Thermal aspects of particle production in nucleus-nucleus collisions (in the LHC era)

A. Andronic – Univ. of Münster / GSI Darmstadt

- The thermal model for the light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Charmonium in the statistical hadronization model
- Summary and outlook

AA, P. Braun-Munzinger, K. Redlich, J. Stachel, JPG 38 (2011) 124081 [arXiv:1106.6321]

AA, P. Braun-Munzinger, J. Stachel, PLB 673 (2009) 142 [arXiv:0812.1186]

AA, P. Braun-Munzinger, J. Stachel, H. Stöcker, PLB 697 (2011) 203 [arXiv:1010.2995]

Thermal fits of hadron abundances

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

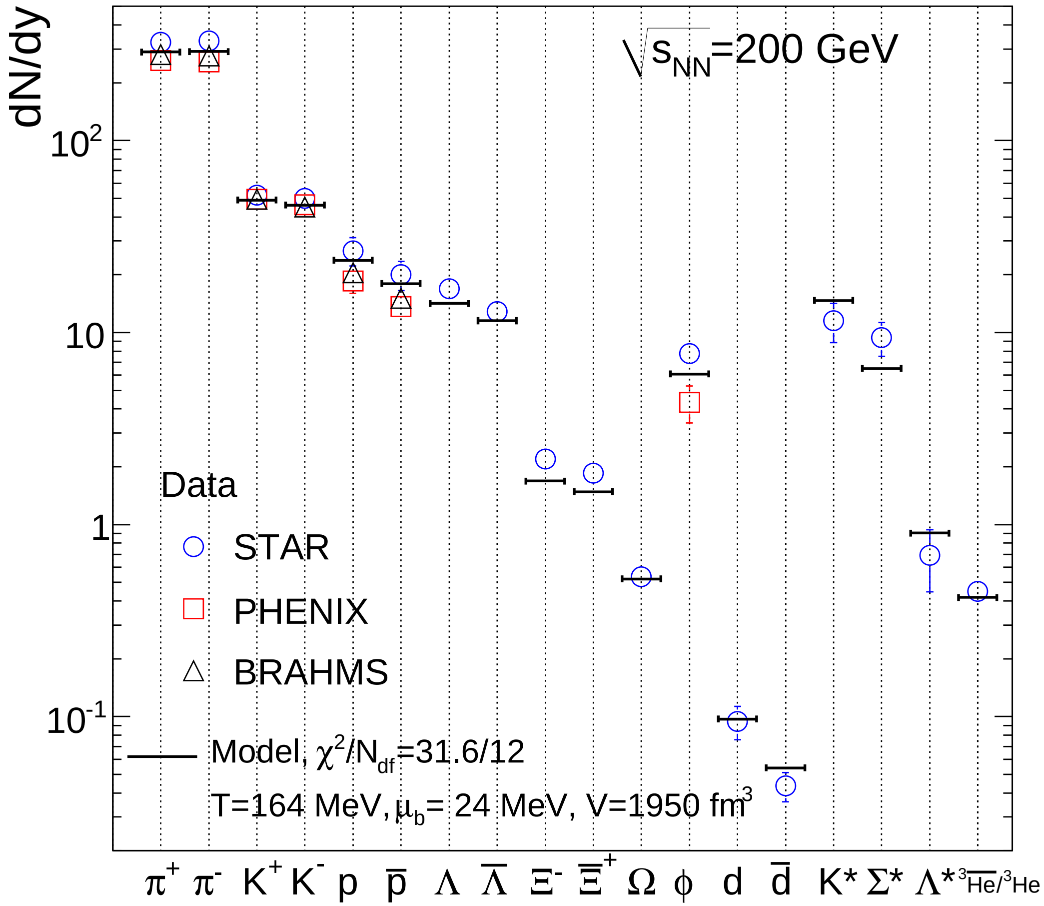
quantum no. conservation:

$$\mu_i = \mu_b B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$$

Latest PDG hadron mass spectrum (up to 3 GeV, 485 species)

Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

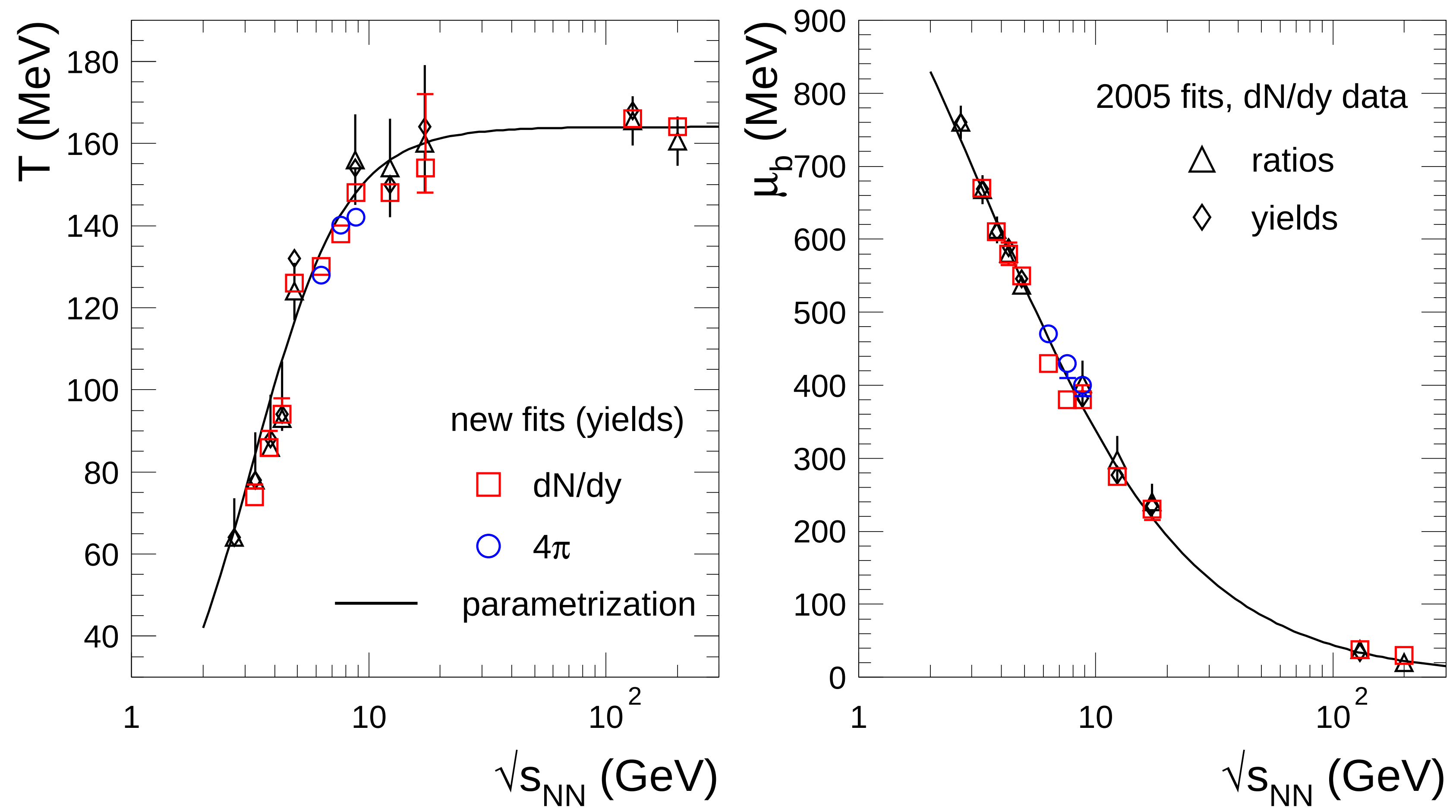
N_i: hadron yield $\Rightarrow (T,\ \mu_b,\ V)$



only STAR data: T=162 MeV, μ_b=24 MeV, V=2400 fm^3, χ^2/N_{df}=17.5/15

Hadron abundances consistent with a thermally equilibrated system

Energy dependence of T, μ_b (central collisions)

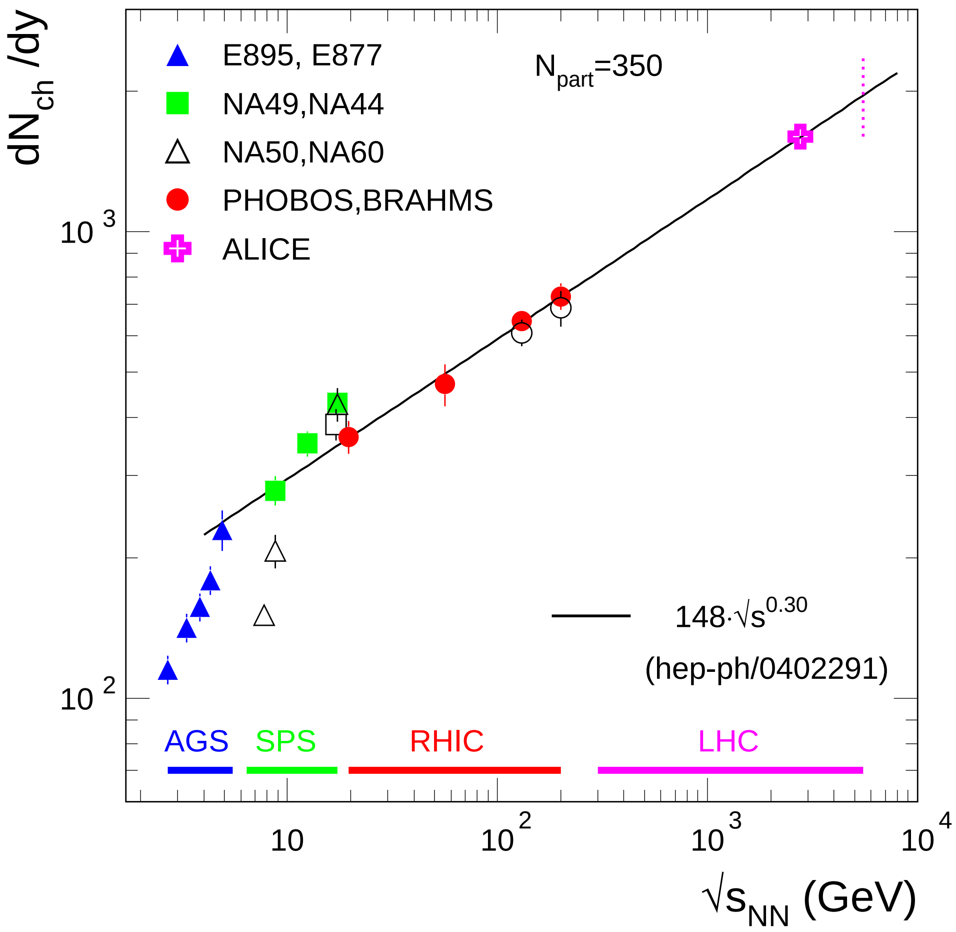


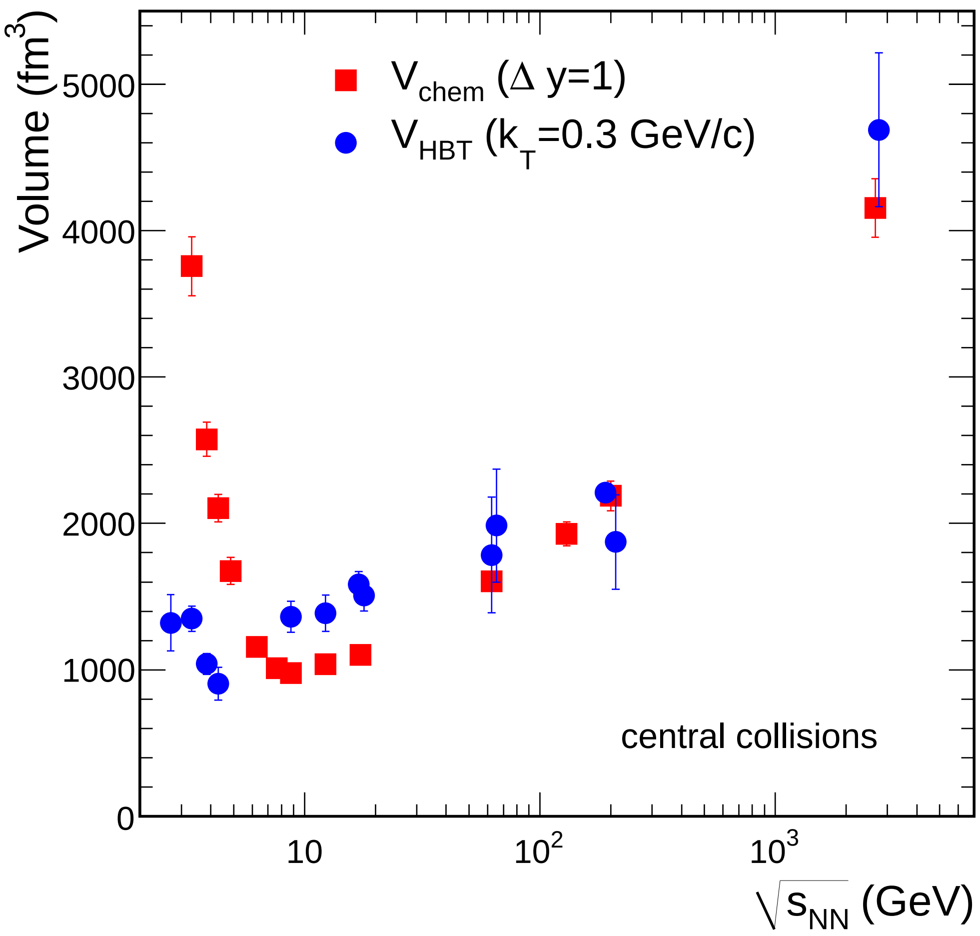
thermal fits exhibit a limiting temperature: $T_{lim} = 164 \pm 4$ MeV

$$T = T_{lim} \frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}(\mathrm{GeV})})/0.45)}, \qquad \mu_b[\mathrm{MeV}] = \frac{1303}{1+0.286\sqrt{s_{NN}(\mathrm{GeV})}}$$

PLB 673 (2009) 142

Volume in central collisions

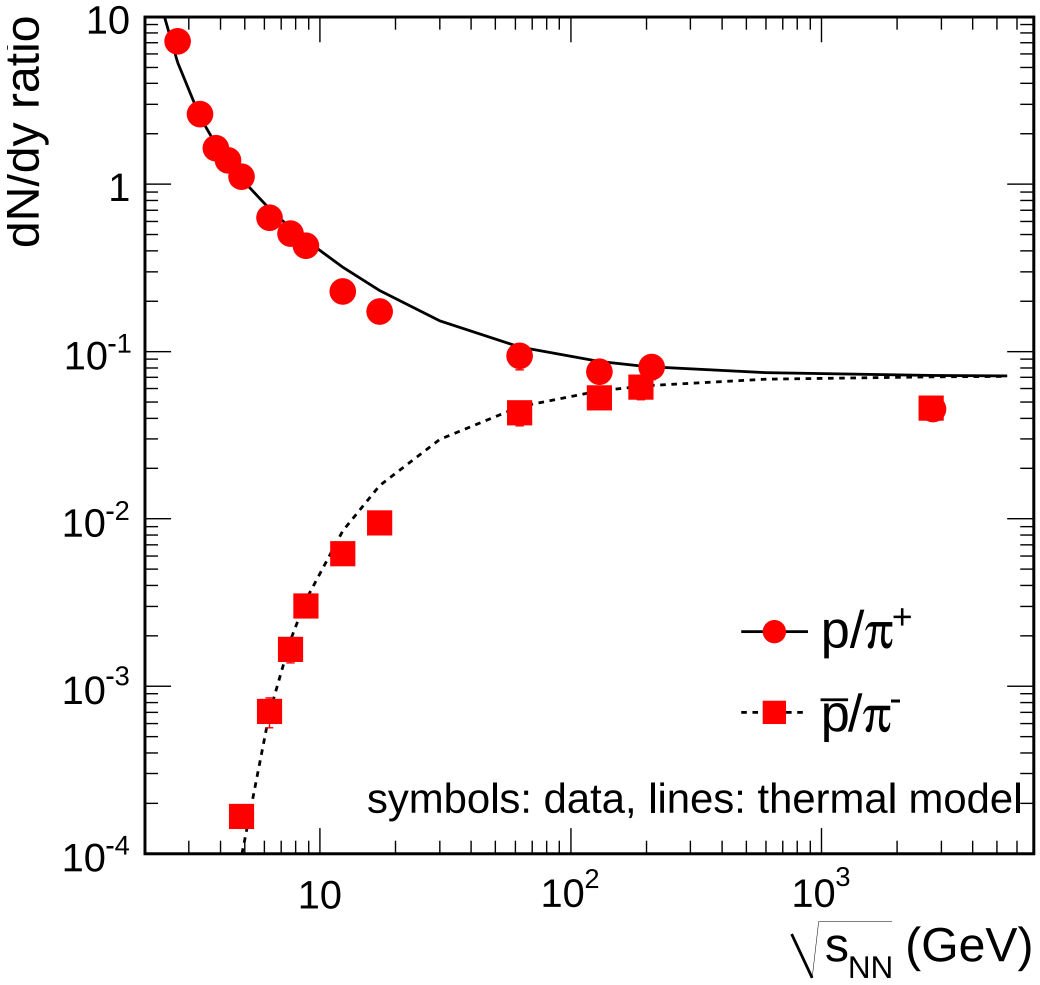


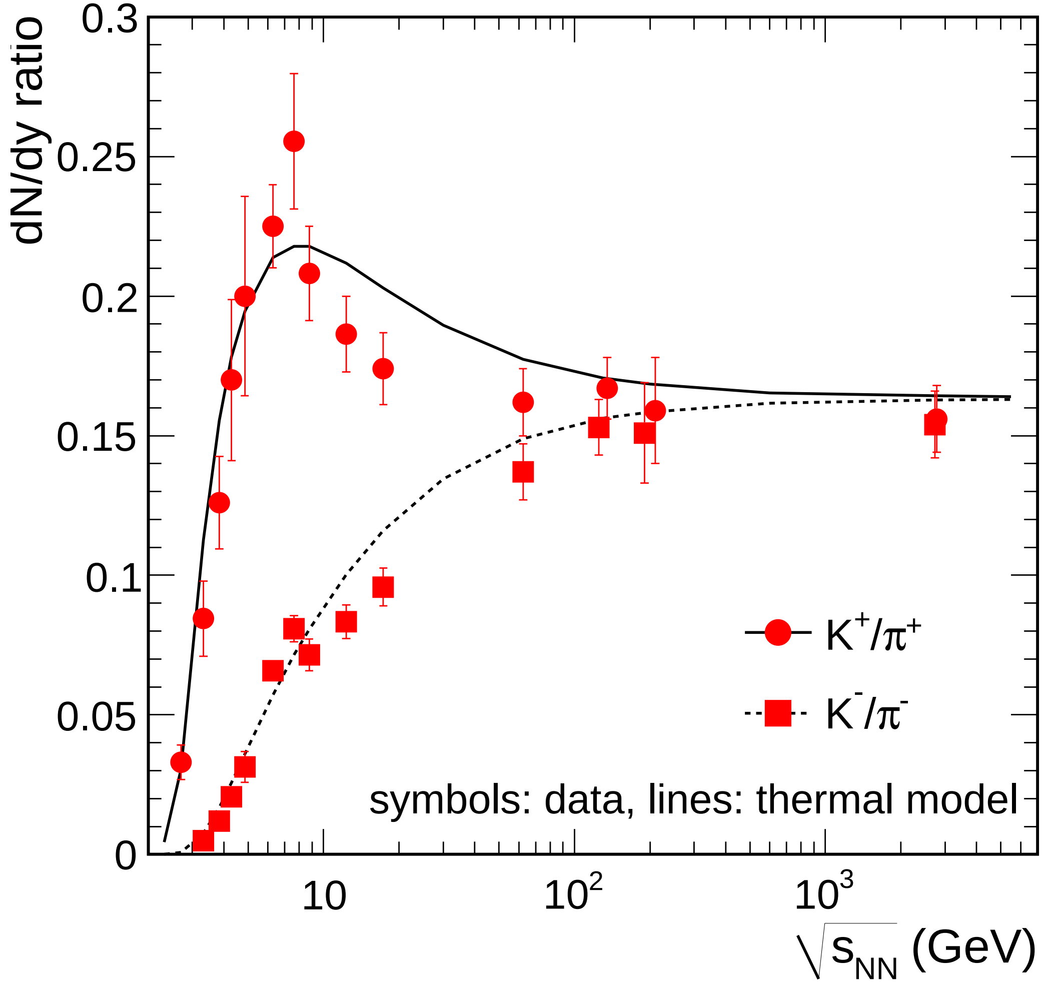


$$V_{chem}(\Delta y = 1) = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$

$V_{HBT} = (2\pi)^{3/2} R_{side}^2 R_{long}$ ...data from ALICE, PLB 696, 328 (2011)

Overview of some hadron ratios



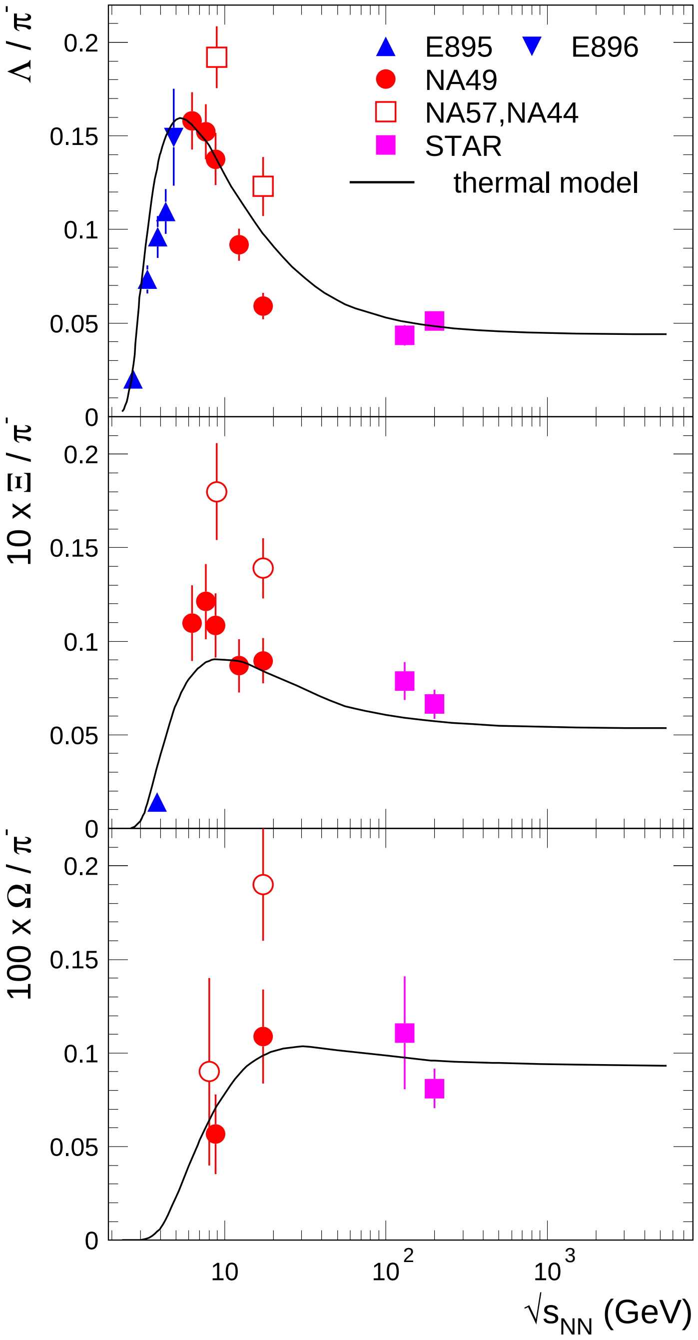


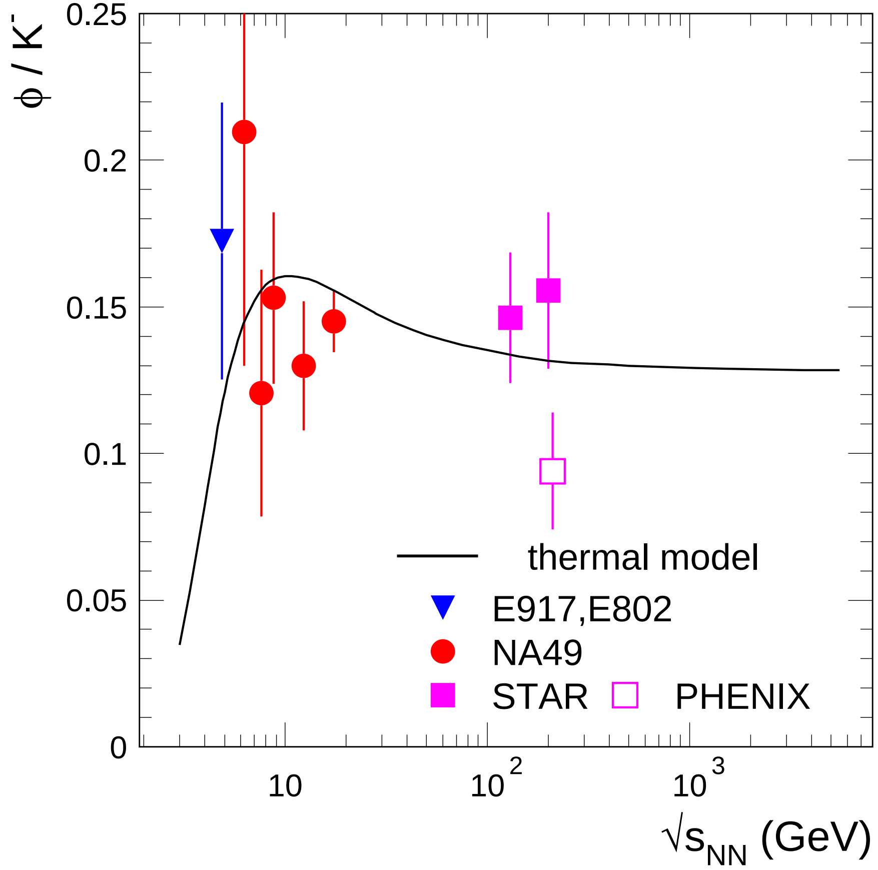
good agreement data-model

...but something special about protons (ALICE preliminary) at LHC?

p,$\bar{p}$ data of STAR ad-hoc "corrected" by -25% for feed-down

...and the state of other "horns"

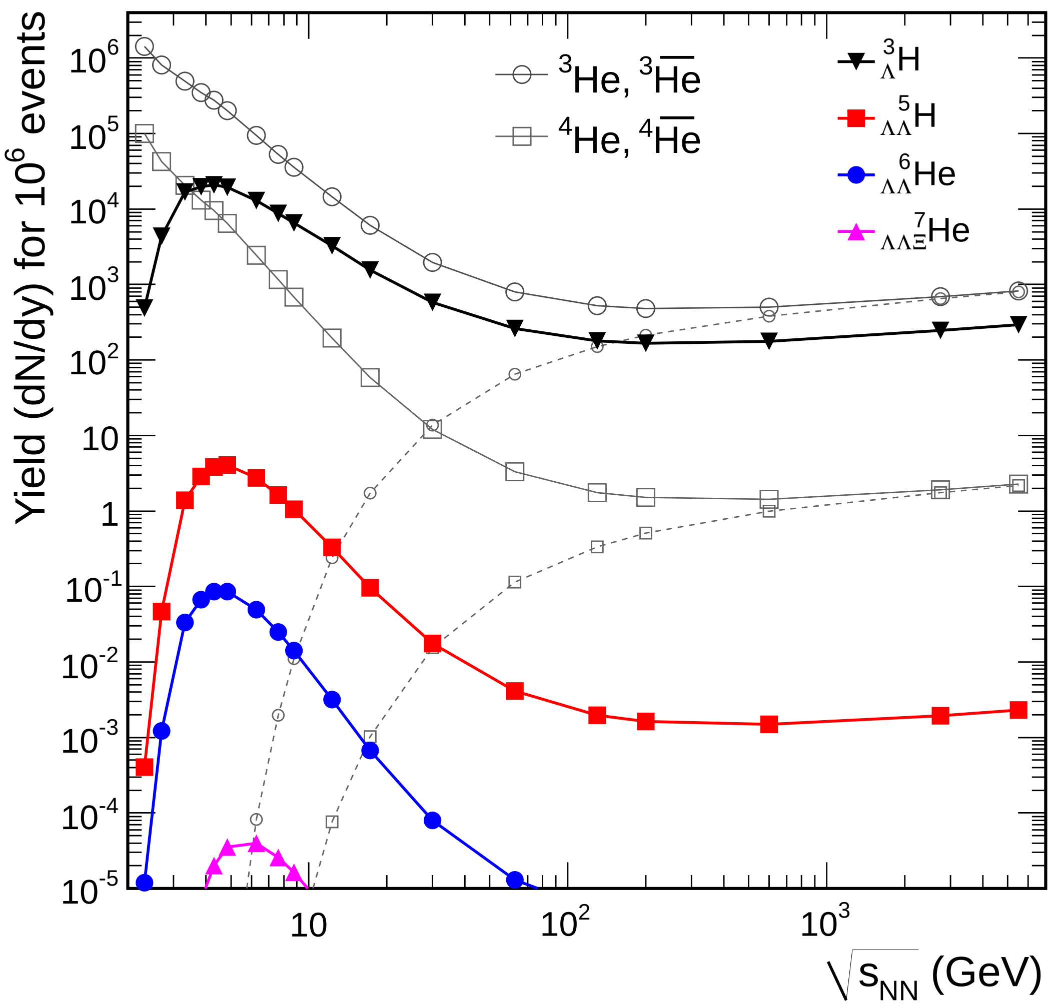




overall agreement model-data

Acta Phys. Pol. 40 (2009) 1005

(Hyper-)nuclei predictions



RHIC ($\sqrt{s_{NN}}$=200 GeV):
T=164 MeV, $\mu_b = 24 \pm 2$ MeV

Ratio	Exp. (STAR)	Model
$^3\bar{H}e/^3He$	0.45±0.02±0.04	0.42±0.03
$^3_{\bar{\Lambda}}\bar{H}/^3_\Lambda H$	0.49±0.18±0.07	0.45±0.03
$^3_\Lambda H/^3He$	0.82±0.16±0.12	0.35±0.003
$^3_{\bar{\Lambda}}\bar{H}/^3\bar{H}e$	0.89±0.28±0.13	0.37±0.003

...discrepancy for $^3_\Lambda H/^3He$?

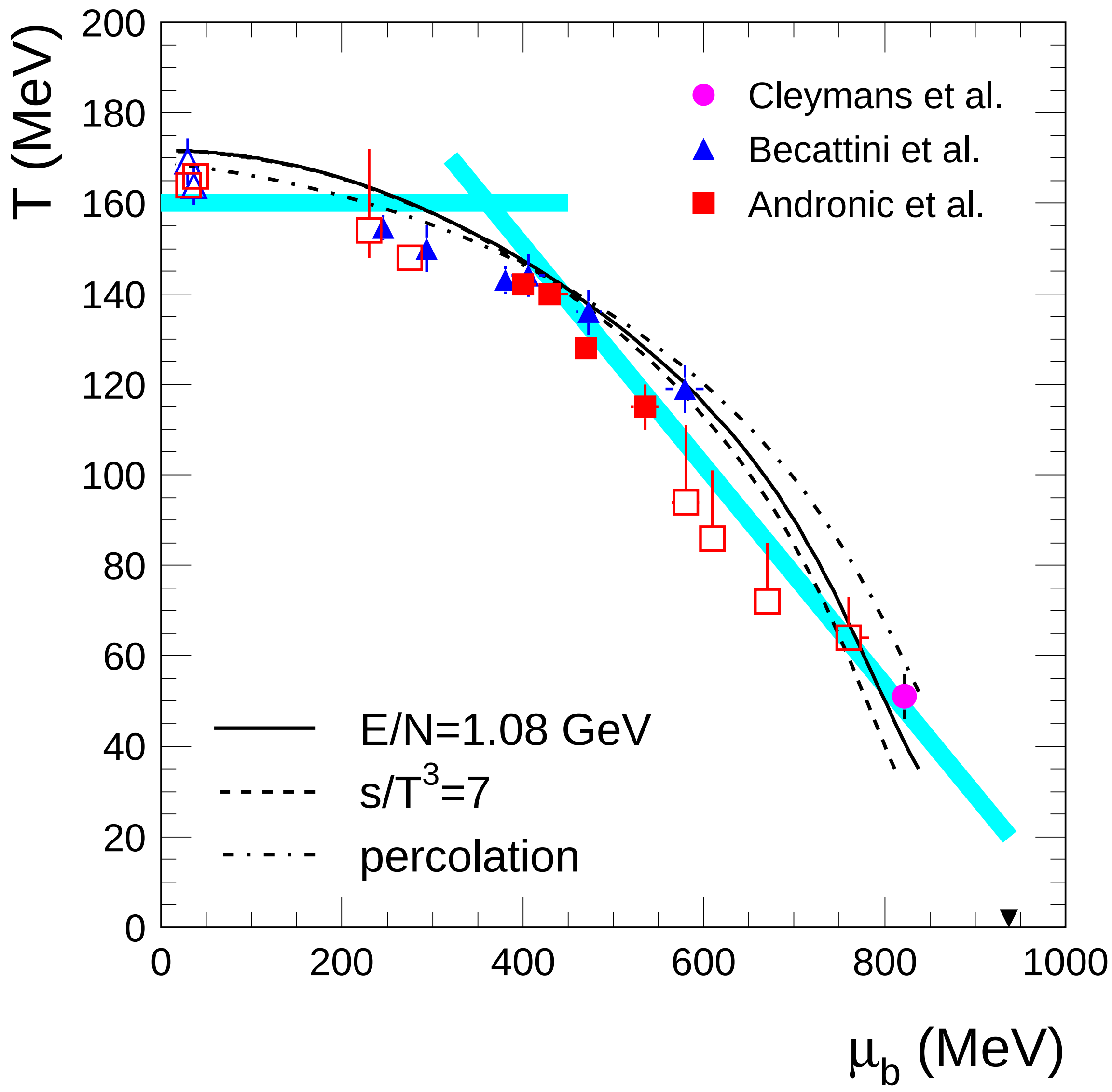
could be resolved if an excited state of $^3_\Lambda H$ exists

Phys.Lett.B697,203(2011)

STAR, Science **328** (2010) 58.

The phase diagram of QCD

as $T \rightarrow T_{lim}$, is chemical freeze-out a determination of the phase boundary?



if yes, how is thermalization achieved?

- for SPS energies and higher: driven by the deconfinement transition

  PBM, Stachel, Wetterich, PLB 596 (2004) 61

- for lower energies (SIS100): is the quarkyonic phase transition the "thermalizer"?

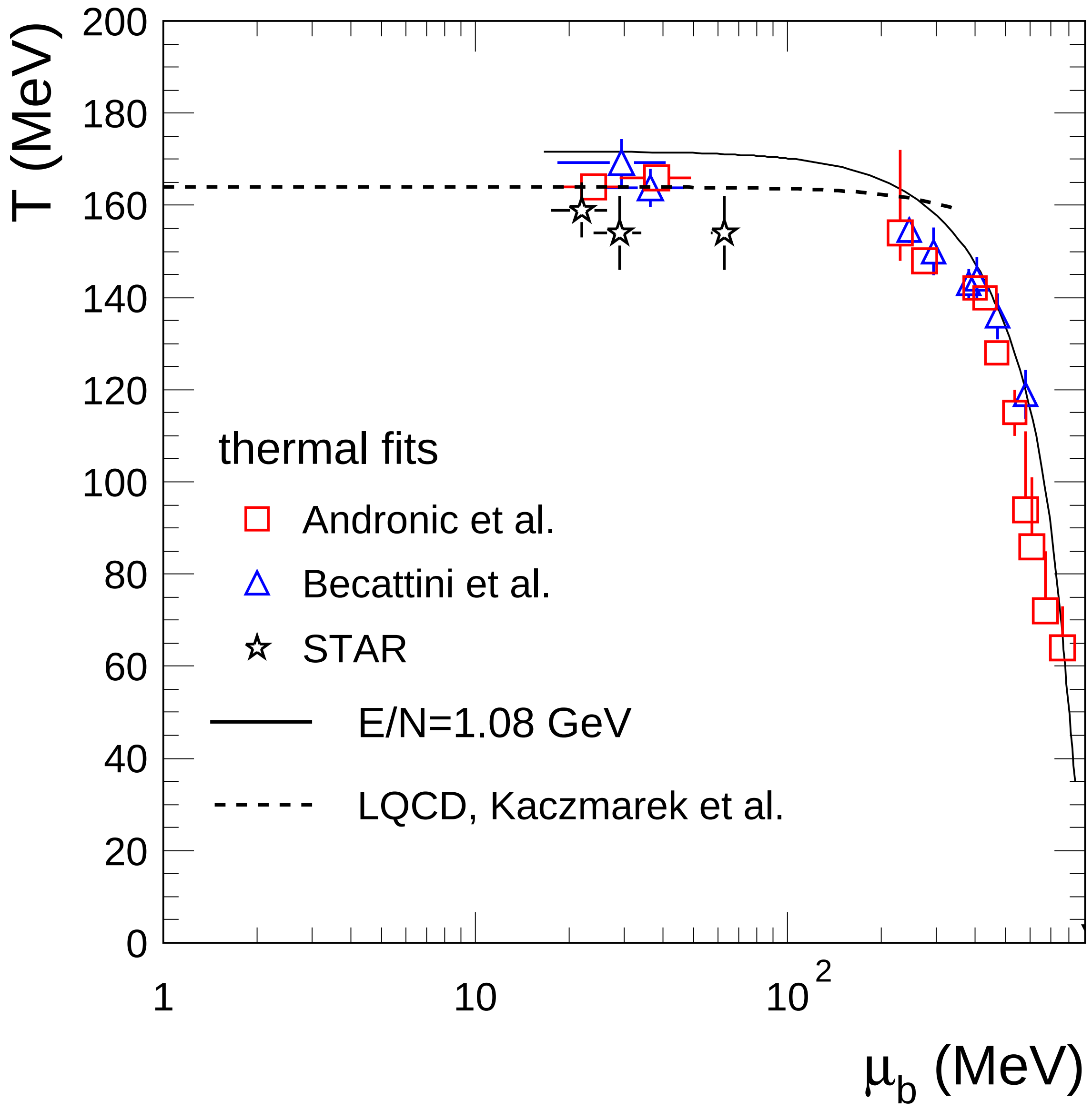
  McLerran, Pisarski, NPA 796 (2007) 83

  AA et al., NPA 837 (2010) 65

...or maybe not?

Floerchinger, Wetterich, arXiv:1202.1671

The phase diagram of QCD



what will we find at LHC?

relevance for LQCD
$(\mu_s = \mu_{I_3} = 0)$

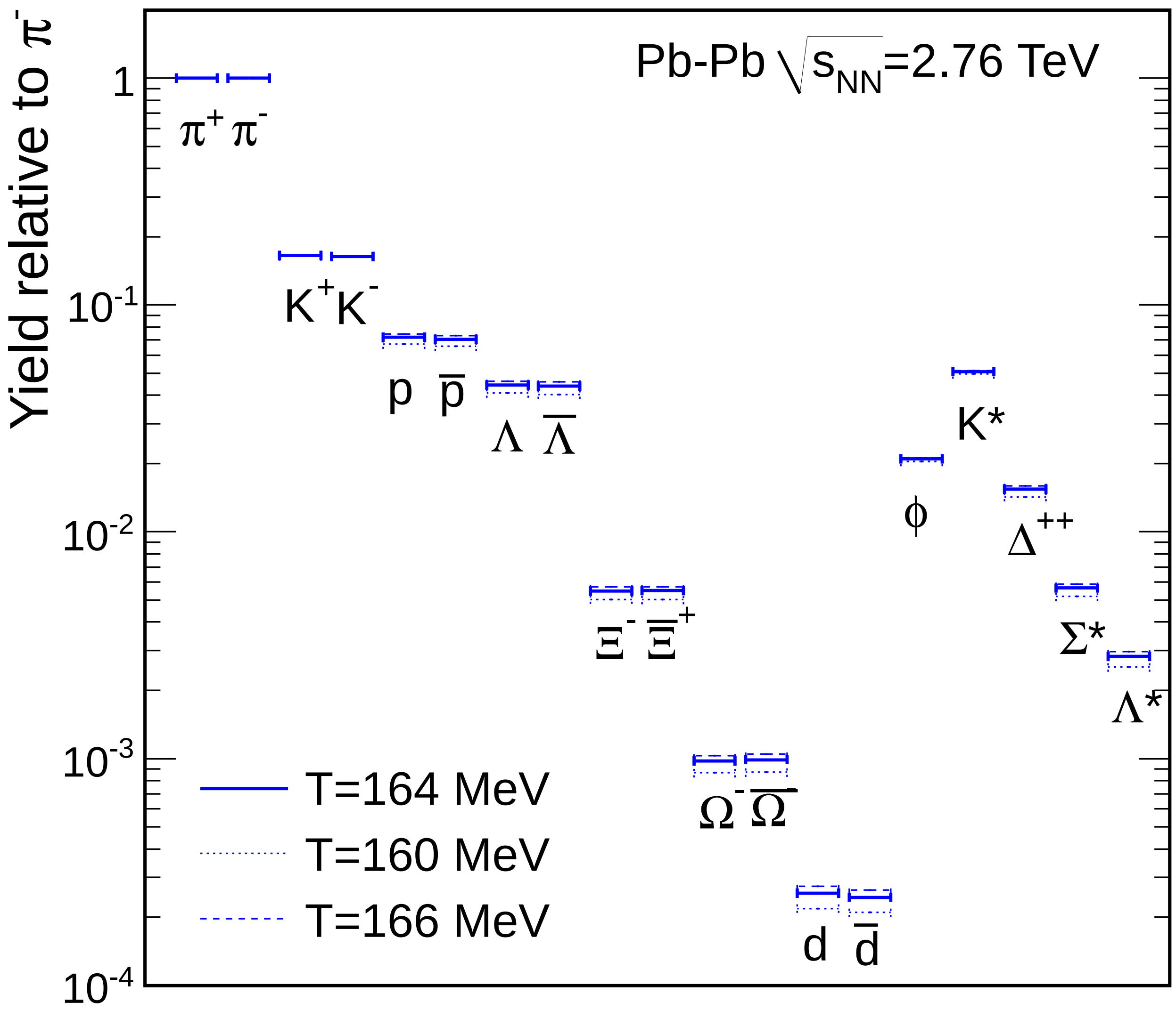
O. Kaczmarek et al., PRD 83, 014504 (2011)

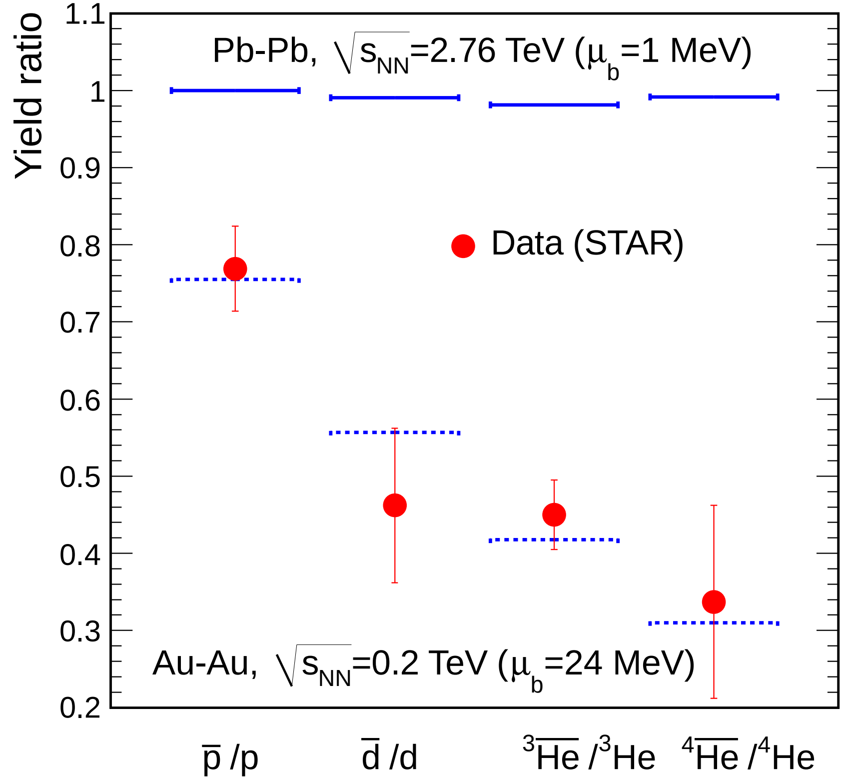
does freeze-out curve follow the chiral phase transition or crossover line at $\mu_b \neq 0$?

J. Cleymans, K. Redlich PRL 81, 5284 (1998)

P. Braun-Munzinger, J. Stachel, arXiv:1101.3167

...and here are the predictions





RHIC: T=164 MeV, μ_b=24 MeV

LHC: T=164 MeV, μ_b=1 MeV

$^4\bar{H}e$ discovery: STAR, Nature 473, 353 (2011)

Charmonium and the QGP

the original idea: Matsui & Satz, Phys. Lett. B 178 (1986) 178

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. ... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon-plasma formation."

"Debye screening": no J/ψ if $\lambda_D < r_{J/\psi}$

Debye length in QGP: $\lambda_D \simeq 1/(g(T) \cdot T)$ ...so J/ψ is "thermometer" of QGP

Coulomb Debye screening: $\phi(r) = \frac{Q}{4\pi\varepsilon r} \exp(-\frac{r}{\lambda_D})$, $\lambda_D = \sqrt{\frac{k\varepsilon_0 k_B T}{e^2 \sum z^2 n_j^0}}$

Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

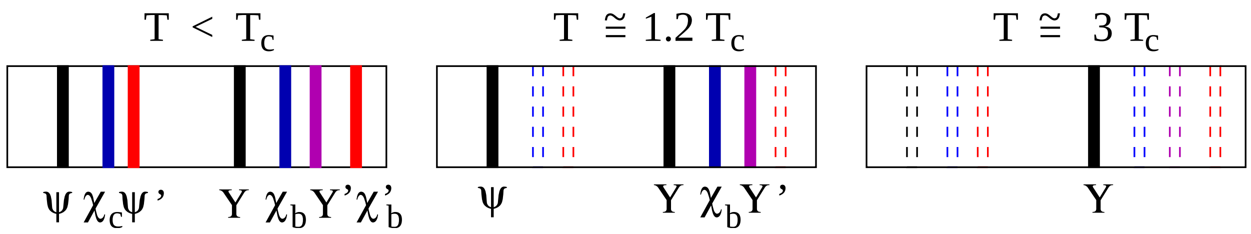
for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi} \simeq$0.3-0.4 fm

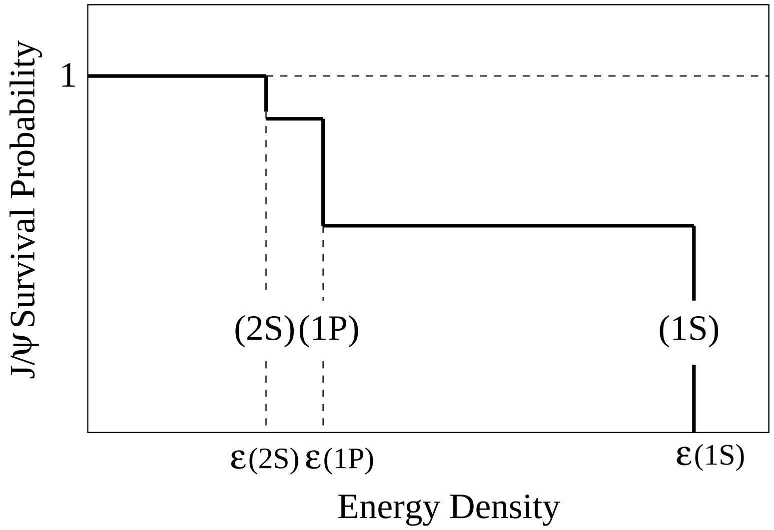
Dynamical picture: $J/\psi + g \rightarrow c + \bar{c}$

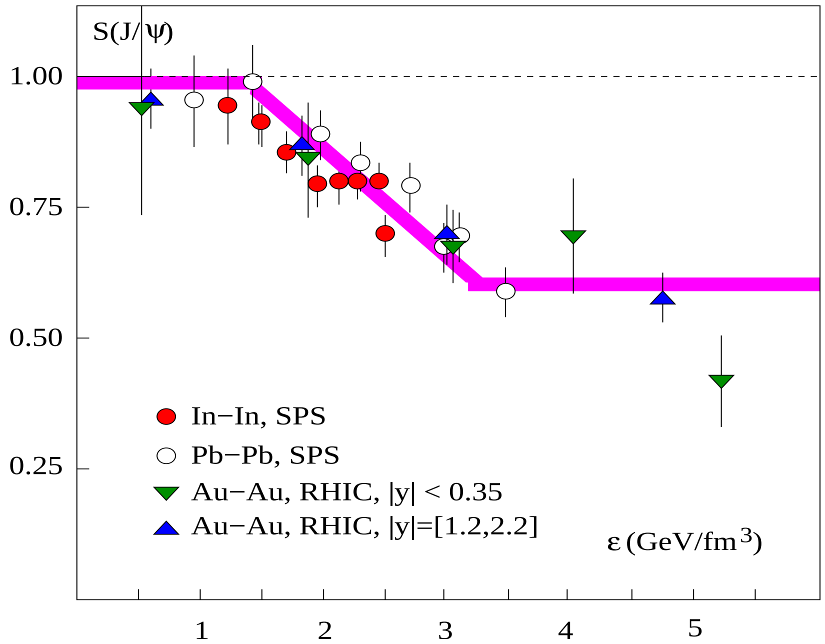
Sequential J/ψ suppression (2006, Matsui-Satz 20th anniv.)

H.Satz, hep-ph/0609197 ...more "thermometry"

LQCD results (still debated)





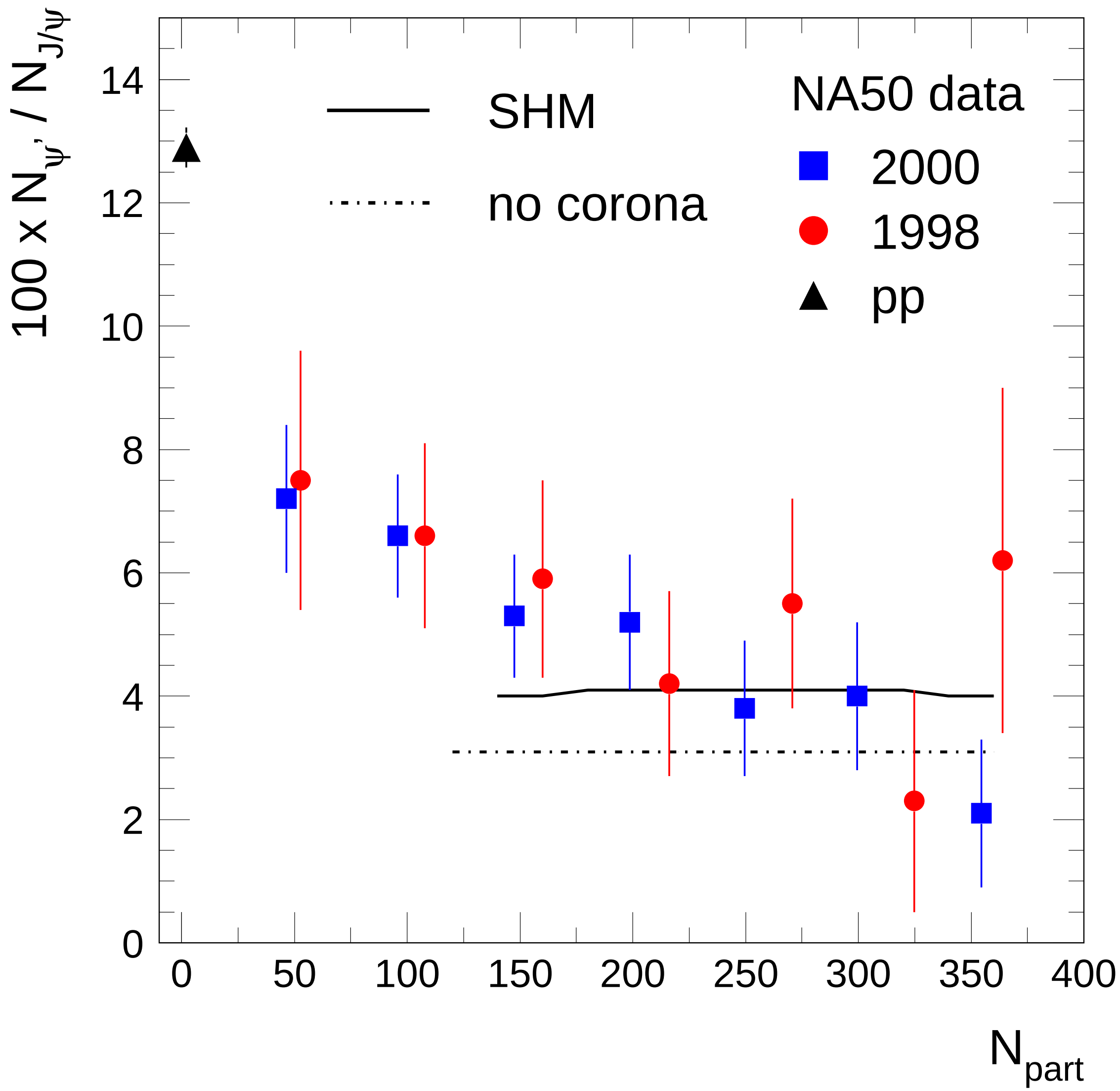


- NB: derived quantities:
  - $S(J/\psi)$: "anomalous" suppression
  - ε is not directly measurable (τ_0=1 fm/c)
- all suppression is from ψ',χ_c
  Karsch, Kharzeev, Satz, PLB 637 (2006) 75

  ! assumes 40% J/ψ from ψ' (10%), χ_c (30%)

ψ' at SPS and the thermal model

Nucl. Phys. A 789 (2007) 334



NA50 Data:
PbPb: EPJ G49 (2007) 559
pp: PLB 466 (1999) 408

$N_{\psi'}/N_{\psi} \neq 0$!

$=0$ in the screening model

(LQCD: ψ' melted at T_c)

$\Rightarrow$ ψ' prod. by stat. hadr.!

$N_{J/\psi}/N_{\psi'} = \exp\left(-\frac{m_{\psi'}-m_{J/\psi}}{T}\right)$

corona is important but alone cannot explain ψ' production

Statistical hadronization of heavy quarks: assumptions

P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196

- all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)
- survive and thermalize **in QGP** (thermal, but not chemical equilibrium)
- charmed hadrons are formed at chemical freeze-out together with all hadrons
  statistical laws, quantum no. conservation; stat. hadronization $\neq$ coalescence

  is freeze-out at(/the?) phase boundary?

  ...we believe yes ...based on data in the light-quark sector (support from LQCD?)
- no J/ψ survival in QGP (full screening)

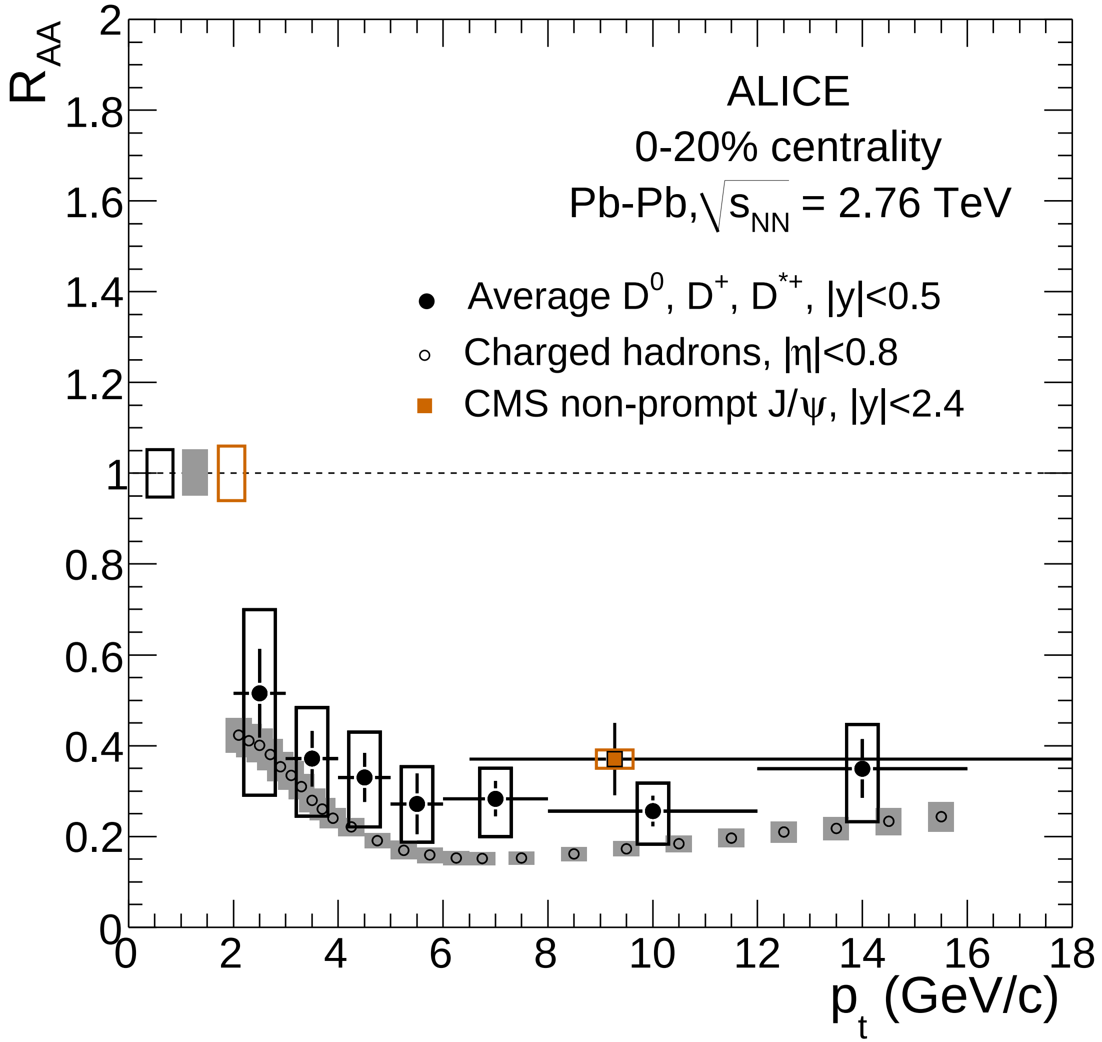
  can J/ψ survive above T$_c$? ...not settled yet (LQCD)

  Asakawa, Hatsuda, PRL 92 (2004) 012001; Mocsy, Petreczky, PRL 99 (2007) 211602

if all this supported by data, J/ψ looses status as "thermometer" of QGP
...and gains status as a powerful observable for the phase boundary

Heavy quarks "thermalize" at LHC

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



ALICE, arXiv:1203.2160

heavy quarks do loose energy in QGP (maybe a bit less than lighter ones, as expected?)
Dr. Caffarri

they also flow (discovery at RHIC)
Dr. Bianchin

...so they thermalize (in bulk, at least)

it makes sense to treat them in the thermal model

Statistical hadronization of charm: method and inputs

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

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

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

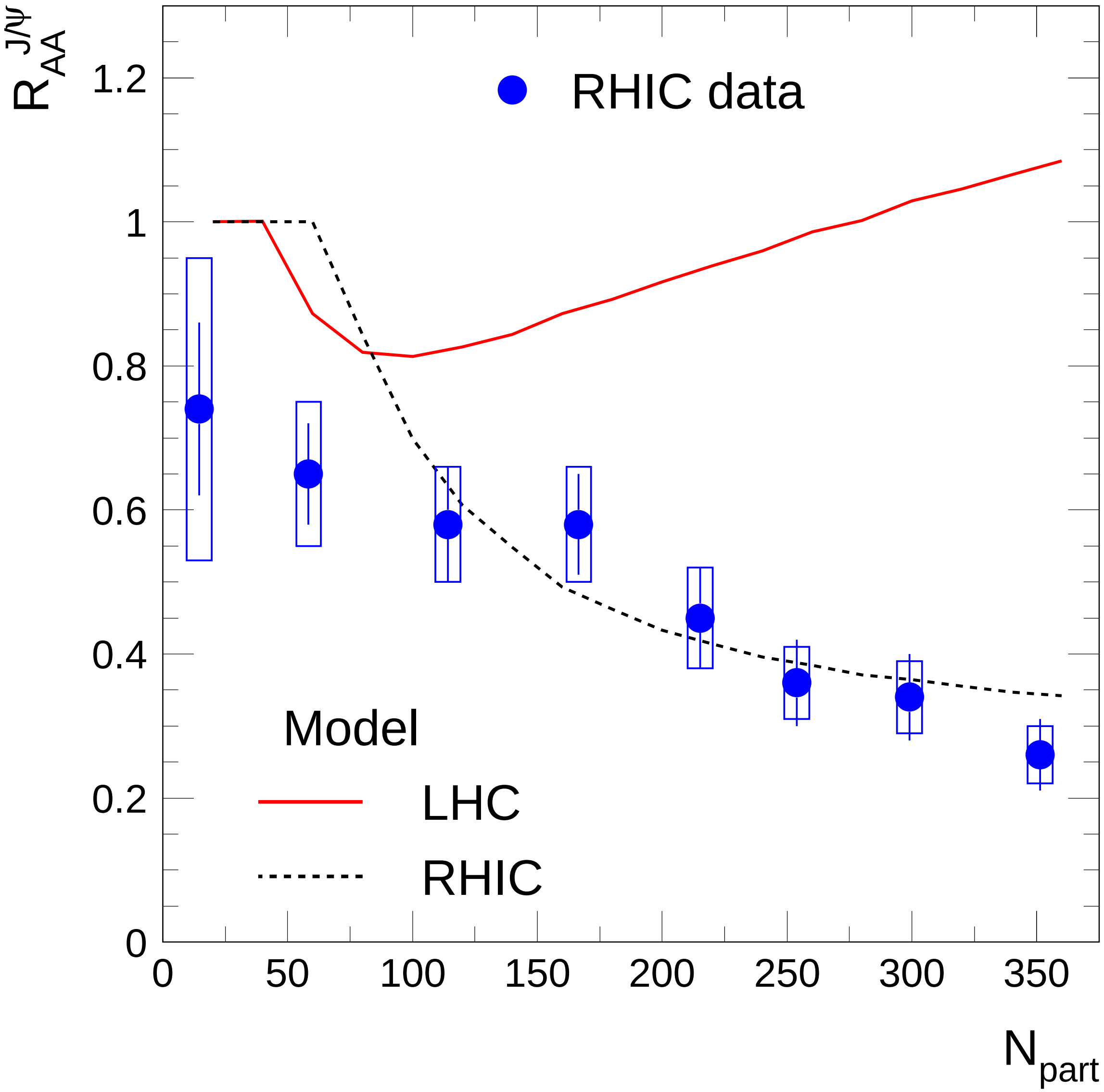
$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \longrightarrow g_c \text{ (charm fugacity)}$$

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, $V_{\Delta y=1} (= (\mathrm{d}N_{ch}^{exp}/\mathrm{dy})/n_{ch}^{th})$, $N_{c\bar{c}}^{dir}$ (pQCD or exp.)

Minimal volume for QGP: V_{QGP}^{min}=400 fm^3

Charmonium in the thermal model



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

- "suppression" at RHIC
- "enhancement" at LHC

$N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$

What is so different at LHC?

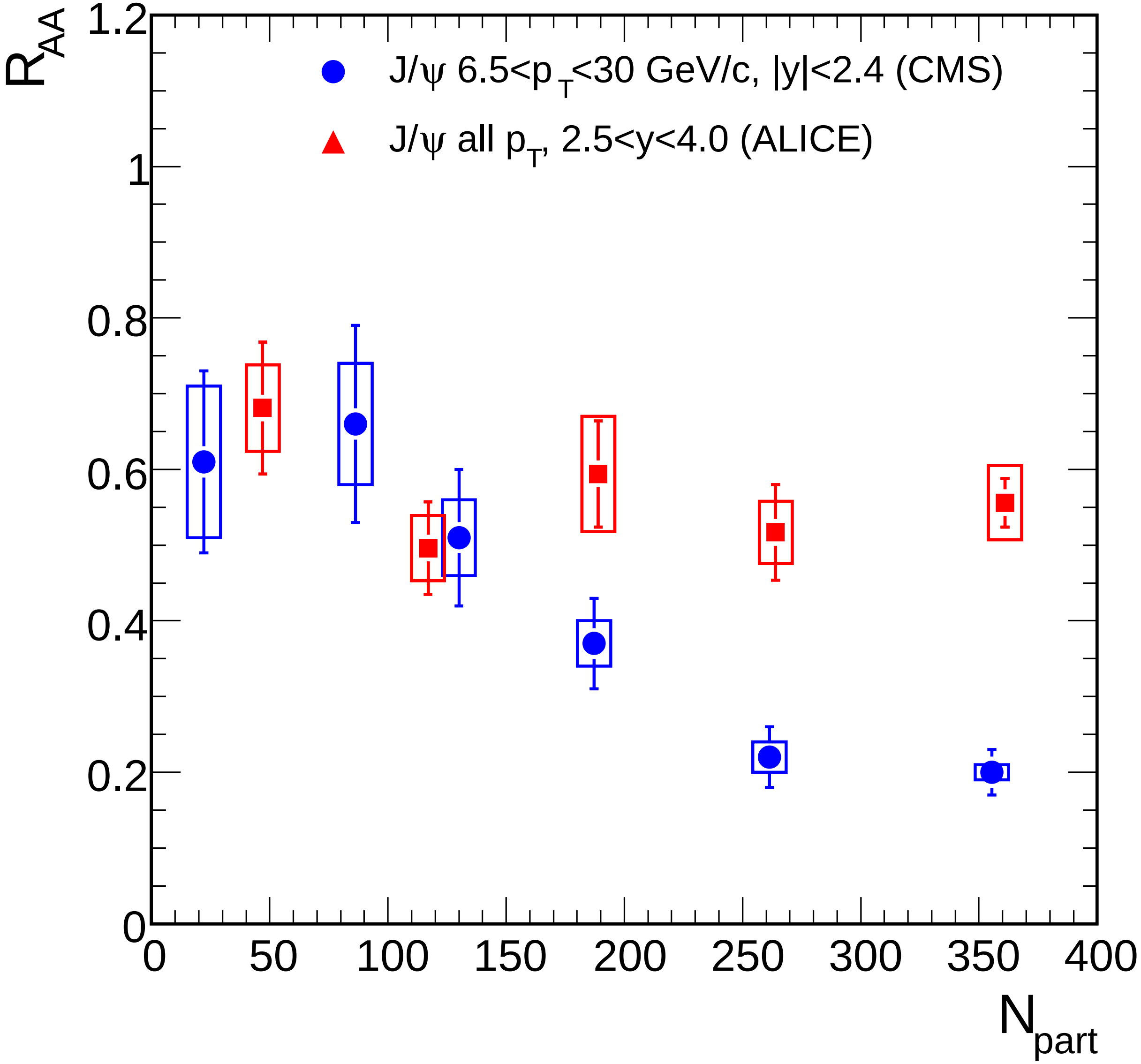
(compared to RHIC)

$\sigma_{c\bar{c}}$: ∼10x, Volume: 2.2-3x

A.Andronic et al., PLB 652 (2007) 259

generic prediction of the model

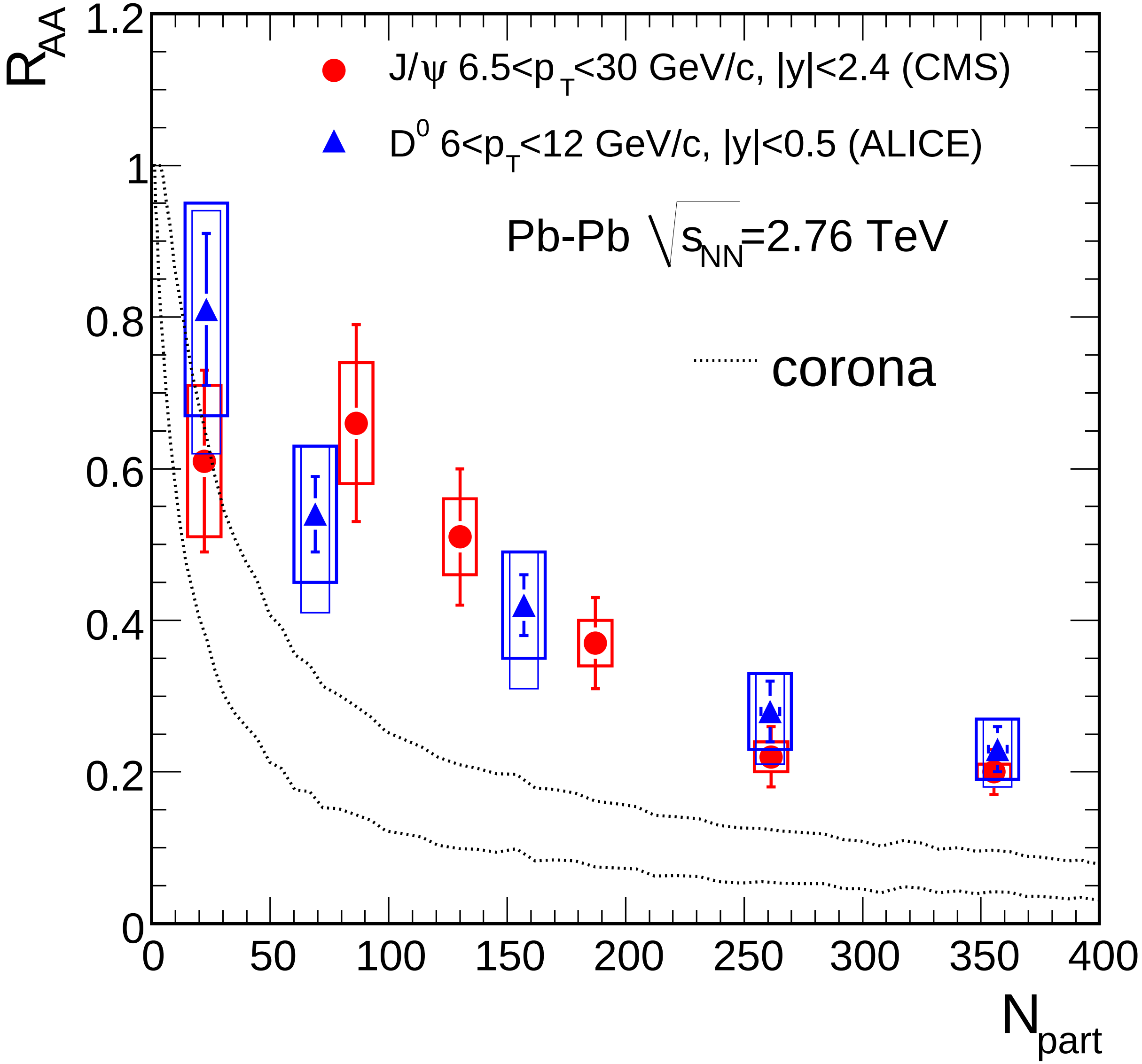
Charmonium at the LHC



ALICE, arXiv:1202.1383
CMS, arXiv:1201.5069

Charmonium less suppressed at low-p_t (ALICE)

Charm and charmonium at the LHC



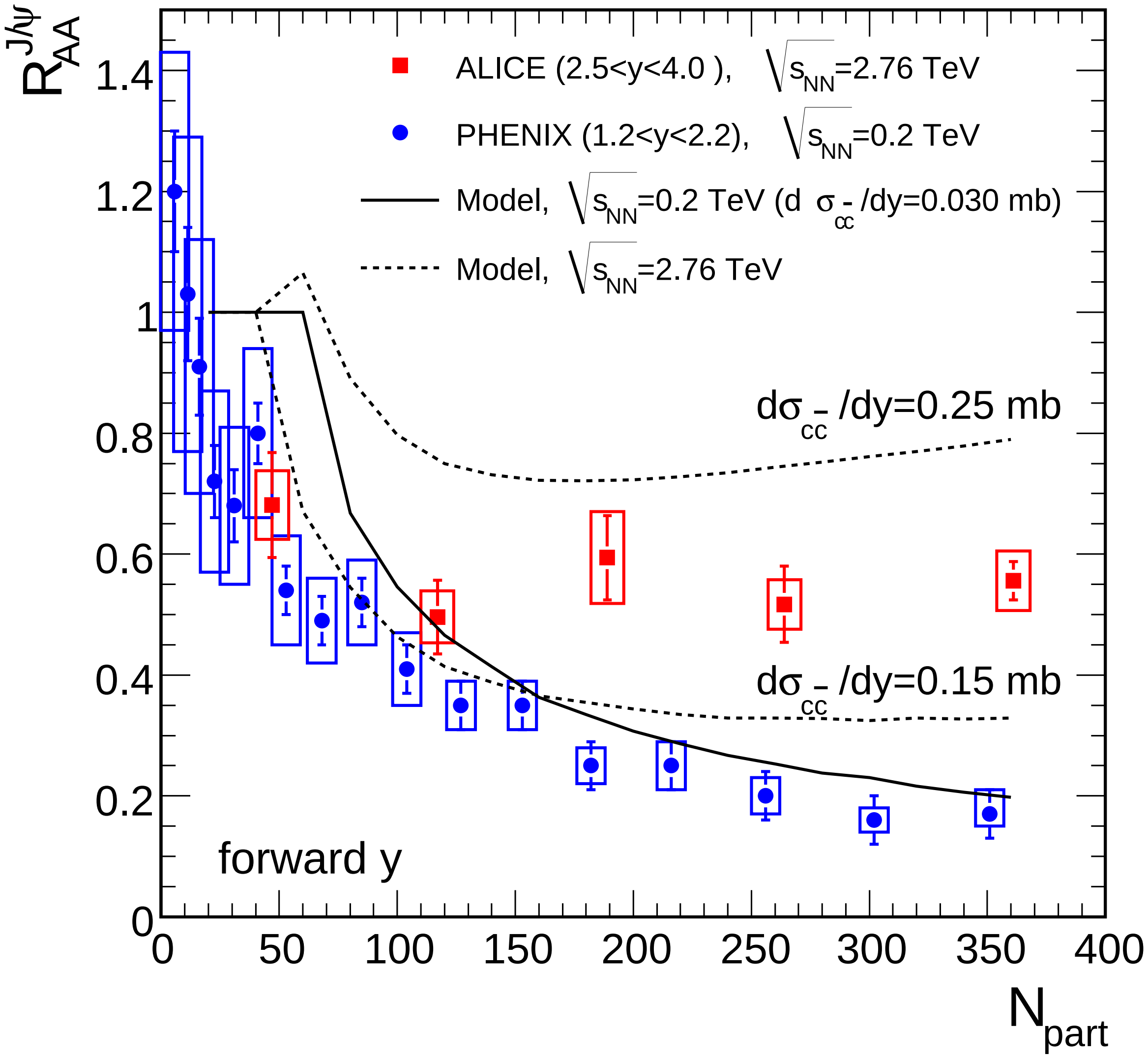
CMS, arXiv:1201.5069

ALICE, arXiv:1203.2160 [D.Caffarri]

Open charm hadrons and charmonium equally suppressed at high-p_t

Corona scenario = full QGP opacity (lowest limit on R_{AA})

Charmonium in the thermal model



- "suppression" at RHIC
- "enhancement" at LHC

  $N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$

  What is so different at LHC?

  (compared to RHIC)

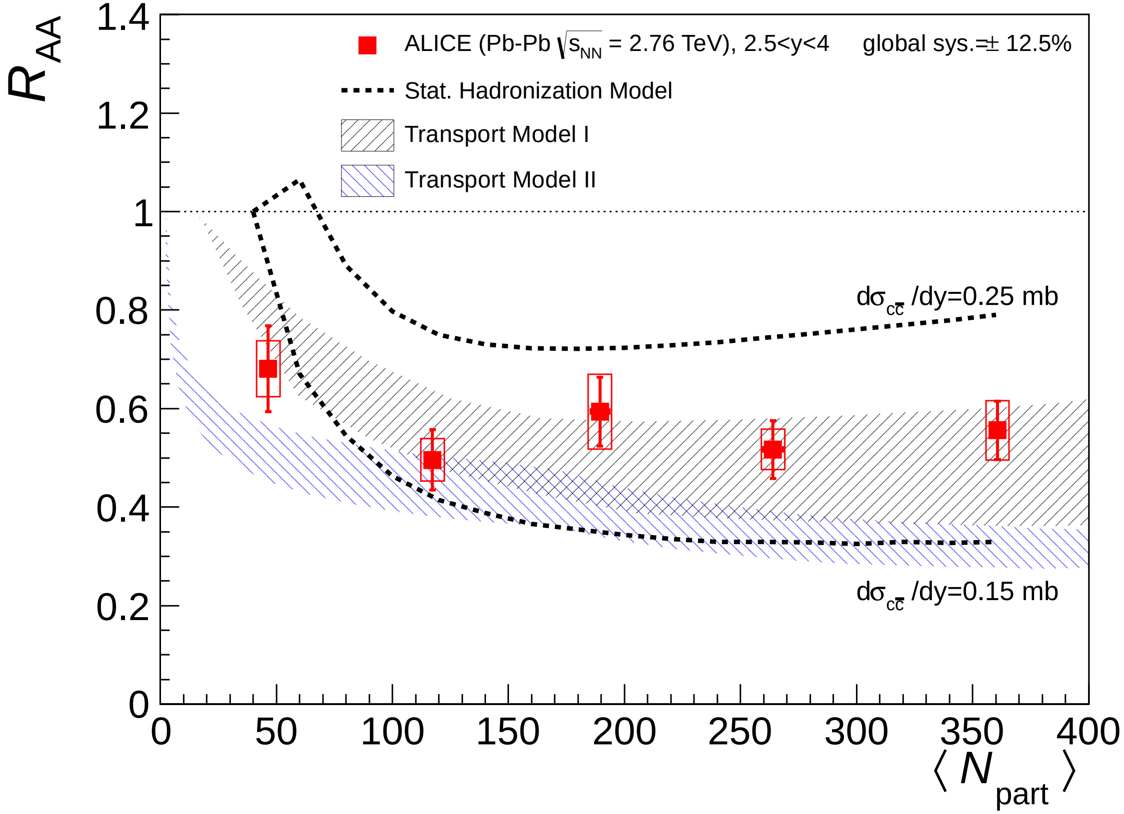
  $\sigma_{c\bar{c}}$: ∼10x, Volume: 2.2-3x

A.Andronic et al., arXiv:1106.6321

...an ultimate observable to measure the phase boundary

...after melting and with charm quarks equilibrating in the deconfined stage

...and in transport models



ALICE, arXiv:1202.1383

in transport models a rate eq. is used to treat formation and destruction from c and $\bar{c}$ quarks in QGP

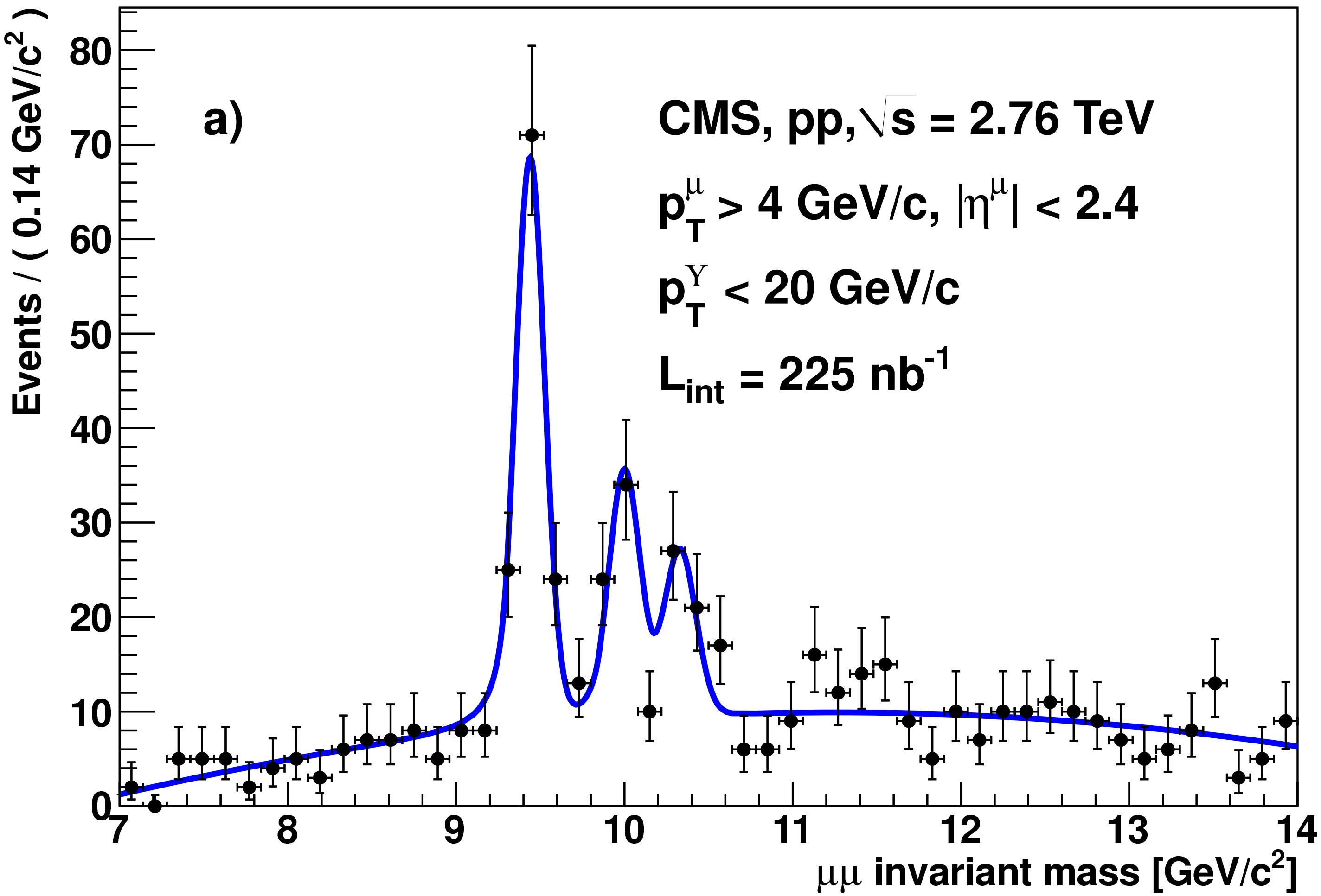
result also dependent on $\sigma_{c\bar{c}}$

in both transport models >50% of J/ψ is from regeneration (rest is survived primary production)

I: Zhao, Rapp, Nucl. Phys. A 859 (2011) 114 (2/3 from regener., central coll.)
II: Liu, Qu, Xu, Zhuang, Phys. Lett. B 678 (2009) 7 (regeneration dominates)
Stat. hadr. (thermal): Andronic et al., arXiv:1106.6321 (pure generation)

Bottonium in pp

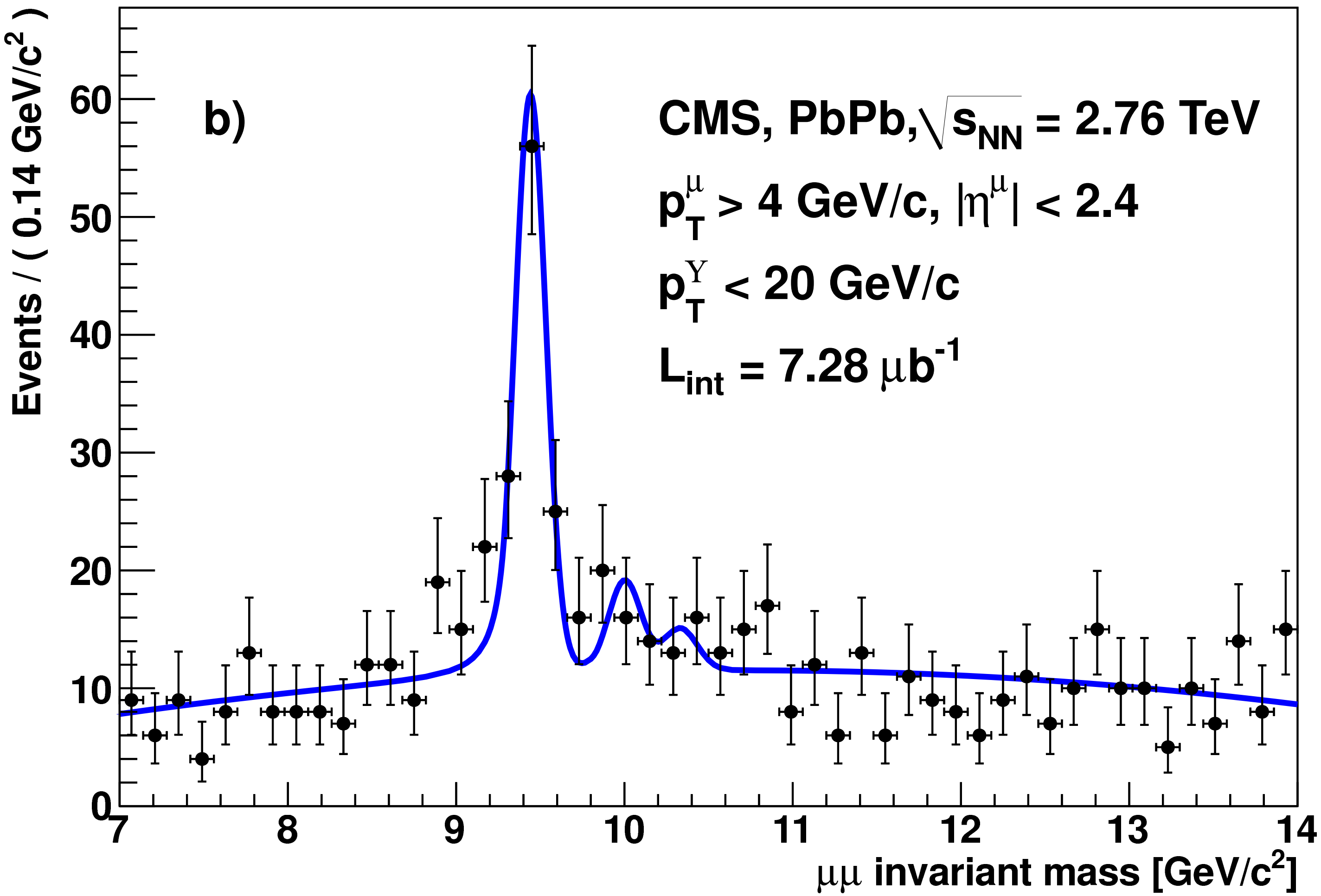
CMS, arXiv:1105.4894 (PRL 107 (2011) 052302



ratio of excited states to Υ: $\Upsilon(2S)/\Upsilon(1S)$=0.32, $\Upsilon(2S)/\Upsilon(1S)$=0.15

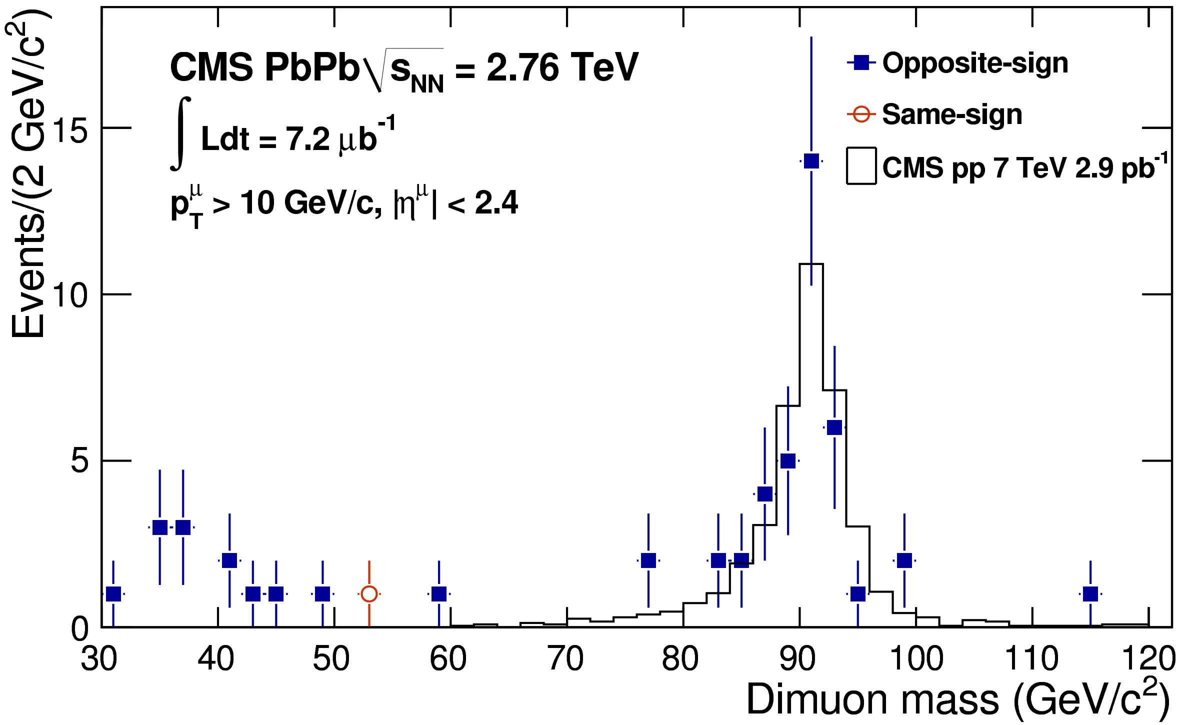
Bottonium in PbPb

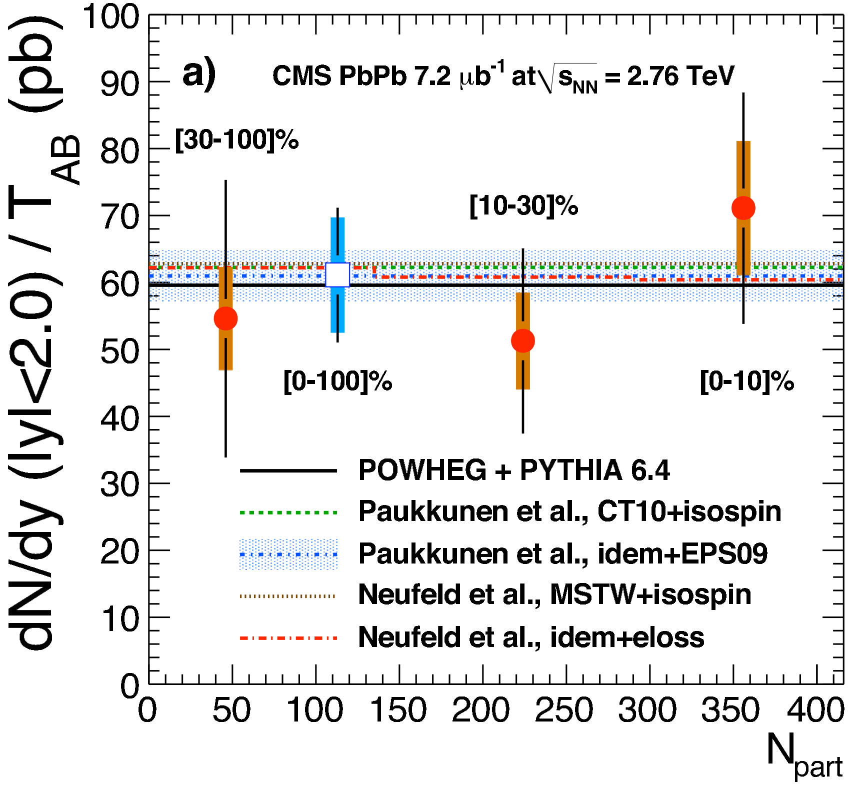
CMS, arXiv:1105.4894 (PRL 107 (2011) 052302)



thermal model expectation in Pb: $\Upsilon(2S)/\Upsilon(1S)$=0.033, $\Upsilon(2S)/\Upsilon(1S)$=0.005
...consistent with thermal expectation

Not everything disappears ...Z^0 don't





CMS, arXiv:1102.5435 (PRL 106 (2011) 212301) (39 Z^0's)

...also photons (high-p_t) survive (CMS, arXiv:1201.3093)

Summary and outlook

- The thermal model quite successful for light-quark hadrons (central collisions)

  despite imperfect fits at SPS and RHIC (and more data at low energies needed)

- It works also for heavy quarks
  (...produced exclusively in hard collisions, survive and thermalize in QGP)
  Good agreement with J/ψ (and ψ') data at SPS and RHIC
  (...with a smallish $\sigma_{c\bar{c}}$ tough)

  main uncertainty is charm cross section ... experiments will provide more precise measurements, in particular in AA (shadowing ...also in pA)

The thermal model ready to be fully confronted with the LHC data

...while compatibility to (new) RHIC data is further scrutinized

Backup slides

The hadron mass spectrum as of 2008

Particle Data Group, Phys. Lett. B **667** (2008) 1

relative increase of calc. dens.

Additions (compared to 2005):

Many new resonances up to 3 GeV

+(86)4 (non)strange mesons

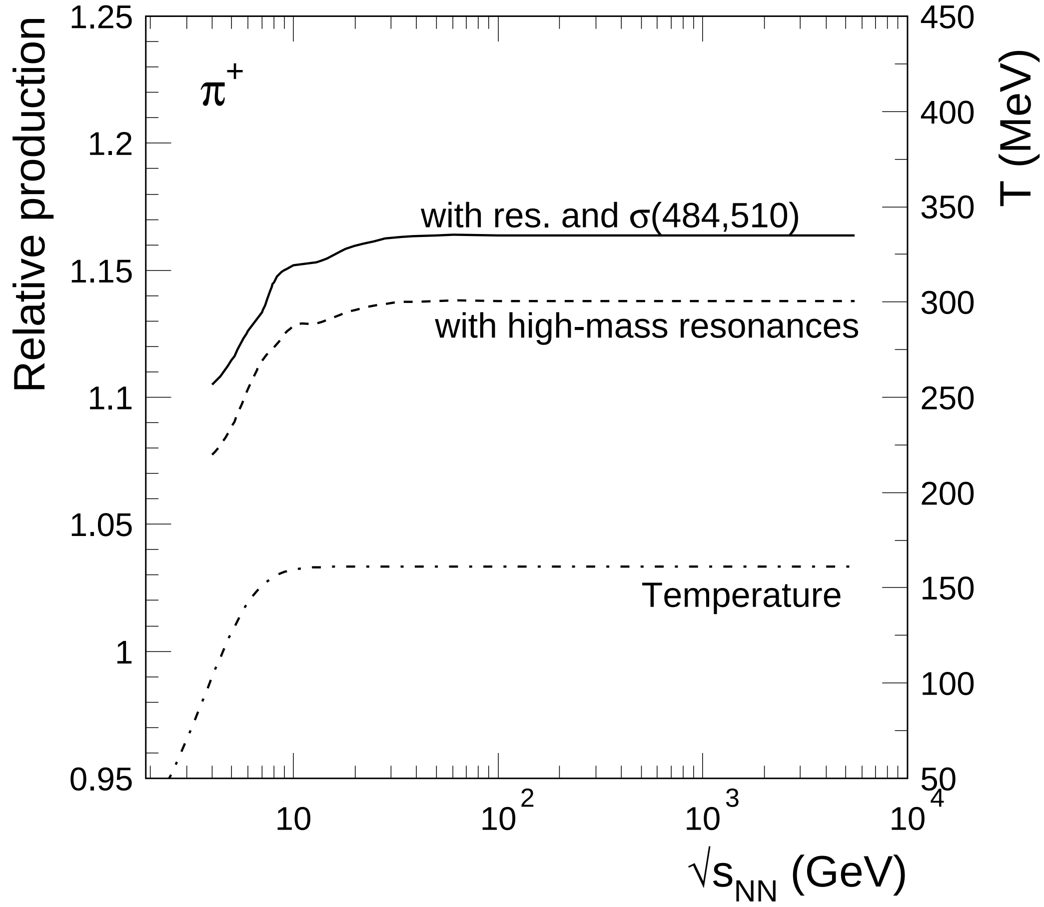
+(36)30 (non)strange baryons

σ meson ($f_0(600)$):

m_σ=484±17 MeV,Γ_σ=510±20 MeV

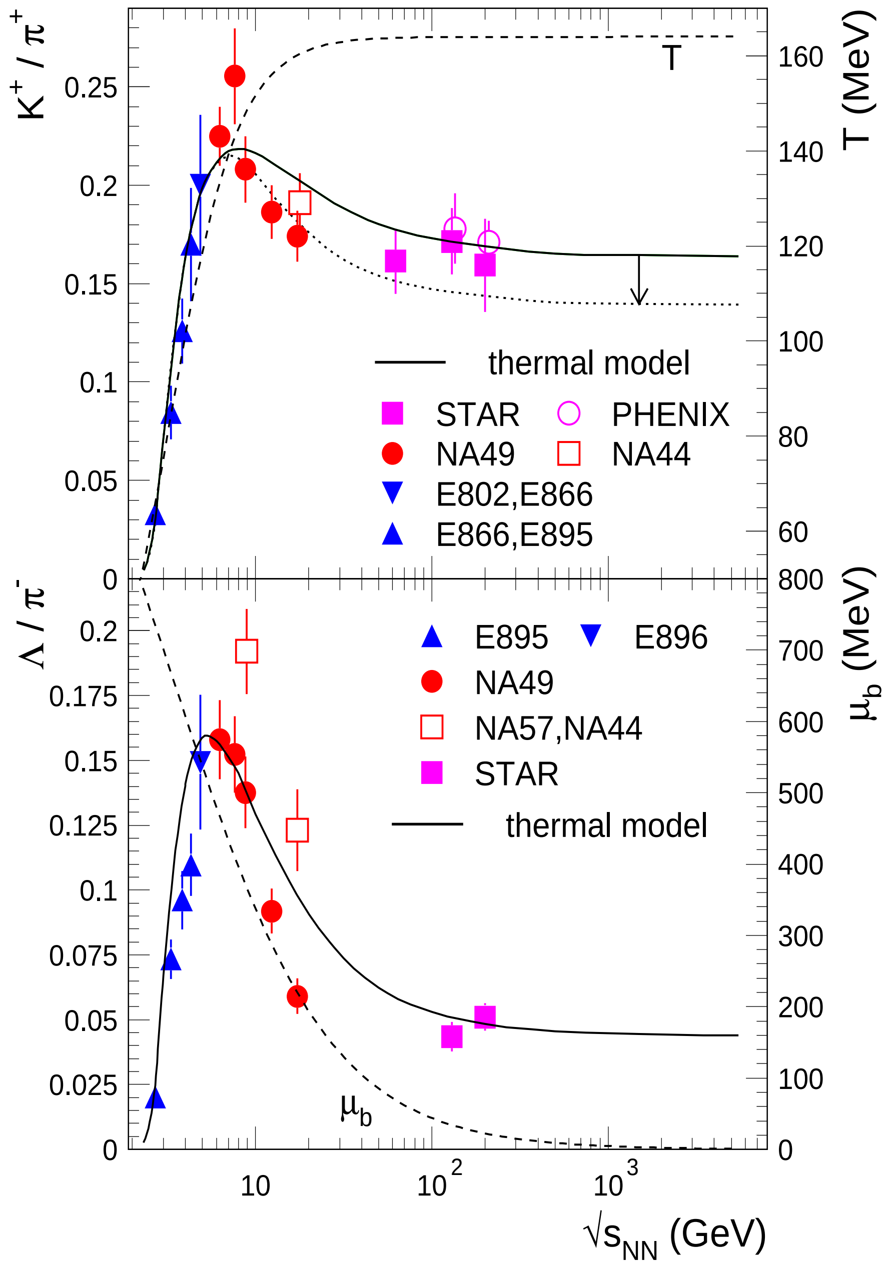
García-Martín, Peláez, Ynduráin, Phys. Rev. D **76** (2007) 074034

(in total 485 hadron species, incl. composites)



PLB 673 (2009) 142

“The horn” as of 2009



much better explained by the model

...as due to detailed features of the hadron mass spectrum

...which leads to a limiting temperature (“Hagedorn”, $T < T_H$)

...and contains the QCD phase transition

the horn’s sensitivity to the phase boundary is determined (via strangeness neutrality condition) by the Λ abundance (determined by both T and μ_b)

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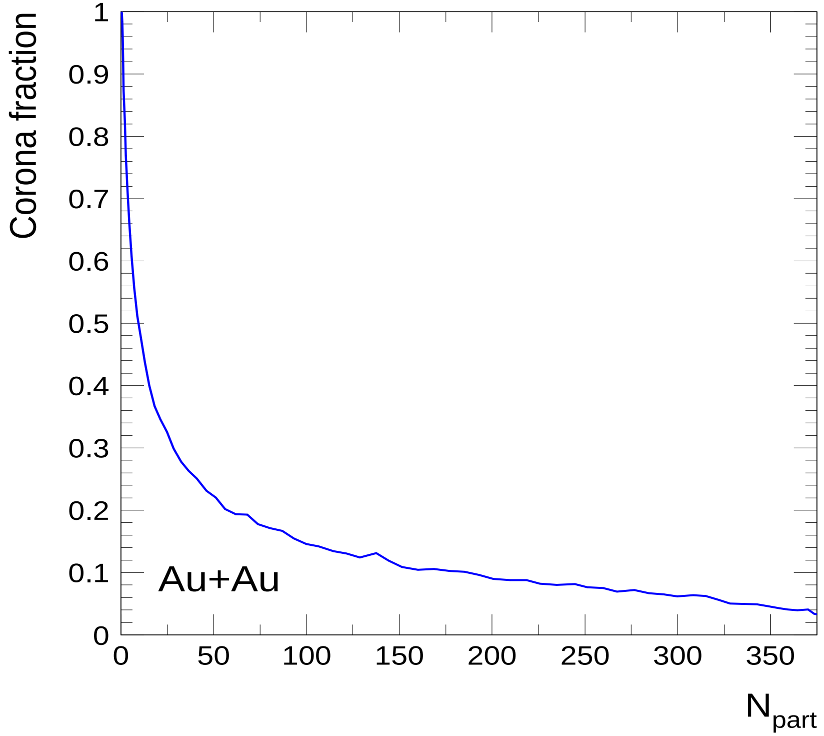
J/ψ: "core" and "corona"

realistic nuclei: "core" (QGP, apply stat. hadr.) and "corona" (NN coll.)

$$N_{J/\psi}^{core} = g_c^2 n_{J/\psi}^{th} V^{core}$$

$$g_c \sim N_{c\bar{c}}^{dir} = N_{coll}^{core} \sigma_{c\bar{c}}^{pp} / \sigma_{inel}^{pp}$$

$$N_{J/\psi}^{corona} = N_{coll}^{corona} \sigma_{J/\psi}^{pp} / \sigma_{inel}^{pp}$$



$$\Rightarrow N_{J/\psi} = N_{J/\psi}^{core} + N_{J/\psi}^{corona}$$

Timescales for charm(onium) production

Karsch & Petronzio, PLB 193 (1987) 105, Blaizot & Ollitrault, PRD 39 (1989) 232

- QGP formation time, t_{QGP}
  - SPS (FAIR): $t_{QGP} \simeq 1$ 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 SPS/FAIR energies? $(T_d \sim T_c)$

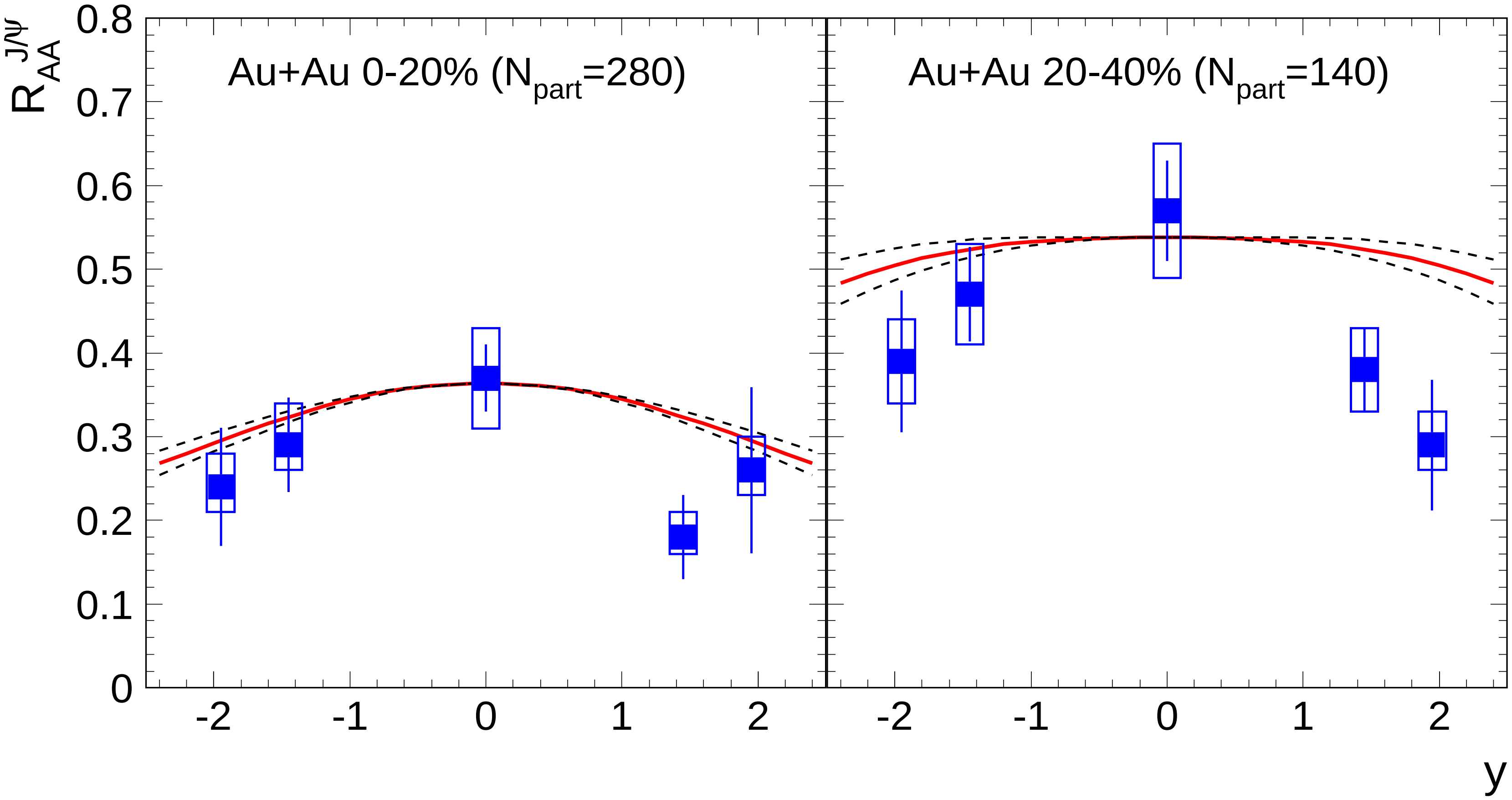
- collision time, $t_{coll} = 2R/\gamma_{cm}$
  - SPS (FAIR): $t_{coll} \gtrsim t_{J/\psi}$
  - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} << t_{J/\psi}$

cold nuclear suppression (breakup by initial nucleons) important at SPS/FAIR energies but not at RHIC and LHC

shadowing is yet another (cold nuclear) effect - important at LHC (RHIC?)

NB: the only way to distinguish: measure $\sigma_{c\bar{c}}$ in pA and AA

J/ψ at RHIC: rapidity dependence, R_{AA}



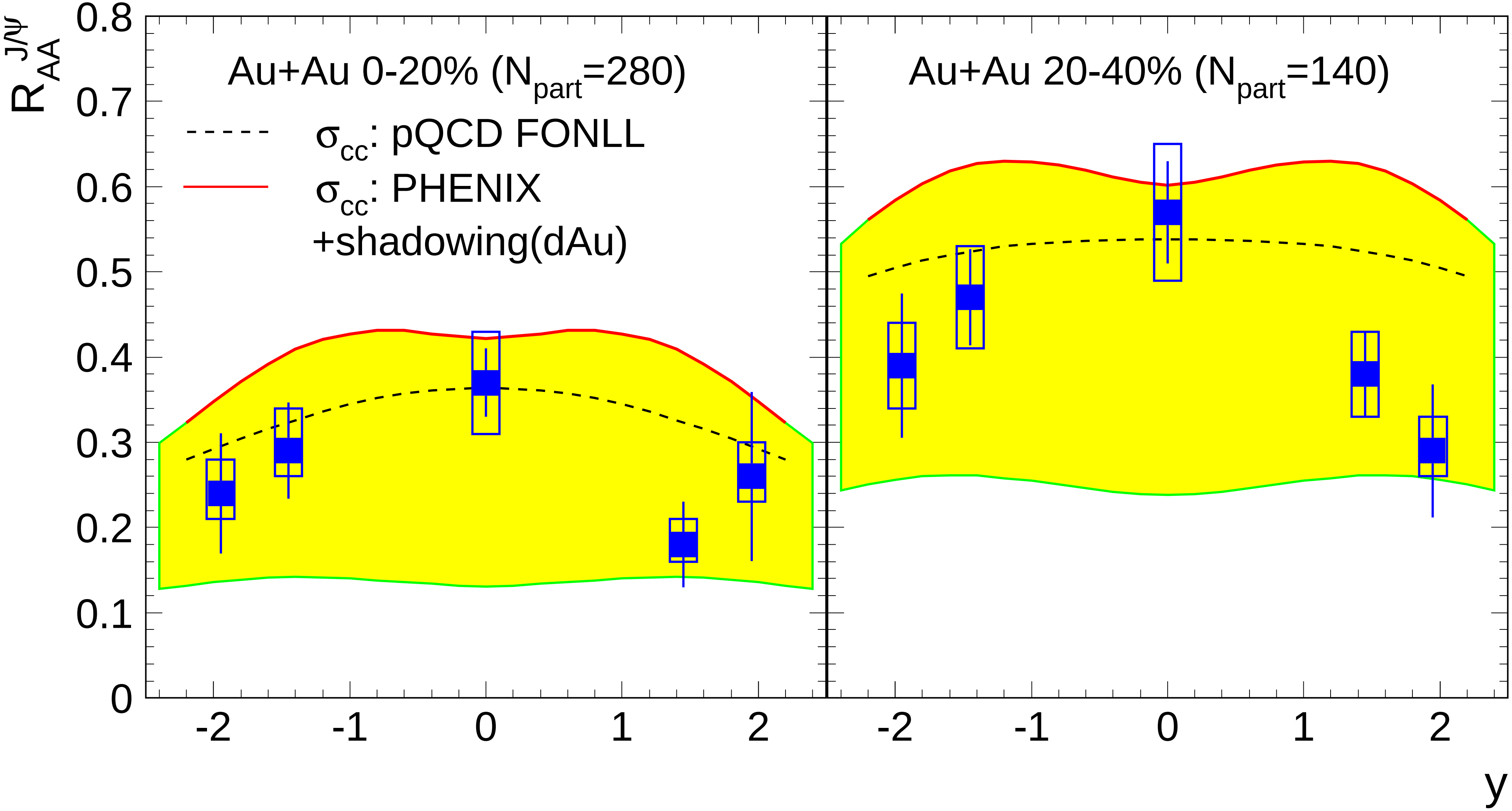
model reproduces data (PHENIX, nucl-ex/0611020) very well (pQCD $\sigma_{c\bar{c}}$)

direct indication of J/ψ generation at hadronization (enhanced at y=0)

(constant R_{AA} expected within Debye screening model)

Phys. Lett. B 652 (2007) 259

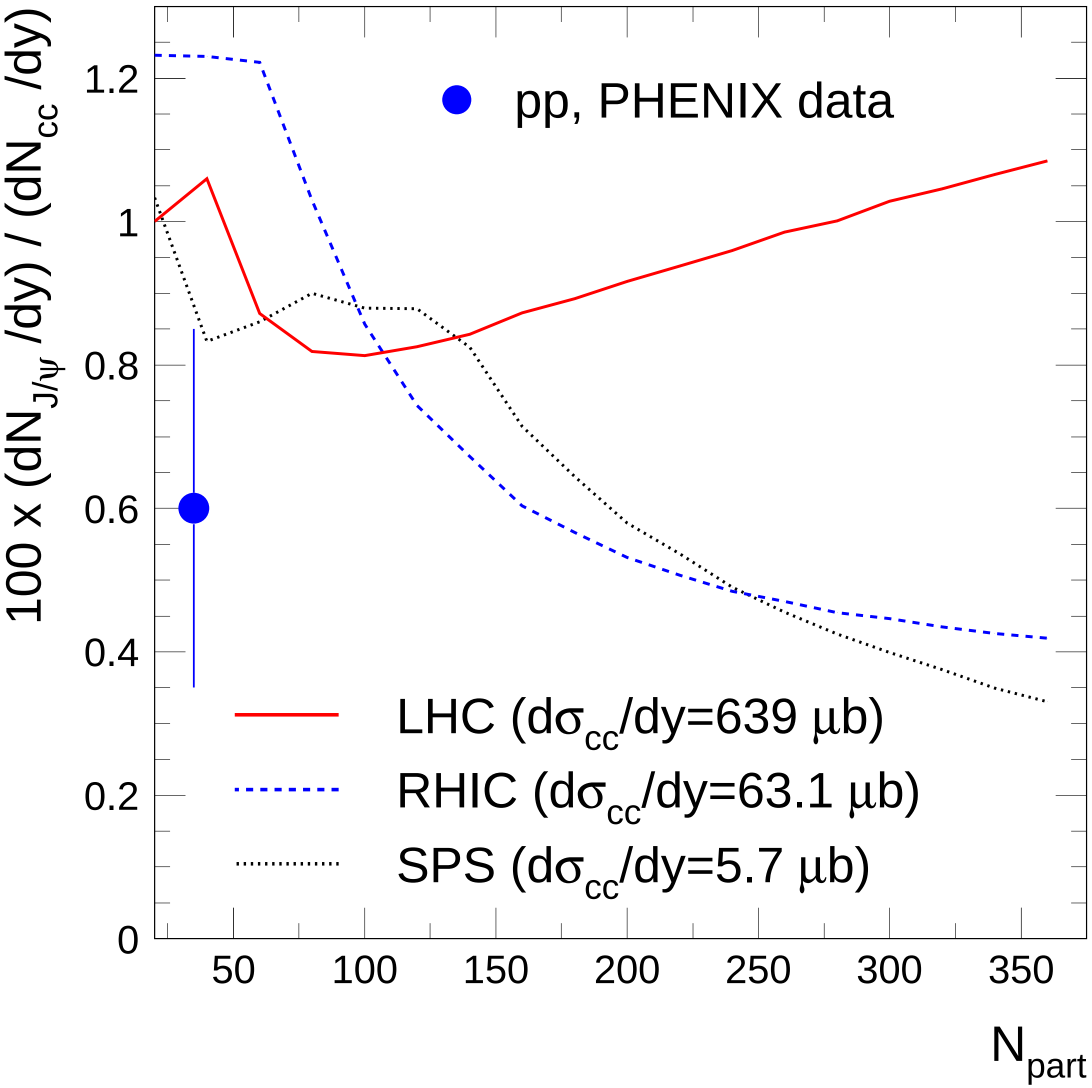
J/ψ at RHIC: effect of shadowing



model describes data with PHENIX $\sigma_{c\bar{c}}$ (lower error plotted)

J. Phys. G 35 (2008) 104155

J/ψ production relative to charm



- ...the most "solid" observable
  ...with similar features as R_{AA}
- similar values at RHIC and SPS
  ...with differences in fine details
  ...determined by canonical suppression of open charm
- enhancement-like at LHC
  can. suppr. lifted, quadratic term dominant

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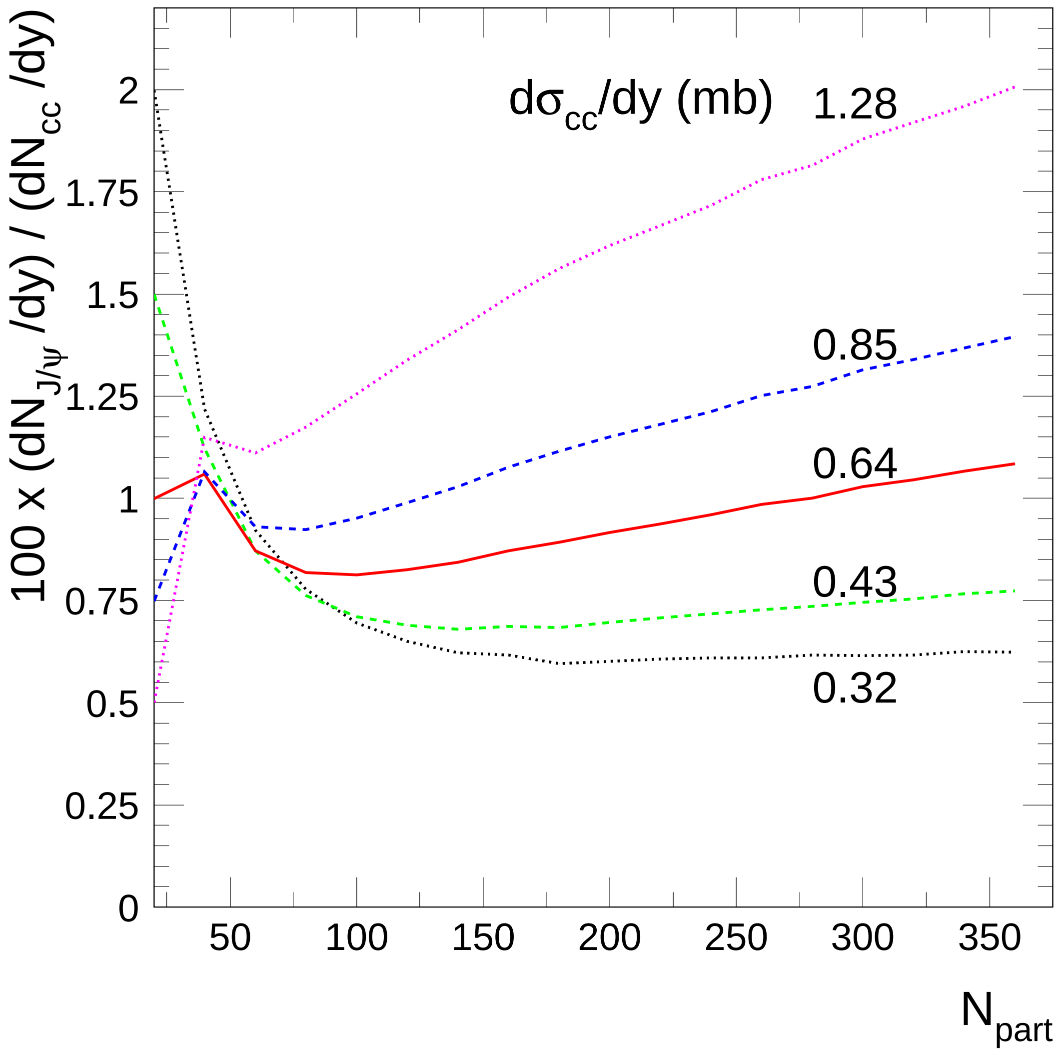
J/ψ at LHC



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solid expectations for LHC

...providing we know well (from measurements) the charm production cross section in Pb-Pb

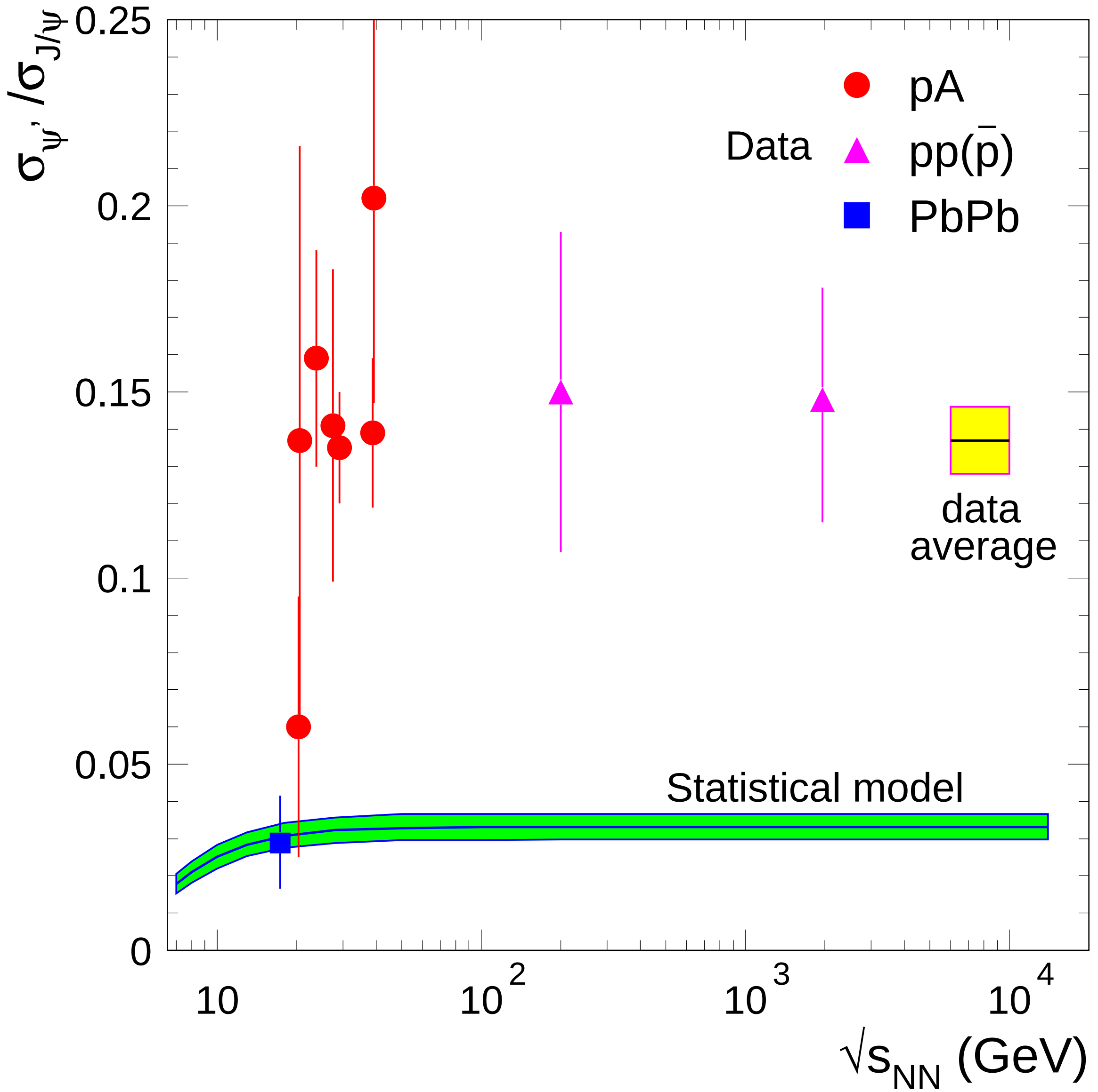
agreement that (re)generation is the game at LHC?

Liu, Qu, Xu, Zhuang, arXiv:0907.2723
Song, Park, Lee, arXiv:1002.1884

"2-component" (kinetic, coalescence) models

...as Grandchamp, Rapp, PLB 523 (2001) 60, NPA 709 (2002) 415

The "null hypothesis"

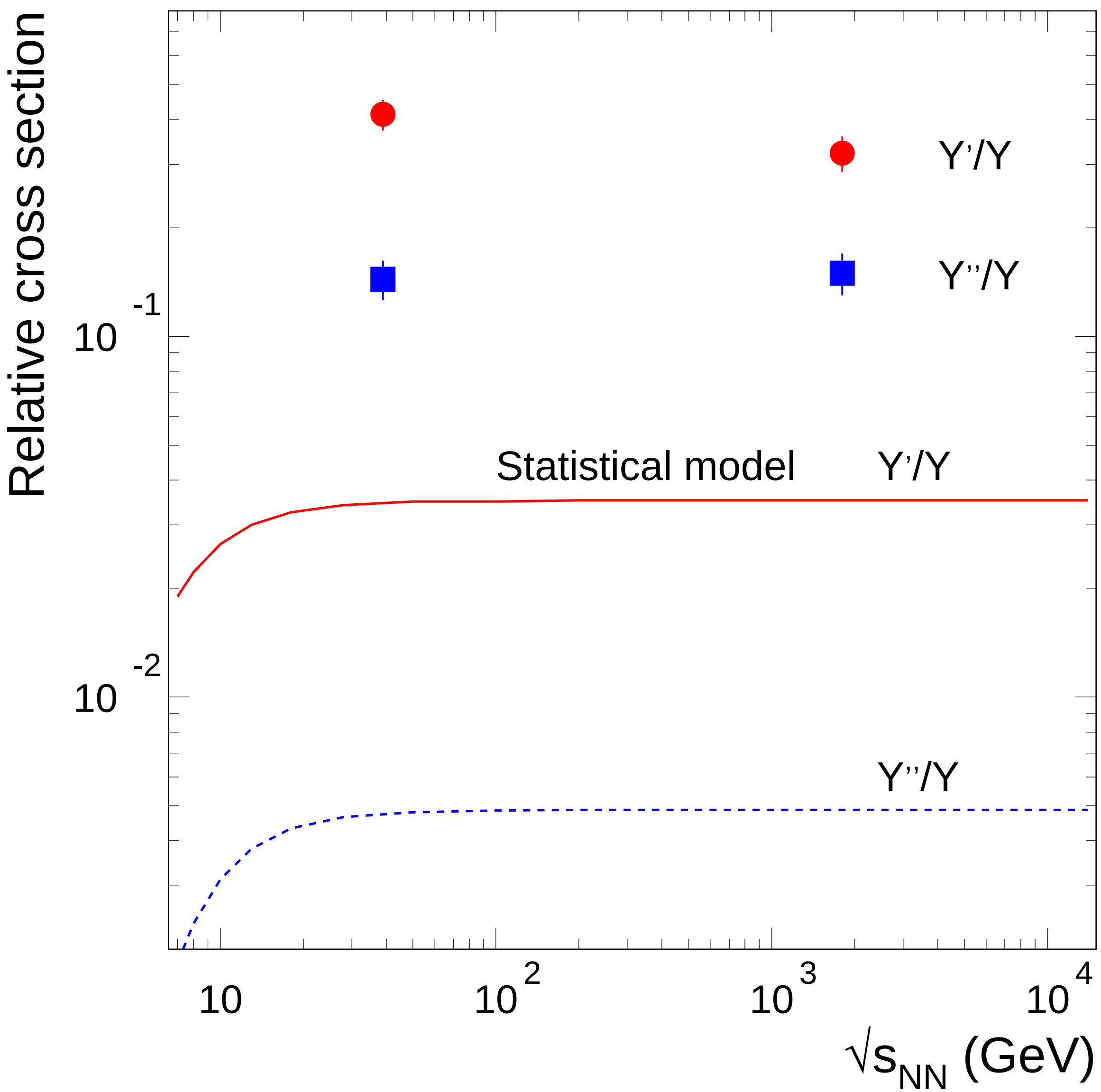


charmonium in pp(A) collisions

...is far from thermalized (model is for AA)

...while a thermal value is reached in central PbPb (NA50, SPS)

The “null hypothesis” for bottonium



bottonium in pp(A) collisions

...is far from thermalized (model is for AA)

...will we find a thermal value at LHC?