QGP Physics − From SPS to LHC

9. J/ψ and Quarkonia as probes of deconfinement

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SS 2011

9.1 Quarkonia

- Quarkonia are heavy quark antiquark bound states, i.e. ccbar and bbar
- since masses of charm and beauty quarks are high as compared to QCD scale parameter Λ_{QCD} ~ 200 MeV
  non-relativistic Schrödinger equation can be used to find bound states

$$(-\frac{\nabla^2}{2(m_Q/2)} + V(r))\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-quark potential of the form

$$V(r) = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1 \cdot \vec{s}_2}{m_Q^2}\delta(\vec{r}) + ...$$

confinement

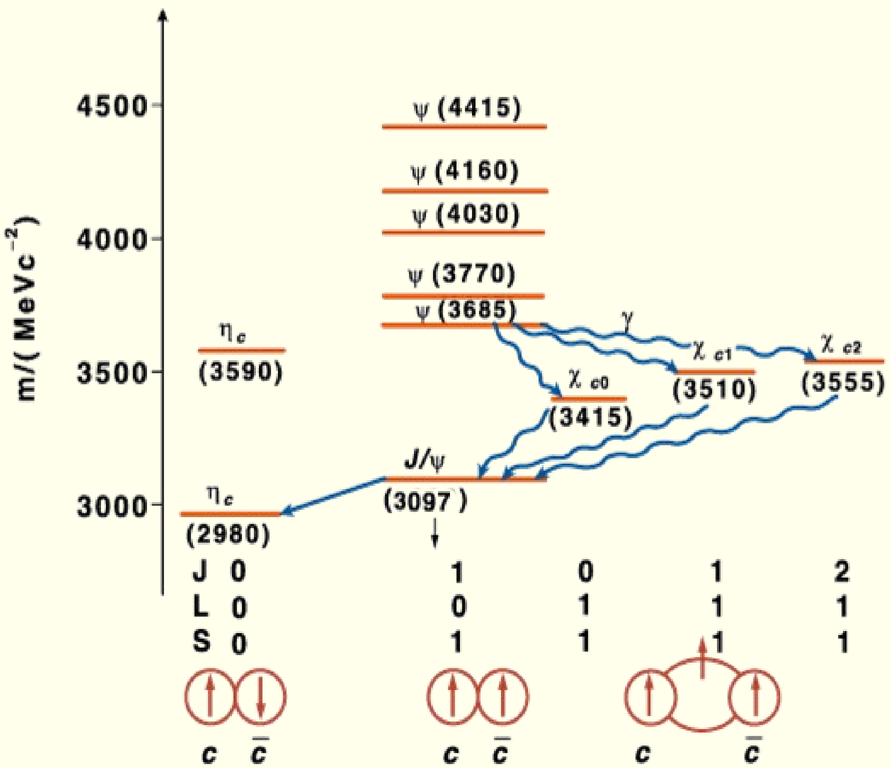
color Coulomb int.

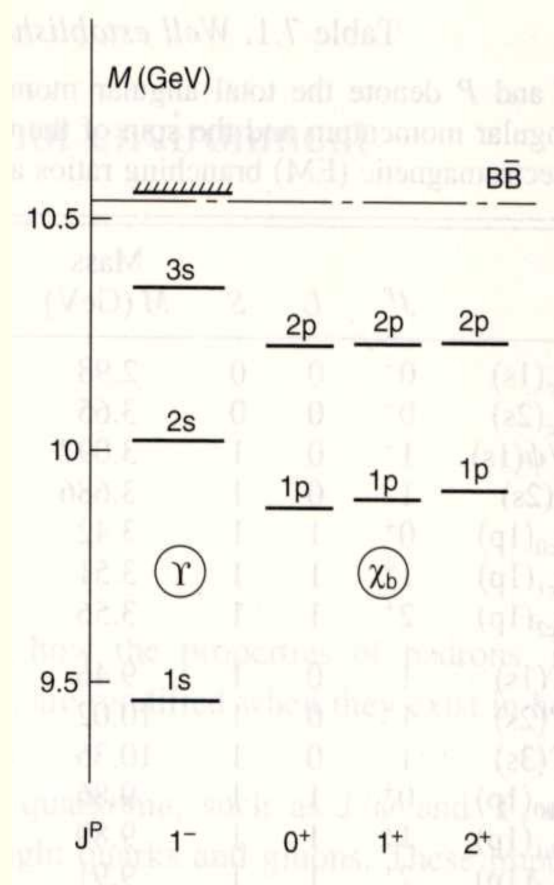
spin-spin int.

tensor, spin-orbit, higher order rel. corr.

- with σ ~ 0.9 GeV/fm, $\alpha_s(m_Q)$ ~ 0.35 and 0.20 for m_c = 1.5 GeV and m_b = 4.6 GeV obtain spectrum of quarkonia

Charmonium and Bottomonium spectra





color singlet states

Charmonium and Bottomonium spectra

	J^P	L	S	Mass M (GeV)	Total width Γ_{tot} (MeV)	EM branching ratios
$\eta_c(1s)$	0^-	0	0	2.98	~16	$B(\gamma\gamma) \sim 0.046\%$
$\eta_c(2s)$	0^-	0	0	3.65	<55	
$J/\psi(1s)$	1^-	0	1	3.097	~0.09	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 6\%$
$\psi(2s)$	1^-	0	1	3.686	~0.28	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 0.75\%$
$\chi_{c0}(1p)$	0^+	1	1	3.42	~11	$B(\gamma\, J/\psi) \sim 1\%$
$\chi_{c1}(1p)$	1^+	1	1	3.51	~0.9	$B(\gamma\, J/\psi) \sim 32\%$
$\chi_{c2}(1p)$	2^+	1	1	3.56	~2.1	$B(\gamma\, J/\psi) \sim 20\%$
$\Upsilon(1s)$	1^-	0	1	9.46	~53	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 2.4\%$
$\Upsilon(2s)$	1^-	0	1	10.02	~43	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 1.3\%$
$\Upsilon(3s)$	1^-	0	1	10.36	~26	$B(\mu^+\mu^-) \sim 1.8\%$
$\chi_{b0}(1p)$	0^+	1	1	9.86		
$\chi_{b1}(1p)$	1^+	1	1	9.89		
$\chi_{b2}(1p)$	2^+	1	1	9.91		

9.2 Charmonia at finite temperature

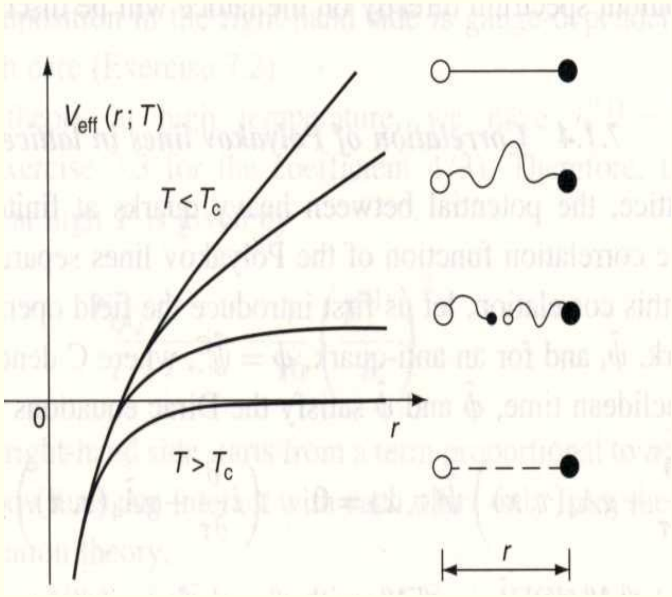
Consider T« m_c so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks

Consider c cbar in environment of gluons and light quarks

$$V(r) \rightarrow V_{eff}(r,T) \,\text{and}\, m_Q \rightarrow m_Q(T)$$

In QGP color singlet and color octet ccbar states can mix by absorption or emission of a soft gluon

Modification of V_{eff}



- reduced string tension at T approaches Tc
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for T>Tc confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

$$V_{eff}(r,T) \rightarrow -\frac{4}{3}\frac{\alpha_s}{r}e^{r/\lambda_D}$$

$$\omega_D = 1/\lambda_D$$

Debye screening mass and length

Debye screening of quarkonia

unlike Coulomb potential, Yukawa potential does not always have bound states

→ dissociation of quarkonia if ω_D sufficiently large at high T

idea: T. Matsui, H. Satz, Phys. Lett. B 178 (1986) 416

compare Bohr radius of charmonia r_B and Debye screening length λ_D

> for r_B smaller than λ_D bound states exist even for $\sigma = 0$
>
> for r_B larger than λ_D no bound states

equivalently to QED where $r_B(\text{hydrogen}) = 1/(m_e \alpha)$ we have: $r_B = 3/(2 m_Q \alpha_s)$

and the Debye screening mass: $$\omega_D^2 = \frac{4\pi\hbar c}{3} \alpha_s T^2 (N_c + \frac{1}{2} N_f)$$

(see textbooks, e.g. Yagi, Hatsuda, Miake, chapter 4, finite temperature field theory)

bound states then disappear for

$$T \geq 0.15 \times m_Q \sqrt{\alpha_s} \approx 0.16\,\text{GeV for J}/\psi\,\text{and}\,0.46\,\text{GeV for}\,\Upsilon$$

Different quarkonia melt at different temperatures

using $$V(r,T) = \frac{\sigma}{\omega_D(T)}(1 - \exp(-\omega_D(T)r)) - \frac{\alpha}{r}\exp(-\omega_D(T)r)$$

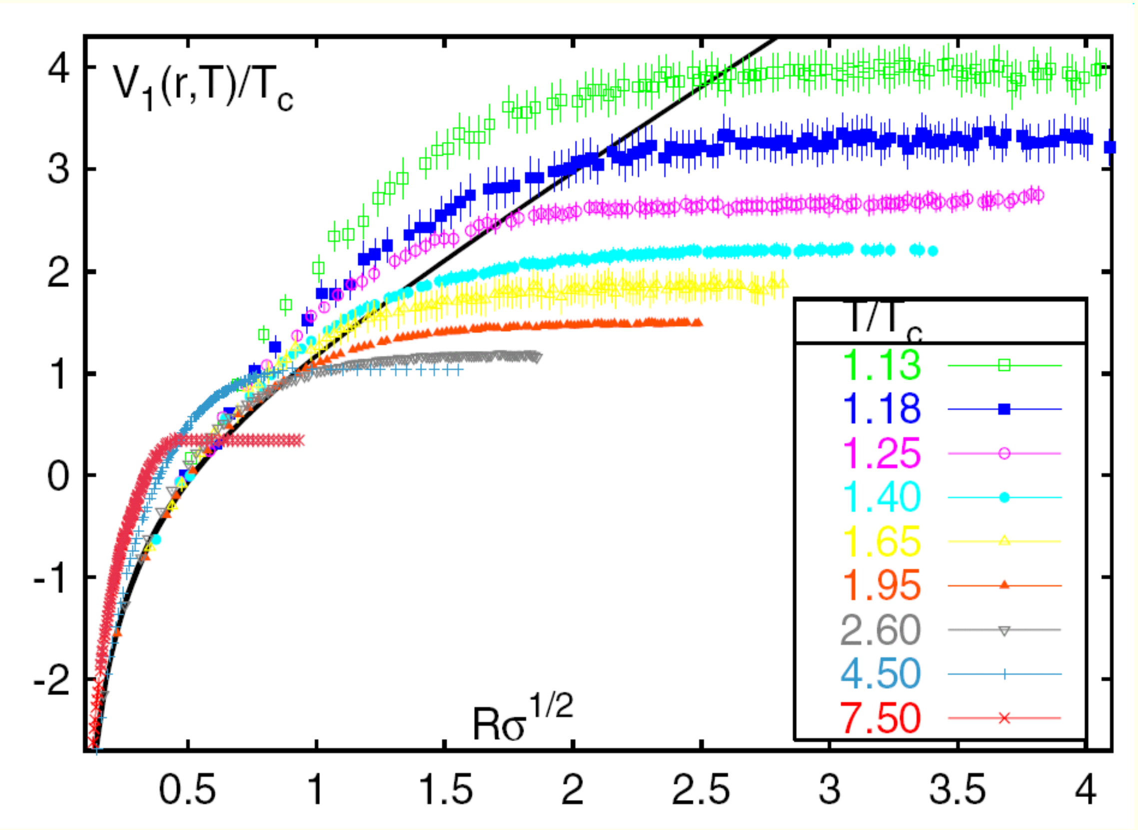
F. Karsch and H. Satz (Z.Physik C51 (1991) 209) obtain:

	J/ψ	ψ'	χ_c	Υ	Υ'
state	1s	2s	1p	1s	2s
mass(GeV)	3.1	3.7	3.5	9.4	10.0
r (fm)	0.45	0.88	0.70	0.23	0.51
T_D/T_c	1.17	1.0	1.0	2.62	1.12
ϵ_D (GeV/fm^3)	1.92	1.12	1.12	43.3	1.65

exact values very model dependent, but basic feature: J/psi, psi', chic, Upsilon' not bound at or little above Tc, Upsilon survives much longer

Results on Debye screening from lattice QCD

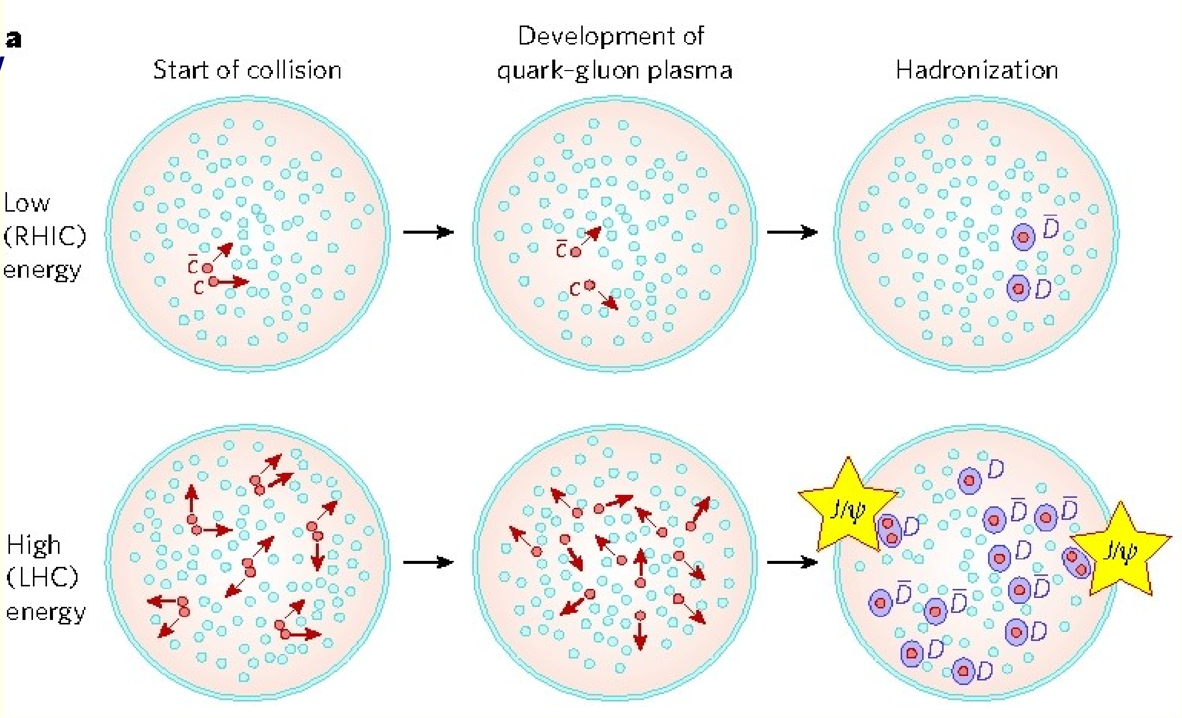
agree qualitatively, quantitatively still a lot of debate, unclear, how to extract effective heavy quark potential
One attempt: correlation of Polyakov lines but there are others



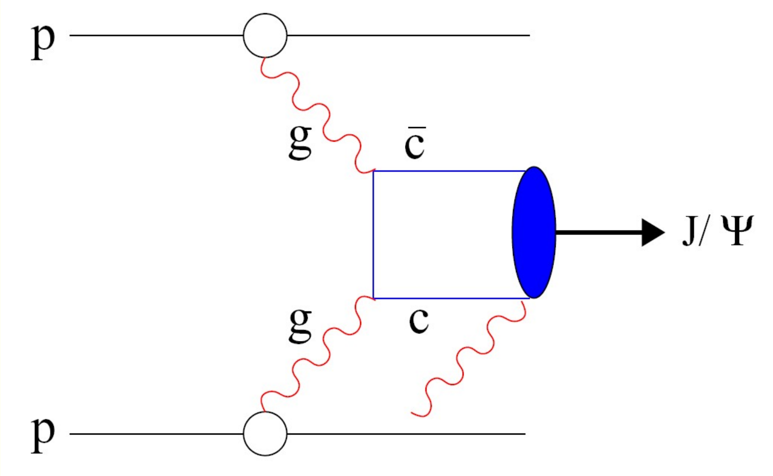
Hadronization of charm quarks

all charm quarks have to appear in charmed hadrons
at hadronization of QGP J/ψ can form again from deconfined quarks
in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \sim N_{cc}^{2}$
(P. Braun-Munzinger and J. Stachel,Phys. Lett. B490 (2000) 196)

expect J/psi suppression at low beam energies (SPS, RHIC)
and
J/psi enhancement at high energies (LHC)



9.3 Production of charmonia in hadronic collisions



- charm and beauty quarks are produced in early hard scattering processes
- most important Feynman diagram: gluon fusion
- formation of quarkonia requires transition to a color singlet state

not pure perturbative QCD anymore, some modelling required
CEM Color Evaporation Model
CSM Color Singlet Model
still only moderately successful

relevant time scales

formation of ccbar: in hard initial scattering on time scale $1/2m_c$
with m_c = 1.3 GeV -> τ_{ccbar} = 0.08 fm/c

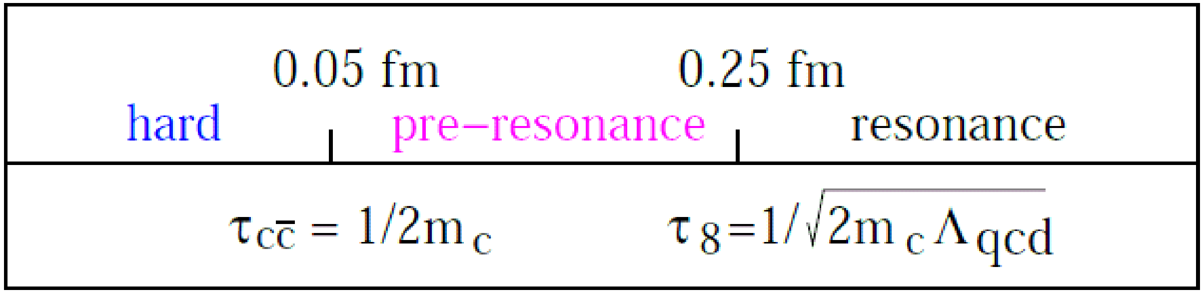
typical hadron formation time: τ_{hadron} order 1 fm/c
(Blaizot/Ollitrault 1989 Hüfner, Ivanov, Kopeliovich, and Tarasov 2000)
W. Brooks, QM09: description of recent JLAB and HERMES hadron production data in color dipole model - > time scale 5 fm/c

comparable to or longer than QGP formation time: $\tau_{QGP} \cong 1$ fm/c at SPS, < 0.5 fm/c at RHIC, $\cong$ 0.1 fm/c at LHC

at LHC even color octet state not formed before QGP
(H.Satz 2006) $\tau_8 = 1/\sqrt{2\mathrm{m_c}\Lambda_{\mathrm{QCD}}} \approx 0.25\mathrm{fm}$

collision time: $\mathrm{t_{coll}} = 2\mathrm{R}/\gamma_{\mathrm{cm}}$ at RHIC 0.1 fm/c at LHC < 5 10^{-3} fm/c

time scales continued



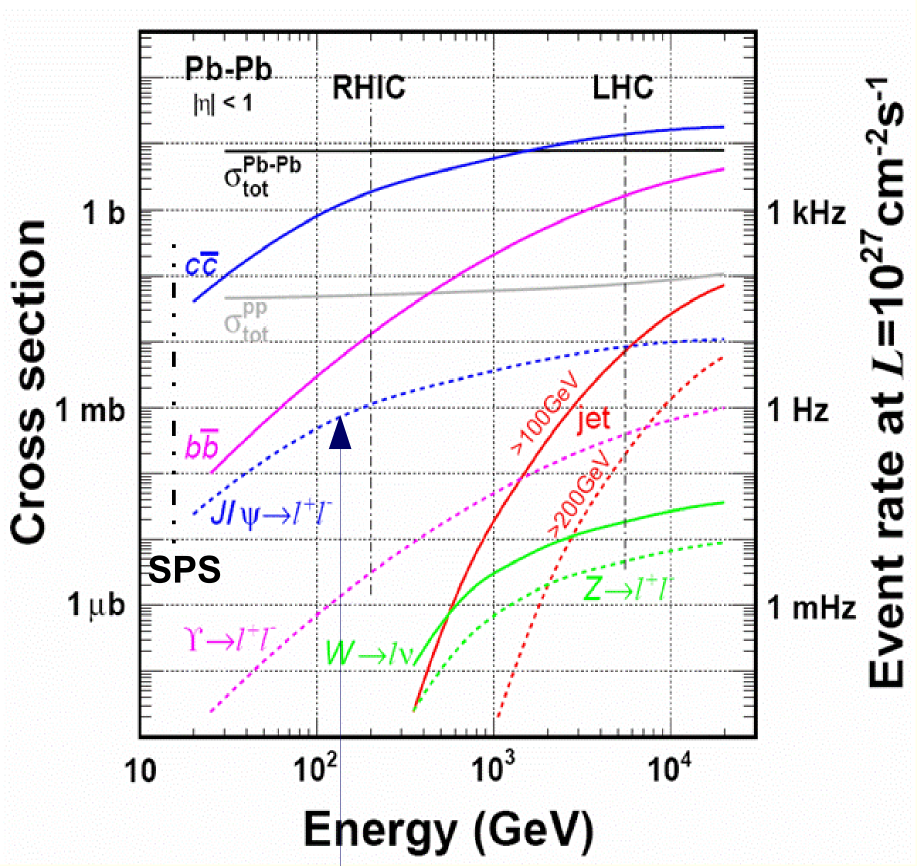
ccbar pairs are formed at collision time scale $t_{coll} = \tau_{ccbar}$

collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS $t_{coll} = \tau_{ccbar} \cong \tau_{QGP} \cong \tau_{hadron}$

but at RHIC and much more pronounced at LHC there is the following hierarchy: $t_{coll} = \tau_{ccbar} \ll \tau_{QGP} \ll \tau_{hadron}$

expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC

Production of charm and beauty



number of heavy quark pairs per central PbPb or AuAu collision from these cross sections:

N($q\bar{q}$) per central AA (b=0)

	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5

J/Ψ is only a small fraction of order of 1% of these 6% detected via l^+l^- decay

9.4 Measurement of quarkonia

$$\mathrm{BR}(\mathrm{J}/\psi \to \mathrm{hadrons}) \approx 0.88$$

$$\mathrm{BR}(\mathrm{J}/\psi \to \mathrm{e}^+\mathrm{e}^-) \approx 0.06$$

$$\mathrm{BR}(\mathrm{J}/\psi \to \mu^+\mu^-) \approx 0.06$$

$$\mathrm{BR}(\psi' \to \mathrm{hadrons}) \approx 0.98$$

of these $\mathrm{BR}(\psi' \to \mathrm{J}/\psi) \approx 0.60$

$$\mathrm{BR}(\psi' \to \mu^+\mu^-) \approx 0.008$$

$$\mathrm{BR}(\Upsilon \to \mathrm{hadrons}) \approx 0.90$$

$$\mathrm{BR}(\Upsilon \to \mathrm{e}^+\mathrm{e}^-) \approx 0.025$$

$$\mathrm{BR}(\Upsilon \to \mu^+\mu^-) \approx 0.025$$

J/Ψ, Ψ' and Y via e+e- or μ+μ-

χ_c very difficult, usually done via

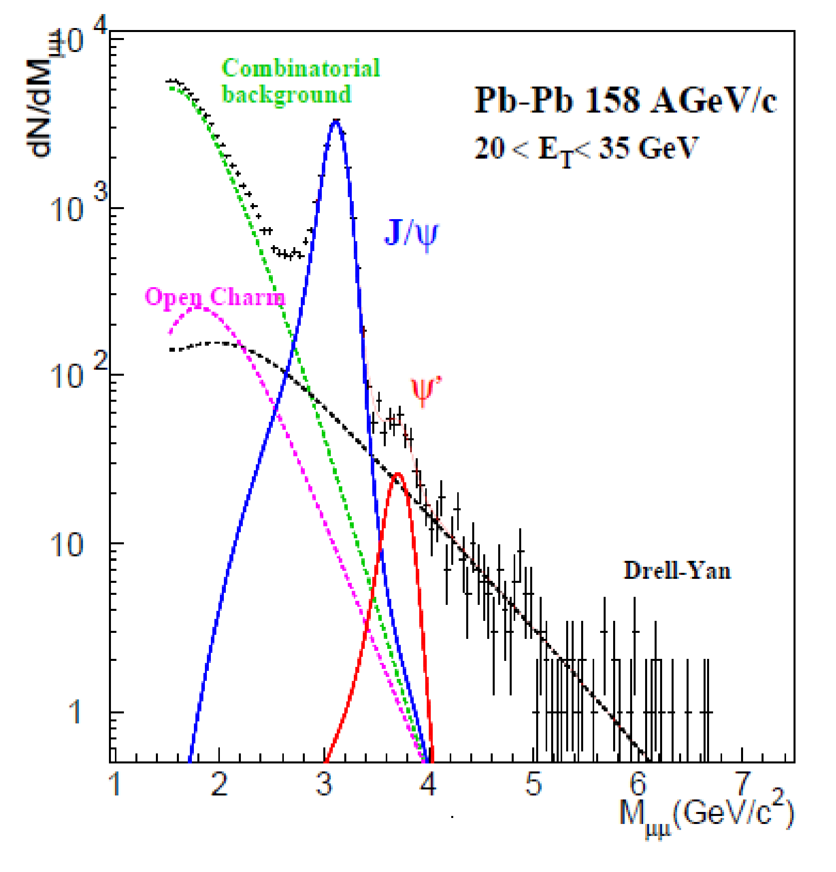
$$\chi_\mathrm{c} \to \mathrm{J}/\psi + \gamma$$

of measured J/Ψ typically

$\approx 60\%$ directly produced

$\approx 10\%$ from $\psi' \to J/\psi$

$\approx 30\%$ from $\chi_c \to J/\psi$



NA50 at CERN SPS

9.5 Charmonia in nuclear collisions

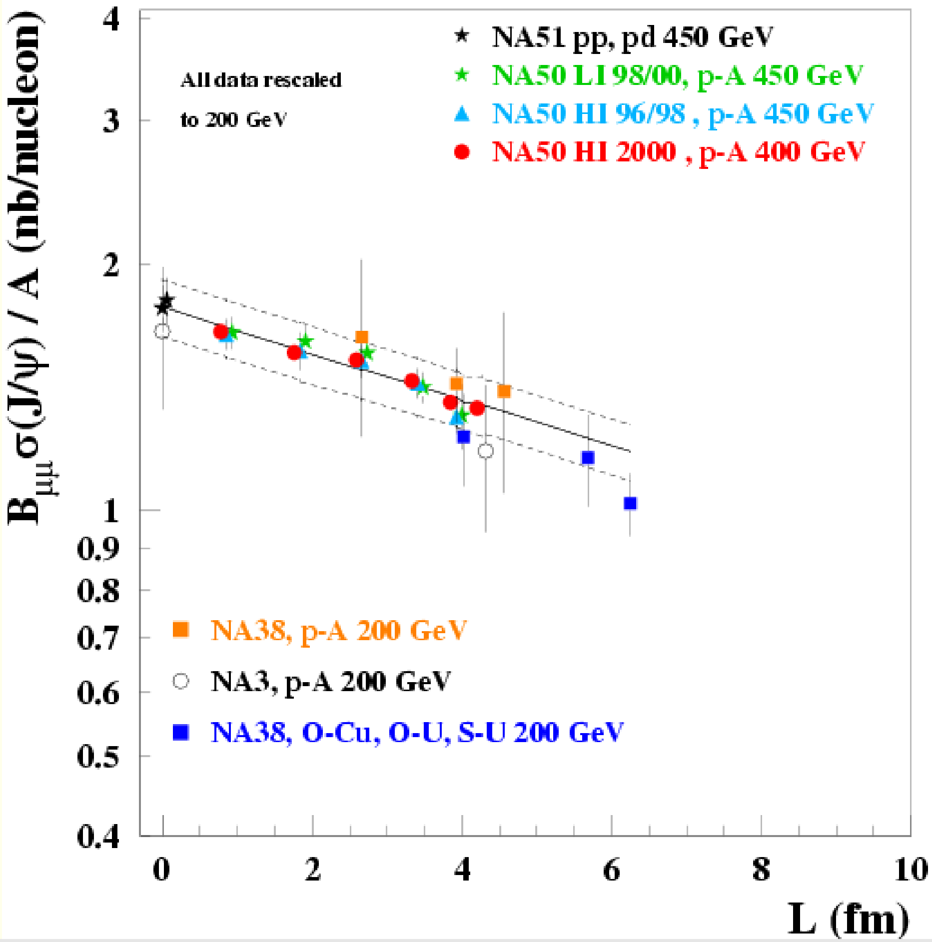
In pA collisions at moderate energies (200-450 GeV) universal picture: prehadronic state absorbed in nuclear matter

$$\sigma(J/\psi) \propto \exp(-\rho \sigma_{abs} L)$$

with $\rho = 0.17/\mathrm{fm}^3$
and $\sigma_{\mathrm{abs}} = (4.1 \pm 0.4)\,\mathrm{mb}$

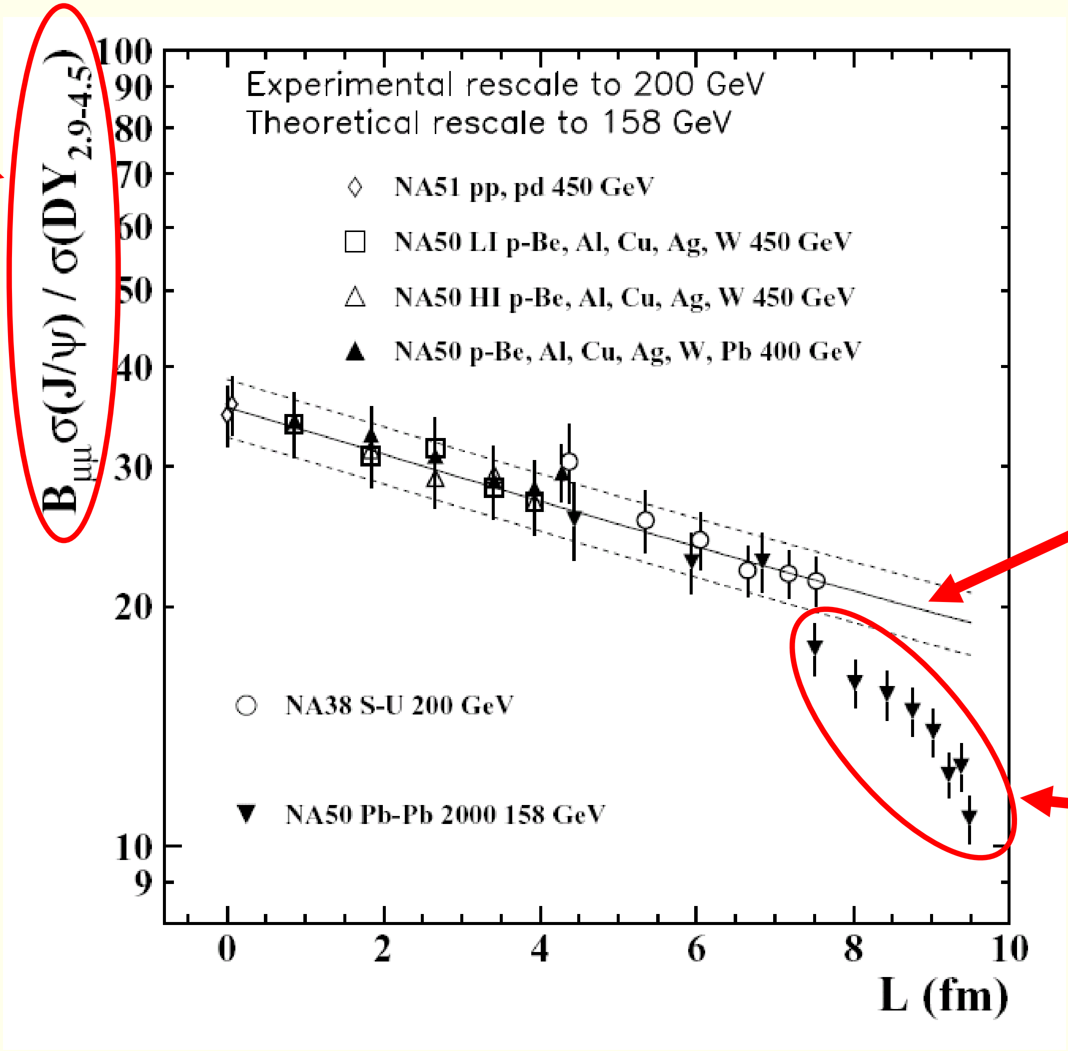
light nuclear collisions follow the same picture

NA50, Eur. Phys. J. C39 (2005) 335



J/Psi production in PbPb collisions at SPS energy

normalization to Drell-Yan process



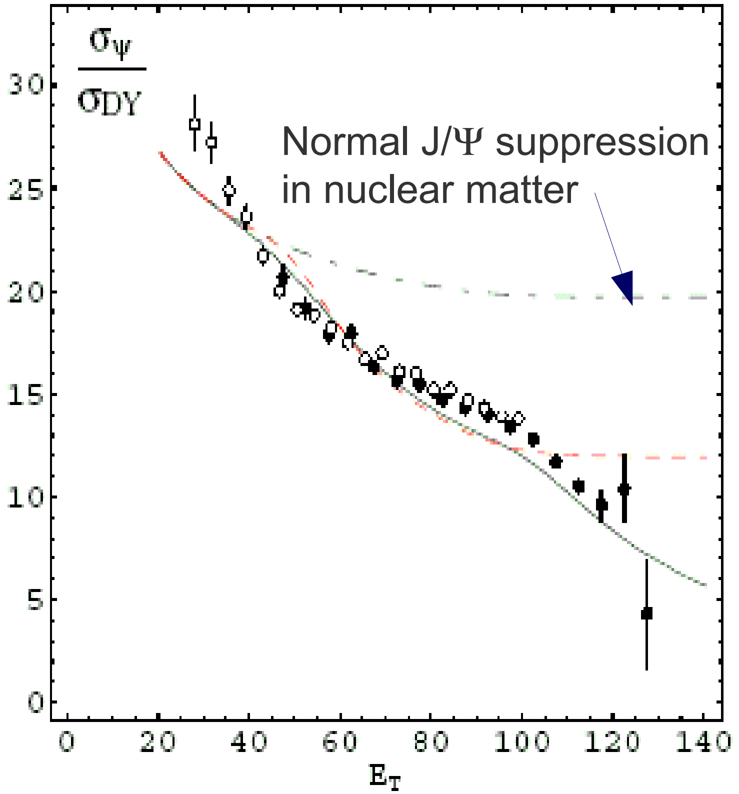
Normal J/Ψ suppression on nuclear matter

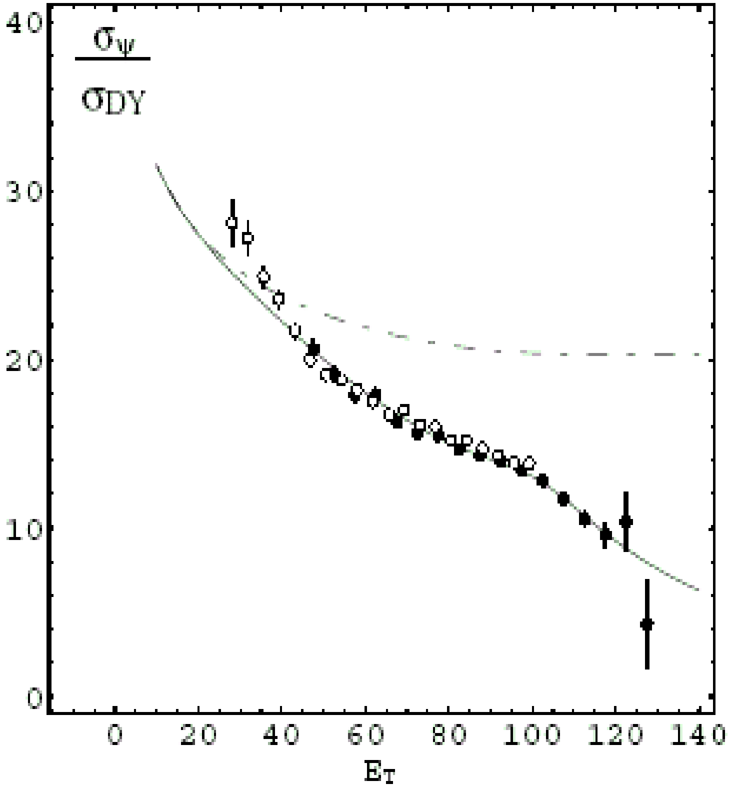
Anomalous J/Ψ suppression due to QGP?

In central PbPb collisions about 40% less J/Ψ than expected from pA systematics

SPS data consistent with suppression at critical density

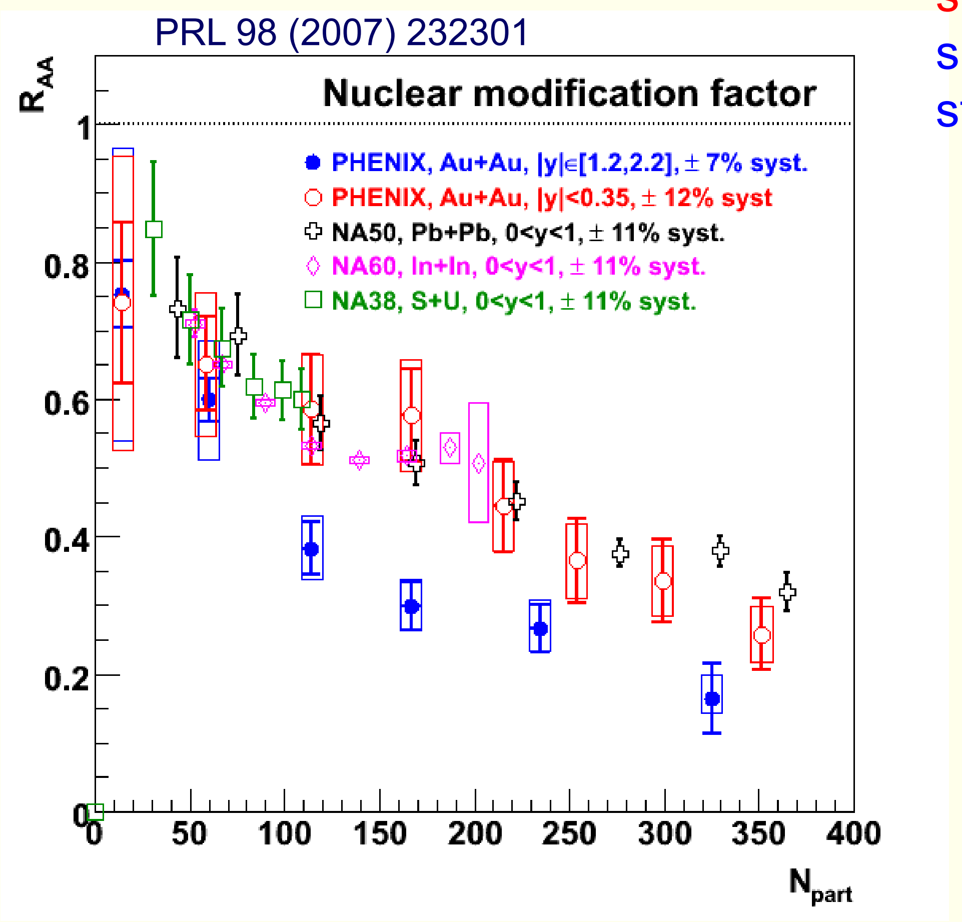
Dissolution in QGP at critical density n_c (red dashes) and in addition with energy density fluctuations (solid)





J.P. Blaizot, P.M. Dinh, J.Y. Ollitrault, PRL 85 (2000) 4012

J/Psi production in AuAu collisions at RHIC



at mid-rapidity suppression at RHIC very similar to SPS

suppression at forward/backward rapidity stronger!

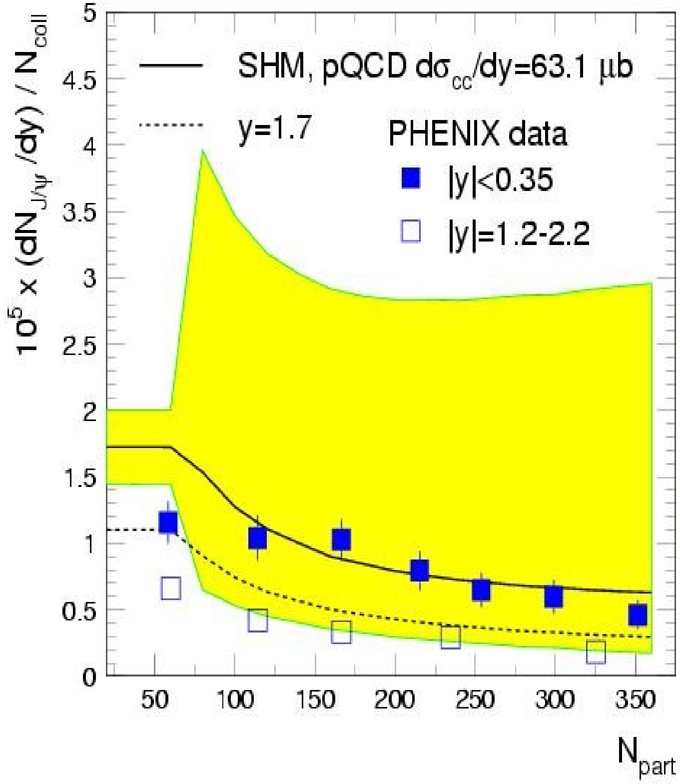
but prediction:

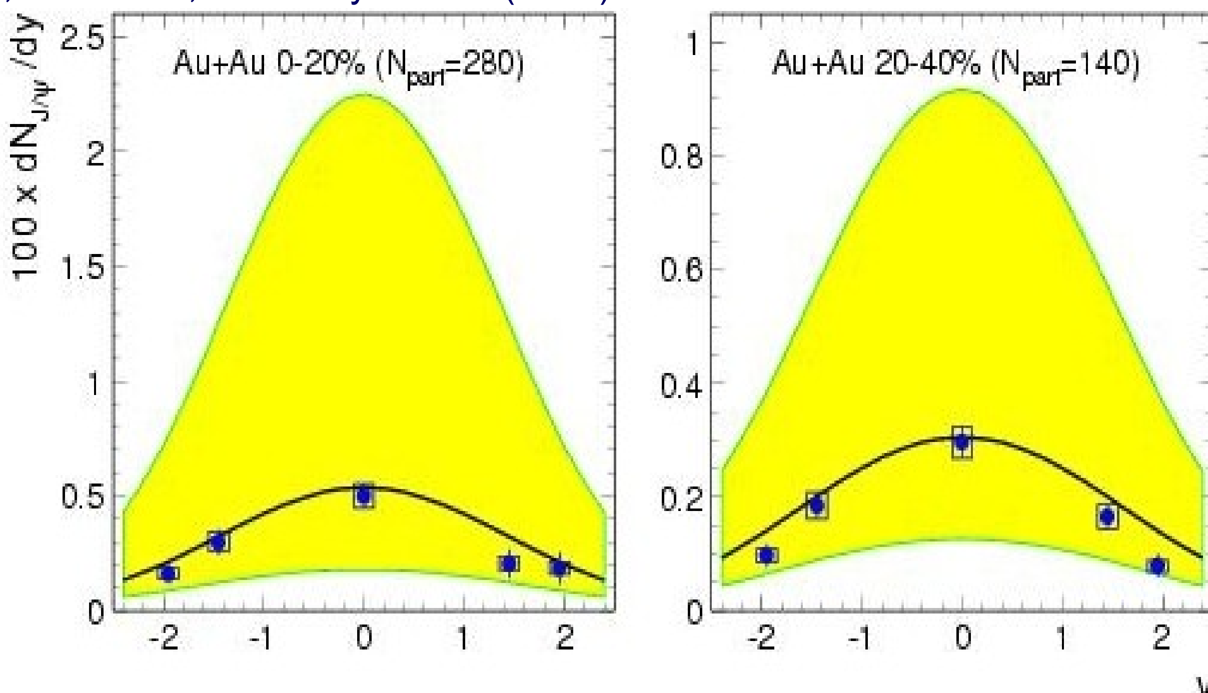
at hadronization of QGP J/Ψ can form again from deconfined quarks, in particular if number of ccbar pairs is large

$$N_{J/\Psi} \propto N_{cc}^2$$

comparison of statistical model predictions to RHIC data: centrality dependence and rapidity distribution

P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A789 (2007) 334 nucl-th/0611023





pp open charm cross section FONLL Cacciari et al.,
PRL 95 (2005) 122001 $\sigma_{cc} = 256^{+400}_{-146}$ μb

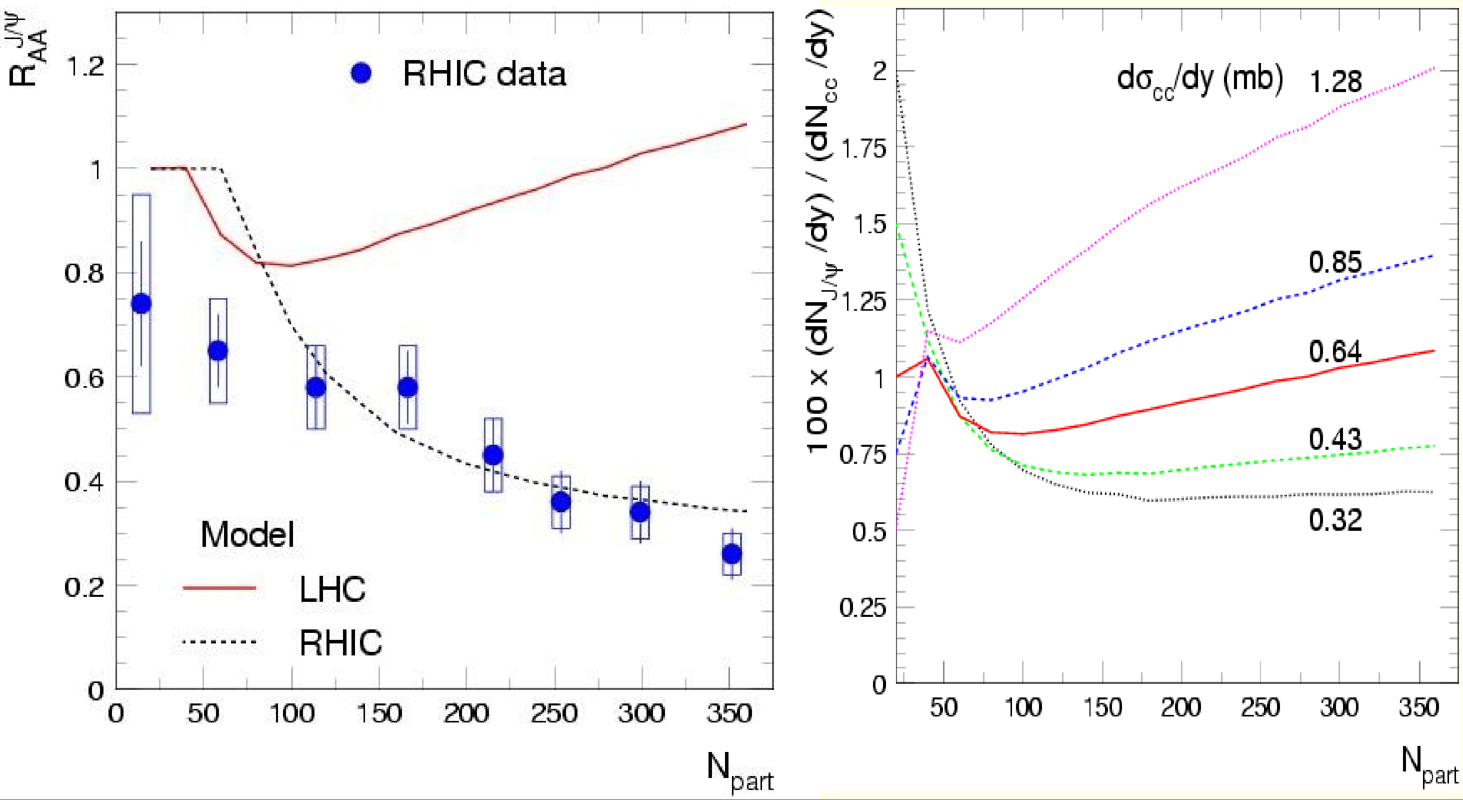
good agreement, no free parameters

↔

but need for good open charm measurement obvious
(this is a lesson for LHC as well!)

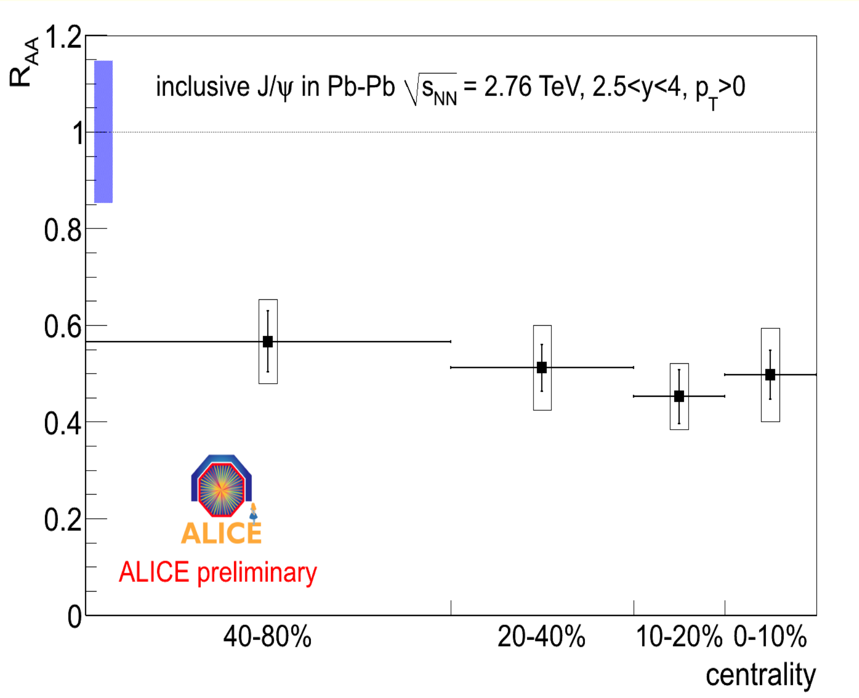
energy dependence of quarkonium production in statistical hadronization model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

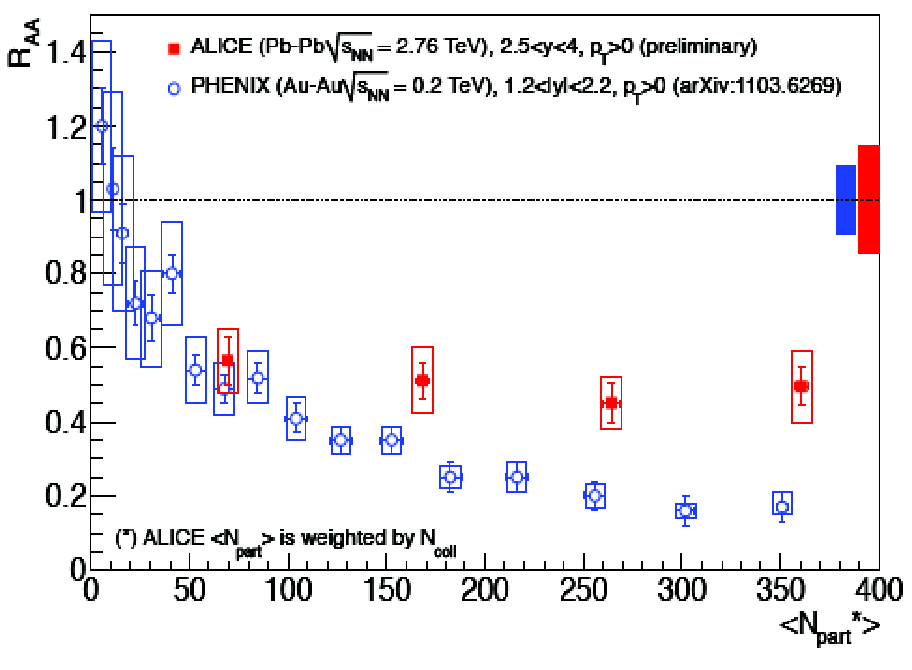


note: stat. model does not make any prediction about ccbar production cross section, this is input; depending on ccbar cross section in nuclear collisions at LHC there can be J/psi enhancement

First data from PbPb collisions at the LHC

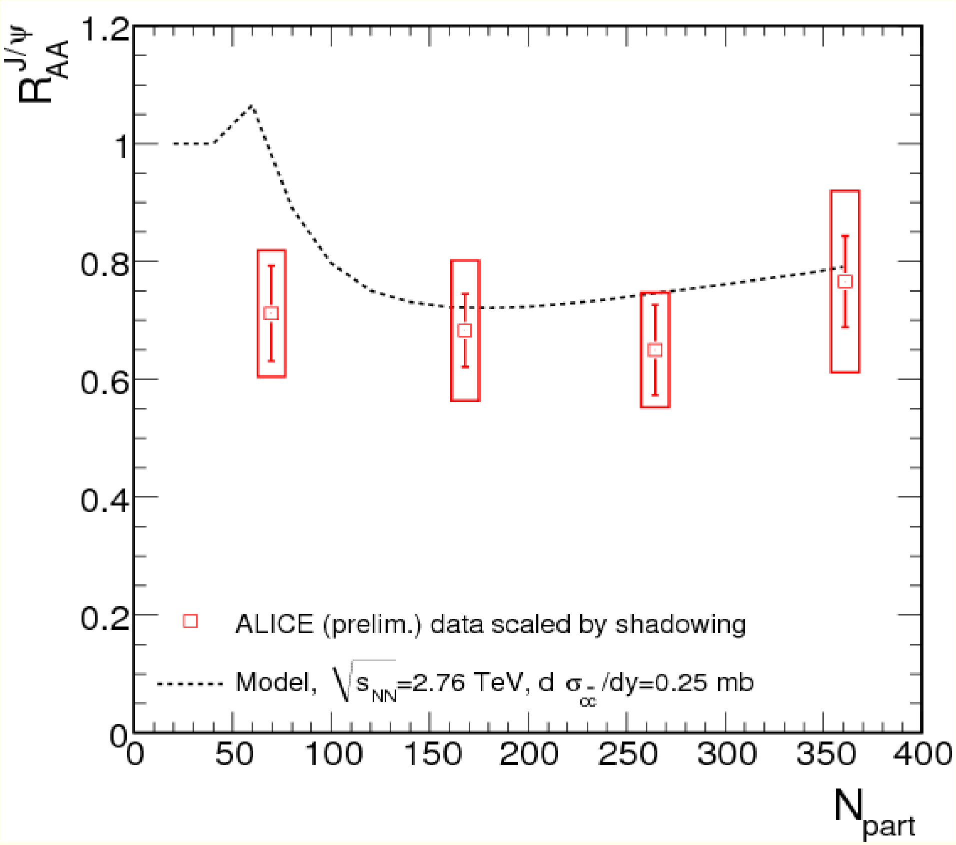


Contribution from B feed-down small:
~ 10% from p-p measurement
(LHCb, arXiv:1103.0423)



J/psi RAA in central collisions is larger at LHC in 2.5<y<4 than at RHIC in 1.2<|y|<2.2
And shadowing at LHC estimated to be large
Conclusion: the R_{AA} for J/psi is large!

statistical hadronization of charmonia at LHC?

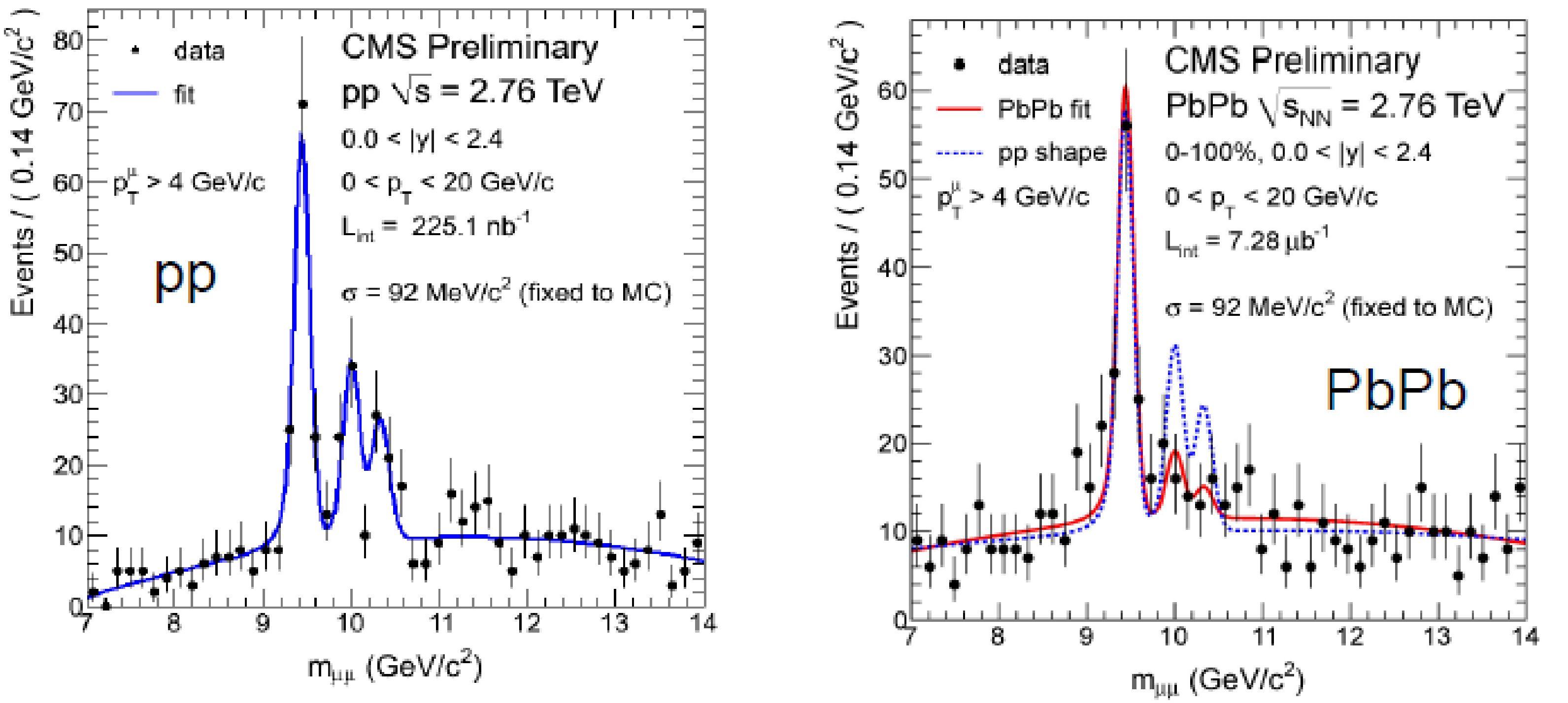


A. Andronic et al, QM2011

this looks compatible!
but is very preliminary
no measured ccbar cross section in PbPb at this energy yet

way out: scale data with calculated shadowing
compare to ccbar cross section from pQCD

First information on Upsilon states for PbPb at LHC



$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

Consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed