The freeze-out and the QCD phase diagram: the current status

A. Andronic – GSI Darmstadt

- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Chemical freeze-out of heavy quarks (charmonium)
- Outlook

work in collaboration with P. Braun-Munzinger, K. Redlich, J. Stachel

Hadron yields - central collisions

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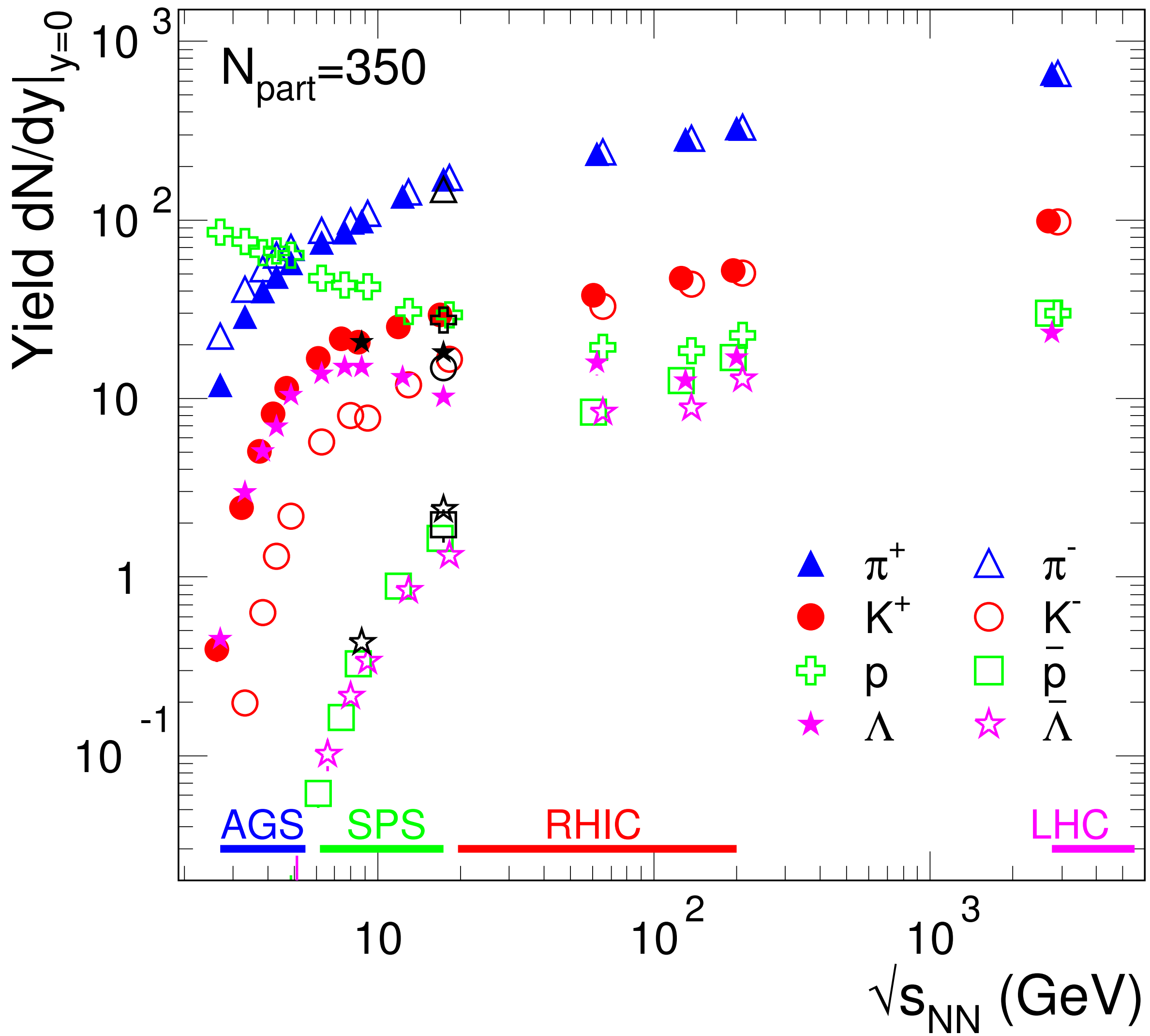

- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

  $\pi^{\pm}$ $(u\bar{d},\, d\bar{u})$, m=140 MeV
  $K^{\pm}$ $(u\bar{s},\, \bar{u}s)$, m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- 3 decades in energy and
  3 decades of experimental effort

mass hierarchy in production ...natural to think of the thermal model

The statistical (thermal) model

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grand canonical partition function for specie i ($\hbar = c = 1$):

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

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;
$E_i = \sqrt{p^2 + m_i^2}$ total energy; $+$ for fermions – for bosons
$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

μ ensure conservation (on average) of quantum numbers, fixed by "initial conditions"

i) isospin: $V_{cons} \sum_i n_i I_{3i} = I_3^{tot}$, with $V_{cons} = N_B^{tot} / \sum_i n_i B_i$
I_3^{tot}, N_B^{tot} isospin and baryon number of the system ($\simeq$0 at high energies)

ii) strangeness: $\sum_i n_i S_i = 0$

iii) charm: $\sum_i n_i C_i = 0$.

Hadron densities

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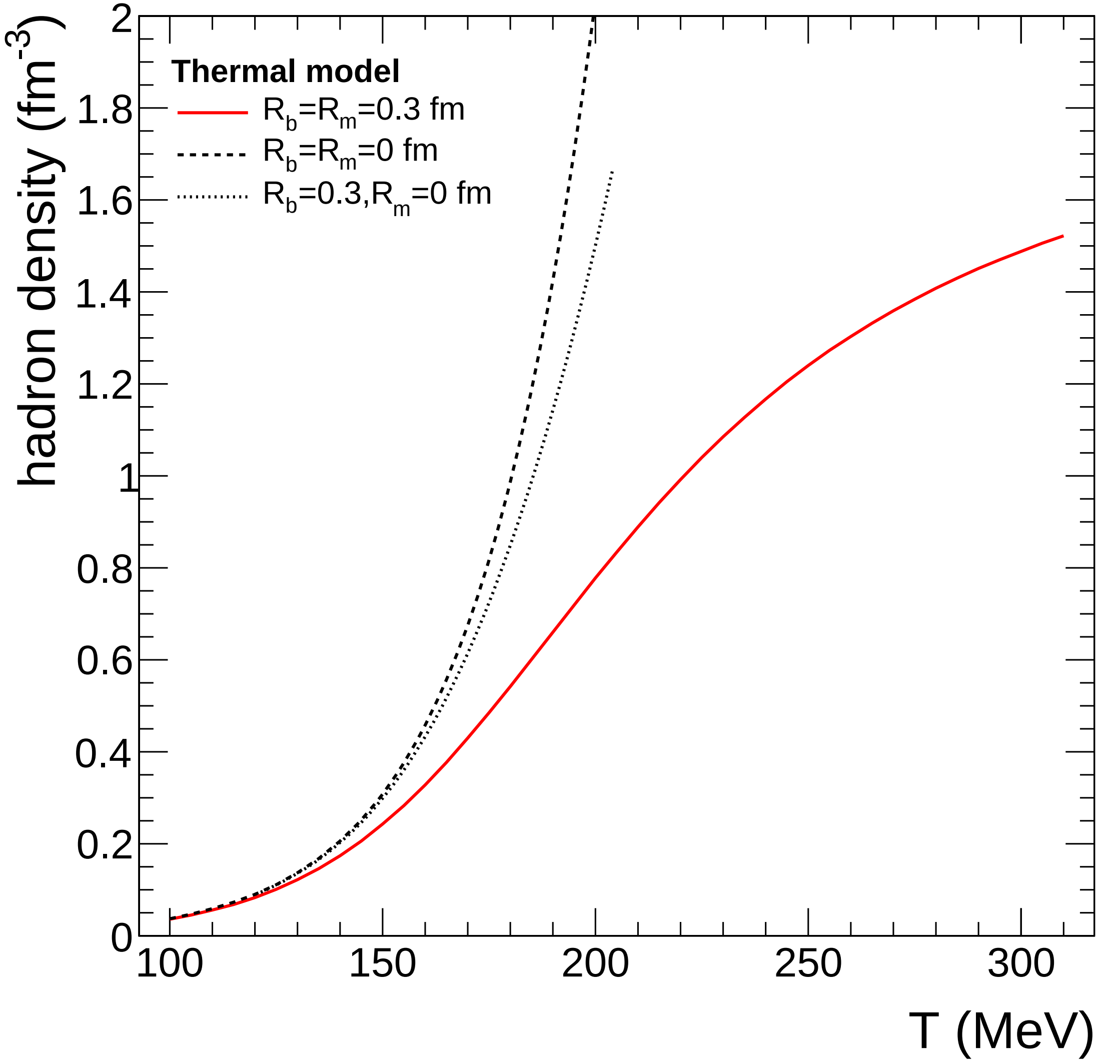

a dense system for $T \gtrsim 170$ MeV (for point-like hadrons)

the usual case is $R_b = R_m = 0.3$ *fm*

Thermal fits of hadron abundances

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

Latest PDG hadron mass spectrum ...quasi-complete up to m=2 GeV;

our code: 555 species (including fragments, charm and bottom hadrons)

for resonances, the width is considered in calculations

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

N_i hadron yield, σ_i experimental uncertainty (stat.+syst.)

$\Rightarrow (T, \mu_B, V)$

canonical treatment whenever needed (small abundances)

Thermal fit – LHC, Pb–Pb, 0-10%

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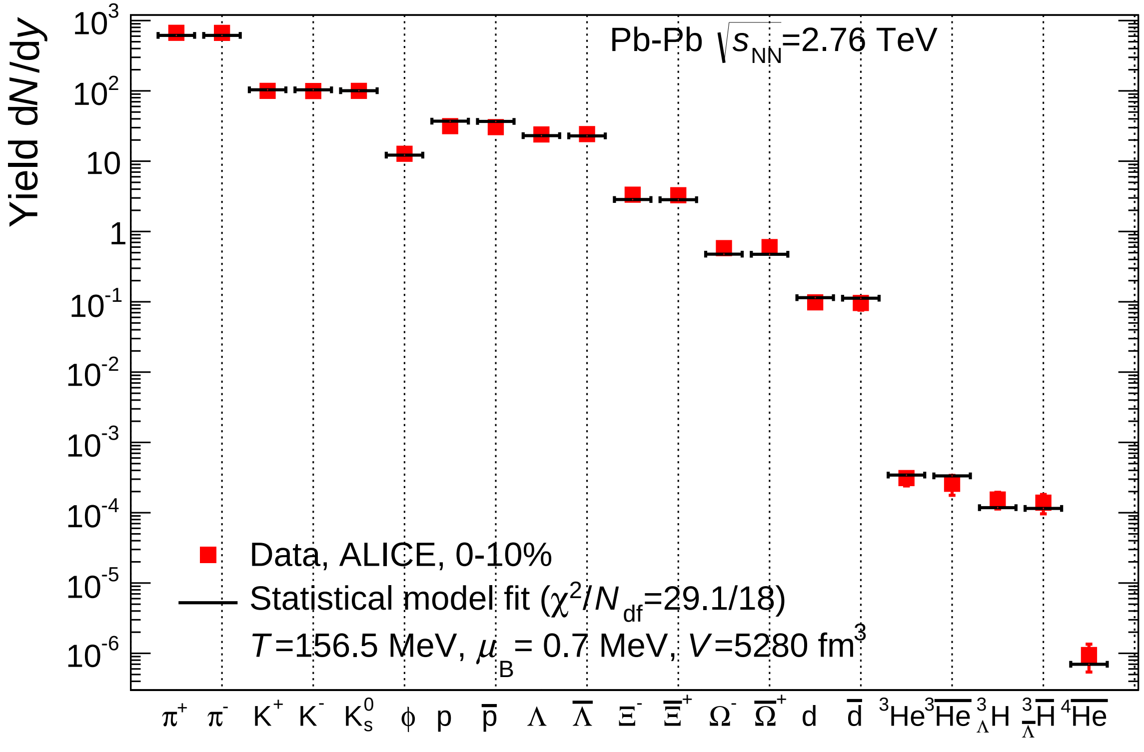

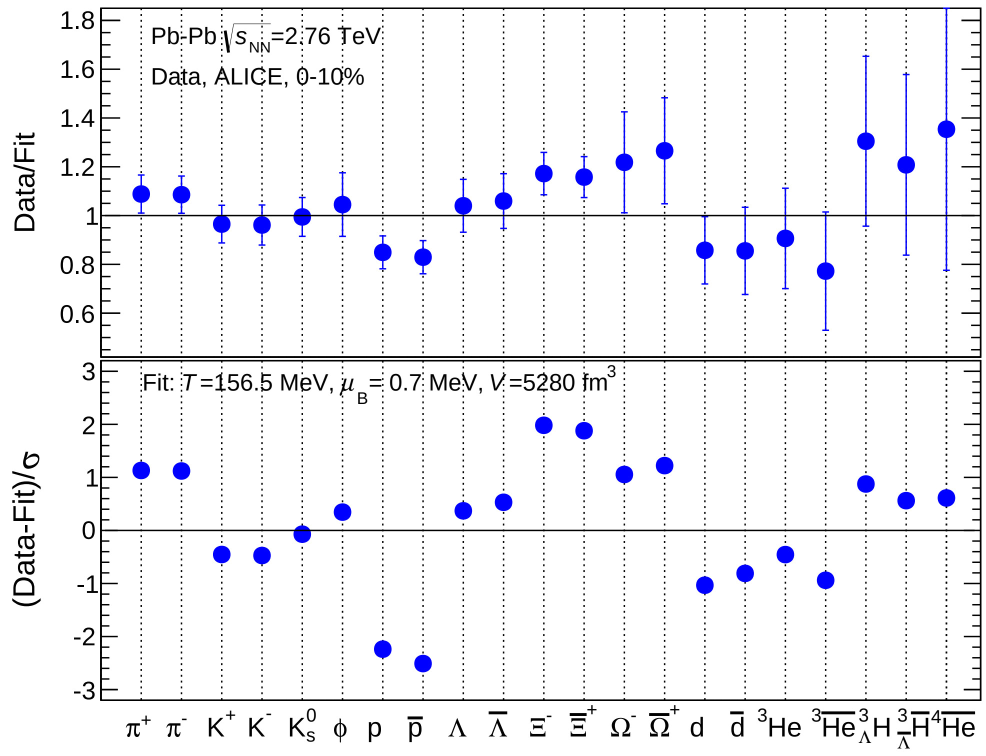

all species in fit

π, $K^{\pm}$, K^0 from charm included (0.7%, 2.9%, 3.1% for the best fit)

$T = 156.5 \pm 1.5$ MeV, $\mu_B = 0.7 \pm 3.8$ MeV, $V_{\Delta y=1} = 5280 \pm 410$ fm^3

Thermal fit – LHC, Pb–Pb, 0-10%

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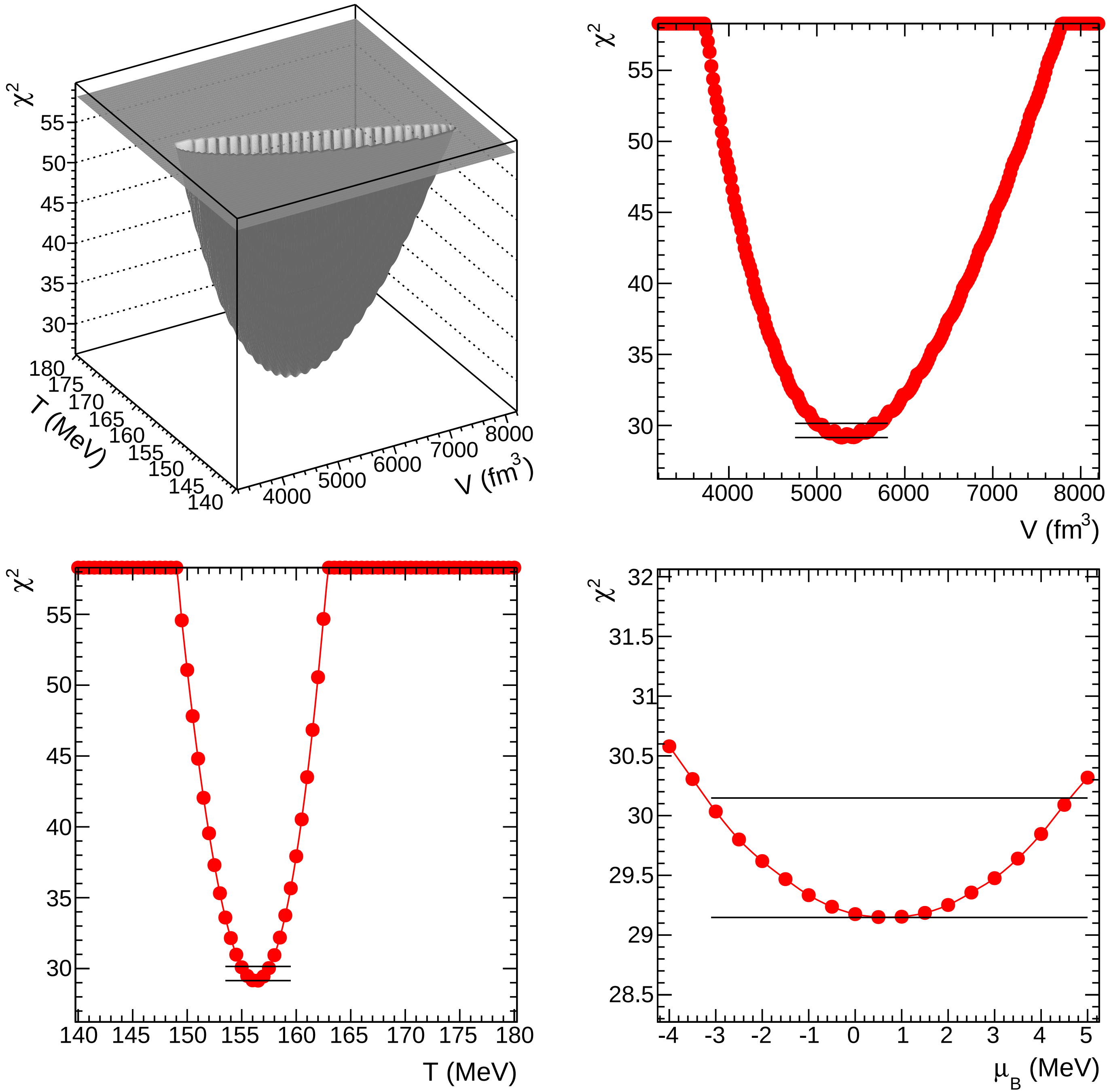

Systematic uncertainties in the model

hadron spectrum ...embodies low-energy QCD

well-known for $m < 2$ GeV; many confirmed states above 2 GeV, still incomplete

for high m, BR not well known, but can be reasonably guessed

T found to be robust in fits with spectrum truncated above 2 GeV

σ $[f_0(500)]$ meson proposed recently to be discarded (3-4% less pions)

Giacosa, Begun, Broniowski, arXiv:1603.07687

hadron eigenvolumes ...to mimick interactions (beyond low-density, Dashen-Ma)

we consider that $R_{meson} = 0.3, R_{baryon} = 0.3$ *fm is a reasonable case*
point-like hadrons lead to same T, but volume larger by 20-25%

an extreme case, $R_{meson} = 0, R_{baryon} = 0.3$ fm leads to
$T = 161.0 \pm 2.0$ MeV, $\mu_B = 0$ *fixed*, $V = 3470 \pm 280$ fm^3

NB: in this case, the result is rather sensitive on the set of hadrons in the fit
for instance, using hadrons up to Ω, cannot constrain T (unphysically large)
Vovchenko, Stöcker, arXiv:1512.08046, arXiv:1606.06350

...and anything else can be imagined, see (R dependent on mass & strangeness)
Alba, Vovchenko, Gorenstein, Stöcker, arXiv:1606.06542

Energy dependence of T, μ_B (central collisions)

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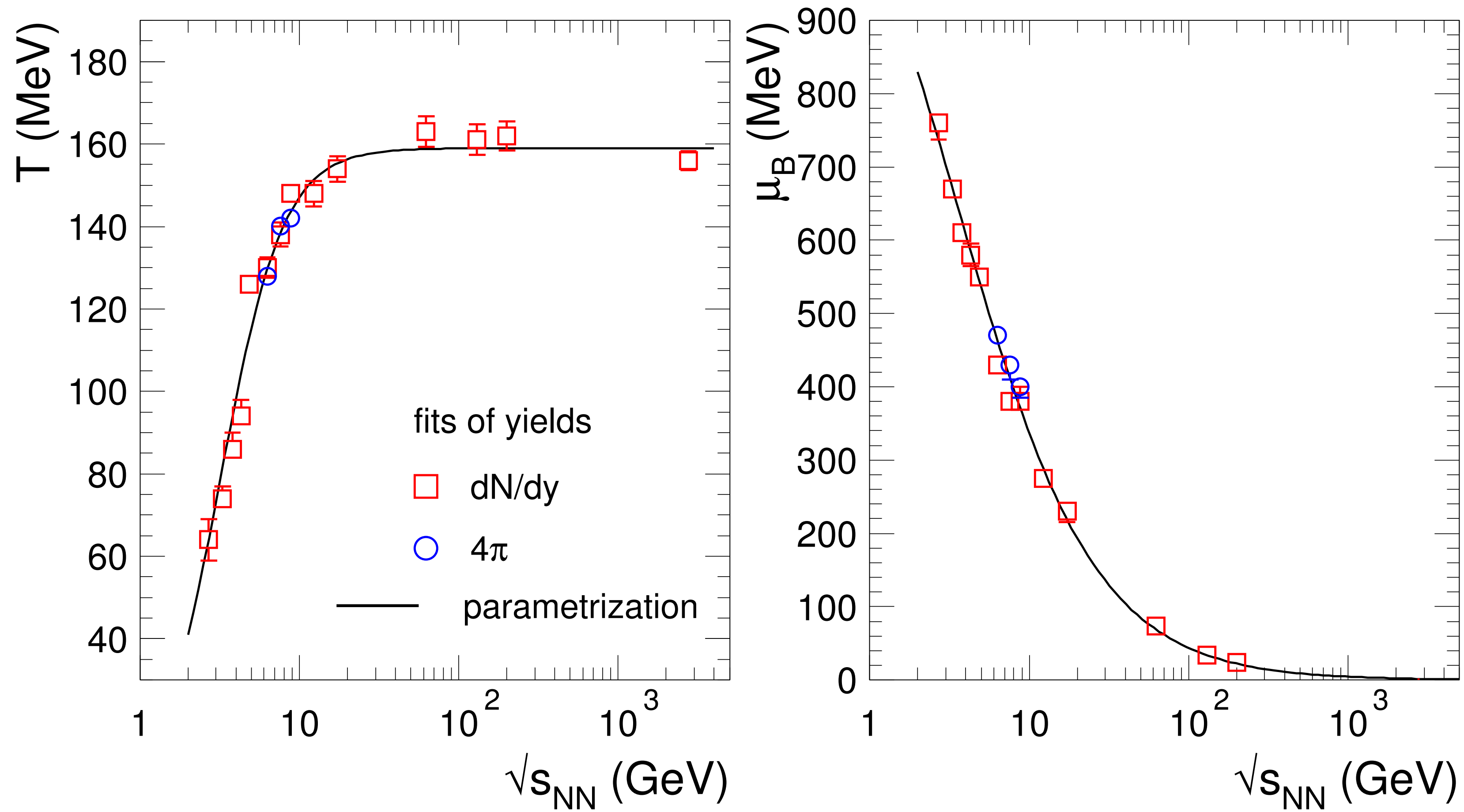

thermal fits exhibit a limiting temperature: $T_{lim} = 159 \pm 2$ MeV

$$T = T_{lim}\frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\mathrm{GeV}))/0.45)}, \qquad \mu_B[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

NPA 772 (2006) 167, PLB 673 (2009) 142 ...with updates, 2012

A “global” look (ratios)

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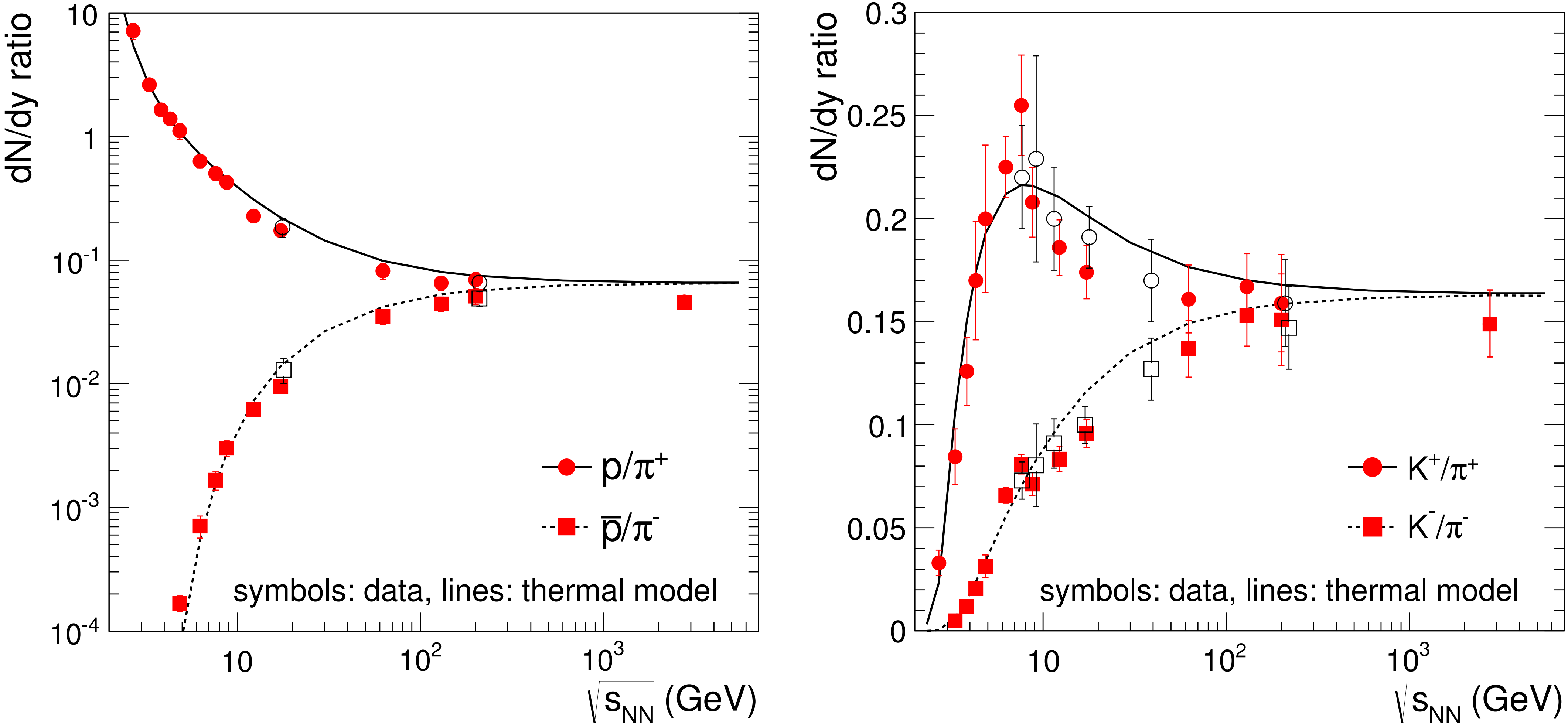
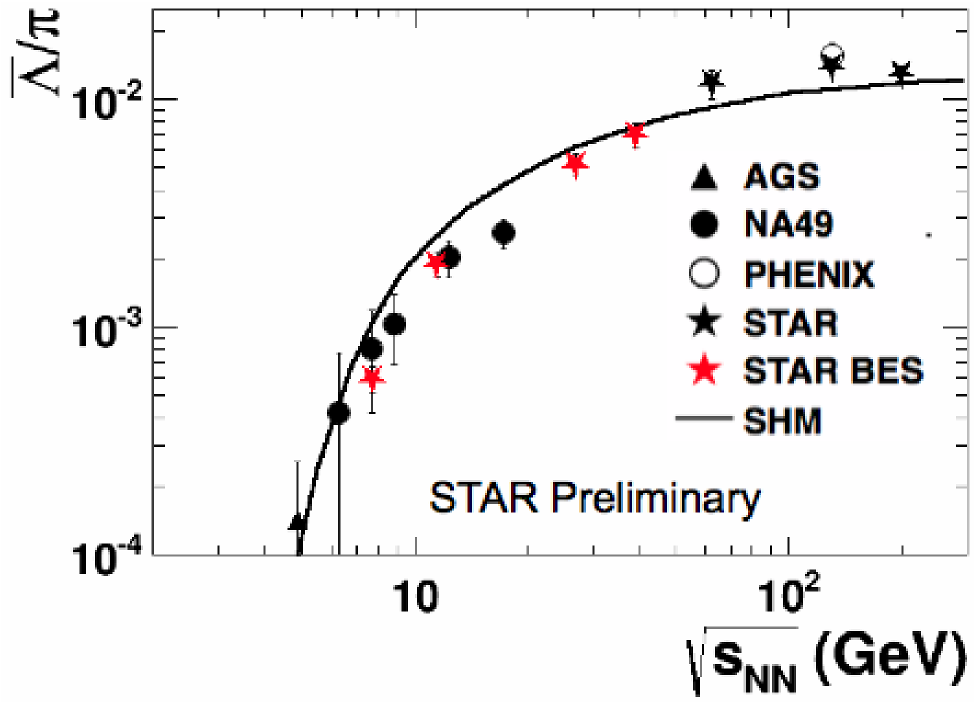
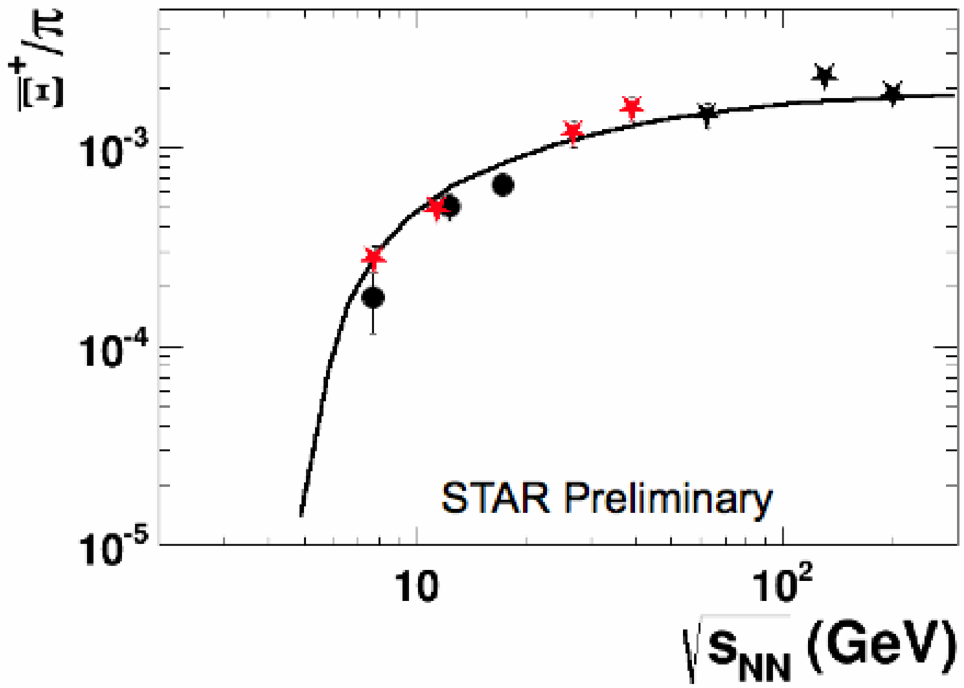


full: NA49 & STAR (p, $\bar{p}$ from w.d. subtracted); at 17 GeV open symbols NA44; at 200 GeV open symbols BRAHMS, lower energies STAR BES (prelim.)





Statistical Hadron gas Model: A. Andronic et al., Nucl. Phys. A 772, 167 (2006)

Shusu Shi (STAR), talk yesterday

Fragment production

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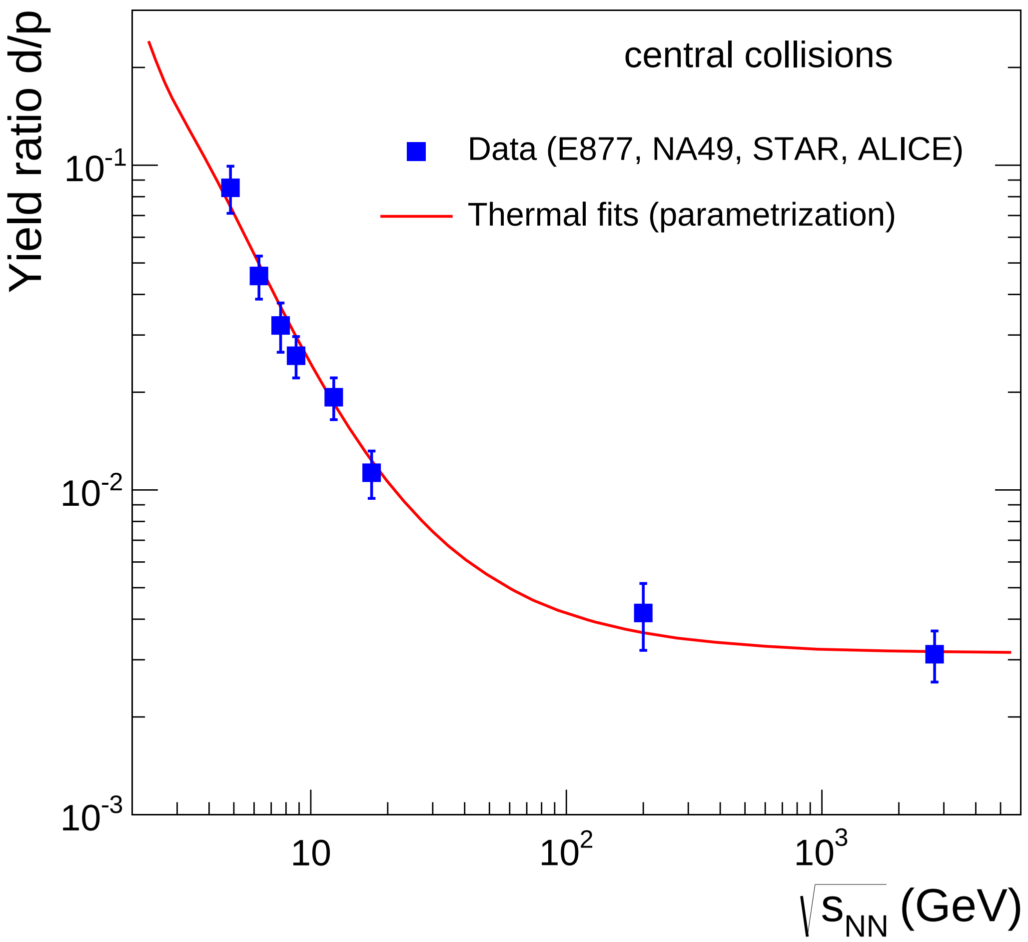

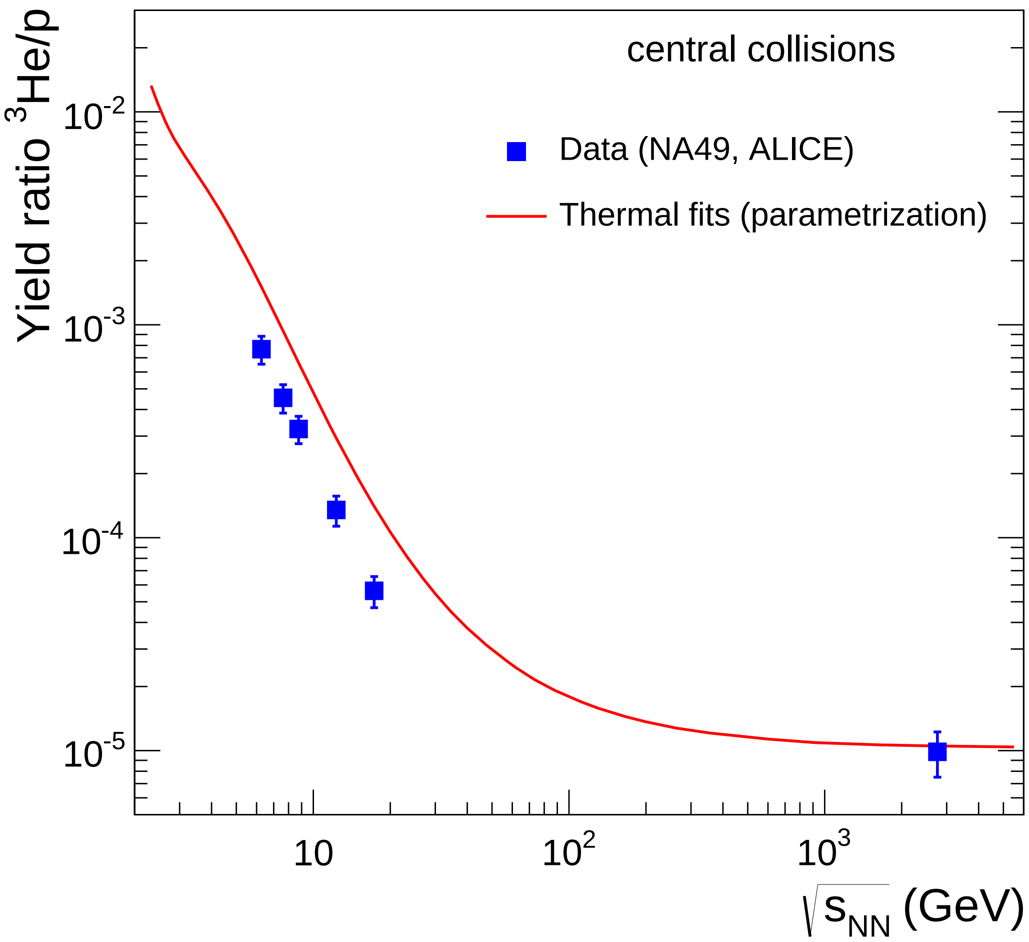

new NA49 data, arXiv:1606.04234 (midrapidity)

Connection to the phase diagram of QCD

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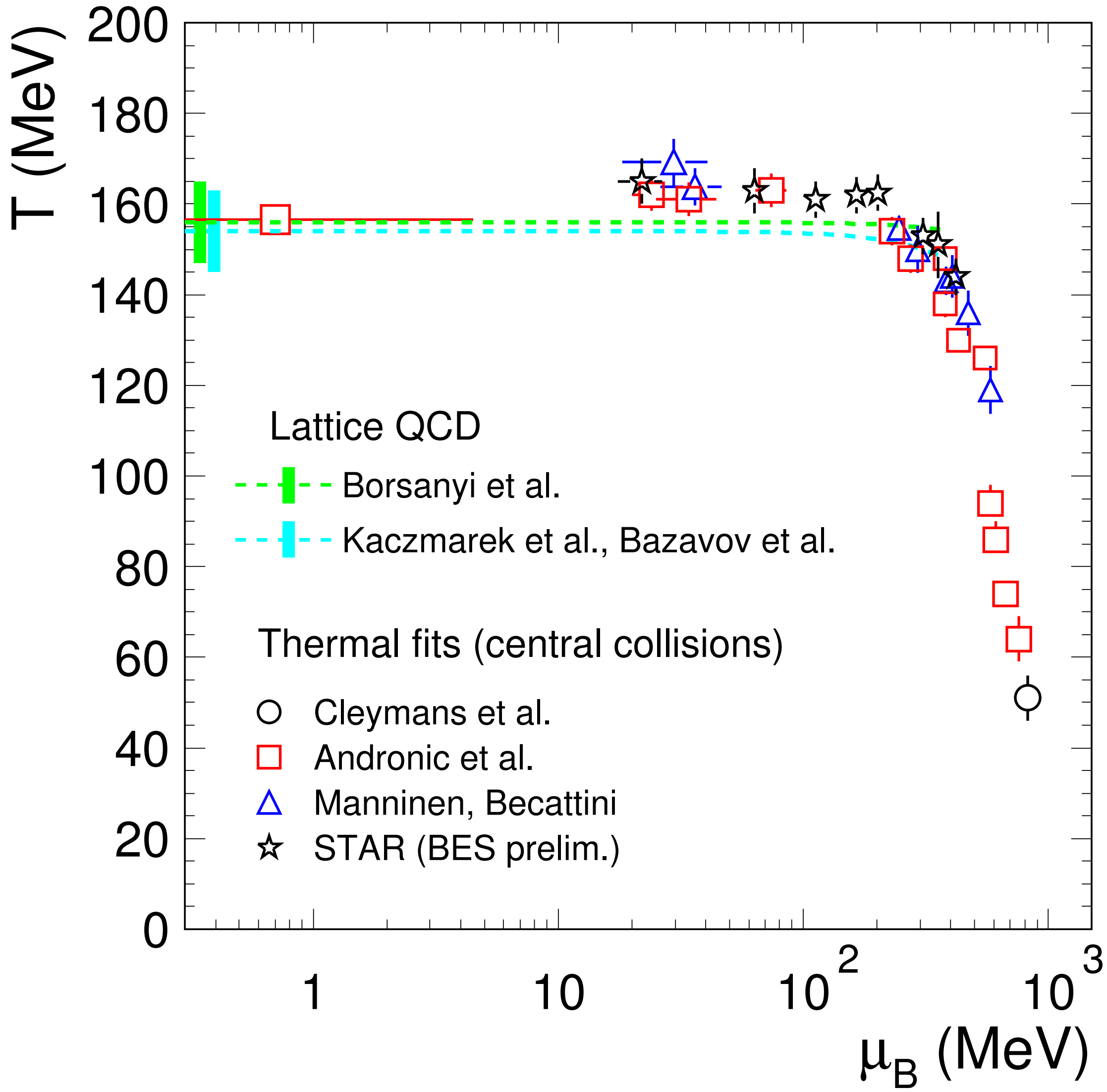
(as $T \to T_{lim}$) is chemical freeze-out a determination of the phase boundary?



...Yes (at low μ_B)

Lattice QCD, $\mu_B = 0$:
crossover T=145-165 MeV

Borsanyi et al.,
JHEP 1009 (2010) 073, JHEP 1208 (2012) 053

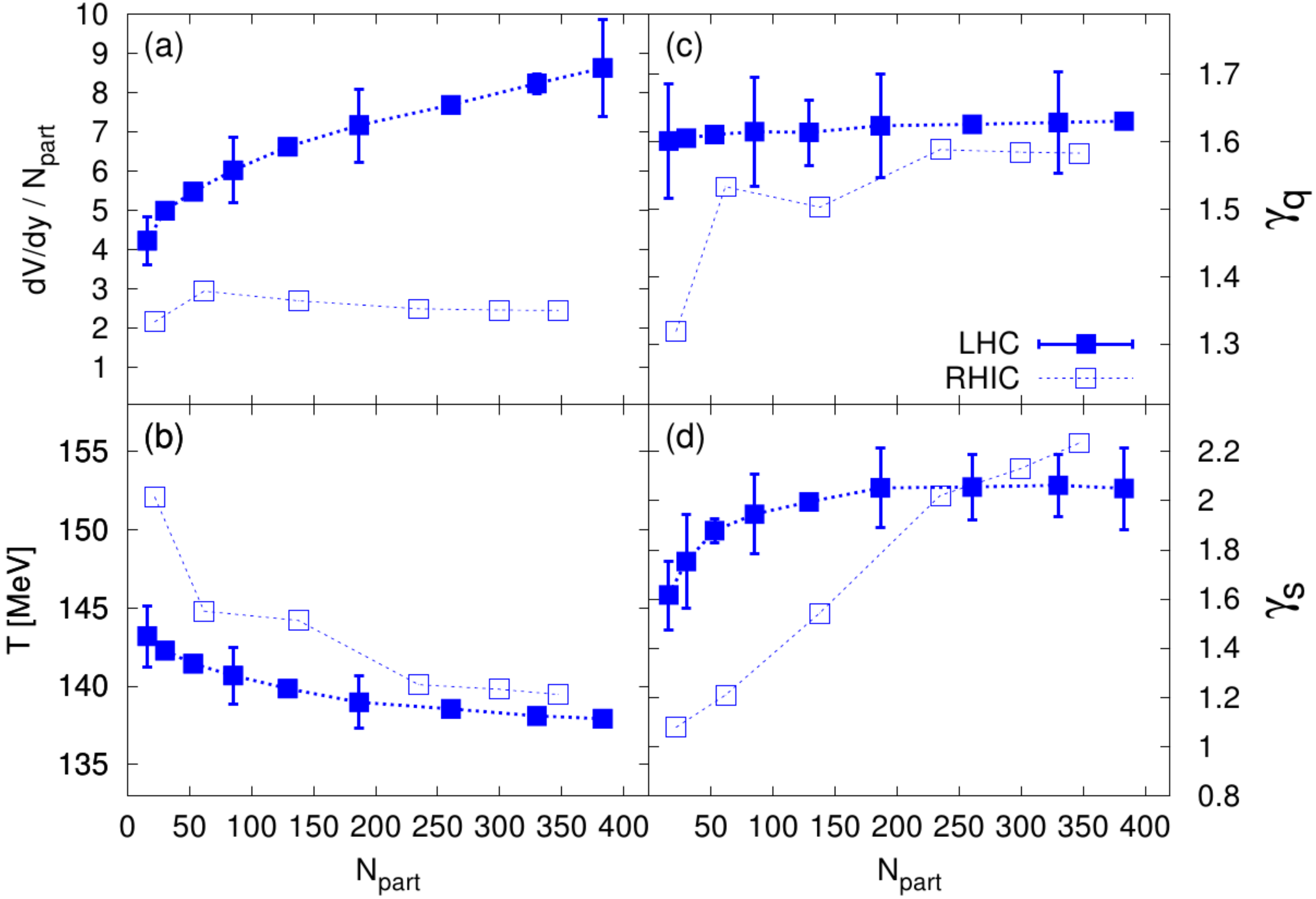
HotQCD, PRD 90 (2014) 094503, PRD 83, 014504 (2011)

...for entire μ_B range?

PBM, Stachel, Wetterich, PLB 596 (2004) 61
McLerran, Pisarski, NPA 796 (2007) 83
AA et al., NPA 837 (2010) 65
Floerchinger, Wetterich, NPA 890 (2012) 11

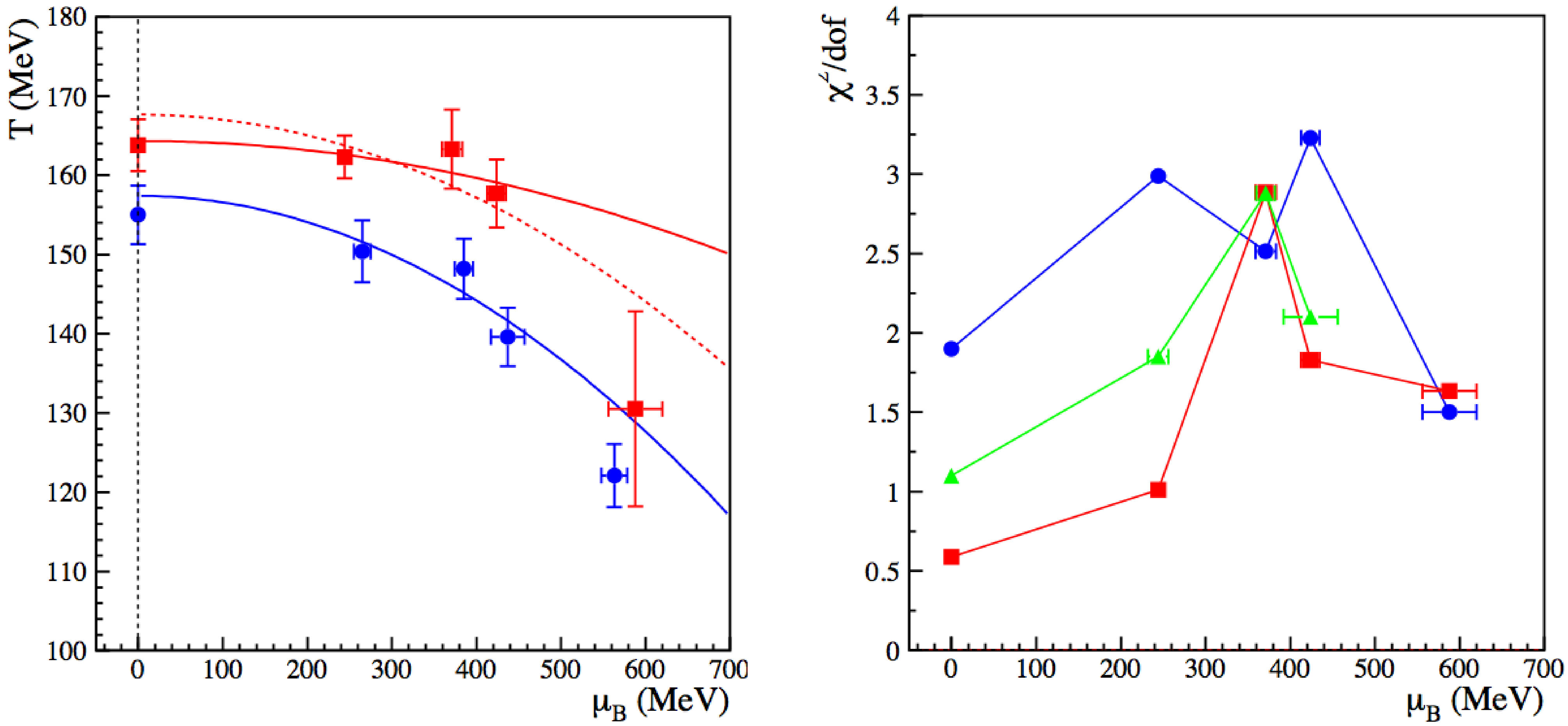
Are the larger T values at RHIC significant (physics)?

Competing views

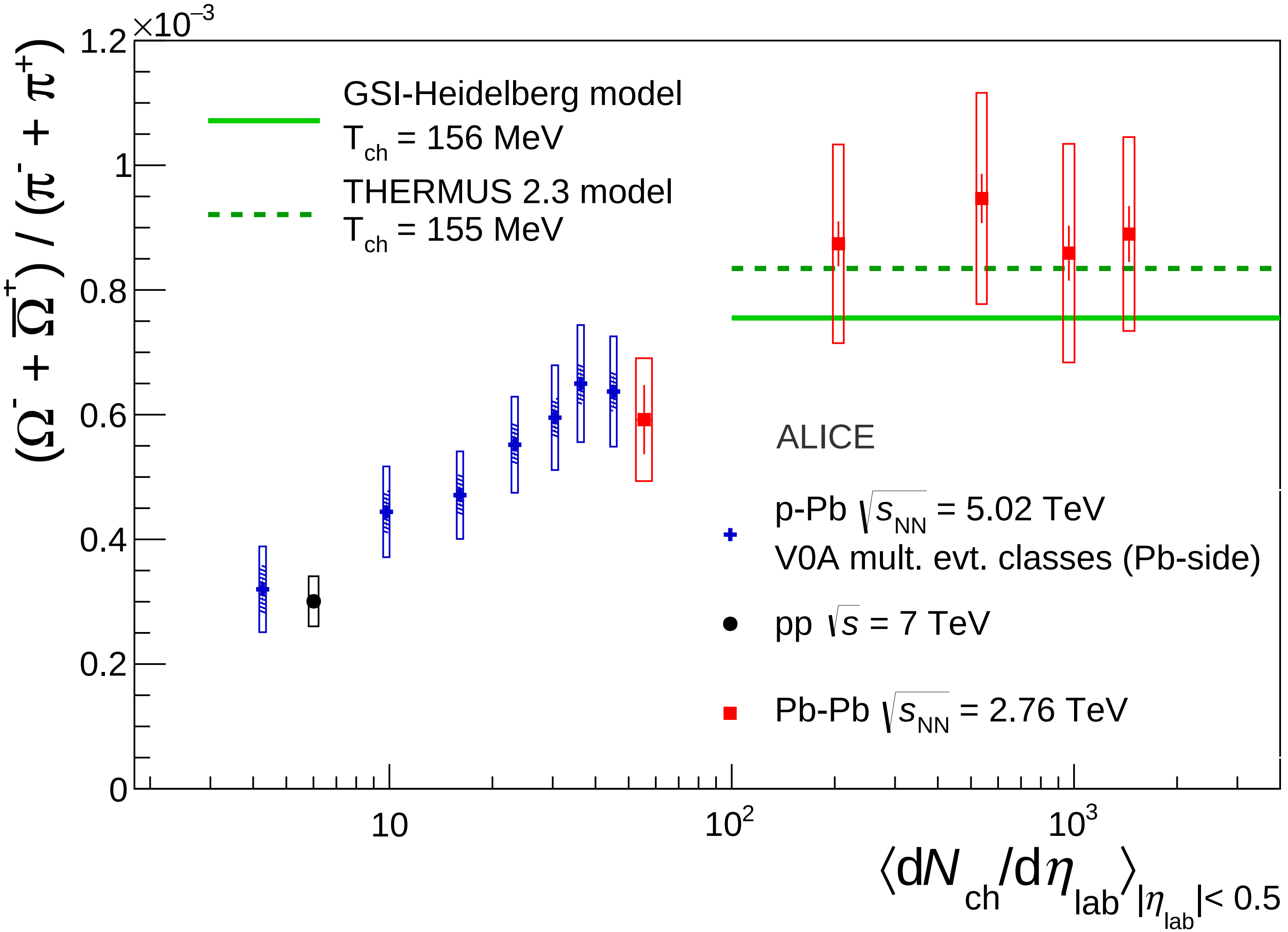


Rafelski, Petran, arXiv:1406.1871

beyond sudden freeze-out (model a hadronic phase with "chemical activity" with UrQMD)

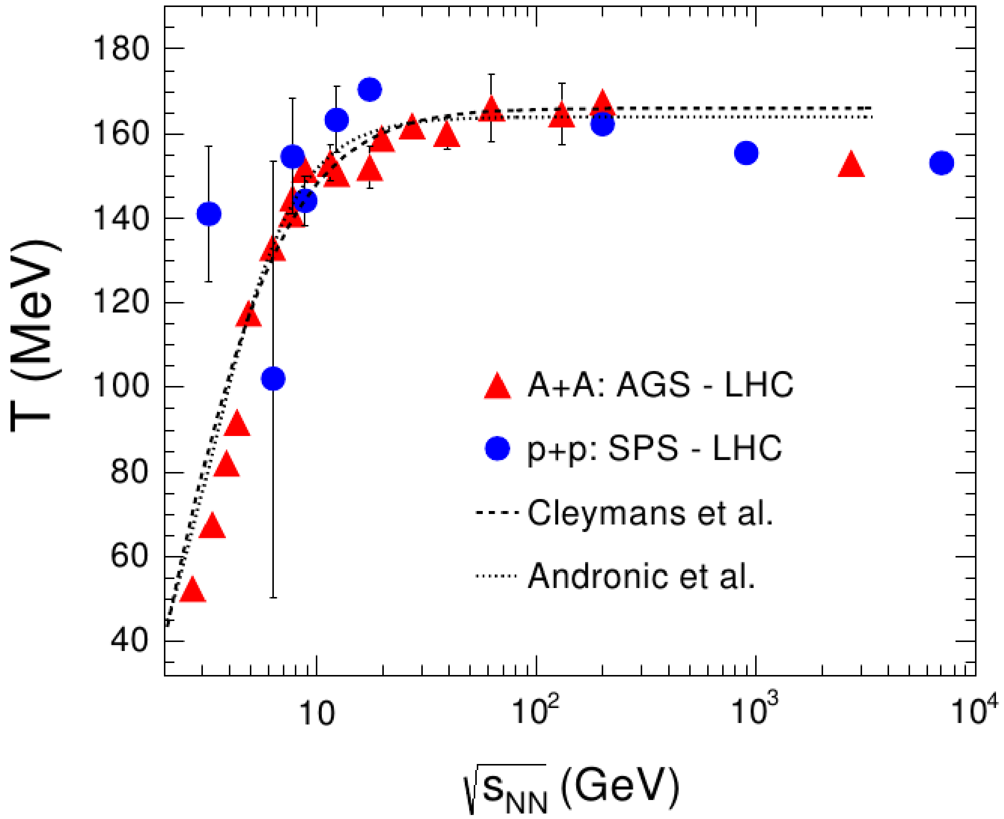


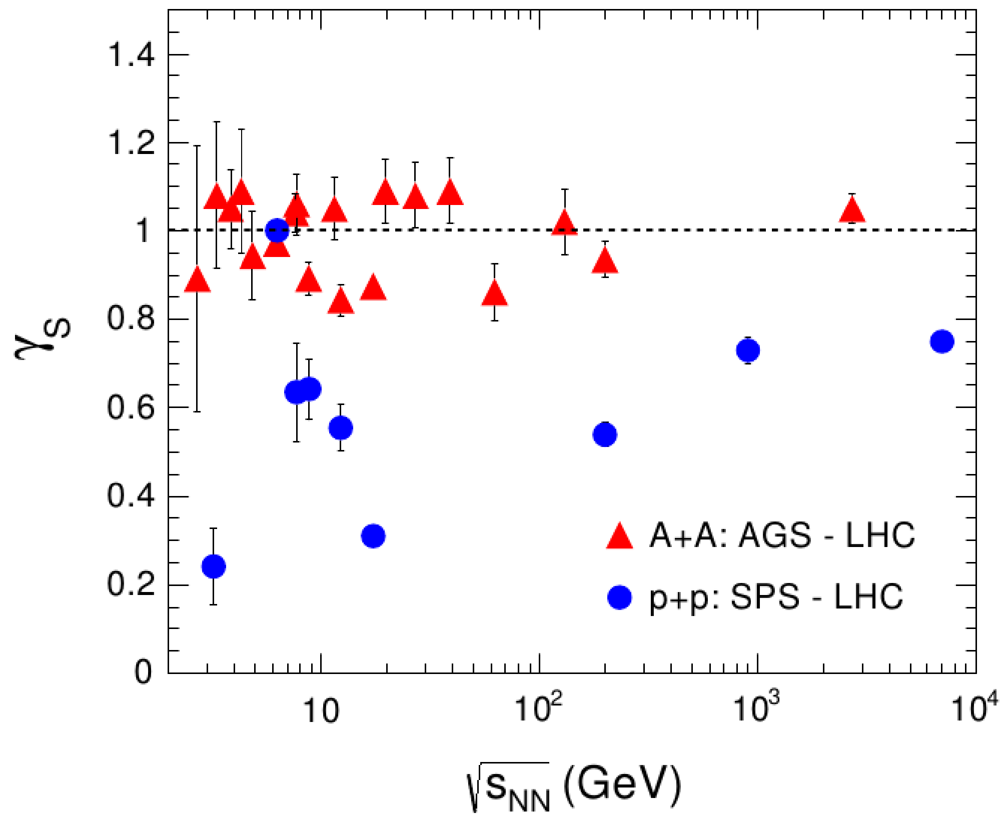
F. Becattini et al, arXiv:1605.09694



ALICE, arXiv:1512.07227

In first order, effect of (strangeness) canonical suppression (at low $\mathrm{d}N_{ch}/\mathrm{d}\eta$)





S. Das et al., arXiv:1605.07748

see also,

Cleymans et al., arXiv:1603.09553; Vovchenko et al., arXiv:1512.08025
HADES, arXiv:1512.07070

We turn now to quarkonium

Statistical hadronization of heavy quarks: assumptions

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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 and Lattice QCD
- no J/ψ survival in QGP (full screening; Matsui, Satz)

  can J/ψ survive above T$_c$? ...yet to be settled (LQCD)

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

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

Statistical hadronization of charm: 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):

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

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

The only new input parameter: $N_{c\bar{c}}^{dir}$ (from experiment or pQCd)

Minimal volume for QGP: V_{QGP}^{min}=100 fm^3

Charmonium in the statistical hadronization model

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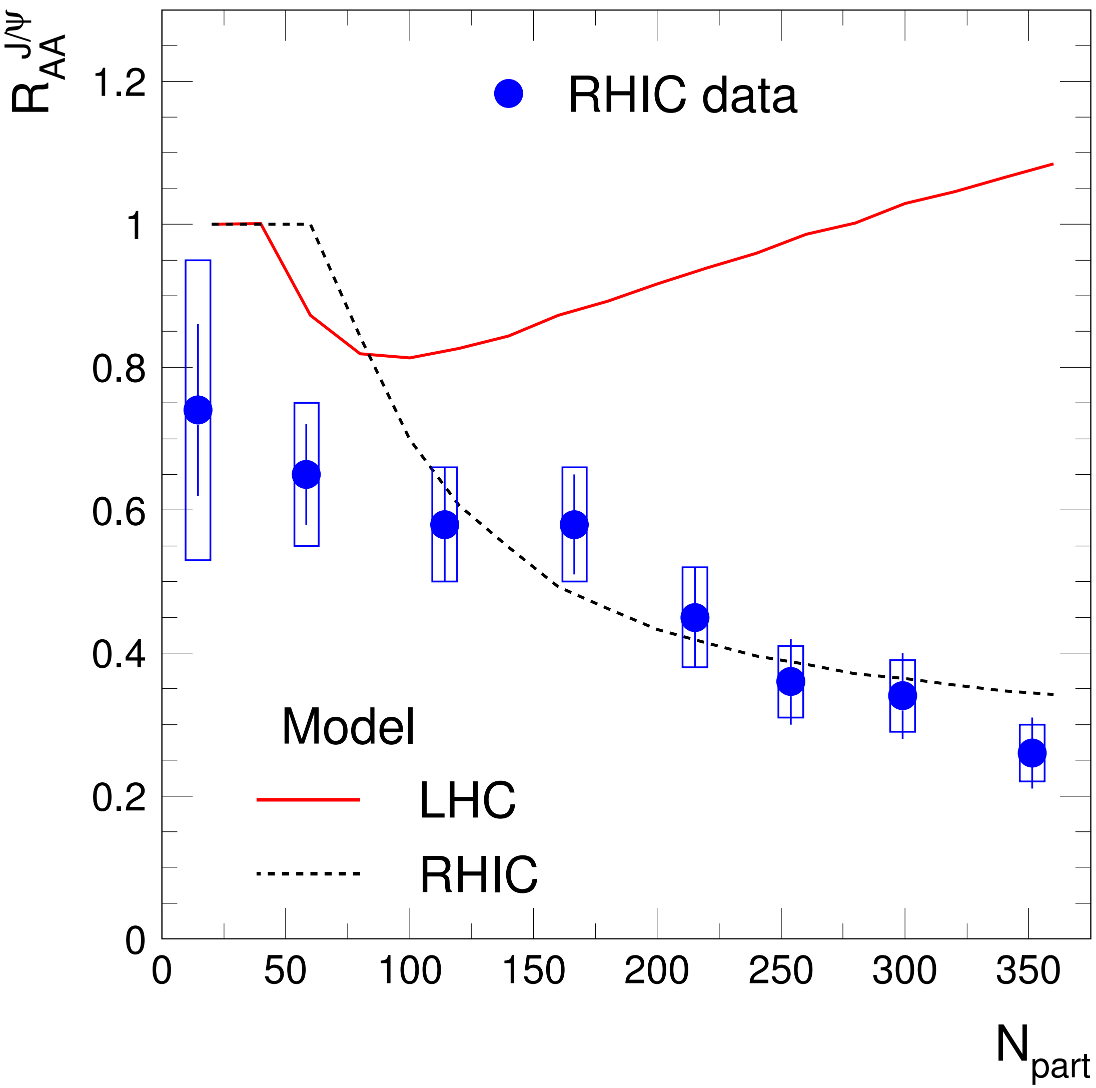

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AA}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- "suppression" at RHIC (and SPS)
- "enhancement" at the 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: ∼2.2x

PLB 571 (2003) 36, NPA 789 (2007) 334, PLB 652 (2007) 259

this was for top LHC energy ... but is a generic prediction of the model

Charmonium in the statistical hadronization model

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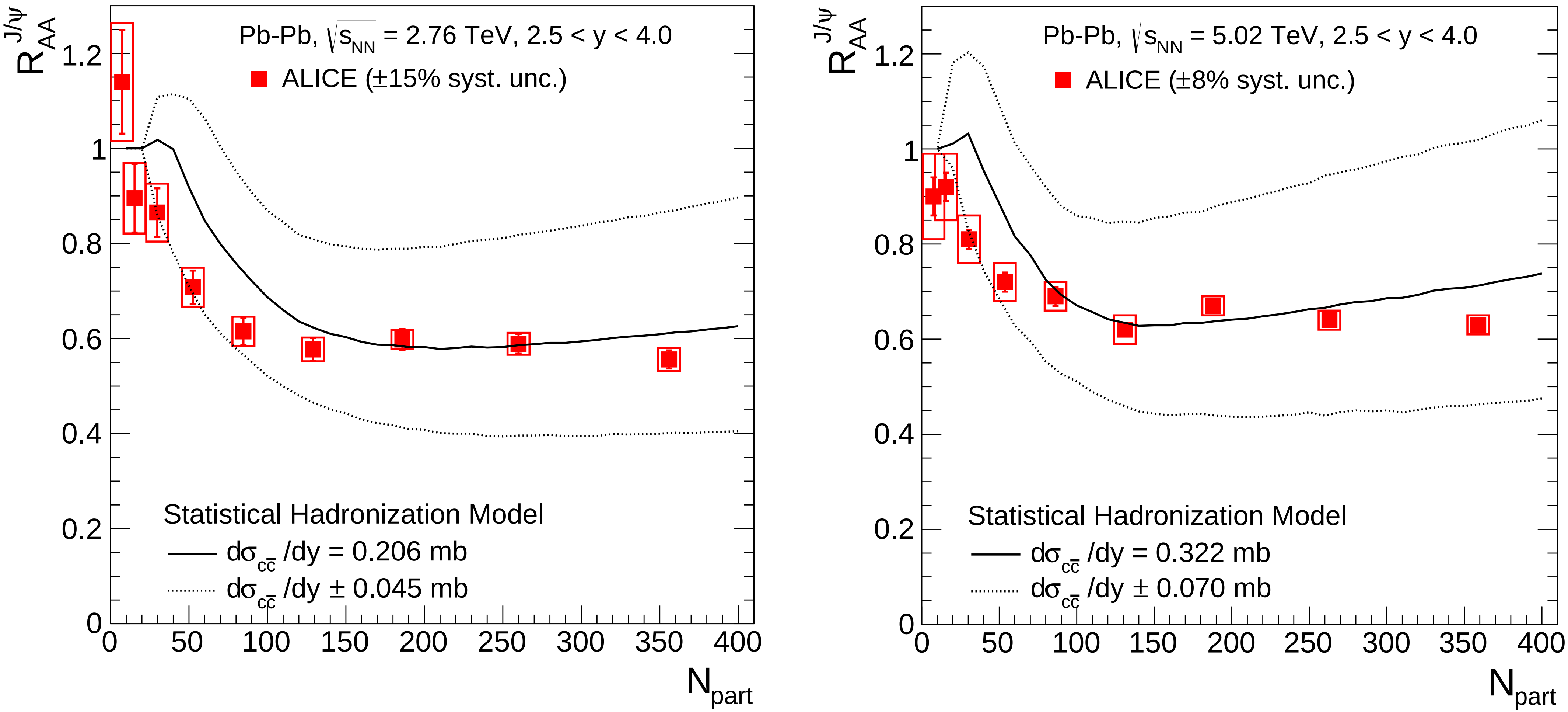

the generic prediction by the model is confirmed by data arXiv:1606.08197

establishes charmonium as a powerful new observable of the phase boundary

Charmonium in the statistical hadronization model

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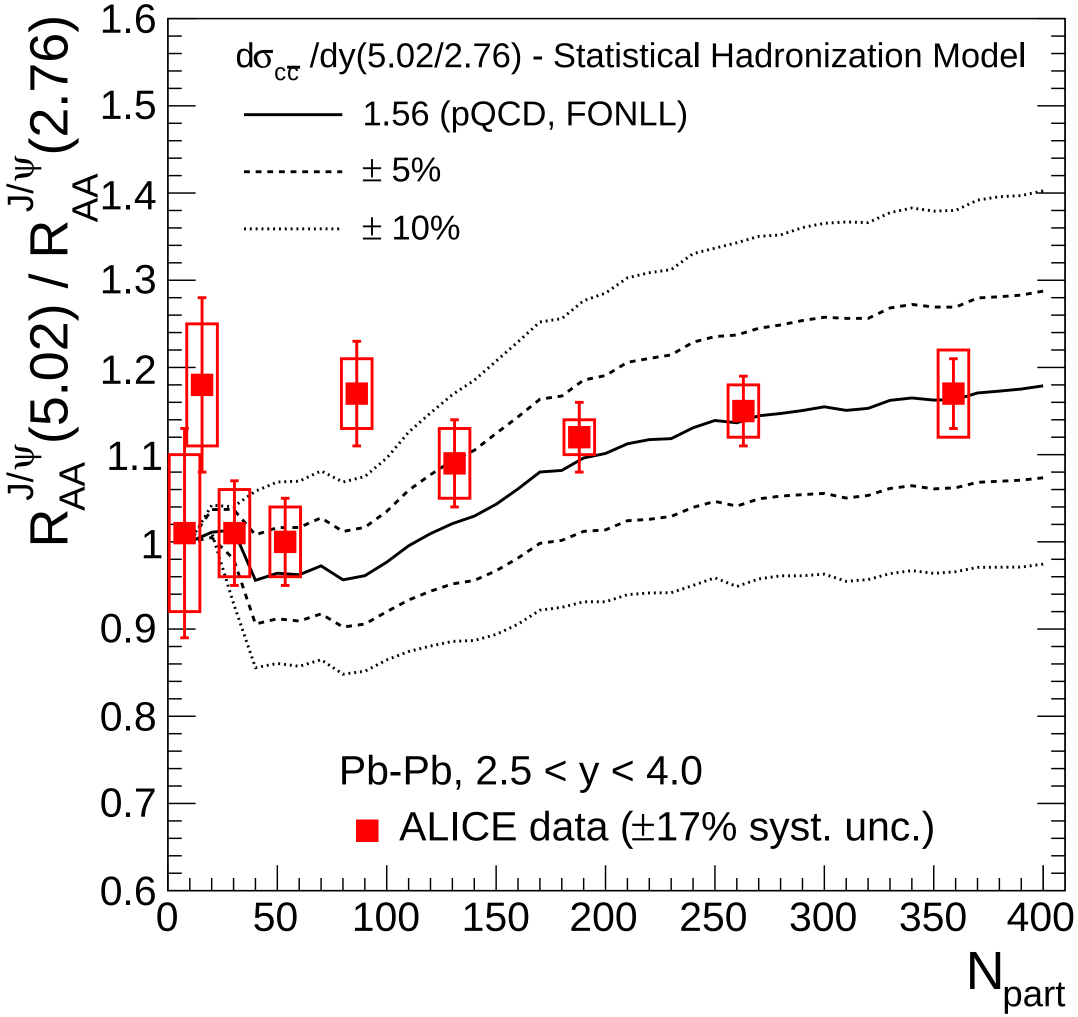
the model predicts absolute yields (R_{AA} is calculated with the pp reference as for data)



$2.5 < y < 4.0$

$\sigma_{c\bar{c}}$ from pp, $\sqrt{s}$=7 TeV, LHCb, NPB 871 (2013) 1

$p_T < 8\,GeV/c, 2.0 < y < 4.5$

$\sigma_{c\bar{c}} = 1419 \pm 12(stat) \pm 116(syst) \pm 65(frag)\,\mu$b

energy scaling via FONLL pQCD

shadowing calculations (R.Vogt): 0.71±0.10

$V_{\Delta y=1}$: 2.76 TeV: 4120 fm^3; 5.02 TeV: 5150 fm^3

Syst. uncert. of data apply fully-correlated to the model calculations

Charmonium and the phase boundary

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...an important connection, but not decissive (yet)

(recall that only $\sigma_{c\bar{c}}$ is a new parameter in the statistical model)

...as transport models describe data equally well (and predict $R_{AA}(p_T)$ and v_2)

see K. Zhou's talk on Monday
(NB: a larger $\sigma_{c\bar{c}}$ value is used in transport models)

is there a way to make the distinction?

$\psi(2S)$ production

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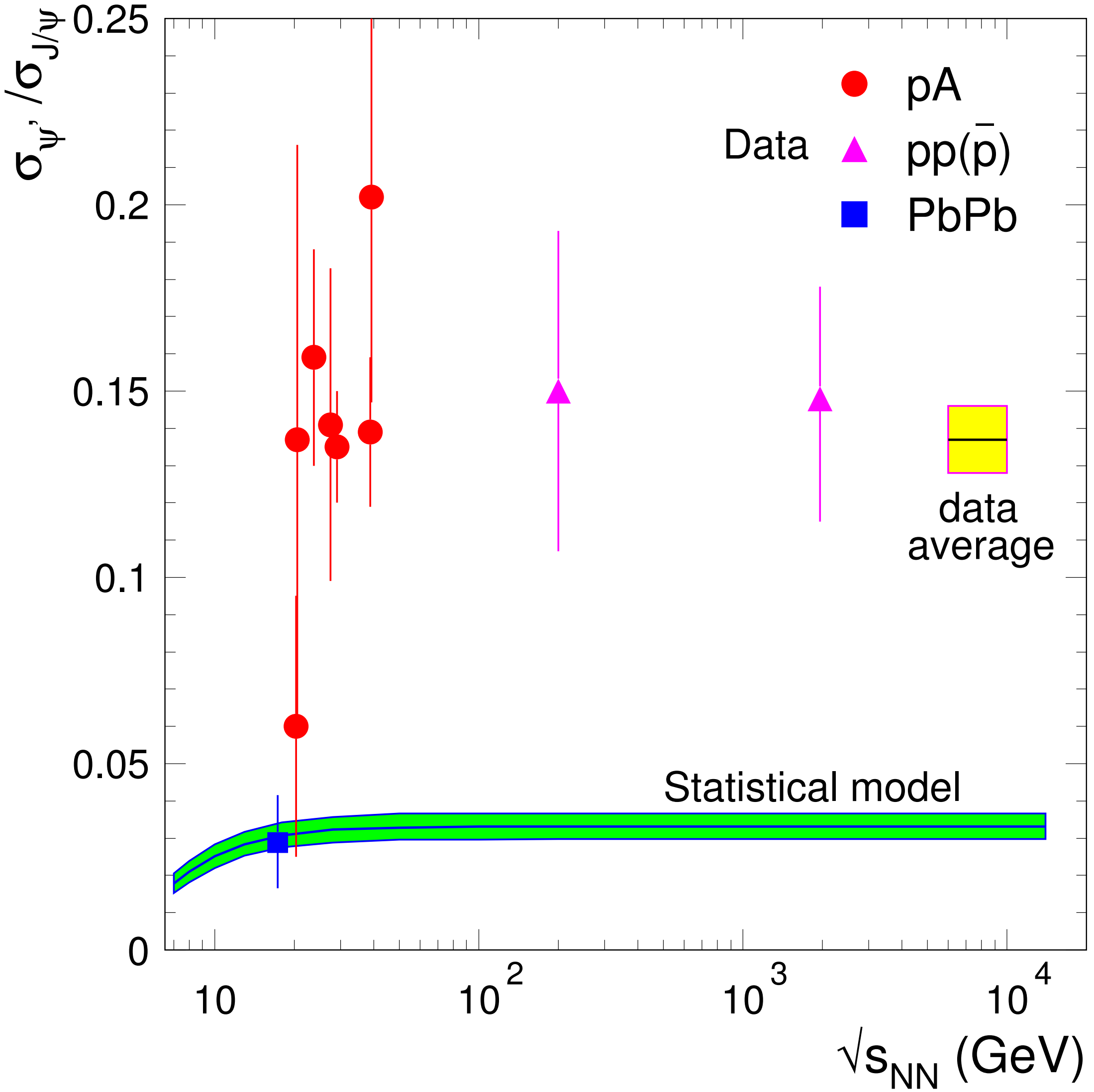


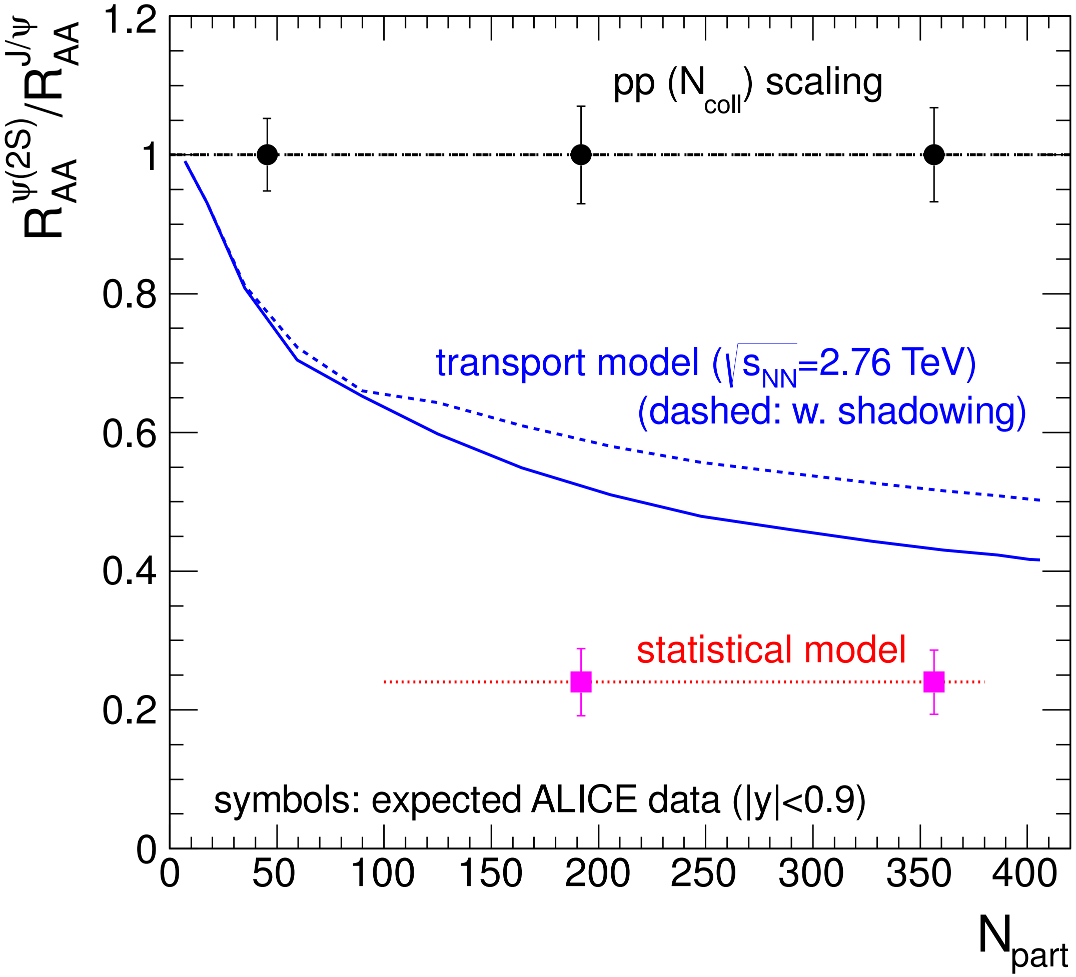
AA et al., PLB 678 (2009) 350 (see also NPA 789 (2007) 334)

The weight of the $\psi(2S)$ measurement

$R < 1$ expected in both models, different magnitudes predicted ($p_{\rm T}$-integrated)

Transport model:
Zhao, Rapp, NPA 859 (2011) 114
and priv. comm.

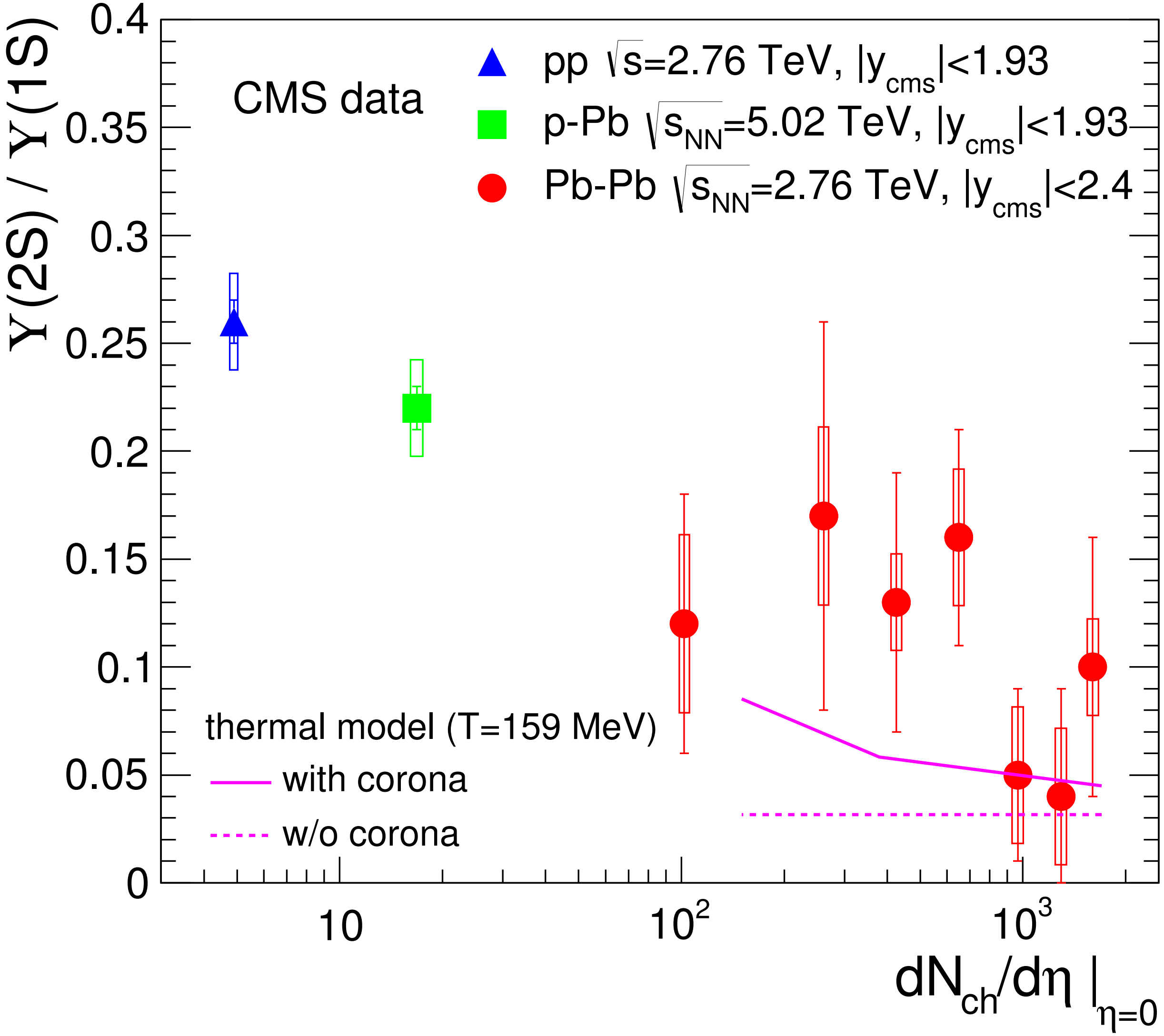
see Du, Rapp, arXiv:1504.00670



Central Barrel: measurement possible only with upgrade (10 nb^{-1})
Muon Spectrometer: a first glimpse with baseline data (1 nb^{-1}), a real measurement only with upgraded ALICE

ALICE, JPG 41 (2014) 087001

Bottomonium at the LHC



The data approach the thermal limit for central Pb-Pb coll.

fair description by model

also for R_{AA} of $\Upsilon(1S)$

CMS, PRL 109 (2012) 222301

Summary

- abundance of hadrons with light quarks consistent with chemical equilibration

  there is a variety of approaches ... *a personal bias: the "minimal model"*

  a minimal set of parameters, means a well-constrained model

  the thermal model provides a simple way to access the QCD phase boundary

  ...at high energies (at low energies canonical suppression needs more care)

- (I think:) everybody agrees that we see (re)combination of charm quarks at the LHC

  ...a new observable for the QCD phase boundary (...maybe similar at RHIC)

- interesting (sequential?) "disappearance" pattern in the bottom (Υ) sector

  do bottom quarks also thermalize at the LHC? (at RHIC?)

  will Υ add more weight to the phase boundary?

Backup slides

LHC, Pb–Pb, 0-10% - 3 models

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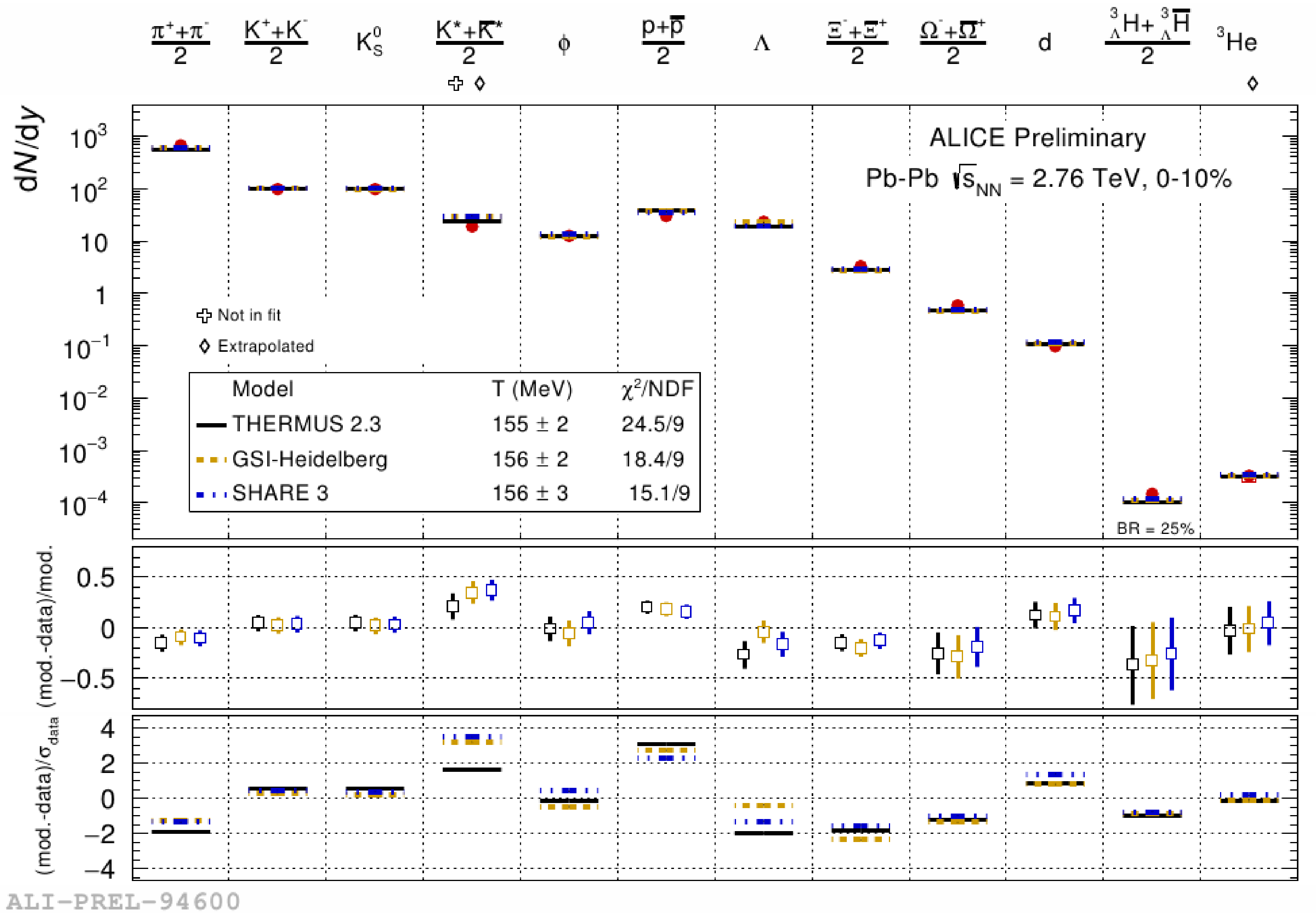

B. Guerzoni (ALICE), SQM 2015 (J. Phys.: Conf.Ser. 668 (2016) 012058)

LHC, Pb–Pb, 0-10% - ALICE data

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- $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, arXiv:1303.0737
- ϕ, arXiv:1404.0495
- K_s^0, Λ, arXiv:1307.5530

  $\bar{\Lambda}$ from S.Schuchmann, PhD Thesis, Goethe-University Frankfurt (July 2015)
- Ξ, Ω, arXiv:1307.5543
- d, ^{3}He, arXiv:1506.08951

  derive anti-particles from published ratios
- $^3_\Lambda$H, arXiv:1506.08453, assume B.R.=25%
- $^4\bar{\mathrm{He}}$, *preliminary*

Volume in central collisions

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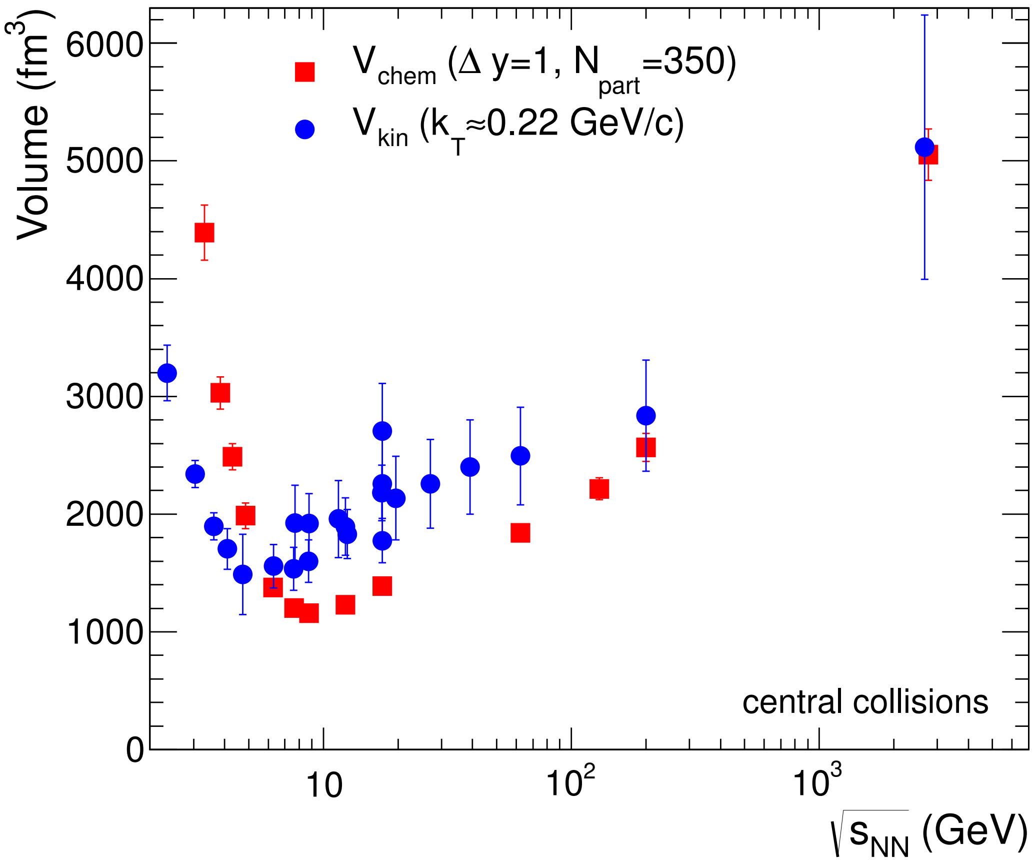

$$V_{chem}^{\Delta y=1} = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$

$$V_{kin} = V_{HBT} = (2\pi)^{3/2} R_{side}^2 R_{long}$$

HBT data: ALICE, PLB 696, 328 (2011)