Hadron Production in ultra-relativistic nuclear collisions and the QCD phase boundary

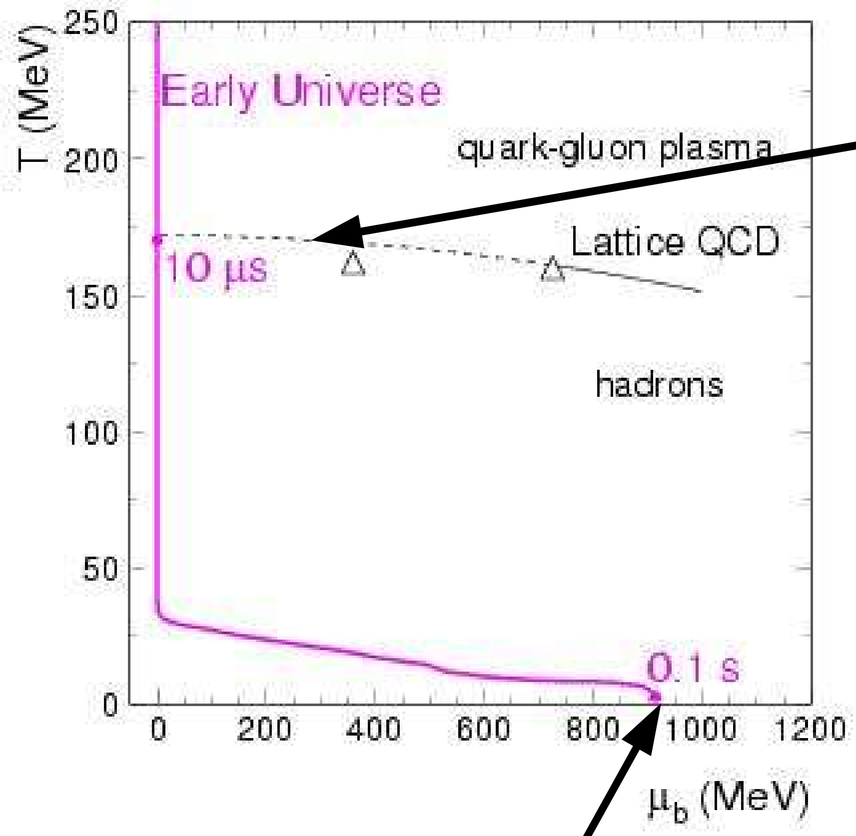
- introductory remarks
- the thermal/statistical model
- results for AA collisions
- a note on thermal models in elementary collisions
- the special role of heavy quarks
- interpretation of the chemical freeze-out curve at small mu_b
- speculation on the chemical freeze-ot curve at large mu_b

Symposium on Dense Baryonic Matter
GSI, March 2009

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

Peter Braun-Munzinger

Evolution of the Early Universe



QCD Phase Boundary

Homogeneous Universe in Equilibrium, this matter can only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

The fireball emits hadrons fron an equilibrium state

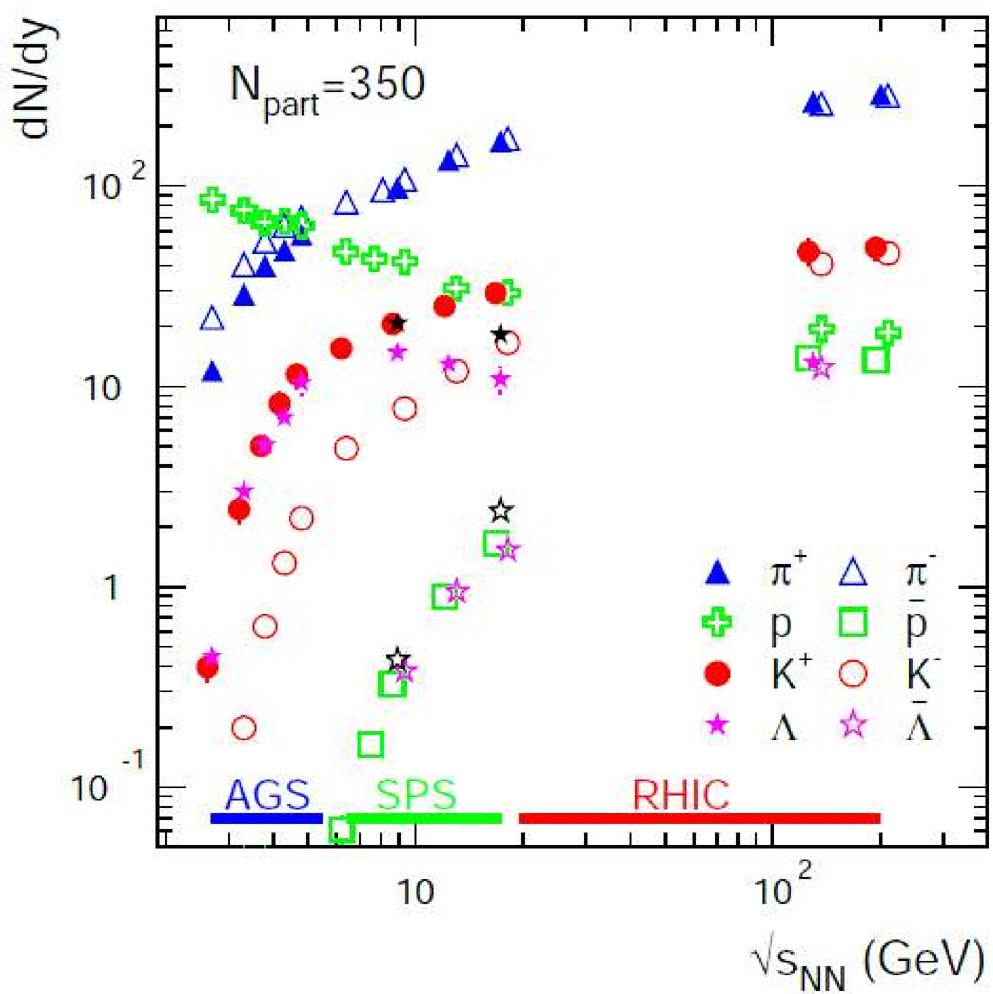
- From low AGS energy on, all hadron yields in central PbPb collisions reflect grand-canonical equilibration
- Strangeness suppression observed in elementary collisions is lifted
- Equilibration at SIS energy?

how do we get information on the phase boundary?

For a recent review see:

pbm, Stachel, Redlich, QGP3, R. Hwa, editor, Singapore 2004, nucl-th/0304013

Particle production in central AA collisions



a summary of 15 years of experimental research

Thermal model description of hadron yields

Grand Canonical Ensemble

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

$$n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\, dp}{\exp((E_i - \mu_i)/T) \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

for every conserved quantum number there is a chemical potential μ
but can use conservation laws to constrain:

- Baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \quad \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered

for rapidity slice fix volume e.g. by dN_{ch}/dy

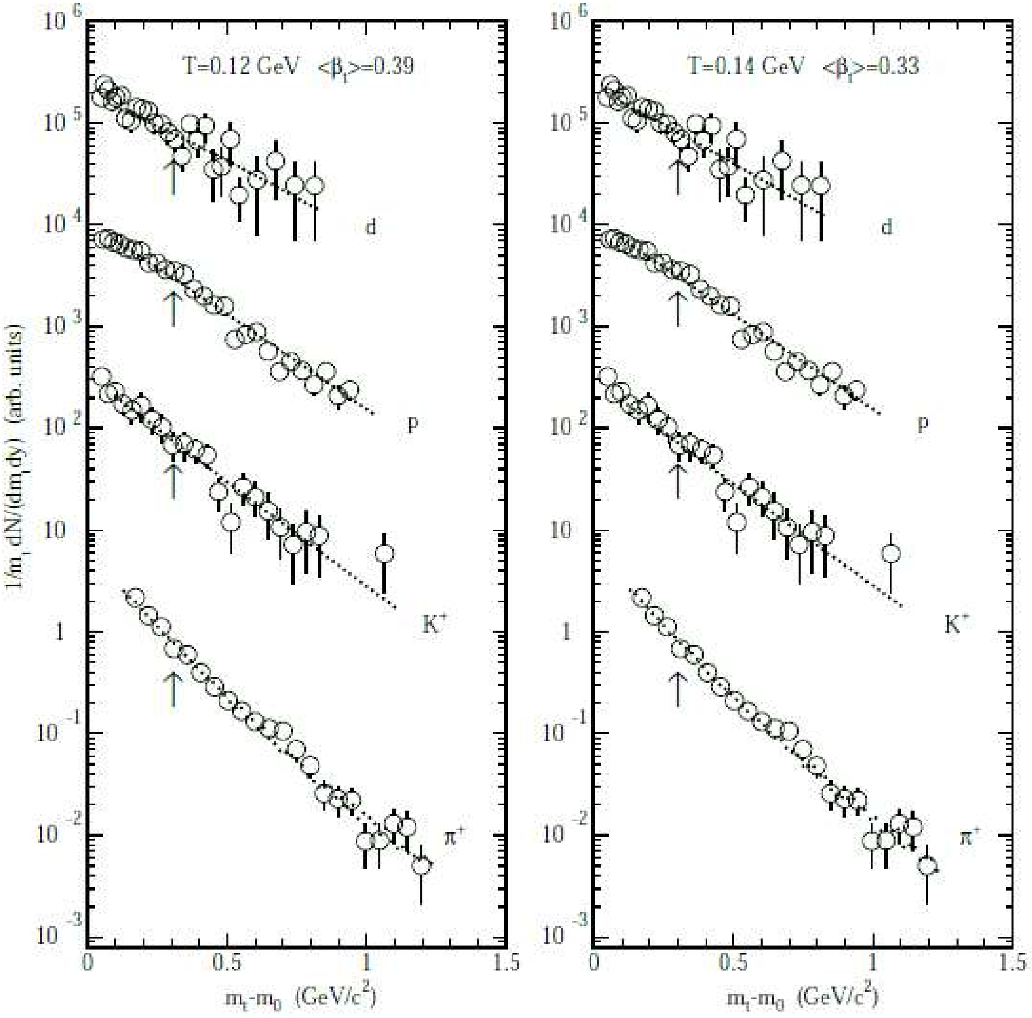
Fit at each energy provides values for T and μ_b and volume V when fitting yields

First thermal model results in 1994 for AGS data

Phys. Lett. B344 (1995) 43
nucl-th/9410026

T = 120 MeV, mu_b = 540 MeV

pion spectra exhibit increase at low pt due to the Delta resonance

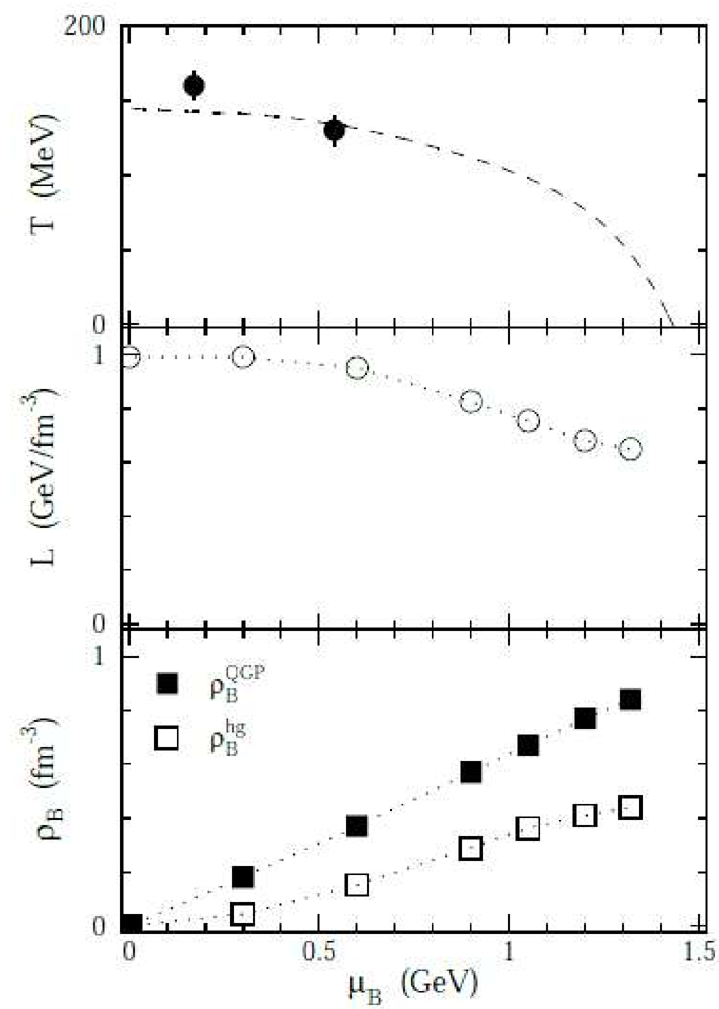


First attempt to establish connection to phase boundary

Phys. Lett. B365 (1996) 1
nucl-th/9508020

equation of state from a bag model, transition 1[st] order by construction

only 2 data points at AGS and SPS

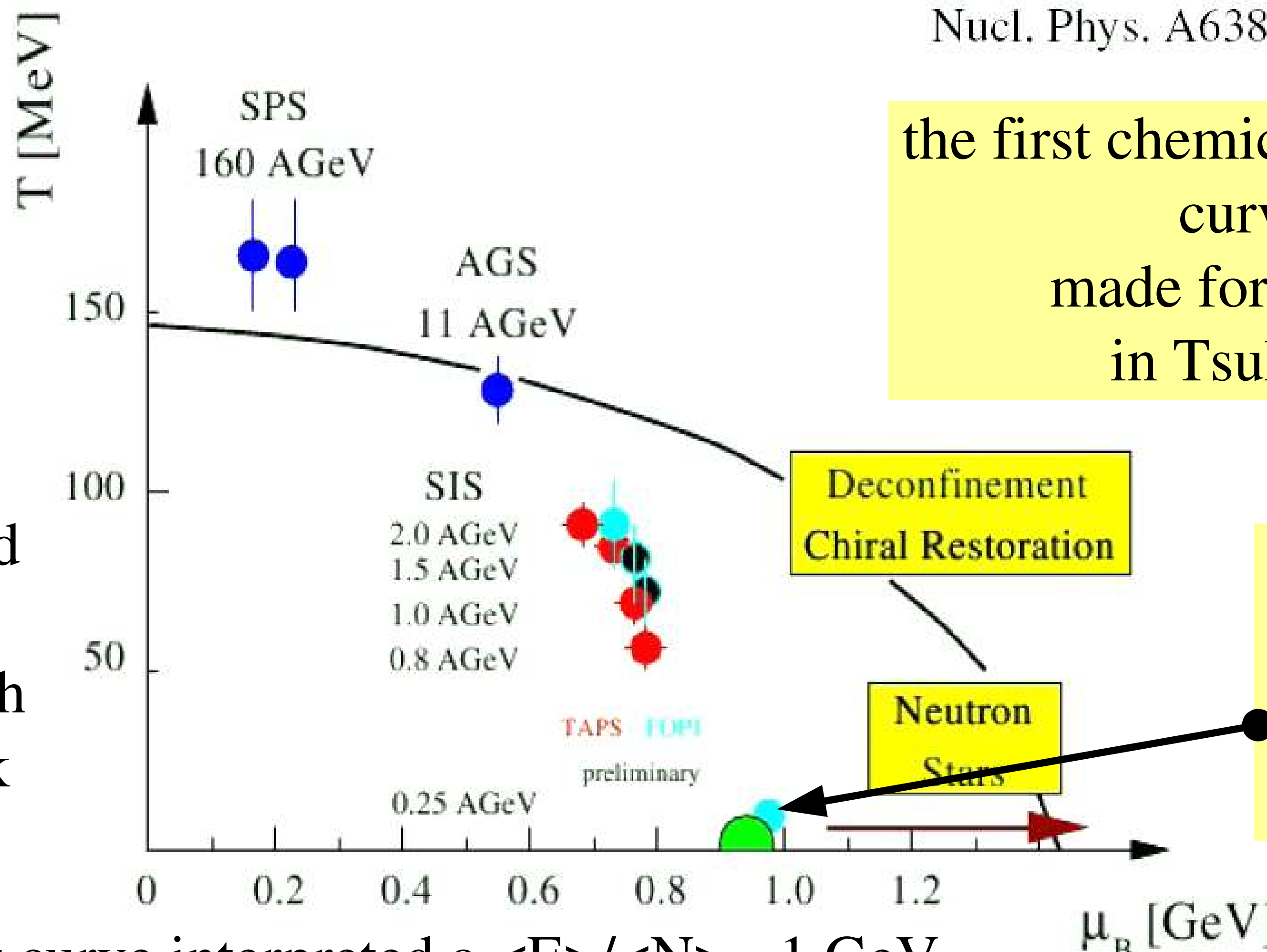


Establishing the chemical freeze-out curve

P.Braun-Munzinger and J. Stachel, nucl-th/9803015, Nucl. Phys. A638 (1998) 3

the first chemical freeze-out curve
made for QM97
in Tsukuba

compilation of TAPS and FOPI data together with R. Averbeck



note the entry at T = 15 MeV!

freeze-out curve interpreted a <E>/<N>= 1 GeV
by Cleymans and Redlich, Phys. Rev. Lett. 81 (1998) 5284
nucl-th/9808030

Energy dependence of hadron ratios

empirical energy dependence along chemical freeze-out line

$$T[\mathrm{MeV}] = T_{lim}\left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\mathrm{GeV})) - 2.9)/1.5}\right)$$

$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})},$$

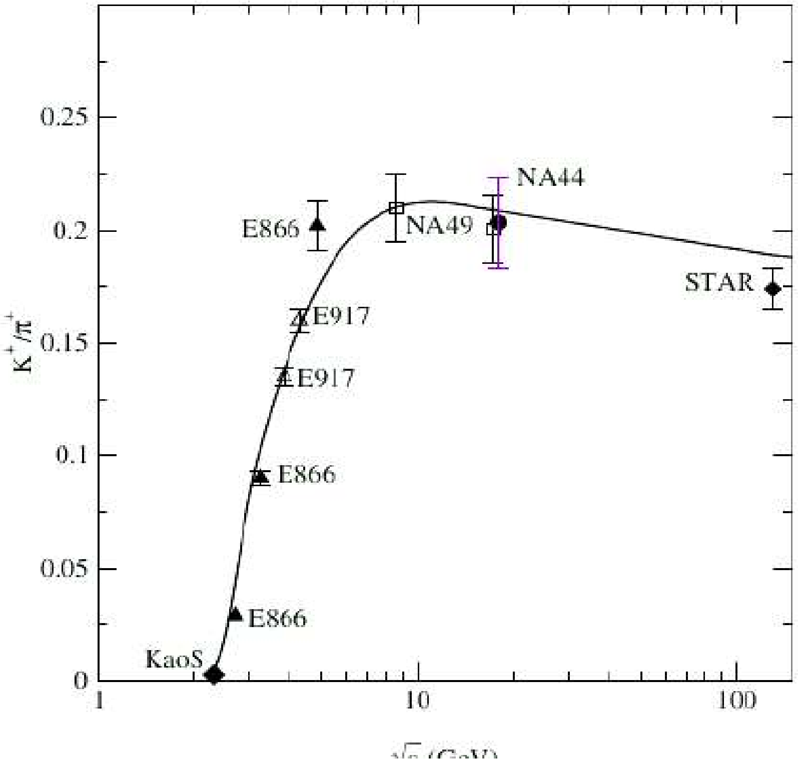
and $a = 1290 \pm 115$ MeV and $b = 0.28 \pm 0.047$ GeV^{-1}

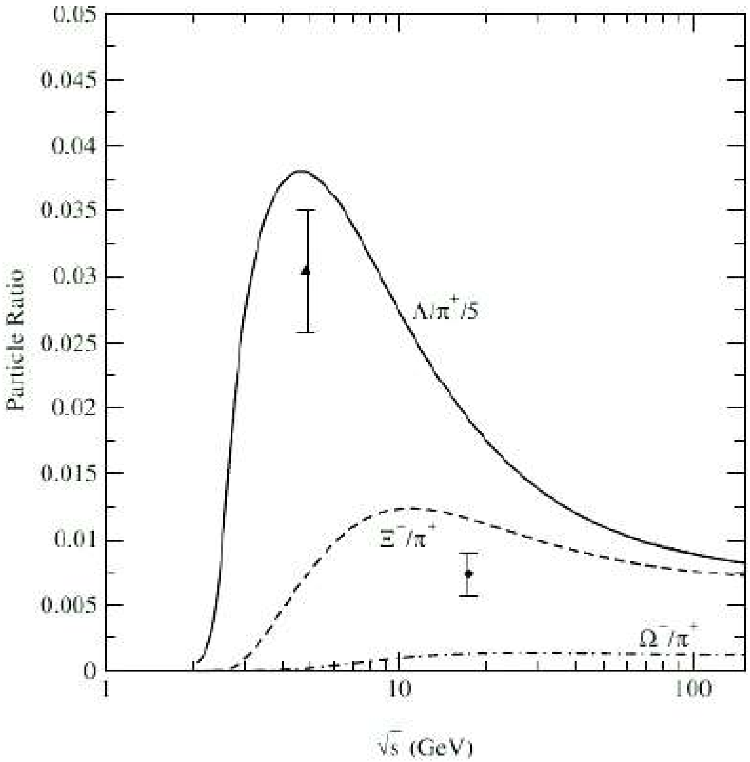
implies non-trivial energy dependence of hadron ratios

First attempt in 2001

pbm, J. Cleymans, H. Oeschler, K. Redlich,
Nucl. Phys. A697 (2002) 902

prediction of horn in Lambda/pi+
and shoulder in K+/pi+





2005 Analysis of all then available data

improved hadron resonance spectrum
widths of resonances is explicitely taken into account
fits of 4pi and mid-rapidity data

Hadro-chemistry at RHIC -- weakly decaying particles

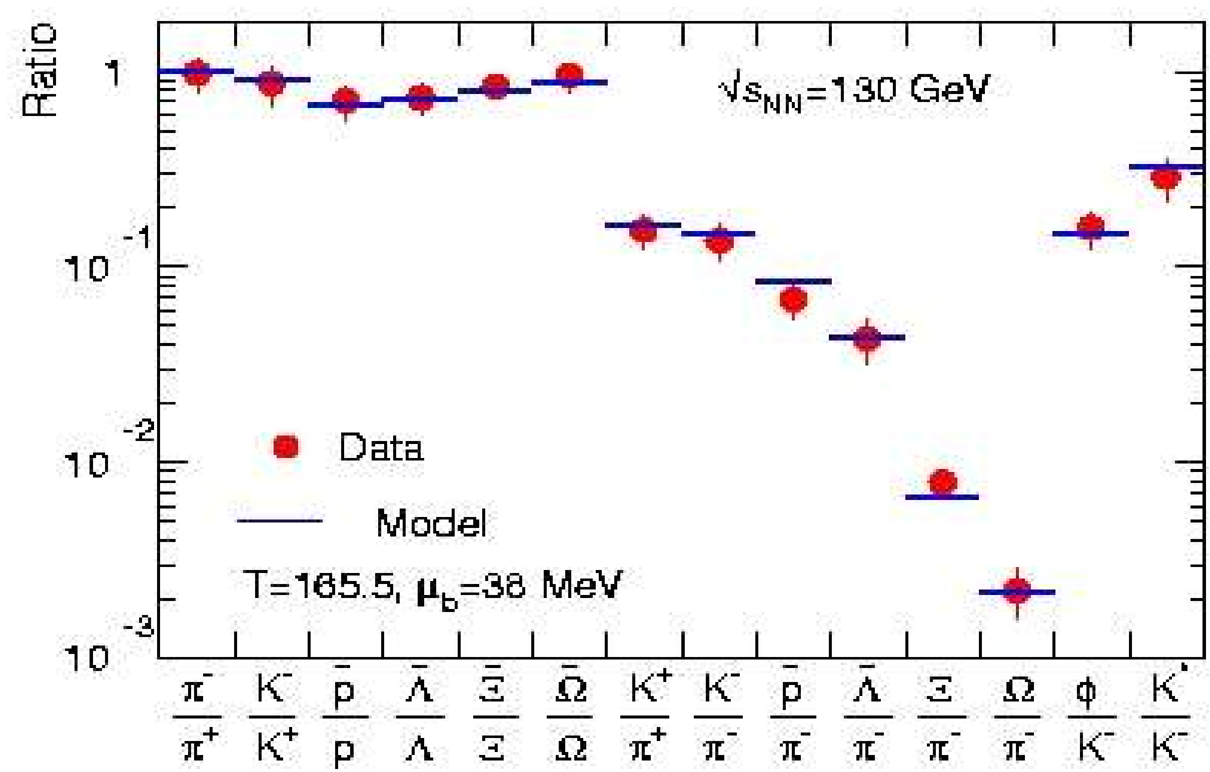
HELMHOLTZ GEMEINSCHAFT

All data in excellent agreement with thermal model predictions

chemical freeze-out at: T = 165 ± 8 MeV

fit uses vacuum masses

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



pbm, d. magestro, j. stachel, k. redlich, Phys. Lett. B518 (2001) 41; see also Xu et al., Nucl. Phys. A698(2002) 306; Becattini, J. Phys. G28 (2002) 1553; Broniowski et al., nucl-th/0212052.

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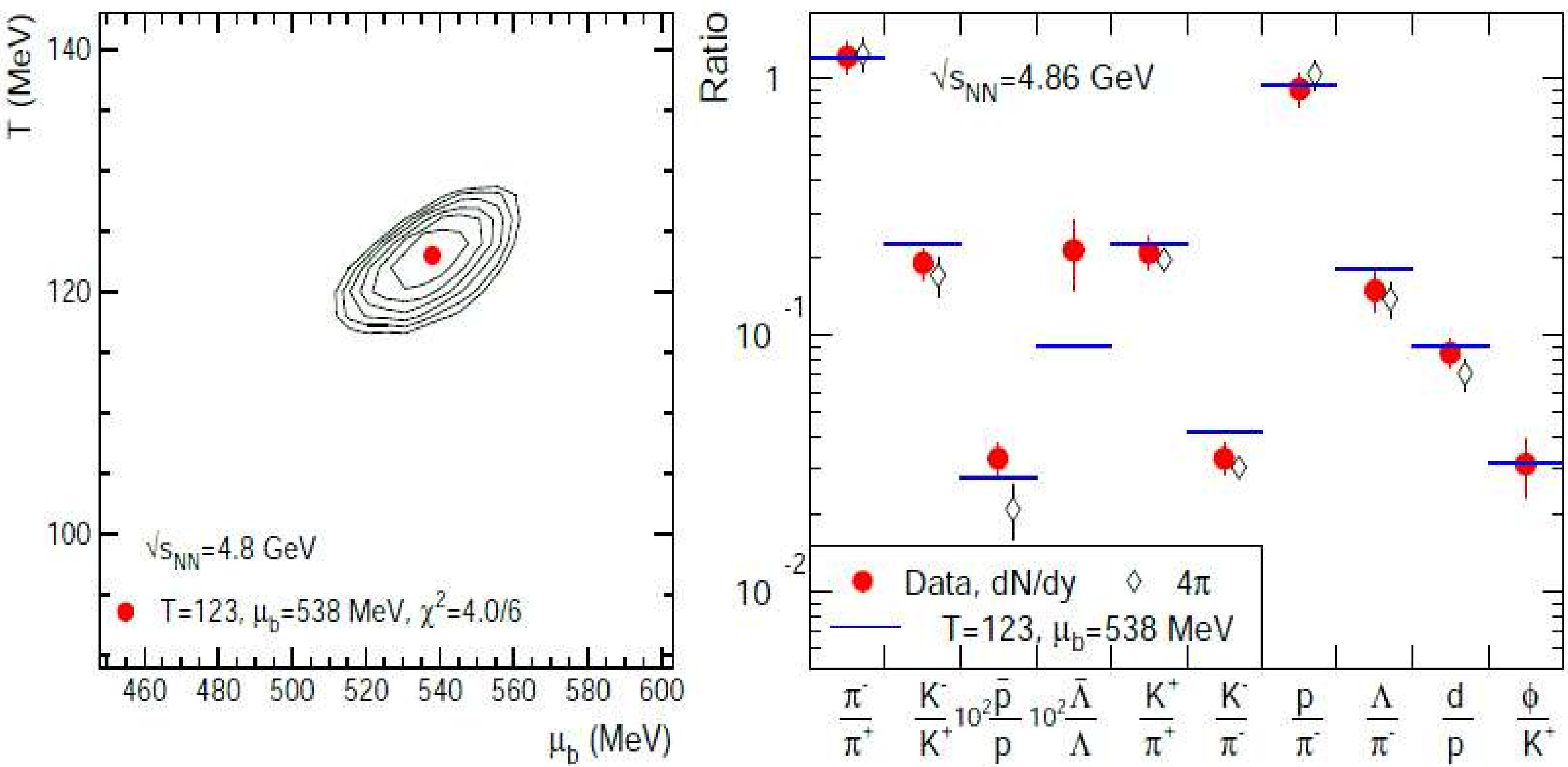
Hadrochemistry at AGS energy



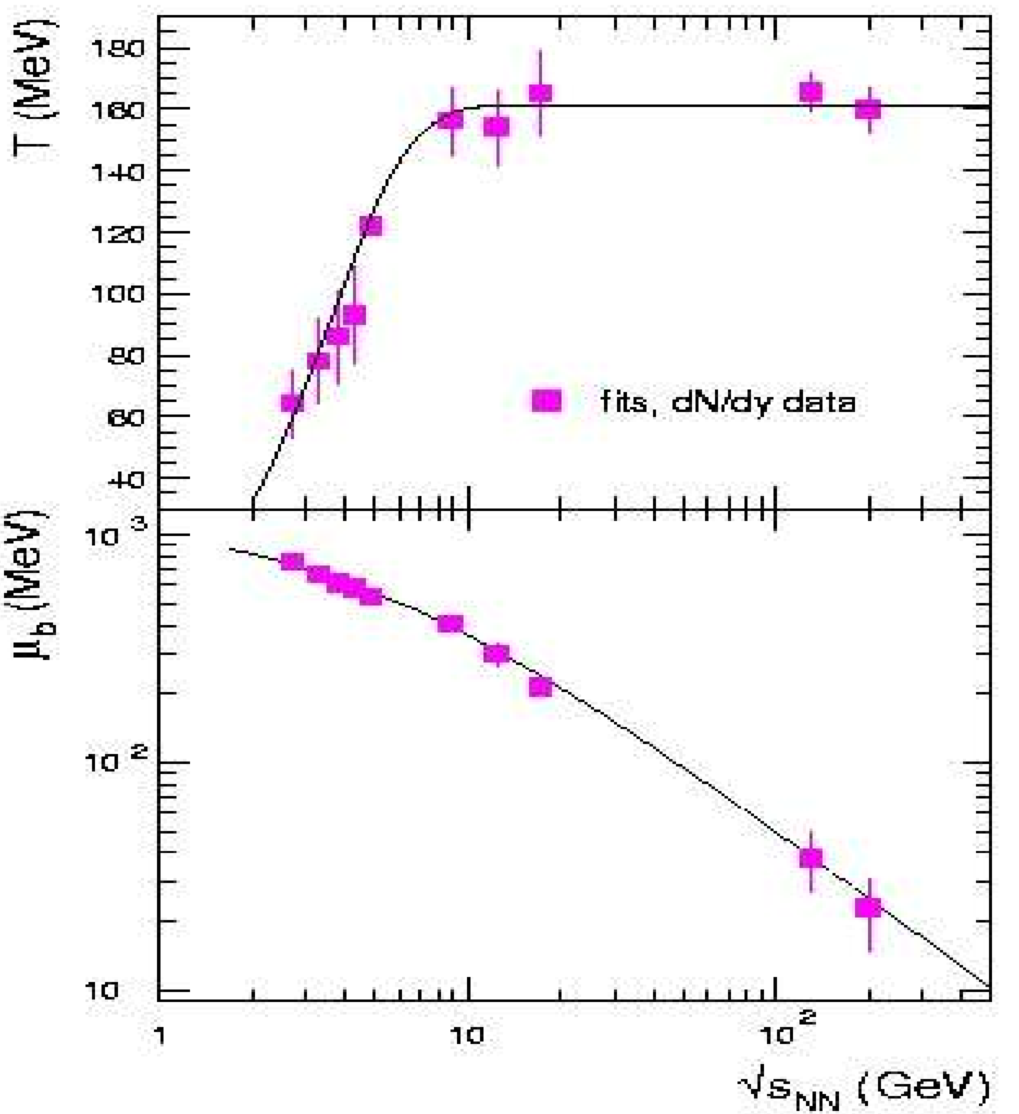
Parameterization of all freeze-out points

note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_B for all energies

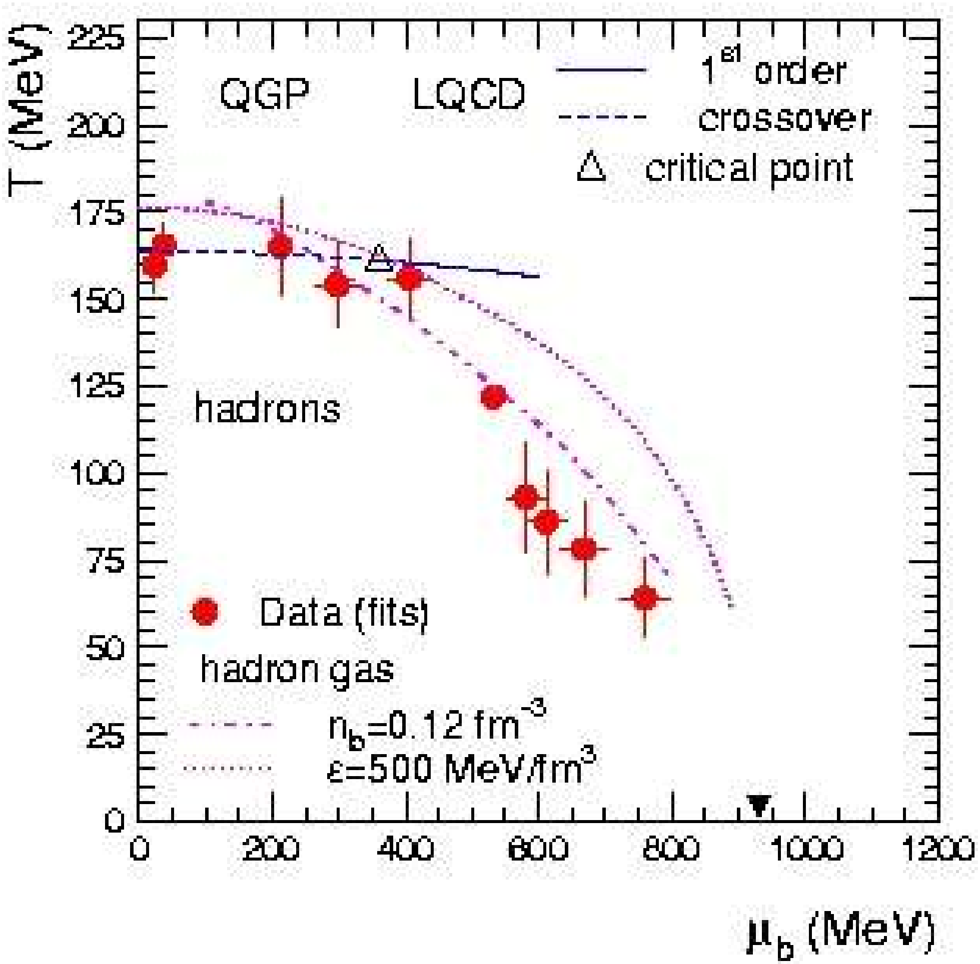
A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167 nucl-th/0511071



The QCD phase diagram and chemical freeze-out

Main result: chemical freeze-out points seem to delineate the QCD phase boundary at small (μ < 400 MeV)

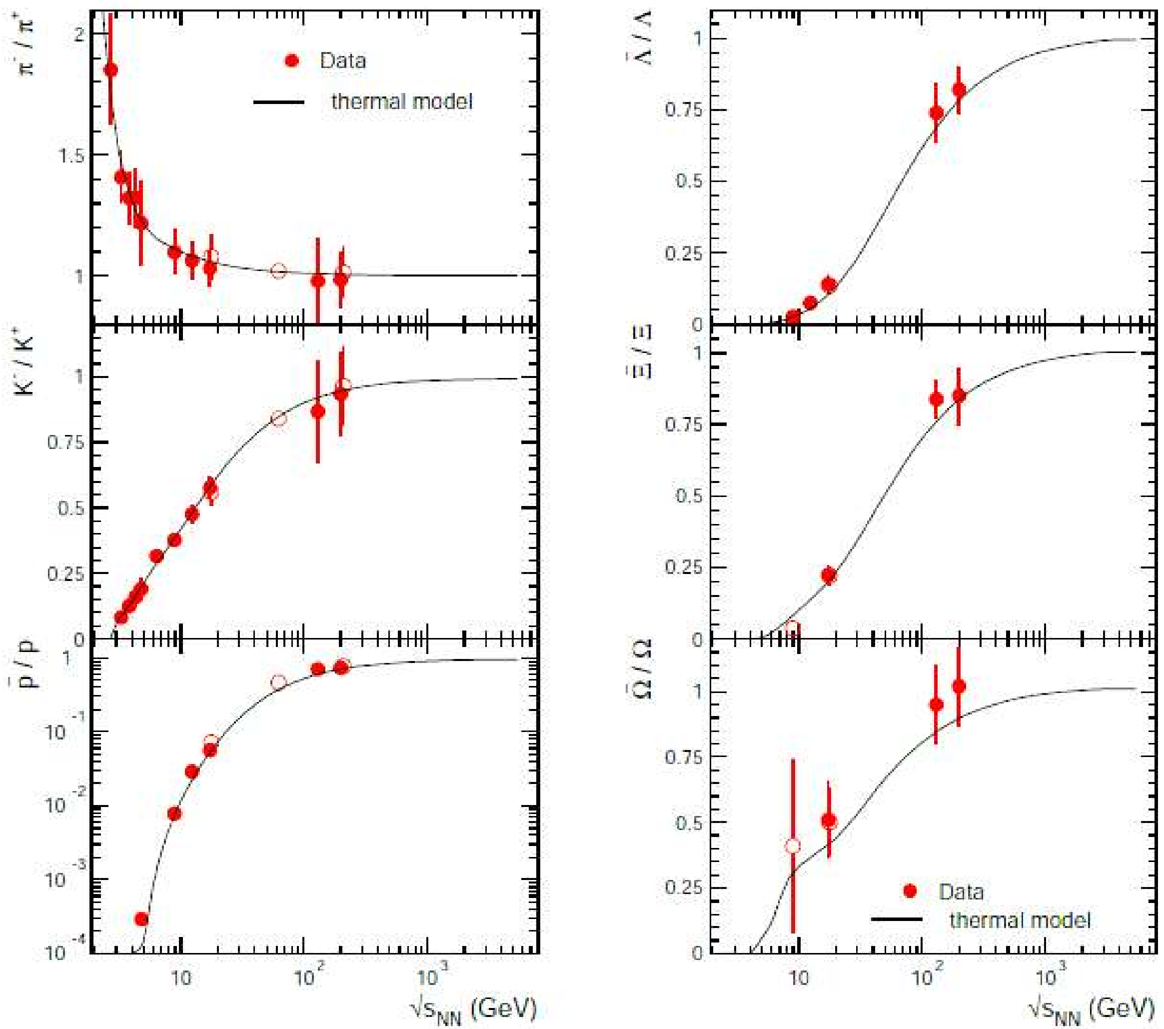
what happens at large μ ?



Energy dependence from 2005 analysis

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

particle/antiparticle ratios
are well described

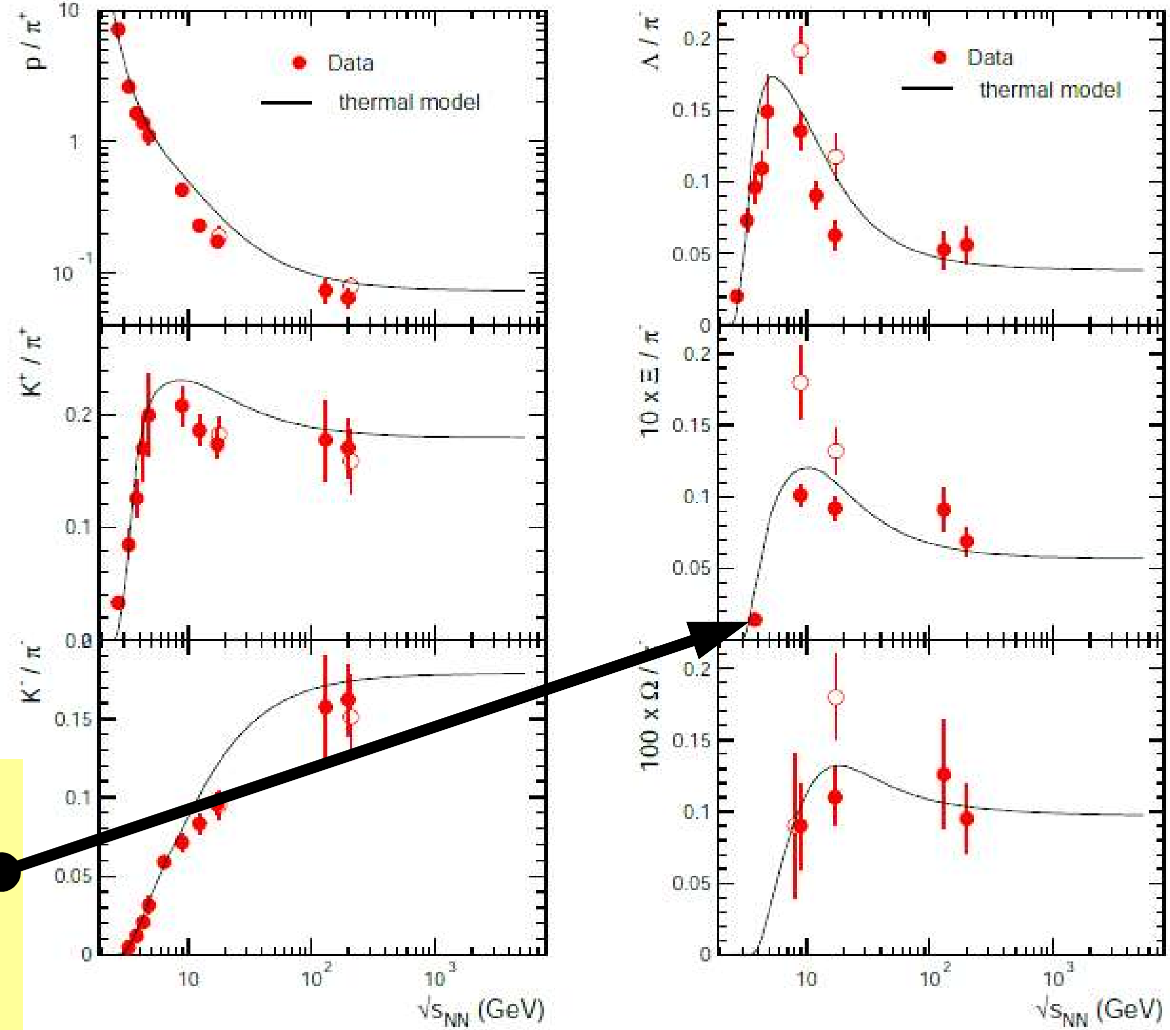


2005 analysis continued

is there a kaon anomaly?

„horn“ not well described

note:
cascade/pi ratio is well described at Elab/A = 6 GeV (AGS)

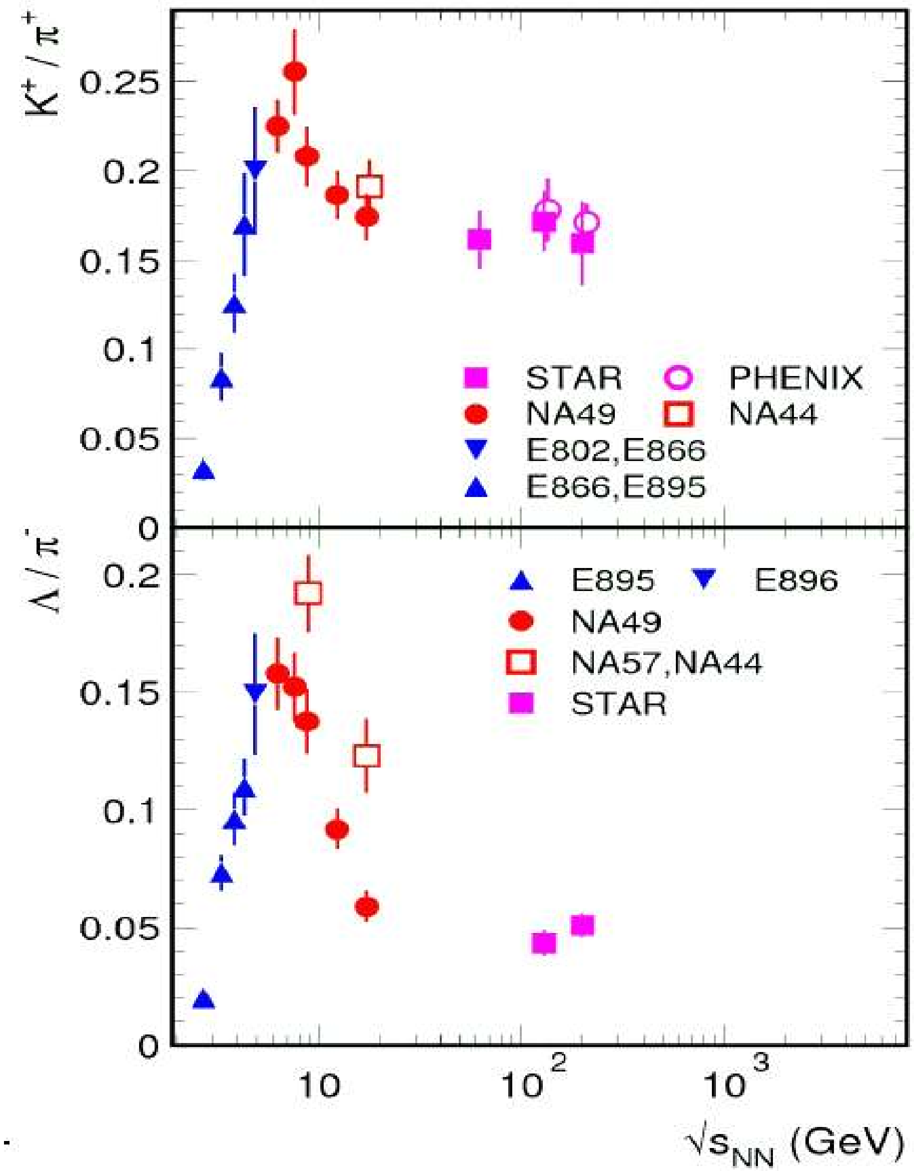


Final data from NA49 and RHIC data

clear evidence for horn structure in K+/pi+ and Lambda/pi+

is this outside the scope of the thermal model?

is the issue related to the hadronic mass spectrum?



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New approach 2008

A. Andronic, pbm, J. Stachel,
Phys. Lett. B (2009)
arXiv:0812.1186 [nucl-th]

new info on hadronic mass spectrum from PDG08

		2005 paper	now		
mesons	nonstrange	37	+ 86	=	123
	strange	28	+ 4		32
	charmed	15	+ 25		40
	beauty	16	+12		28
baryons	nonstrange	30	+ 36		66
	strange	33	+ 30		63
	charmed	10	+22		32
	beauty	0	+14		14
composites		28			28
total		197	+ 229		426

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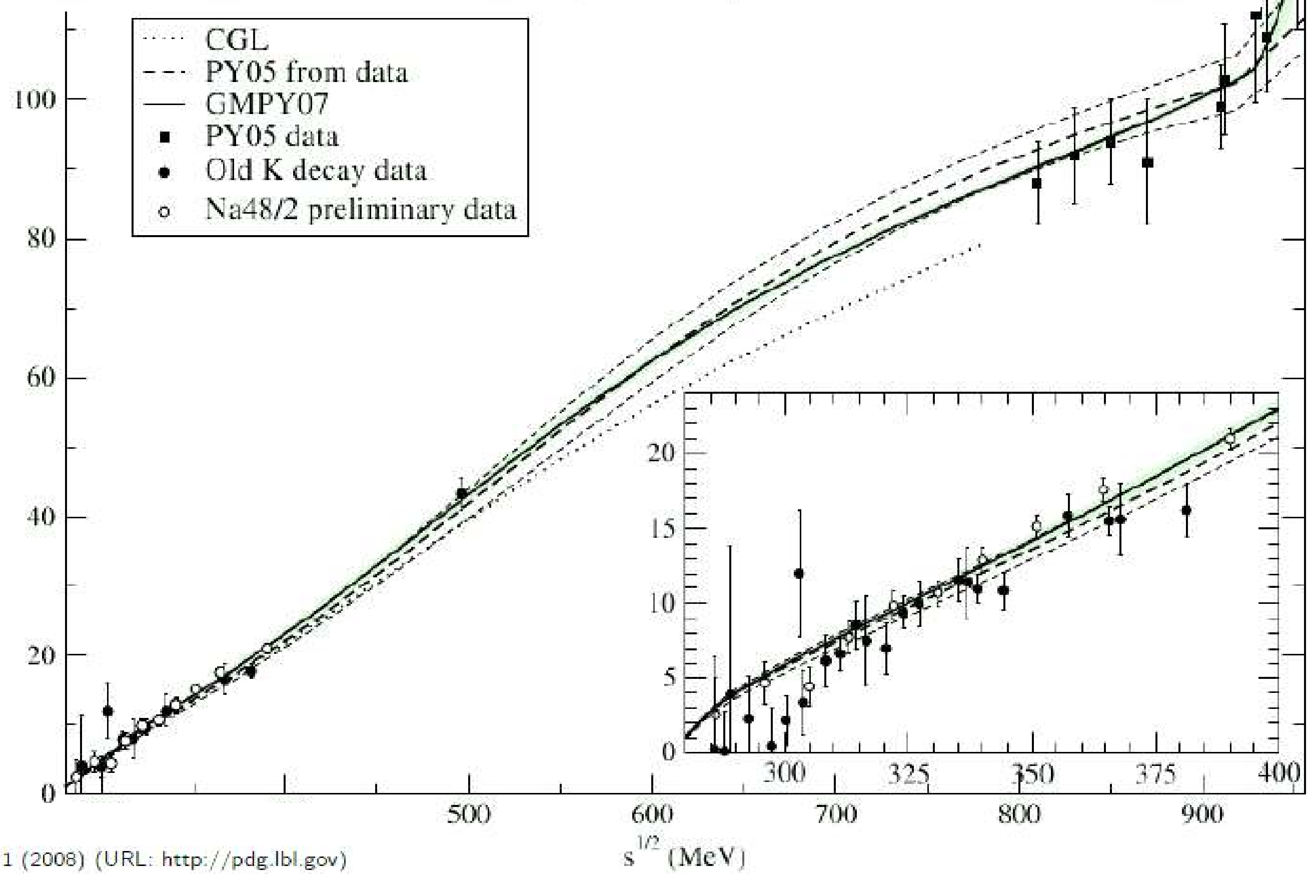
Evidence for the sigma meson

new data on pi-pi s wave scattering provide more solid evidence for the sigma meson

see Garcia-Martinez et al., Phys. Rev. D76 (2007) 074034

so let's include this with appropriate branching ratio

$$M_\sigma = 484 \pm 17 \text{ MeV}, \quad \Gamma_\sigma/2 = 255 \pm 10 \text{ MeV}$$

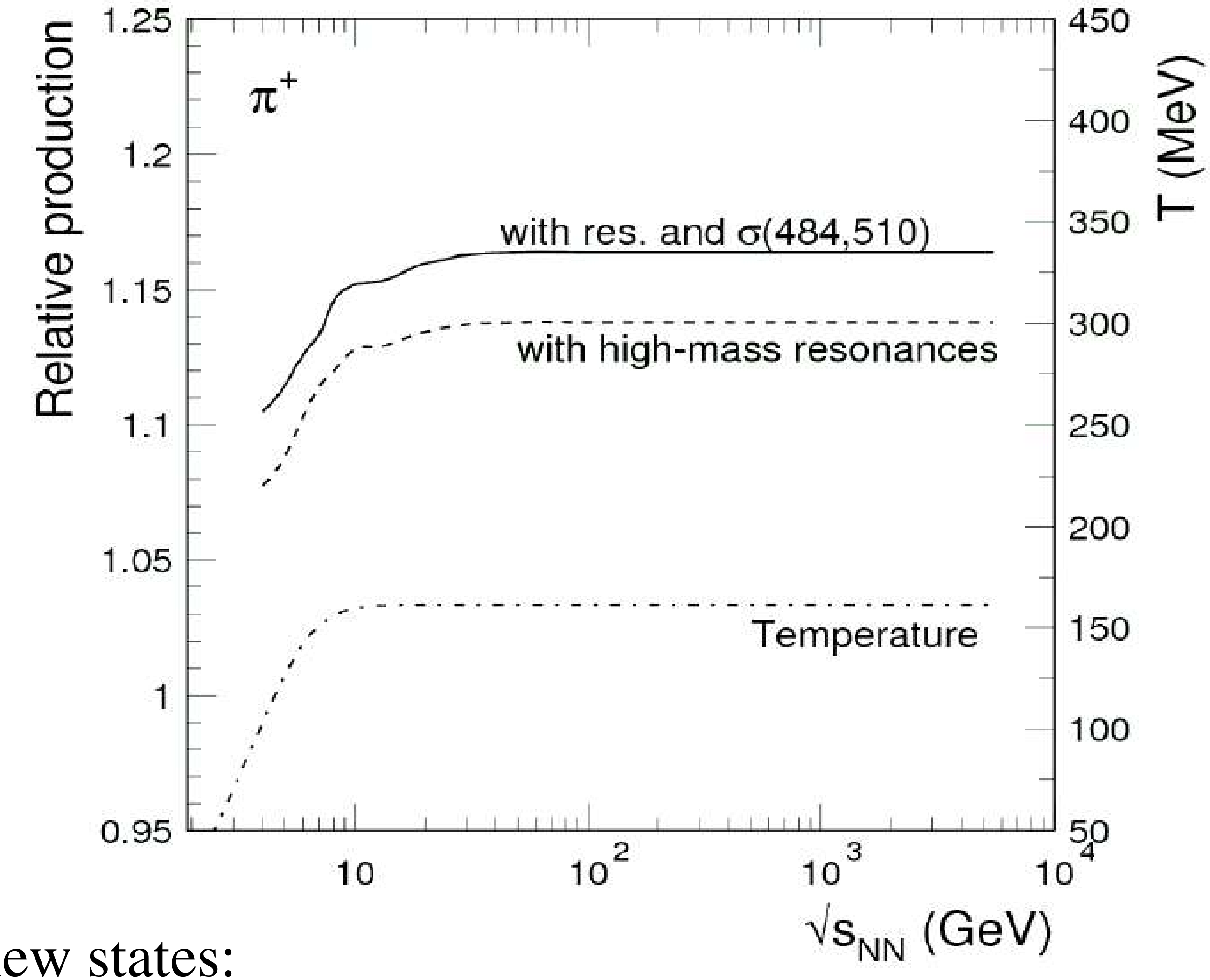


Citation: C. Amsler *et al.* (Particle Data Group), PL **B667**, 1 (2008) (URL: http://pdg.lbl.gov)

$f_0(600)$ or σ

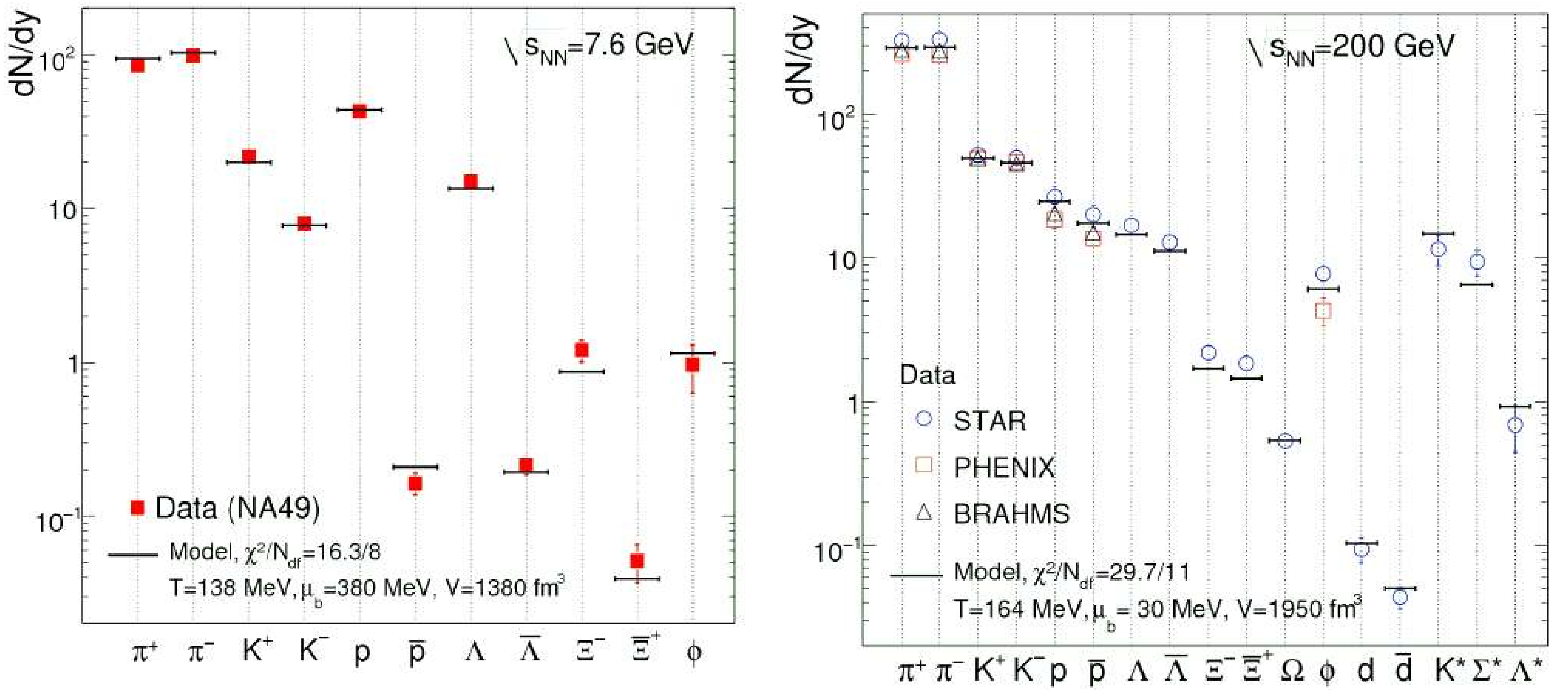
$$I^G(J^{PC}) = 0^+(0^{++})$$

Relative pion production probability



role of new states:
strong enhancement near energy where
T levels off

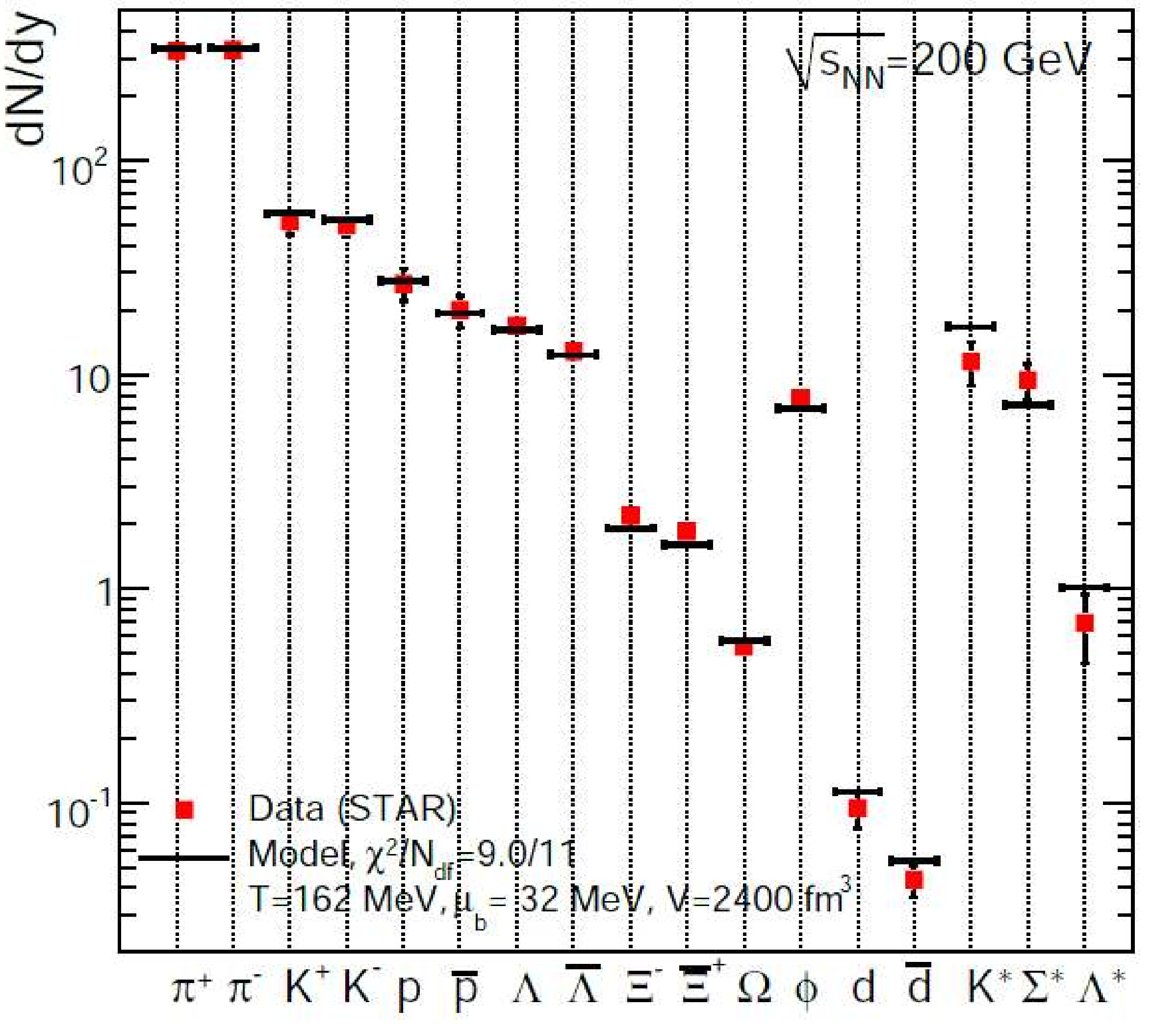
New fits very similar in quality



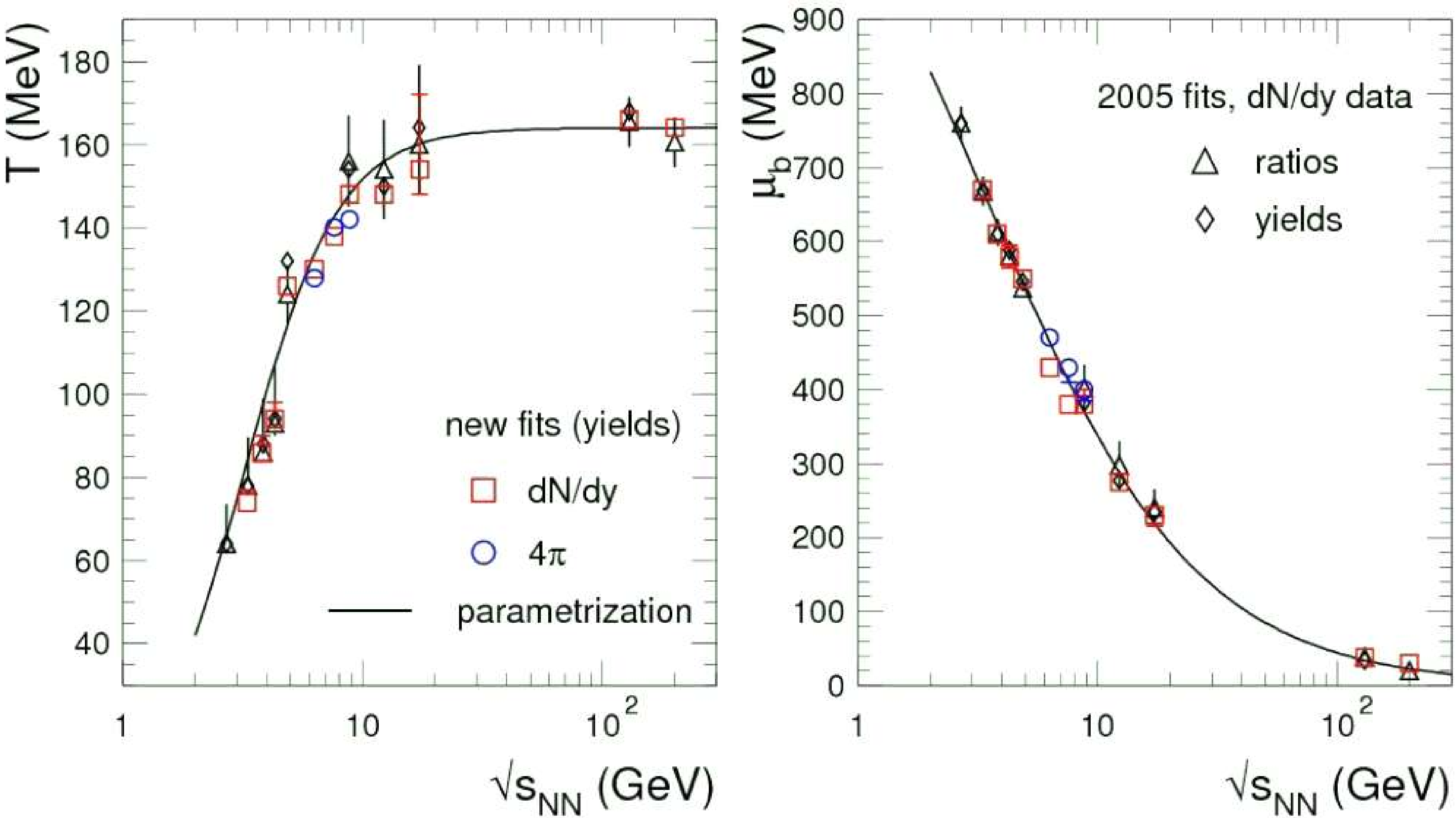
Fit to STAR data alone

very good fit, even including strongly decaying resonances

no evidence for special role of wide states

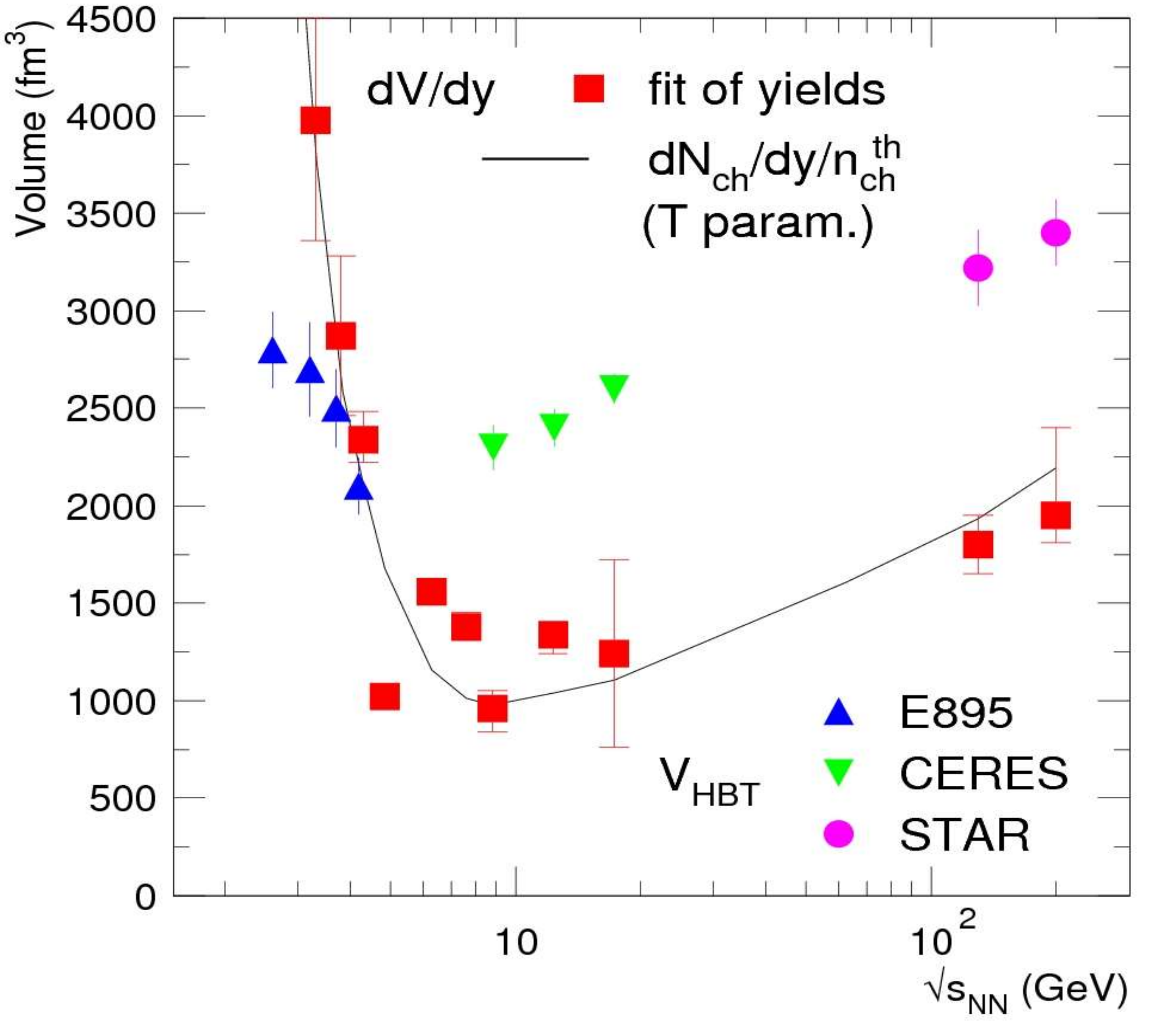


T and mu dependence is essentially unchanged



and, by the way, non-trivial structure also in energy dependence of V

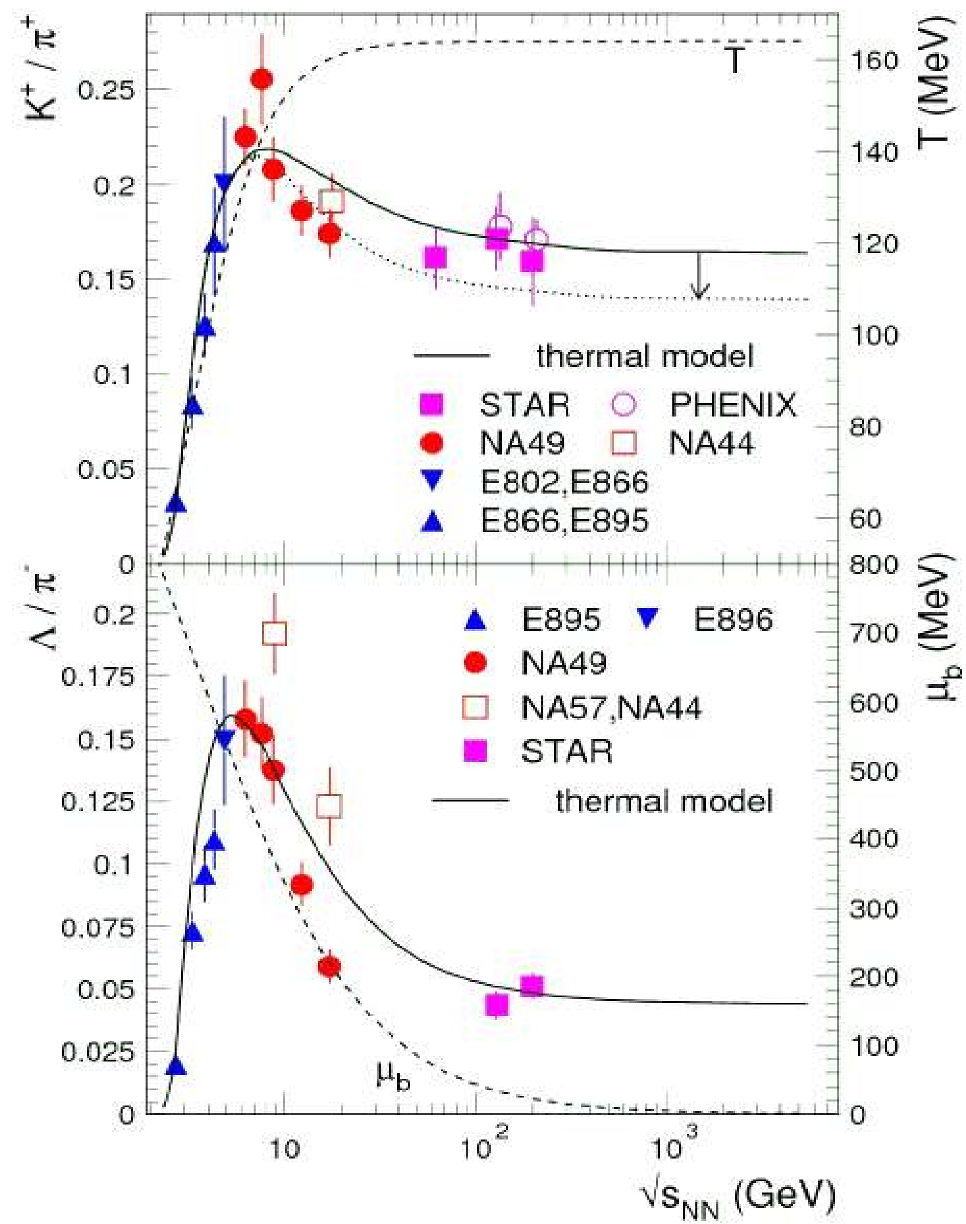
very similar to 2005 analysis



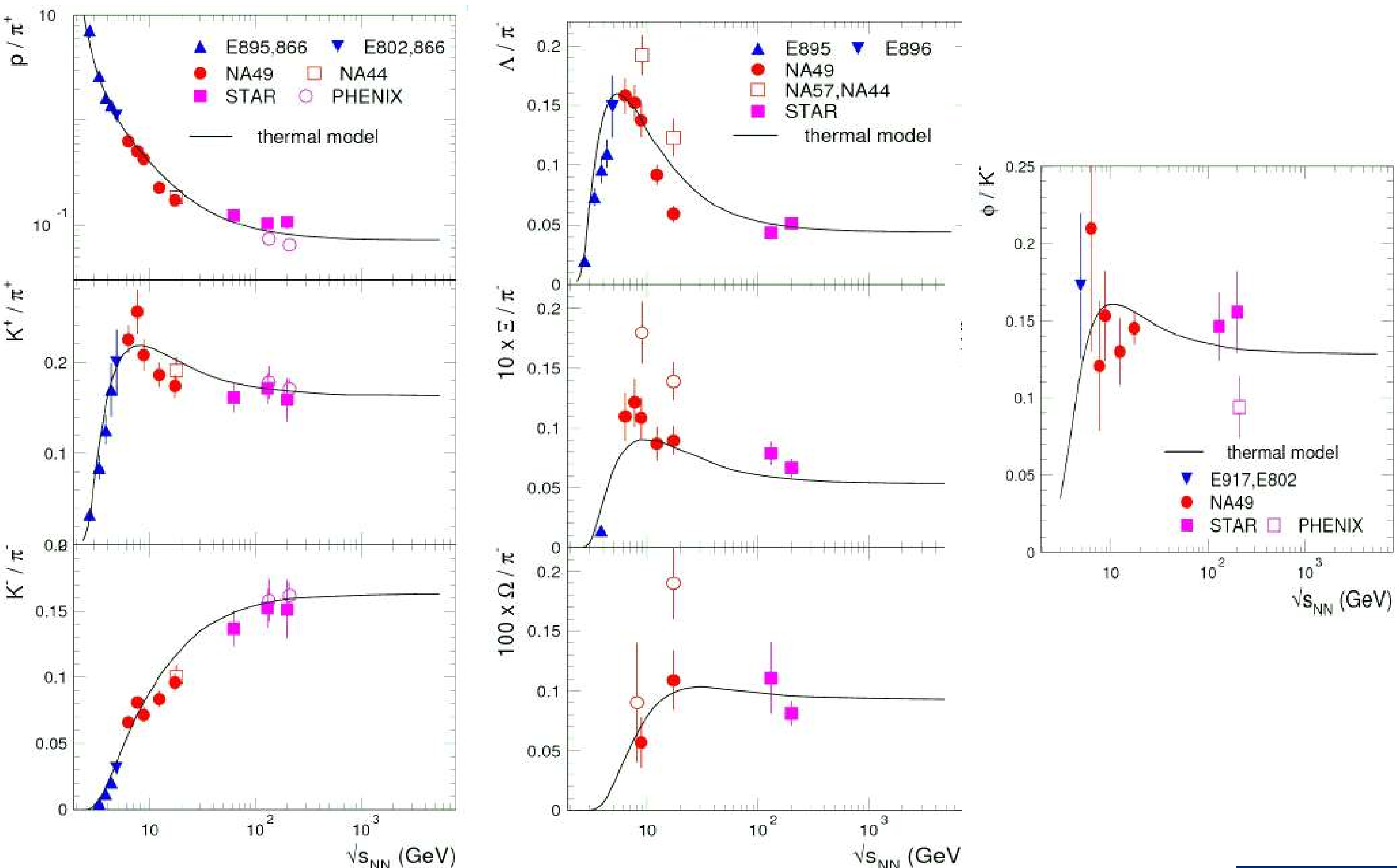
Horn structure well described

rapid saturation of contributions from higher resonances in conjunction with additional pions from the sigma describes horn structure well

crucial input is saturation of T due to the phase boundary

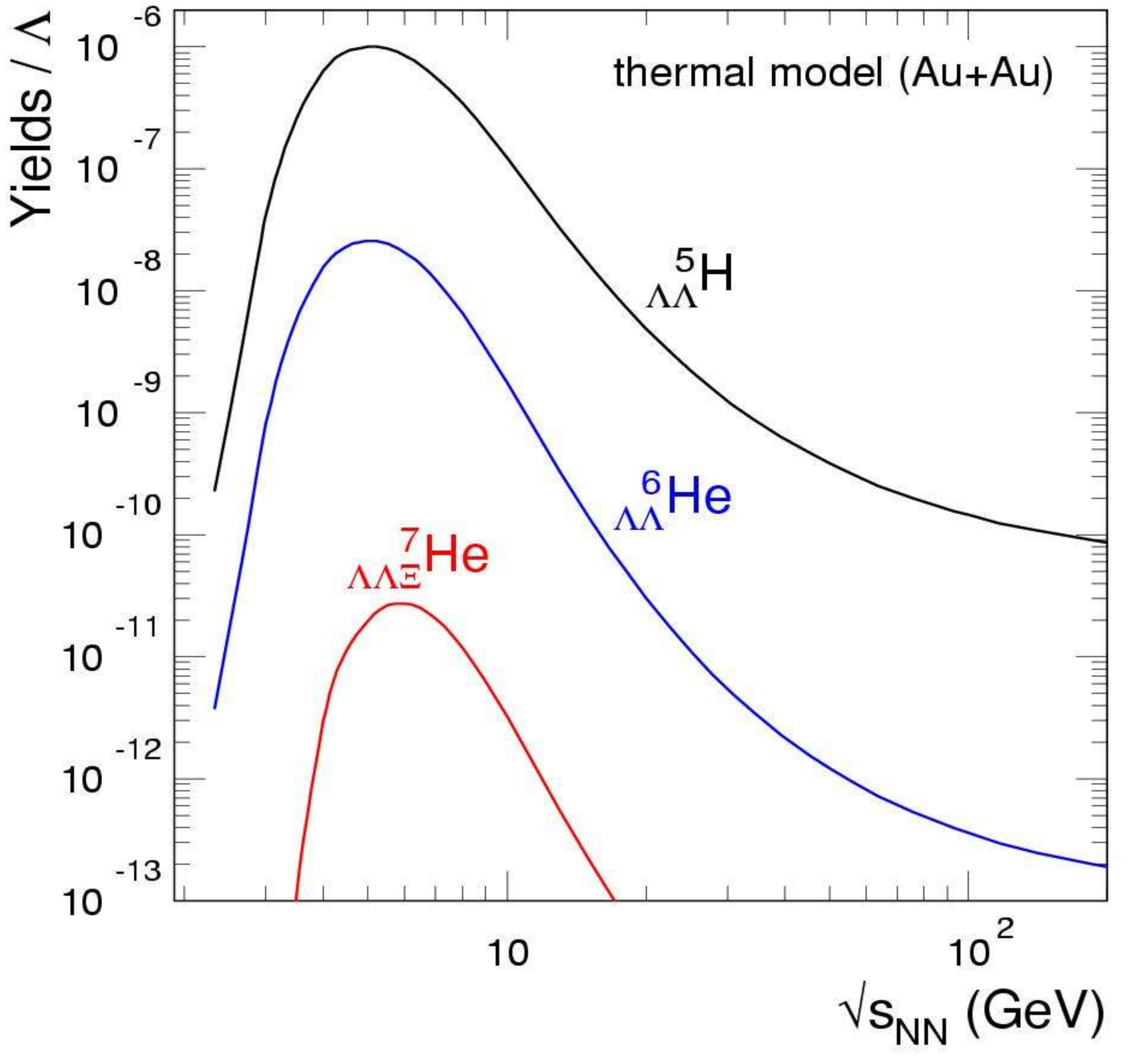


Summary of reanalysis 2008



also yields of exotic objects

measurable yields
in CBM energy range
if such objects are bound



Hagedorn's Limiting Temperature

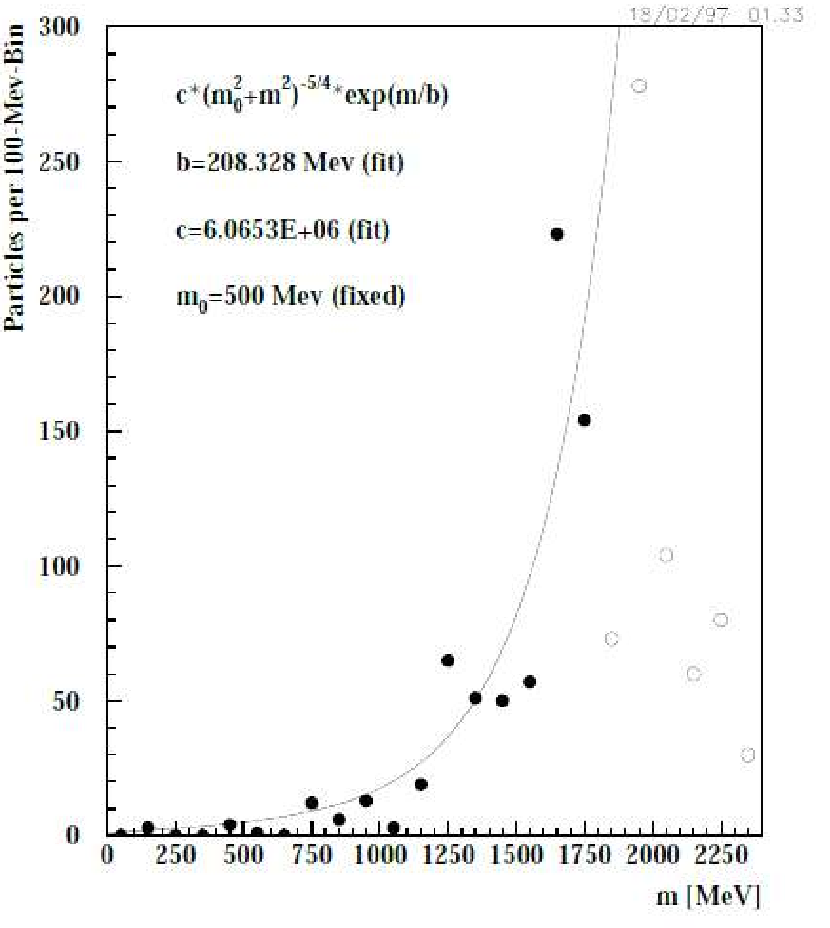
fit with

Hagedorn mass formula

hadronic mass spectrum as of 1998

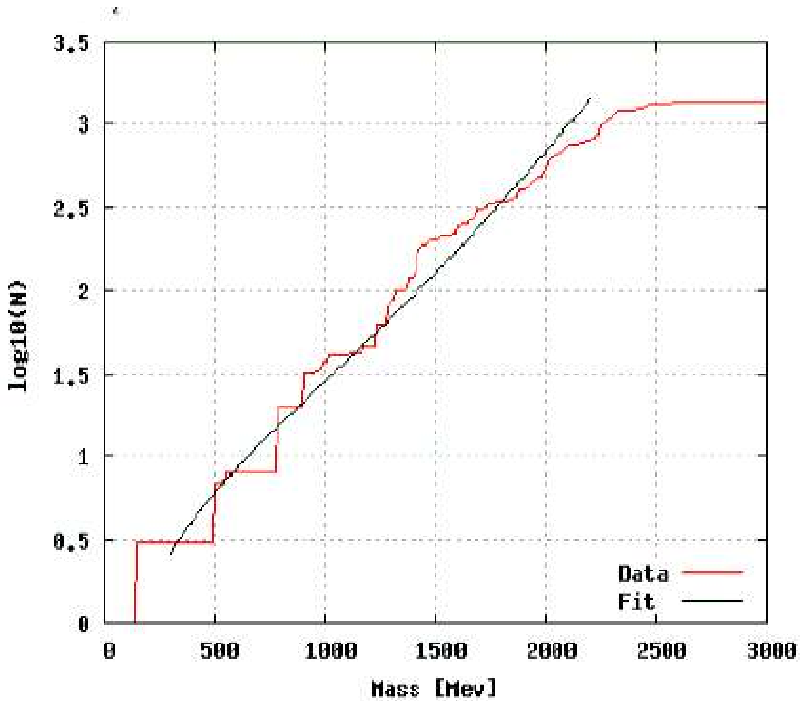
$$\rho_m \propto (m_0^2 + m^2)^{(-5/4)} \exp{(m/b)}$$

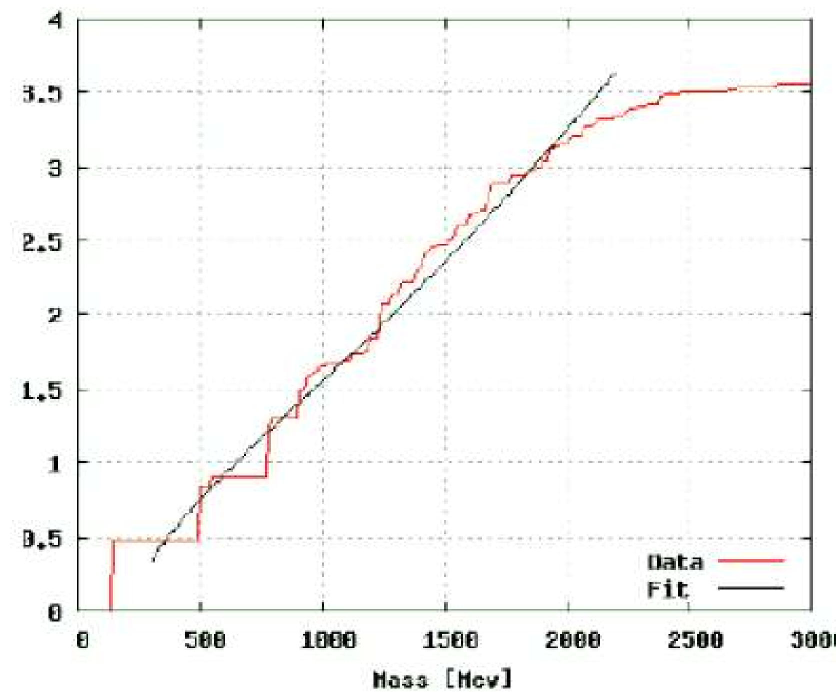
$b = T_{limit} = 200 \pm 30$ MeV



Reanalysis 2008

Maciej Sobczak – analysis of states listed in PDG2008 compilation



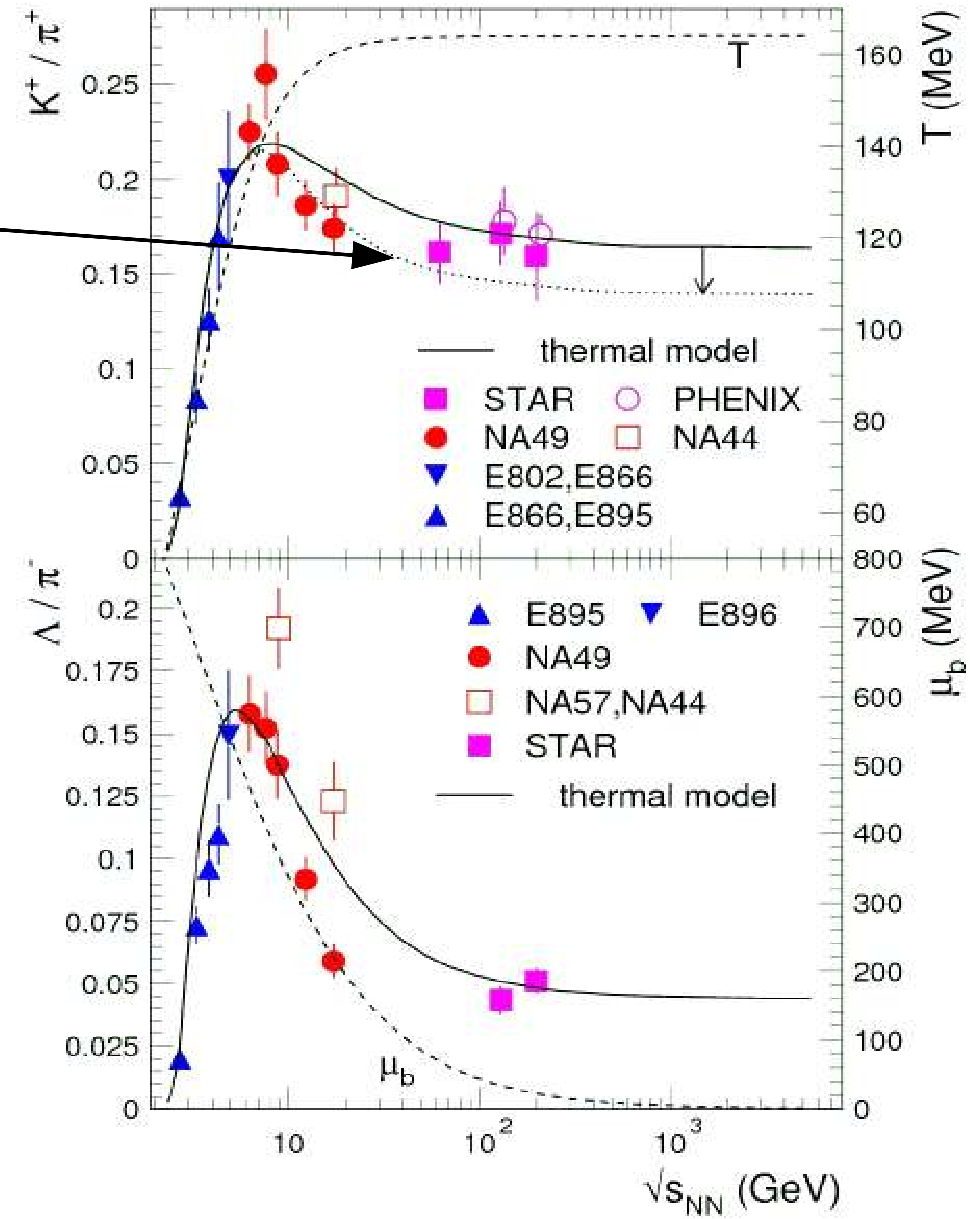


T_H= 180 – 210 MeV   depending on cut-off

note: if T_H is close to T_{chem} then chemical analysis will diverge,   take 200 MeV in the following

influence of resonances with M > 3 GeV

inclusion of even higher resonances decreases the K+/pi+ ratio because of strangeness conservation: higher K*s decay into 1 K and many pi's!



crucial input is saturation of T due to the phase boundary and a Hagedorn temperature around 200 MeV

Hadron Production in elementary collisions

as first noticed by F. Becattini in 1996

F. Becattini, Z. Phys. C **69** (1996) 485

thermal features observed for overall production pattern but:

recent results:

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0804.4132

thermal fit is possible only
with several external, non-statistical parameters
(gamma$_S$, production probability of c and b quarks, ...)

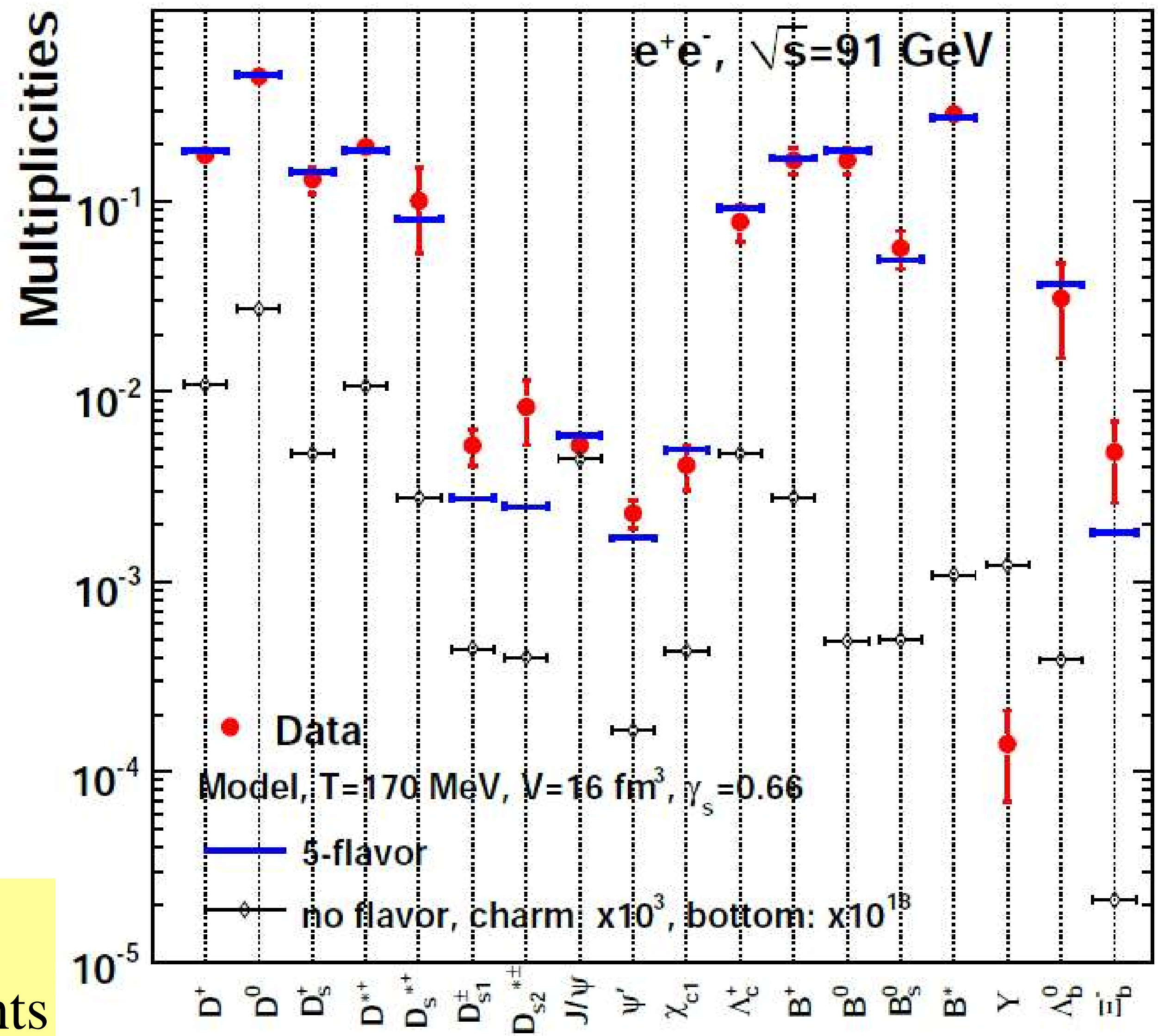
also: fit quality is rather poor

Thermal features of charmed hadrons in e+e- collisions

open charm and open beauty hadrons well described,

Y production is 17 orders of magnitude off! No thermal production of charm.

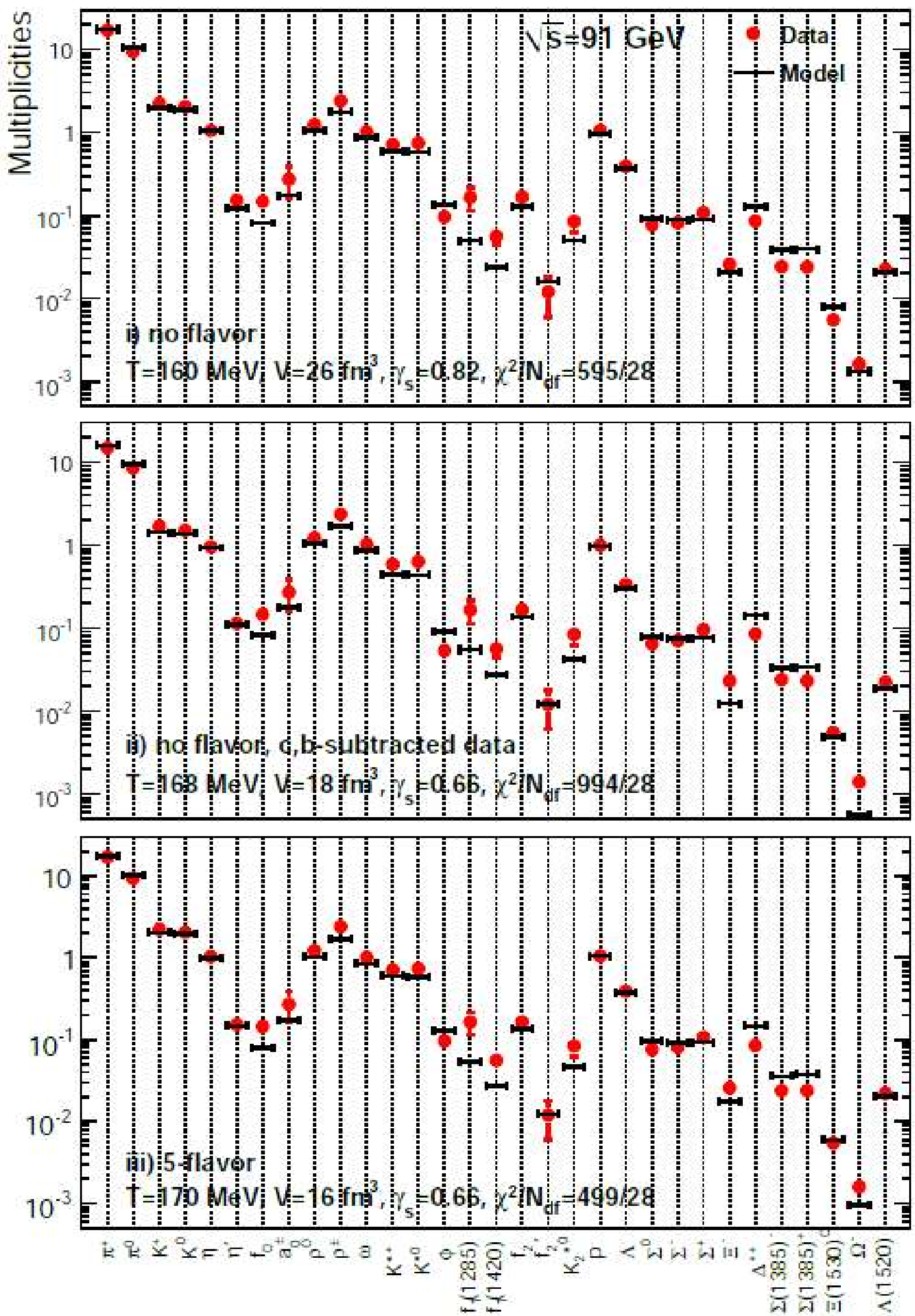
Andronic et al, arXiv:0804.4132 [hep-ph]



hadronization of heavy quarks well described by thermal weights quarkonia cannot be described

Thermal fit to e+e- data at 91 GeV

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0804.4132



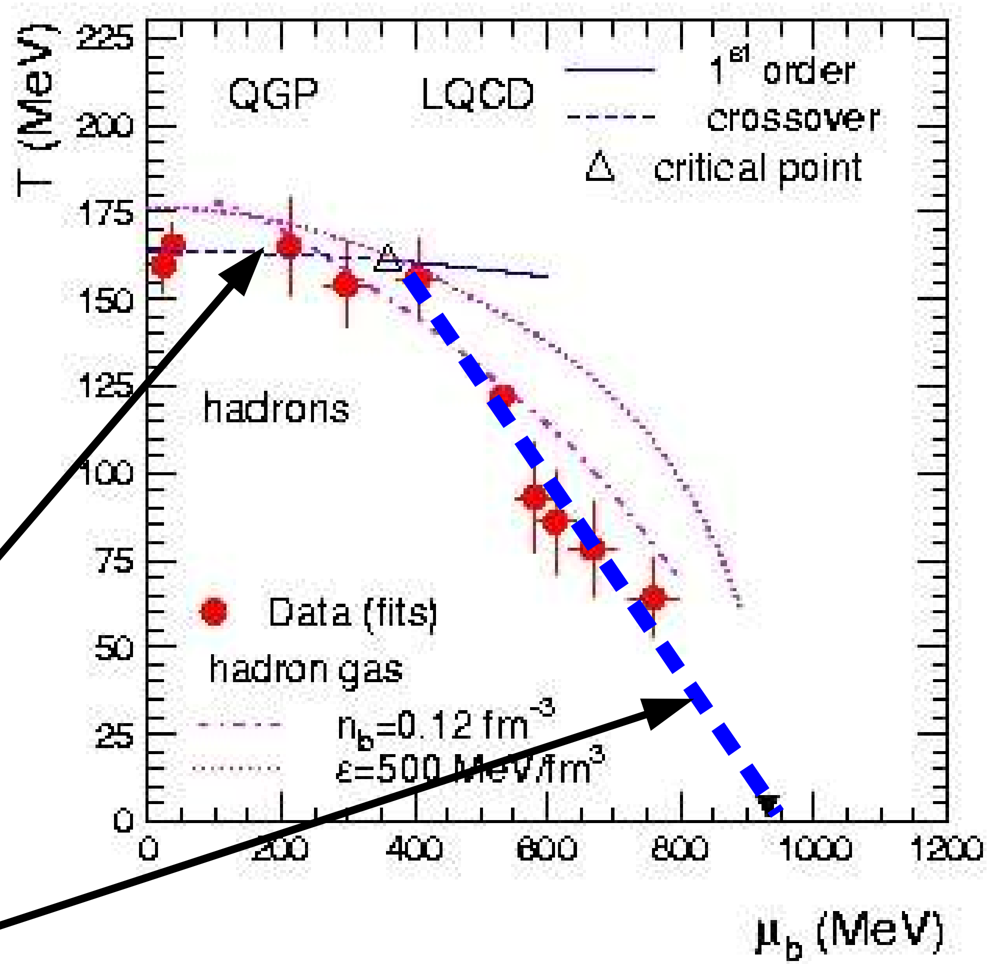
several non-thermal, external parameters

thermal production of strange quarks
poor fit quality despite additional free parameter gamma_s
no equilibration in strange quark sector

Chemical freeze-out driven by phase boundaries?

Main result: chemical freeze-out points seem to delineate the QCD phase boundary at small (μ < 400 MeV)

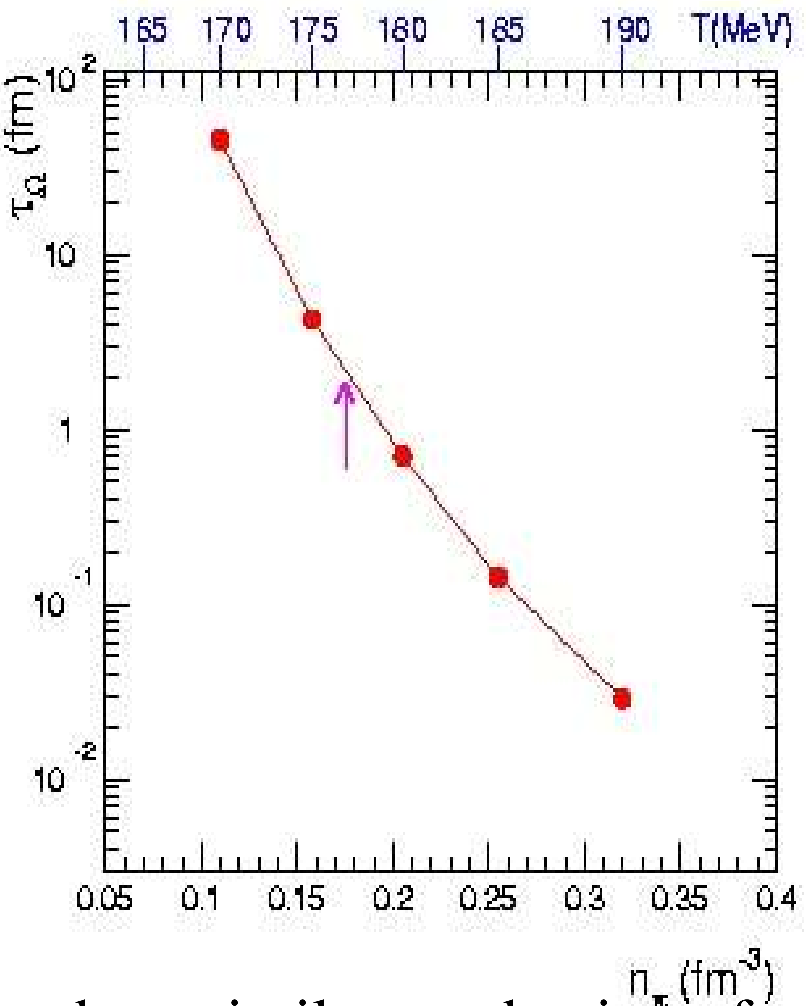
what happens at large μ ?



QGP phase boundary

quarkyonic matter boundary?
McLerran & Pisarski
Nucl. Phys. A796 (2007) 83

The QGP phase transition drives chemical equilibration for small μ_b



are there similar mechanisms for large μ_b?

- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within a very narrow temperature window.

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

Summary

• the thermal model contains much of QCD via the hadron resonance spectrum
• hadron (including multi-strange baryon) production in AA collisions is well described by the thermal approach from low AGS energy on provided that the full spectrum is accounted for
• the resulting thermal parameters provide strong evidence for a limiting temperature
• even subtle structures such as the „horn“ are well described as an interplay between QGP phase boundary and the resonance spectrum, providing further support for a close connection between the limiting temperature and the QGP T_{crit} at low μ_b
• what produces equilibration at large μ_b?