the variable driving the suppression

One step further: the NA60 experiment

NA60 Based on the NA50 experimental apparatus improved with a pixel vertex detector in the target region

➡ High quality data, thanks to the improved experimental apparatus

- ~30000 J/ψ
- J/ψ width ~70MeV
- ~5% background+DY under the J/ψ

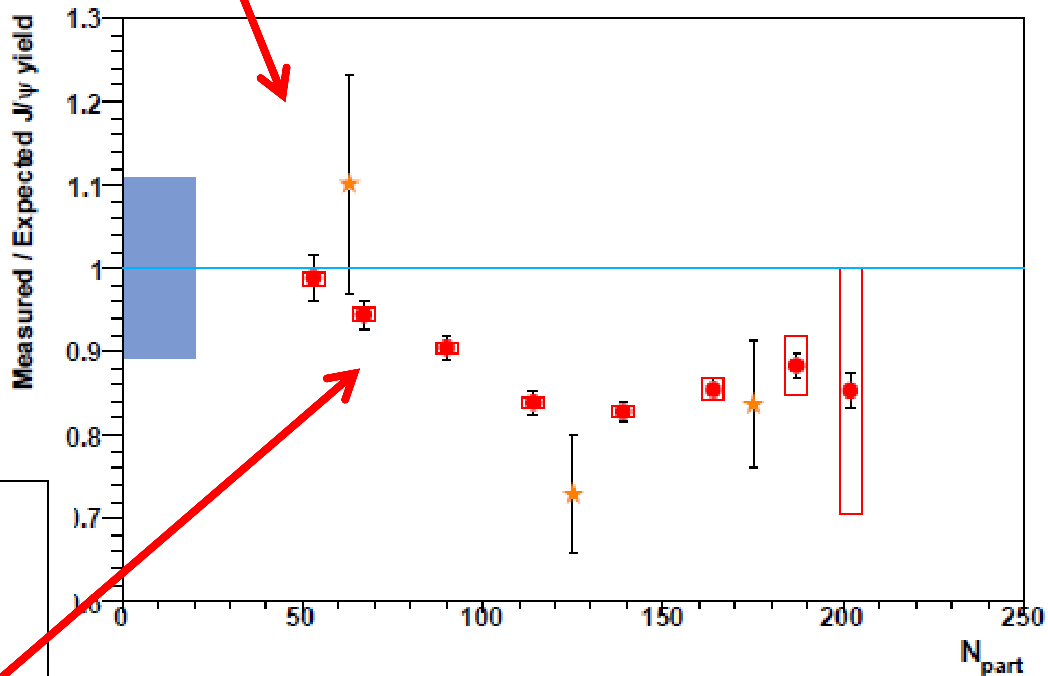


➡ Lighter colliding system: In-In @ 158GeV

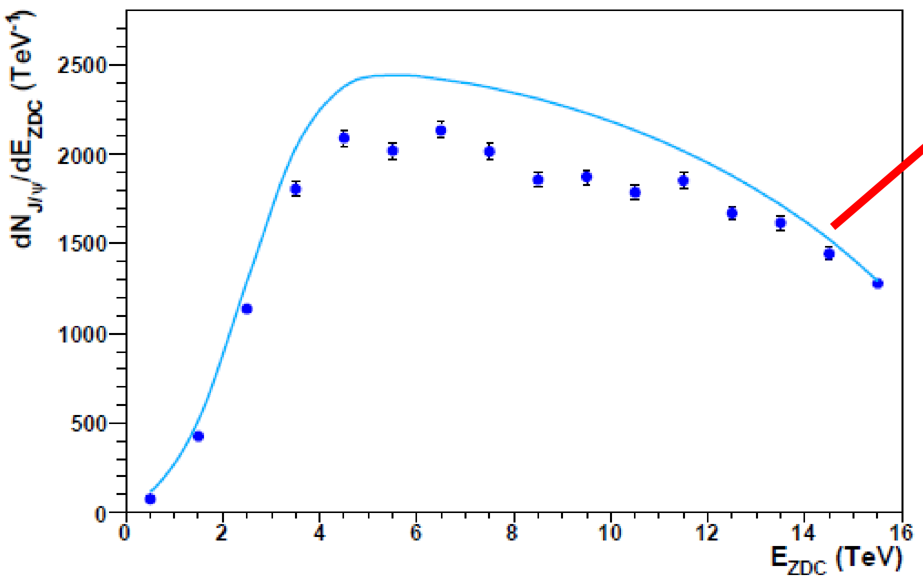
to get further insight in the J/ψ suppression comparing lighter and heavier systems at the same energy

How NA60 studied J/ψ suppression?

- Not enough Drell-Yan statistics (~300 ev. $M>3.2$ GeV/c^2) to study the centrality dependence of the J/ψ/DY ratio



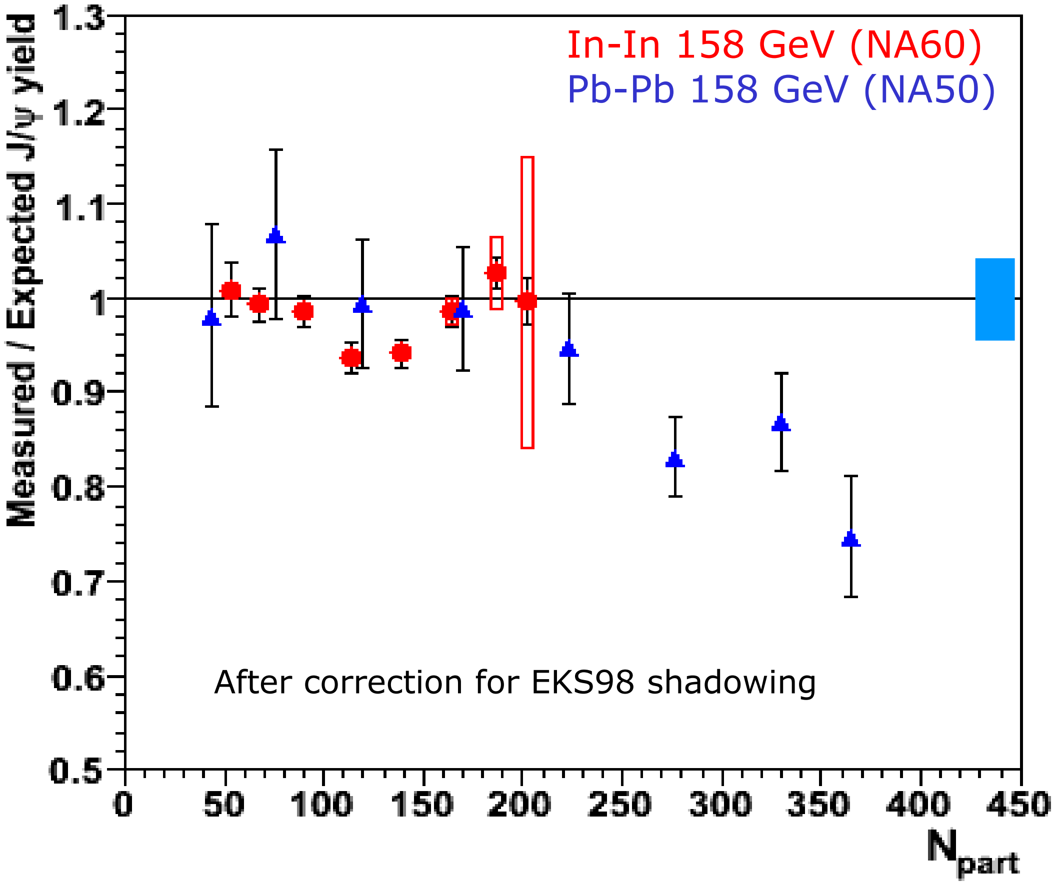
- The J/ψ centrality dependence is directly compared to theoretical expectation based only on cold nuclear matter effects (Glauber calculation)



SPS results

Let's compare NA50 and NA60 final results:

To understand anomalous suppression, the reference determination is crucial → important step further with the reference based on NA60 pA data @ 158GeV, the same energy of the AA data



- Anomalous suppression visible for central PbPb collisions
- Agreement between PbPb and InIn in the common Npart region
- PbPb data not precise enough to clarify the details of the pattern!

J/ψ studies at RHIC

PHENIX/STAR

Similar strategy as the one adopted at SPS:

AuAu @ $\sqrt{s}$=200GeV
CuCu @ $\sqrt{s}$=200GeV ← lighter system
pp @ $\sqrt{s}$=200GeV ← for reference
dAu @ $\sqrt{s}$=200GeV ← to determine cold nuclear matter effects

PHENIX $J/\psi \to e^+e^-$ $|y|<0.35$ & $J/\psi \to \mu^+\mu^-$ $|y| \in [1.2, 2.2]$

STAR $J/\psi \to e^+e^-$ $|y|<1$

➡ Results based on a smaller statistics wrt SPS

- ~ 15000 J/ψ in the forward region
- ~ 1000 J/ψ at midrapidity

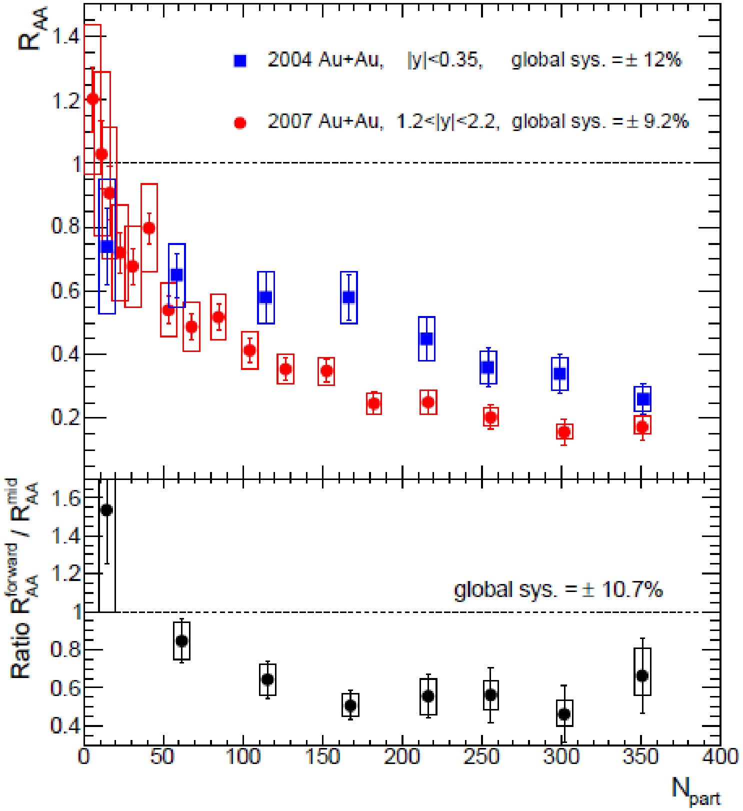
arXiv:1103.6269

➡ The J/ψ suppression is studied through the nuclear modification R_{AA} or the R_{CP} factors

➡ Recent comparison with dAu data, in order to account for cold nuclear matter effects in AuAu

RHIC results

arXiv:1103.6269

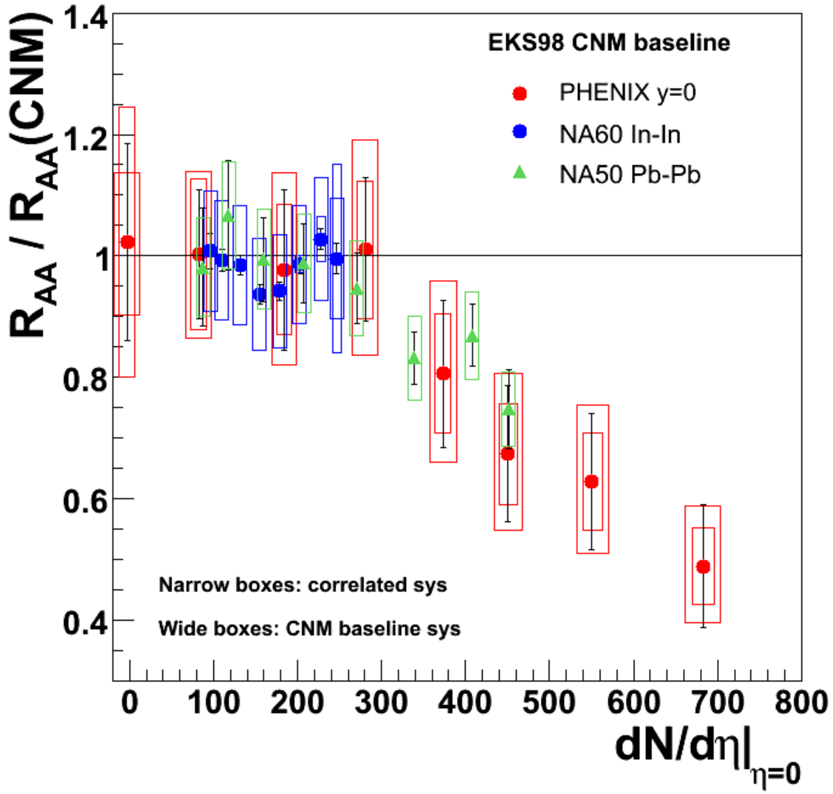


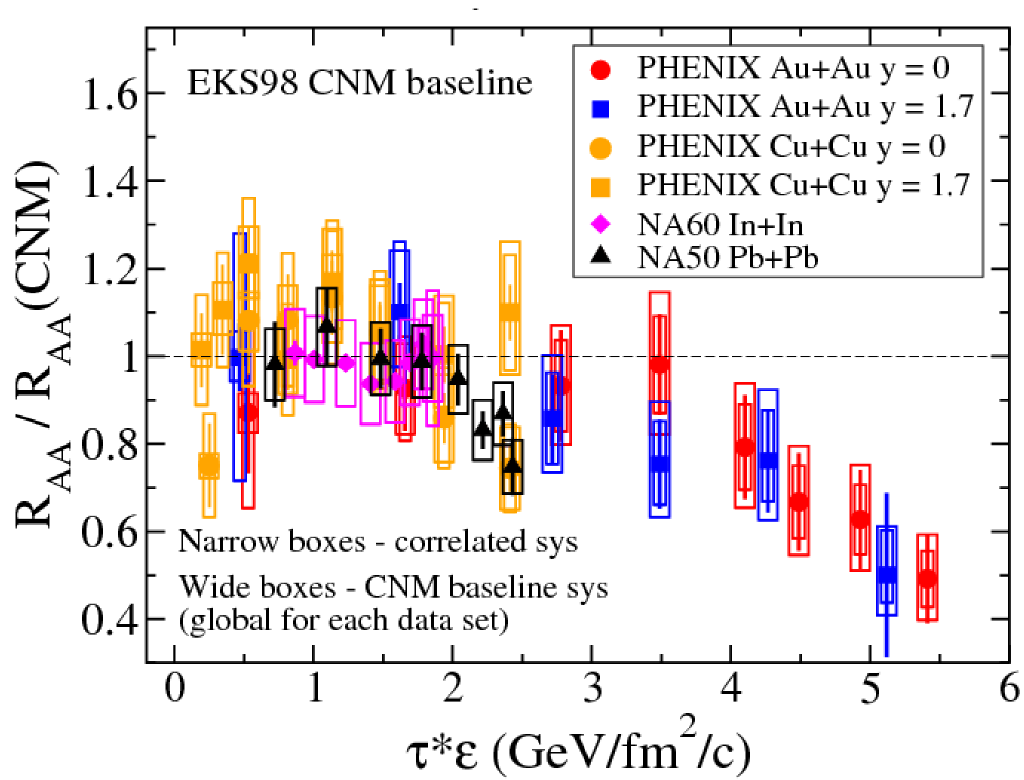
- Stronger suppression at forward rapidity than at midrapidity
- No satisfactory theoretical description
- Suppression larger than CNM expectations
- Comprehensive understanding of the numerous CNM effects not yet available → quantitative estimate of hot matter effects still missing!

- In a similar way, as at SPS, CNM have been evaluated from dAu R_{CP}
- $\sigma_{breakup}$ has a strong y dependence and it is larger at forward rapidity → suppression beyond CNM similar at y=0 and at y=1.7
- Recent results shown that CNM do not properly describe R_{dAu}, making their extrapolation to AA more uncertain (J. Nagle, arXiv:1011.4534)

Comparison SPS and RHIC:open questions

Have SPS and RHIC results already provided a clear picture of J/ψ behaviour in a hot matter?





Results are shown as a function of the multiplicity of charged particles (~energy density, assuming $\tau_{SPS} \sim \tau_{RHIC}$)

Comparison done also in terms of τ * Bjorken energy density → complicate issue, in particular comparing several experiments

Theoretical interpretations

➡ Several theoretical models have been proposed to explain the similar suppression at SPS and RHIC:

1) Only J/ψ from ψ' and χ_c decays are suppressed at SPS and RHIC

→ same suppression is expected at SPS and RHIC
→ reasonable if T_{diss} (J/ψ) ~ $2T_c$

2) Also direct J/ψ are suppressed at RHIC but cc multiplicity high

→ J/ψ regeneration ($\propto N_{cc}^2$) contributes to the J/ψ yield

→ The 2 effects may balance: suppression similar to SPS

➡ Unfortunately data do not allow to clearly assess if recombination can play a role at RHIC

Recombination is measured in an indirect way

J/ψ elliptic flow
→ J/ψ should inherit the heavy quark flow

J/ψ y distribution
→ should be narrower wrt pp

J/ψ p_T distribution
→ should be softer ($<p_T^2>\downarrow$) wrt pp

What have we learnt at SPS and RHIC?

After the study of AA collisions at SPS and RHIC, several lessons have been learnt…even if the J/ψ picture in the hot matter is not yet clear

The understanding of CNM effects is crucial to correctly quantify the hot matter effects

Complicate interplay between different effects, with strong kinematic/energy dependences
→ not yet well defined
→ have to be evaluated from pA data at the same energy as AA
→ can pA data be used at all ?

High precision data are required to precisely define the centrality dependence of the J/ψ yield

→ Well defined centrality pattern are needed to compare lighter/heavier systems or results as a function of different variables

Deeper understanding comparing different experiments?

→ In principle yes…but different CNM effects, different systematics, not straightforward comparison in terms of energy density…

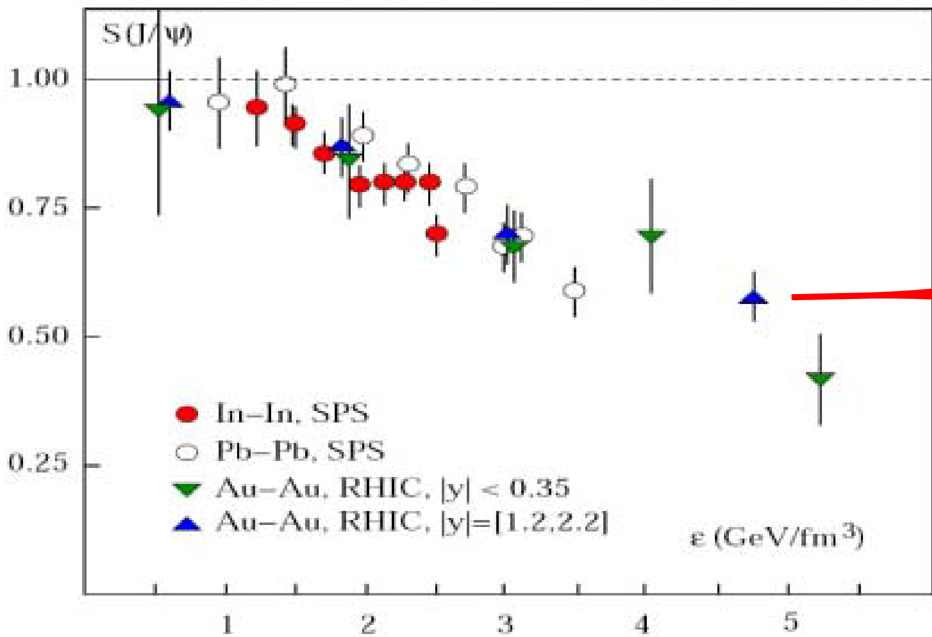
What should we expect at LHC?

...many questions still to be answered at LHC energy!

Role of the large charm quark multiplicity

$$\sigma c\bar{c}\,(LHC) = 10 \times \sigma c\bar{c}\,(RHIC)$$

→ **will J/ψ regeneration dominate the J/ψ picture?**

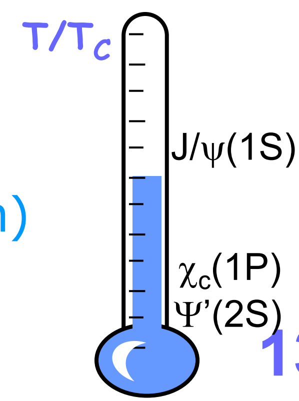


Regeneration?

Further suppression?

Role of other quarkonia states (in particular bottomonium)

still (almost) unexplored in HI collisions
(<100 ϒ(1S+2S+3S) in AuAu@200GeV – STAR)



The HI program at LHC

Three of the LHC experiments foresee to study quarkonium in AA collisions

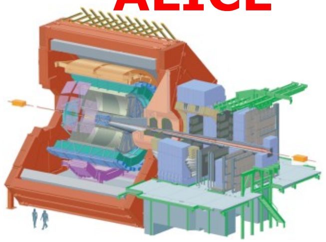
ALICE

$J/\psi \rightarrow \mu^+\mu^-$ $2.5<y<4$

$J/\psi \rightarrow e^+e^-$ $|y|<0.9$

p_T coverage down to $p_T \sim 0$

ALICE



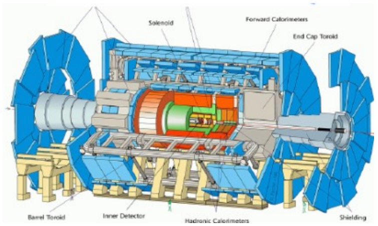
ATLAS

$J/\psi \rightarrow \mu^+\mu^-$ $|y|<2.4$

$p_{T\mu}>3$GeV, $|\eta_\mu|<2.5$ $\rightarrow$ p_T $J/\psi>6.5$GeV/c

(separation between B and prompt J/ψ)

ATLAS



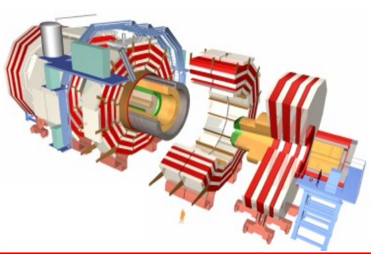
CMS

$J/\psi \rightarrow \mu^+\mu^-$ $|y|<2.4$

p_T coverage depending on the y region

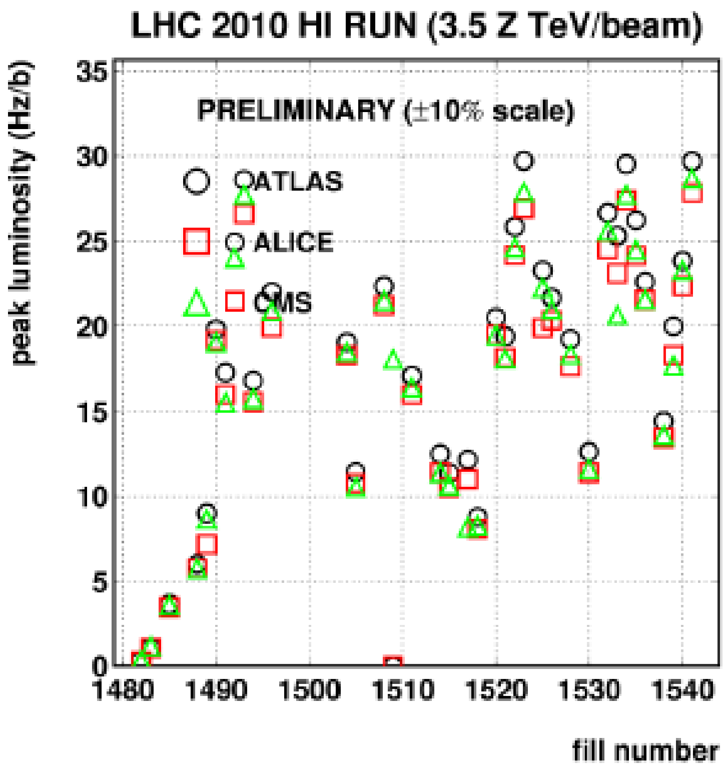
(separation between B and prompt J/ψ)

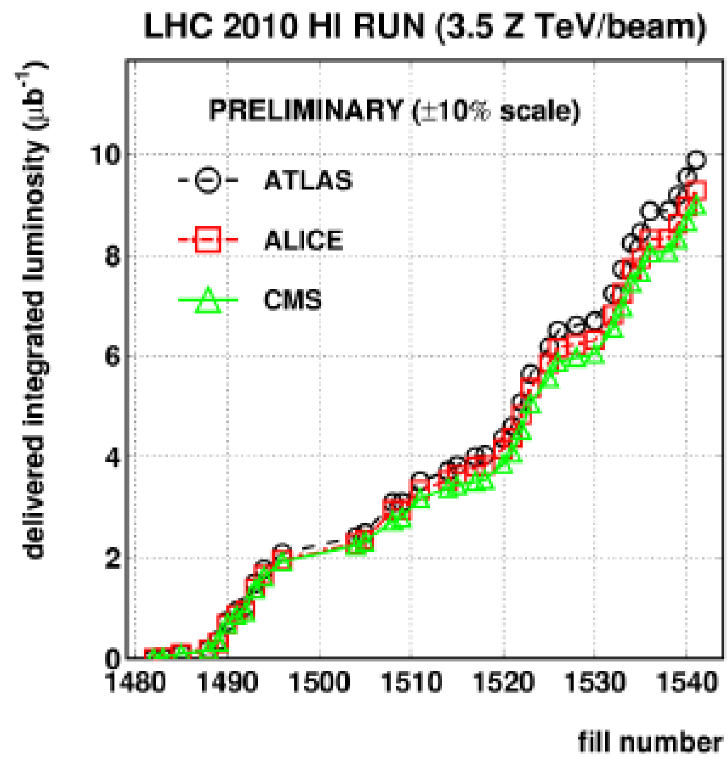
CMS



The 2010 PbPb LHC run

- The first LHC heavy ion run took place in November 2010
  - PbPb collisions at √s=2.76 TeV





- Peak luminosity increasing from 3×10^{23} to 3×10^{25} Hz/cm^2
- Similar integrated luminosity for ALICE, ATLAS, CMS ~9 μb^{-1}

2011-2012 Heavy-ions LHC run

First schedule discussed at the 2011 Chamonix workshop.
Two years of data taking before the 2013 long shutdown

2011

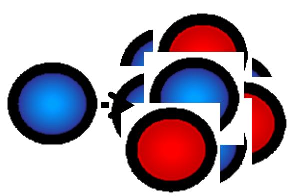
It should be possible to obtain the following peak and integrated luminosity (presently foreseen 4weeks of data taking)

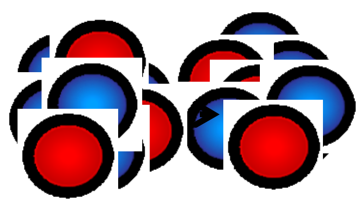
$$L = 1\text{-}1.4 \times 10^{26}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

$$\int L\,dt = 30 - 50\ \mu b^{-1}$$

~ factor 4-5 improvement wrt 2010 (due to more squeezed beams and a higher bunch number)

2012



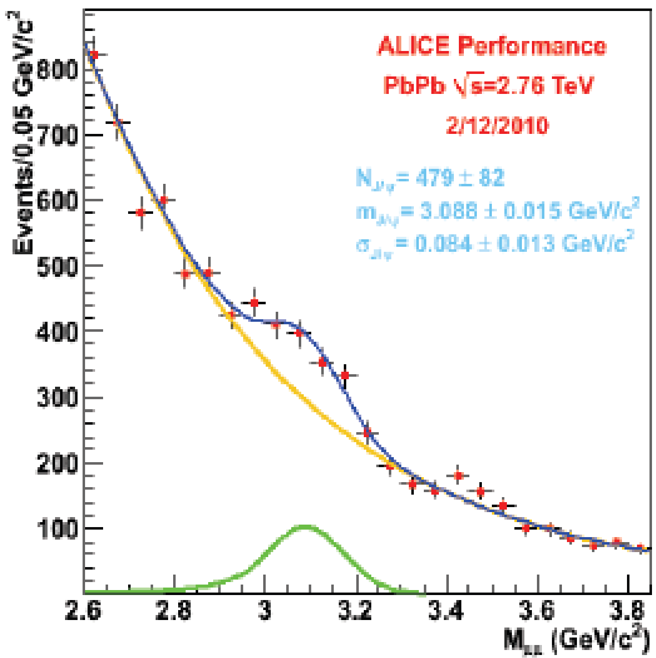


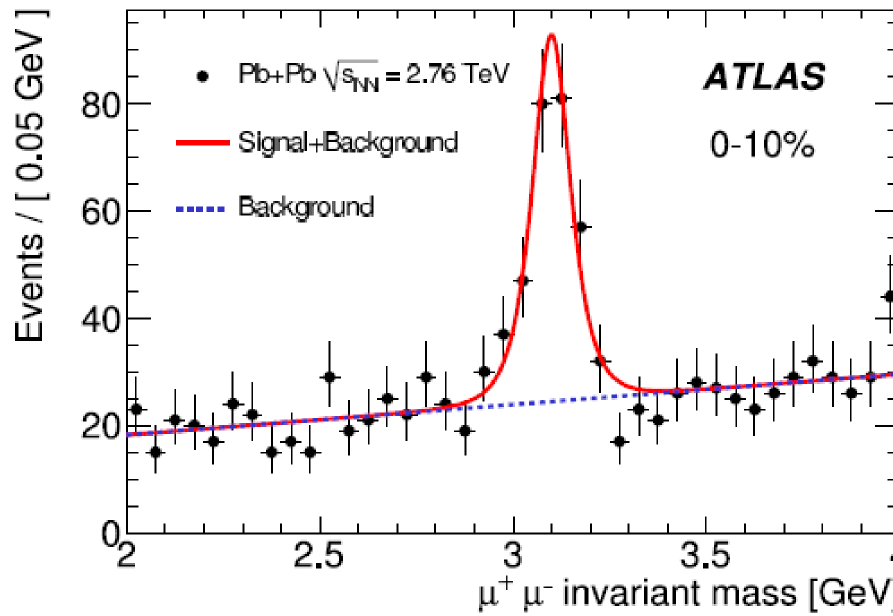
Data taking scenario not yet clear! Two possibilities under study:

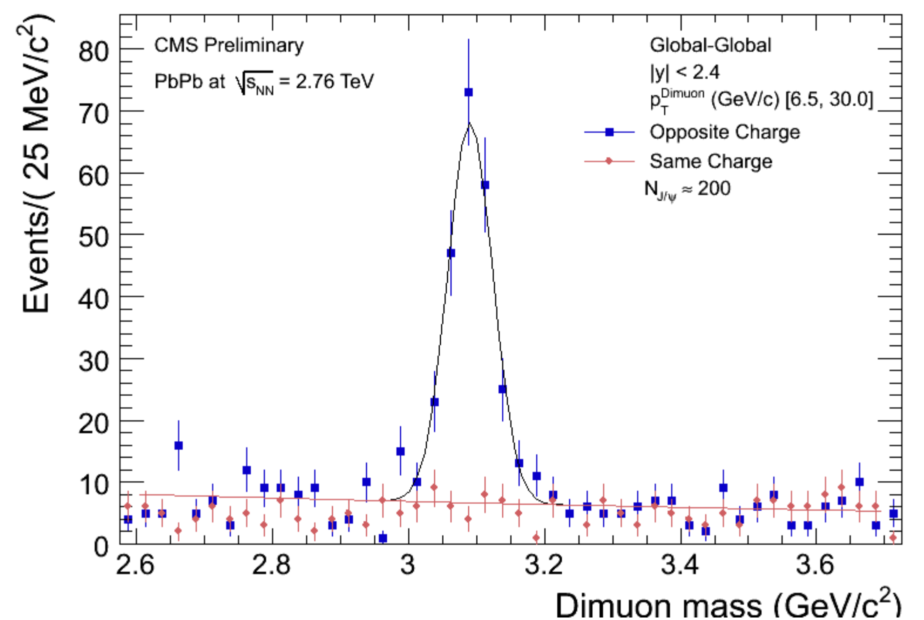
- PbPb data taking to reach the goal of $1\,nb^{-1}$ data (if a luminosity increase can be foreseen)
- p-Pb (Pb-p) data taking?

(M. Ferro-Luzzi, J.M.Jowett, 2011 Chamonix workshop)

First J/ψ invariant mass spectra







- Expected J/ψ width ~ 50-80 MeV/c²
- S/B depends on centrality (~0.2 – ~3)

Which J/ψ statistics has been collected?

2010

Let's start from ATLAS published result (Phys.Lett B 697 (2011)294):

Analyzed L~6.7 μb^{-1} → measured J/ψ ~ 600 { $p_{T\mu}$>3GeV, $|\eta_\mu|$<2.5 → p_T J/ψ>6.5GeV/c

CMS acceptance is similar, so let's assume a similar number of J/ψ

(both ATLAS and CMS should be able, as in pp, to reach a lower p_T, in a restricted y range, but with a larger background contribution)

ALICE has a different acceptance region, down to p_T J/ψ =0

Focusing on the dimuon channel and taking into account that the J/ψ production cross section is higher at low p_T , we can assume, roughly, a factor 2 more wrt ATLAS

→ measured J/ψ ~ 1500

...and in 2011?

2011

Let's assume the same running efficiency, and the same beam quality as 2010

The machine will deliver $L \sim 30\text{-}50\ \mu b^{-1}$

ATLAS/CMS (for p_T J/ψ >6.5GeV):

$\sim 2000 - 3500\ J/\psi$

ALICE ($2.5<y<4$):

$\sim 5000 - 8000\ J/\psi$

What can be done with this J/ψ statistics?

How long should LHC run to reach SPS statistics?

- Based on these numbers, which is the luminosity that LHC should collect in order to have the SPS J/ψ statistics?

- Let's consider the NA50 and the ALICE case:

  - NA50 (2000 data taking): 100000 J/ψ

  To collect this number of J/ψ in ALICE, we would need an integrated luminosity

  - 100000 J/ψ → $L \sim 600\ \mu b^{-1}$

- Hardly reachable unless a large luminosity increase will be provided by the machine

  - with the design luminosity ($L = 5\times10^{26}\ cm^{-2}s^{-1}$) this would require 10^6s

  - assuming a 12% running efficiency, this means ~ 3 months (1month/year devoted to nuclear collisions at LHC)

How many centrality bins can be done?

Let's start from the ATLAS paper (but similar evaluations hold also for ALICE/CMS):

2010

$N_{J/\psi}$ ~600 → 4 centrality bins (0-80%)

~90 – 200 J/ψ in each bin

→ Statistical error ~10%
→ System. uncertainty ~8%

Total Error ~13%

What should we expect in 2011?
Let's consider the most optimistic case:

2011

$N_{J/\psi}$ =8000 → it's possible to increase the number of bins

Smaller statistical error, but we will be dominated by the systematic uncertainties → ~10% total error?

…neglecting in these estimates any systematic uncertainty related to the unknown J/ψ polarization

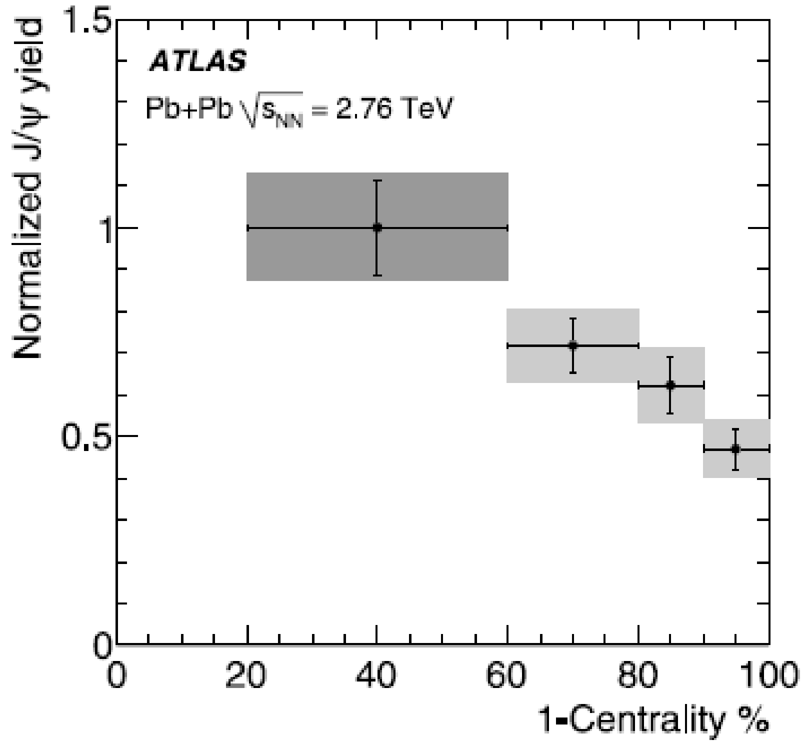
What can we study?

The easiest approach is the study of the RCP ratio, to study the relative centrality dependence of the pattern:

$$R_{CP} = \frac{dN^{central}/\langle N_{coll}^{central}\rangle}{dN^{peripheral}/\langle N_{coll}^{peripheral}\rangle}$$

Non centrality-dependent systematic uncertainties cancel out

Atlas, Phys.Lett B697(2011)294-312



To quantify the PbPb modifications, wrt pp, the R_{AA} has to be evaluated

$$R_{AA} = \frac{\sigma_{J/\psi\, AA}}{\langle N_{Coll}\rangle\, \sigma J/\psi_{pp}}$$

More complicate result because it strongly depends on:

- systematic uncertainties evaluation
- J/ψ production cross section in pp collisions at 2.76 TeV

The reference: 2.76 TeV pp data

- The correctly quantify the J/ψ behaviour in AA, it is crucial to have a well defined reference
  → $\sigma_{J/\psi}$ in proton-proton at the same centre of mass energy as PbPb

- Two possibilities:

  - In March 2011 LHC has provided pp collisions at 2.76TeV
    → advantage: already at the same PbPb energy
    → drawback: only few days of data taking. Enough J/ψ?

  - Evaluate $\sigma_{J/\psi}$ at 2.76 TeV, relying on the measurement at 7 TeV (high statistics) and rescaling it via FONLL and CEM calculations
    (F. Bossu' et al. arXiv:1103.2394)

    - Systematic uncertainty on the extrapolated value is ~15%

Reference processes

- Further insight on the quarkonia behaviour in a hot matter can be obtained comparing the measured yield to a reference process not affected by the medium

- At SPS, J/ψ was studied wrt Drell-Yan process, not affected by the created medium
  - …however low Drell-Yan rate at LHC.

- Several proposals: Z^0, open charm, open beauty…

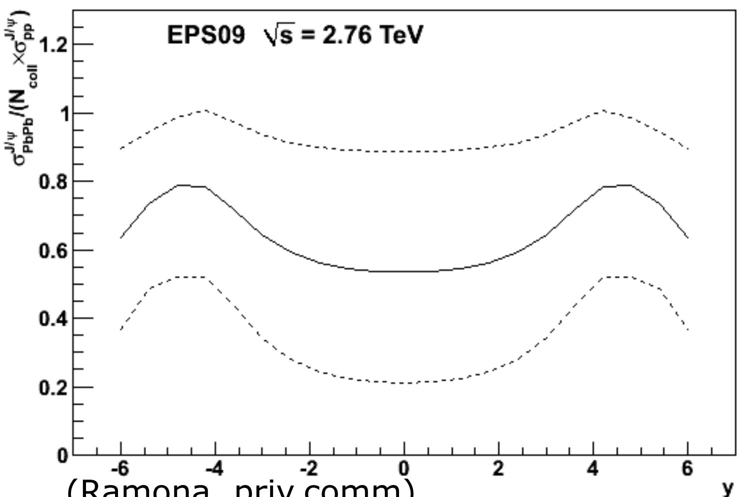
Helmut’s golden reference

  - best reference should share the same production mechanism with quarkonium
  - initial and final state effects should be under control

How can we compare to models?

- According to these rough estimates, the J/ψ centrality pattern could be affected by roughly:
  - ~ 10% systematic +statistical error
  - ~ 15% systematic error on $\sigma_{J/\psi}^{pp}$ (for R_{AA})
  - → ~18% total error

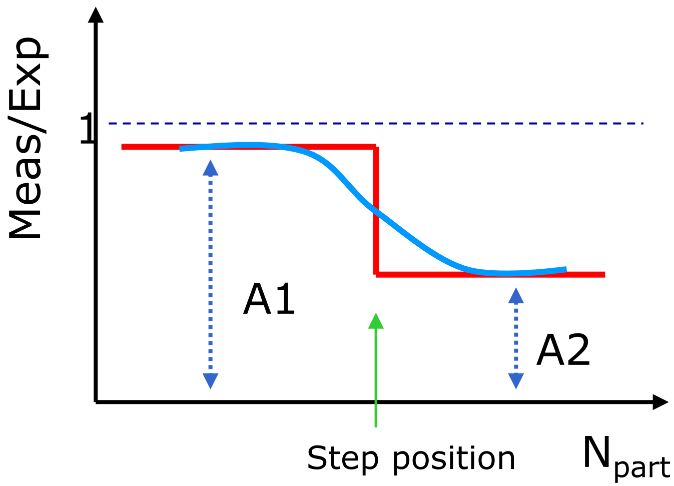
- however also large uncertainties on the size of relevant effects complicate the comparison



(Ramona, priv.comm)

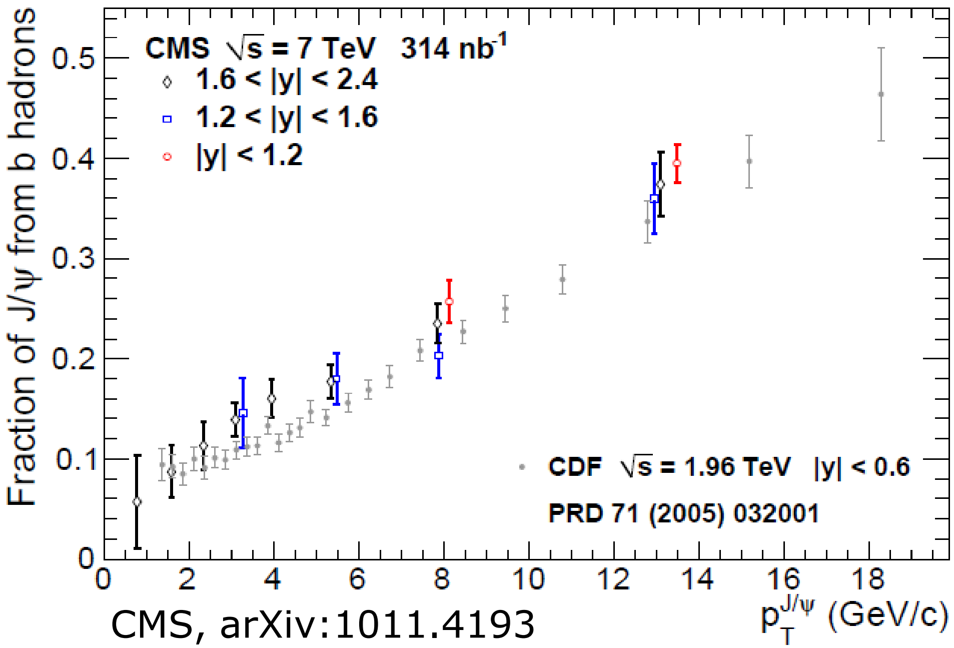
- if shadowing has ~50% systematic uncertainty, the experimental result, whatever its error, will hardly clarify any hot-matter related scenario

- On top of this, experimental resolution should be taken into account, since it may wash out, for example, a step-wise suppression pattern



What about J/ψ from B?

- J/ψ from B can complicate even more the picture



CMS, arXiv:1011.4193

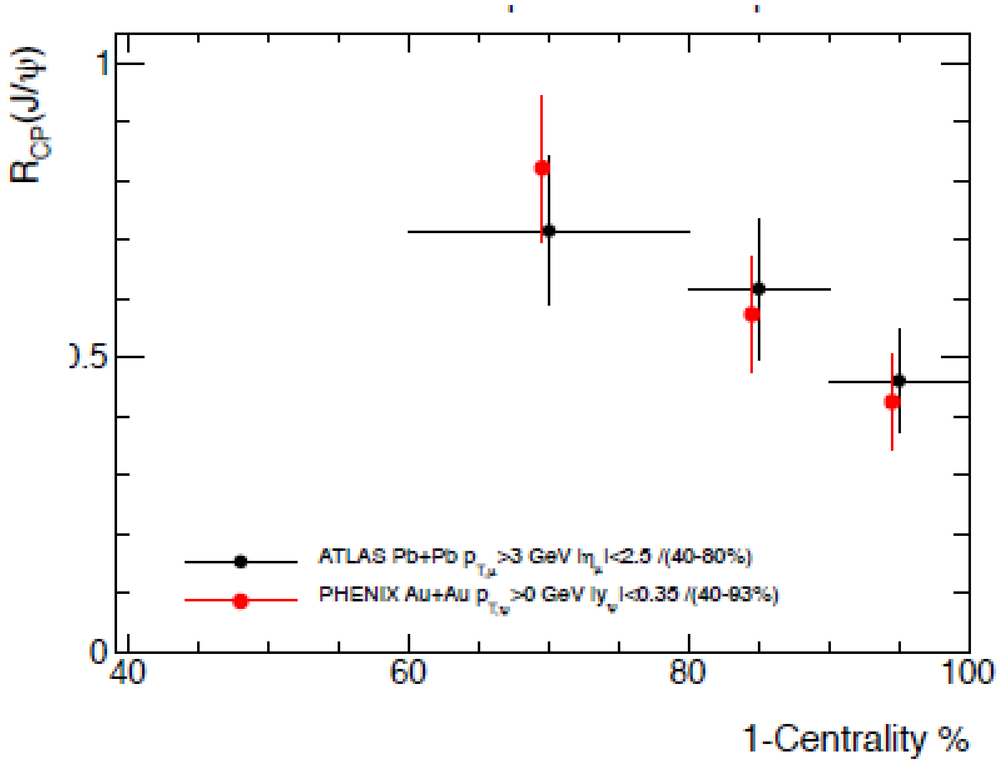
- 7 TeV pp results show that the fraction of J/ψ from b hadrons does not strongly depend on energy
  → we can assume the same trend at 2.76 TeV

- Fraction of J/ψ coming from B do not suffer suppression in the medium
  - ...but if B is strongly quenched by the medium, the fraction of J/ψ from b hadrons (vs p_T) will change

- More hints from ATLAS and CMS which will be able to separate prompt J/ψ from those from B decay also in PbPb (?)

Comparison with lower √s data

Preliminary comparison of ATLAS and PHENIX data



P. Steinberg, LPCC HI@LHC, March 2011

Centrality dependence of J/ψ suppression seems invariant with beam energy in spite of different

- √s (factor x14)
- initial energy density (~3)
- kinematic range (p_T>0 for PHENIX, p_T>6.5GeV ATLAS)
- no B feed-down correction (4% PHENIX, 20% ATLAS)

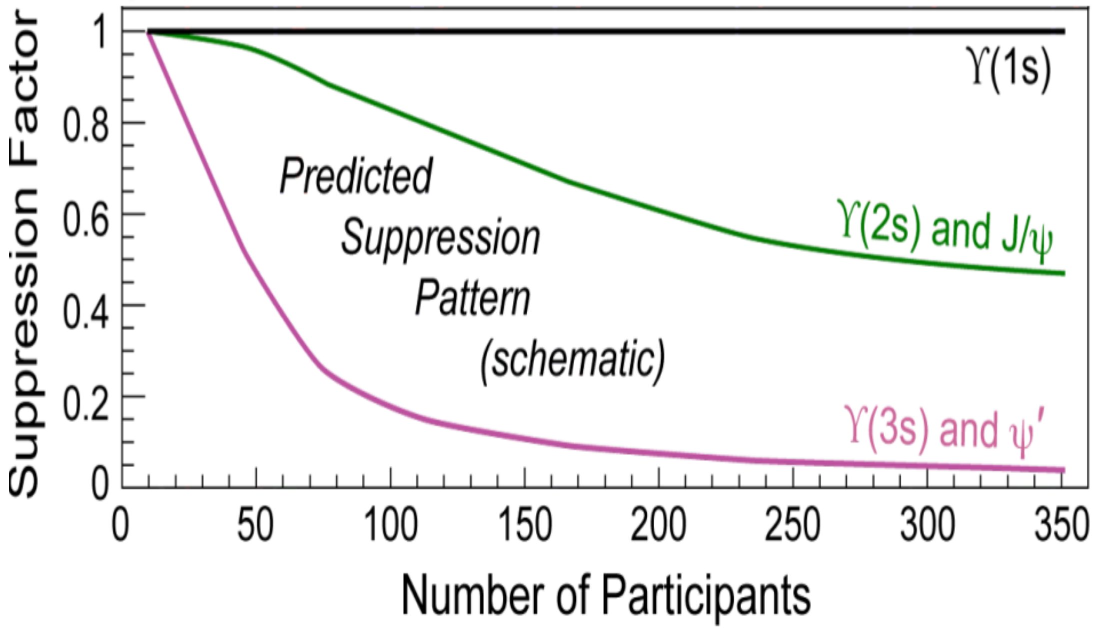
At a first glance…first LHC results do not seem to clarify all open questions…
Maybe one should look also at open charm pattern (Helmut)

What about the Υ?

Bottomonium states should be a cleaner probe, accessible at LHC

- More robust theoretical calculations
- No b hadron feed-down

…but with a lower production cross section



Will we able to separate the Υ states?

A good resolution is crucial to separate the 3 Υ states, which have different dissociation temperatures . Υ(1S) more easily separated (higher significance)

Foreseen width: ~80-100 MeV
S/B: ~0.3 - 2

How many ϒ can we collect?

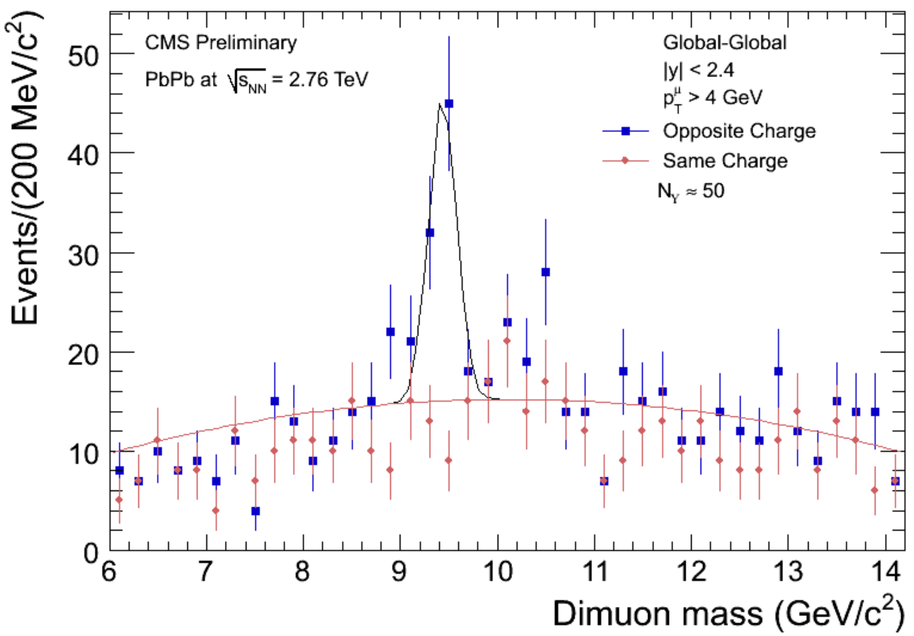
- In the ALICE acceptance roughly a factor 100 is expected between J/ψ and ϒ(1S) yields (J.Phys. G32,1295 (2006))

  2010 ~1500 J/ψ → ~15 ϒ(1S)
  2011 ~5000-8000 J/ψ → ~50-80 ϒ(1S)
  → <20 ϒ(2S), ϒ(3S)

- ATLAS/CMS: ϒ acceptance is larger than the J/ψ one, reaching p_T~0 → higher ϒ statistics (ATLAS,J.Phys.G 34 (2007), CMS note 2006/89)

  2010 ~700 J/ψ
  → ~100 ϒ(1S)

  2011 ~2500-4000 J/ψ
  → ~400-600 ϒ(1S)
  → ~100-200 ϒ(2S)
  → <100 ϒ(3S)



- ϒ centrality dependence out of reach in 2010?
  …but maybe feasible in 2011!

Conclusions

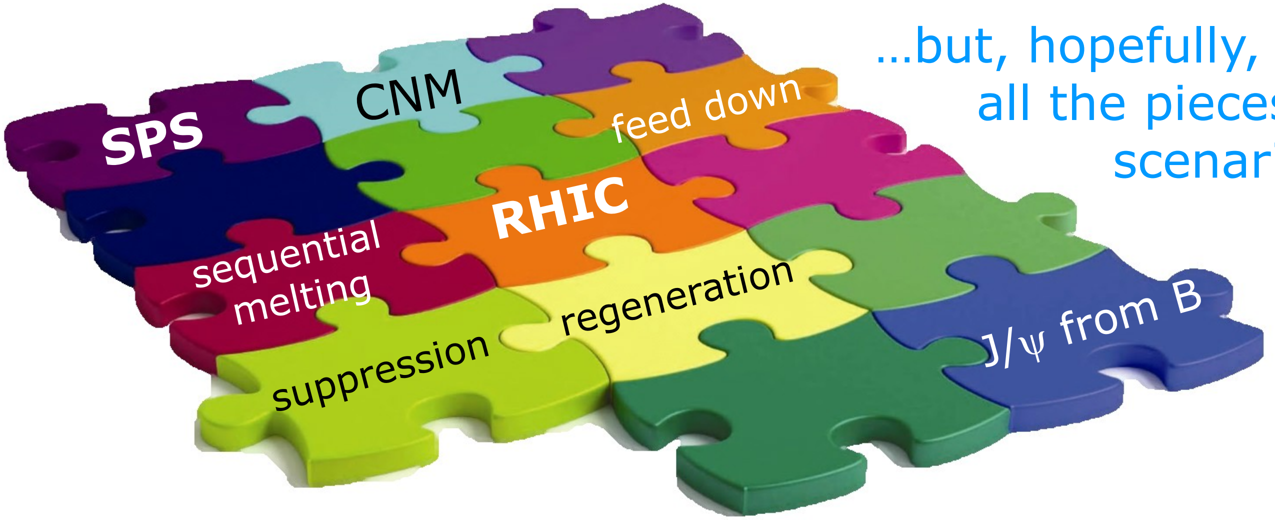
Quarkonia study in heavy ion collisions is already a 25 years long story

SPS and RHIC data provided many insight on the quarkonium behaviour in AA, but many questions are still open

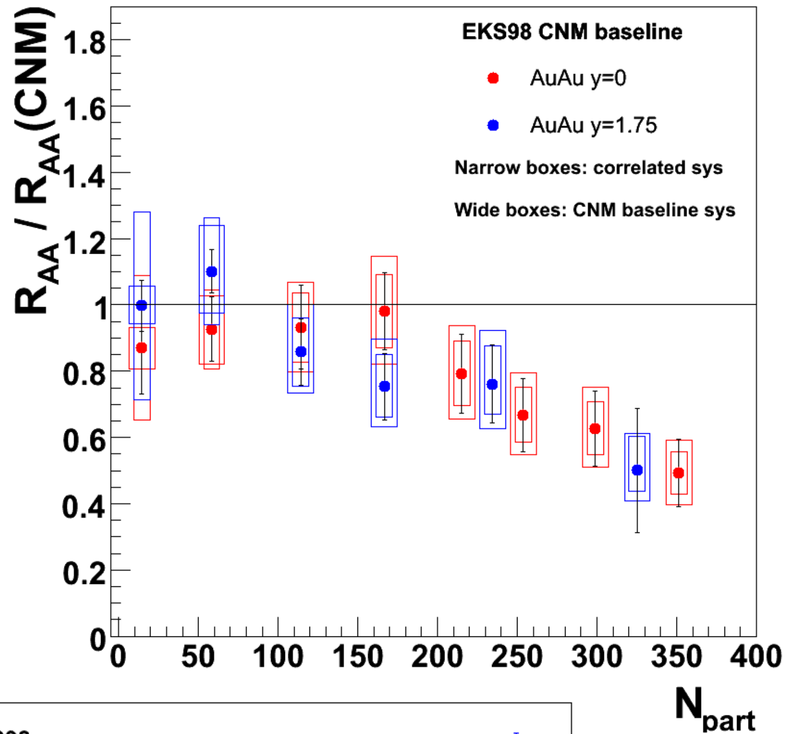
Many questions are looking for an answer from LHC data!

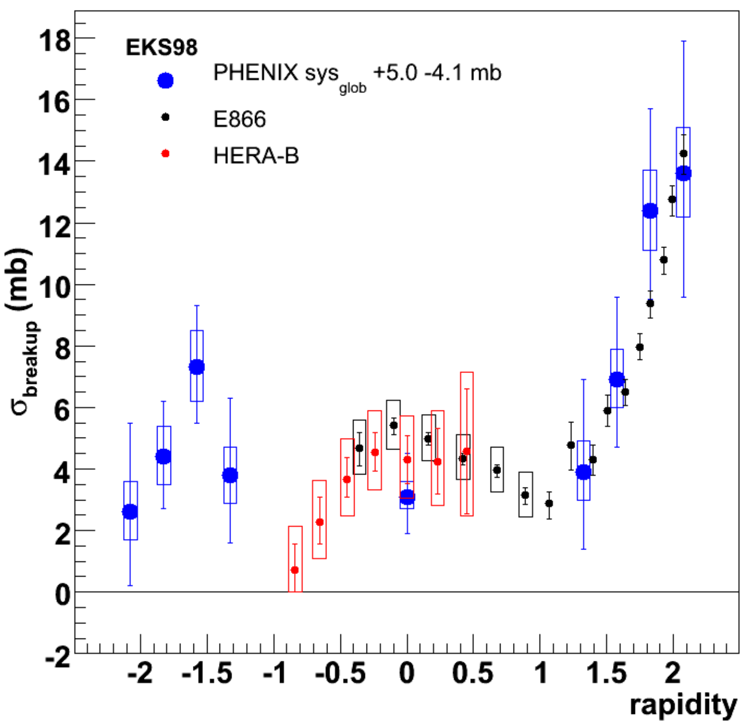
the picture seems indeed quite complicate,

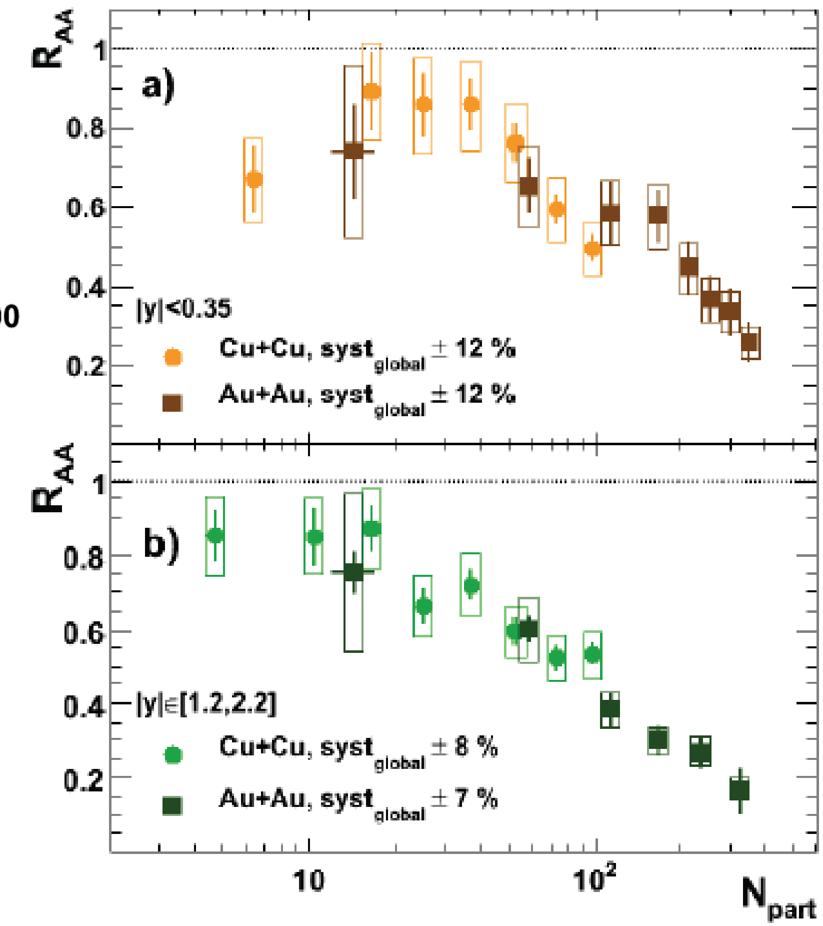
…but, hopefully, putting together all the pieces of the puzzle the scenario will be clarified!



Backup


EKS98 CNM baseline
AuAu y=0
AuAu y=1.75
Narrow boxes: correlated sys
Wide boxes: CNM baseline sys
R_{AA} / R_{AA}(CNM)
N_{part}


EKS98
PHENIX sys_{glob} +5.0 -4.1 mb
E866
HERA-B
$\sigma_{breakup}$ (mb)
rapidity


a)
|y|<0.35
Cu+Cu, $syst_{global}$ ± 12 %
Au+Au, $syst_{global}$ ± 12 %
b)
|y|∈[1.2,2.2]
Cu+Cu, $syst_{global}$ ± 8 %
Au+Au, $syst_{global}$ ± 7 %
R_{AA}
N_{part}