Charmonium production in heavy ion collisions.

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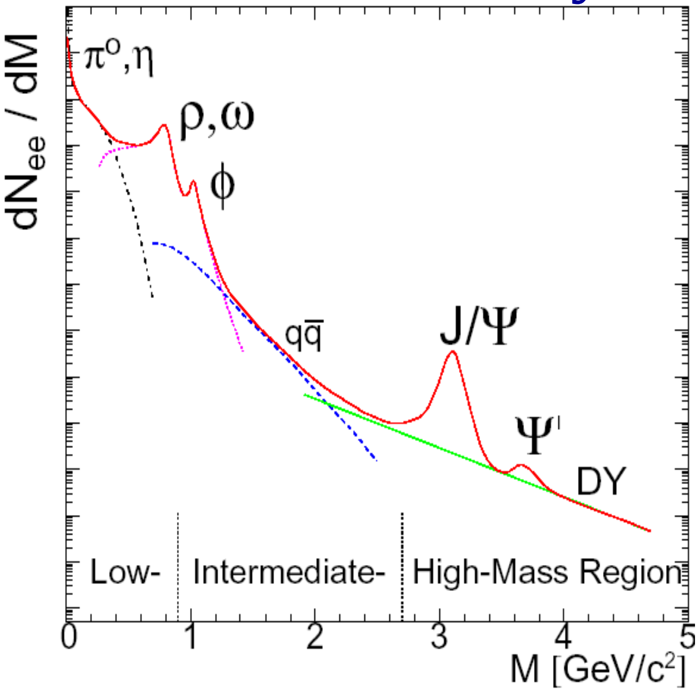
1. Physical motivaion.
2. Experimental situation.
3. Fixed target suggestion.
3. Summary.

Charmonium

- 1974 г.: discovery of J/ψ, 1986 г.: Matsui & Satz:



colour screening in deconfined matter
→ J/ψ suppression
→ possible signature of QGP formation

Experimental and theoretical investigations
→ situation is more complicated

cold nuclear matter (CNM)/initil states.

- **"normal" nuclear suppression**
- **(anti)shadowing**
- **saturation, color glass condensate**

suppression via comovers
feed down from χ_c, ψ'
sequential screening (first : χ_c, ψ', J/ψ only well above T_c)

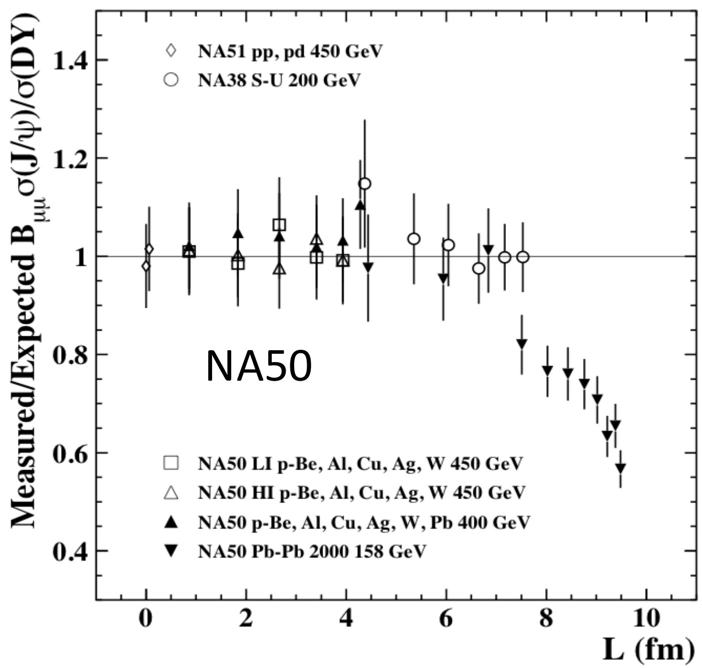
regeneration via statistical hadronization or charm coalescence

J/ψ production from *b*-hadron

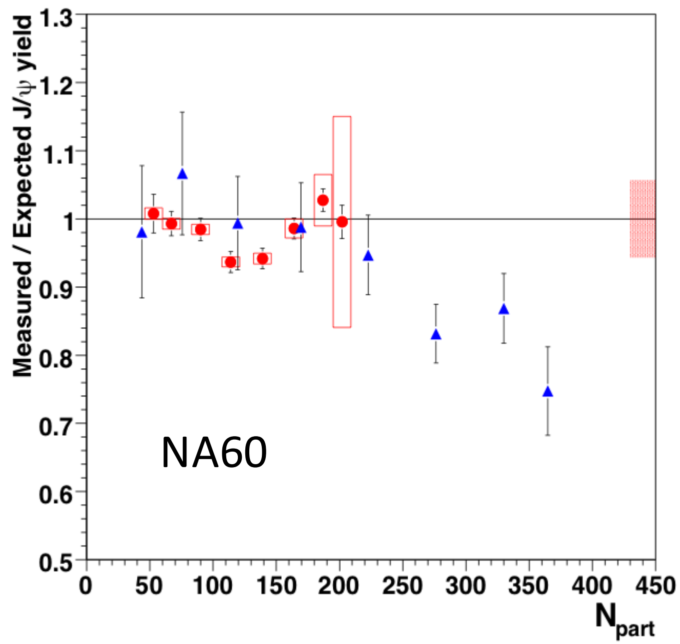
Important for "large" charm yield, i.e. RHIC and LHC

J/ψ suppression at SPS

NA50



NA60



Suppression (~40%);

ψ' suppression is measured

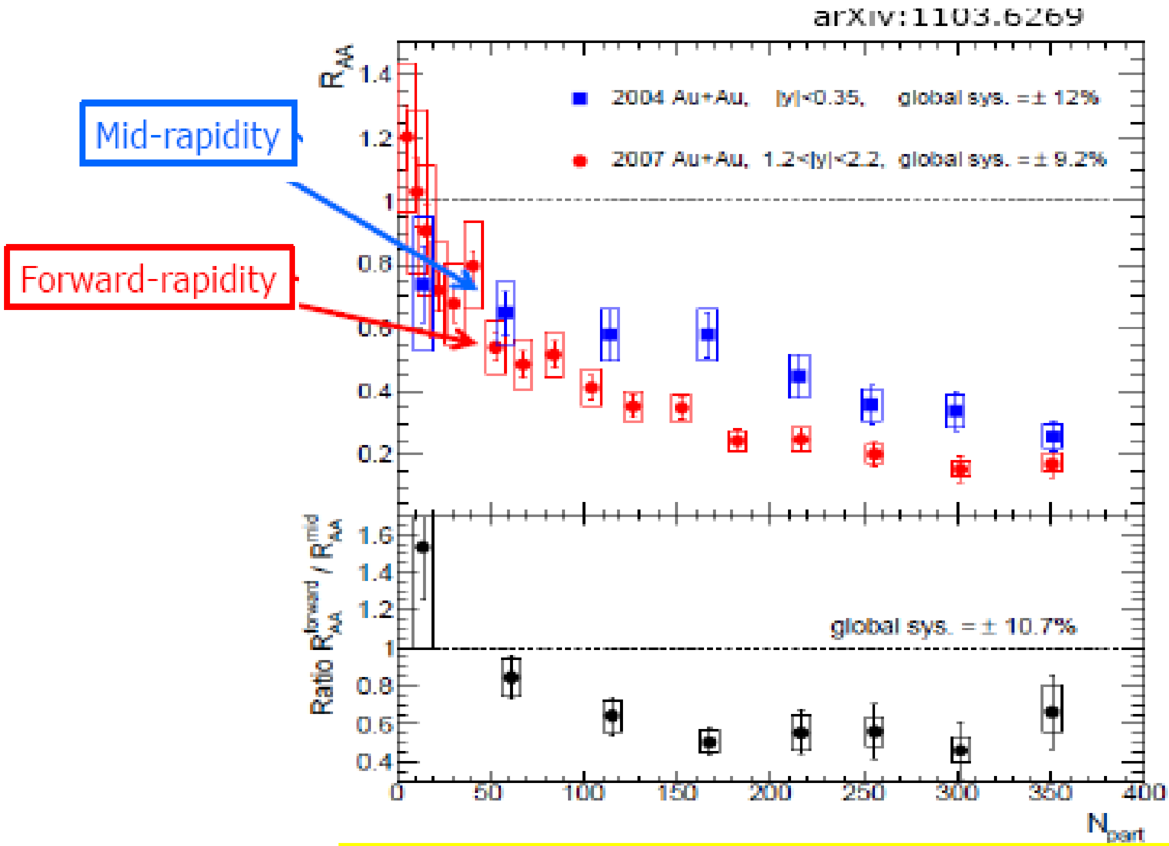
σ_{abs} **depends on energy ;**

Suppression (~20-30%);

$\sigma_{abs}^{J/\psi}$ (158 GeV) = 7.6 0.7 0.6 mb

$\sigma_{abs}^{J/\psi}$ (400 GeV) = 4.3 0.8 0.6 mb

J/ψ suppression at PHENIX, RHIC



Suppression (~40-80%);
Larger suppression at forward rapidity

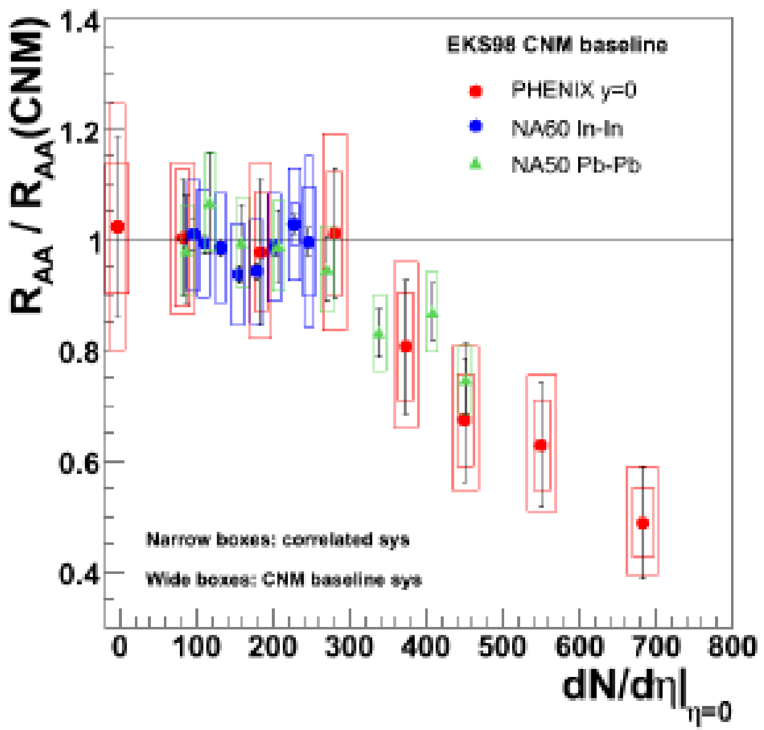
$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2\sigma^{NN} / dp_T d\eta}$$

N-N cross section

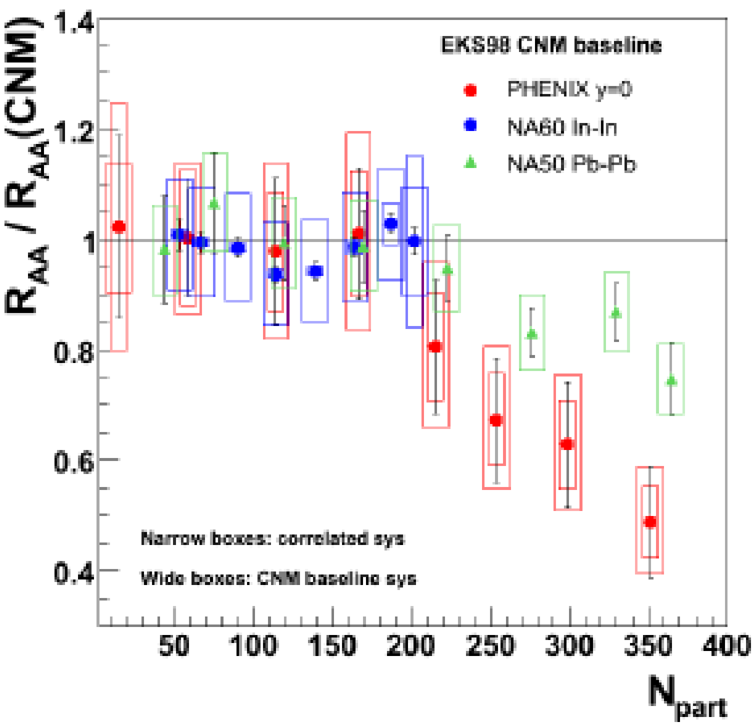
$<N_{binary}>/\sigma_{inel}^{p+p}$

Comparison of SPS and RHIC data at mid rapidity

R_{AA} as a function of multiplicity (~ε)



R_{AA} as a function of N_{part}

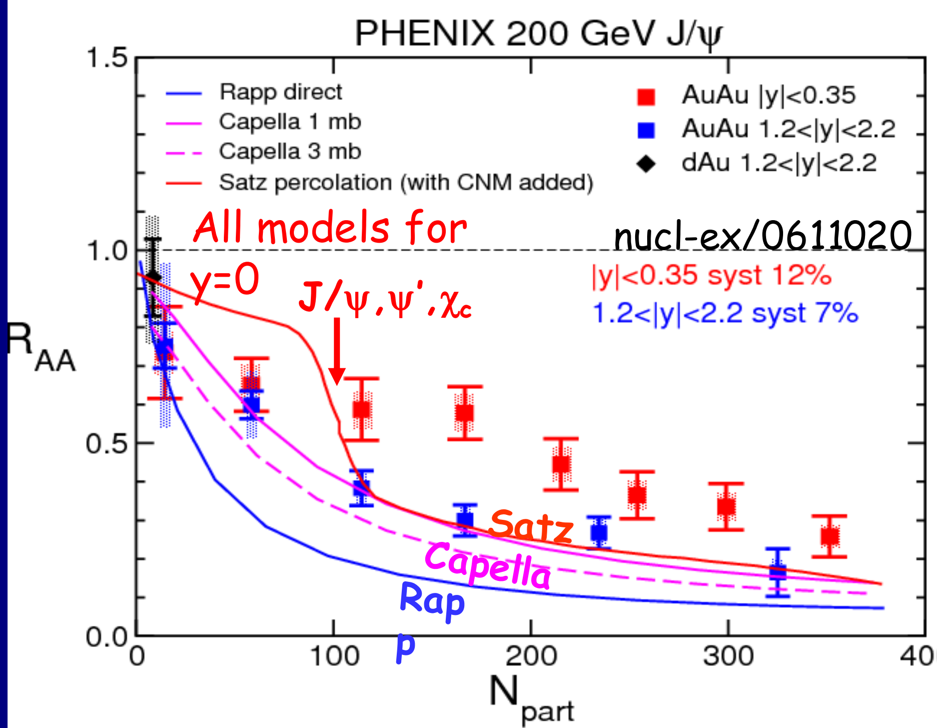


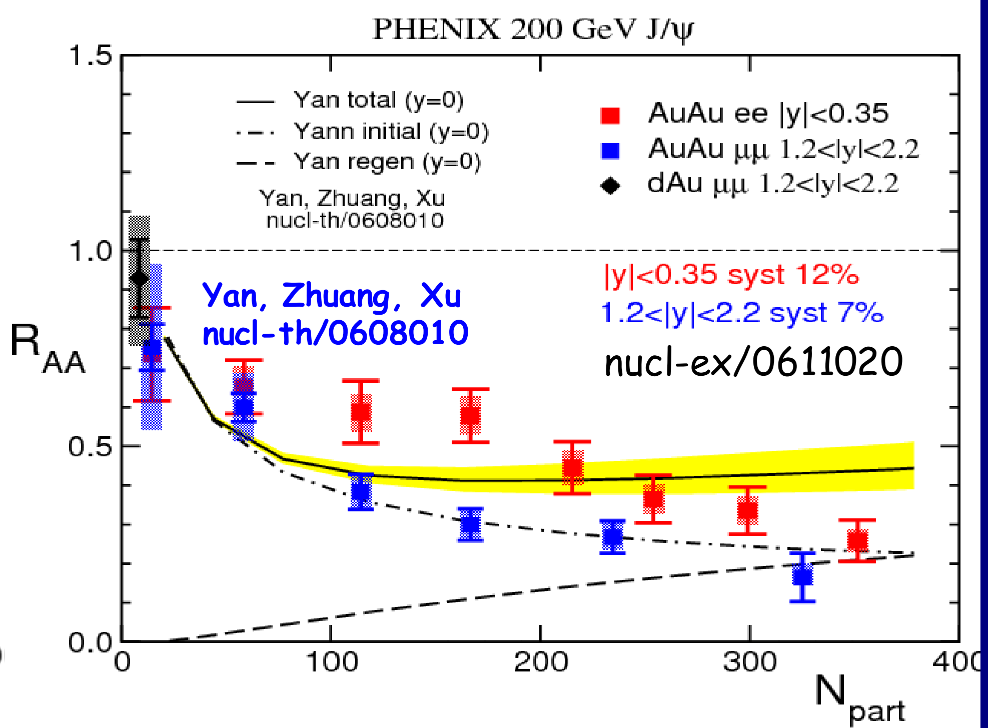
Which dependence to choose?

With last NA60 data (σ_{abs} depends on energy) suppression of charmonium production at PHENIX larger that at NA50

R_{AA} suppression vs N_{part} at RHIC

PHENIX Au-Au



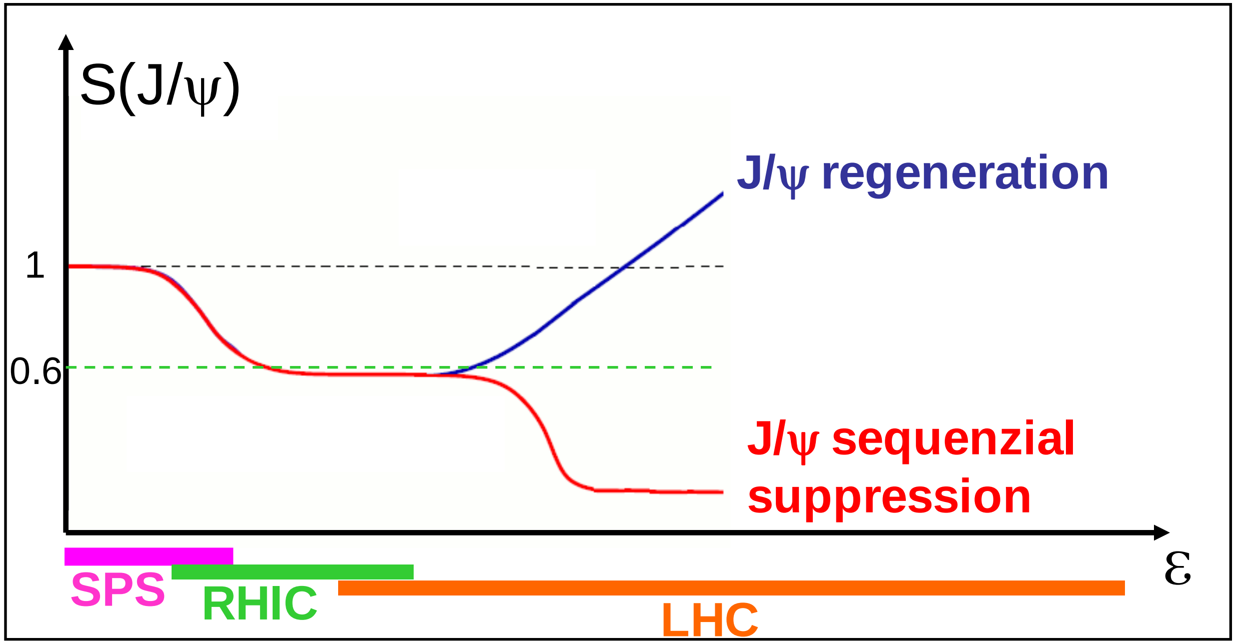


Theoretical models for Au-Au at y=0

Without regeneration — With regeneration

J/ψ production in heavy ions collisions

At LHC energy ?



✶ Contributions of sequential suppression and regeneration define the J/Ψ yield

Possible bottomonium production at LHC

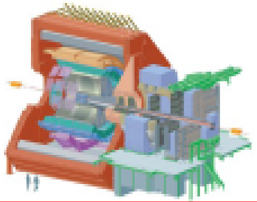
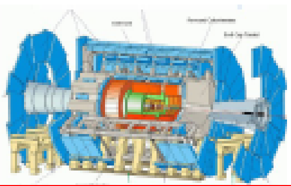
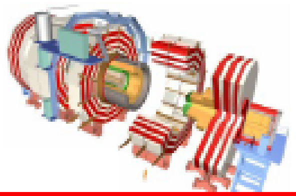
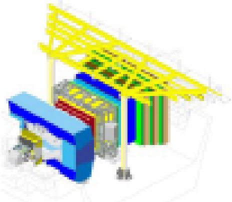
State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	$\geq$4.0	1.76	1.60	1.19	1.17

✶ Υ(1S) melts only at LHC

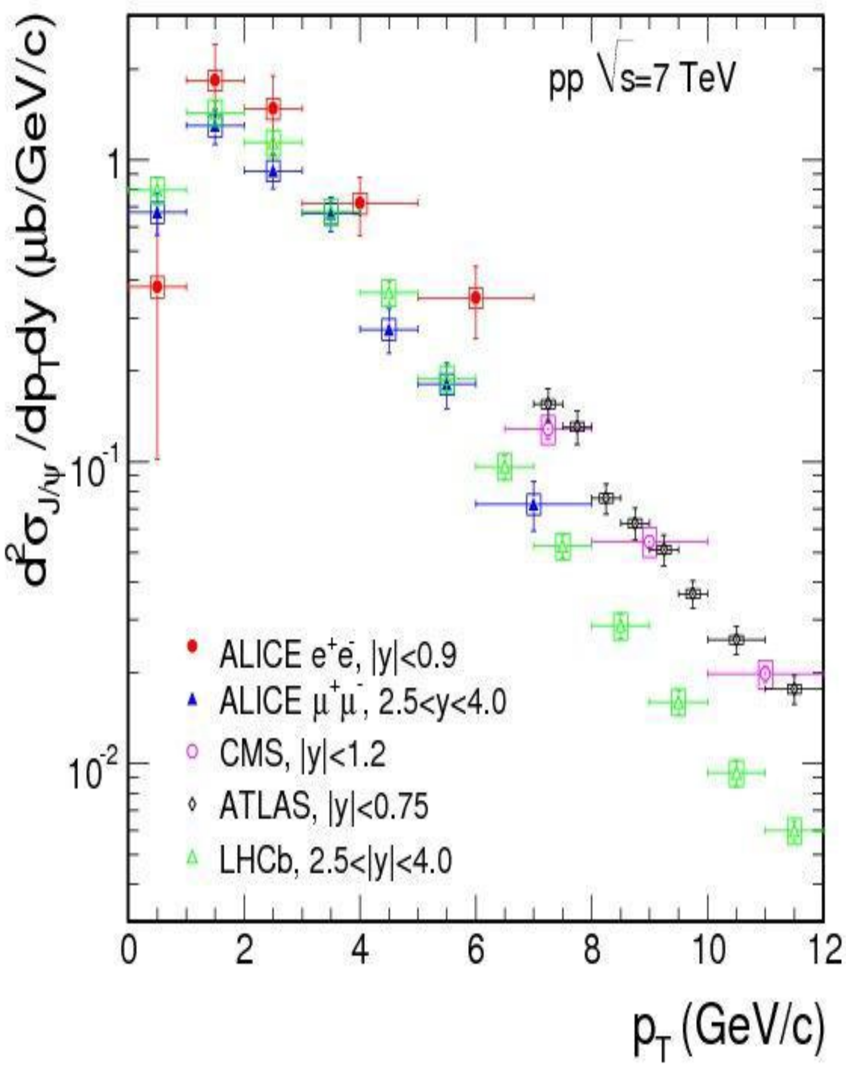
✶ Υ(2S) behaves as J/ψ ($T^D_{\Upsilon(2S)} \sim T^D_{J/\psi}$) and expected that regeneration of Υ(2S) would be small at LHC

→ Υ(2S) measurements are very important for comparison regeneration and suppression of J/ψ

Charmonium production at LHC: ALICE, ATLAS, CMS and LHCb .

ALICE	$J/\psi \rightarrow \mu^+\mu^-$ $J/\psi \rightarrow e^+e^-$ (up tp now only inclusive J/ψ results)	$2.5<y<4$ $\|y\|<0.9$	p_T coverage down to $p_T \sim 0$	
ATLAS	$J/\psi \rightarrow \mu^+\mu^-$ (separation between B and prompt J/ψ)	$\|y\|<2.4$	$p_{T\mu}>3$GeV, $\|\eta_\mu\|<2.5$ $\rightarrow$ p_T $J/\psi>6.5$GeV/c	
CMS	$J/\psi \rightarrow \mu^+\mu^-$ (separation between B and prompt J/ψ)	$\|y\|<2.4$	p_T coverage depending on the y region	
LHCb	$J/\psi \rightarrow \mu^+\mu^-$ (separation between B and prompt J/ψ) (no heavy ion physics program)	$2.5<y<4$	p_T coverage down to $p_T \sim 0$	

Charmonium production in *pp*- collisions at LHC: ALICE, CMS, ATLAS and LHCb .



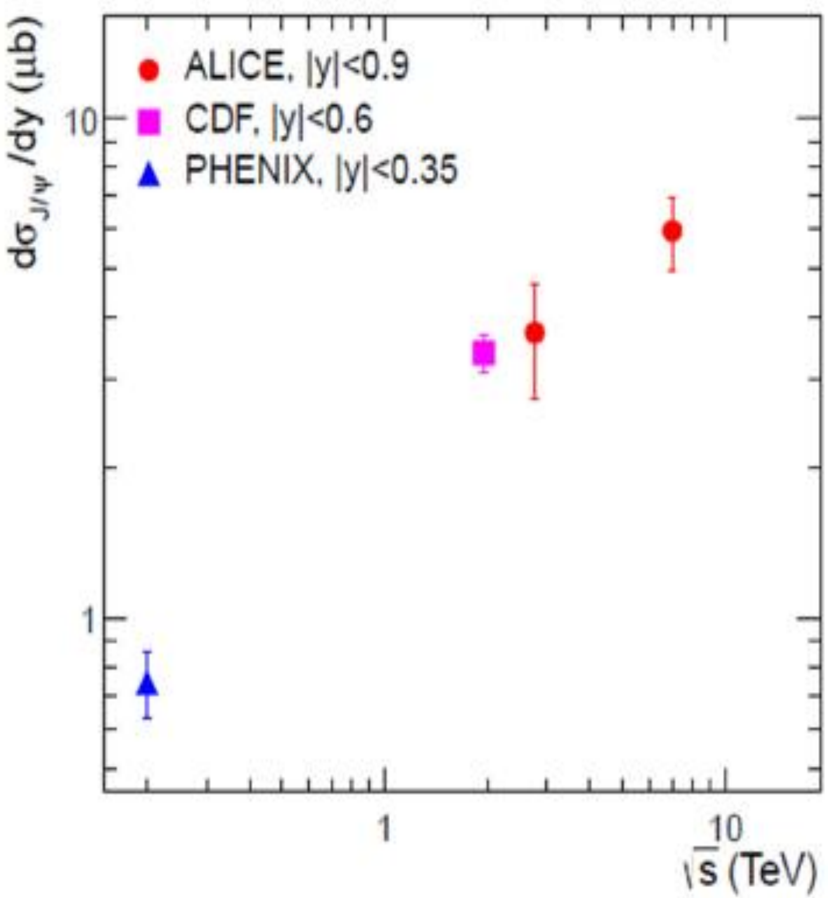
Good agreement of experimental data of ALICE, CMS and ATLAS for mid-rapidity

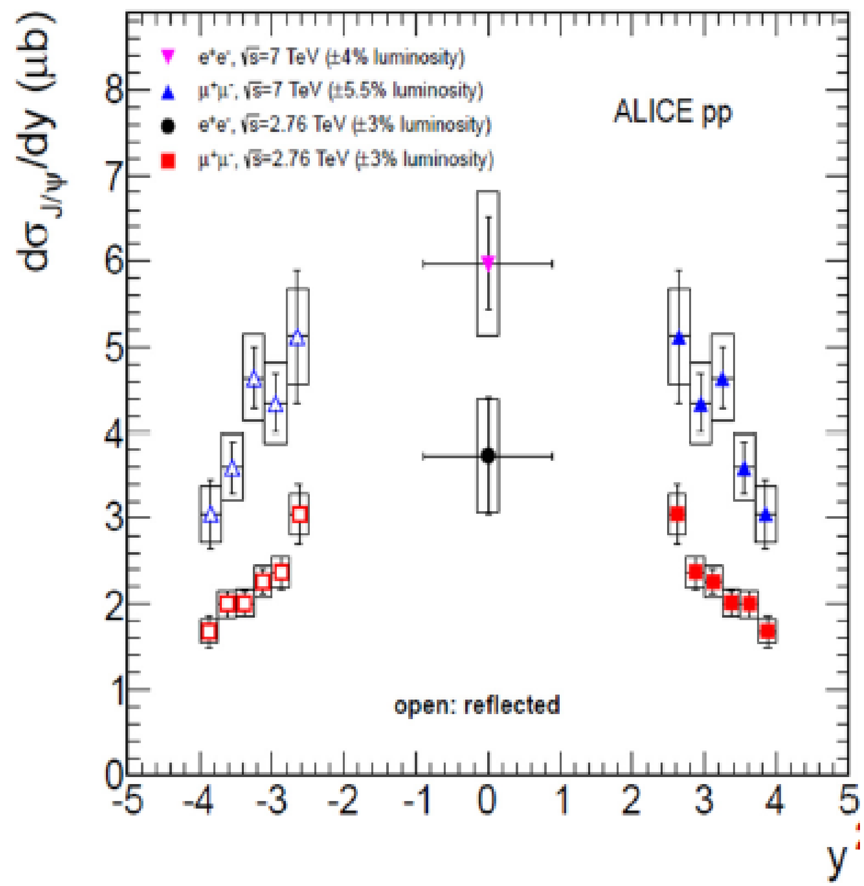
and ALICE and LHCb for forward-rapidity

Dependence on rapidity

PL B704 (2011) 442

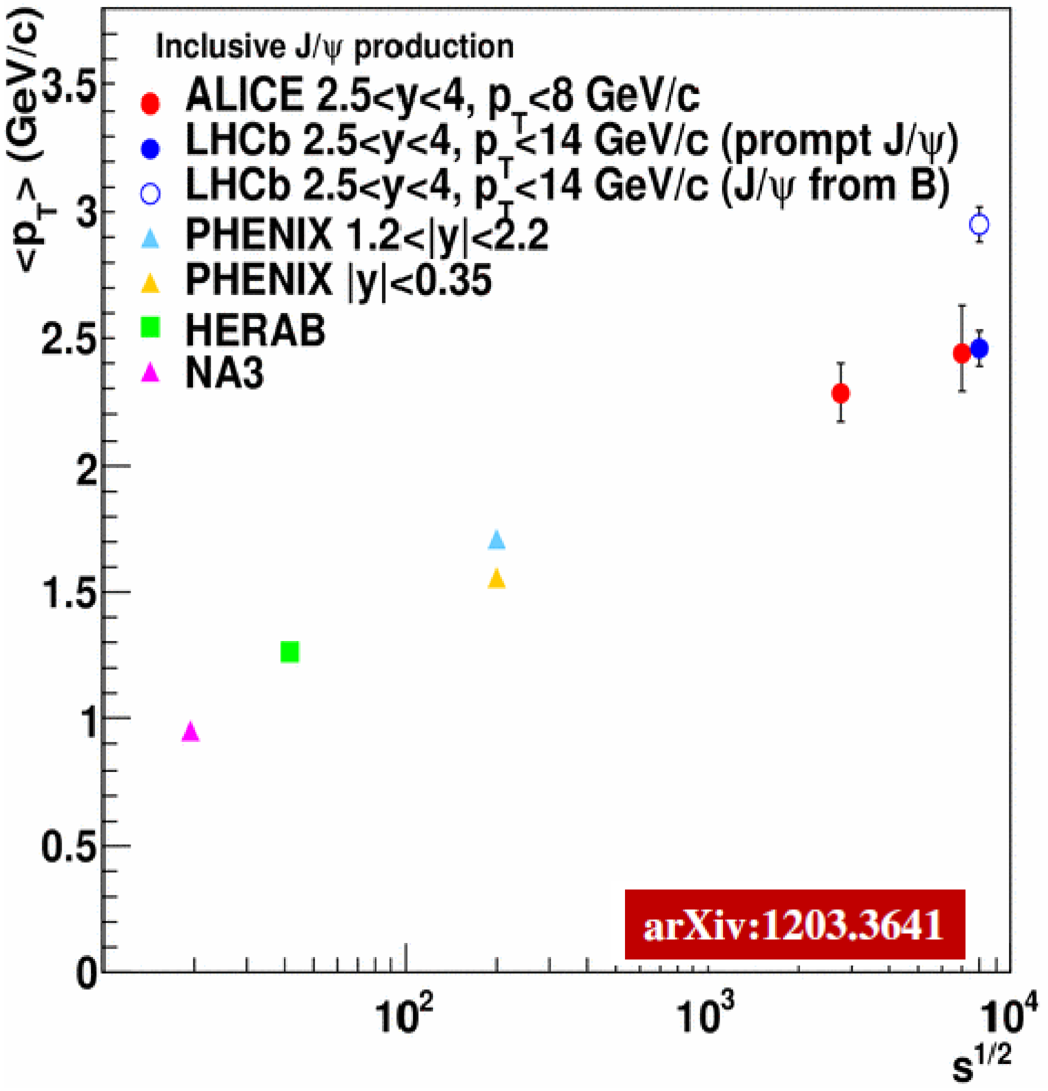
J/ψ production in *pp*-collisions and dependence on energy and rapidity



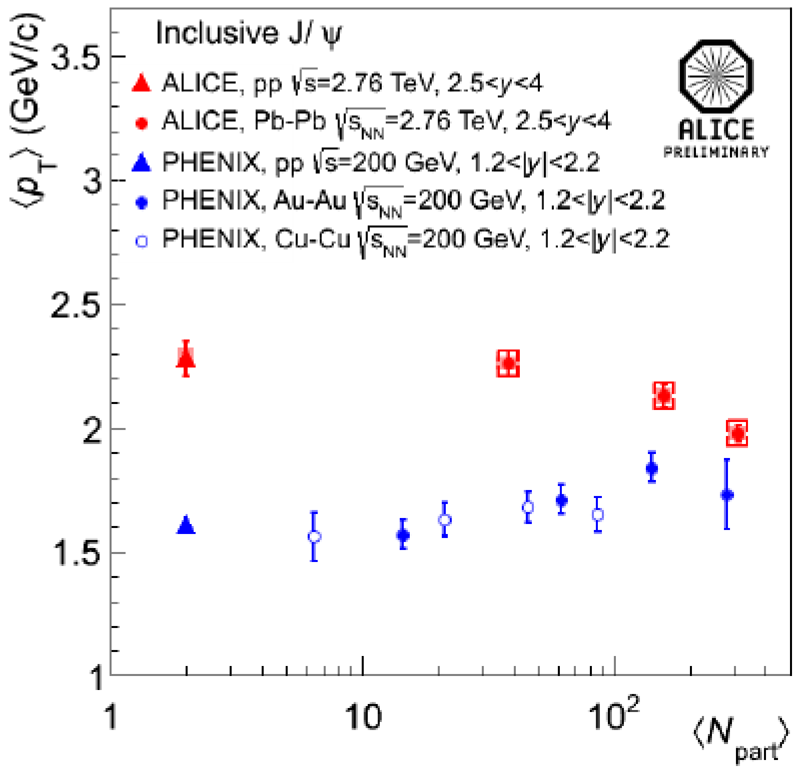


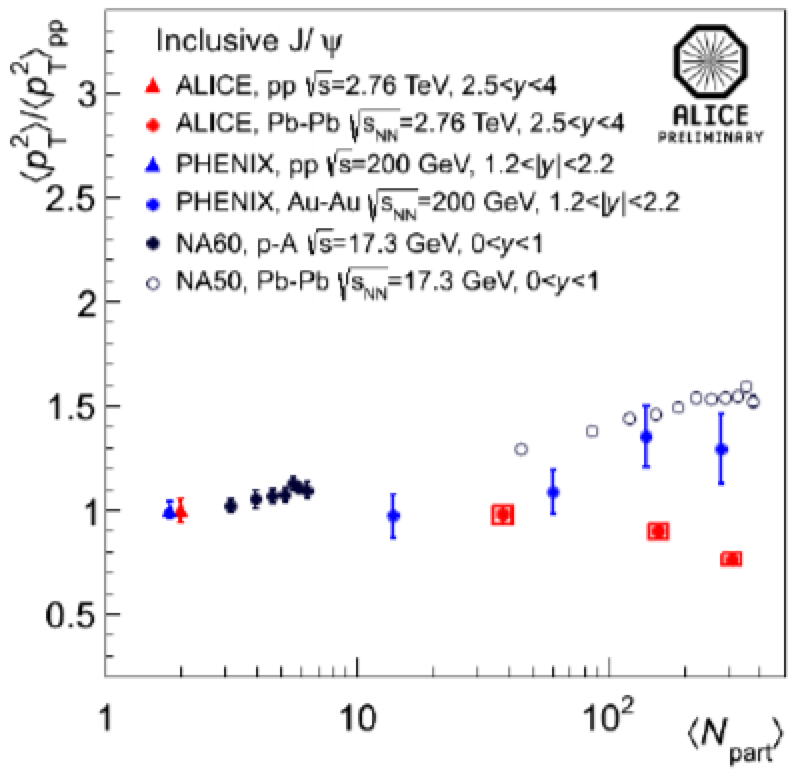
arXiv:1203.3641

Mean transverse momentum of J/ψ vs energy



ALICE inclusive J/ψ mean $<p_T>$ and $<p_T^2>$ in comparison with SPS and RHIC data.

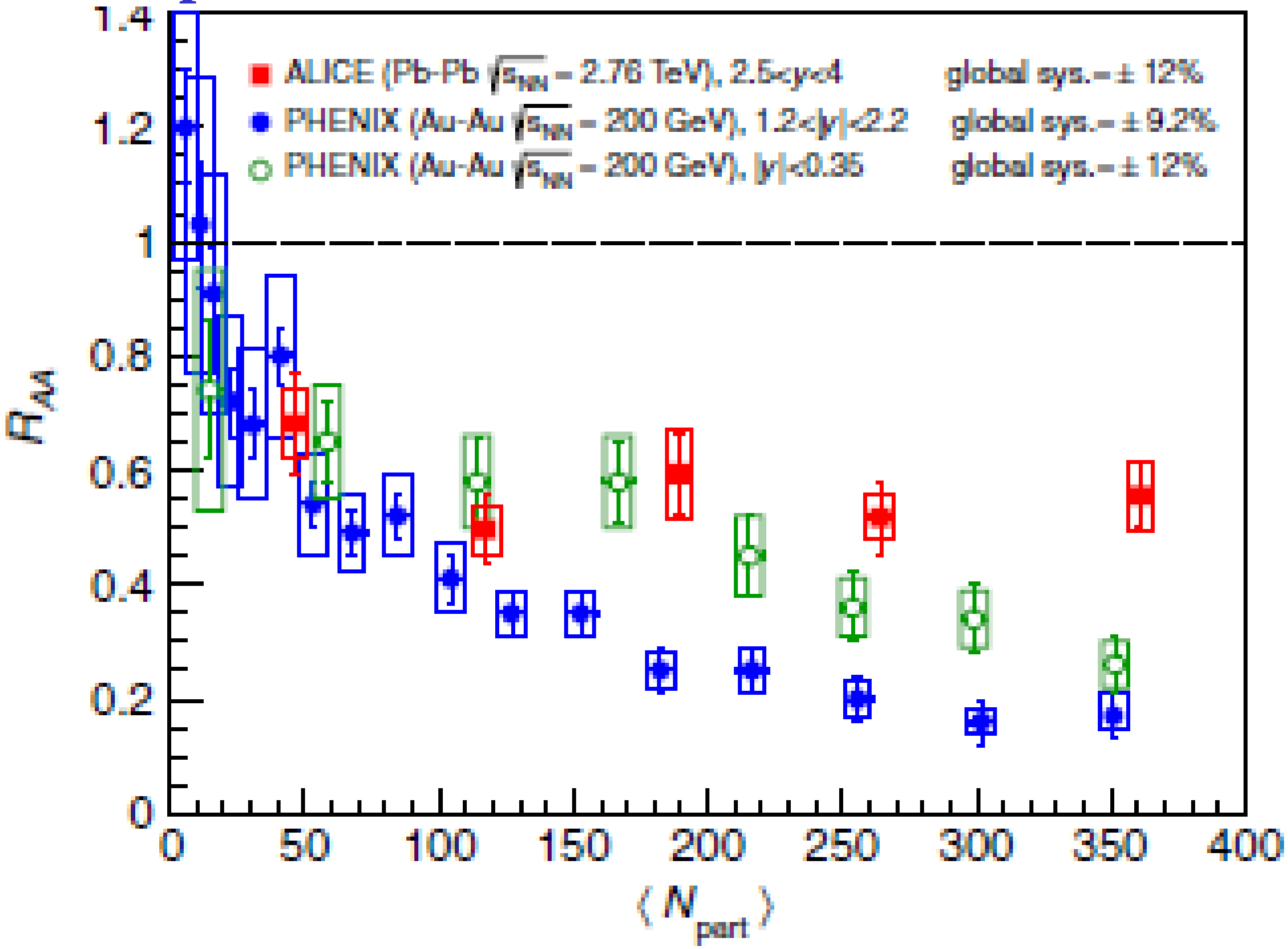




Behavior at ALICE is different from obtained at lower energies at SPS and RHIC where increase of the mean transverse momentum and the mean square transverse momentum was obtained.

E.Scomparin, QM12

R_{AA} vs number of participant.
Comparison of ALICE and PHENIX data.

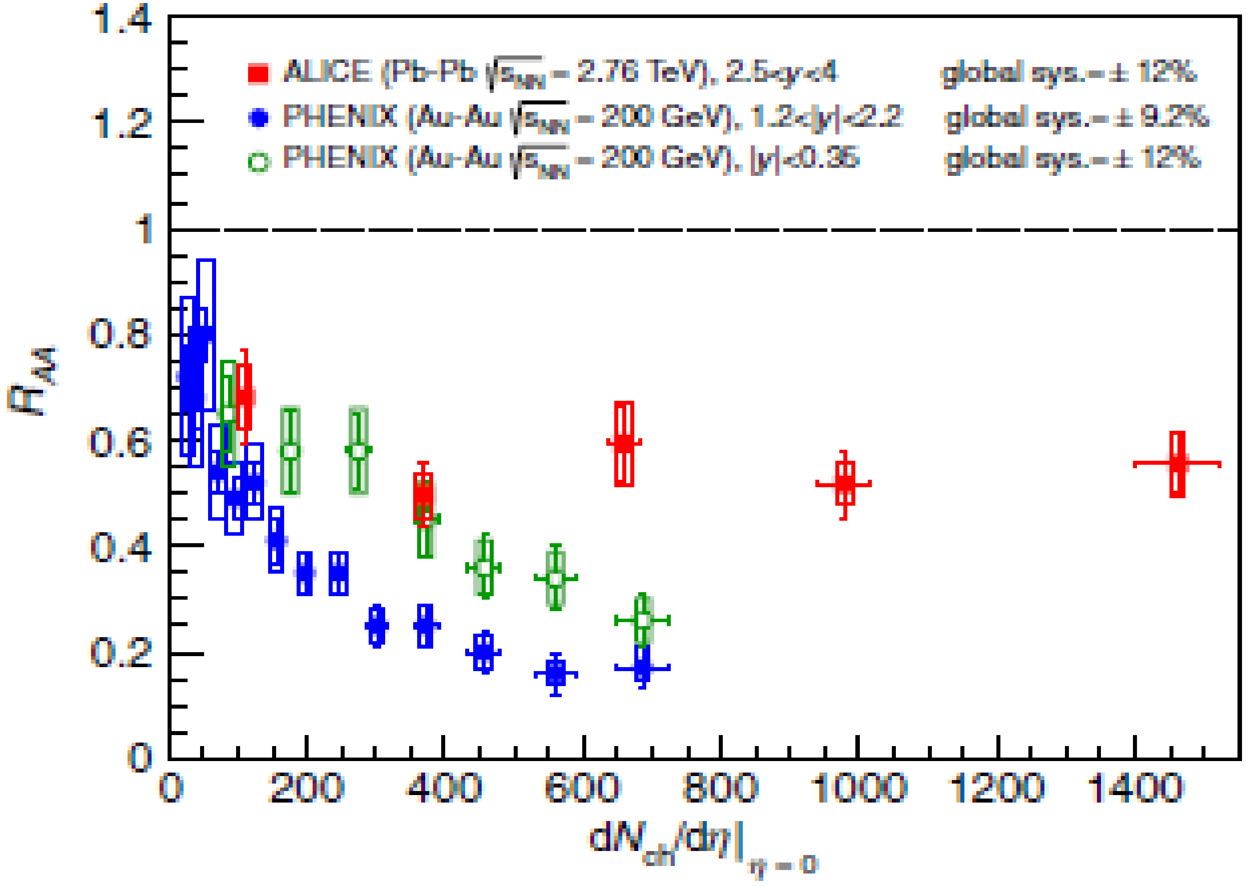


Suppression for forward rapidity at ALICE lower than at PHENIX.

No significant centrality dependence.

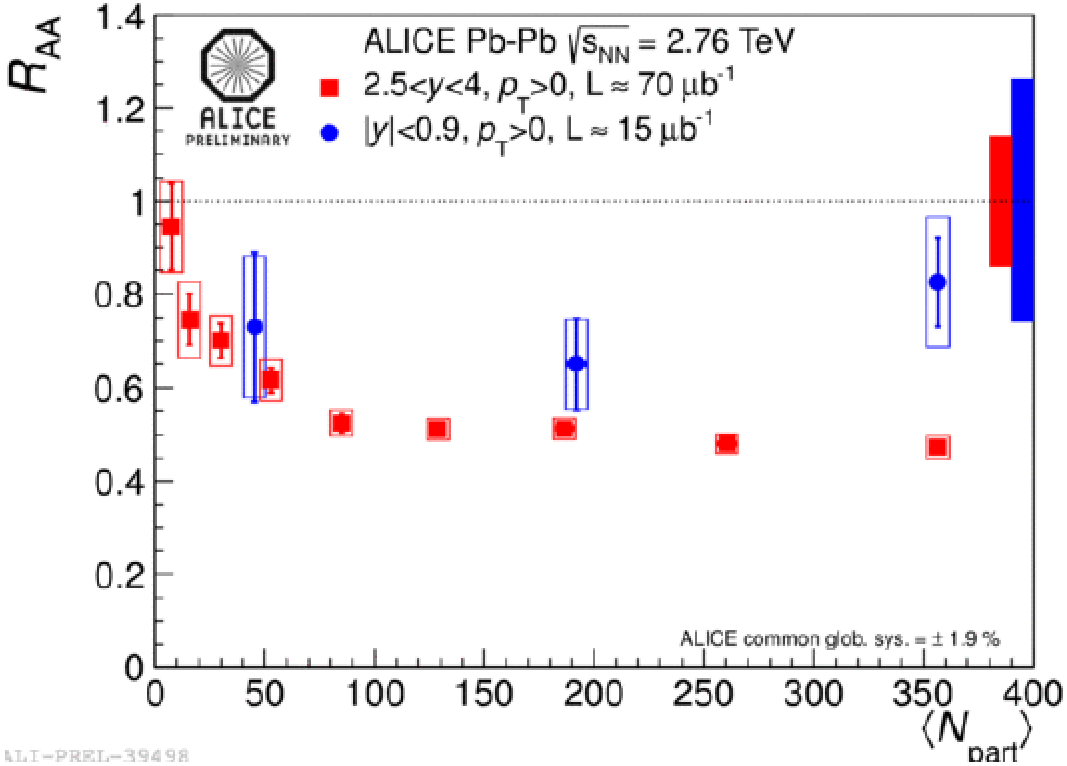
Phys.Rev.Lett.109,072301(2012)

Comparison R_{AA} at ALICE and PHENIX as a function of multiplicity.



Phys.Rev.Lett.109,072301(2012)

ALICE inclusive R_{AA} at forward and central rapidities.

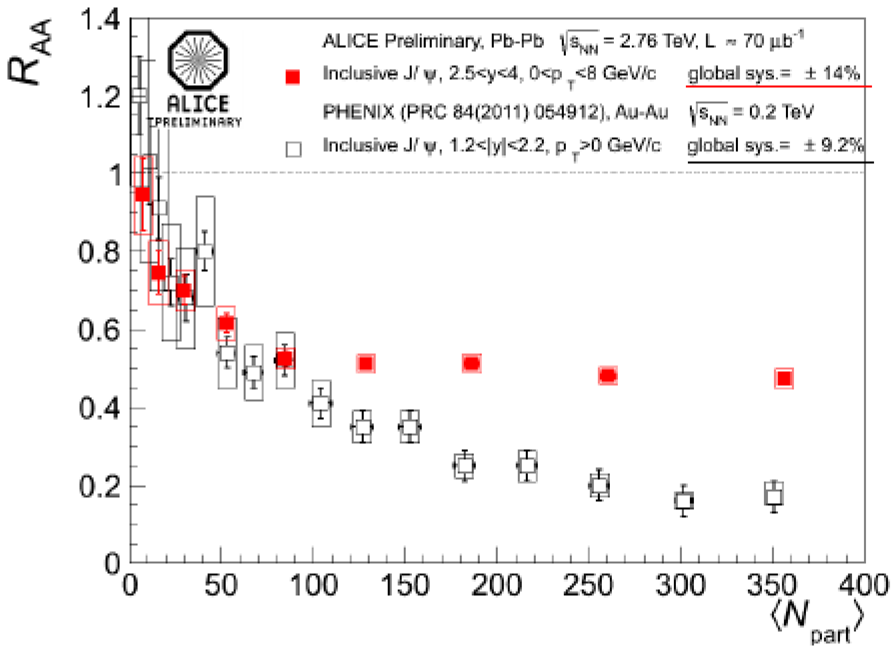


Large uncertainty on the mid-rapidity *pp*- reference.
Different behaivior?

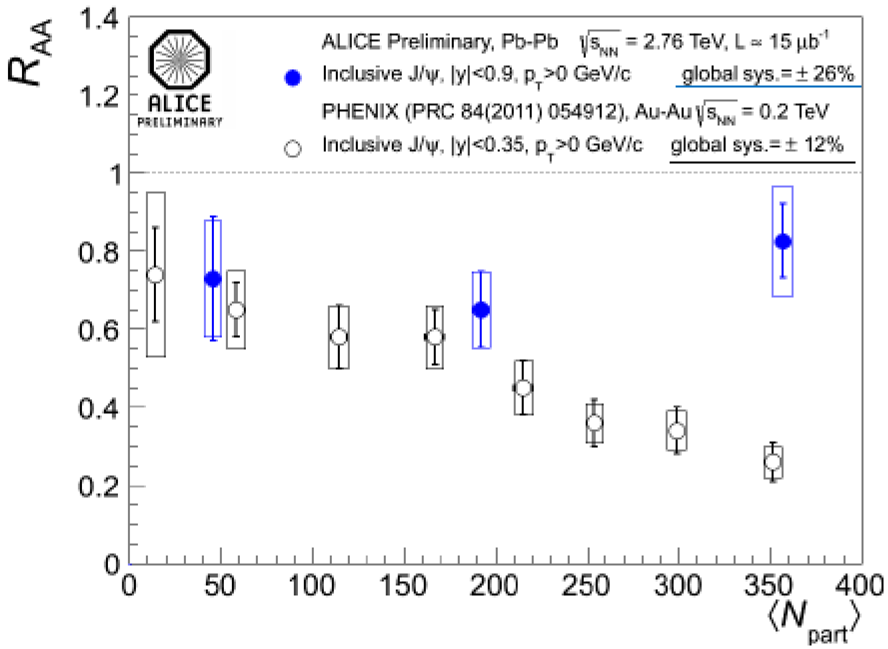
E.Scomparin, QM12

R_{AA} vs number of participant for different rapidity regions. Comparison of ALICE and PHENIX data.

Forward rapidity



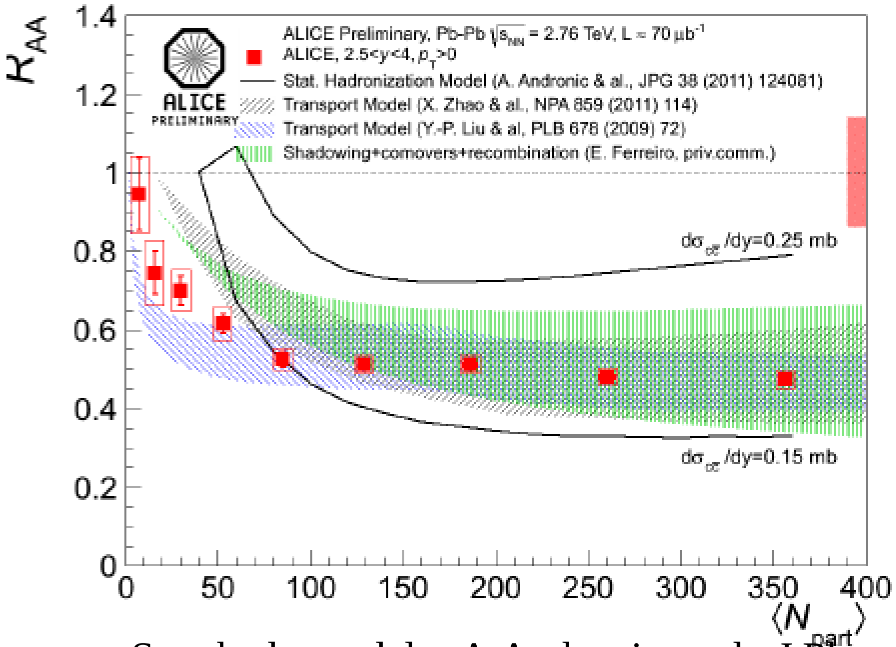
Mid- rapidity

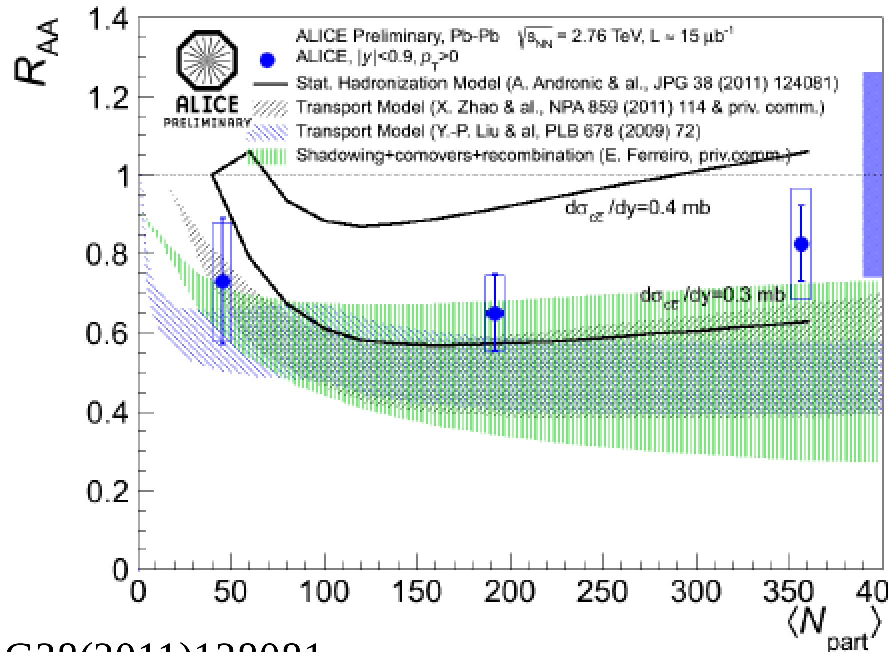


Smaller suppression with respect to RHIC, compatible with J/ψ regeneration model

E.Scomparin, QM12

Comparison with the statistical hadronization model and transport models.



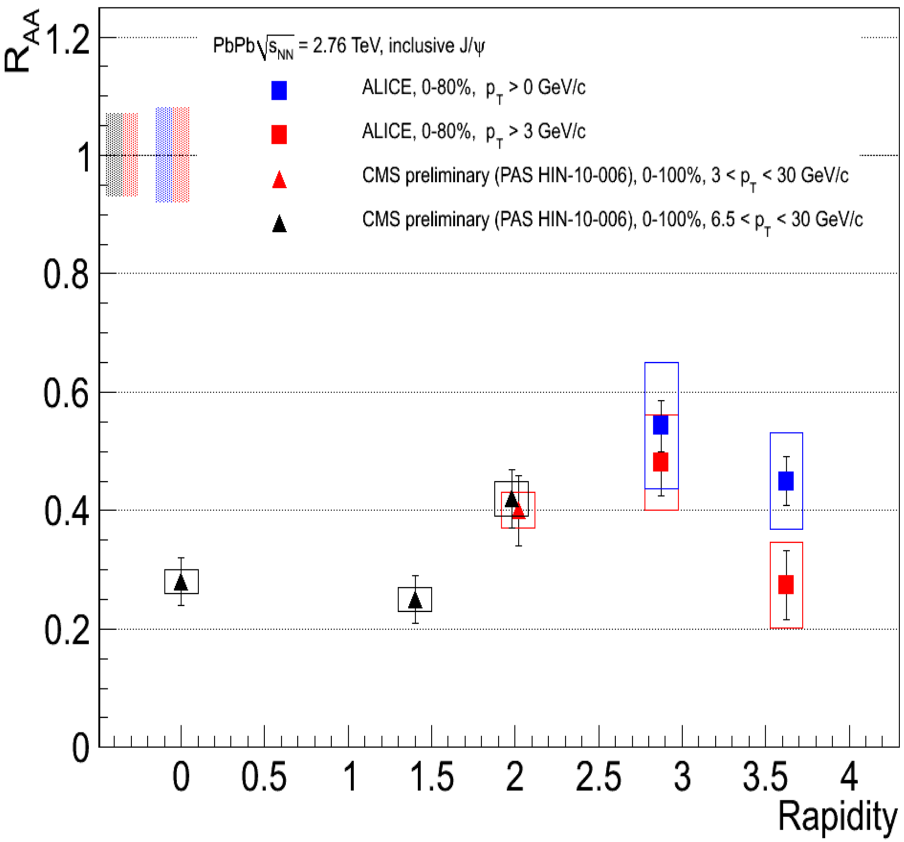


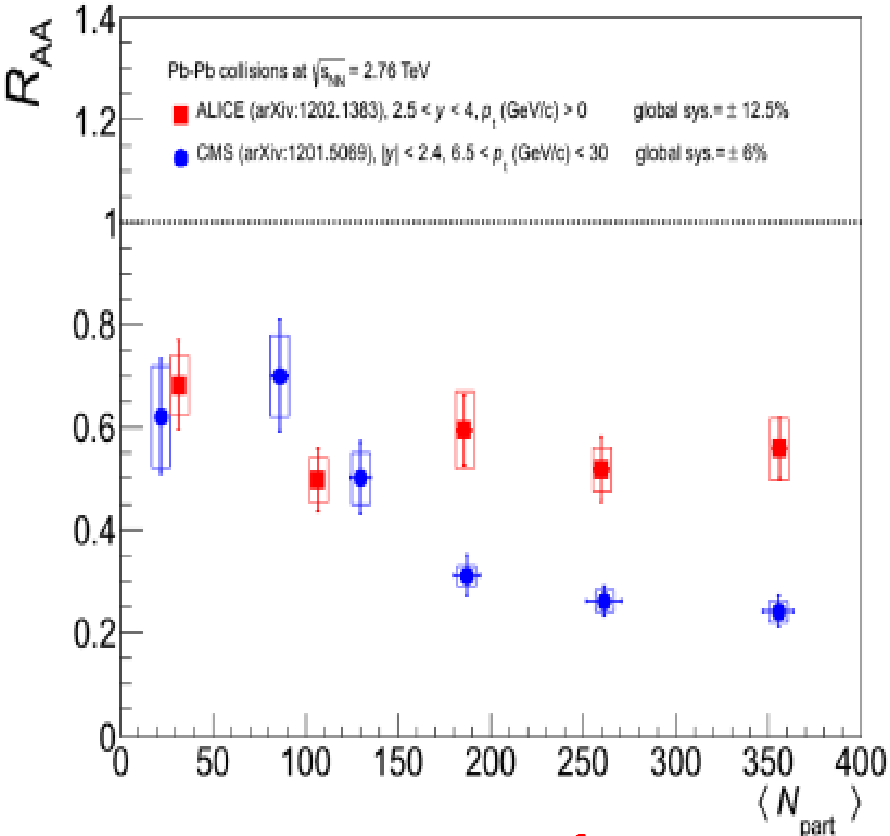
Stat. hadr. model – A.Andronic et al., J.Phys.G38(2011)128081
Transport models- X.Zhao and R.Rapp, N.Phys.A859(2011)114,
Y.Liu et al.,P.Lett.B678(2009)72
Shadowing+comovers+recomb.- Capella et al., E.Phys.G C58(2008)437 and
E.Ferreiro,priv.comm.

Models with all J/ψ produced at hadronization or models including large fraction (>50% in central collisions) of J/ψ produced from recombinations can describe results.

E.Scomparin, QM12

R_{AA} vs rapidity and comparison of ALICE and CMS data





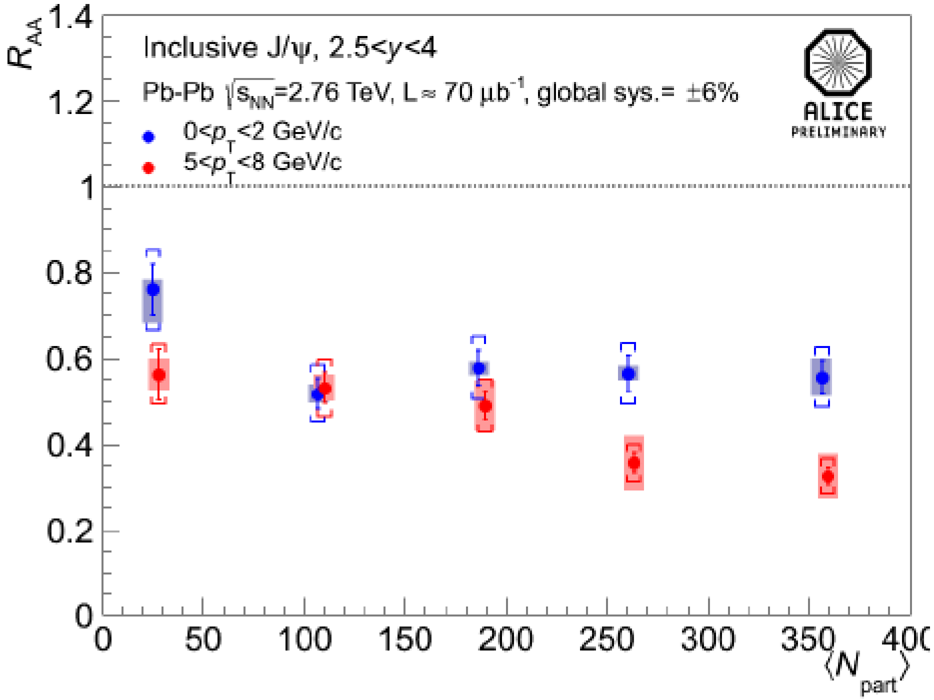
At large rapidity suppression is higher for p_T >3 GeV/c

Suppression at ALICE for 2.5<y<4 lower, than at CMS for y <2.4 and p_T >6.5 GeV/c.

Cold nuclear effects in p-Pb collisions need to be evaluated

arXiv:1202.1383

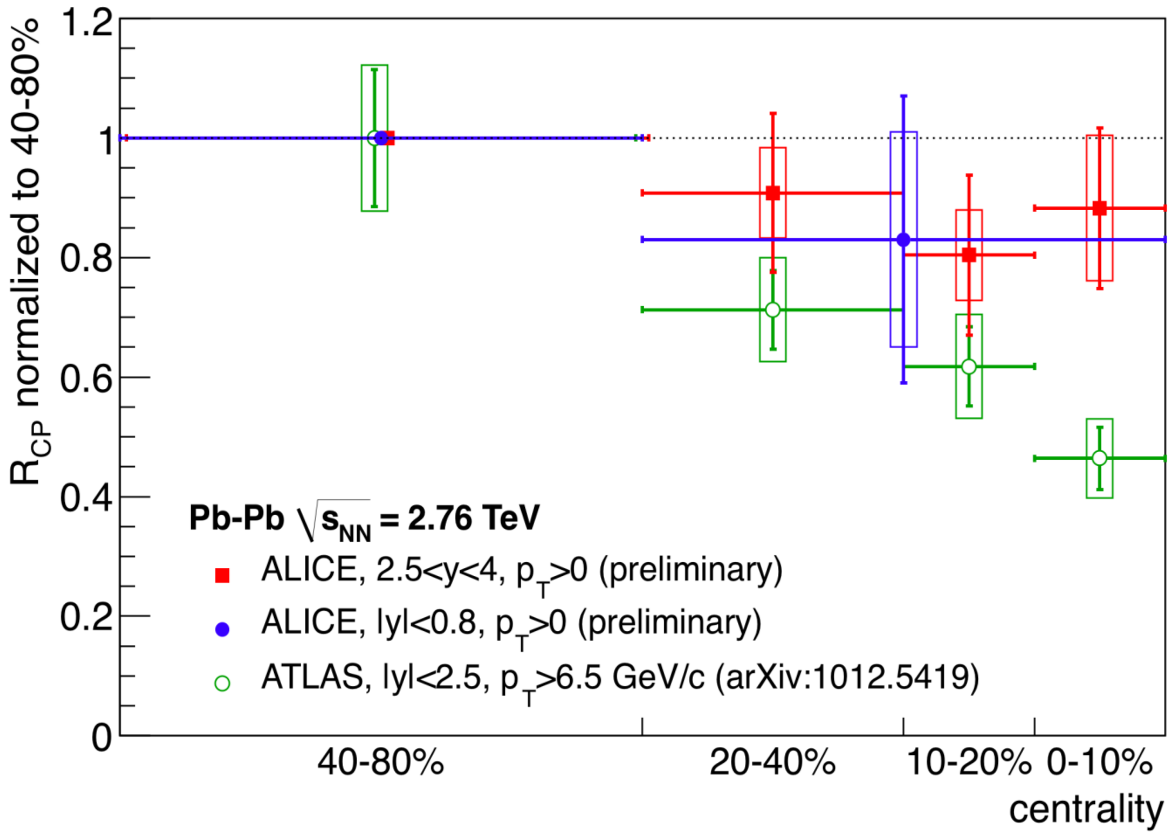
ALICE inclusive R_{AA} at low and high transverse momentum.



Suppression is higher for higher transverse momentum.

E.Scomparin, QM12

R_{CP} as a function of centrality. Comparison ALICE and ATLAS data.

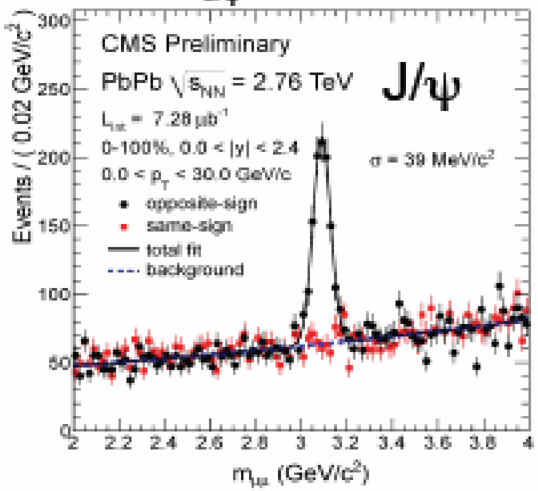


Suppression at ALICE for 2.5<y<4 lower, than at ATLAS for y <2.5 and p_T >6.5 GeV/c.

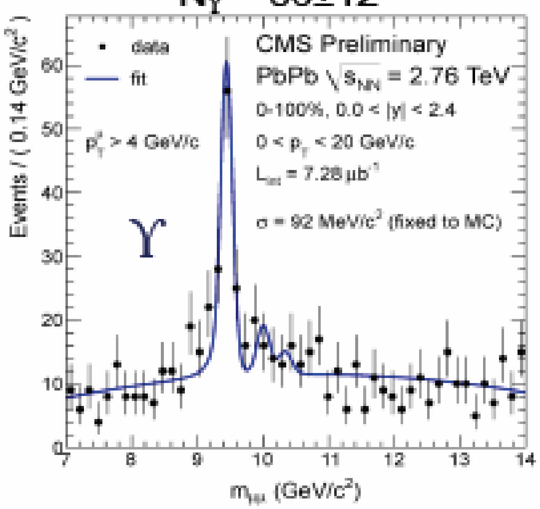
R_{AA} data at CMS .

Suppression of Quarkonia (J/ψ and ϒ)

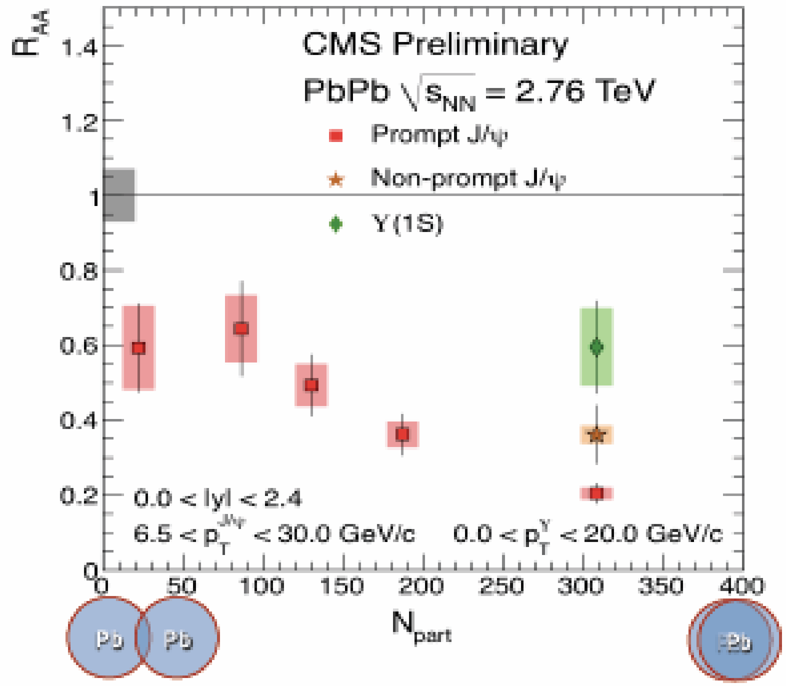
$N_{J/\psi}$ =734±54



N_{Υ} = 86±12



- Muon acceptance: $|\eta|<2.4$, $p_{T,\mu}>2\text{-}4$ GeV/c
- Mass resolution ~1%, comparable to pp
- Displaced vertices to separate prompt J/ψ and B-decays



- High p_T J/ψ is strongly suppressed
- Inclusive ϒ(1S) is suppressed

Summary

2010 -2011.

At LHC in *p-p* and Pb-Pb collisions:

- **measured suppression of charmonium and bottomonium states production.**
- **the importance of regeneration process for charmonium production was shown, and feed-down contribution from B ~ 10%.**

2012 .

Measuring of *p-p* collisions is going.

Plan to measure *p*-Pb collisions.

Our suggestion to measure charmonium production at LHC with fixed target for lower energy with high statistic to clarify the mechanism of production.

A.B.Kurepin, N.S.Topilskaya, M.B.Golubeva

Charmonium production in fixed-target experiments
with SPS and LHC beams at CERN.

Phys.Atom.Nucl.74:446-452, 2011,
Yad.Fiz.74:467-473, 2011.

Fixed-target data (SPS, FNAL, HERA)

AA collisions
SU, PbPb, InIn

SPS: NA38, NA50, NA60
$\sqrt{s}$(GeV) 19.4 17.3

pA collisions

HERA-B, E866, NA50/51, NA38/3, NA60
$\sqrt{s}$(GeV) 41.6 38.8 29.1/27.4 19.4 27.4/17.3

Colliders (RHIC,LHC)

AA collisions

RHIC CuCu, AuAu $\sqrt{s}$ =130 GeV, 200 GeV
LHC PbPb $\sqrt{s}$ = 2.76 TeV (max 5.5 TeV)

pA collisions

RHIC pp, dAu $\sqrt{s}$ =130 GeV, 200 GeV
LHC pp $\sqrt{s}$ = 7 (8) TeV (max 14TeV)

Fixed-target (LHC) – new opportunity – energy between SPS and RHIC

AA collisions

Pb-Pb 2750 GeV/nucleon, $\sqrt{s}$ = 71.8 GeV

pA collisions

p-A 7000 GeV , $\sqrt{s}$ = 114.6 GeV
(5000 GeV, $\sqrt{s}$ = 96.9 GeV)

No theoretical model that could reproduce all data.

Fixed target experiment at LHC for charmonium production at the energy range between SPS and RHIC in p-A and A-A collisions with planning proton beam at T=7 TeV ($\sqrt{s}$ = 114.6 GeV) and Pb beam at 2.75 TeV ($\sqrt{s}$ = 71.8 GeV) is possibility to clarify the mechanism of charmonium production, to separate two possibilities:

i): hard production and suppression in QGP and/or hadronic dissociation or

ii): hard production and secondary statistical production with recombination, since the probability of recombination decrease with decreasing energy of collision in thermal model.

As it was already used for the experiment on collider with a fixed target at HERA-B K.Ehret, Nucl. Instr. Meth. A 446 (2000) 190, the target in the form of thin ribbon could be placed around the main orbit of LHC. The life time of the beam is determined by the beam-beam and beam-gas interactions. Therefore after some time the particles will leave the main orbit and interact with the target ribbon. So for fixed target measurements only halo of the beam will be used. Therefore no deterioration of the main beam will be introduced. The experiments at different interaction points will not feel any presence of the fixed target.

Geometrical acceptances for J/ψ at ALICE

Pb-Pb, √s=5.5 TeV

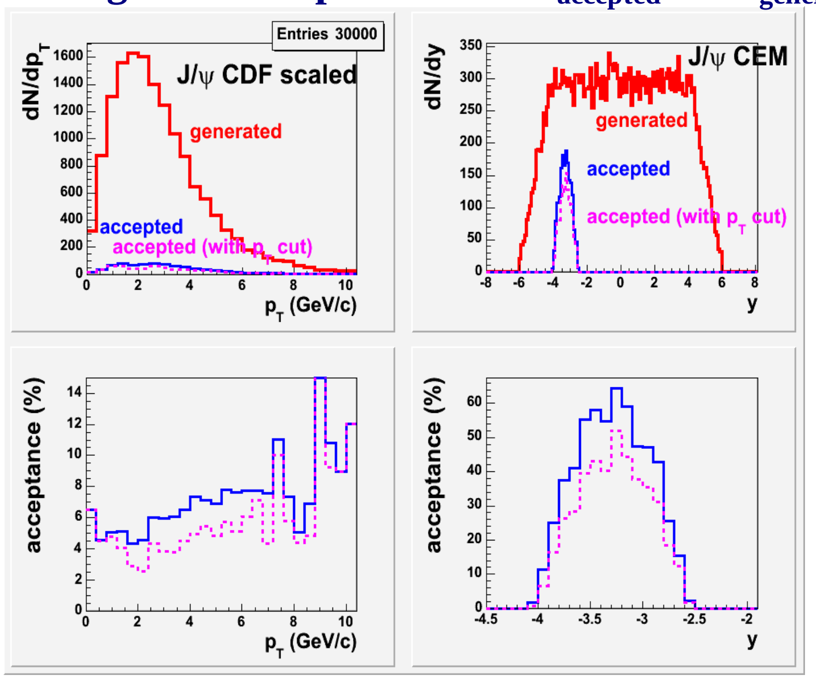
J/ψ are generated using CEM y-spectra and CDF scaled p_T-spectra and including shadowing for Pb-Pb.

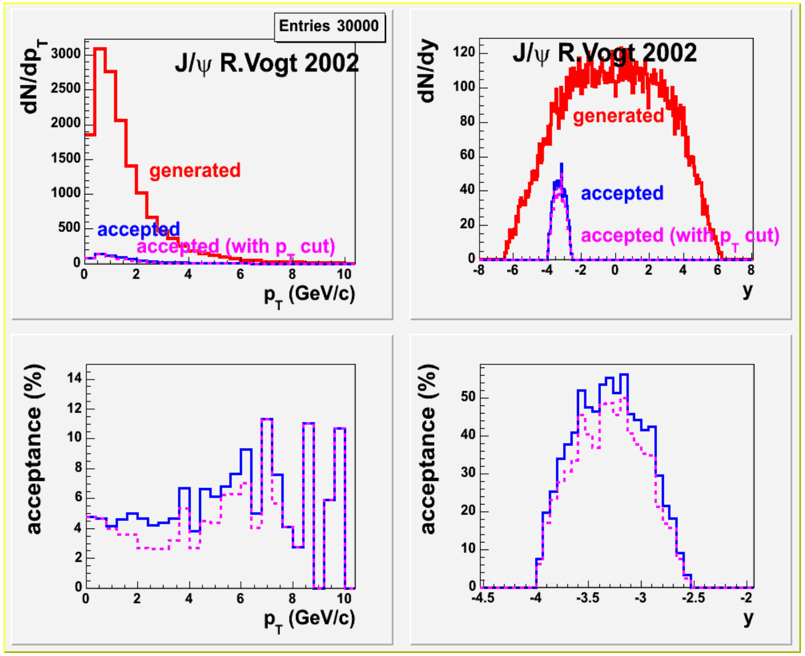
pp, √s=14 TeV

J/ψ are generated according R.Vogt 2002 approximation for p_T -spectra and y - distribution.

I_{acc} = Integrated acceptance = $N_{accepted}/N^{total}_{generated}$

$N_{gen}(J/\psi)=30000$





I_{acc}= 5.76% -w/o p_T cut
4.26% - with cut p_T >1 GeV/c

I_{acc}= 4.71% -w/o p_T cut
4.01% - with cut p_T >1 GeV/c

Fixed target experiment

Pb-Pb, T=2750 GeV, $\sqrt{s}$=71.8 GeV.

J/ψ are generated at z=0 and outside of ITS at z=+50 cm.

J/ψ are generated using p_T-spectra with HERA and PHENIX form, consistent with COM model, but parameters are energy scaled:
$dN/dp_T \sim p_T[1+(35\pi \cdot p_T/256 \cdot \langle p_T \rangle)^2]^{-6}$ with $\langle p_T \rangle$= 1.4, and using y-spectra as Gaussian with mean value y_{cm}=0 and σ=1.1

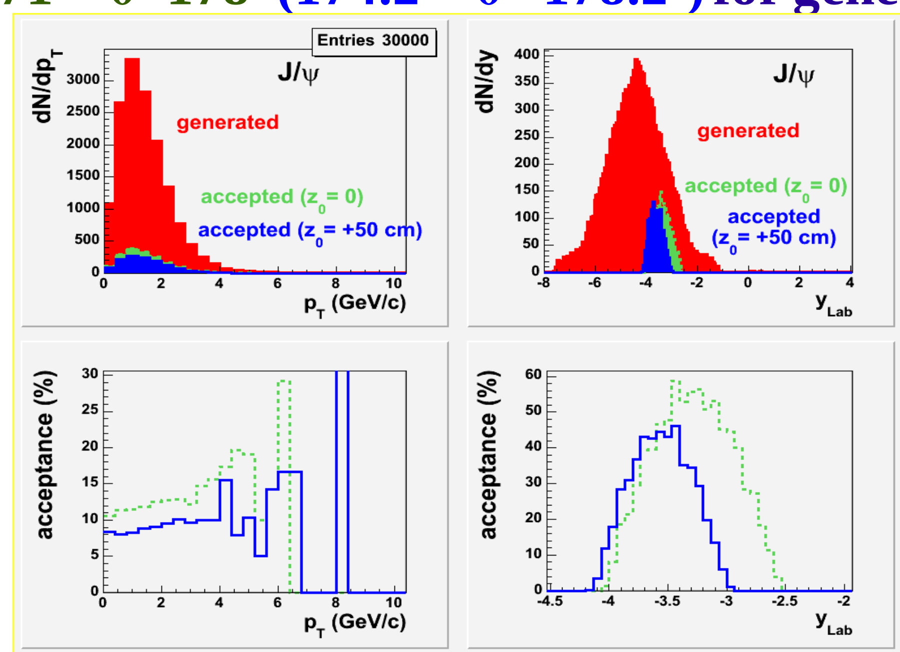
J/ψ are accepted in the rapidity range $-2.5<\eta<-4.0$ ($-2.98<\eta<-4.14$), and each of 2 muons in the degree range $171^0<\theta<178^0$ ($174.2^0<\theta<178.2^0$) for generation J/ψ at z=0 (z=+50 cm).

z=0

I_{acc} = 12.0%

z=+50 cm

I_{acc} = 8.79%

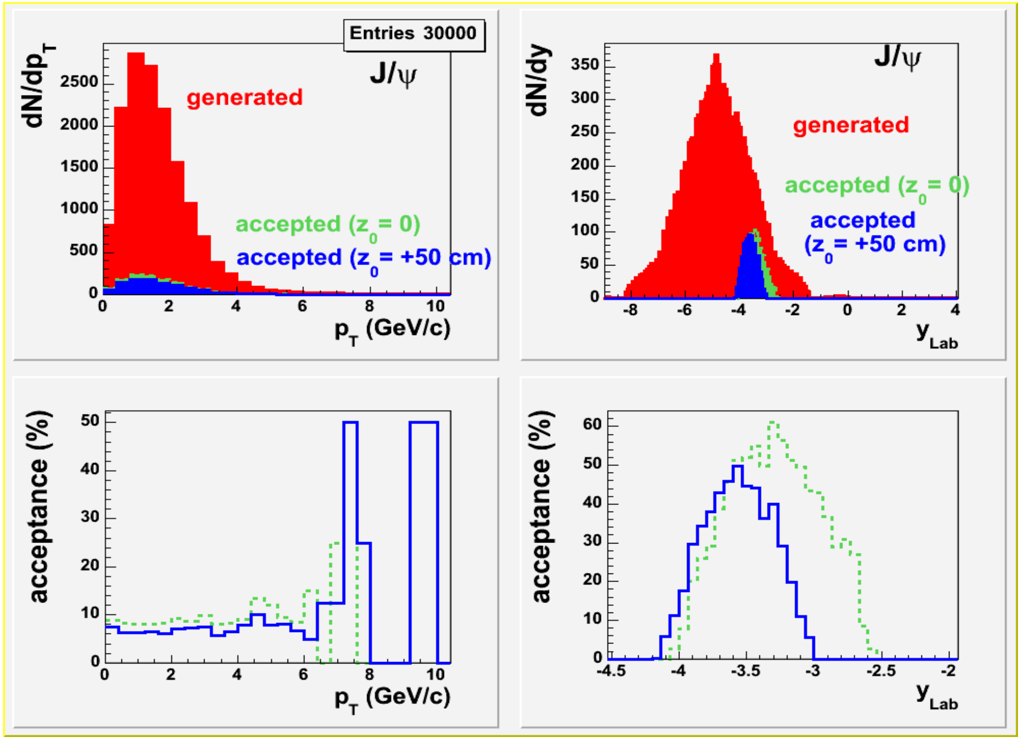


Fixed target experiment

pA, T=7000 GeV, $\sqrt{s}$=114.6 GeV.

J/ψ are generated at z=0 and outside ITS at z=+50 cm.

J/ψ are generated using p_T-spectra with the same parametrization with energy scaled parameter: $dN/dp_T \sim p_T[1+(35\pi \cdot p_T/256 \cdot \langle p_T \rangle)^2]^{-6}$ where $\langle p_T \rangle$= 1.6, and using y-spectra as Gaussian with mean value y_{cm}=0 and σ=1.25.



z=0

I_{acc} = 8.54%

z=+50 cm

I_{acc} = 5.98%

Geometrical acceptances

System pPb_{fixed}

pt cut	√s (TeV)	z = 0	z = +50 cm	z = -50 cm
no cut	0.1146	8.54	5.98	5.07
pt > 1 GeV/c	0.1146	6.77	4.89	4.11
no cut	0.0718	12.0	7.97	7.44
pt > 1 GeV/c	0.0718	9.79	6.62	6.20
η range		-4.0 ↔ - 2.5	-4.09↔-2.97	-3.76 ↔ -2.5

Luminocity, cross sections(x_F>0) , counting rates

System	$\sqrt{s}$ (TeV)	σ_{nn} (μb)	$\sigma_{pA}=\sigma_{nn}\cdot A^{0.92}$ (μb)	I (%)	$I\cdot B\cdot\sigma_{pA}$ (μb)	L ($cm^{-2}s^{-1}$)	Rate ($hour^{-1}$)
pp	14	32.9	32.9	4.7	0.091	$5\cdot10^{30}$	1635
pp_{RHIC}	0.200	2.7	2.7	3.59	0.0057	$2\cdot10^{31}$	410
pPb_{fixed}	0.1146	0.65	88.2	5.98	0.310	$1\cdot10^{29}$(*)	112
pPb_{fixed}	0.0718	0.55	74.6	7.97	0.349	$1\cdot10^{29}$	126
pPb_{NA50}	0.0274	0.19	25.8	14.0	0.212	$7\cdot10^{29}$	535
$PbPb_{fixed}$	0.0718	0.55	11970	7.97	47.9	$2.2\cdot10^{27}$(**)	378

(*) pPb_{fixed}, 500 μ wire, $3.2\cdot10^{12}$ protons/60 min

(**) $PbPb_{fixed}$, 500 μ wire, $6.8\cdot10^{8}$ ions/60 min

Conclusions

1. The integrated geometrical acceptances for charmonium measurement by dimuon spectrometer of ALICE are 5.76% for $\sqrt{s}$=5.5 TeV Pb-Pb and 4.71% for $\sqrt{s}$=14 TeV pp collisions.
2. For fixed target charmonium measurement in $2.5<y<4$ range the geometrical acceptances are of the same order and even larger: 7.97% for $\sqrt{s}$=71.8 GeV Pb-Pb and 5.98% for $\sqrt{s}$=114.6 GeV pA at z=+50 cm. The acceptances are compartible with the acceptances from other experiments.
3. The energy range for fixed target experiment between SPS and RHIC gives important additional information.

Later French group also suggested

First letter of physics on arXiv (1202.6585)

A Fixed Target ExperRiment

Generalities

- *pp* or *pA* with a 7 TeV *p* beam : $\sqrt{s} \simeq 115$ GeV
- The beam may be extracted using "Strong crystalline field"

without any performance decrease of the LHC !

E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131

- Expected luminosities with 5×10^8 *p*/s extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\int\mathcal{L}$ (pb^{-1}.yr^{-1})
Sol. H_2	0.09	1	26	260
Liq. H_2	0.07	1	20	200
Liq. D_2	0.16	2	24	240
Be	1.85	9	62	620
Cu	8.96	64	42	420
W	19.1	185	31	310
Pb	11.35	207	16	160

- Using **NA51**-like 1.2m-long liquid H_2 & D_2 targets, $\mathcal{L}_{H_2/D_2} \simeq 20$ fb$^{-1}y^{-1}$
- Planned lumi for PHENIX Run14pp 12 pb^{-1} and Run14*d*Au 0.15 pb^{-1}

A Fixed Target ExperRiment

Generalities

- *Pbp* or *PbA* with a 2.75 TeV Pb beam : $\sqrt{s_{NN}} \simeq 72$ GeV
- Crystal channeling is also possible (to extract a fraction of the beam)
- May require crystals highly resistant to radiations: bent diamonds ?

P. Ballin *et al.*, NIMB 267 (2009) 2952

- Expected luminosities with 2×10^5 Pb/s extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (mb^{-1}.s^{-1})=$\int\mathcal{L}$ (nb^{-1}.yr^{-1})
Sol. H_2	0.09	1	11
Liq. H_2	0.07	1	8
Liq. D_2	0.16	2	10
Be	1.85	9	25
Cu	8.96	64	17
W	19.1	185	13
Pb	11.35	207	7

- Planned lumi for PHENIX Run15AuAu 2.8 nb^{-1} (0.13 nb^{-1} at 62 GeV)
- Nominal LHC lumi for PbPb 0.5 nb^{-1}

Conclusion

- Both p and Pb LHC beams can be extracted without disturbing the other experiments
- Extracting a few per cent of the beam $\rightarrow 5 \times 10^8$ protons per sec
- This allows for high luminosity pp, pA and PbA collisions at $\sqrt{s} = 115$ GeV and $\sqrt{s_{NN}} = 72$ GeV
- **Example**: precision quarkonium studies taking advantage of
  - high luminosity (reach in y, P_T, small BR channels)
  - target versatility (CNM effects, strongly limited at colliders)
  - modern detection techniques (e.g. γ detection with high multiplicity)
- This would likely prepare the ground for $g(x, Q^2)$ extraction
- A wealth of possible measurements:
  DY, Open b/c, jet correlation, UPC... (not mentioning secondary beams)
- Planned LHC long shutdown ($<$ 2020 ?) could be used to install the extraction system
- Very good complementarity with electron-ion programs