Quark-Gluon Plasma Physics

9. Quarkonia and Deconfinement

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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

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

confinement

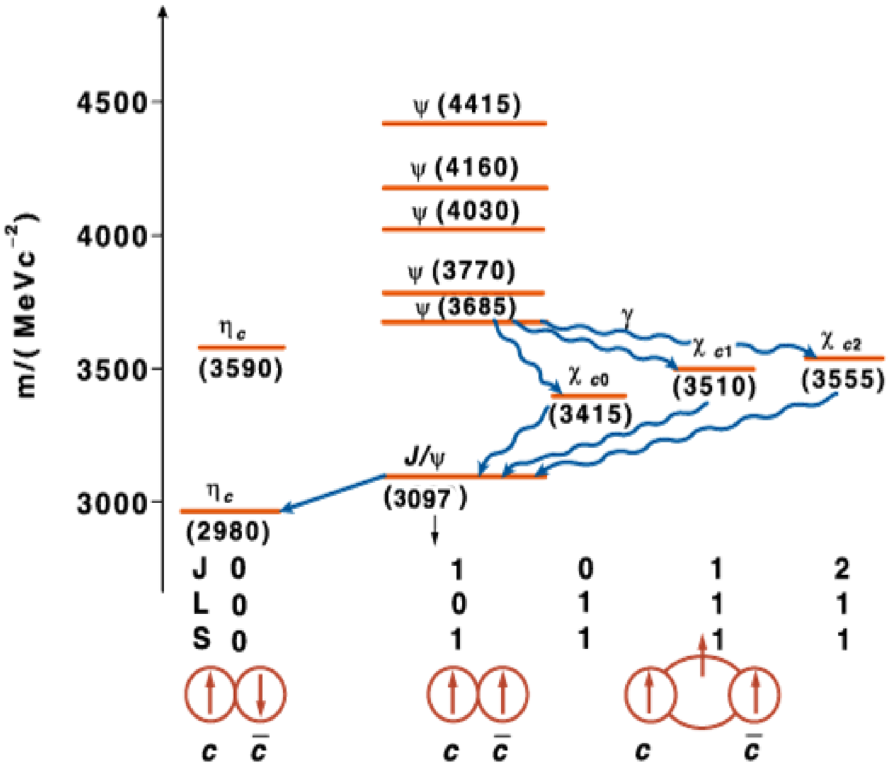
color Coulomb int.

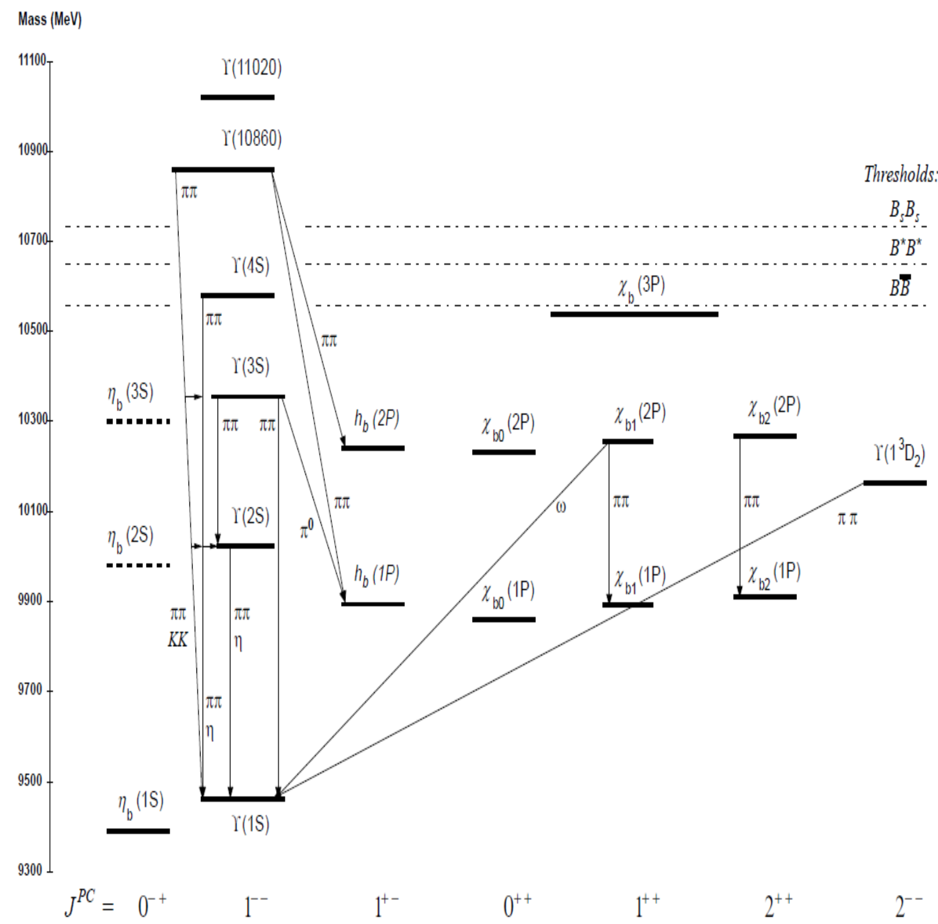
spin-spin int.

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

9.2 Charmonia at finite temperature

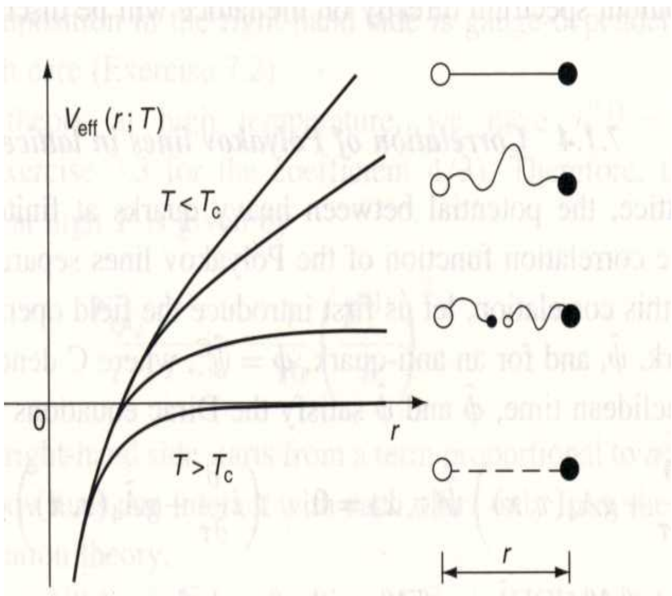
consider T« m_c so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks

consider 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

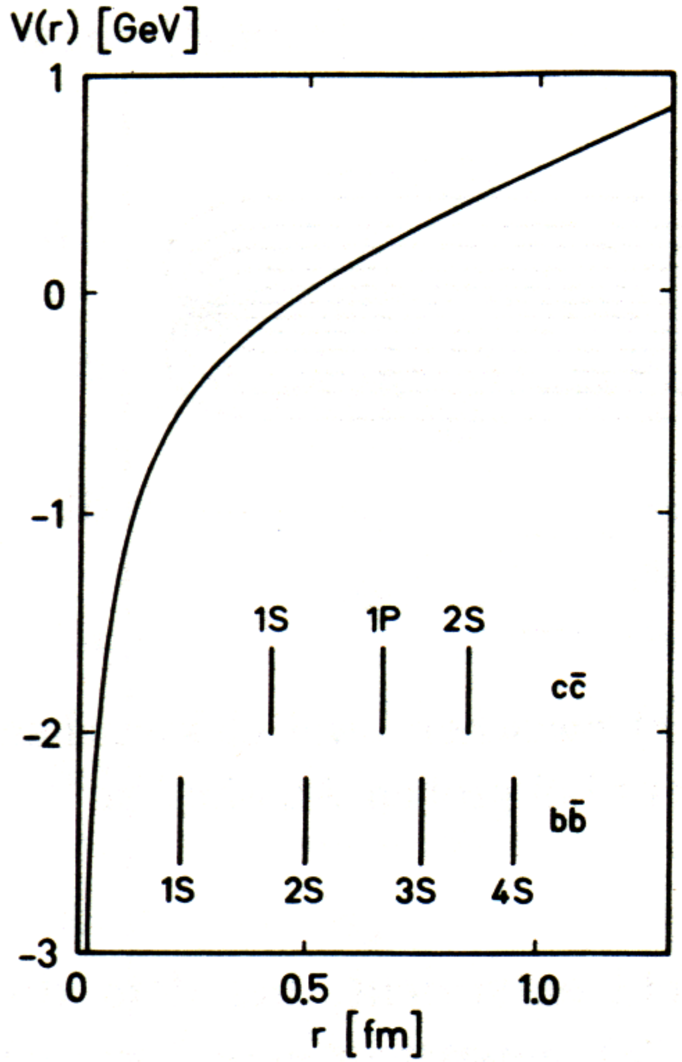
$$T \geq 0.15 \times m_Q \sqrt{\alpha_s} \approx 0.16\,\text{GeV for J}/\psi\,\text{and}\,0.46\,\text{for}\,\Upsilon$$

Different quarkonia melt at different temperatures

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

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 $(\mathrm{GeV/fm^3})$	1.92	1.12	1.12	43.3	1.65

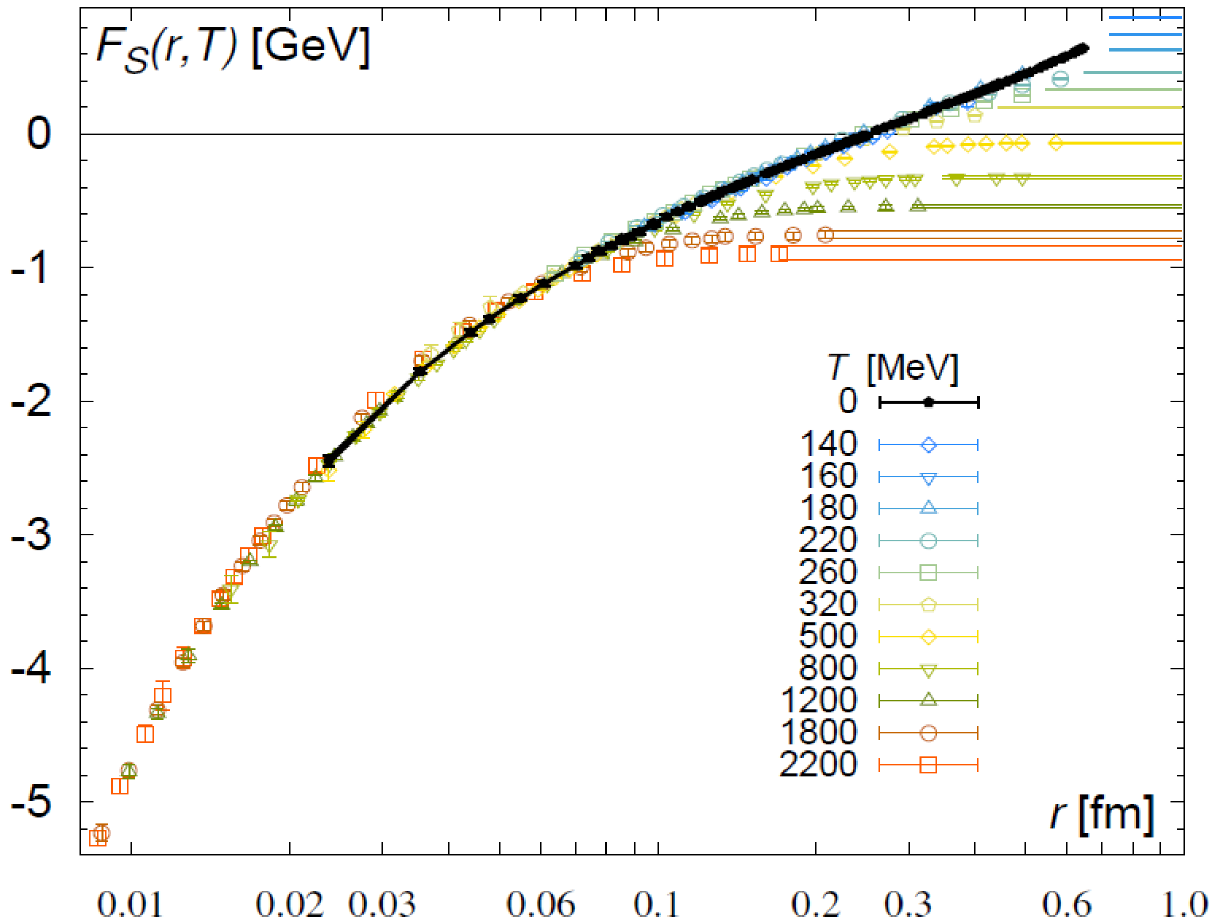


exact values very model dependent, but basic feature: J/ψ, ψ', χ_c, Υ' not bound at or little above T_c, Υ survives longer

Results on Debye screening from lattice QCD

agree qualitatively, quantitatively after a decade 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

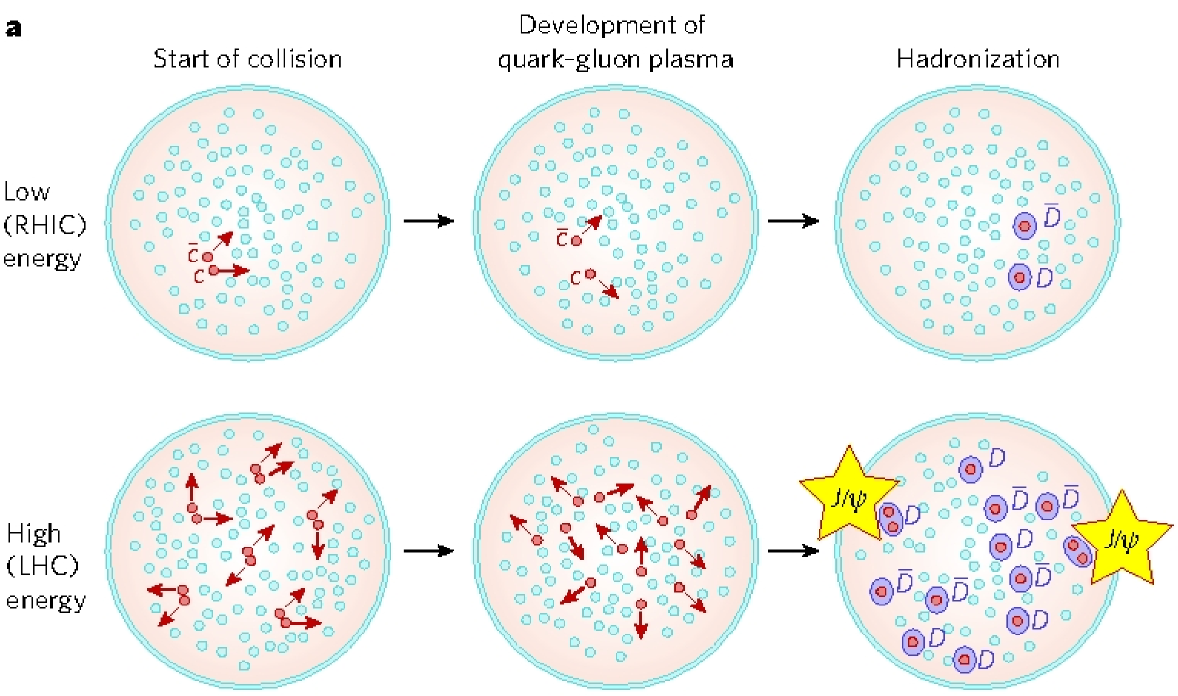
arXiv:1804.10600



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/psi suppression at low beam energies (SPS, RHIC) and
J/psi 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

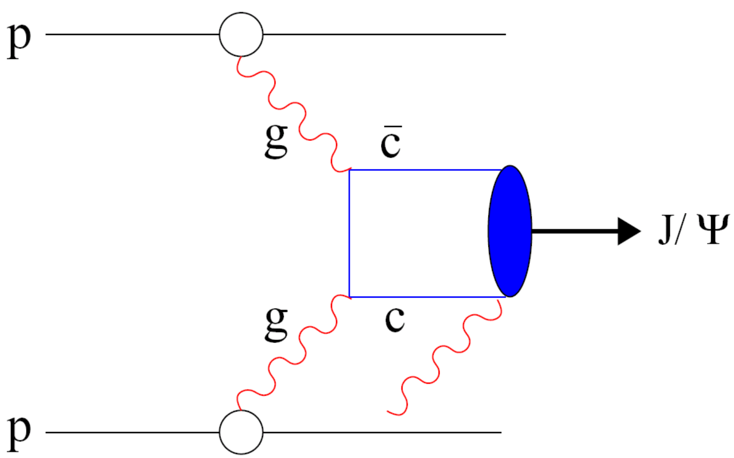
- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (canonical corr. if needed) technically number of charm quarks fixed by a charm-balance equation containing fugacity g_c

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

↑

the only additional free parameter

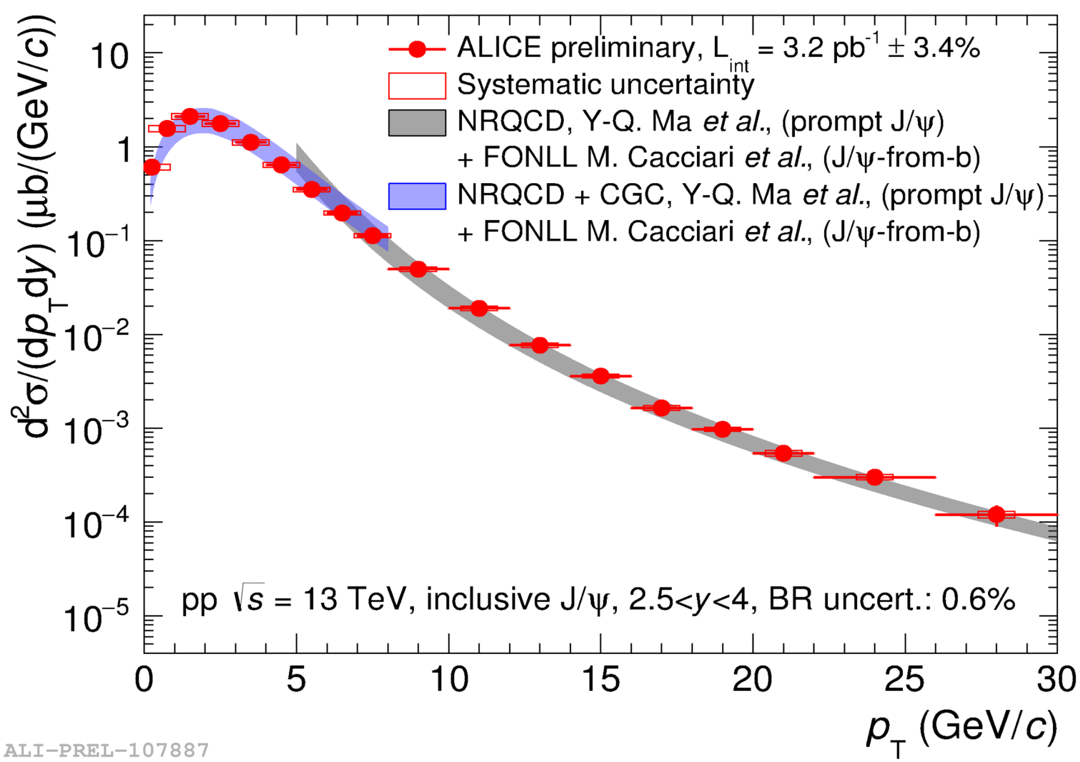
9.3 Production of charmonia in hadronic collisions



- 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

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
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c\Lambda_{qcd}}$	

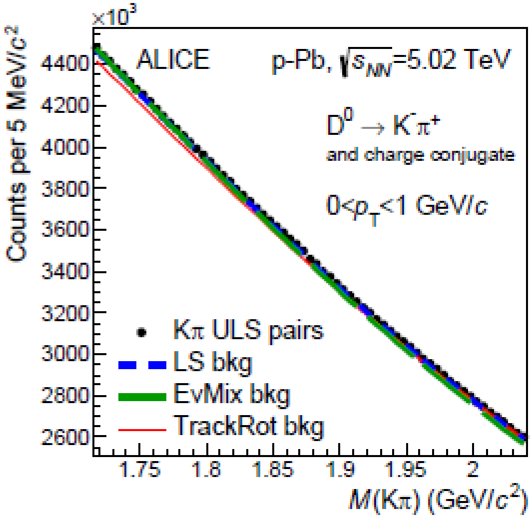
ccbar pairs are formed at collision time scale $t_{coll} = \tau_{ccbar}$

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

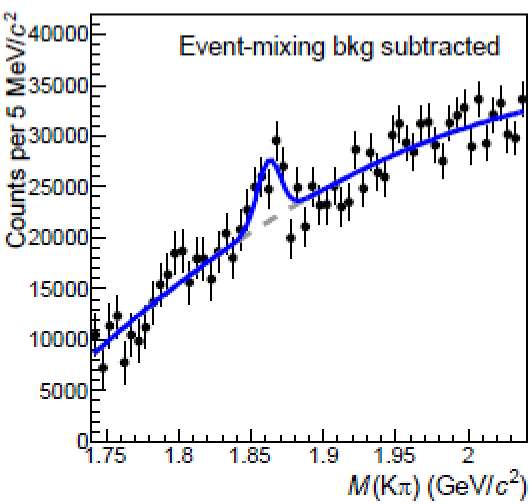
but at RHIC and much more pronounced at LHC there is the following hierarchy: $t_{coll} = \tau_{ccbar} \ll \tau_{QGP} \ll \tau_{hadron}$

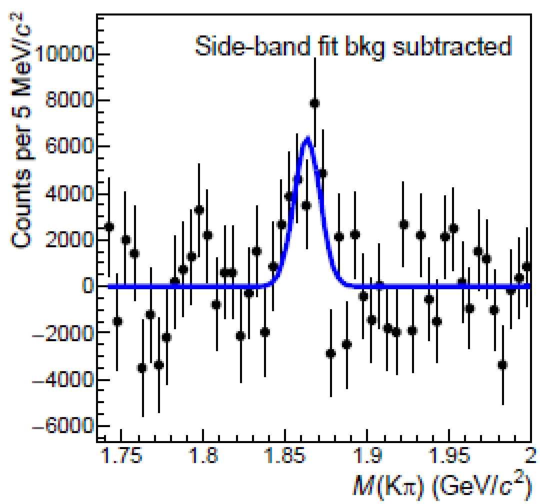
expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC

Measurement of total charm production cross section

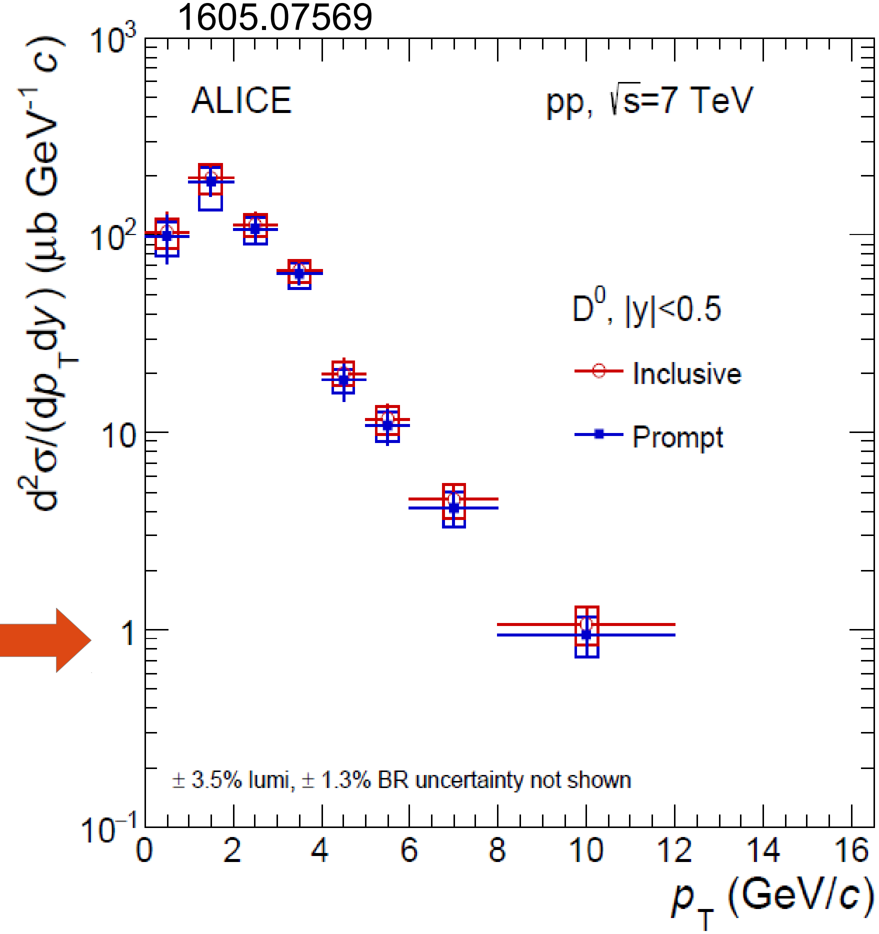


first measurement of cross section down to $p_t = 0$



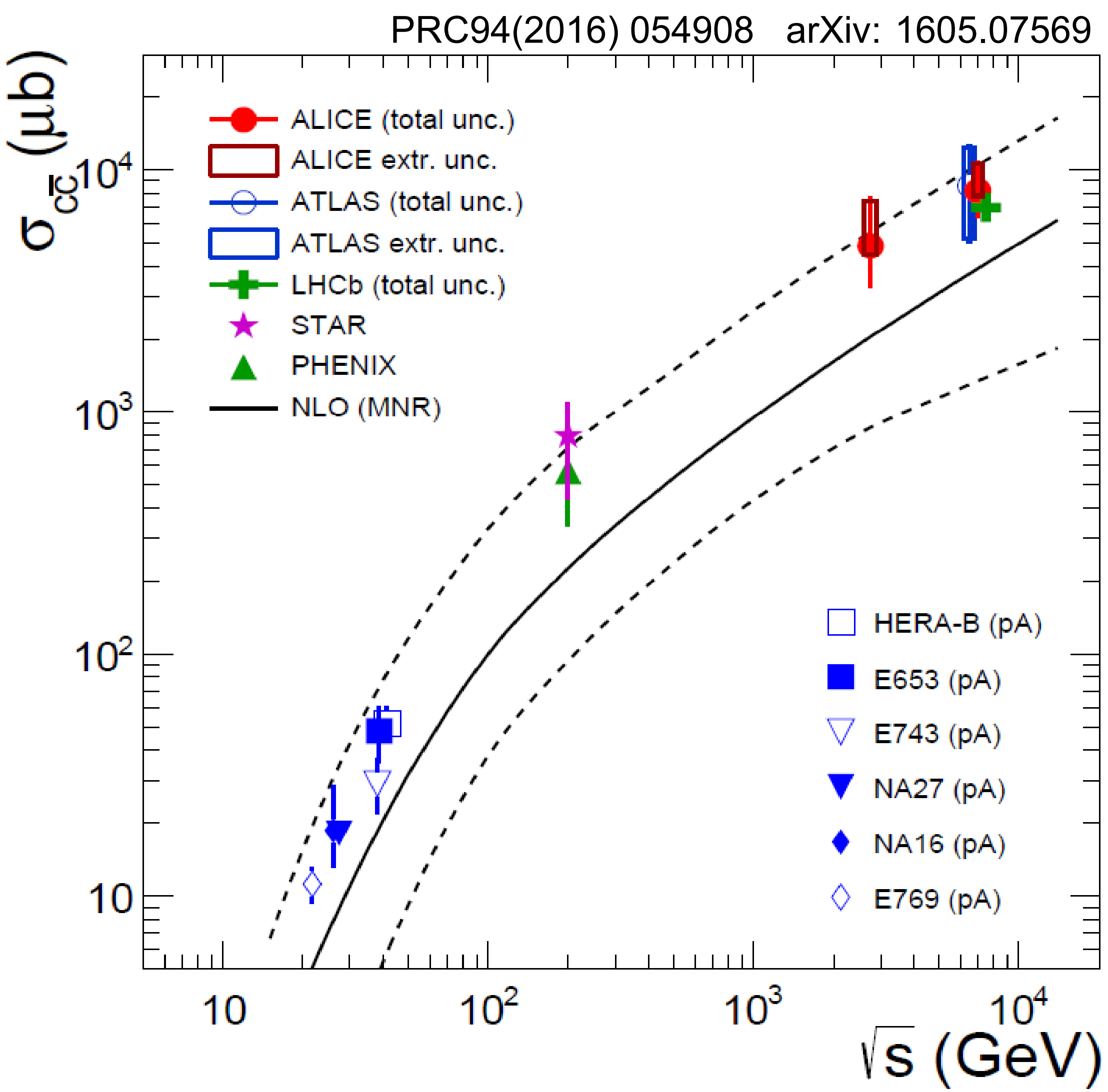


PRC94(2016) 054908 arXiv: 1605.07569



very hard struggle to deal with (irreducible) combinatorial background, successful

the total ccbar cross section in pp at LHC



- good agreement between ALICE, ATLAS and LHCb
- still large syst. error due to extrapolation to low p_t, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of pQCD but well within uncertainty

9.4 Measurement of quarkonia

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

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

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

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

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

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

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

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

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

J/ψ, ψ' and Υ via e+e- or μ+μ-

χ_c very difficult, usually done via

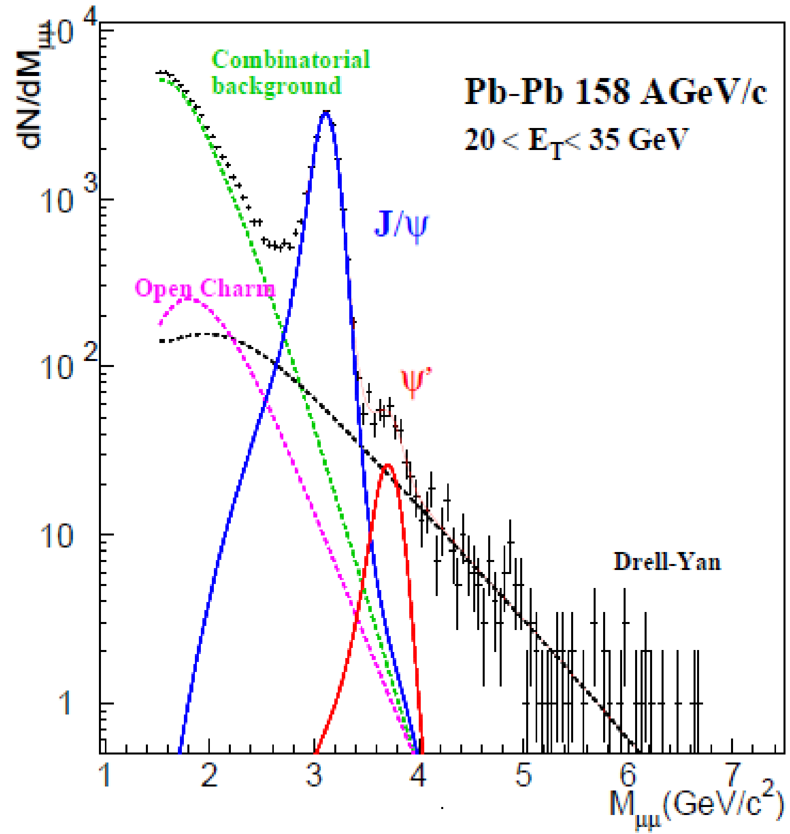
$$\chi_c \to \mathrm{J}/\psi + \gamma$$

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

9.5 Charmonia in nuclear collisions

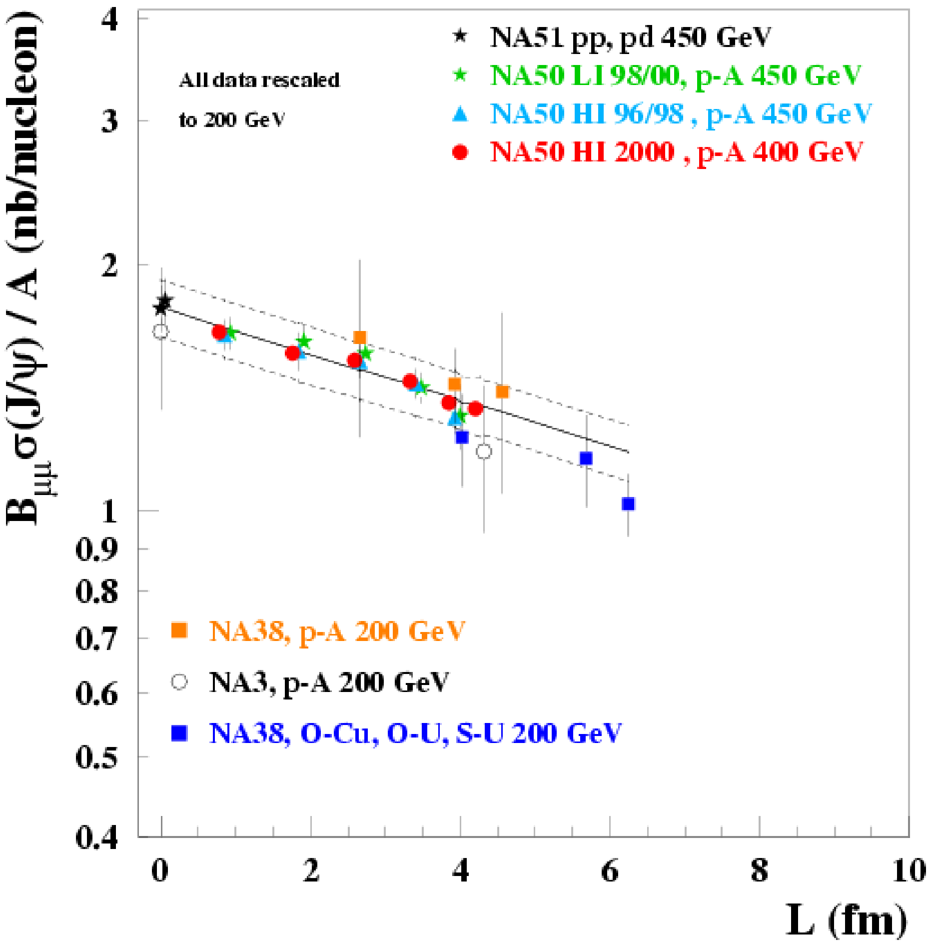
in pA collisions at moderate energies (200-450 GeV) universal picture:
prehadronic state absorbed in nuclear matter

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

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

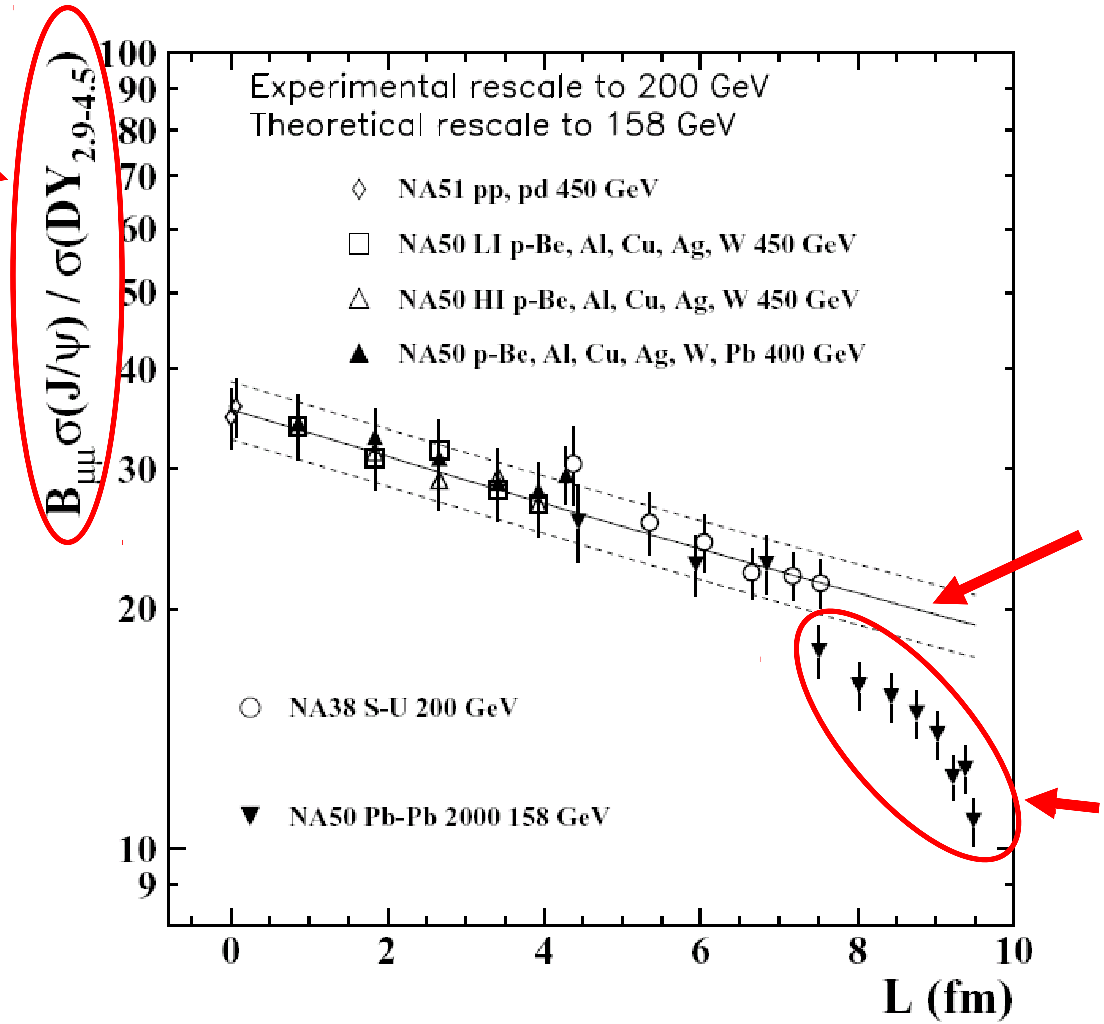
light nuclear collisions follow the same picture

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

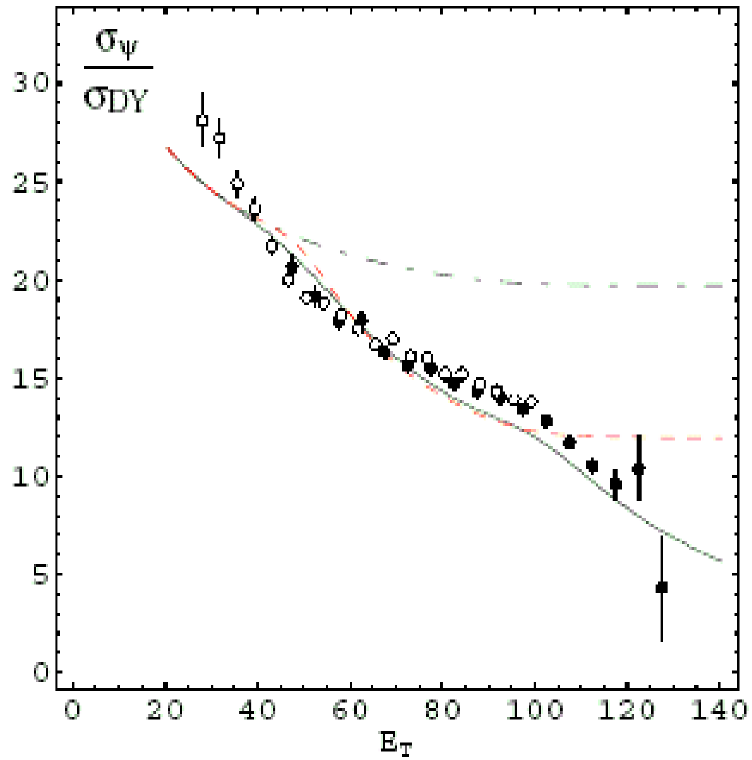
anomalous J/ψ suppression due to QGP?

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

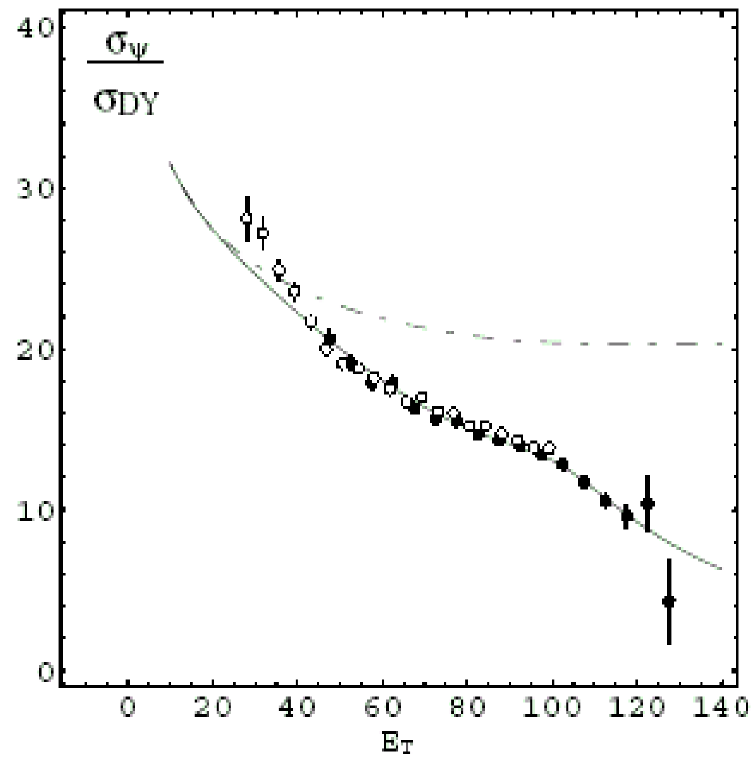
SPS data consistent with suppression at critical density

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

n_c=3.7/fm^2



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

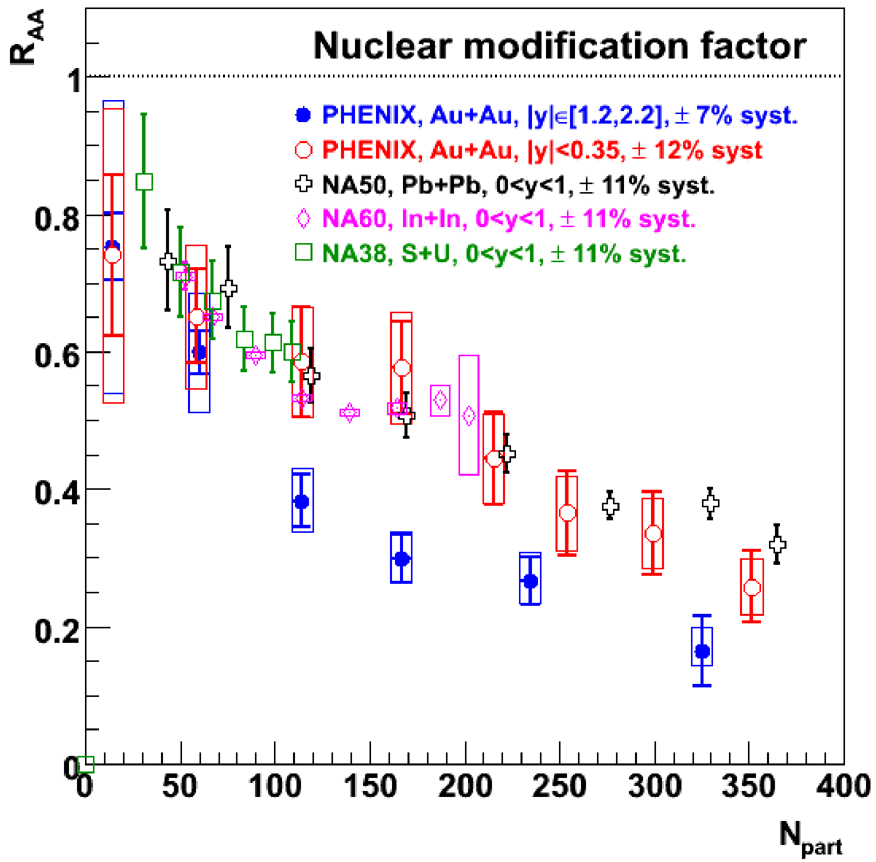


increasing energy density

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

J/psi production in AuAu collisions at RHIC

PRL 98 (2007) 232301



at mid-rapidity suppression at RHIC very similar to SPS

suppression at forward/backward rapidity stronger!

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

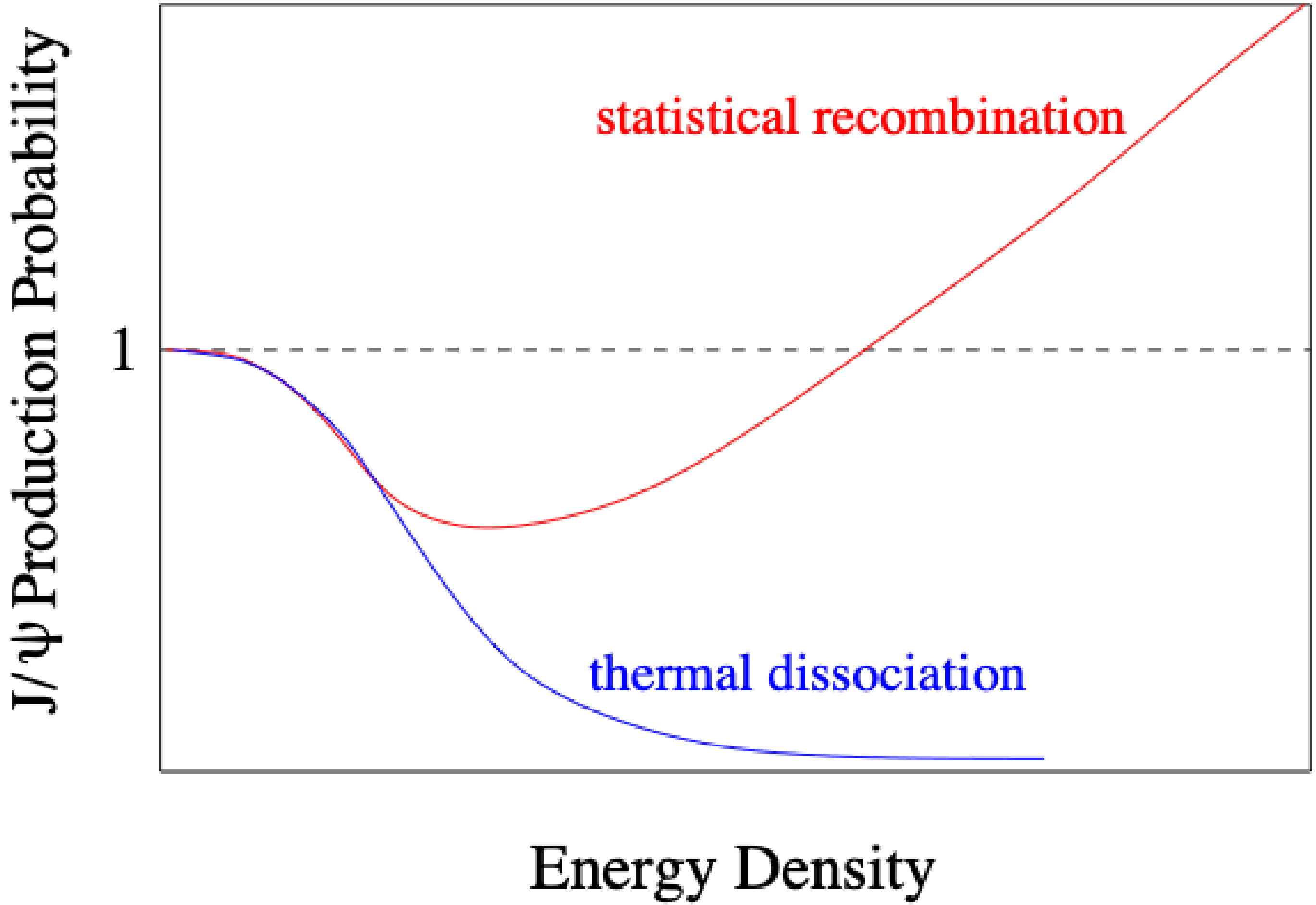
$$\text{where} \quad \langle T_{AB}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$

- but prediction (see above): at hadronization of QGP, J/ψ can form from deconfined quarks, in particular if number of ccbar pairs is large

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

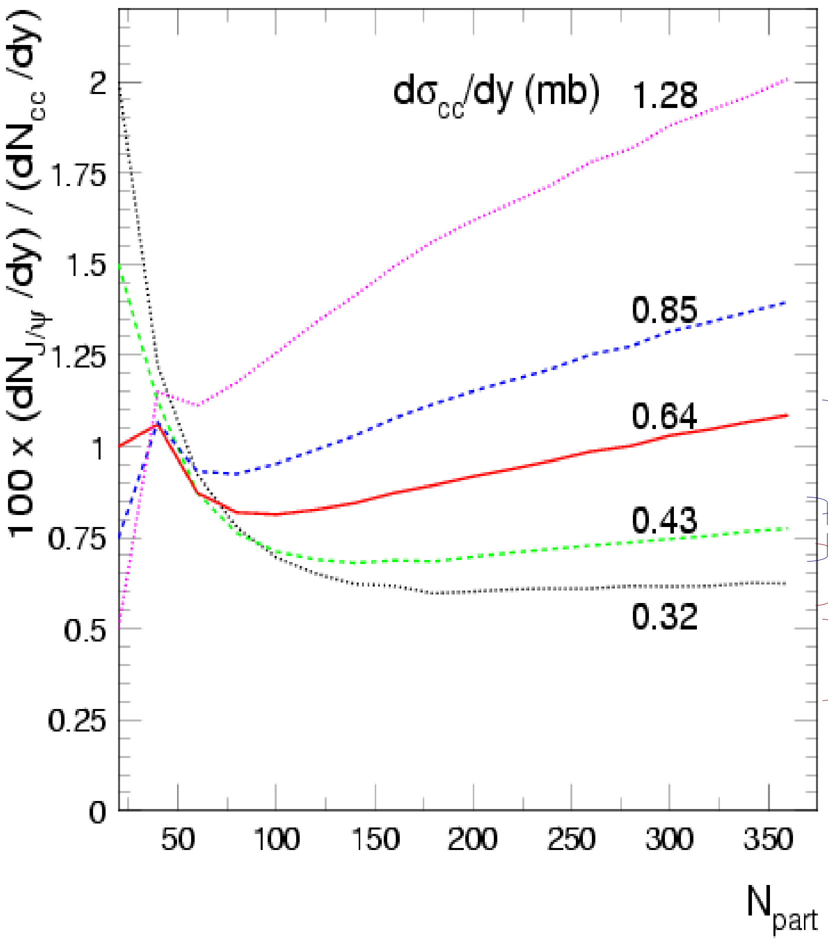
What to expect for LHC?

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

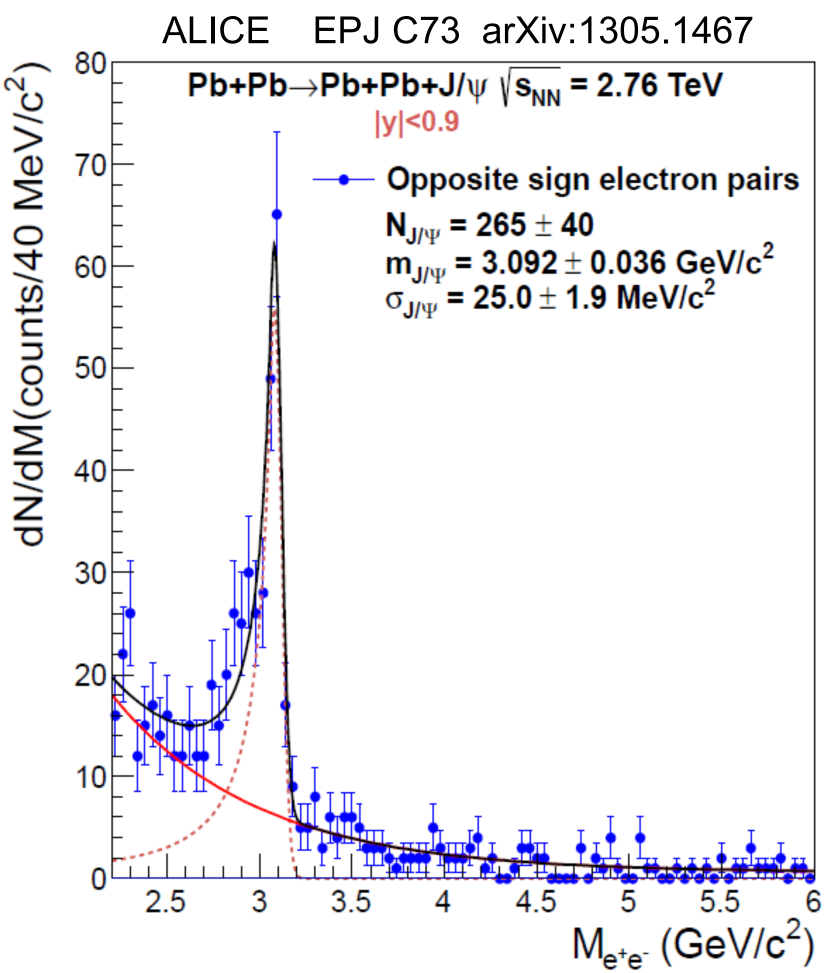


note: stat. model does not make any prediction about ccbar production cross section, this is input; depending on ccbar cross section in nuclear collisions at LHC there can be J/psi enhancement

mid-y LHC 2.76 and 5.02 TeV including shadowing

forward-y LHC 2.76 and 5.02 TeV including shadowing

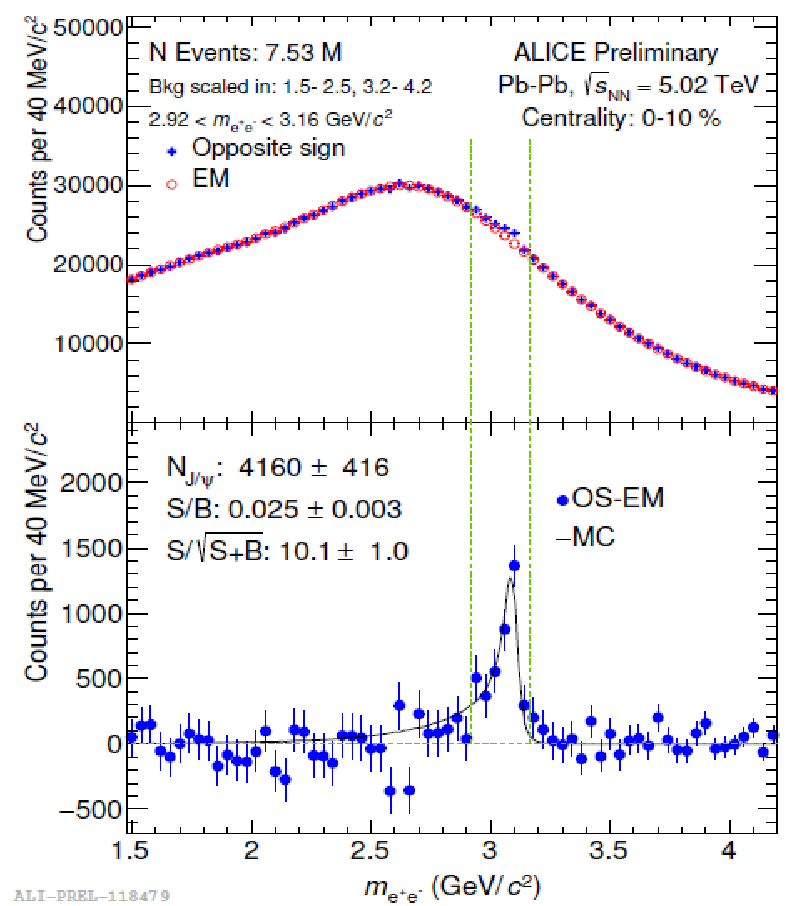
Reconstruction of J/psi in PbPb collisions at LHC



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

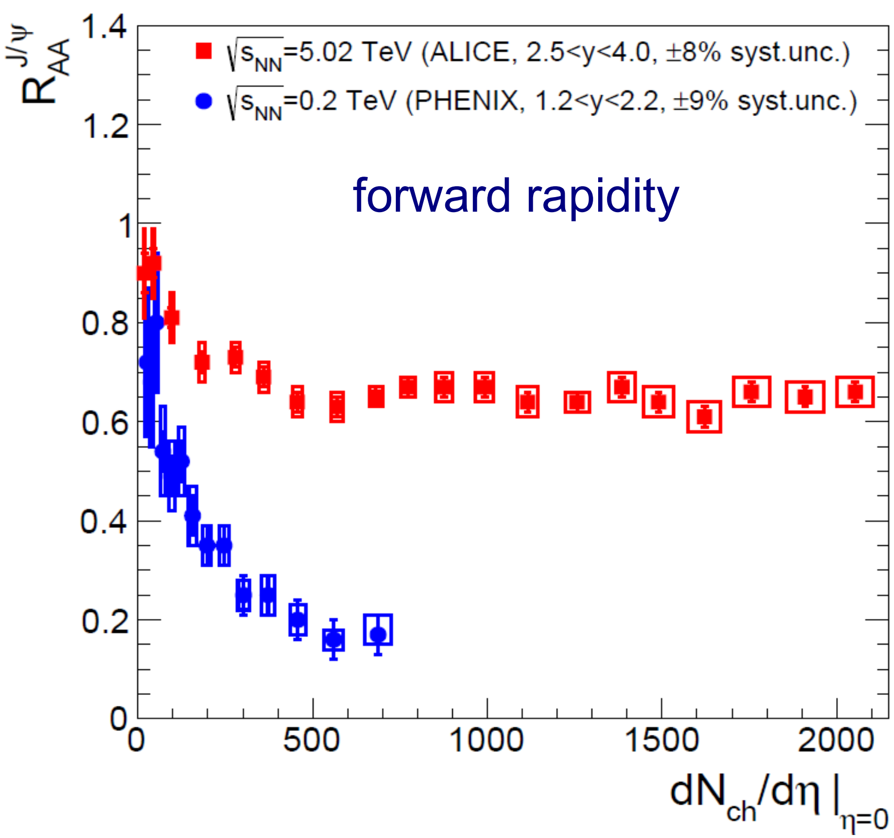
<u>most challenging:</u> central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

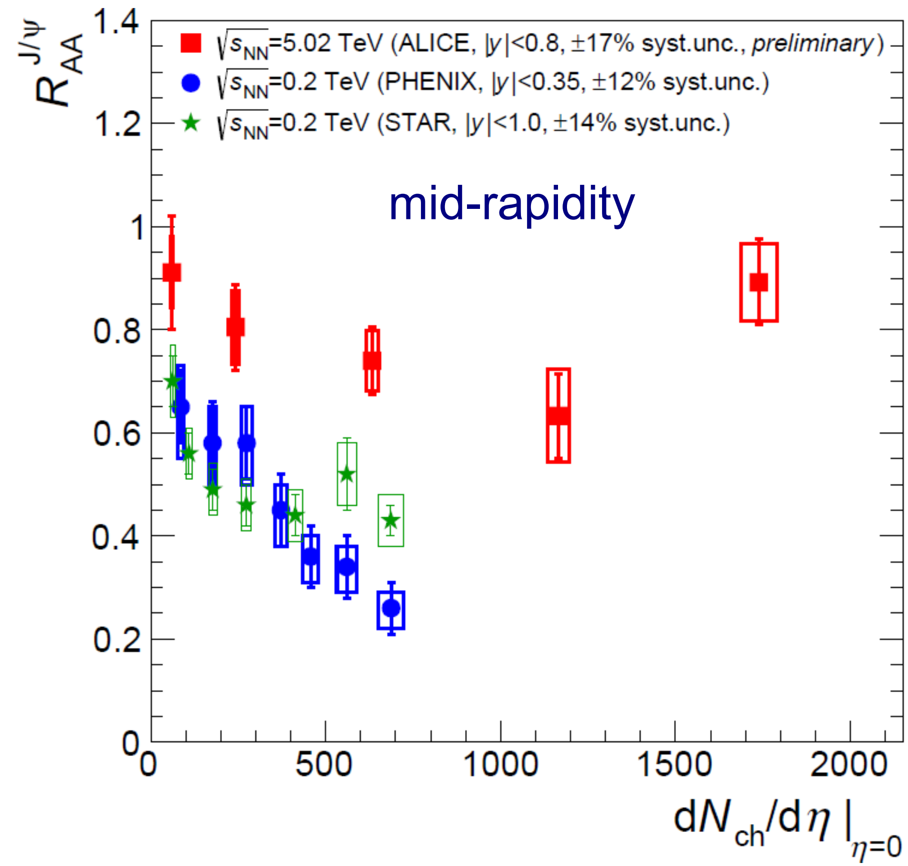
mid |y| < 0.8



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

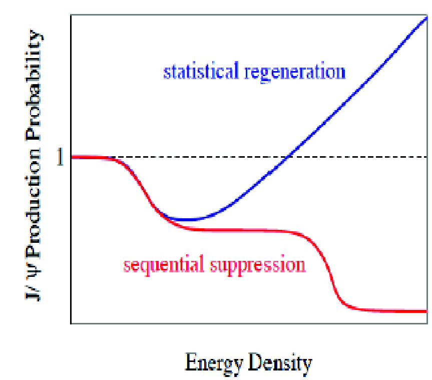
$$R_{AA} = \frac{dN^{AA}/dy}{N_{coll}\, dN^{pp}/dy}$$



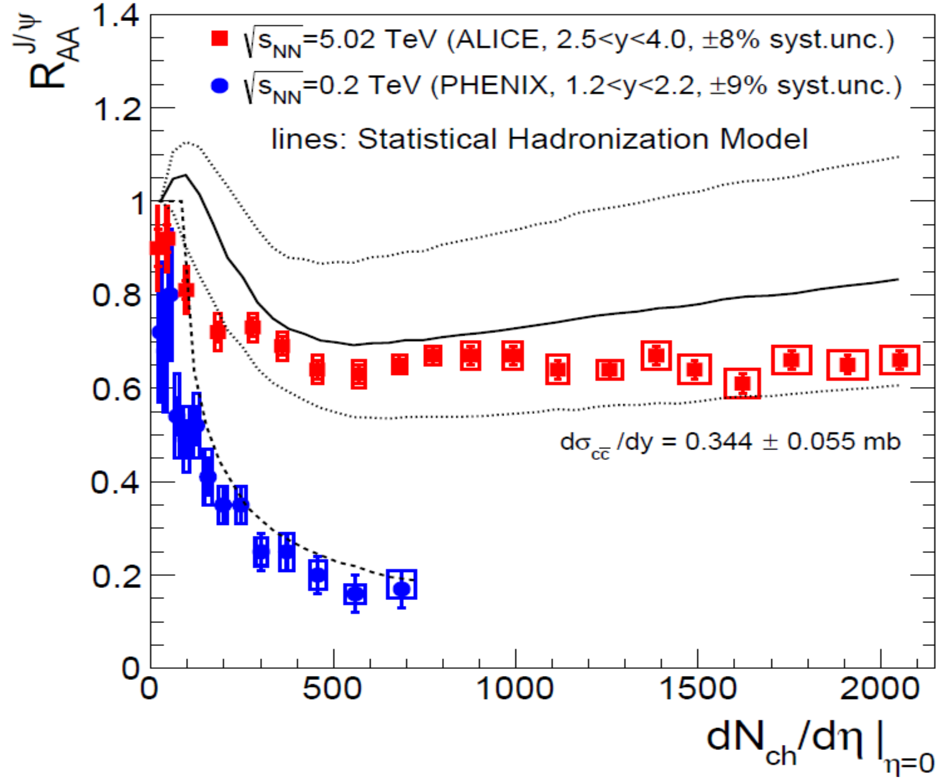


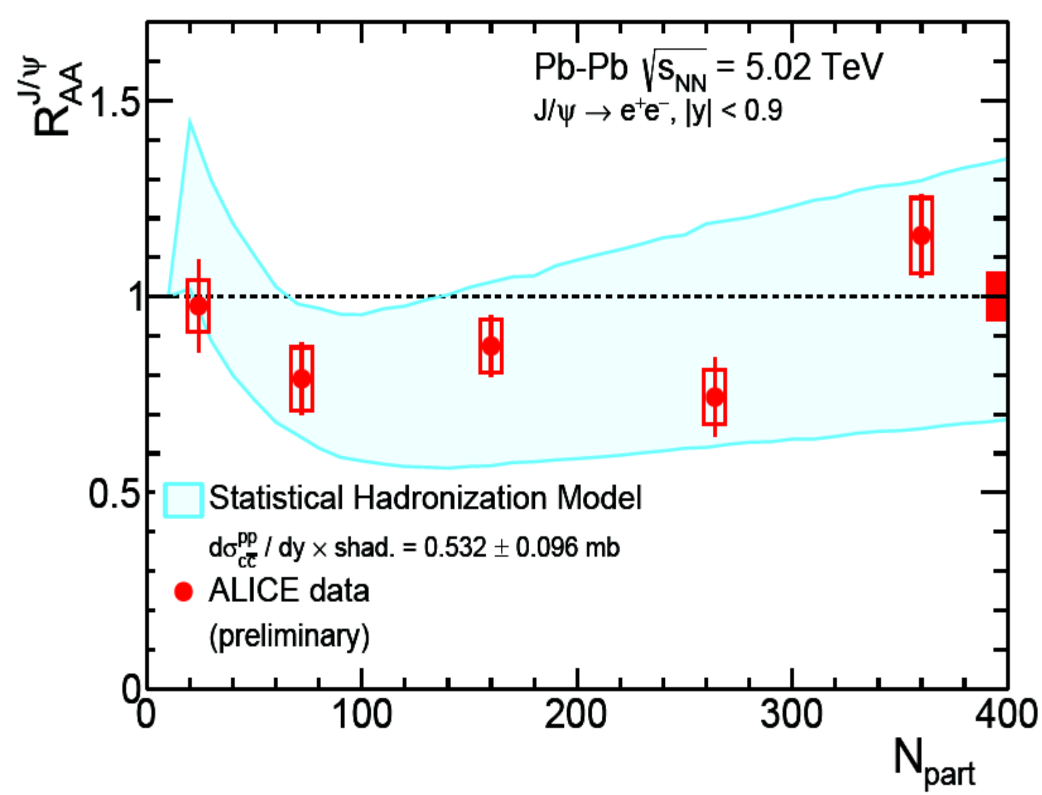
energy density -->

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



J/psi and statistical hadronization

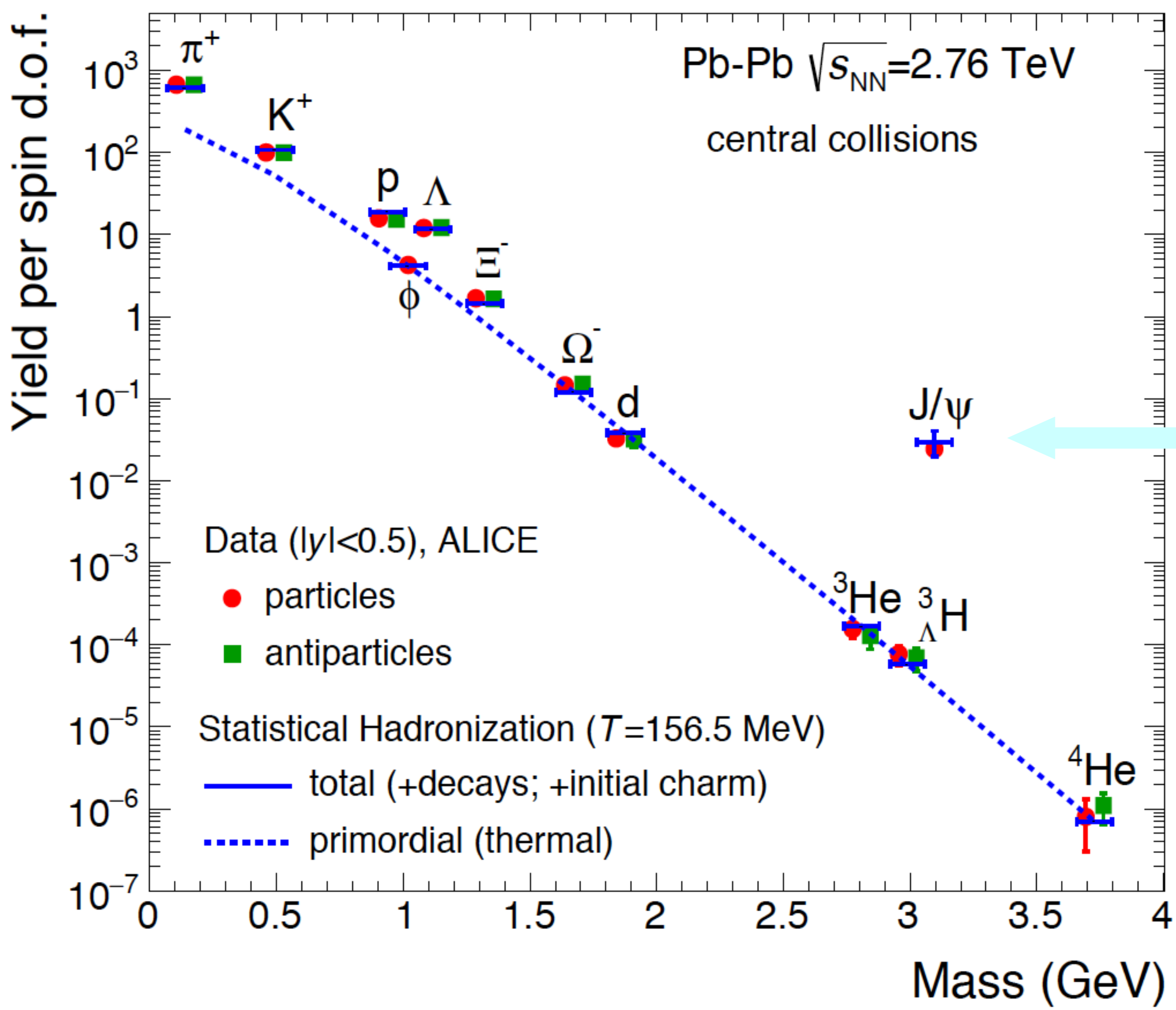




production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

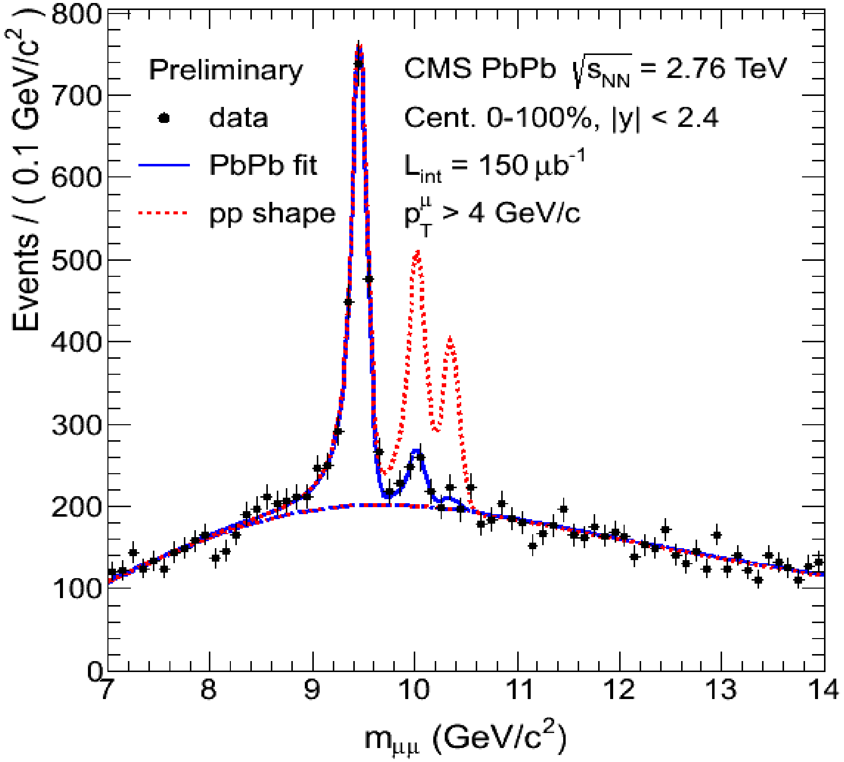
main uncertainties for models: open charm cross section due to shadowing in Pb

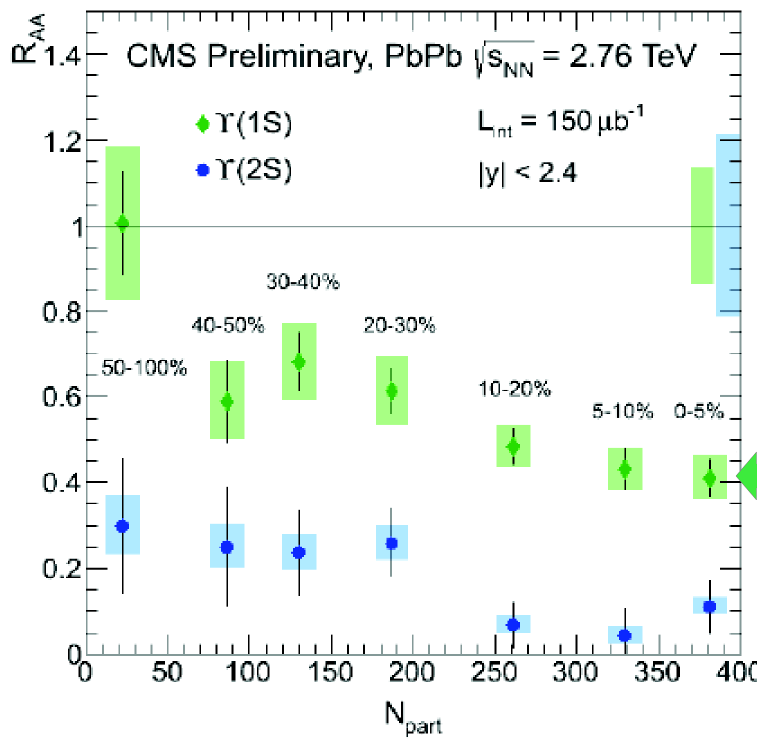
Systematics of hadron production in SHM



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

First information on Upsilon states for PbPb at LHC





CMS-HIN-11-011

too strong for excited state suppression only (recently established by LHCb)

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

open question today: could also Upsilon form statistically at hadronization? Magnitude of R_{AA} ok for this