Hadron production at chemical freeze-out and the QCD phase diagram from high-energy nucleus-nucleus collisions

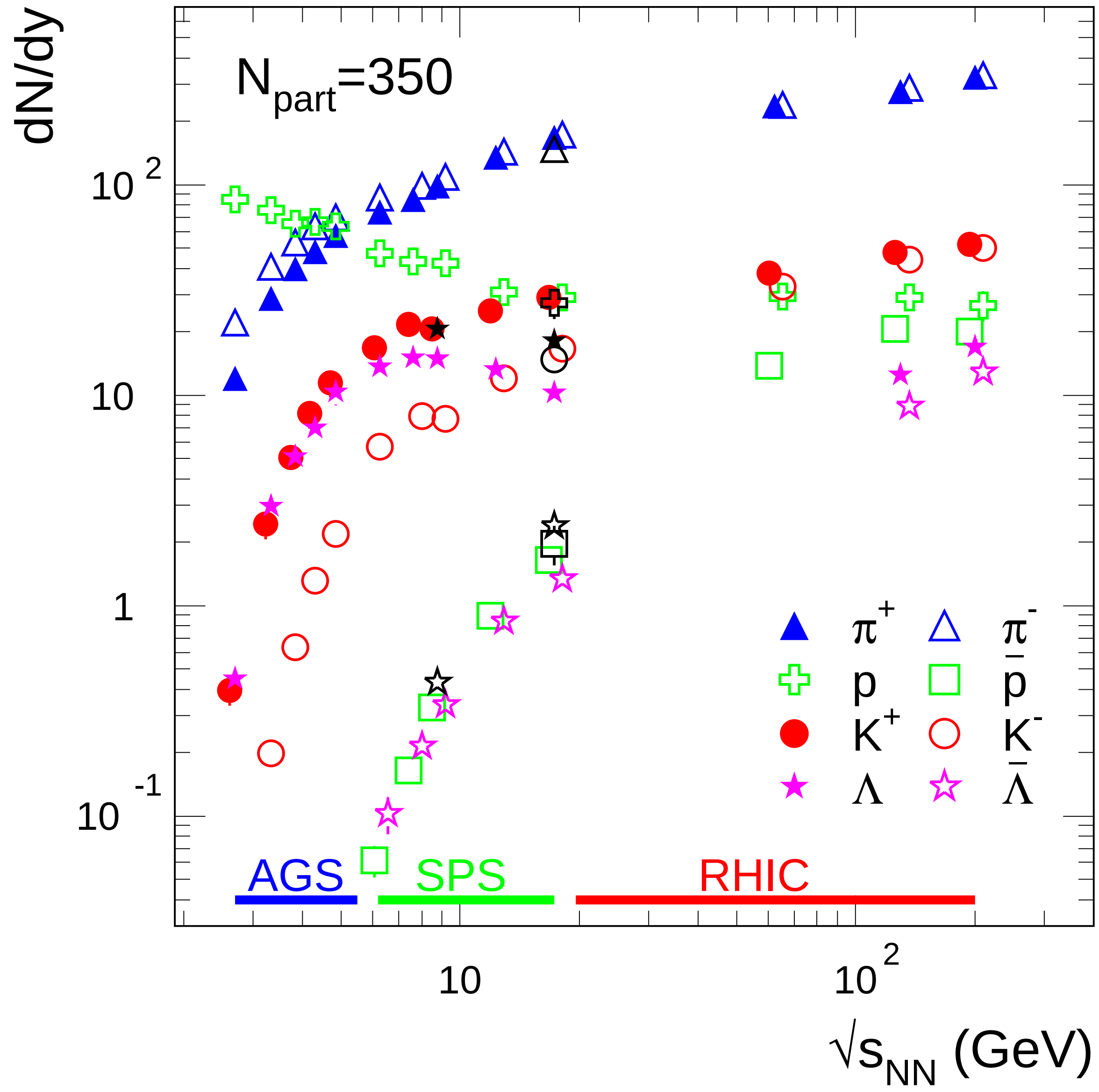
A.Andronic – GSI Darmstadt

- The thermal model in heavy-ion collisions
- Relevance for the QCD phase diagram
  [fits of abundances of light quark (u,d,s) hadrons]
- Charmonium in the statistical hadronization model
- Summary and outlook

AA, P. Braun-Munzinger, J. Stachel, PLB 673 (2009) 142

AA, P. Braun-Munzinger, K. Redlich, J. Stachel, PLB 678 (2009) 350

Hadron yields (at midrapidity, in central collisions)



- 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: $\Xi(dss)$, $\Omega(sss)$...

- mass hierarchy in production (u, d quarks: remnants from the incoming nuclei)

A.Andronic@GSI.de

The thermal model

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:

i) baryon number: $V \sum_i n_i B_i = N_B$

ii) isospin: $V \sum_i n_i I_{3i} = I_3^{tot}$

iii) strangeness: $V \sum_i n_i S_i = 0$

iv) charm: $V \sum_i n_i C_i = 0$.

Widths of resonances taken into account

Short-range repulsive core modelled via excluded volume correction (Rischke)

(leads to an overall 10-20% decrease of densities; no effect on T)

The thermal model

...is in a way the simplest model

the analysis of hadron yields within the thermal model provides a “snapshot” of AA collision at chemical freeze-out
(the earliest in the collision timeline we can look with hadronic observables)

...but the devil is in the details ...one needs:

- a complete hadron spectrum
- canonical approach at low energies (and smaller systems)
- to understand the data well (control fractions from weak decays)

A.Andronic@GSI.de

The hadron mass spectrum as of 2008

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

relative increase of calculated densities with mass spectrum 2008/2005 ↓

Additions (compared to 2005):

Many new resonances up to 3 GeV

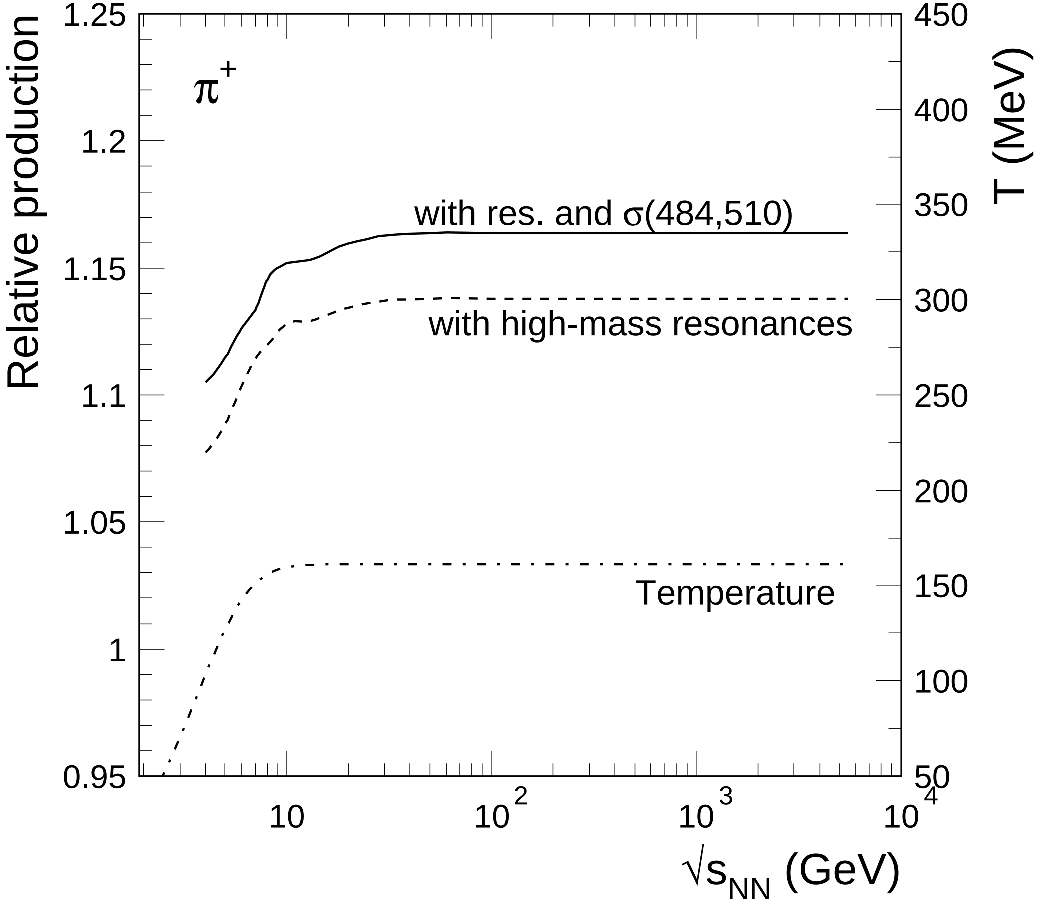
+(86)4 (non)strange mesons

+(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, including composites (t, He, hypernuclei)

vacuum masses

Strangeness suppression factor, γ_s

...a non-thermal fit parameter, to check possible non-thermal production of strangeness

for a hadron carrying "absolute" strangeness $s = |S - \bar{S}|$: $n_i \rightarrow n_i \gamma_s^s$

Examples: $K^{\pm}$ $(u\bar{s}, \bar{u}s)$: $n_K \gamma_s$, Λ (uds): $n_\Lambda \gamma_s$,

$\Xi(dss)$: $n_\Xi \gamma_s^2$, $\Omega(sss)$: $n_\Omega \gamma_s^3$, $\phi(s\bar{s})$: $n_\phi \gamma_s^2$

in principle, usage of γ_S is to be avoided if one tests the basic thermal model

even as some models employ it ($\Rightarrow \gamma_s = 0.6 - 0.8$), all agree that it is not needed at RHIC energies (for central collisions)

here (central AA collisions) we fix γ_s=1

A.Andronic@GSI.de

The thermal fits

$$n_i = \frac{g_i}{2\pi^2}\frac{1}{N_{BW}}\int_{M_{thr}}^{\infty} \mathrm{d}m \int_0^{\infty} \frac{\Gamma_i^2}{(m-m_i)^2+\Gamma_i^2/4}\cdot\frac{p^2\mathrm{d}p}{\exp[(E_i^m-\mu_i)/T]\pm 1}$$

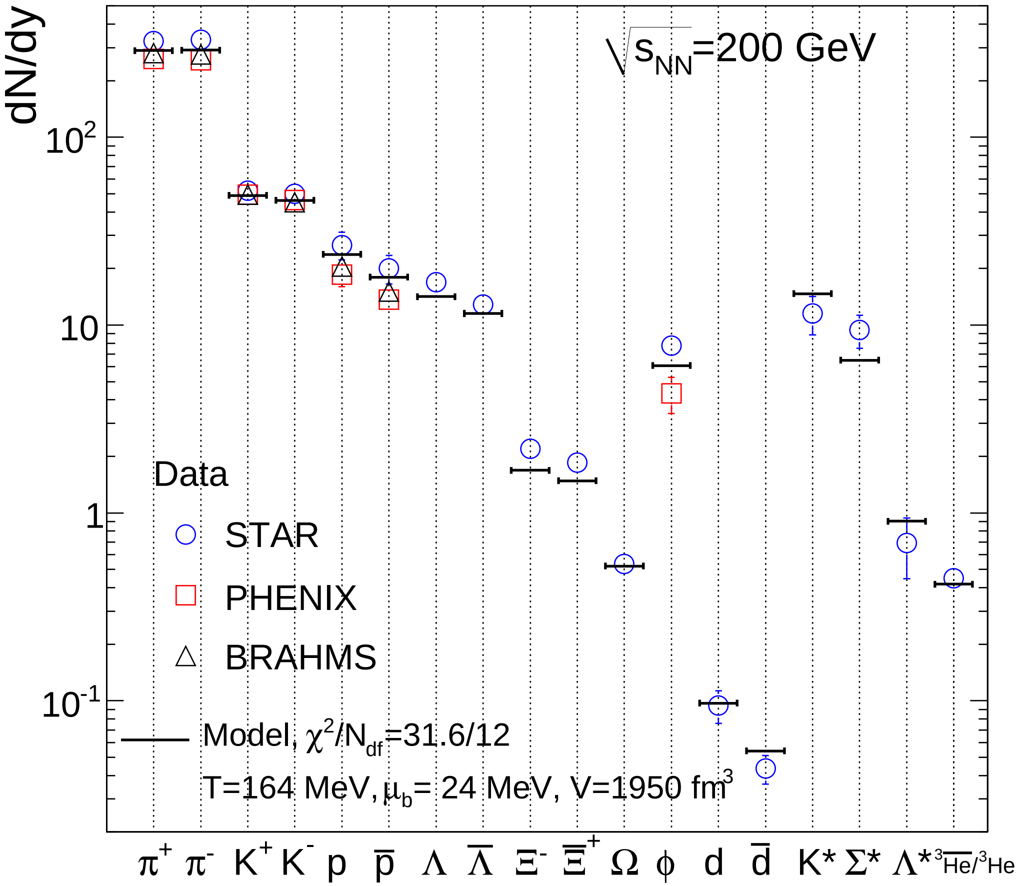
Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

N_i: hadron yield ($\Rightarrow T$, μ_b, V) or yield ratio (no V)

Data: 4π or $\mathrm{d}N/\mathrm{d}y$ (at y=0)

fit only STAR data: T=162 MeV, μ_b=24 MeV, V=2400 fm^3, χ^2/N_{df}=10.9/12

μ_{I_3}=-0.8 MeV; μ_S=6.6 MeV; μ_C=-3.5 MeV



The hadron abundances are in agreement with a thermally equilibrated system

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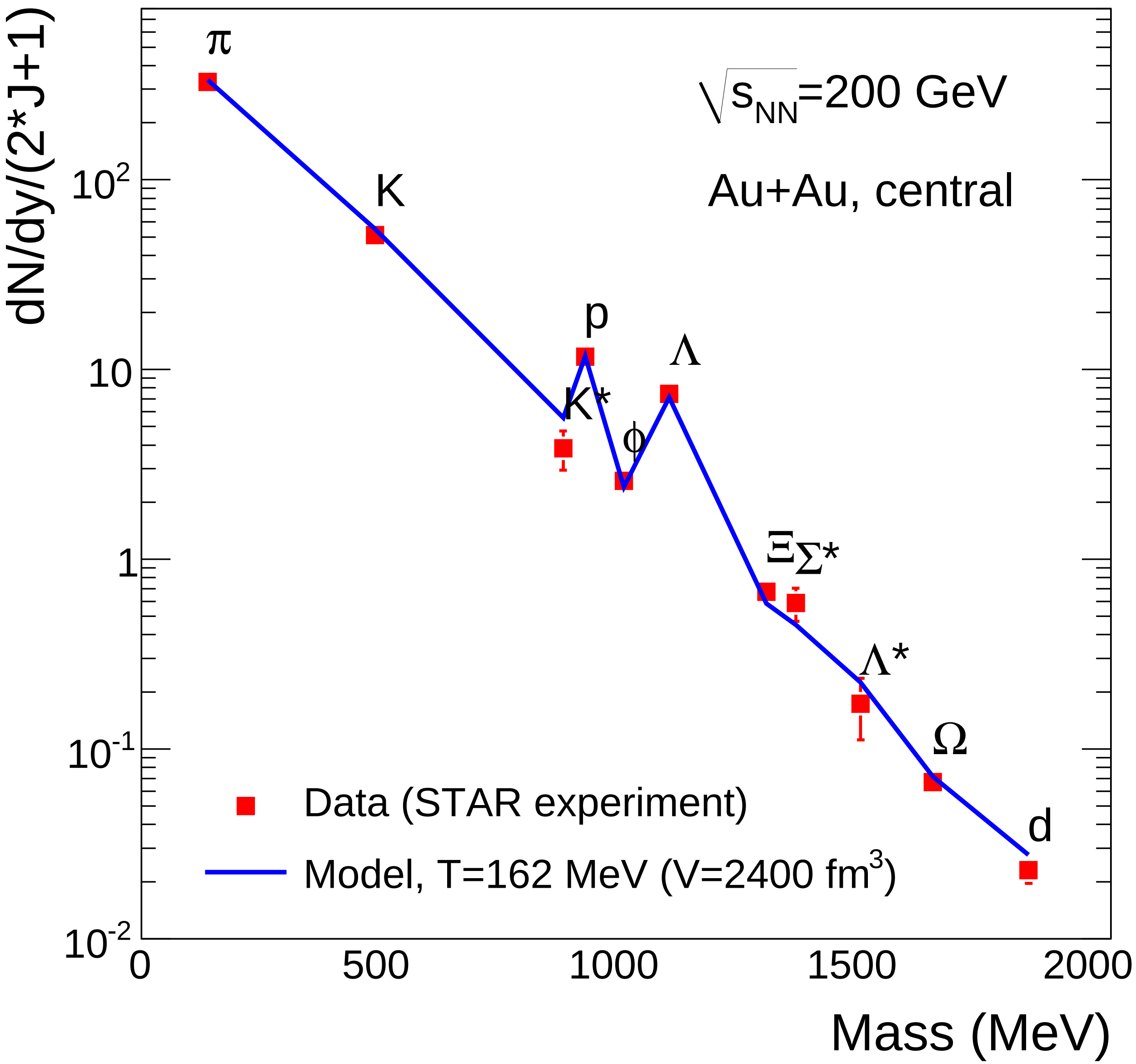
A thermal fit displayed differently



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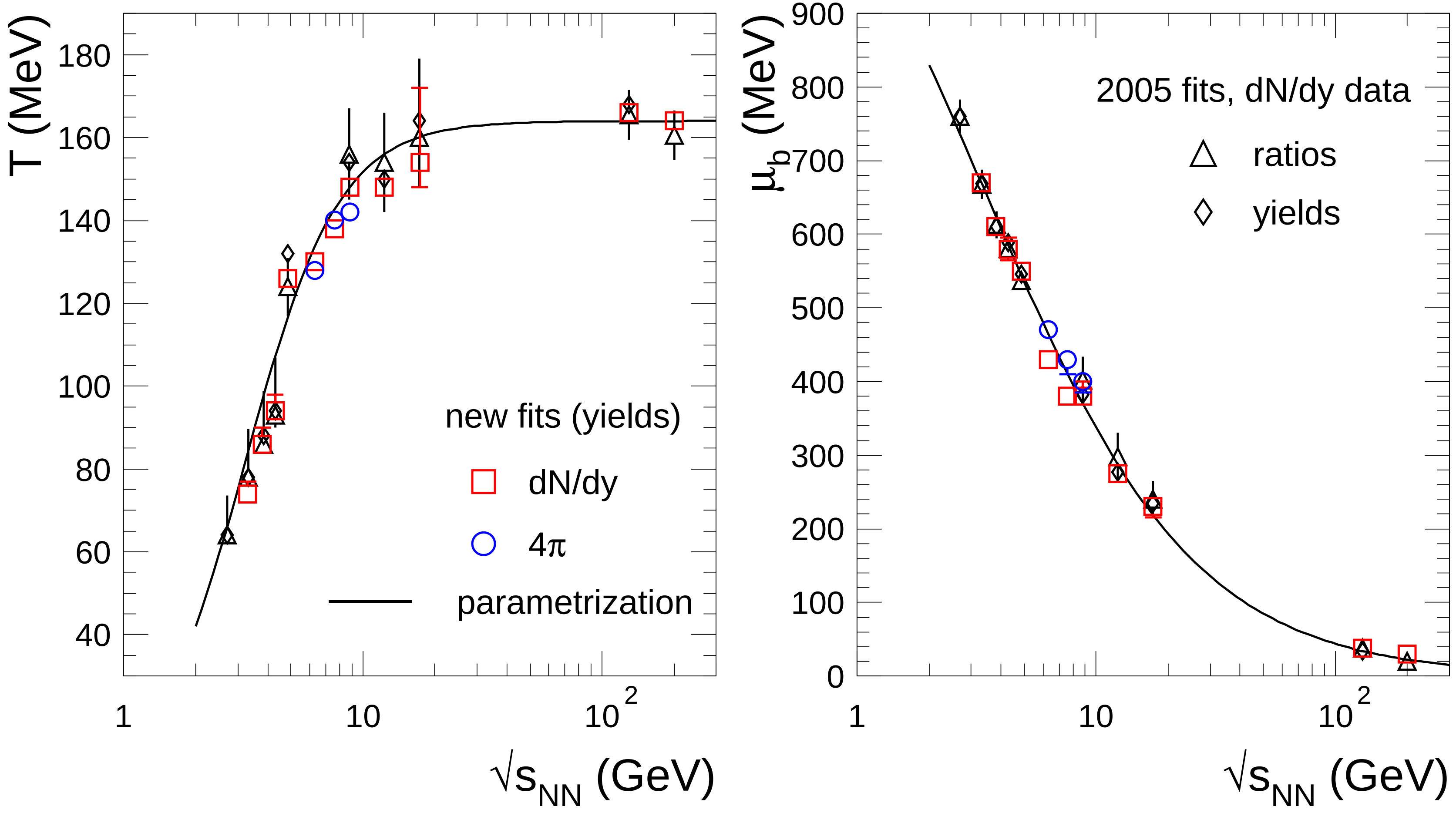
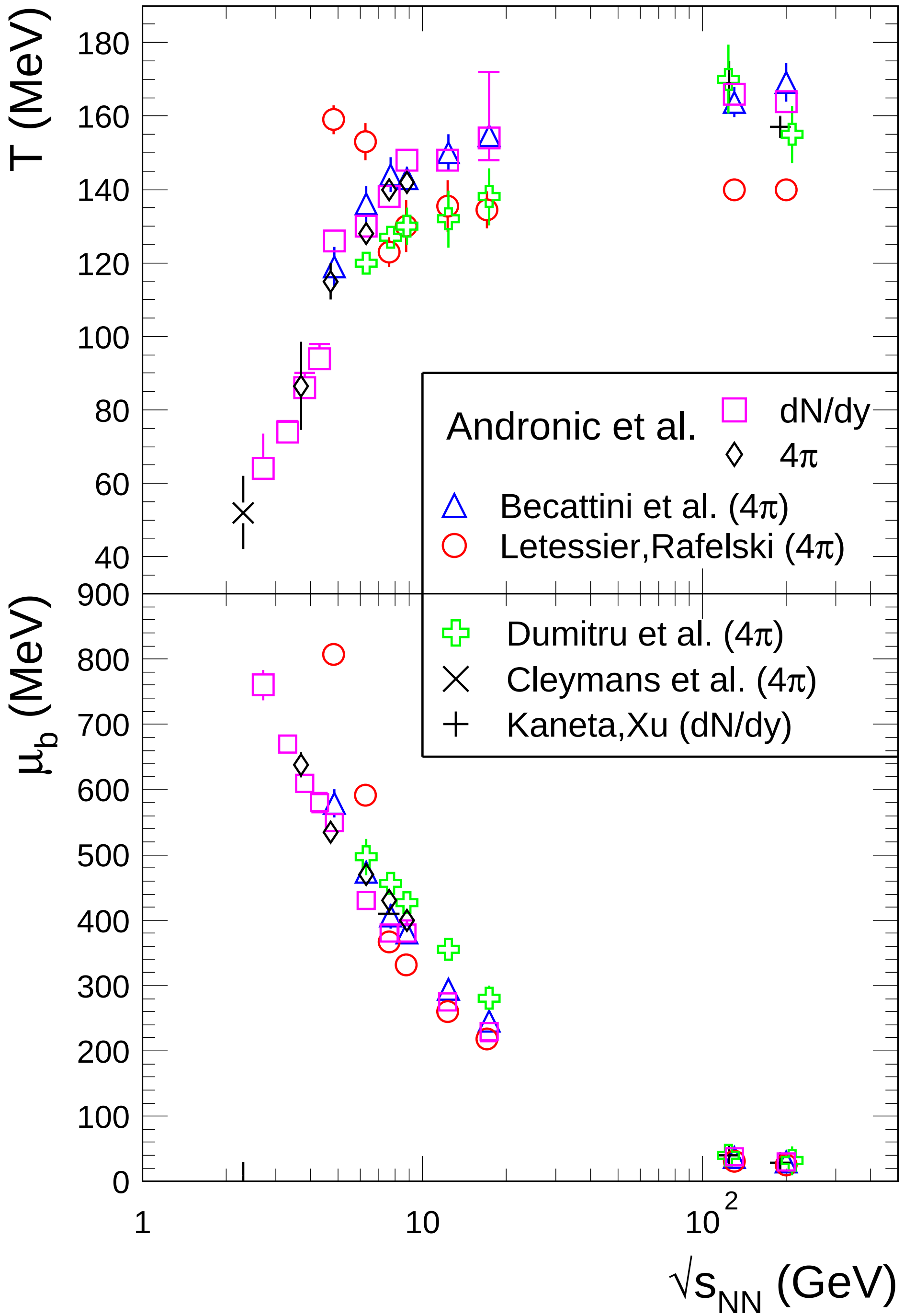
Energy dependence of T, μ_b



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

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

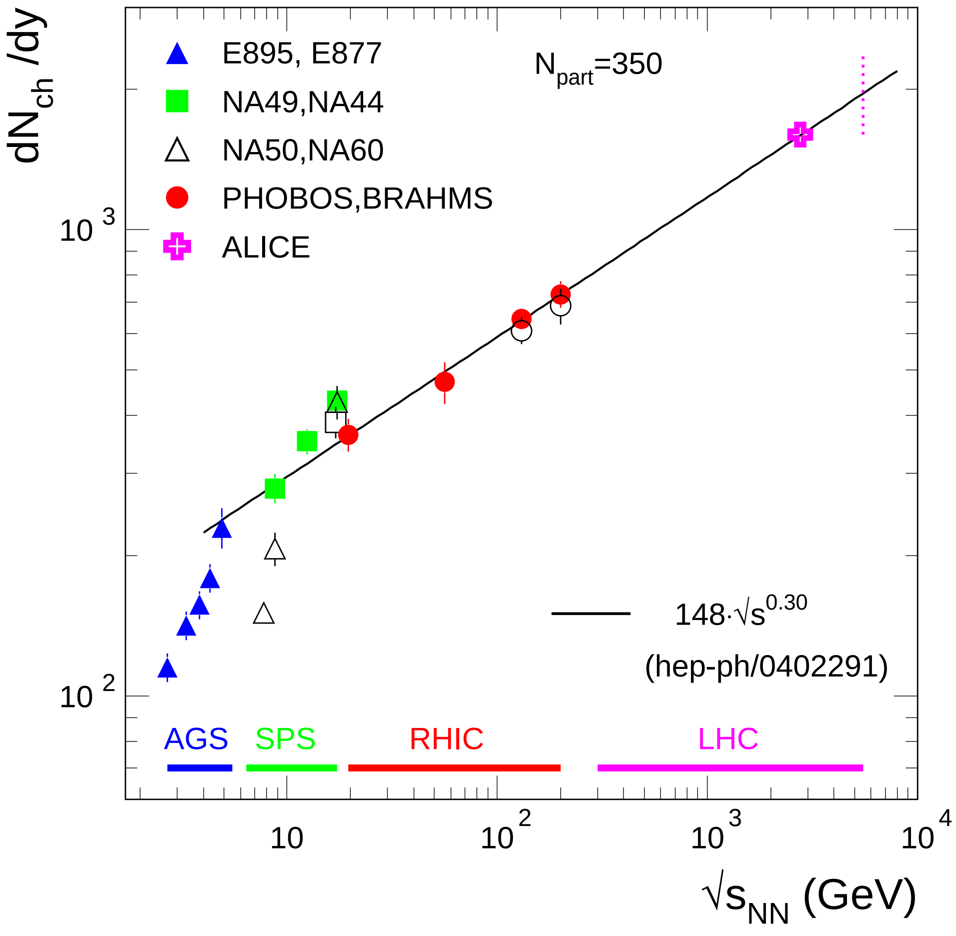
Energy dependence of the thermal parameters

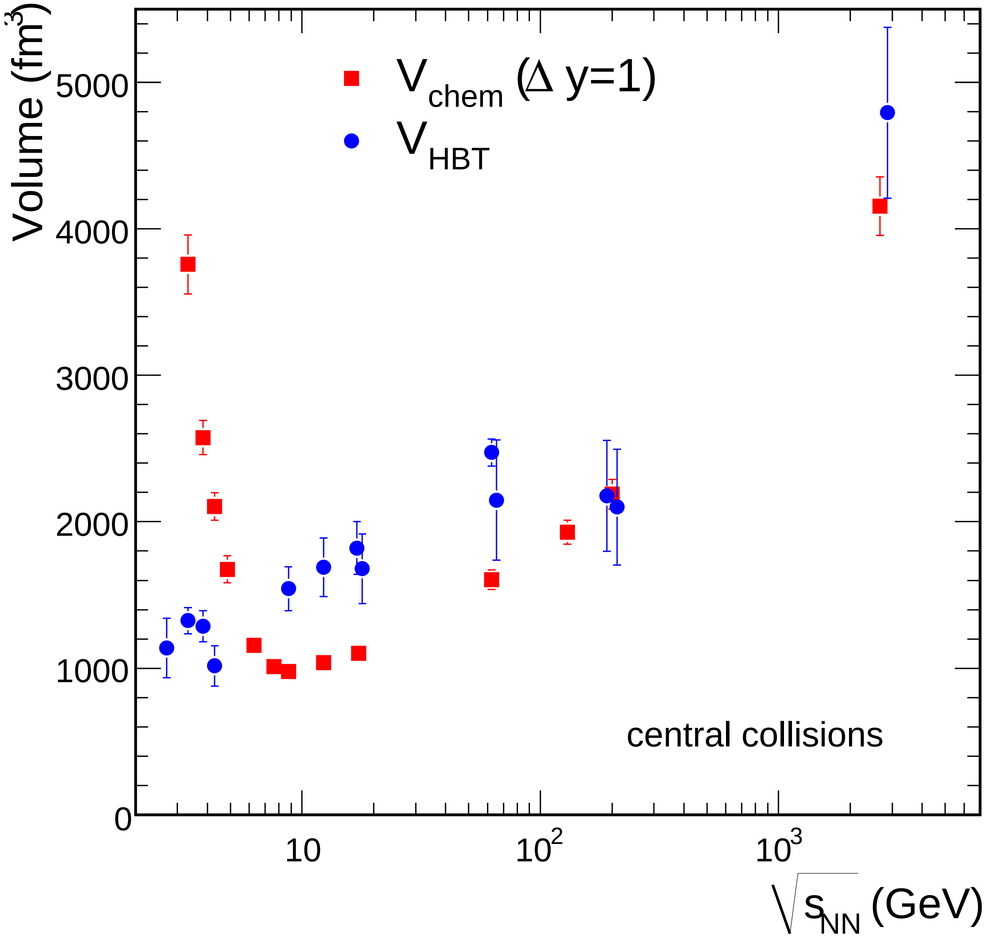


...a comparison of models

- Becattini et al.: $+\gamma_S$
  Phys. Rev. C 73 (2006) 044905
  Phys. Rev. C 78 (2008) 054901
- Rafelski et al.: $+\gamma_{S,q}$, λ_{q,S,I_3}
  Eur. Phys. J. A 35 (2008) 221
  γ_S=0.18,0.36,1.72,1.64,...
  γ_q=0.33,0.48,1.74,1.49,1.39,1.47...
- Dumitru et al.: inhomogeneous freeze-out (δT, $\delta\mu_B$)
  Phys. Rev. C 73 (2006) 024902
- Kaneta, Xu, nucl-th/0405068
- Cleymans et al., Phys. Rev. C 57 (1998) 3319

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)

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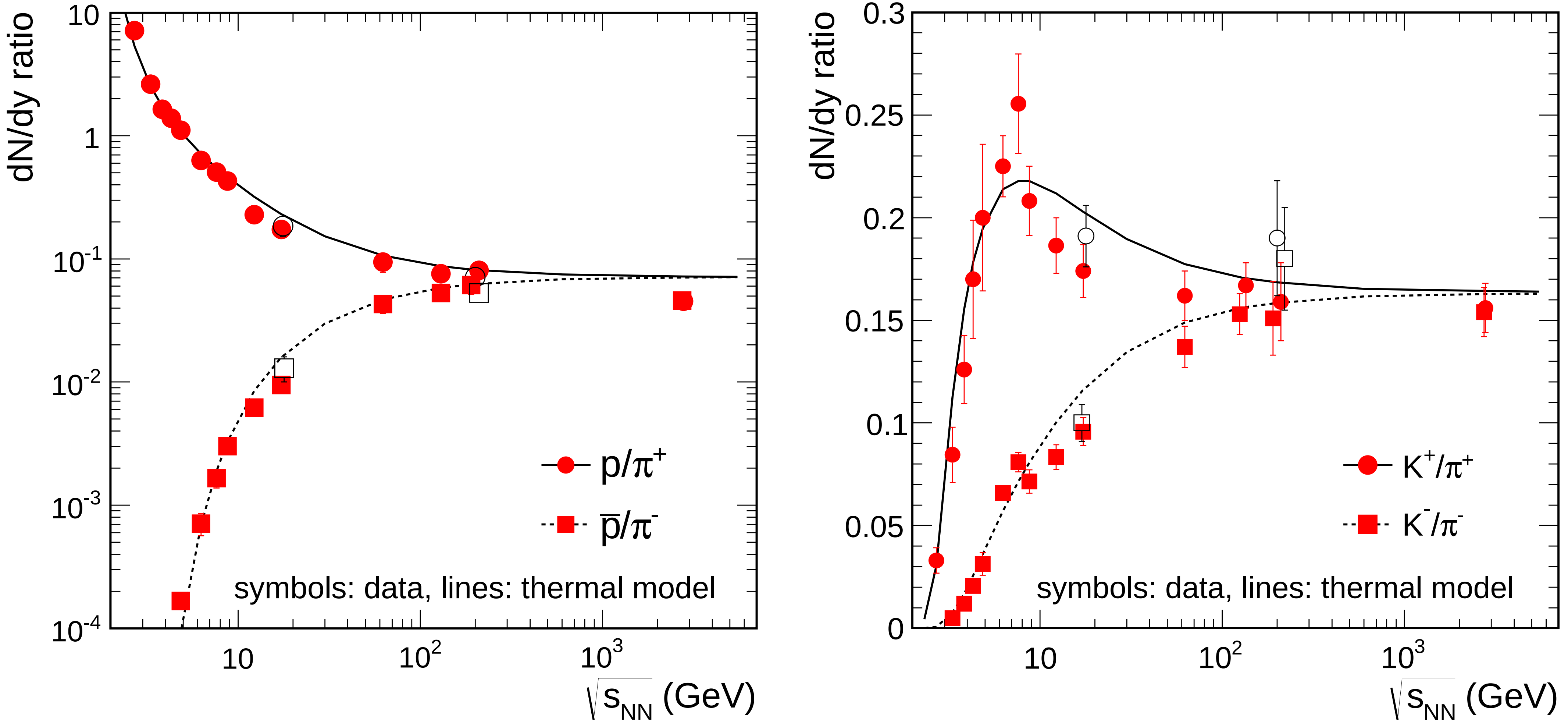
General features of (relative) hadron production



good agreement data-model ...but not free of some "tensions", NB: p/π @LHC

p,$\bar{p}$ data of STAR (62, 130, 200 GeV) ad-hoc "corrected" by -25% for feed-down

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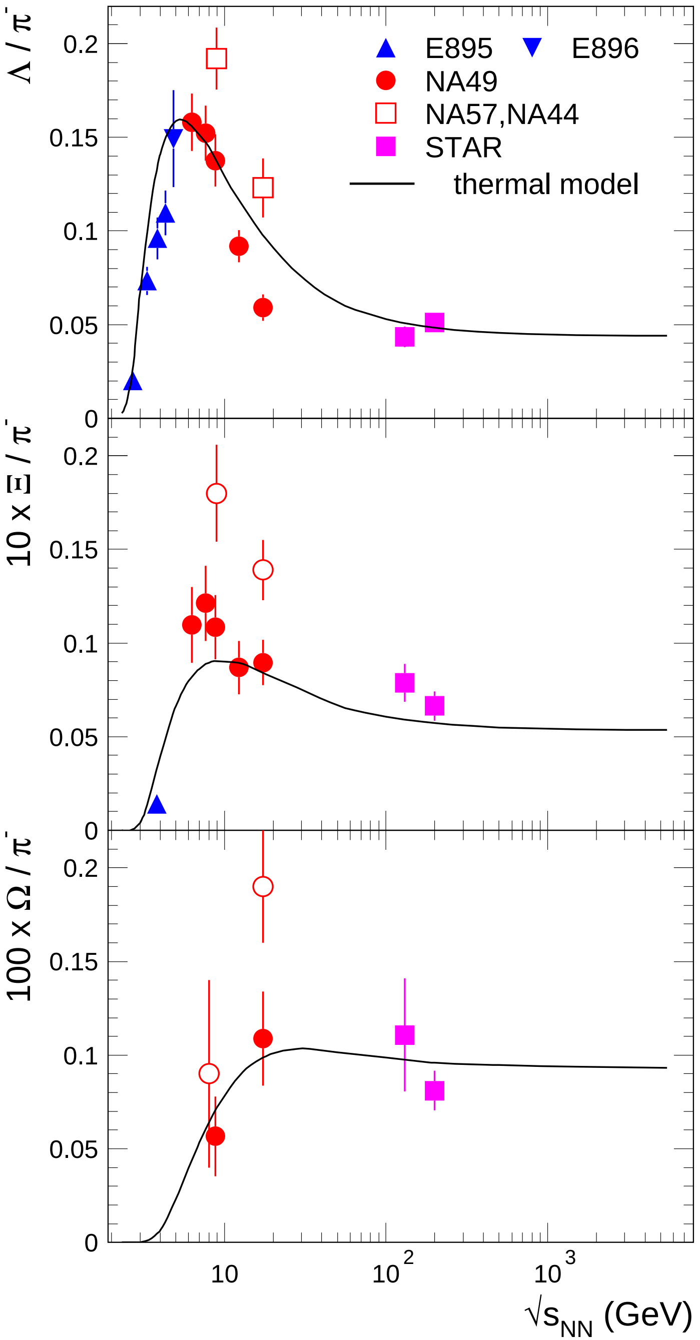
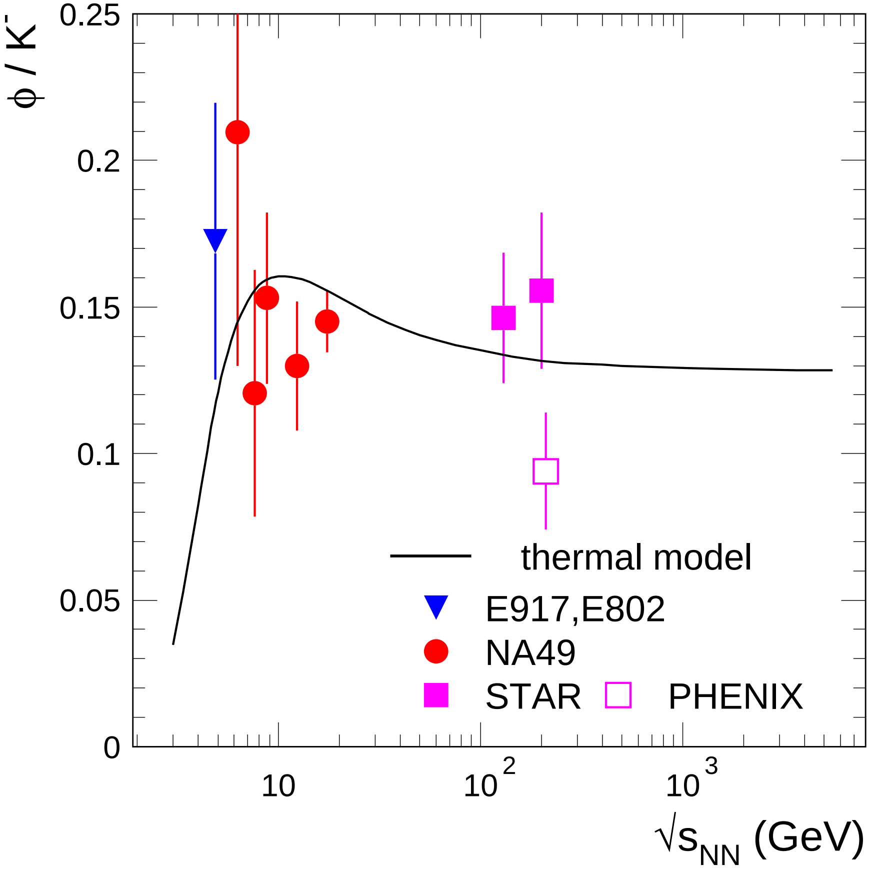
...and the state of other "horns"

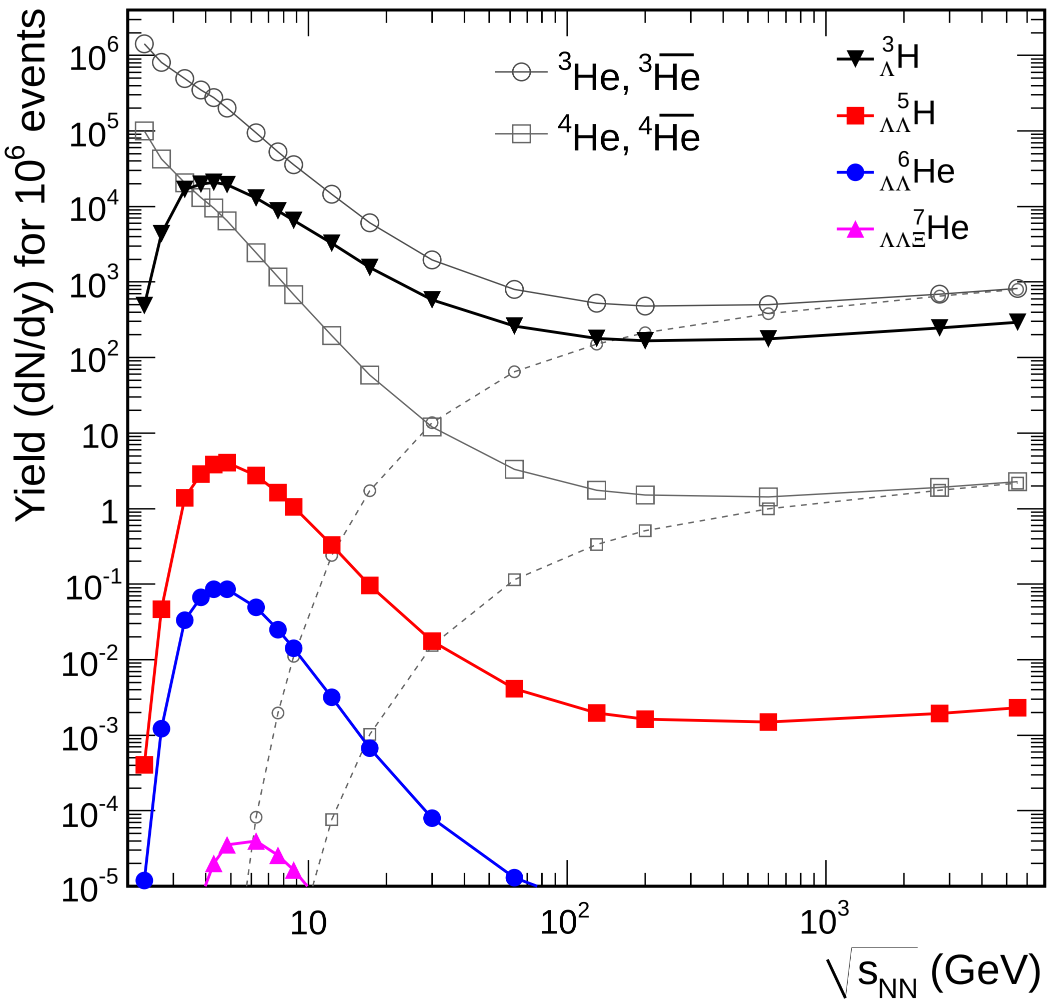




overall agreement model-data

Acta Phys. Pol. 40 (2009) 1005

Extending the mass range: (hyper-)nuclei predictions



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

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

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

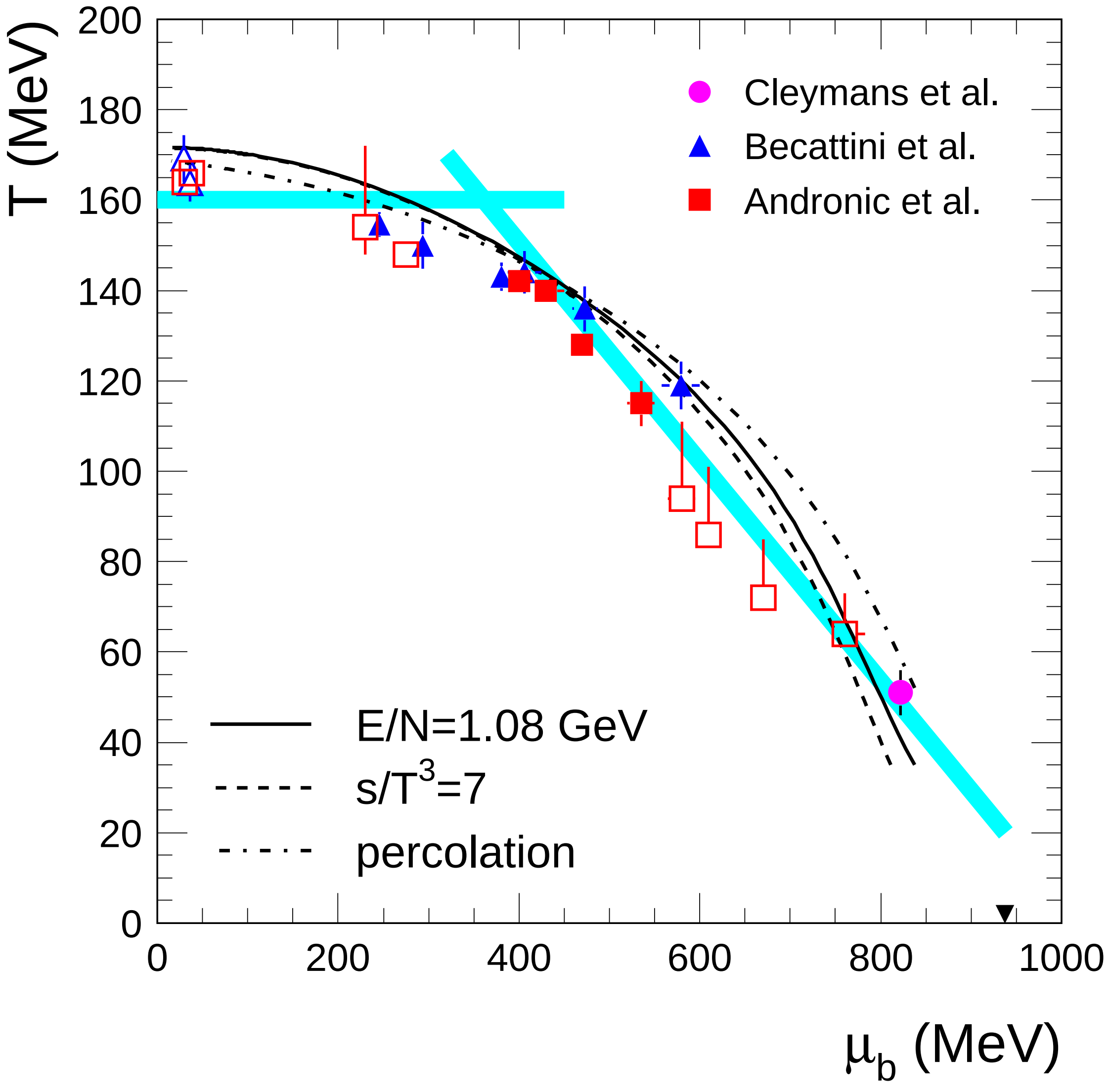
...discrepancy for $^3_\Lambda H/^3He$?

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

Phys.Lett.B697,203(2011)

A.Andronic@GSI.de

The phase diagram of QCD 1



is chemical freeze-out a determination of the phase boundary?
if yes, how is thermalization achieved?

- for low μ_b ($<\sim$300 MeV): driven by the deconfinement transition

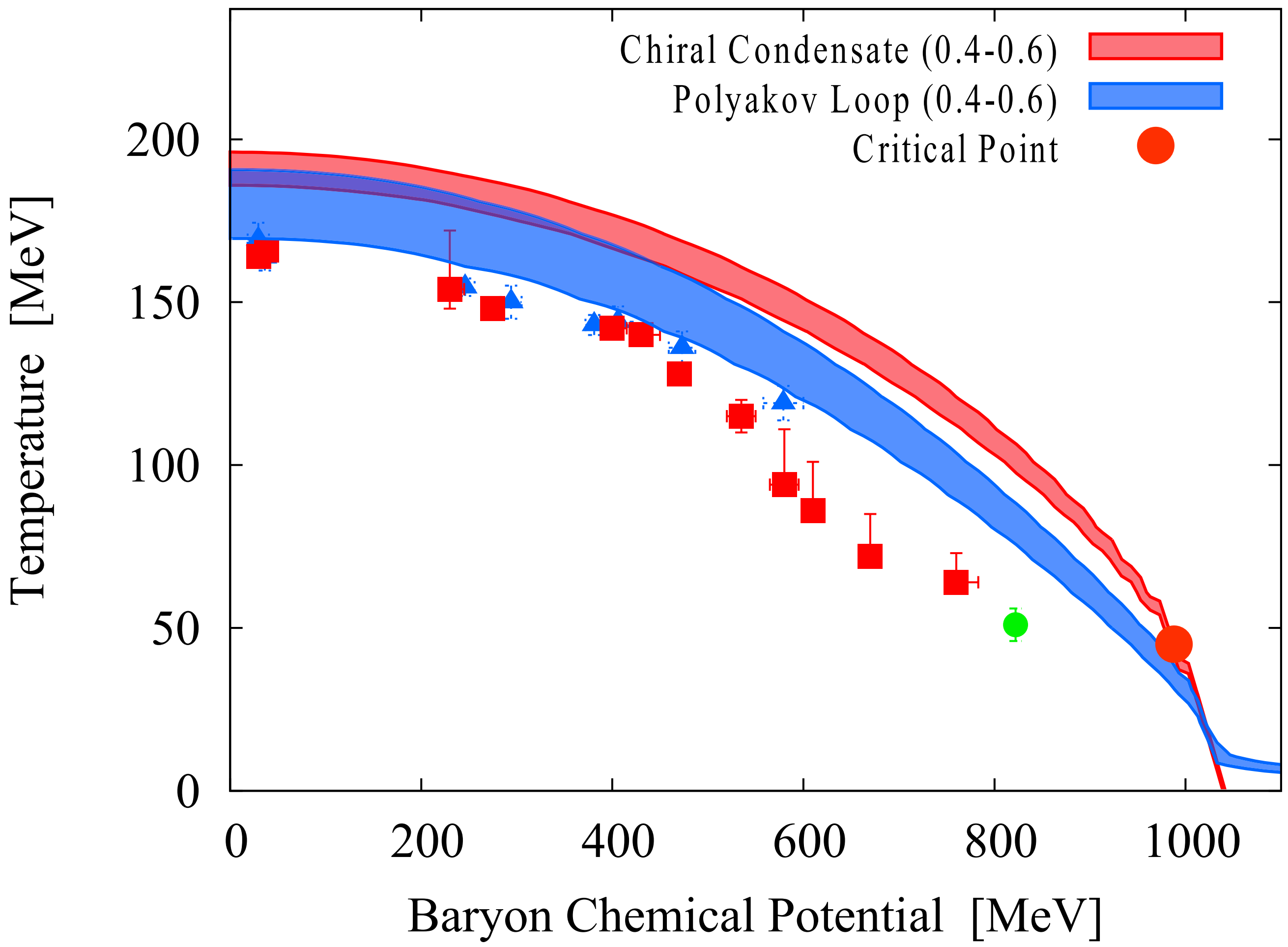
  PBM, Stachel, Wetterich, PLB 596 (2004) 61

- for high μ_b: is the quarkyonic phase transition the "thermalizer"?

  McLerran, Pisarski, NPA 796 (2007) 83

  AA et al., NPA 837 (2010) 65

The phase diagram of QCD 2



K. Fukushima, PLB 695, 387 (2011)

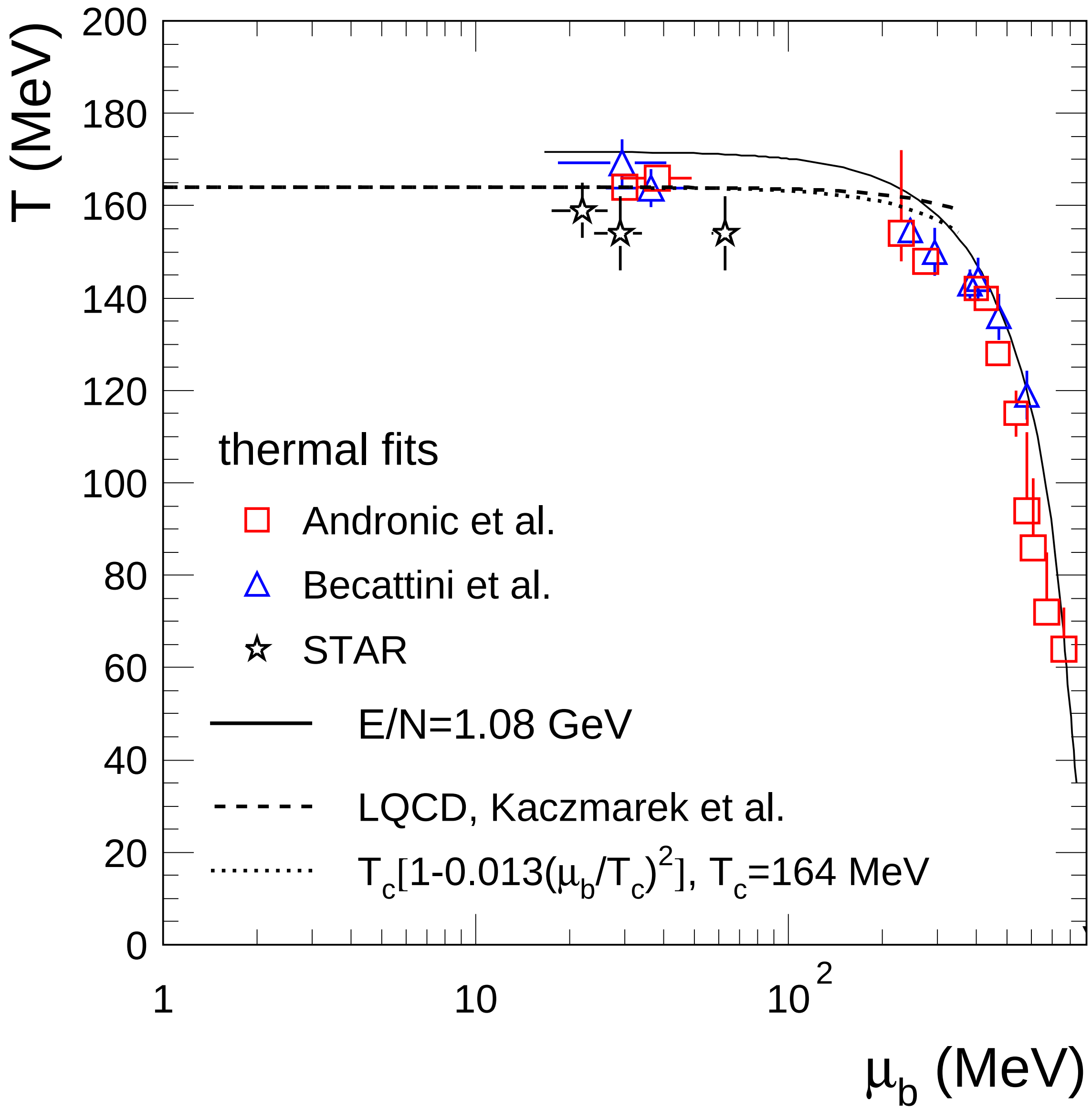
[PNJL, “forced” to agree with stat. model (for large μ_b)]

..but quarkyonic (confined and chirally-symmetric) may not exist

(justifies vacuum masses)

result predicted/confirmed by (RG) QCD approach; B.J. Schaefer, this meeting J.Pawlowski private comm.

The phase diagram of QCD 3



what will we find at LHC?

relevance for LQCD

$(\mu_s = \mu_{I_3} = 0)$

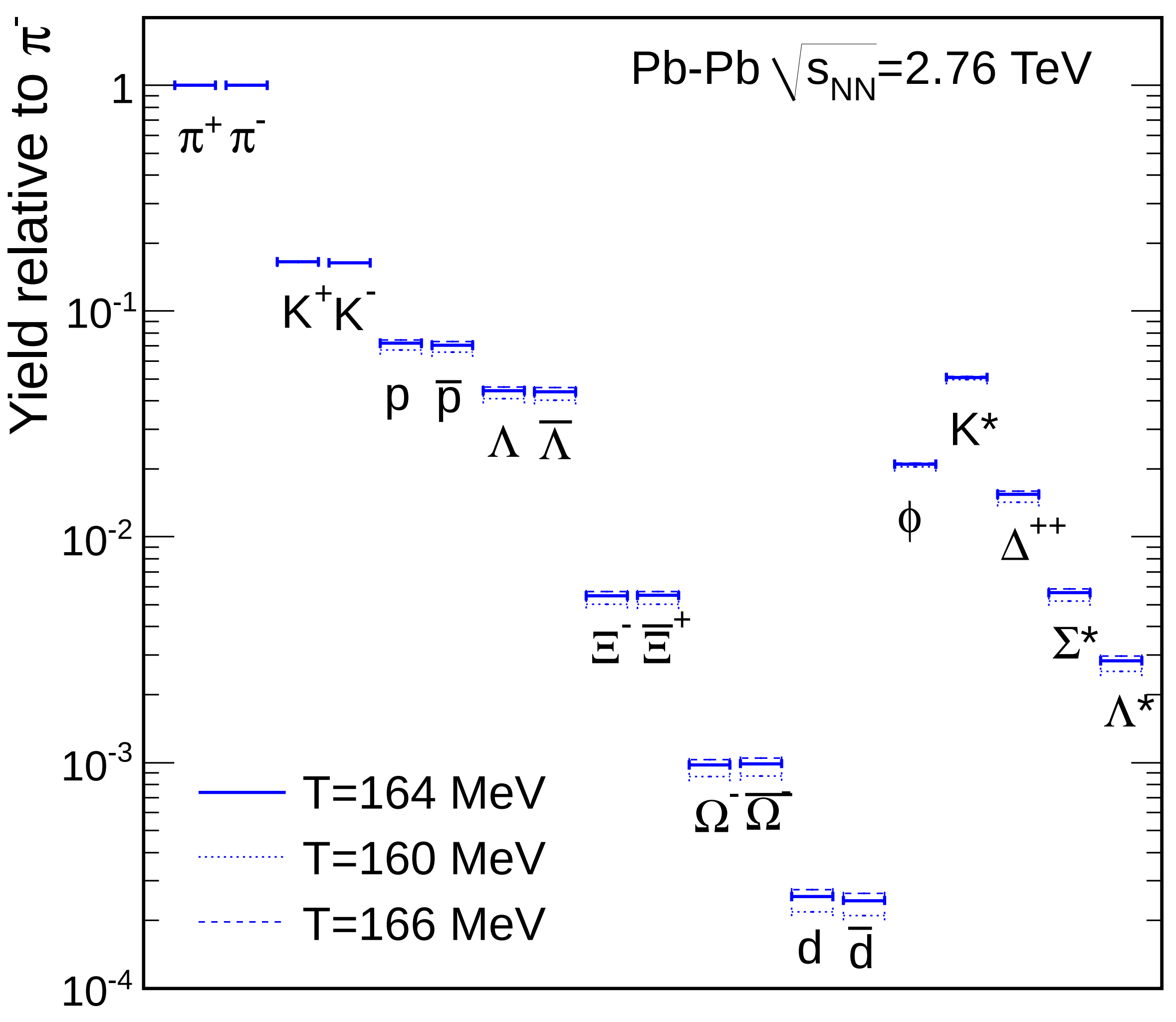
O. Kaczmarek et al., PRD 83, 014504 (2011)

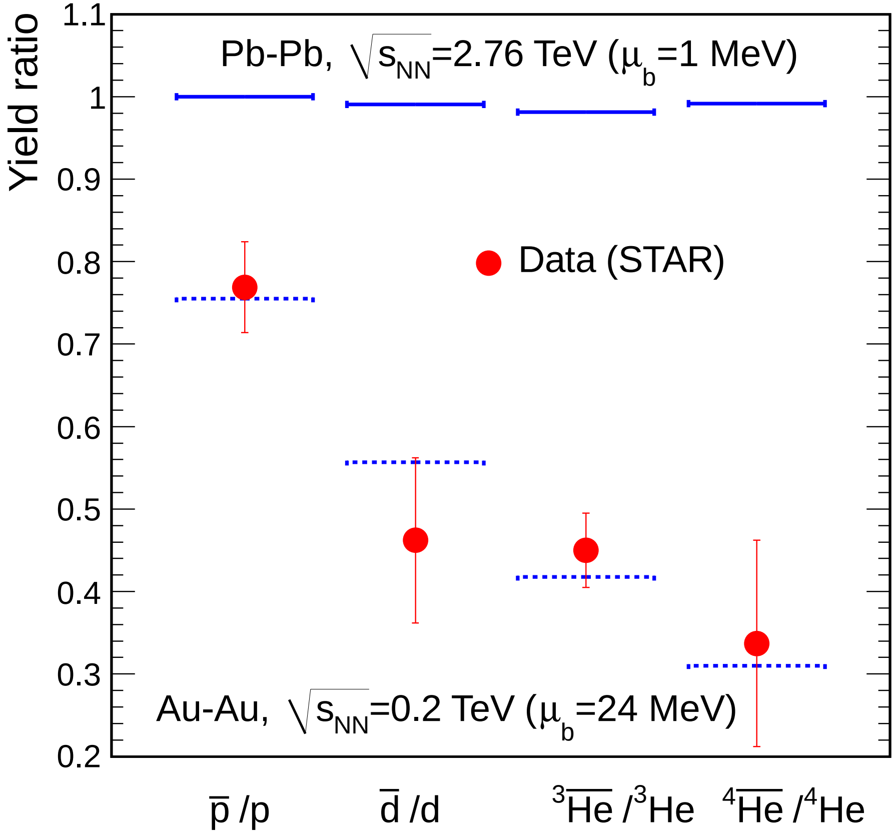
freeze-out points (but not curve, E/N=1.08 GeV) follow the (chiral or crossover) phase transition line ($T_c(\mu_q)/T_c(0) = 1 - 0.059(2)(4)(\mu_q/T)^2$, Kaczmarek et al.) at $\mu_b \neq 0$

[E/N: Cleymans, Redlich PRL 81, 5284 (1998)]

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

...and here are the predictions for LHC

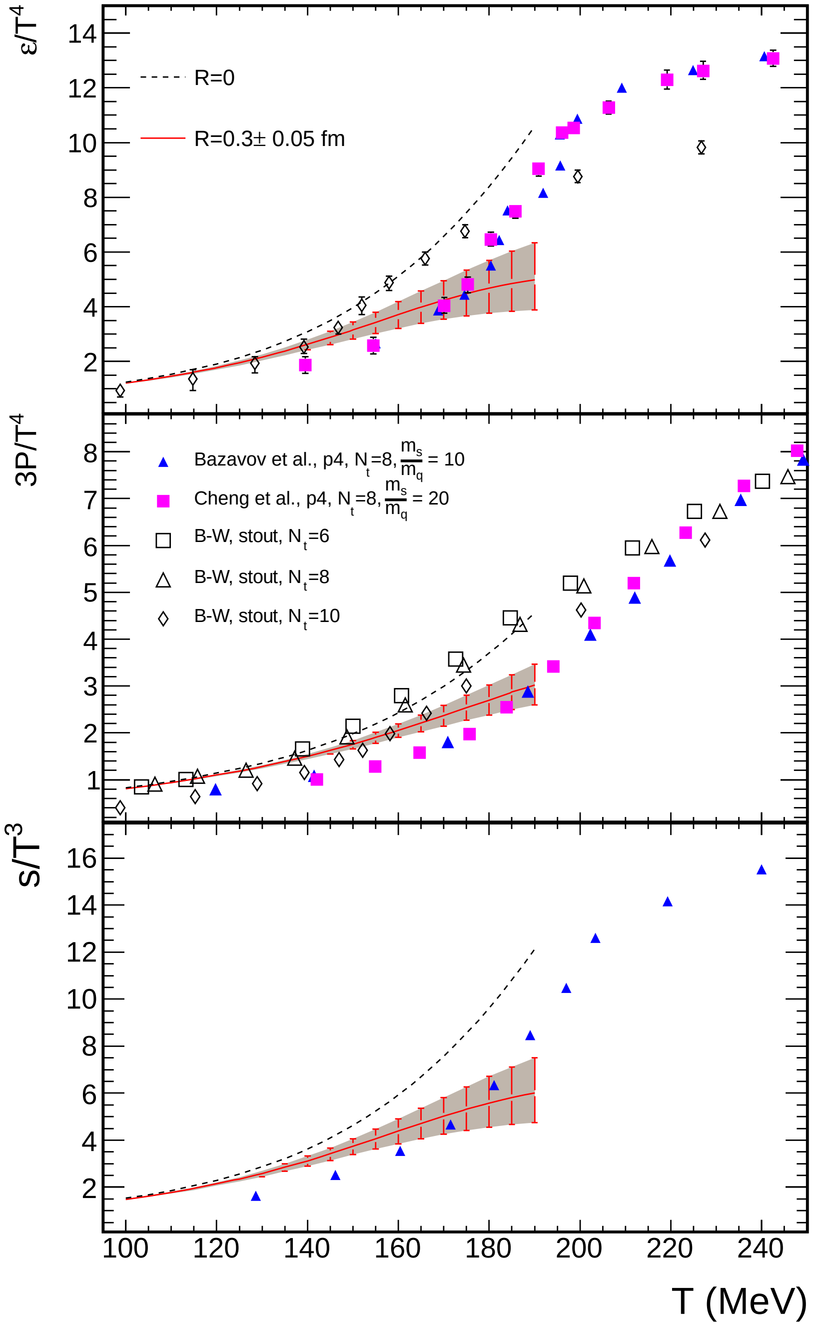




(T=164 MeV)

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

Importance of including interactions



- need to go beyond Dashen, Ma and Bernstein (dilute limit) when densities large enough (even below T_c)

- it is not only a “technical” correction (thermodynamic consistency fulfilled, free of acausal behavior)

  reference for Lattice QCD (for $T < T_c$)

  B-W: arXiv:1011.4229

  A. Bazavov et al., PRD 80 (2009) 014504

  M. Cheng et al., PRD 81 (2010) 054504

- NB: T_c is not $T_{Hagedorn}$

  ...but rather $T_c \simeq T_{lim}$

  ...$T_{Hagedorn}$ is no more

The end?

...not quite... we need something more

we need to look at hadrons for which the statistical model doesn't work in elementary (pp and e^+e^-) collisions

...because it works (albeit less well *and with extra parameters* than in AA) for the large majority of hadrons (and gives similar T)

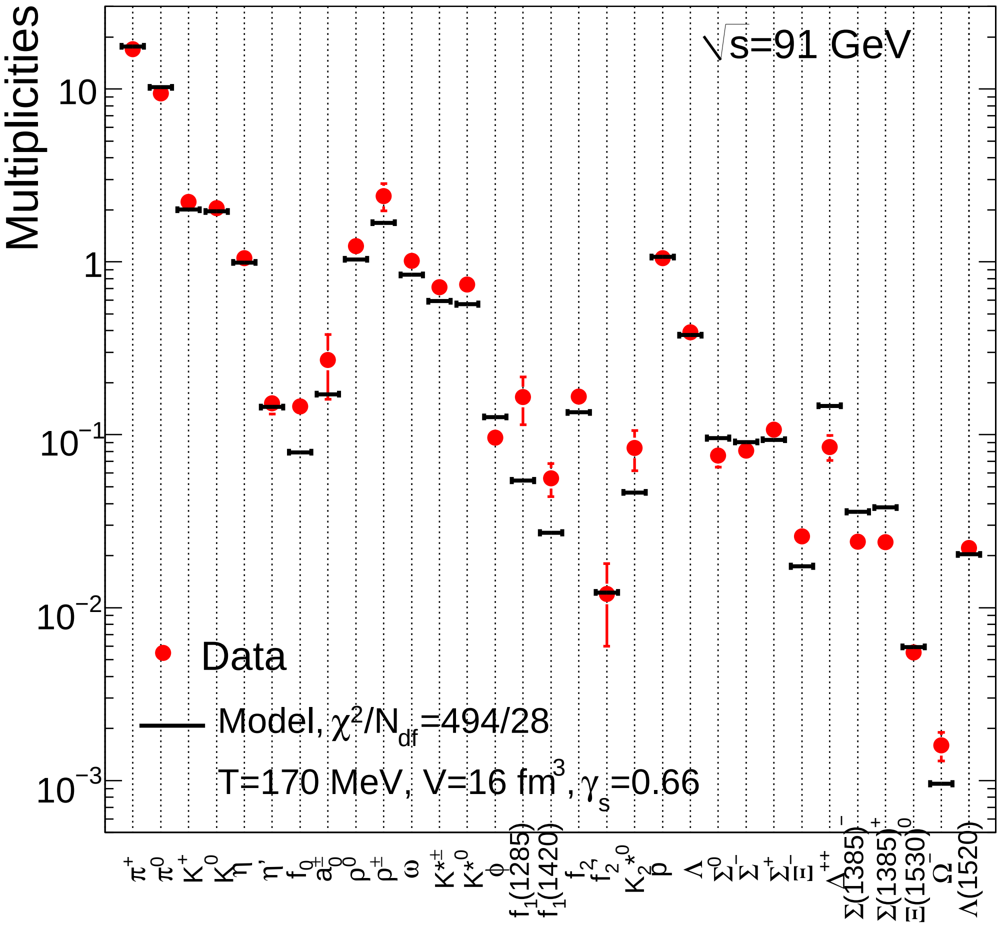
e^+e^- collisions (LEP) $\longrightarrow$

V - volume of 1 jet

mix of $q\bar{q}$ jets (EW) from data

(full canonical calc.)

PLB 675 (2009) 312, 678 (2009) 350



A.Andronic@GSI.de

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
- focus on J/ψ: ...can it survive above T$_c$? ...not settled yet (LQCD)

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

  we assume no J/ψ survival in QGP (full screening)
  in our model the full yield is from generation at the phase boundary

if this supported by data, J/ψ looses 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):

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

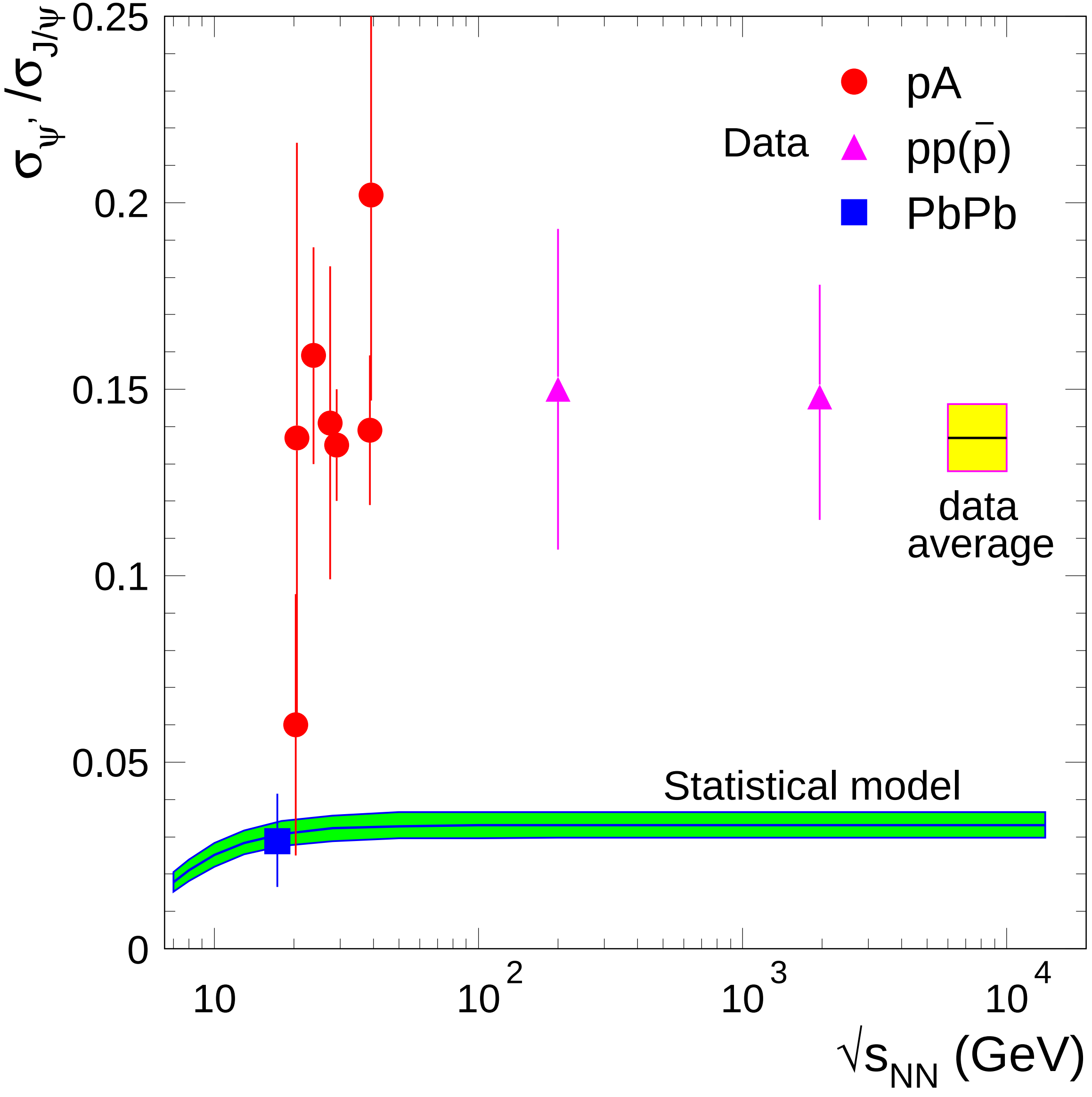
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

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

A.Andronic@GSI.de

The “null hypothesis”

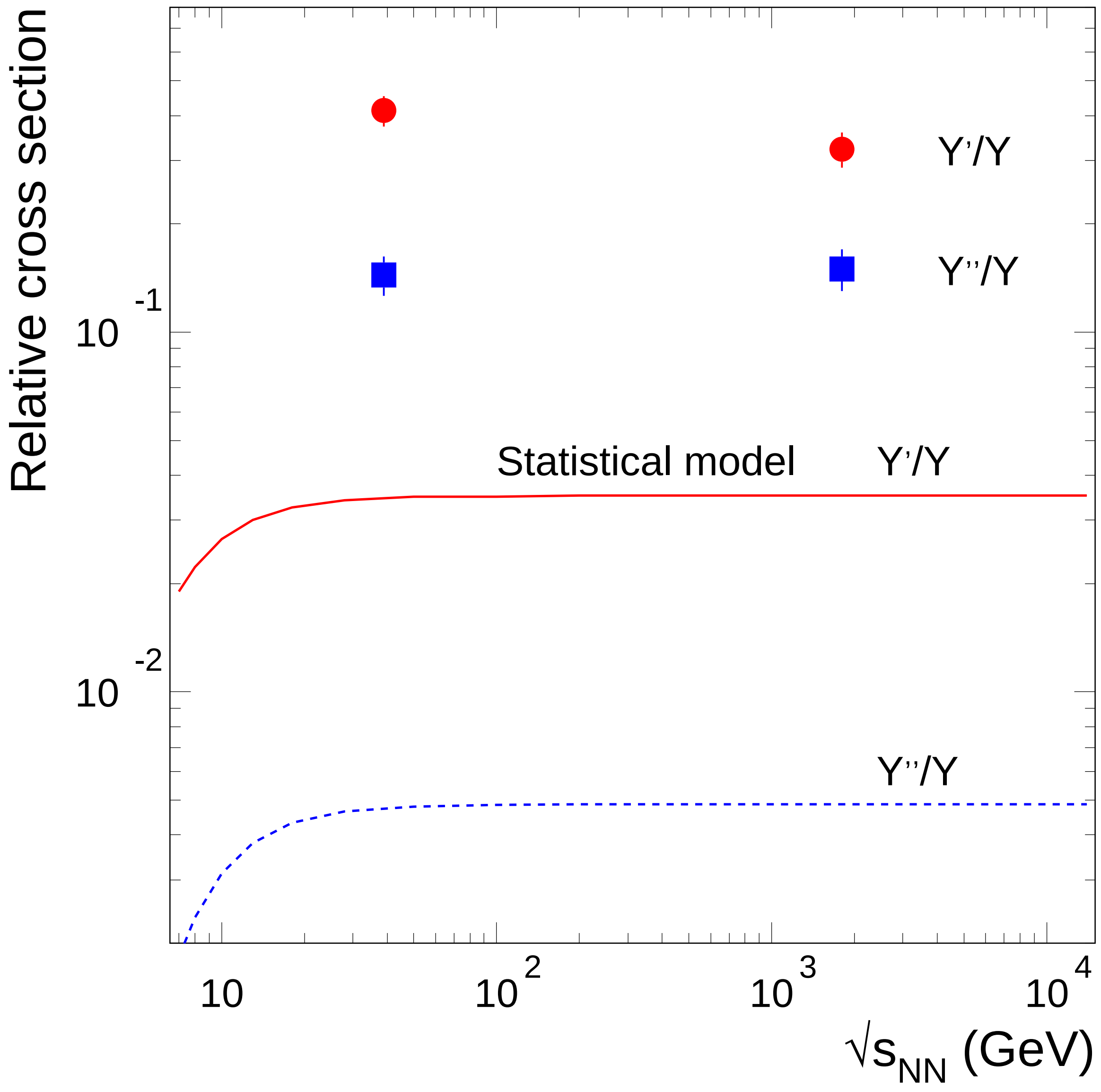


charmonium in pp(A) collisions

...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 thermal values at LHC?

indication for YES in the CMS data (arXiv:1105.4894)

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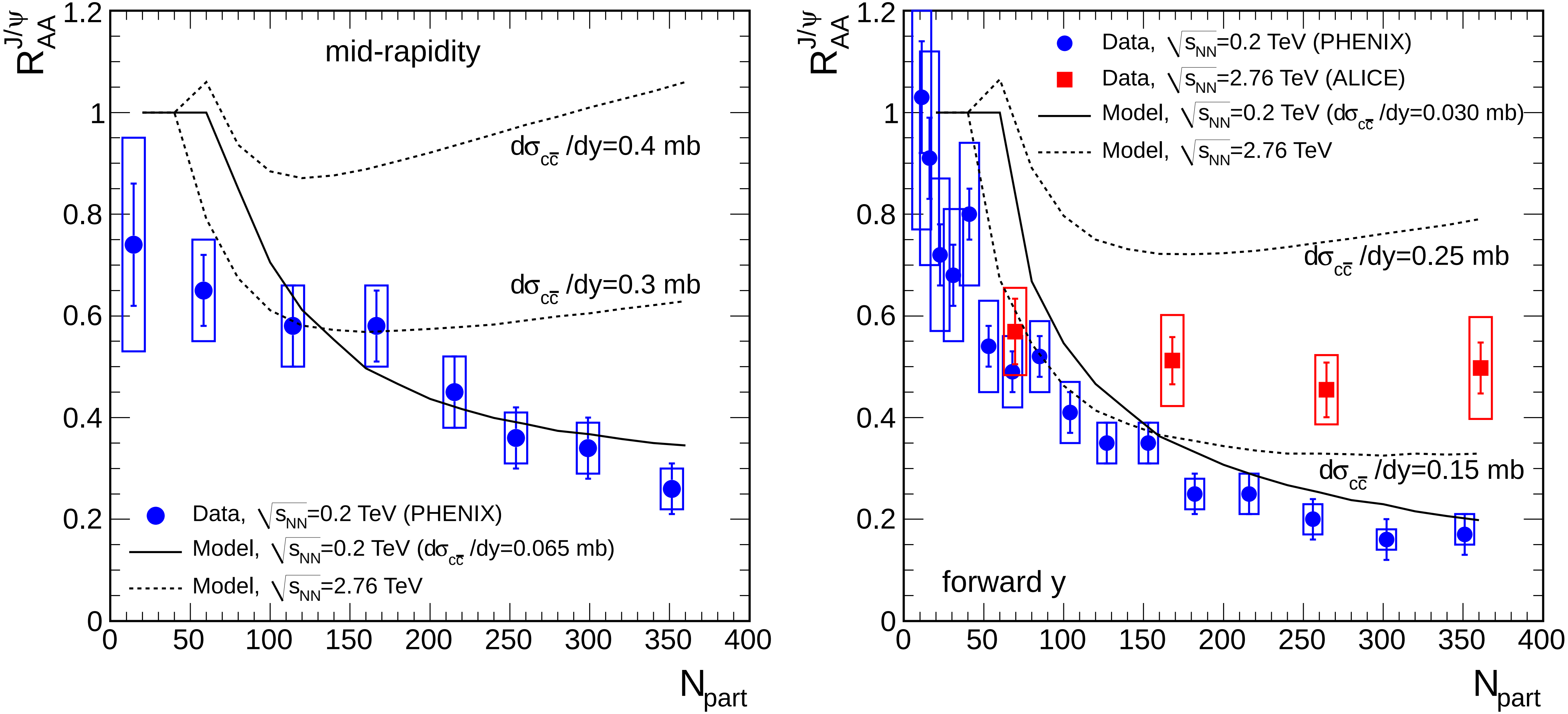
J/ψ production: the ultimate test at the LHC



i) less generation (more suppr.) at forward rapidity; ii) less suppression at LHC

"generic" predictions validated by data (despite uncertainty of $\sigma_{c\bar{c}}$ input, part of uncertainty due to shadowing) arXiv:1106.6321

Summary and outlook

the thermal model provides one clear way to obtain "experimental" ("minimal-theory bias") points on the QCD phase diagram
(with fits of hadron yields; higher moments to follow)

- thermal fits work remarkably well (AGS-RHIC) ⇒ (T,μ_b,V)
- limiting temperature ⇒ phase boundary ($T_{lim} \simeq T_c$)

  → for the skeptics... LHC case decissive ...smaller exp. errors expected

  ...would we be able (do we need?) to constrain also δT?
- indications (bad fits) around the critical point? ...maybe, at SPS...

  ...but not a strong case due to disagreements between experiments

  → RHIC low-energy run (and CBM?) will clarify this

  Needed: a better freeze-out line (or phase boundary?) for μ_b >500 MeV
- Good agreement with J/ψ (and ψ') data ...is scrutinized further

A.Andronic@GSI.de

Backup slides

Canonical correction ("canonical suppression")

needed whenever the abundance of hadrons with a given quantum number is very small ...so that one needs to enforce exact QN conservation

in AA collisions:
strangeness at low energies

$$n_{i,S}^{C} = n_{i,S}^{GC} \cdot \frac{I_s(N_S)}{I_0(N_S)}$$

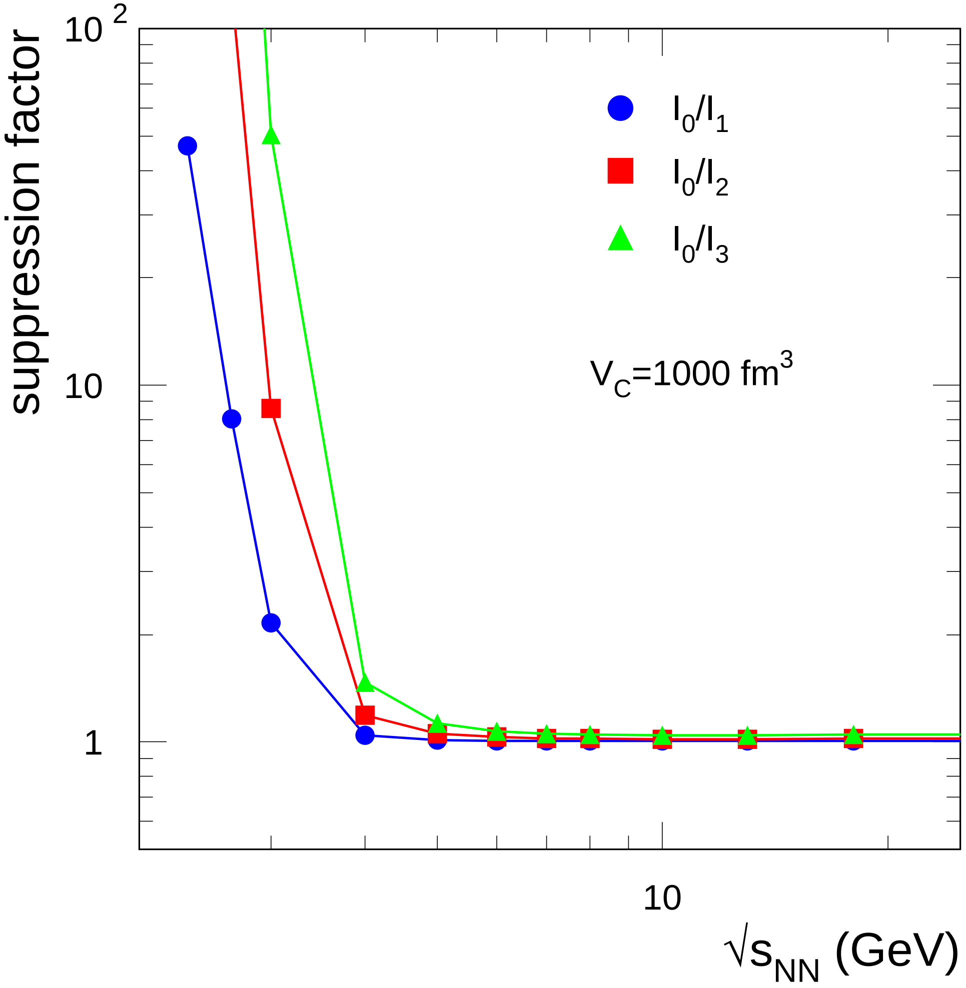
$$N_S = V \cdot \sum S \cdot n_{i,S},$$

total amount of strangeness-carrying hadrons (part.+antipart.)

$$n_{K,\Lambda}^{C} = n_{K,\Lambda}^{GC} \cdot \frac{I_1(N_S)}{I_0(N_S)},$$

$$n_{\phi}^{C} = n_{\phi}^{GC}$$

...negligible for $\sqrt{s_{NN}}$ >5 GeV



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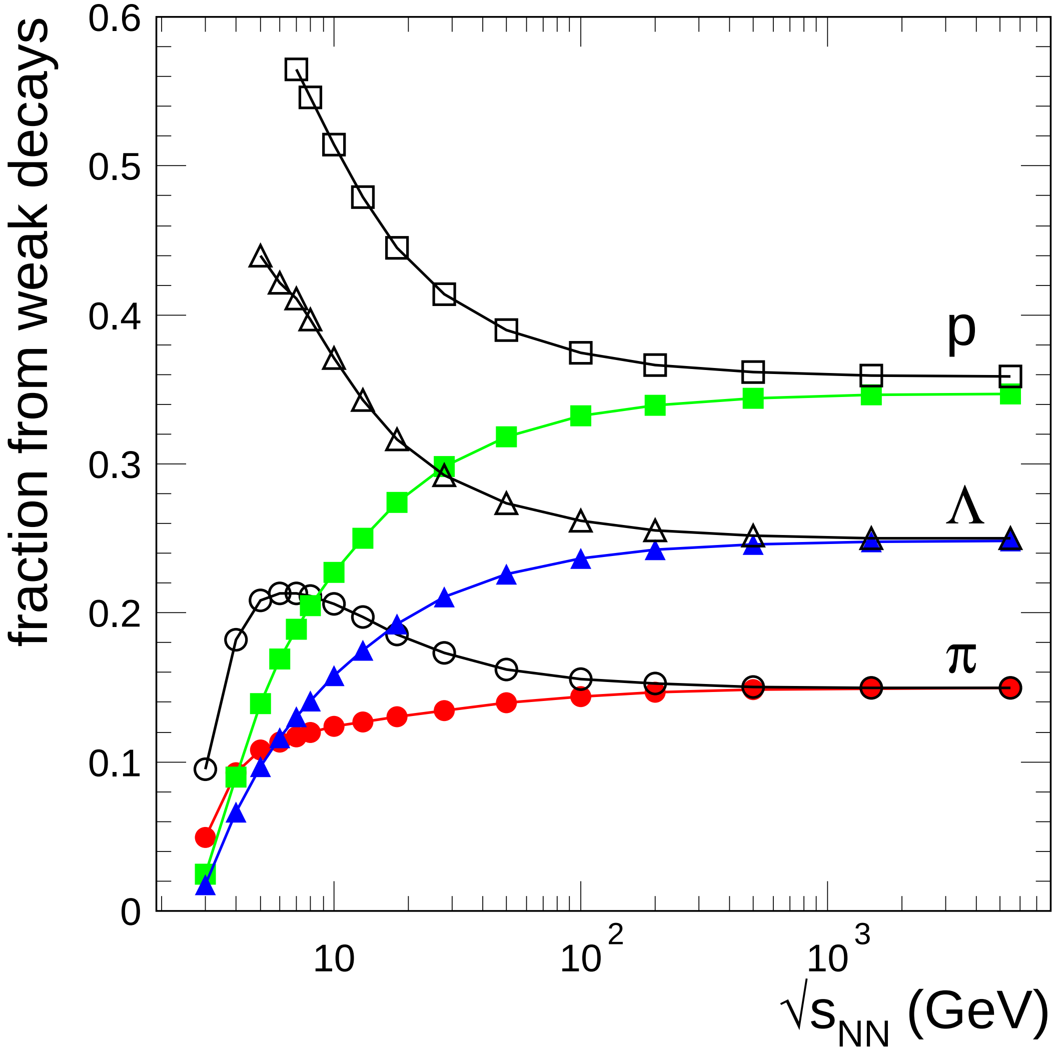
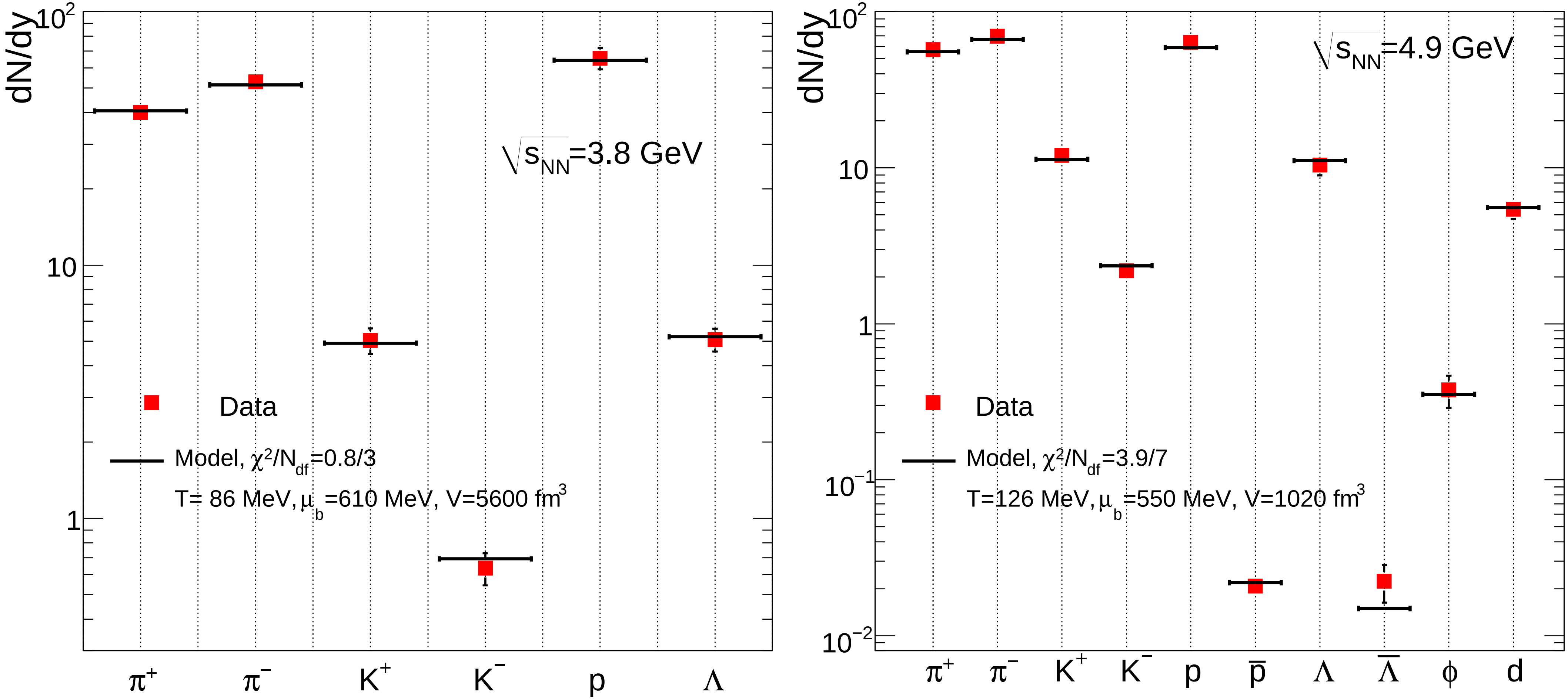
Fraction of yields from weak decays

...is not always well controlled in measurements

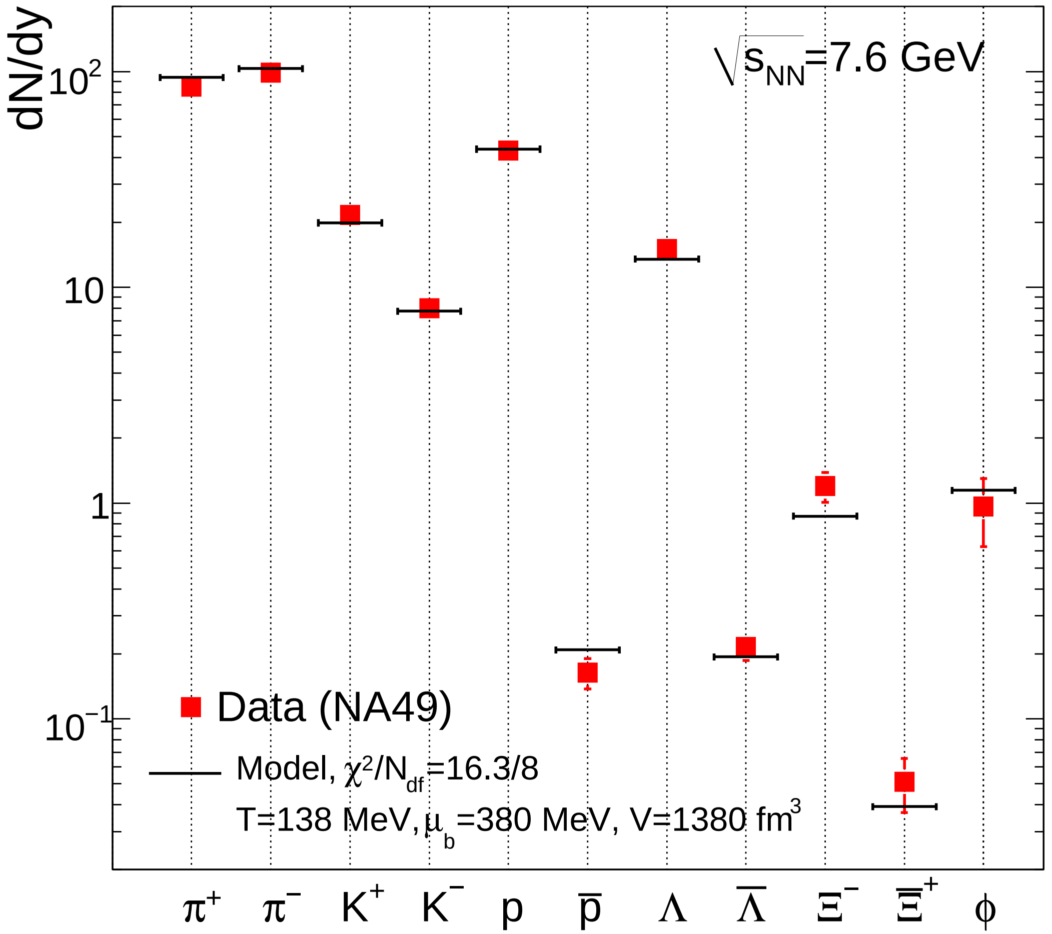


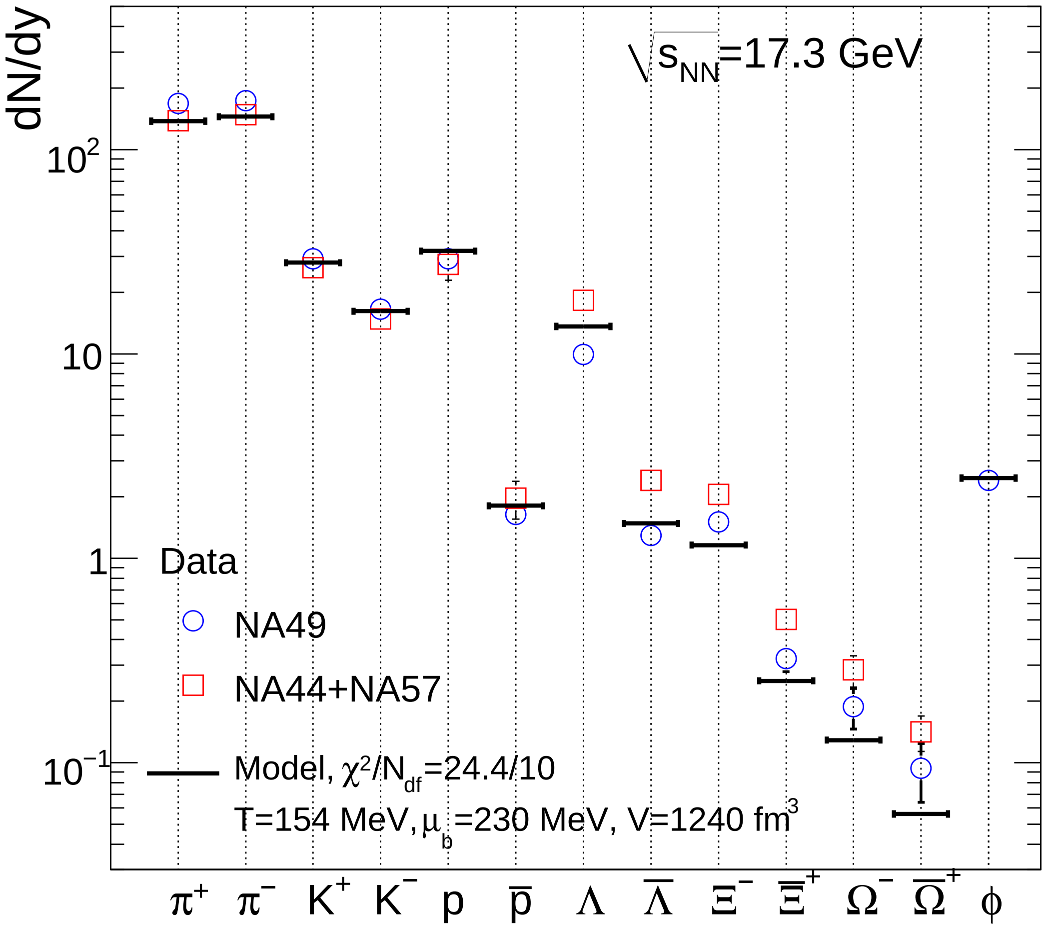
Fits at AGS: 6 and 10.5 AGeV



AGS, 2-8 AGeV: a rather small set of hadron yields measured

Fits at SPS: 30 and 158 GeV



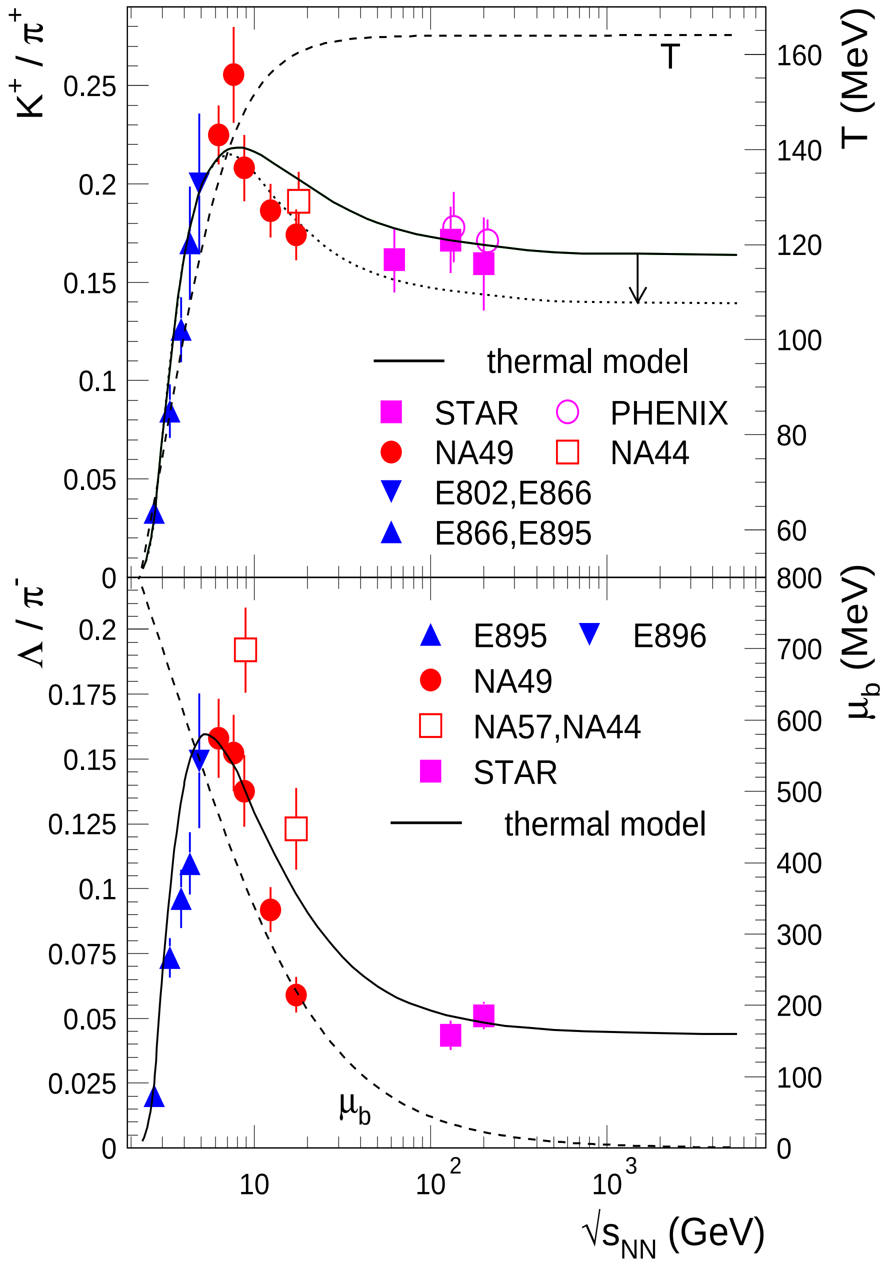


only NA49 data: T=148 MeV, μ_b=215 MeV, V=1660 fm^3, χ^2/N_{df}=36/10

only NA44+NA57: T=172 MeV, μ_b=245 MeV, V=700 fm^3, χ^2/N_{df}=30/10

A.Andronic@GSI.de

“The horn”(s) as of 2009



rather well explained by the model

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

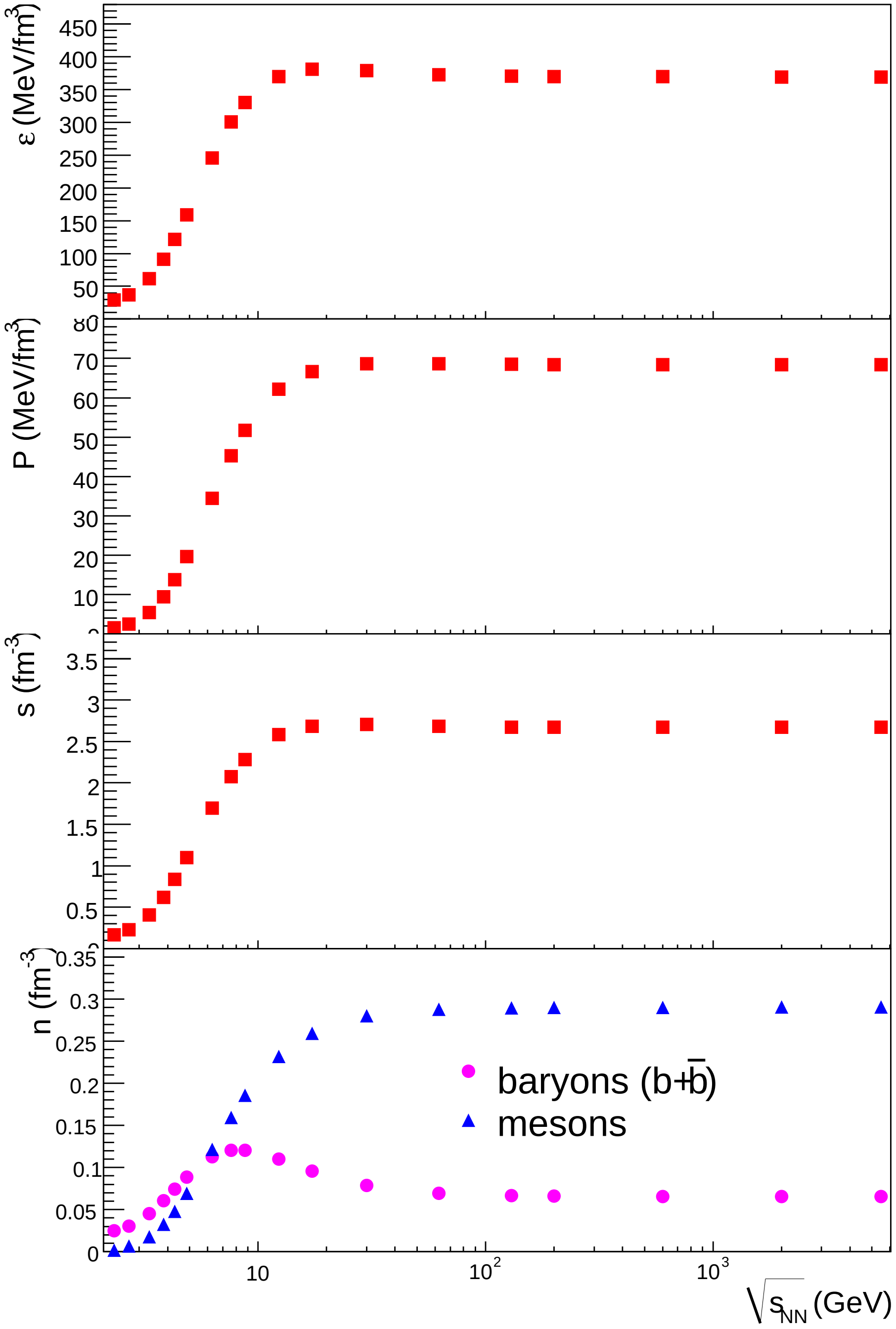
...which leads to a limiting temperature (“Hagedorn”, $T < T_H$)

...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)

PLB 673 (2009) 142

Thermodynamical quantities at chemical freeze-out



...follow T dependence on $\sqrt{s_{NN}}$

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? $(T_d \sim T_c)$

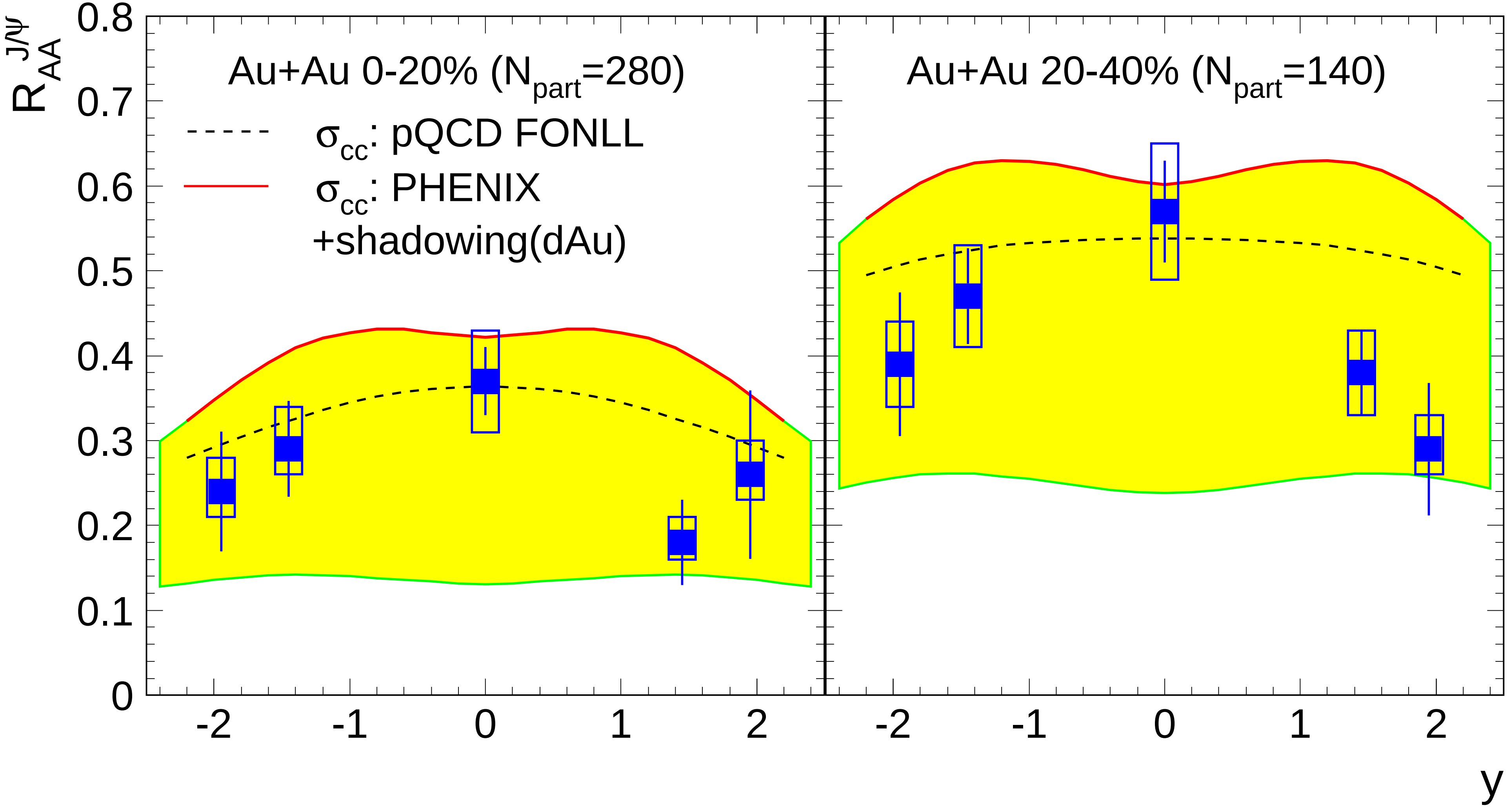
- collision time, $t_{coll} = 2R/\gamma_{cm}$
  - SPS (FAIR): $t_{coll} \gtrsim t_{J/\psi}$
  - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} << t_{J/\psi}$

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: effect of shadowing



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

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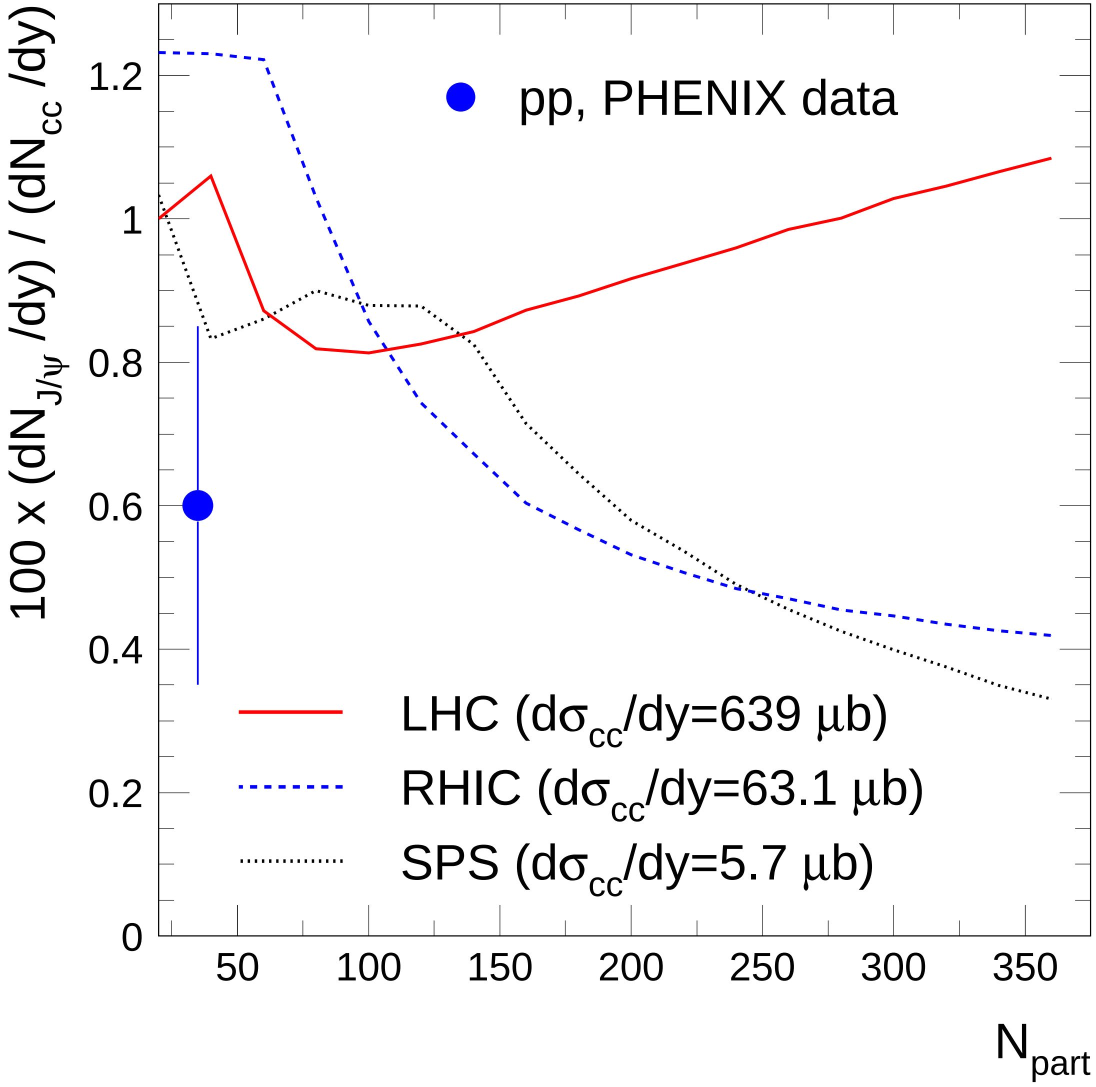
J/ψ production relative to charm



- ...the most "solid" observable

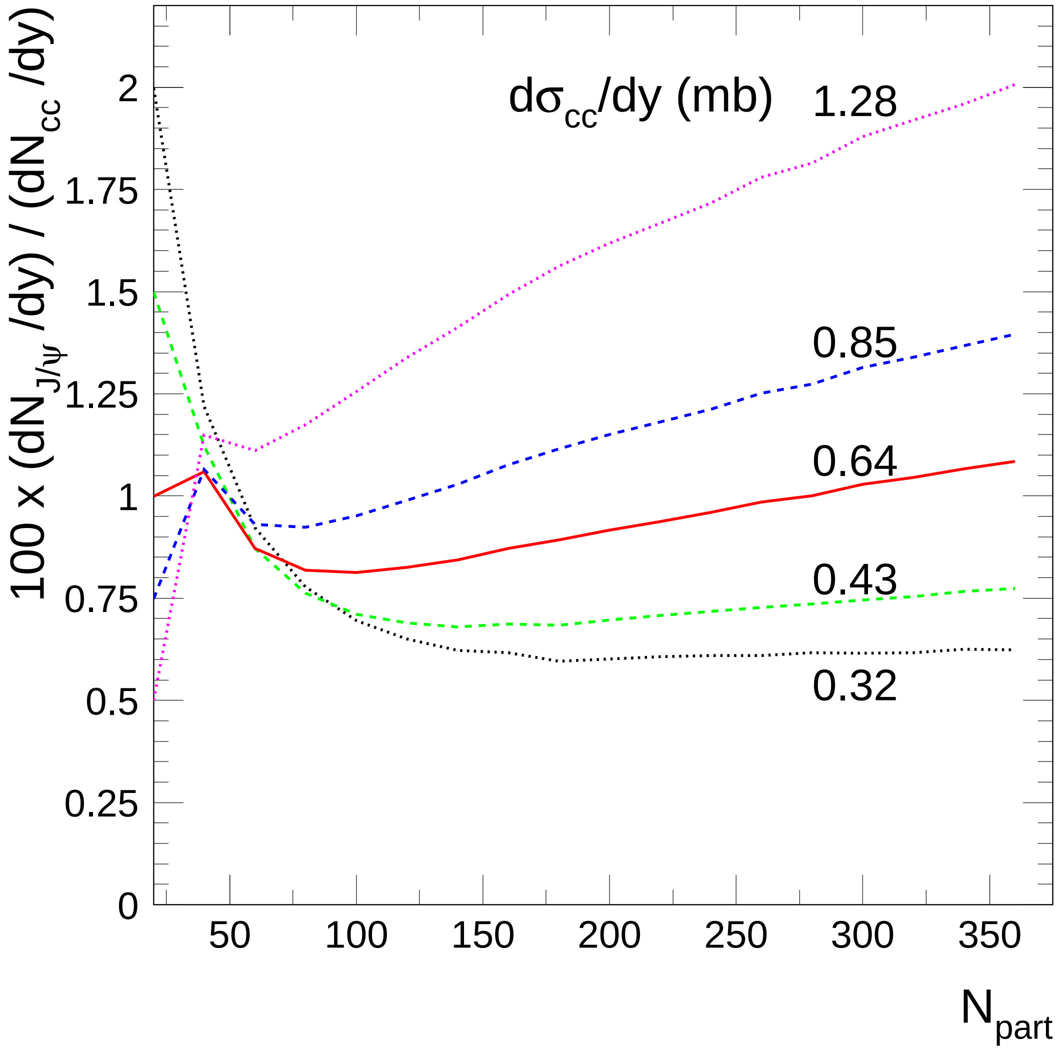
  ...with similar features as R_{AA}
- similar values at RHIC and SPS

  ...with differences in fine details

  ...determined by canonical suppression of open charm
- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant

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