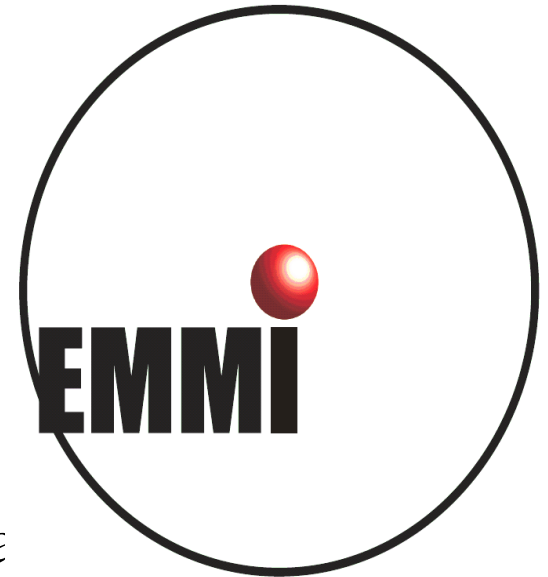


Hadron Production in ultra-relativistic nuclear collisions and the QCD phase boundary

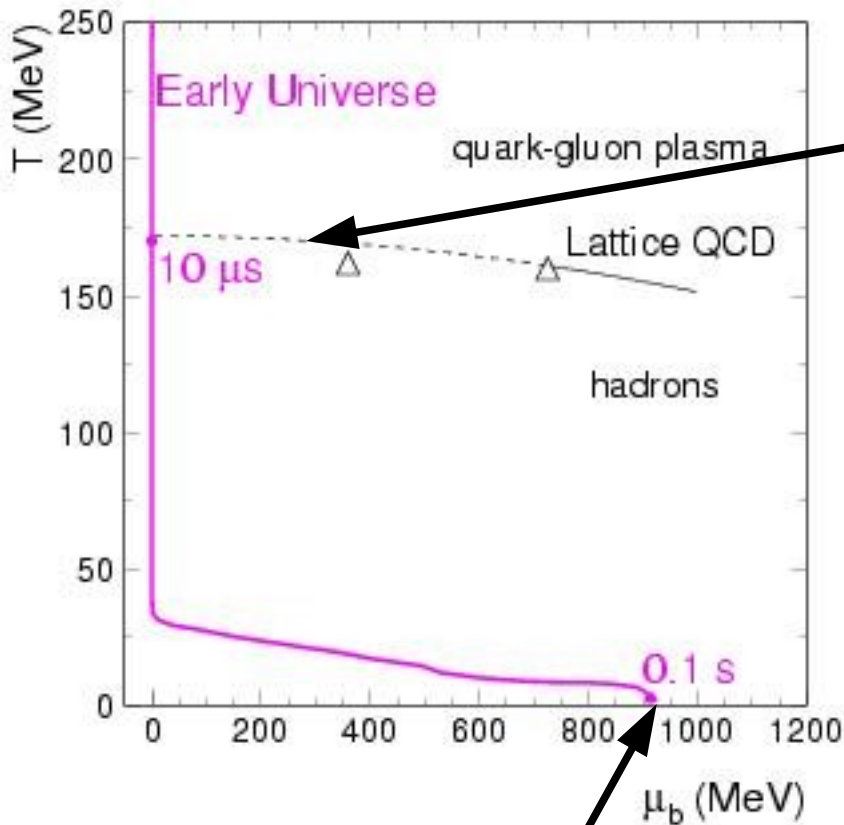
- introductory remarks
- the thermal/statistical model
- results for AA collisions
- a note on thermal models in elementary collisions
- interpretation of the chemical freeze-out curve at small μ_b
- speculation on the chemical freeze-out curve at large μ_b



Quantum Field Theory in Extreme Environments
Paris, April 2009

FIAS-Frankfurt

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 from an equilibrium state

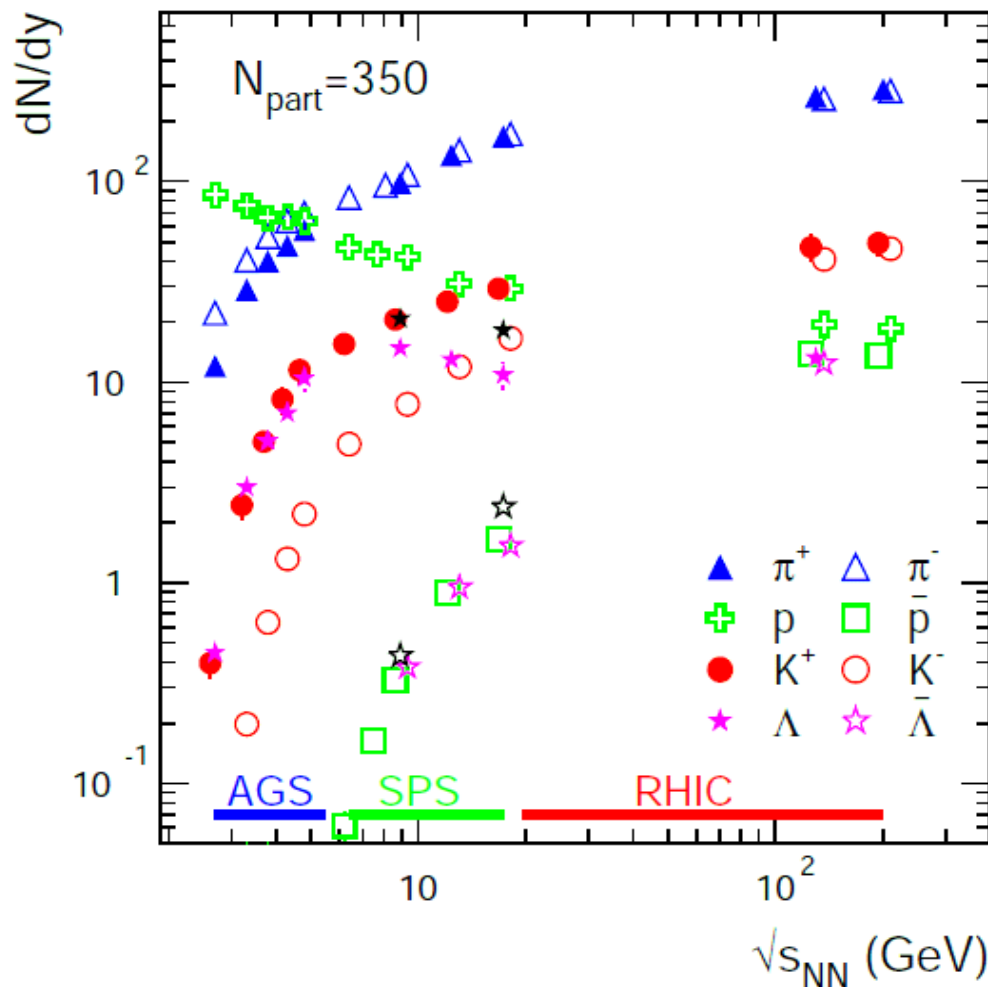
- From low AGS energy on, all hadron yields in central PbPb collisions reflect grand-canonical equilibration
- Strangeness suppression observed in elementary collisions is lifted
- Equilibration at SIS energy?

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

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

$$n_i = N/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp((E_i - \mu_i)/T) \pm 1}$$
$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

Fit at each energy provides values for T and μ_b

and volume V when fitting yields

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

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

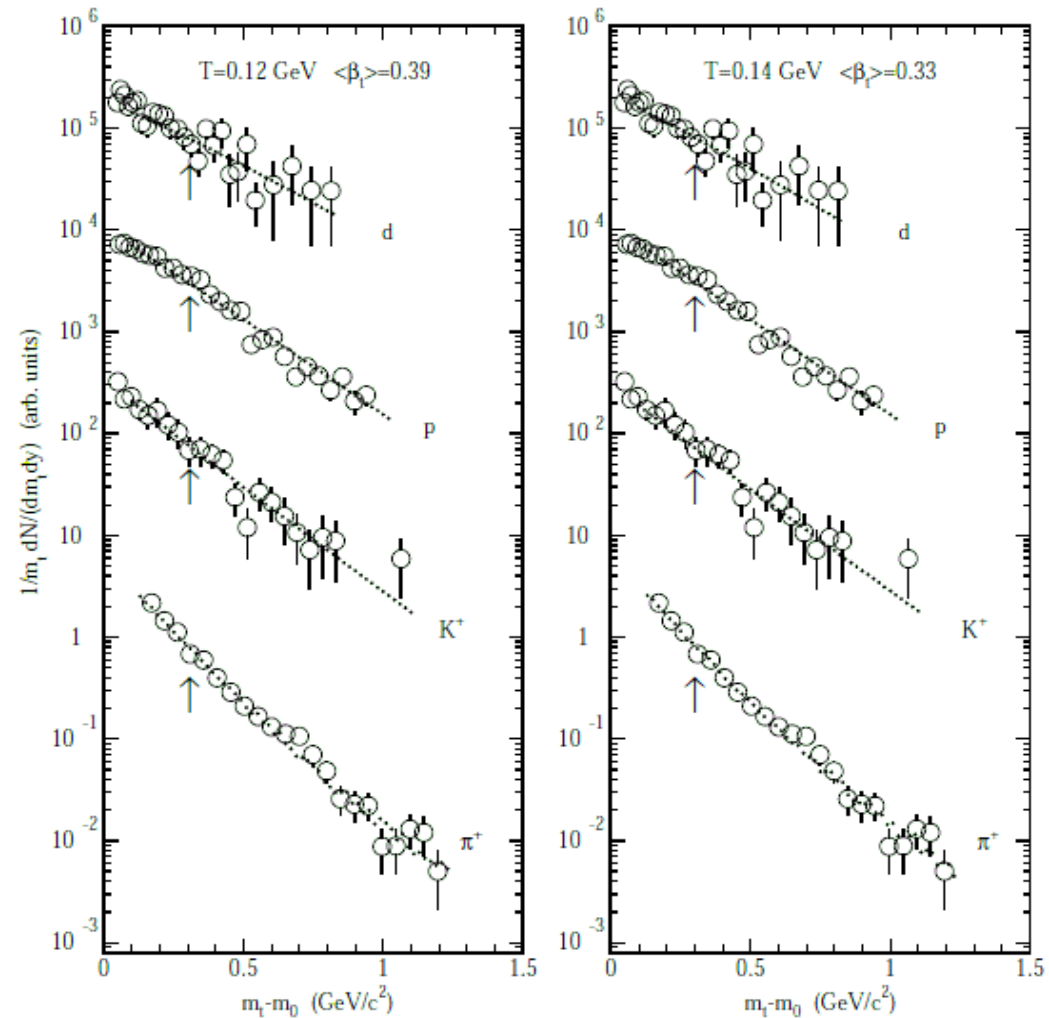
This leaves only μ_b and T as free parameter when 4π considered for rapidity slice fix volume e.g. by dN_{ch}/dy

First thermal model results in 1994 for AGS data

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

$T = 120 \text{ MeV}$, $\mu_b = 540 \text{ MeV}$

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

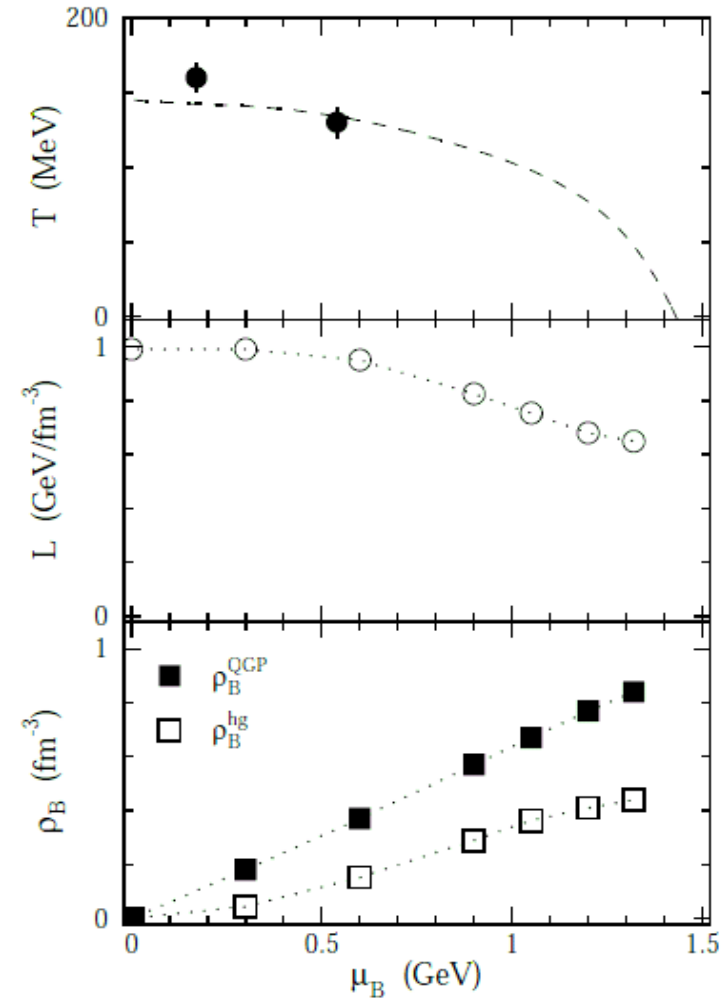


First attempt to establish connection to phase boundary

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

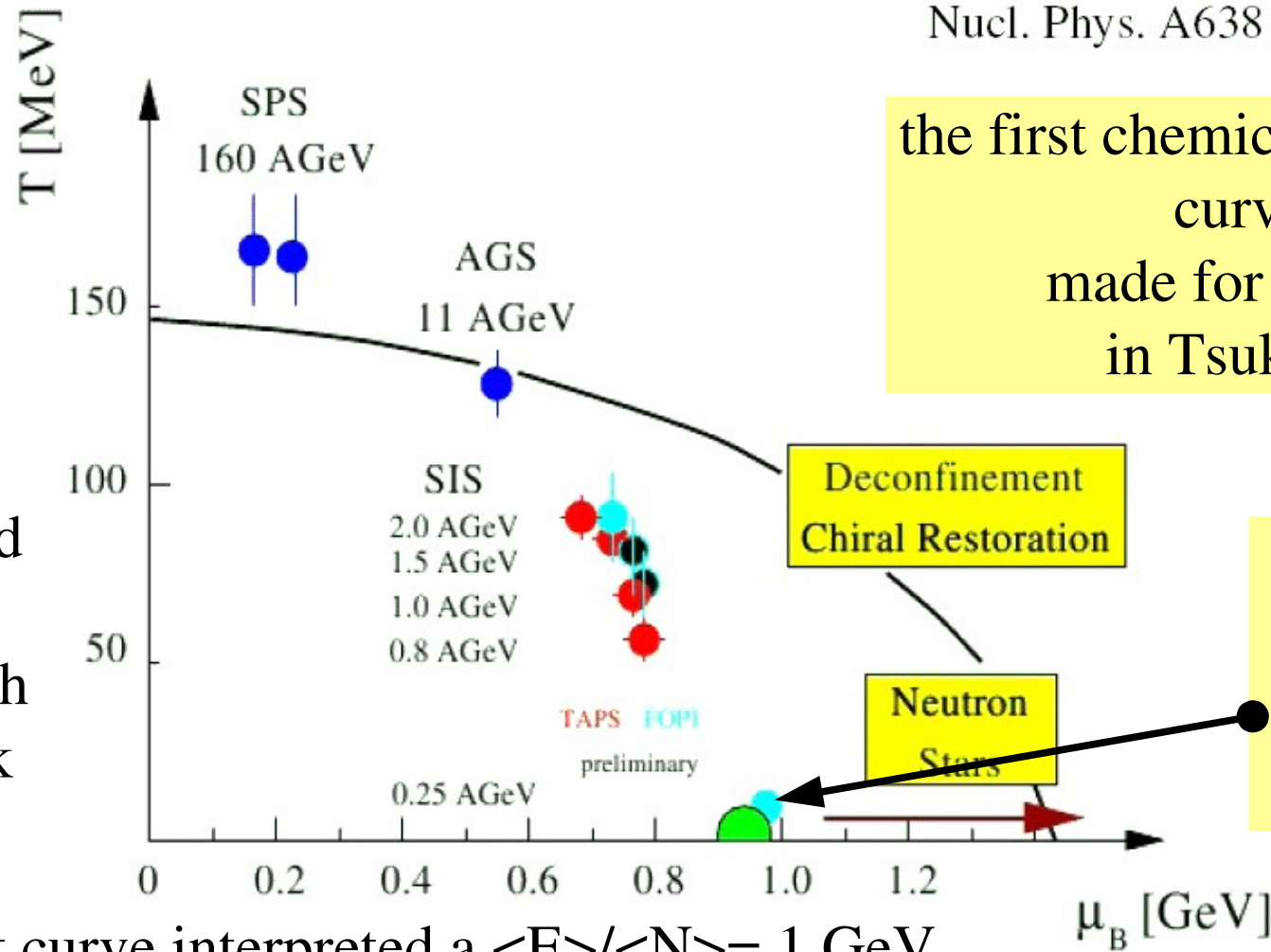
equation of state from a bag
model, transition 1st order by
construction

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

note the entry
at $T = 15$ MeV!

compilation
of TAPS and
FOPI data
together with
R. Averbeck

freeze-out curve interpreted a $\langle E \rangle / \langle N \rangle = 1$ 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

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

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

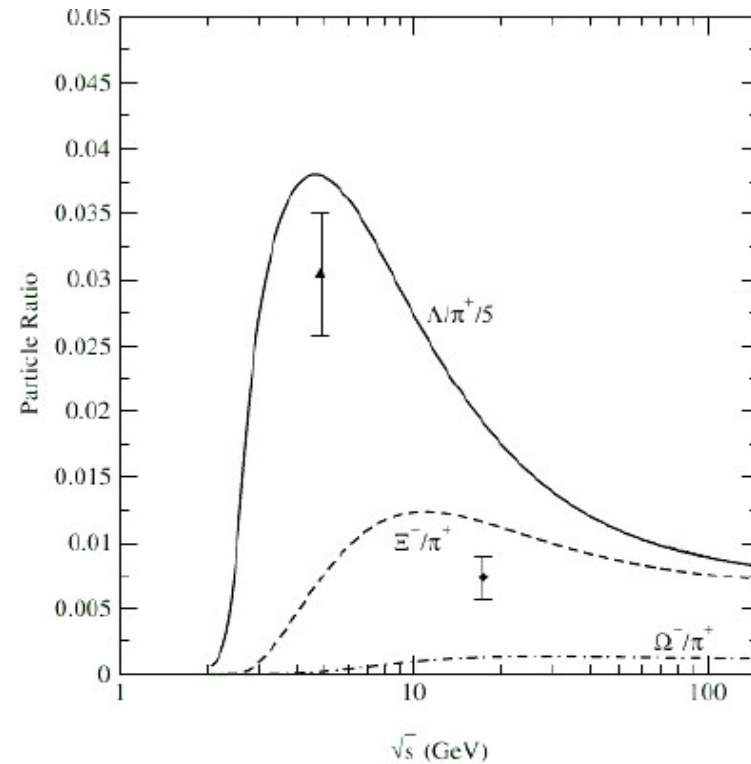
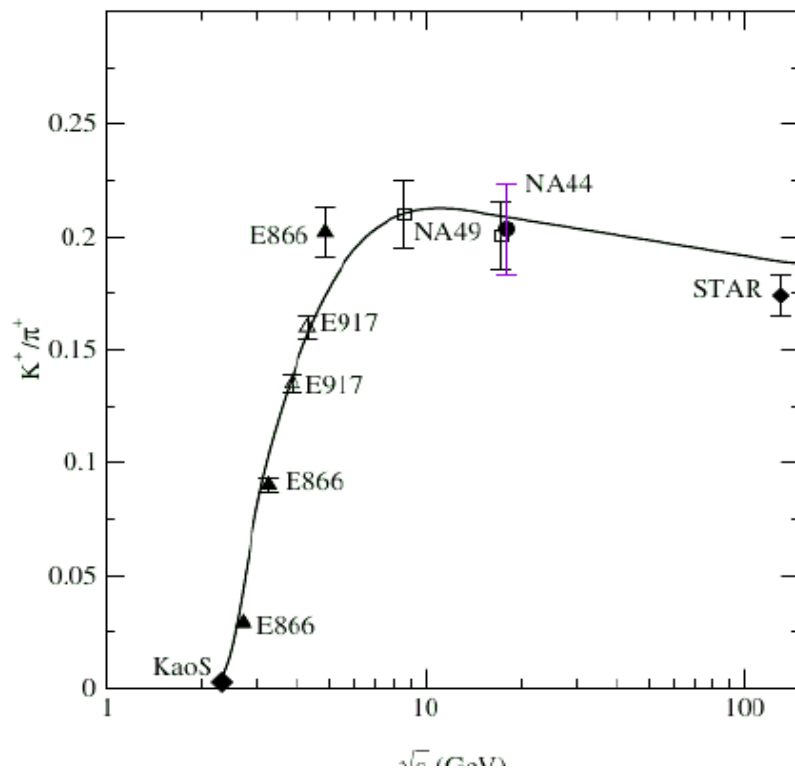
and $a = 1290 \pm 115 \text{ MeV}$ and $b = 0.28 \pm 0.047 \text{ GeV}^{-1}$

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 Λ/π^+
and shoulder in K^+/π^+



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

Hadro-chemistry at RHIC -- weakly decaying particles

All data in excellent agreement with thermal model predictions

chemical freeze-out at: $T = 165 \pm 8$ MeV

fit uses vacuum masses

most recent analysis:

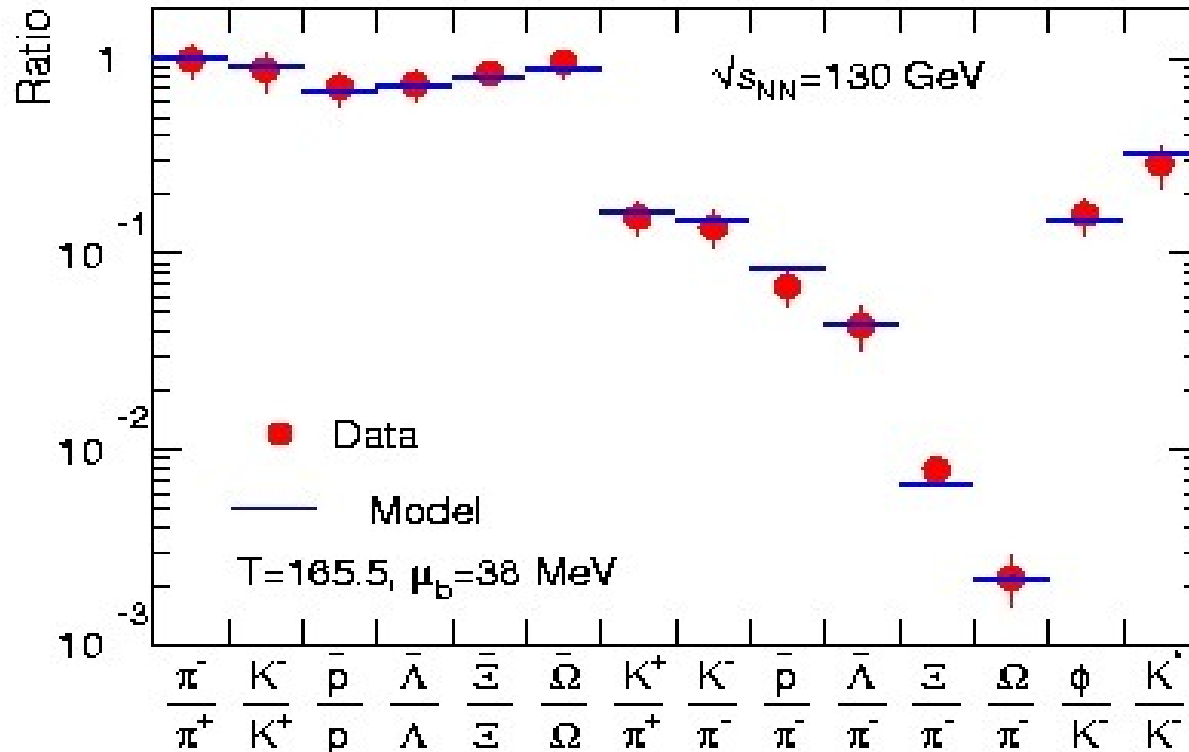
A. Andronic, pbm, J.

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.

Why vacuum masses?

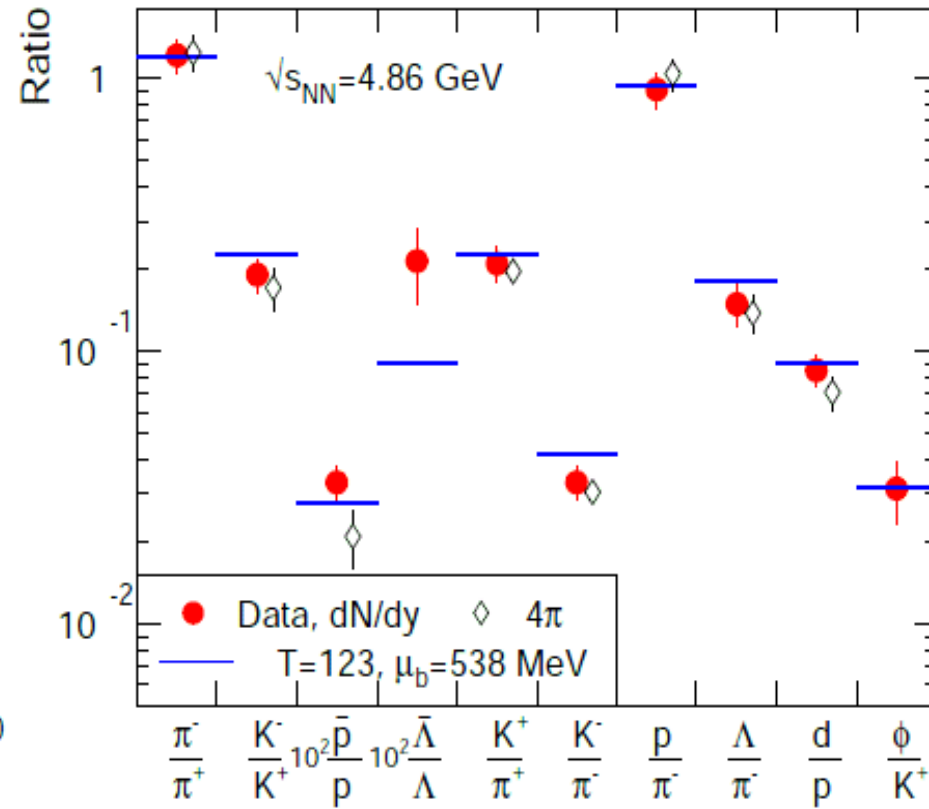
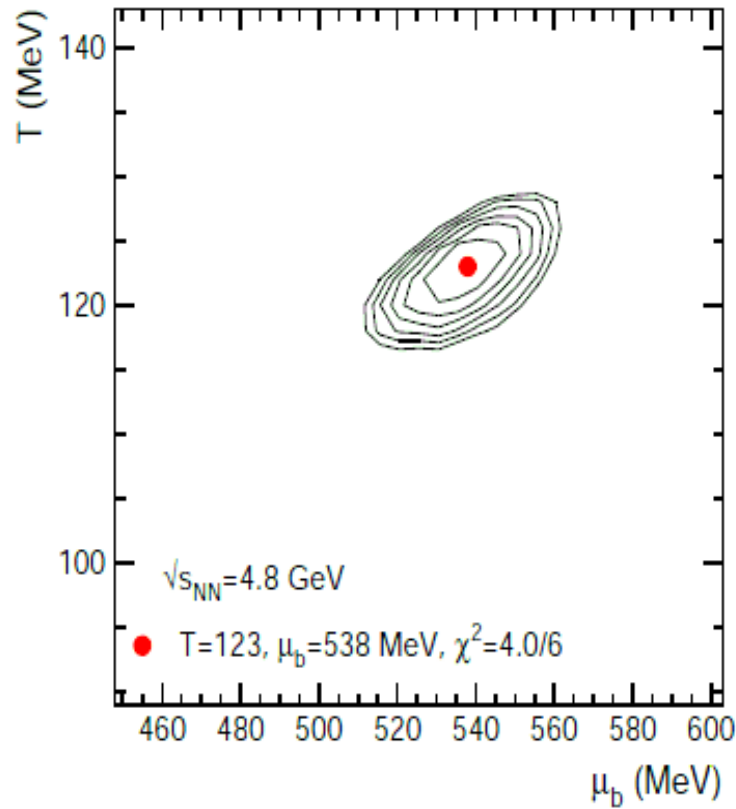
Masses of particles should change in the hot, dense medium

See, e.g. J.-P Blaizot and R. Mendez Galain
Phys. Lett. 271 (1991) 32
for a very early reference on this

But fit needs vacuum masses:

Strong density change near T_c ?
1st order phase transition?
??? this is an open issue

Hadrochemistry at AGS energy



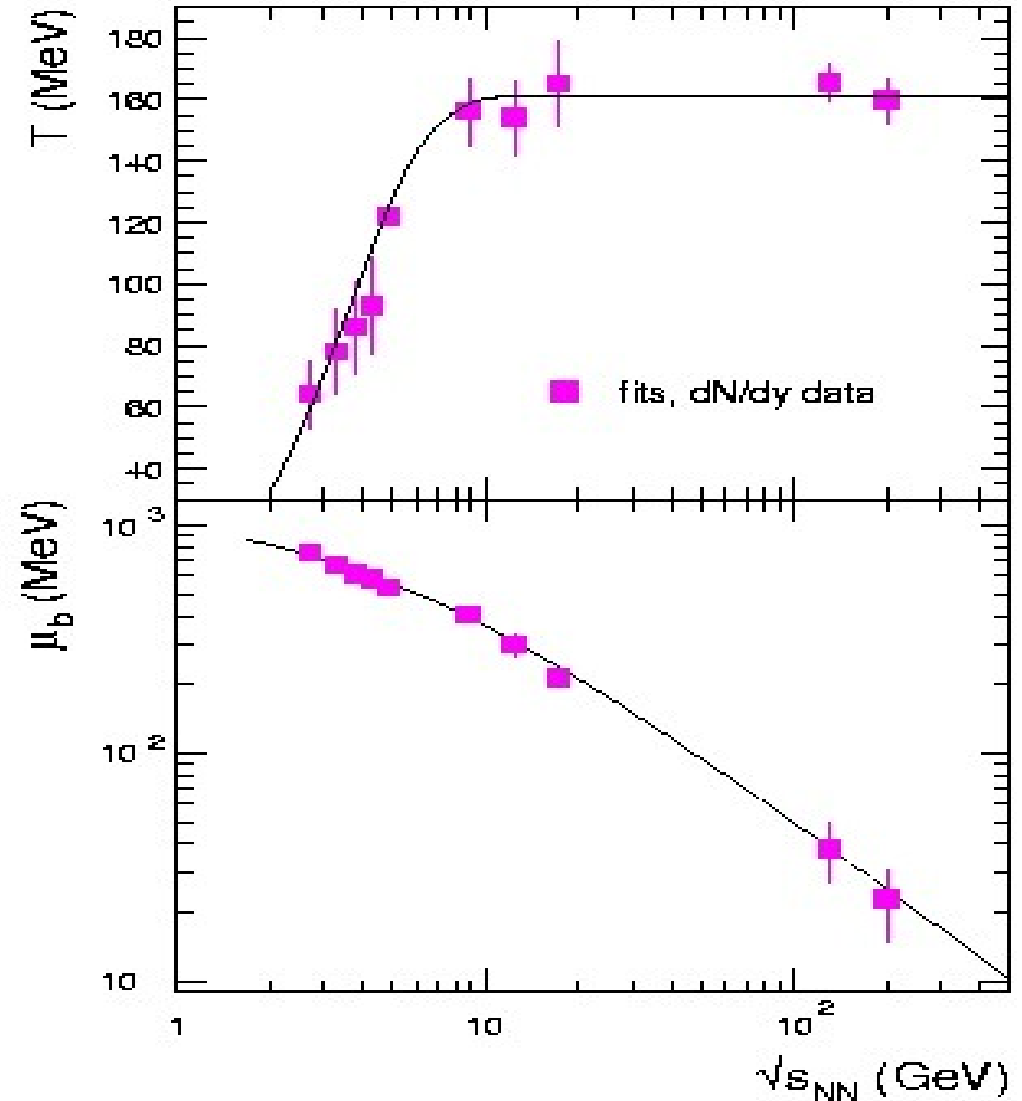
Parameterization of all freeze-out points

note: establishment of limiting temperature

$$T_{\text{lim}} = 160 \text{ MeV}$$

get T and μ_B for all energies

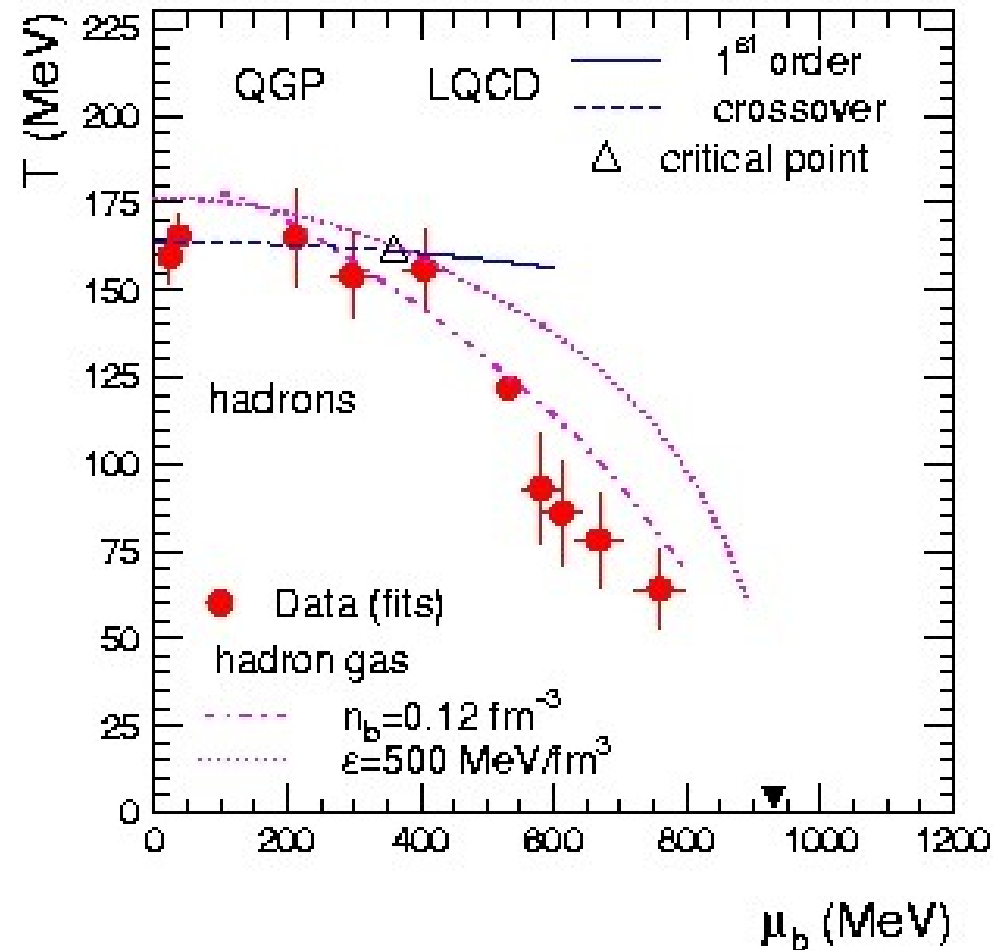
A. Andronic, pbm, J. Stachel,
Nucl. Phys. A772 (2006) 167
nucl-th/0511071



The QCD phase diagram and chemical freeze-out

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

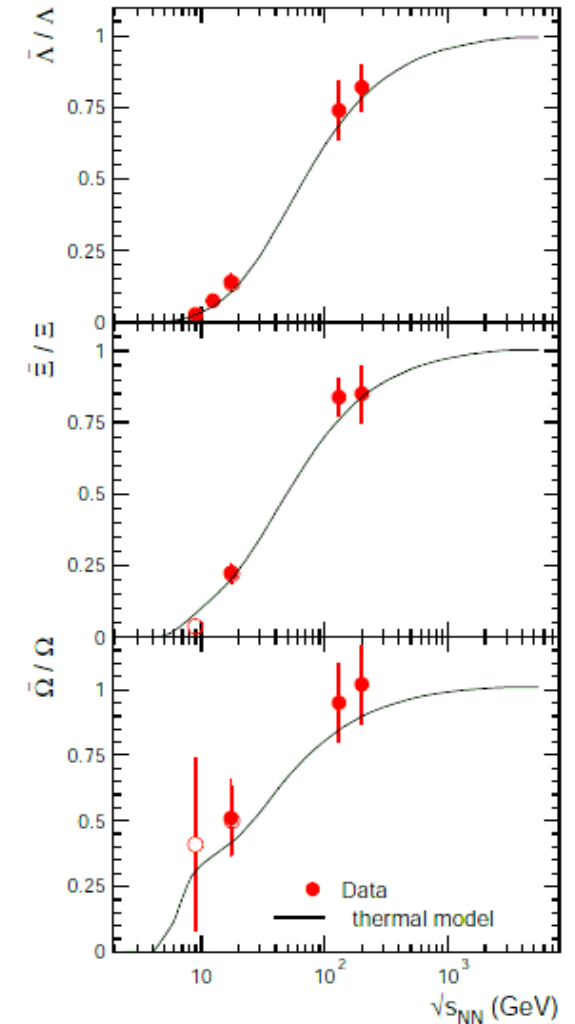
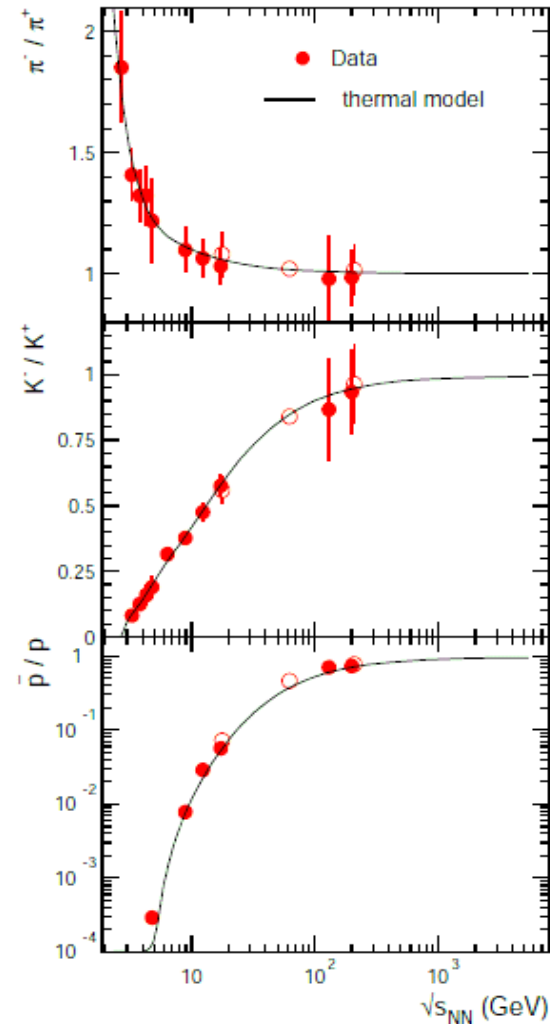
what happens at large μ ?



Energy dependence from 2005 analysis

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

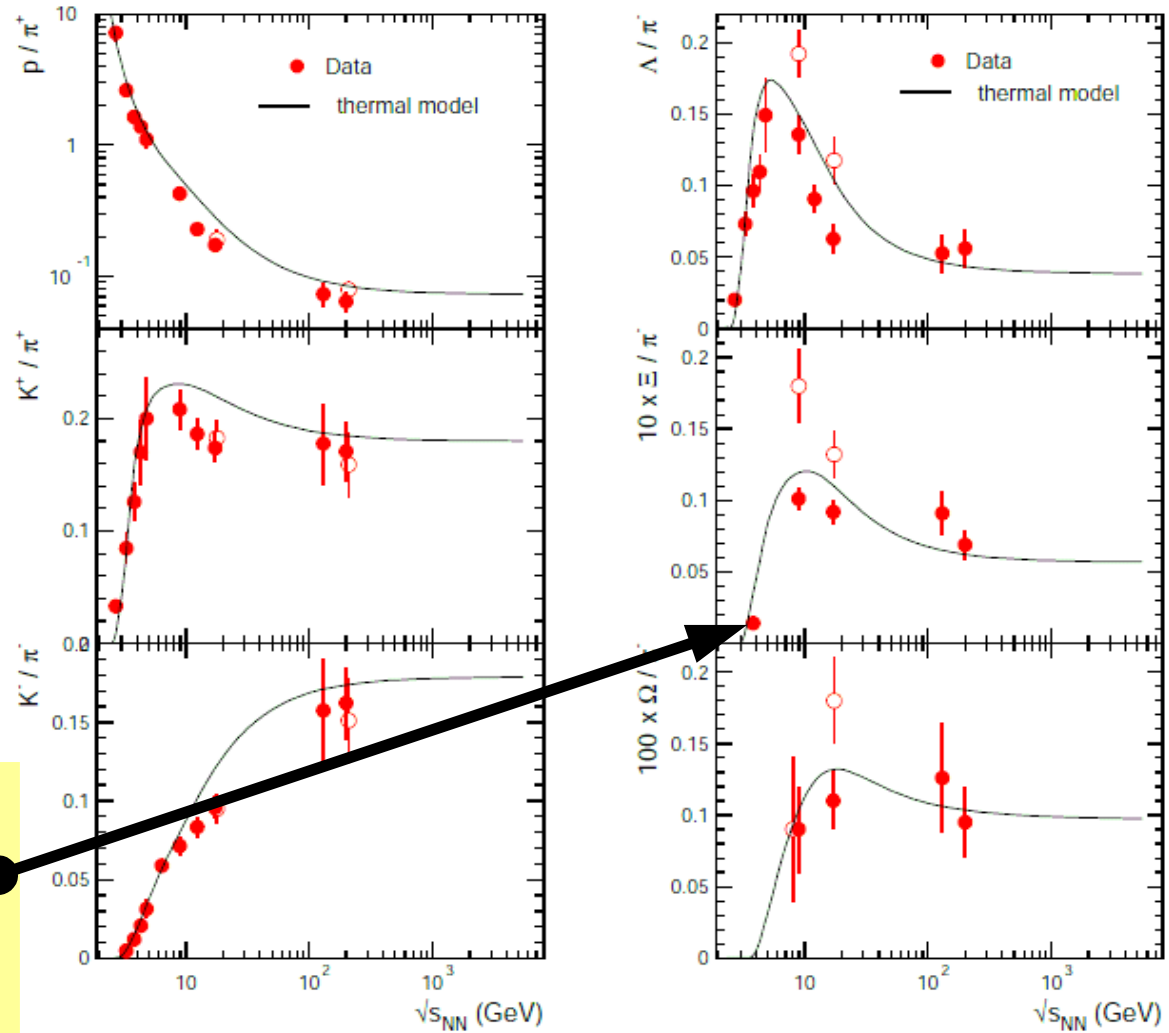
particle/antiparticle ratios
are well described



2005 analysis continued

is there a kaon
anomaly?

„horn“ not well
described



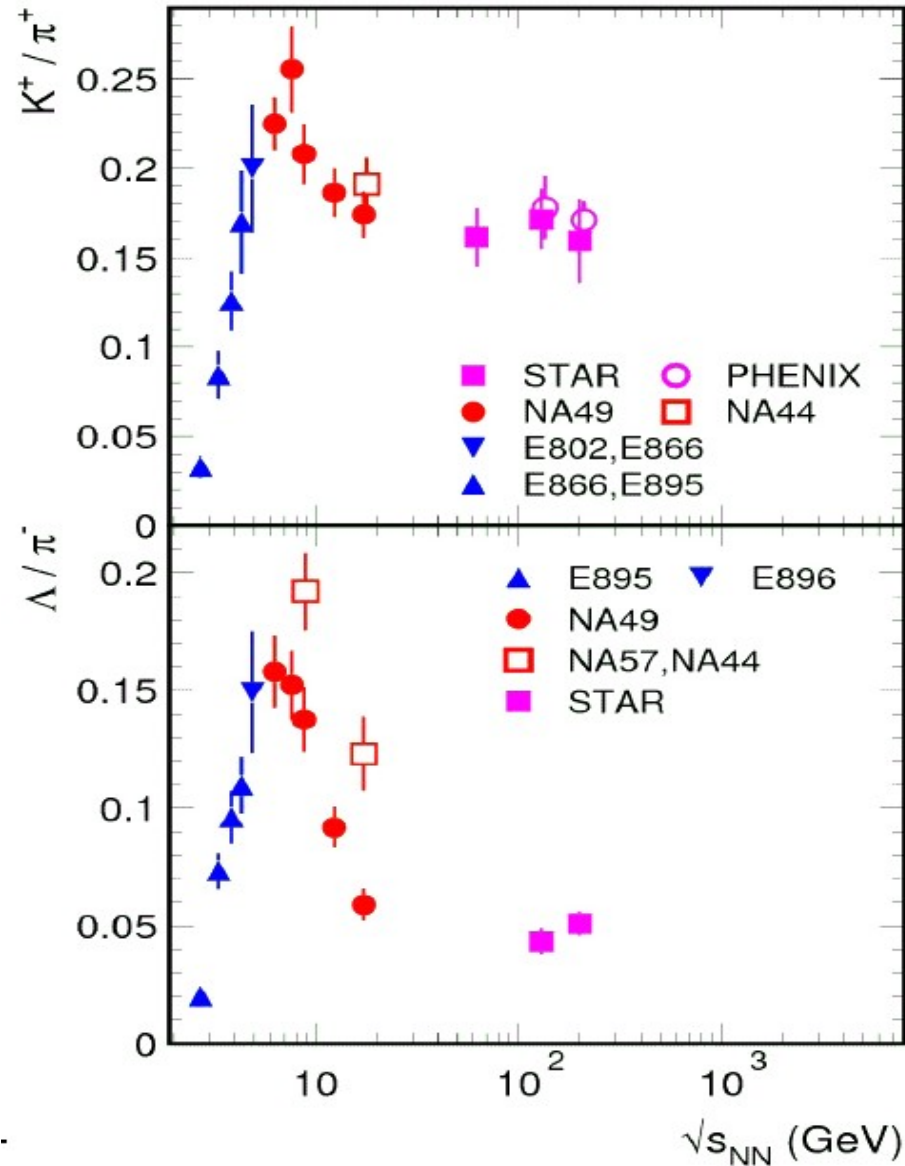
note:
cascade/pi ratio is
well described at
 $E_{lab}/A = 6 \text{ GeV}$
(AGS)

Final data from NA49 and RHIC data

clear evidence for
horn structure in
 K^+/π^+ and
 Λ/π^+

is this outside the
scope of the thermal
model?

is the issue related to
the hadronic mass
spectrum?



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

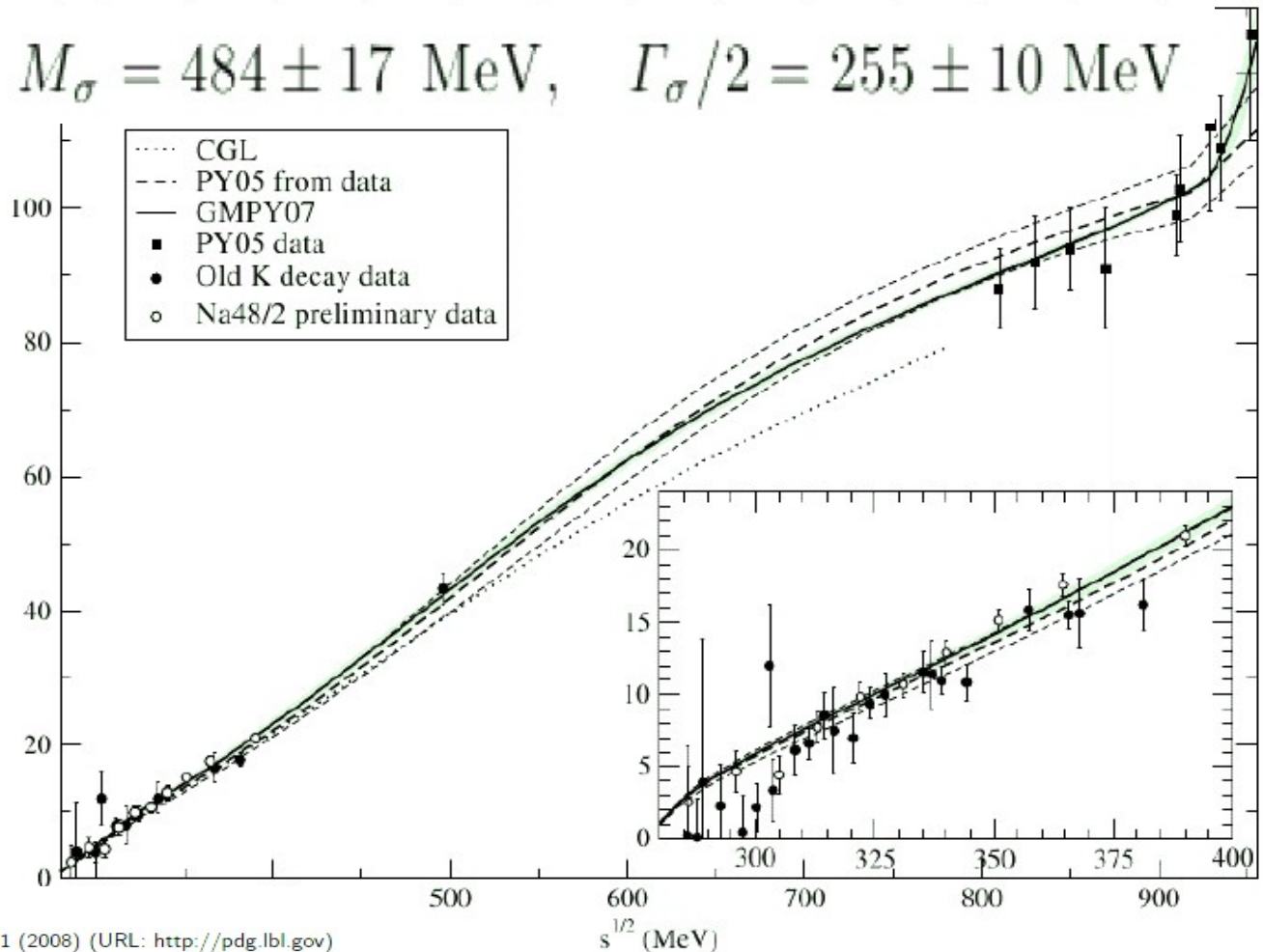
	2005 paper	now	
mesons nonstrange	37	+ 86	= 123
strange	28	+ 4	32
charmed	15	+ 25	40
beauty	16	+12	28
baryons nonstrange	30	+ 36	66
strange	33	+ 30	63
charmed	10	+22	32
beauty	0	+14	14
composites	28		28
total	197	+ 229	426

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

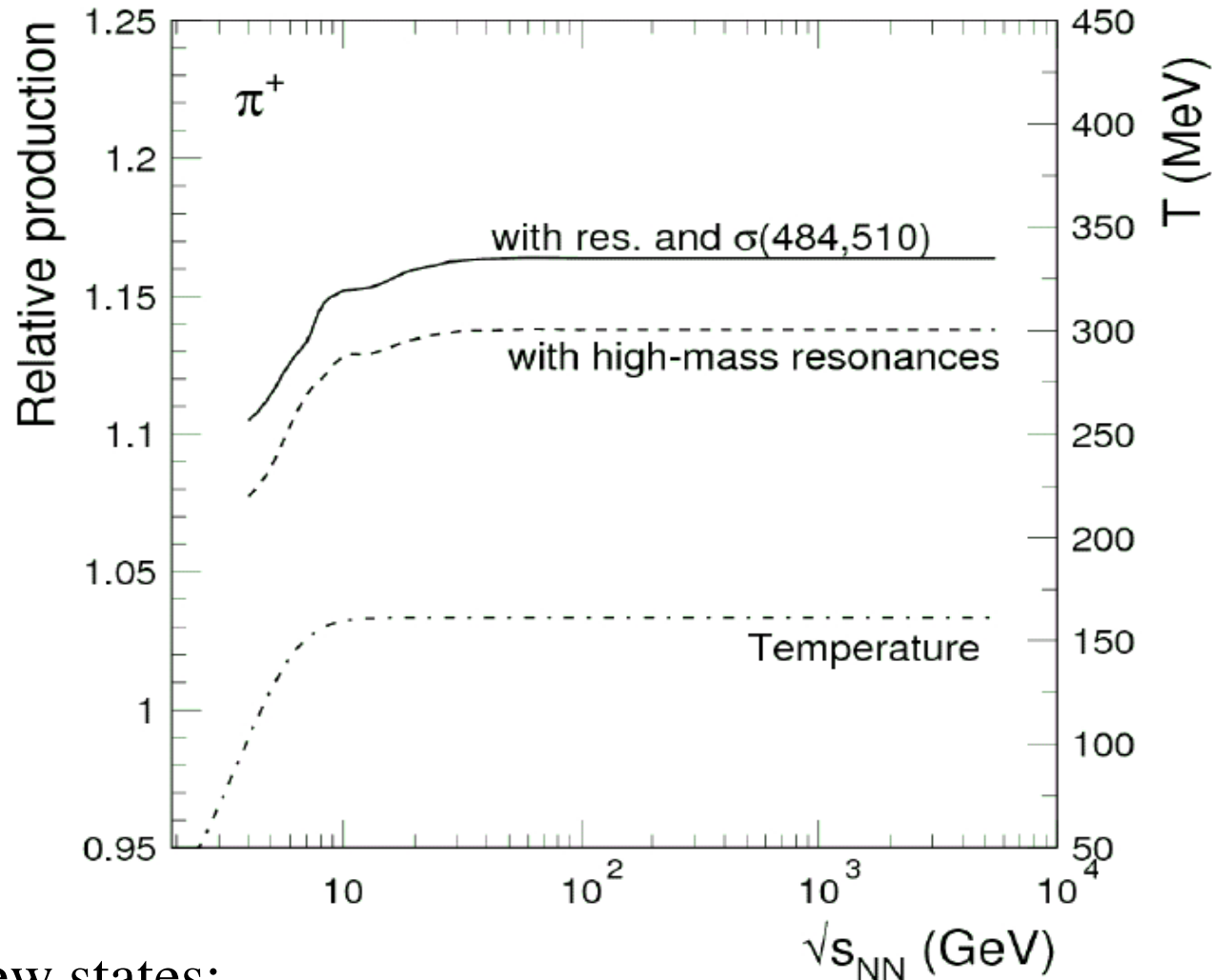


Citation: C. Amsler et al. (Particle Data Group), PL B667, 1 (2008) (URL: <http://pdg.lbl.gov>)

$f_0(600)$
or σ

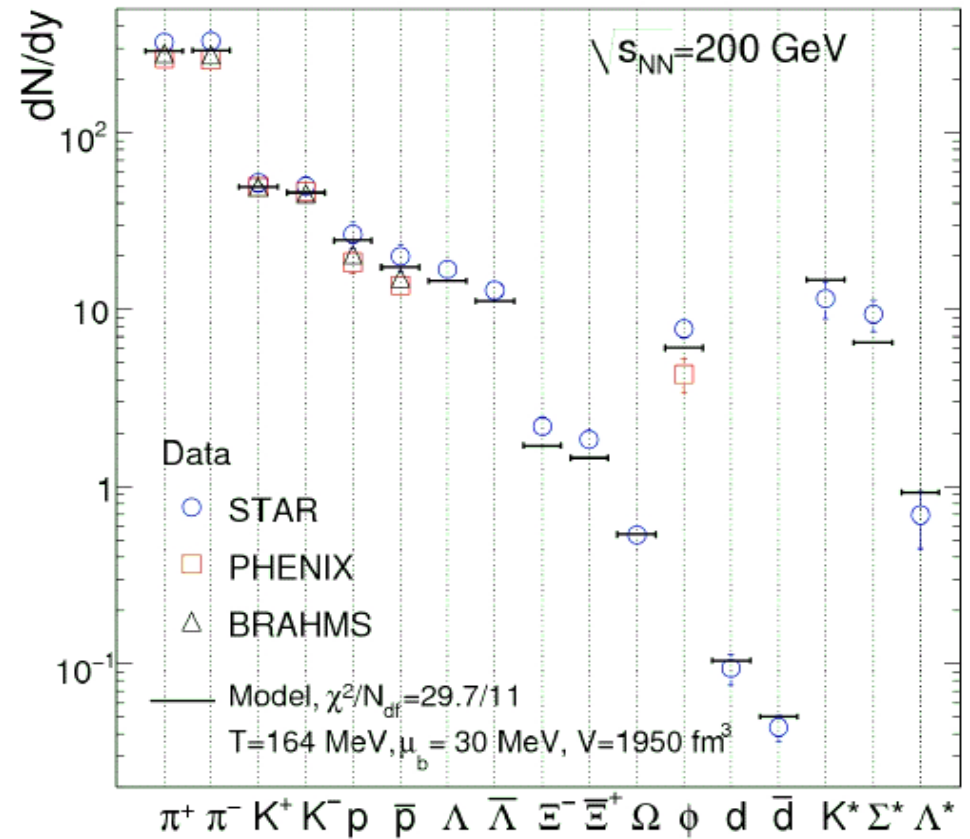
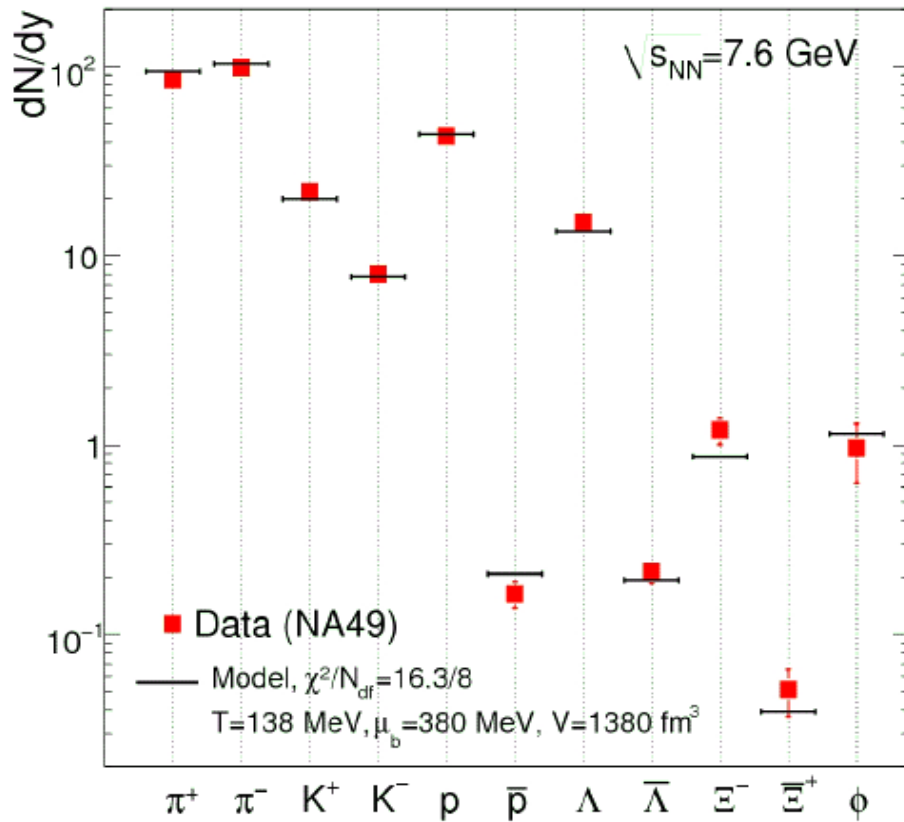
$$I^G(J^{PC}) = 0^+(0^{++})$$

Relative pion production probability



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

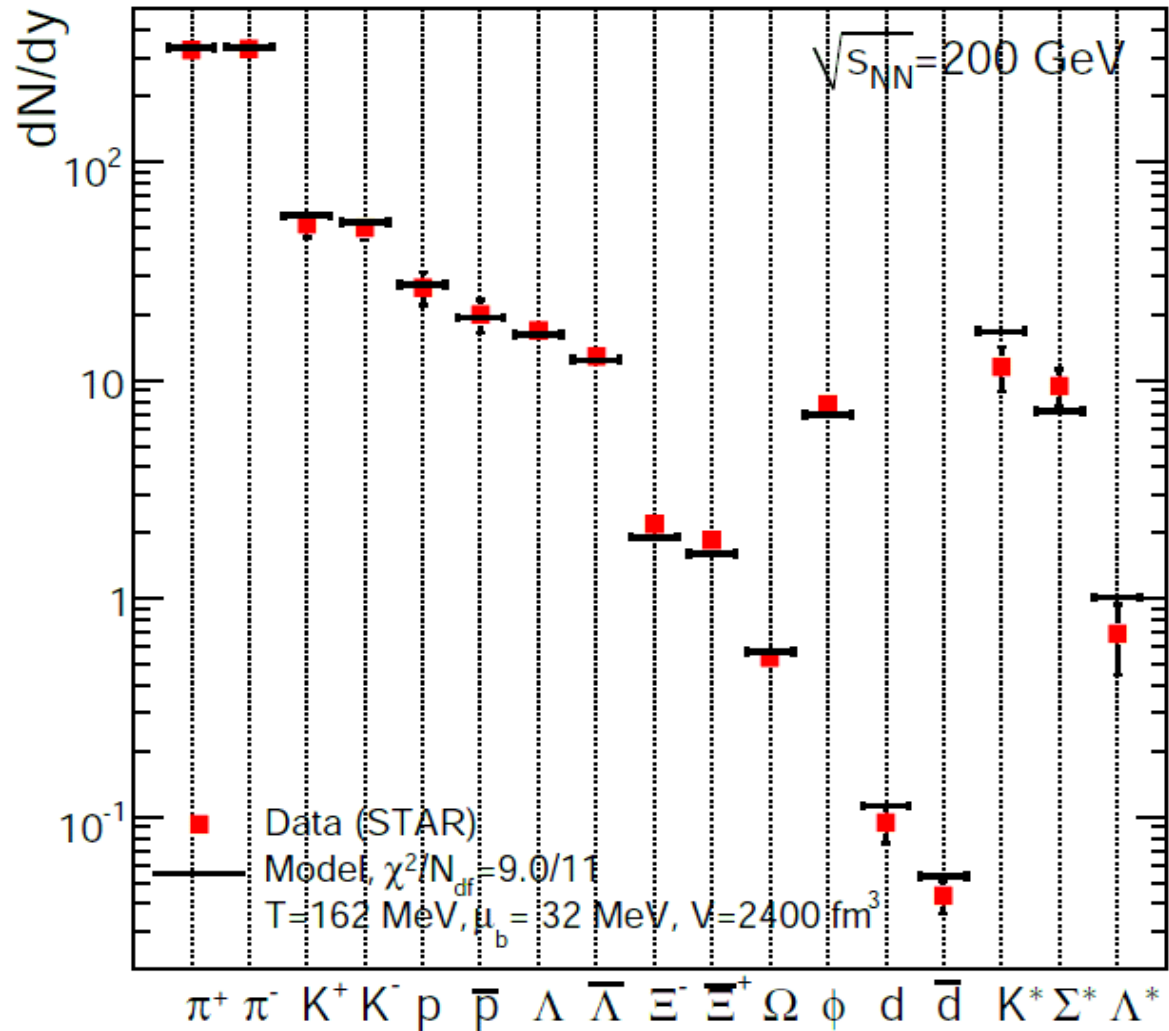
New fits very similar in quality



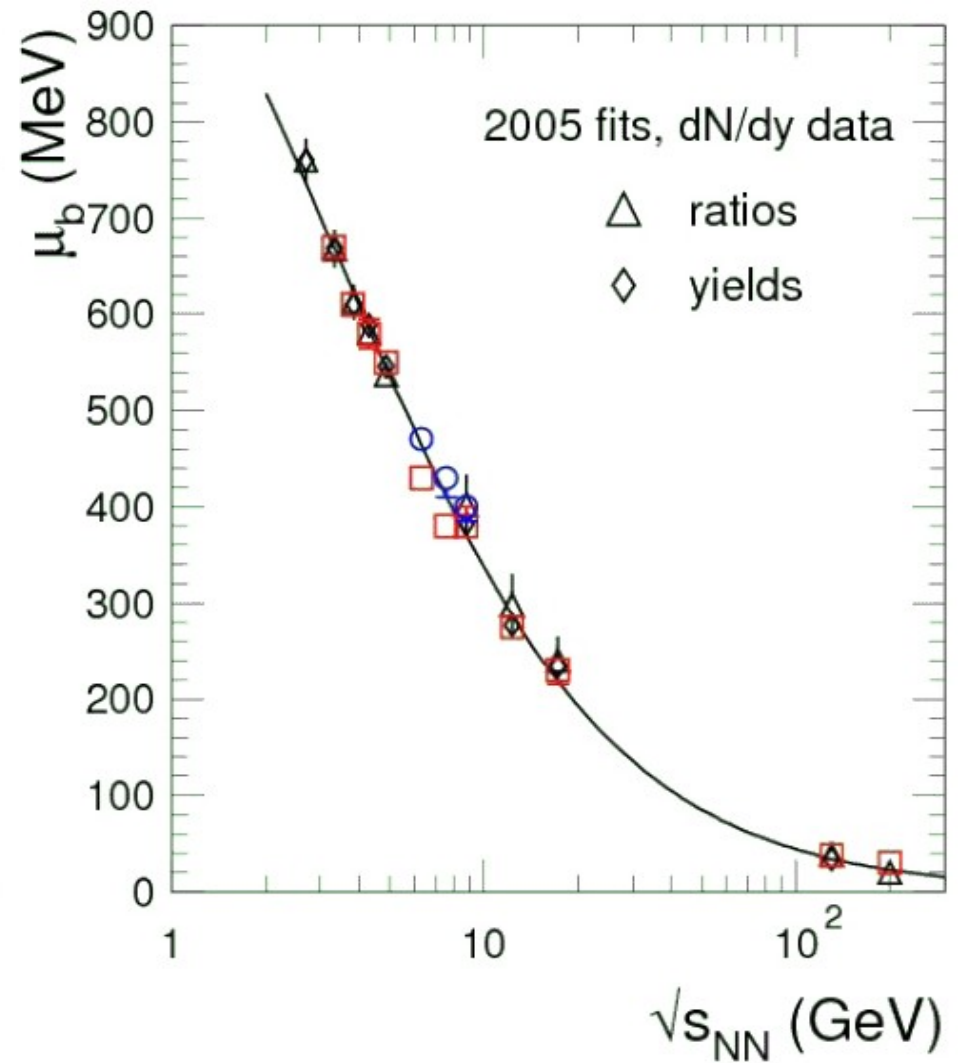
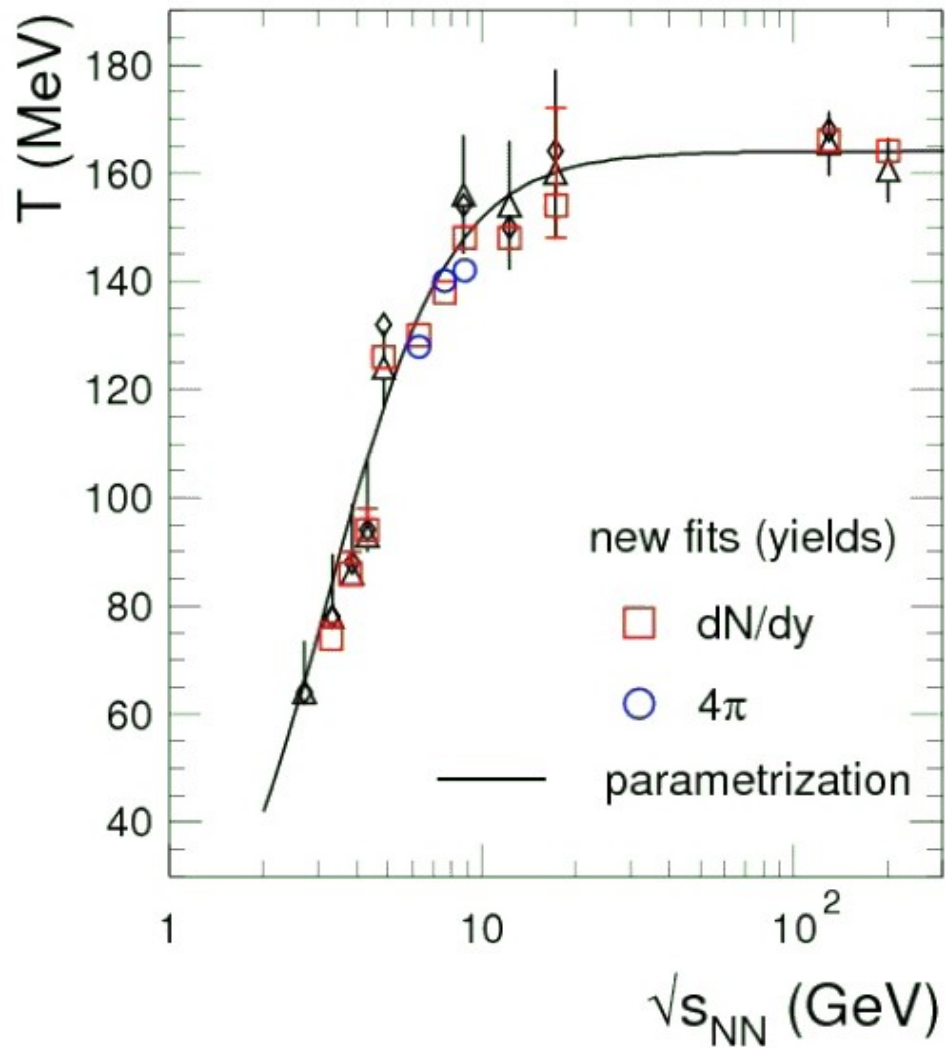
Fit to STAR data alone

very good fit, even including strongly decaying resonances

no evidence for special role of wide states

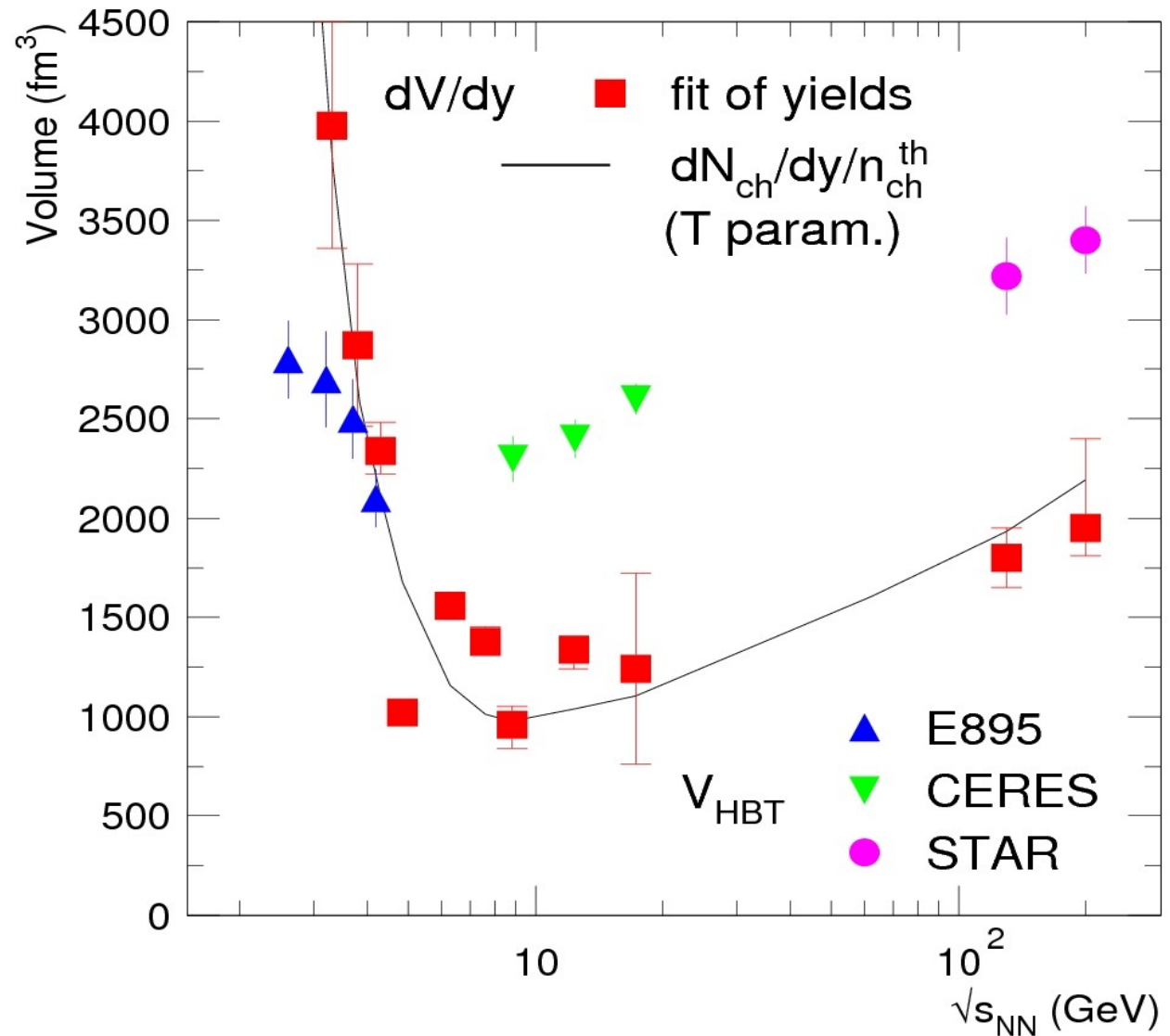


T and mu dependence is essentially unchanged



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

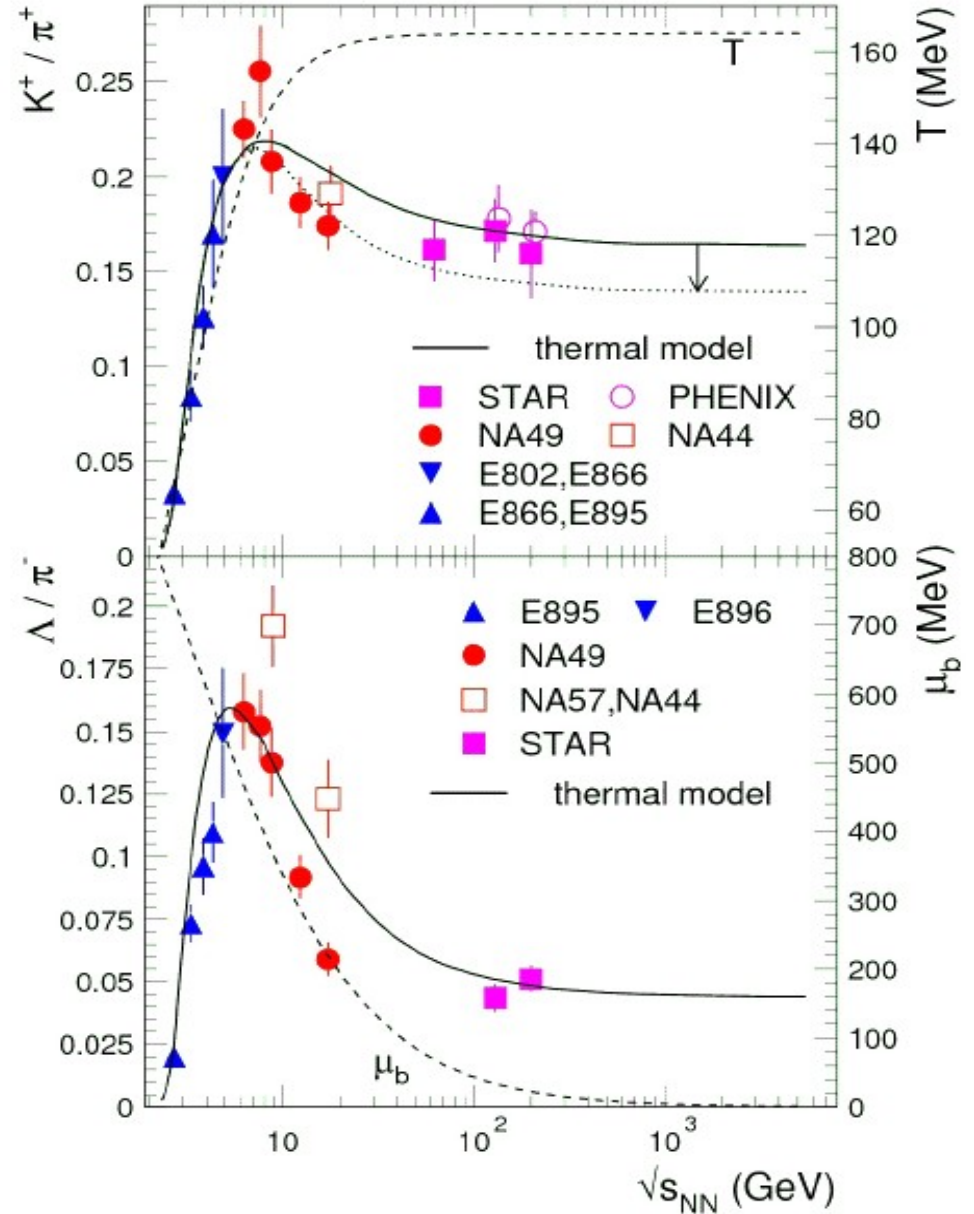
very similar to 2005 analysis



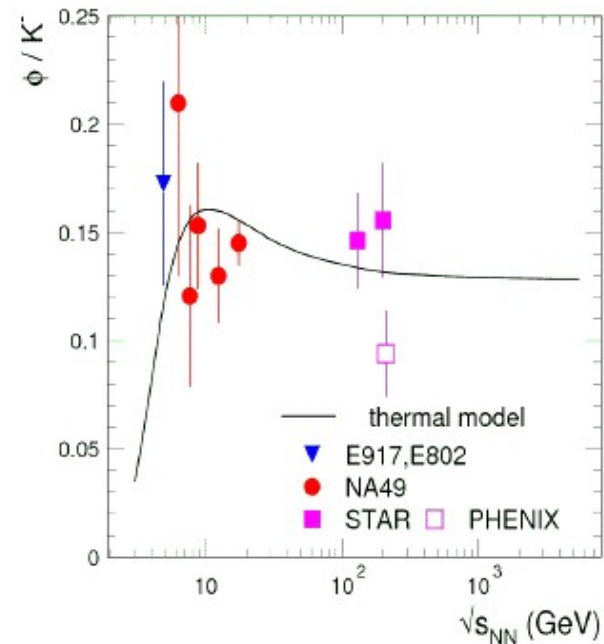
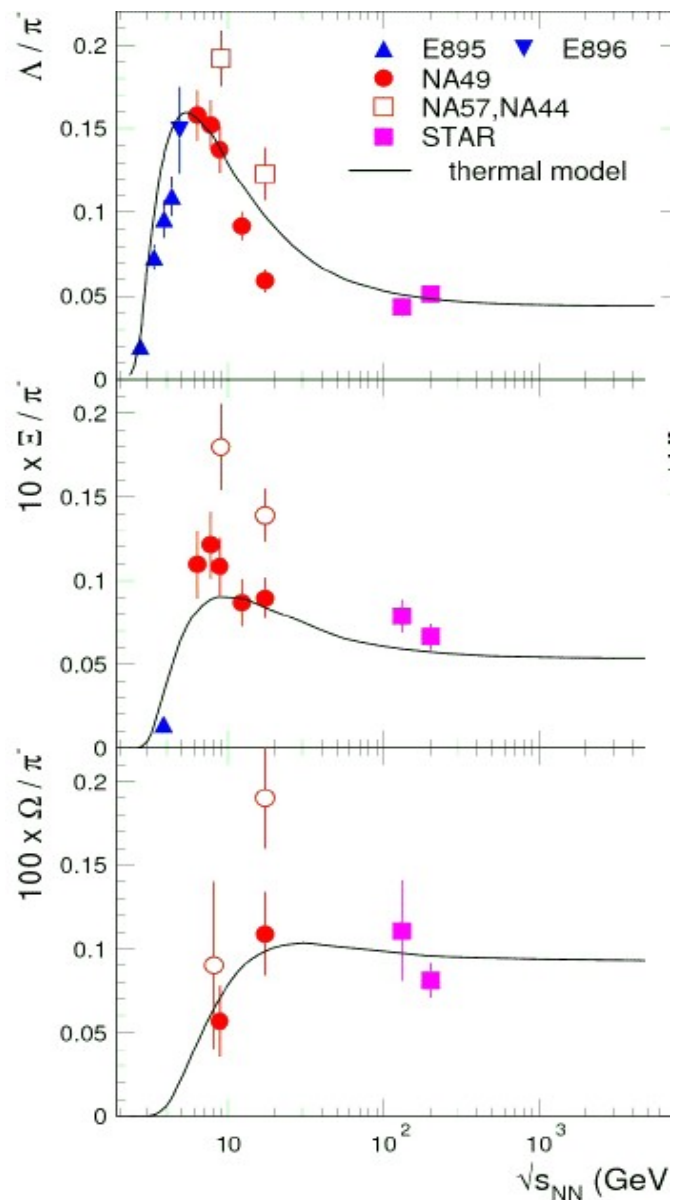
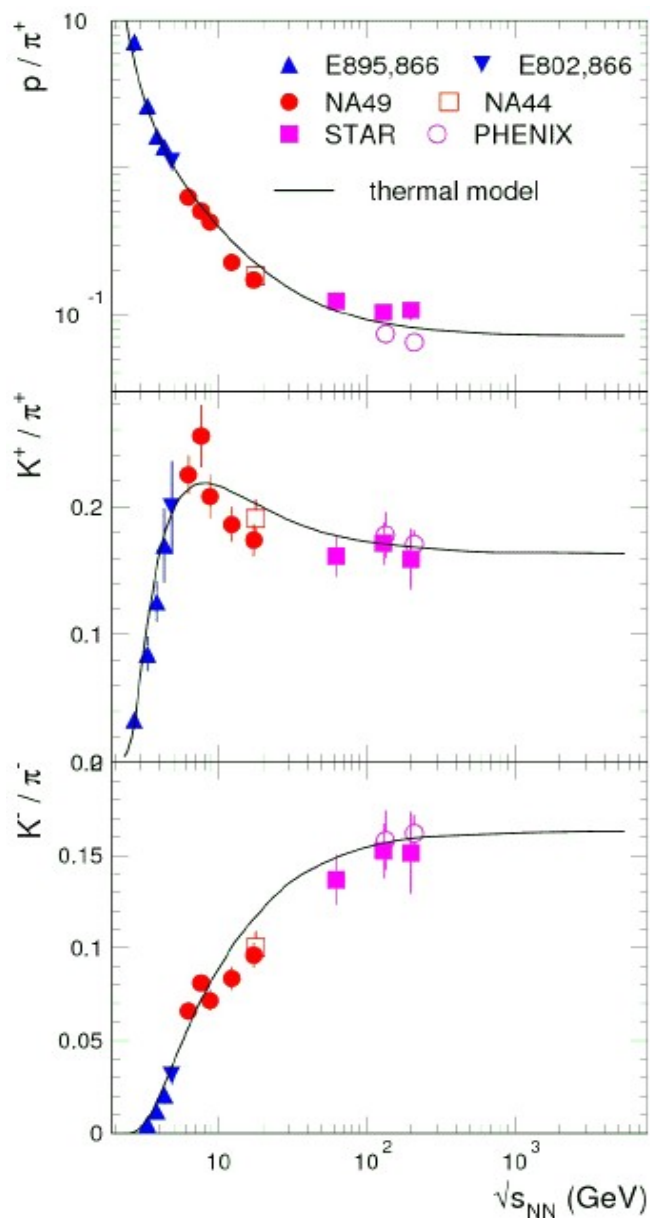
Horn structure well described

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

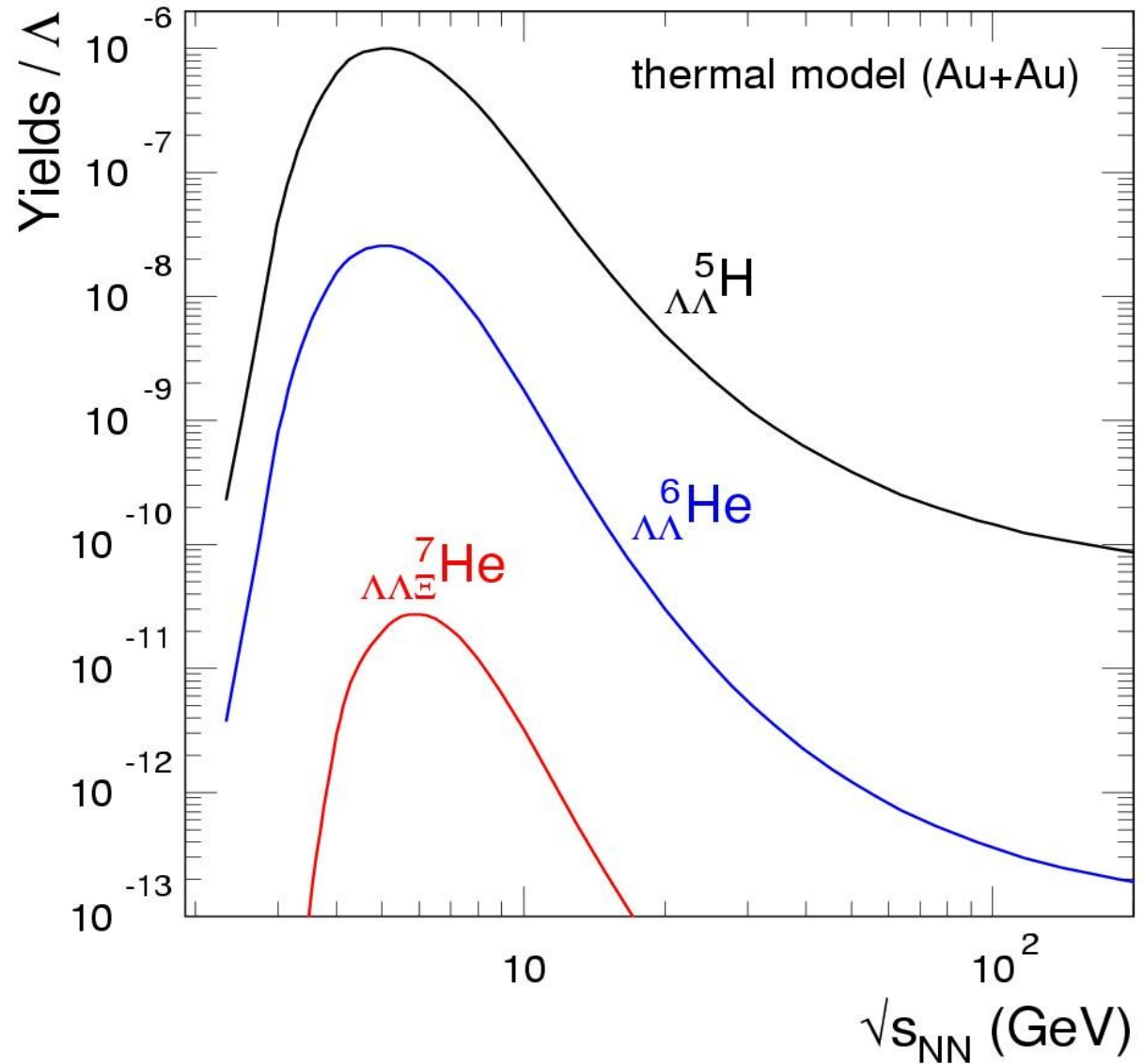


Summary of reanalysis 2008



also yields of exotic objects

measurable yields
in CBM energy range
if such objects are bound



Hagedorn's Limiting Temperature

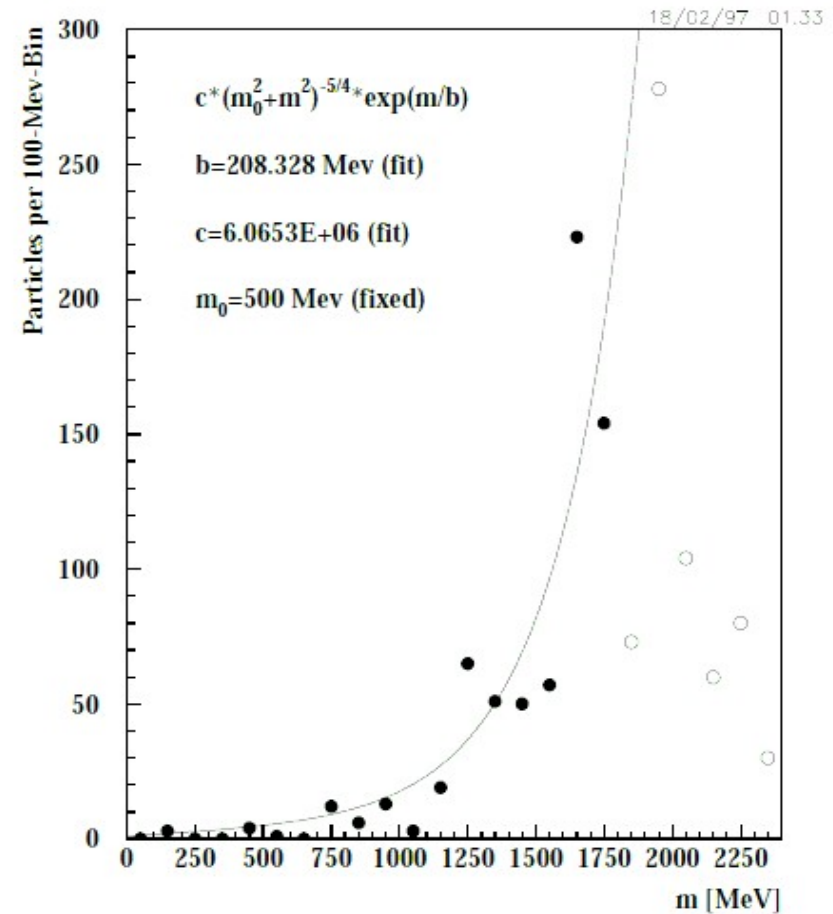
fit with

Hagedorn mass formula

hadronic mass spectrum as of 1998

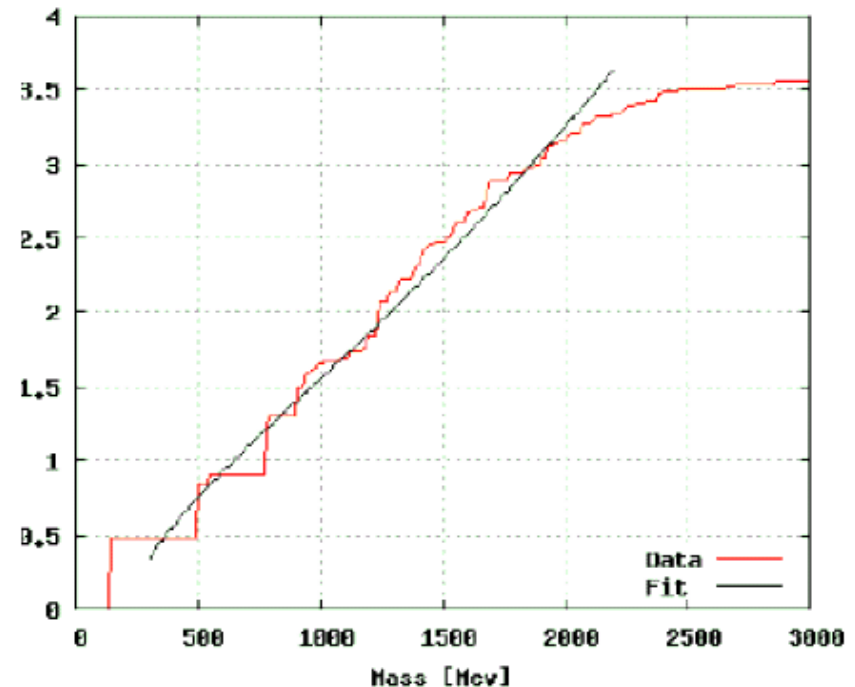
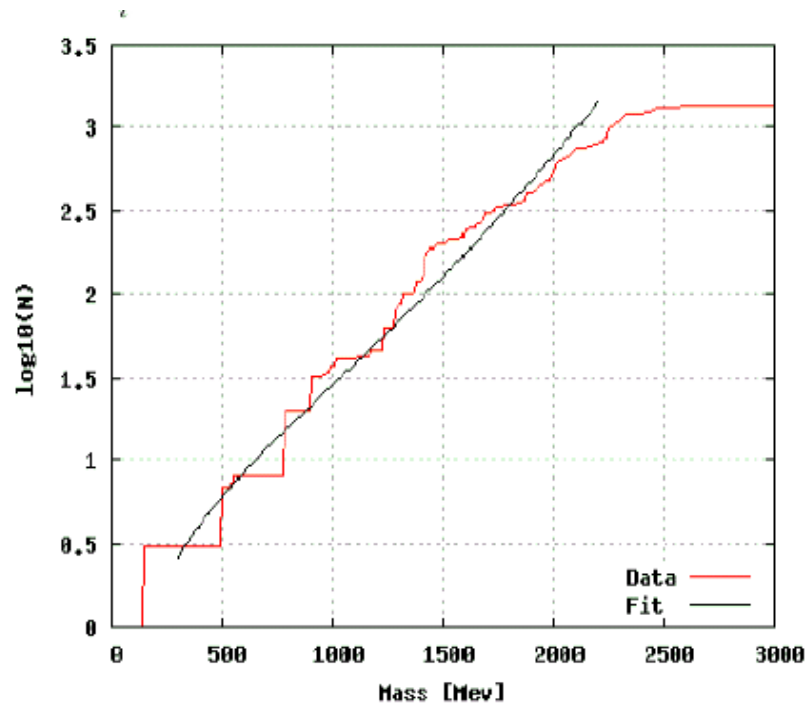
$$\rho_m \propto (m_0^2 + m^2)^{-5/4} \exp(m/b)$$

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



Reanalysis 2008

Maciej Sobczak – analysis of states listed in PDG2008 compilation



$T_H = 180 - 210 \text{ MeV}$ depending on cut-off

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

Hagedorn Mass Spectrum

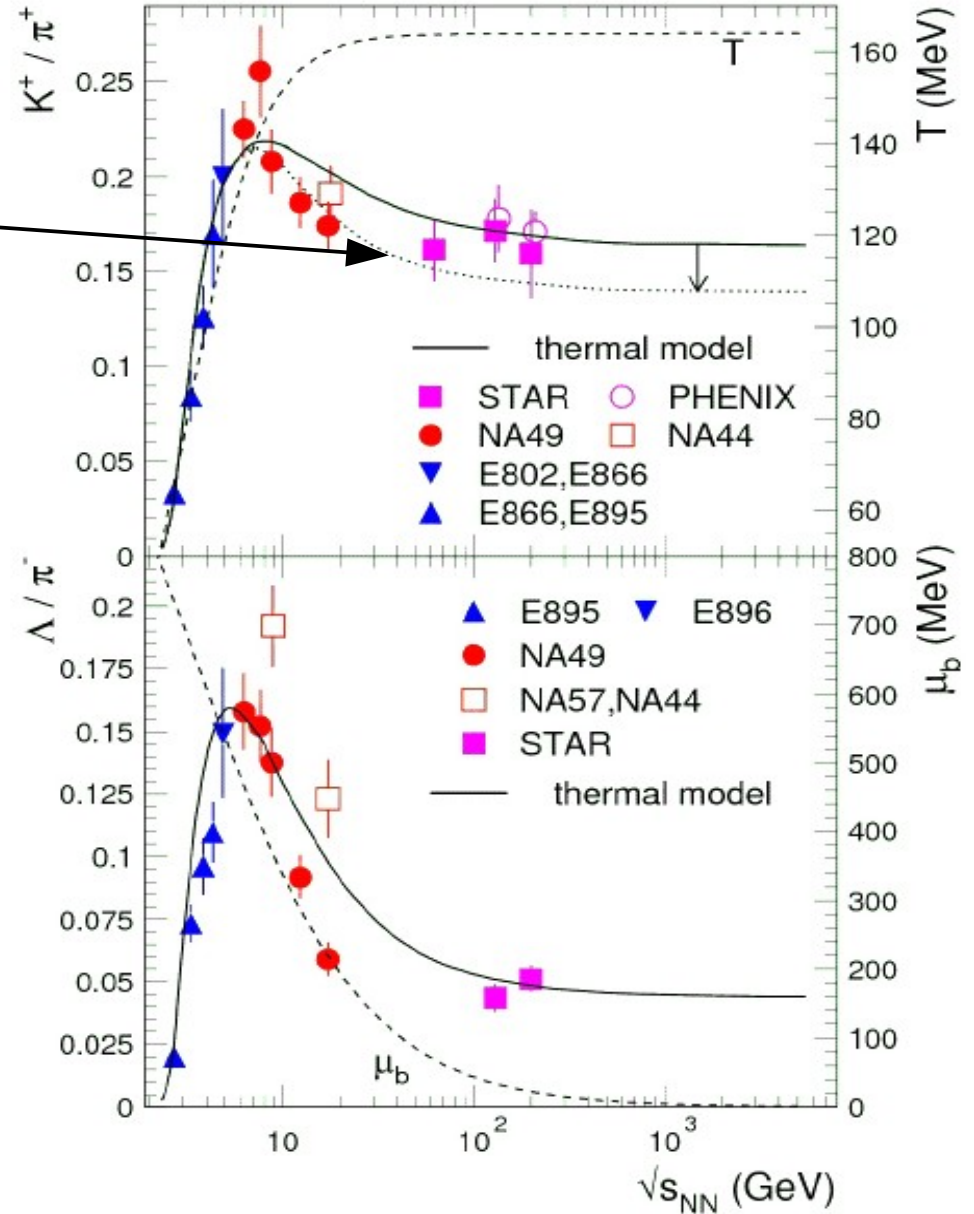
Note: an exponential mass spectrum
is expected also in QCD

at least in the large N_c limit
see T.L Cohen, arXiv:0901.0494

influence of resonances with $M > 3 \text{ GeV}$

inclusion of even higher resonances decreases the K^+/π^+ 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
(γ_{had} , production probability of c and b quarks, ...)

also: fit quality is rather poor

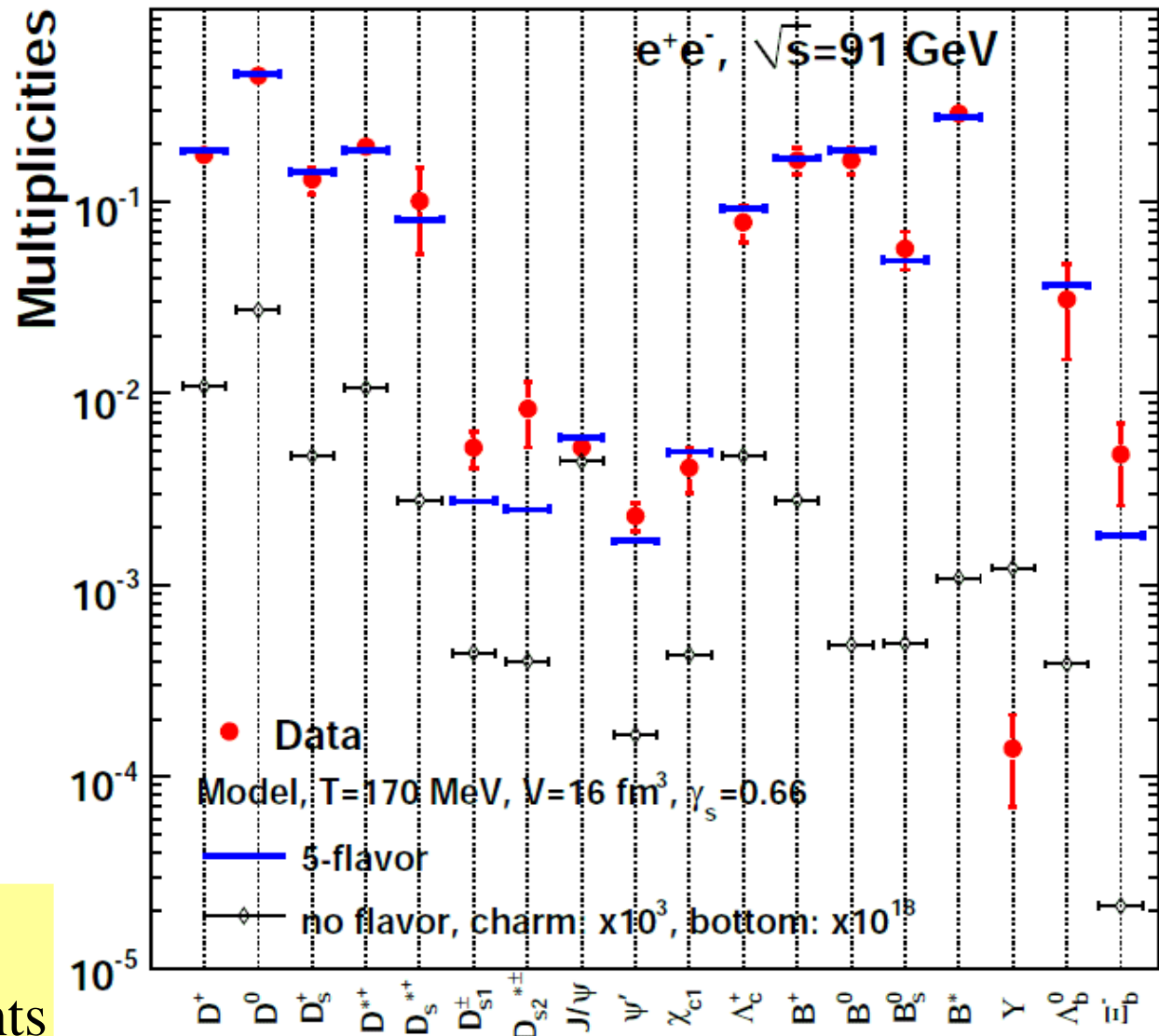
Thermal features of charmed hadrons in e^+e^- collisions

open charm and open beauty hadrons well described,

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

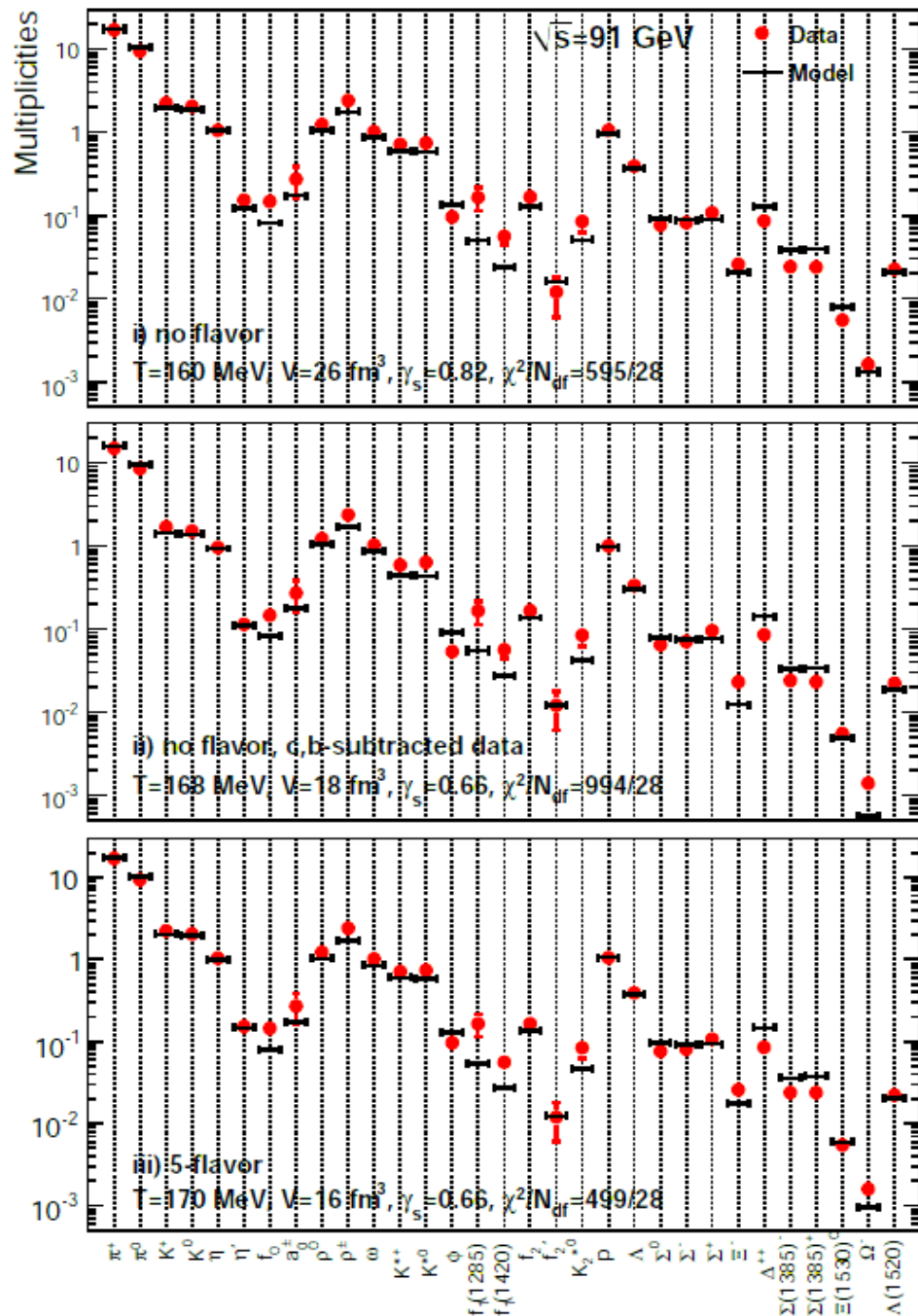
Andronic et al,
arXiv:0804.4132
[hep-ph]

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



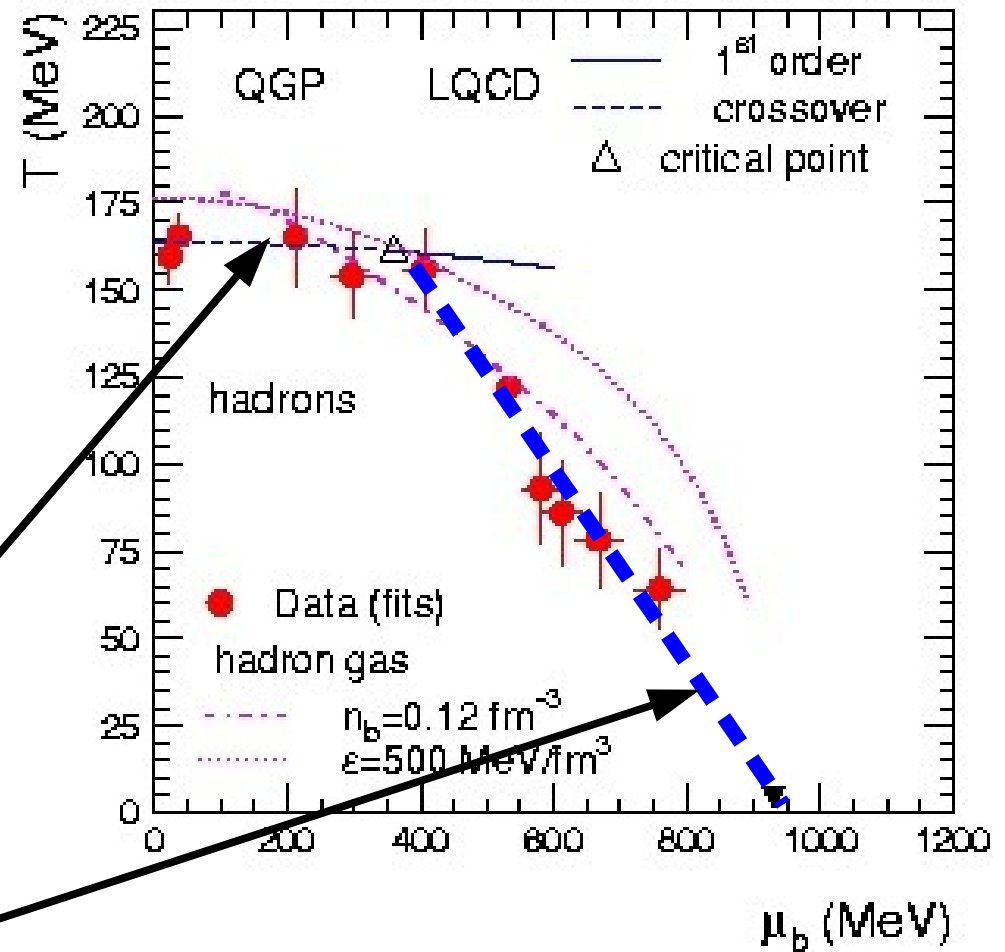
several non-thermal,
external parameters

thermal production of strange quarks
poor fit quality despite additional free
parameter γ_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 ($\mu < 400$ MeV)

what happens at large μ ?

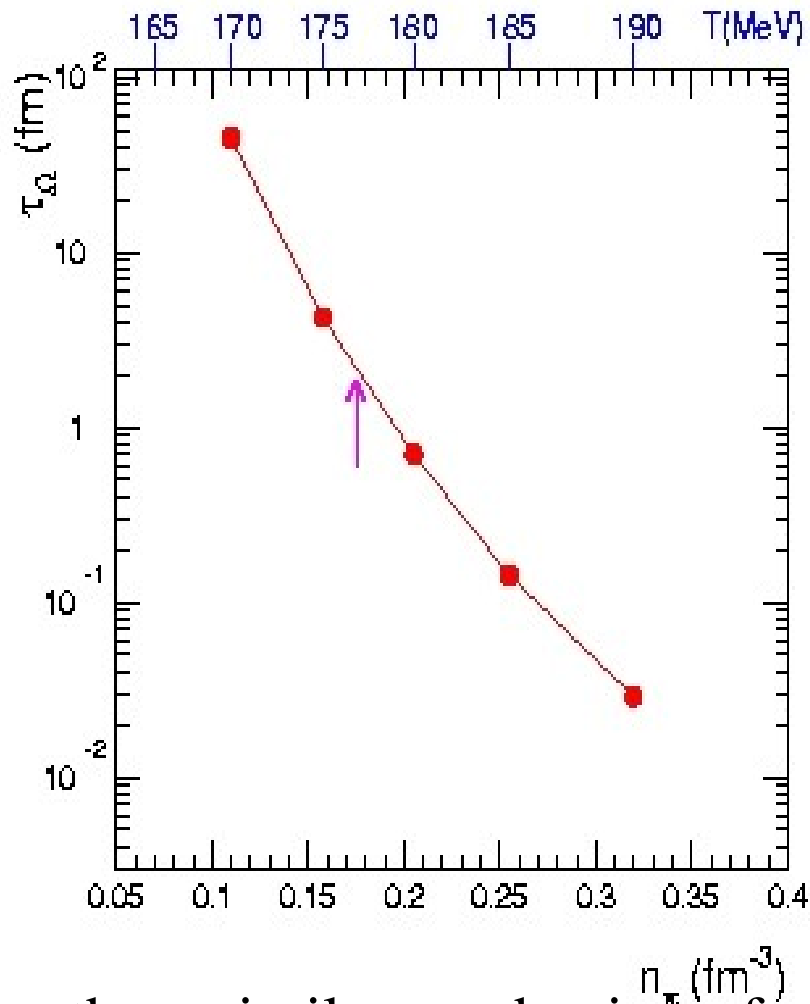


QGP phase boundary

quarkyonic matter boundary?

McLerran & Pisarski
Nucl. Phys. A796 (2007) 83

The QGP phase transition drives chemical equilibration for small μ_b



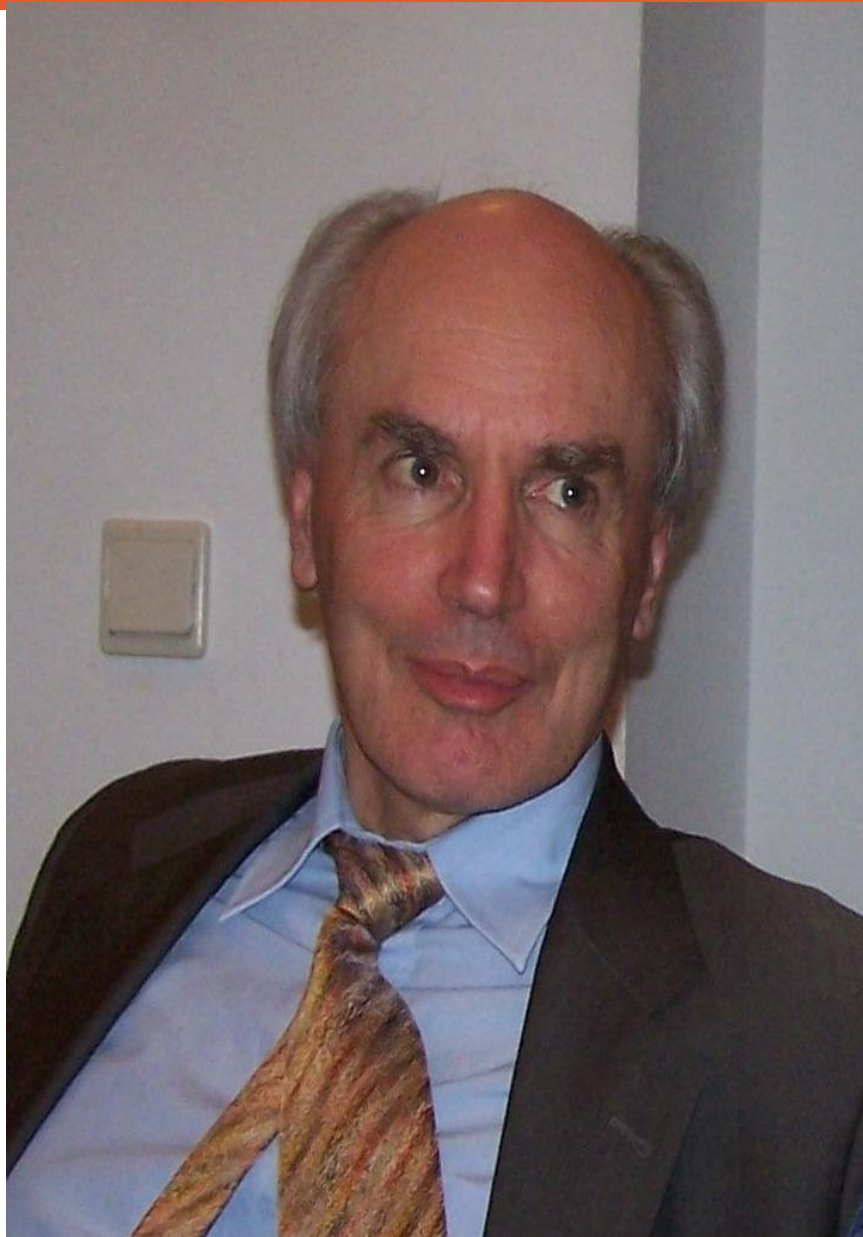
are there similar mechanisms for large μ_b ?

- Near phase transition particle density varies rapidly with T .
- For small μ_b , reactions such as $KKK\pi\pi \rightarrow \Omega N_{\text{bar}}$ 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

- 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 ?

Happy Birthday, Jean-Paul and Larry



Peter Braun-Munzinger

