

The thermal model (at low energies) and the significance of hadron yields measurements at FAIR & NICA

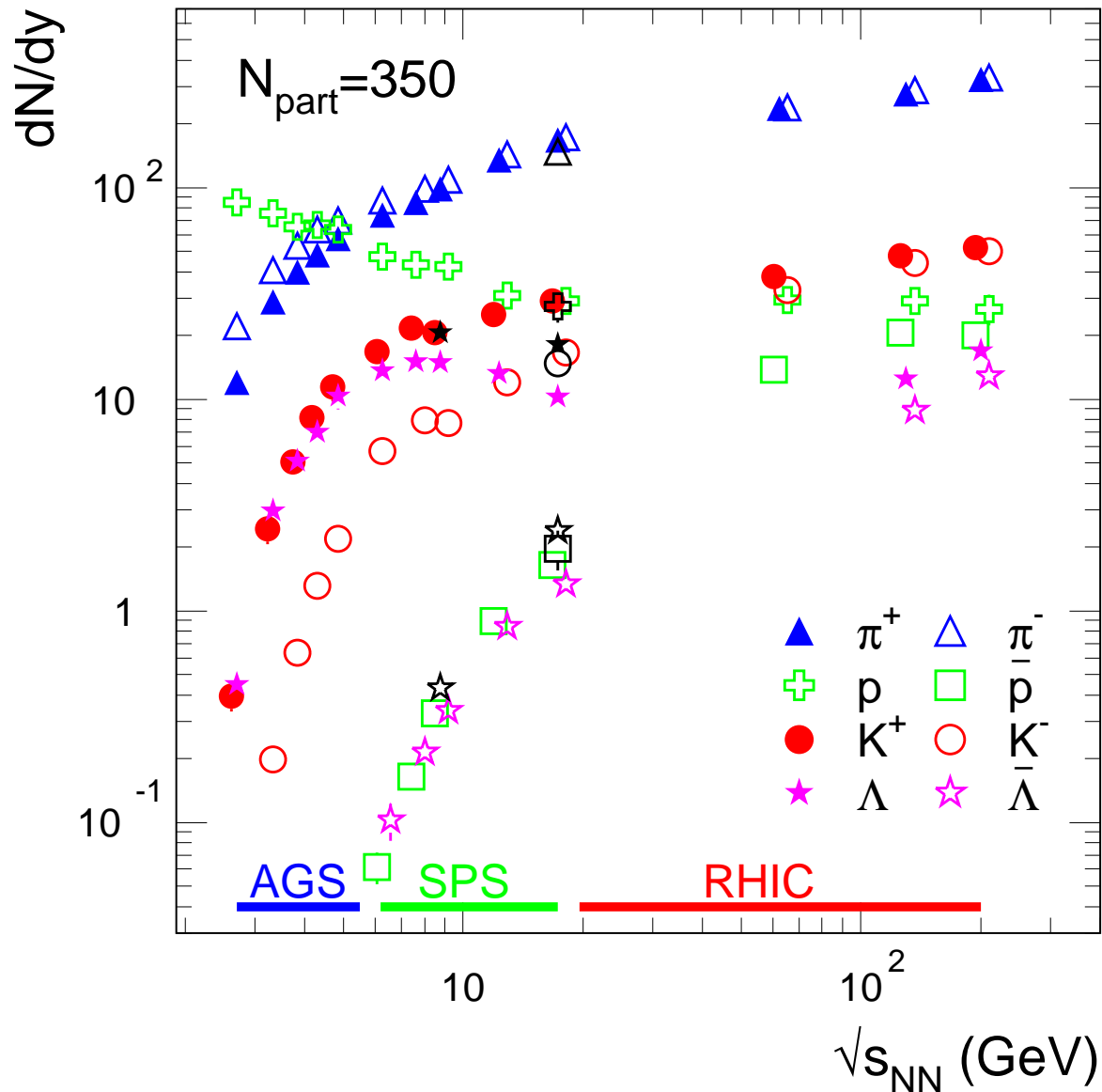
A.Andronic – GSI Darmstadt

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

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

AA, P. Braun-Munzinger, J. Stachel, H. Stöcker, PLB 697 (2011) 203

Hadron yields (at midrapidity, in central collisions)



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

The thermal model

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

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

$g_i = (2J_i + 1)$ 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)

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

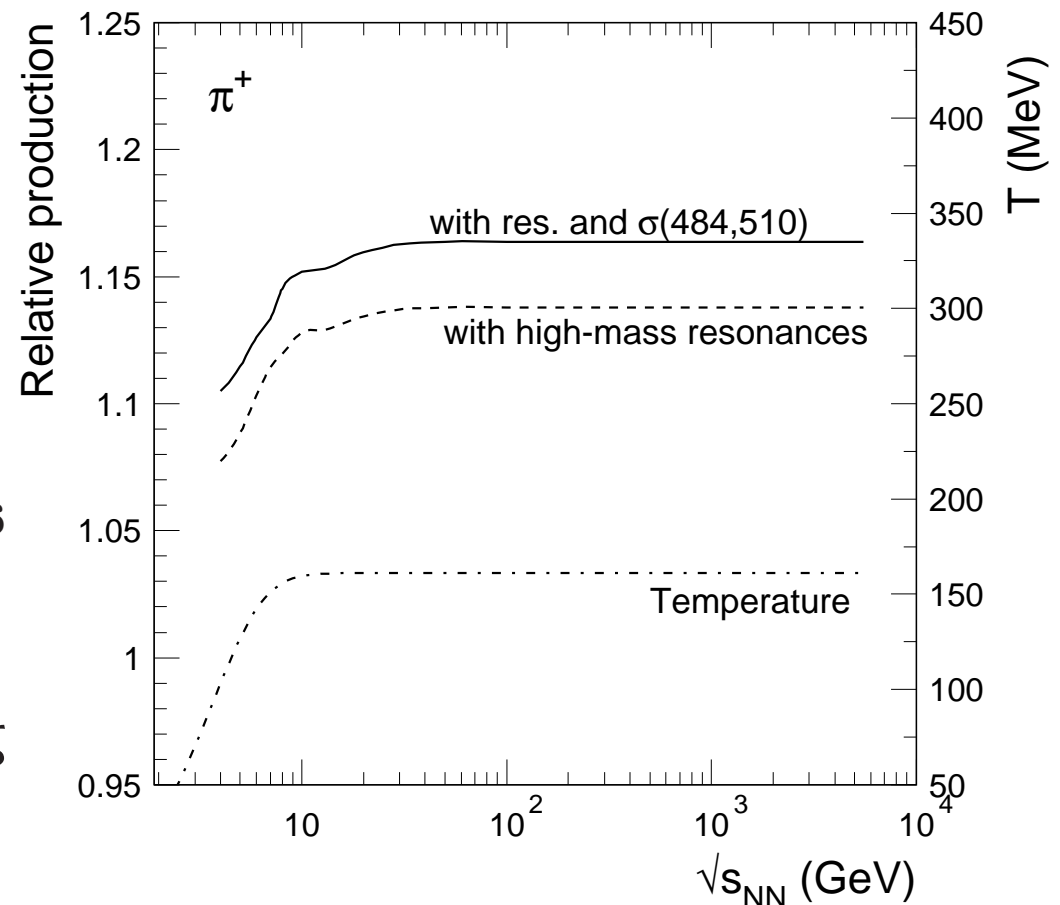
σ meson [$f_0(600)$]:

$m_\sigma = 484 \pm 17$ MeV, $\Gamma_\sigma = 510 \pm 20$ 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: $K^\pm (u\bar{s}, \bar{u}s)$: $n_K \gamma_s$, $\Lambda (uds)$: $n_\Lambda \gamma_s$,

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

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 $\gamma_s=1$

The thermal fits

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

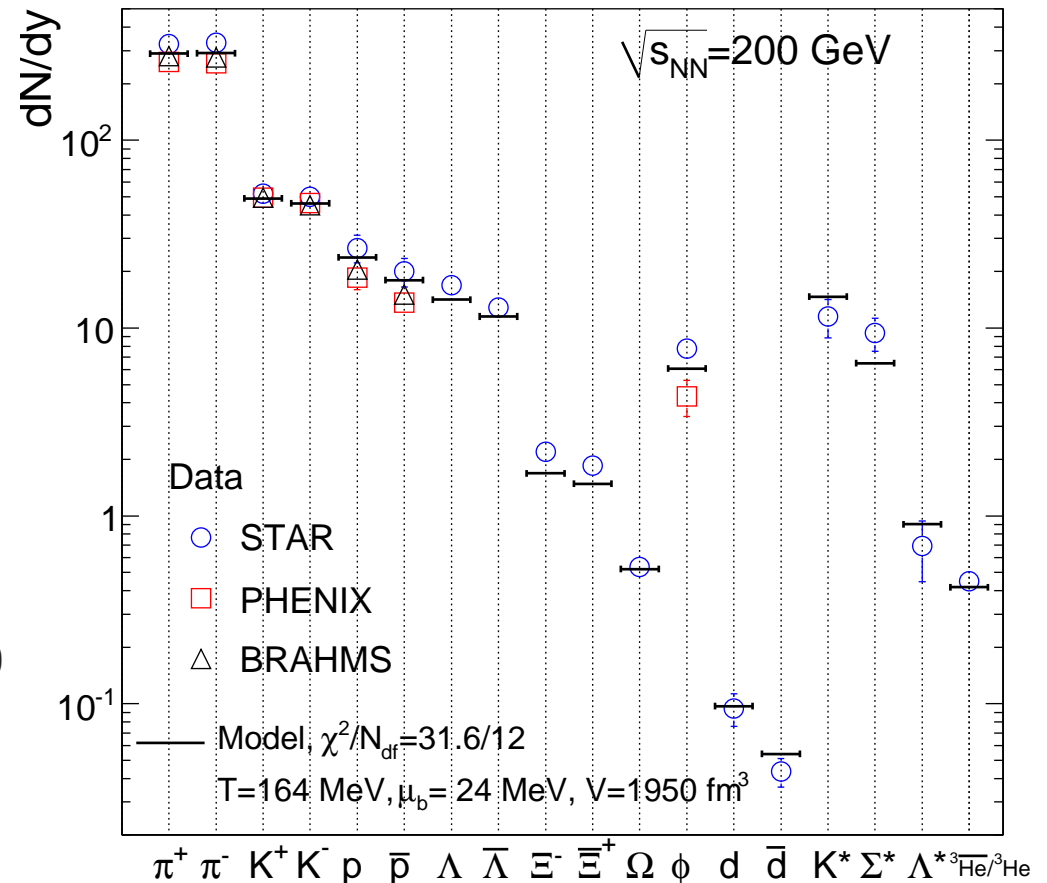
Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

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

Data: 4π or dN/dy (at $y=0$)

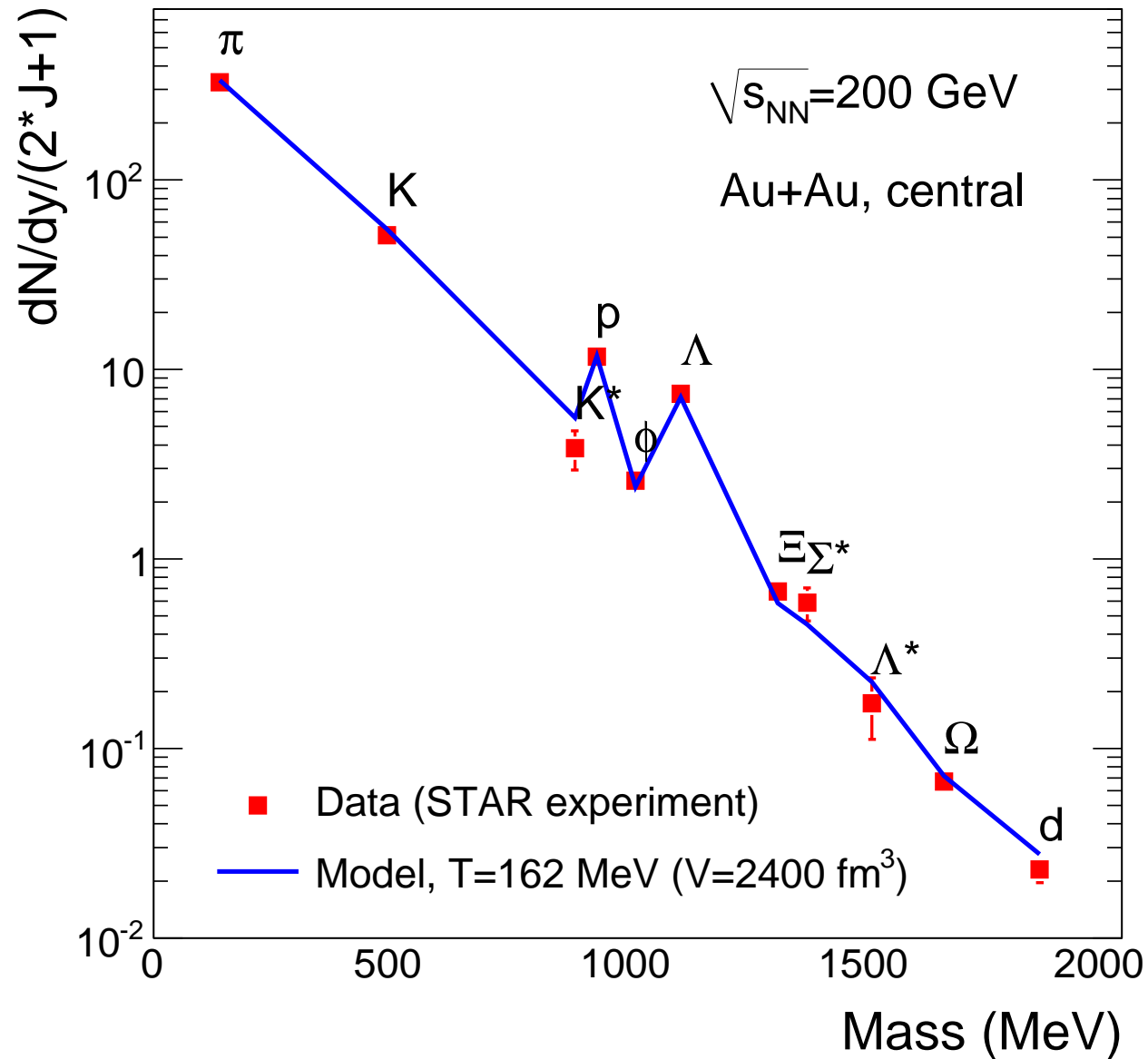
fit only STAR data: $T=162$ MeV, $\mu_b=24$ MeV, $V=2400$ fm^3 , $\chi^2/N_{df}=10.9/12$

$\mu_{I_3}=-0.8$ MeV; $\mu_S=6.6$ MeV; $\mu_C=-3.5$ MeV

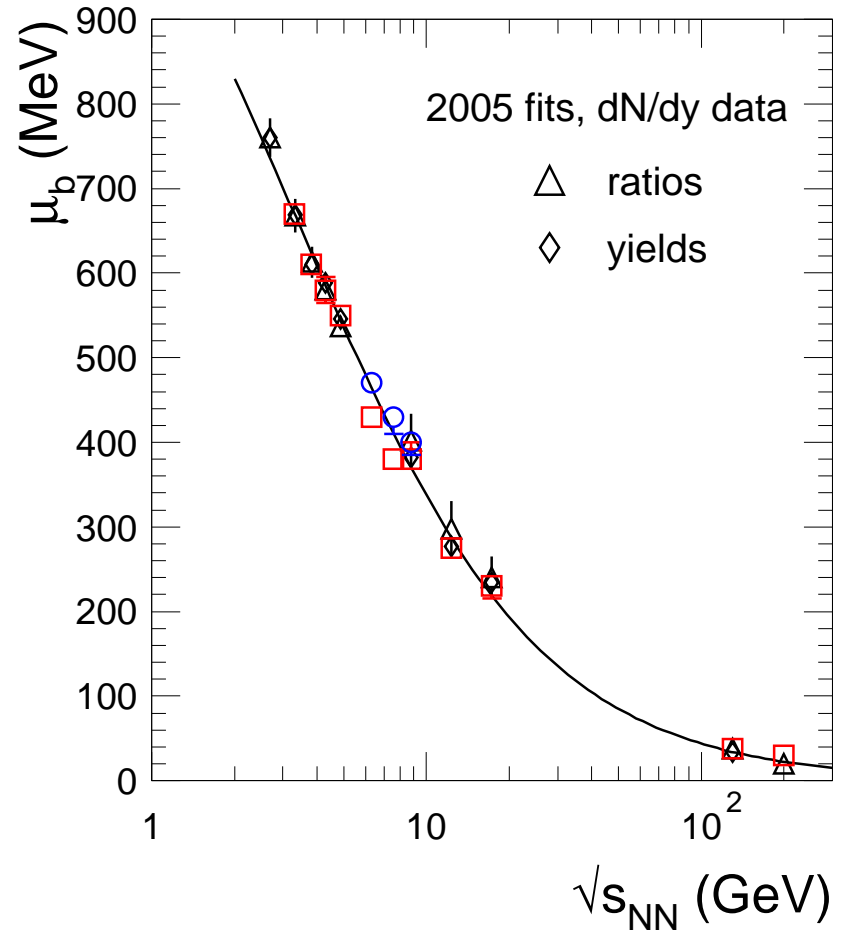
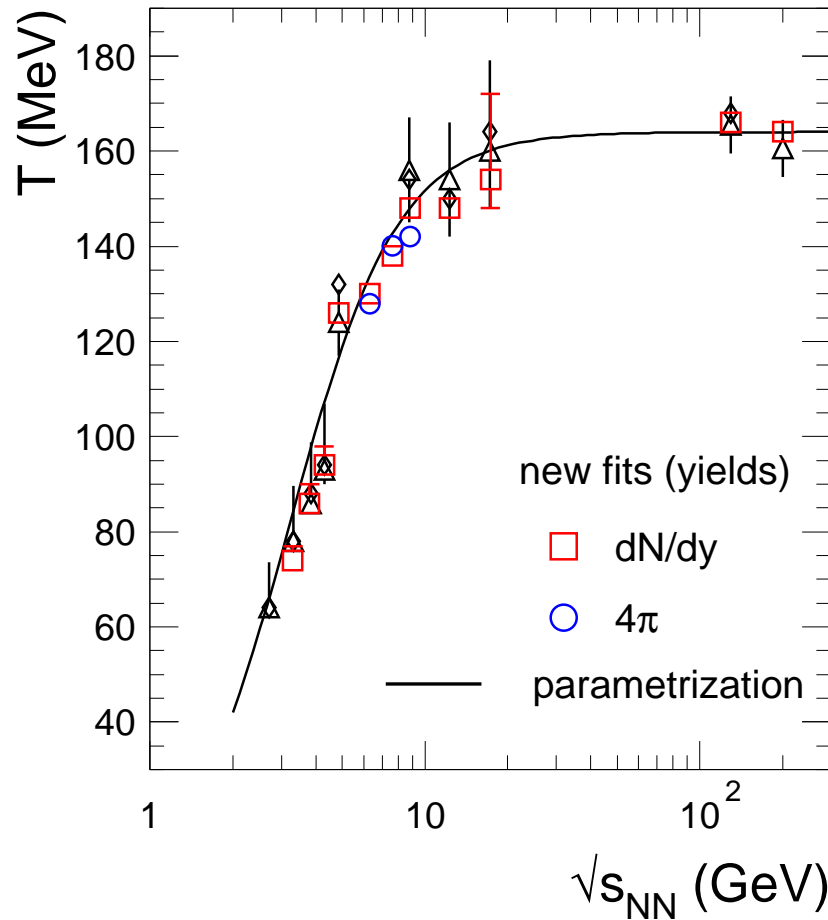


The hadron abundances are in agreement with a thermally equilibrated system

A thermal fit displayed differently



Energy dependence of T , μ_b



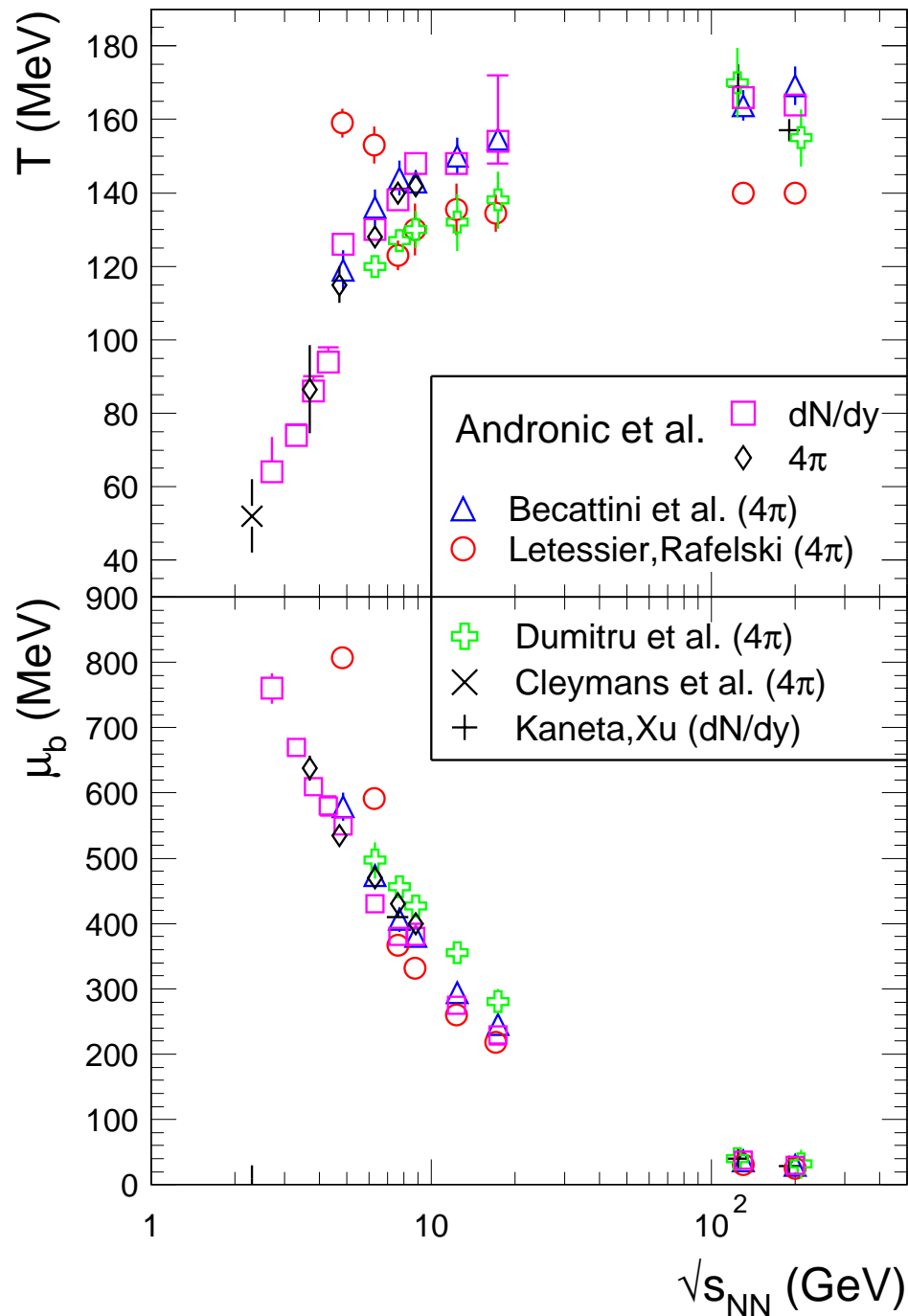
thermal fits exhibit a limiting temperature:

$$T = T_{lim} \frac{1}{1 + \exp(2.60 - \ln(\sqrt{s_{NN}}(\text{GeV}))/0.45)},$$

$$T_{lim} = 164 \pm 4 \text{ MeV}$$

$$\mu_b[\text{MeV}] = \frac{1303}{1 + 0.286\sqrt{s_{NN}}(\text{GeV})}$$

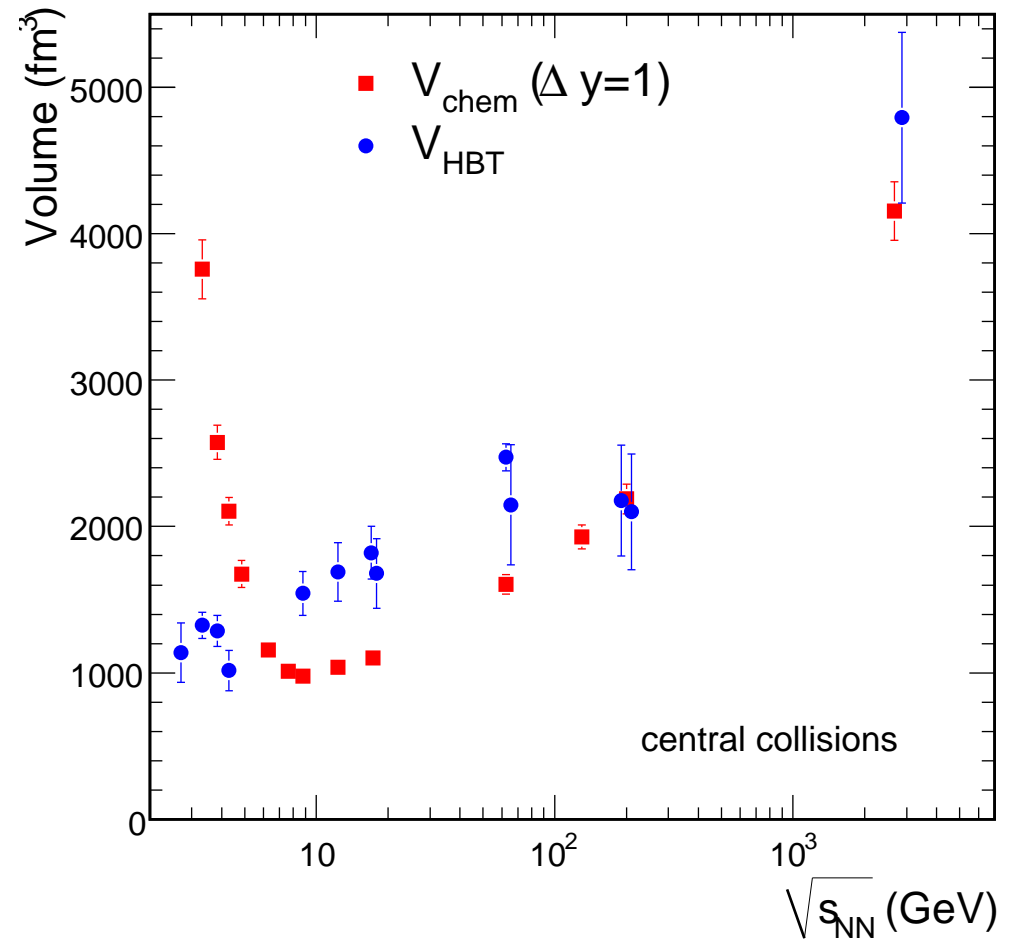
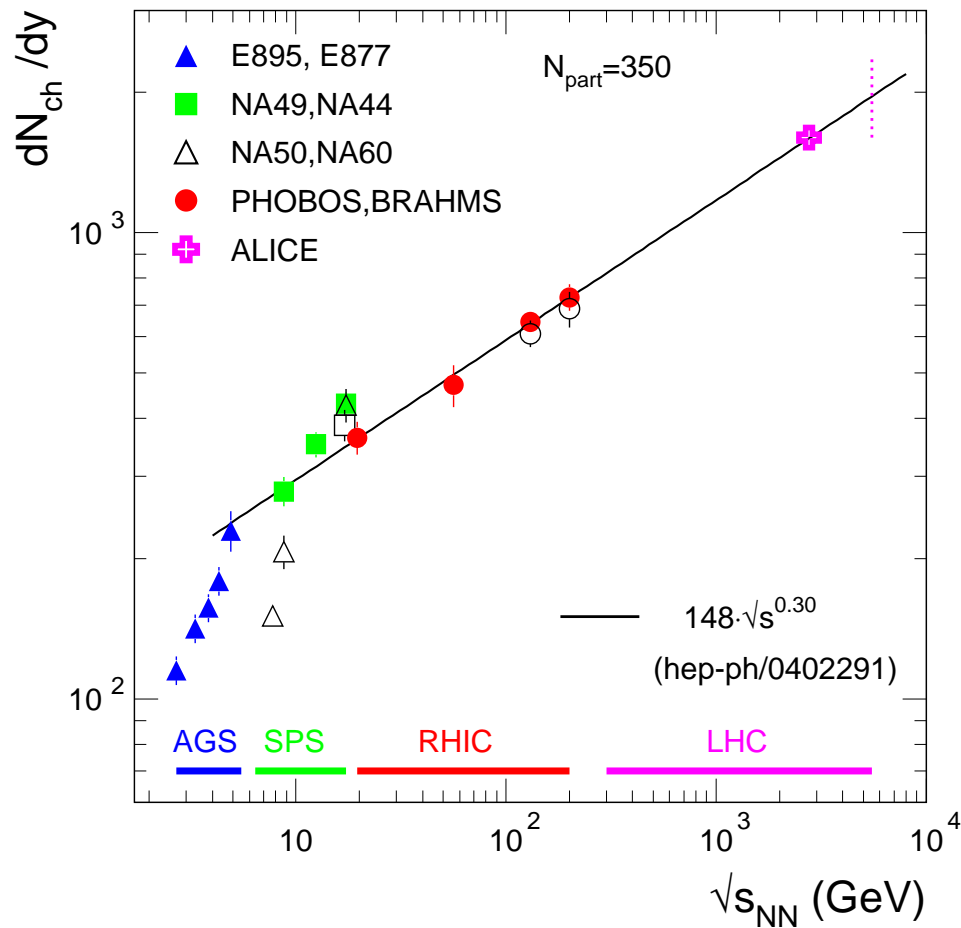
Energy dependence of the thermal parameters



...a comparison of models

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

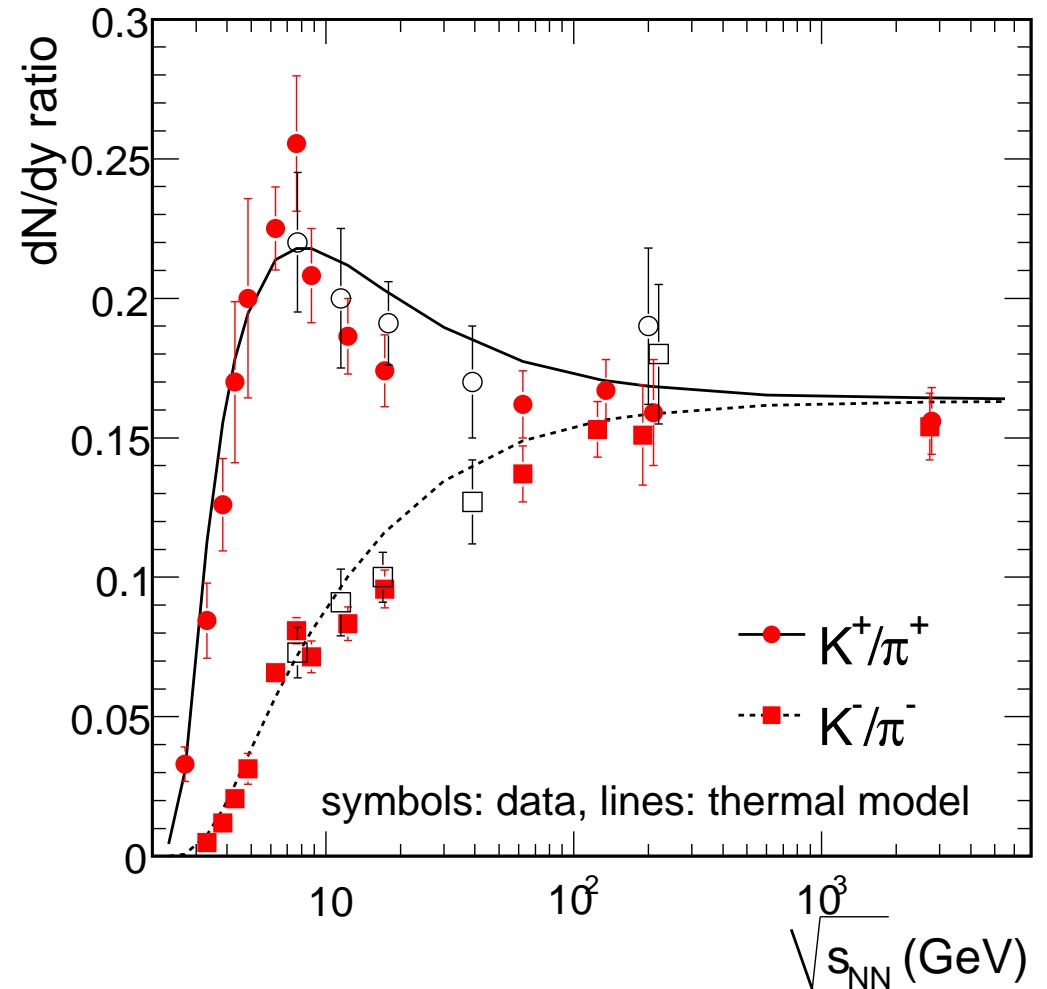
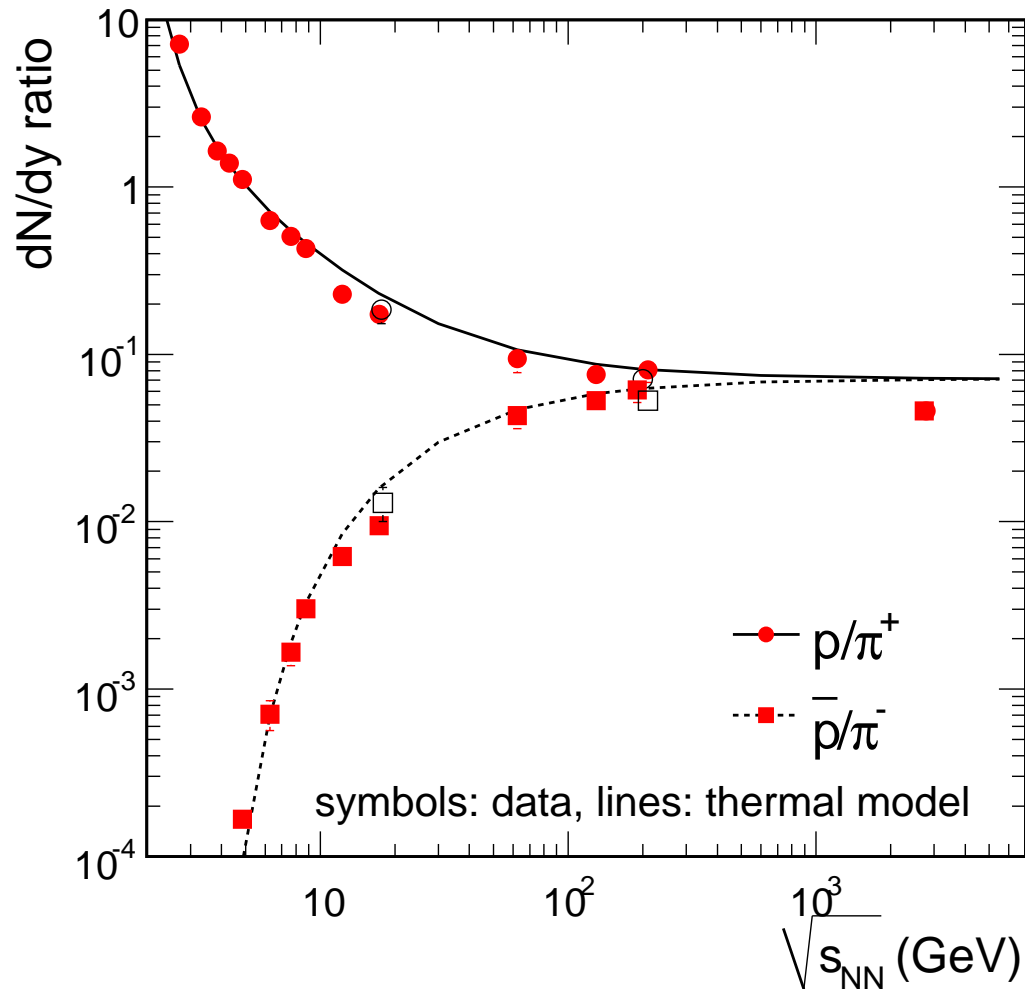
Volume in central collisions



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

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

General features of (relative) hadron production

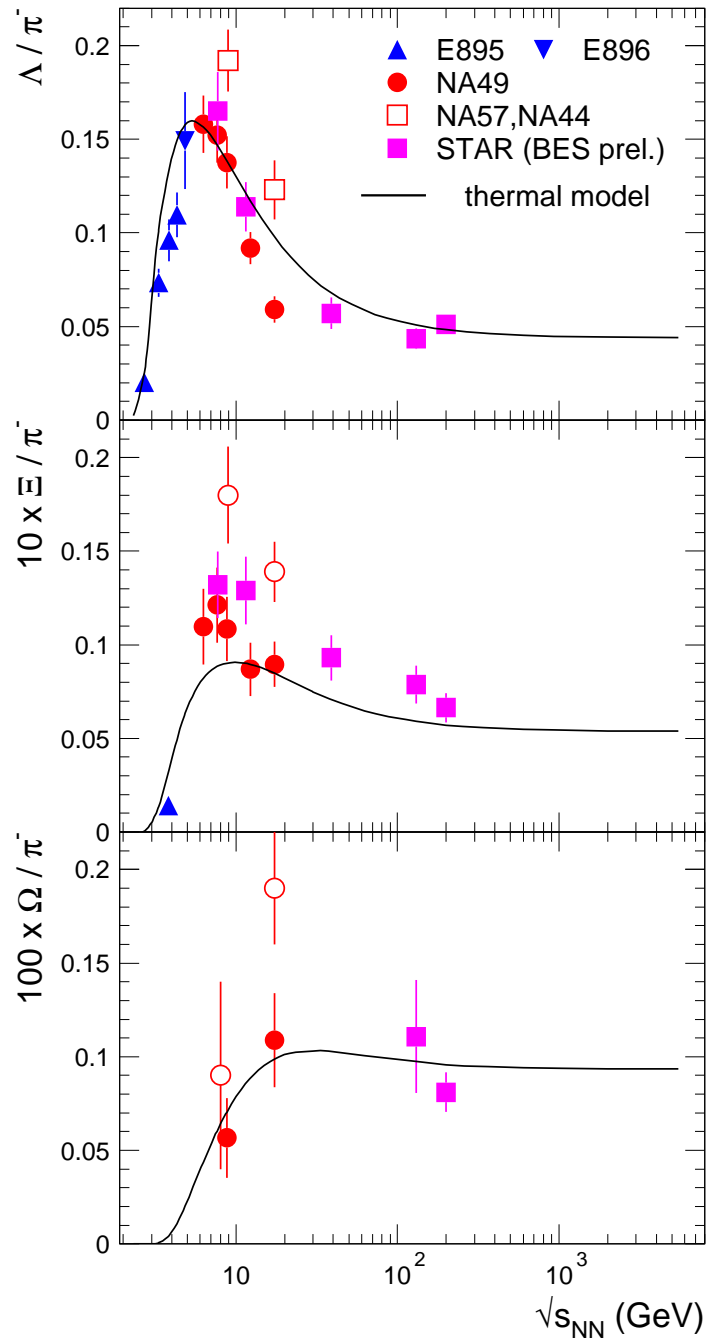


good agreement data-model

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

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

...and the state of other “horns”

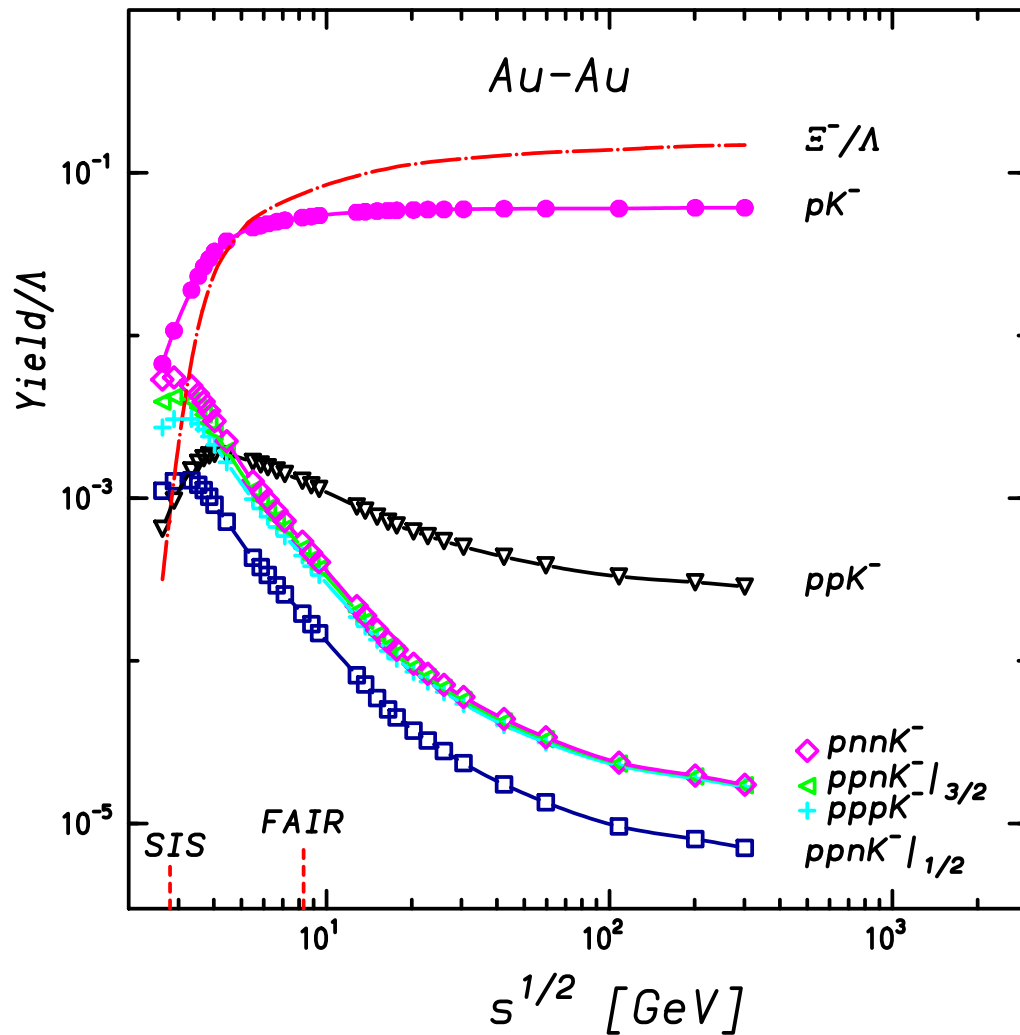


overall agreement model-data

Acta Phys. Pol. 40 (2009) 1005

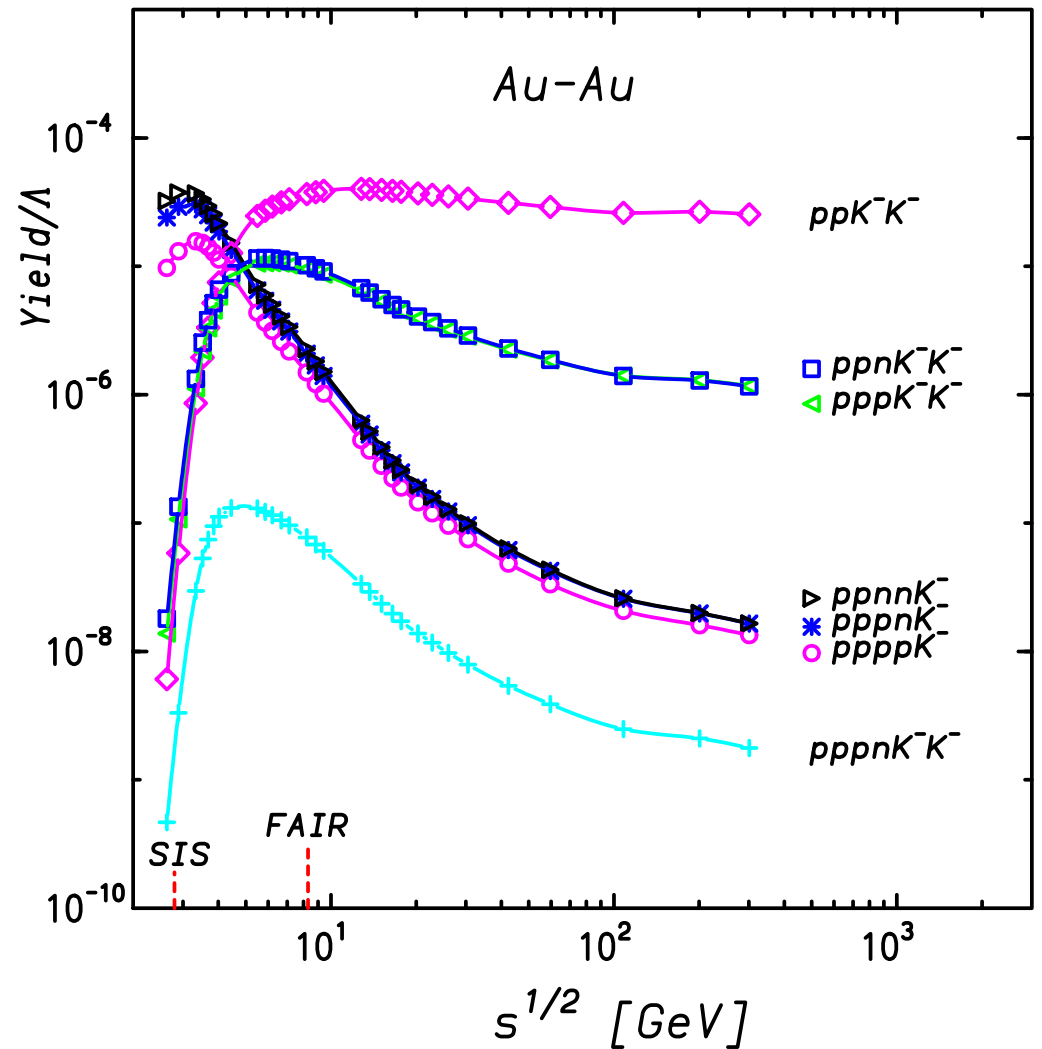
STAR BES prelim., arXiv:1203.5183

...and more exotic "horns"



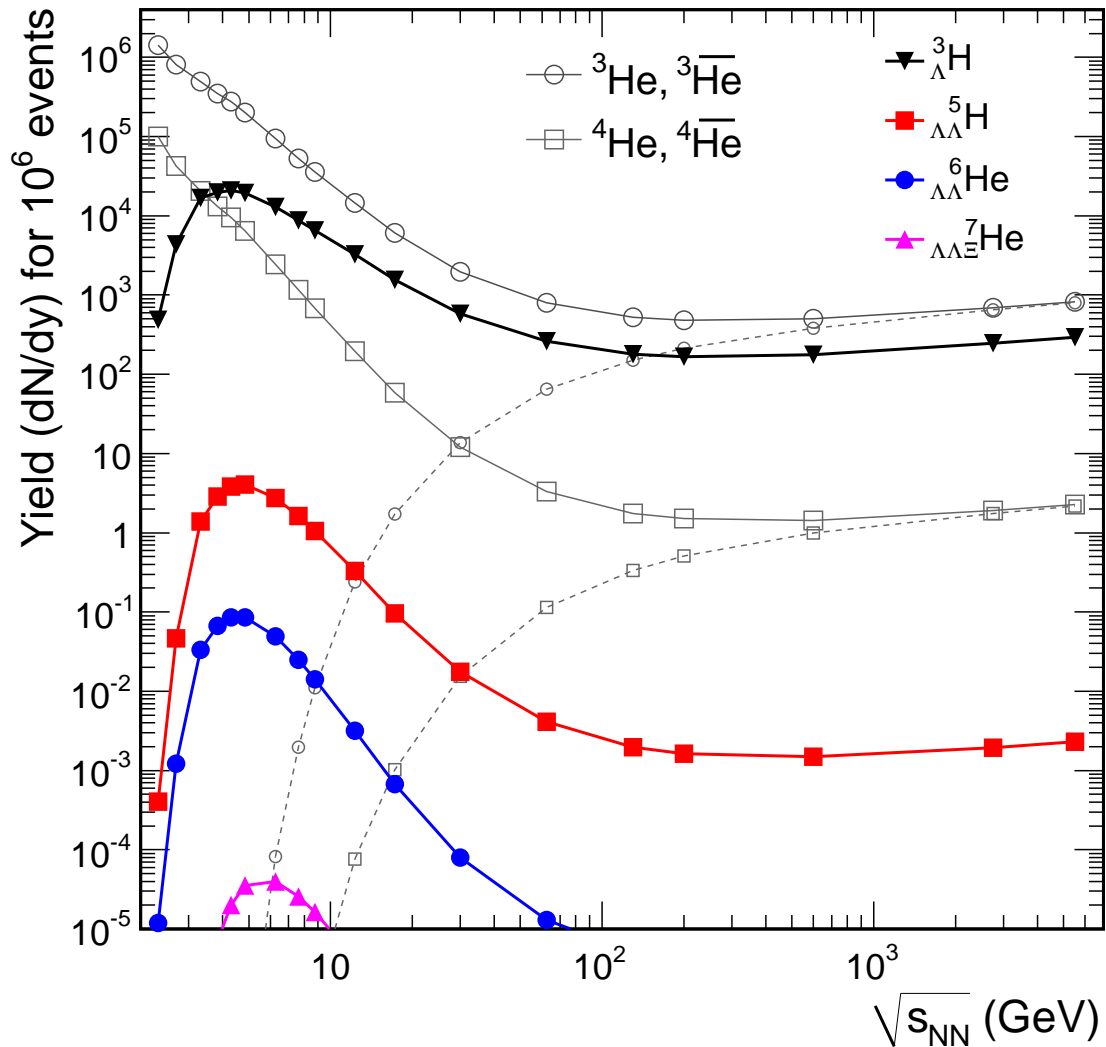
AA, PBM, K.Redlich, NPA 765 (2006) 211

...if only such composites would exist



Akaishi, Yamazaki, PRC 65 (2002) 044005

Extending the range: (hyper-)nuclei predictions



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

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

RHIC ($\sqrt{s_{NN}}=200$ GeV):

$T=164$ MeV, $\mu_b = 24 \pm 2$ MeV

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

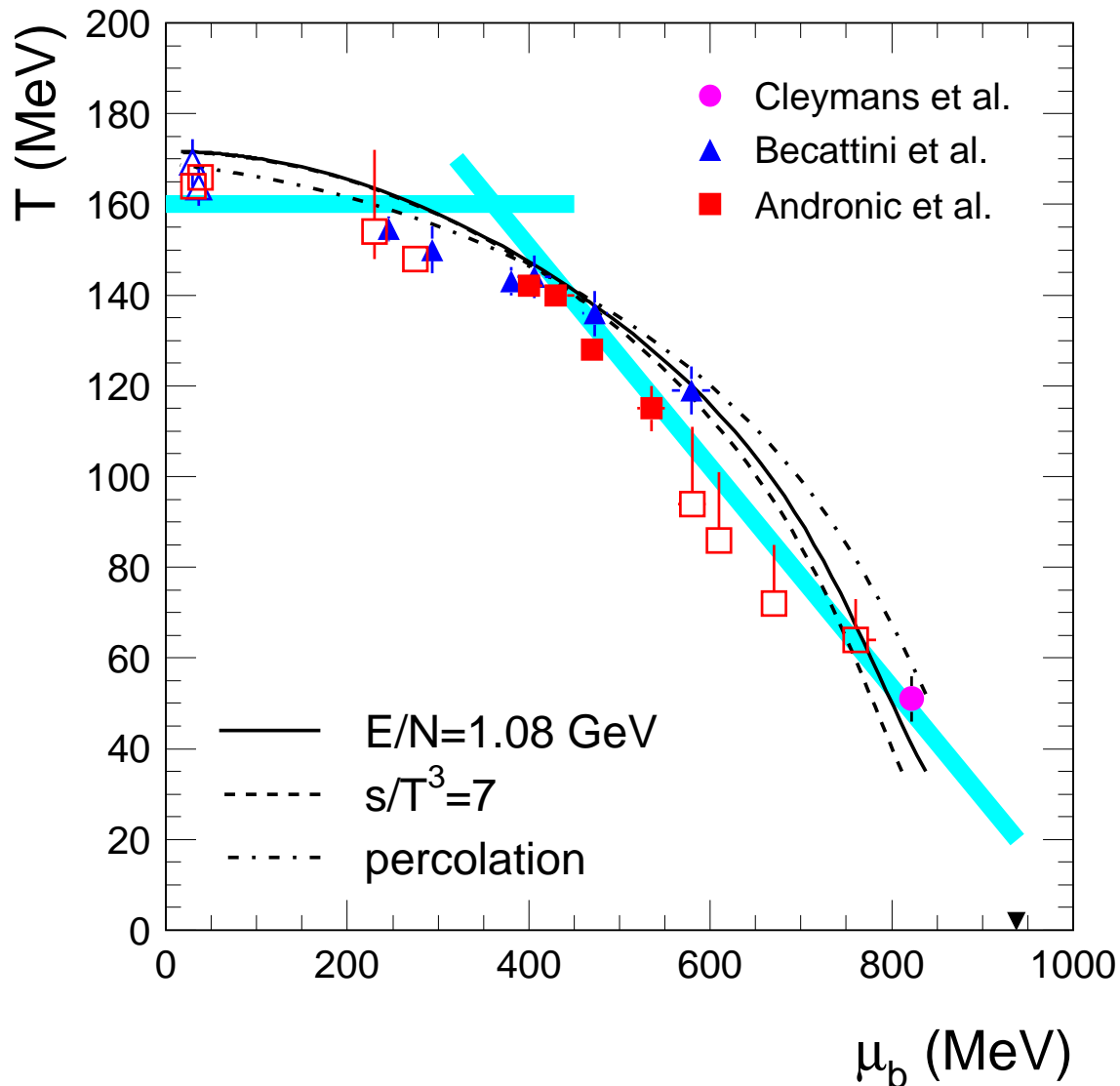
could be resolved if an excited state of ${}^3_{\Lambda}H$ exists

Phys.Lett.B697,203(2011)

a fertile ground for discoveries at FAIR - NICA

The phase diagram of QCD 1

as $T \rightarrow T_{lim}$, 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”?

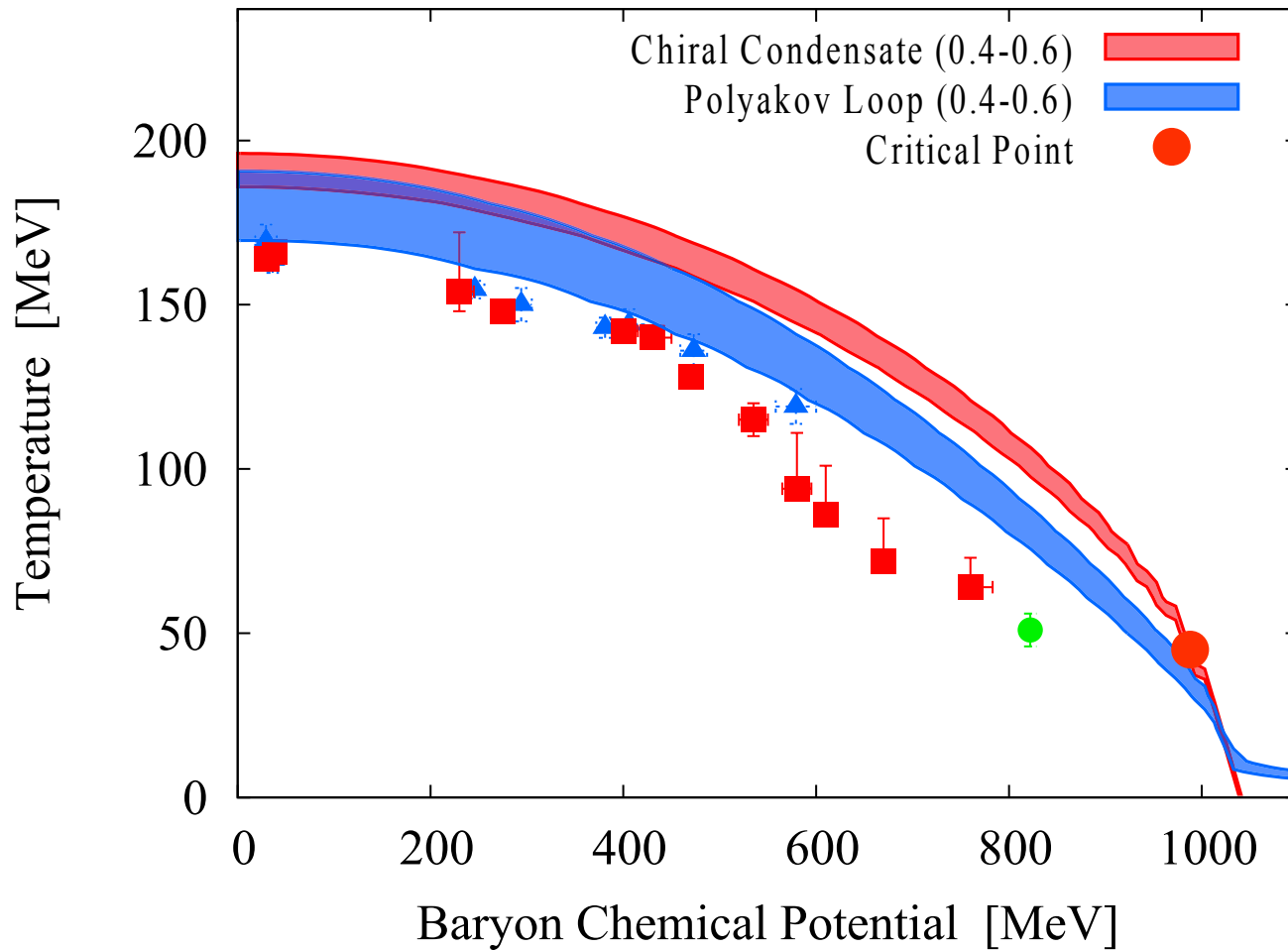
McLerran, Pisarski, NPA 796 (2007) 83

AA et al., NPA 837 (2010) 65

...or maybe not?

Floerchinger, Wetterich, arXiv:1202.1671

The phase diagram of QCD 2



K. Fukushima, PLB 695, 387 (2011)

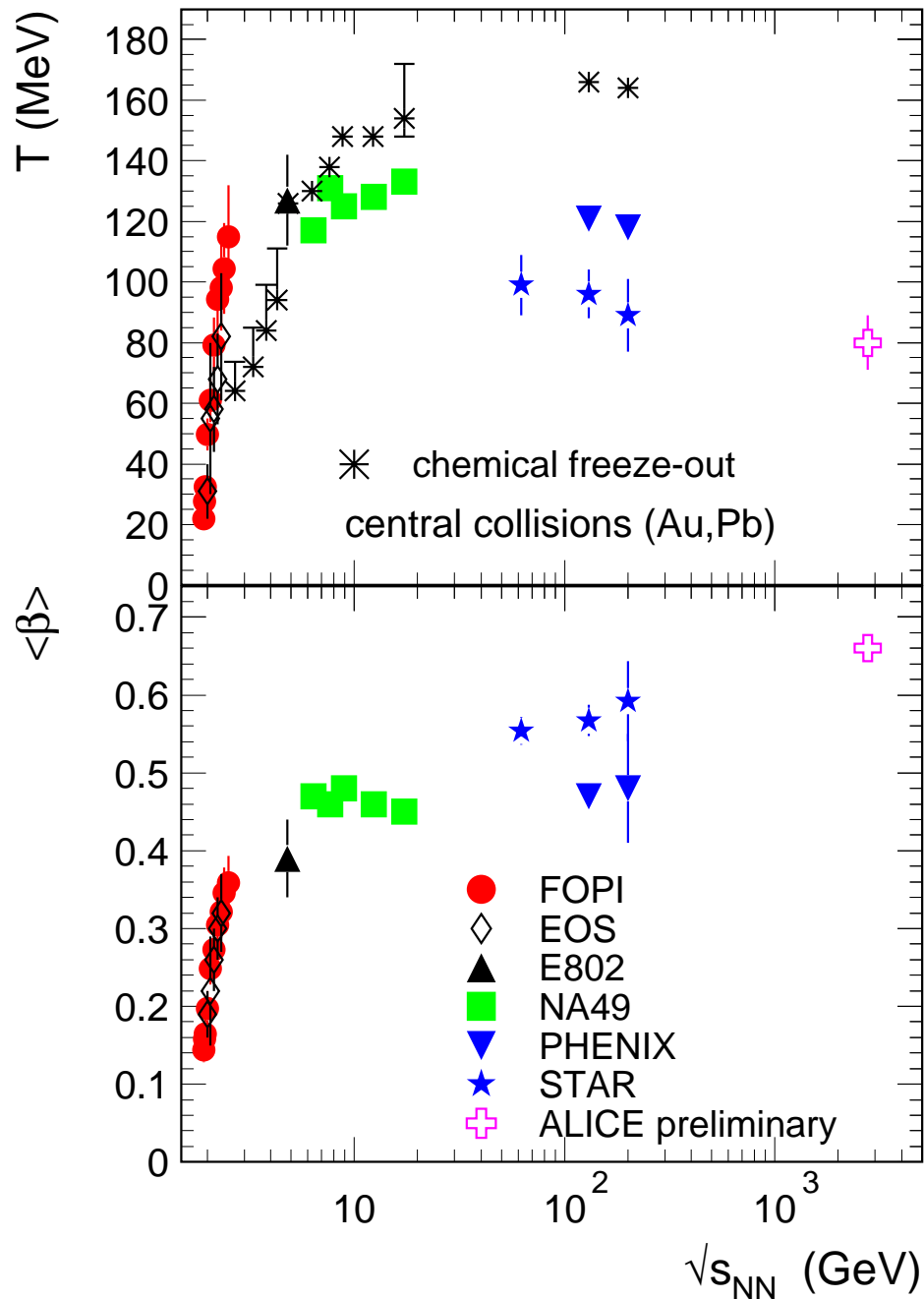
[PNJL, “forced” to agree with stat. model (for large μ_b)]

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

(justifies vacuum masses)

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

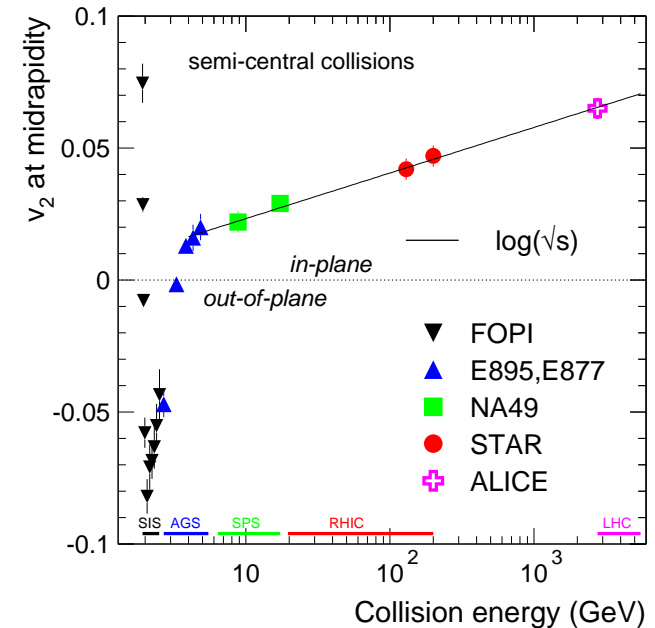
The chemical vs. kinetic freeze-out



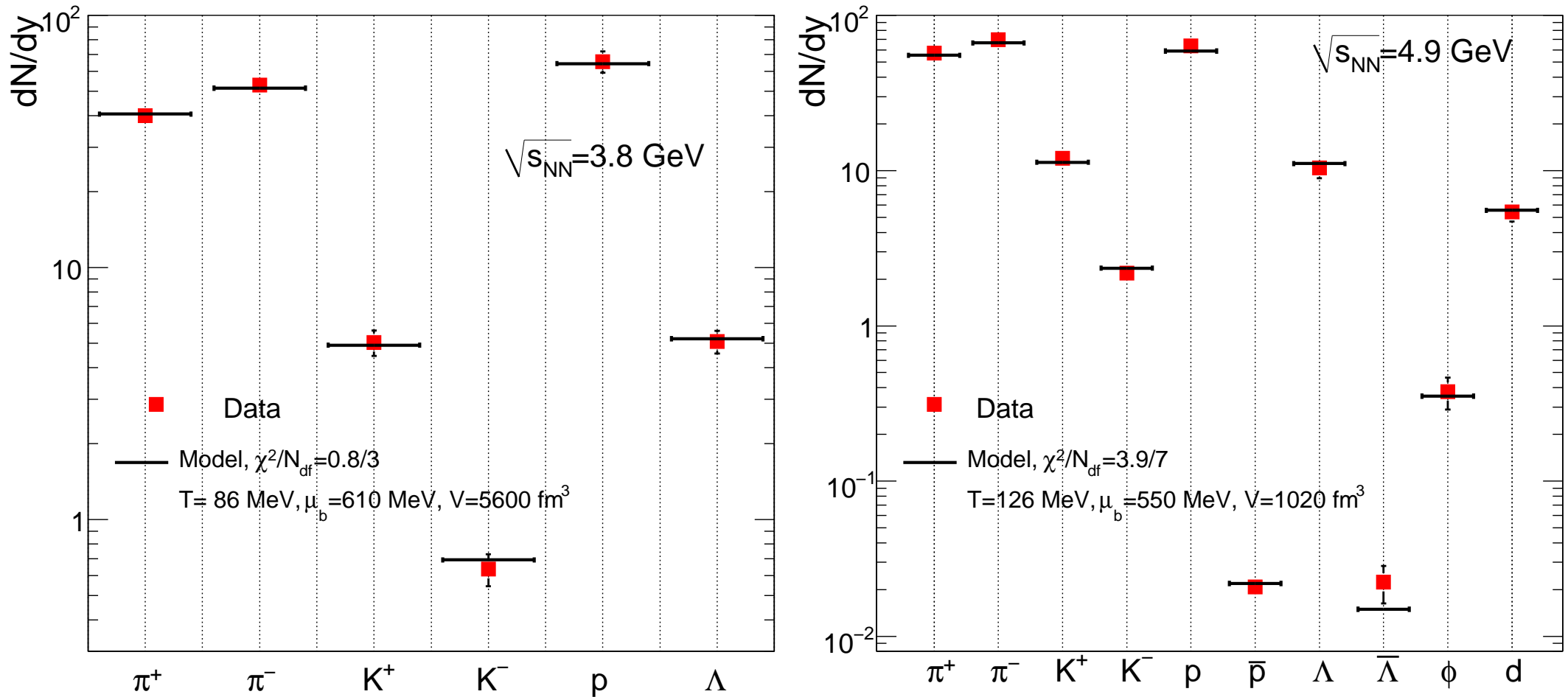
not quite the right ordering at low energies

begs for a clarification (at SIS100)

[together with a host of flow features]

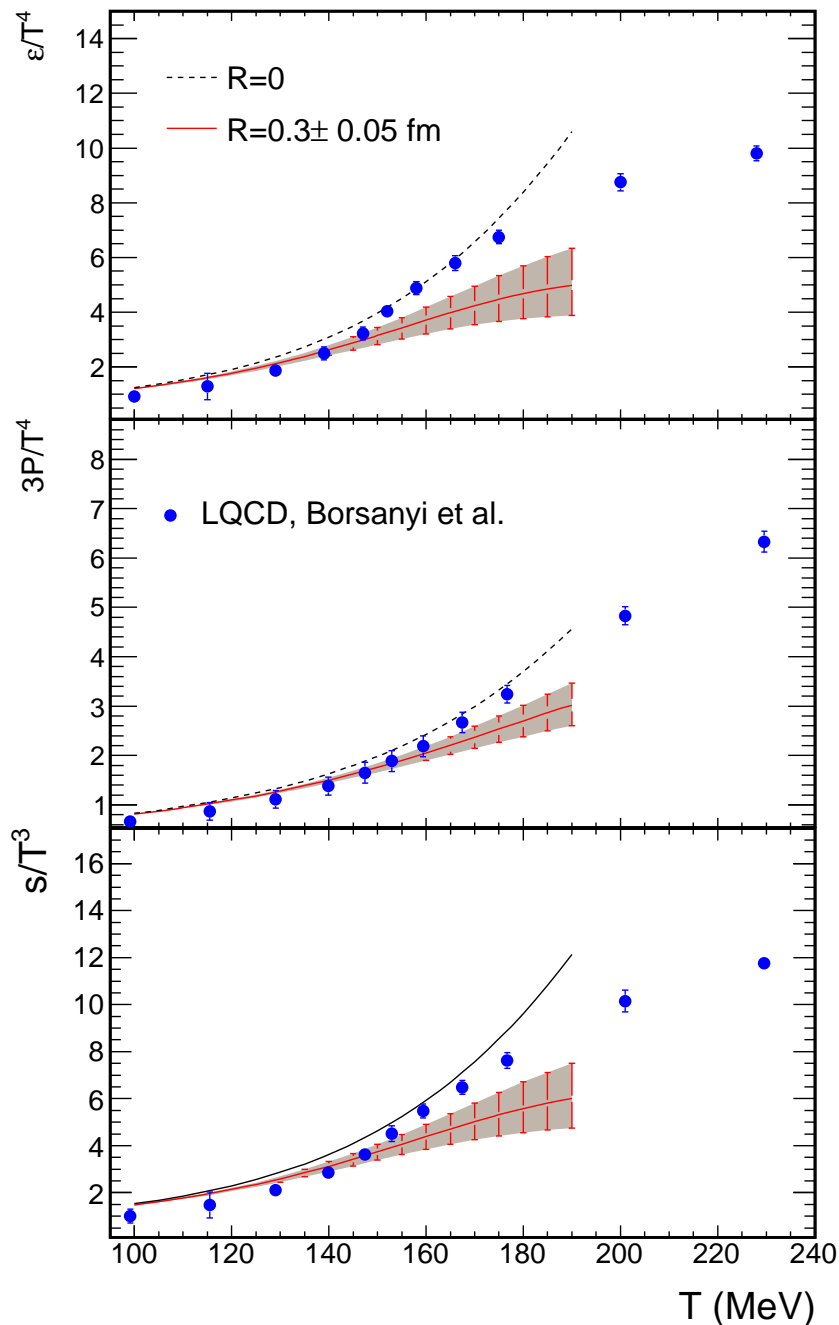


Fits at AGS: 6 and 10.5 AGeV



AGS, 2-8 AGeV: a rather small set of hadron yields measured
 this may lead to a downward bias on T

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 $T < T_c$)
Borsanyi et al., arXiv:1011.4229
- 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

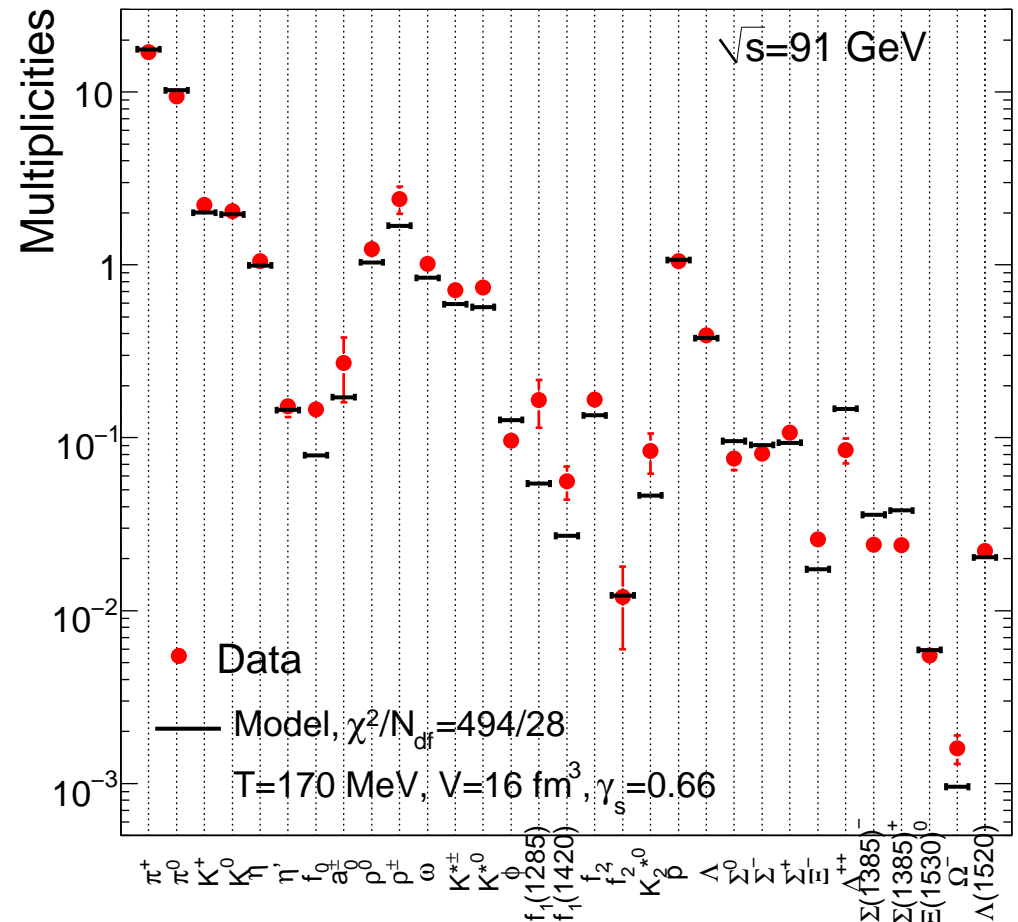
...because it works (albeit less well
and with extra parameters than in
AA) for the large majority of hadrons
(and gives similar T)

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



Statistical hadronization of heavy quarks: assumptions

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

- all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq 0.1 \text{ fm}/c$)
- 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 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 : $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2}g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$
- $N_{c\bar{c}} \ll 1 \rightarrow$ Canonical (J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137):

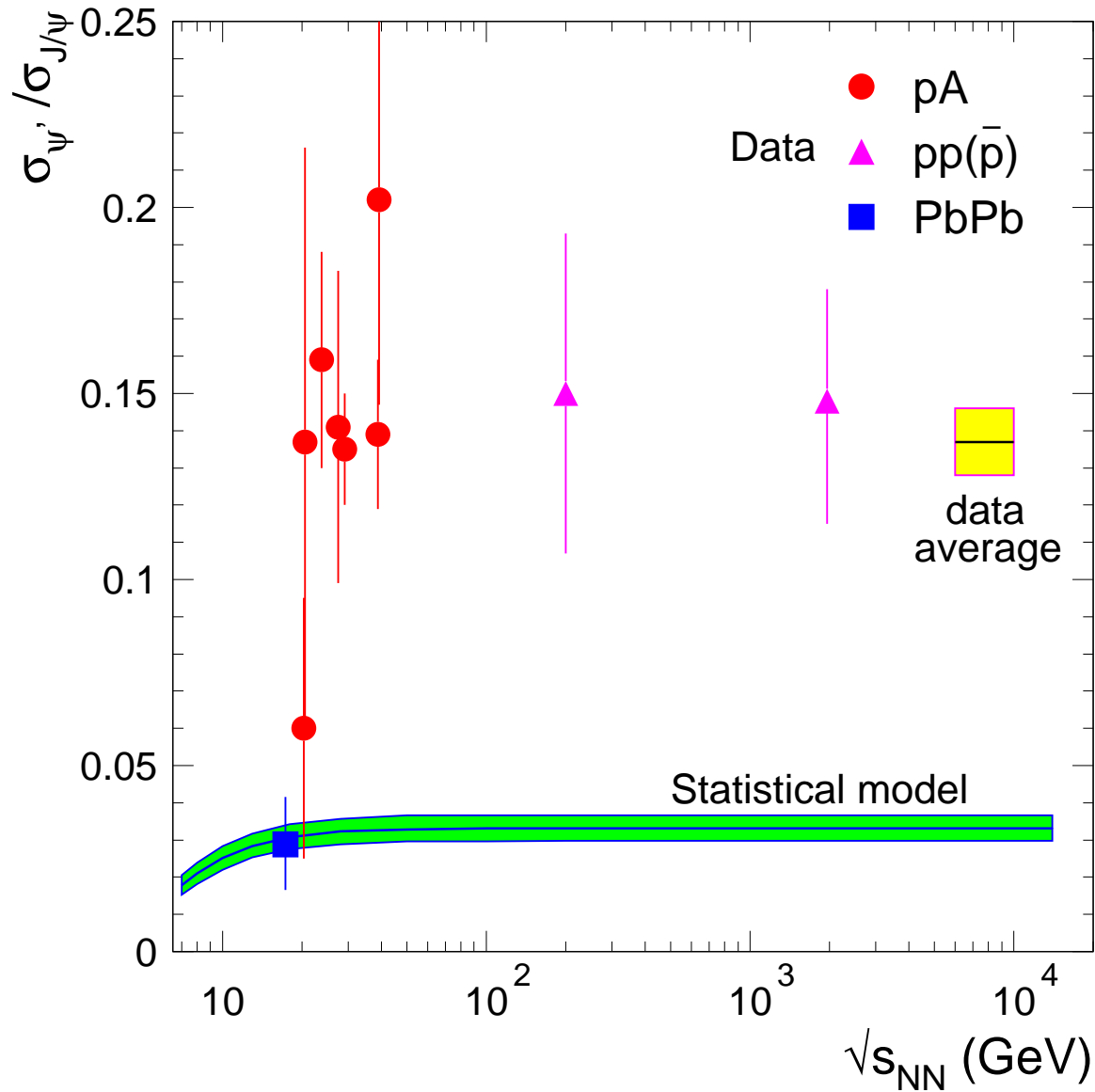
$$N_{c\bar{c}}^{dir} = \frac{1}{2}g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \rightarrow g_c \text{ (charm fugacity)}$$

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

Inputs: $T, \mu_B, V_{\Delta y=1} (= (dN_{ch}^{exp}/dy)/n_{ch}^{th}), N_{c\bar{c}}^{dir}$ (pQCD or exp.)

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

The “null hypothesis”

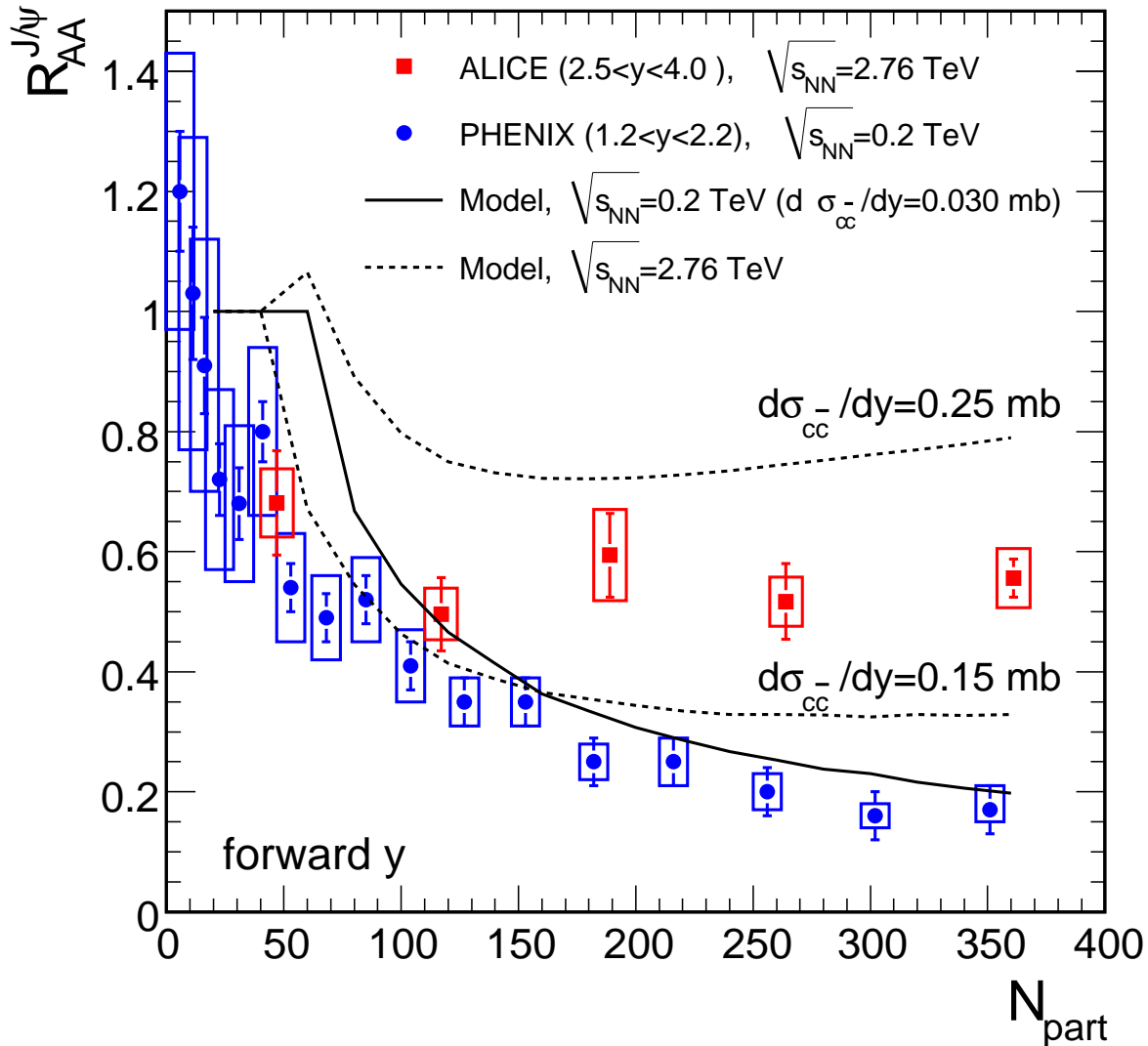


charmonium in pp(A) collisions

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

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

Charmonium in the thermal model



- "suppression" at RHIC

- "enhancement" at LHC

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

"generic" predictions
validated by data

What is so different at LHC?
(compared to RHIC)

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

A.Andronic et al., arXiv:1106.6321

...an ultimate observable to measure the phase boundary (how low in $\sqrt{s_{NN}}$?)

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

Summary and outlook

the thermal model provides one clear way to obtain “experimental” points on the QCD phase diagram

(with fits of hadron yields; higher moments to follow)

- thermal fits work remarkably well (AGS-RHIC) $\Rightarrow (T, \mu_b, V)$
- limiting temperature \Rightarrow phase boundary ($T_{lim} \simeq T_c$)
→ for the skeptics... **LHC case decisive** ...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 $\mu_b > 500$ MeV
- **Good agreement with J/ψ (and ψ') data ...is scrutinized further (LHC)**

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

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

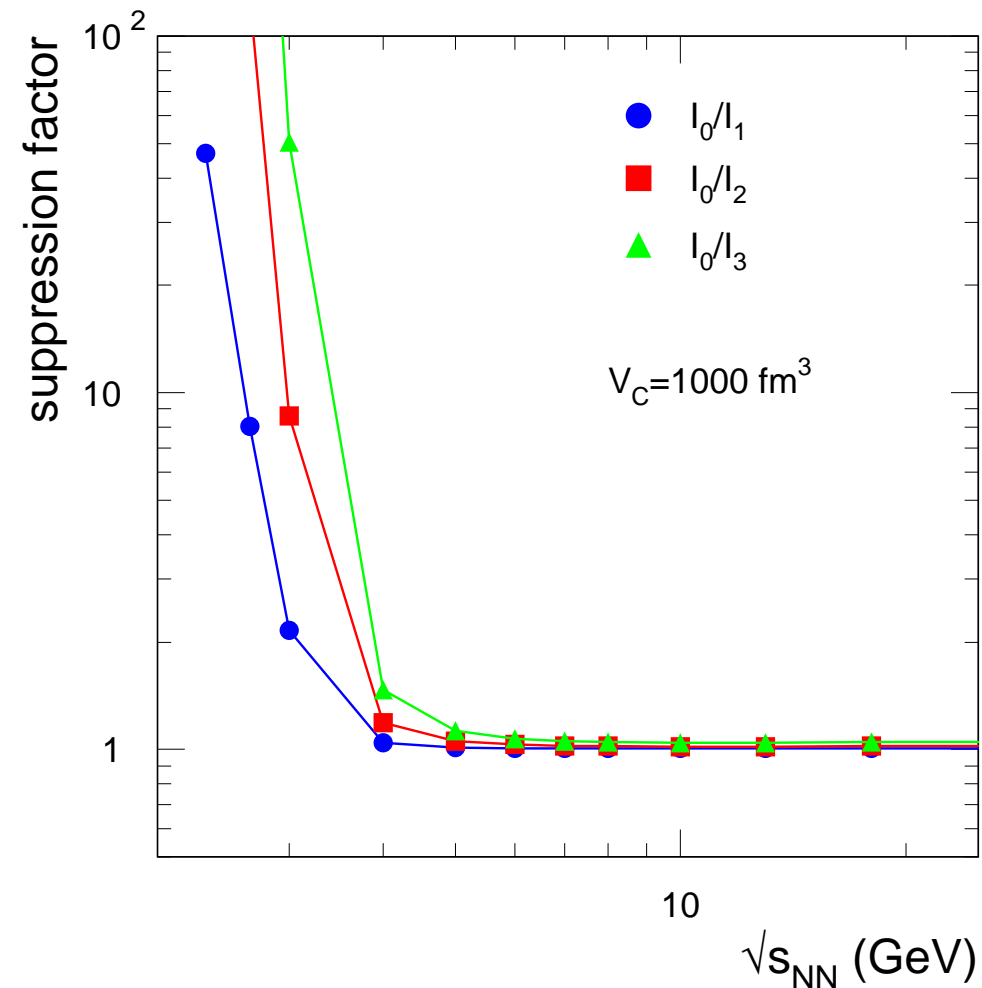
$$N_S = V \cdot \sum S \cdot n_{i,S},$$

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

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

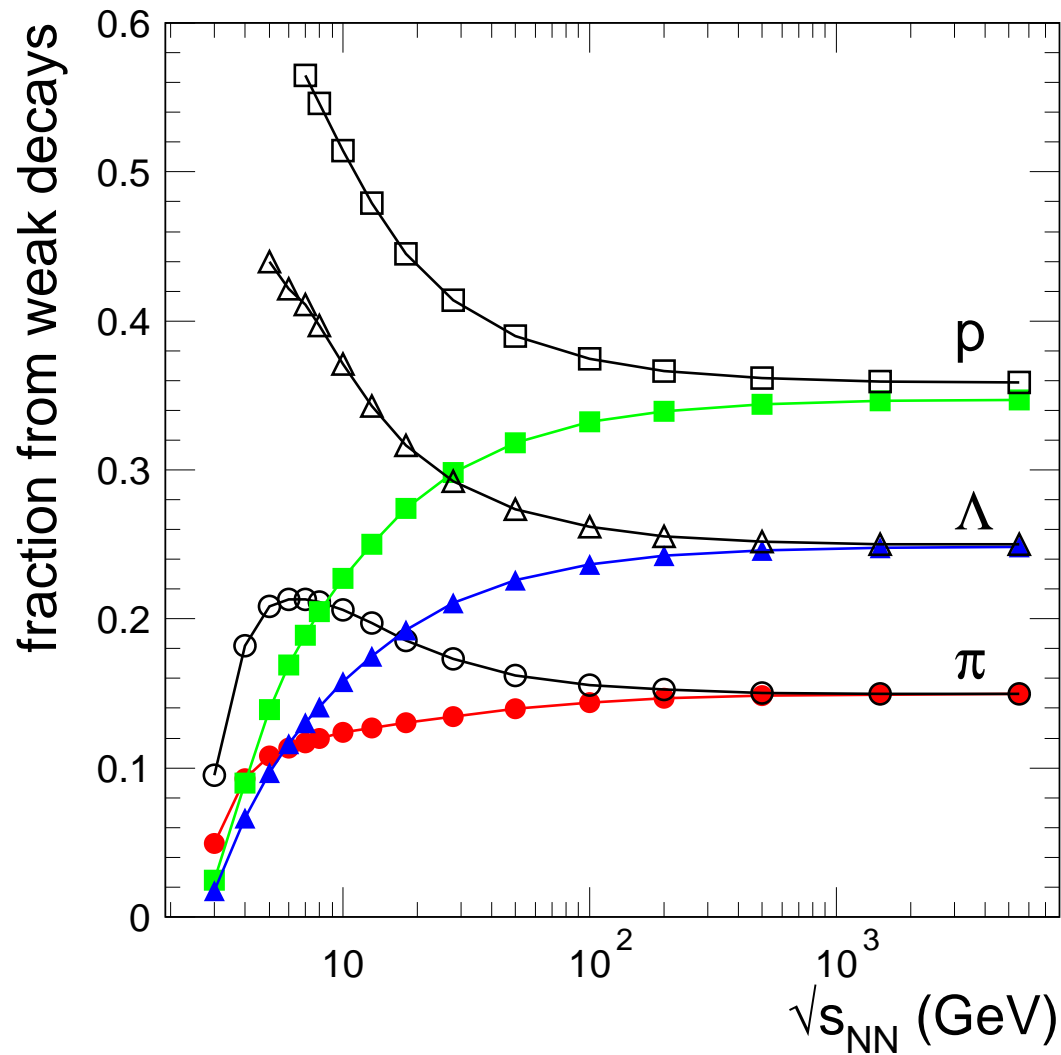
$$n_{\phi}^C = n_{\phi}^{GC}$$

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

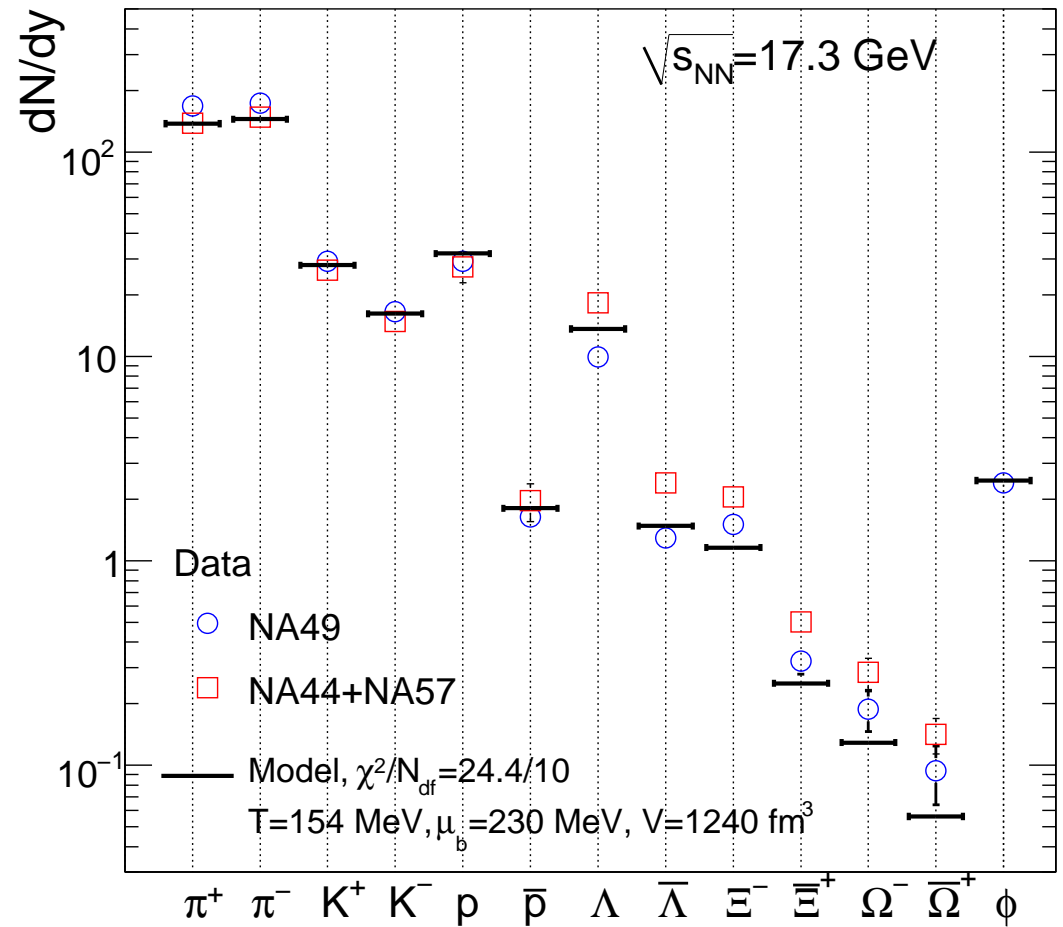
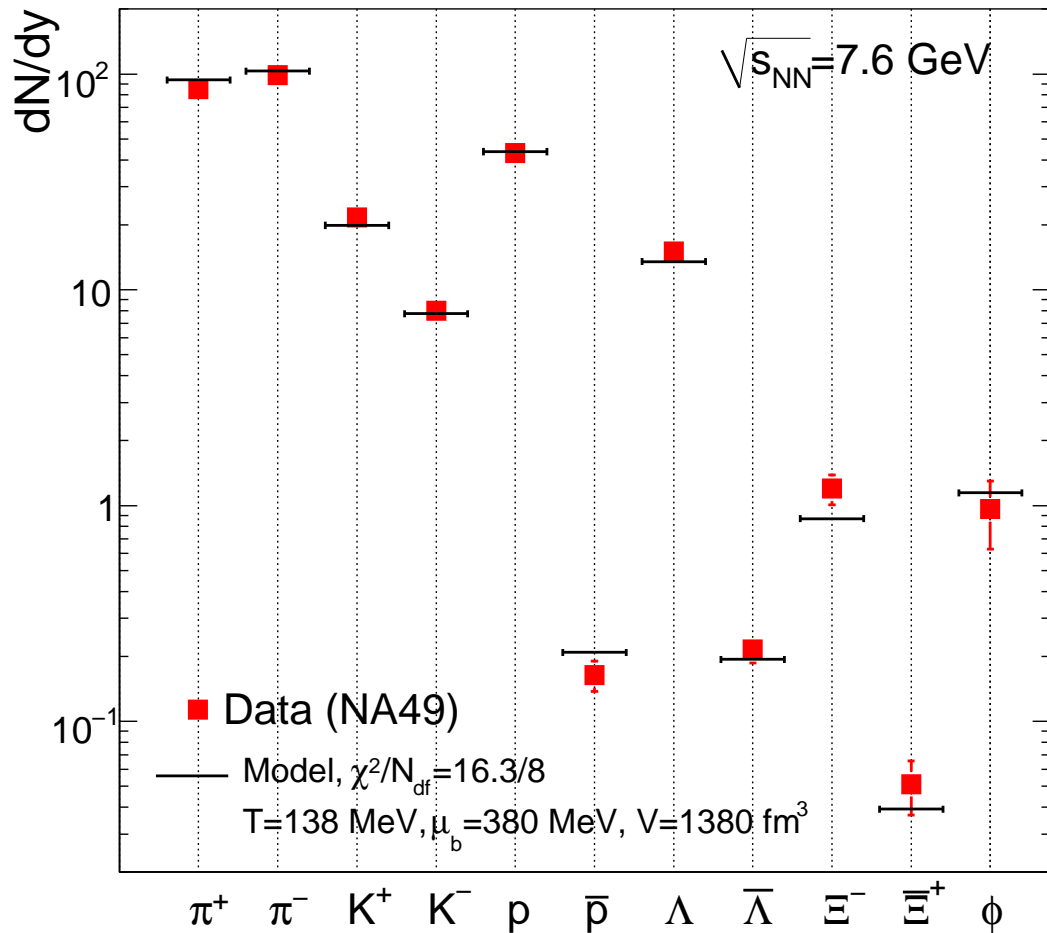


Fraction of yields from weak decays

...is not always well controlled in measurements



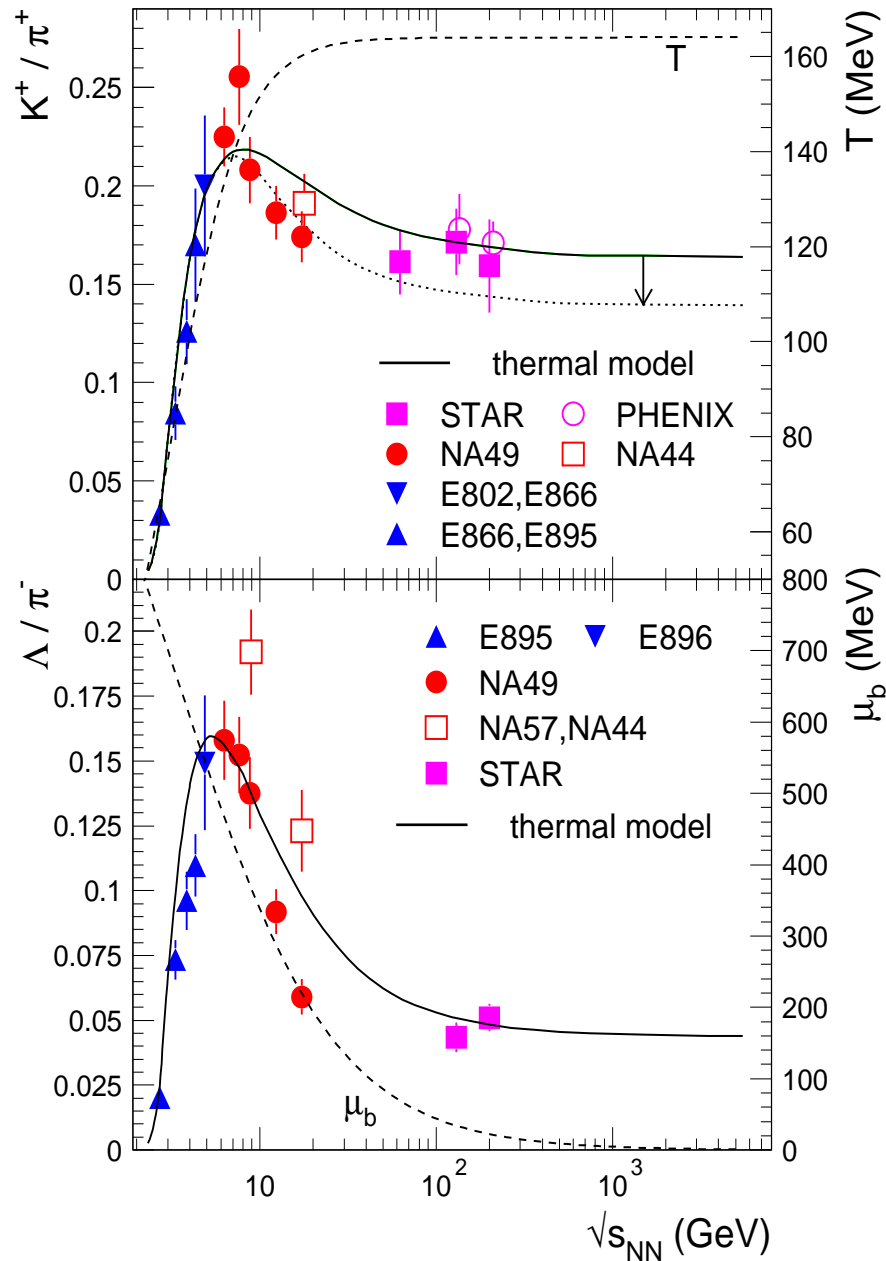
Fits at SPS: 30 and 158 GeV



only NA49 data: $T = 148 \text{ MeV}, \mu_b = 215 \text{ MeV}, V = 1660 \text{ fm}^3, \chi^2/N_{df} = 36/10$

only NA44+NA57: $T = 172 \text{ MeV}, \mu_b = 245 \text{ MeV}, V = 700 \text{ fm}^3, \chi^2/N_{df} = 30/10$

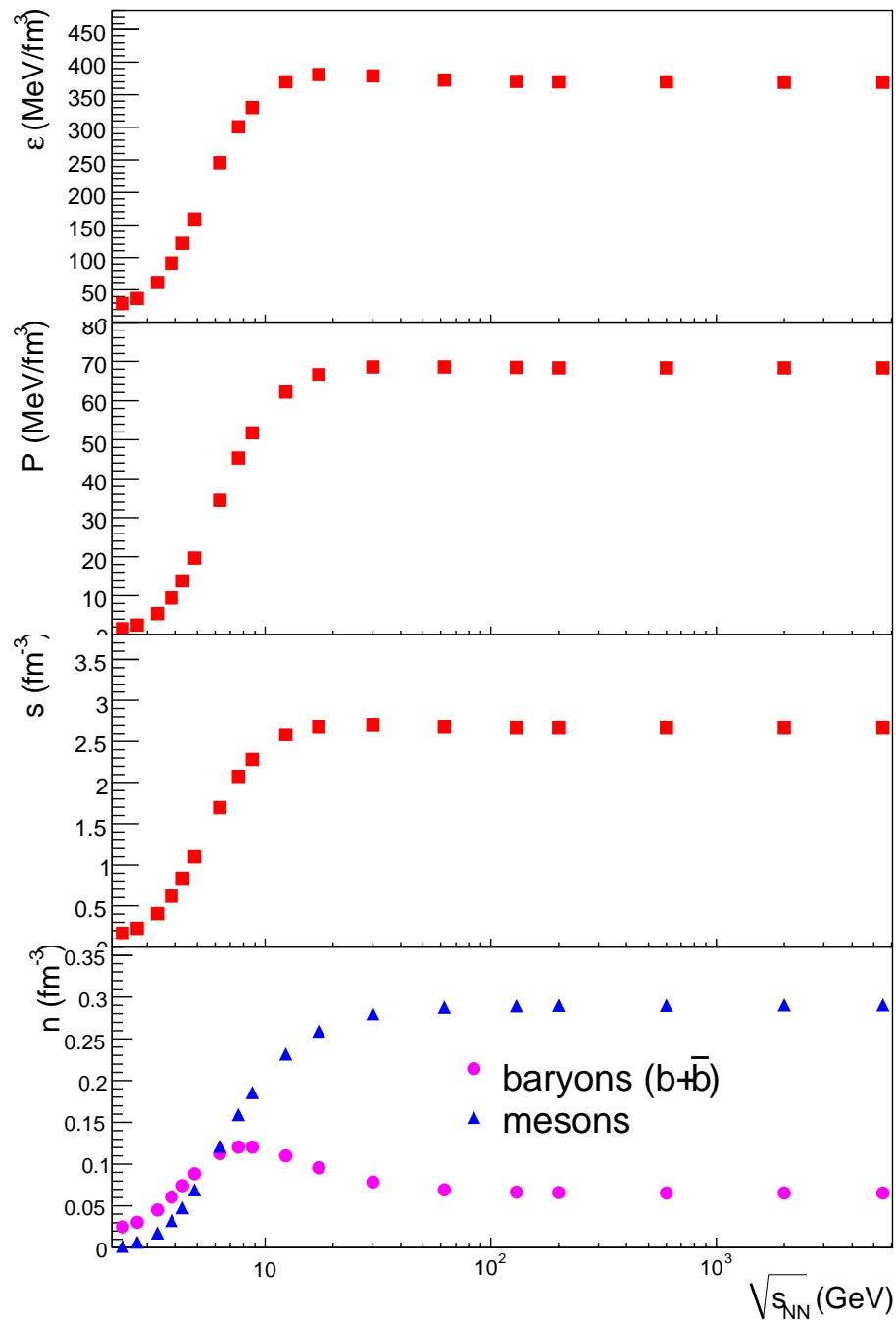
“The horn” (s) as of 2009



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): $t_{QGP} \simeq 1 \text{ fm}/c \sim t_{J/\psi}$
 - RHIC, LHC: $t_{QGP} \lesssim 0.1 \text{ fm}/c \sim t_{c\bar{c}}$

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

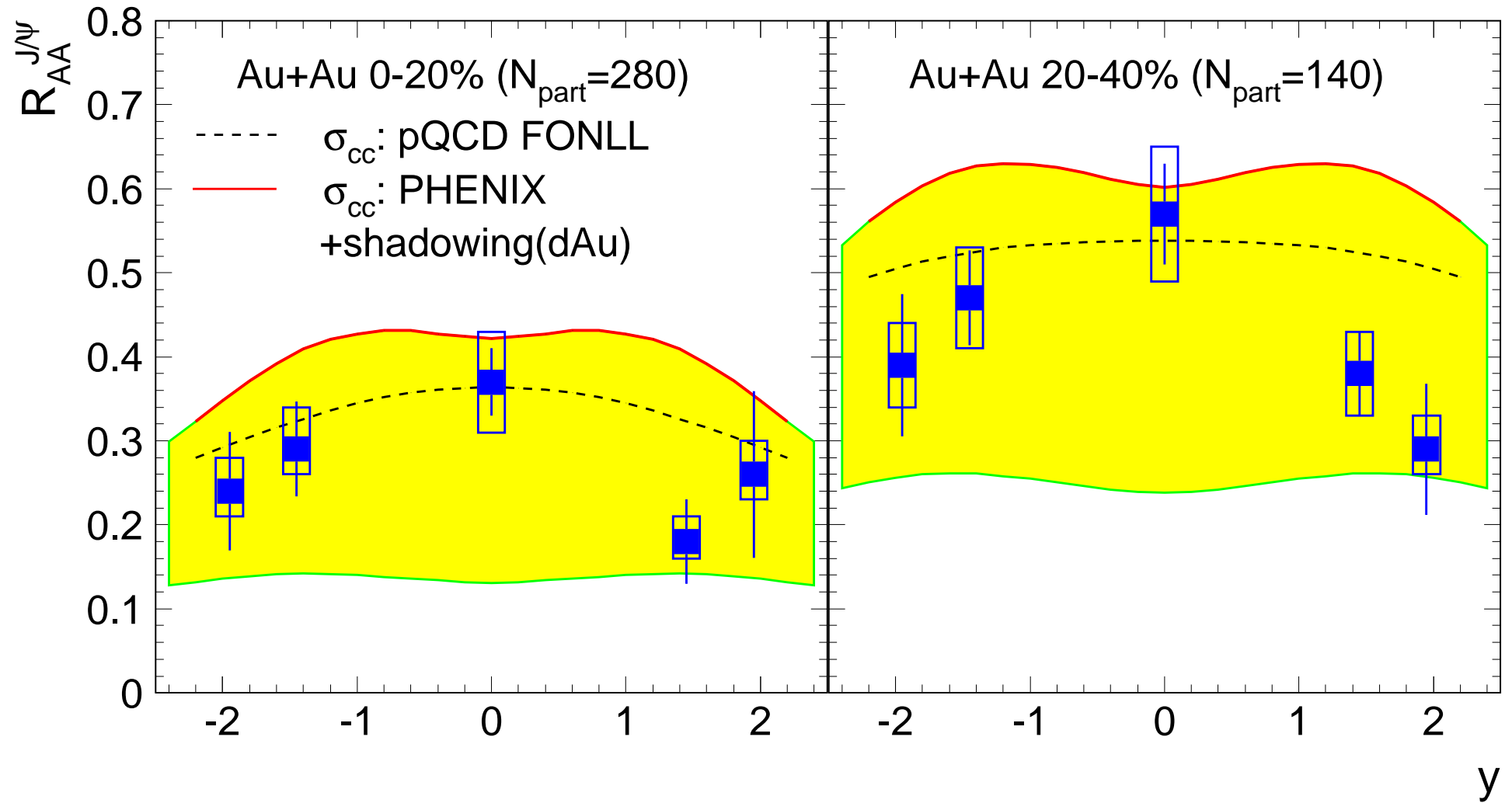
- collision time, $t_{coll} = 2R/\gamma_{cm}$
 - SPS (FAIR): $t_{coll} \gtrsim t_{J/\psi}$
 - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} \ll t_{J/\psi}$

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?)

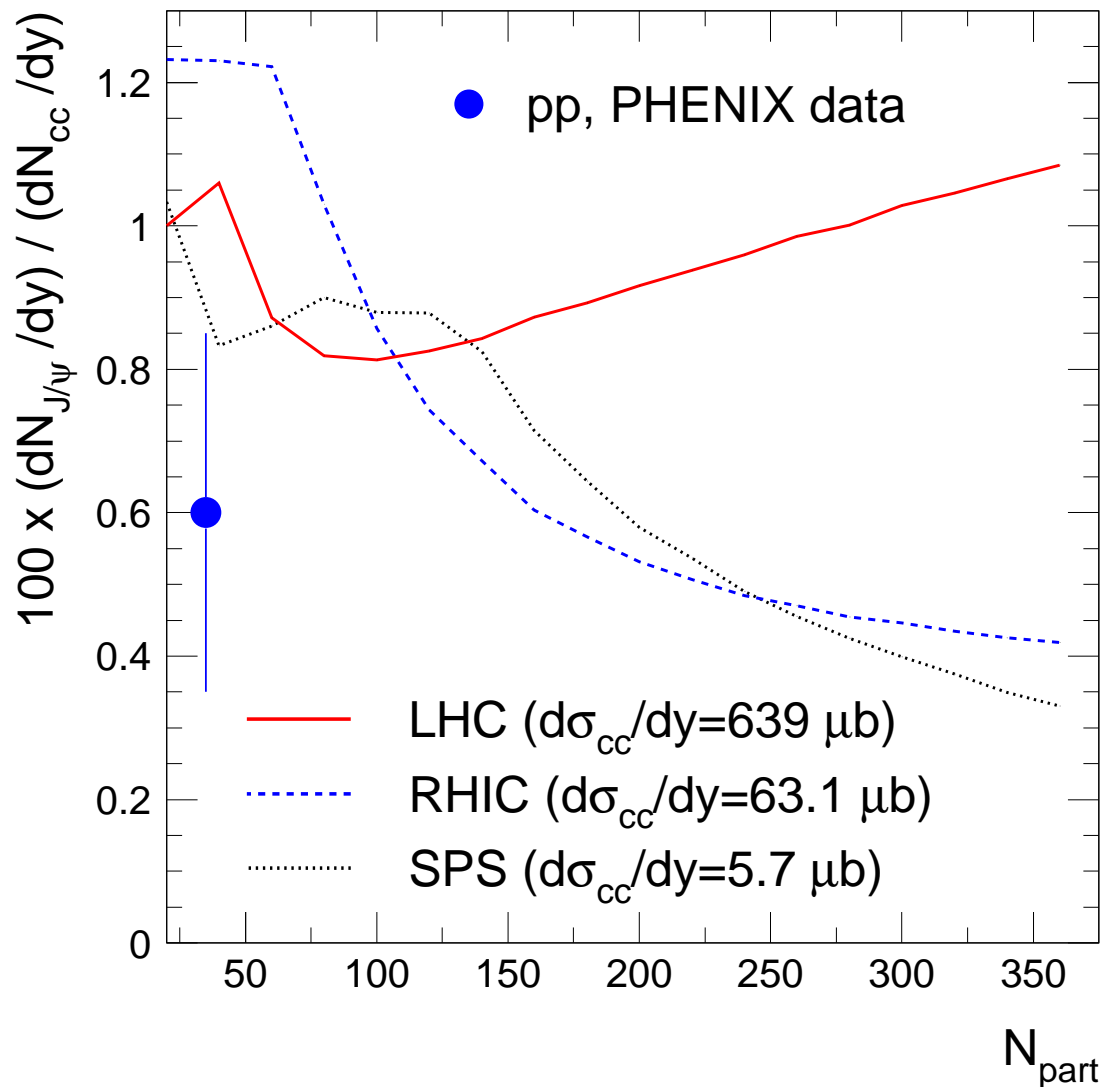
NB: the only way to distinguish: measure $\sigma_{c\bar{c}}$ in pA and AA

J/ψ at RHIC: effect of shadowing



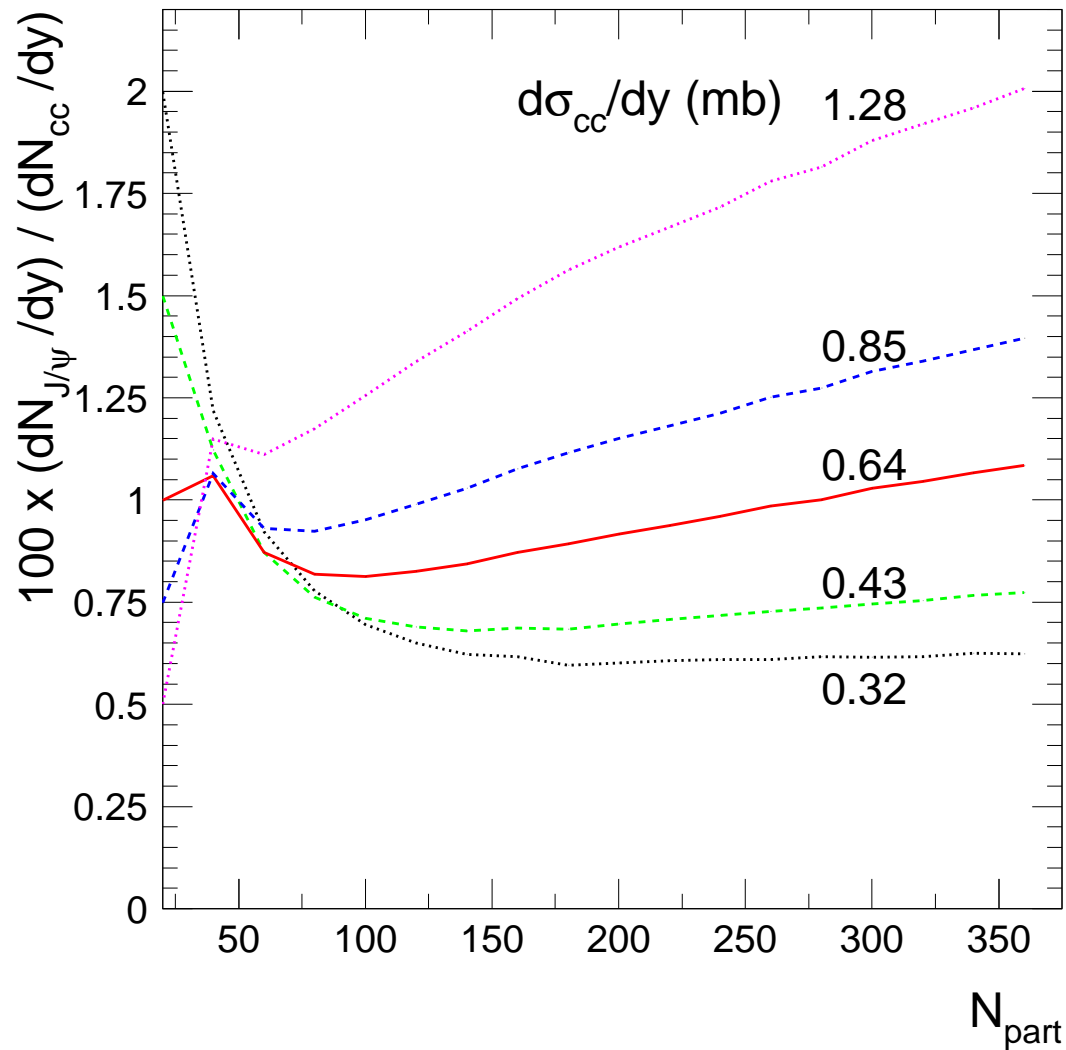
model describes data with PHENIX $\sigma_{c\bar{c}}$ (lower error plotted)

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



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