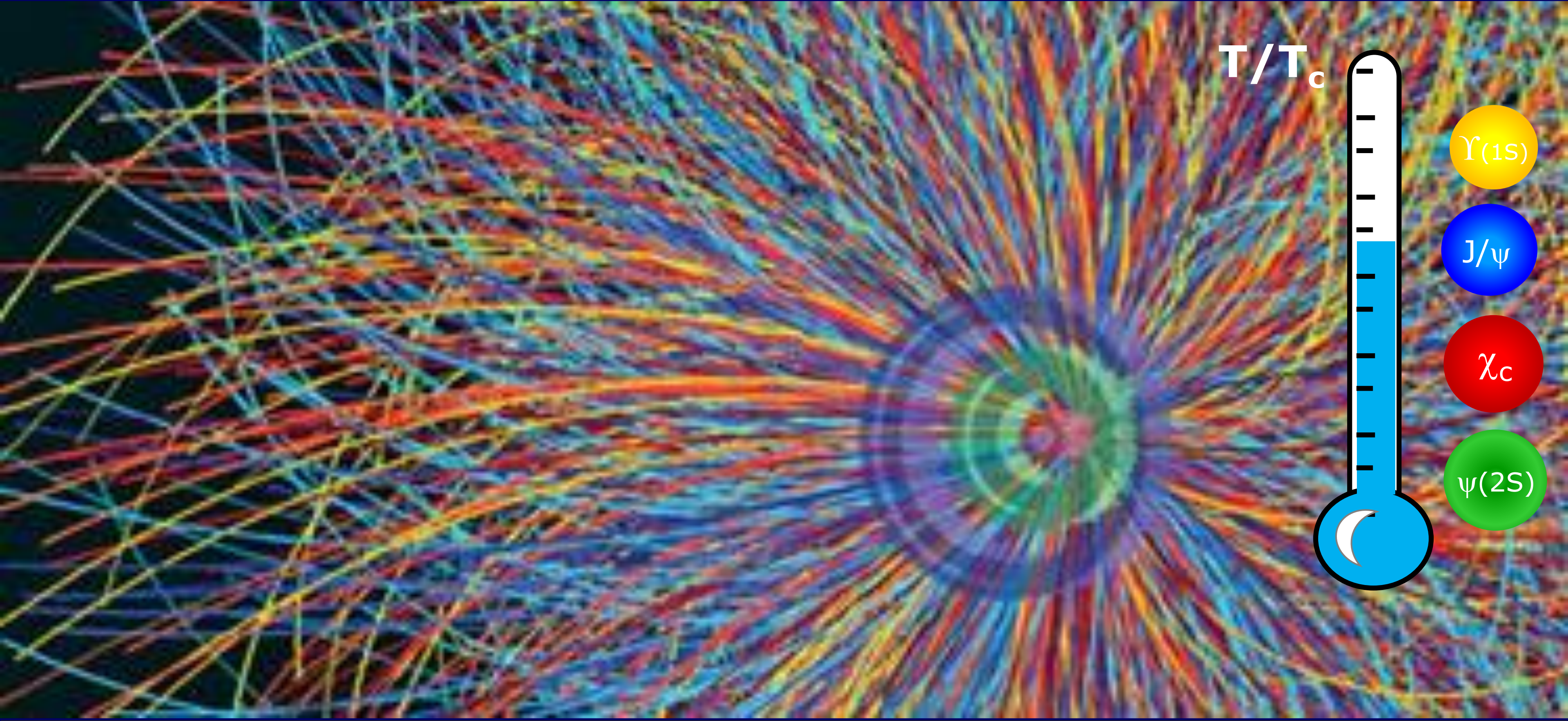
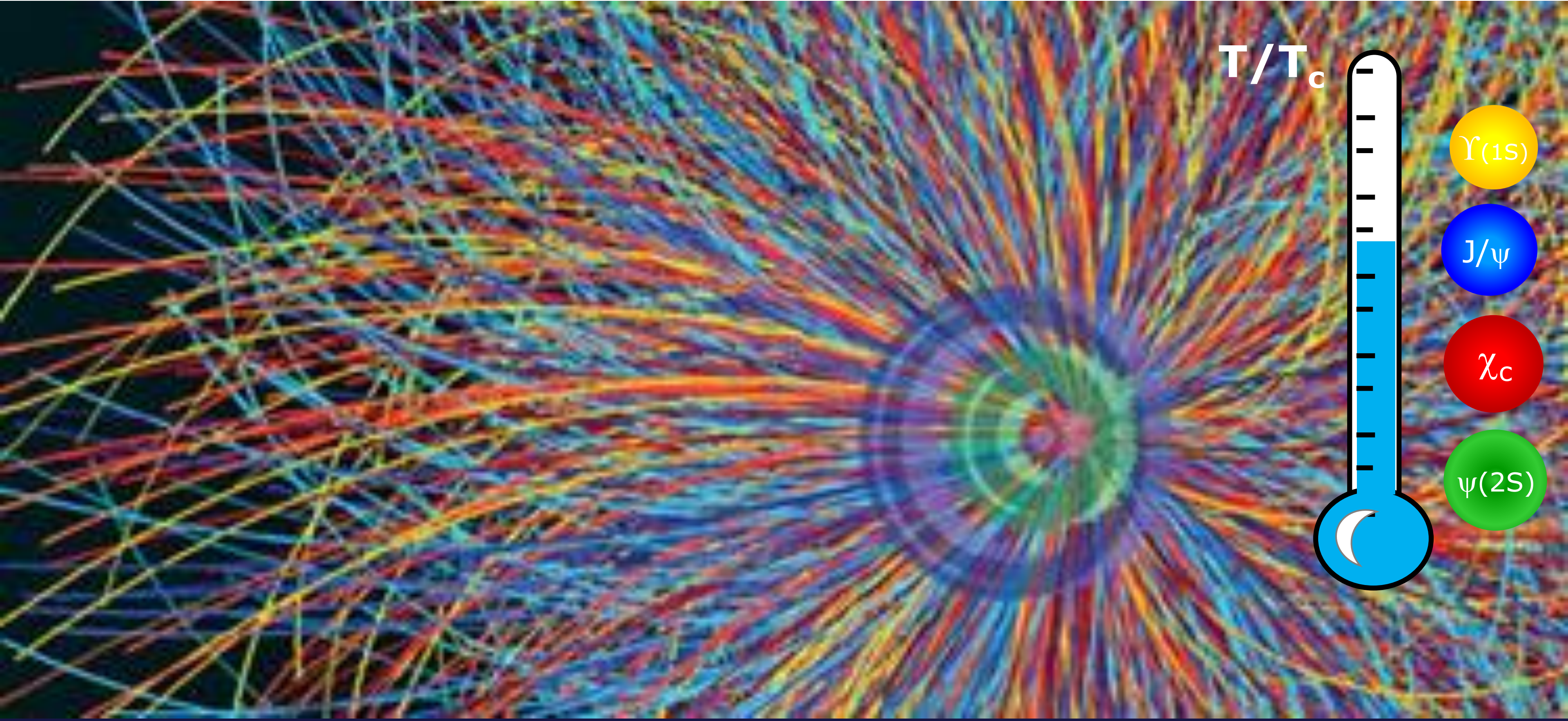


Quarkonium and Quark Gluon Plasma: from SPS to LHC energies

Roberta Arnaldi
INFN Torino

GSI Colloquium, May 26th 2015

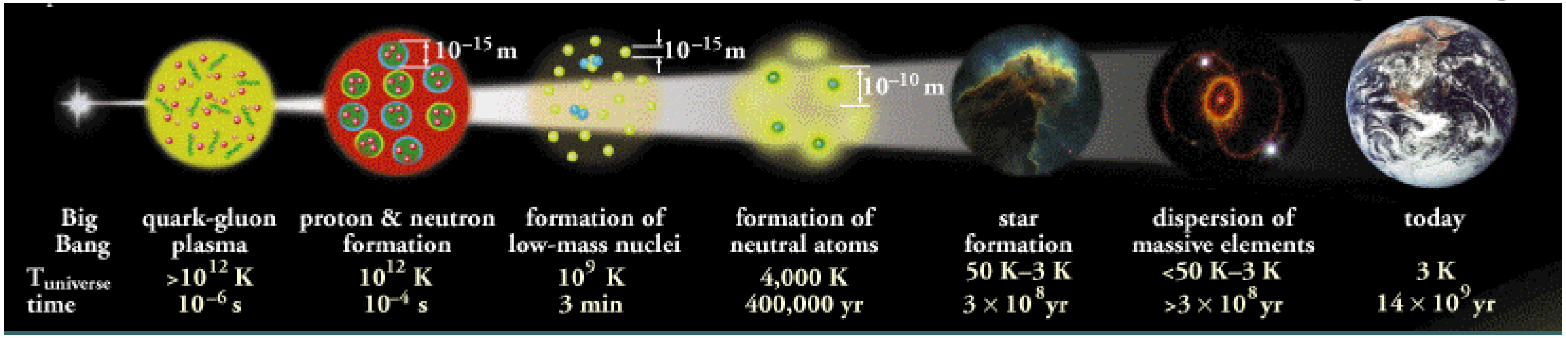


Outlook

- The Quark Gluon Plasma: a very short introduction!
- Why a qq bound state (quarkonium) is one of the most important probes of Quark Gluon Plasma formation?
- Quarkonium studies in heavy ion collisions: from low energy experiments to LHC

HEAVY IONS AND QUARK GLUON PLASMA

- Quark Gluon Plasma is a state of strongly interacting matter in which quarks and gluons are no more confined into hadrons
- QGP is formed at high temperatures and/or density → conditions similar to those achieved few micro-seconds after the Big-Bang

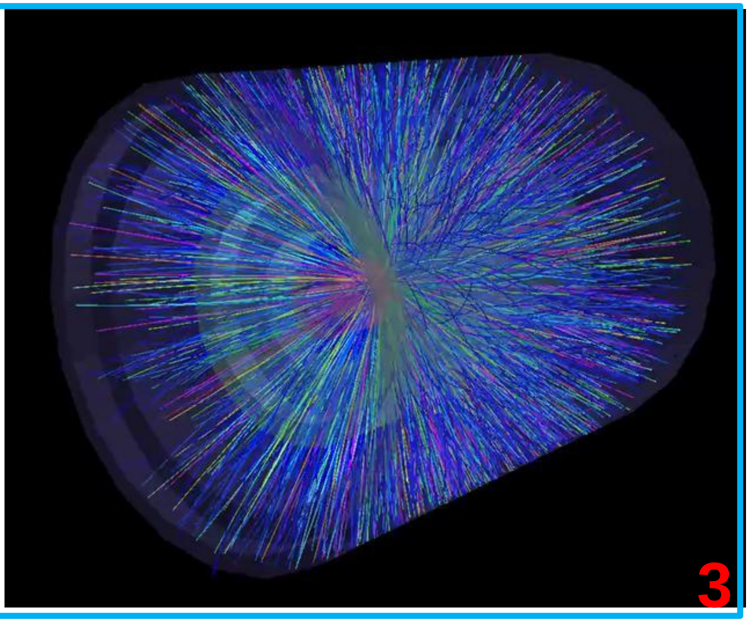


- How can QGP be produced in laboratory?

↓ heavy-ion collisions

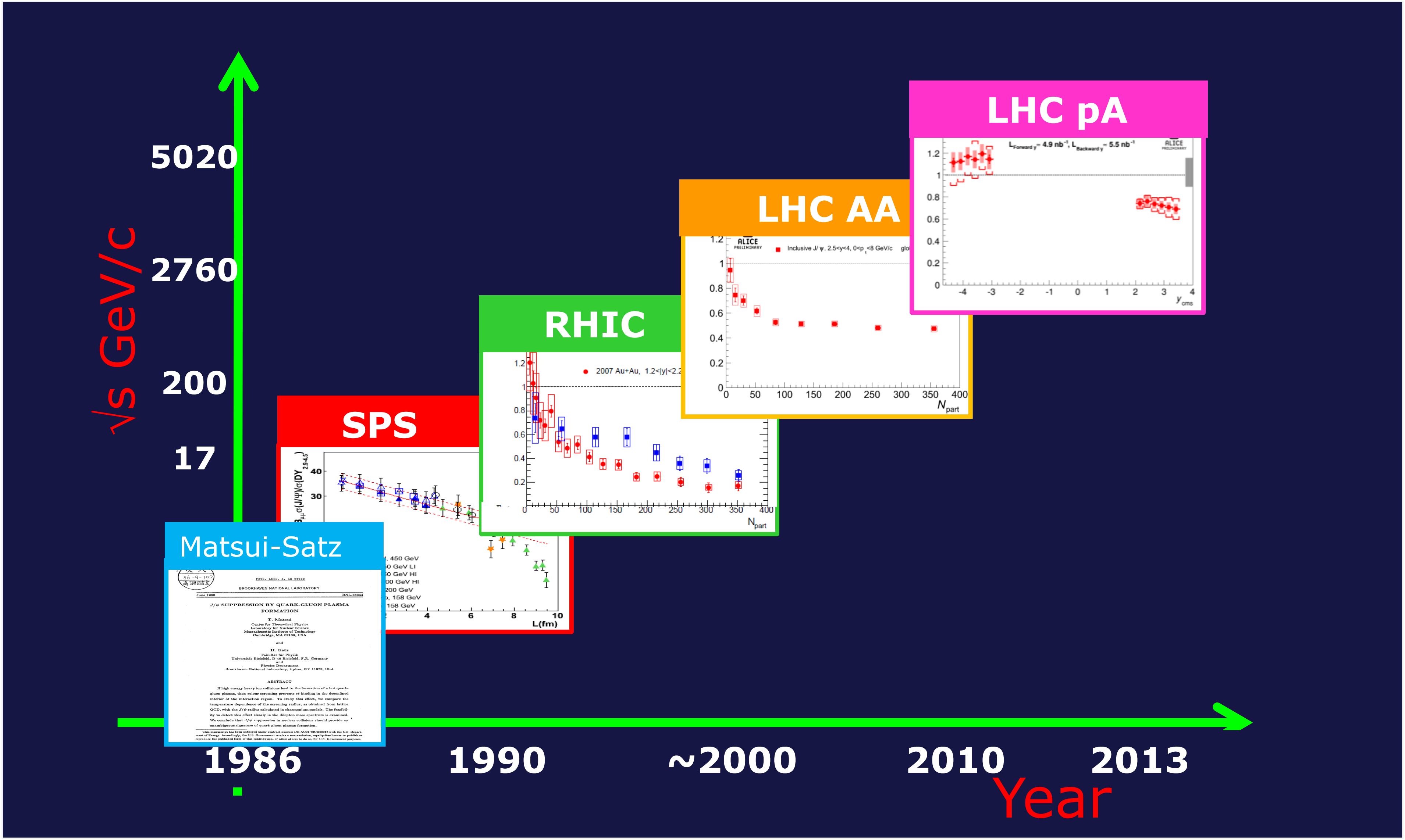
- How to understand the properties of the created hot medium?

↓ study specific probes as jets, open heavy flavors, quarkonium…



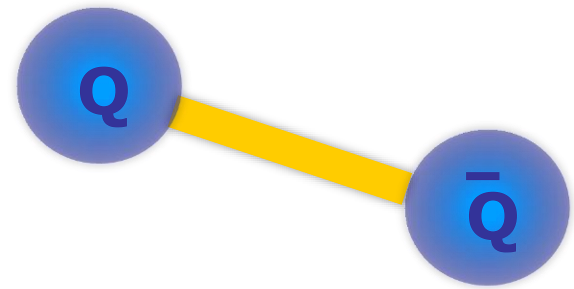
HISTORY OF HEAVY-ION QUARKONIUM STUDIES

The experimental investigation of quarkonium as one of the most striking signatures for QGP formation is a **30 years long story**!



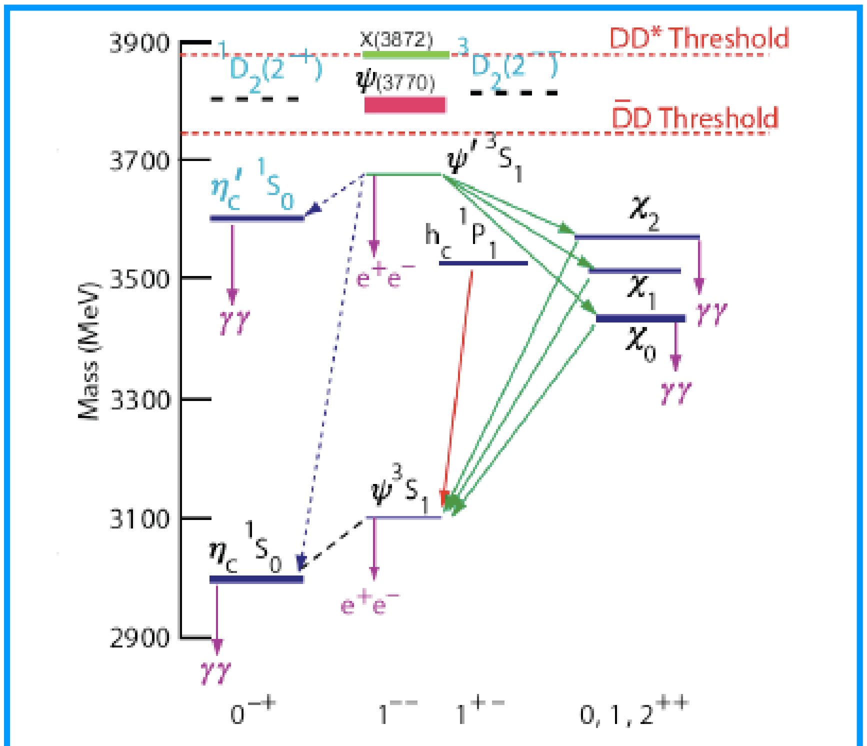
WHAT IS QUARKONIUM?

- Quarkonium is a bound state of Q and $\overline{Q}$ with $m_{QQ}<2m_D(m_B)$

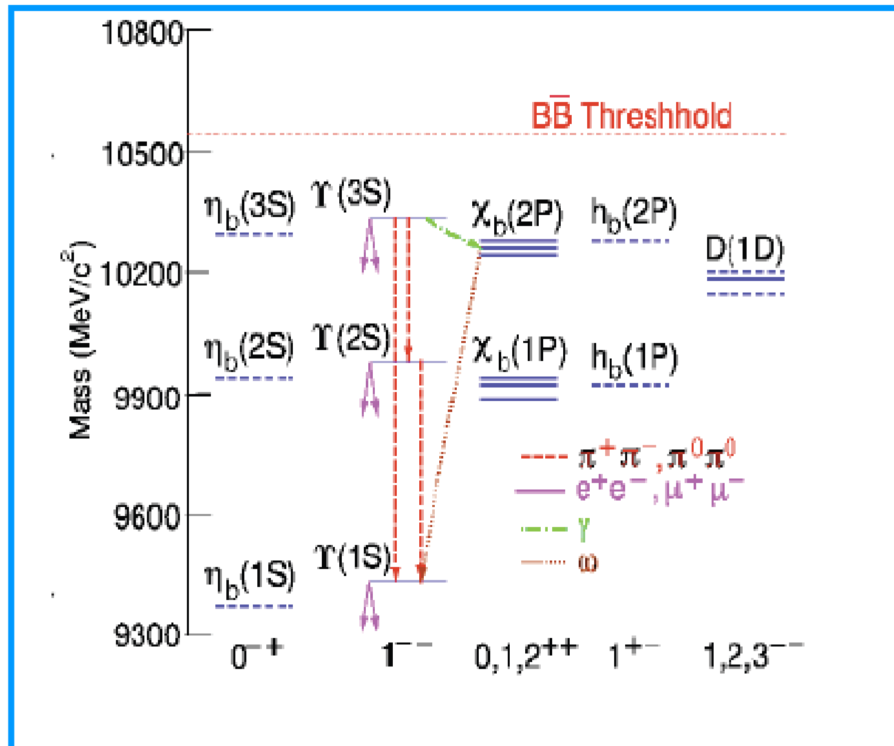


- Several quarkonium states exists, characterized by different quantum numbers

Charmonium ($c\overline{c}$) family



Bottomonium ($b\overline{b}$) family



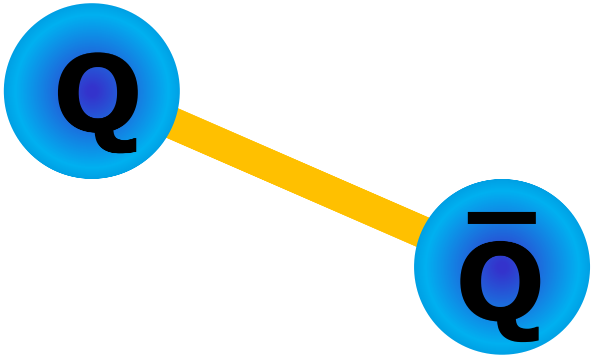
QUARKONIUM AT T=0

- At T=0, the binding of the Q and $\bar{Q}$ quarks can be expressed using the Cornell potential:

$$V(r) = -\frac{\alpha}{r} + kr$$

coulombian contribution, induced by a g exchange between Q and $\bar{Q}$

confinement term



QUARKONIUM IN A QGP

➡ What happens to a $q\bar{q}$ pair placed in the QGP?

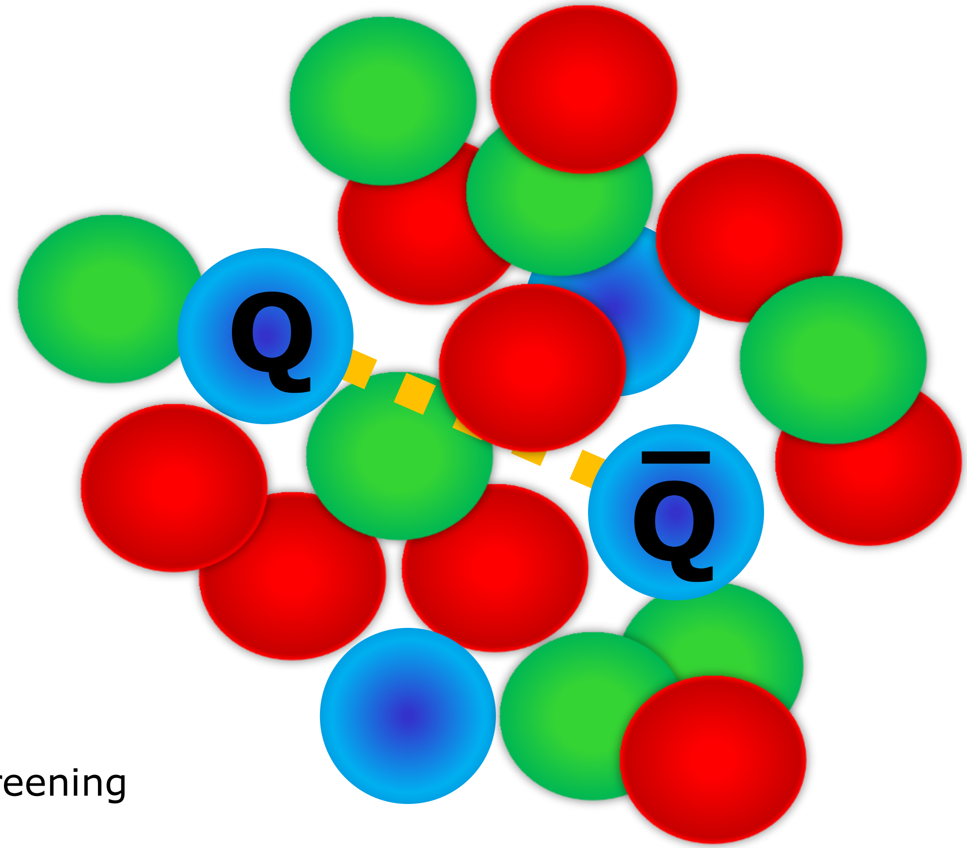
The QGP consists of deconfined colour charges

$$V(r) = -\frac{\alpha}{r} + kr$$

↓

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

λ_D: screening radius

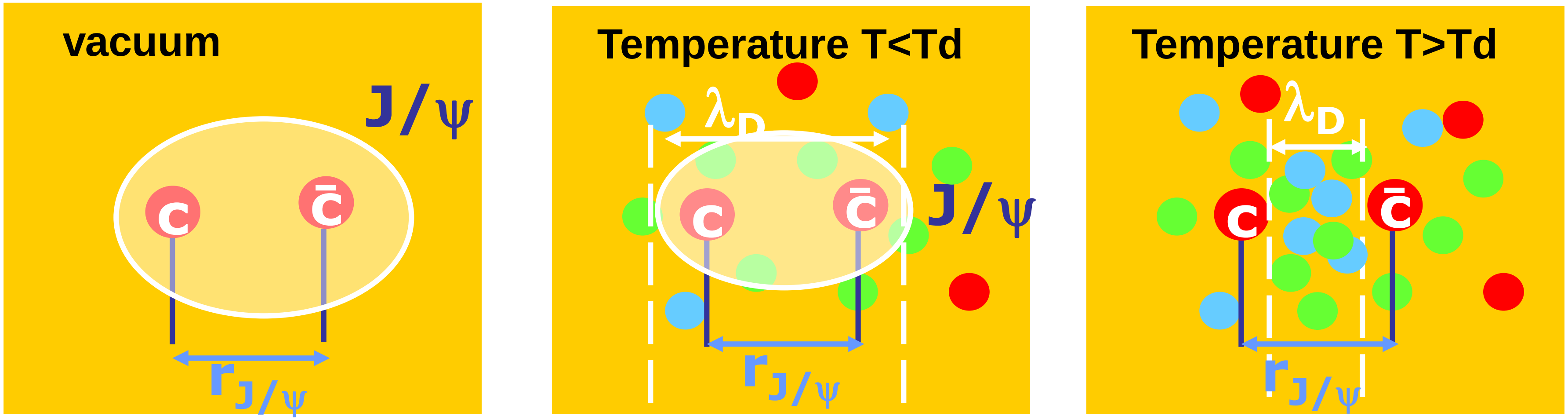


➡ the binding of a $q\bar{q}$ pair is subject to the effects of colour screening:

- the “confinement” contribution disappears
- the coulombian term of the potential is screened by the high color density

DEBYE SCREENING

➡ The screening radius $\lambda_D(T)$ (i.e. the maximum distance which allows the formation of a bound QQ pair) decreases with the temperature T



At a given T:

if resonance radius < $\lambda_D(T)$
→ resonance can be formed

if resonance radius > $\lambda_D(T)$
→ no resonance can be formed

QUARKONIUM SUPPRESSION

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

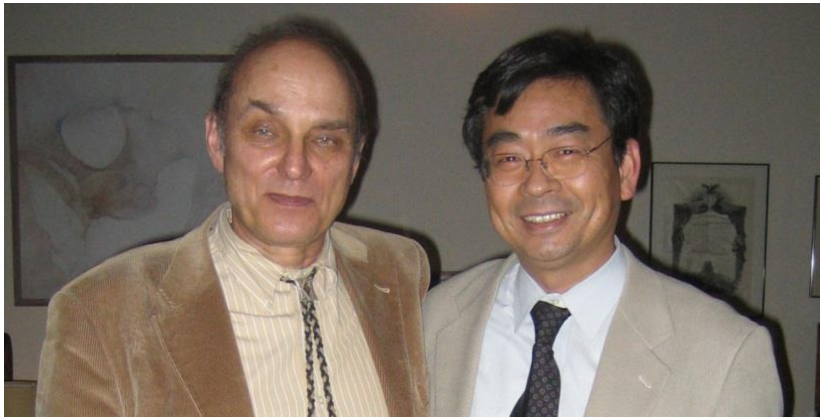
H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

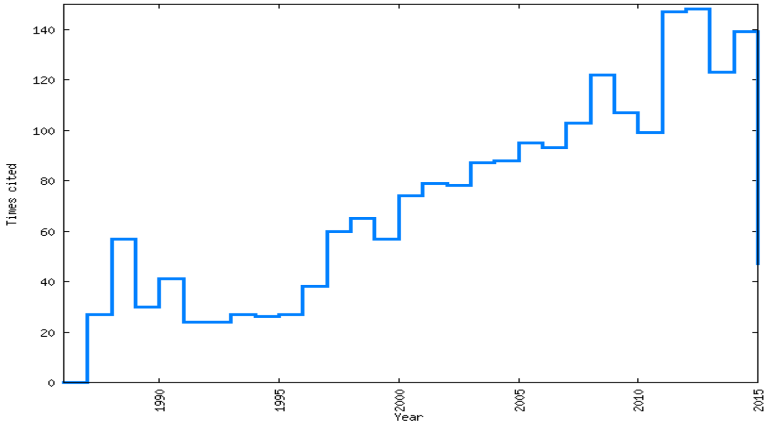
If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice 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.

This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

This is the idea behind the suggestion (by Matsui and Satz) of the J/ψ as a signature of QGP formation (~30 years ago!)



very famous paper cited ~2150 times!



SEQUENTIAL SUPPRESSION

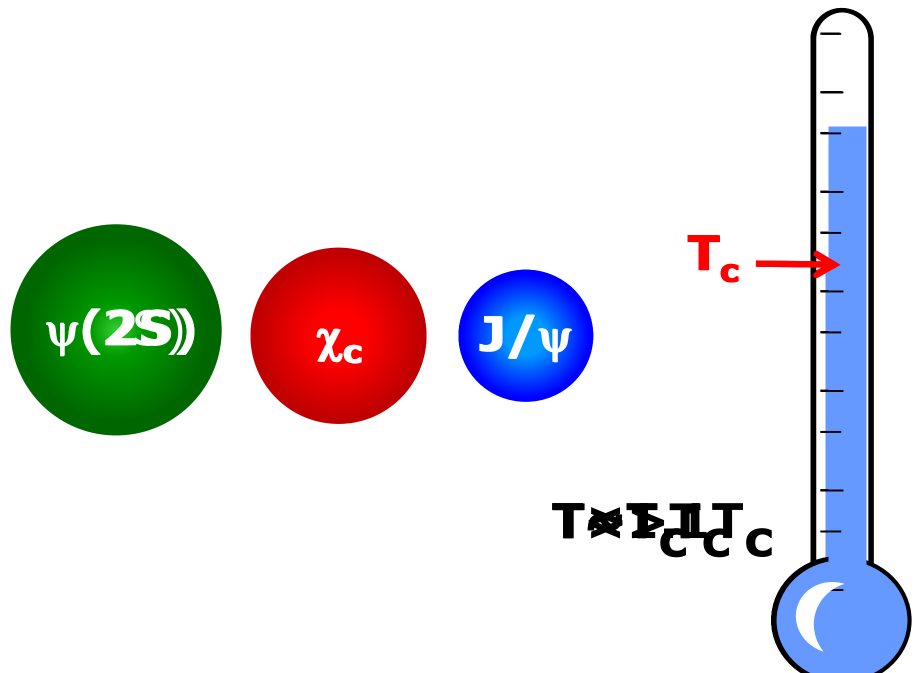
- Strongly bound states have smaller sizes
- Debye screening condition $r_0 > \lambda_D$ will occur at different T

state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.51	3.69
ΔE (GeV)	0.64	0.22	0.05
r_o(fm)	0.50	0.72	0.90

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

- Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature

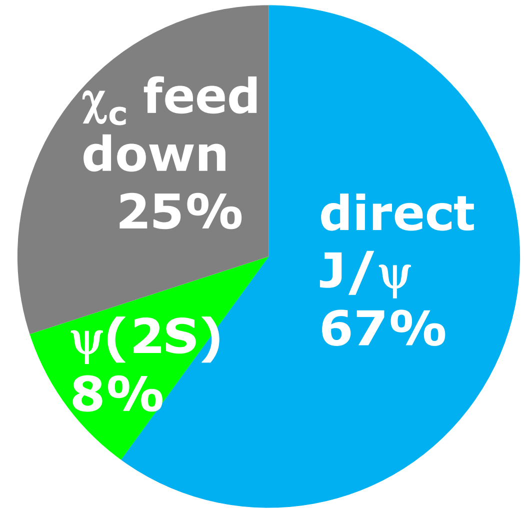
thermometer of the initial QGP temperature

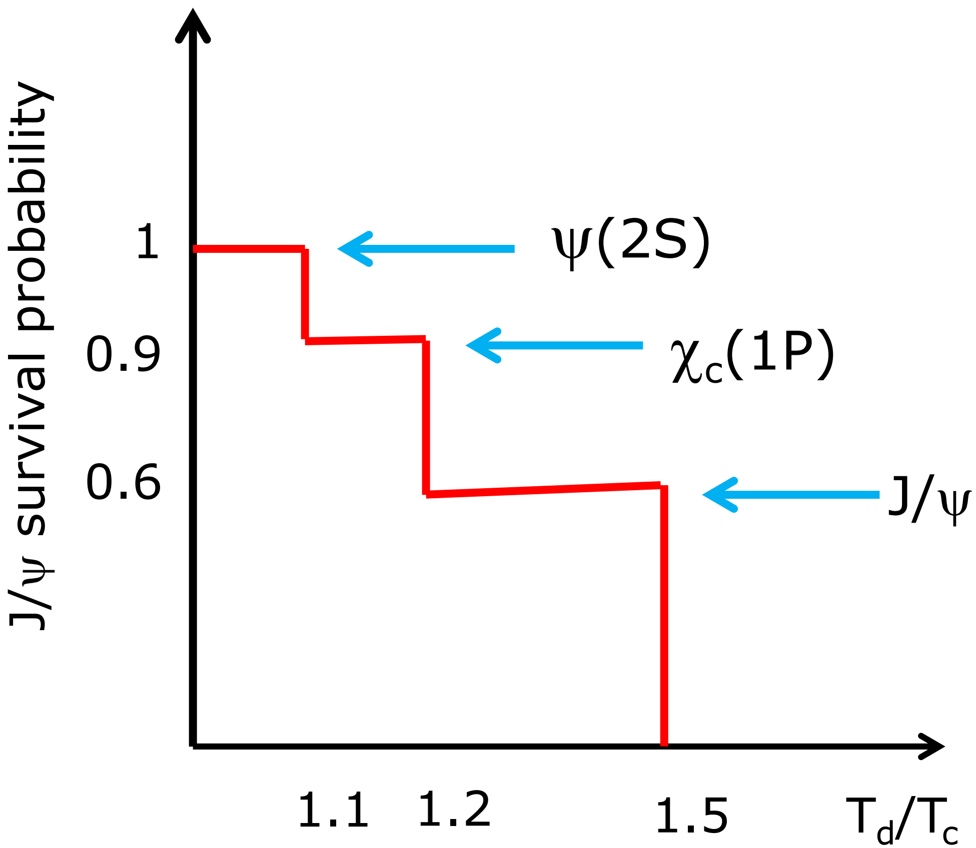


(Digal,Petrecki,Satz PRD 64(2001) 0940150)

SUPPRESSION PATTERN

- Feed-down process: charmonium "ground state" resonances can be produced through decay of larger mass quarkonia (J/ψ production from B decays neglected)
- Effect : ~30-40% for J/ψ, ~50% for ϒ(1S)





- Dissociations temperatures are computed with lattice QCD or potential models calculations

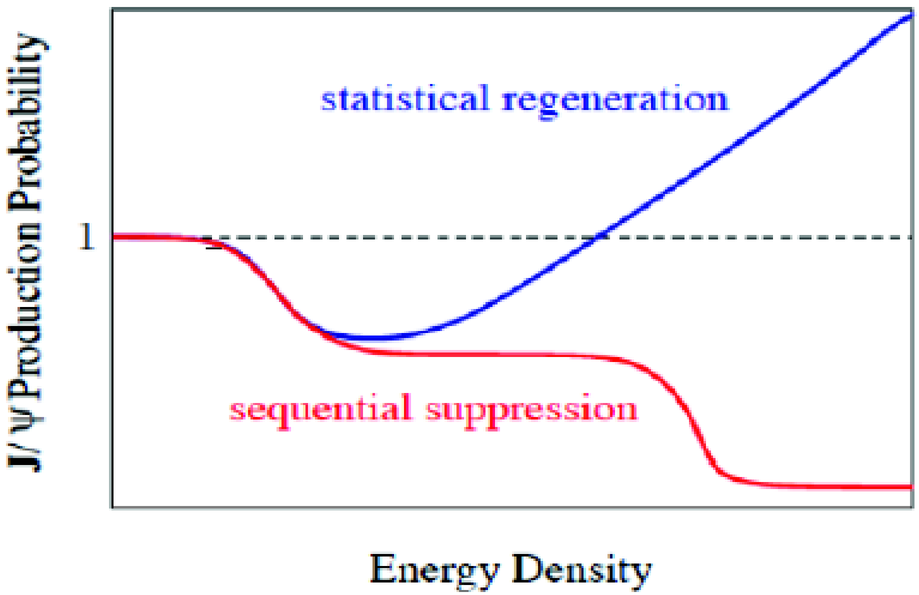
	J/ψ	$\chi_c(1P)$	ψ(2S)
T_d/T_c	~1.5	~1.1	~1.1

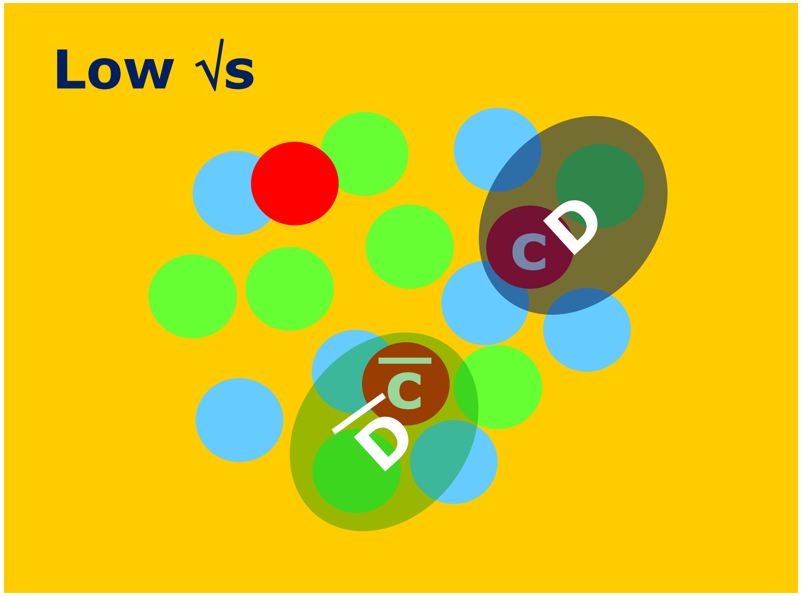
H.Satz, arXiv:1310.1209

FROM SUPPRESSION. . .TO (RE)COMBINATION

- Increasing the energy of the collision the cc pair multiplicity increases

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





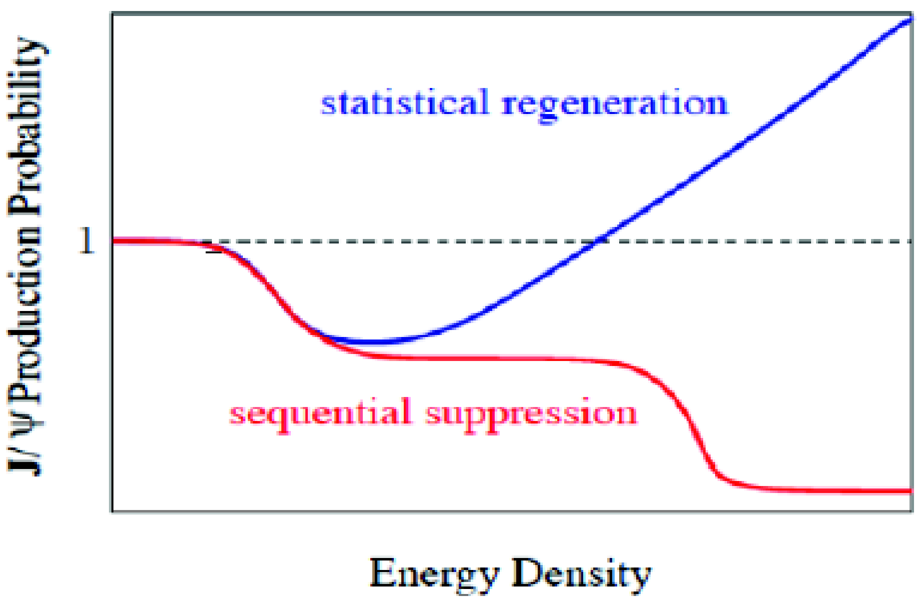
- An enhancement via (re)combination of cc pairs producing quarkonia can take place at hadronization or during QGP stage

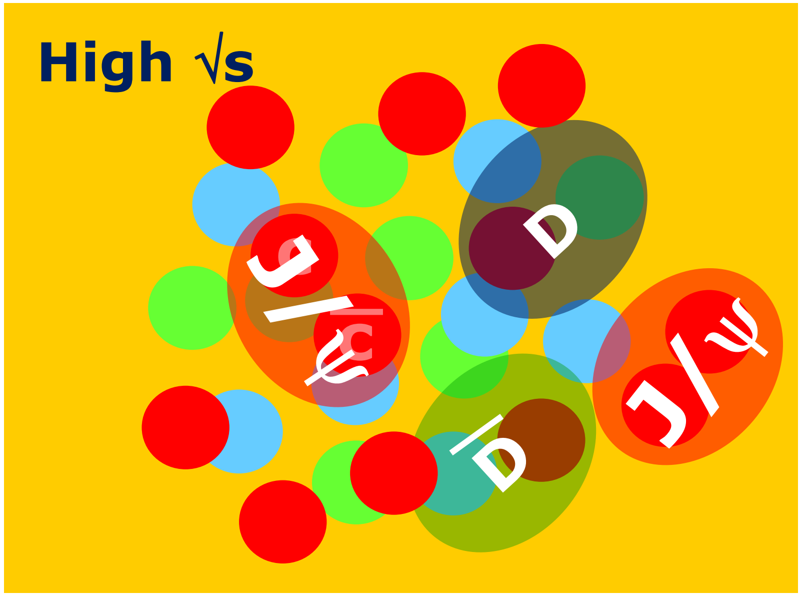
P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196, R. Thews et al, Phys.ReV.C63:054905(2001)

FROM SUPPRESSION. . .TO (RE)COMBINATION

- Increasing the energy of the collision the cc pair multiplicity increases

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





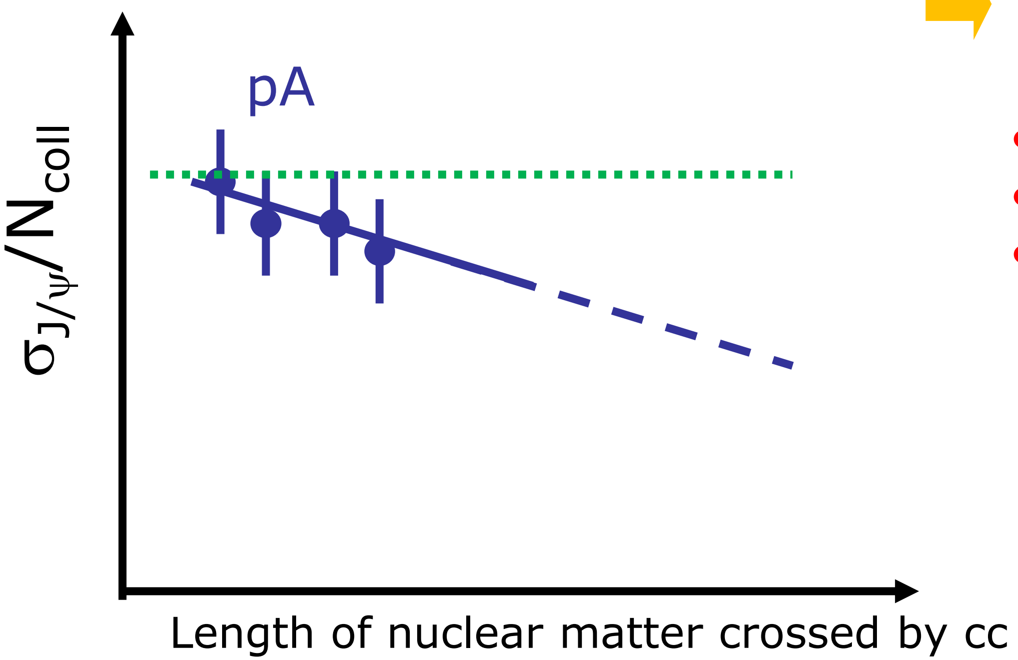
- An enhancement via (re)combination of cc pairs producing quarkonia can take place at hadronization or during QGP stage

P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196, R. Thews et al, Phys.ReV.C63:054905(2001)

WHAT ABOUT COLD NUCLEAR MATTER?

What is the fate of a J/ψ placed in a cold nuclear medium?

→ in principle, no J/ψ suppression
→ however a reduction of the yield per nucleon-nucleon collisions is observed



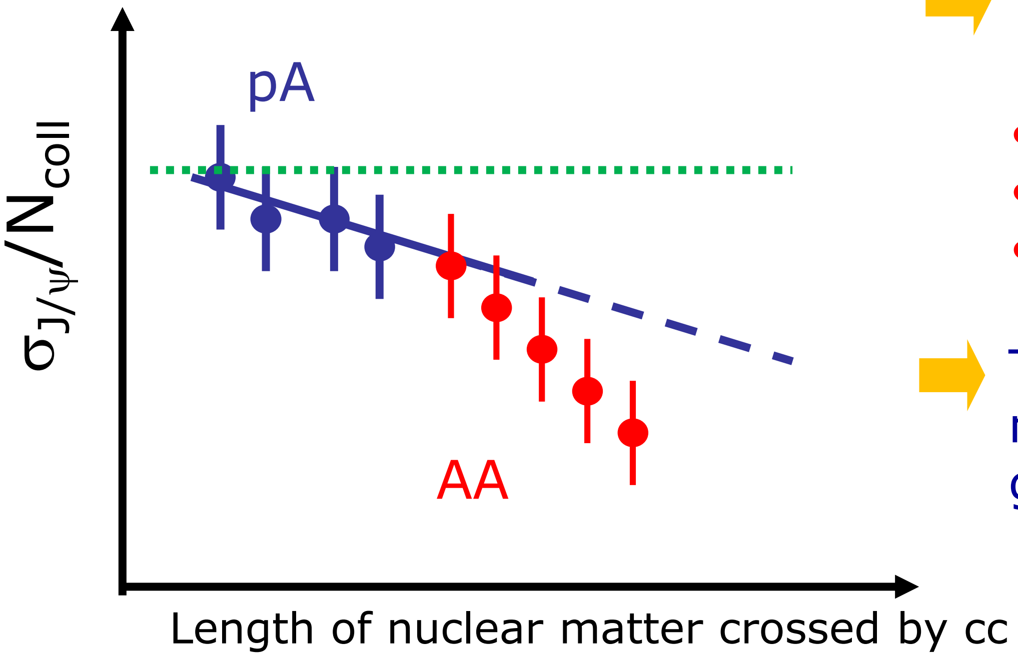
Charmonium is modified by cold nuclear matter effects as

- nuclear parton shadowing
- energy loss
- cc dissociation in the medium…

WHAT ABOUT COLD NUCLEAR MATTER?

What is the fate of a J/ψ placed in a cold nuclear medium?

→ in principle, no J/ψ suppression
→ however a reduction of the yield per nucleon-nucleon collisions is observed



Charmonium is modified by cold nuclear matter effects as

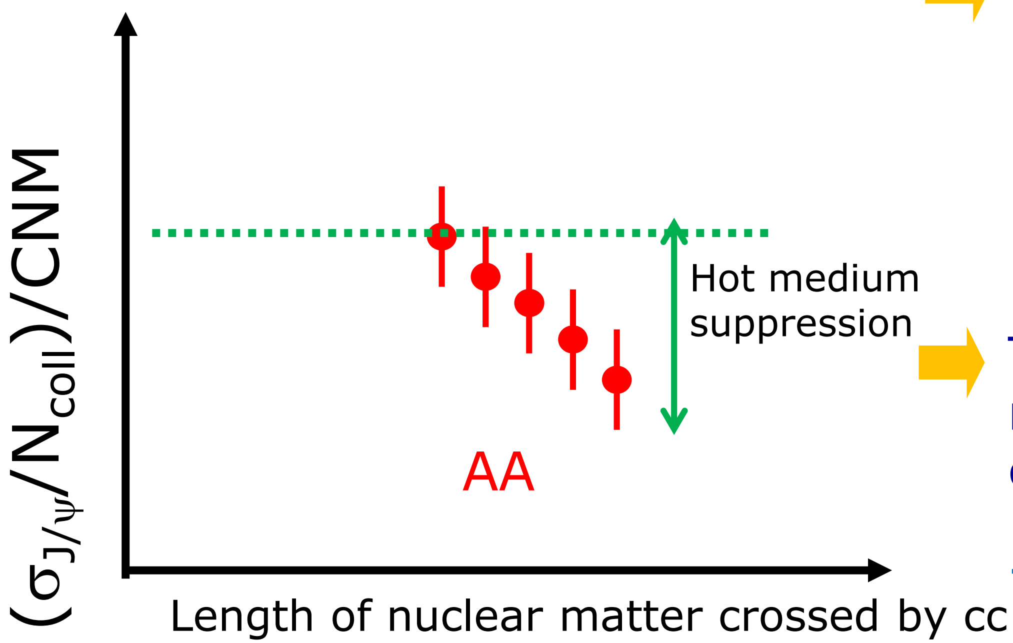
- nuclear parton shadowing
- energy loss
- cc dissociation in the medium…

The J/ψ suppression in cold nuclear matter (CNM) can mask genuine QGP effects in AA

WHAT ABOUT COLD NUCLEAR MATTER?

What is the fate of a J/ψ placed in a cold nuclear medium?

→ in principle, no J/ψ suppression
→ however a reduction of the yield per nucleon-nucleon collisions is observed



Charmonium is modified by cold nuclear matter effects as

- nuclear parton shadowing
- energy loss
- cc dissociation in the medium…

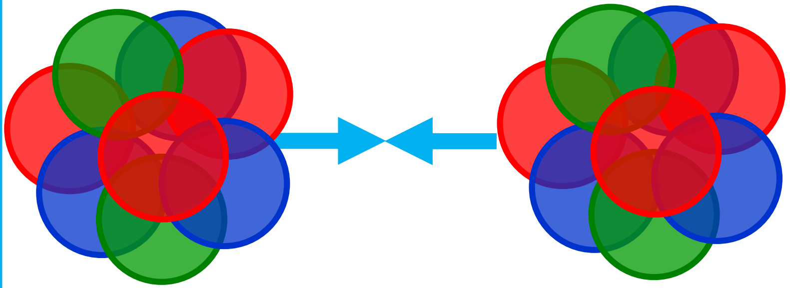
The J/ψ suppression in cold nuclear matter (CNM) can mask genuine QGP effects in AA

→ These CNM effects need to be calibrated and factorized out

CNM can be studied in pA collisions

HOW CAN WE STUDY QUARKONIUM IN HI?

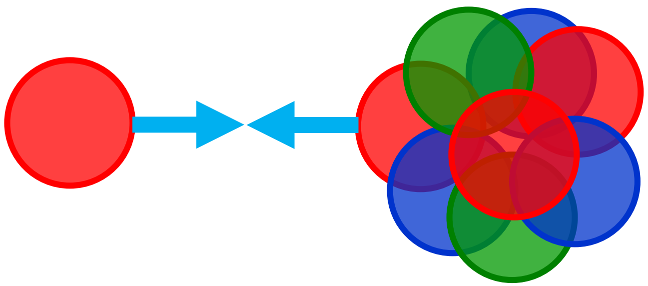
A-A



Quarkonium strongly affected by the hot matter (QGP): suppression vs regeneration

Studies are done as a function of the collision centrality

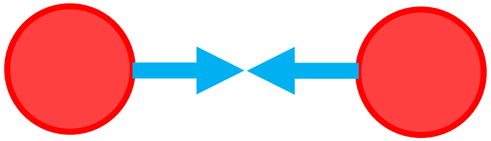
p-A



Quarkonium affected by cold nuclear matter effects (CNM)

Crucial tool to disentangle genuine QGP effect is AA collisions

p-p



Reference process to understand behaviour in pA, AA collisions

Useful to investigate production mechanisms can be investigated (NRQCD, CEM models...)

HOW CAN WE MEASURE MEDIUM EFFECTS?

Nuclear modification factor R_{AA}:

compare quarkonium cross sections in AA and pp, scaled by the nucleus mass number A

$$R_{AA}^{J/\psi}(p_T) = \frac{dN_{AA}^{J/\psi}/dp_T}{N_{coll} \times dN_{pp}^{J/\psi}/dp_T}$$

If yield scales with the number of binary collisions

→ $R_{AA} = 1$

If there are medium effects

→ $R_{AA} \neq 1$

Cold Nuclear Matter effects (CNM):

- Nuclear parton shadowing
- Parton energy loss
- cc in medium dissociation

Hot Medium effects:

- quarkonium suppression
- enhancement due to recombination

(as long as the total charm cross section remains unmodified)

knowledge of CNM effects fundamental to disentangle genuine QGP induced suppression in AA

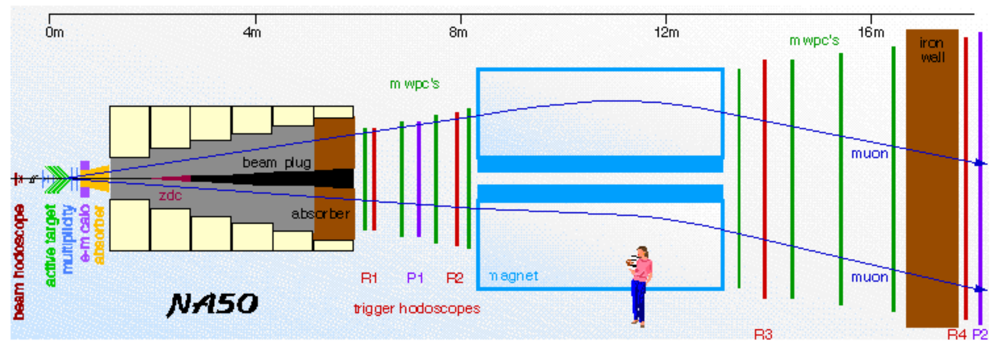
HOW IS QUARKONIUM DETECTED?

➡ Experimentally quarkonia are detected through the decay channels:

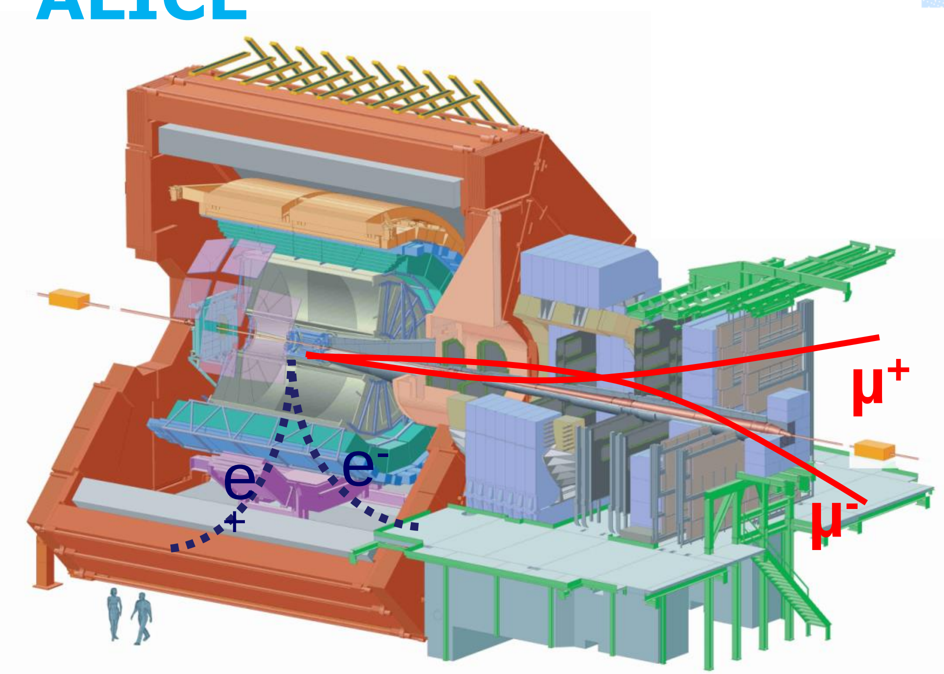
$J/\psi \rightarrow \mu^+\mu^-$ (B.R.= 5.93%)

$J/\psi \rightarrow e^+e^-$ (B.R.= 5.94%)

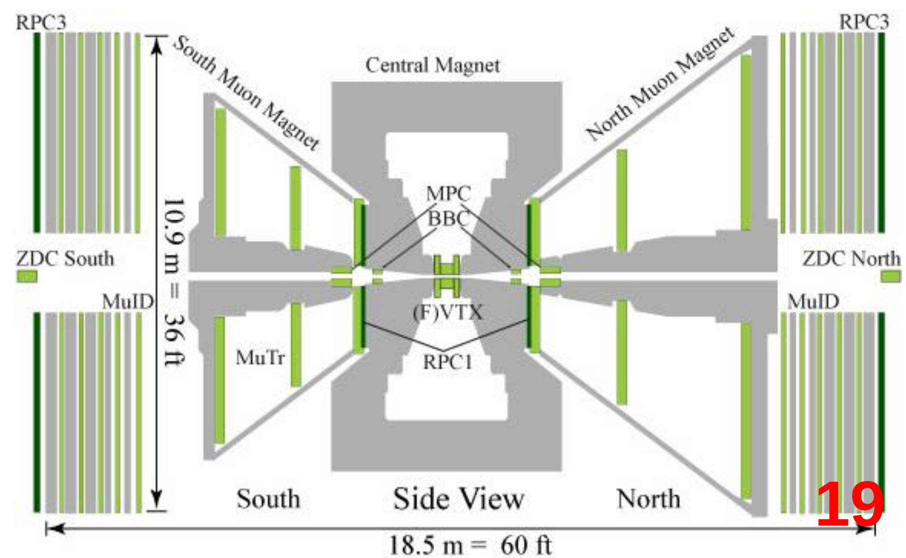
NA50



ALICE

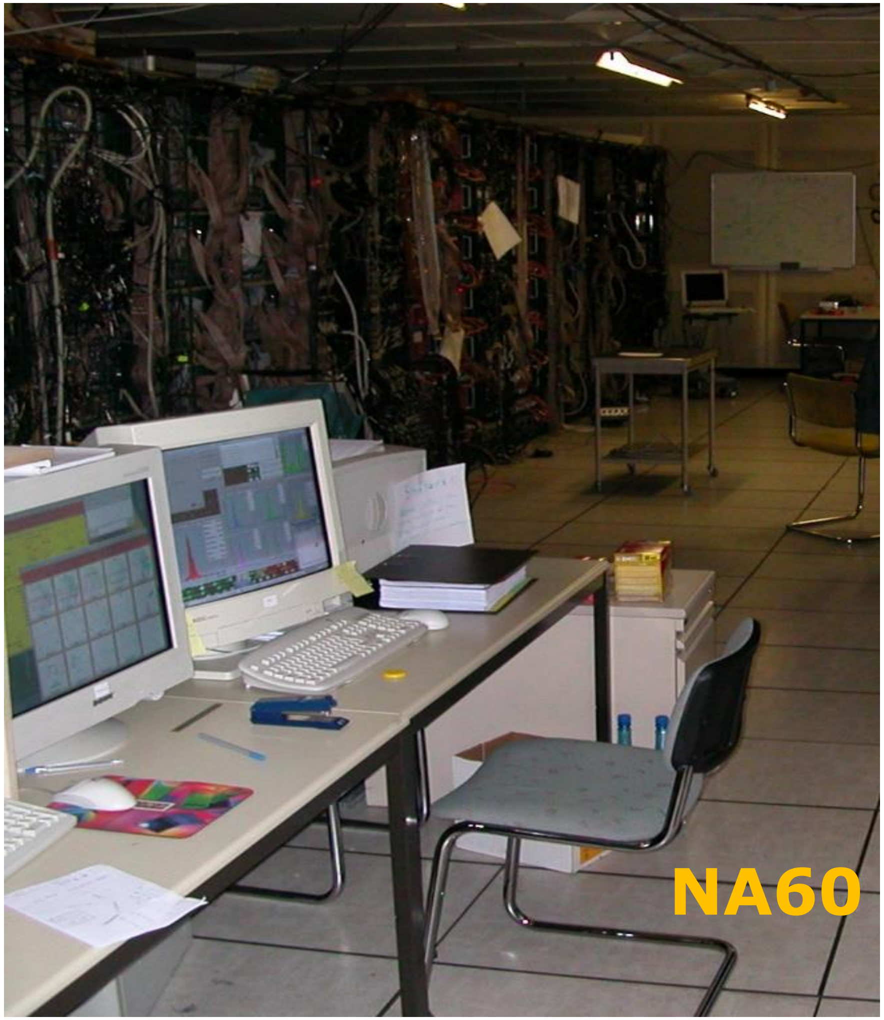


PHENIX



FROM SPS TO LHC

- 30 years of data taking: counting rooms…

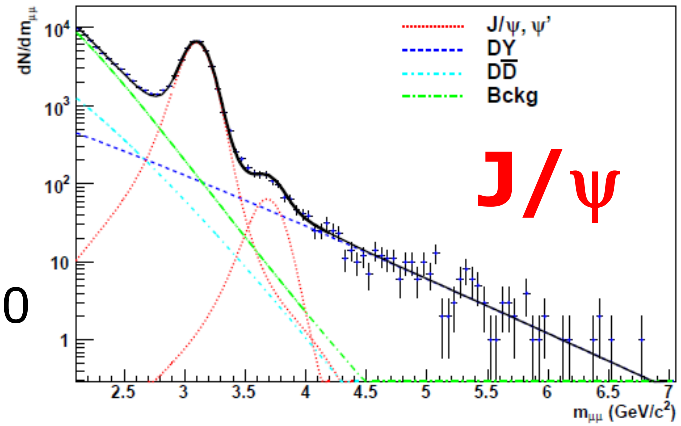


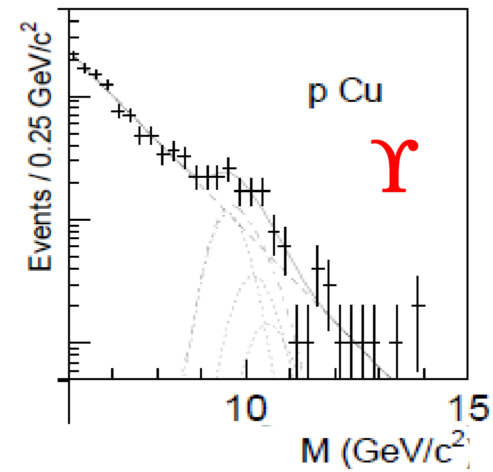
FROM SPS TO LHC

➡ Invariant mass spectra…

NA50/NA60 @ SPS

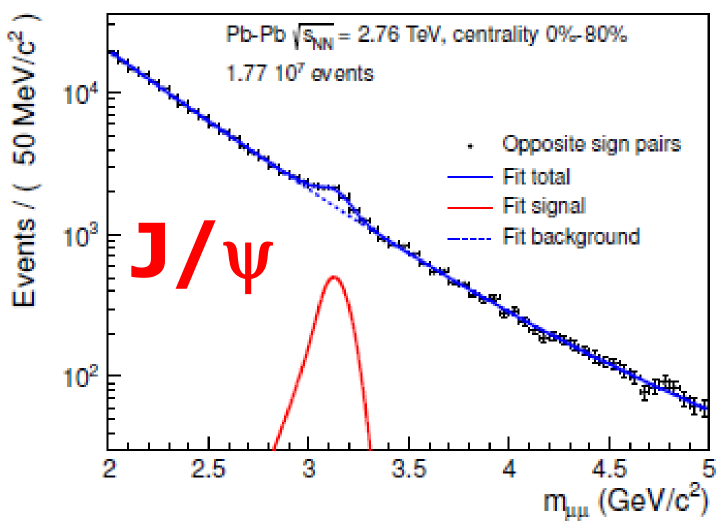
Fixed target experiments
- high J/ψ statistics: 10^5 in NA50, $4{\cdot}10^4$ in NA60
- ~300 ϒ in pA (limited resolution)

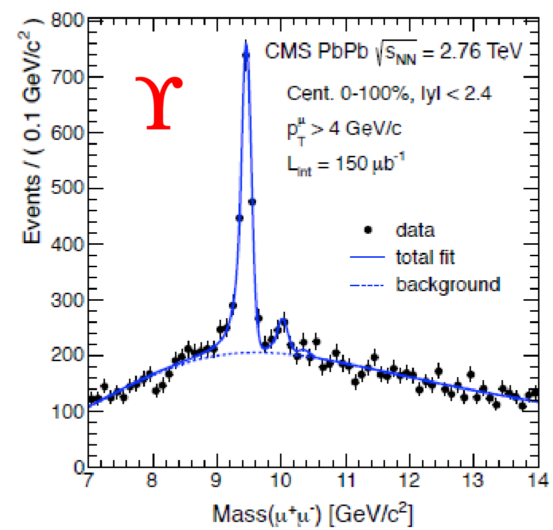




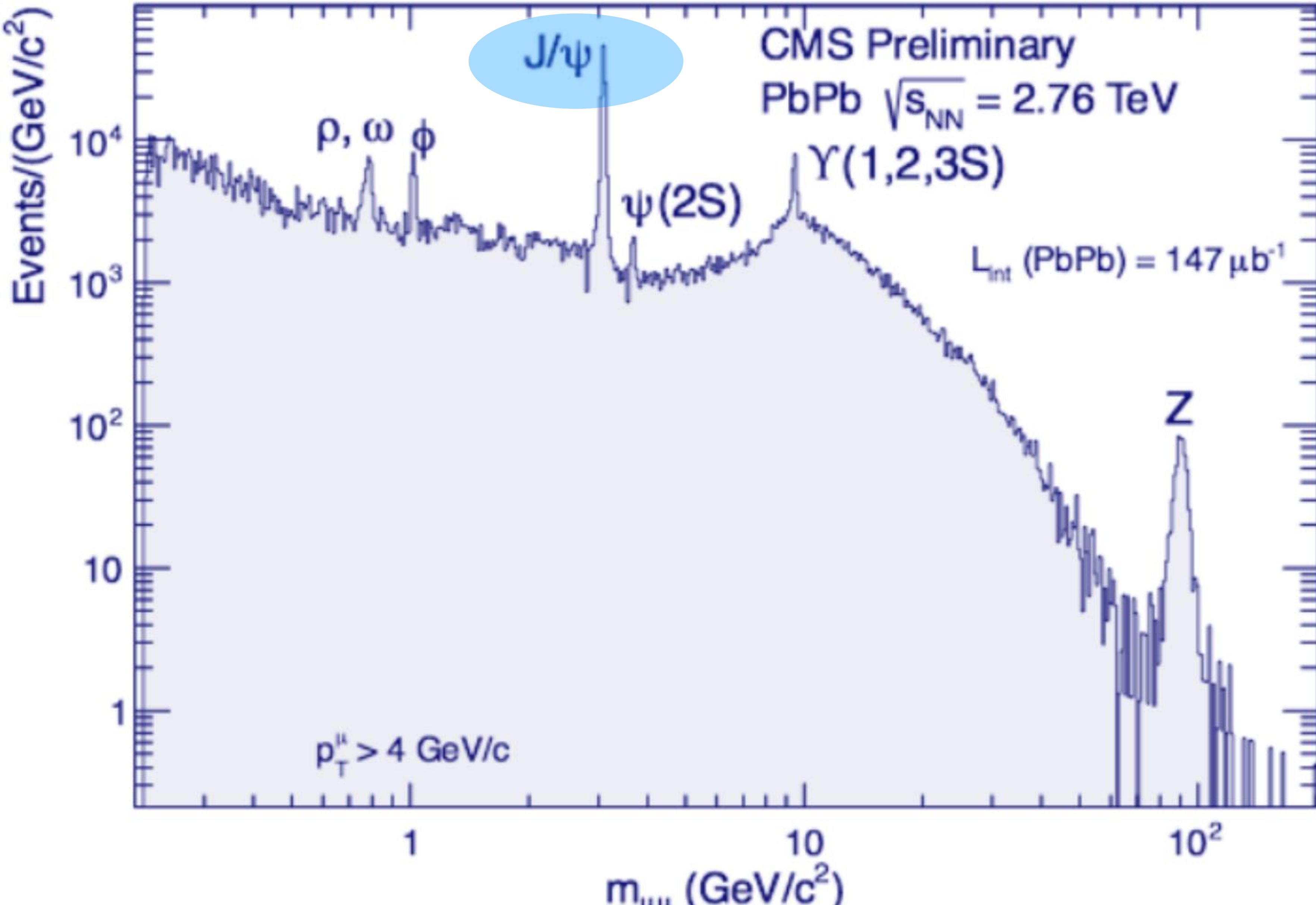
ALICE/CMS @ LHC

Collider experiments
- max J/ψ statistics
  in ALICE: ~25000
  in CMS: ~8000
  (2000 ϒ(1S))



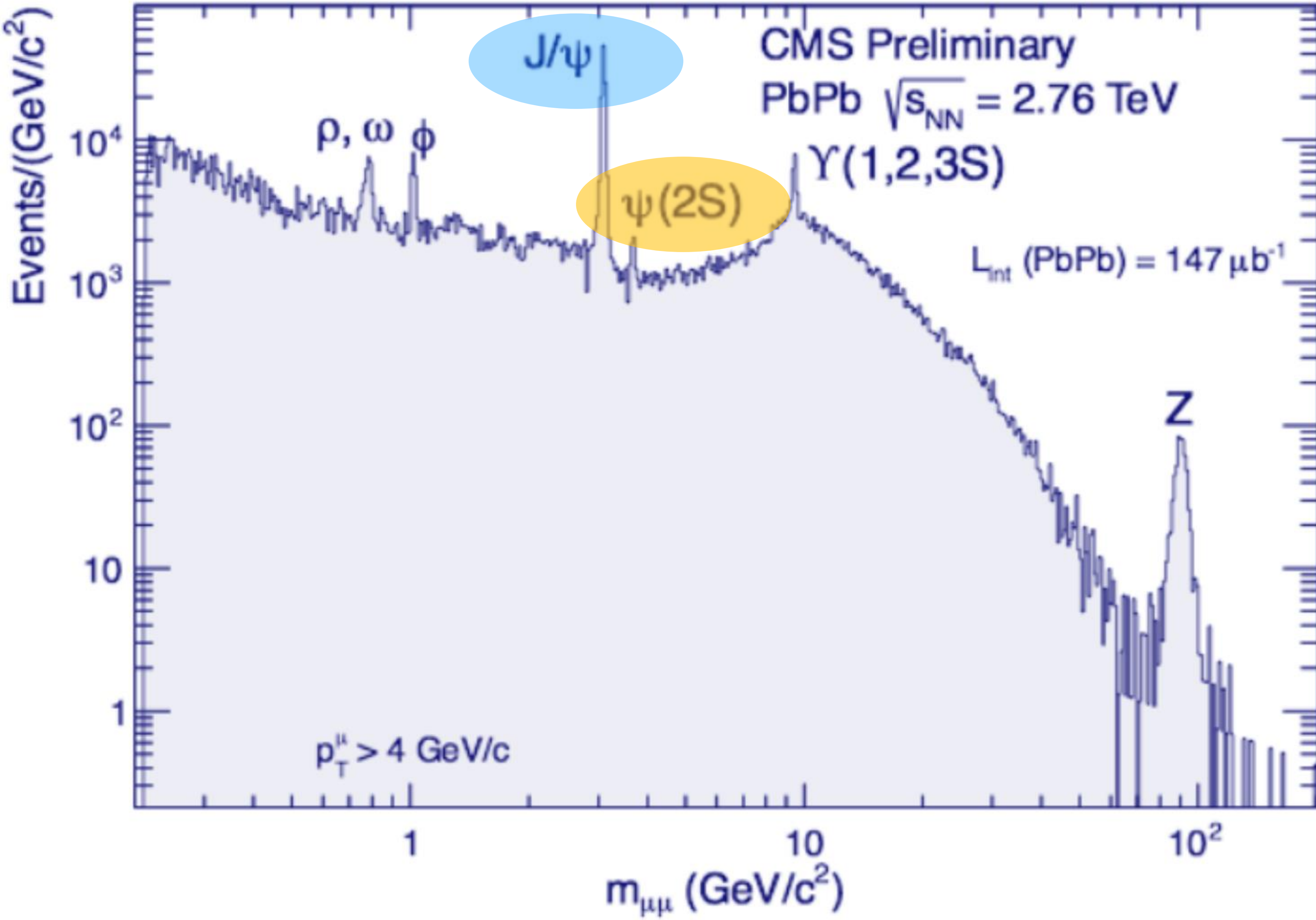


QUARKONIUM



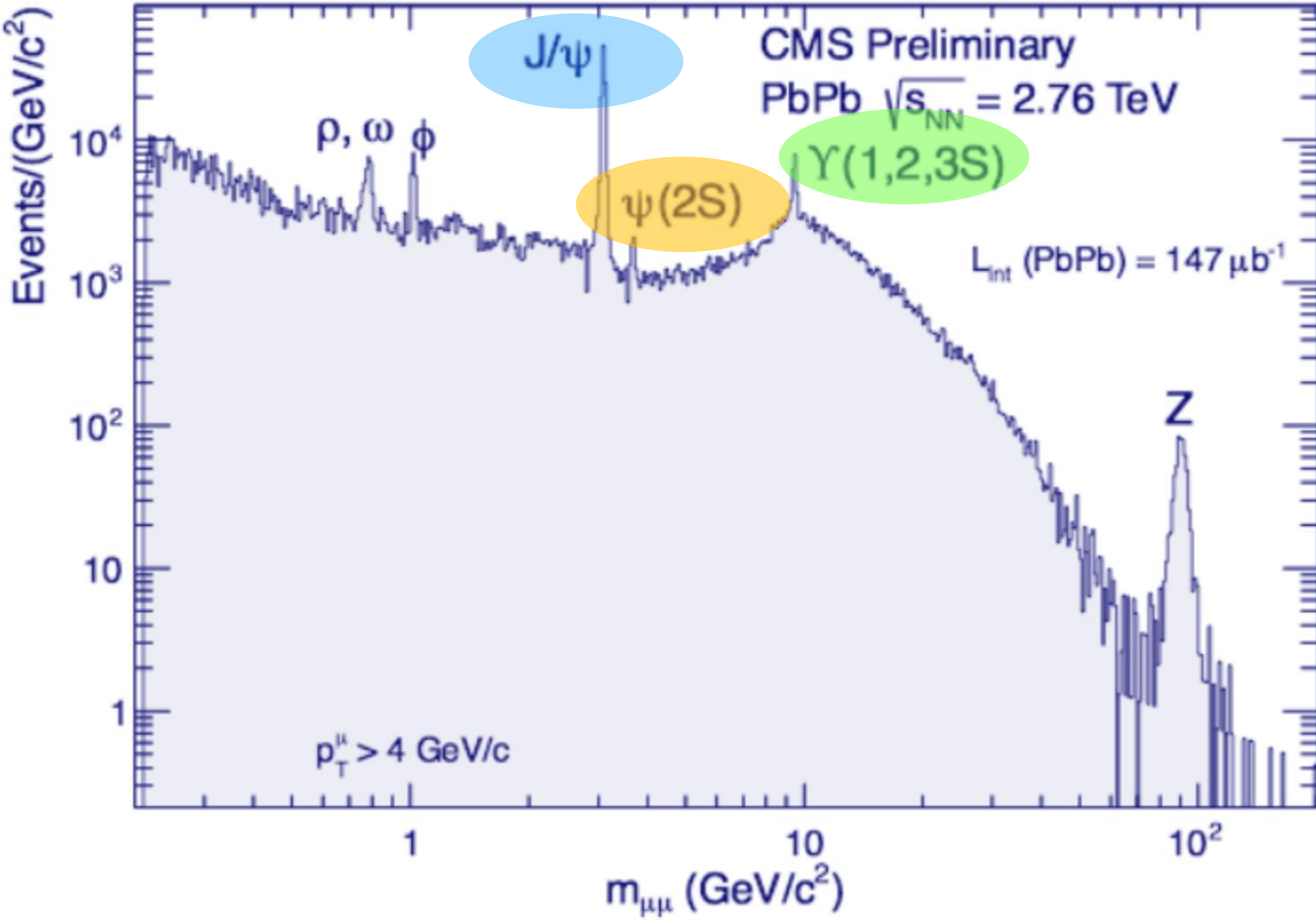
CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
J/ψ
ρ, ω
φ
ψ(2S)
Υ(1,2,3S)
L_{int} (PbPb) = 147 μb^{-1}
Z
p_T^{μ} > 4 GeV/c
Events/(GeV/c^2)
10^4
10^3
10^2
10
1
$m_{\mu\mu}$ (GeV/c^2)
1
10
10^2

QUARKONIUM



J/ψ
CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
ρ, ω
ϕ
ϒ(1,2,3S)
ψ(2S)
L_{int} (PbPb) = 147 μb^{-1}
Z
p_T^{μ} > 4 GeV/c
Events/(GeV/c^2)
10^4
10^3
10^2
10
1
$m_{\mu\mu}$ (GeV/c^2)
10
10^2

QUARKONIUM

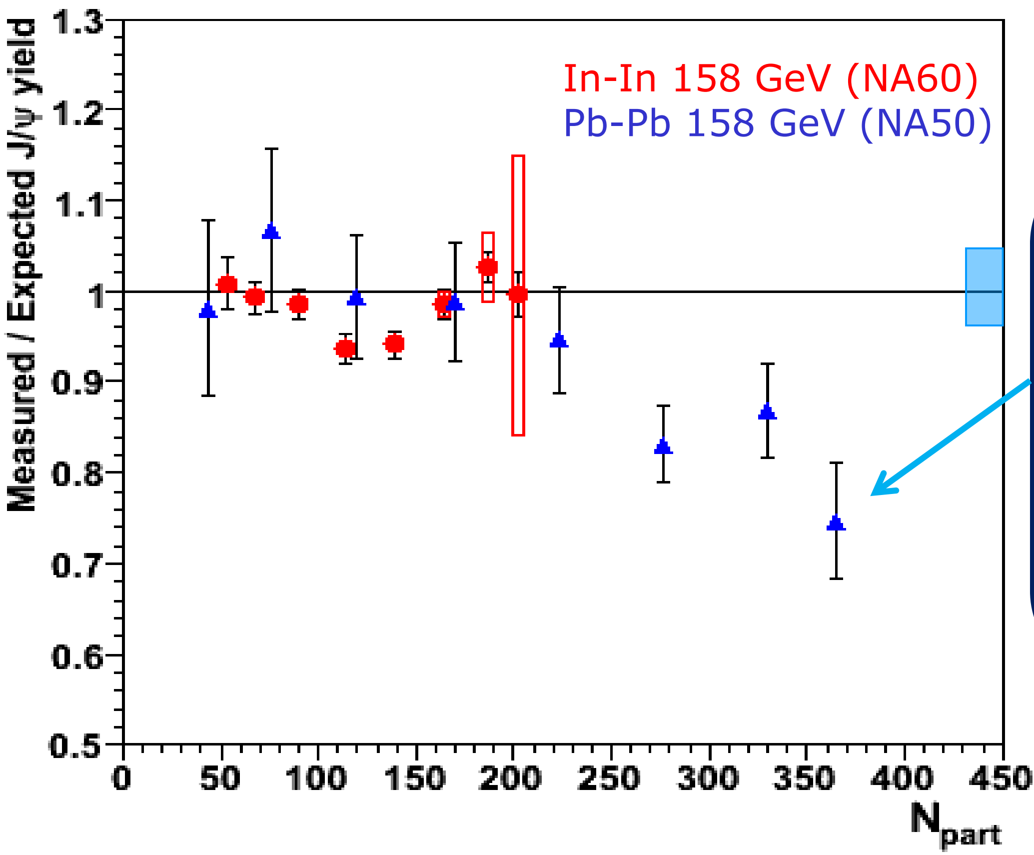


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} (PbPb) = 147 μb^{-1}
J/ψ
ψ(2S)
ϒ(1,2,3S)
ρ, ω
φ
Z
p_T^μ > 4 GeV/c
Events/(GeV/c^2)
$m_{\mu\mu}$ (GeV/c^2)
10^4
10^3
10^2
10
1
1
10
10^2

FIRST J/ψ MEASUREMENTS AT LOW ENERGY: SPS

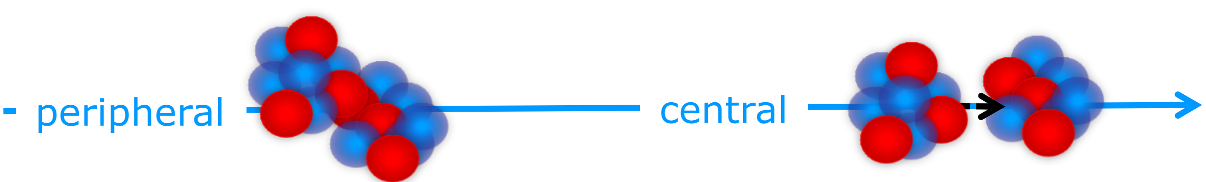
- Charmonium production deeply investigated at

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



SPS:
first evidence of anomalous suppression (i.e. beyond CNM expectations) in Pb-Pb at $\sqrt{s}$= 17 GeV

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



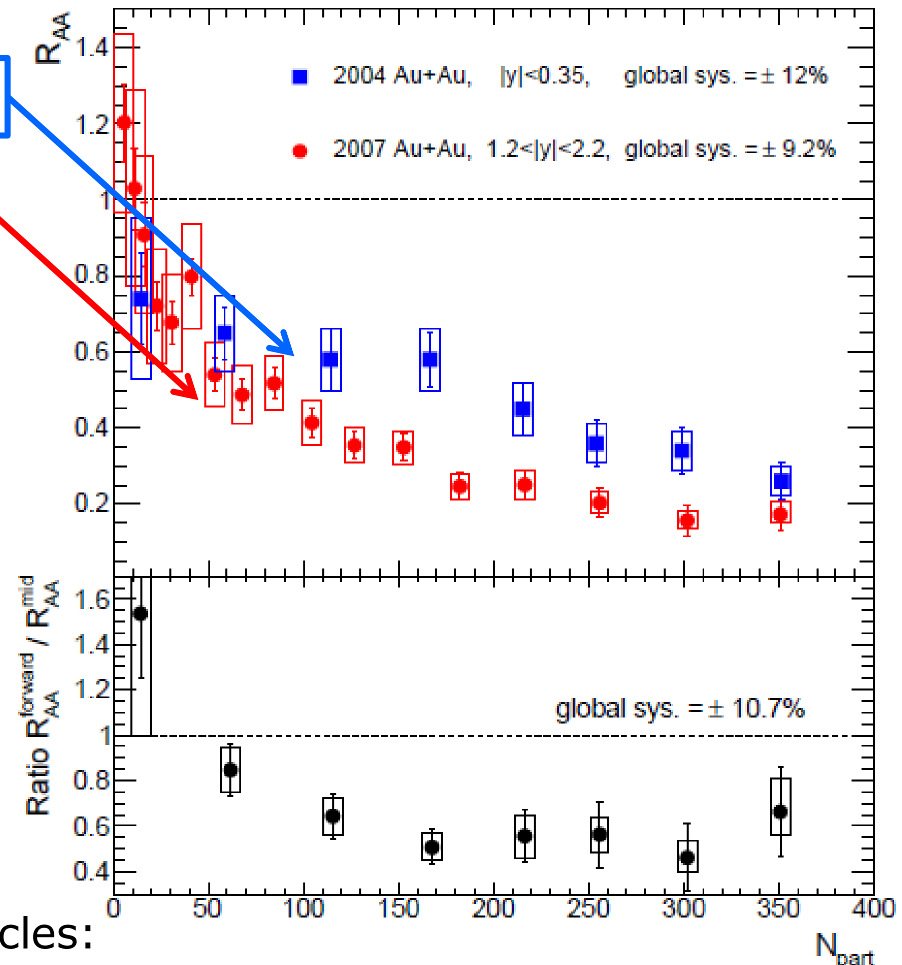
FIRST J/ψ MEASUREMENTS AT LOW ENERGY: RHIC

- Charmonium production deeply investigated at

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

Mid-rapidity

Forward-rapidity



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

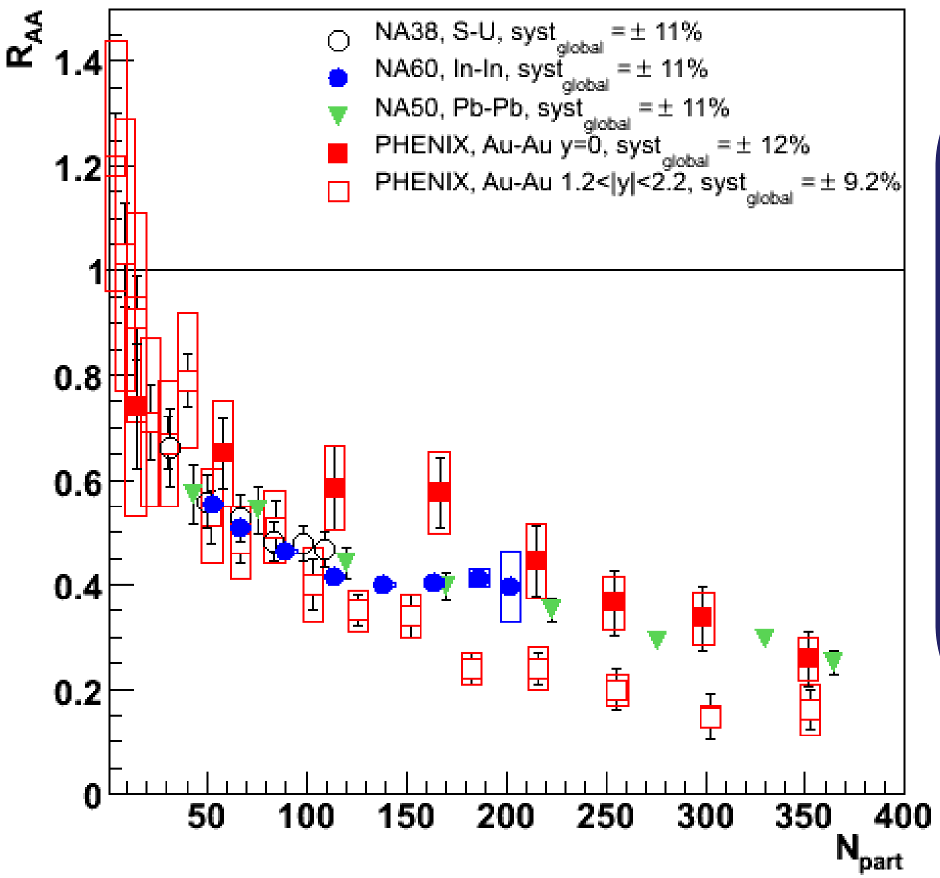
Stronger suppression at forward y
→ not expected if suppression increases with energy density (larger at mid-y)

Rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ For relativistic particles: y ~ η=-ln[tan(θ/2)]

COMPARISON OF SPS AND RHIC RESULTS

- Charmonium production deeply investigated at

SPS (NA50, NA60) $\sqrt{s_{NN}}$ = 17 GeV
RHIC (PHENIX,STAR) $\sqrt{s_{NN}}$ =39,62.4,200GeV



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

- Puzzles from SPS and RHIC
  - RHIC: stronger suppression at forward rapidities
  - SPS vs. RHIC: similar R_{AA} pattern versus centrality

- Hint for (re)combination at RHIC?

No final theoretical explanation

QUARKONIUM AT LHC

Decisive inputs expected from LHC results, having access to:

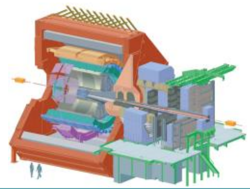
higher energies
→ stronger quarkonium suppression?

more charm
→ larger (re)combination?

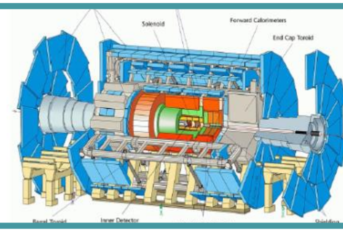
more bottom
→ Υ can be investigated

QUARKONIUM AT LHC

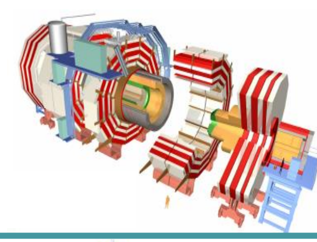
ALICE J/ψ, $\psi(2S)\rightarrow\mu^+\mu^-$
$\Upsilon\rightarrow\mu^+\mu^-$
$J/\psi\rightarrow e^+e^-$



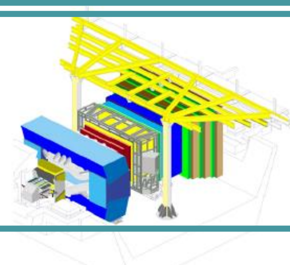
ATLAS $J/\psi\rightarrow\mu^+\mu^-$



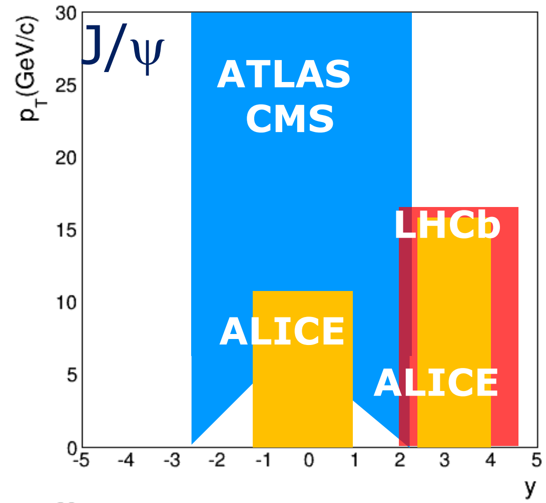
CMS J/ψ, $\psi(2S)\rightarrow\mu^+\mu^-$
$\Upsilon\rightarrow\mu^+\mu^-$

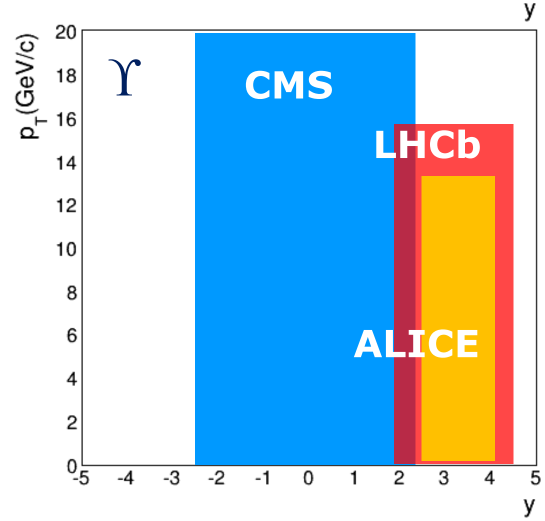


LHCb J/ψ, $\Upsilon\rightarrow\mu^+\mu^-$
(no heavy ion physics program)



➡ Kinematic coverage of quarkonium measurements:



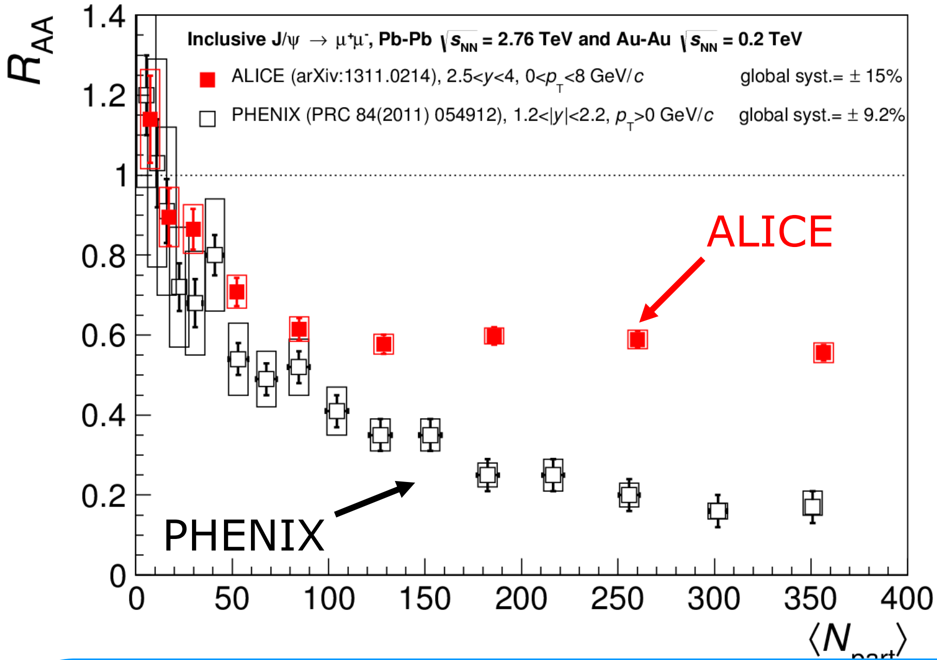


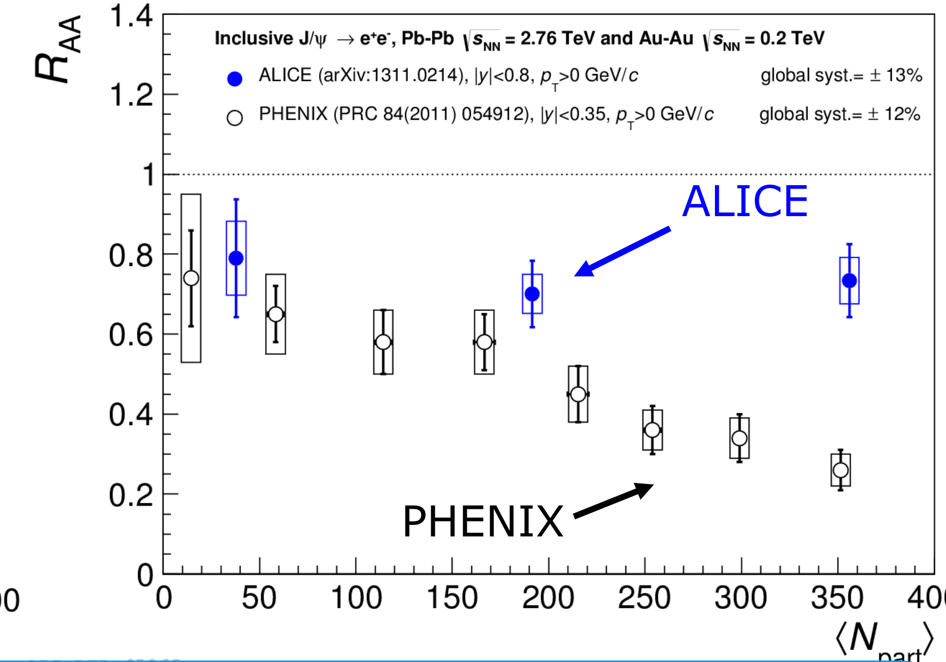
➡ Complementary quarkonium results from LHC experiments!

J/ψ R_{AA} VS CENTRALITY: ALICE VS PHENIX

- Centrality dependence of the J/ψ inclusive R_{AA} studied by ALICE in both central and forward rapidities down to zero p_T

ALICE Coll. PLB 734 (2014) 314





ALICE results:

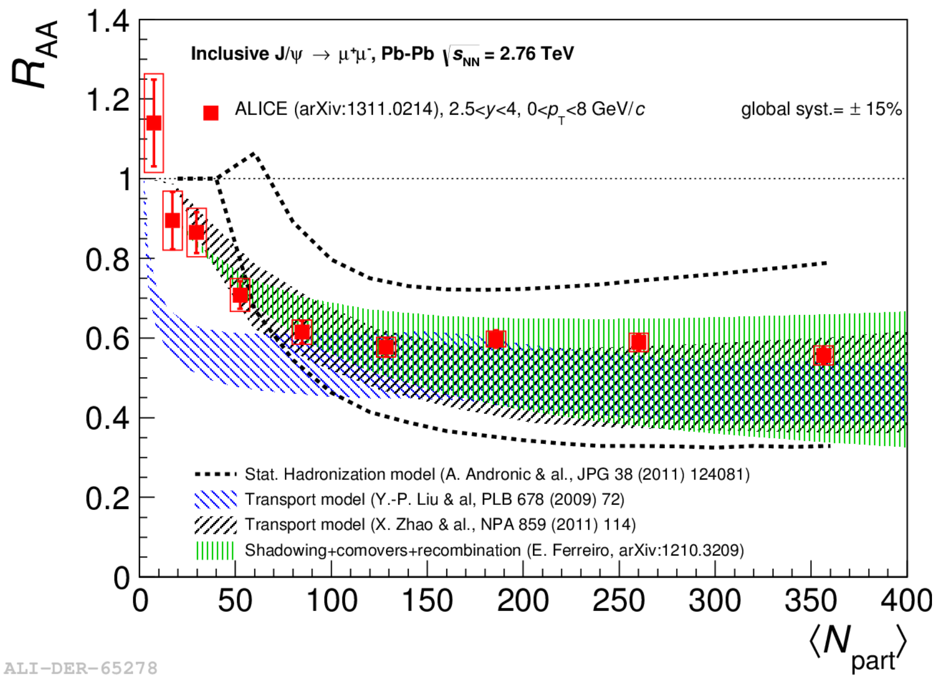
→ clear J/ψ suppression with almost no centrality dependence for N_{part}>100

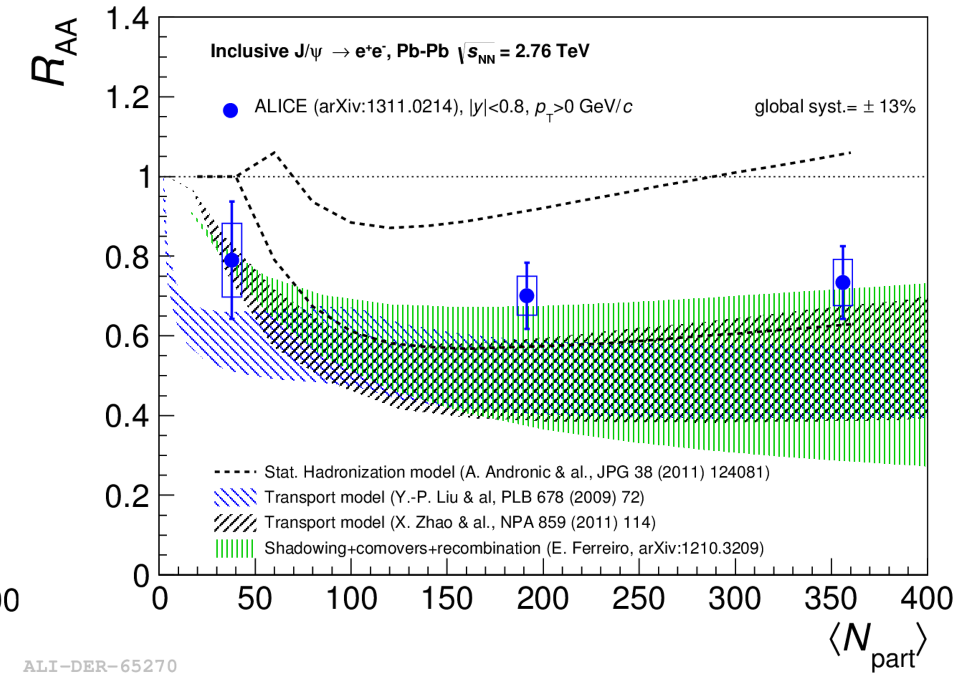
Comparison with PHENIX:

→ 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





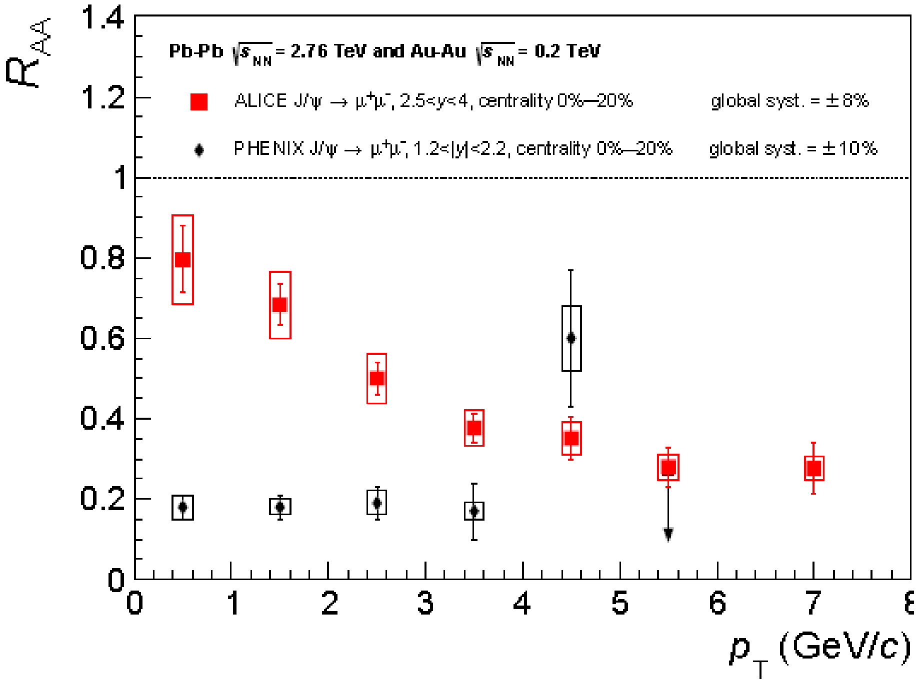
Comparison to theory calculations:

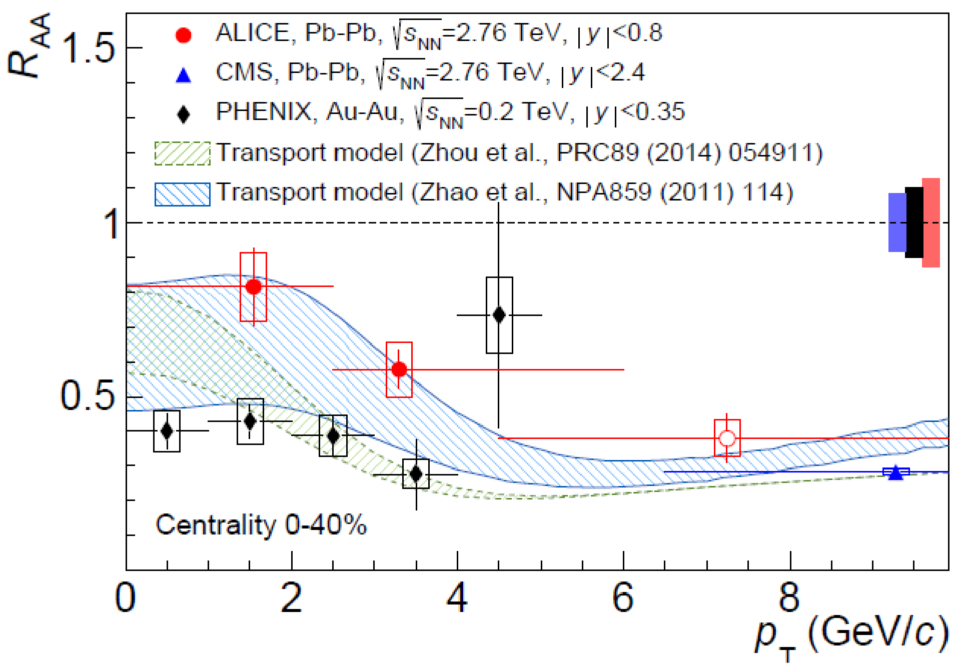
- Models including a large fraction (> 50% in central collisions) of J/ψ produced from (re)combination or models with all J/ψ produced at hadronization provide a reasonable description of ALICE results
- Still rather large theory uncertainties: models will benefit from a precise measurement of σ_{cc}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

ALICE: R_{AA} VS P_T

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

arXiv:1504.07151

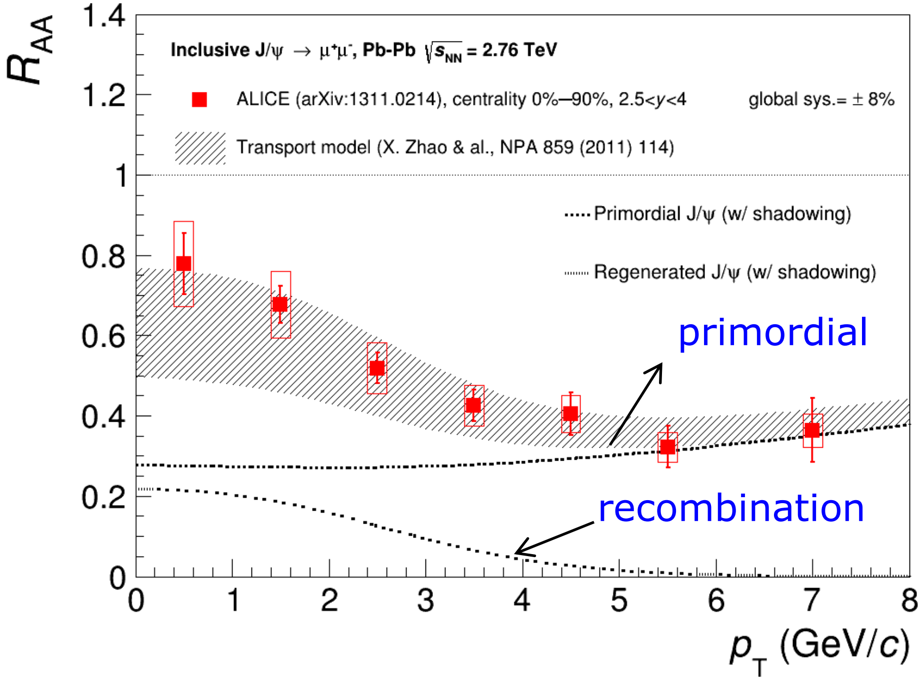


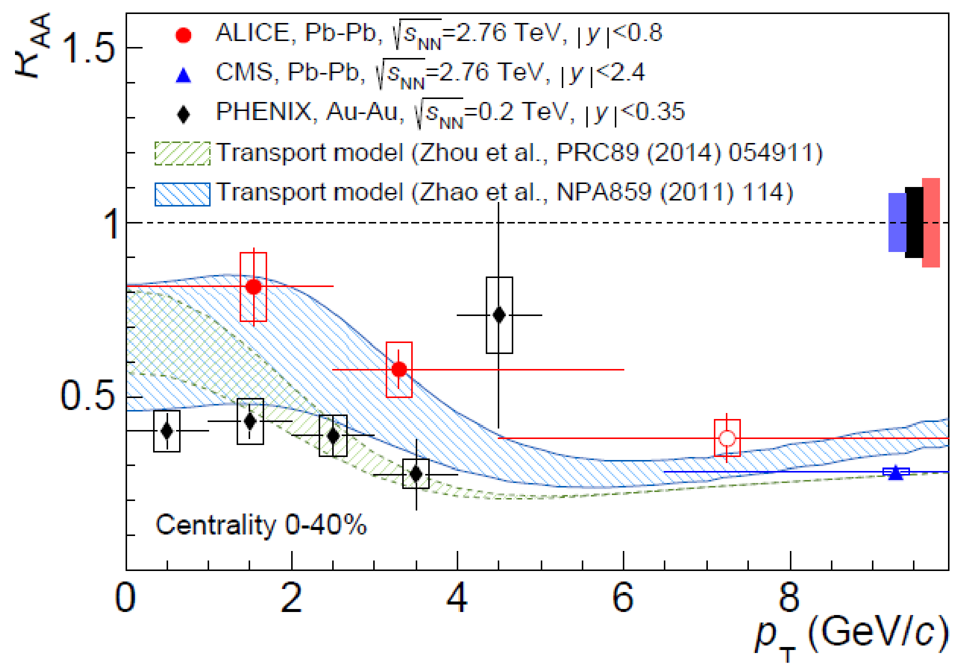


- Different suppression for low and high p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ
- Striking difference, at low p_T, between PHENIX and ALICE patterns

ALICE: R_{AA} VS P_T

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

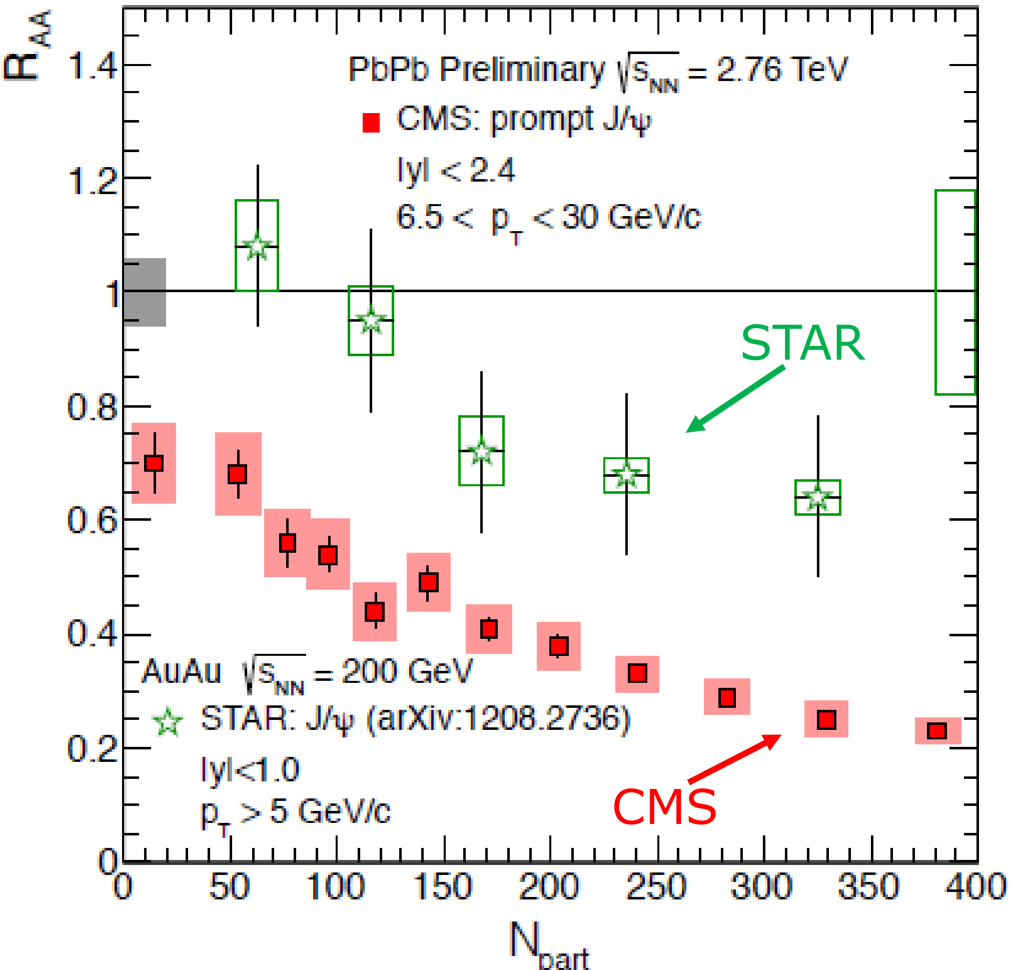




- Different suppression for low and high p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ
- Models: ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible

HIGH P_T J/ψ: CMS & STAR

- At LHC high p_T J/ψ have been investigated by CMS



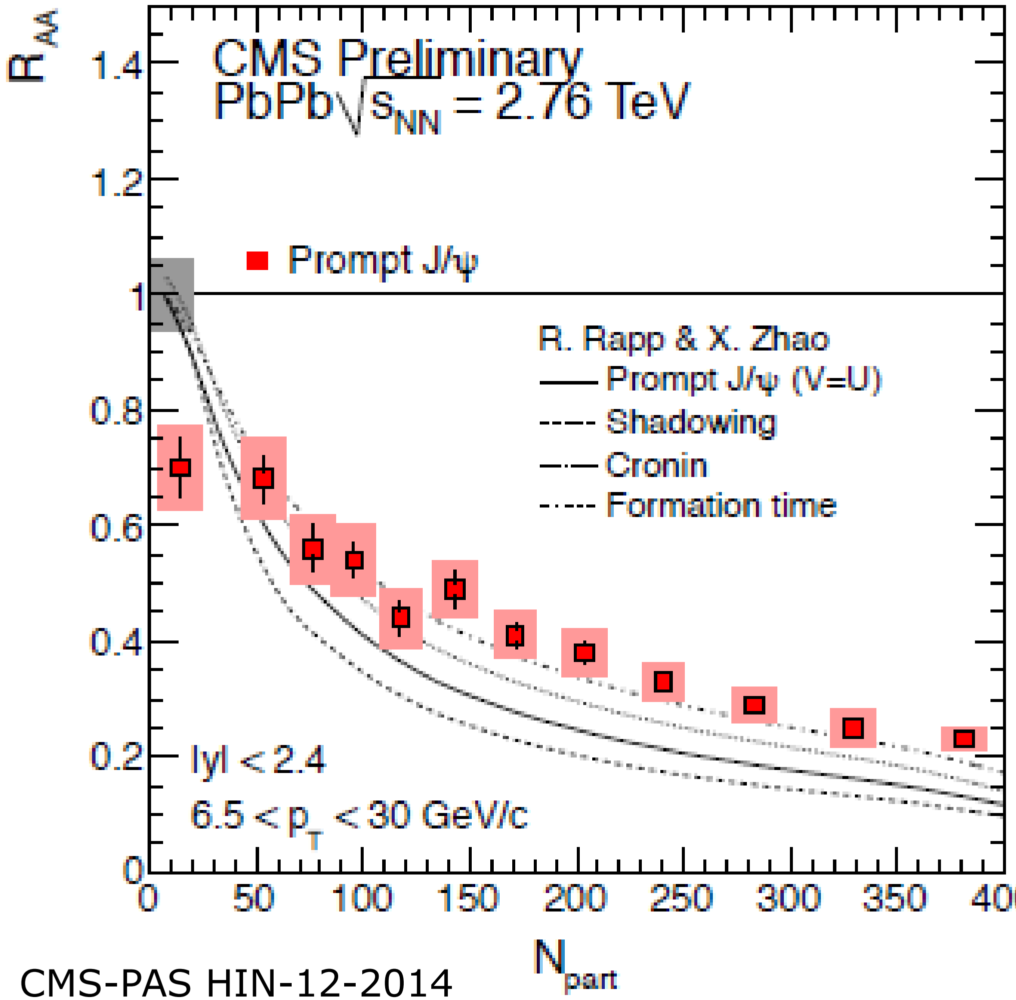
- Limits in the CMS low-p_T J/ψ acceptance since muons need to overcome the magnetic field and energy loss in the absorber:
  - mid-y: p_T>6.5 GeV/c
  - forward y: p_T>3 GeV/c

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

CMS-PAS HIN-12-2014

HIGH p_T J/ψ: CMS & STAR

- At LHC high p_T J/ψ have been investigated by CMS



CMS-PAS HIN-12-2014

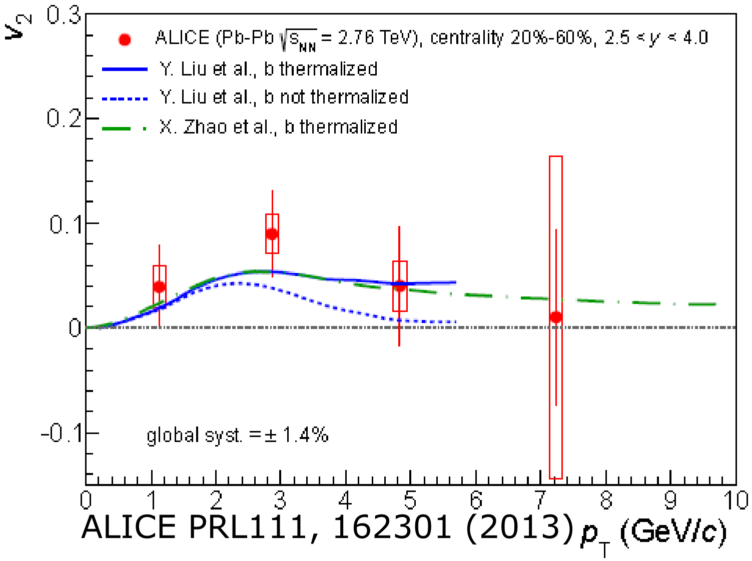
- Limits in the CMS low-p_T J/ψ acceptance since muons need to overcome the magnetic field and energy loss in the absorber:
  - mid-*y*: p_T>6.5 GeV/c
  - forward *y*: p_T>3 GeV/c

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

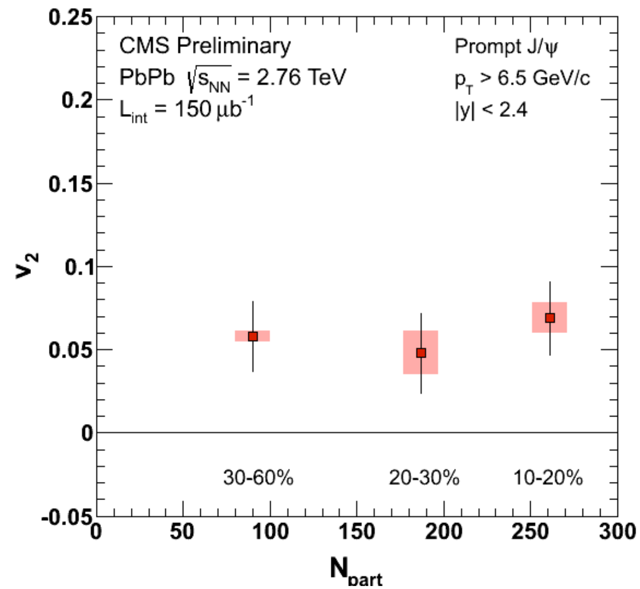
- negligible (re)generation effects expected at high p_T

J/ψ FLOW

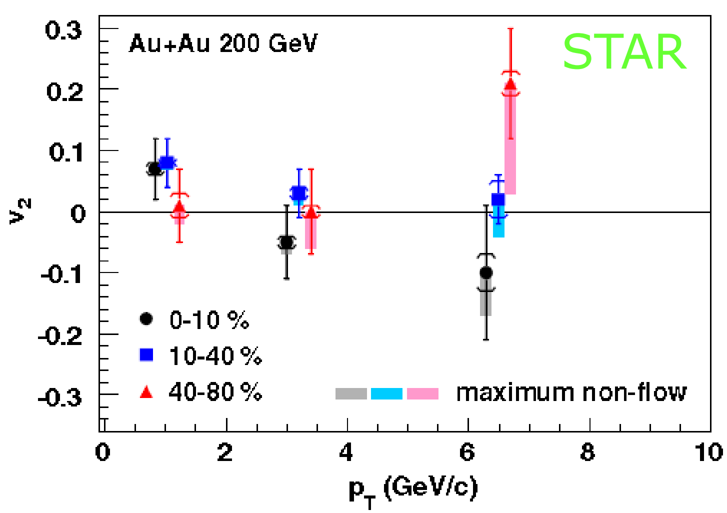
- The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy



ALICE PRL111, 162301 (2013)



D.Moon, HP2013



STAR, PRL 052301(2013)

- Hint for J/ψ flow at LHC, contrary to v_2~0 observed at RHIC!

- ALICE: qualitative agreement with transport models including regeneration
- CMS: path-length dependence of energy loss?

Υ(1S) PRODUCTION IN PB-PB COLLISIONS

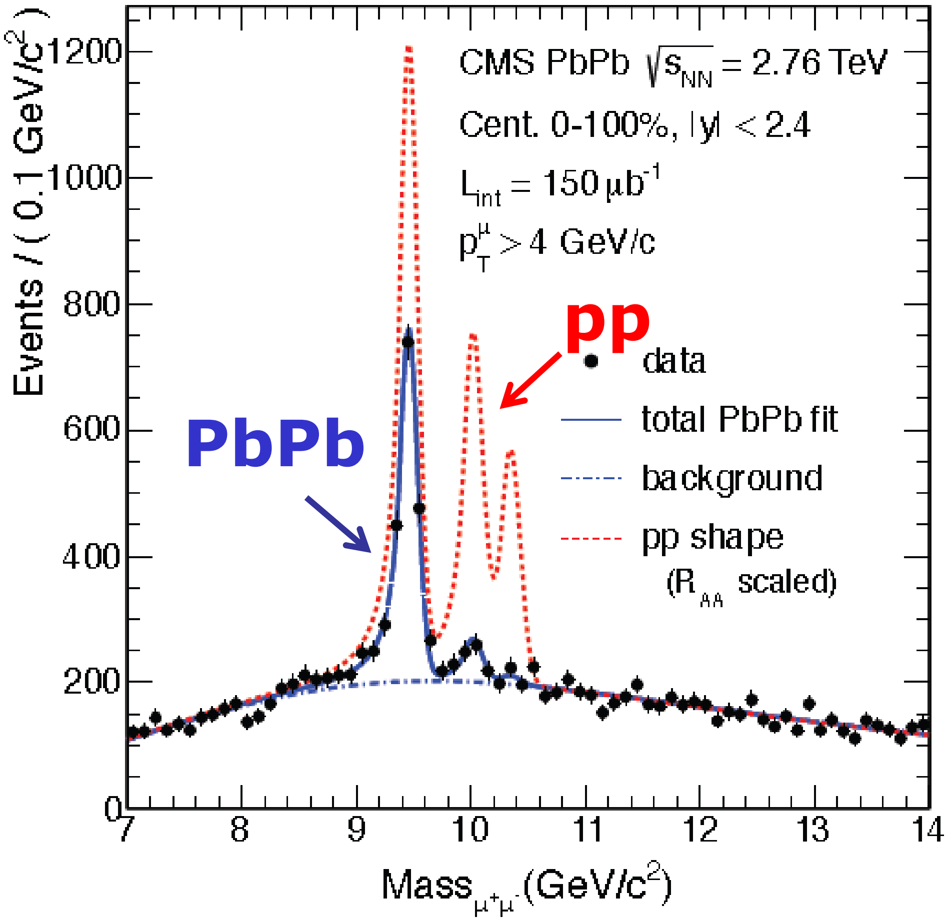
LHC is the machine for studying bottomonium in AA collisions

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

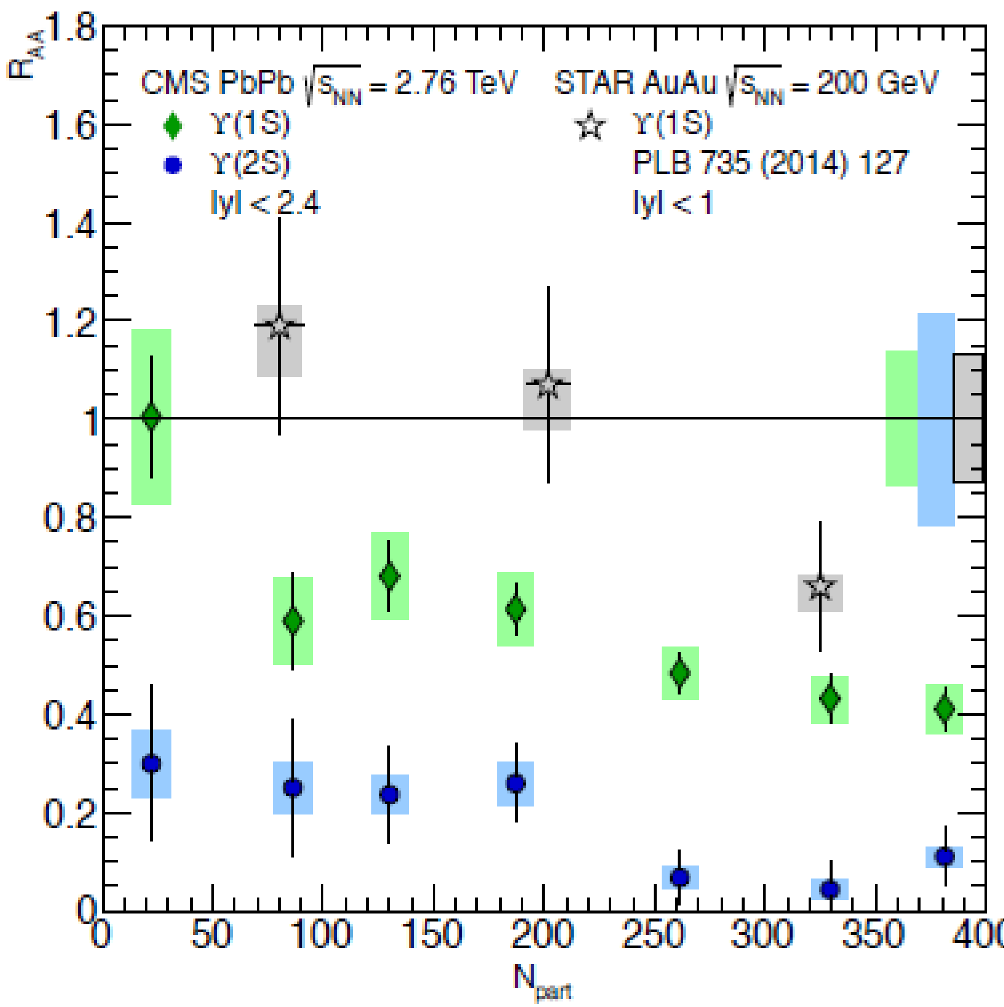
with a drawback...smaller production cross-section

PRL 109, 222301 (2012)



Clear suppression of Υ states in PbPb with respect to pp collisions

Υ(1S) PRODUCTION IN PB-PB COLLISIONS



- Clear suppression of Υ(2S)
- Υ(1S) suppression compatible with suppression of excited states (50% feed-down)
- Sequential suppression of the three Υ states according to their binding energy:

$$R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$$

$R_{AA}(\Upsilon(1S))$ = 0.56 ± 0.08 (stat) ± 0.07 (syst)
$R_{AA}(\Upsilon(2S))$ = 0.12 ± 0.04 (stat) ± 0.02 (syst)
$R_{AA}(\Upsilon(3S))$ <0.1 (at 95% C.L)

- Suppression at LHC is stronger than at RHIC

QUARKONIUM IN AA: WHERE ARE WE?

- ~30 years after first suppression prediction, this is observed with very good accuracy!

- Two main mechanisms at play:

  1. Suppression in a deconfined medium
  2. (charmonium) re-combination at high $\sqrt{s}$ and low p_T

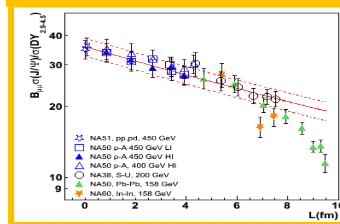
  can qualitatively explain the main features of the results

- To move towards a more quantitative understanding, a precise knowledge of CNM effects is crucial!

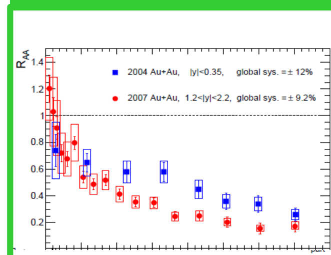
- pA results, where no hot medium should be formed, are needed to:

  1. investigate initial/final state CNM effects
  2. build a reference for AA collisions

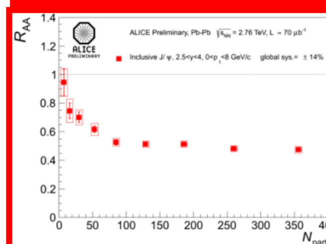
SPS



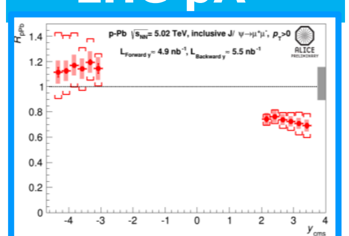
RHIC dA, AA



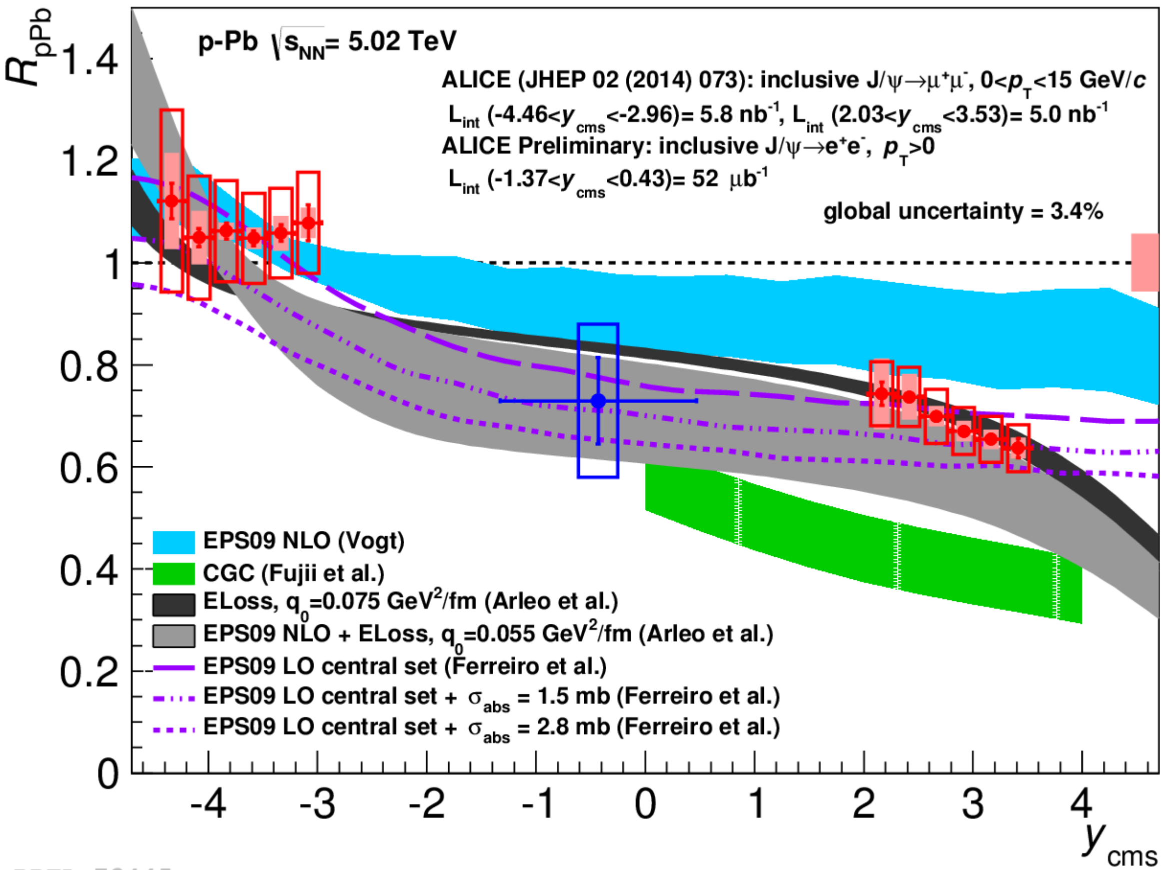
LHC AA

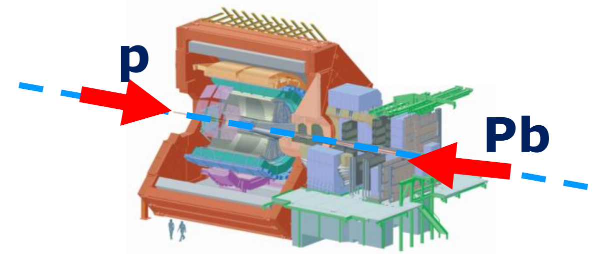


LHC pA



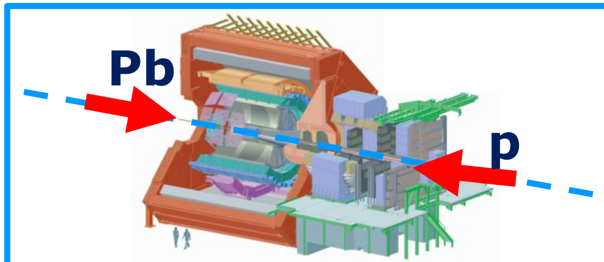
J/ψ IN pA COLLISIONS





$2.03<y_{CMS}<3.53$

$10^{-5}<x<8\cdot10^{-5}$



$-4.46<y_{CMS}<-2.96$

$10^{-2}<x<5\cdot10^{-2}$

➡ J/ψ production in modified also in pA because of CNM effects: R_{pA} decreases towards forward *y*

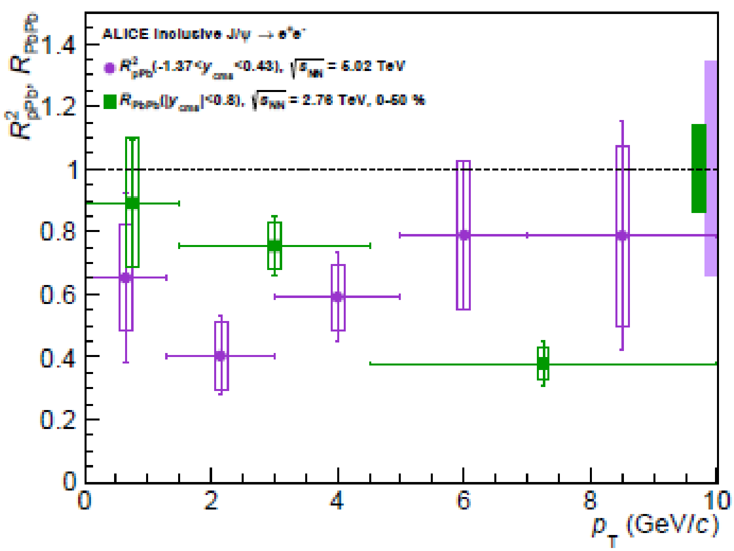
➡ Theoretical predictions: reasonable agreement with

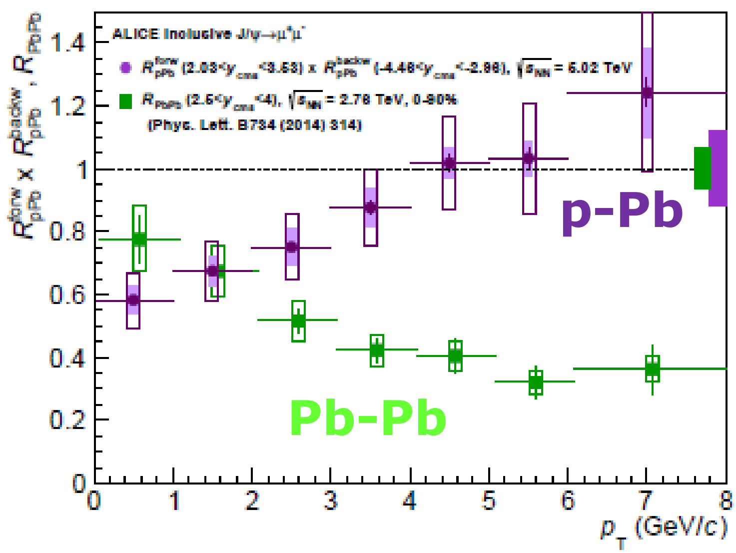
- shadowing calculations and models including coherent parton energy loss
- CGC description seems not to be favoured

CNM EFFECTS FROM p-Pb TO Pb-Pb

Once CNM effects are measured in pA, what can we learn on J/ψ production in PbPb?

Hypothesis:
- 2→1 kinematics for J/ψ production
- CNM effects (dominated by shadowing) factorize in p-A
- CNM obtained as R_{pA} x R_{Ap} (R_{pA}^2), similar x-coverage as PbPb





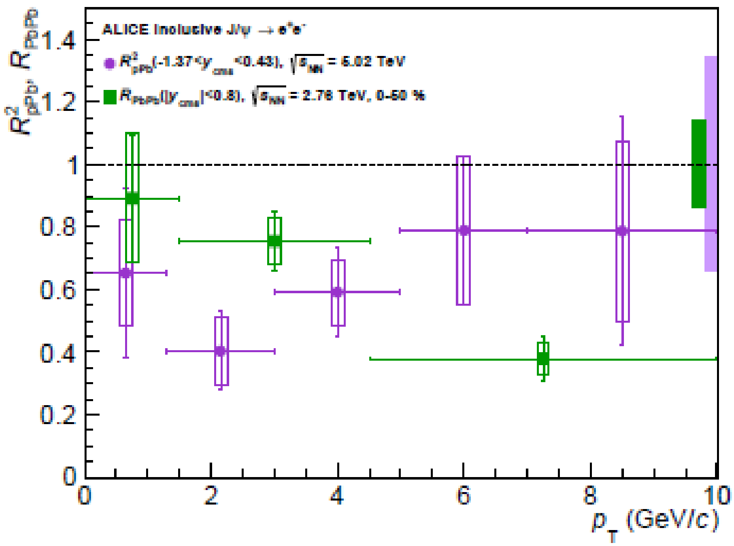
Sizeable p_T dependent suppression still visible
→ CNM effects not enough to explain AA data at high p_T

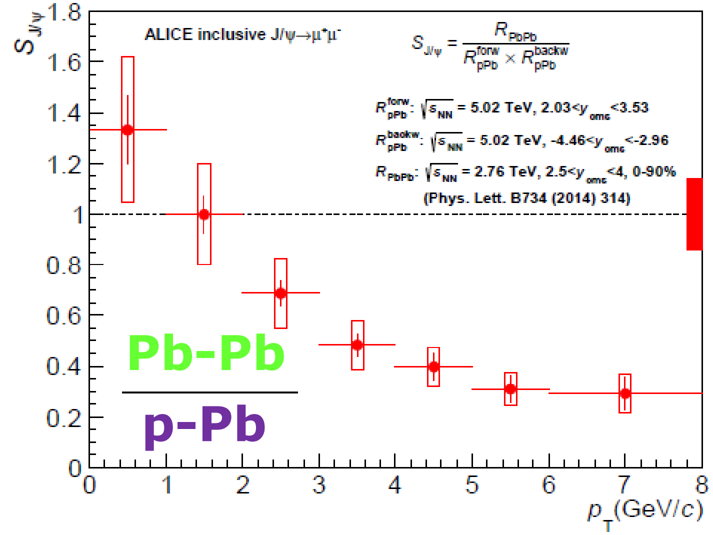
we get rid of CNM effects, by doing the ratio AA / pA

CNM EFFECTS FROM p-Pb TO Pb-Pb

➡ Once CNM effects are measured in pA, what can we learn on J/ψ production in PbPb?

Hypothesis:
- 2→1 kinematics for J/ψ production
- CNM effects (dominated by shadowing) factorize in p-A
- CNM obtained as R_{pA} x R_{Ap} (R_{pA}^2), similar x-coverage as PbPb



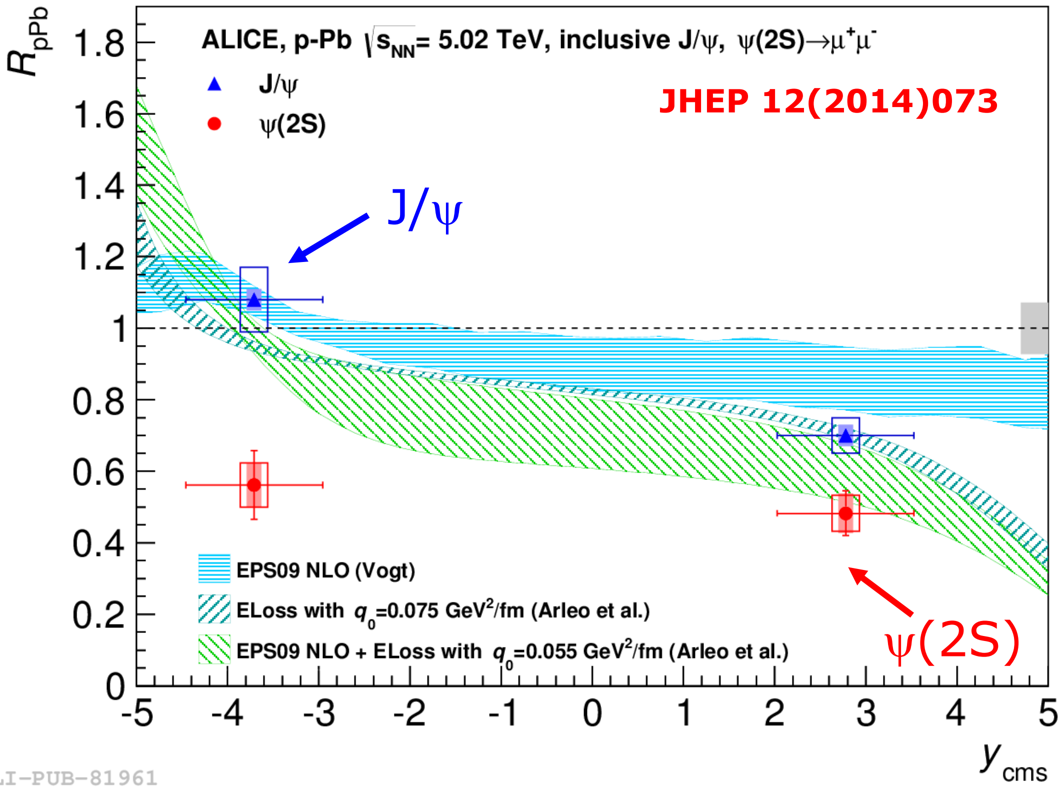


➡ Sizeable p_T dependent suppression still visible
→ CNM effects not enough to explain AA data at high p_T

➡ we get rid of CNM effects, by doing the ratio AA / pA

$\psi(2S)/J/\psi$ in p-Pb

- A strong decrease of the $\psi(2S)$ production in p-Pb, relative to J/ψ, is observed with respect to the pp measurement ($2.5<y_{cms}<4$, $\sqrt{s}$=7TeV)



ALI−PUB−81961

- Similar effect seen by PHENIX in d-Au at $\sqrt{s_{NN}}$=200 GeV

- same initial state CNM effects (shadowing & coherent energy loss) for J/ψ and $\psi(2S)$

  ⬇

  theoretical predictions in disagreement with $\psi(2S)$ result

- Final state effects related to the (hadronic) medium created in the p-Pb collisions?

At the end of LHC Run-I...

Large wealth of results at LHC complementing SPS and RHIC measurements!

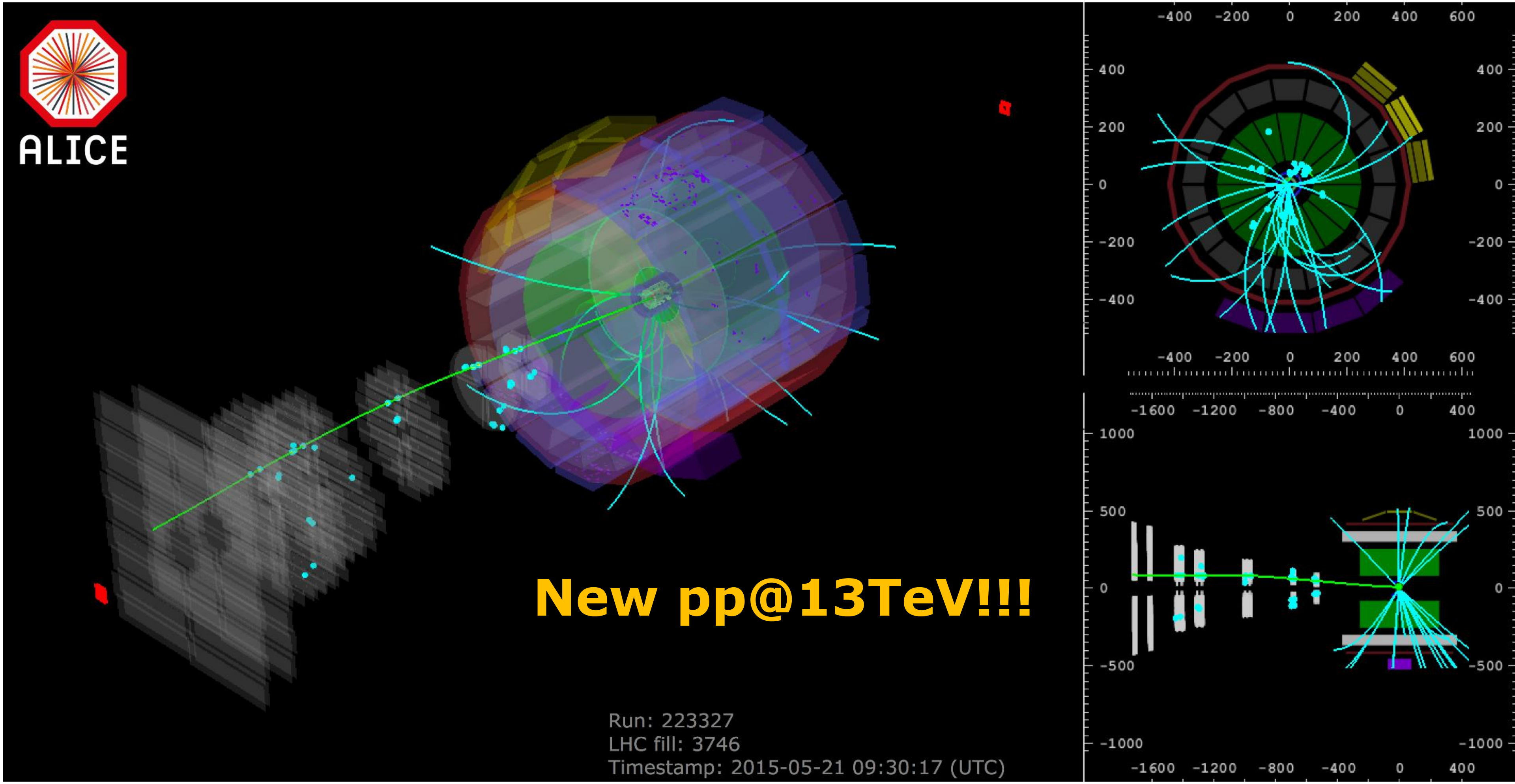
- Very interesting observations, qualitative understanding of the main quarkonium features in A-A:
  - important role of charmonium (re)generation processes at low p_T
  - bottomonium sequential suppression observed

- In p-A collisions:
  - interplay of shadowing and coherent energy loss can satisfactorily describe the J/ψ results
  - loosely bound ψ(2S) is likely influenced by the hadronic final state

Results from LHC Run2 eagerly awaited!

- Energy increase ($\sqrt{s_{NN}}$=5TeV) will allow for confirmation of the (re) combination role at low p_T
- Statistics increase will allow to sharpen Run-I results

AND NOW. . .LHC RUN-II

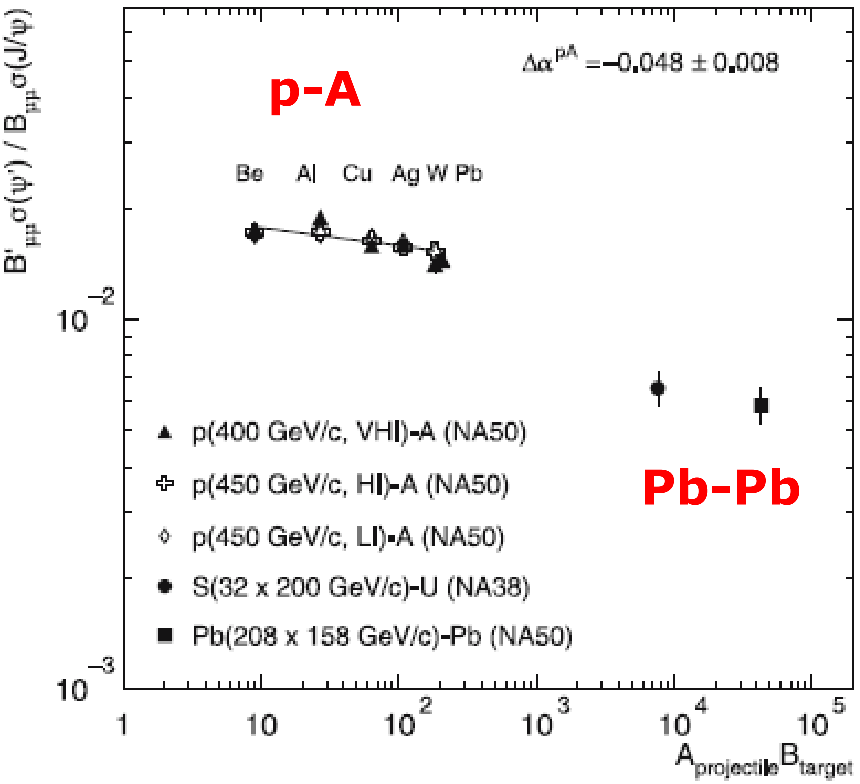


Backup slides

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

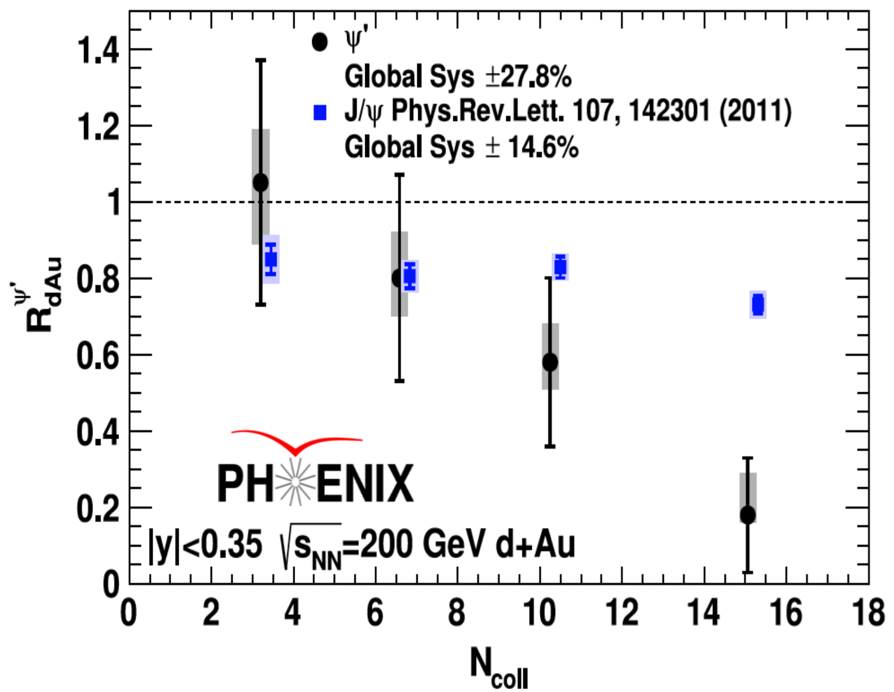
SPS (NA50) pA, AA @ $\sqrt{s_{NN}}$ = 17 GeV

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



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

PRL 111, 202301 (2013)

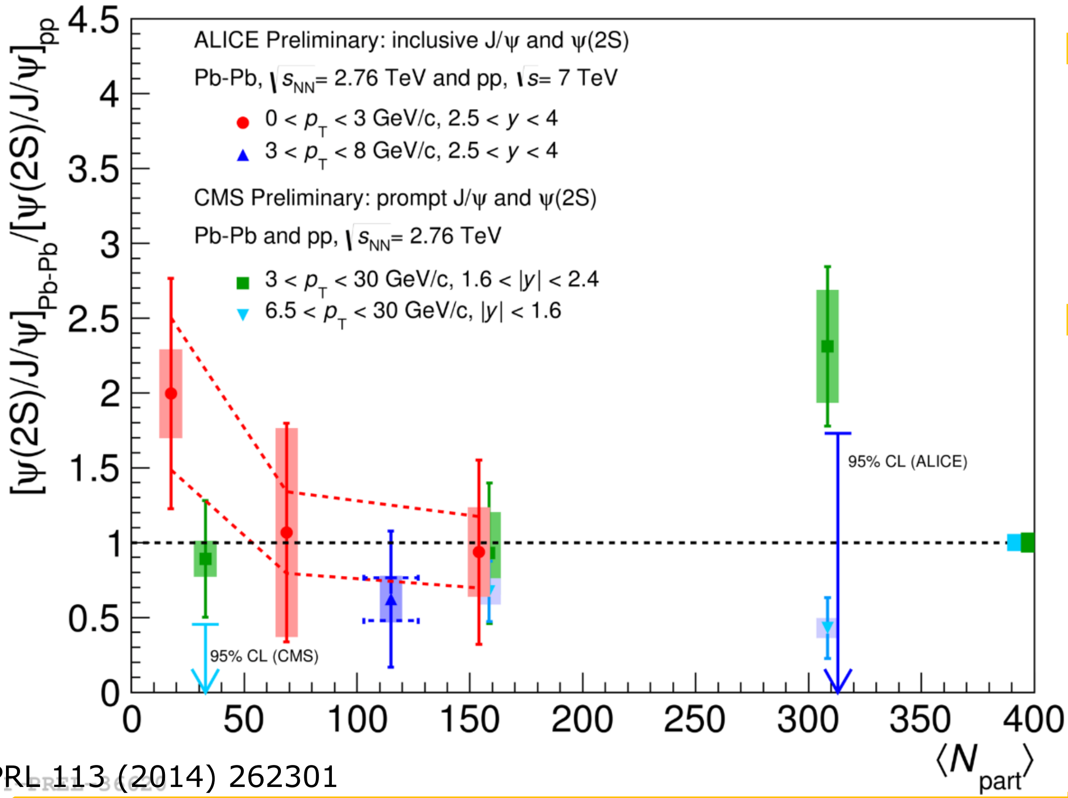


ψ(2S) is more suppressed than J/ψ already in pA collisions and the suppression increases in Pb-Pb

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

ψ(2S)/J/ψ IN PB-PB @LHC

- Being a more weakly bound state than the J/ψ, the ψ(2S) is another interesting probe to investigate charmonium behaviour in the medium
- The ψ(2S) yield is compared to the J/ψ one in Pb-Pb and in pp



PRL 113 (2014) 262301

- **ALICE:** reference pp@√s=7TeV

  low p_T ($0<p_T<3$GeV/c) → ψ(2S) more suppressed than J/ψ

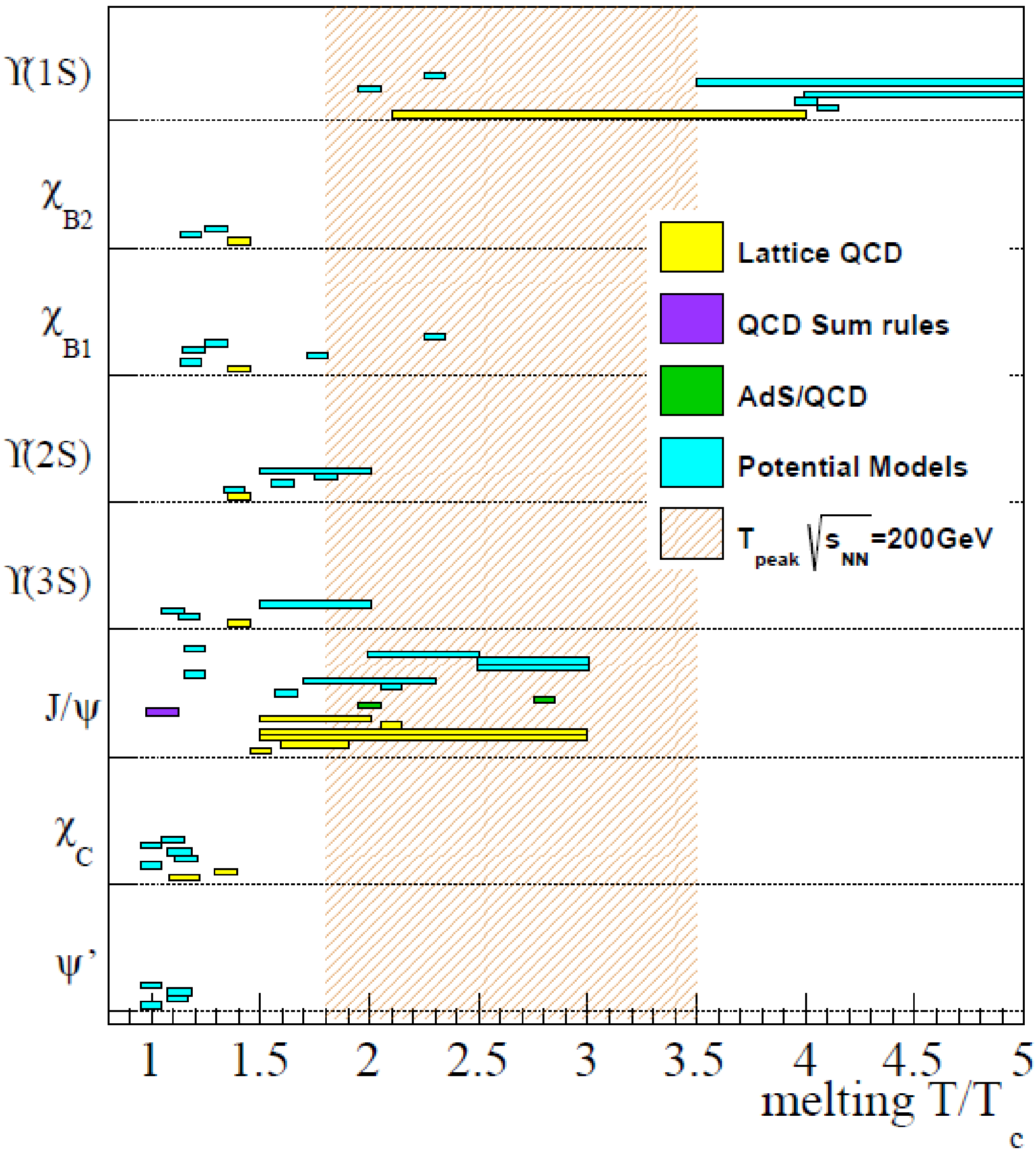
- **CMS:** reference pp@√s=2.76TeV

  $p_T>3$ GeV/c & $1.6<|y|<2.4$ → ψ(2S) less suppressed than J/ψ

  $p_T>6.5$ GeV/c & $|y|<1.6$ → ψ(2S) more suppressed than J/ψ

- 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

DISSOCIATION TEMPERATURES



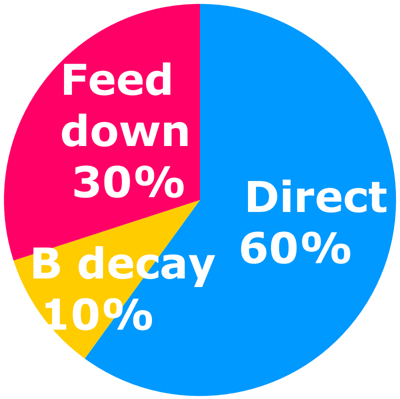
arXiv:1404.2246

Quarkonium production and decay

J/ψ production

Quarkonium production can proceed:

- directly in the interaction of the initial partons
- via the decay of heavier hadrons (feed-down)



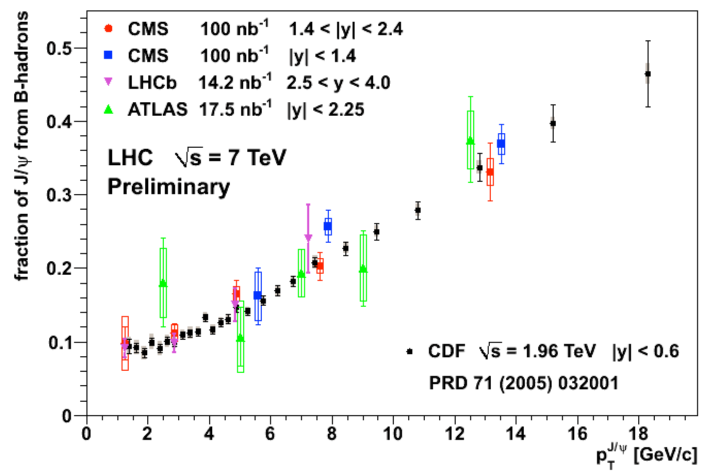
For J/ψ (LHC energies) the contributing mechanisms are:

Prompt

- ➡ Direct production
- ➡ Feed-down from higher charmonium states:
  ~ 8% from ψ(2S), ~25% from χ_c

Displaced

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



J/ψ decay

J/ψ can be studied through its decays:

$J/\psi \rightarrow \mu^+\mu^-$ **$J/\psi \rightarrow e^+e^-$** (~6% branching ratio)

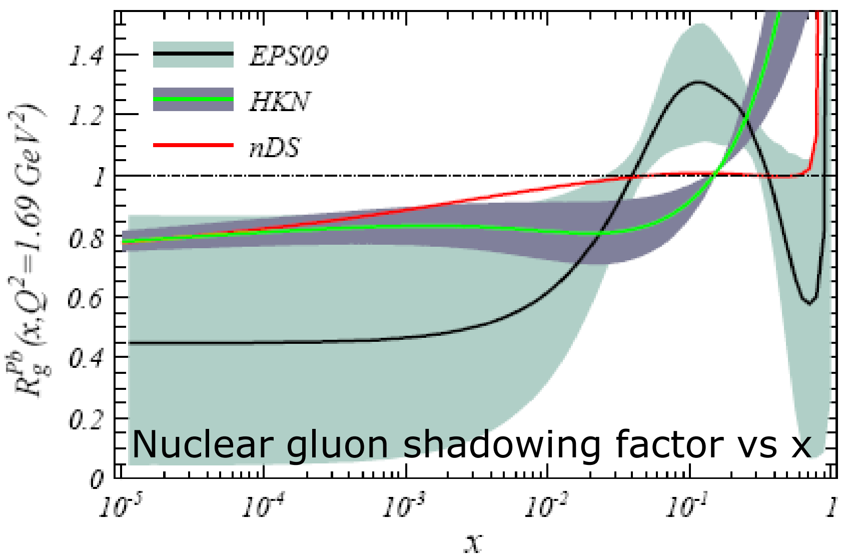
Nuclear shadowing

- PDF in nuclei are strongly modified with respect to those in a free nucleon

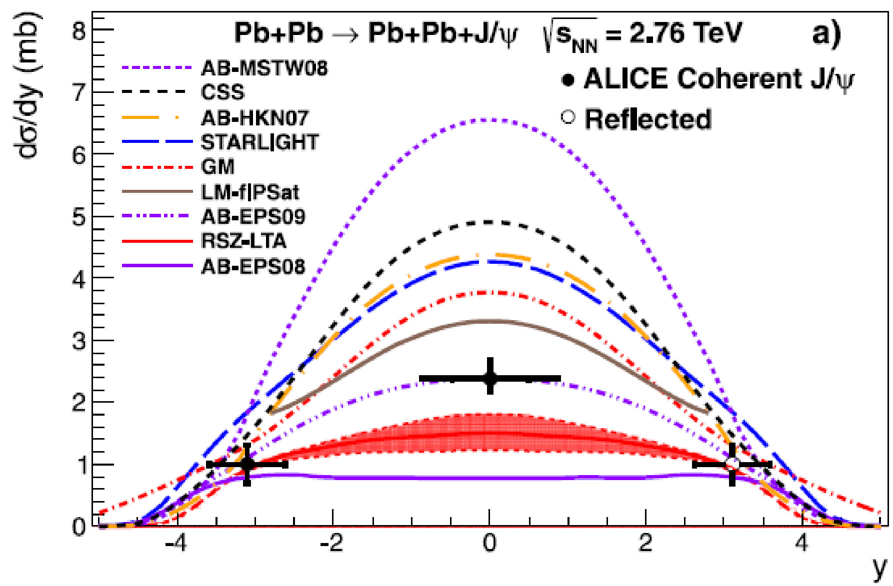
$$f_i^A(x,Q^2) = R_i(A,x,Q^2) \times f_i^p(x,Q^2)$$

nPDF: PDF of proton in a nucleus — free proton PDF

$$R_i(A,x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$



- LHC data cover the low x domain (Bjorken $x \sim 10^{-2} - 10^{-5}$)



- J/ψ photoproduction cross section is a powerful tool to constrain gluon shadowing

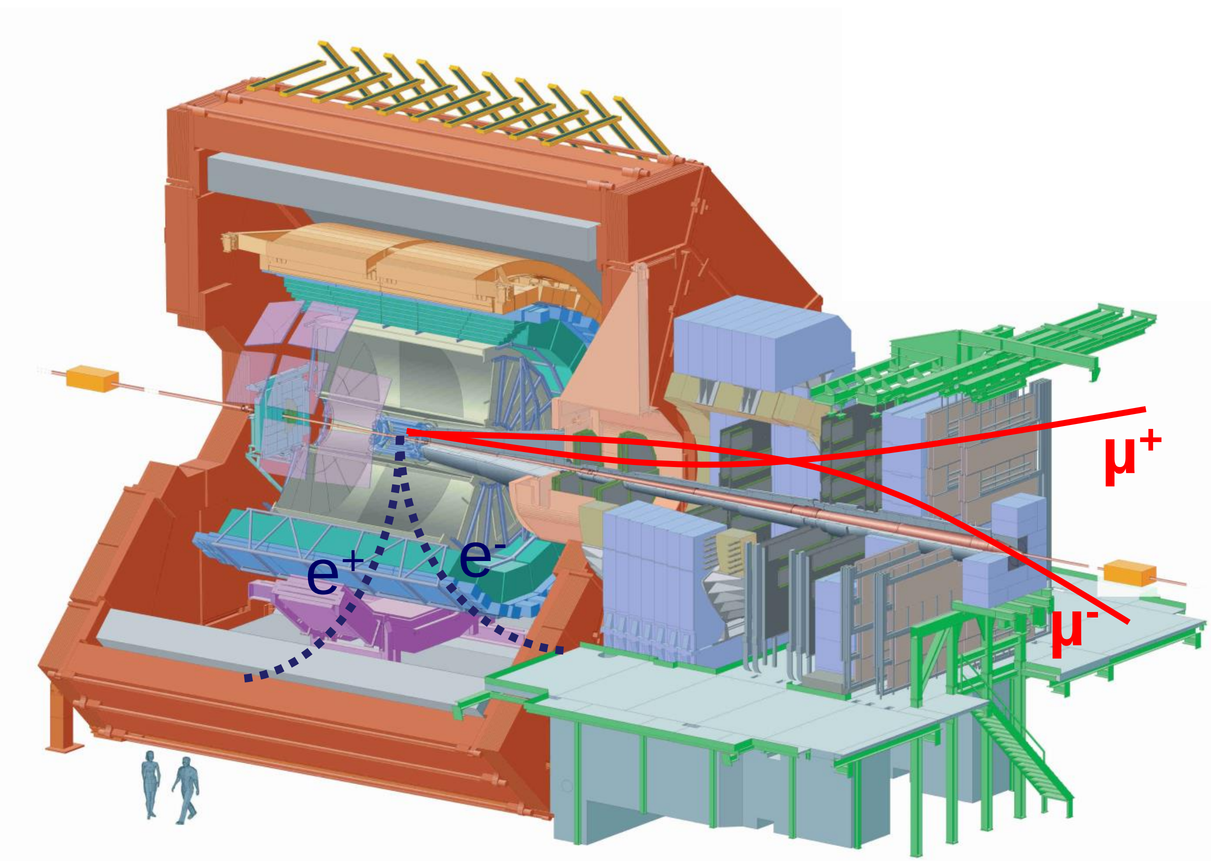
ALICE: low p_T J/ψ

Central Barrel **J/ψ → e^+e^-**
($|y_{LAB}|<0.9$)

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

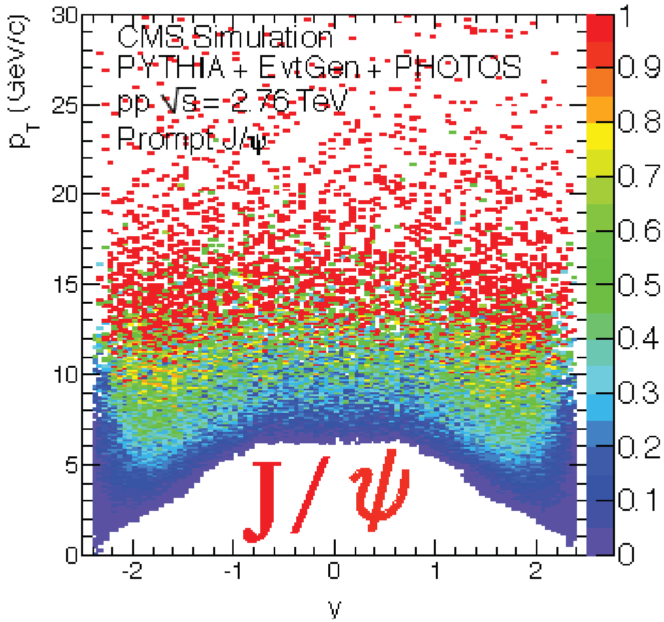
Forward muon arm **J/ψ → $\mu^+\mu^-$**
($2.5<y_{LAB}<4$)

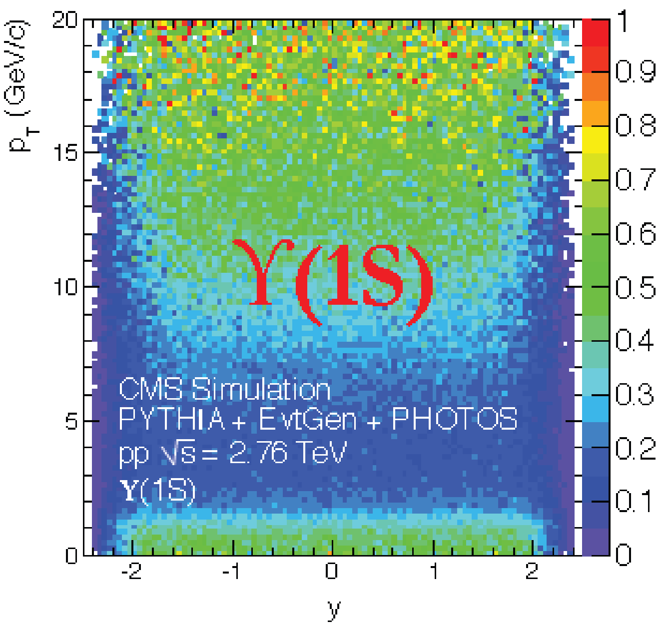
Muons identified and tracked in the muon spectrometer



- Acceptance coverage in both *y* regions down to zero p_T
- ALICE results refer to inclusive J/ψ production

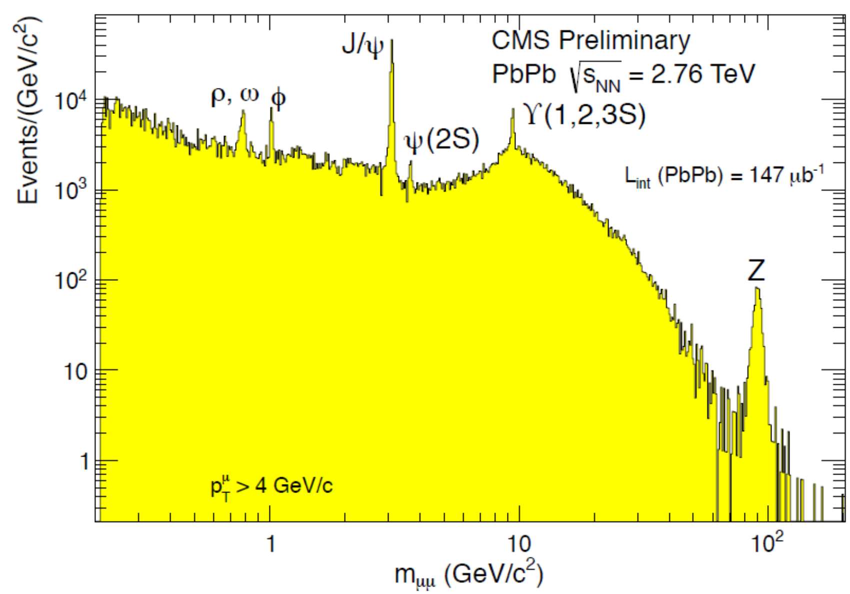
CMS: high p_T J/ψ





- Muons need to overcome the magnetic field and energy loss in the absorber: p_{min}~3-5 GeV/c to reach muon stations
  - Limits J/ψ acceptance:
    - Midrapidity: p_T>6.5 GeV/c
    - Forward rapidity: p_T>3 GeV/c

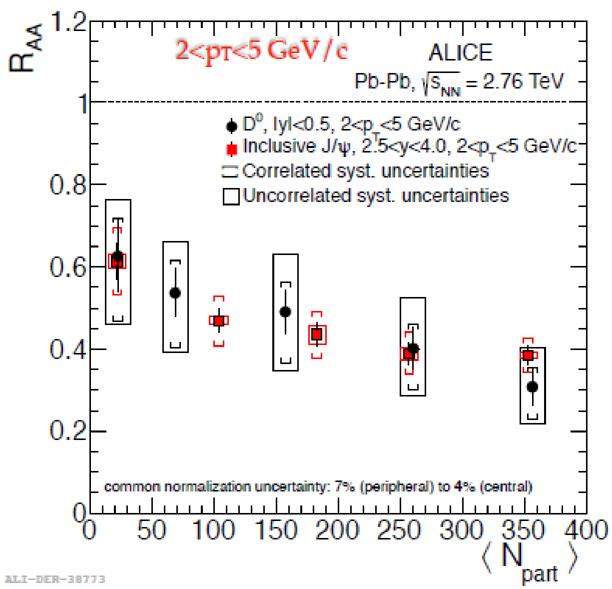
  ..but not the Υ one (p_T > 0 everywhere)

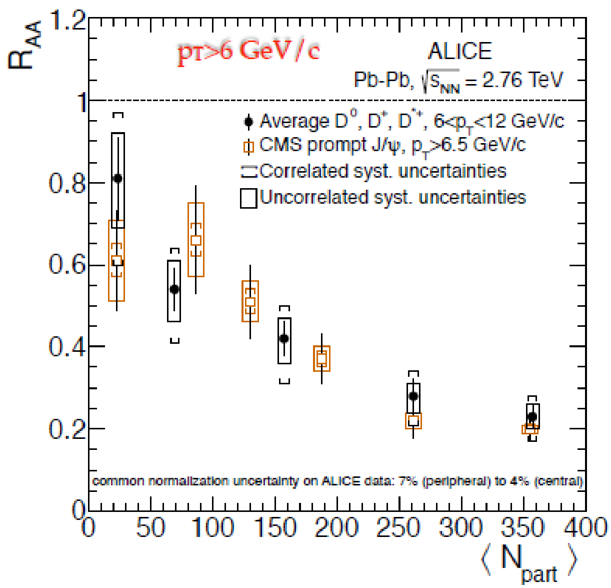


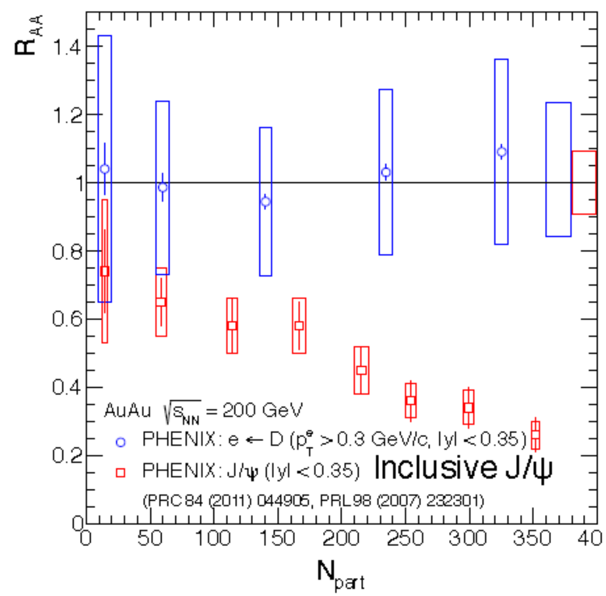
- Prompt and B-decay J/ψ are measured

J/ψ vs D in AA collisions

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







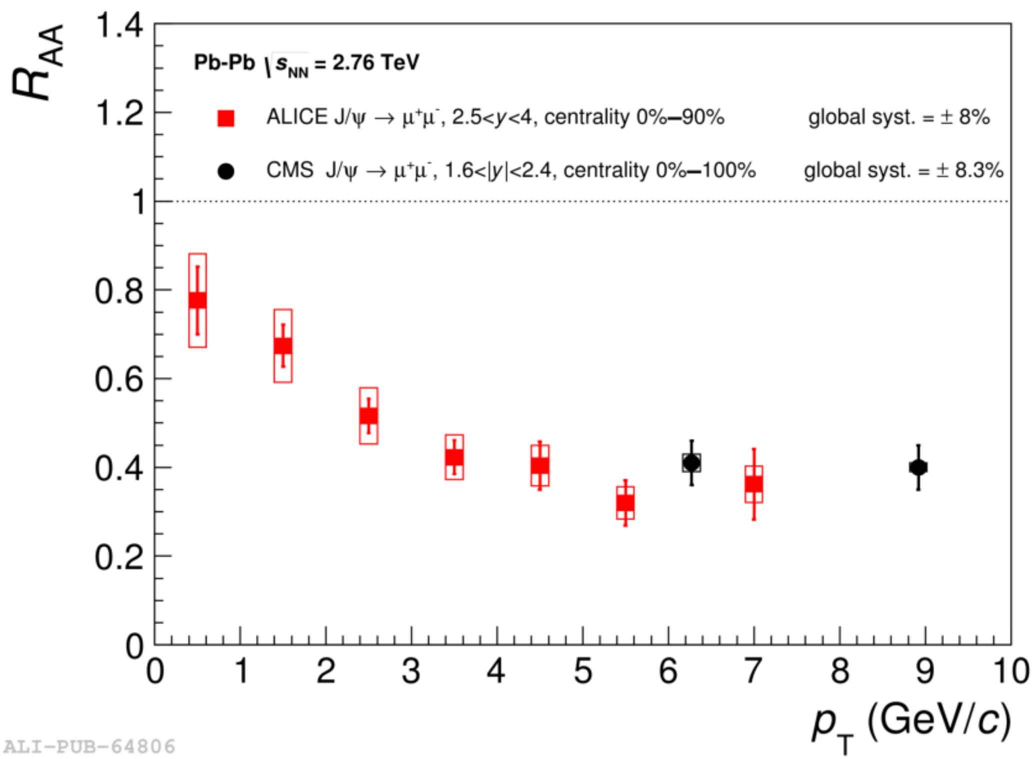
- Interesting comparison between ALICE and CMS J/ψ compared to D

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

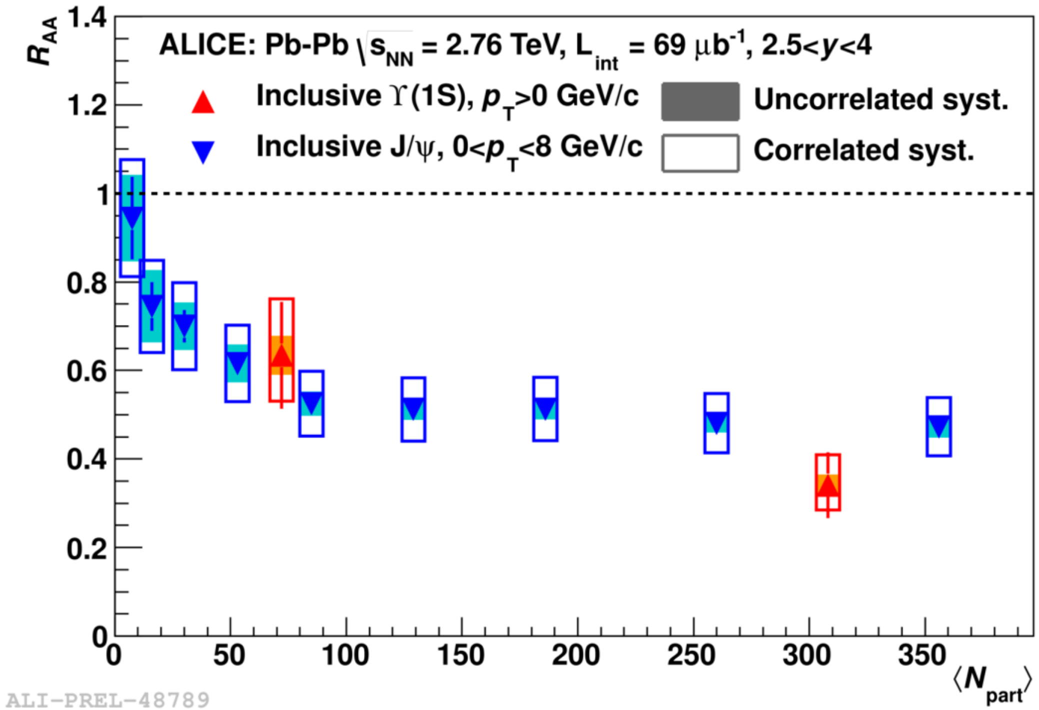
CMS: high p_T J/ψ

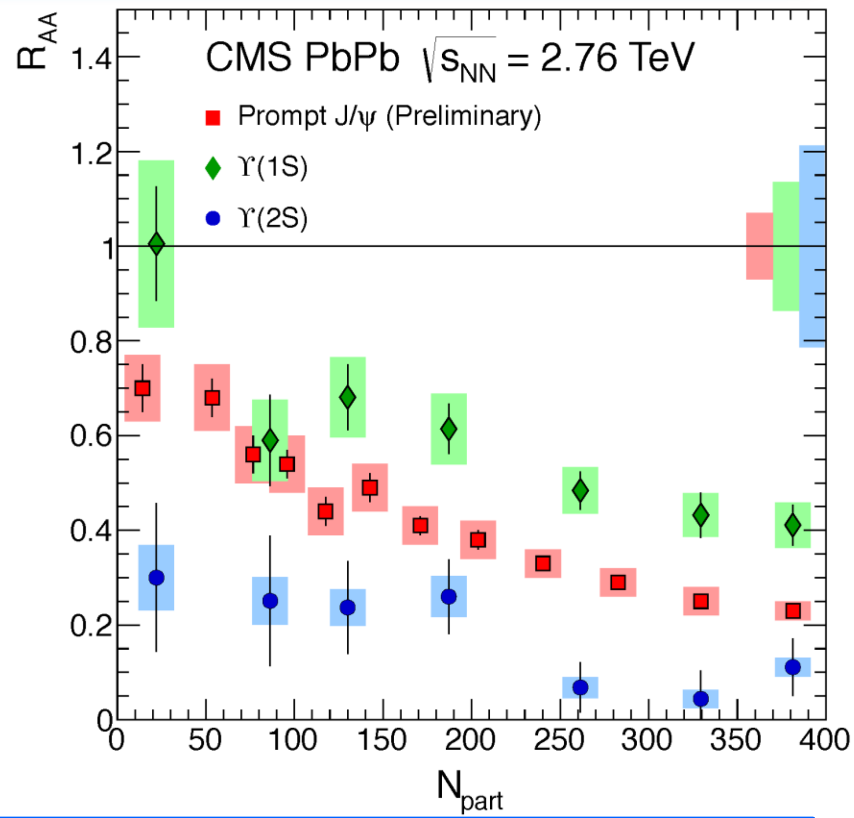
➡ The high p_T region can be investigated by CMS!



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

Comparison ϒ and J/ψ



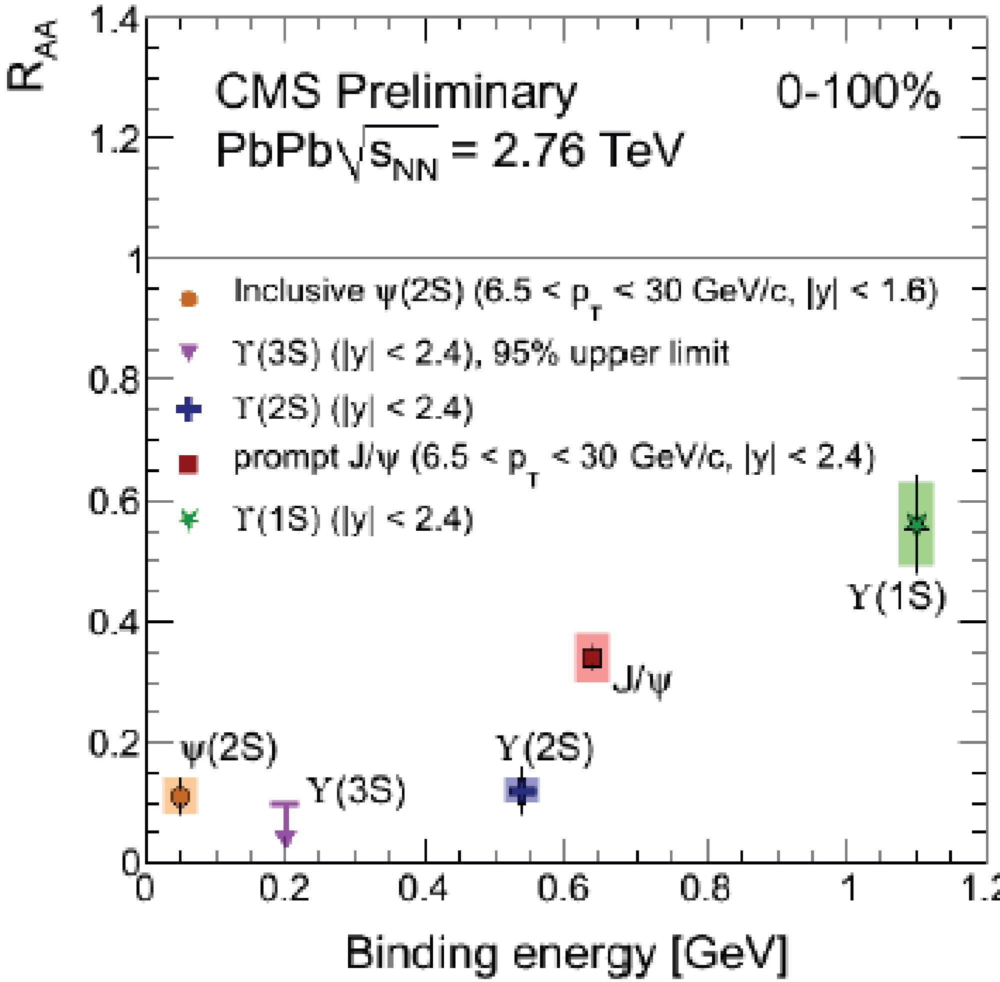


- Similar R_{AA} for low p_T inclusive J/ψ and ϒ(1S)
- Sequential suppression observed for prompt J/ψ and ϒ(nS) at high p_T

- interplay of the competing mechanisms for J/ψ and ϒ can be different and dependent on kinematics!

Where are we?

➡ 27 years after first suppression prediction, this is finally observed also in the ϒ sector with very good accuracy!



Two main mechanisms at play:

1. Suppression in a deconfined medium
2. Re-combination (for charmonium) at high √s

can qualitatively explain the main features of the results

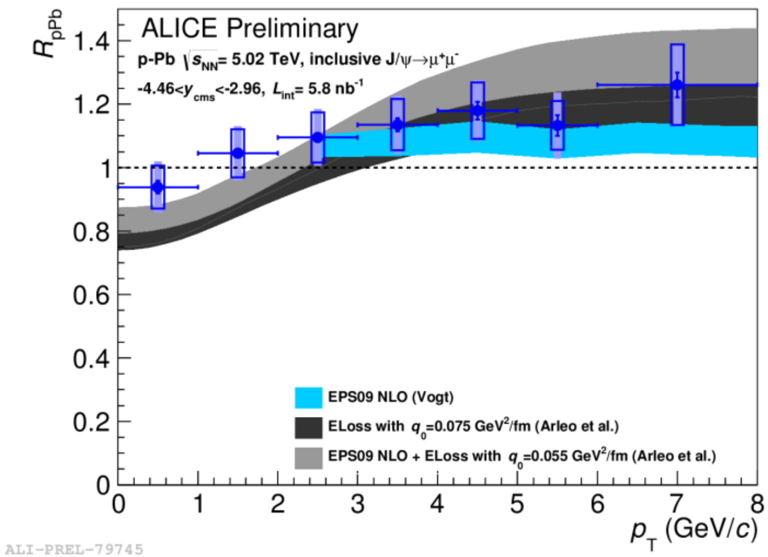
R_{AA} vs binding energy: looser bound states more suppressed than the tighter ones

however hot and cold effects not yet disentangled…need pA results!

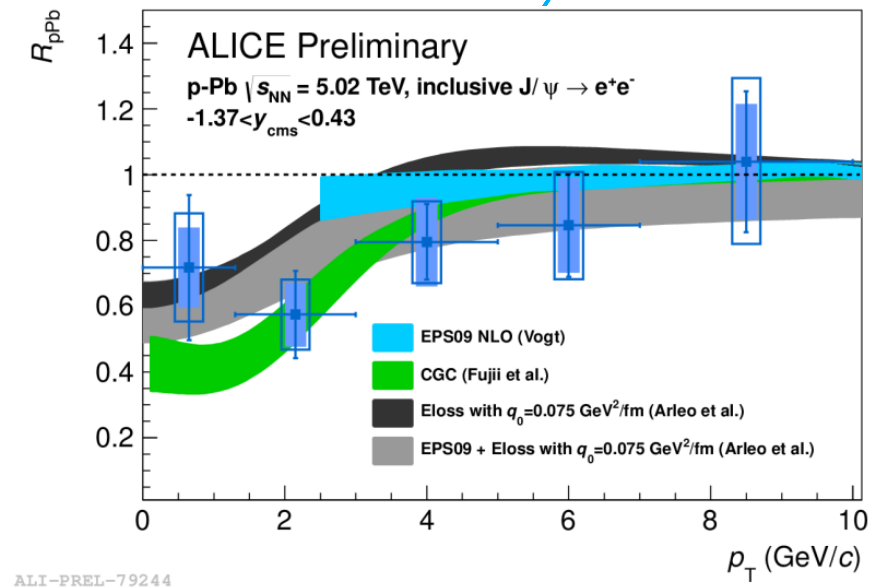
Nucl.Phys.A 904-905 (2013) 194c-201c

p-Pb: role of CNM effects on J/ψ

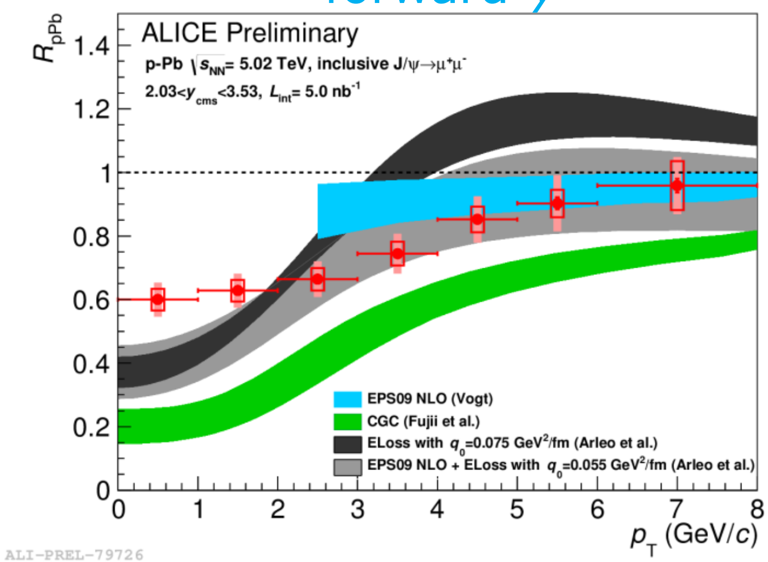
backward-y



mid-y



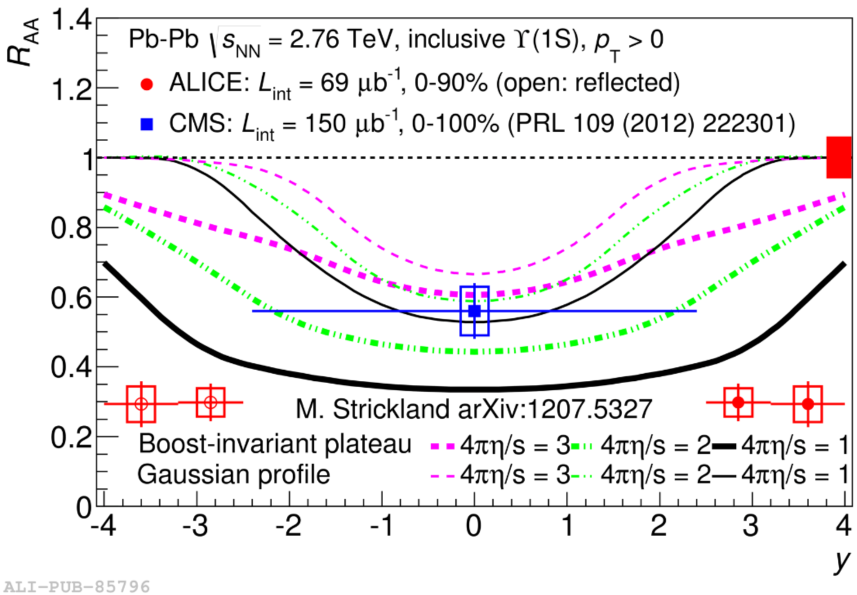
forward-y

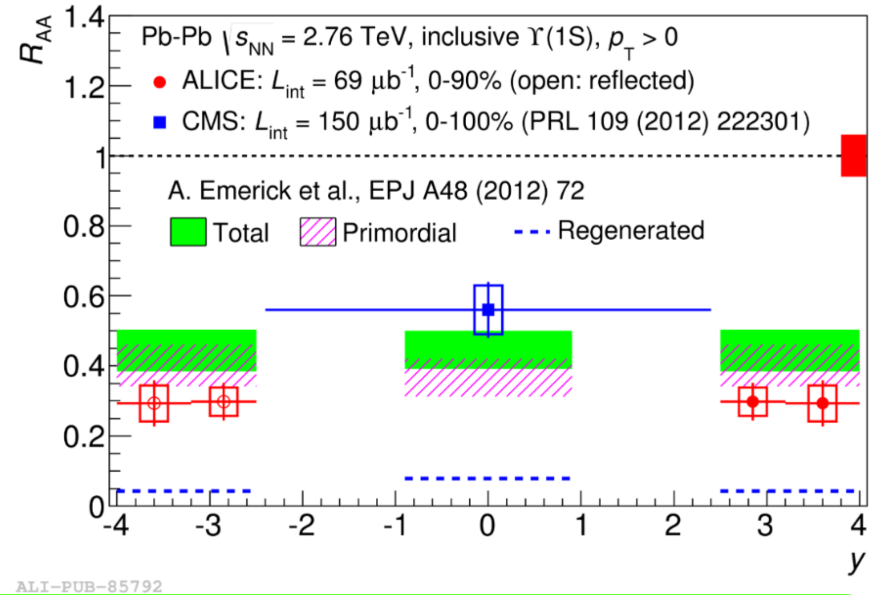


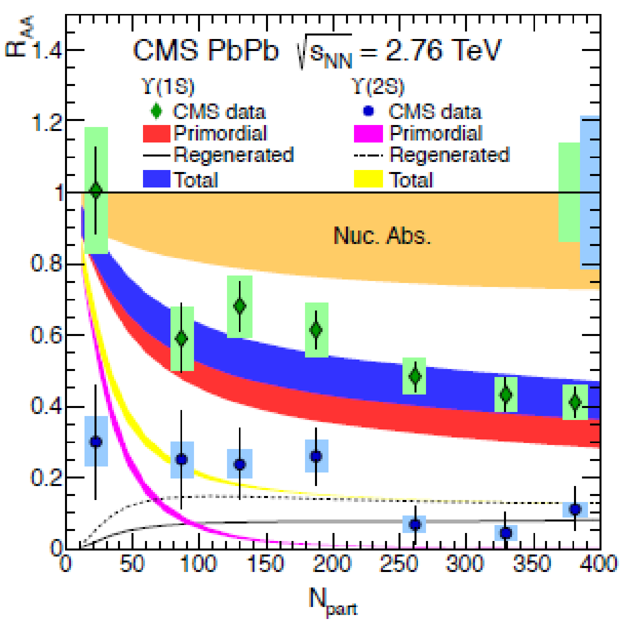
R_{pA} p_T dependence:

fair agreements with models based on shadowing + energy loss except at forward-y and low p_T

COMPARISON WITH THEORY



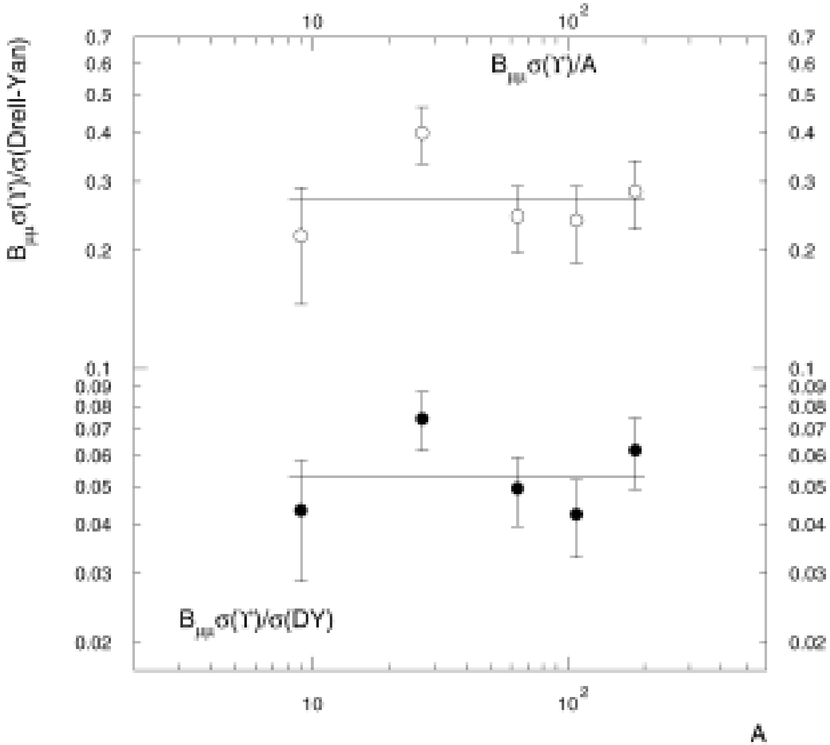




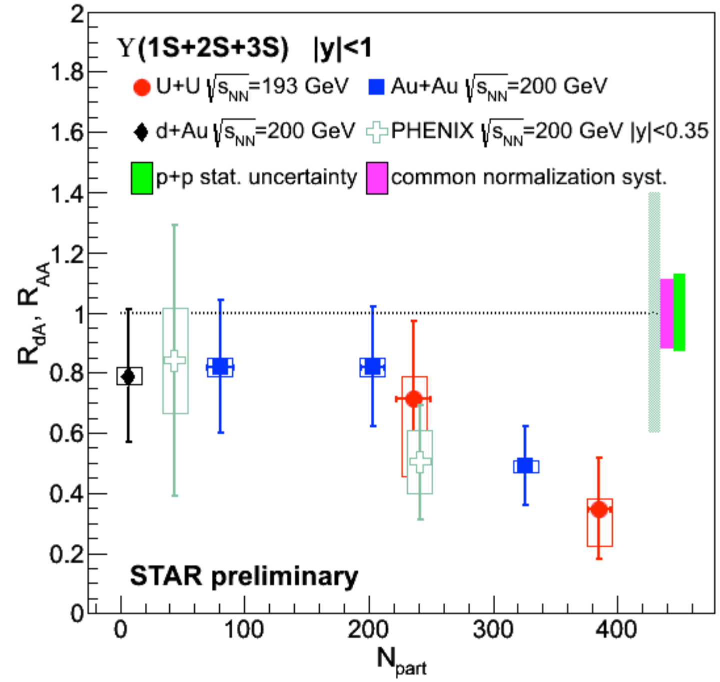
- Stronger suppression at forward rapidity (ALICE) than at mid-rapidity (CMS)
- Theory still meets difficulties in describing simultaneously the R_{AA} centrality and rapidity dependence (suppression slightly overestimated at forward-y, while better reproduced at mid-y)

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

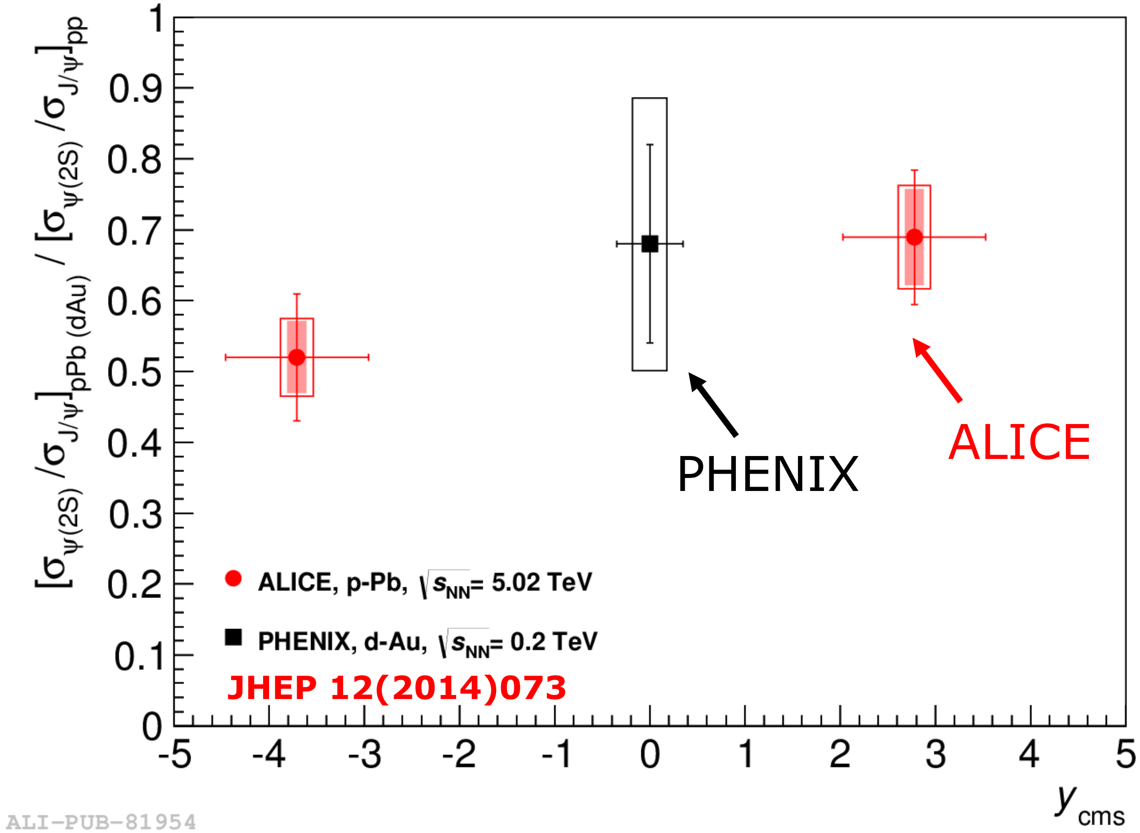
- ϒ R_{AA} compatible with suppression of excited states but large uncertainties prevents further insights

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

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

$\psi(2S)/J/\psi$ IN p-Pb

A strong decrease of the $\psi(2S)$ production in p-Pb, relative to J/ψ, is observed with respect to the pp measurement ($2.5<y_{cms}<4$, $\sqrt{s}$=7TeV)



- Double ratio allows a direct comparison of the J/ψ and $\psi(2S)$ production yields between experiments

- Similar effect seen by PHENIX in d-Au collisions, at mid-y, at $\sqrt{s_{NN}}$=200 GeV

$[\psi(2S)/J/\psi]_{pp}$ variation between ($\sqrt{s}$=7TeV, $2.5<y<4$) and ($\sqrt{s}$=5.02TeV, $2.03<y<3.53$ or $-4.46<y<-2.96$) based on CDF and LHCb data (~8% included in the systematic uncertainty)

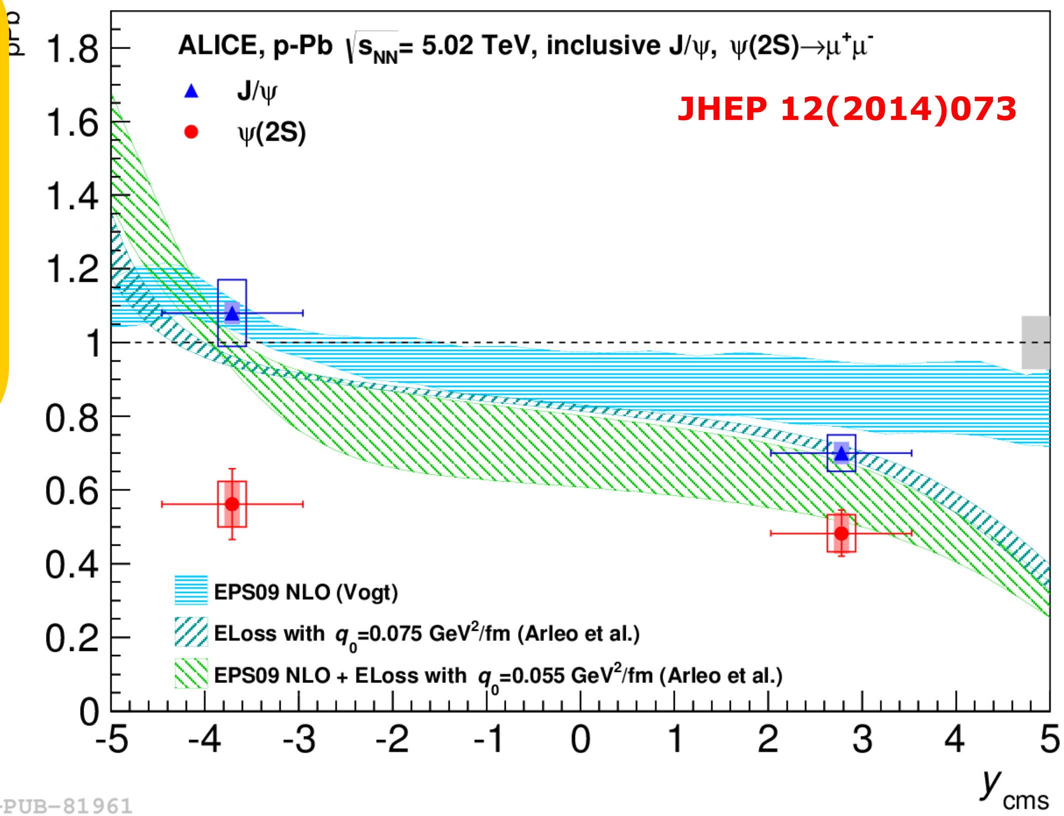
$\psi(2S)$ R_{pA} VS RAPIDITY

$\psi(2S)$ suppression stronger than the J/ψ one, reaching a factor ~2 wrt pp

can the stronger $\psi(2S)$ suppression be due to break-up of the fully formed resonance in CNM?

possible if:

formation (τ_f) < crossing time (τ_c)



forward-y: $\tau_c \sim 10^{-4}$ fm/c

backward-y: $\tau_c \sim 10^{-1}$ fm/c

while τ_f ~0.05-0.15 fm/c

forward-*y*: break-up effects excluded

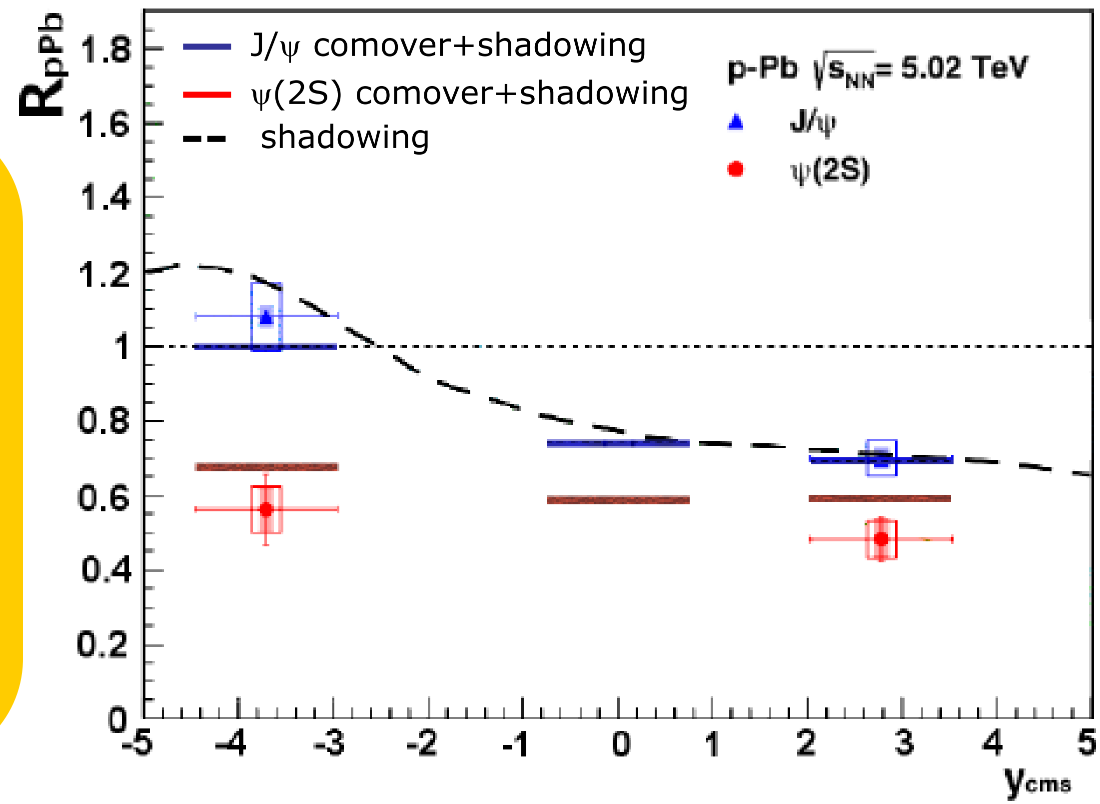
backward-*y*: $\tau_f \sim \tau_c$, hence break-up in CNM hardly explains the strong J/ψ and $\psi(2S)$ difference

ψ(2S) R_{pA} VS RAPIDITY: COMOVERS?

Final state effects related to the (hadronic) medium created in the p-Pb collisions?

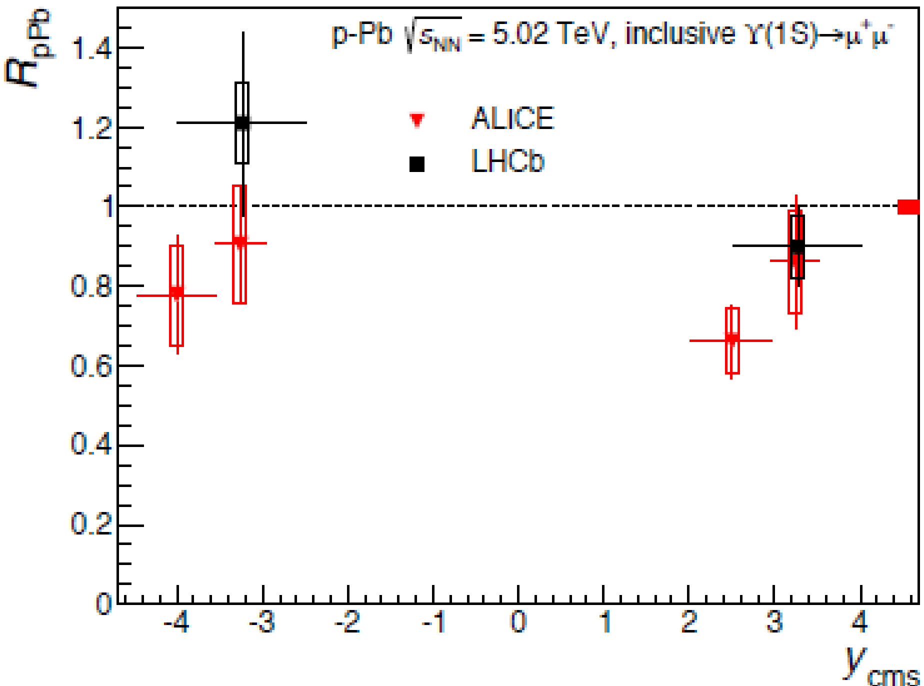
Charmonium interaction with comoving particles:

- Comovers dissociation affects more strongly the loosely bound ψ(2S) than the J/ψ
- Comovers density larger at backward rapidity



E. Ferreiro arXiv:1411.0549

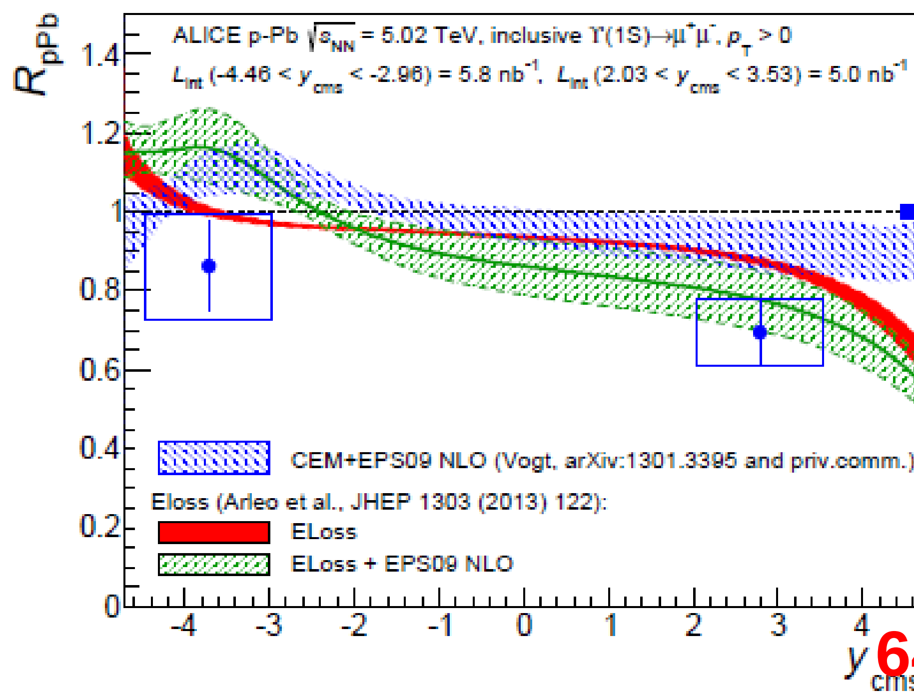
ϒ(1S) PRODUCTION IN p-Pb



- ϒ(1S) measured at mid-*y* by CMS and at forward-*y* by both ALICE and LHCb

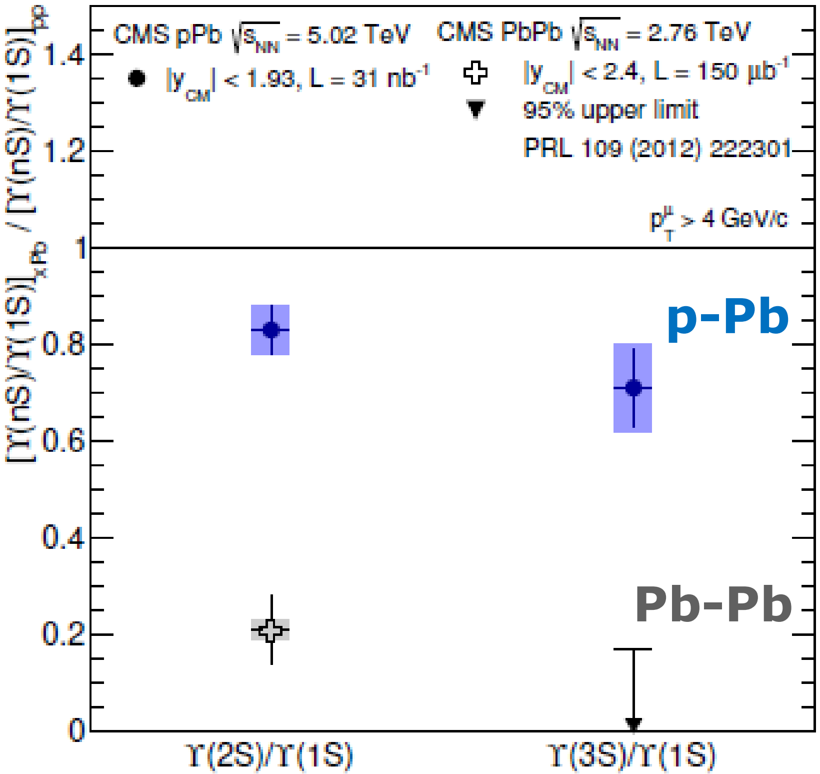
  → Compatible R_{pA} results within uncertainties (but LHCb systematically higher)

- Hint for stronger suppression at forward-*y* (similarly to J/ψ)
- Theoretical calculations based on initial state effects seem not to describe simultaneously forward and backward *y*



ALICE: arXiv:1410.2234, accepted by PLB
LHCb: JHEP 07(2014)094

Υ(nS)/Υ(1S) PRODUCTION IN p-Pb



➡ Initial state effects similar for the three Υ states

p-Pb vs pp @mid-y:
different/stronger final states effects in p-Pb affecting the excited states

p-Pb vs PbPb @mid-y :
even stronger suppression of excited states in PbPb

CMS HIN-13-003, JHEP 04 (2014) 103, PRL 109 (2012)

➡ ALICE (and LHCb) observes:

Υ(2S)/Υ(1S) (ALICE)
2.03<y<3.53: 0.27±0.08±0.04
-4.46<y<-2.96: 0.26±0.09±0.04

Compatible with pp results
0.26±0.08 (ALICE, pp@7TeV)

➡ CMS analyses the double ratio $[\Upsilon(2S)/\Upsilon(1S)]/[\Upsilon(nS)/\Upsilon(1S)]_{pp}$ and finds

0.83±0.05±0.05