Quark-Gluon Plasma Physics

10.b Quarkonia and Deconfinement

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10.1 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-antiquark potential of the form

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

confinement

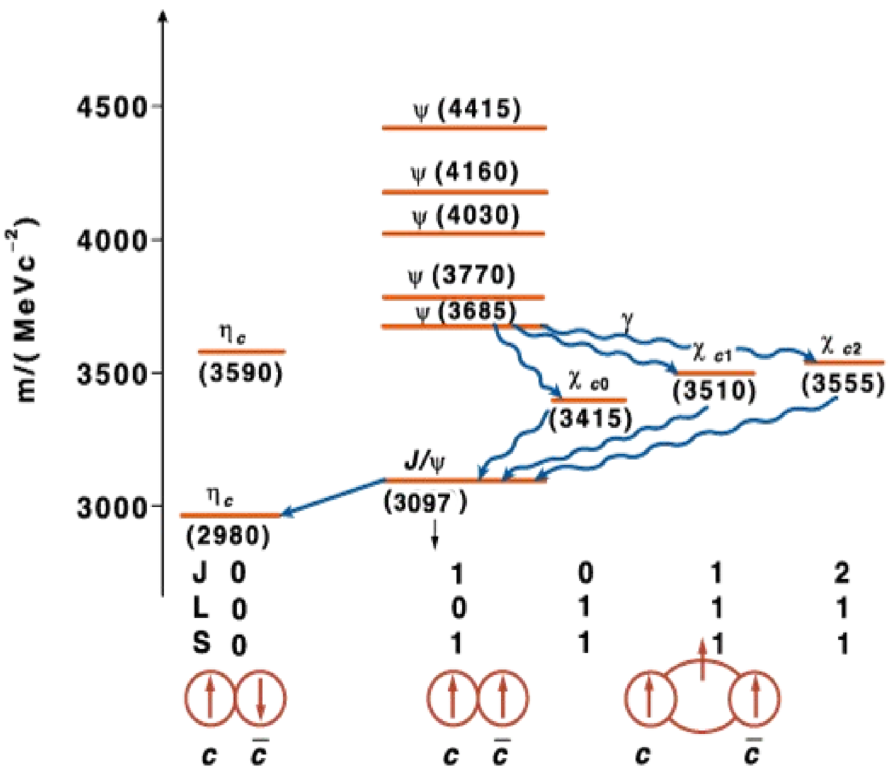
color Coulomb int.

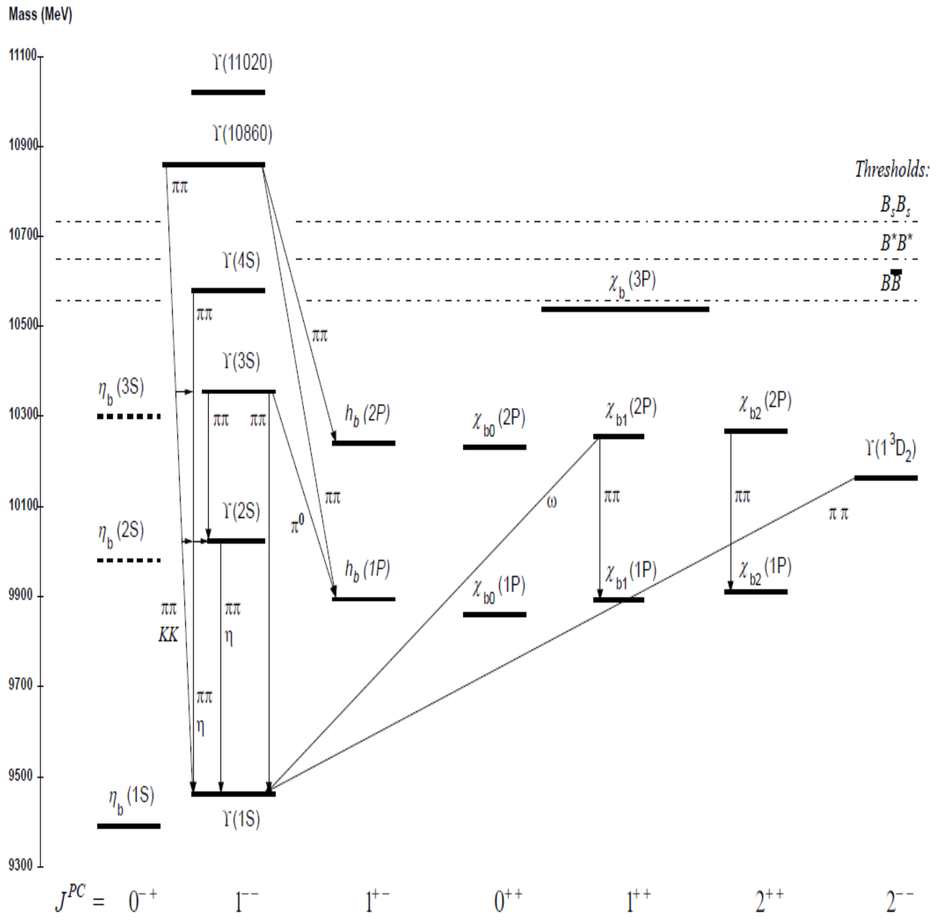
spin-spin int.

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 and m_b=4.6 GeV
  obtain spectrum of quarkonia

Charmonium and Bottomonium spectra





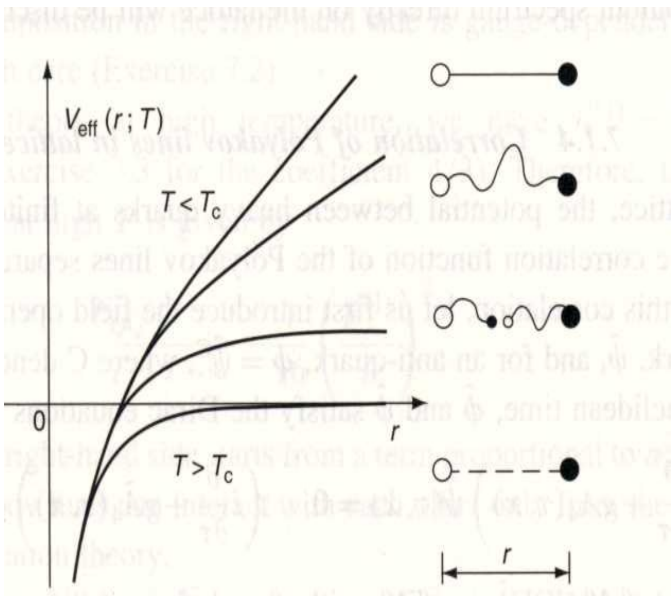
color singlet states

10.2 Charmonia at finite temperature

consider T« m_c so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks
consider ccbar in thermal environment of gluons and light quarks

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

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

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

$$\omega_D = 1/\lambda_D$$

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 σ=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)

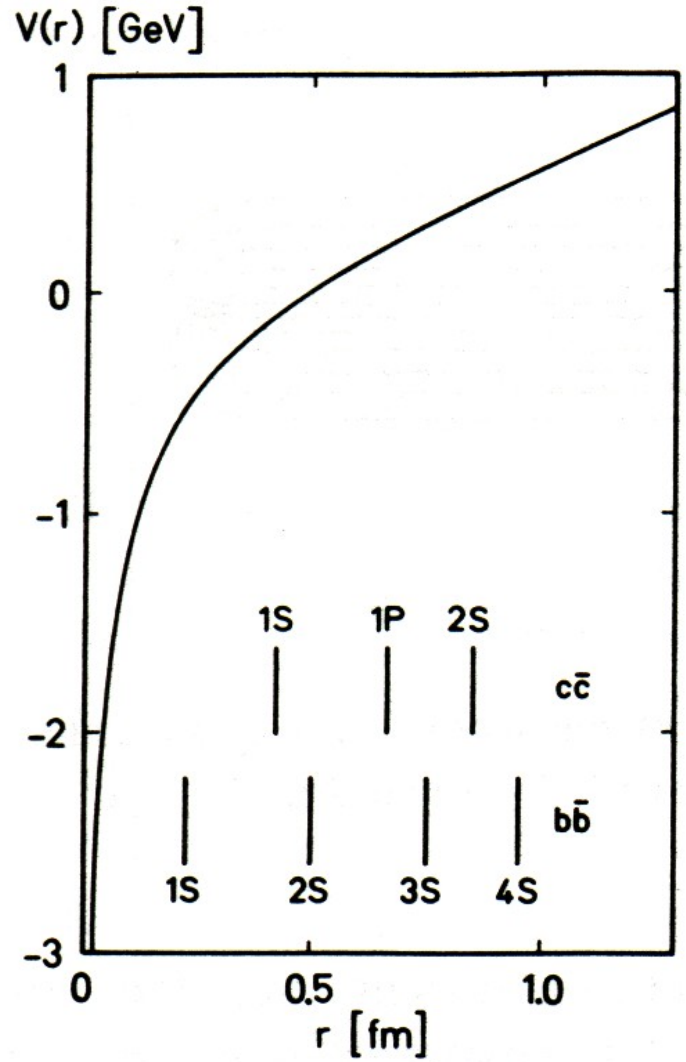
bound states then disappear for $T \geq 0.15 \times m_Q \sqrt{\alpha_s} \approx 0.16\,\text{GeV for J}/\psi\,\text{and}\,0.46\,\text{for}\,\Upsilon$

Different quarkonia melt at different temperatures

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

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

	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



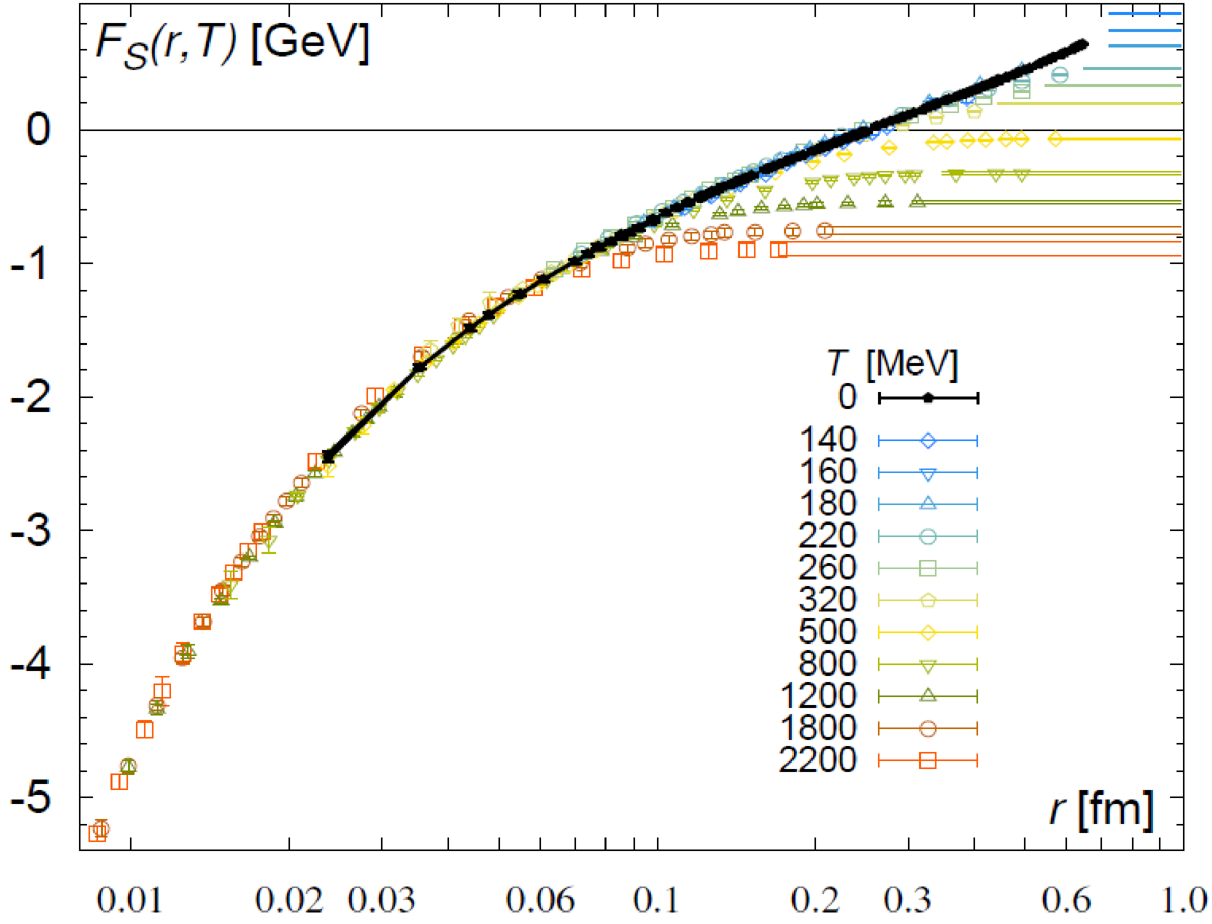
exact values very model dependent, but basic feature: J/ψ, ψ', χ_c, Υ' not bound at or little above T_c, Υ survives longer

Results on Debye screening from lattice QCD

- after two decades of debate, now some agreement how to extract effective heavy quark potential
- starting from: color singlet free energy → general consensus: potential has real and imaginary part

- at LHC all quarkonia should be Debye screened
- considering formation time of hadrons, they should not form at high T at all

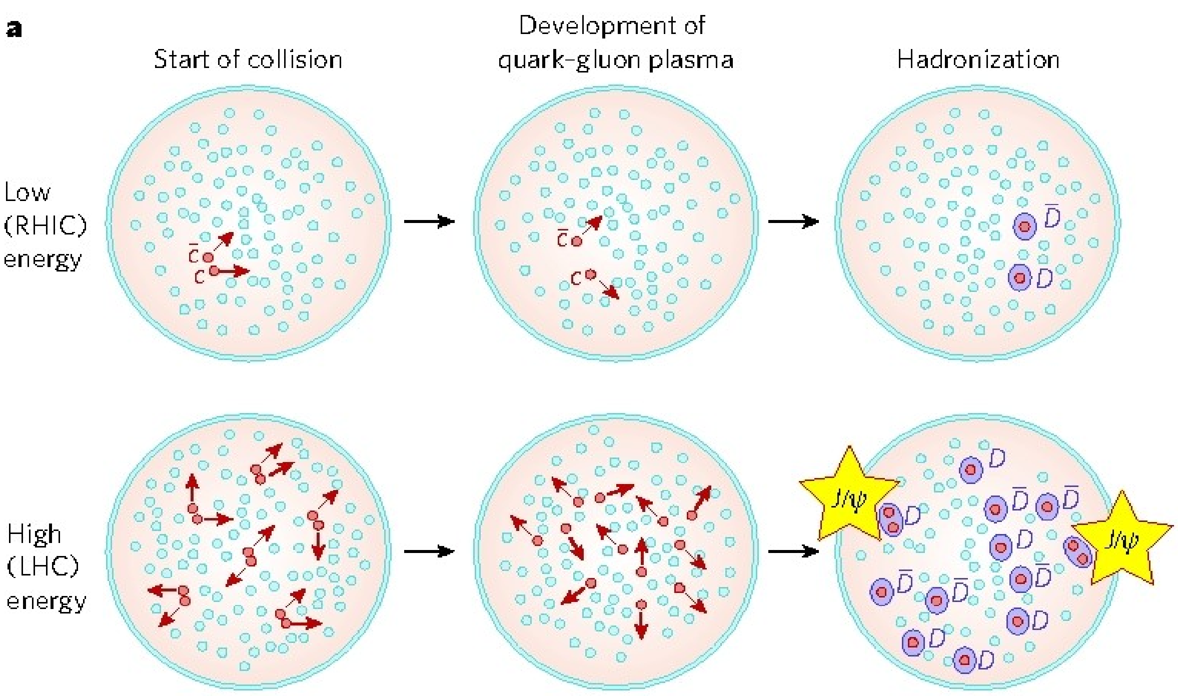
TUMQCD arXiv:1804.10600



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) - $N_{J/\psi} \propto N_{cc}^2$
(P. Braun-Munzinger and J. Stachel,Phys. Lett. B490 (2000) 196)

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



Extension of statistical model to include charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
  $N_{c\bar{c}}^{direct}$ from data (total charm cross section) or from pQCD

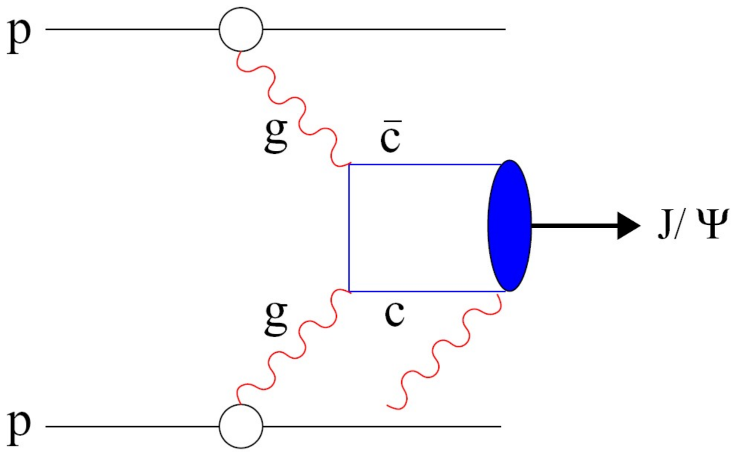
- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (canonical corr. if needed) technically number of charm quarks fixed by a charm-balance equation containing fugacity g_c

$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}\right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm}\right) + \ldots$$

↑

the only additional free parameter

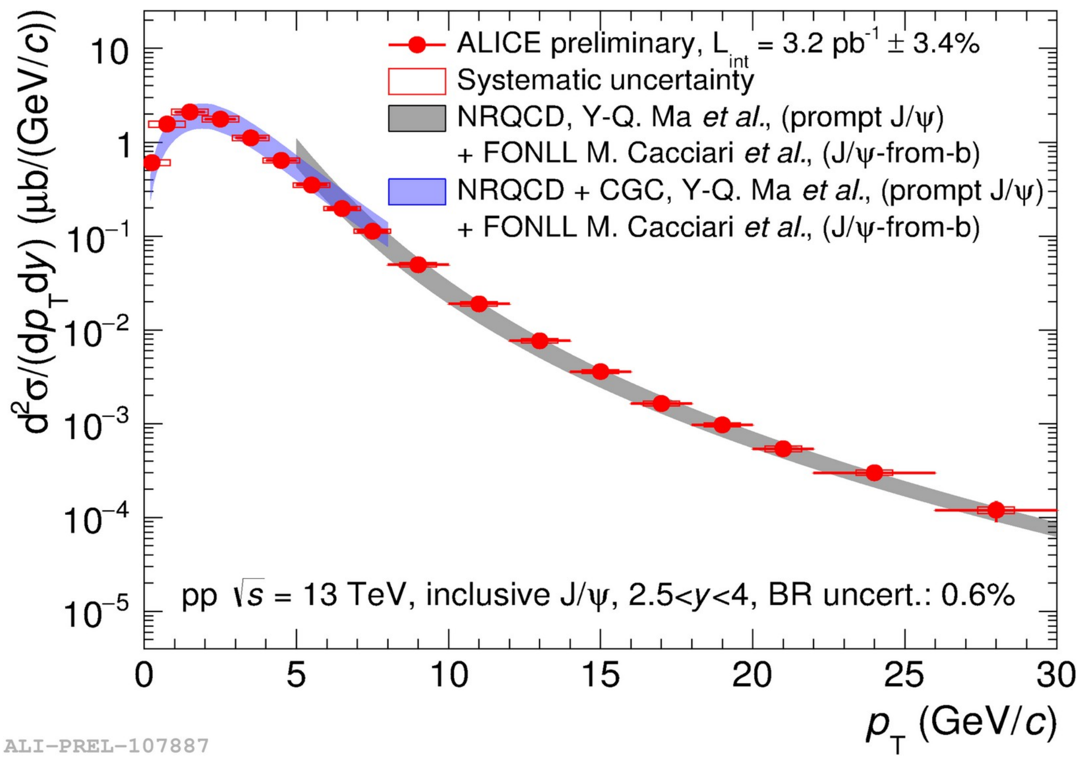
10.3 Production of charmonia in hadronic collisions



- 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

by now rather 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

hard	0.05 fm	pre–resonance	0.25 fm	resonance
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c\Lambda_{qcd}}$	

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

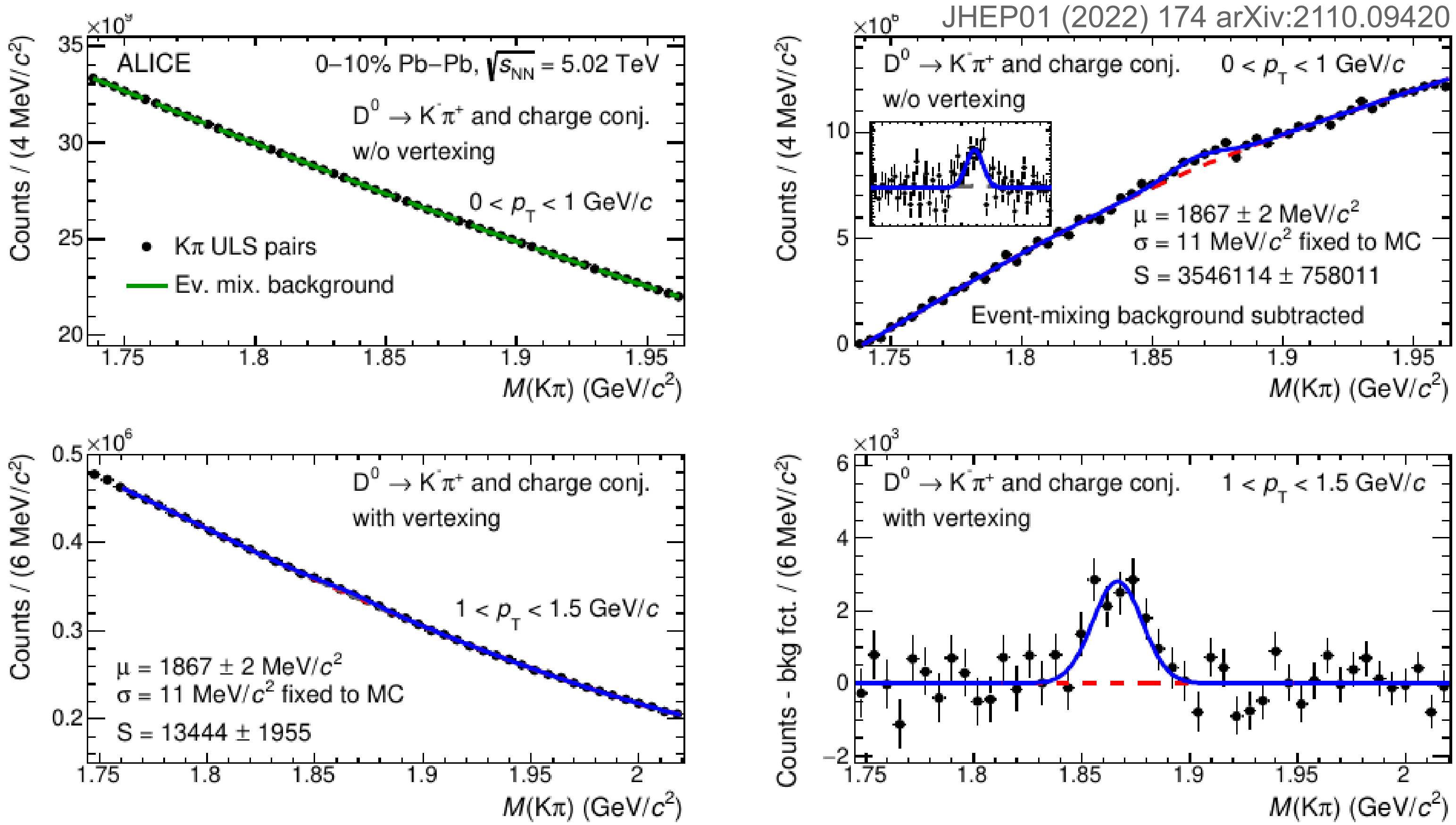
collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS $t_{coll} = \tau_{ccbar} \cong \tau_{QGP} \cong \tau_{hadron}$
making theoretical treatment difficult

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

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

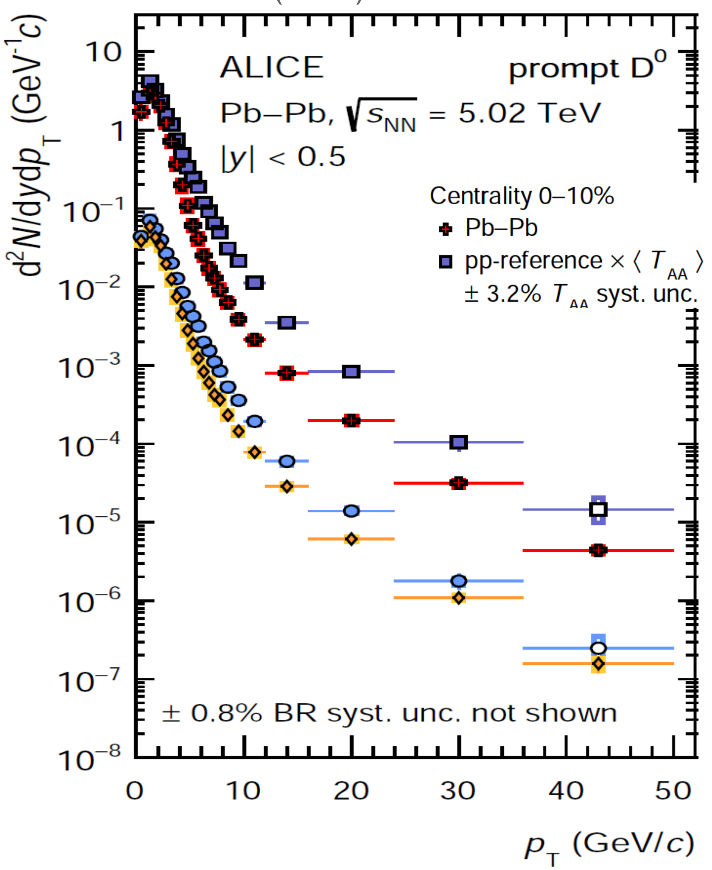
Measurement of charm cross section in PbPb collisions

a huge experimental challenge due to the large combinatorial background
requires excellent vertexing capabilities of experiment and particle identification



Measurement of charm cross section in PbPb collisions

JHEP01 (2022) 174 arXiv:2110.09420



first D^0 measurement in central PbPb down to p_t=0

$$dN/dy = 6.819 \pm 0.457\ (\text{stat.})\ ^{+0.912}_{-0.936}\ (\text{syst.}) \pm 0.054\ (\text{BR})$$

assume fragmentation like in SHMc → charm cross section

$dN_{ccbar}/dy = 13.7 \pm 2.1$ corresponing to $g_c = 31.4 \pm 4.8$

use this as new basis for PbPb predictions from SHMc

outlook to LHC Run3/4: with upgraded ALICE detector and 50 kHz PbPb collisions → precision measurement of all singly charmed hadrons down to p_t=0

10.4 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 ϒ via e+e- or μ+μ-

χ_c very difficult, usually done via

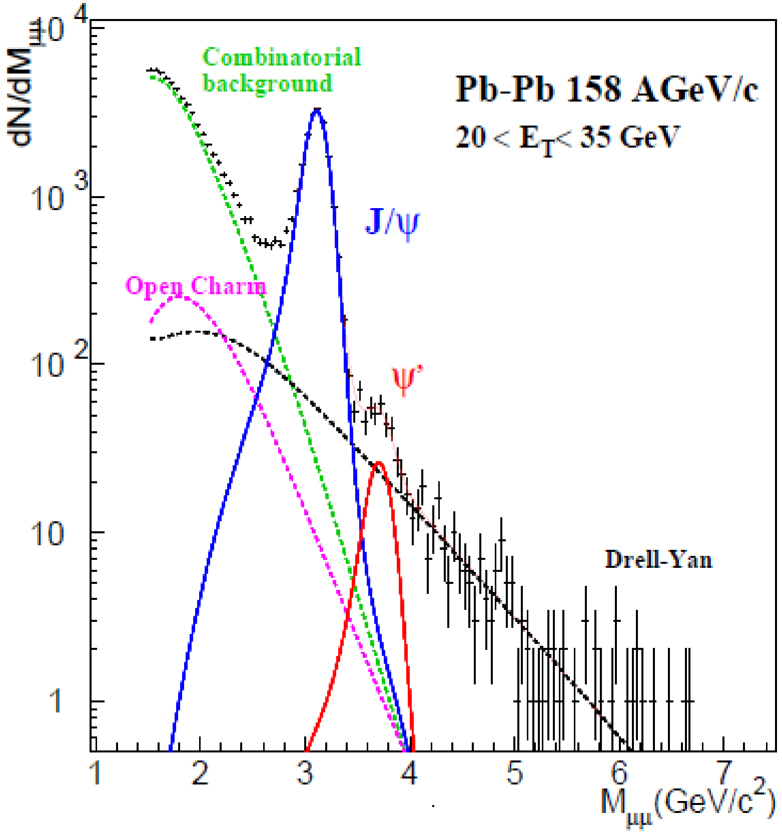
$$\chi_c \to \mathrm{J}/\psi + \gamma$$

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

10.5 Charmonia in nuclear collisions

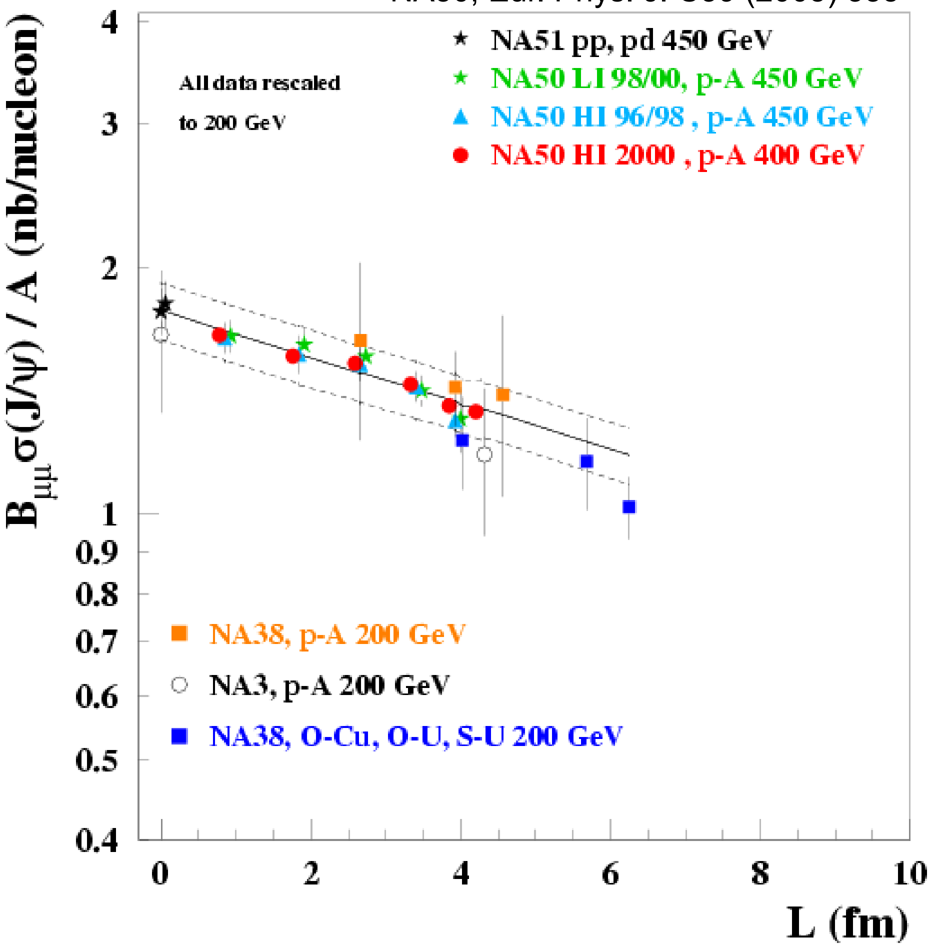
in pA collisions at moderate energies (200-450 GeV) universal picture: prehadronic state absorbed in nuclear matter (Gerschel, Hüfner 1992)

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

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

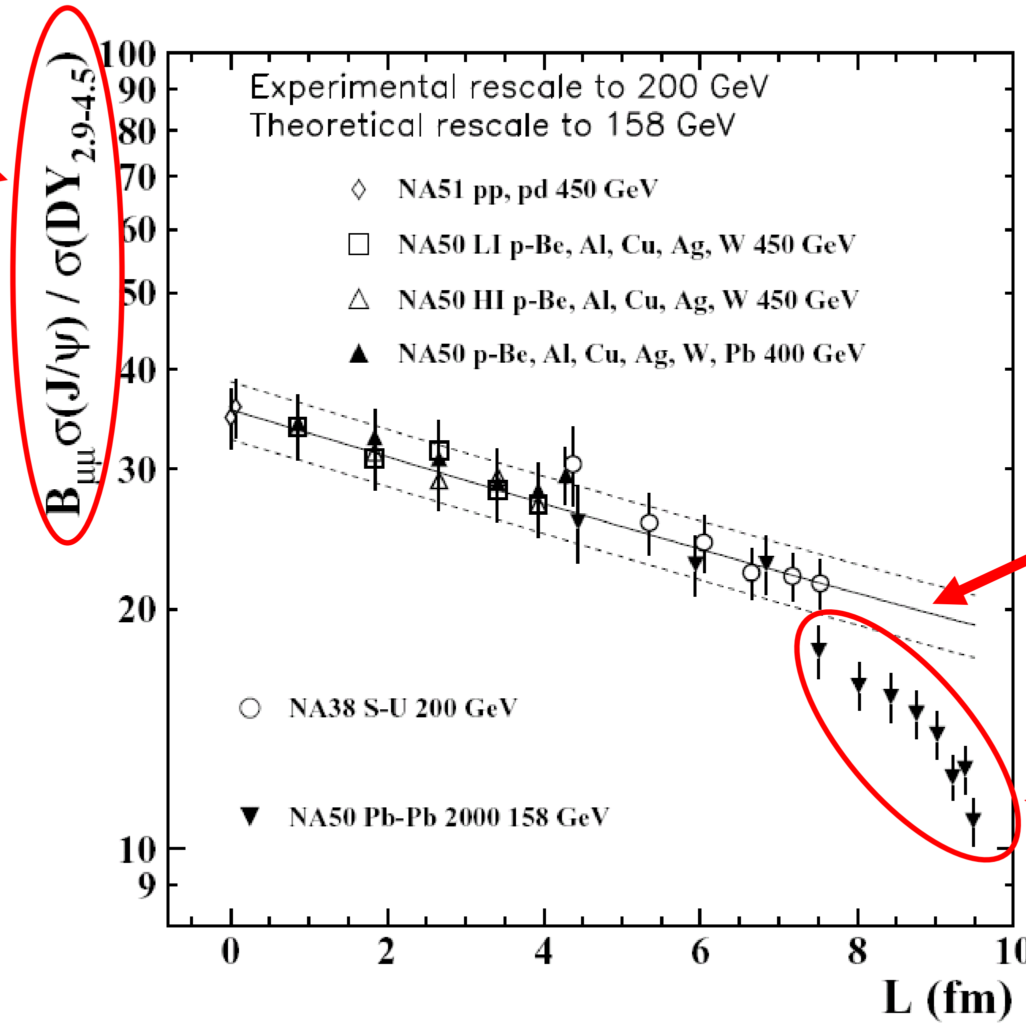
light nuclear collisions follow the same picture

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



J/ψ production in PbPb collisions at SPS energy

normalization to Drell-Yan process



'normal' J/ψ suppression on nuclear matter

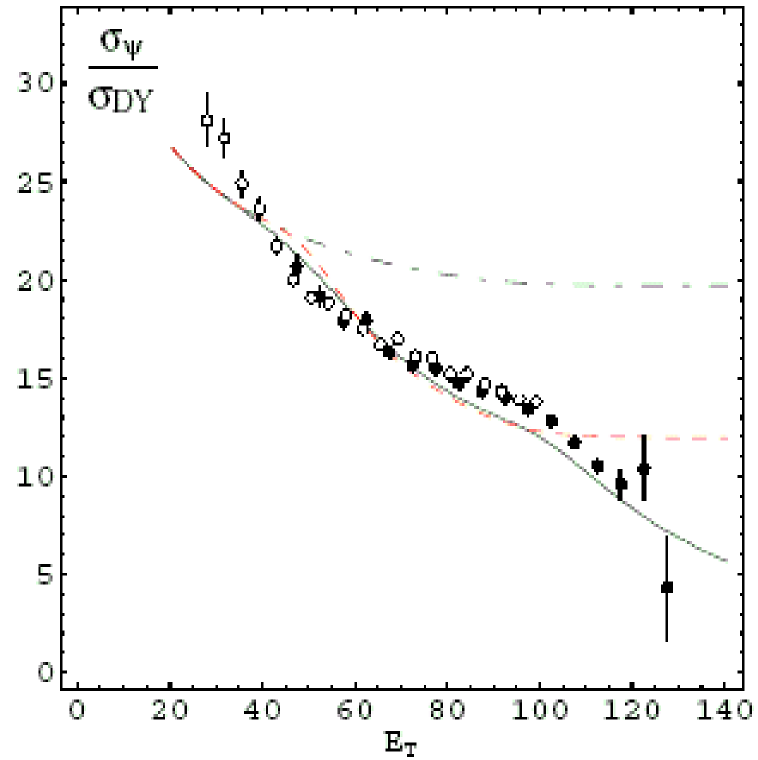
'anomalous' J/ψ suppression due to QGP?

in central PbPb collisions about 40% less J/ψ than expected from pA systematics

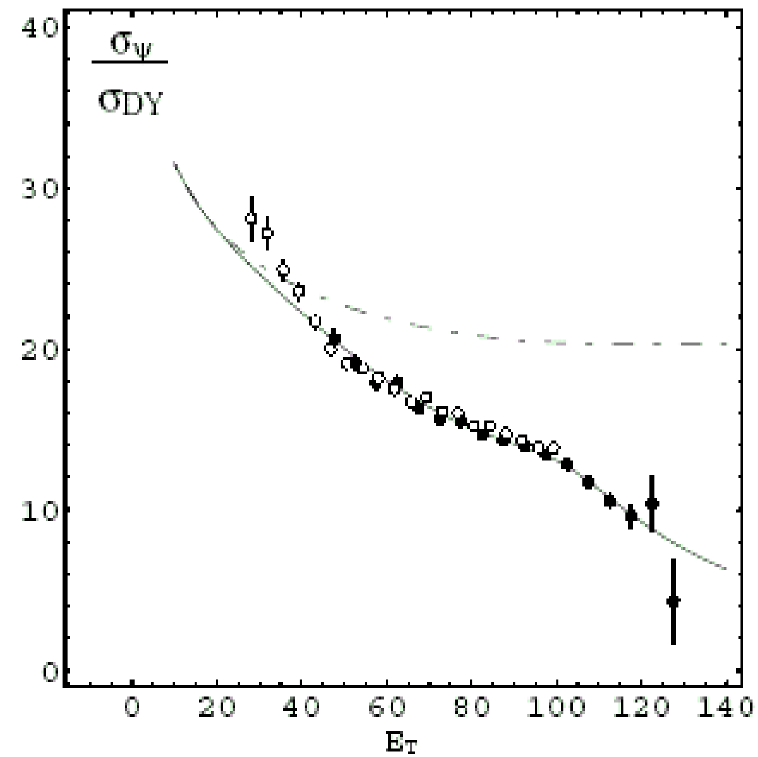
SPS data consistent with suppression at critical density

dissolution in QGP at critical density n_c (red dashes) and in addition effect of energy density fluctuations (solid)

$n_c = 3.7/\mathrm{fm}^2$



$n_{c1} = 3.3$ and $n_{c2} = 4.2/\mathrm{fm}^2$

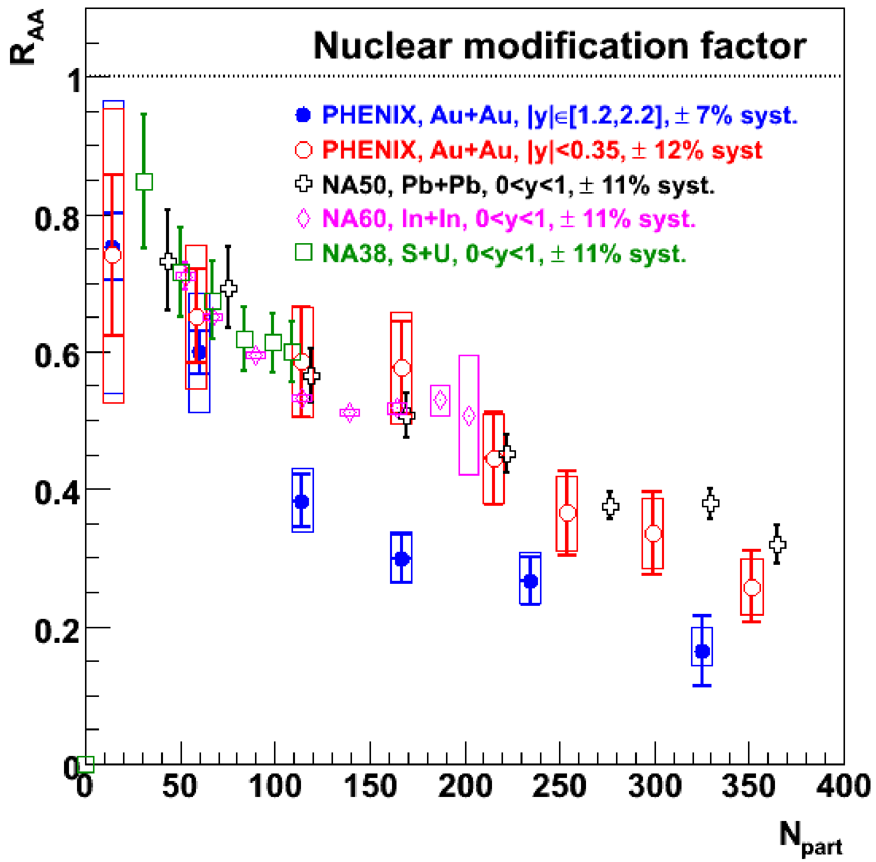


→ increasing energy density

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

J/ψ production in AuAu collisions at RHIC

PHENIX PRL 98 (2007) 232301



$$R_{AB} = \frac{dN/dp_T|_{A+B}}{\langle T_{AB}\rangle \times d\sigma_{inv}/dp_T|_{p+p}},$$

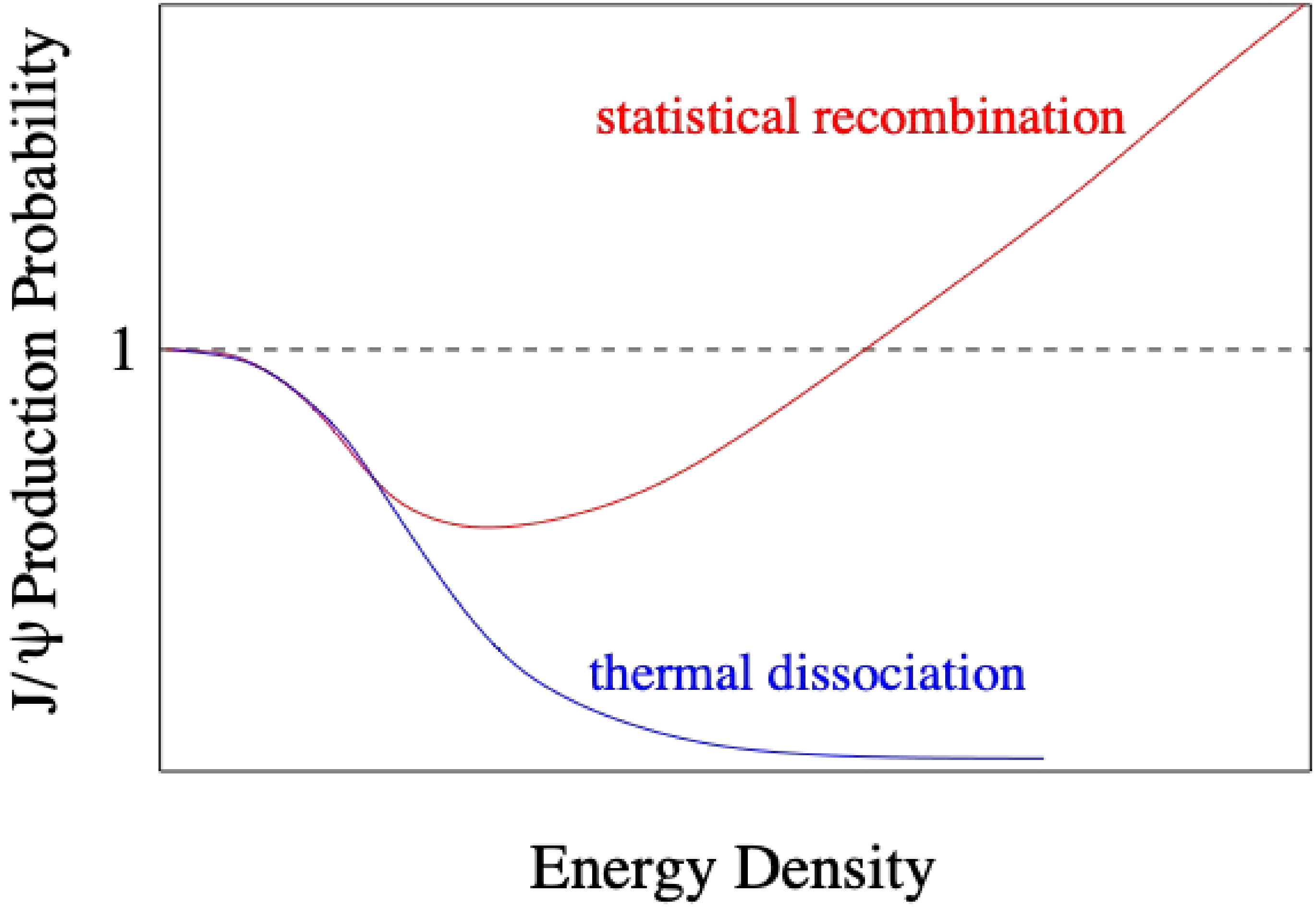
$$\text{where} \quad \langle T_{AB}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$

at mid-rapidity suppression at RHIC very similar to SPS
suppression at forward/backward rapidity stronger!

- but prediction (see above): at hadronization of QGP, J/ψ can form from deconfined quarks, in particular if number of ccbar pairs is large
  $N_{J/\psi} \propto N_{cc}^2$

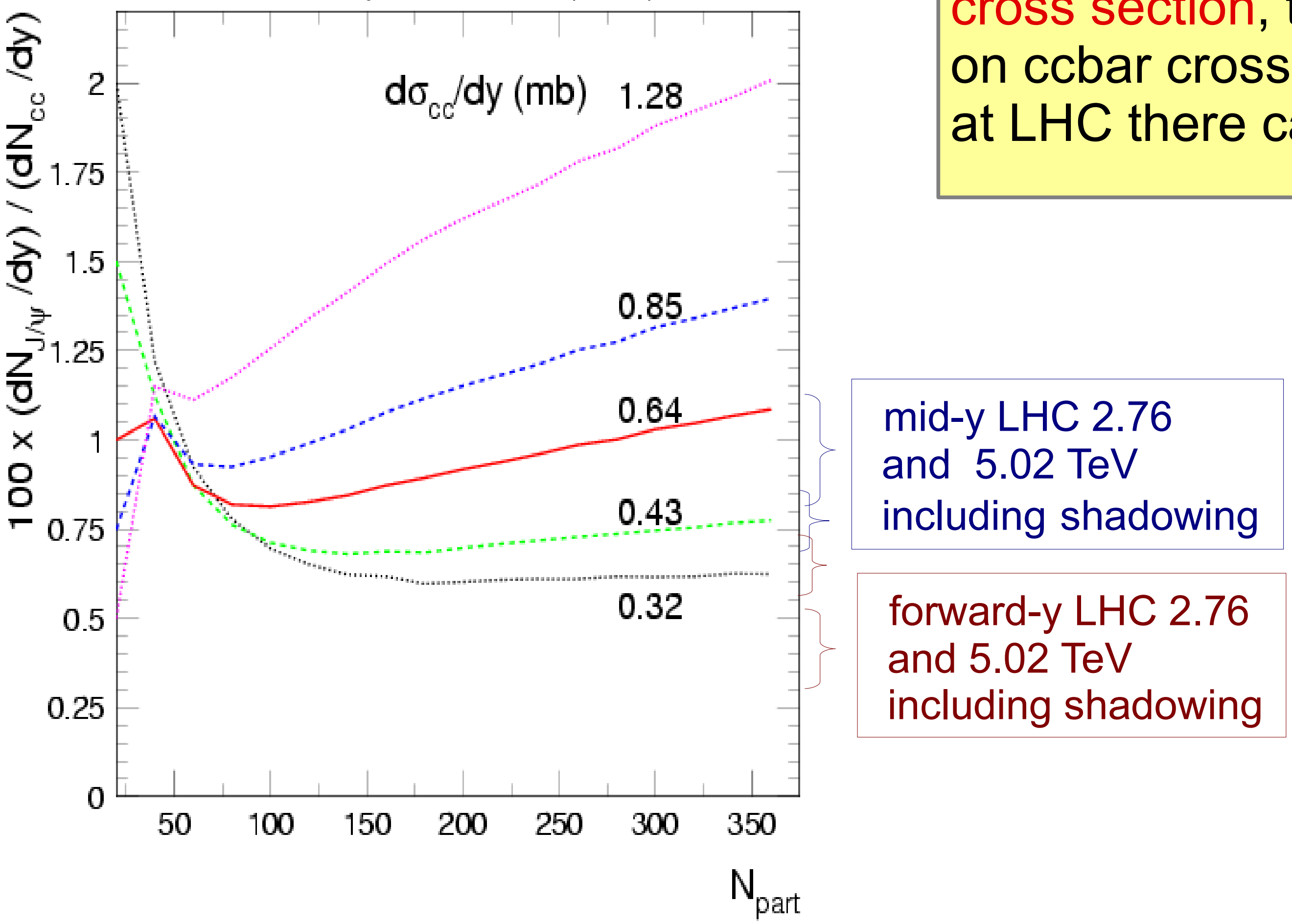
What to expect for LHC?

Kluberg, Satz, arXiv:0901.3831



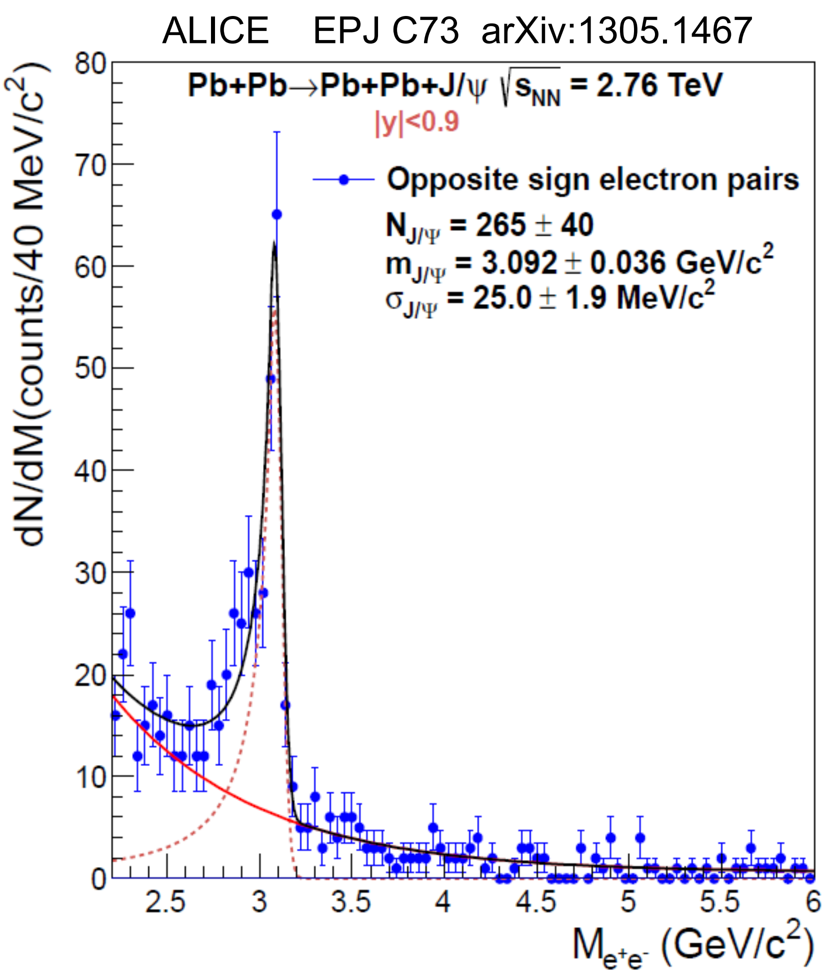
Energy dependence of quarkonium production in statistical hadronization model

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/ψ enhancement

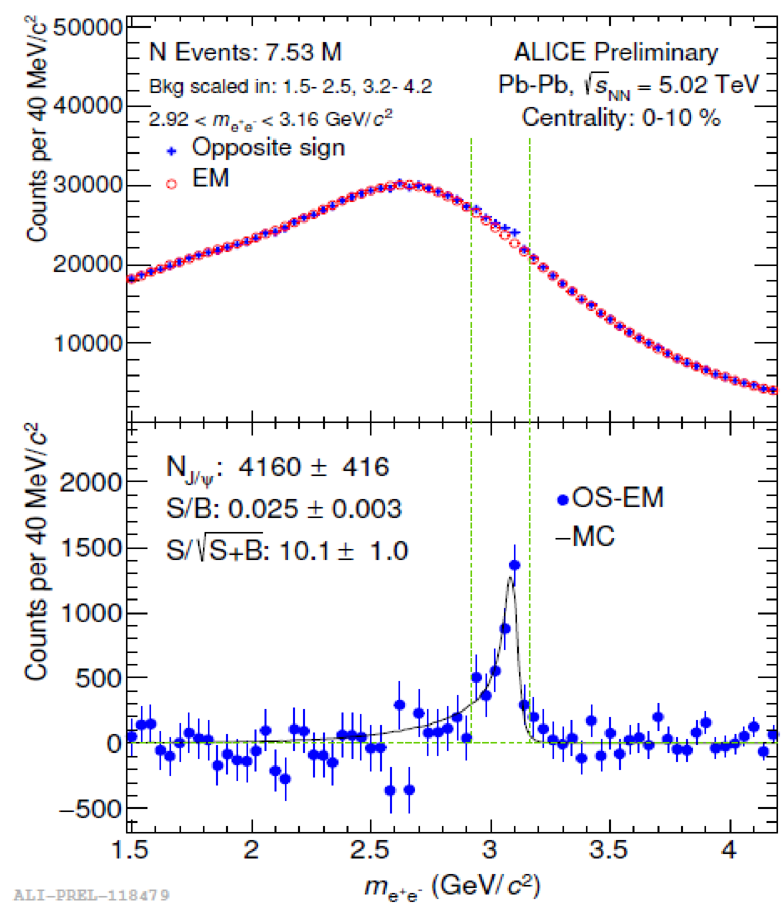
Reconstruction of J/ψ in PbPb collisions at LHC



photoproduction in ultra-peripheral PbPb collisions – excellent signal to background very good understanding of line shape

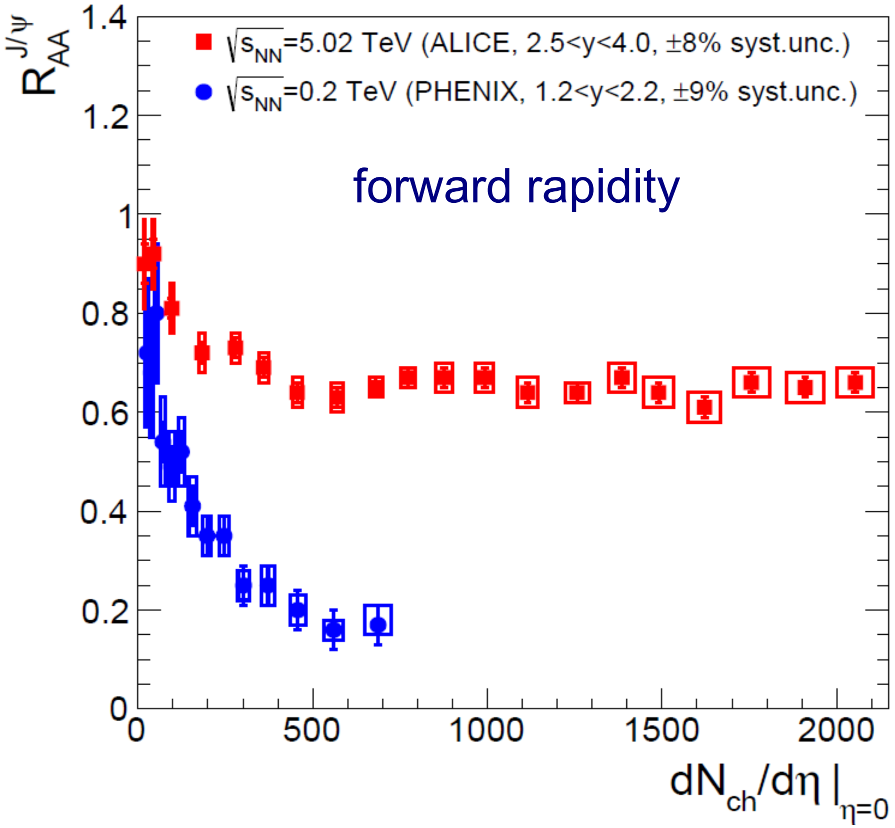
<u>most challenging:</u> central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

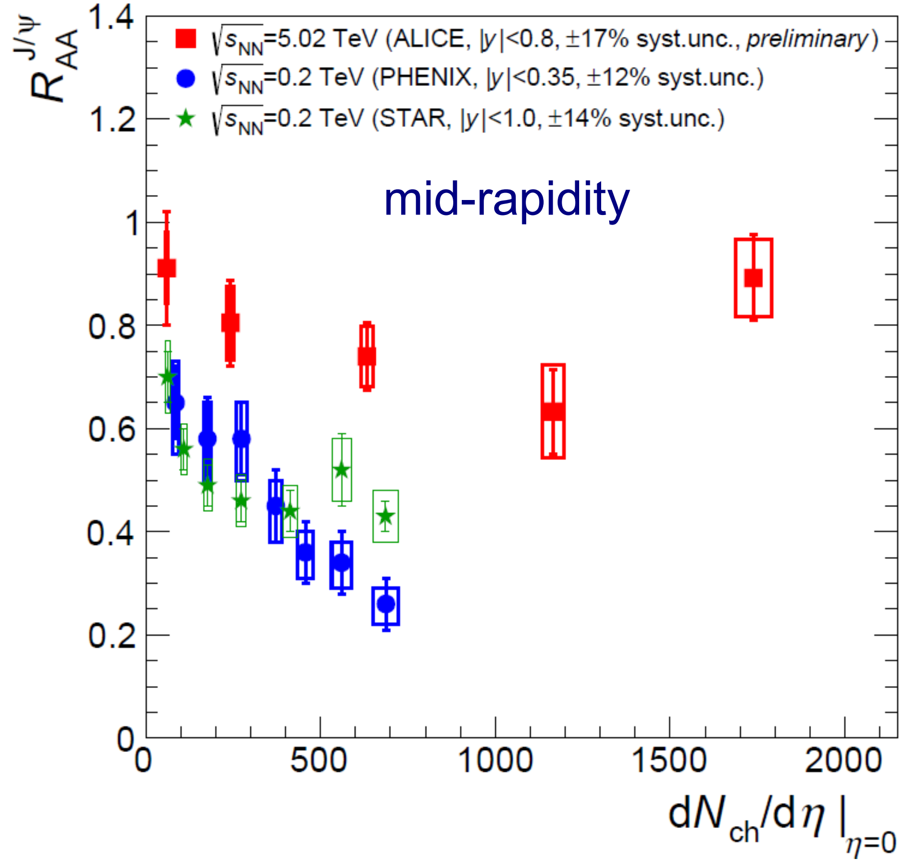
mid |y| < 0.8



J/ψ production in PbPb collisions: LHC relative to RHIC

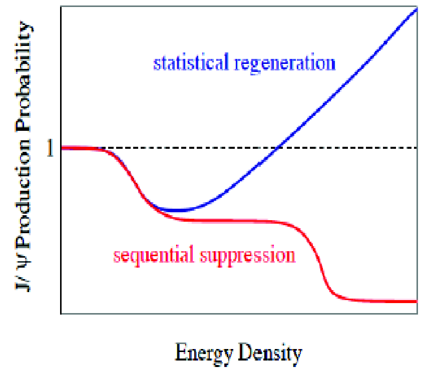
$$R_{AA} = \frac{dN^{AA}/dy}{N_{coll}\, dN^{pp}/dy}$$



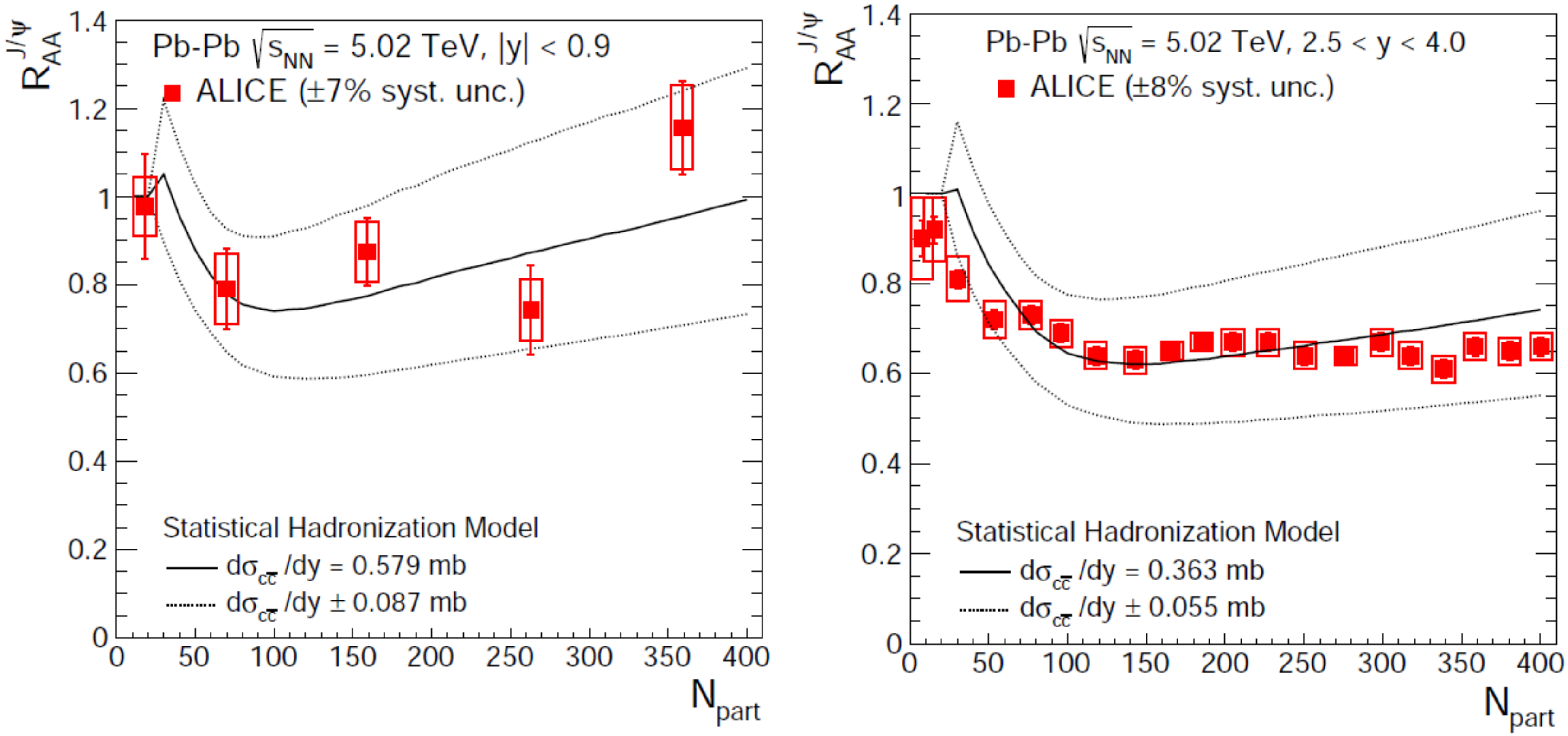


energy density -->

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)



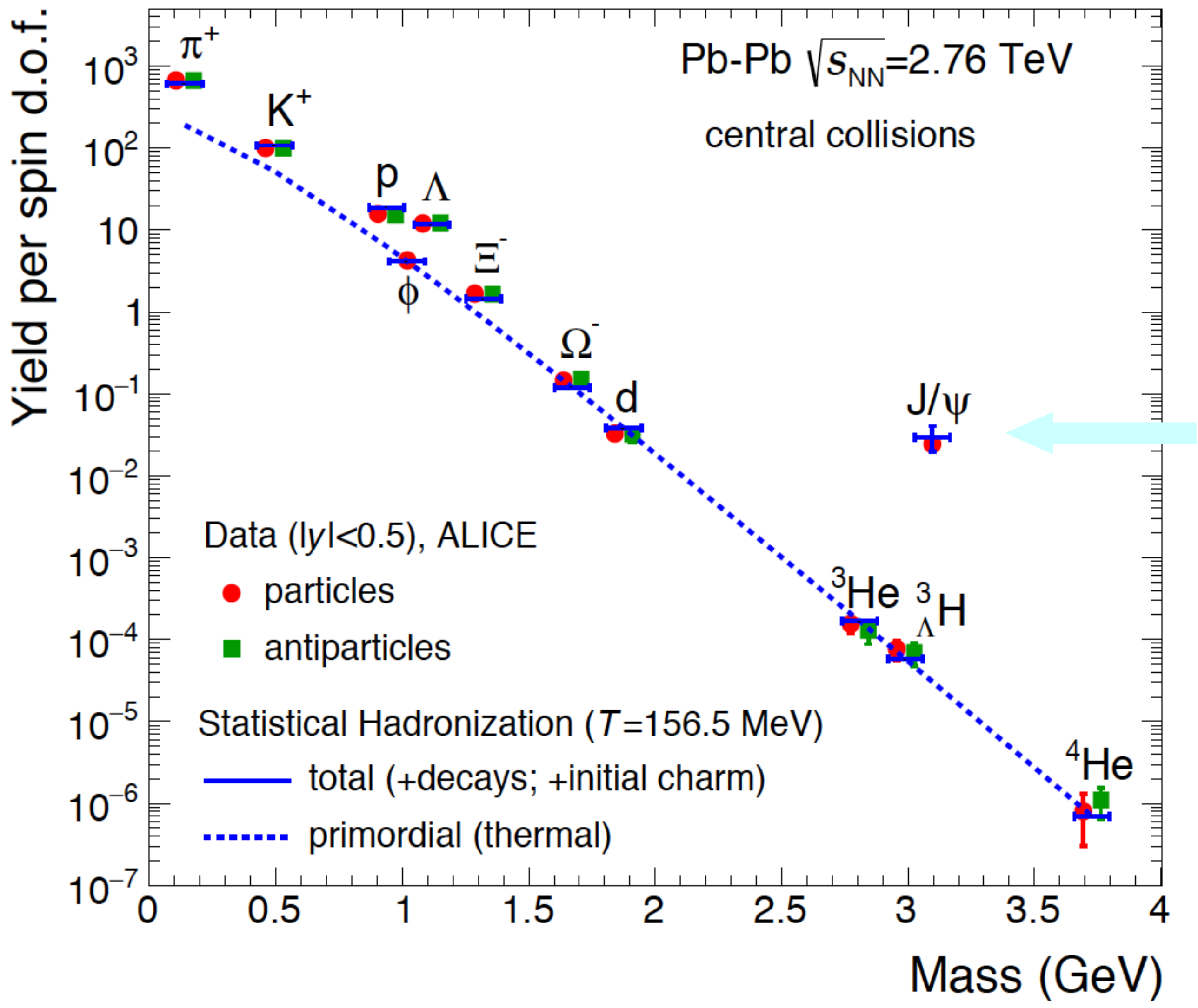
J/ψ and statistical hadronization



production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

main uncertainties for models: open charm cross section

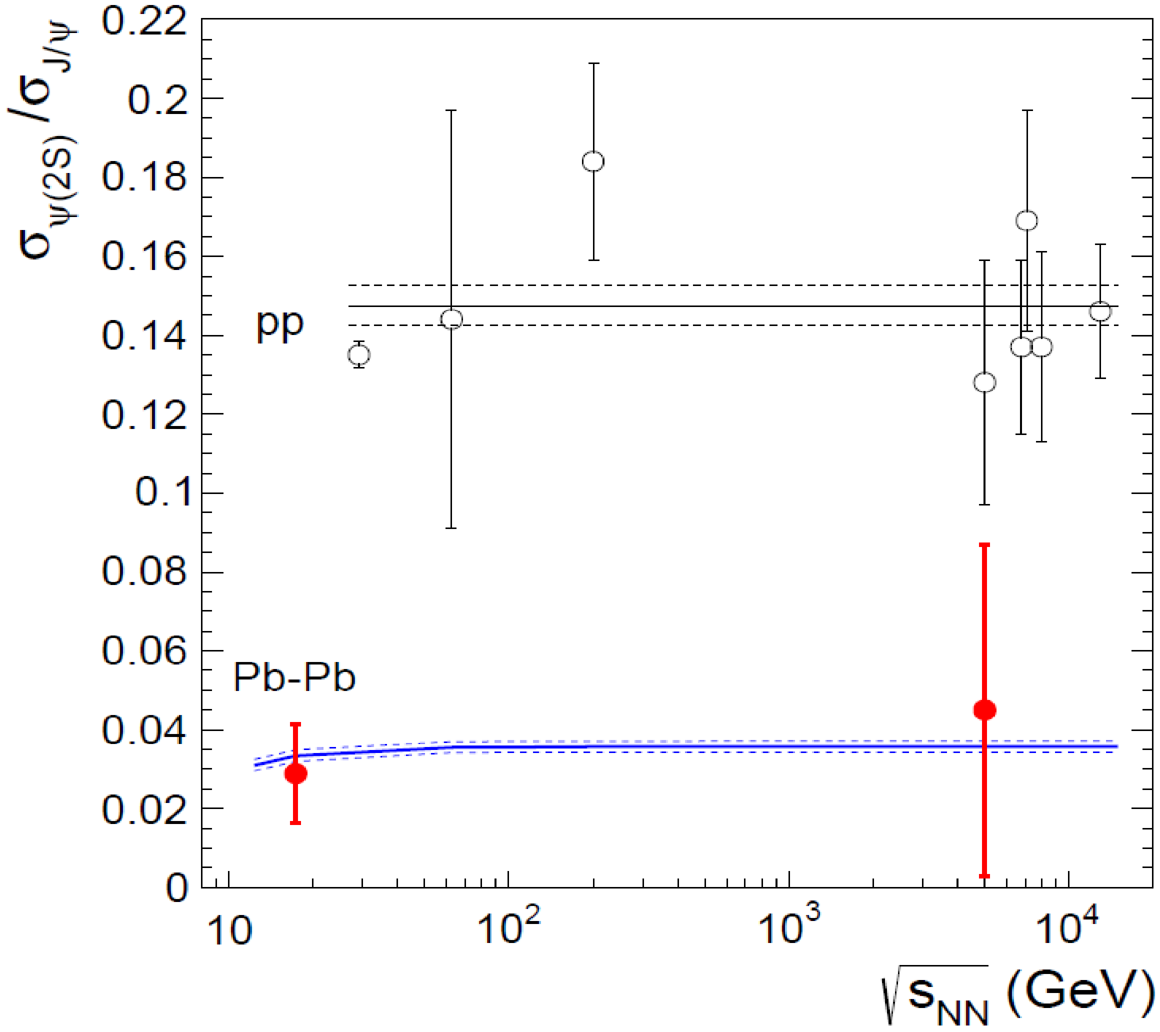
Systematics of hadron production in SHM



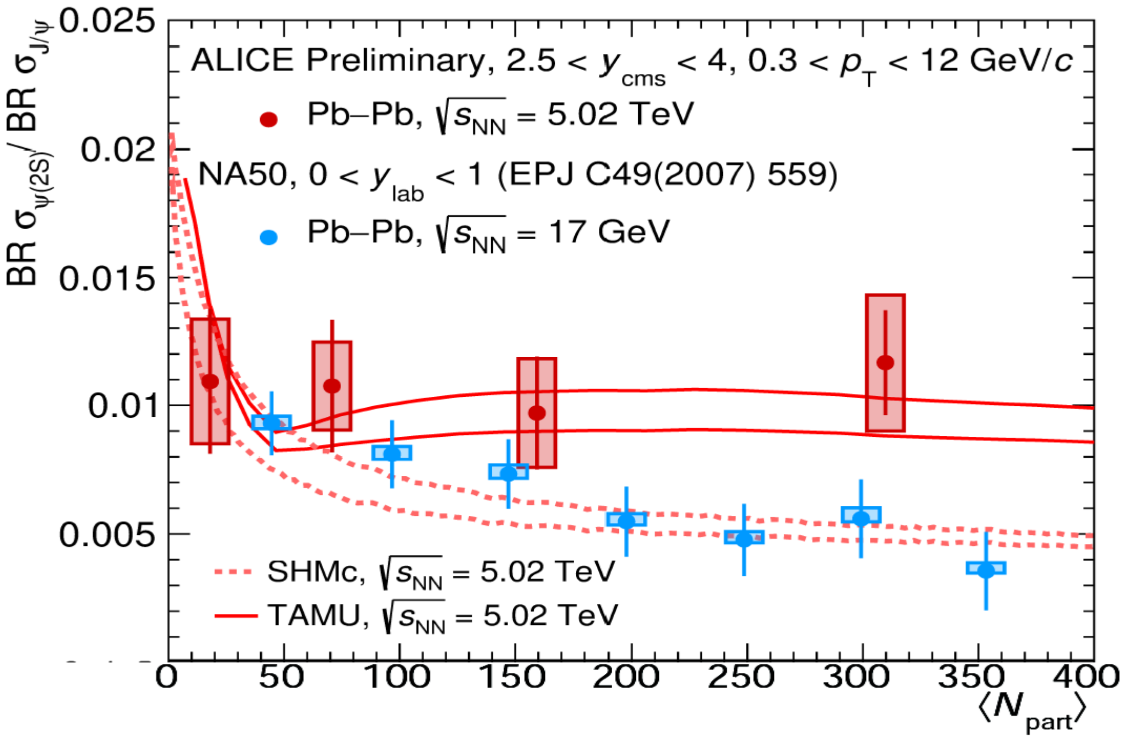
yield exactly reproduced with stat hadr. of deconfined and thermalized c-quarks from initial hard scattering (fugacity)

Systematics of ψ(2S) production

in picture where ψ is created from deconfined quarks in QGP or at hadronization, ψ(2S) is suppressed more than J/ψ



ψ(2S) in PbPb collisions at the LHC



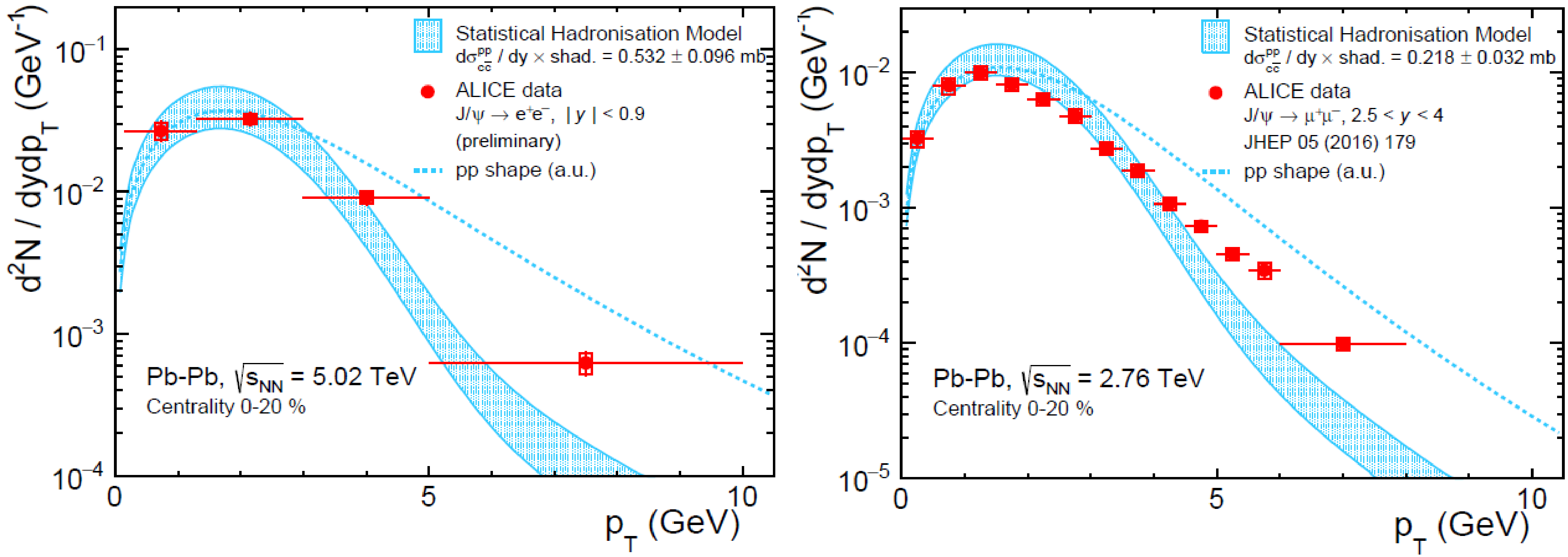
excited state population suppressed by Boltzmann factor
- first measurement in PbPb down to p_t=0
- data 1.8 σ above SHMc for most central bin

future opportunity:
higher precision ψ(2S), also mid-y
χ_c maybe only in ALICE3?

} deconfinement temperature from charmonium spectrum (see homework)

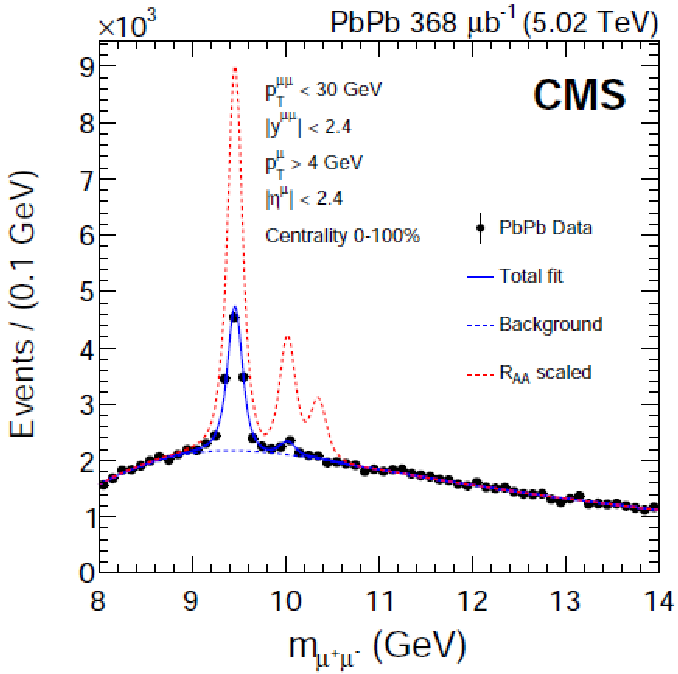
J/ψ transverse momentum spectra from stat. hadr.

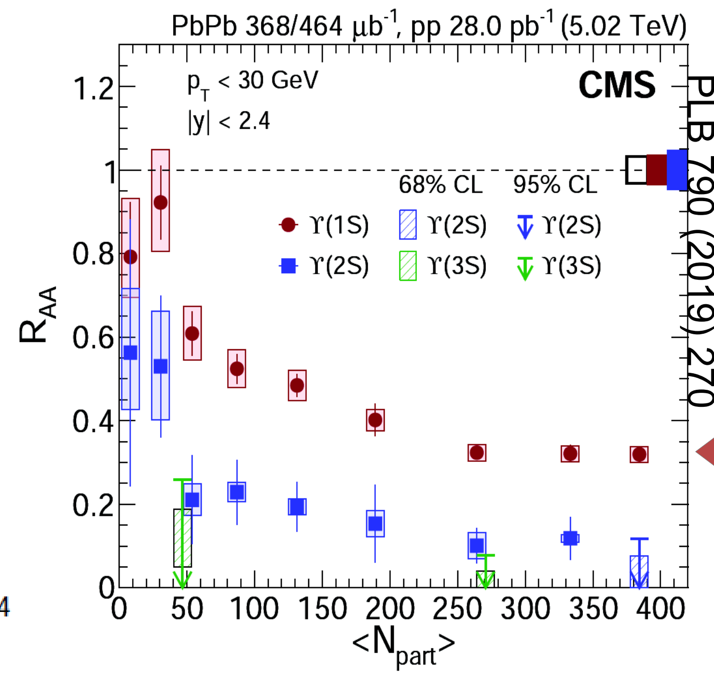
M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236



good agreement up to 5 GeV/c without any free parameters
J/ψ formed at hadronization at T_C from thermalized charm quarks flowing with the rest of the medium

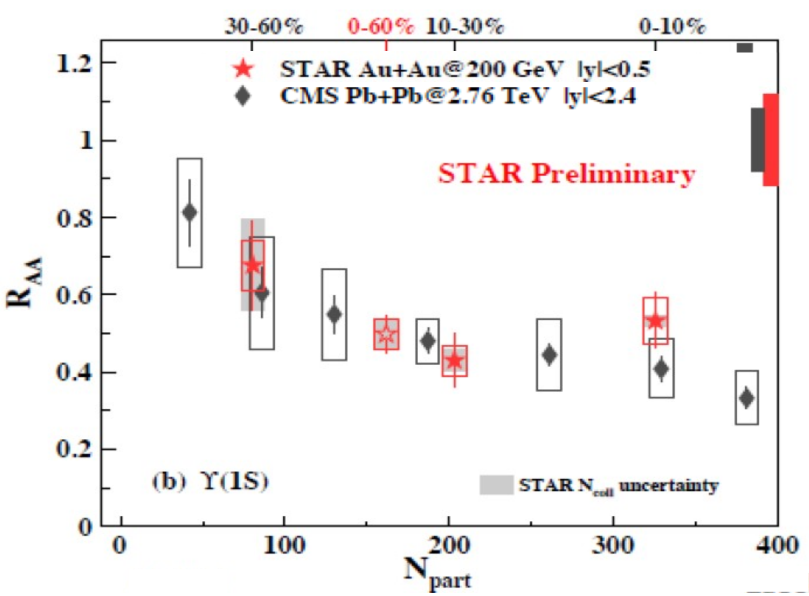
10.6 Bottomonium states





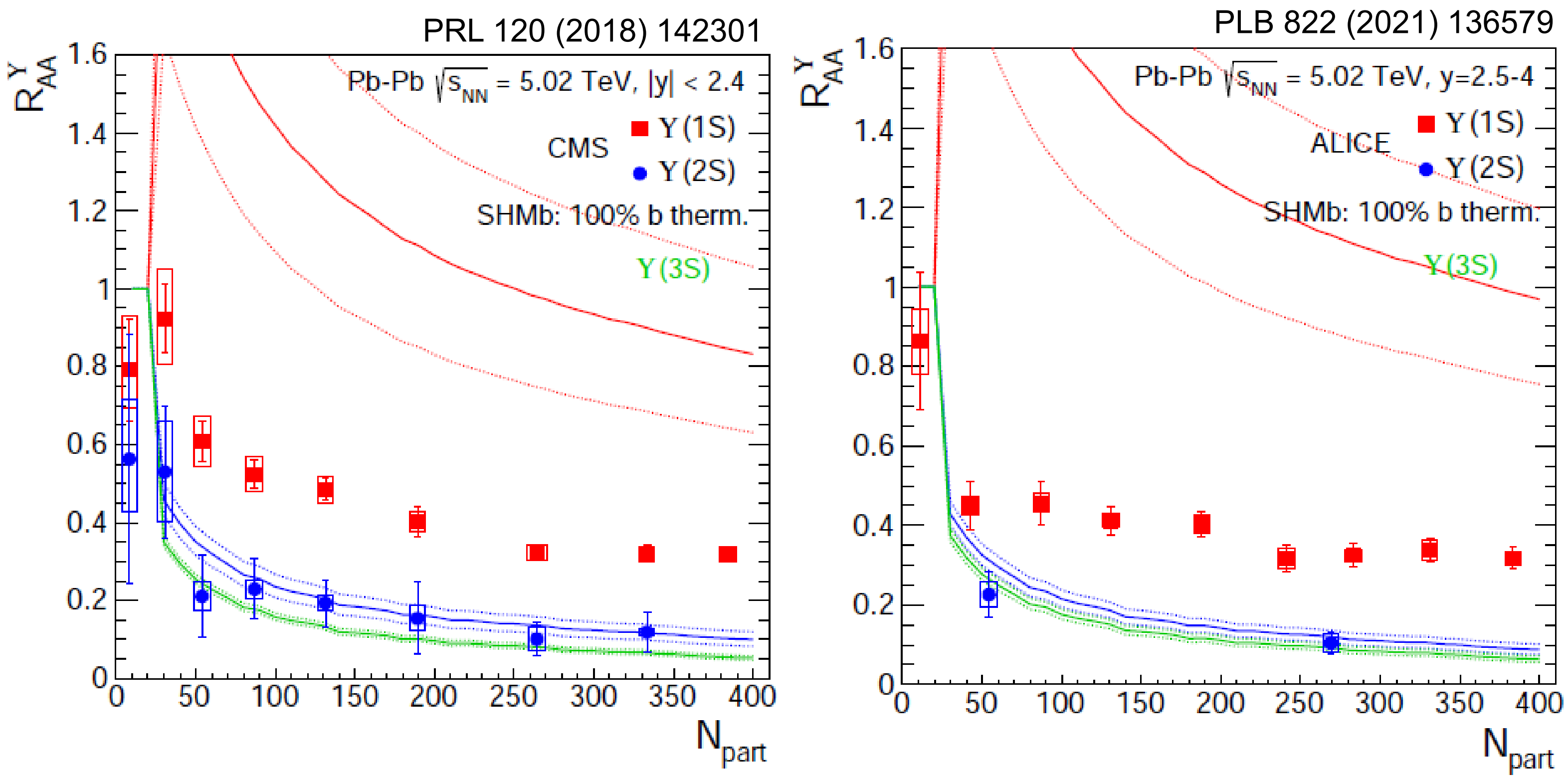
consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed

not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)



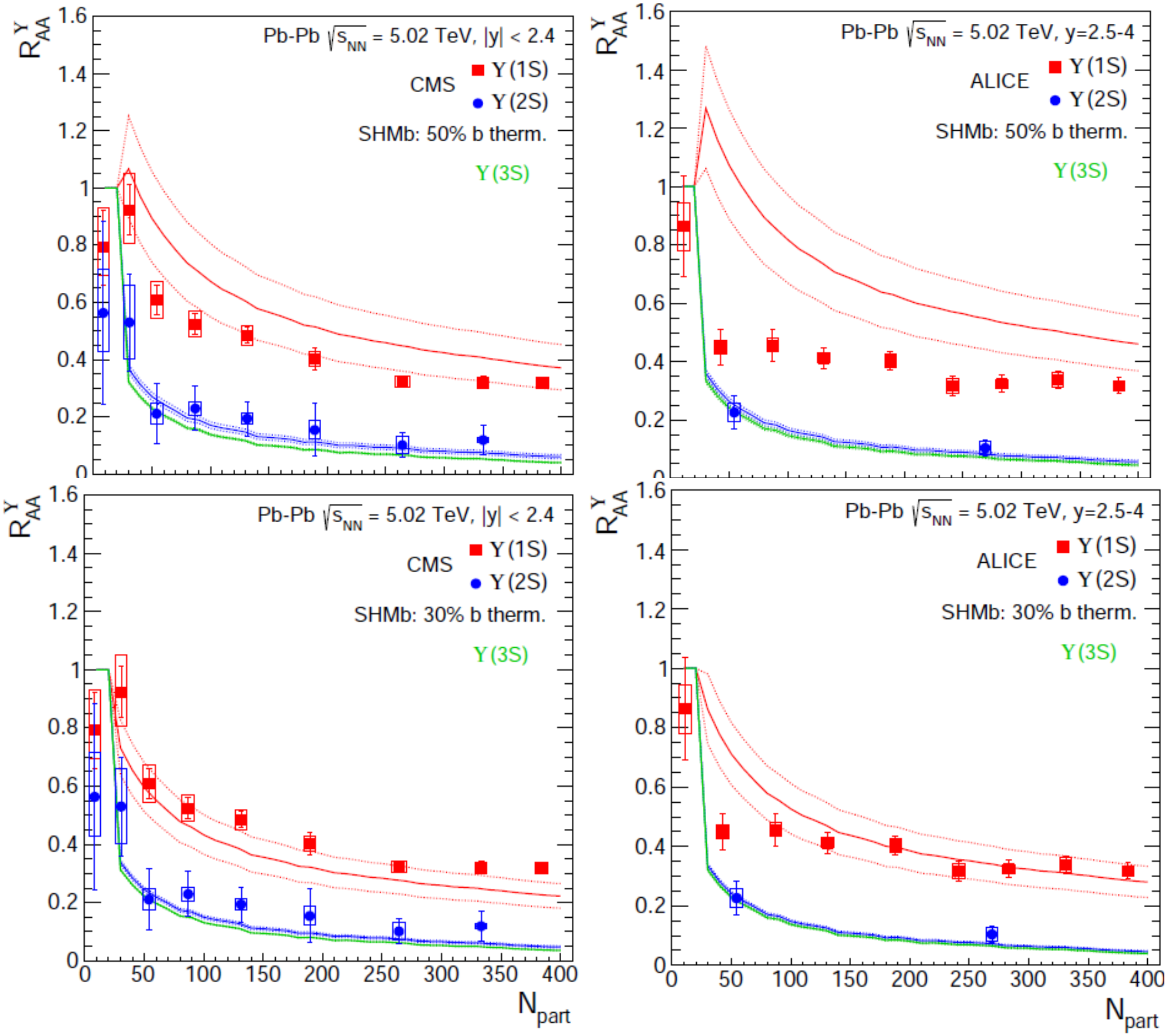
genuine ϒ suppression
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for J/ψ
- possibility of statistical hadronization?

Bottomonia in SHMb assuming full thermalization



- indeed, assumption of fully thermalized b-quarks fails to reproduce $\Upsilon(1S)$ by factor 2-3 for central collisions
  but: $g_b = 10^9$ i.e. Υ is scaled up from thermal yield by 10^{18}
- so, to come without any free parameter within a factor 2-3 is not a minor feat

Bottomonia assuming partial thermalization



30 – 50 % thermalization fraction reproduces Υ yields
→ could be in line with open beauty energy loss and flow