Hadron yields and the QCD phase diagram

experimental data and statistical model
the horn
centrality dependence
systematics of parameters and phase diagram
the freeze-out point delineate the phase boundary – a model
e+e- and pp collisions don't lead to an equilibrated system
phase transition to quarkyonic matter
future program at LHC and what ALICE can do
first ALICE results
some comments on light nuclei and resonances

Johanna Stachel, Physikalisches Institut Universitaet Heidelberg
Hirschegg 2010

analysis of yields of produced hadronic species in statistical model – grand canonical

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

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

for every conserved quantum number there is a chemical potential:

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

but can use conservation laws to constrain V, μ_S, μ_{I_3} →

Fit at each energy provides values for T and μ_b

technical details:

van der Waals type interaction via excluded volume correction following
Rischke, Gorenstein, Stoecker, Greiner, 1991

finite volume correction a la Balian and Bloch

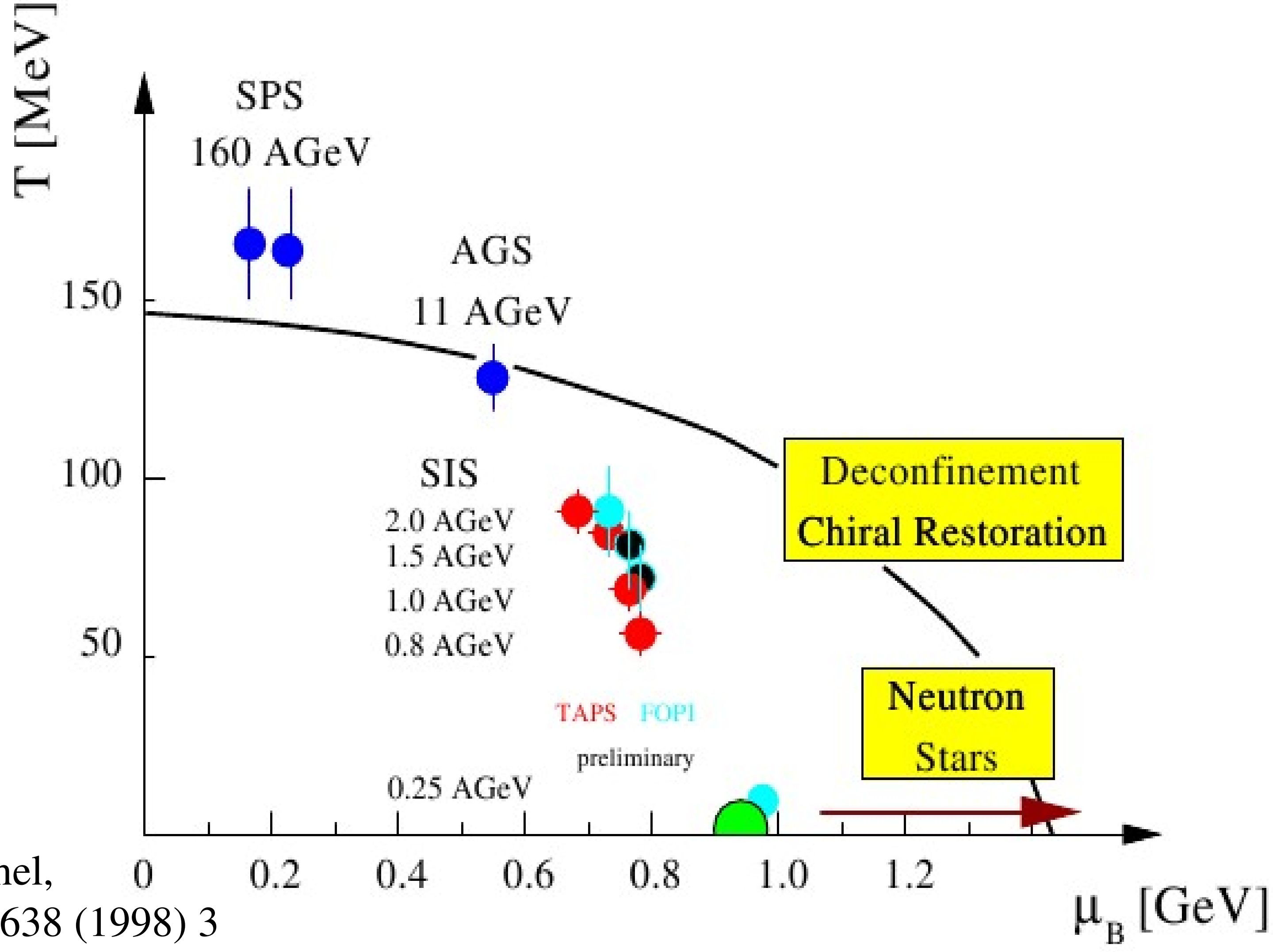
width of all resonances included by integrating over Breit-Wigner distributions

For a review see: Braun-Munzinger, Redlich, Stachel, QGP3,
R. Hwa ed. (Singapore 2004) 491-599; nucl-th/0304013

attempts go way back: Shuryak for pp at ISR
J. Cleymans Quarkmatter 1990 - at that time not very successful

first successful description of data for SiPb collisions at AGS:
P.Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, Phys. Lett. B344 (1994) 43

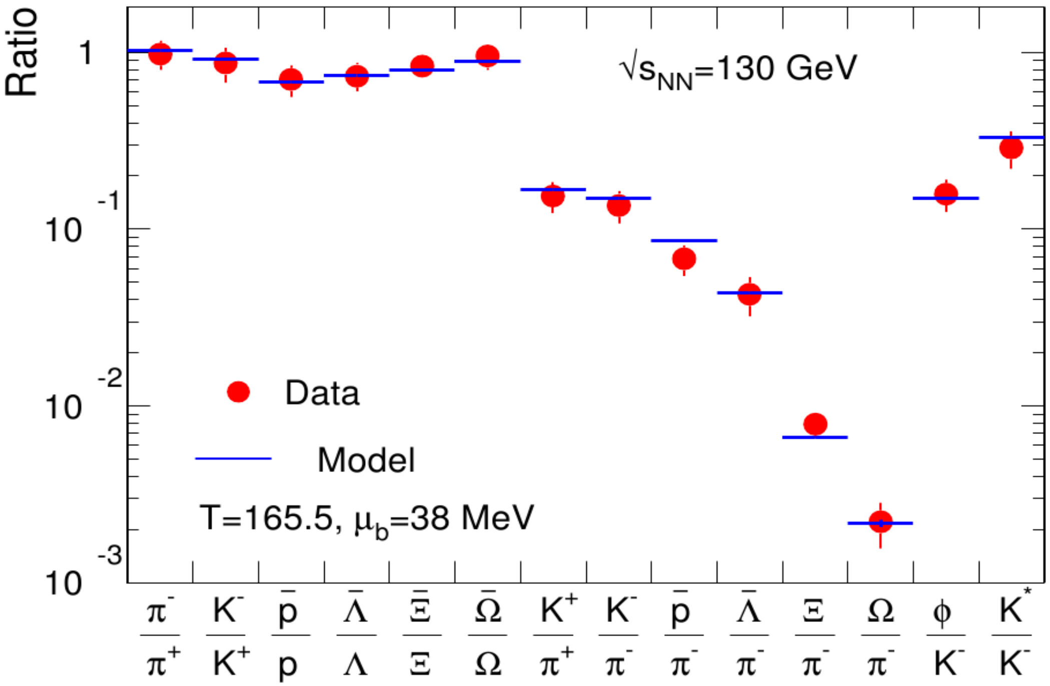
leading eventually to the first phase diagram with experimental points



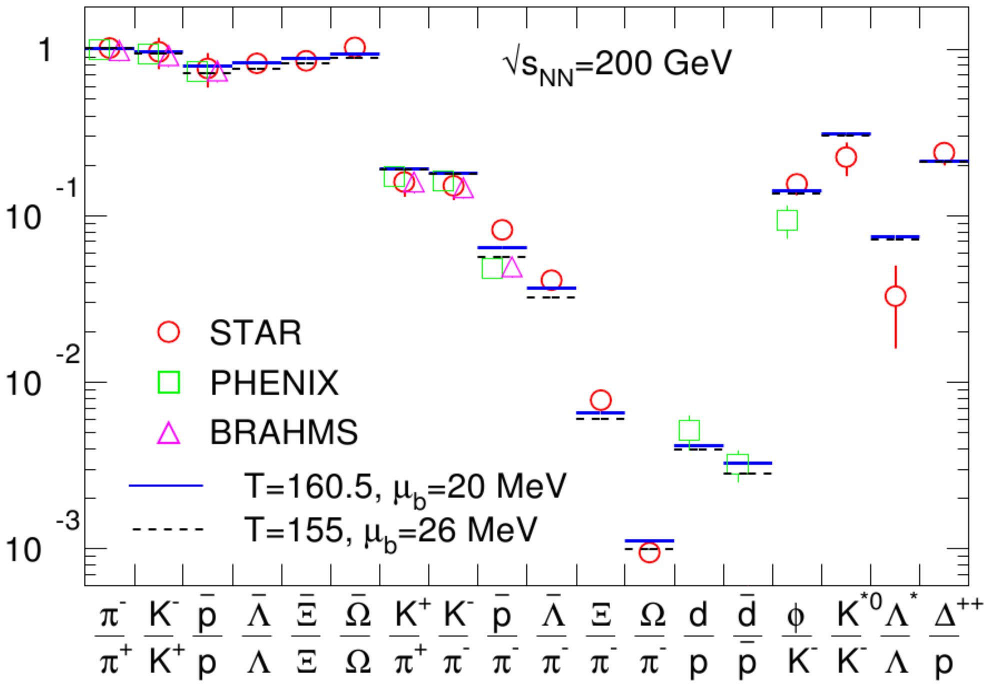
P.Braun-Munzinger and J. Stachel,
nucl-th/9803015, Nucl. Phys. A638 (1998) 3

for RHIC hadron yields are reproduced really well compared to statistical model (GC)

130 GeV data in excellent agreement
with thermal model predictions



prel. 200 GeV data fully in line
still some experimental discrepancies



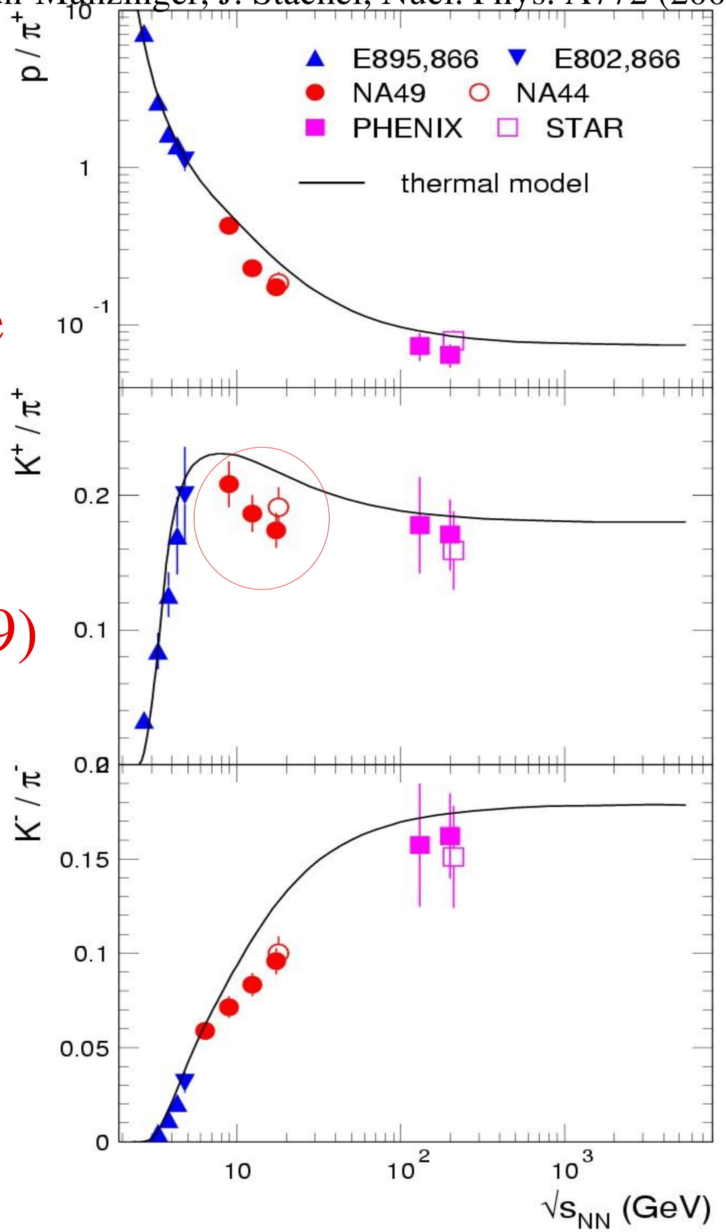
chemical freeze-out at: T = 165 ± 5 MeV

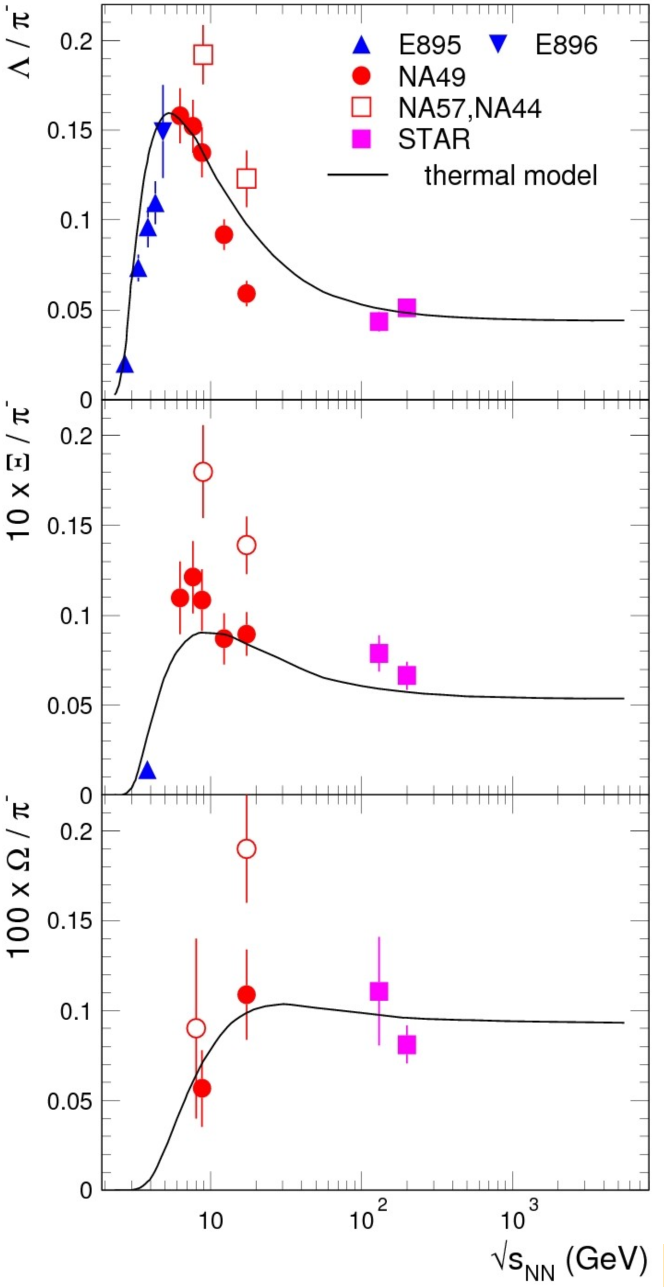
P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel, Phys. Lett. B518 (2001) 41
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167
confirmed by Xu and Kaneta and by F. Becattini

detailed $\sqrt{s}$ dependences: predicted features as peak in Λ/K appear, but K^+/π^+ cannot be really well reproduced

A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167

instead: suggestion of evidence for the onset of deconfinement (Gazdzicki, Gorenstein 1999)





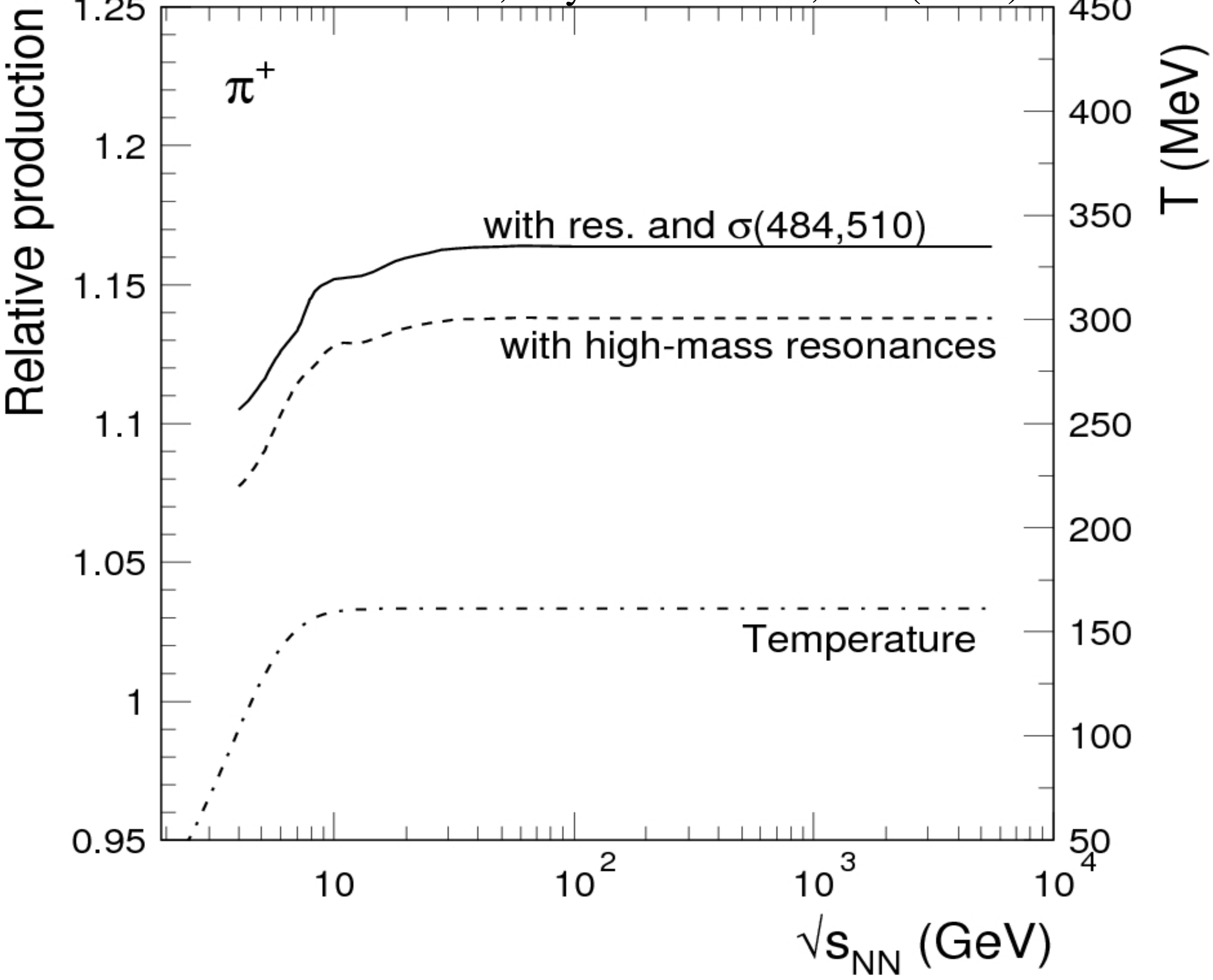
Recent developments

- extended and finalized data by NA49 and low energy point from STAR
- study effect of consequences of extended hadronic mass spectrum using all information as of PDG2008
  in total 229 states were added to a total of 426
  (was required for precision e+e- data)
- include also σ meson due to new solidified evidence
- study consequence of potentially still incomplete hadron spectrum

net effect of model extension: more pions relative to other hadrons

relative change in pion yield with more high mass resonances and the σ

A. Andronic, P. Braun-Munzinger, J. Stachel,
arXiv:0812.1186, Phys. Lett. B673, 142 (2009)



as T levels off,
so does the increase in
pion yield

what do we know today about Hagedorn spectrum?

Maciej Sobczak – analysis of states listed in PDG2008 compilation

$$f_{FIT}(m) = log_{10}\left(\int_0^m \frac{c}{(x^2+m_0^2)^{5/4}} exp(x/T_H)\right) \qquad \rho(m) = \frac{c}{(m^2+m_0^2)^{5/4}} exp(m/T_H)$$

$$N_{exp}(m) = \sum_i g_i \Theta\left(m - m_i\right)$$

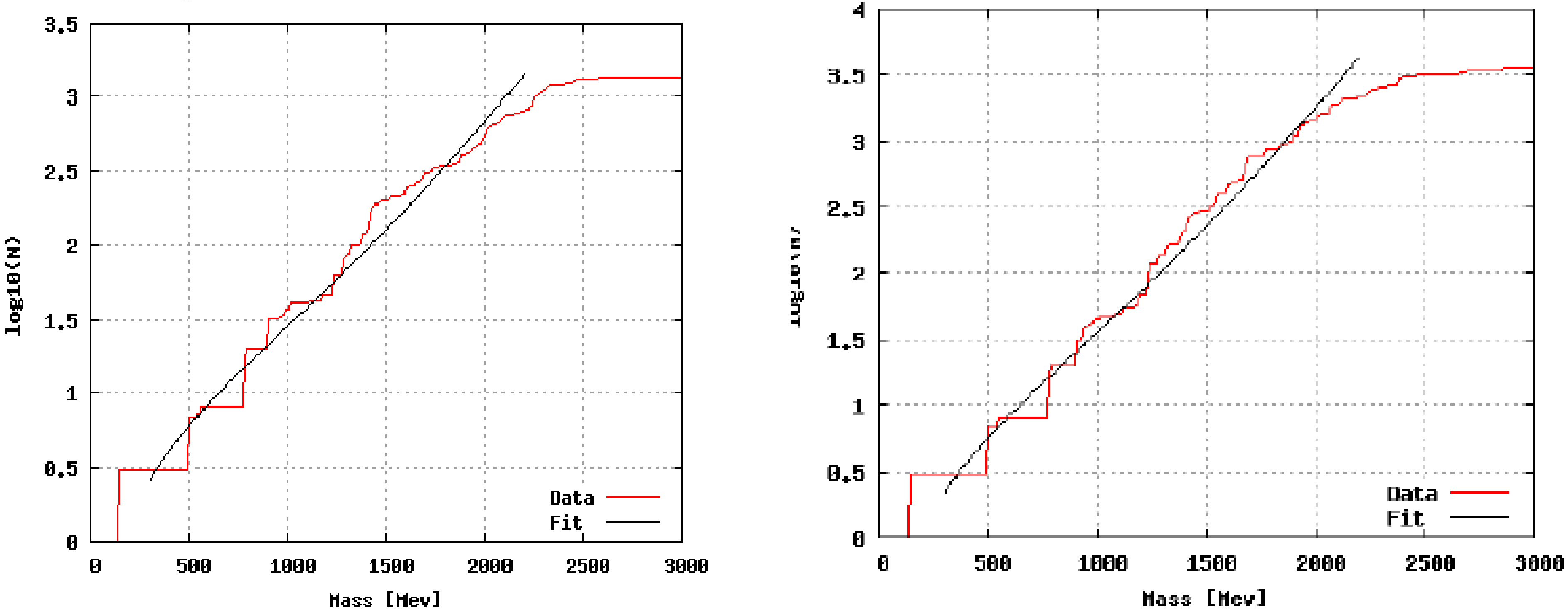


Figure 2: All mesons $T_H = 203.315$, $c = 25132.674$, range: $300 - 2200\ MeV$: All hadrons $T_H = 177.086$, $c = 18726.494$, range: $300 - 2200\ MeV$

Note: an exponential mass spectrum is expected also in QCD at least in the large Nc limit (T.L Cohen, arXiv:0901.0494)

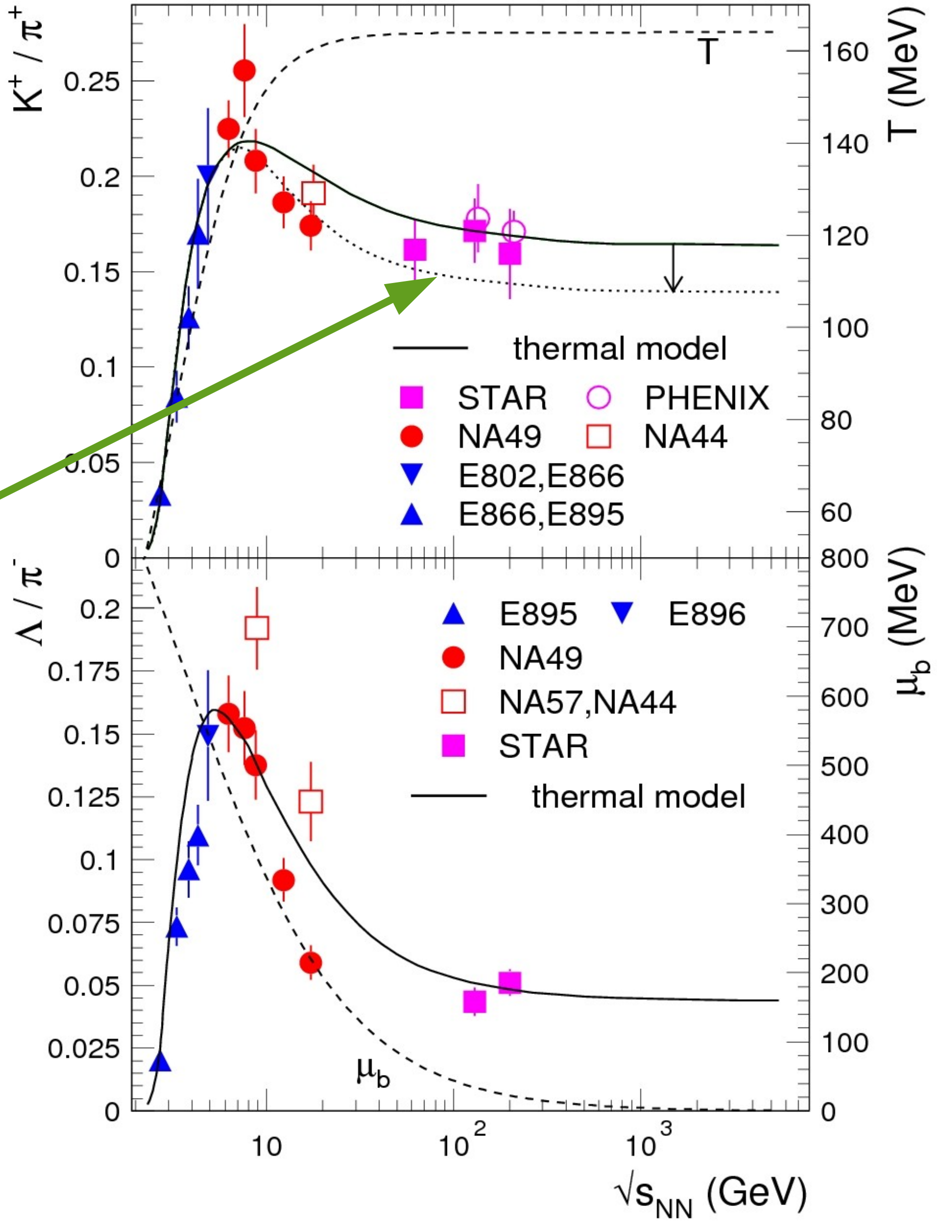
How would this affect K^+/π^+?

estimate effect by extending mass spectrum beyond 3 GeV based on T_H = 200 MeV and assumption how states decay

strongest contribution to kaon from K* producing one K

all high mass resonances produce multiple pions

-> further reduction of K^+/π^+



A. Andronic, P. Braun-Munzinger, J. Stachel, arXiv:0812.1186, Phys. Lett. B673, 142 (2009)

centrality dependence

J. Cleymans, B. Kämpfer, M. Kaneta, S. Wheaton, N. Xu Phys. Rev. C71 (2005) 054901; hep-ph/0409071

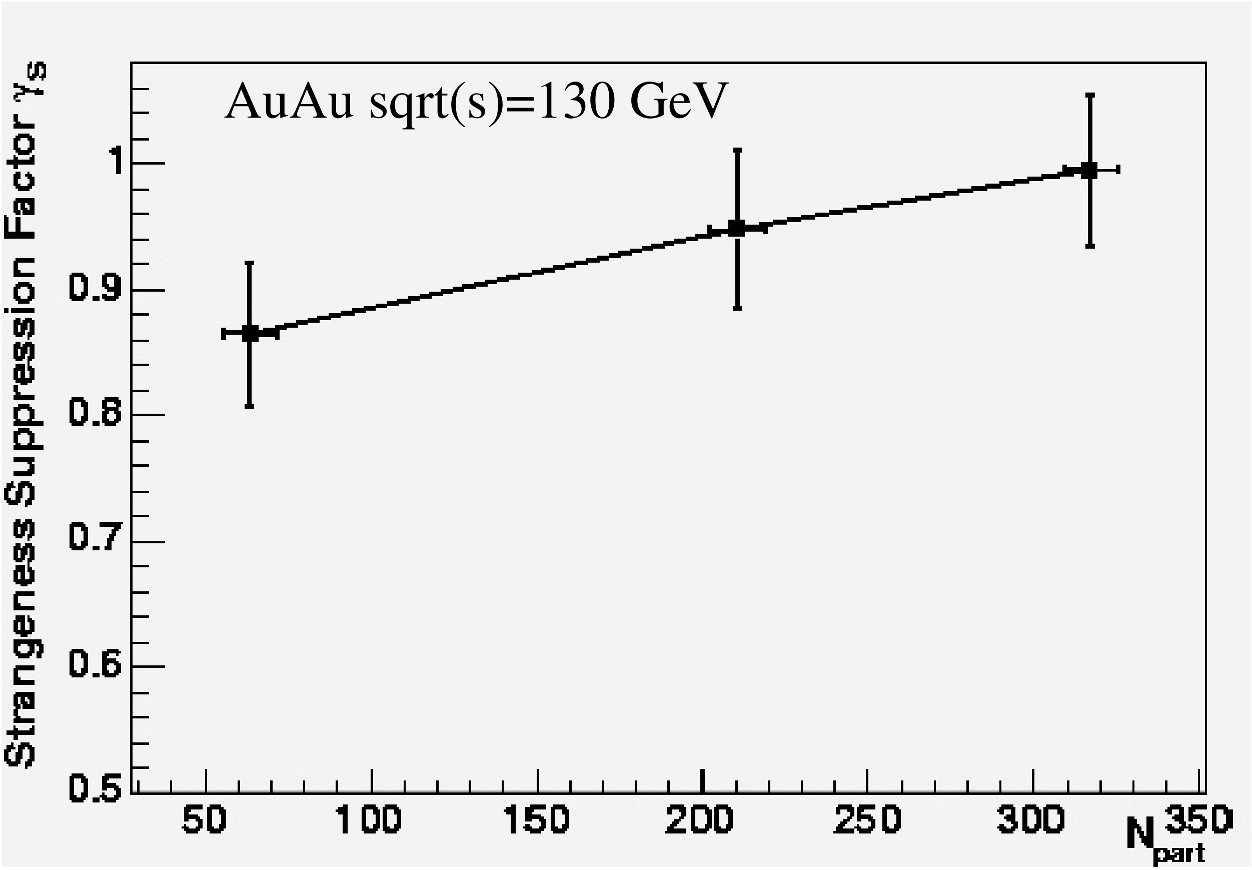
apparent temperature shows no significant centrality dependence

but need to introduce γ_s

strangeness is suppressed

in more peripheral collisions

steeper decrease at SPS energy



centrality dependence

recent study by J. Aichelin and K. Werner, arXiv: 0810.4465[nucl-th]

$$M^i(N_{\rm part}) = N_{\rm part}\left[f(N_{\rm core})\cdot M^i_{\rm core} + (1 - f(N_{\rm core}))\cdot M^i_{\rm corona}\right]$$

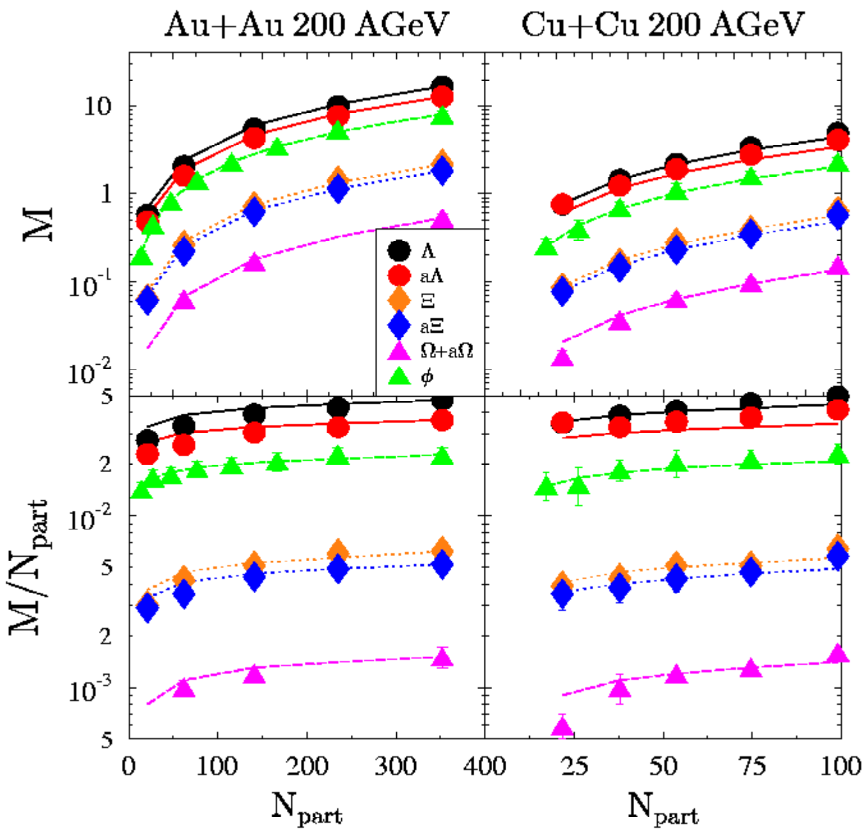
$$M^i_{\rm corona} = \frac{1}{2}\frac{dn^i}{dy}\Big|^{pp}_{y=0}$$

$$M^i_{\rm core} = \frac{1}{N_{\rm part}}\frac{dn^i}{dy}\Big|_{y=0} \text{ from stat. model or most central HI collision}$$

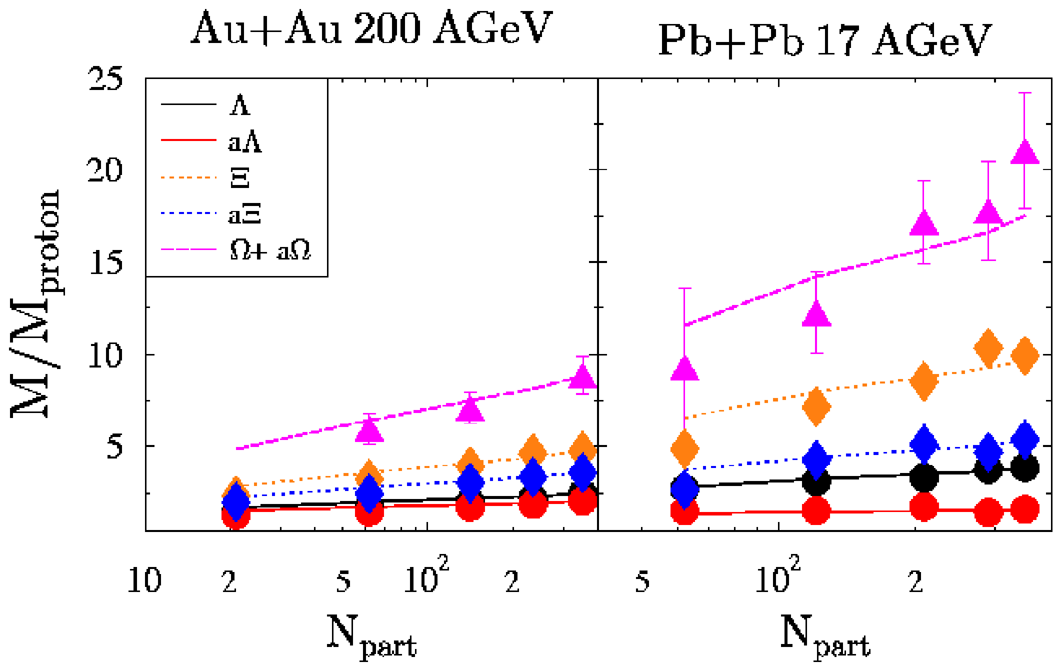
$$1 - f(N_{\rm core}) = \text{fraction of nucleons which have scattered only once}$$

$$(\rightarrow \text{Glauber})$$

Centrality dependence of hadron multiplicities compared to core-corona model



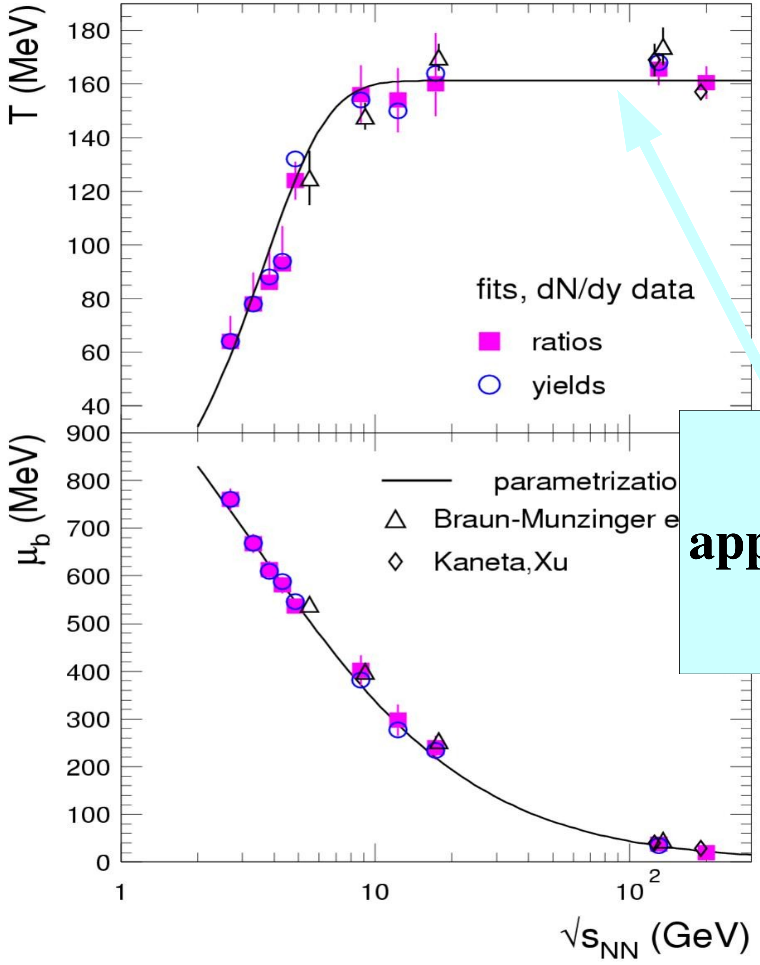
experimental data well reproduced if for core thermal values and for corona pp values are used – no new parameters

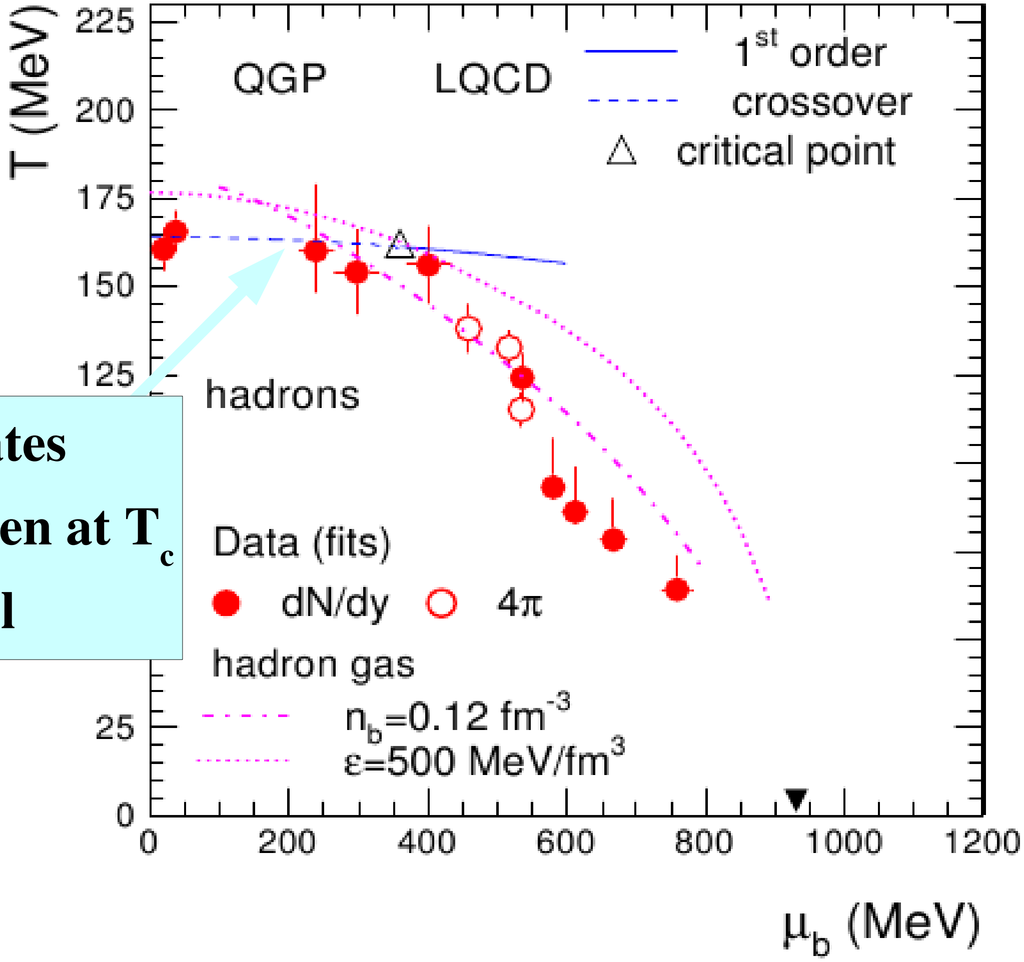


J. Aichelin and K. Werner, arXiv: 0810.4465[nucl-th]

hadrochemical freeze-out points and the phase diagram

A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167





T_{chem} saturates

appears to happen at T_c

not trivial

how is equilibrium achieved?

why freeze-out at phase boundary?

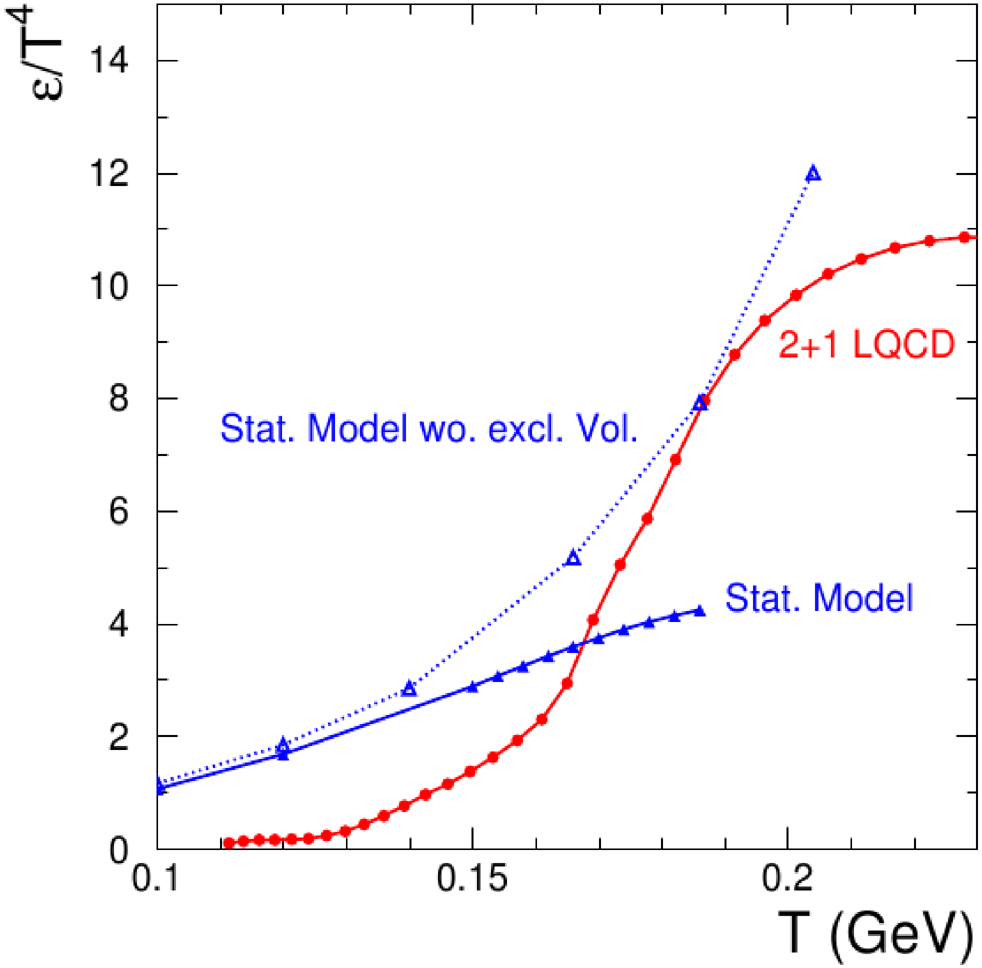
How is chemical equilibration achieved?

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004) 61

scenario for top SPS energies and above:

- Strangeness saturation takes place in the QGP phase and/or during hadronzation
- Phase transition is crossed from above.
- Near T_c new dynamics associated with collective excitations will take place and trigger the transition.
- Propagation and scattering of these collective excitations is expressed in the form of multi-hadron scattering.
  Near T_c multi-hadron processes will therefore be dominant.
  Chemical equilibrium is reached via these multi-hadron scattering events.

key is the rapid change in energy and entropy density near T_c



- The density of particles varies rapidly (factor 2 within 8 MeV) with T near the phase transition due to increase in degrees of freedom.
- also: system spends time at Tc -> volume has to triple (entropy cons.)
- Multi-particle collisions are strongly enhanced at high density and lead to chem. equilibrium very near to T_c
- independently of cross section all particles can freeze out within narrow temperature interval

natural consequence that chemical freeze-out takes place at T_c!

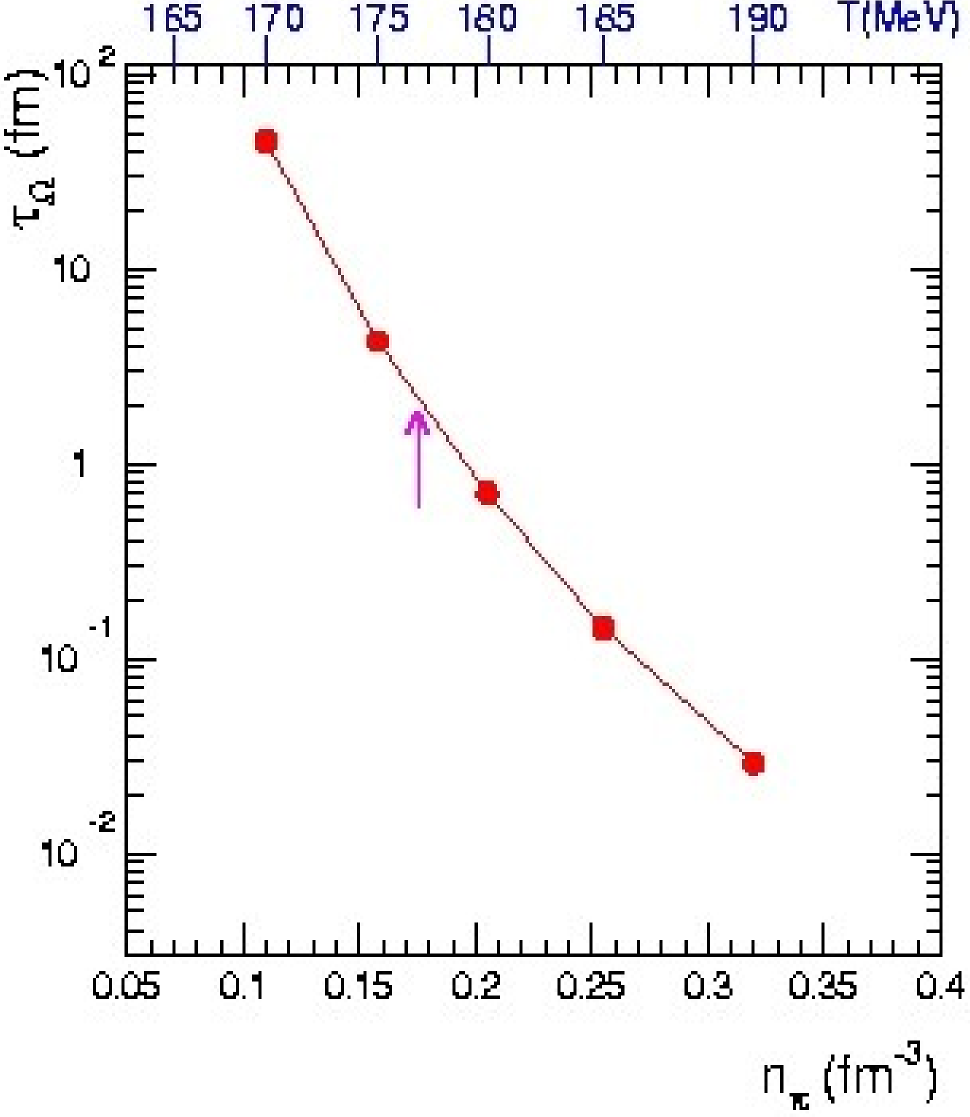
P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

Density dependence of characteristic time for strange baryon production

- typical reaction $\Omega + \bar{N} \rightarrow 2\pi + 3K$

  assume cross section equal to the measured one for $p + \bar{p} \rightarrow 5\pi$

  at proper energy above threshold, i.e. $\sqrt{s}$ = 3.25 GeV ➞ 6.4 mb



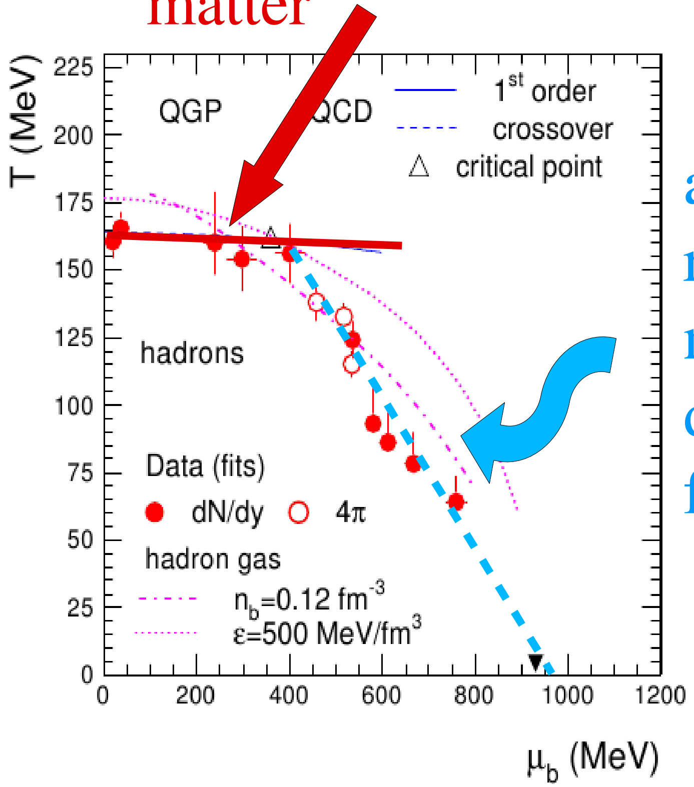
- **Near phase transition particle density varies rapidly with T**
- **For small μ_b, reactions such as 2π+KKK→ Ω Nbar bring multi-strange baryons close to equilibrium.**
- **in region around T_c equilibration time $\tau_\Omega \propto T^{-60}$!**
- **increase ρ_π by 1/3 or 8 MeV: τ = 0.2 fm/c**

  decrease ρ_π by 1/3: τ = 27 fm/c
- **All particles freeze out within a very narrow temperature window.**

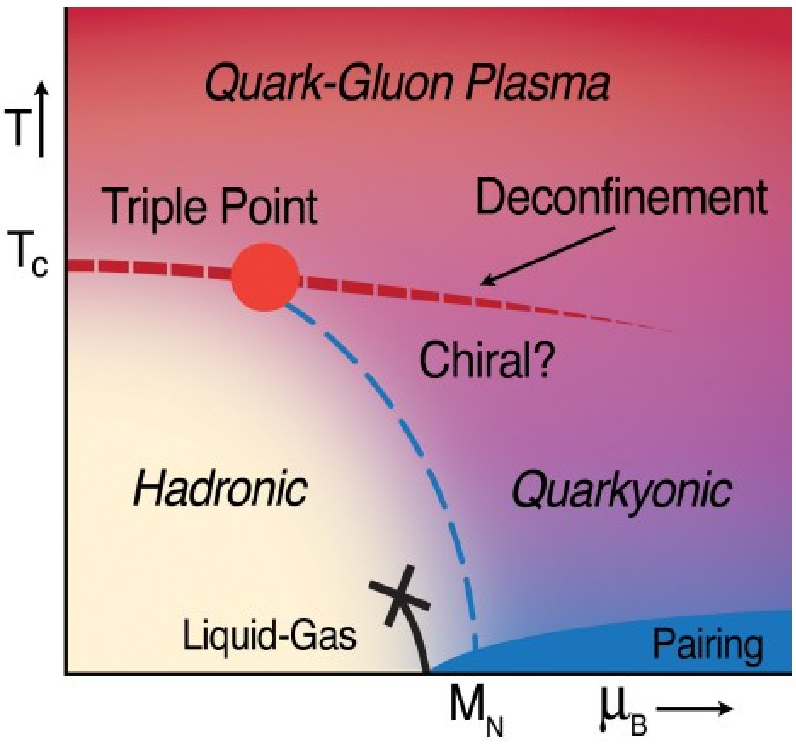
P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

what governs freeze-out at larger chemical potential?

phase transition to deconfined matter



another region of rapid increase in number of degrees of freedom



suggestion: this is transition between hadronic and quarkyonic matter

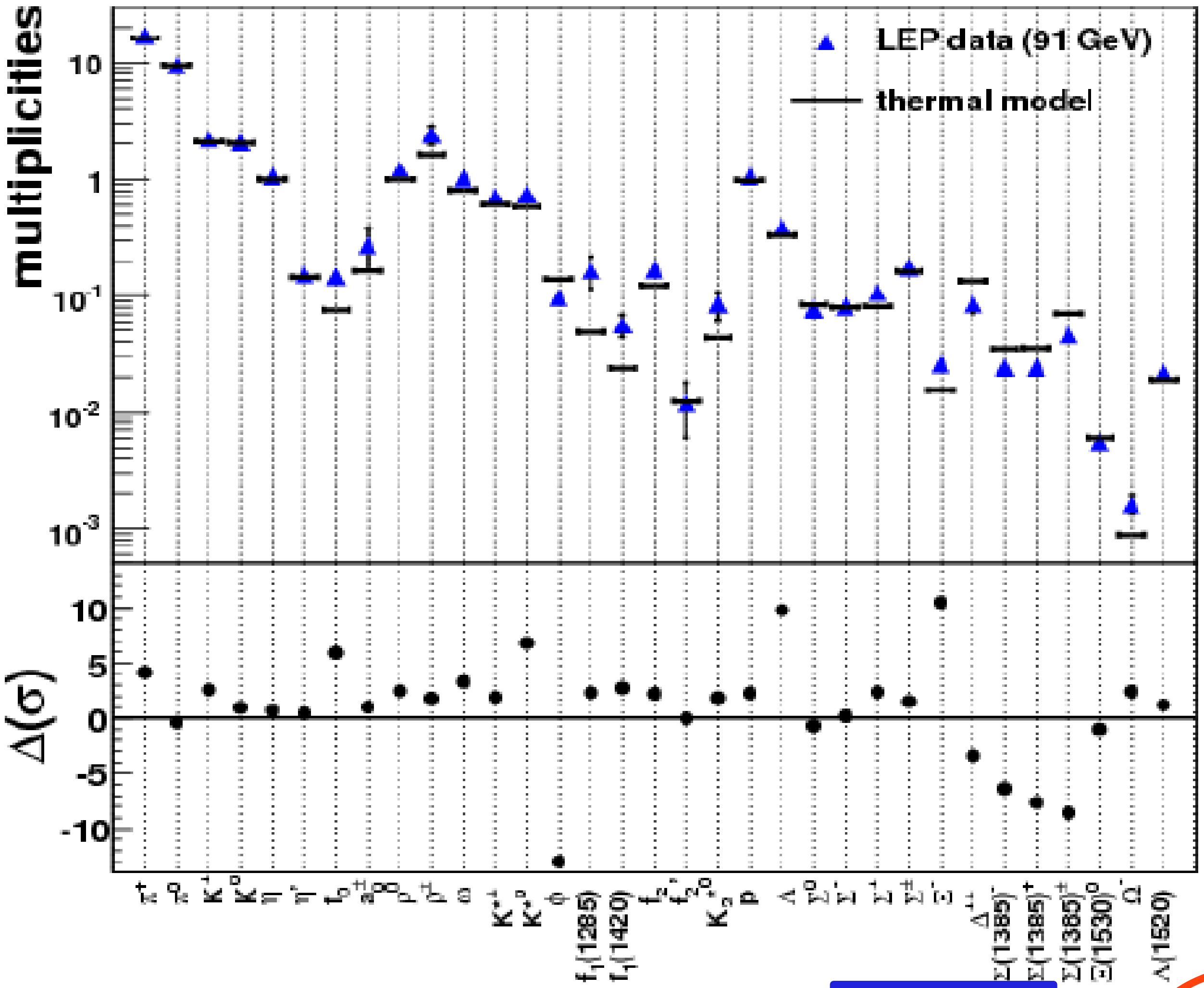
phase transition in baryonic matter: with increasing density baryon mobility becomes jammed

order parameter: inverse mobility of baryons - another Mott type transition

A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, H. Oeschler, R.D. Pisarski, L. McLerran, K. Redlich, C. Sasaki and J.S, arXiv: 0911.4806.

e+e- collisions: initialize thermal model with u,d,s,c,b – jets according to measurement (weak isospin)

A. Andronic, P. Braun-Munzinger, F. Beutler, K. Redlich, J. Stachel, Phys. Lett. B678 (2009)
arXiv 0804.4132

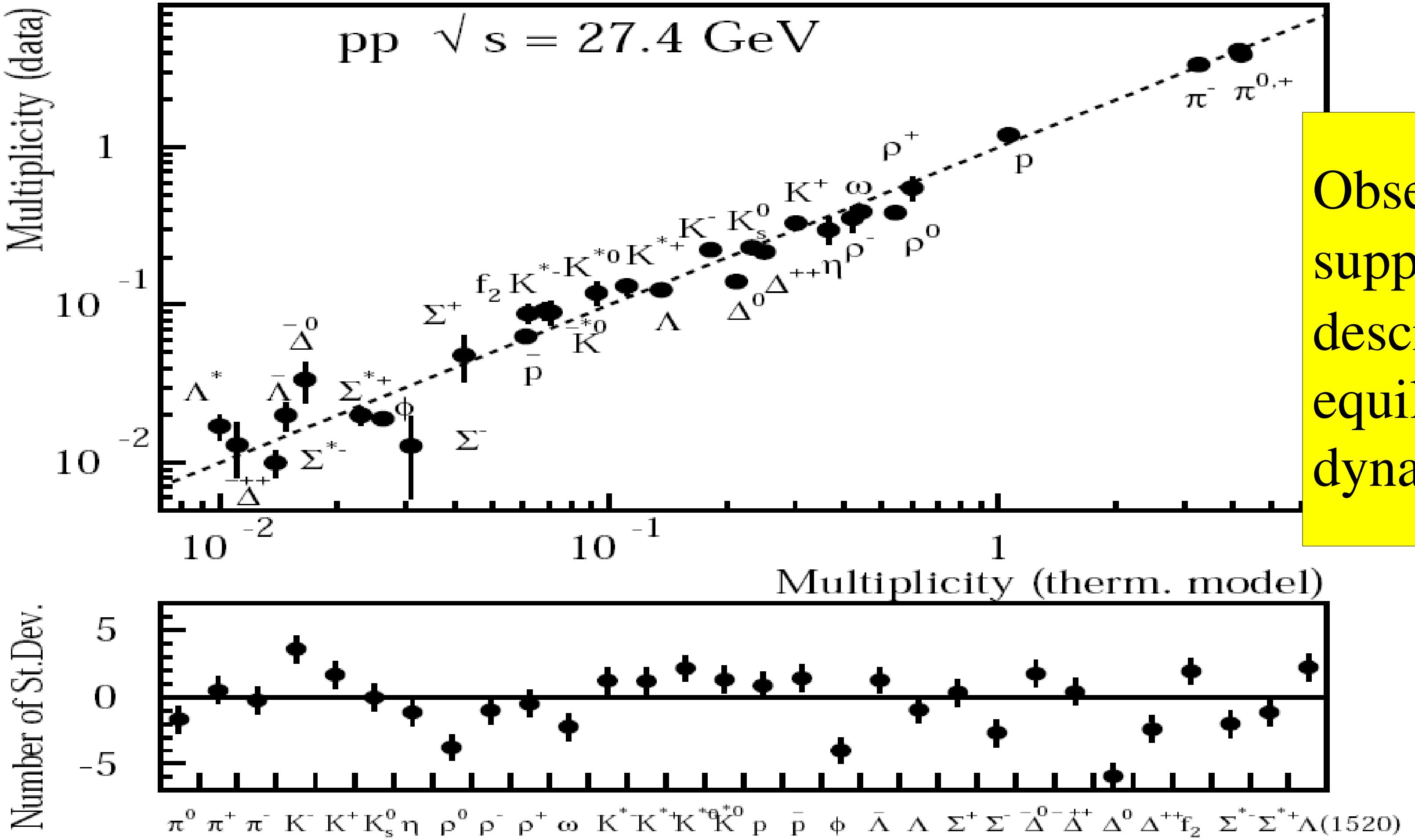


strangeness suppressed – fit still not good!

parameter set: T=164 MeV, V=20 fm^3, $\boxed{\gamma_s=0.72}$ with $\chi^2=718/30$

Results for pp collisions within canonical stat. model – best data set, but not as good as e+e-

F. Becattini and U. Heinz, Z. Phys. C76 (1997) 269 T = 169 ± 5 MeV $\gamma_s = 0.51$ red $\chi^2 = 5$

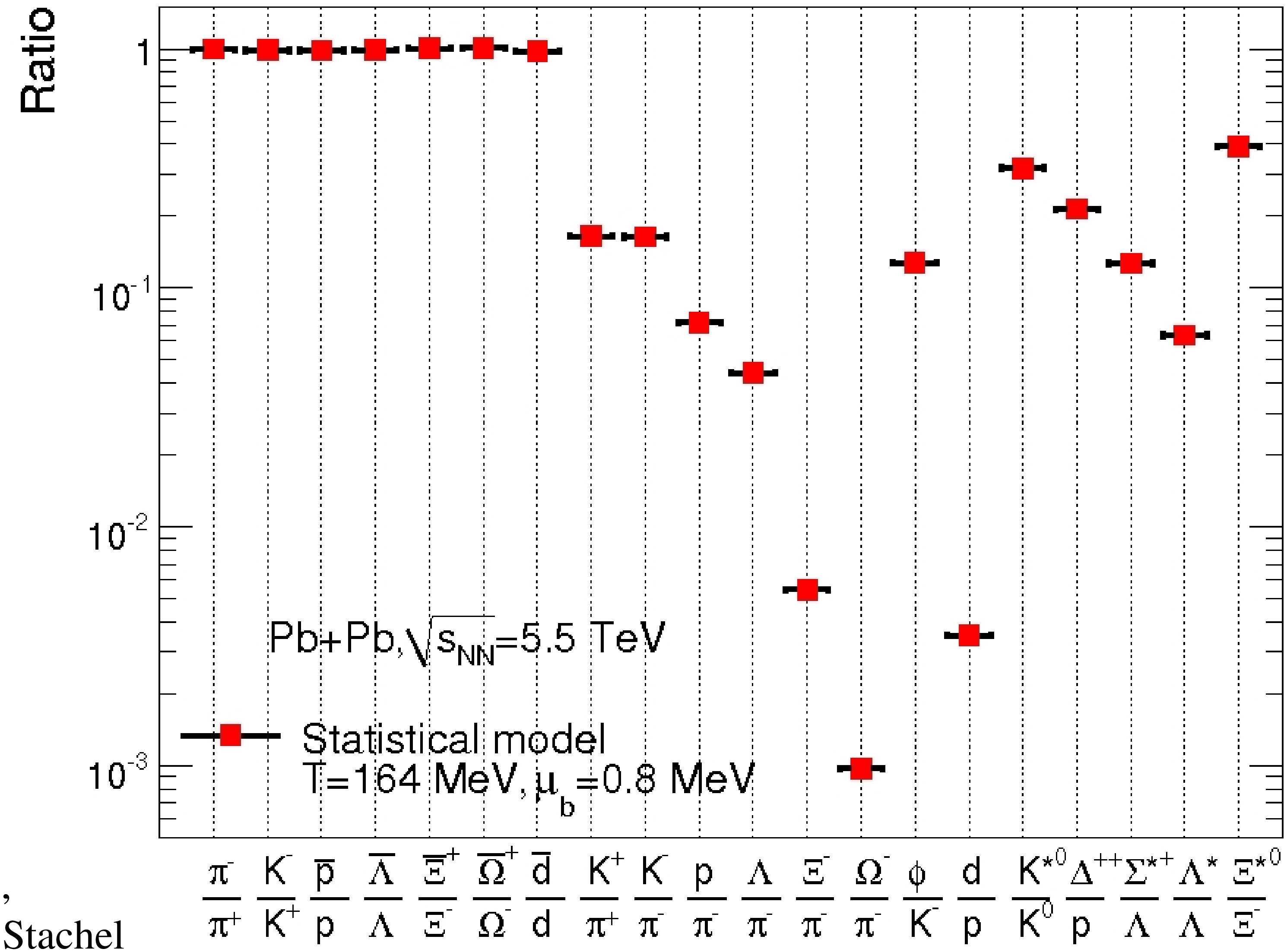


Observed strangeness suppression is **not** described by equilibrium thermo-dynamics

canonical effects where shown to be small (P. Braun-Munzinger, K. Redlich, J. Stachel, Quark Gluon Plasma 3, nucl-th/0304013)

-> strangeness genuinely suppressed and fit still not very good

What is next? LHC has started operation



prediction: A. Andronic,
P. Braun-Munzinger, J. Stachel
J. Phys. G35 (2008) 054001

what to expect from ALICE?

Year1: 10^9 pp and 10^7 PbPb collisions

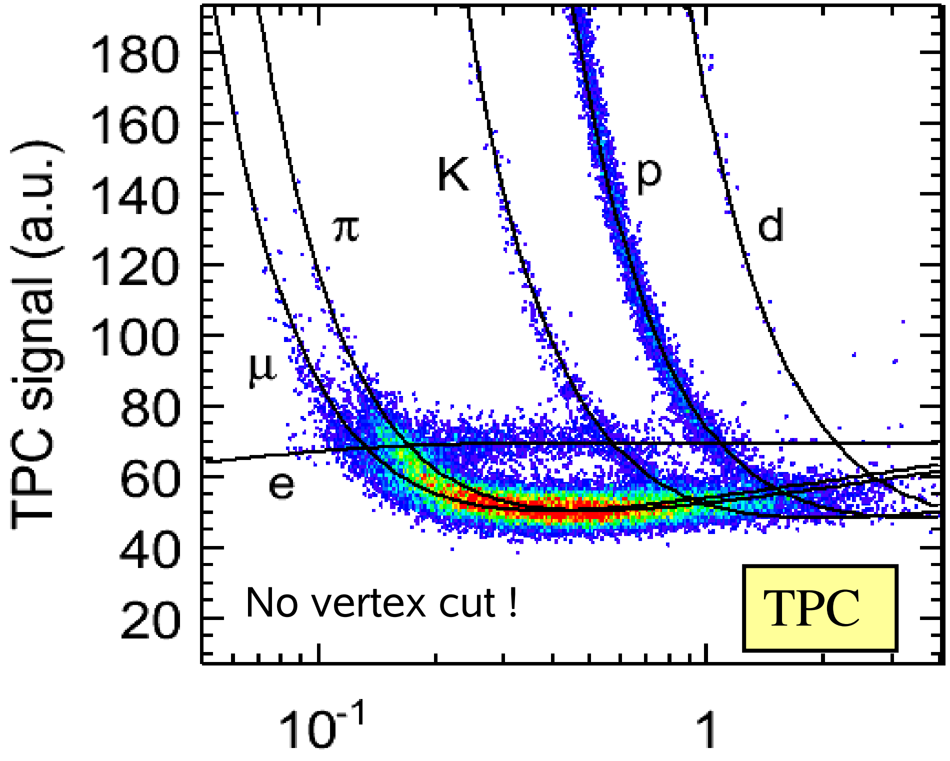
meson and baryon abundancies up to Ω in pp and PbPb collisions

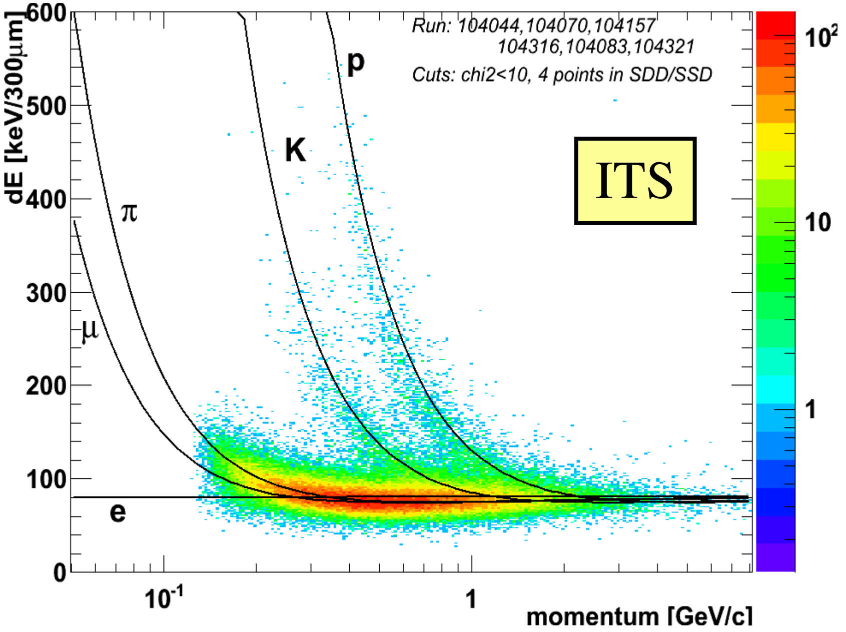
in the longer run: nuclei and antinuclei

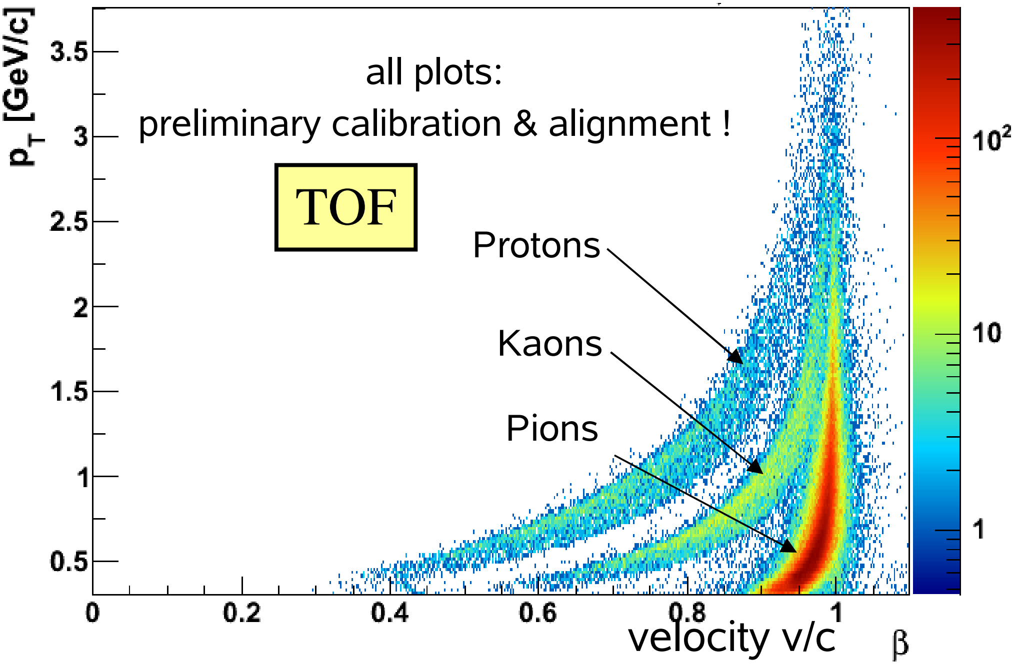
resonances

exotica

ALICE has very good particle identification
a first look at 250 k pp collisions at $\sqrt{s}$=900 GeV



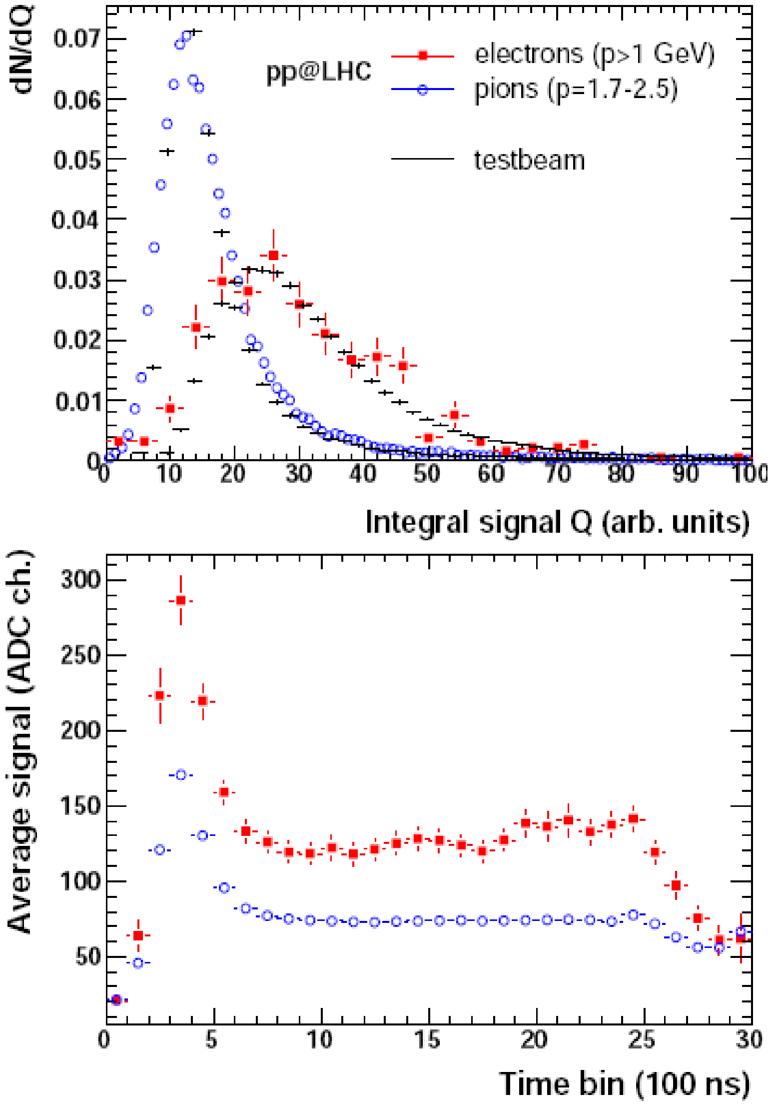




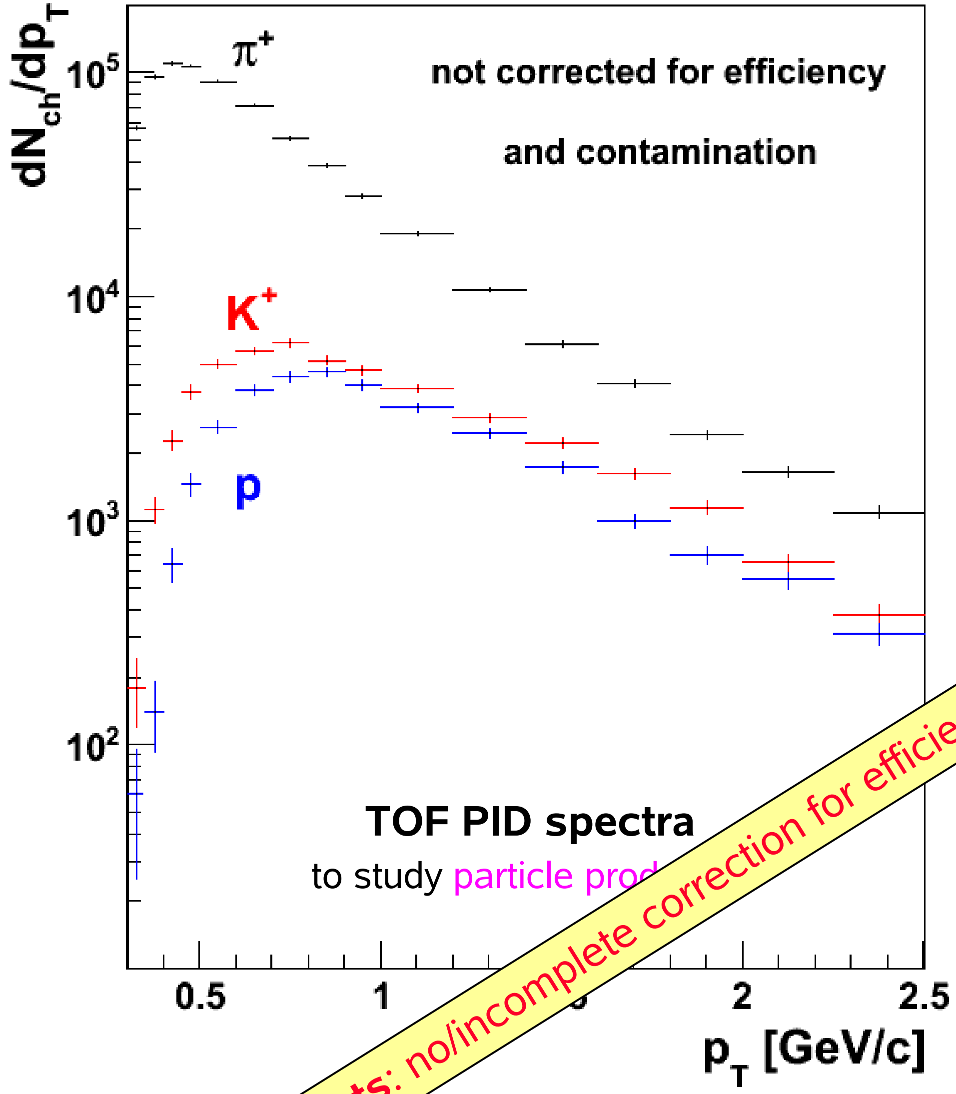
all plots:
preliminary calibration & alignment !

the TRD is designed for electron identification but also he in PID via dE/dx

first performance pictures from 250 k pp collisions at $\sqrt{s}$ = 900 GeV in Dec. 2009



a first look at 250 k pp collisions at √s=900 GeV



not corrected for efficiency

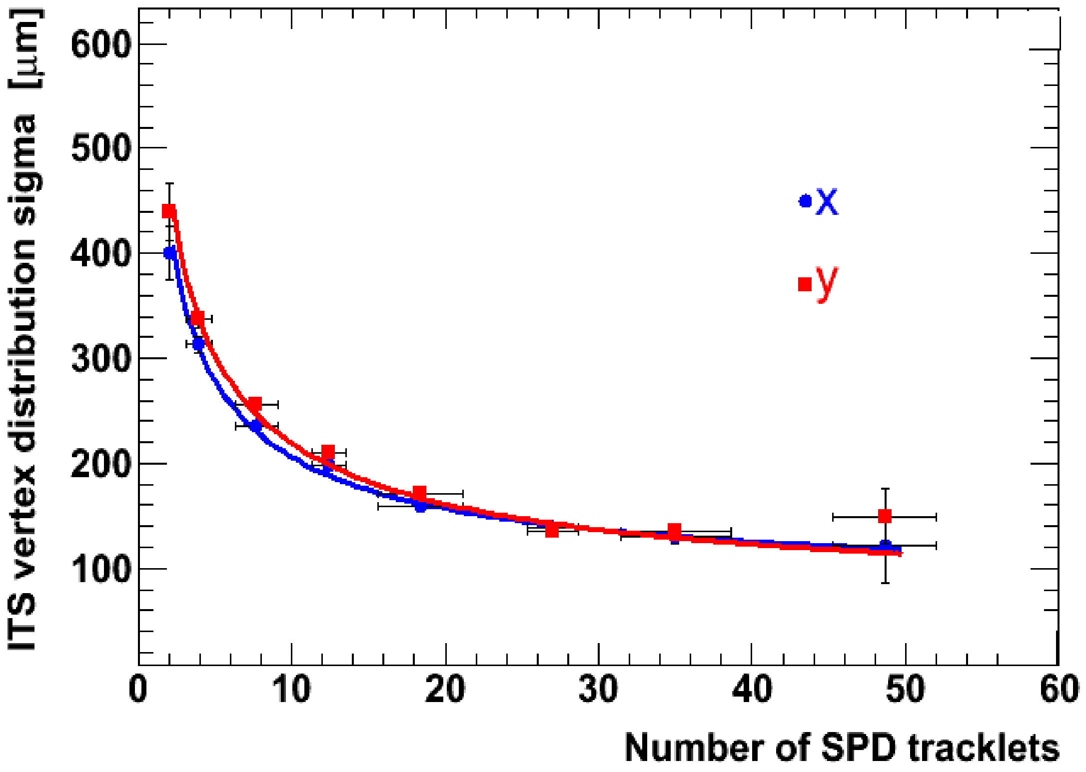
and contamination

TOF PID spectra

to study particle prod

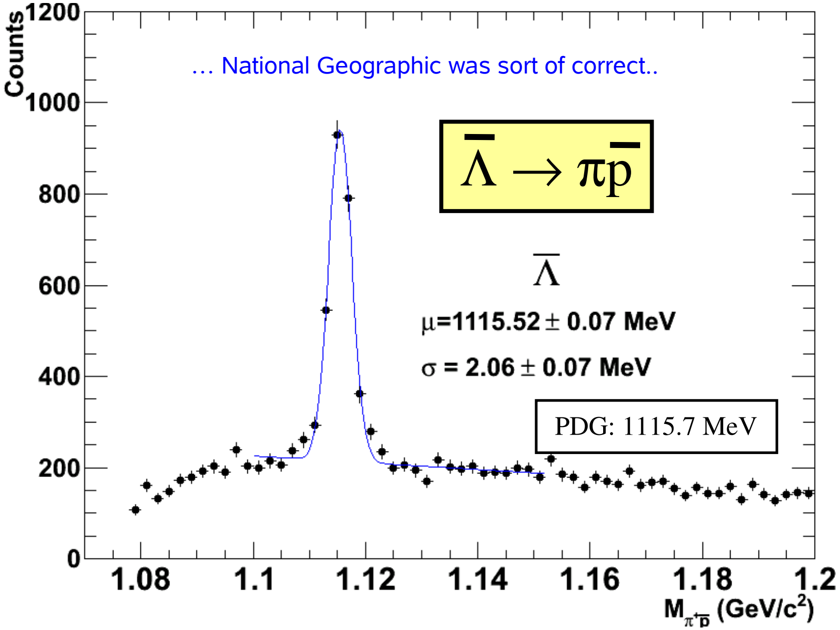
'raw' plots: no/incomplete correction for efficiency, acceptance, resolution, background, ...

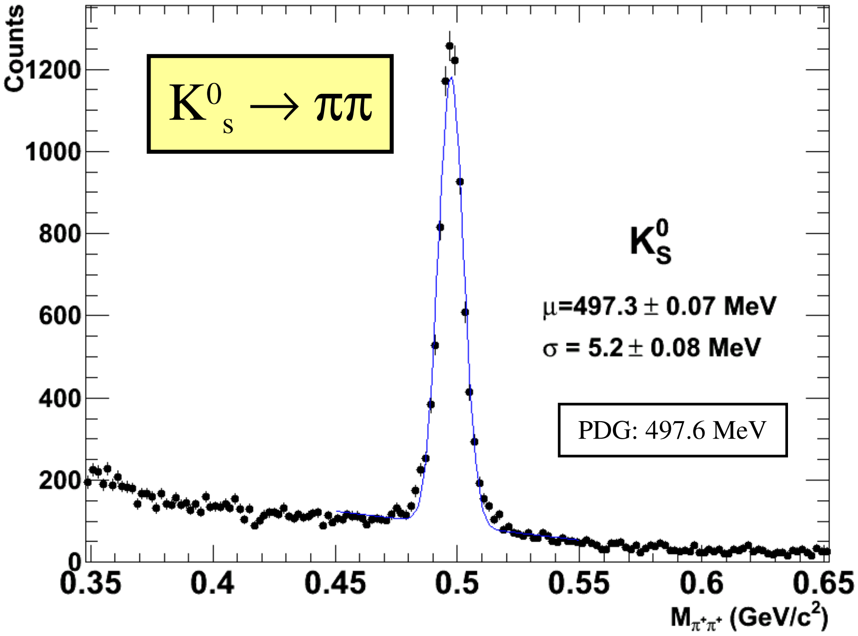
for secondaries from weak decays good vertexing necessary – ALICE has it from day1

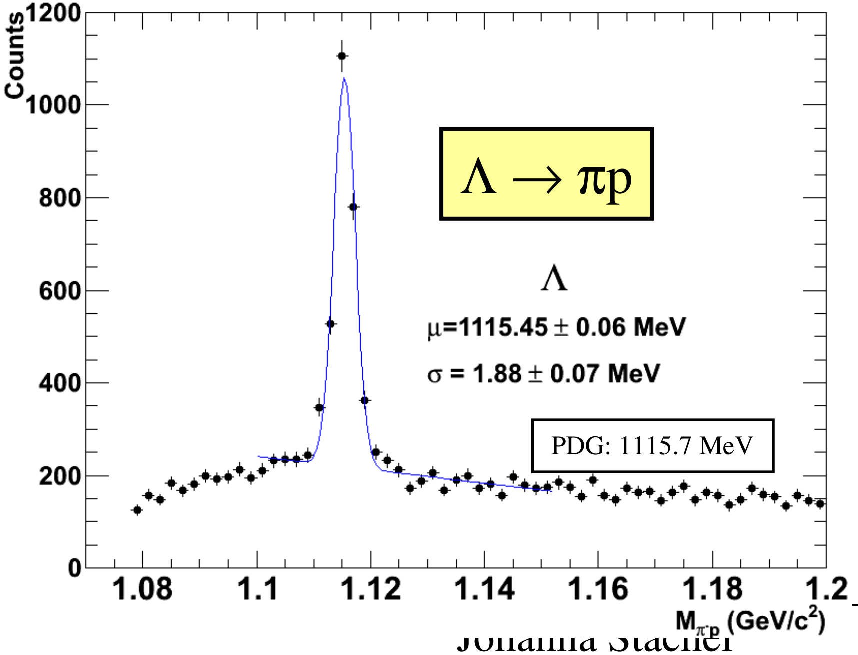


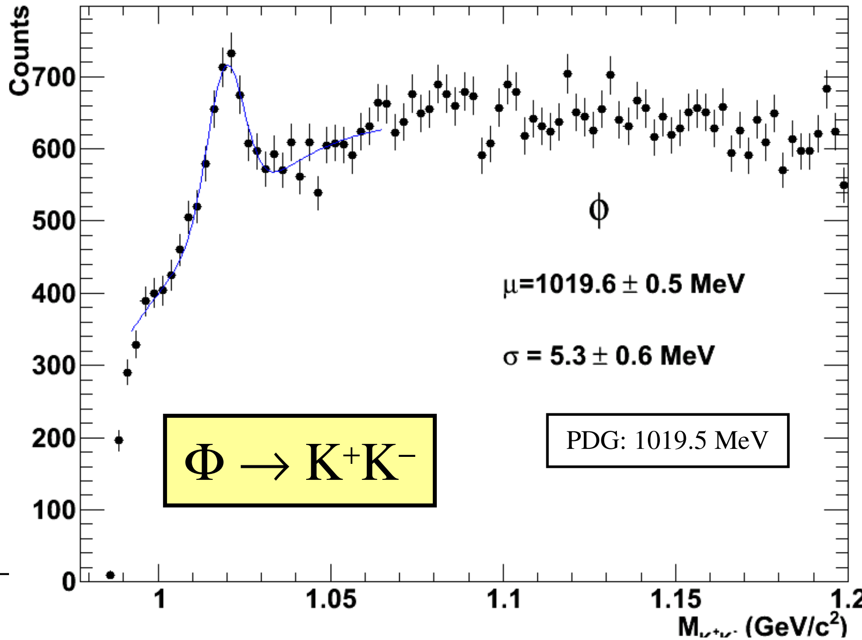
vertex resolution of silicon pixel detector with present preliminary alignment

a first look at 250 k pp collisions at √s=900 GeV

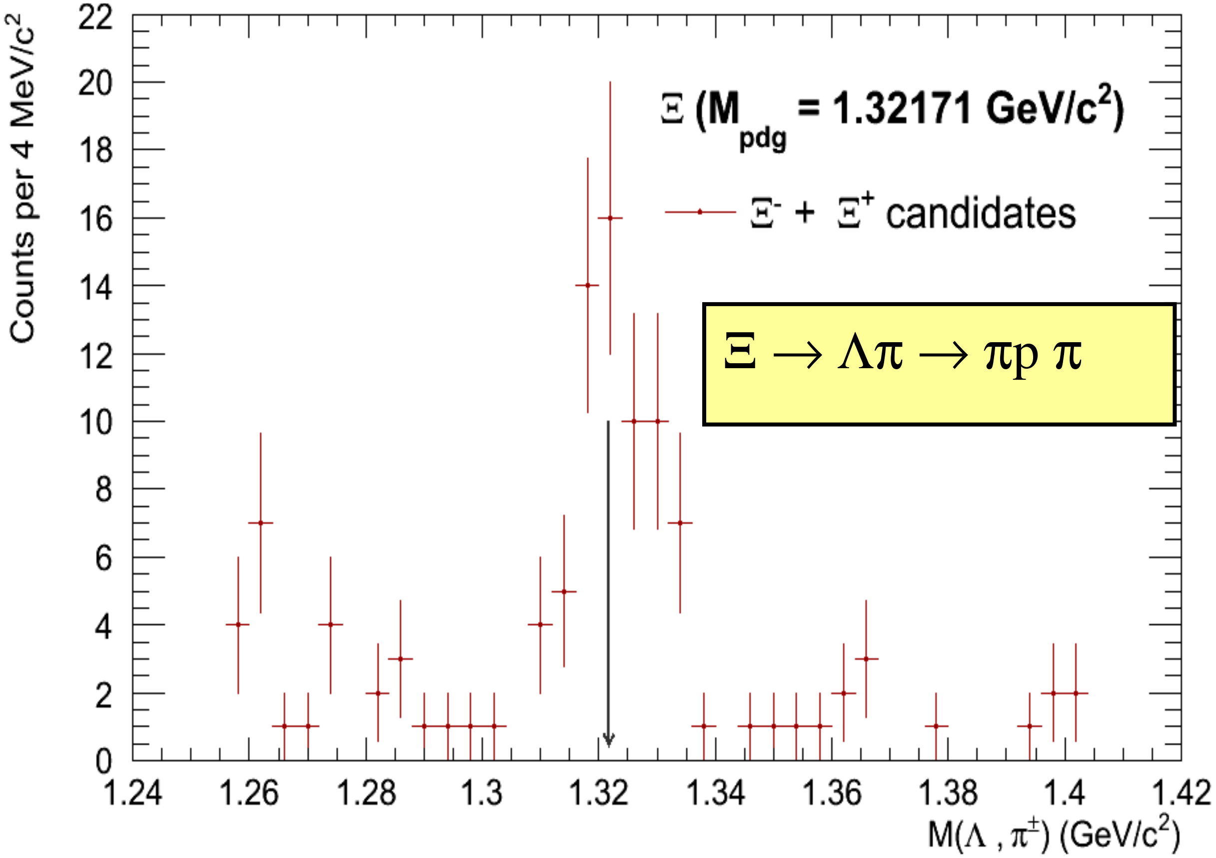








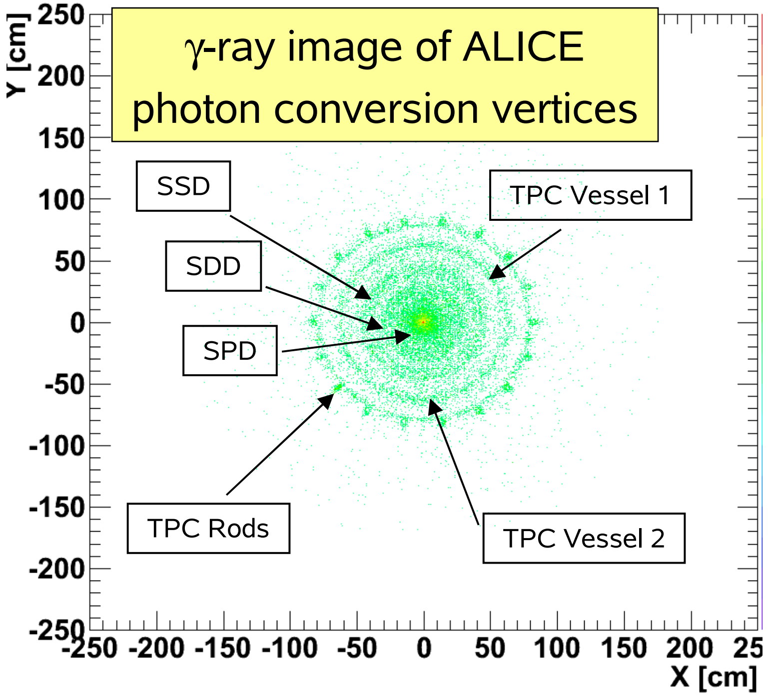
a first look at 250 k pp collisions at √s=900 GeV

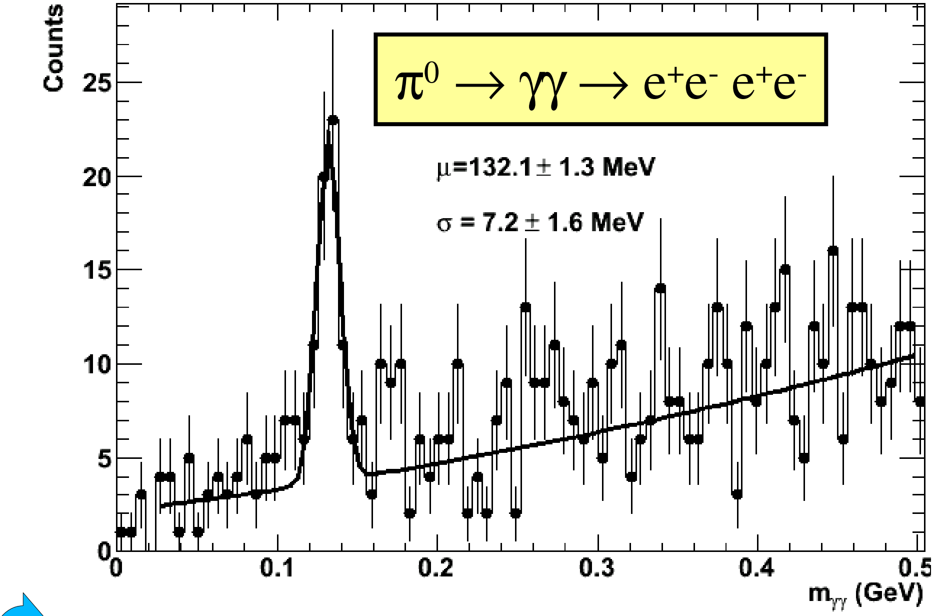


$\Xi \rightarrow \Lambda\pi \rightarrow \pi p\ \pi$

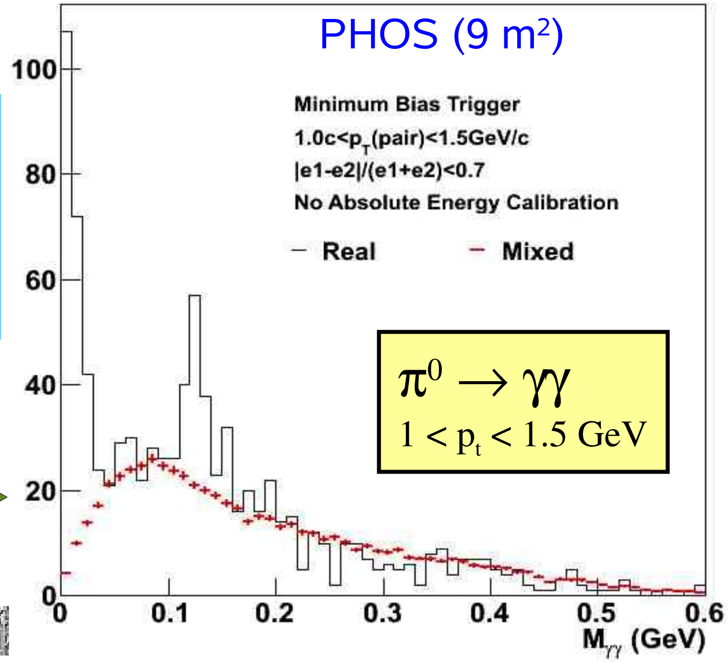
there is already a hint of a cascade...

a first look at 250 k pp collisions at $\sqrt{s}$=900 GeV





photons via conversions into e+e- using the TPC - nice reconstruction of the conversion sources and even a good π^0

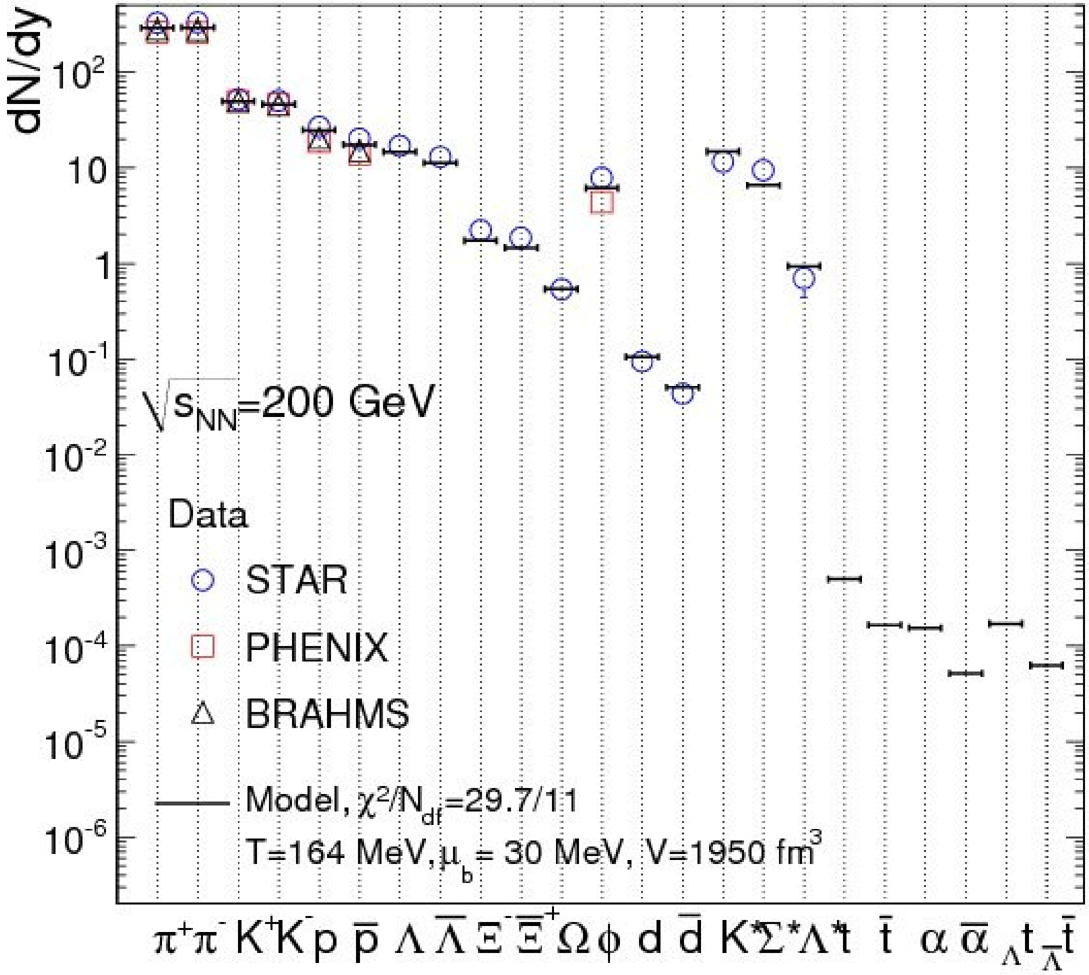


but also with crystals we see the π^0

Resonances and light nuclei

at top AGS energy: data on production of light nuclei (up to mass 7) consistent with thermal production at same conditions as all other hadrons

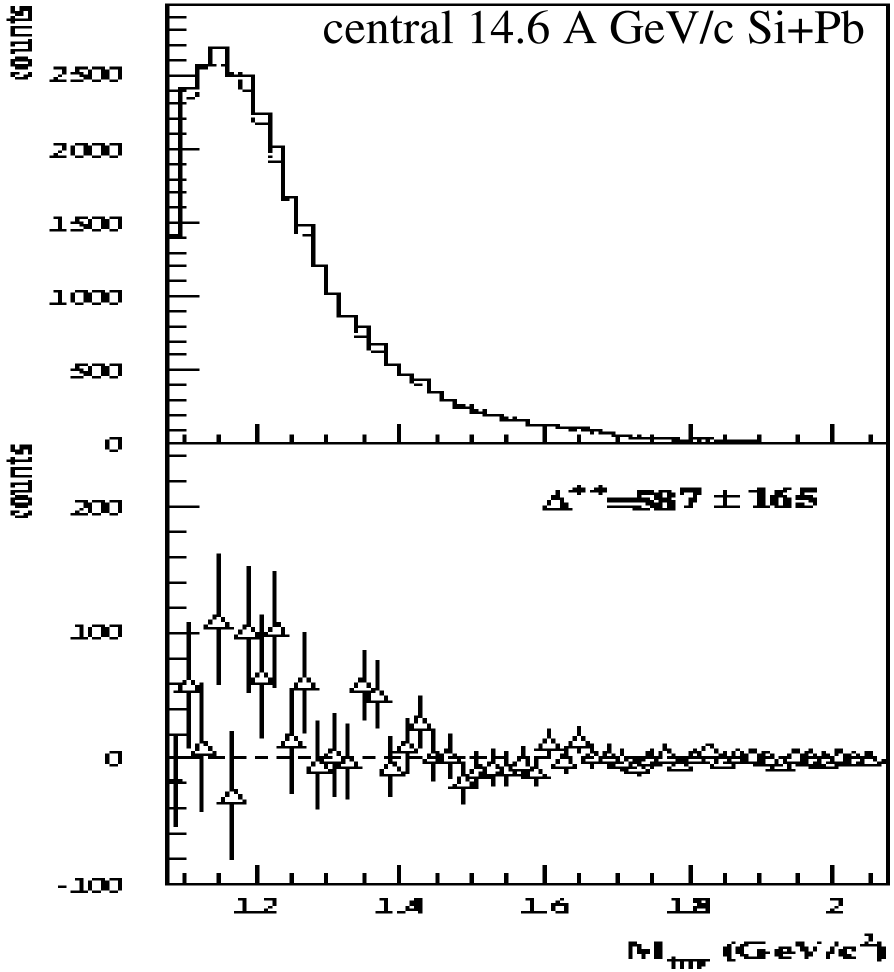
RHIC:



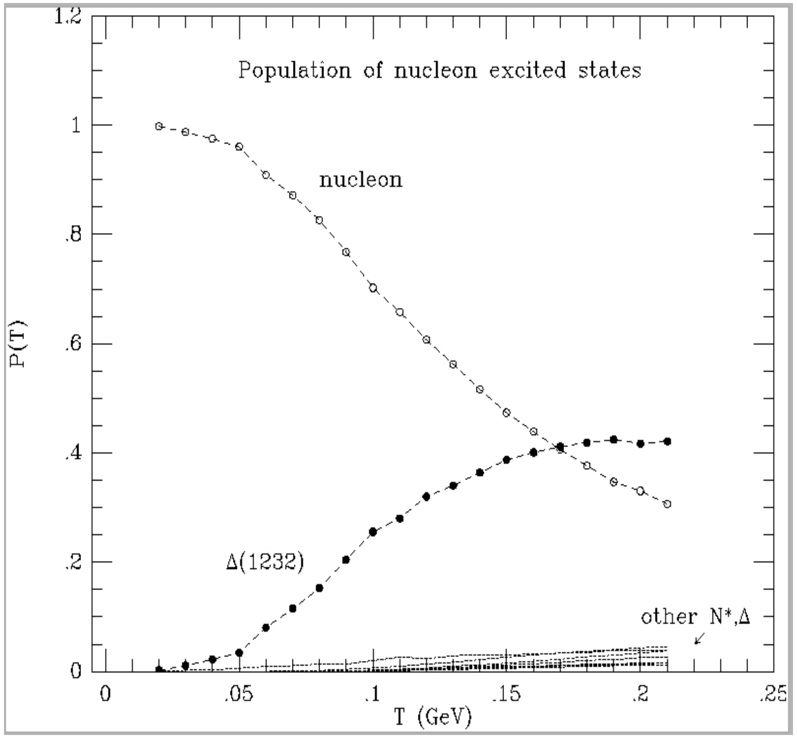
	STAR	model
$_{\bar{\Lambda}}\bar{t}/_{\Lambda}t$	0.49 (18)	0.37
$^3\overline{\mathrm{He}}/^3\mathrm{He}$	0.45 (2)	0.34
$_{\bar{\Lambda}}\bar{t}/^3\overline{\mathrm{He}}$	0.89 (28)	1.21
$_{\Lambda}t/^3\mathrm{He}$	0.82 (16)	1.11

strongly decaying resonances would be very interesting vis-a-vis question of evolution after hadronization

most interesting candidates are Delta and rho – but those are also the most difficult!



E814 Phys. Lett. B351 (1995) 93

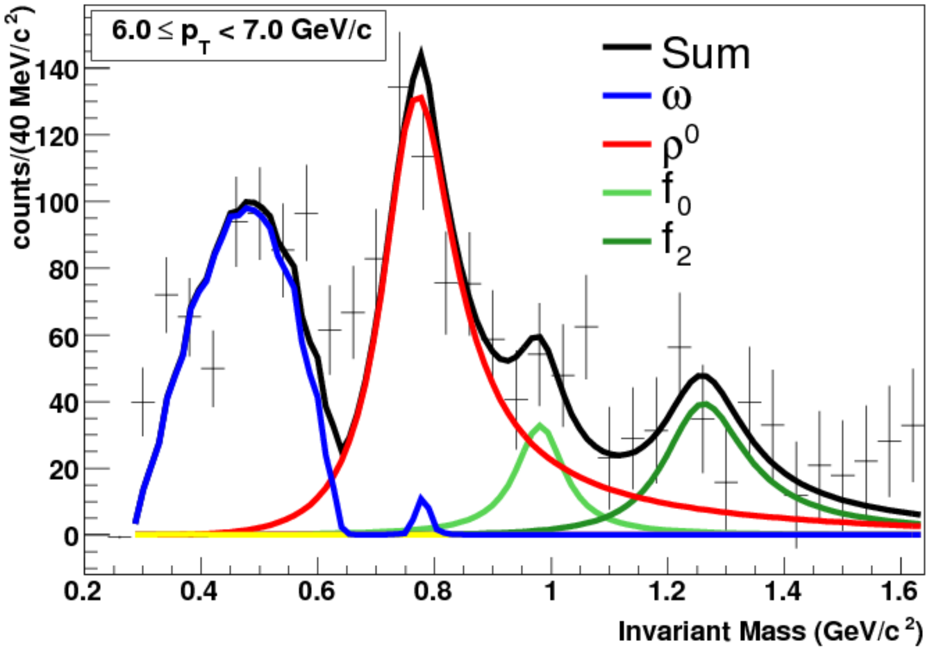


in E814 at AGS: delta abundance in agreement with thermal population

35% of all nucleons in Δ_{33} T = 138±20 MeV

at RHIC attempts for ρ and Δ

P. Fachini, STAR, QM2008



works for AuAu only at high pt

subtraction of combinatorial background very tricky? e.g. also K* with misidentified Kaon falls into same mass window

we will do our best in ALICE, no promises

Conclusions