Charmonium Production and the Quark-Gluon Plasma

- introductory remarks on charmonium and QGP
- discussion of time scales and open charm conservation equation
- remarks on 'cold nuclear matter effects'
- the statistical hadronization model
- results for SPS and RHIC energies
- a short digression towards the charm threshold
- charmonium production at LHC energy

Erice workshop on heavy ion collisions from the Coulomb barrier to the QGP, Sep. 2008

in collaboration with A. Andronic, K. Redlich, J. Stachel

Charmonium as a probe for the properties of the QGP

the main idea: implant charmonia into the QGP and observe their modification, in terms of suppressed (or enhanced) production in nucleus-nucleus collisions with or without plasma formation

Charmonium suppression

original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

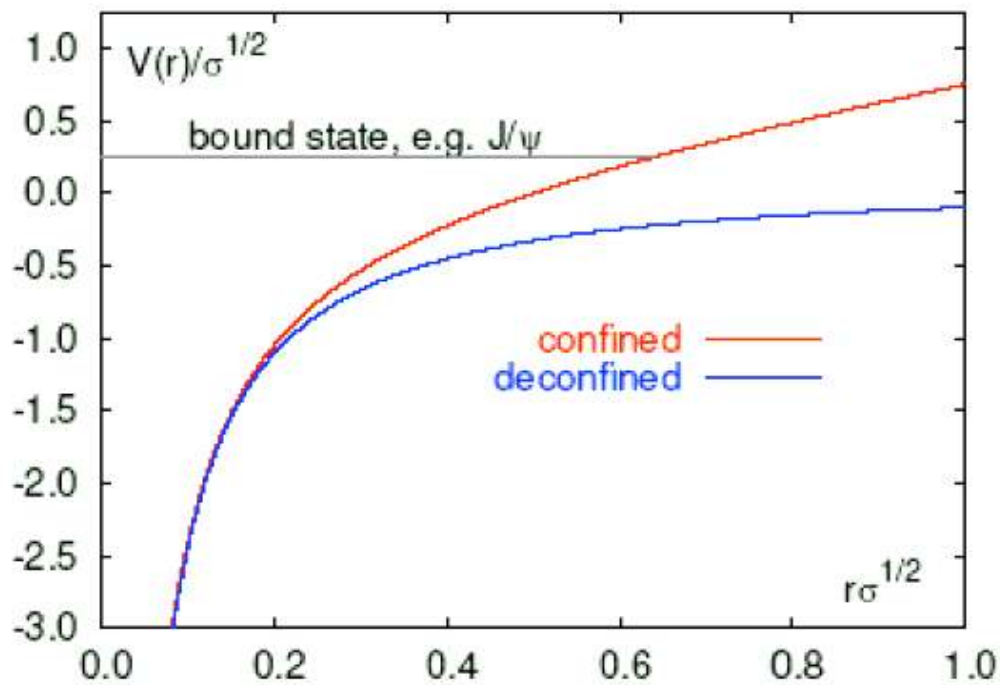
- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond T_c

$\rightarrow$ sequential suppression pattern due to feeding

Debye screening

V(r,T large) no bound state

V(r,T small) bound state



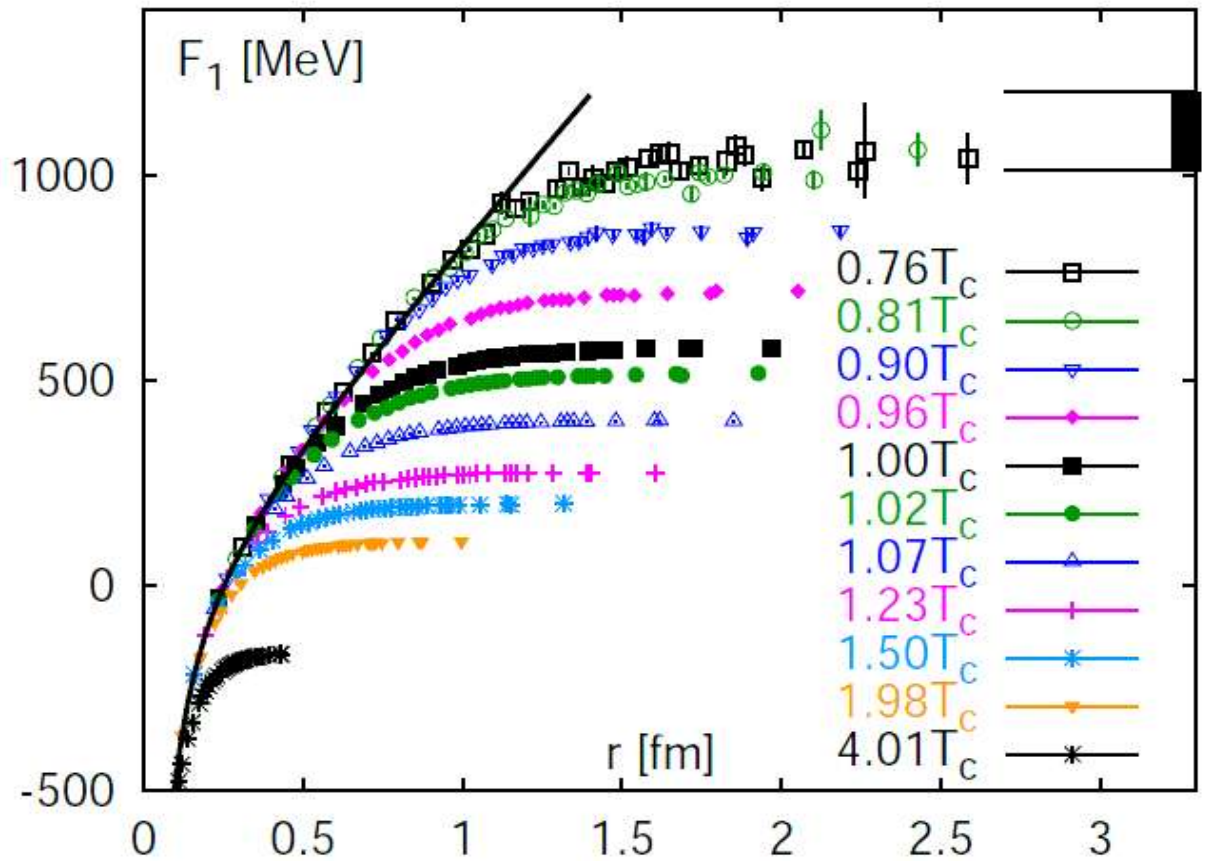
σ = string tension = 1 GeV/fm
= 0.2 GeV^2

Free energy of a heavy quark-antiquark pair

color singlet free energy
$F_1(T) = U(T) - T\,S(T)$

note: J/ψ is bound
by 640 MeV

J/ψ disappears for T
> 1.6 T_c



O. Kaczmarek, F.Zantow, PRD 71(2005)114510

Quarkonium Properties and Debye Screening

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

table from H. Satz, J. Phys. G32 (2006) R25

$r_{Debye}(T) \sim 1/[g(T)T]$

In the QGP, the screening radius $r_{Debye}(T)$ decreases with increasing T. If $r_{Debye}(T) < r_{charmonium}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

Can Charmonia survive in the QGP?

lattice and potential studies indicate yes for J/psi

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.1	1.2	1.1

lattice inspired potential models

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	> 2.0	< 1.1	?

analysis in full two-flavor QCD

from: H. Satz, J. Phys. G32 (2006) R25

might there be sequential melting of charmonia?

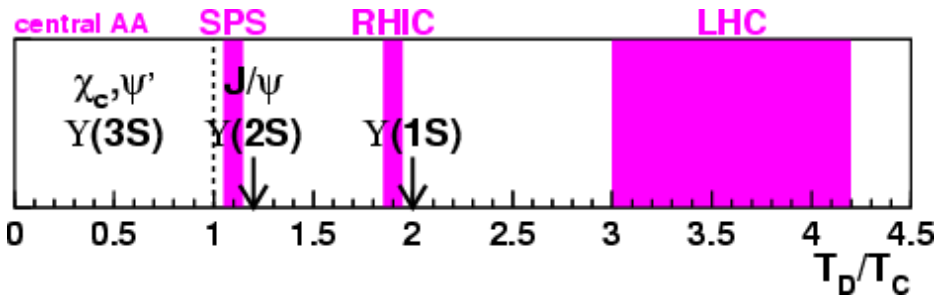
Survival of Quarkonia in the QGP

new development:
J/ψ does not survive above T_c

predicted quarkonium dissociation temperatures

in the QGP

A. Mocsy & P. Petreczky, Phys. Rev. Lett. 99 (2007) 211602



expect all charmonia to be destroyed
by QGP
but: regeneration at the phase boundary!

Collision broadening in QGP

collisions of charmonia with quarks and gluons in the QGP broaden the width of these states

estimate: density of partons in QGP $n = 4.25\ T^3$

3 massless flavors

mean free path of J/ψ $\lambda = 1/(n\ \sigma)$

σ = J/ψ parton cross section take 2 mb as reference

(factor 2 smaller than NA50 absorption cross section)

velocity of J/ψ in the QGP $v = \sqrt{(3\ T/m)} \approx v_{rel}$

in-medium width $\Gamma = v_{rel}/\lambda$

final result:

T = 200 MeV	Γ =	80 MeV
T = 300 MeV	Γ =	320 MeV
T = 500 MeV	Γ =	1940 MeV

Collision broadening in QGP

for T > 200 MeV charmonia, if they exist there, will decay inside the QGP and will not be reconstructed by experiments

p(decay inside) = $1-\exp(-\Gamma\ \tau_{QGP})$

τ_{QGP} = 5 fm Γ = 100 eV --> p = 0.92

In-medium modifications of charmed hadrons

decreasing plateau in the free energy may also imply a reduction in D meson masses: the light constituent quark loses its mass near T_c

this may lead to a reduced in-medium charm quark mass

at low energy, also mass increases are possible

we will explore the consequences of such mass reductions

Remarks on production of open charm and charmonia

- charm quark mass >> Λ_{QCD} production described in QCD perturbation theory
- all calculations employ gluon fusion as starting point
- argument is energy independent until global energy conservation very close to threshold becomes important
- production of charm quark pairs takes place at timescale $1/2m_c$
  $m_c = 1.3$ GeV --> $t_c = 0.08$ fm
- to build up wave function of mesons including those with open charm needs about t = 1fm **-->** charm production and charmed hadron formation are decoupled
- overall cross section is due to production of charm quark pairs
- time scale is much too short to dress the charm quarks
  essential to take current quarks for production

Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

$v = 0.55$ for J/ψ see, e.g. G.T. Bodwin et al., hep-ph/0611002

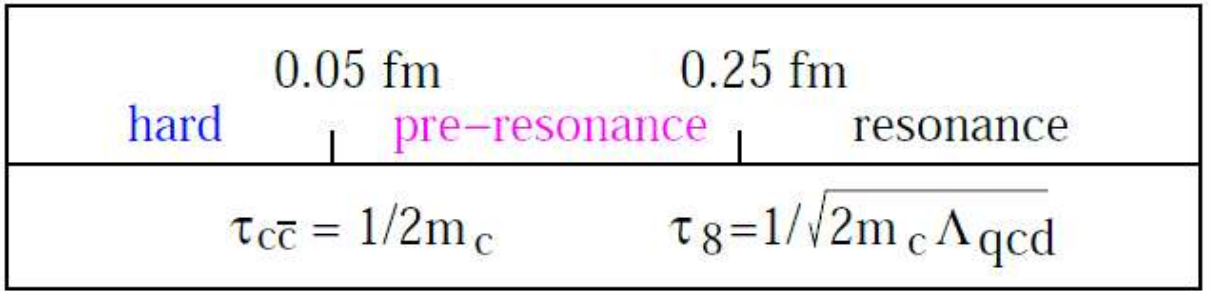
minimum formation time: $t = \text{radius}/v = 0.45$ fm

see also: Huefner, Ivanov, Kopeliovich, and Tarasov,
Phys. Rev. D62 (2000) 094022; J.P. Blaizot and J.Y. Ollitrault,
Phys. Rev. D39 (1989) 232
formation time of order 1 fm

formation time is not short compared to plasma formation time
especially at high energy

Time scales continued

at LHC energies, even the color octet state is not formed before the QGP



from H. Satz, J. Phys. G32 (2006) R25

formation time of open charm hadrons not well understood

presumably similar to charmonia

separation of time scales for initial hard process and late hadronization/hadron formation is called „factorization“

rigorously proven for deep inelastic scattering

charm conservation equation

no medium effect

$$\sigma_{c\bar{c}} = 1/2\ \left[\sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \ldots\right]$$

medium effects on charmed hadrons affect redistribution of charm, but not overall cross section

it is not consistent with the charm conservation equation to reduce all charmed hadron masses in the medium for an enhanced cross section

More timescales

formation and destruction of J/ψ (charmed hadrons)

- QGP formation time, t_{QGP}
  - FAIR, SPS: $t_{QGP} \simeq 1$ fm/c $\sim t_{J/\psi}$
  - RHIC, LHC: $t_{QGP} \lesssim 0.1$ fm/c $\sim t_{c\bar{c}}$

survival of initially-produced J/ψ at FAIR/SPS energies? $(T_d \sim T_c)$

- collision time, $t_{coll} = 2R/\gamma_{cm}$
  - FAIR, SPS: $t_{coll} \gtrsim t_{J/\psi}$
  - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} << t_{J/\psi}$

cold nuclear suppression important at FAIR/SPS energies?

Role of cold nuclear matter effects

what is it:

destruction of charmonia by colliding nuclei before QGP formation

- may be important at SPS and lower energies
- charmonium formation time long compared to QGP formation time, especially at LHC --> **no cold nuclear matter effects at LHC**

what it is not:

rapidity dependent reduction of charm and charmonium production due to shadowing or saturation

need to normalize charmonium production to open charm cross section in AA collisions

Role of cold nuclear matter effects

investigation of 'anomalous' charmonium production in AA collisions

need to normalize charmonium production to open charm cross section in AA collisions

pp and pA collisions are needed to study possible shadowing or saturation effects, not for charmonium suppression or enhancement in the QGP

is there any evidence for saturation or shadowing from RHIC data?? $\sigma_{ccbar}(AA) = N_{coll}\, \sigma_{ccbar}(pp)$??

Are charmonia (and charmed hadrons) produced thermally?

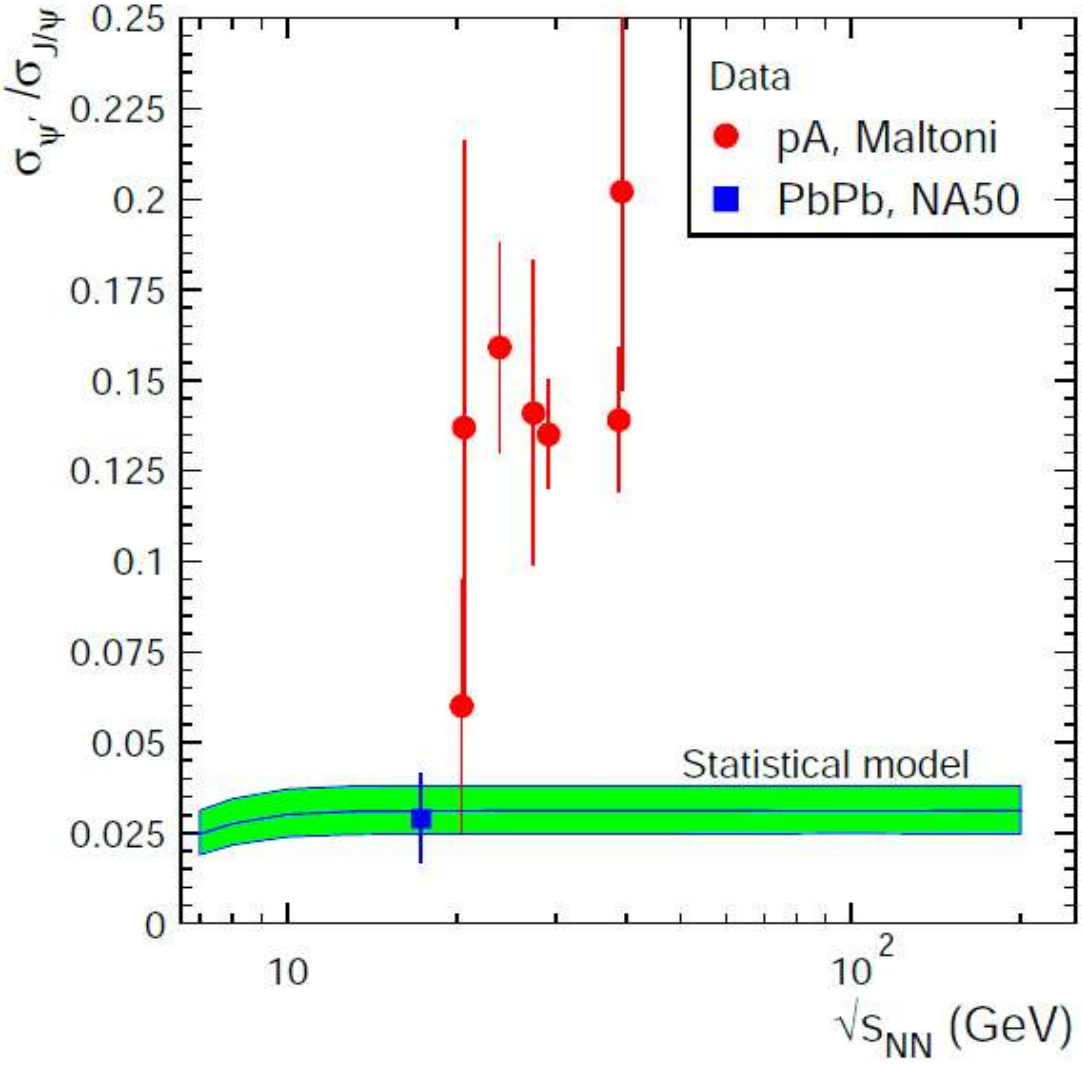
ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)
but: (J/ψ)/ψ' ratio is far from thermal in pp collisions
see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the (J/ψ)/ψ' ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy

further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003
result: (J/ψ)/pi is approximately constant at SPS energy for PbPb

However, thermal production of charm quarks is appreciable
only at very high temperatures
(T > 800 MeV, pbm&Redlich, Eur. Phys. J. C16 (2000) 519).

solution: charm quarks produced in hard collisions, then statistical hadronization at the phase boundary.

Summary of psi'/psi measurements



Charmonium regeneration models

- statistical hadronization model

  original proposal: pbm, J. Stachel, Phys. Lett. B490 (2000) 196

  assumptions:
  - all charm quarks are produced in hard collisions, N_c const. in QGP
  - all charmonia are dissolved in QGP or not produced before QGP
  - charmonium production takes place at the phase boundary with statistical weights

    $\rightarrow$ yield ~ N_c^2 -- quarkonium enhancement at high energies

    -- no feeding from higher charmonia

- charm quark coalescence model

  original proposal: R.L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. C63 (2001) 054905

  assumptions:
  - all charm quarks are produced in hard collisions
  - all charmonia are produced in the QGP via charm quark recombination

    $\rightarrow$ yield ~ N_c^2 -- quarkonium enhancement at high energies

Many more papers on late generation

L. Grandchamp, R. Rapp, Phys. Lett. B523 (2001) 60
R. Rapp et al., PRL 92, 212301 (2004)
and refs. there
R. Thews et al, Eur. Phys. J C43, 97 (2005)
and refs. there
M. I. Gorenstein et al., Phys. Lett. B509 (2001)277, ib. 524 (2002) 265
A.P. Kostyuk et al., Phys. Lett. B531 (2002) 195, Phys. Rev. C68 (2003) 041902
Yan, Zhuang, Xu, nucl-th/0608010
Bratkovskaya et al., PRC 69, 054903 (2004)
A. Andronic et al, Phys. Lett. B571 (2003) 36
A. Andronic et al, nucl-th/0611023, Nucl. Phys. A789 (2007) 334
A. Andronic, pbm, J. Stachel, K. Redlich,
nucl-th/0701079, Phys. Lett. B562 (2007) 259
pbm, nucl-th/0701093 J. Phys. G34 (2007) S471
A. Andronic et al, Phys. Lett. B659 (2008) 149

Method and inputs

Thermal model calculation (grand canonical) T, μ_B: $\rightarrow n_X^{th}$

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$$

$N_{c\bar{c}} << 1 \rightarrow$ Canonical: J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137

charm balance equation

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c$$

Outcome: $N_D = g_c V n_D^{th} I_1 / I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

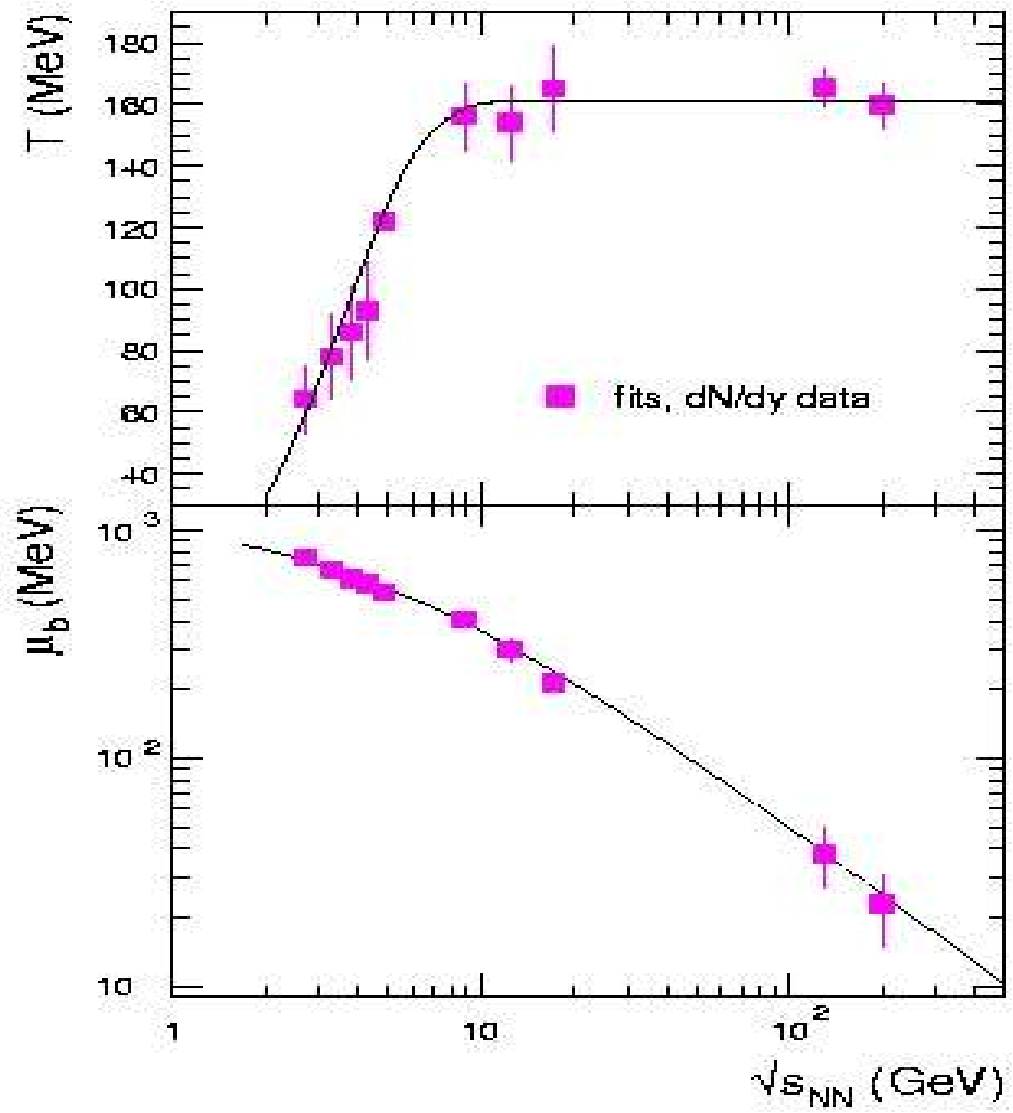
Inputs: T, μ_B, $V = N_{ch}^{exp} / n_{ch}^{th}$, $N_{c\bar{c}}^{dir}$ (pQCD)

Parameterization of all freeze-out points

note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_B for all energies



A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167
nucl-th/0511071

Ingredients for prediction of quarkonium and open charm cross sections

- open charm (open bottom) cross section in pp or better AA collisions

- quarkonium production cross section in pp collisions (for corona part)

result: quarkonium and open charm cross sections as function of
energy, centrality, rapidity, and transverse momentum

Review of results from SPS and RHIC

new aspects:

- absolute normalization of yields
- rapidity dependence
- comparison to results from pp collisions

Definition of Modification of Charmonium in the Fireball

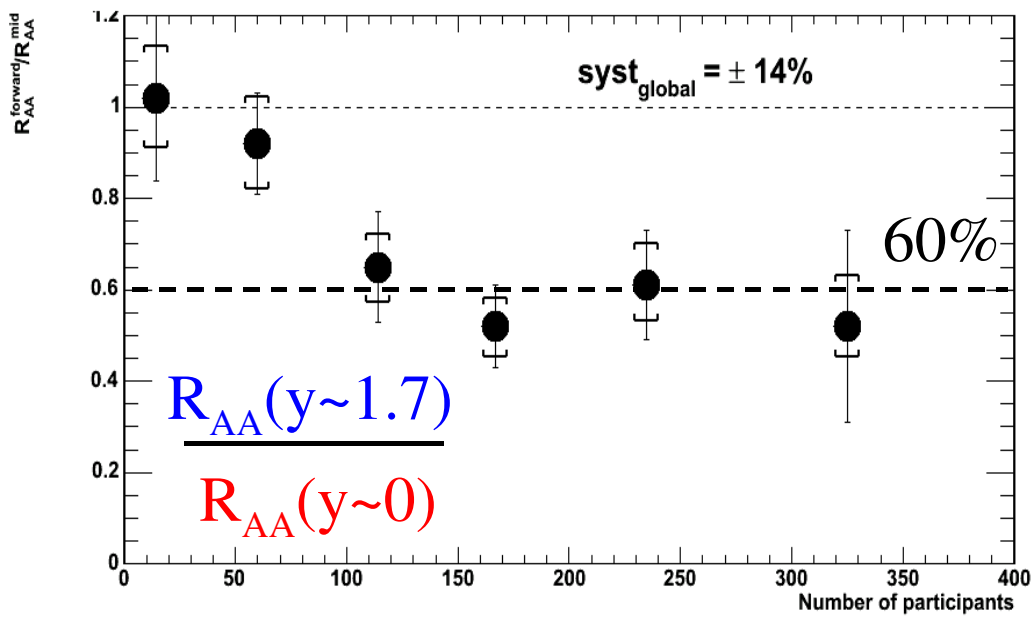
use R_{AA} to define charmonium modification experimentally
no need to normalize to Drell-Yan process

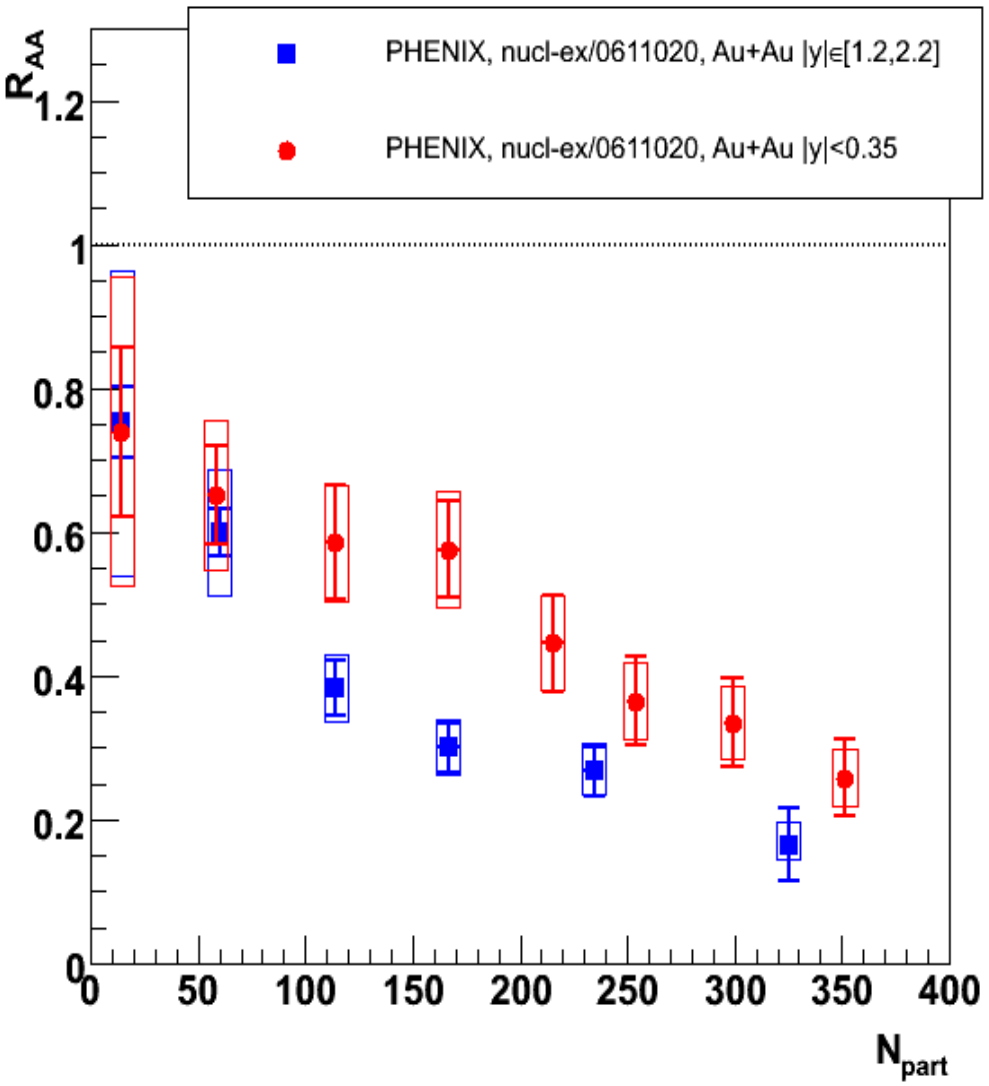
$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

if $\sigma_{\text{Drell-Yan}} \propto N_{\text{coll}}$, R_{AA} is equivalent to NA50 definition, except for 'cold nuclear matter' effects

charmonium suppression at RHIC

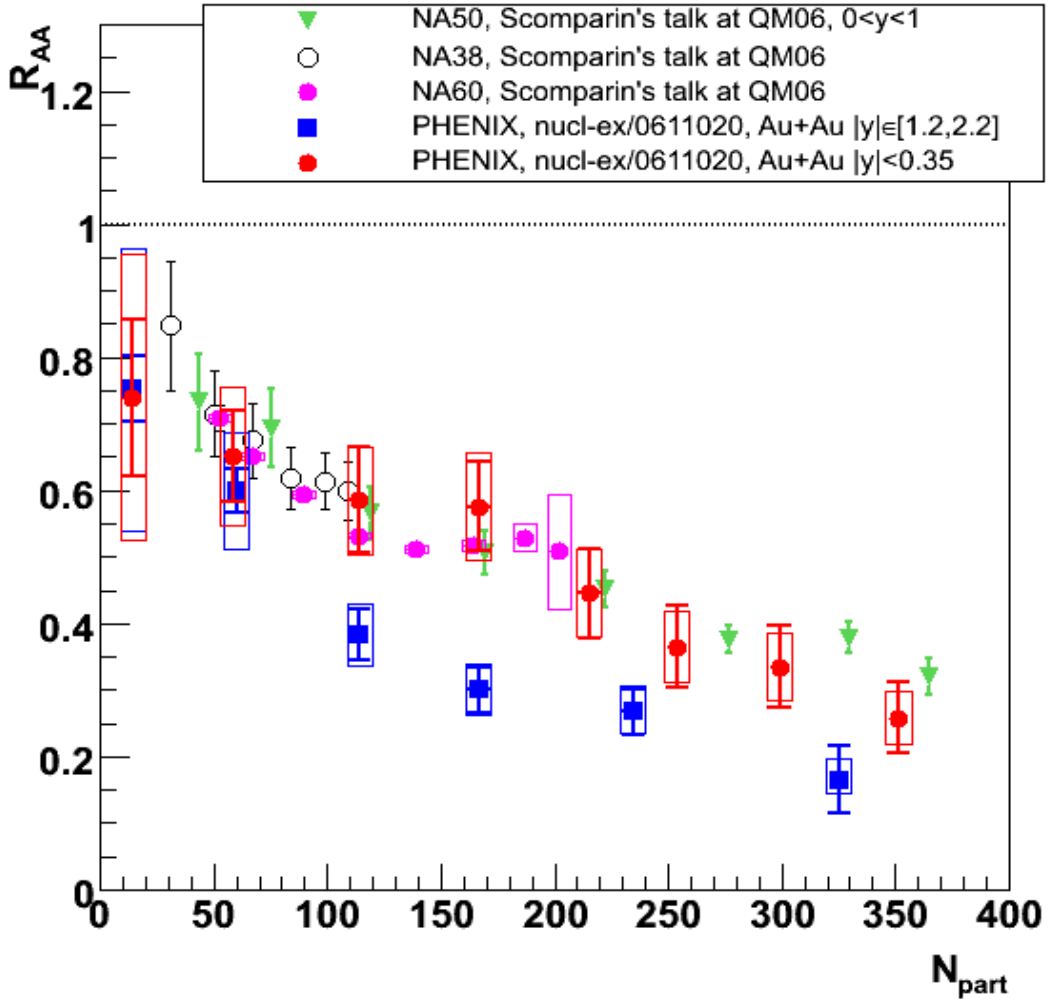
surprize:
suppression is weakest at mid-rapidity





Comparison of RHIC and SPS Results

surprize:
no energy dependence
but unexpected
rapidity dependence

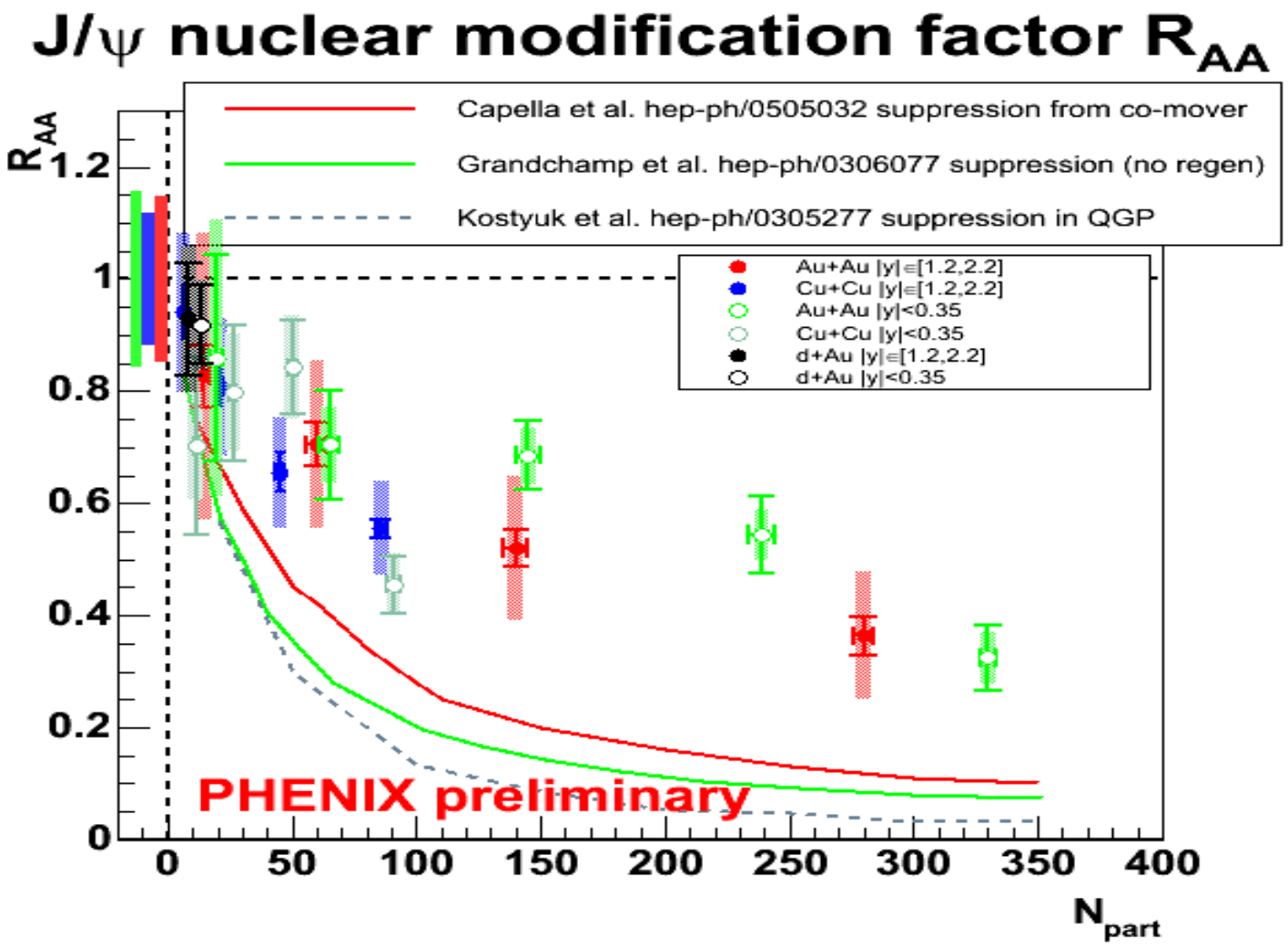


comparison produced by
R. Granier de Cassagnac

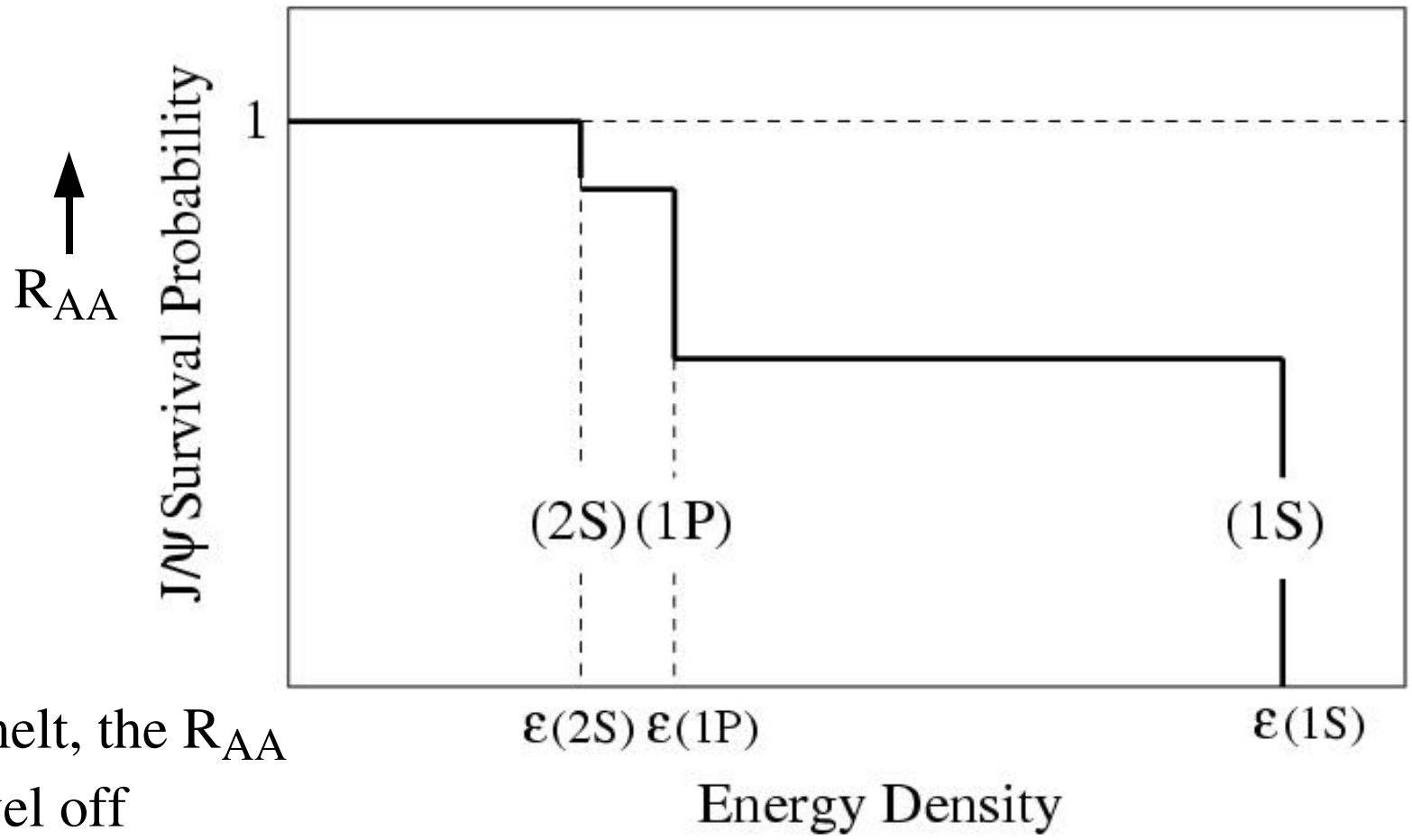
Too much suppression at RHIC in Standard QGP Scenario

standard scenario: all charmonia melt near T_c

models tuned for SPS data fail at RHIC



Sequential Melting – schematical picture

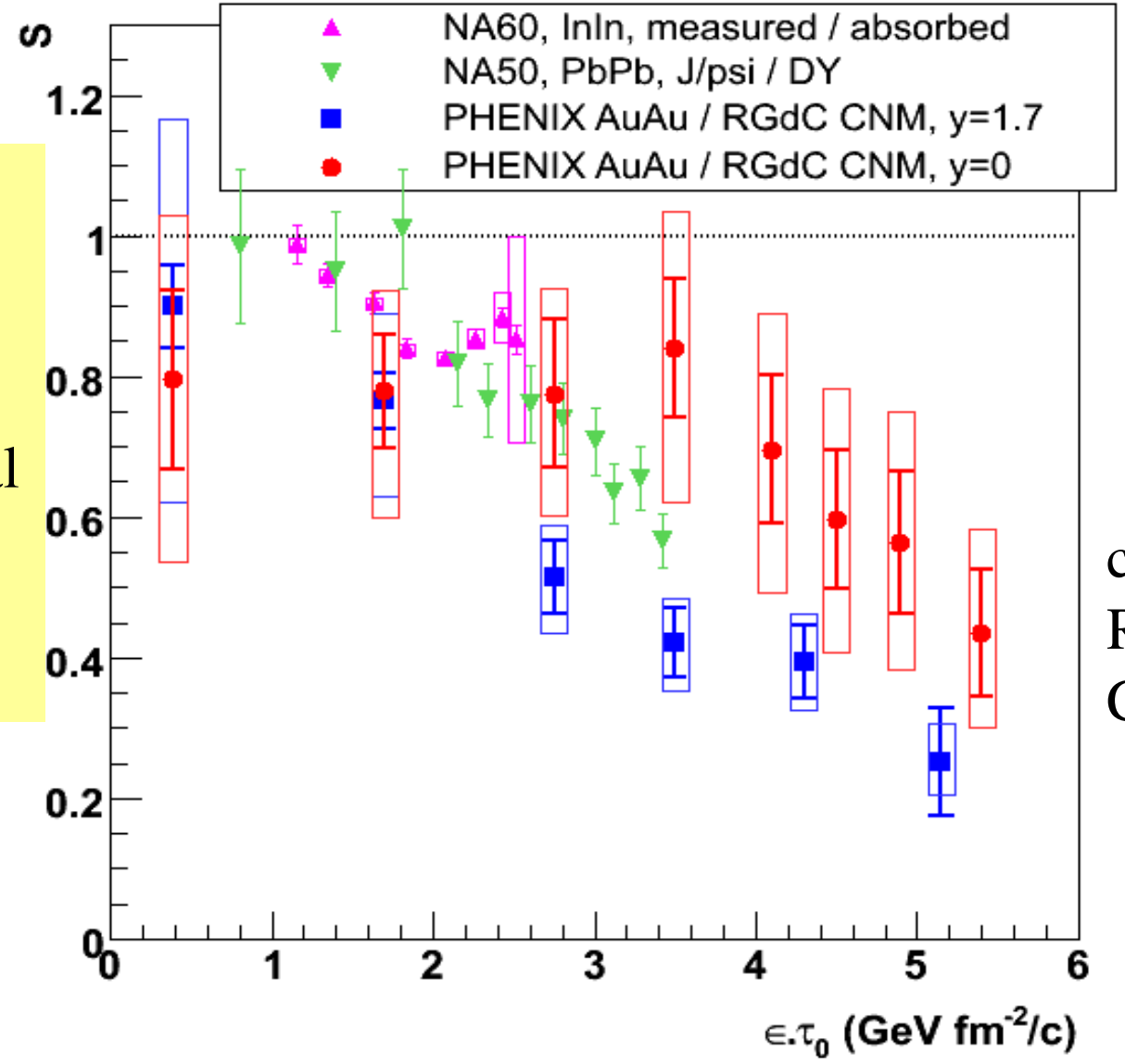


if J/ψ does not melt, the R_{AA} factor should level off at around $R_{AA} > 0.6$ (loss of feeding from χ_c and ψ')

note: χ_c and ψ' not measured at RHIC
pA data at lower energies (HeraB) suggest:
$\chi_c/(J/\psi) < 0.35$

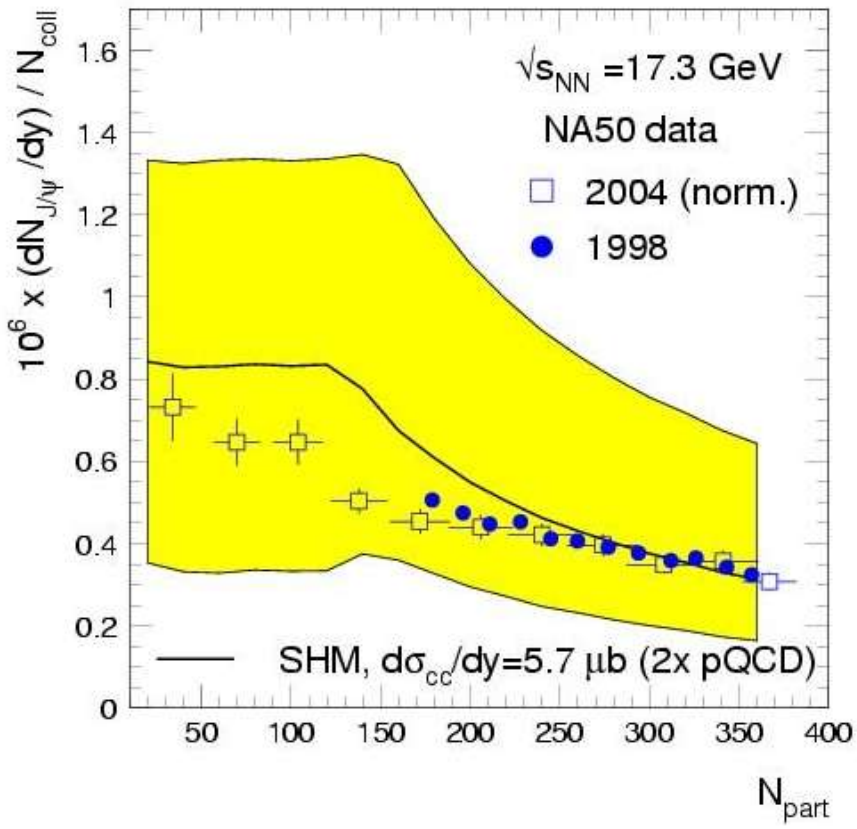
No experimental evidence for sequential melting

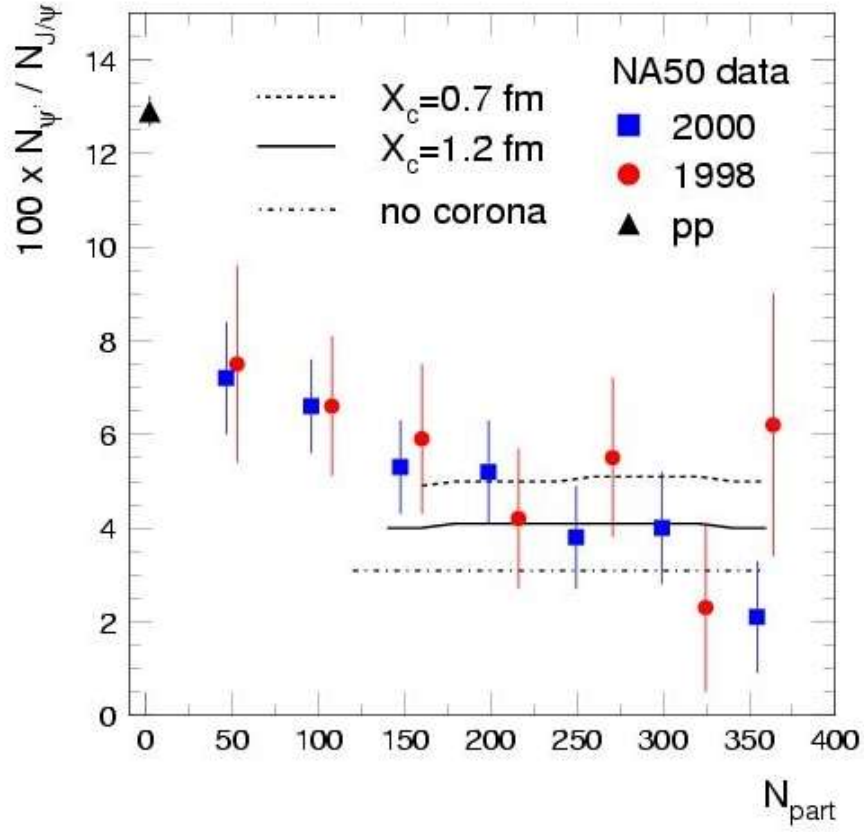
new data at various rapidities rule out sequential melting



compilation by R. Granier de Cassagnac

results for SPS energy



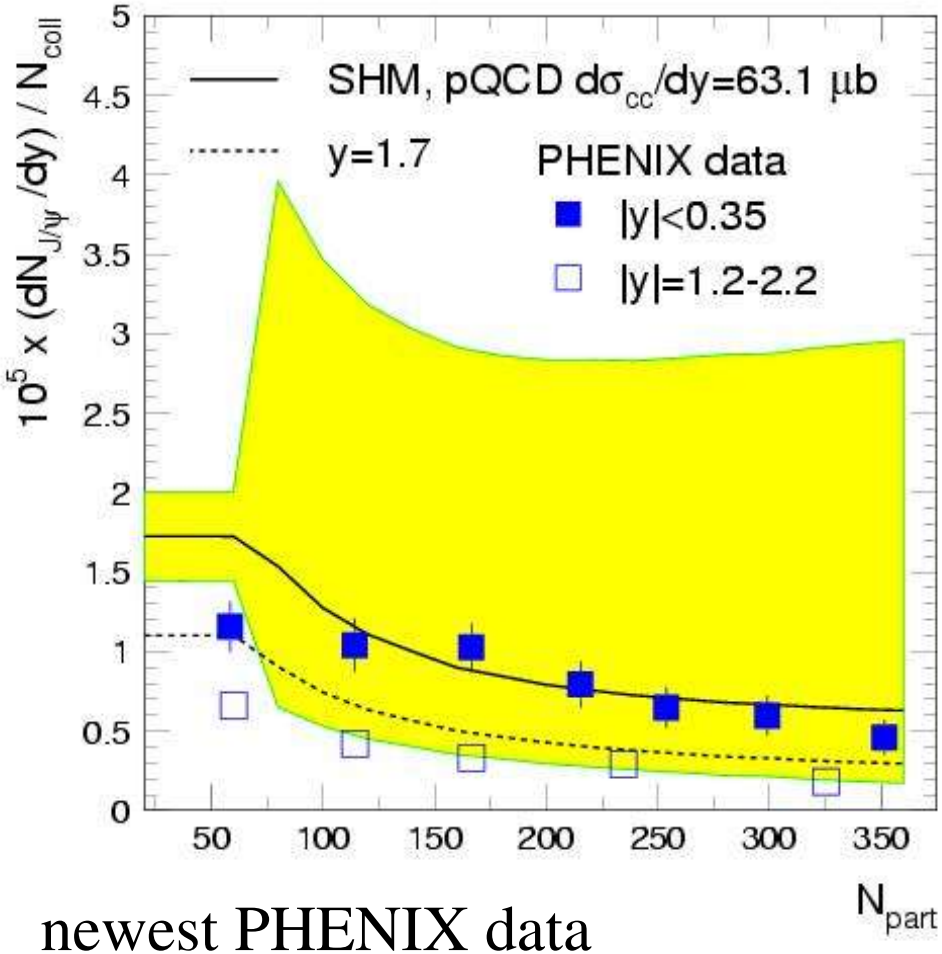


only moderately enhanced (2 x pQCD) cc_bar cross section needed

extrapolation to pp for ψ'/ψ ratio still problematic in the model, although intuitively clear

Comparison of model predictions to RHIC data: centrality dependence

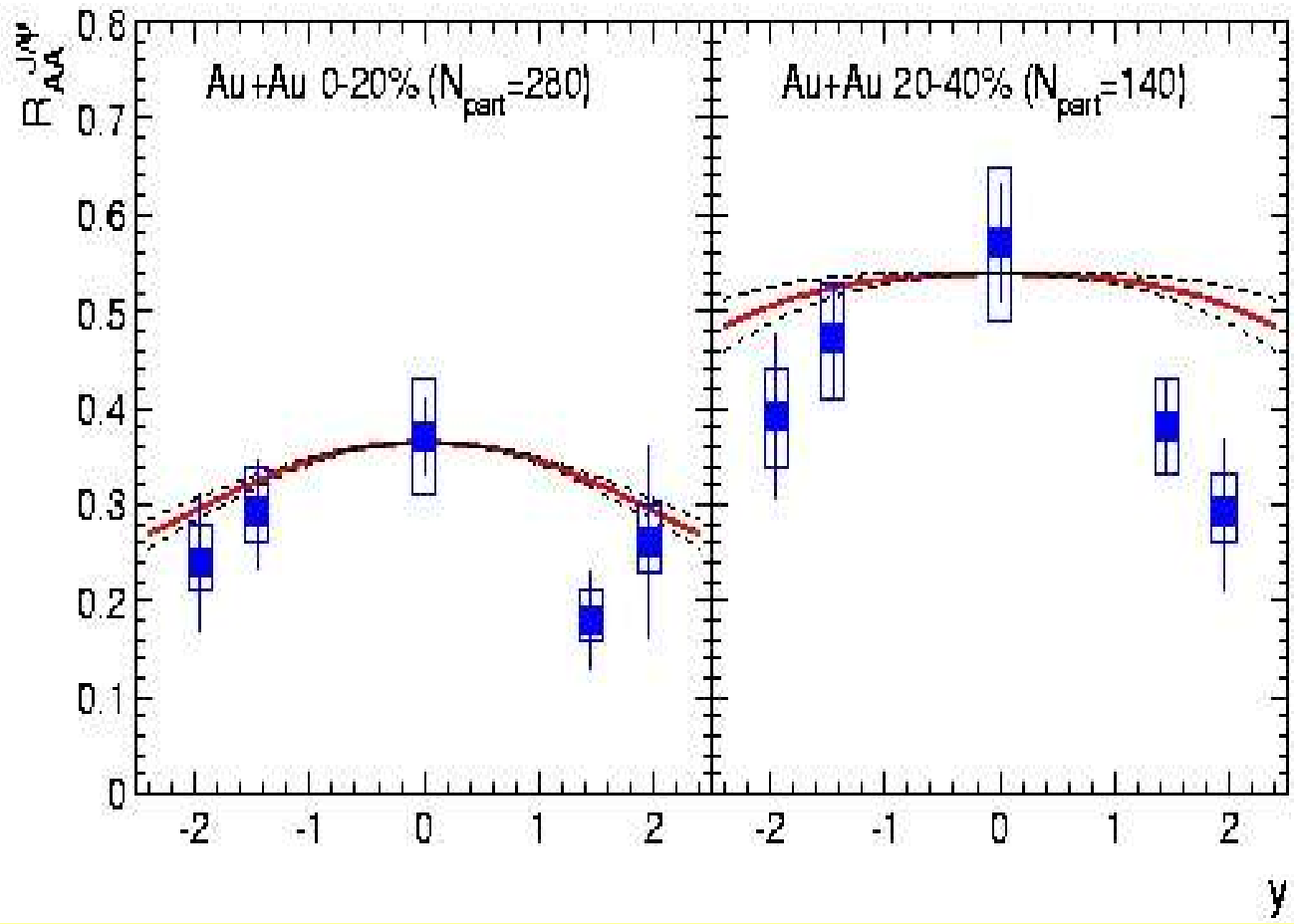
predictions for J/ψ production using NNLO pQCD results for open charm cross section by M. Cacciari, P. Nason, R. Vogt, Phys. Rev. Lett. 95 (2005) 122001, hep-ph/0502203



newest PHENIX data

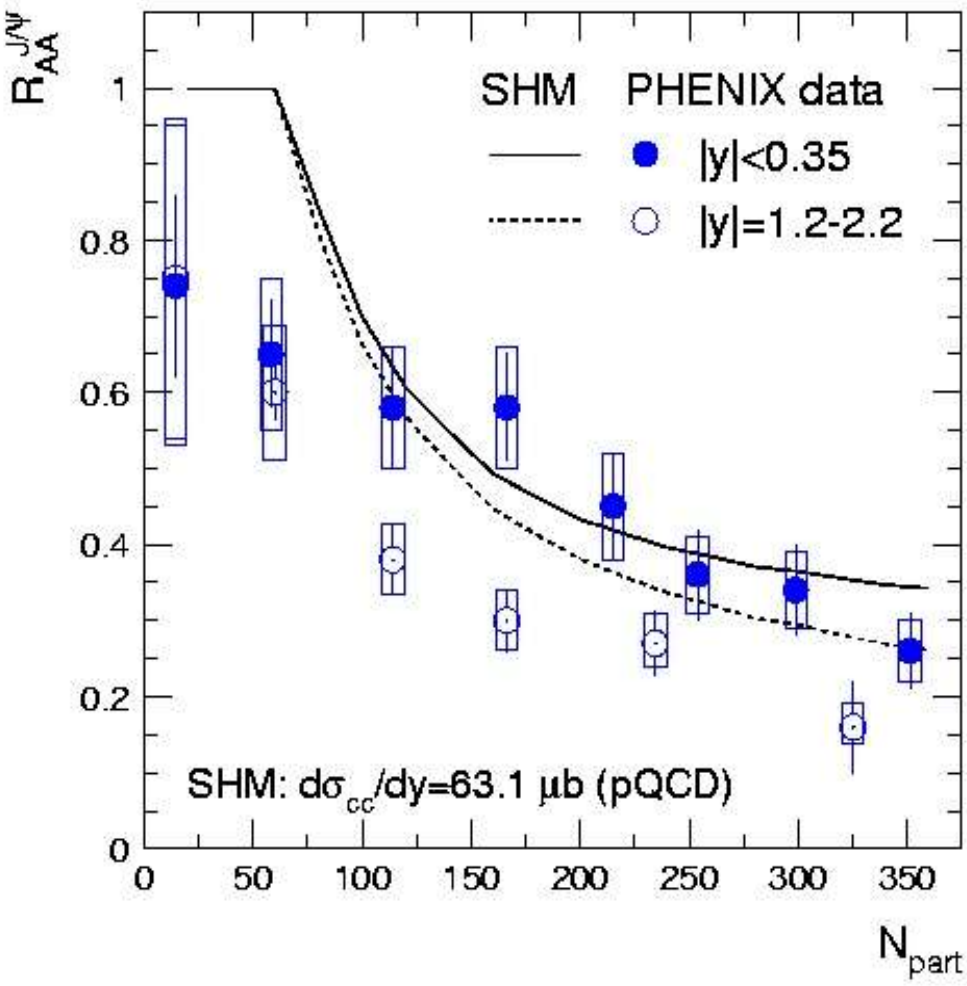
good agreement, no free parameters

Comparison of model predictions to RHIC data: rapidity dependence



suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary

Centrality dependence of nuclear modification factor



data well described
by our regeneration model
without any new
parameters

Saturation model for J/psi production

basis: strong gluon saturation in the wave function of the colliding nuclei

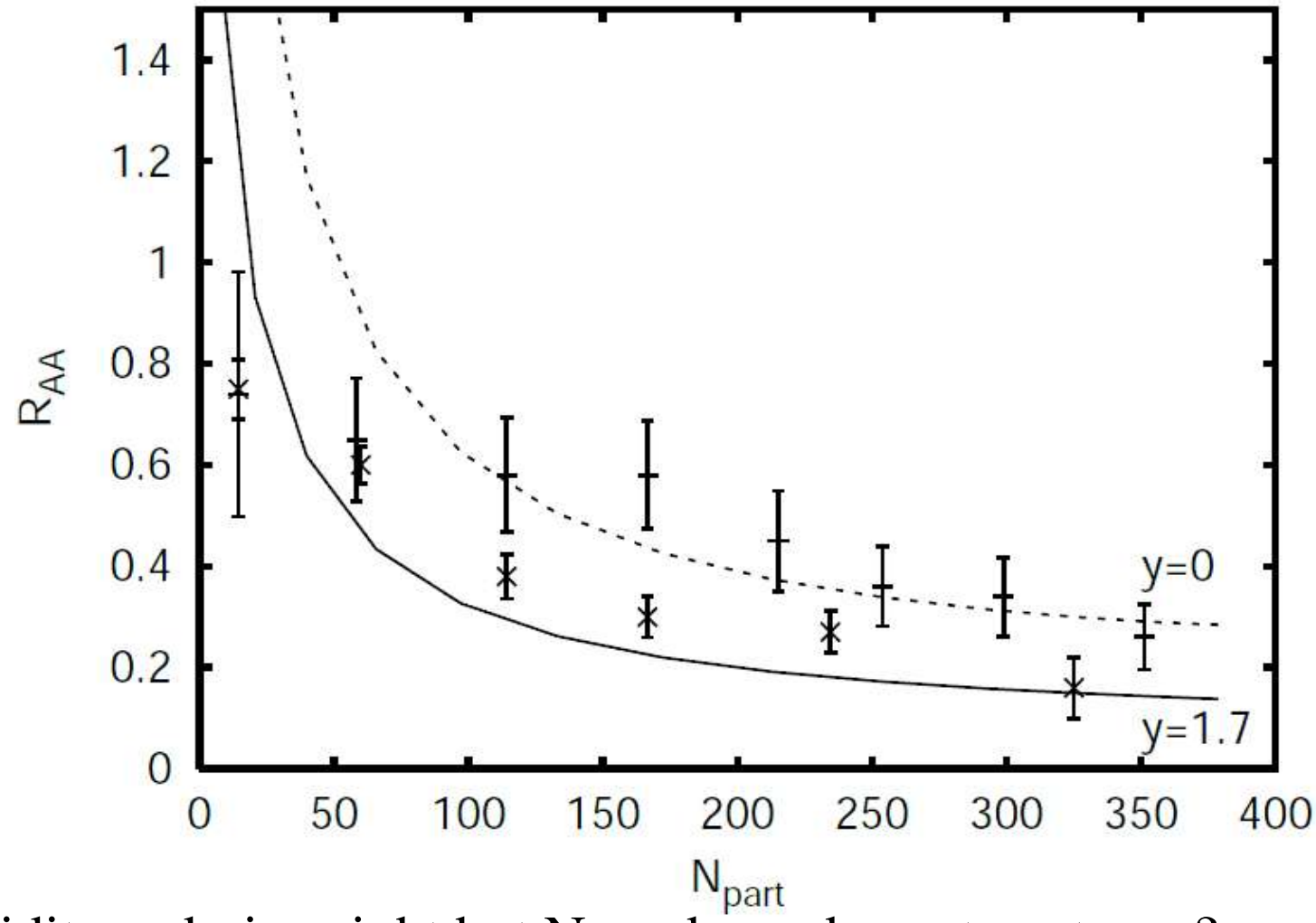
this leads to increasing suppression of the charm and J/psi cross section away from mid-rapidity as the size of the colliding nuclei increases

assumes incoherent superposition of color fields of the colliding nuclei -- ultra-high energy limit

would provide stronger overall suppression at LHC energy

Kharzeev, Levin, Nardi, Tuchin, arXiv:0809.2933

Saturation model for J/psi production



gets rapidity ordering right but N_{part} dependence too strong?

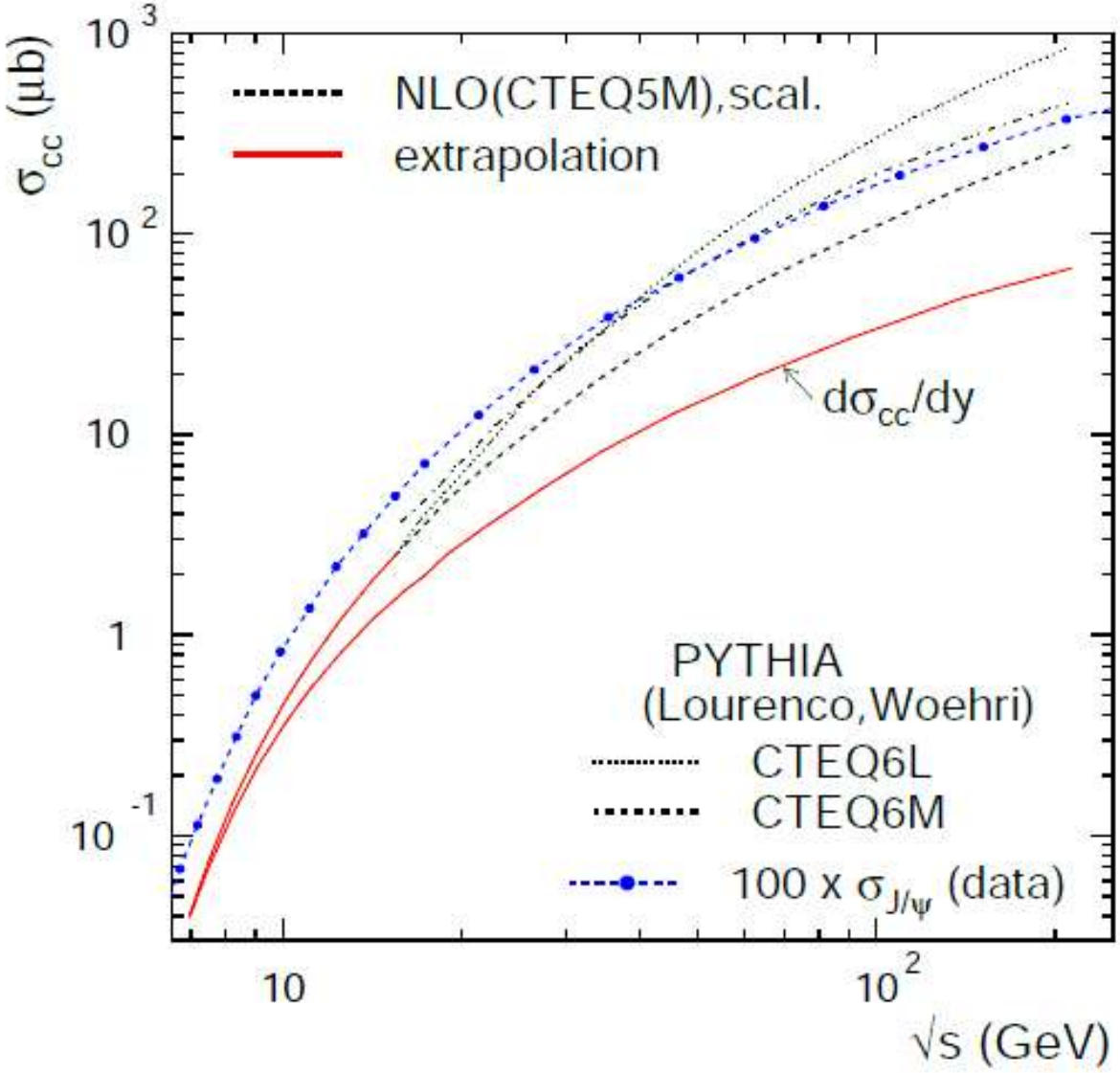
LHC data will be decisive

Kharzeev, Levin, Nardi, Tuchin, arXiv:0809.2933

An attempt to look at near threshold production

- charm cross section unknown
- but: $N_{ccbar} << 1$: only diagonal terms in recombination
- independent of energy, charm production
  still a hard process

Extrapolation of pQCD cross section to low energies



charm threshold in NN: 5.1 GeV

absolute threshold in Pb-Pb collisions:

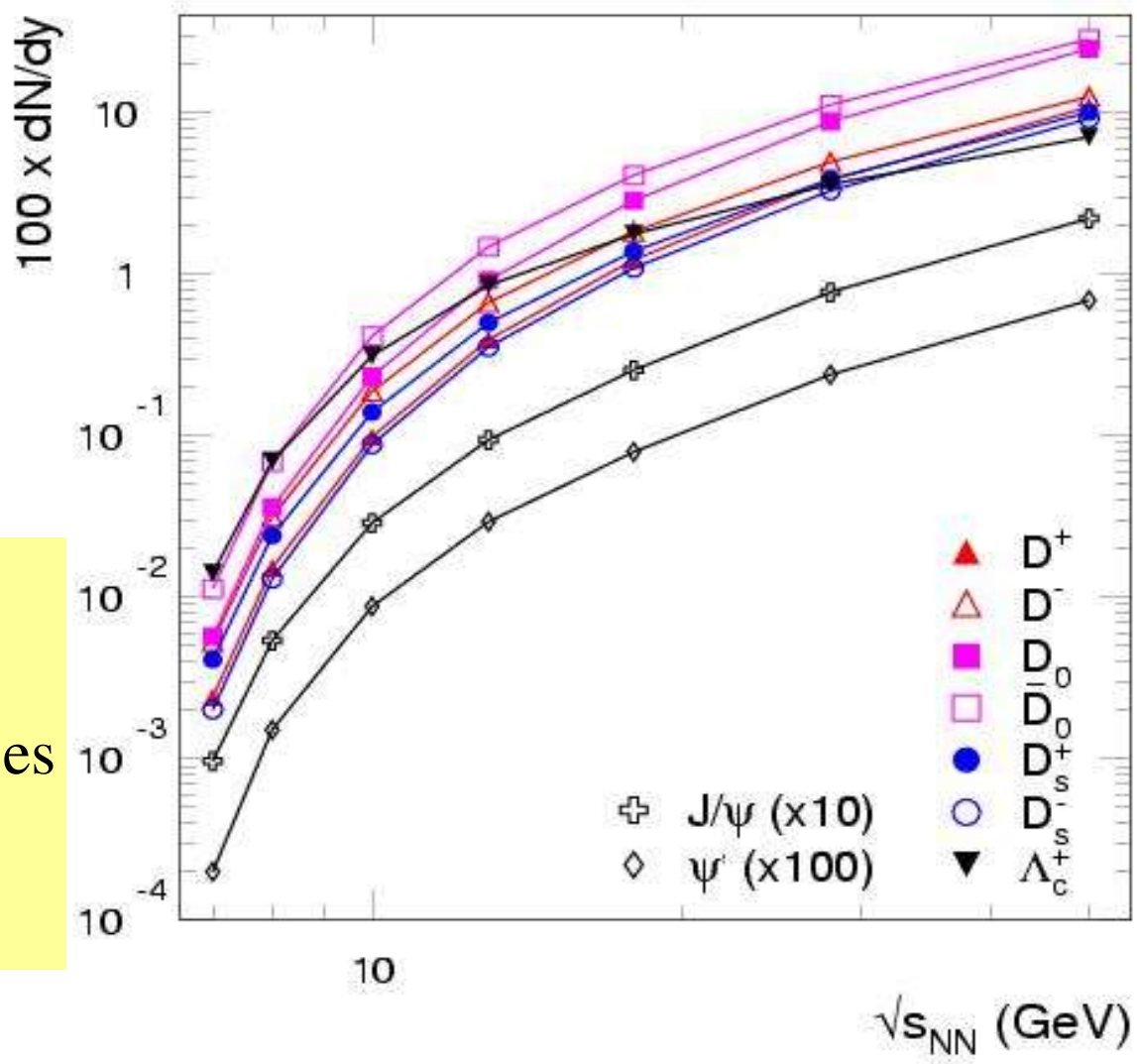
$T_{lab}/A = 31$ MeV

SIS300 full energy

SPS full energy

Statistical hadronization predictions for open and hidden charm at low energies

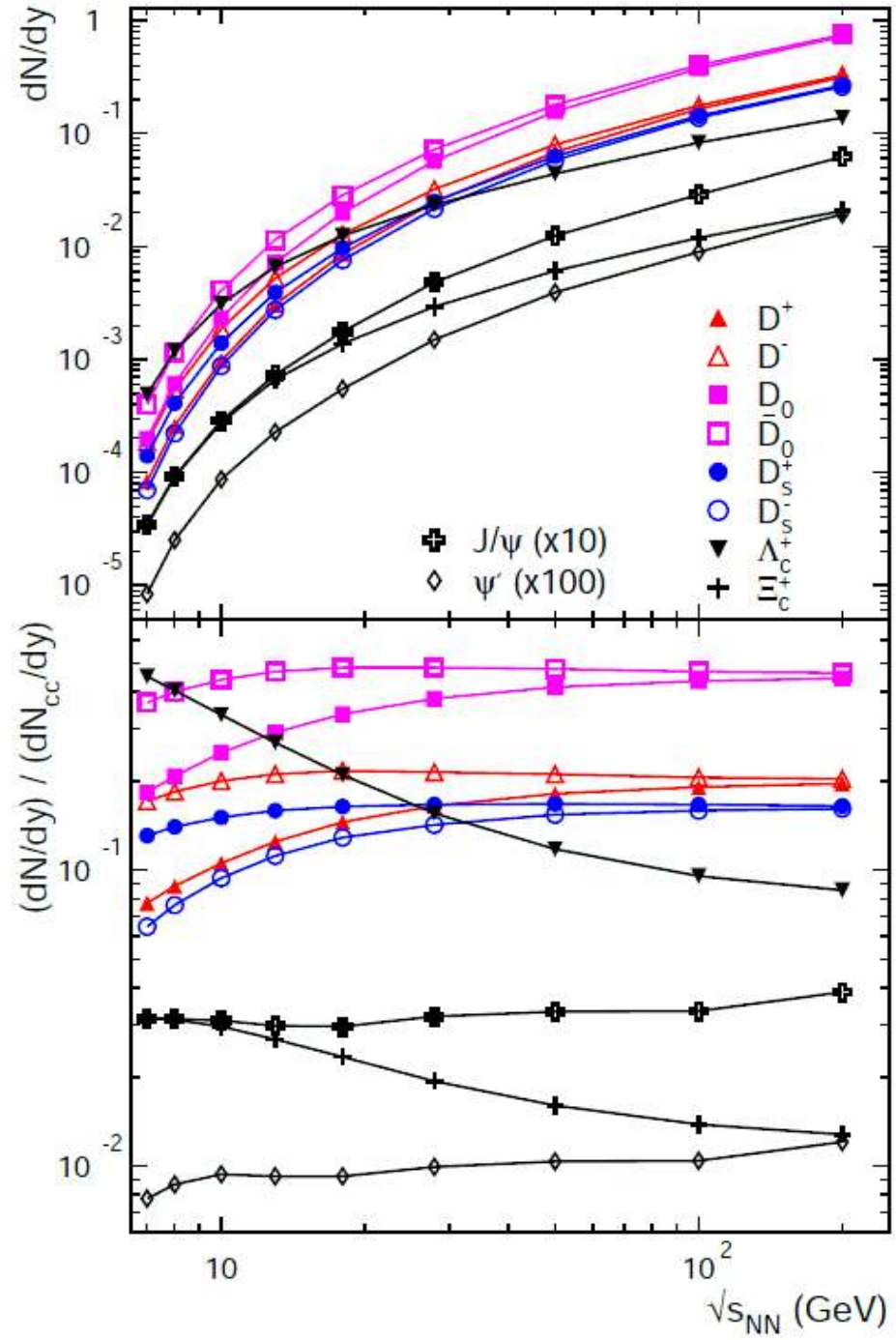
vacuum masses



Model predictions without any medium modifications

note in particular the role of charmed baryons

at SIS300 energies it is crucial to measure those



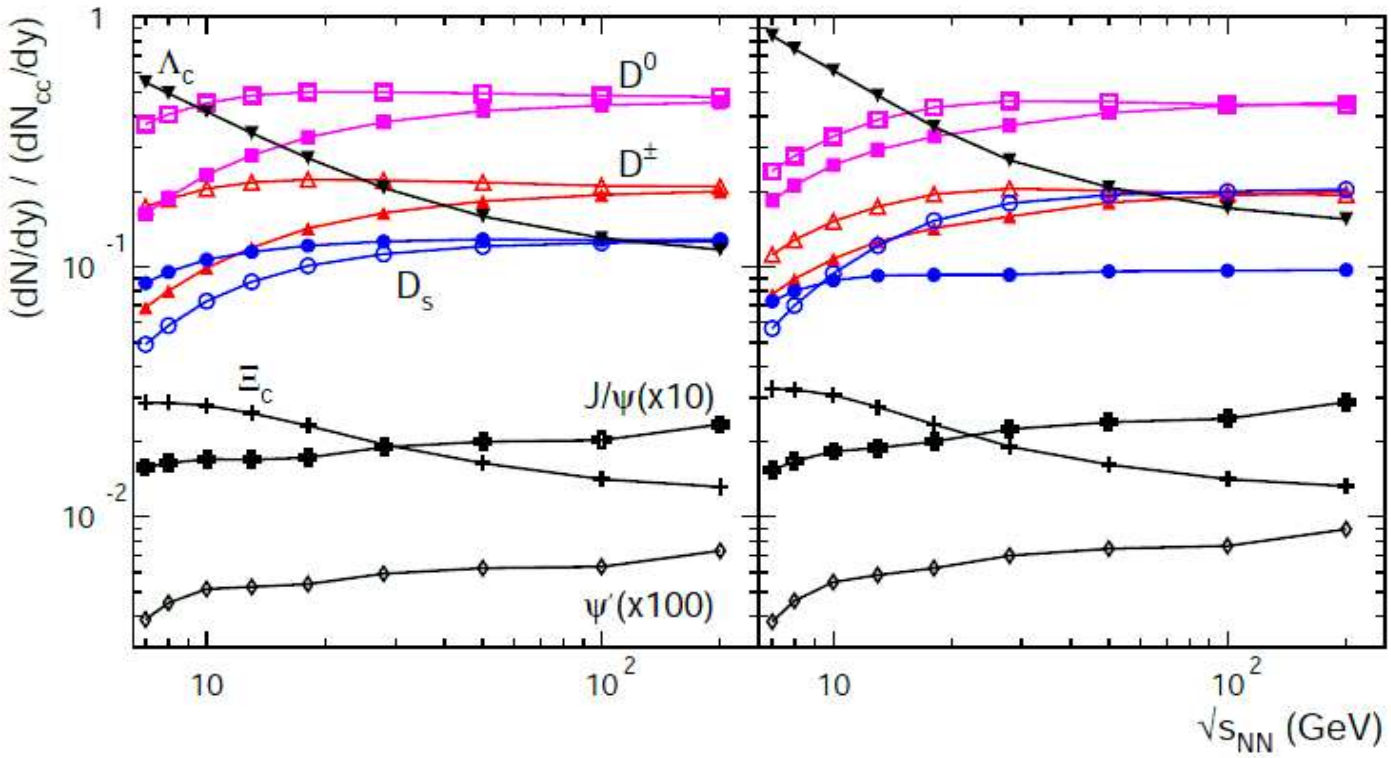
Scenarios of in-medium modified masses

modification of the constituent quark masses of light (u and d) quarks
(no change of J/ψ mass, $\Delta m_{\Lambda_c}/2$ for Ξ_c)

case	Δm_D	$\Delta m_{\Lambda_c,\Xi_c}$
i)	-50 MeV ($D, \bar{D}$)	-100 MeV ($\Lambda_c, \bar{\Lambda}_c$)
ii) (FAIR)	-100 MeV (D), +50 MeV ($\bar{D}$)	-200 MeV (Λ_c), +100 MeV ($\bar{\Lambda}_c$)
iii)	-50 MeV ($D, \bar{D}$)	-50 MeV ($\Lambda_c, \bar{\Lambda}_c$)

Tsushima et al.,PRC 59 (1999) 2824 [nucl-th/9810016].
Sibirtsev et al., EPJA 6 (1999) 351 [nucl-th/9904016]; PLB 484 (2000) 23 [nucl-th/9904015].
Hayashigaki, PLB 487 (2000) 96 [nucl-th/0001051].
Cassing et al., NPA 691 (2001) 753 [nucl-th/0010071].
Friman et al., PLB 548 (2002) 153 [nucl-th/0207006].
Grandchamp et al., PRL 92 (2004) 212301 [hep-ph/0306077].
Tolos et al, PLB 635 (2006) 85 [nucl-th/0509054].
Lutz, Korpa, PLB 633 (2006) 43 [nucl-th/0510006].

Results including medium modifications



scenario 1 scenario 2

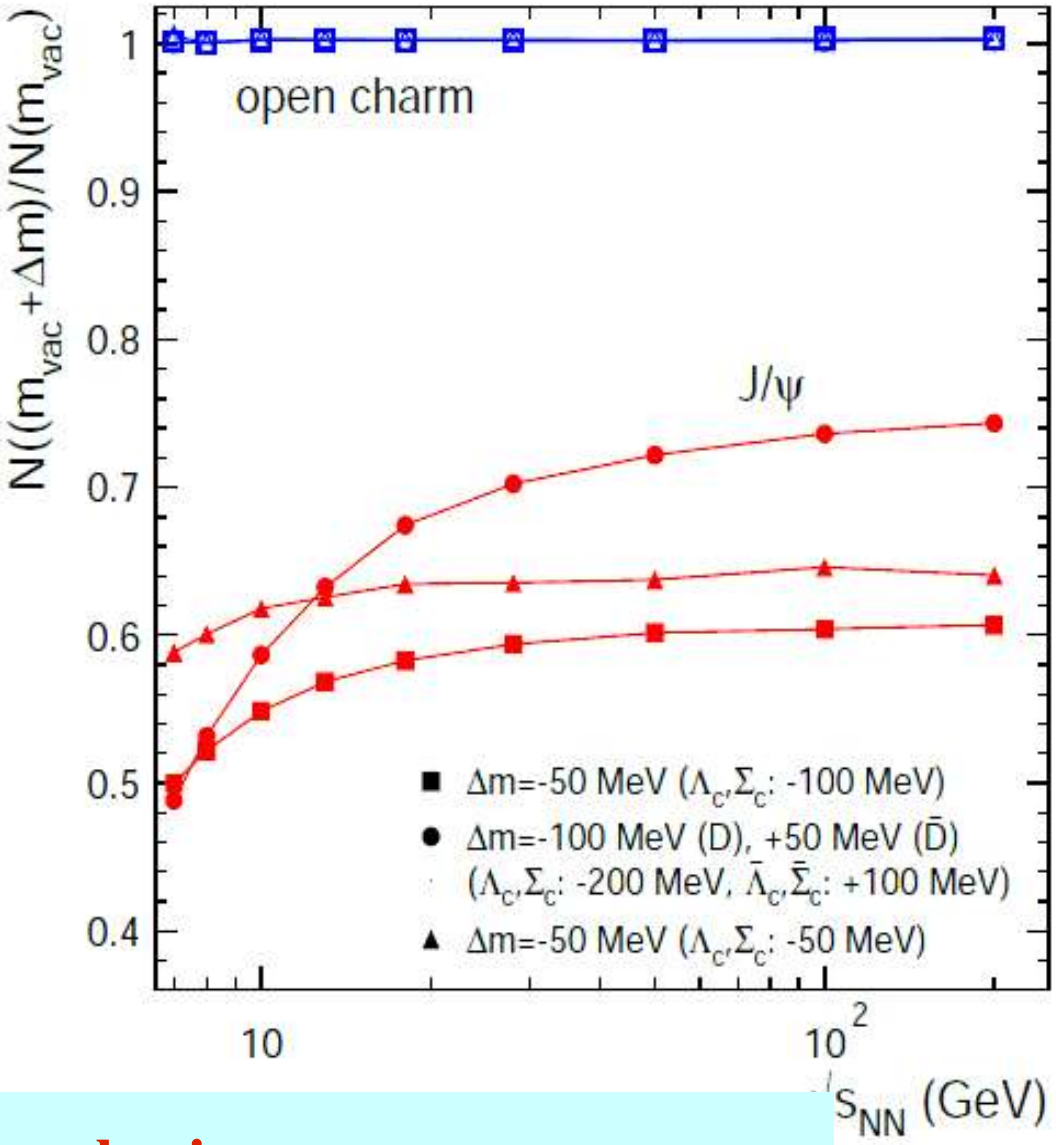
note: changes are subtle and show up ONLY when normalized to total charm cross section

Changes for charmonium assuming scenarios 1 – 3

charmonium masses unchanged

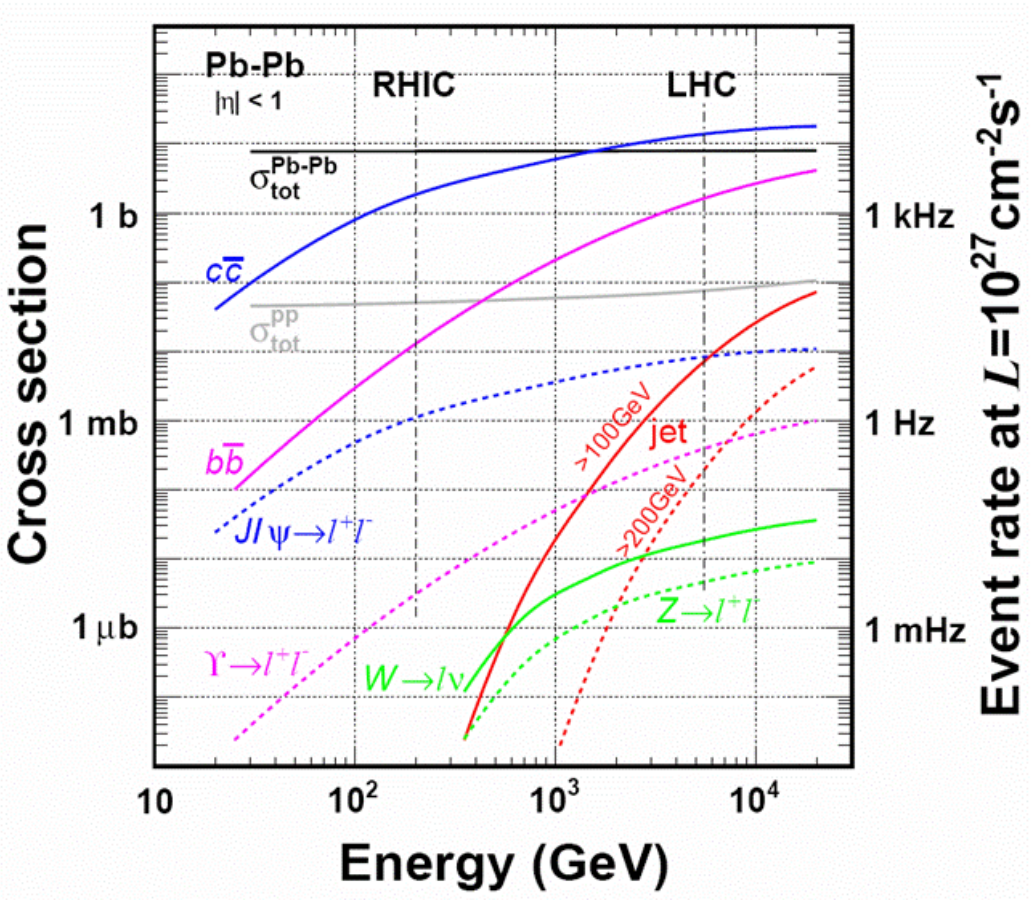
yield of charmonium may change by up to factor of 2

difficult how to normalize



however, no strong physics reasons for investigation of charm and charmonia at different energies, no clear change in physics expected

Heavy Quarks at LHC energy



$\sigma_c(LHC) = \sigma_c(RHIC) \times 10$

$\sigma_b(LHC) = \sigma_b(RHIC) \times 100$

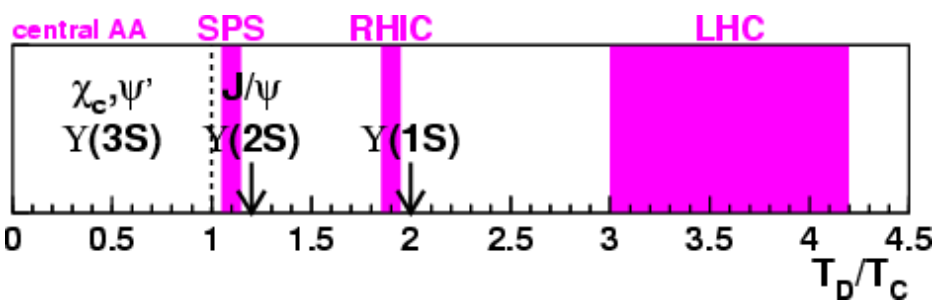
$\sigma_W(LHC) = \sigma_\Upsilon(RHIC) \times 10$

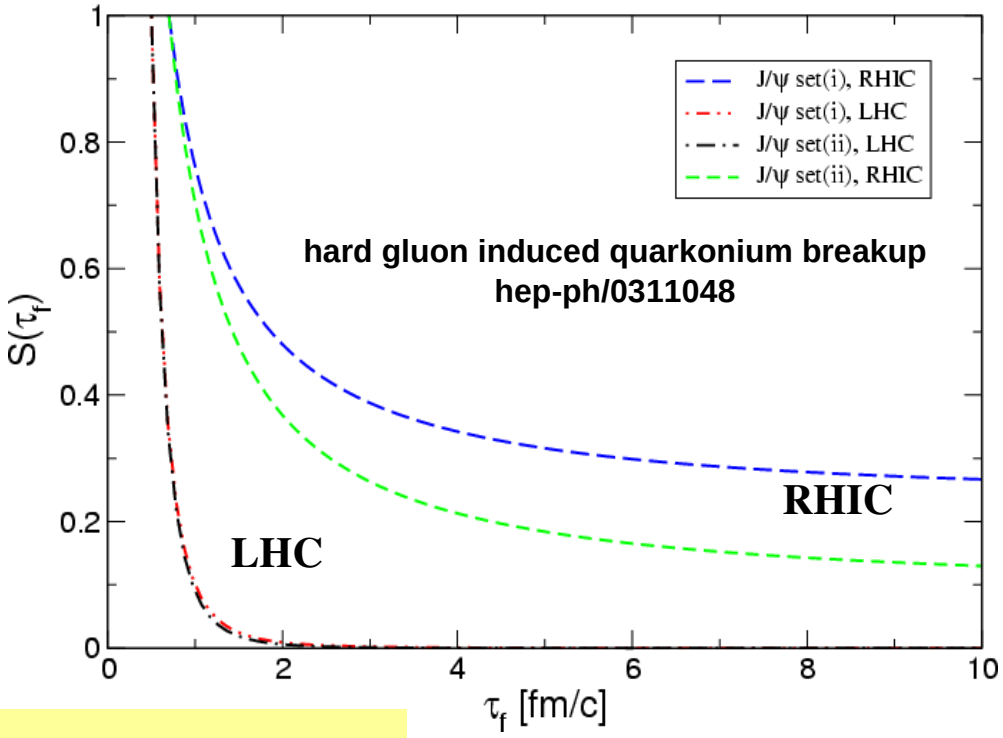
$\sigma_Z(LHC) = \sigma_\Upsilon(RHIC)$

All quarkonia within experimental reach (ALICE, ATLAS, CMS)

predicted quarkonium dissociation temperatures in the QGP

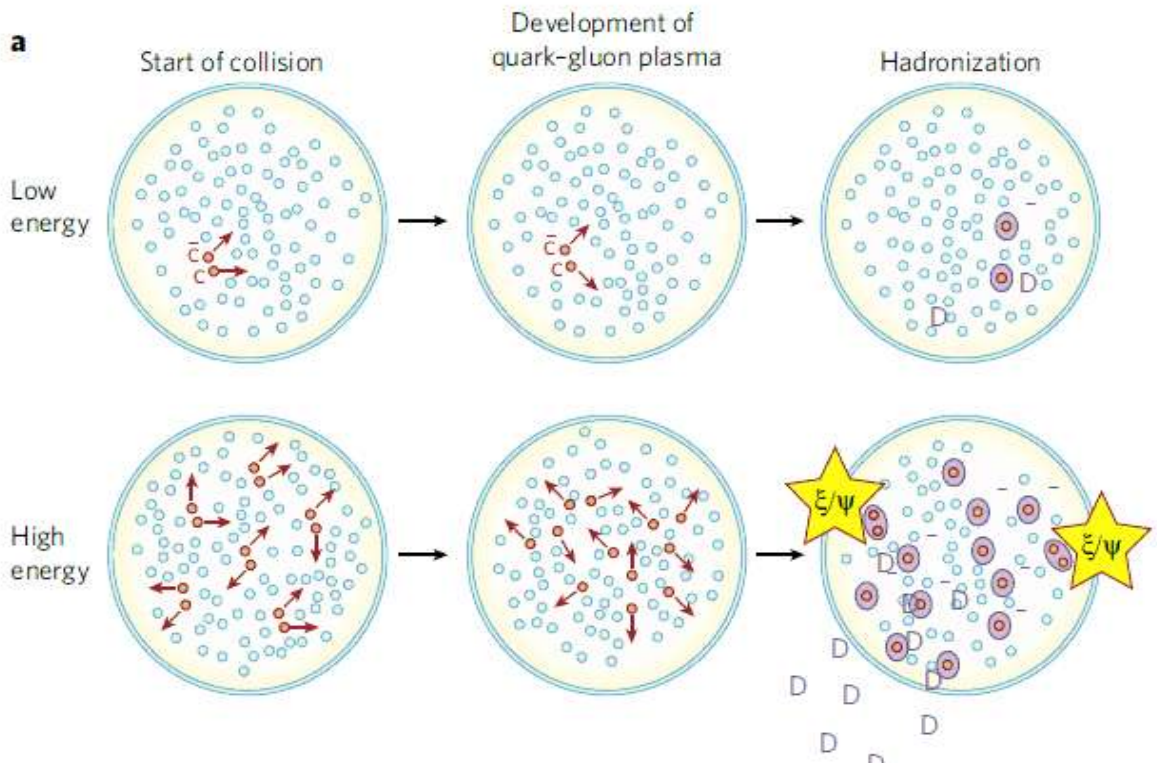
A. Mocsy & P. Petreczky, Phys. Rev. Lett. 99 (2007) 211602

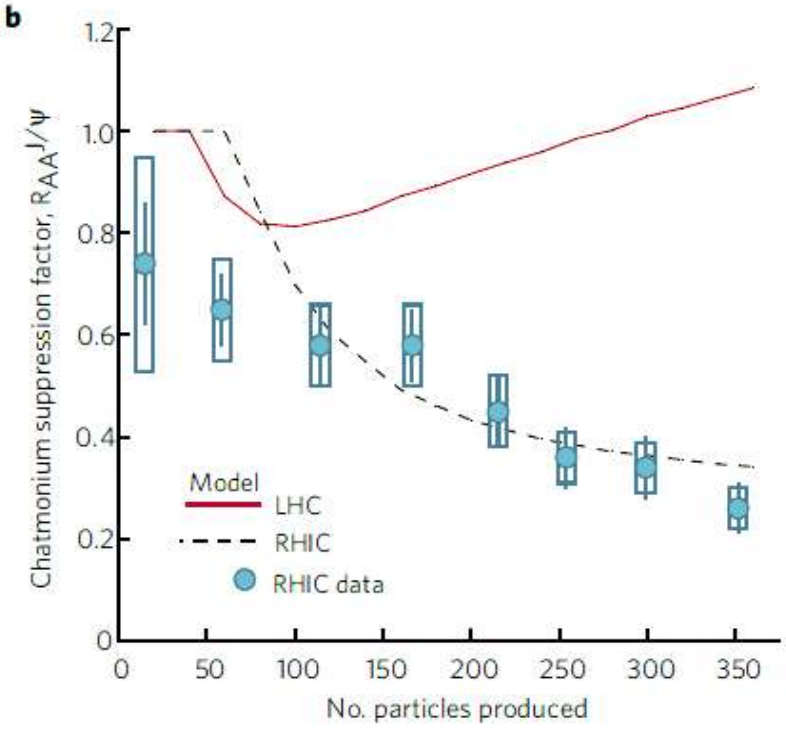




expect all charmonia to be destroyed
by QGP and hard gluons
but: regeneration at the phase boundary!

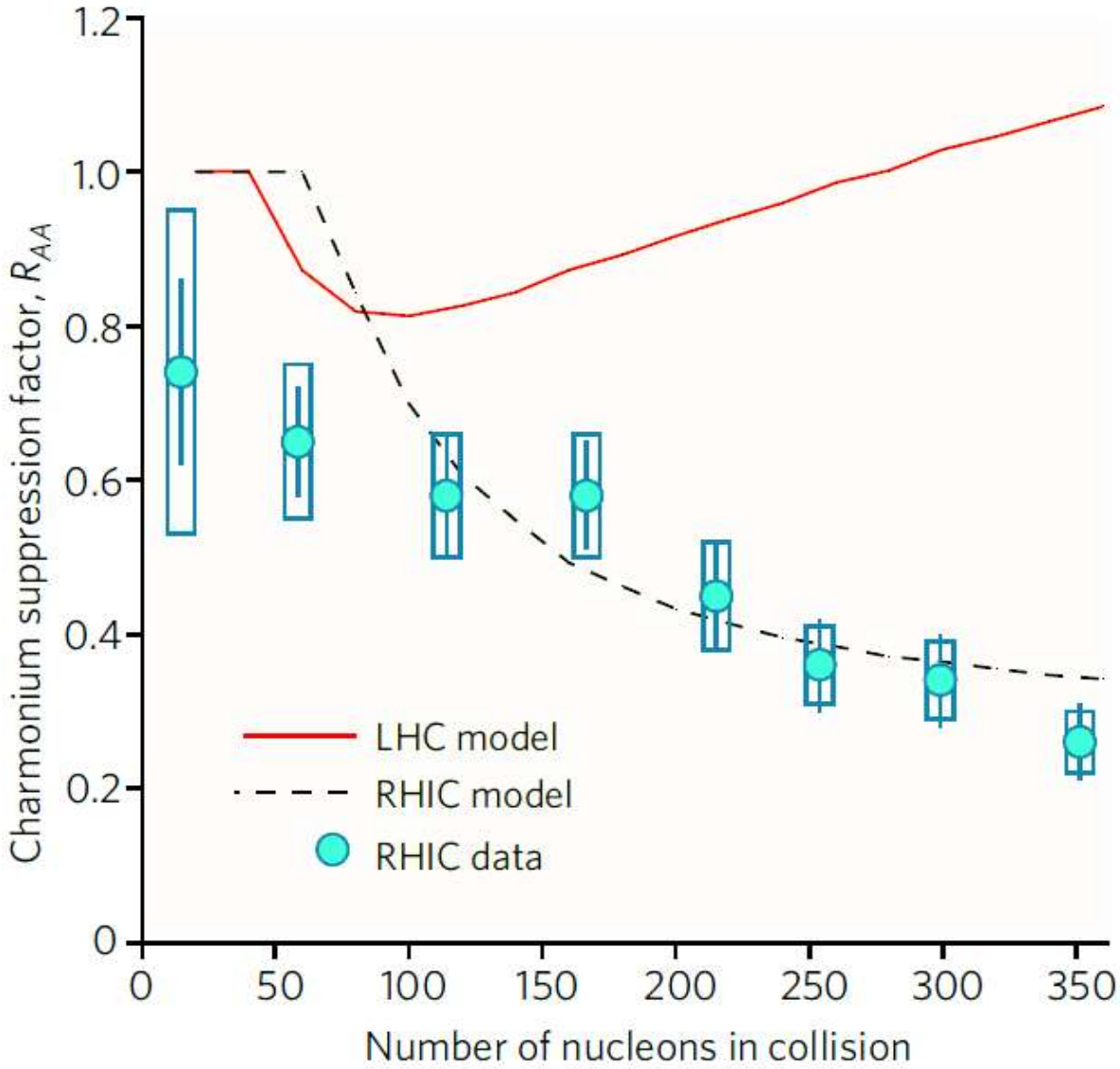
Quarkonium as a probe for deconfinement at the LHC





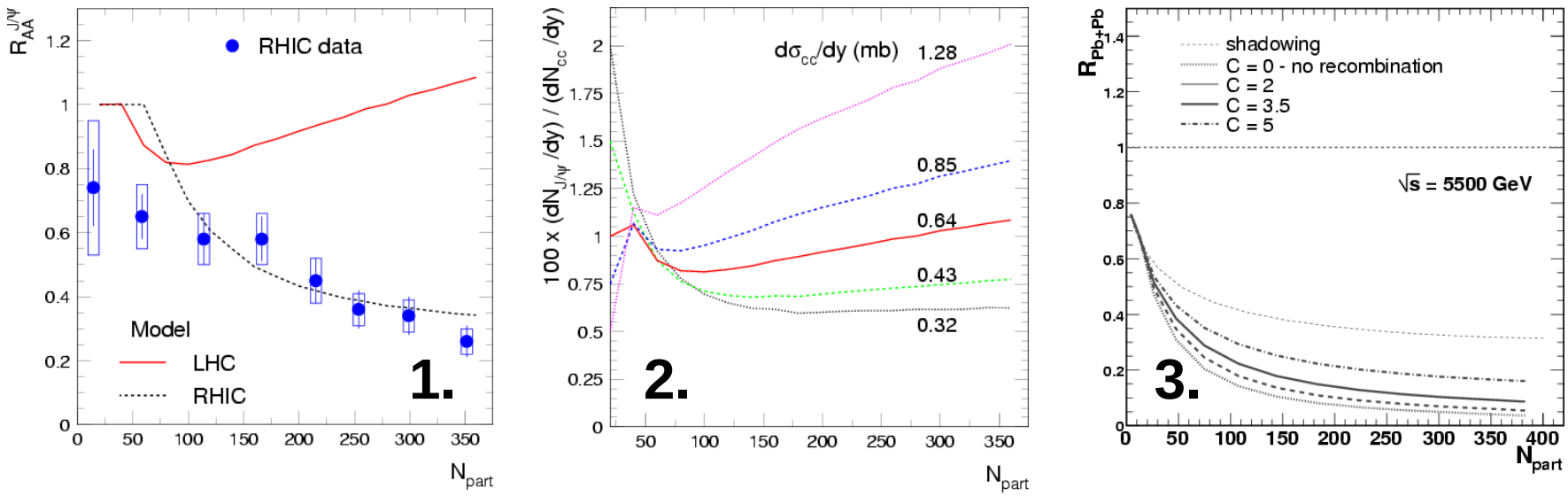
charmonium enhancement as fingerprint of deconfinement at LHC energy

Comparison to RHIC data and predictions for LHC



deconfined charm quarks lead in large numbers to charmonium enhancement rather than suppression

Prediction for LHC energy: enhancement depends on charm cross section!



1 and 2: stat. hadronization

3: shadowing and regeneration in the hadronic phase only

A. Capella et al., arXiv:0712.4331 [hep-ph]

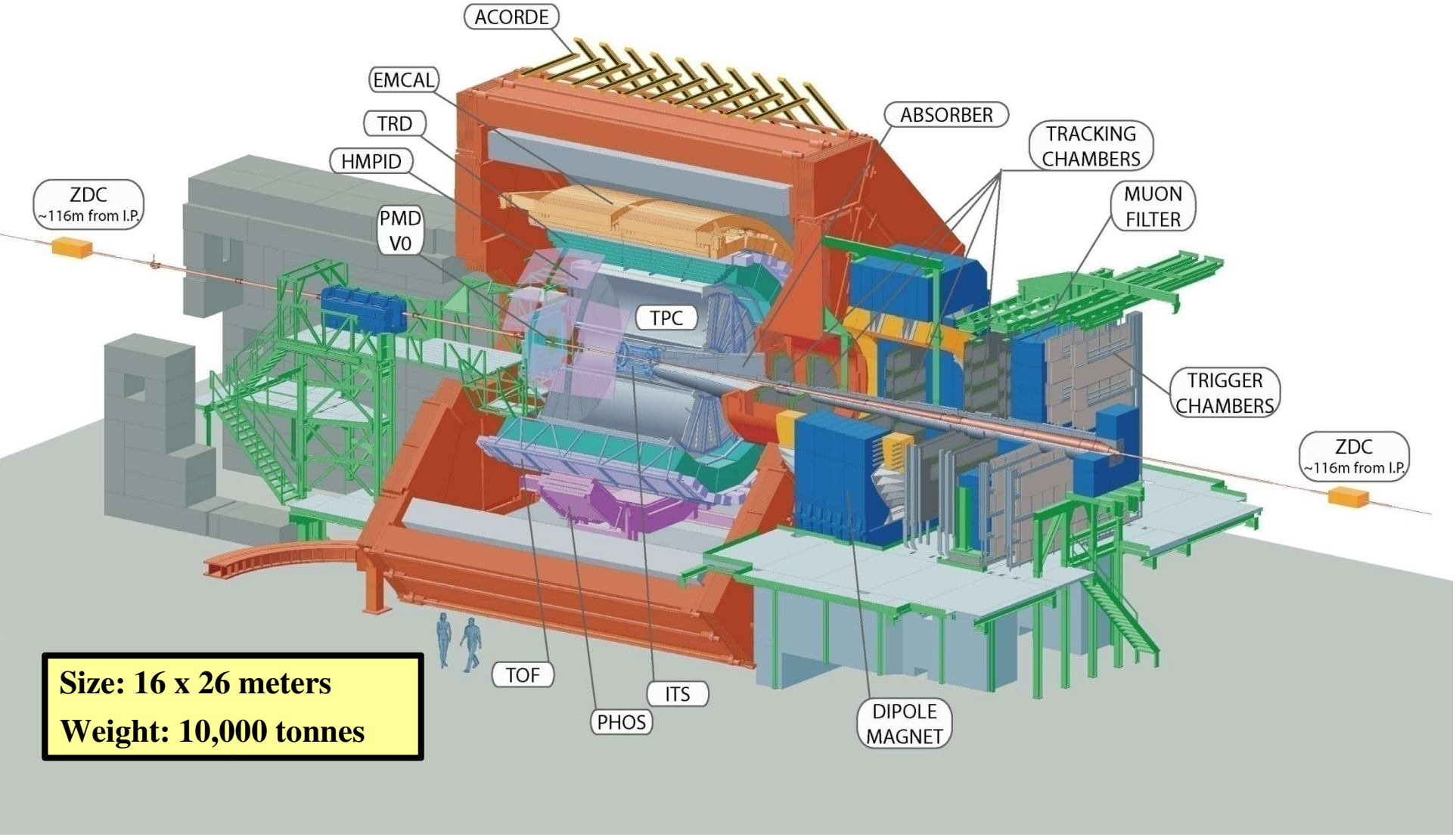
Summary

- heavy quark production - a hard process
- charmonia: most likely destroyed in QGP
  but regenerated at the phase boundary
  yield ~ N_c^2 -- quarkonium enhancement at high energies
- first signature for regeneration from RHIC data
- SPS and lower energies: only weak medium effects
- LHC: charmonium enhancement – fingerprint of deconfinement

first LHC data soon

backup slides

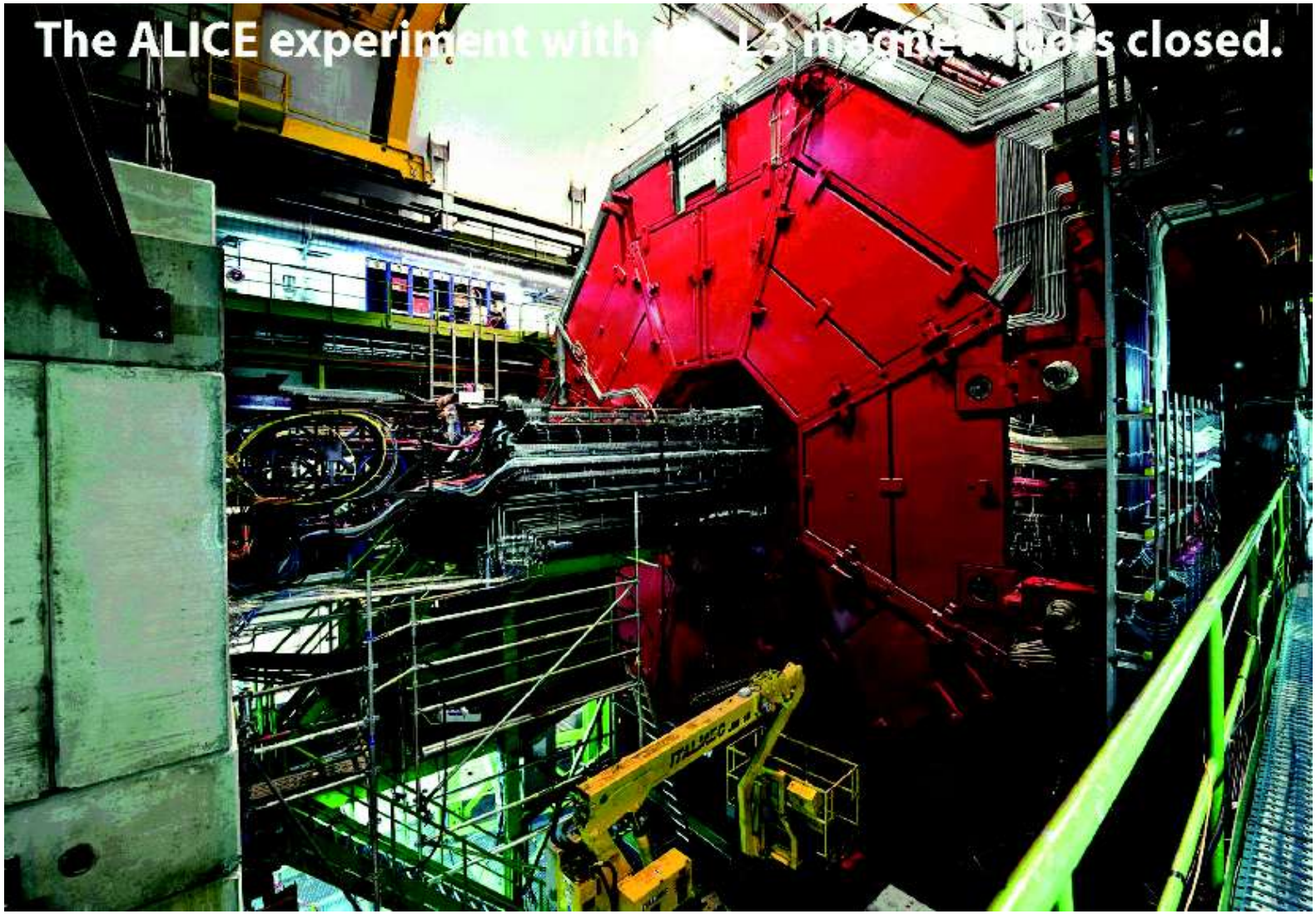
ALICE: A Large Ion Collider Experiment at CERN-LHC



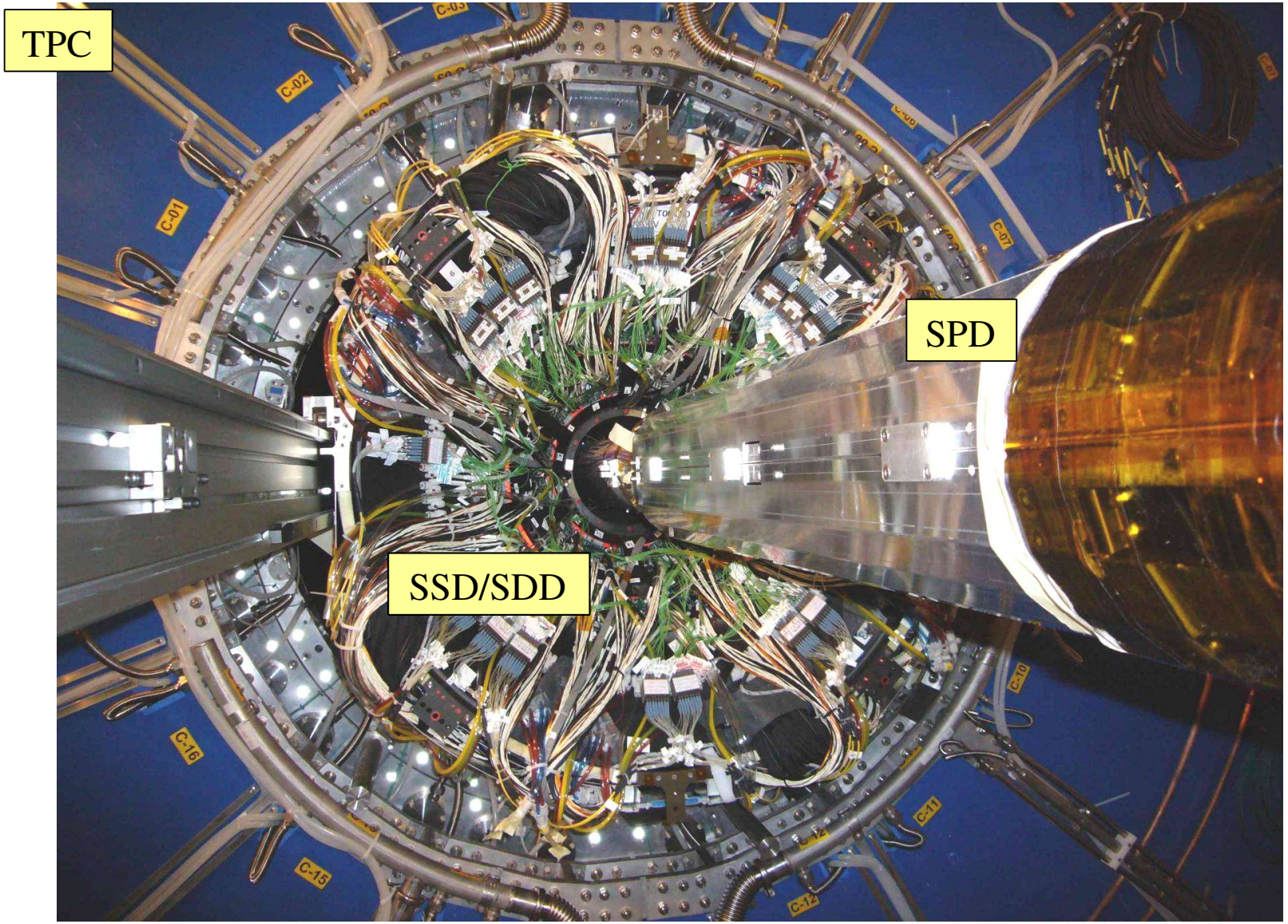
Size: 16 x 26 meters

Weight: 10,000 tonnes

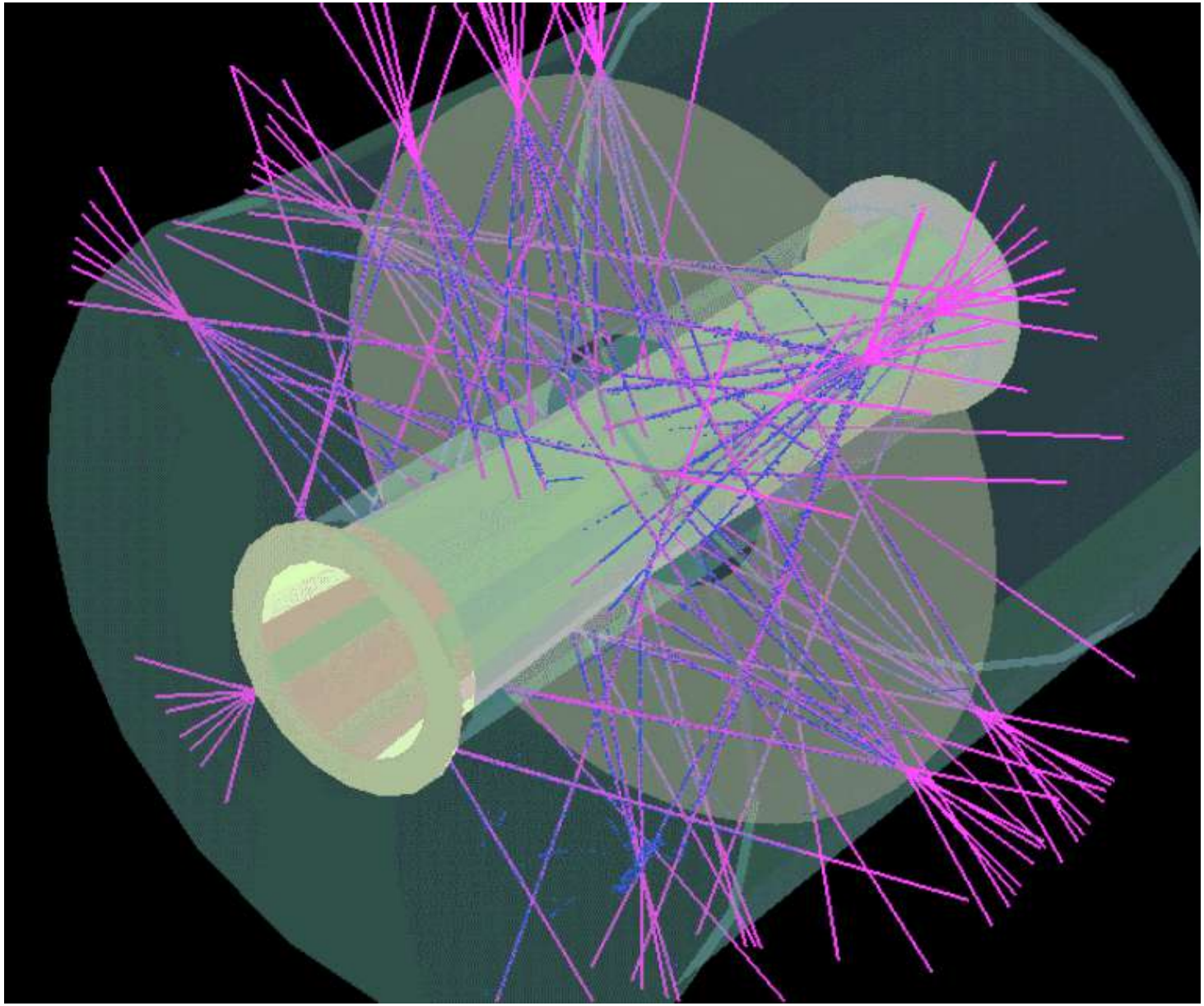
ALICE is ready for action



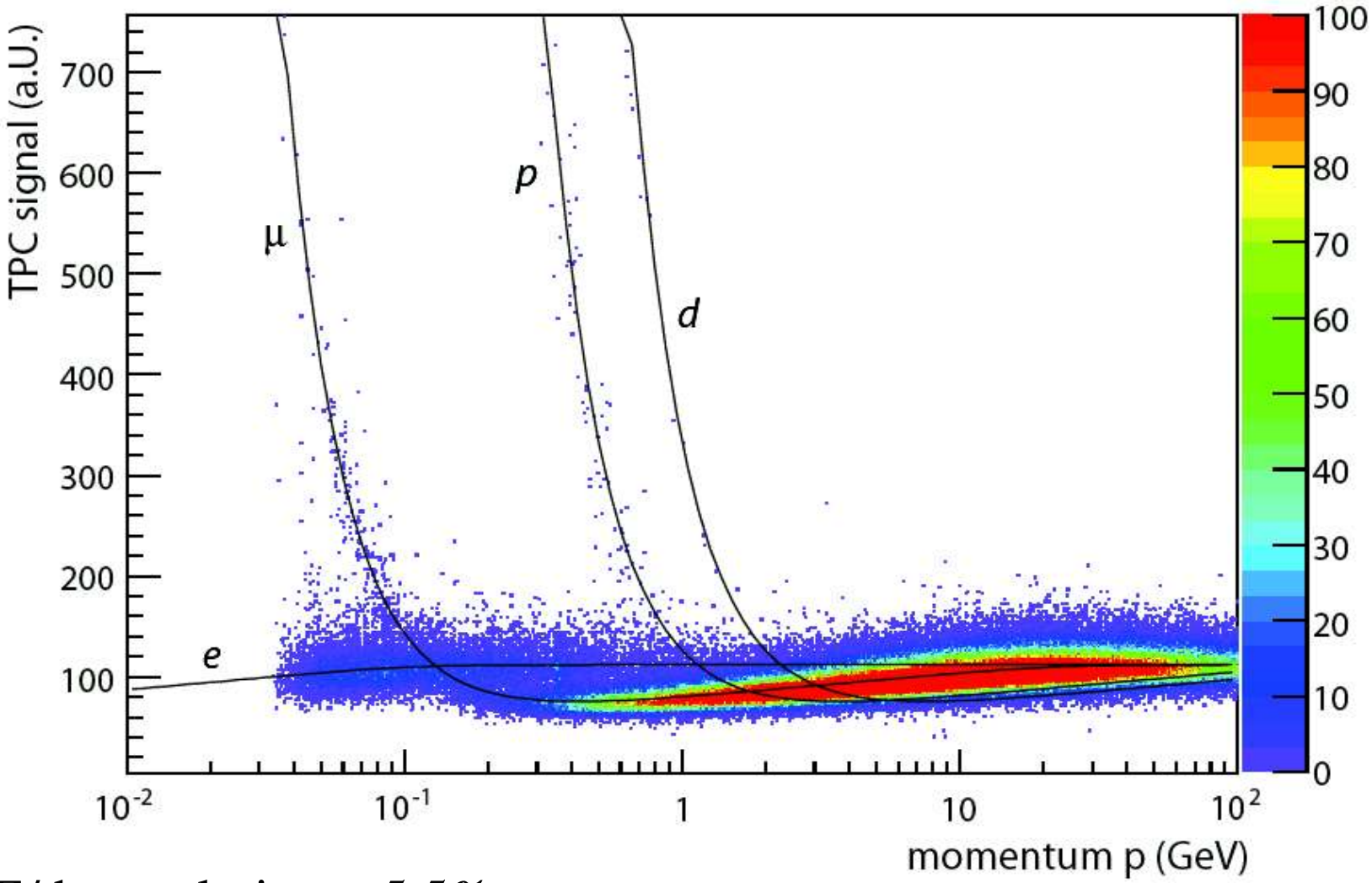
Insertion of the Inner Tracking Detector into the TPC



reconstructed laser tracks in the ALICE TPC

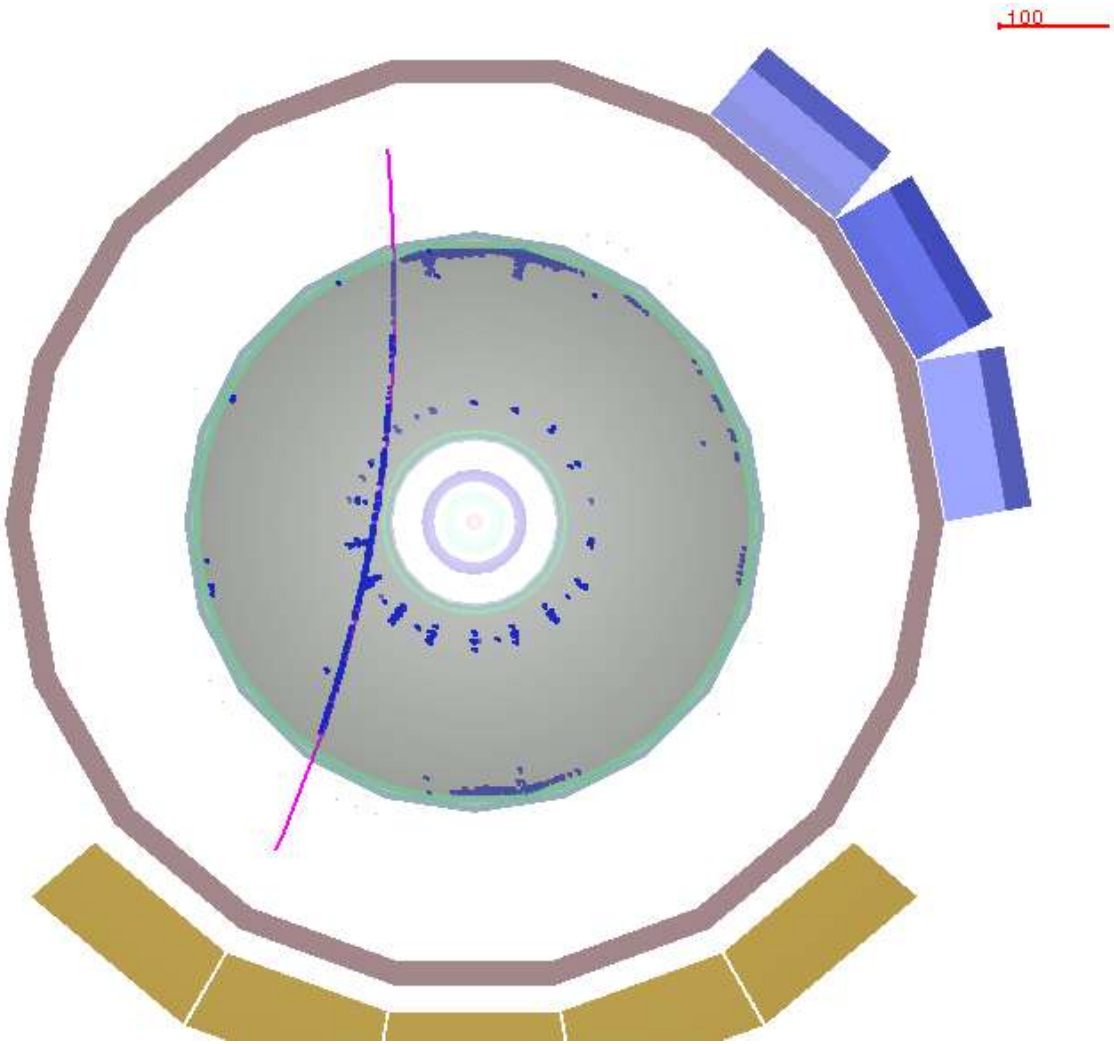


dE/dx calibration of the ALICE TPC with cosmics

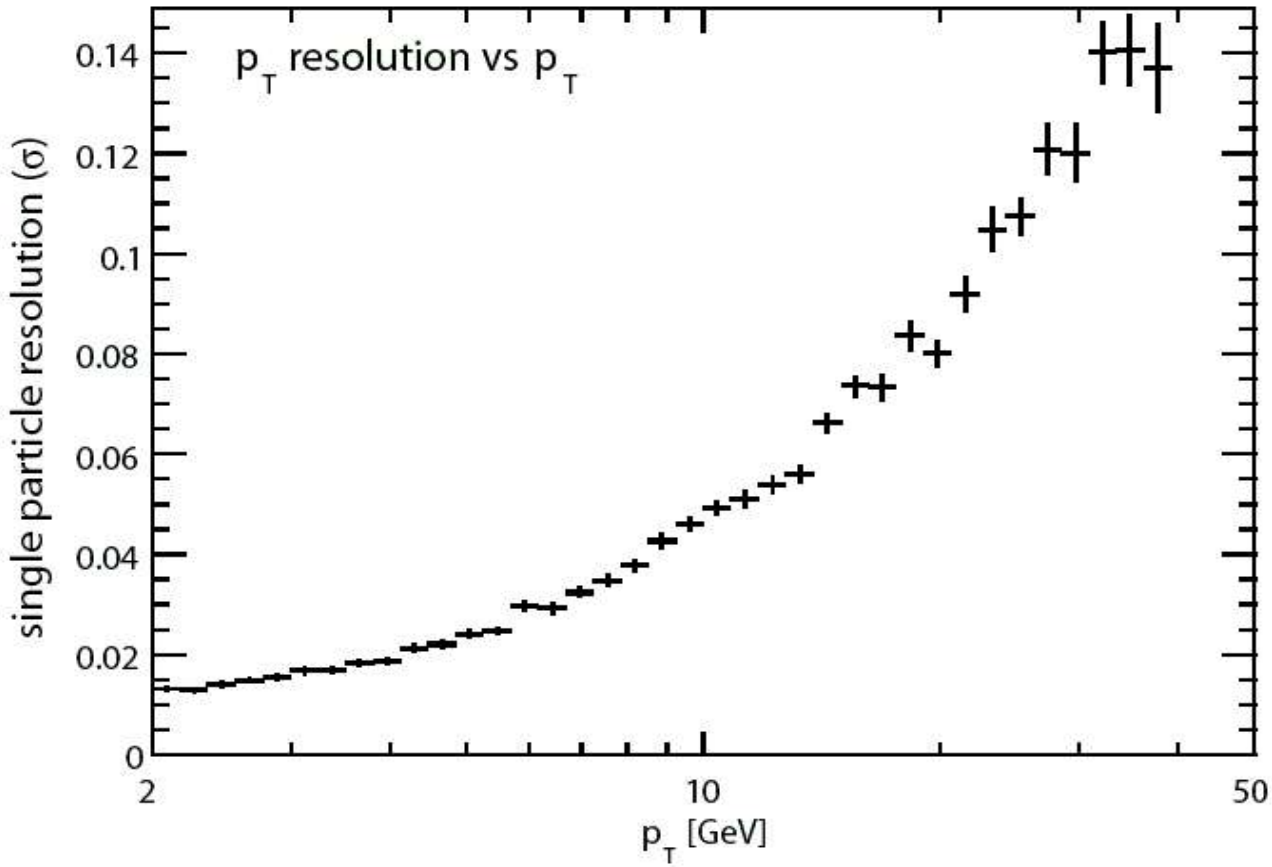


dE/dx resolution < 5.5%

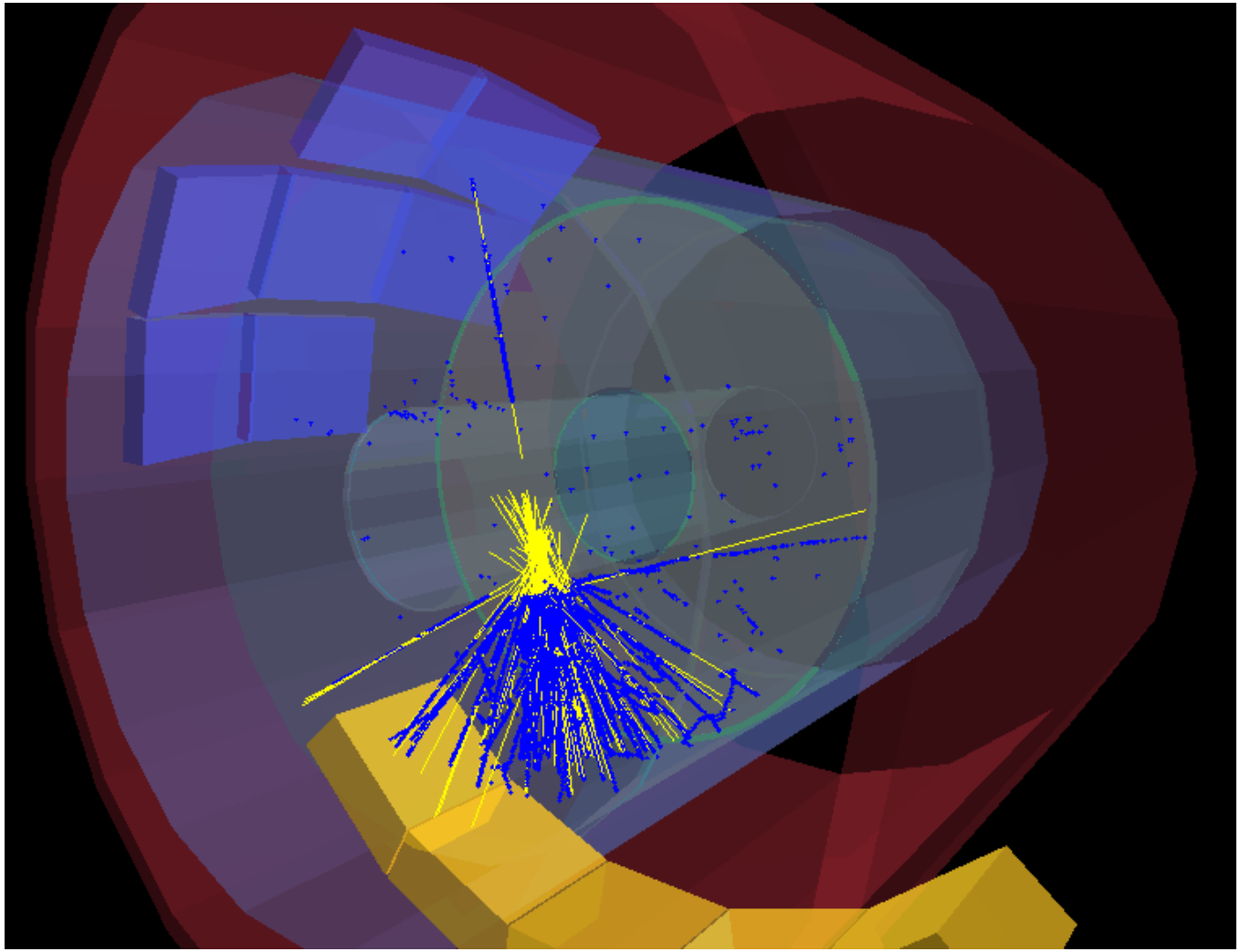
a muon track with B = 0.5 T



momentum resolution of the ALICE TPC



TPC fully operational



a large cosmic shower in the muon absorber fully tracked

first results with pp collisions in a few weeks

stay tuned

WARNING: different simulation frameworks & different assumptions

bkg assumes dN/dη = 2500-5000, S & S/√S+B: one month min-bias PbPb (CC for ALICE e^+e^-)

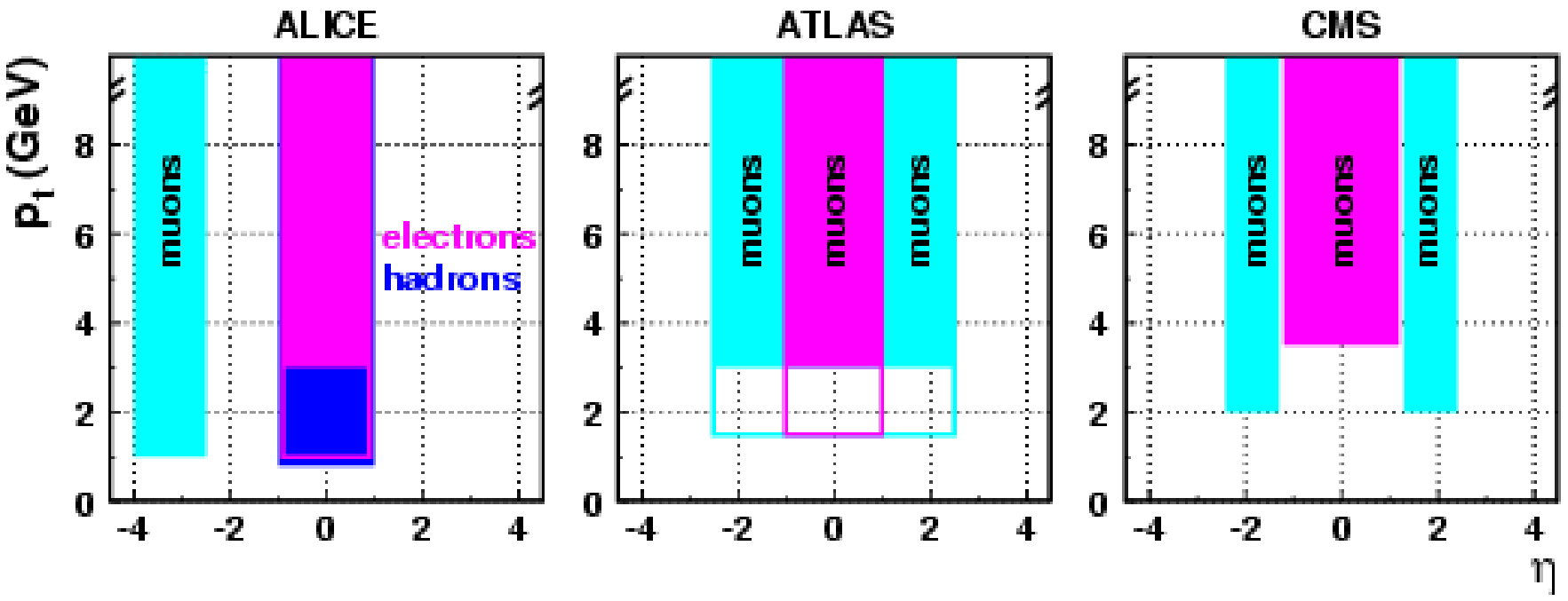
	ALICE $\mu^+\mu^-$	ALICE e^+e^-	CMS $\mu^+\mu^-$	ATLAS $\mu^+\mu^-$
acceptance	$-4<\eta<-2.5$	$\lvert\eta\rvert<0.9$	$\lvert\eta\rvert<2.4$	$\lvert\eta\rvert<2.5$
	charmonia			
$\sigma(J/\psi)$ (MeV)	74	30	35 (w/o bkg)	68
S ($\times 10^3$)	677	120	146	8-216 (p_t)
$S/\sqrt{S+B}$	413	245	234	52-164 (p_t)
	bottomonia			
$\sigma(\Upsilon)$ (MeV)	109	90	68-90 (bkg level)	145 ($\lvert\eta\rvert<2$)
S $\Upsilon, \Upsilon', \Upsilon''$	6800,1800,100	900,350,-	20300,5900,3500	10000-15000
$S/\sqrt{S+B}$ $\Upsilon, \Upsilon', \Upsilon''$	67,30,21	21,8	36,-,-	45-46

- **J/ψ, ϒ: first detailed studies within one month**
- **ψ': difficult (small S/B), ϒ', ϒ'': need 2-3 runs**

comparison courtesy Philippe Crochet

From A. Dainese @ HP2006, updated according to ALICE: J. Phys. G 32 (2006) 1295, W. Sommer et al. @ QM2006, CMS: J. Phys. G 34 (2007) 2307, CMS/note-2006/089, ATLAS: L. Rosselet @ HEP2007

Acceptance for heavy flavor measurements at LHC

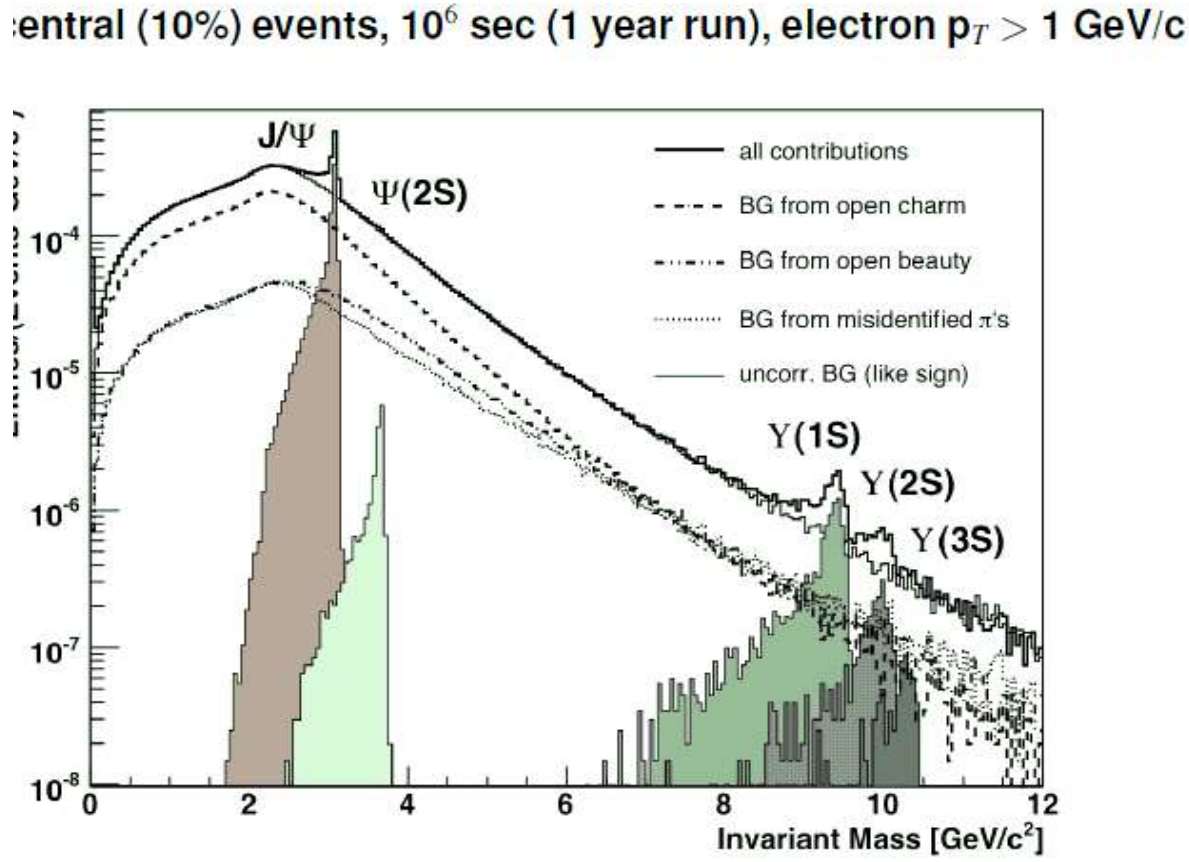


Measurement of Quarkonia with e+e- in ALICE

W. Sommer

Di-electron decays of J/Ψ, Ψ', ϒ

- Hijing generator, $< \frac{dN}{dy} >$ = 3000
- Nuclear shadowing included
- Fast simulation
- Parametrized response of barrel detectors
- Full TRD
- Electron identificaton with TRD and TPC



Quarkonia acceptance

- $-0.9 < \eta < 0.9$
- J/ψ: 5.5%
- ϒ: 9.6%

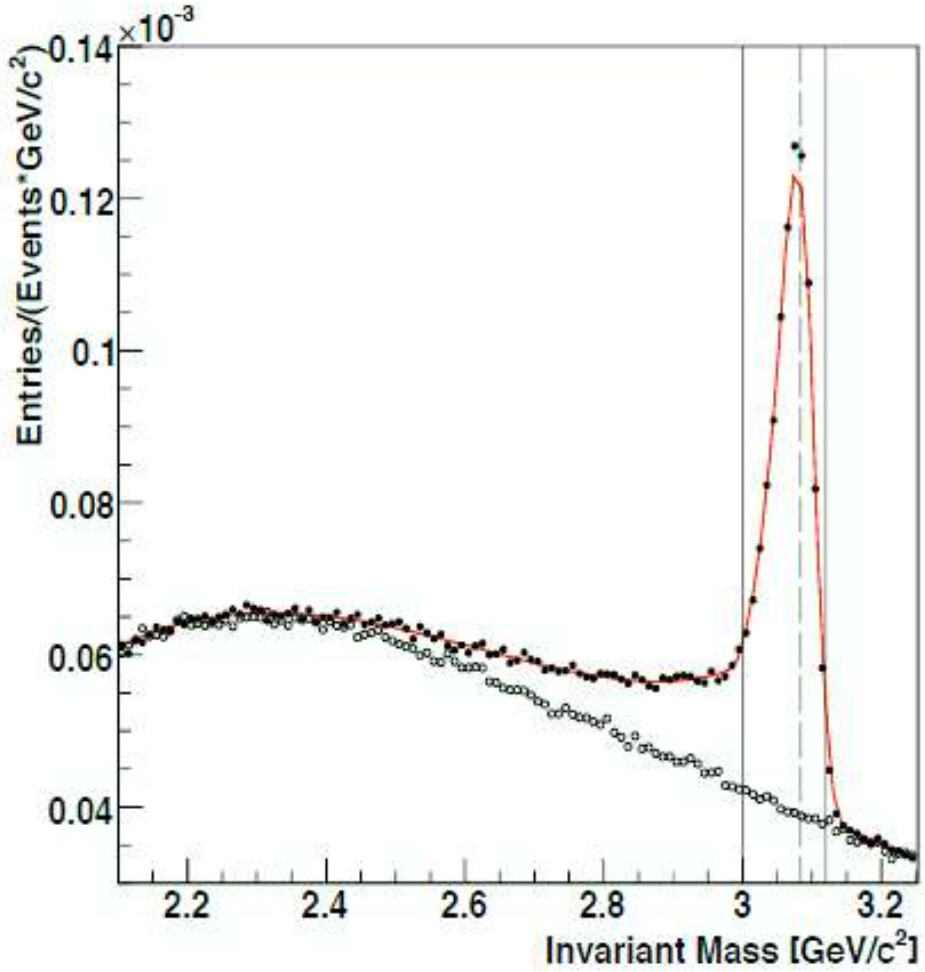
full separation of time scales at LHC energy

At collider energies there will be yet another separation of time scales. At LHC energy, the momentum of a Pb nucleus is p_{cm}=2.76 TeV per nucleon, leading to $\gamma_{cm} = 2940$, hence $t_{coll} < 5 \cdot 10^{-3}$ fm. Even "wee" partons with momentum fraction[3] $x_w = 2.5 \cdot 10^{-4}$ will pass by within a time $t_w = 1/(xp_{cm}) < 0.3$ fm, and will not destroy any charmonia since none exist at that time. We consequently expect that cold nuclear absorption will decrease from SPS to RHIC energy and should be negligible at LHC energy. First indications for this trend are visible in the PHENIX data [22].

A detailed look at the J/psi

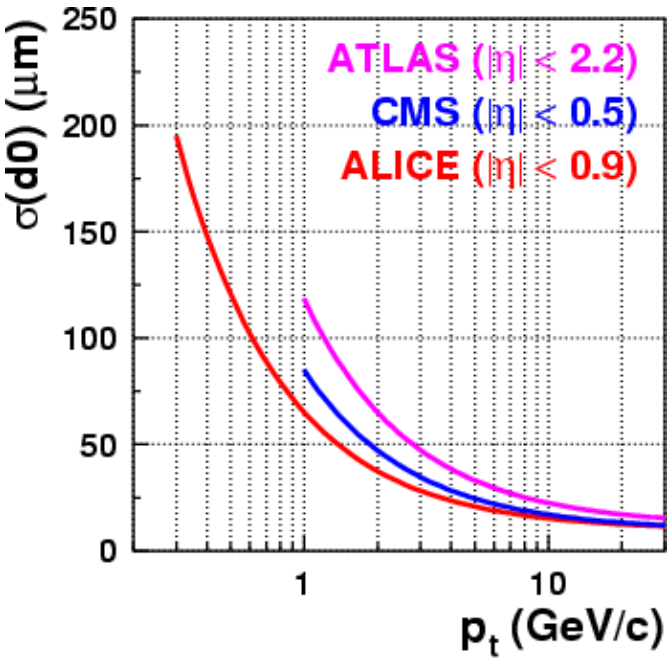
2×10^8 central (10%) events, 10^6 sec (1 year run)

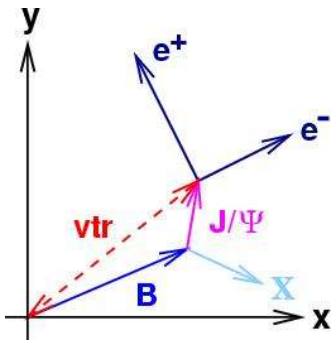
J/ψ:
S/B = 1.47
sgn = 284
signal = 1.3×10^5
FWHM = 65 MeV/c^2

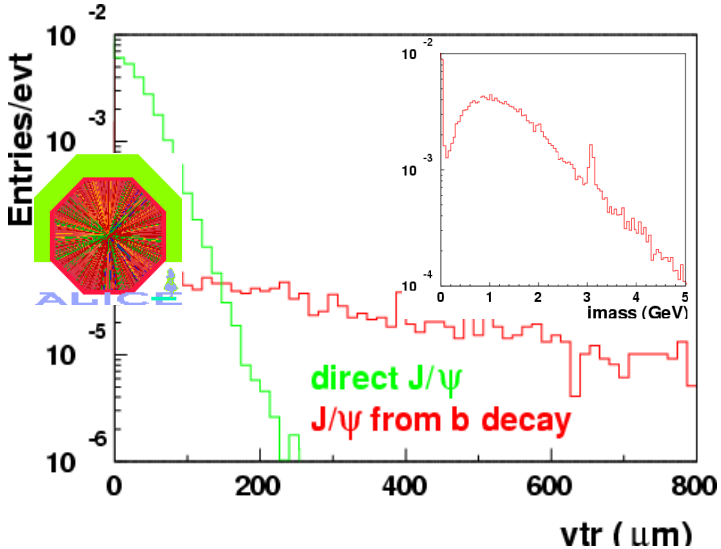


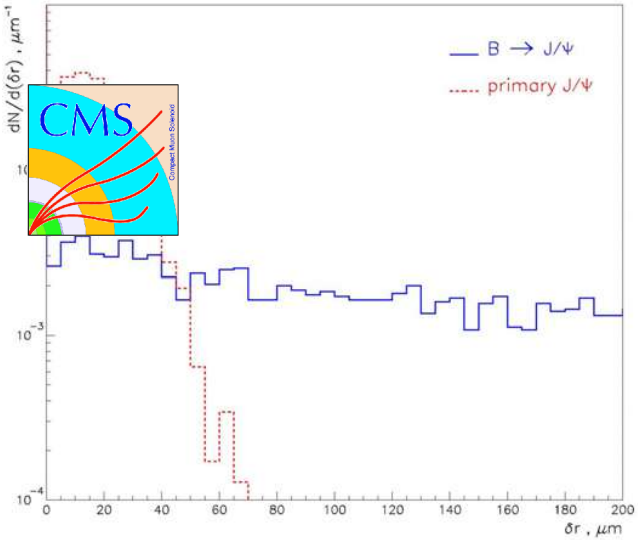
Important at LHC: feed-down from B needs to be measured

N(B → J/ψ) / N(direct J/ψ) ~ 20% in 4π @ LHC









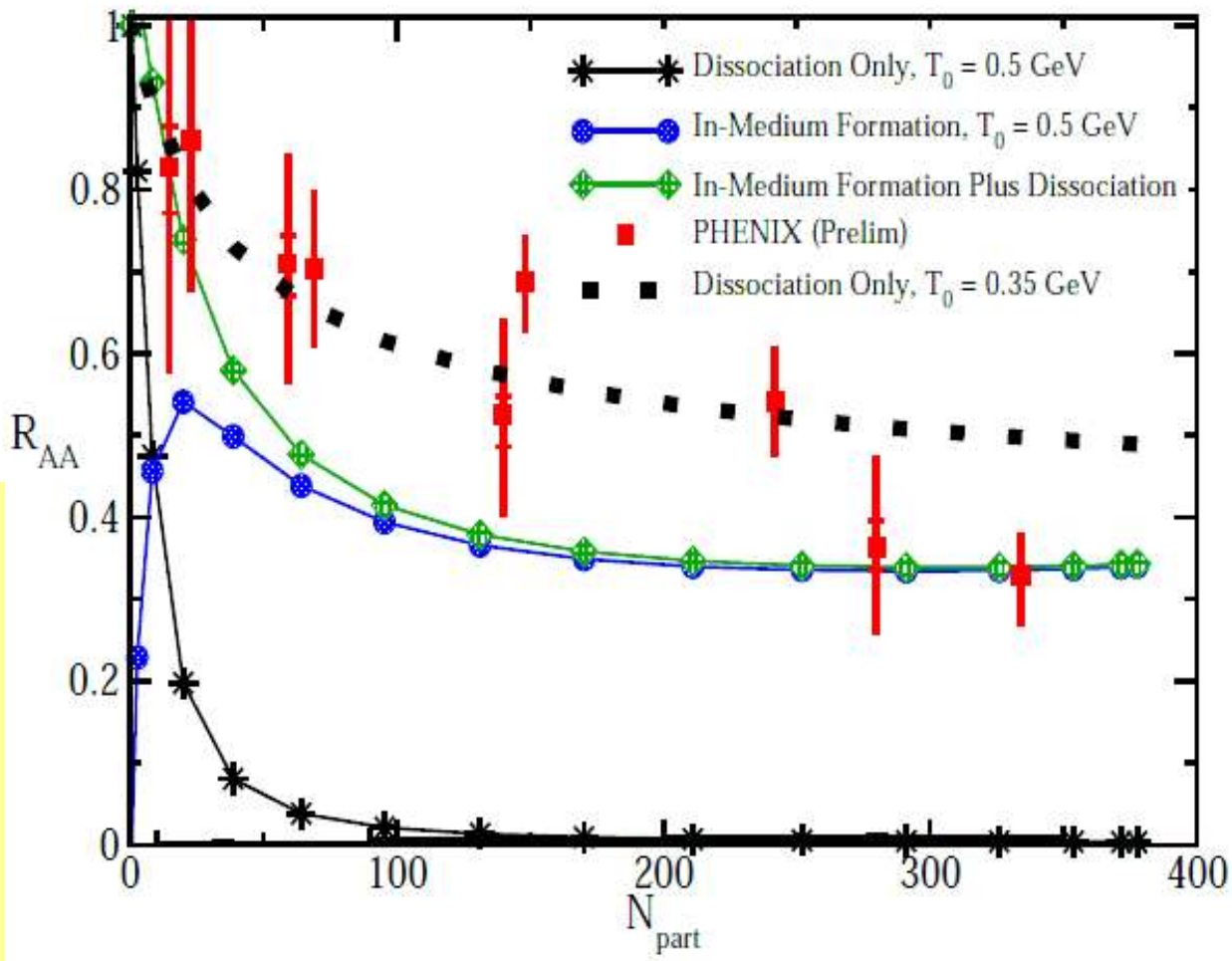
σ(d0) < 50 μm for p_t > 1.5/2/3 GeV/c in ALICE/CMS/ATLAS

- **disentangle primary & secondary J/ψ**
- **measure inclusive b cross-section**
- **probe b quark in-medium energy loss**

ALICE: CERN/LHC 2005-030, CERN/LHCC 99-13,
ATLAS: EPJC 33 (2004) s1023, CMS: CMS NOTE 2006/031, 2001/008

Results from kinetic model

R.L Thews,
nucl-th/0609121
J. Phys. G30 (2004) S369



data described for a specific set of QGP parameters and charmonium production cross section

hard to make a quantitative prediction

will concentrate on statistical hadronization model