Probing Quark Gluon Plasma with quarkonium production

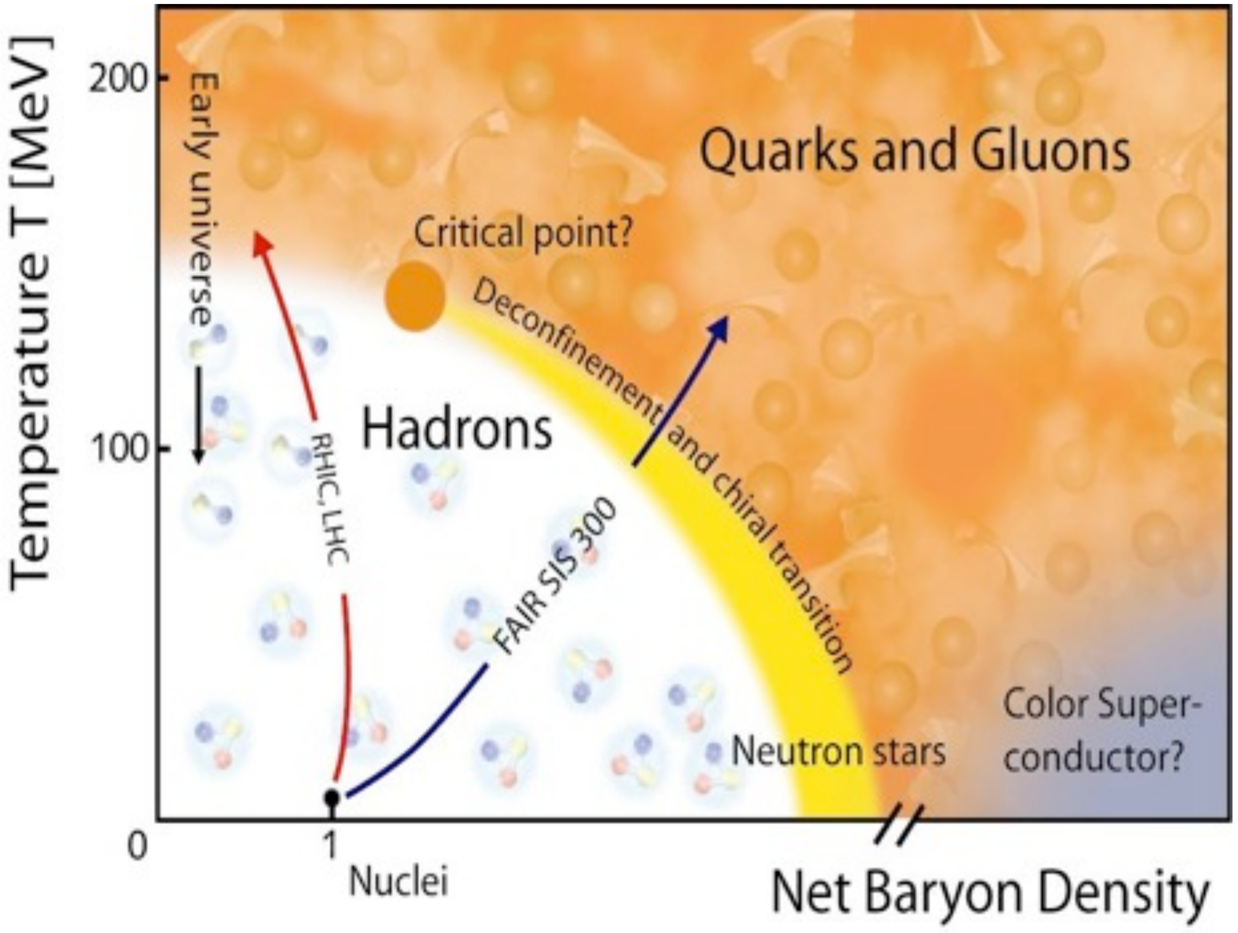
Cynthia Hadjidakis

Charmonium workshop

LAL-Orsay March 7th 2013

- Exploring the Quark Gluon Plasma
- A particular probe: the quarkonium family
- Selected results from SPS to LHC

The QCD phase diagram and the QGP



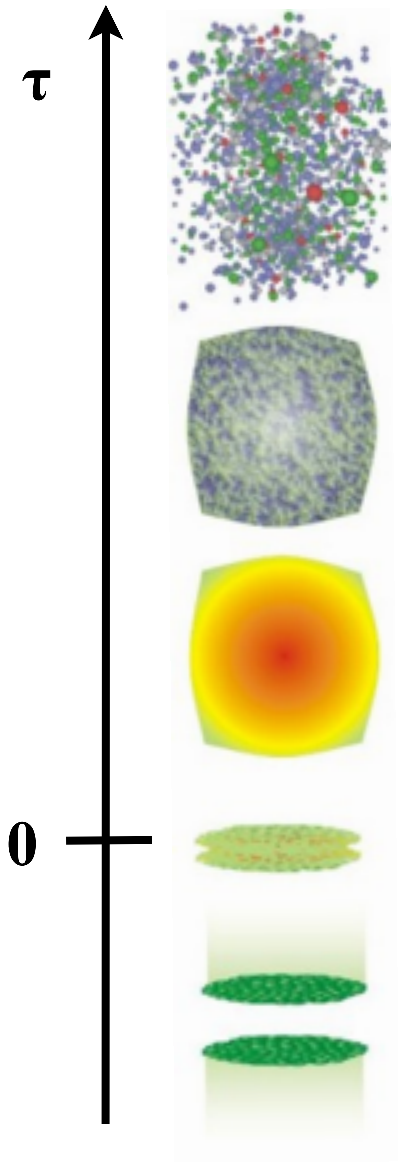
Nuclear matter at high temperature and high density = Quark Gluon Plasma (QGP)

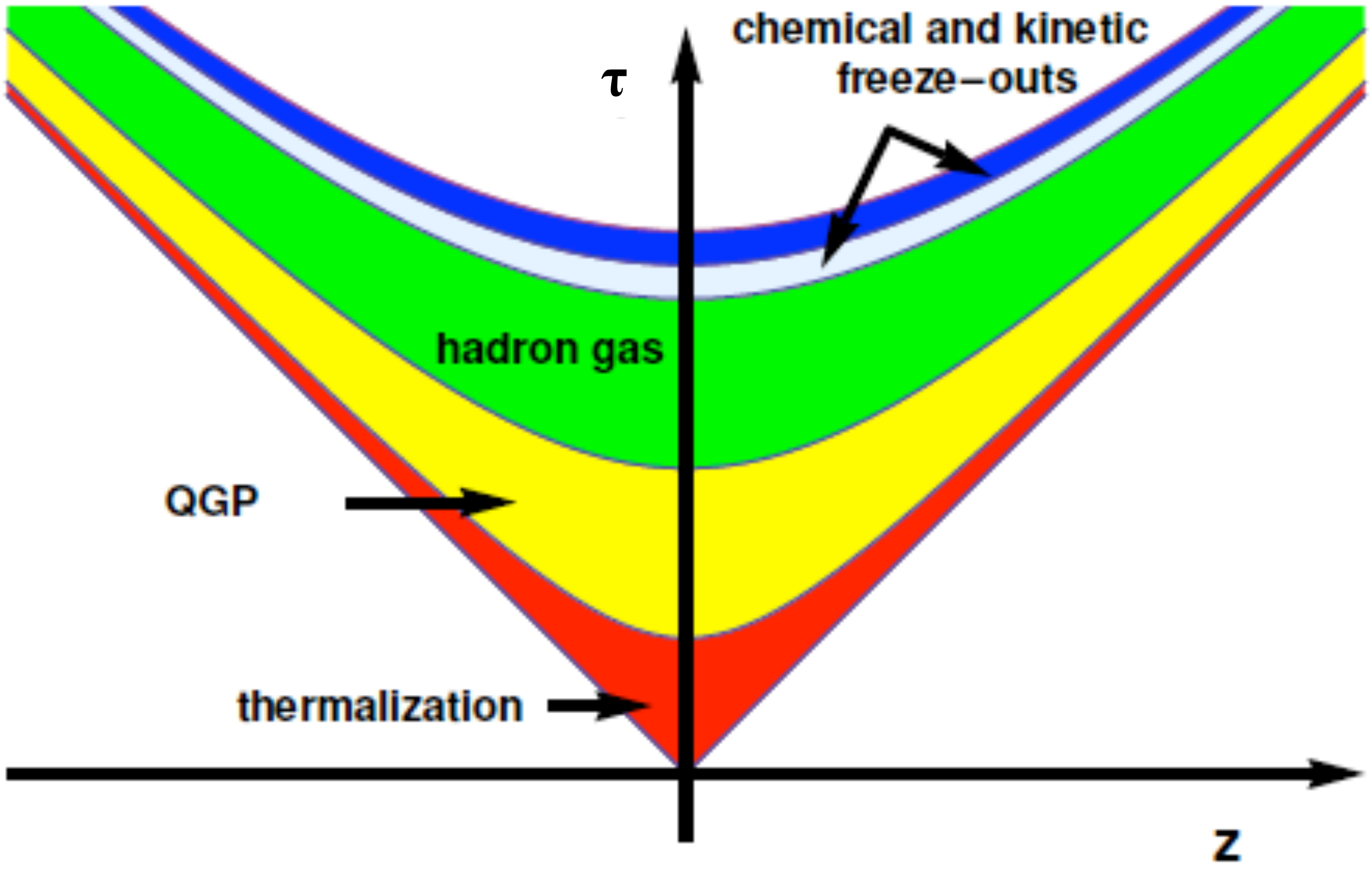
- Partons are deconfined (not bound into composite object)
- Chiral symmetry is restored (partons are massless)

From lattice QCD: At $\mu_b = 0$, $T_c = 170$ MeV ($\varepsilon_c = 1$ GeV/fm^3)

Ultra-relativistic heavy ion collision experiments
Search for the QGP phase and characterize it

A little bang in ultra-relativistic heavy ion collisions (URHIC)





Space-time evolution of an URHIC

$\tau \simeq 20$ fm/c
Kinetical freeze-out
Chemical freeze-out

$\tau \simeq 10$ fm/c $T < T_c$
Hadron gas

$\tau \simeq 4$ fm/c $T = T_c$
Mixed phase

$\tau \simeq 1$ fm/c $T > T_c$
Thermalized QGP

$\tau \simeq 0$
Heavy-ion collision

LHC size and time numbers
1 fm/c ~ $3\ 10^{-24}$ s

QGP volume $\simeq 300$ fm^3

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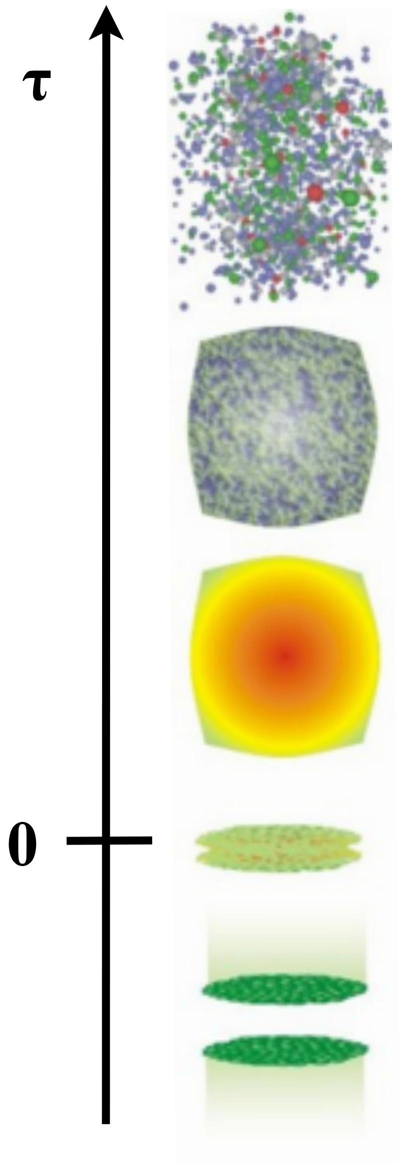

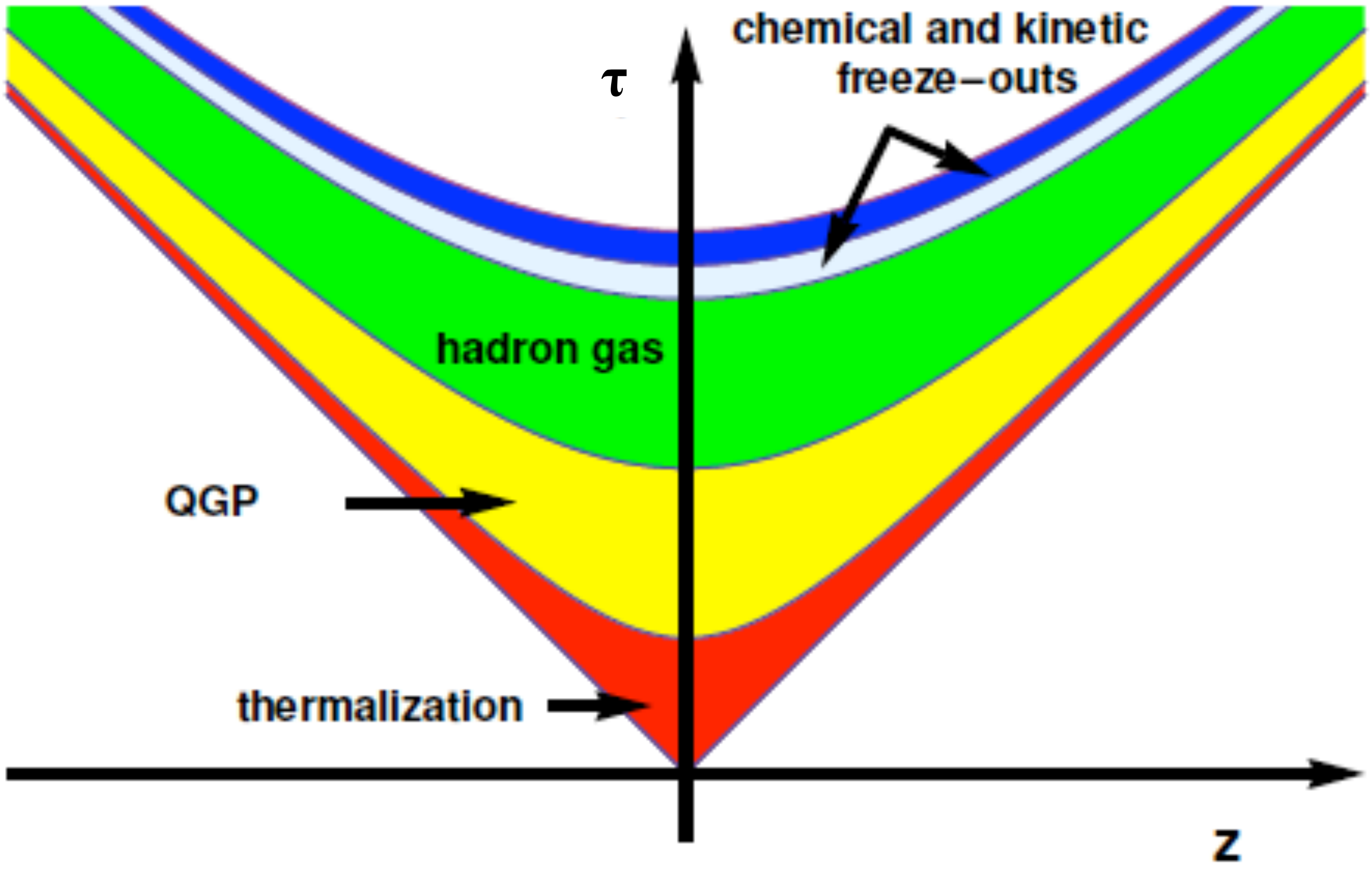

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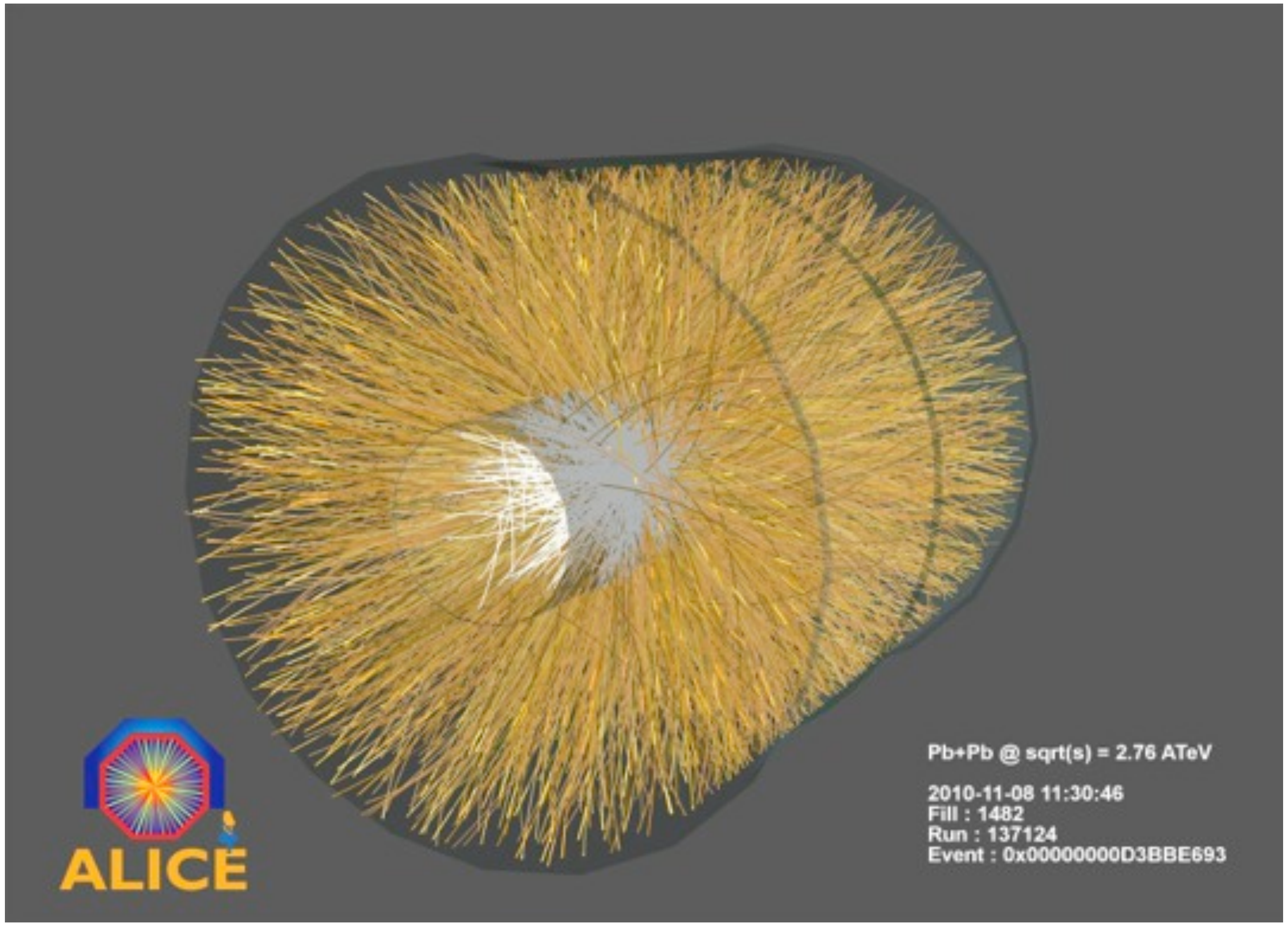
QGP volume ≃ 300 fm^3

At larger energy: larger, hotter, denser, longer life-time plasma

... and finally in the experiment - ALICE



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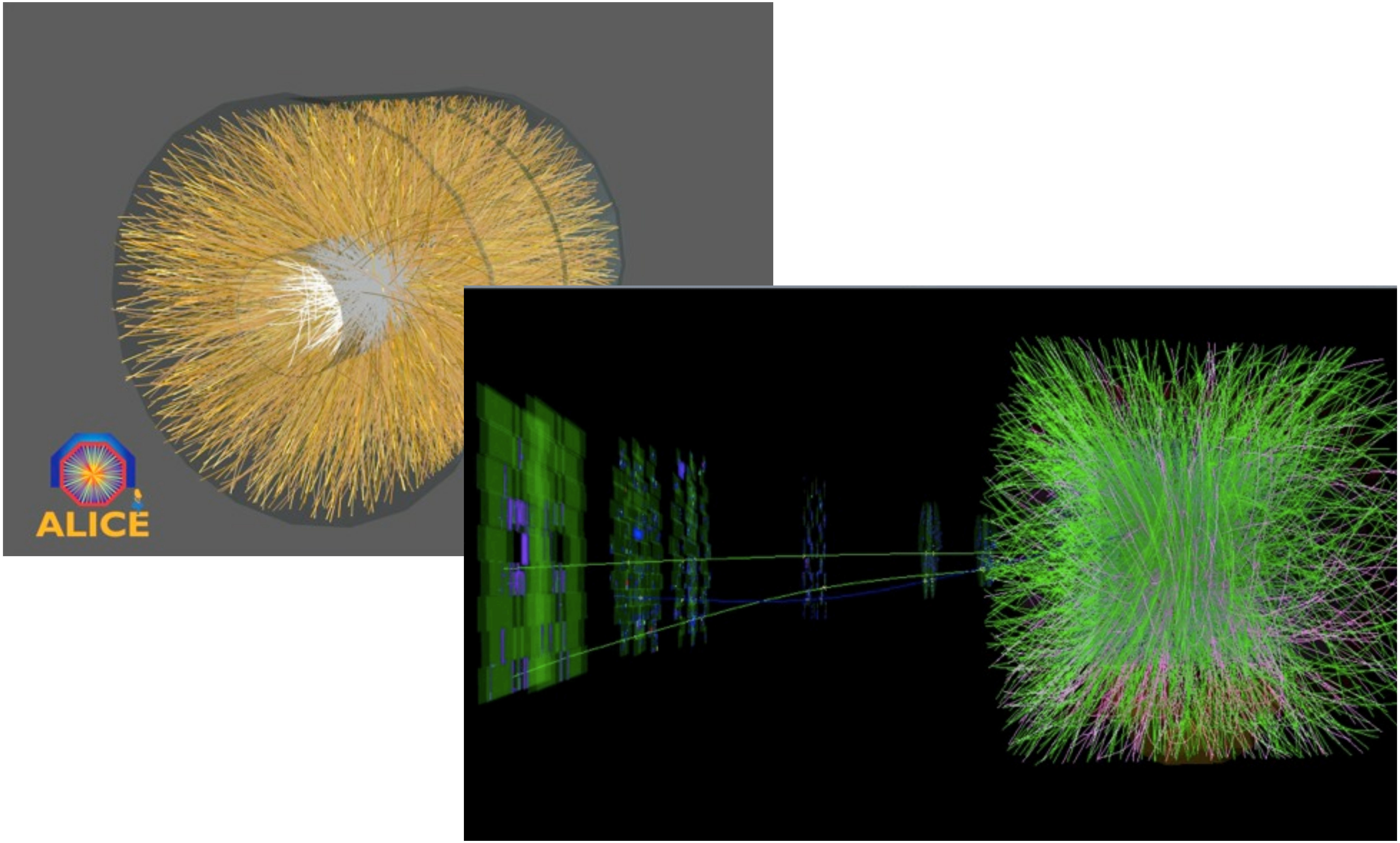

Probing the QGP

Many observables to probe the QGP

- Global observables: multiplicity, total transverse energy, ...
- Initial state observables: probes not affected by QGP as direct γ, $W^{+/-}$, Z^0
- Final state observables: hadron kinematic distributions, hadron species production, flow, high pT correlations, ...
- Hard probes (first stage of the collisions): high p_T particles, jets, open and hidden heavy flavour particles, ...

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2005 - RHIC @ BNL - QGP is a very strongly interacting (almost) perfect liquid
01/2010 - RHIC @ BNL - Highest man-made temperature (4 trillion ^{0}C) in the Guiness Record
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Heavy-ion experiments: from discovery to **quantitative characterization**: measuring QGP parameters (energy, density, size, lifetime, temperature,....)

Probing the QGP with quarkonia

Properties of quarkonium states

- made of heavy quark and anti-quark: $m_c = 1.2\text{-}1.4$ GeV and $m_b = 4.6\text{-}4.9$ GeV
- produced in the initial hard partonic collisions ($\tau \simeq 1/\, m_Q \simeq 0.05\text{-}0.15$ fm/c)
- stable and tightly bound: $M_{ccbar} < 2\ M_D$ and $M_{bbbar} < 2\ M_B$

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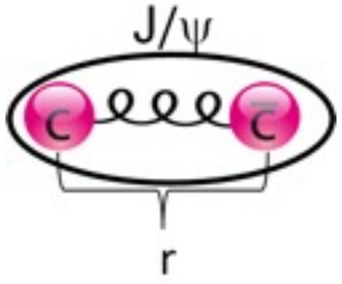
At T = 0, in the vacuum, Cornell potential



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

2 terms:

- Coulombian contribution (gluon exchange)
- Confinement contribution

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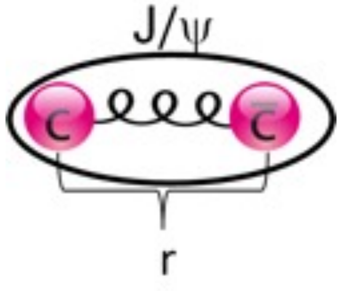

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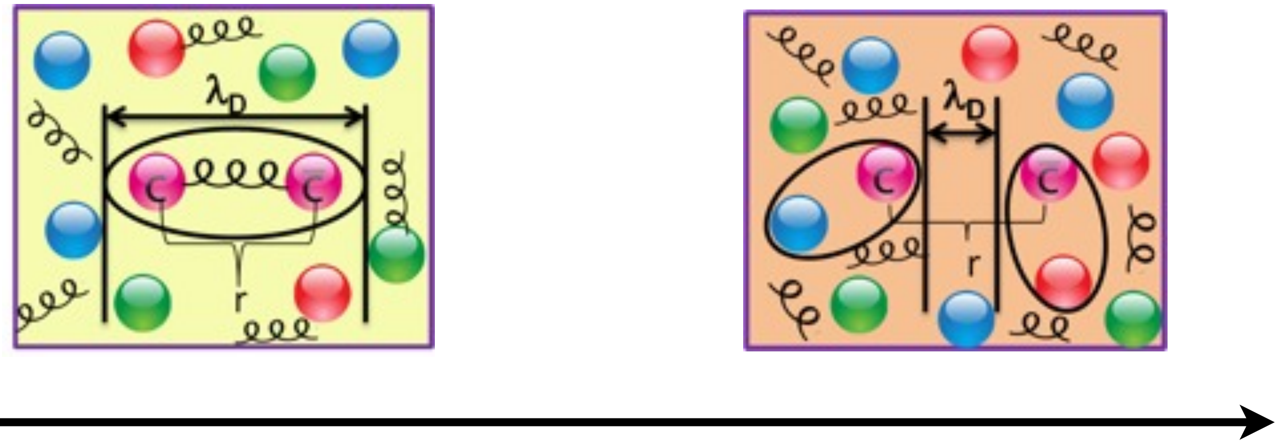
At T >> 0 , debye screening induced by the high density of colour charges

Matsui, Satz PLB178(1986),416

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

λ_D : Debye screening radius

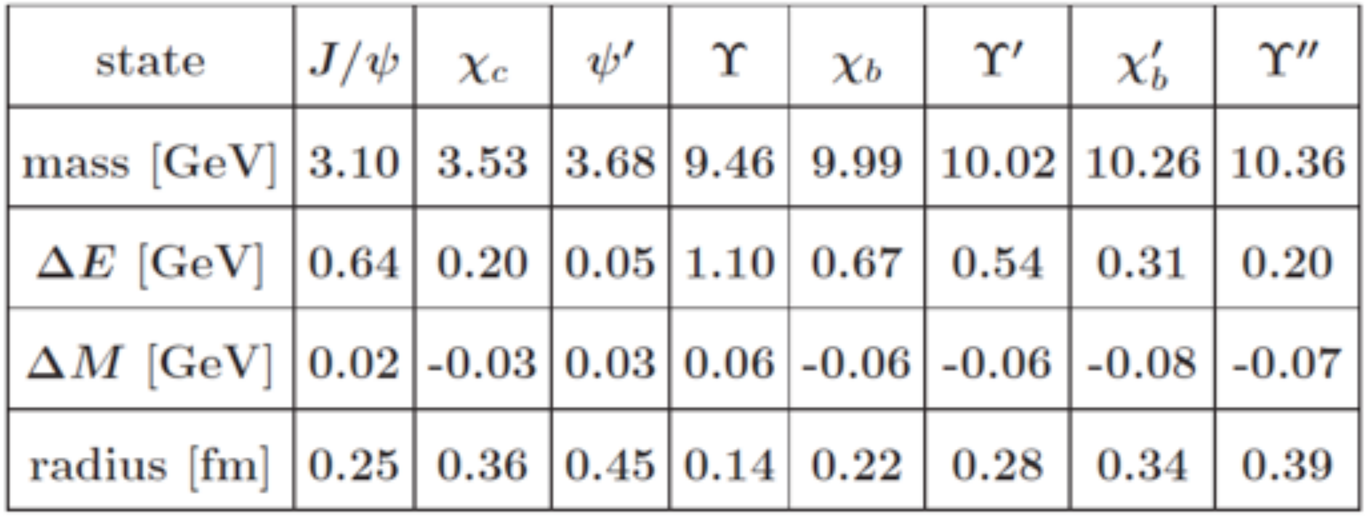
λ_D decreases with T



Temperature

→ Melting of quarkonia at high temperature for λ_D < Quarkonium state radius

Probing the QGP with the quarkonium family



state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

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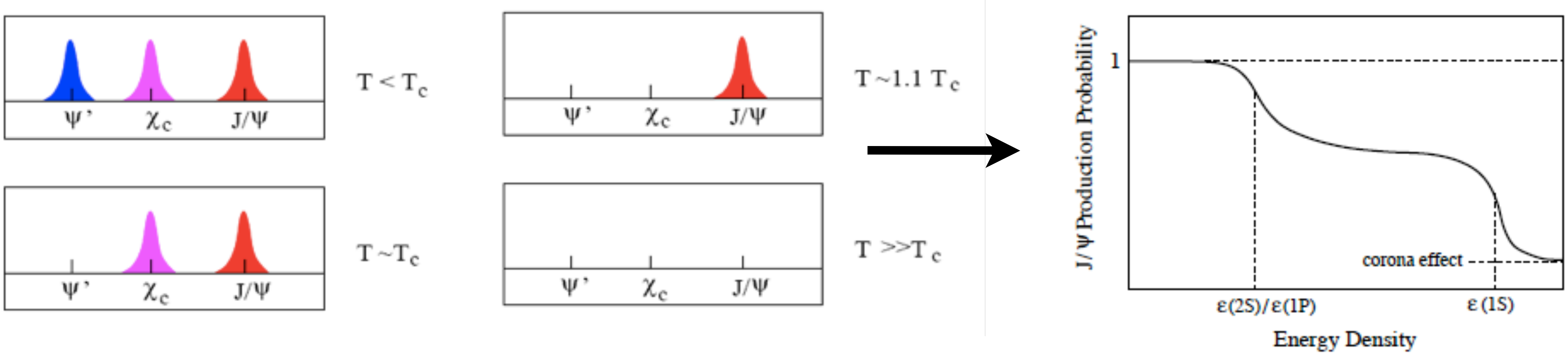
Example of measured J/Ψ

prompt J/Ψ ≃ 60% direct J/Ψ + 30% χ_C + 10% Ψ(2S)

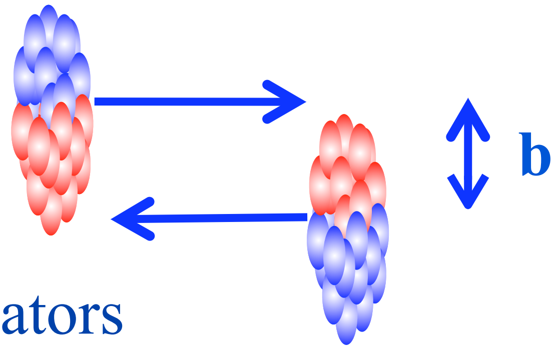


Sequential suppression of the quarkonium family: **QGP thermometer**

Centrality of the collisions

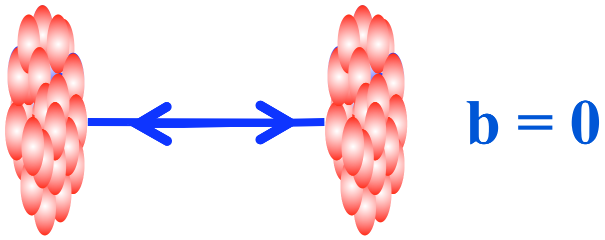
Centrality of the collisions

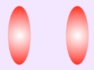
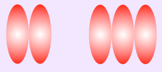
semi-central coll.



Spectators
Participants
Binary collisions

central coll.



	$N_{part} = 2$	$N_{coll} = 1$
	$N_{part} = 5$	$N_{coll} = 6$
Pb-Pb cent.	$N_{part} = 380$	$N_{coll} = 1700$

→ Glauber model used to determine the geometry of the collision

Centrality of the collisions

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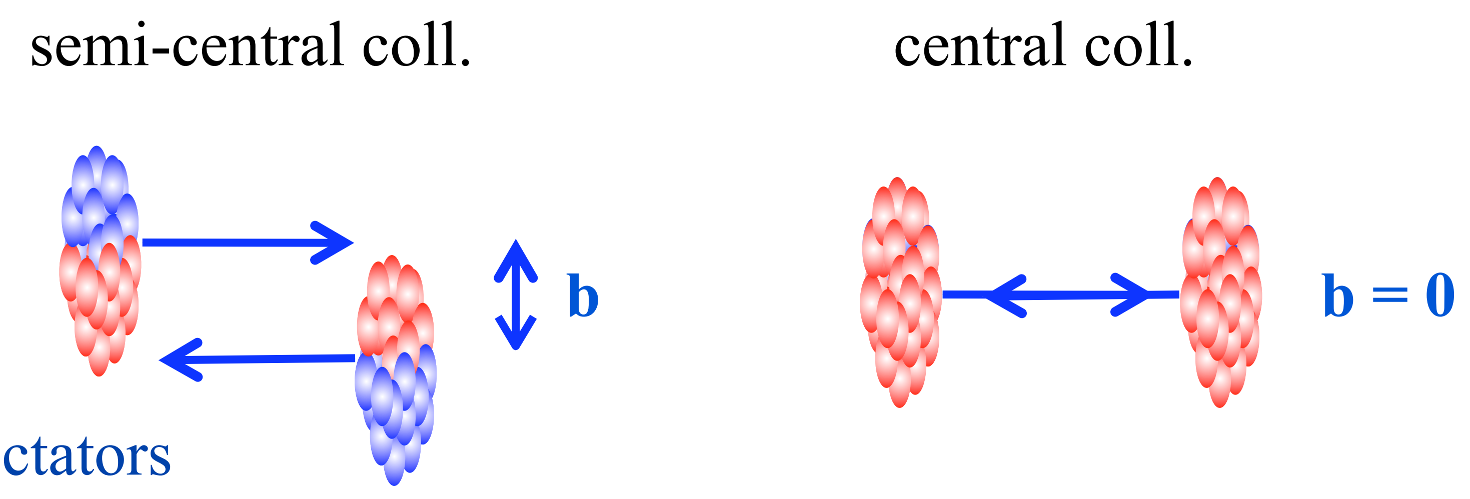

Spectators
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	$N_{part} = 5$	$N_{coll} = 6$
Pb-Pb cent.	$N_{part} = 380$	$N_{coll} = 1700$

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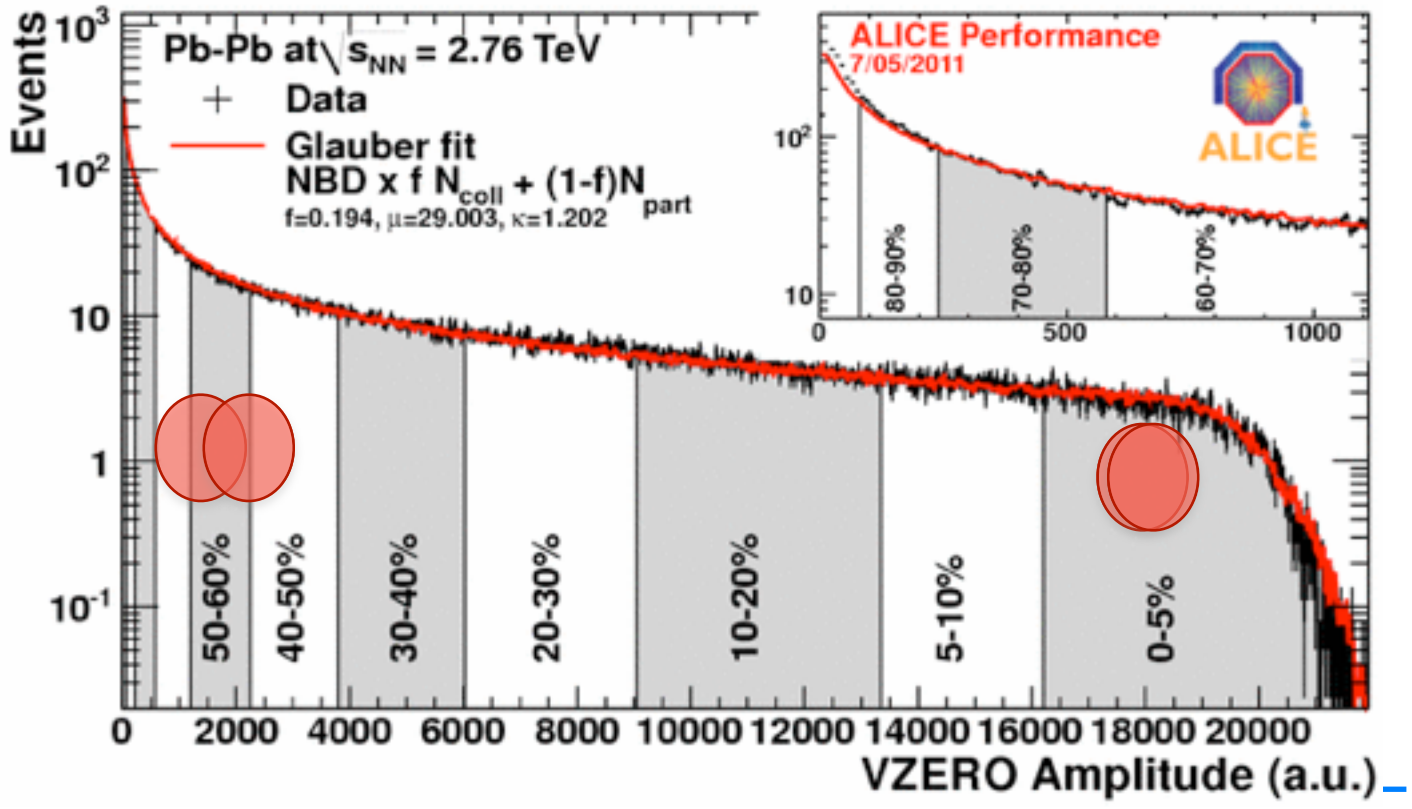
Centrality determination

Multiplicity measurements with forward or central detectors

Relate the measured multiplicity in A-A collisions to N_{part} and N_{coll}



Nuclear modification factor

Nuclear modification factor

$$R_{AA} = \frac{dN^{AA}/dp_T\,dy}{\langle N_{coll}\rangle\, dN^{pp}/dp_T\,dy}$$

Hard process: scale with N_{coll}

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

References

- Production in p-p at the same energy (whenever possible): reference for R_{AA}
- Production in p-A at the same energy (whenever possible): cold nuclear matter determination

Cold nuclear matter (CNM)

- Initial state effect: nuclear shadowing (npdf) -or gluon saturation in the nucleus-, parton energy loss, multiple elastic scatterings of partons (Cronin effect), ...
- Final state effect: breakup of precursor quarkonia by nucleon collisions in the crossing nuclear matter (nuclear absorption), energy loss, ...

Results from SPS and RHIC

SPS: NA38, NA50, NA60
$\sqrt{s_{NN}}$ = 17 GeV
In-In / Pb-Pb
$\sqrt{s_{NN}}$ = 19 GeV
S-U

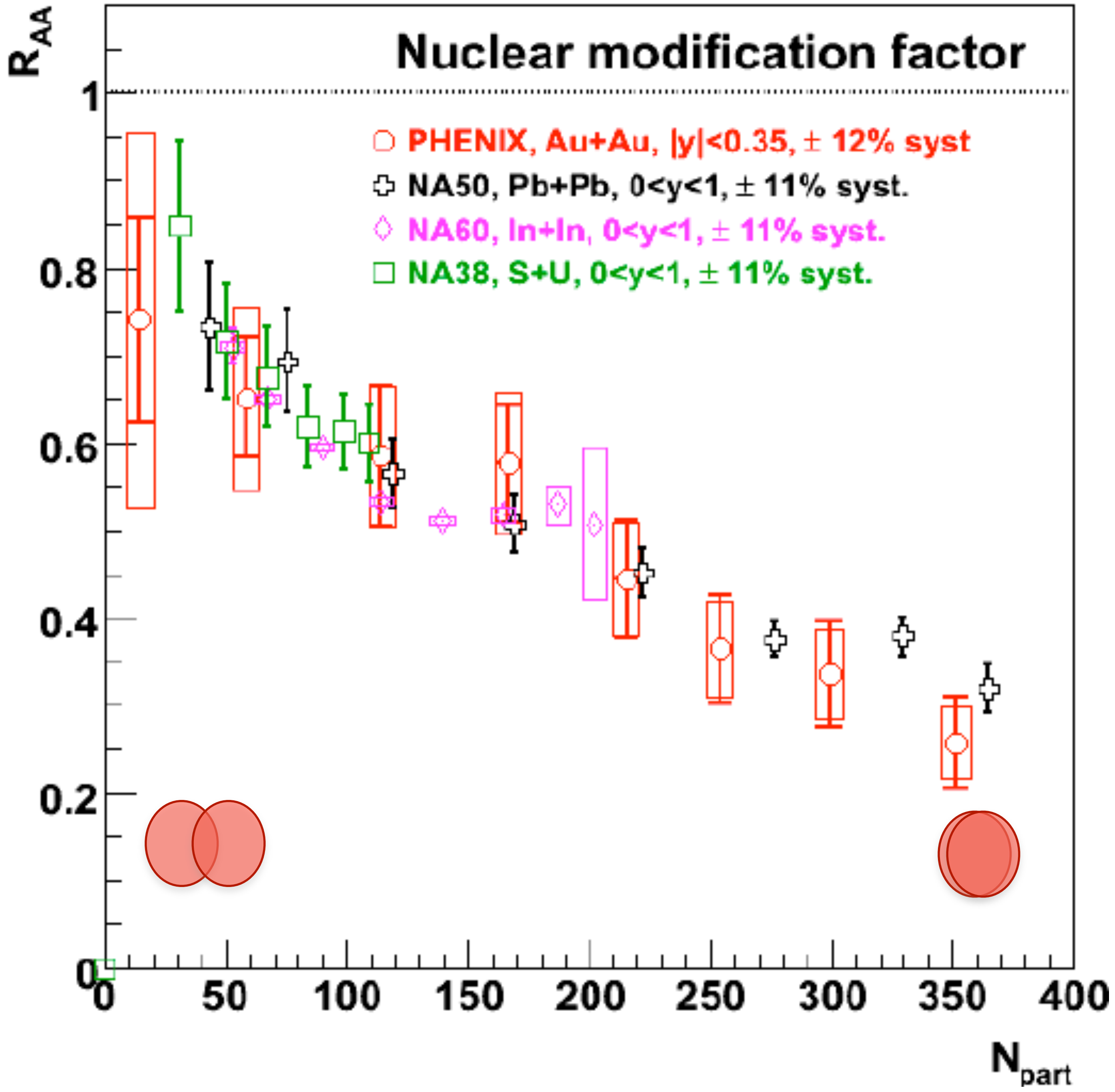
RHIC: PHENIX, STAR
$\sqrt{s_{NN}}$ = 200 GeV
Au-Au

J/Ψ suppression increases with collision centrality

Similar R_{AA} at SPS and RHIC while energy density of formed QGP increases!

But cold nuclear matter effects differ with energy: estimate the CNM

PHENIX Coll. PRL98 (2007) 232301
SPS Coll. @ QM06



Cold nuclear matter effect for J/Ψ

Cold nuclear matter effects estimated in d-Au @ 200 GeV (RHIC) or p-Pb @ 29 GeV and p-In @ 17 GeV (SPS)

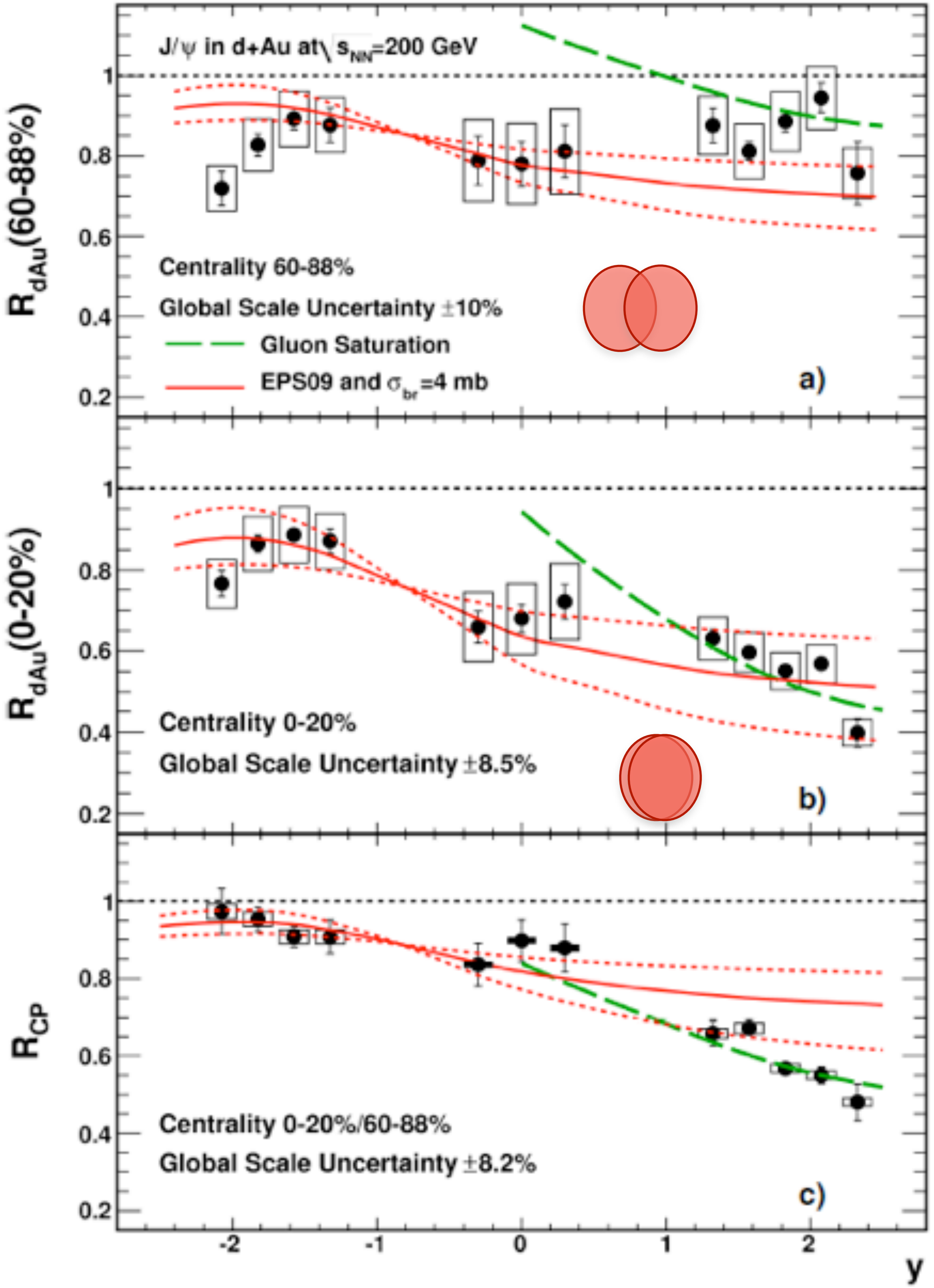
J/Ψ suppressed in d-Au at 200 GeV

Less suppressed at backward and mid-rapidity than forward rapidity for most central collisions

Difficult to understand in terms of shadowing of parton distribution function (npdf) and single nuclear break-up cross-section: how to constrain the cold nuclear matter in a AA collisions?

Try some effective parametrization of CNM...

PHENIX Coll. PRL107 (2011) 142301



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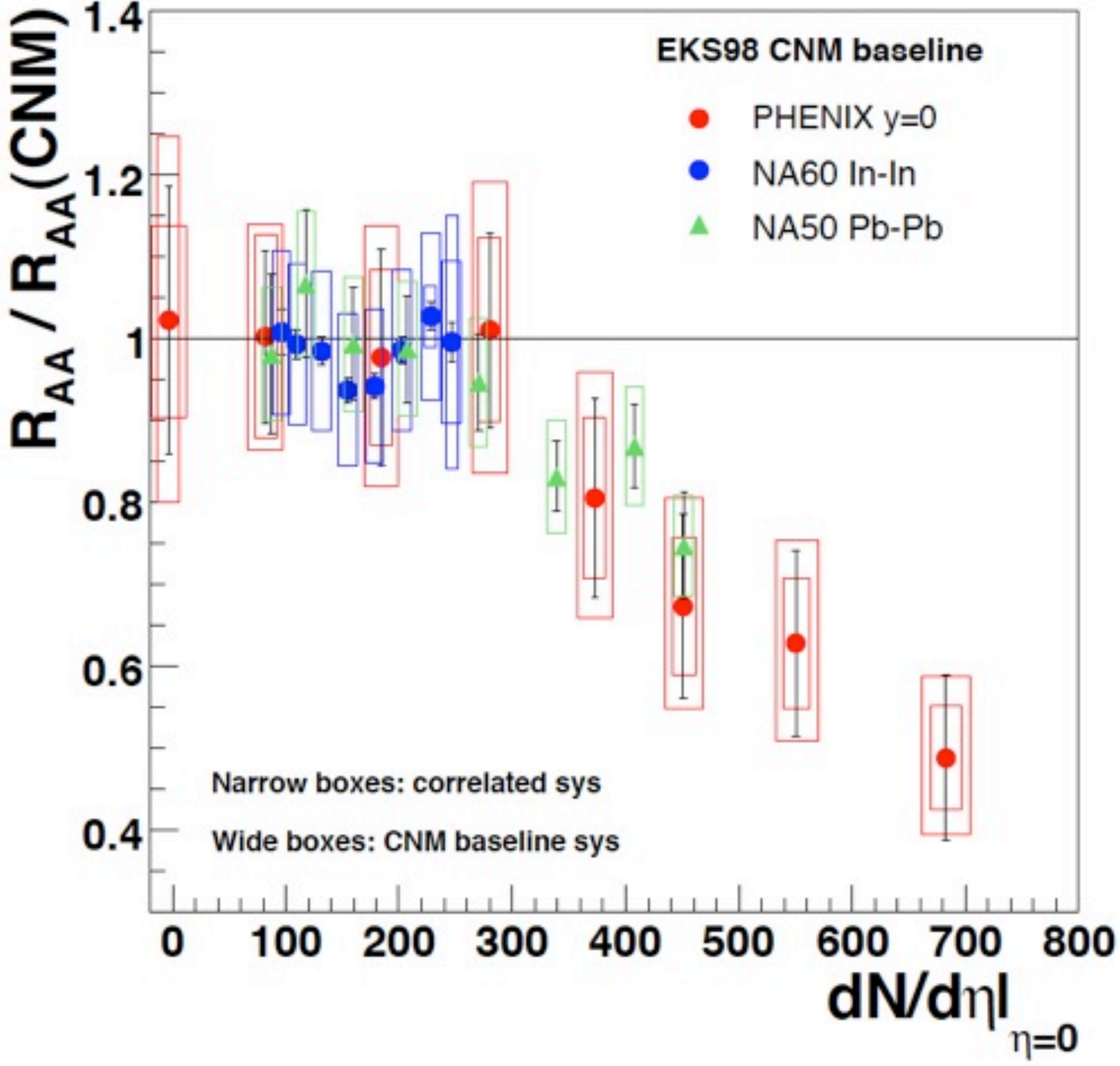
$\sqrt{s_{NN}}$ = 200 GeV
Au-Au

...and assuming that CNM effects factorize...

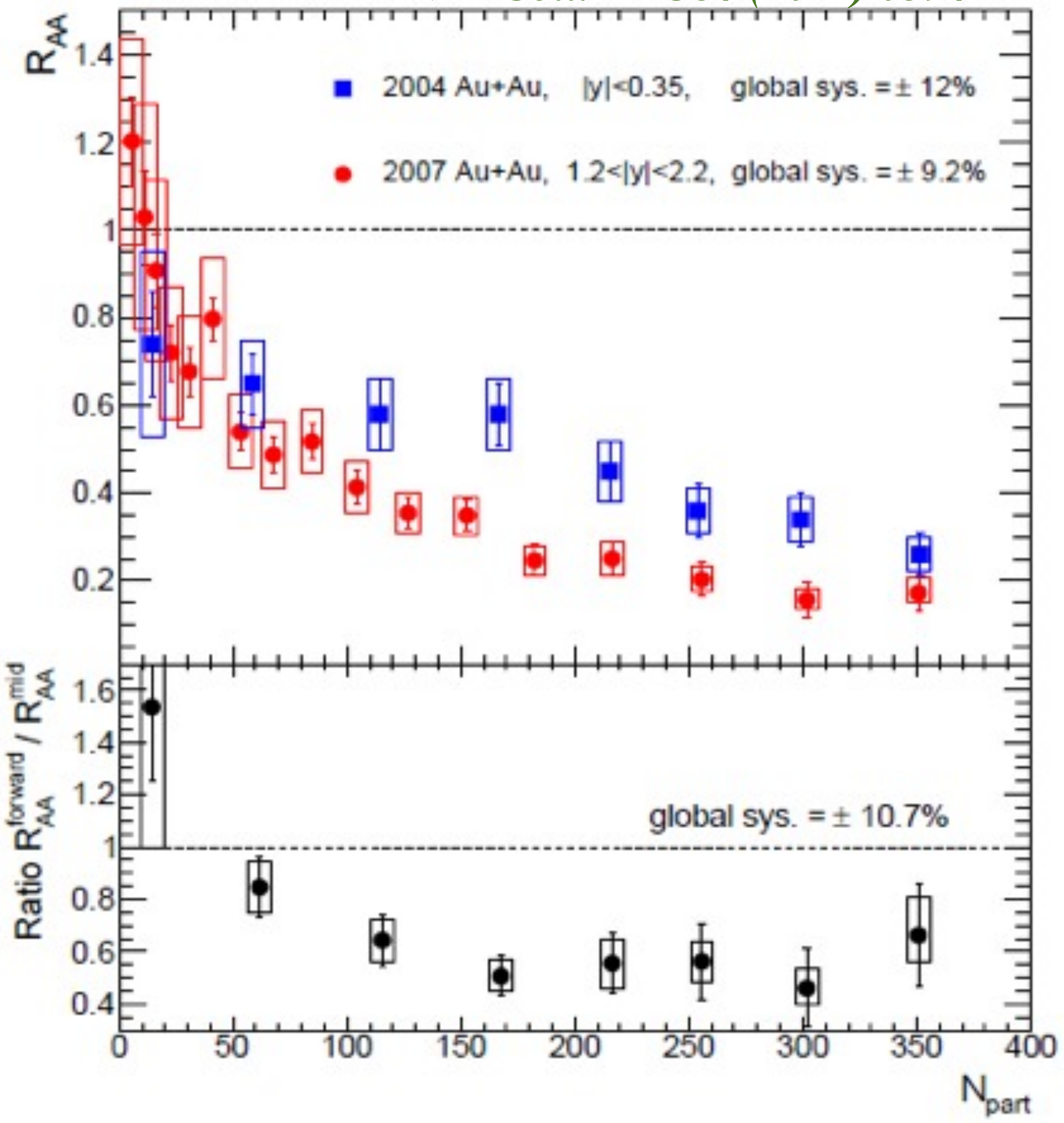
N. Brambilla et al., Eur.Phys.J. C71 (2011) 1534



Anomalous J/Ψ suppression at SPS (up to 25%) and RHIC (up to 50%)
Similar suppression for a given multiplicity

y-dependence of J/Ψ R_{AA} at RHIC

PHENIX Coll. PRC84 (2011) 059412



More suppression (40%) at forward rapidity not expected (density of the QGP higher at mid-rapidity)

Cold nuclear matter effect: R_{dAu} is lower at forward y?

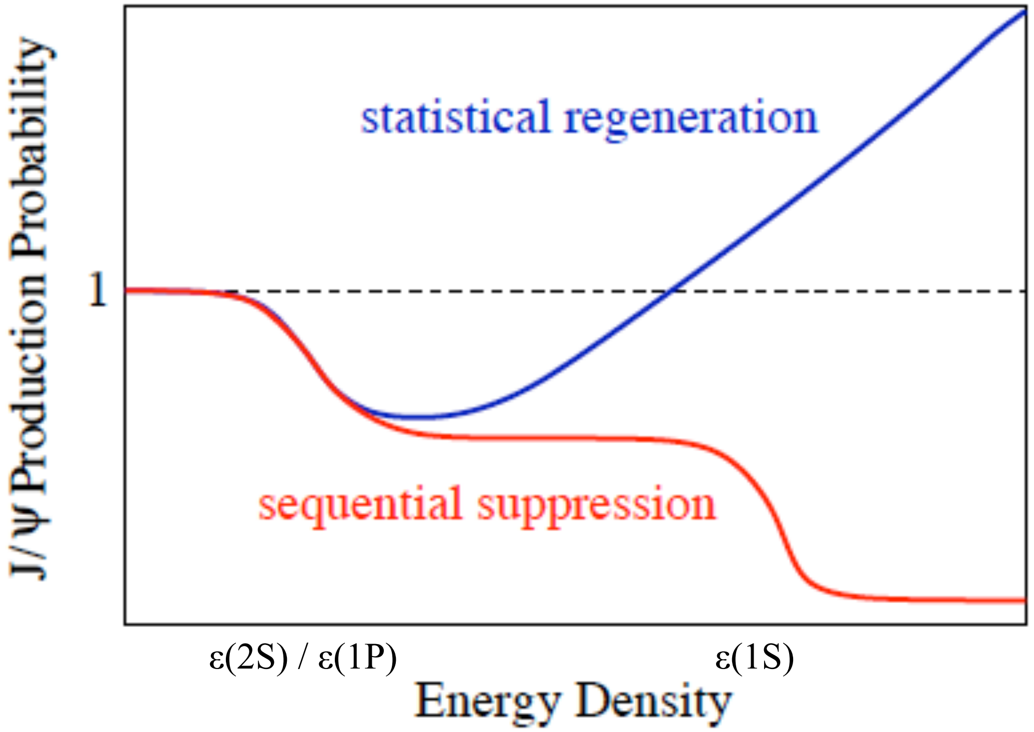
Another mechanism: J/Ψ regeneration?

Secondary J/Ψ production?

Enhancement of J/Ψ in a QGP

c and cbar combination at
the hadronization stage:
J/Ψ regeneration

Expected if total charm
cross-section is large



Total charm production at RHIC

$\sigma_{ccbar} \simeq$ 1 mb @ 200 GeV = 2% of the hadronic cross-section
→ 20 pairs of ccbar created in Au-Au @ 200 GeV for most central collisions

Regeneration implies:
- Evidence of thermalization of charm quarks
- J/Ψ and Ψ(2S) not anymore a QGP thermometer
- Not expected for bottomonium

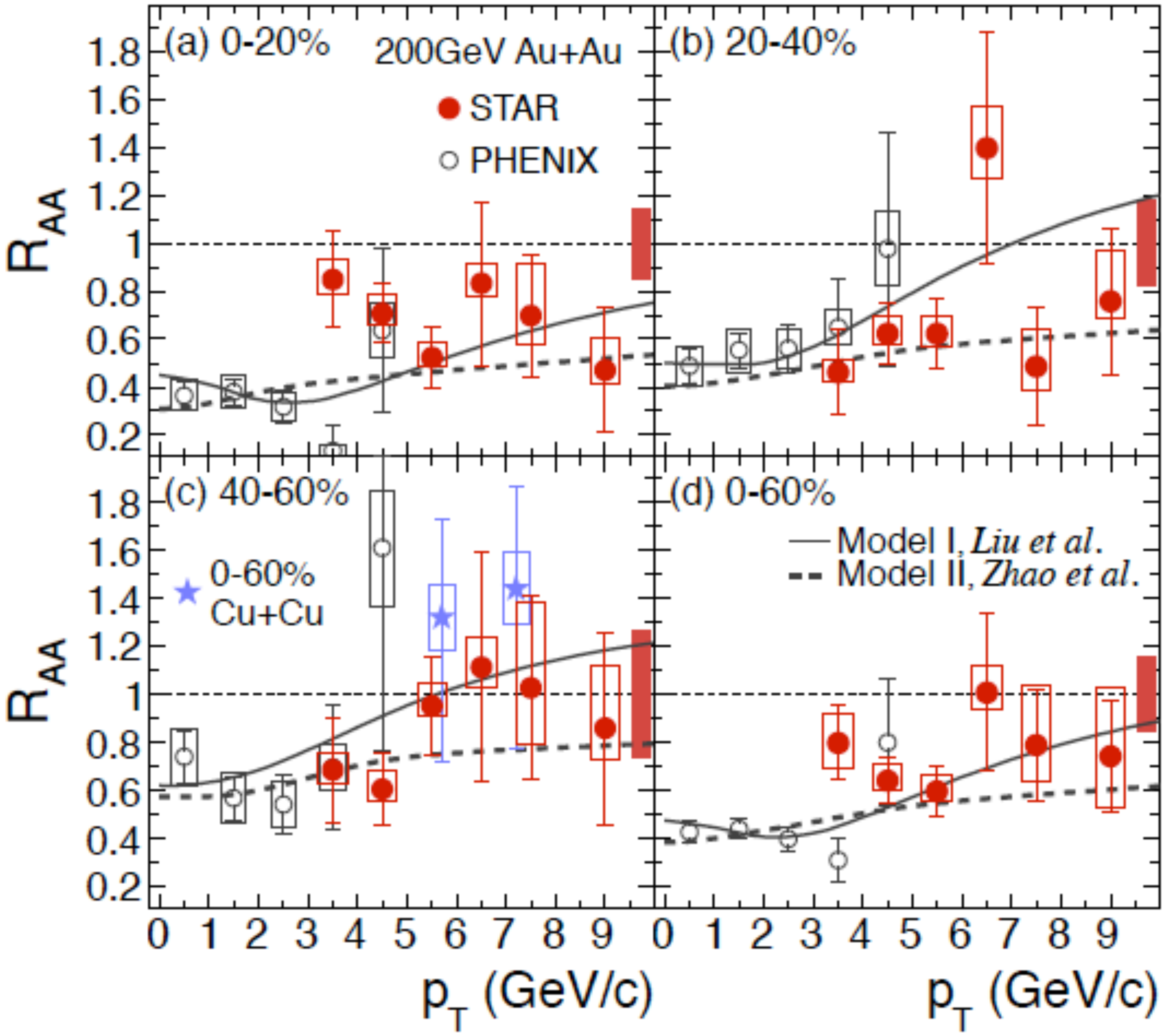
p_T dependence of J/Ψ R_{AA} at RHIC

At large p_T:
No recombination possible
Cold nuclear matter as initial state effect expected to be negligible

Less suppression at large p_T
But still suppression of 40% for most central collisions at $p_T > 5$ GeV/c
p_T dependence not easily understood with color screening and npdfs

Be aware that this is for inclusive J/Ψ while B feed-down contribution is important at large p_T

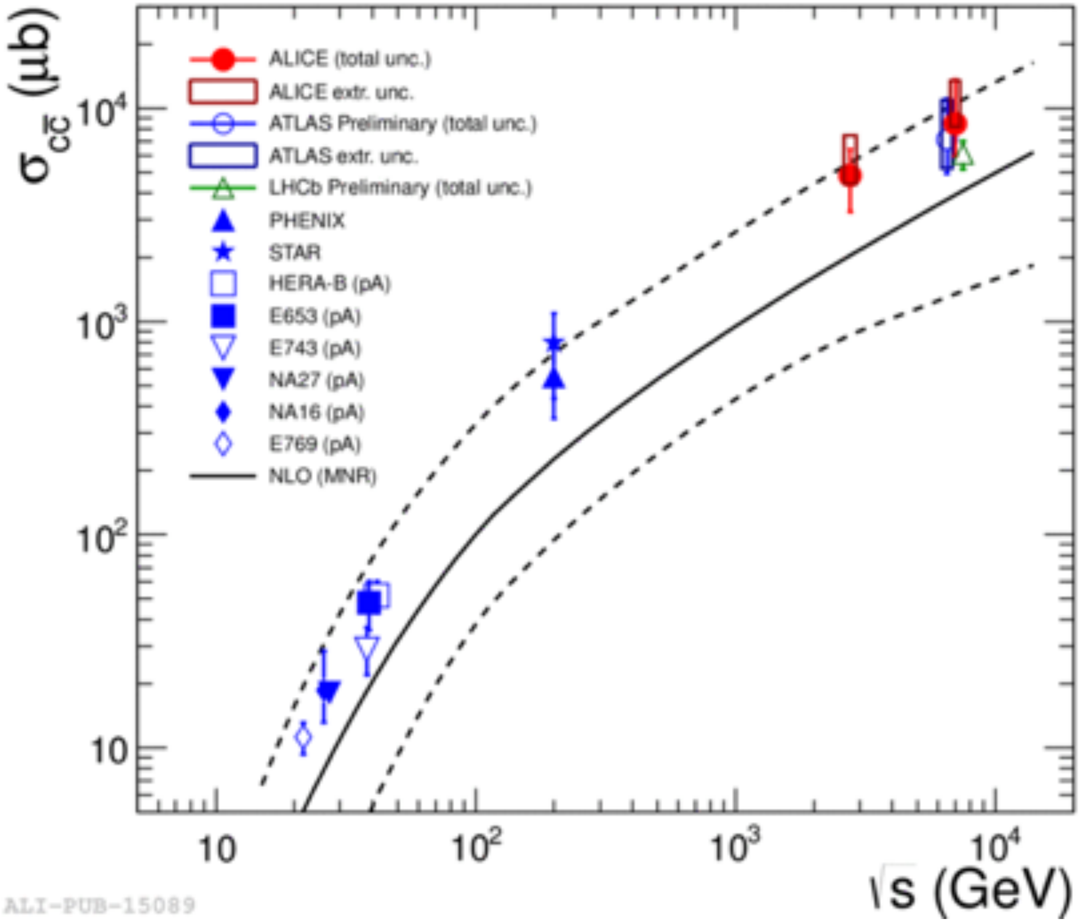
STAR Coll. arXiv:1208.2736



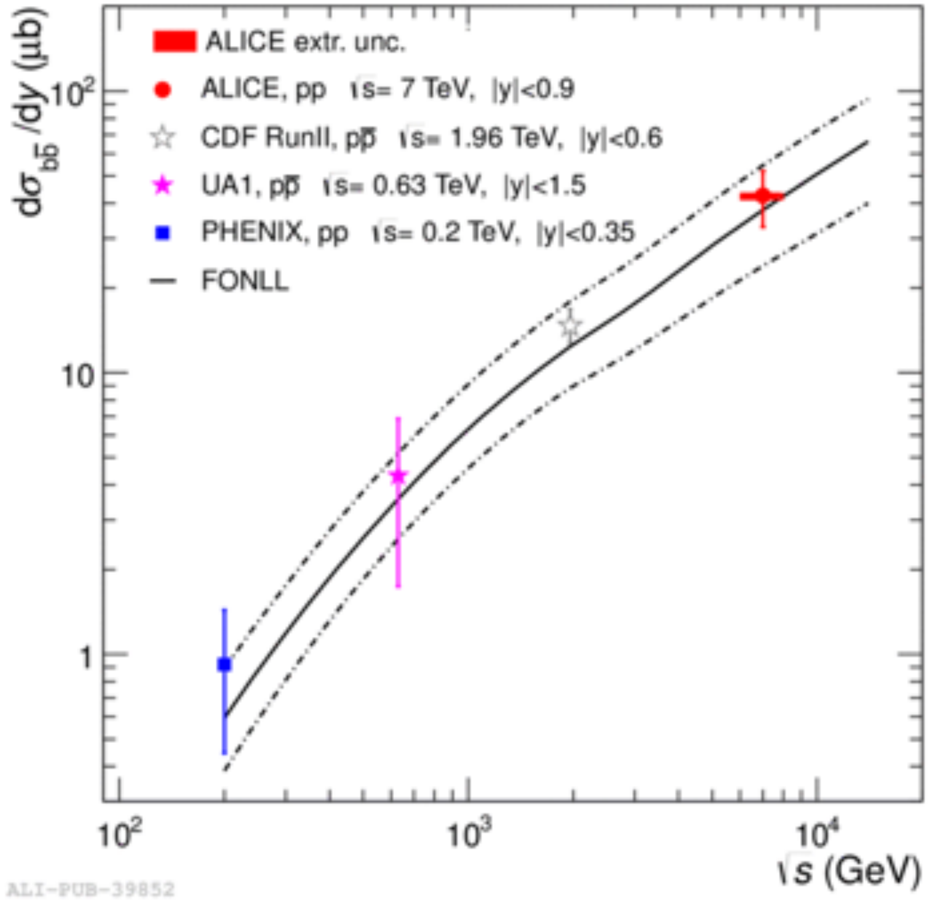
Results from LHC

LHC 10 x higher energy than RHIC: higher rates for open and hidden heavy flavour production

ALICE Coll. JHEP 1207 (2012) 191



ALICE Coll. JHEP 11 (2012) 065

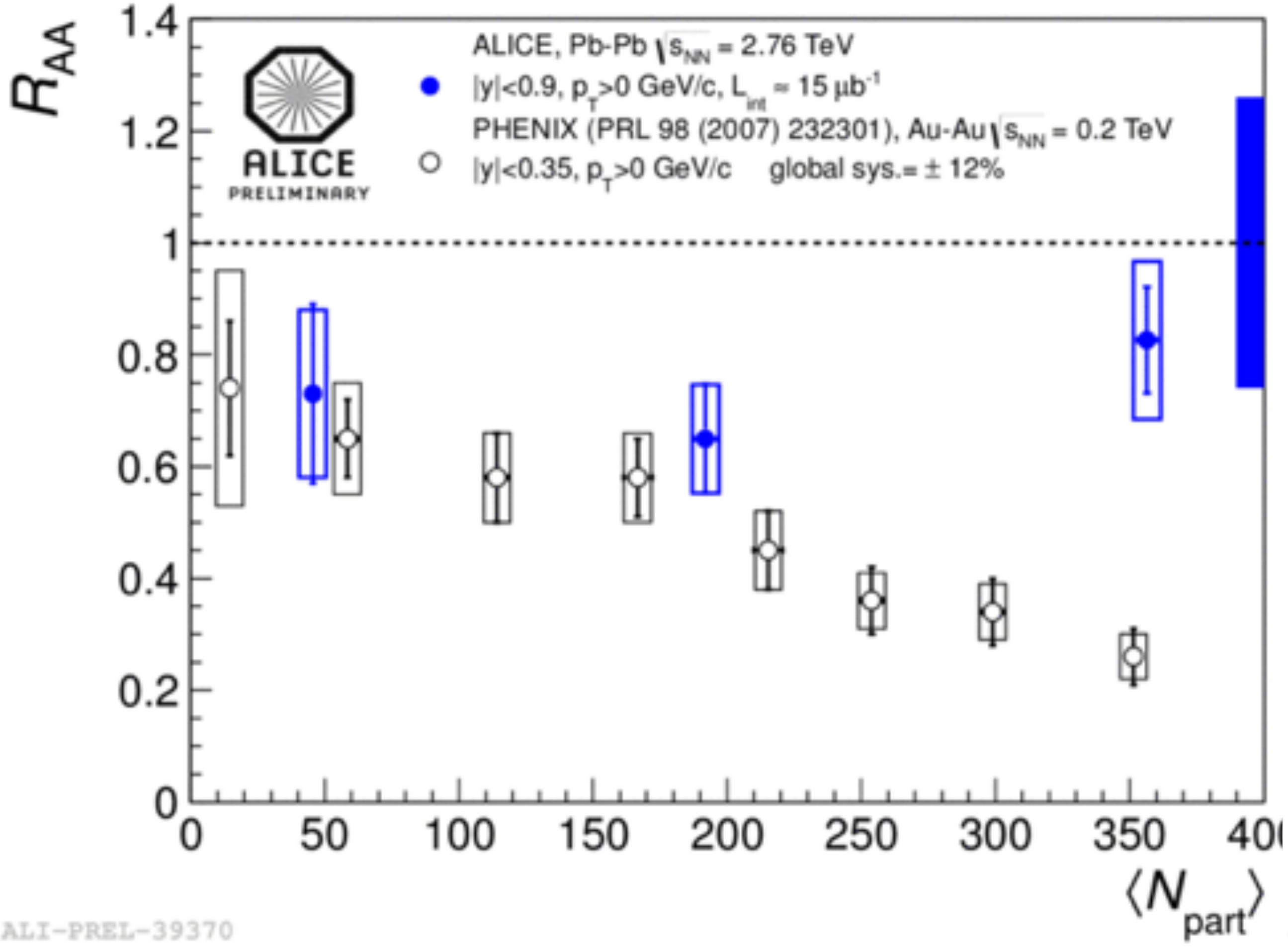


LHC $\sigma_{ccbar} \simeq$ 5 mb @ 2.76 TeV = 7% of the hadronic x-section
→ 115 pairs of ccbar created in Pb-Pb @ 2.76 TeV for most central collisions

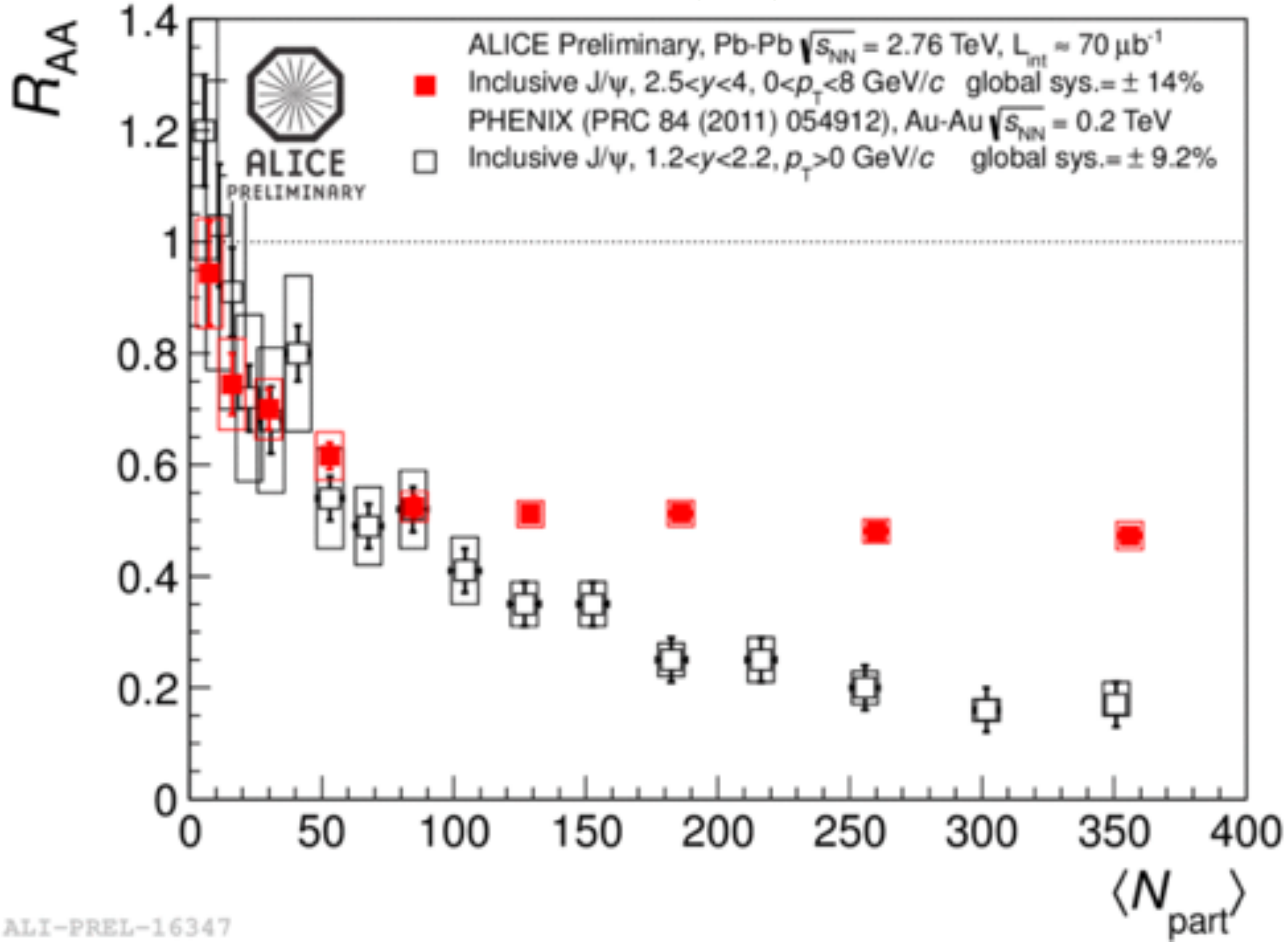
If regeneration of J/Ψ already at RHIC, a higher contribution is expected at LHC

J/Ψ R_{AA} vs centrality

ALICE Coll. Hard Probes 2012



ALICE Coll. Hard Probes 2012

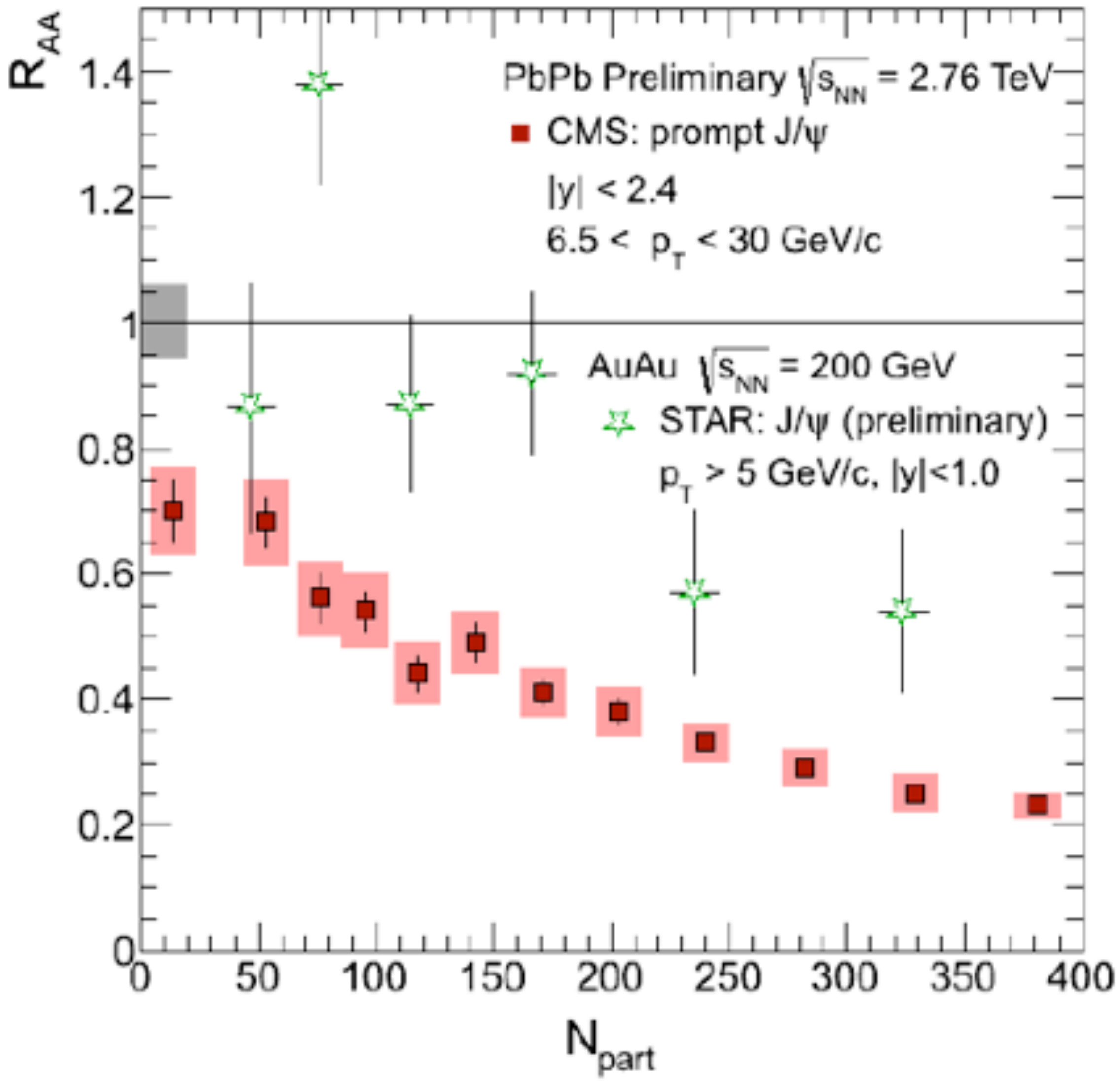


J/Ψ R_{AA} larger at LHC than at RHIC at mid- and forward (for $N_{part} > 100$) rapidity for most central collisions

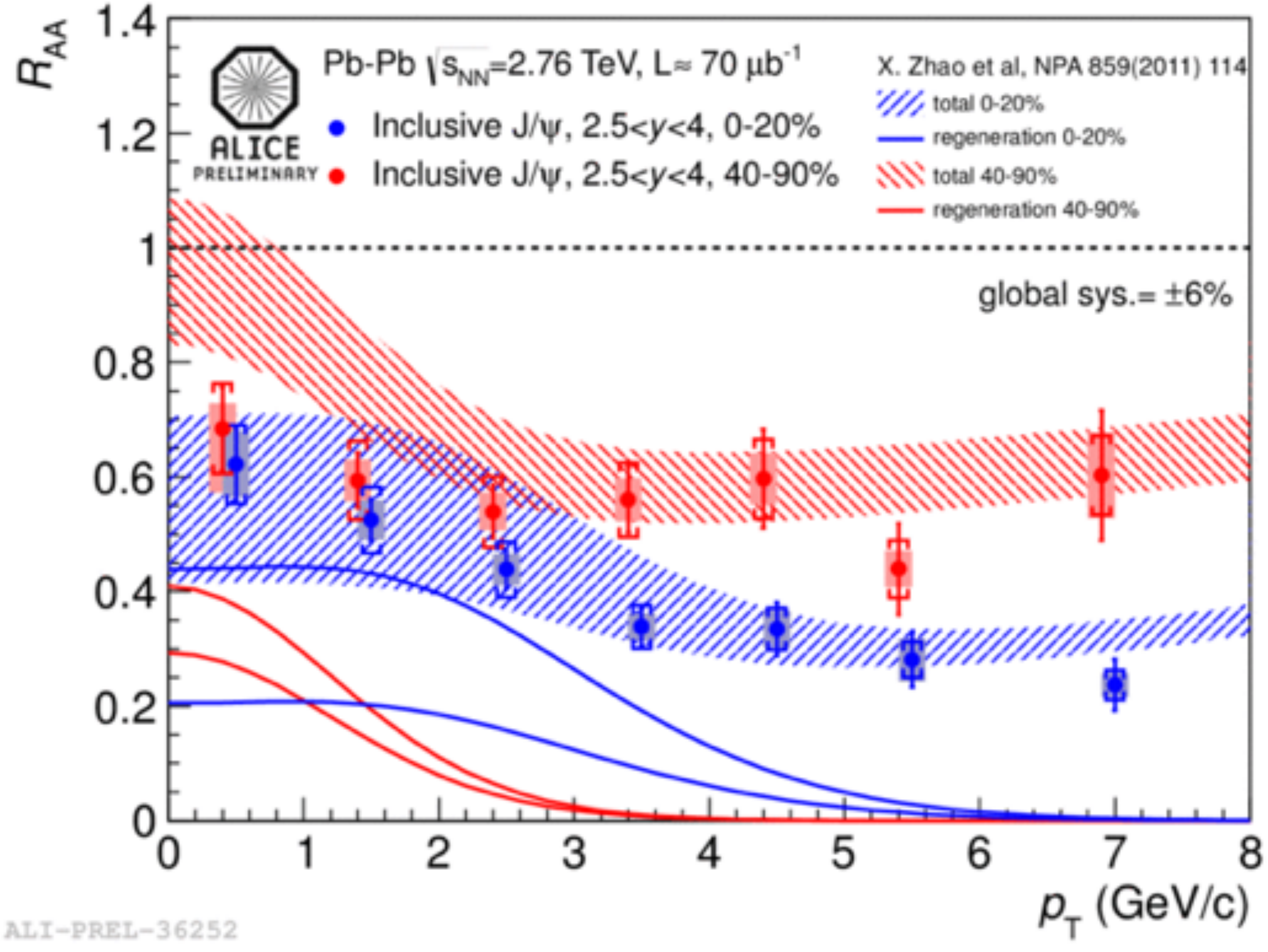
→ consistent with regeneration mechanism

J/Ψ R_{AA} for high p_T and vs p_T

CMS-PAS-HIN-12-014



ALICE Coll. QM 2012

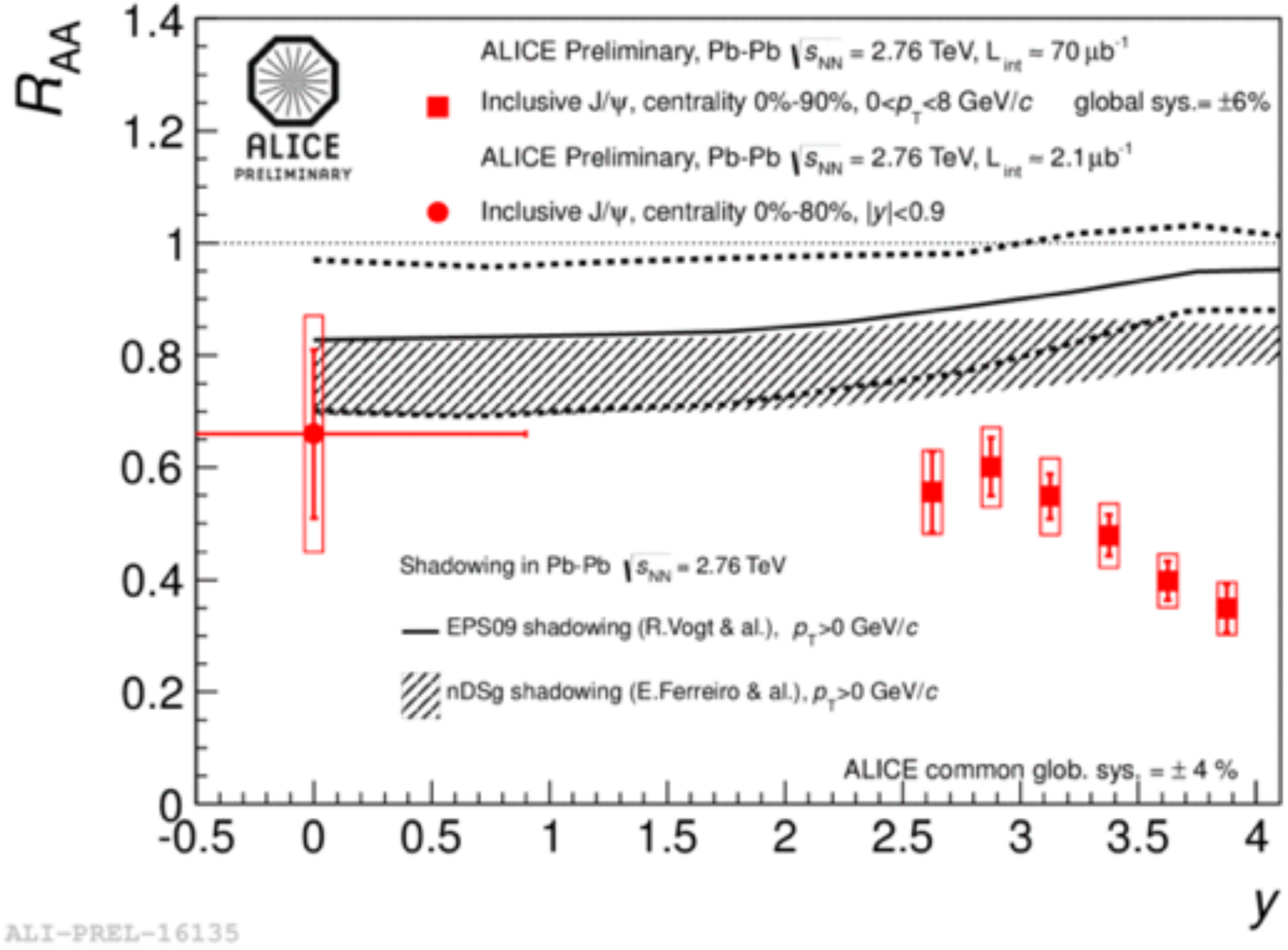


At large p_T, J/Ψ R_{AA} lower at LHC than at RHIC as expected if color screening mechanism only in a QGP

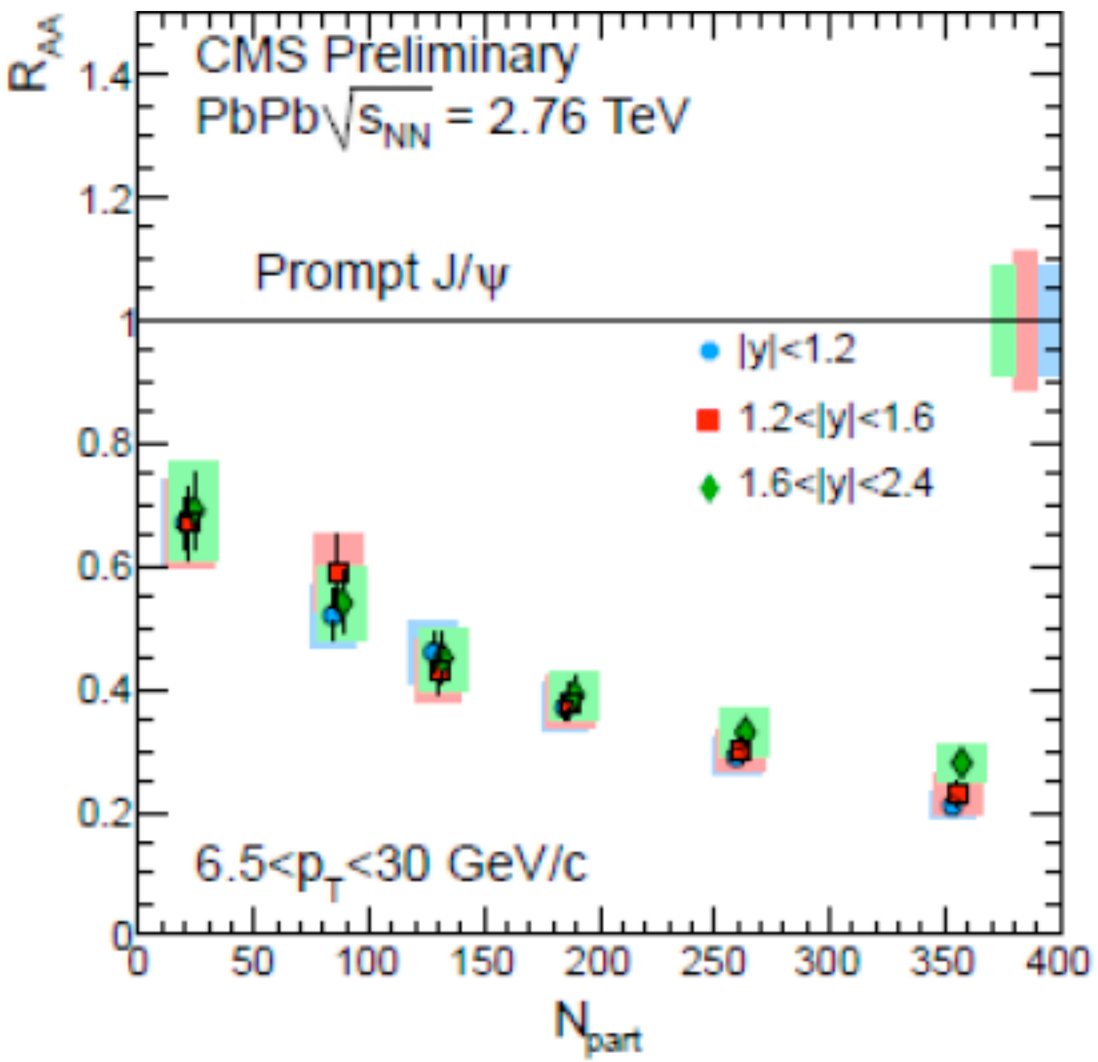
J/Ψ less suppressed at low p_T than high p_T for most central collisions

J/Ψ R_{AA} vs y

ALICE Coll. Hard Probes 2012



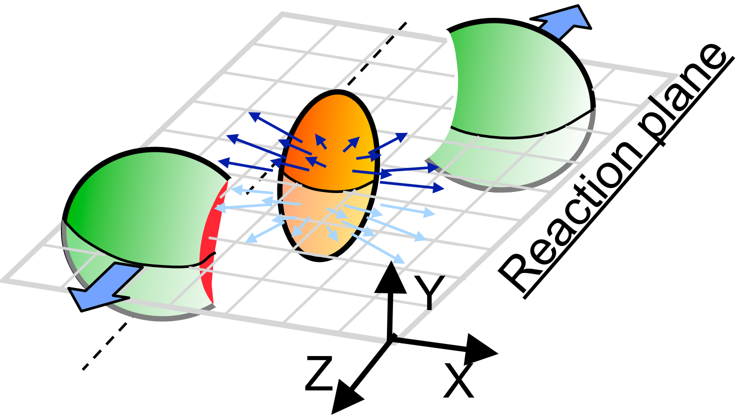
CMS-PAS-HIN-12-014

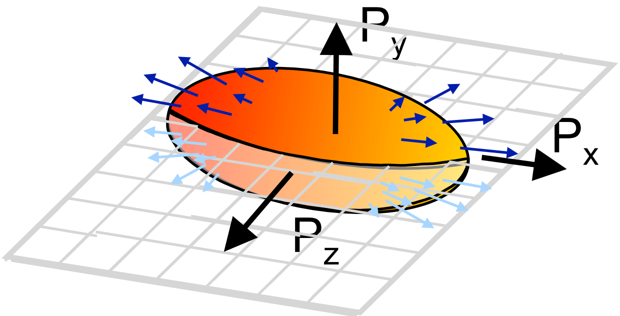


J/Ψ more suppressed at forward rapidity if integrated over p_T
Shadowing models do not account for this rapidity decrease of R_{AA}
No or small rapidity dependence for large p_T

Elliptic flow

In nuclei collisions at finite impact parameter: anisotropy of the geometrical overlap region
For interacting matter (via multiple collisions): spatial asymmetry → anisotropy of the particle momentum distribution





Azimuthal dependence of the particle yield

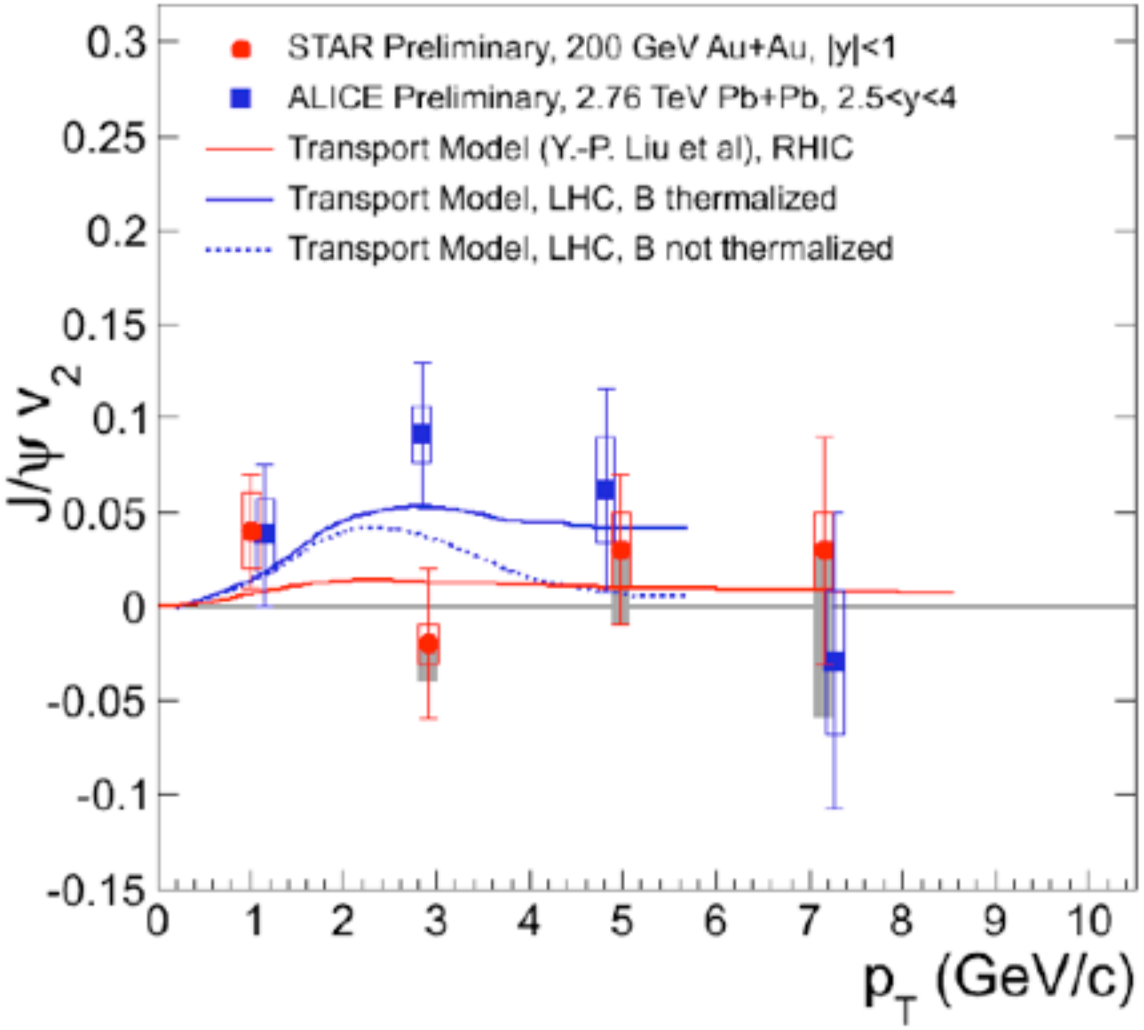
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[n(\phi-\Psi_R)]\right)$$

Elliptic flow n=2
$v_2(p_T) = \langle\cos(2\phi)\rangle(p_T)$

If c quarks participate to the collective motion of the QGP, then they will acquire some elliptic flow
Regenerated J/ψ will inherit their elliptic flow

J/Ψ elliptic flow

ALICE Coll., Hard Probes 2012
STAR Coll, JPG38, 124107 (2011)



Flow compatible with zero measured by STAR (RHIC)
Non-zero J/psi v_2 observed at intermediate p_T for semi-central collisions at LHC
v2 and R_{AA} at low p_T qualitatively described by models including regeneration

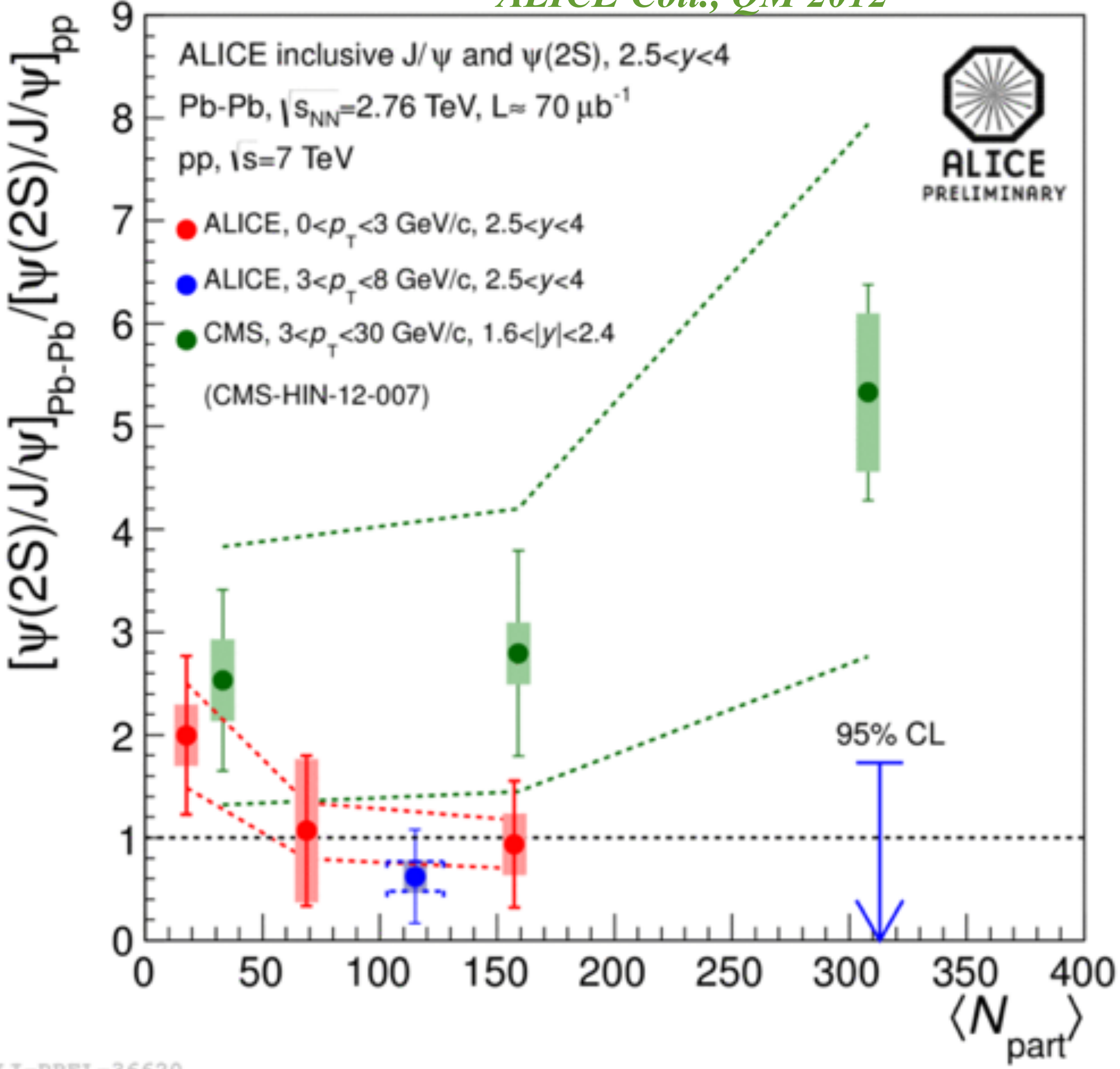
First Ψ(2S) measurements

Double ratio measurement:
Ψ(2S)/ J/Ψ in Pb-Pb over p-p

CMS measures a Ψ(2S) enhancement
wrt J/Ψ for $p_T > 3$ GeV/c

ALICE does not measure a sign of
large Ψ(2S) enhancement

CMS Coll., Hard Probes 2012
ALICE Coll., QM 2012

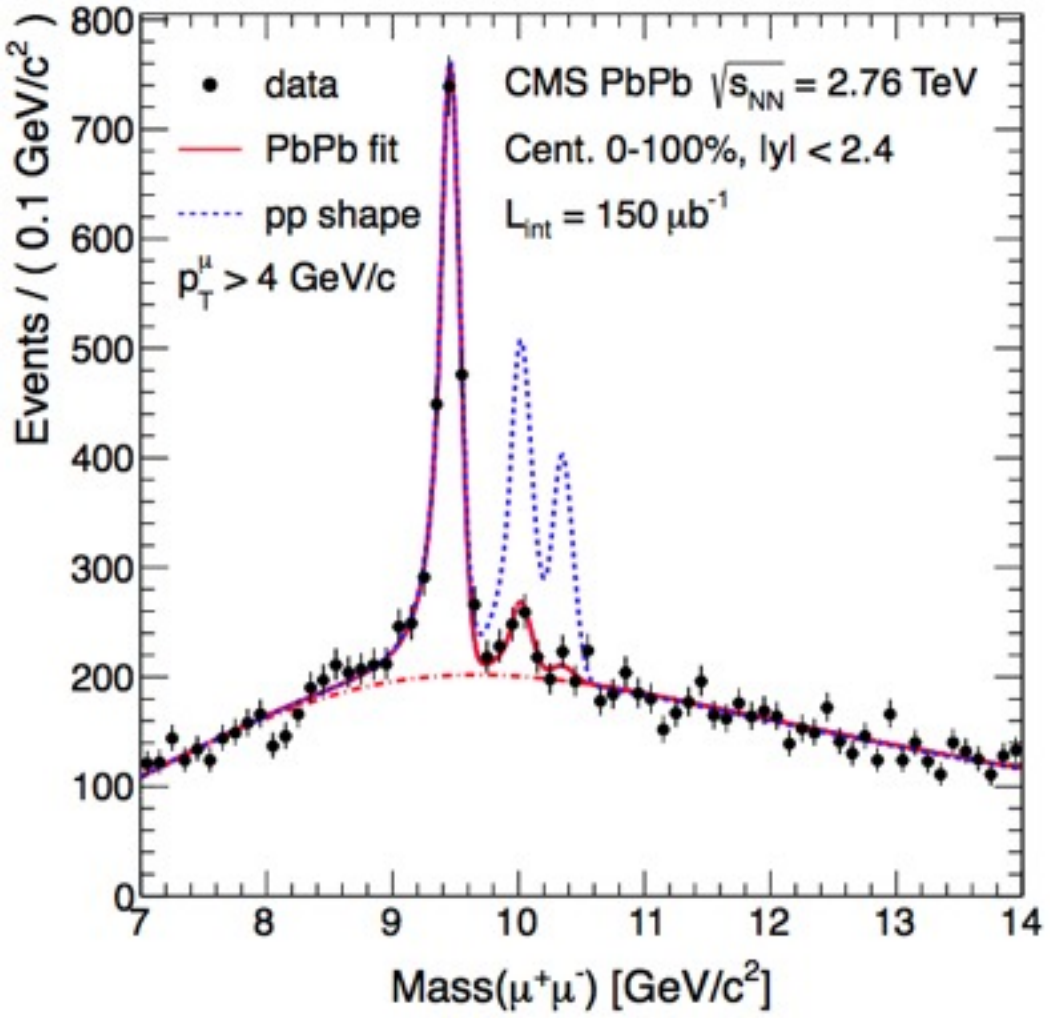


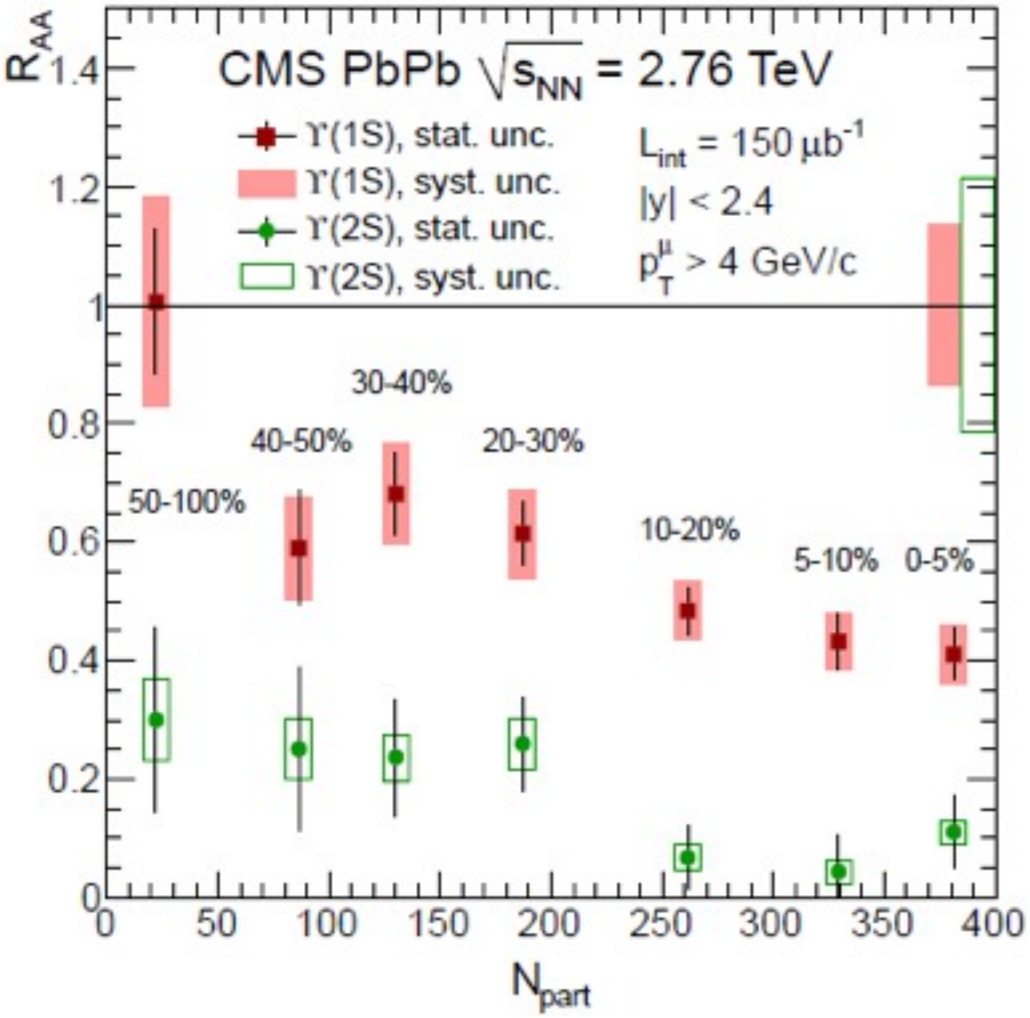
ALI-PREL-36620

Both data are compatible: large uncertainties due to low statistics at $p_T > 3$ GeV/c
and lack of solid pp reference at 2.76 TeV

Bottomonium family

CMS Coll. PRL 109 (2012) 222301





STAR Coll. QM 2012

Y(3s) completely melted

Y(2s) strongly suppressed

Y(1S) suppression consistent with excited states suppression by color screening

RHIC: $R_{AA}(\Upsilon\ (1S+2S+3S)) = 0.56 \pm 0.21 +0.08 -0.16$

LHC: $R_{AA}(\Upsilon\ (1S+2S+3S)) \sim 0.32$

→R_{AA} lower at RHIC than LHC

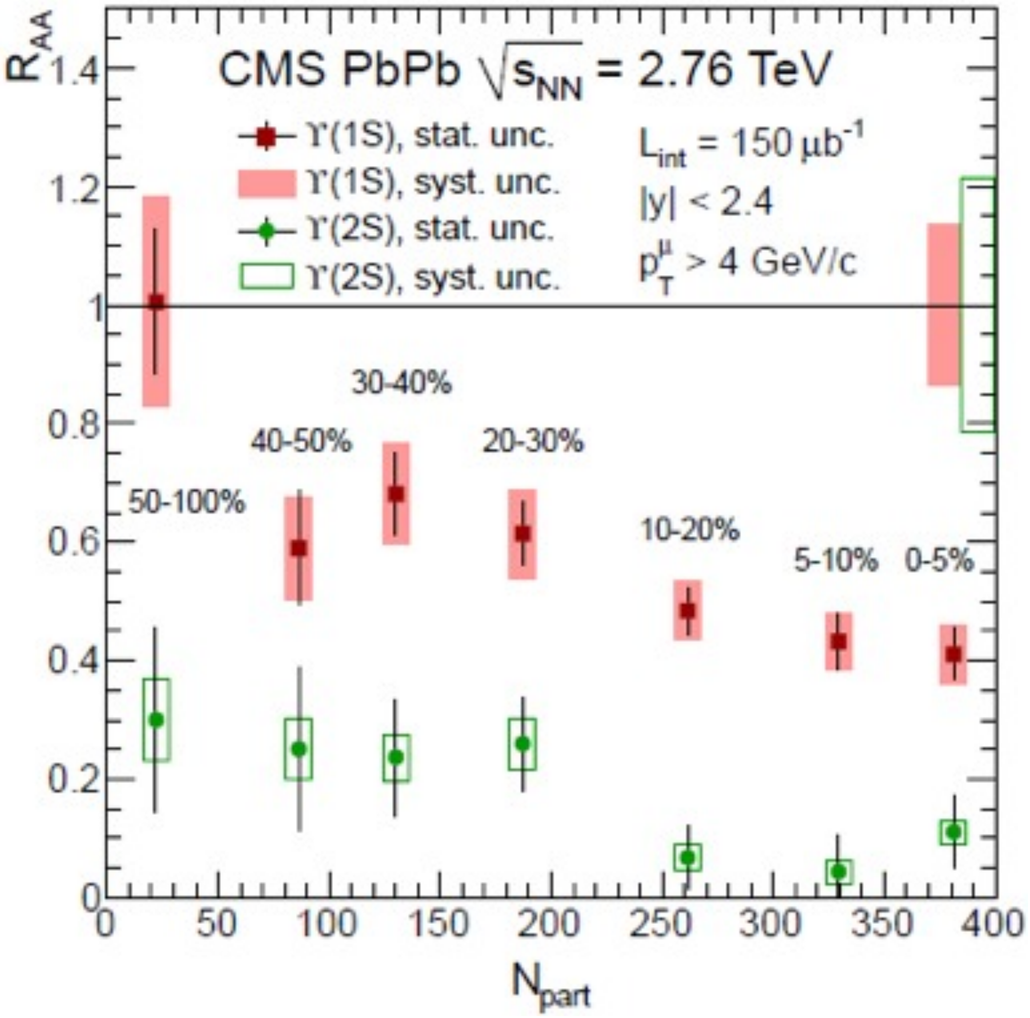
Bottomonium family

CMS Coll. PRL 109 (2012) 222301

Υ (1S): R_{AA}= 0.56±0.08+0.07

Υ (2S): R_{AA}= 0.12±0.04+0.02

Υ (3S): R_{AA} < 0.10 (95% CL)



STAR Coll. QM 2012

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LHC: $R_{AA}(\Upsilon$ (1S+2S+3S)) ~ 0.32

→R_{AA} lower at RHIC than LHC

Conclusion and outlooks

SPS and RHIC data point out for an anomalous J/Ψ suppression by color screening but the rapidity dependence of R_{AA} gives a more complexe picture

At LHC, J/Ψ low p_T and flow measurements with ALICE is consistent with the mechanism of charm and anti-charm regeneration at the hadronization stage

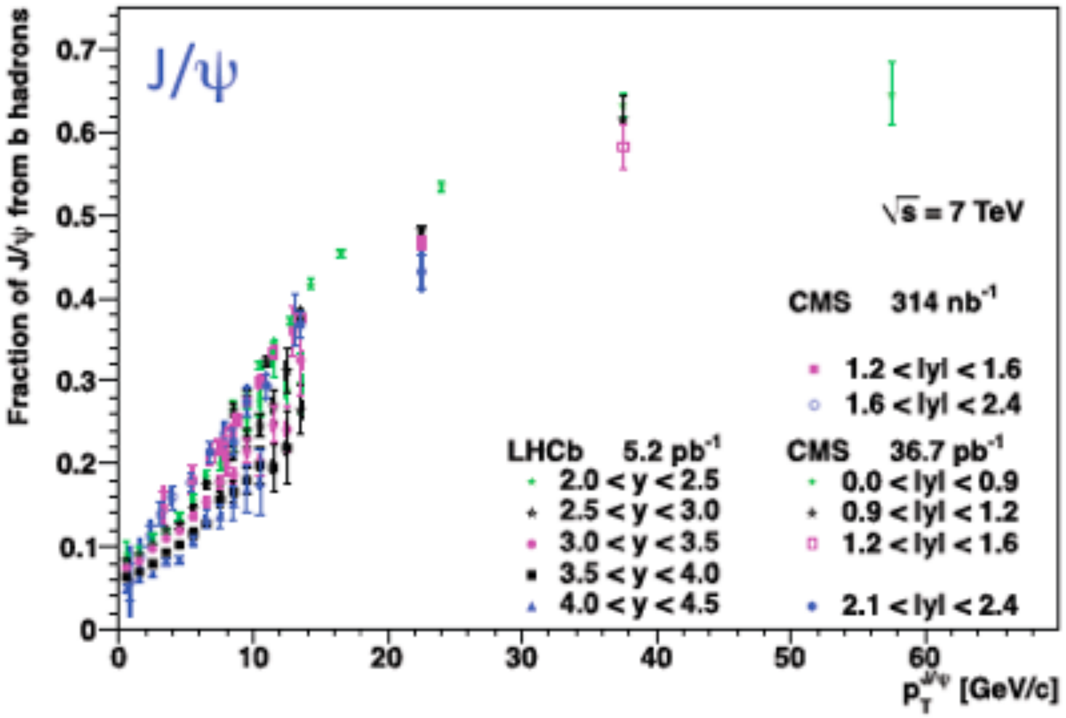
J/Ψ high p_T measured by ALICE and CMS are more suppressed than RHIC data

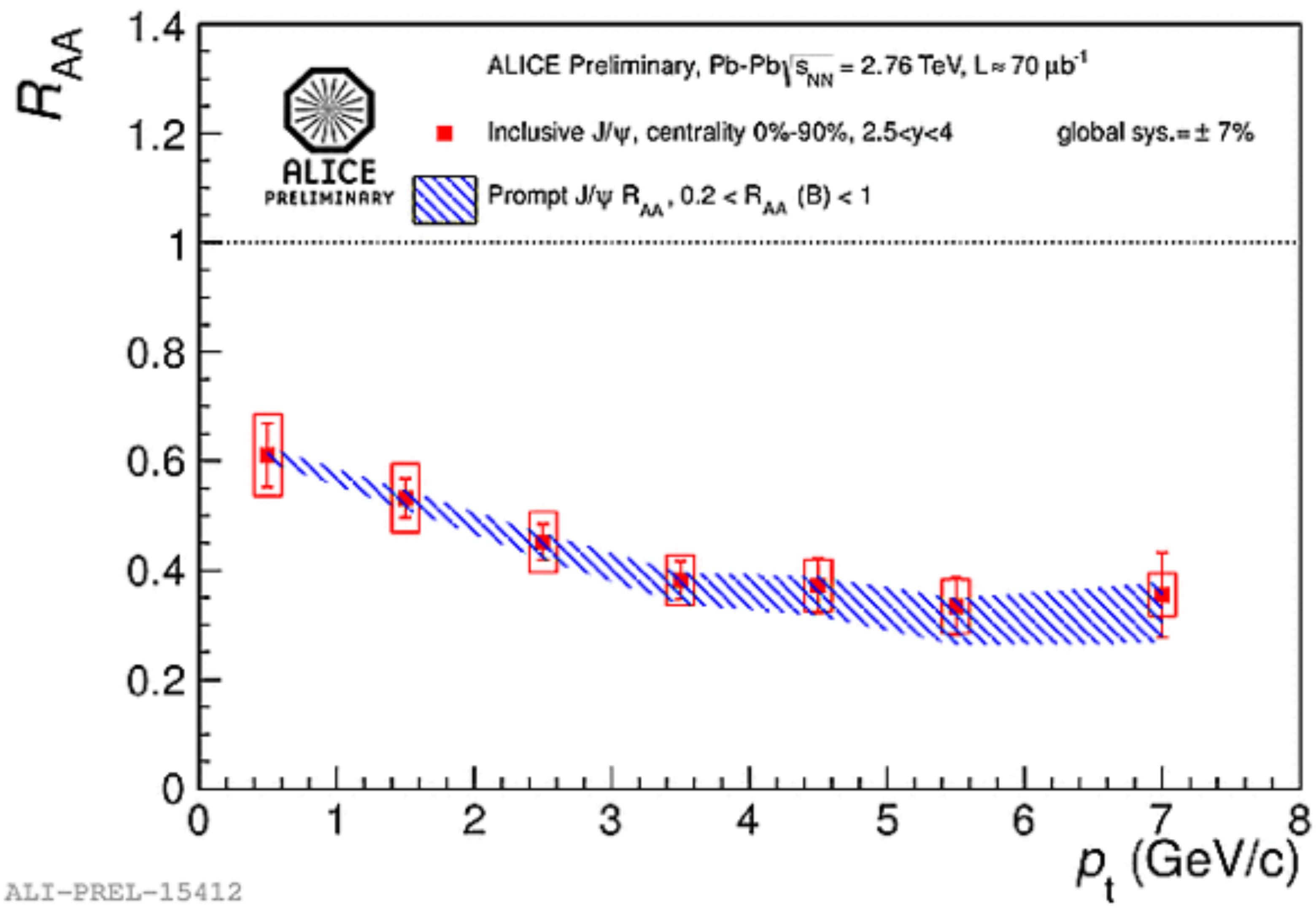
Upsilon suppression measured at CMS is compatible with sequential suppression of excited states

p-Pb results for charmonia and bottomonia production needed at LHC to disentangle hot and cold nuclear effects in Pb-Pb, to confirm these conclusions and to allow quantitative conclusions on the hot nuclear medium formed: p-Pb analysis ongoing

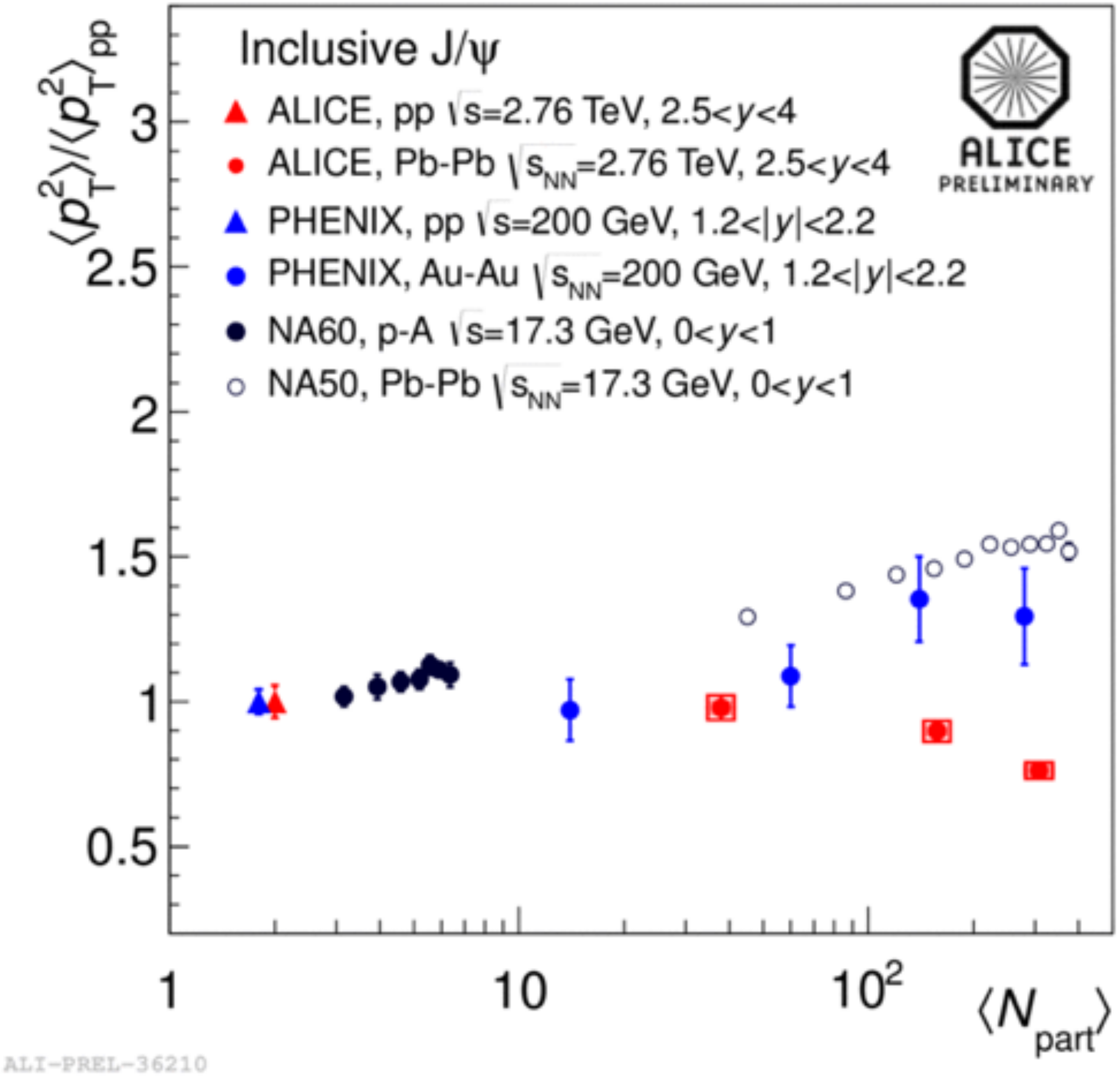
back-up slides

From inclusive to prompt J/Ψ R_{AA}

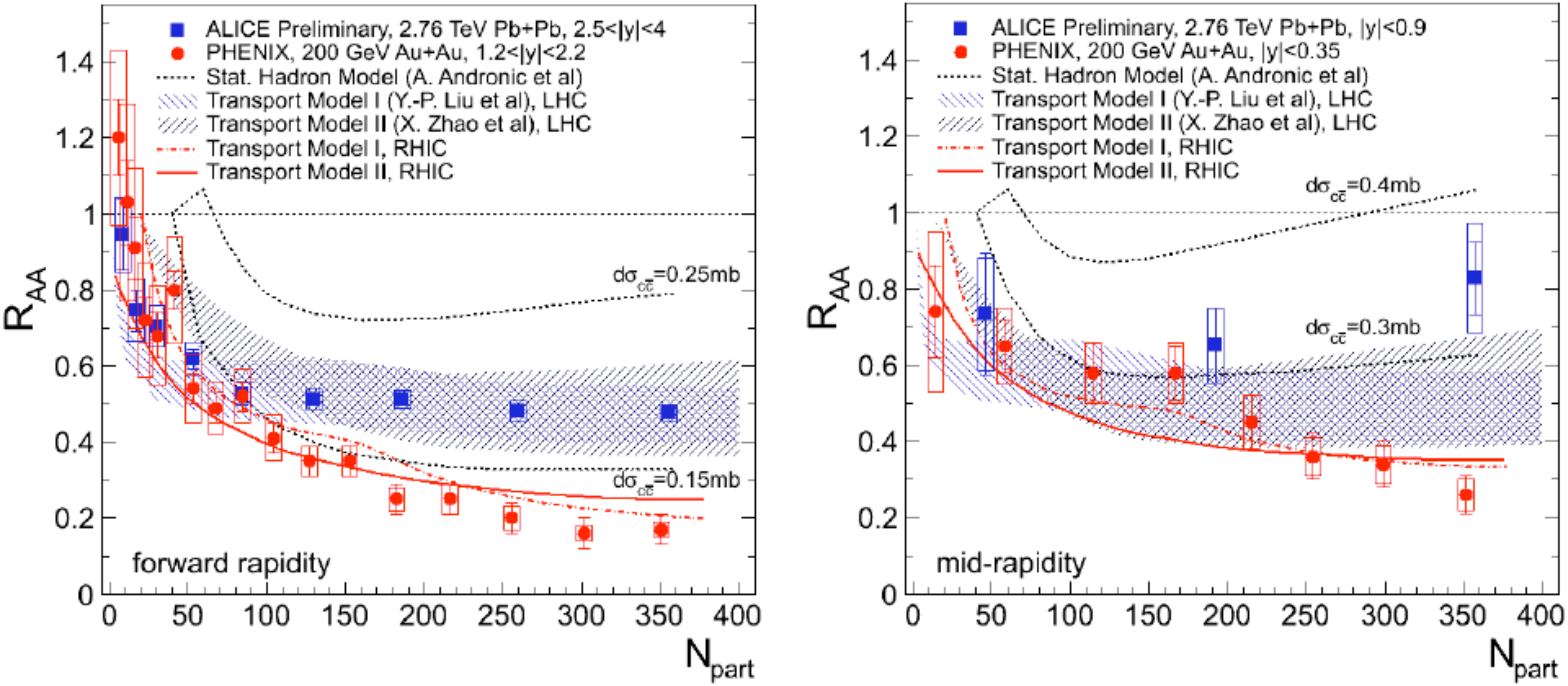




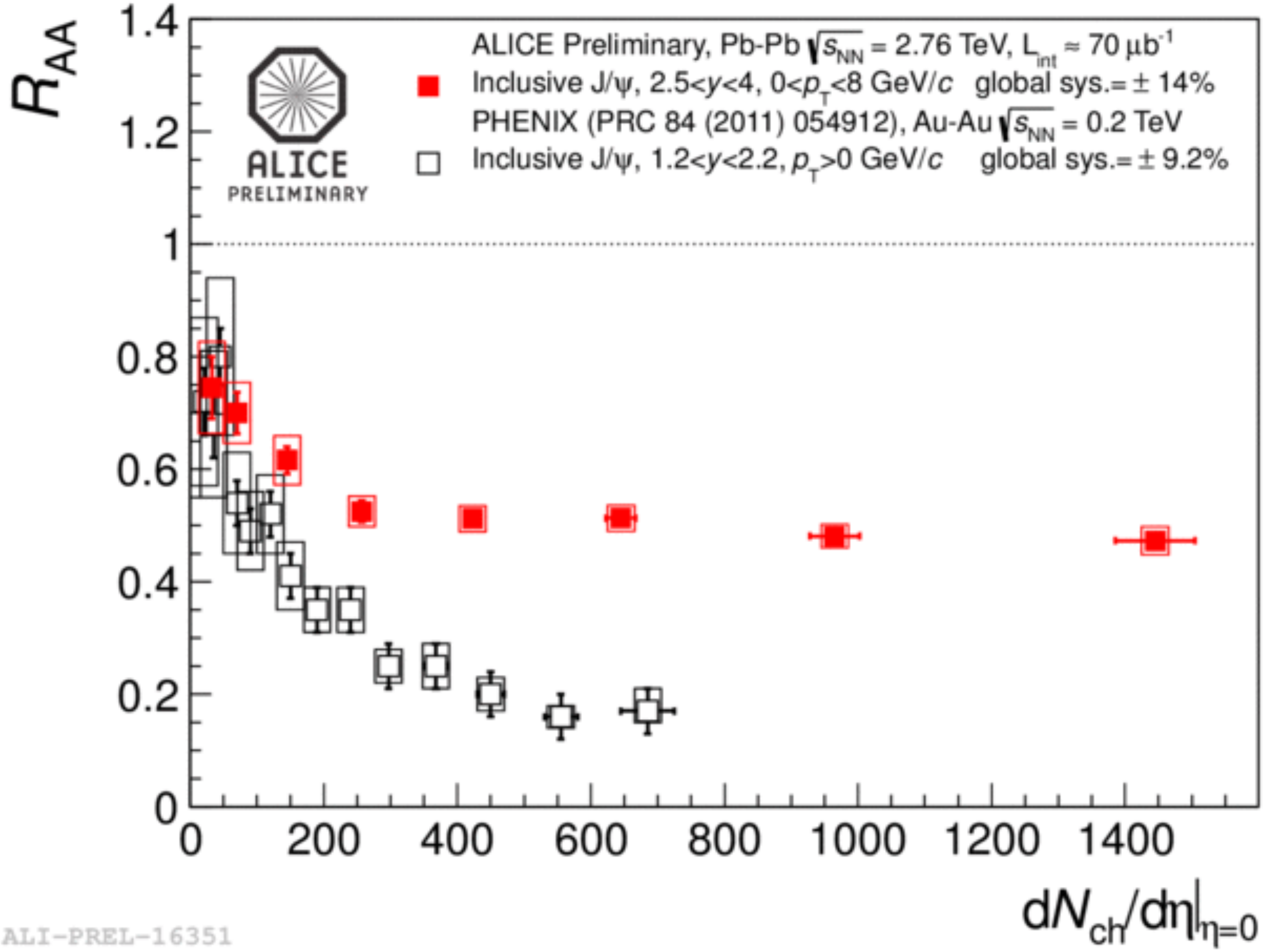
Inclusive J/Ψ <p_T>



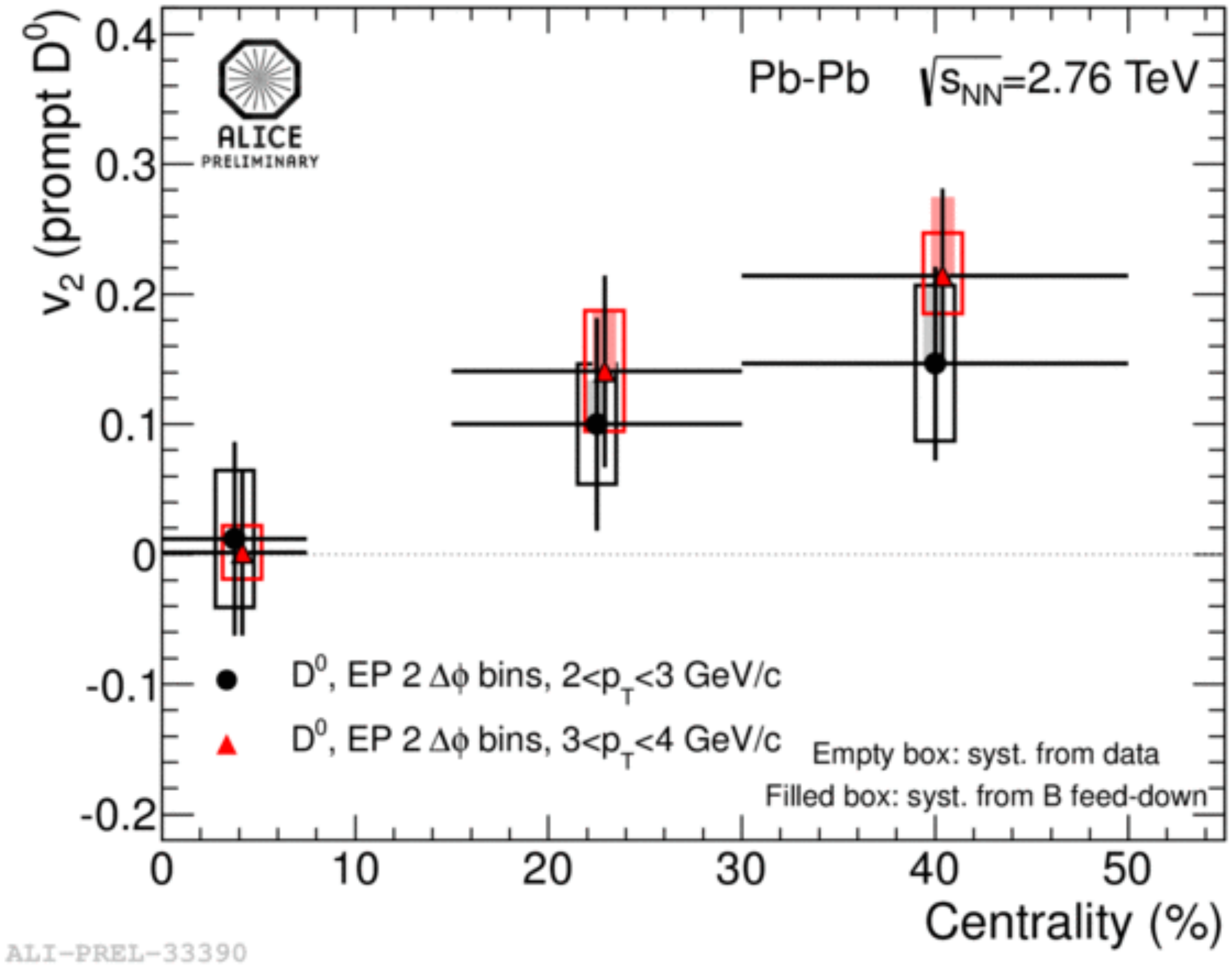
J/Ψ R_{AA} @ LHC and RHIC vs. models



LHC vs RHIC

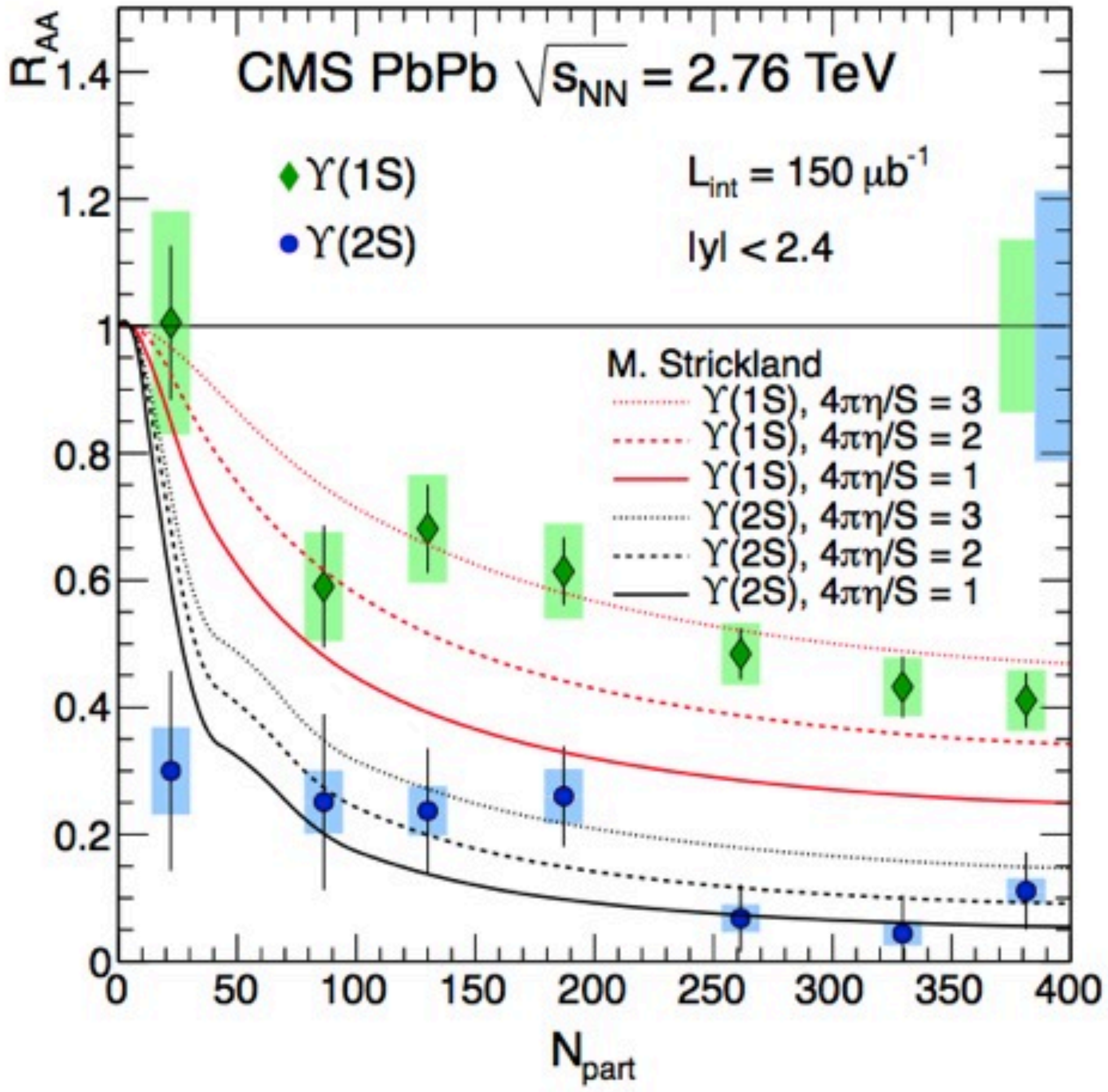

ALICE
PRELIMINARY
ALICE Preliminary, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV, $L_{int} \approx 70\ \mu b^{-1}$
■ Inclusive J/ψ, $2.5<y<4$, $0<p_T<8$ GeV/c global sys.= ± 14%
PHENIX (PRC 84 (2011) 054912), Au-Au $\sqrt{s_{NN}}$ = 0.2 TeV
☐ Inclusive J/ψ, $1.2<y<2.2$, $p_T>0$ GeV/c global sys.= ± 9.2%
R_{AA}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
$dN_{ch}/d\eta|_{\eta=0}$
ALI-PREL-16351

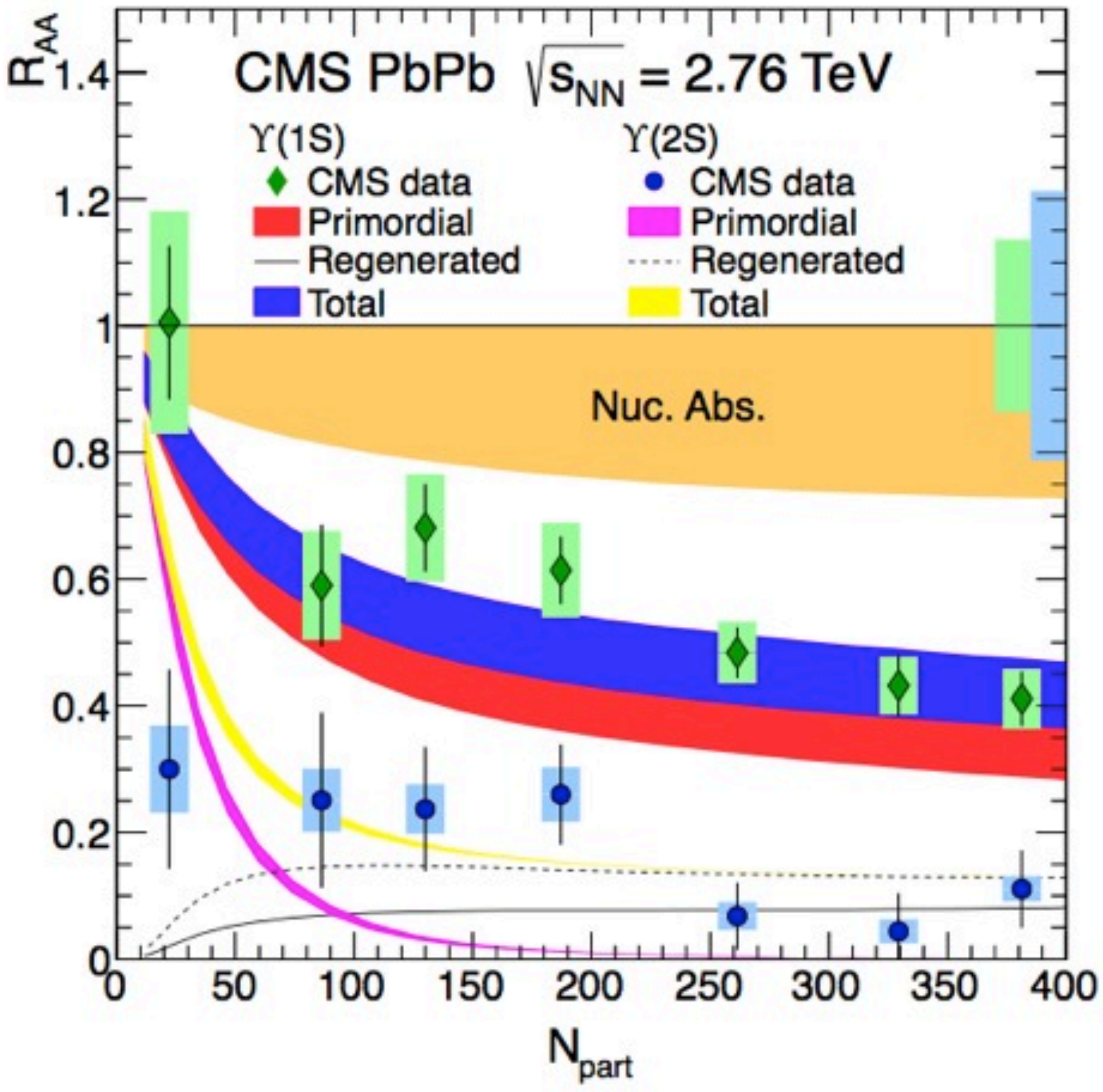
prompt D^0 v_2


v_2 (prompt D^0)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
10
20
30
40
50
Centrality (%)
ALICE
PRELIMINARY
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
● D^0, EP 2 $\Delta\phi$ bins, $2<p_T<3$ GeV/c
▲ D^0, EP 2 $\Delta\phi$ bins, $3<p_T<4$ GeV/c
Empty box: syst. from data
Filled box: syst. from B feed-down
ALI-PREL-33390

Υ R_{AA} @ LHC vs. models

arXiv:1208.2826





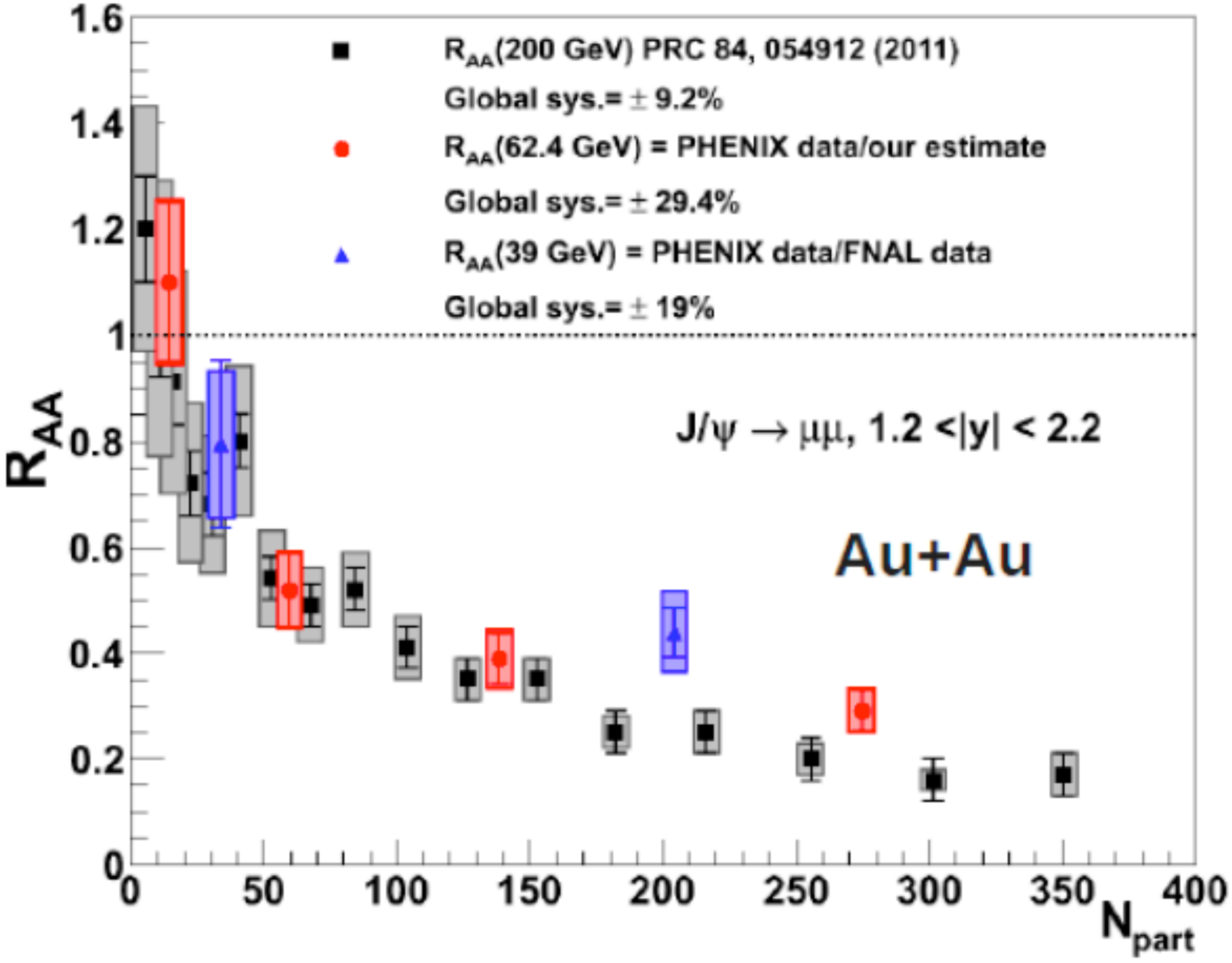
- Strickland, arXiv:1207.5327

– Difficulties to simultaneously describe Y(1S) and Y(2S) with the same η/S value

- Rapp et al., EPJ A48 (2012) 72

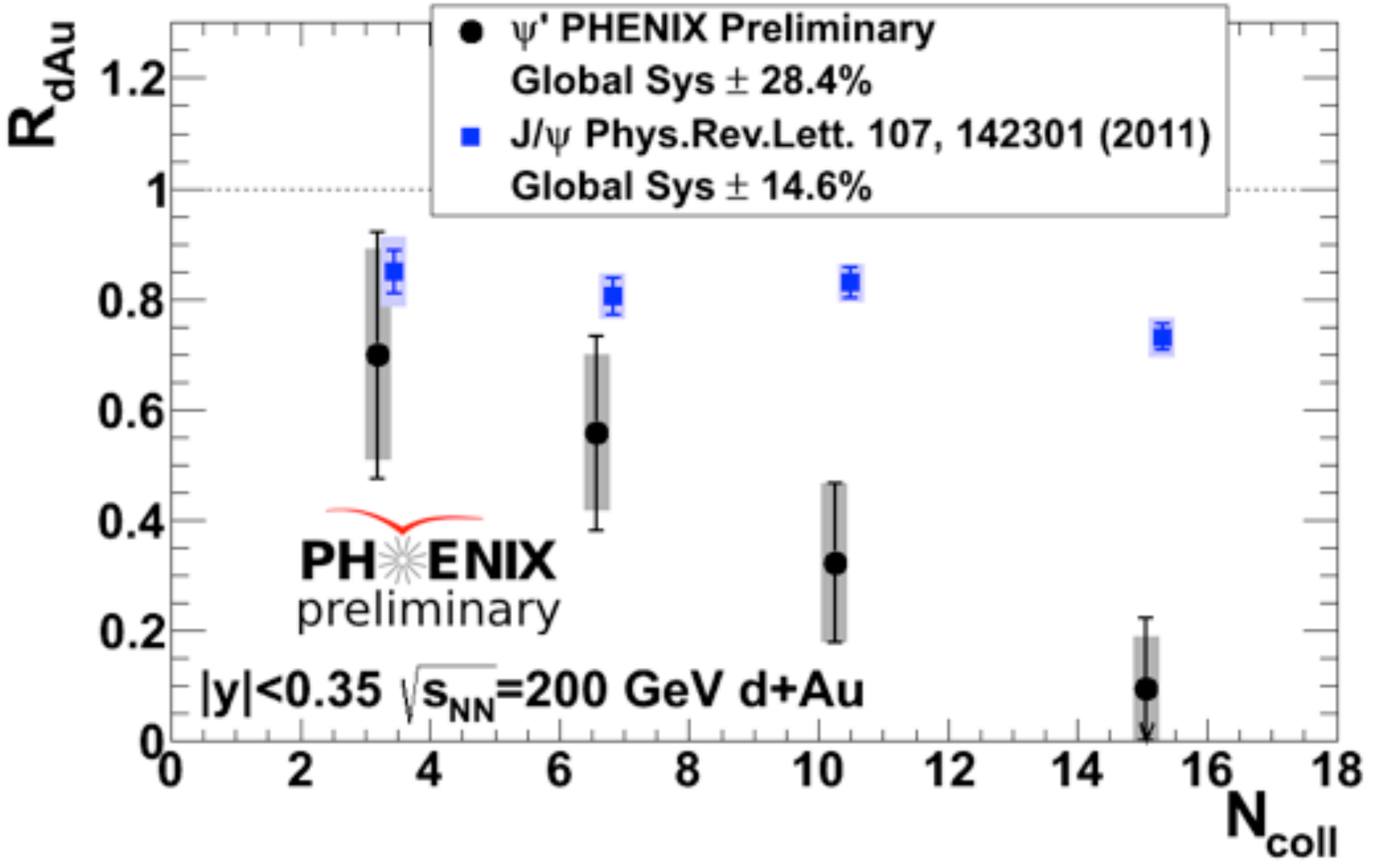
Regeneration and nuclear absorption could be significant also for bottomonia!

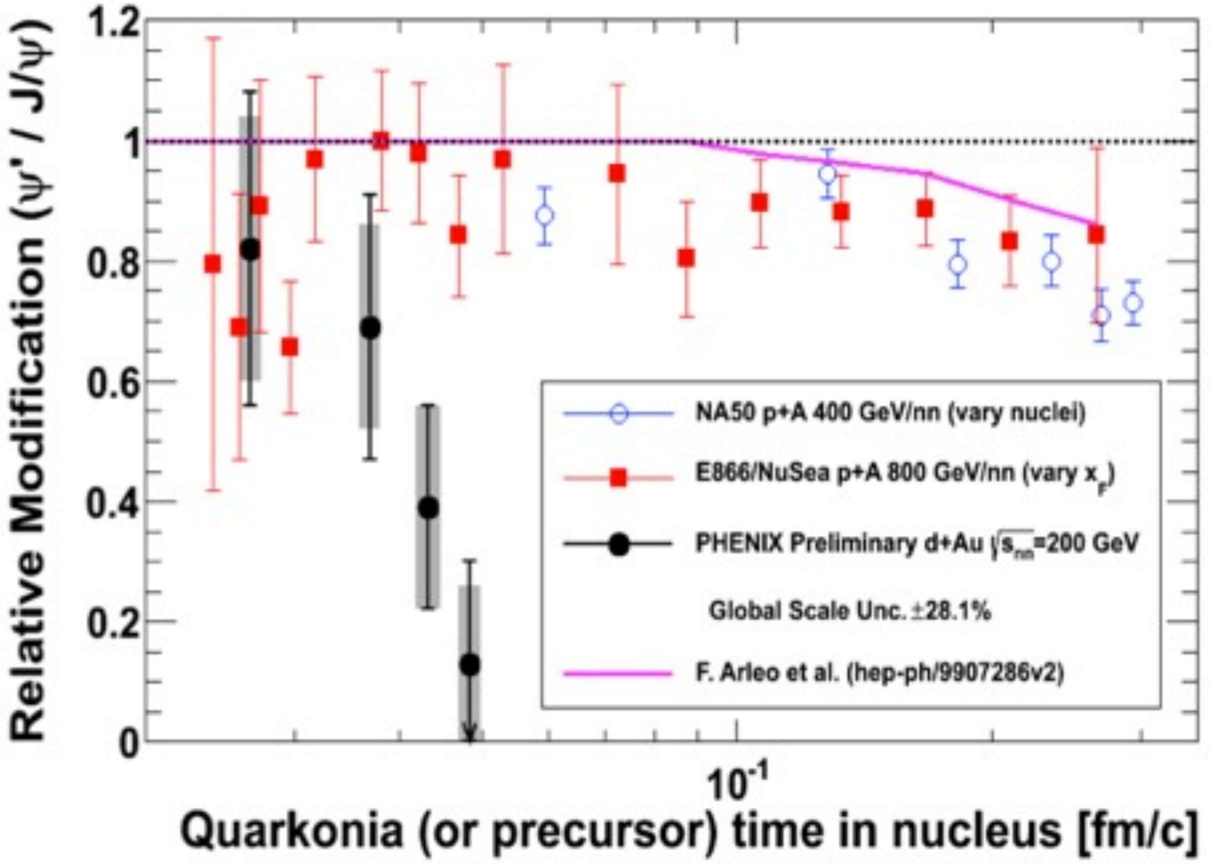
Energy scan at RHIC



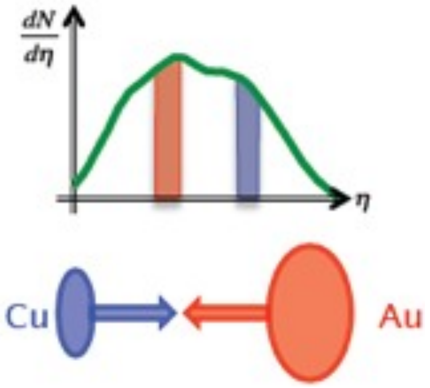
No dAu reference at 62.4 and 39 GeV

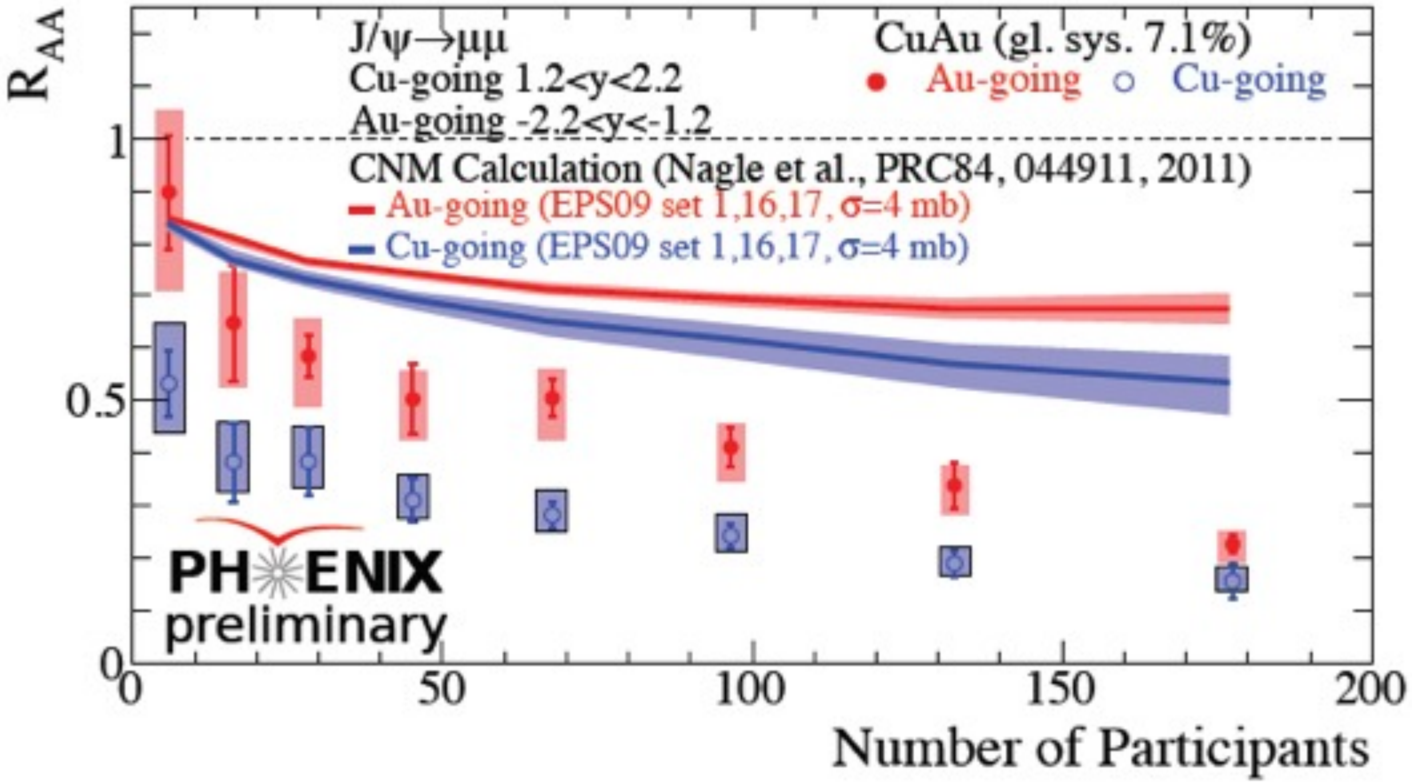
Ψ(2S) also puzzling in d-Au





Different systems at RHIC





In Cu+Au collisions:

- R_{AA}(Au-going) > R_{AA}(Cu-going),
- qualitatively described by CNM but not quantitatively
- Additional suppression suggests hot, dense medium effect