Hadron production at chemical equilibrium

from E_{beam}/A=2 GeV to $\sqrt{s_{NN}}$=200 GeV

(central collisions)

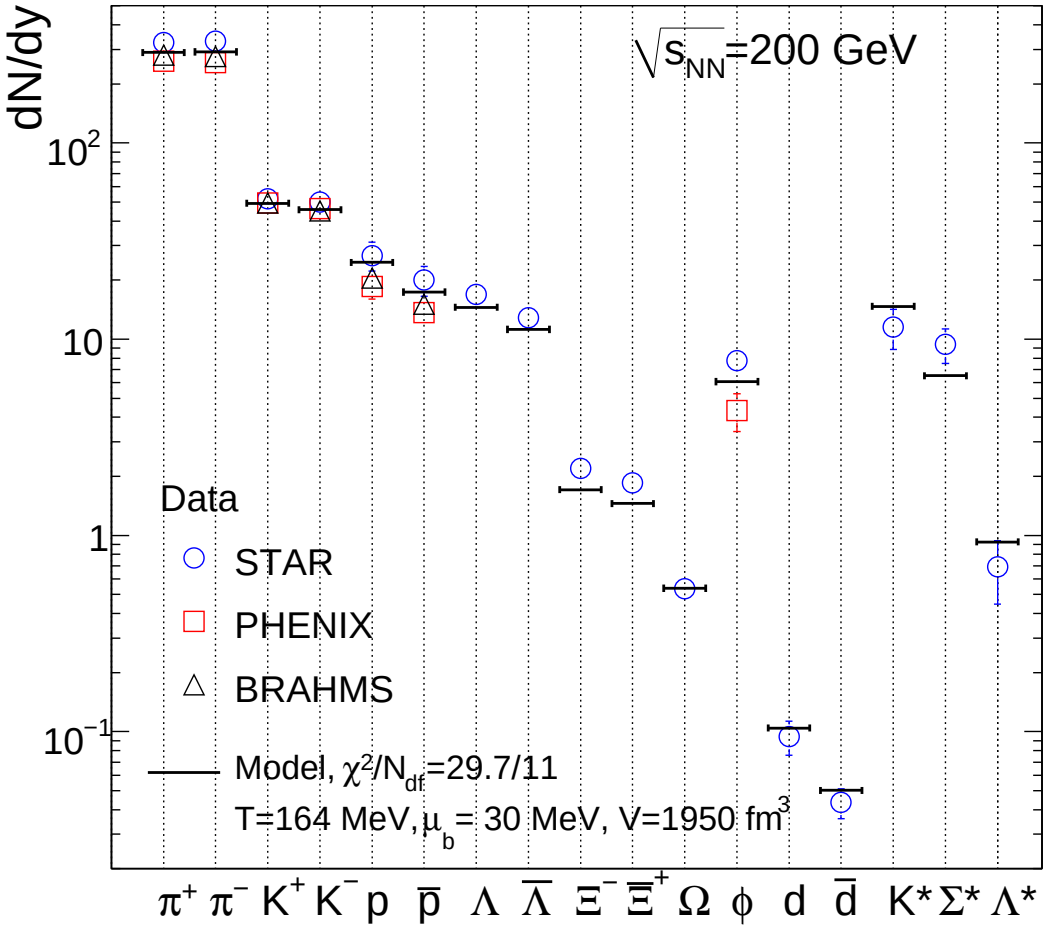
A.Andronic, P.Braun-Munzinger, J.Stachel, NPA 772 (2006) 167, PLB 673 (2009) 142

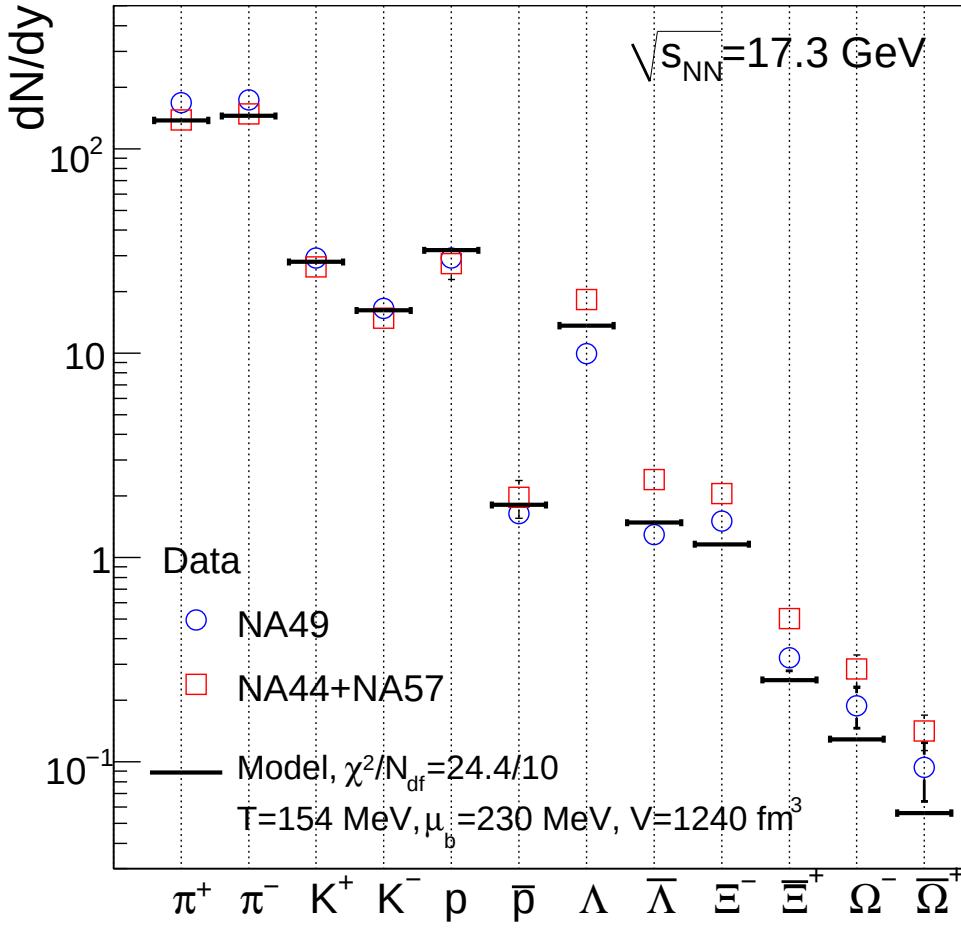
- Status of thermal fits
- Energy dependence of T, μ_b
- Excitation function of particle ratios and yield
- Thermal fits and the QCD phase diagram

Thermal fits

- conservation (on average) of the 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: $V \sum_i n_i C_i = 0$.
- interactions: excluded volume correction
- widths of resonances taken into account
- minimize: $\chi^2 = \sum_i \frac{(R_i^{exp} - R_i^{therm})^2}{\sigma_i^2}$
  - ▷ R_i: hadron yield ($\Rightarrow T$, μ_b, V) or yield ratio (no V)
  - ▷ Data: 4π or $\mathrm{d}N/\mathrm{d}y$ data (our choice, unless stated 4π)
  - ? extra parameters: γ_S, λ's (physical meaning?) (NOT, in our case)
- Latest PDG hadron mass spectrum (up to 3 GeV)

RHIC (200 GeV) and SPS (17.3 GeV)

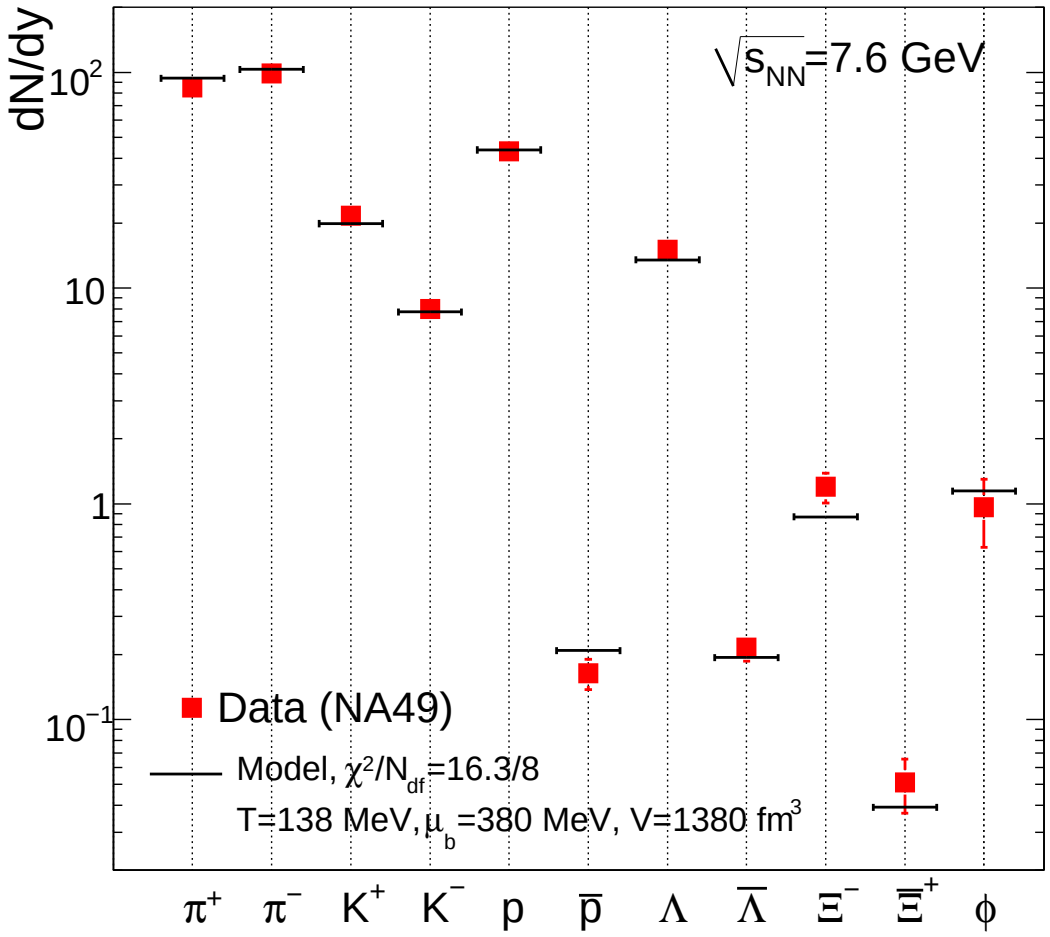


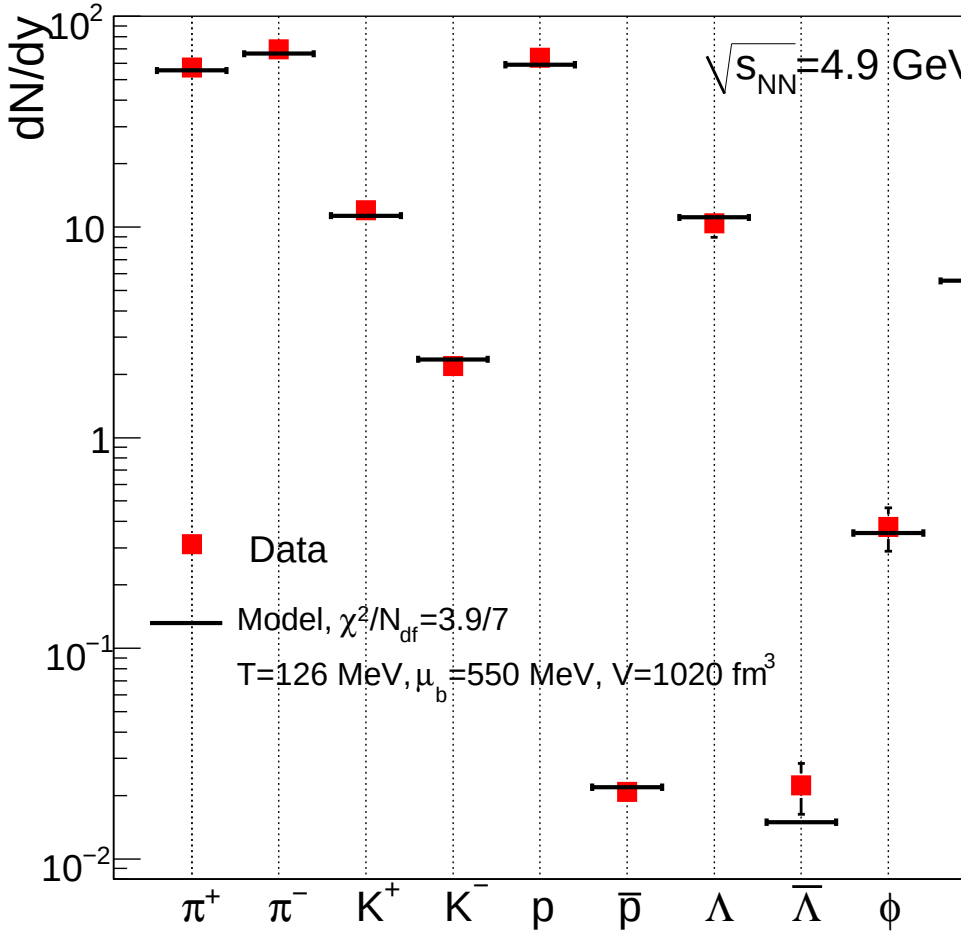


only STAR data: T=162 MeV, μ_b=32 MeV, V=2400 fm^3, χ^2/N_{df}=9.0/11

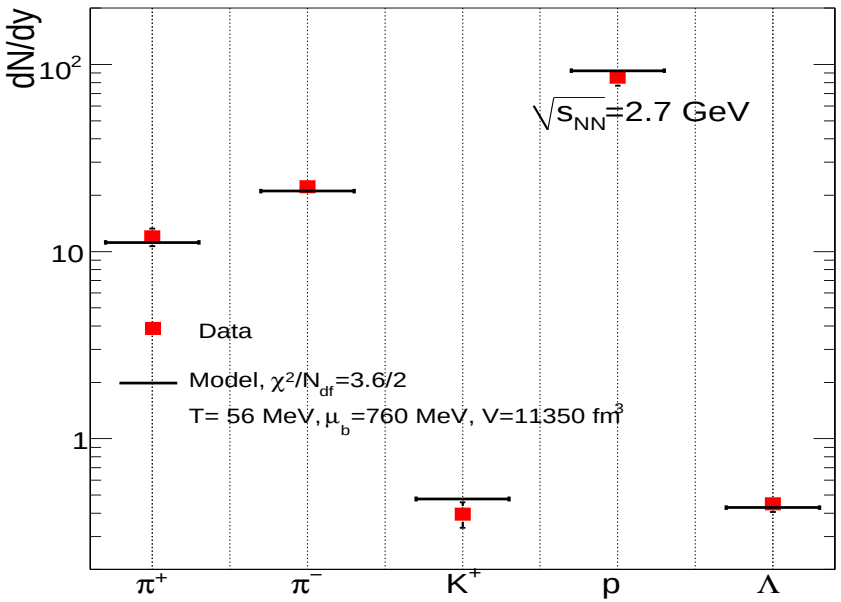
only NA49 data: T=148 MeV, μ_b=215 MeV, V=1660 fm^3, χ^2/N_{df}=36/10

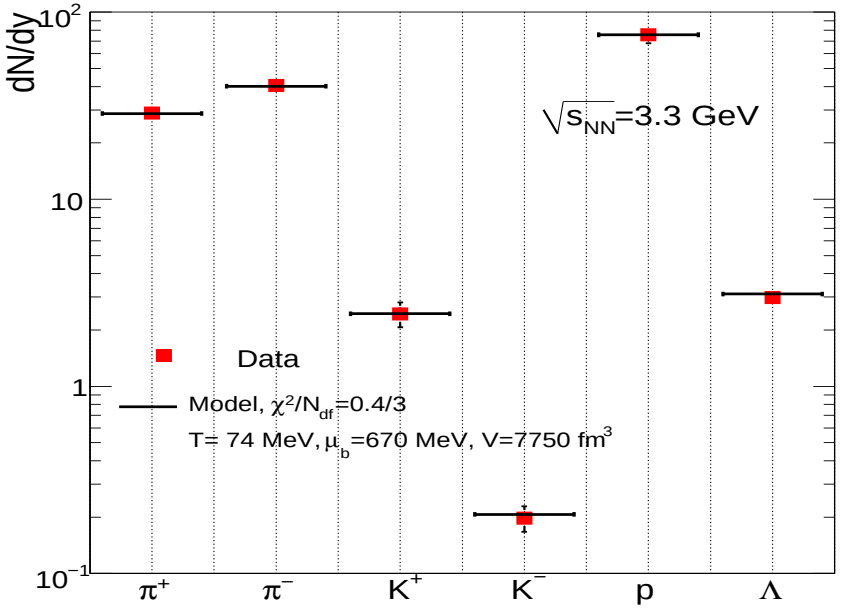
SPS (30 AGeV) and top AGS (10.5 AGeV)

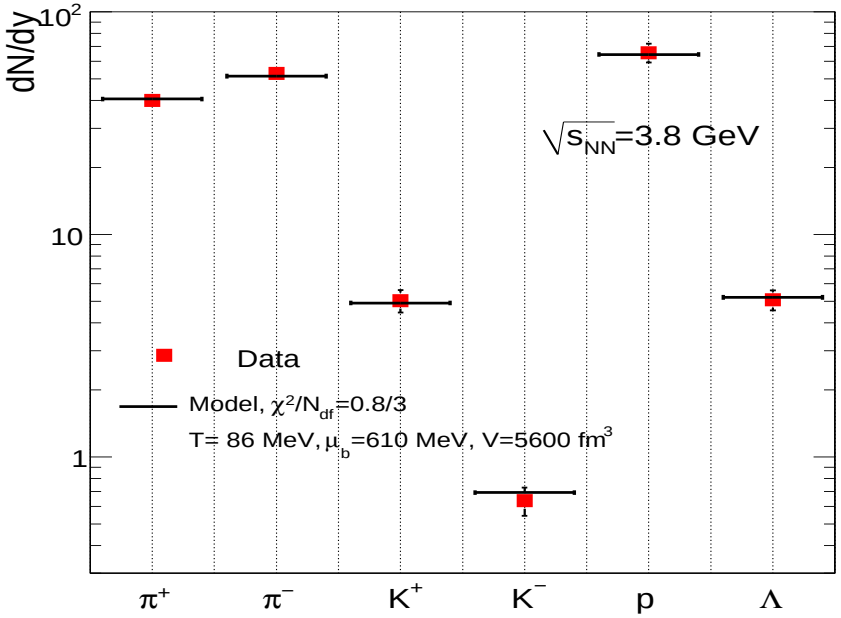


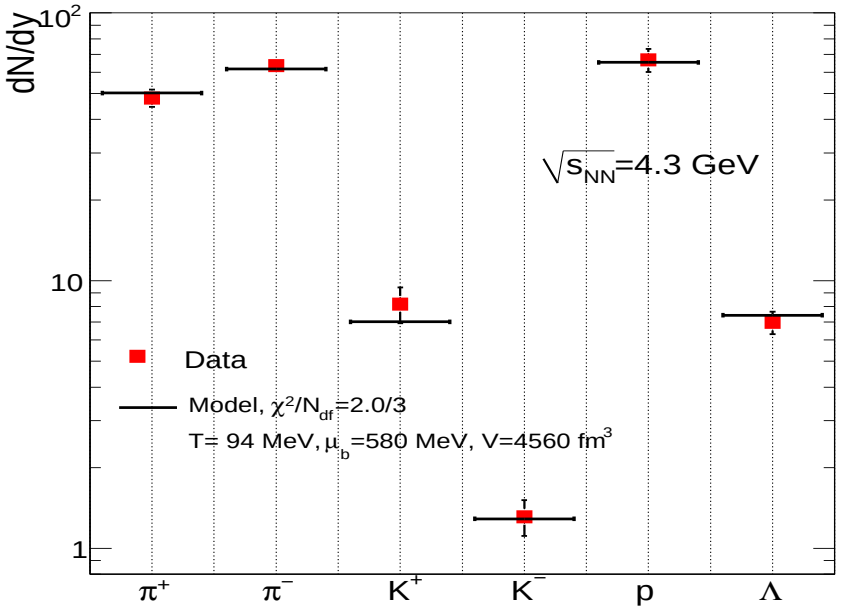


AGS, 2-8 AGeV: small set of hadron yields measured

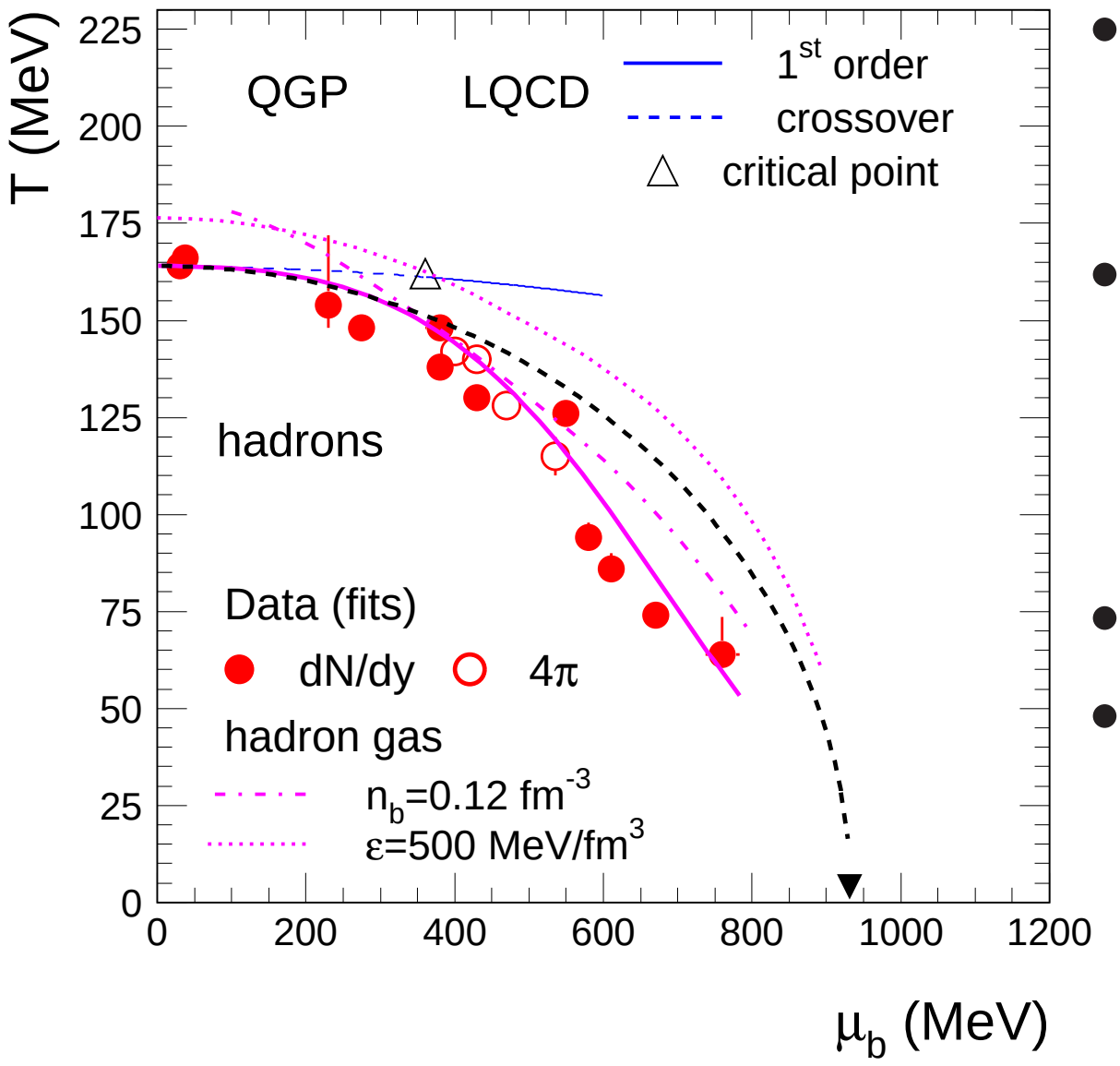








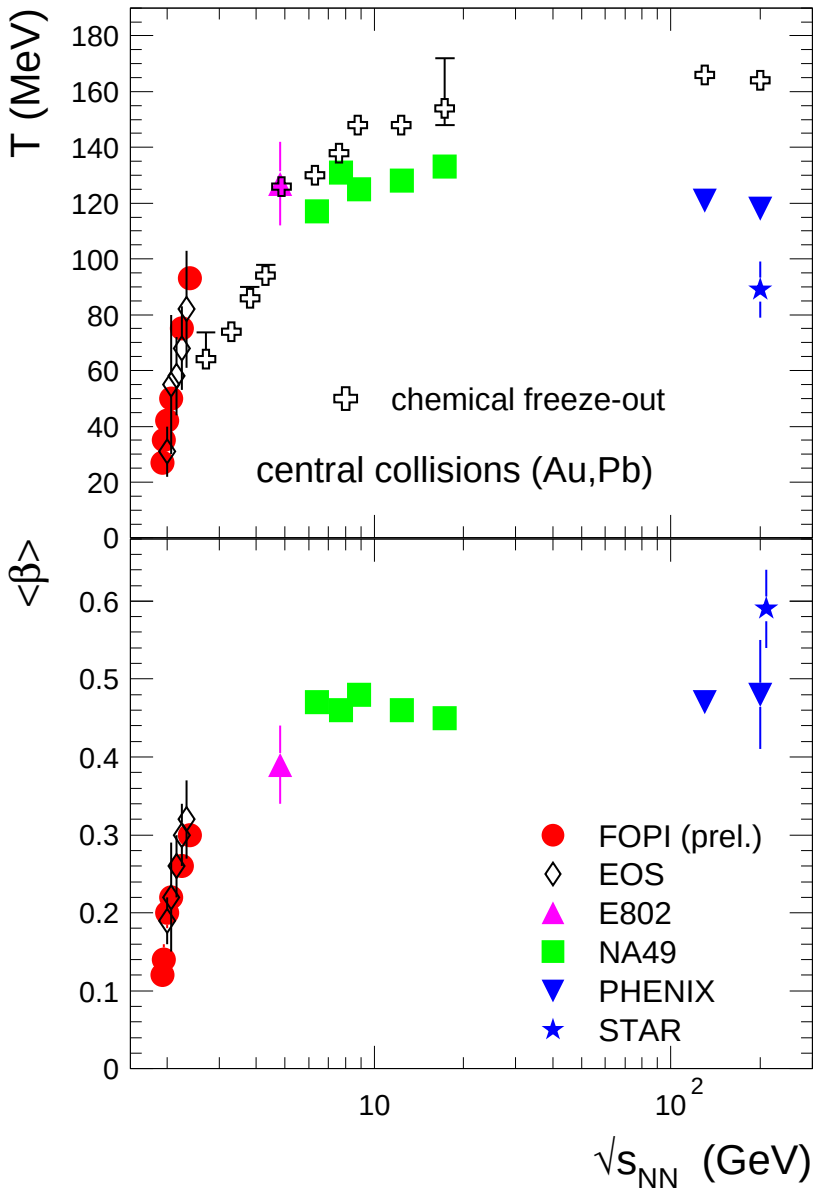
The phase diagram of QCD



- stat. model provides the or
  way to put points on the d
  gram
- ...and a determination of t
  phase boundary
  LQCD (hep-lat/0609068,0609013):
  T_c=151-192 MeV (μ_b=0)
- ...reached at low SPS energ
- ...in the vicinity of the CP
  Fodor,Katz,hep-lat/040200
  is not the final word on it
  $\longrightarrow$ effect on thermal fits?

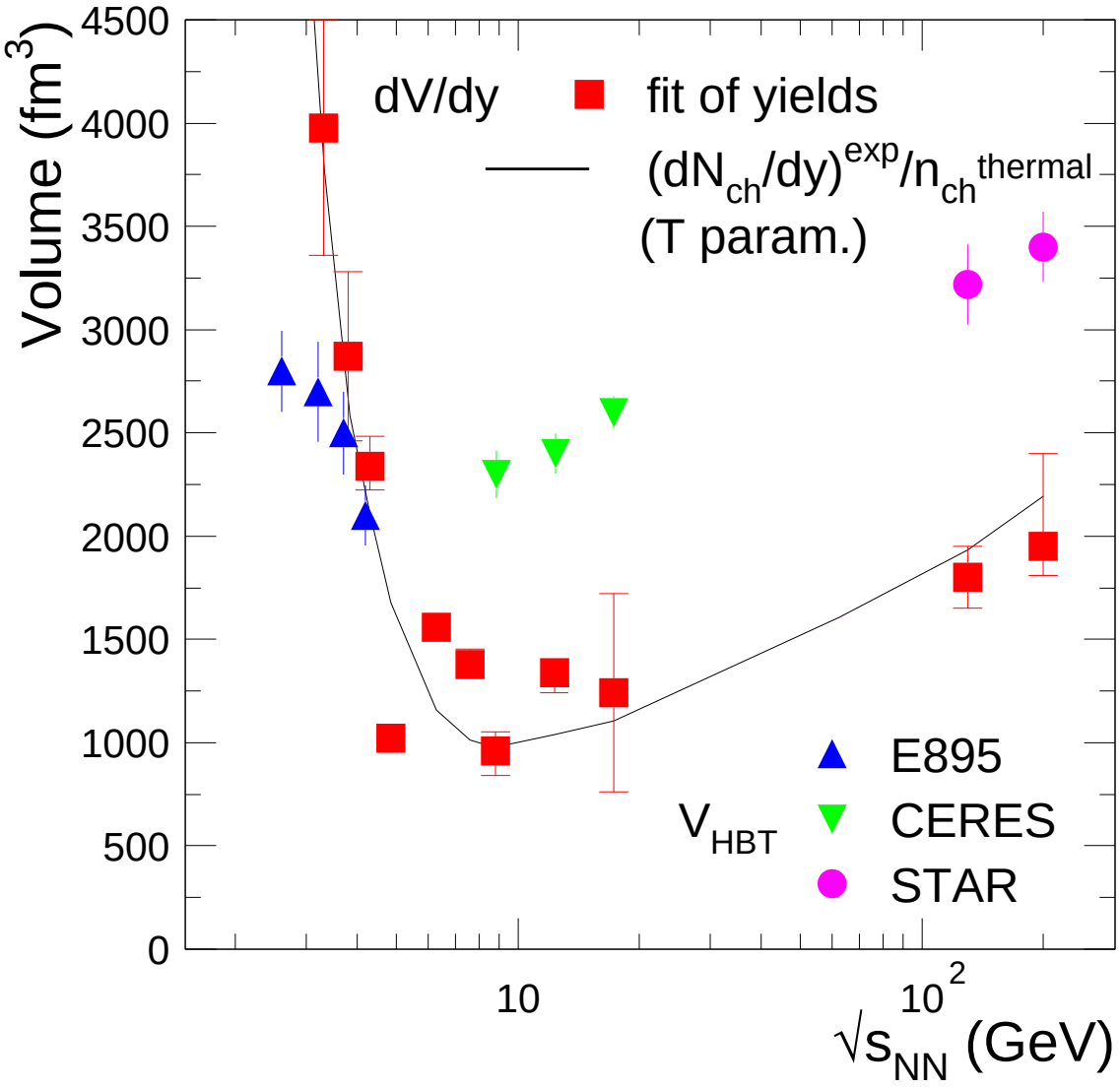
is chemical freeze-out at the phase boundary for SIS100 too?

Chemical vs. kinetic freeze-out



- AGS energies: $T_{chem} < T_{kin}$!
- bias in the thermal fits?

Energy dependence of the freeze-out volume



$\mathrm{d}V/\mathrm{d}y$: volume for one unit rapidity (at midrapidity)

minimum at $T \rightarrow T_{lim}$

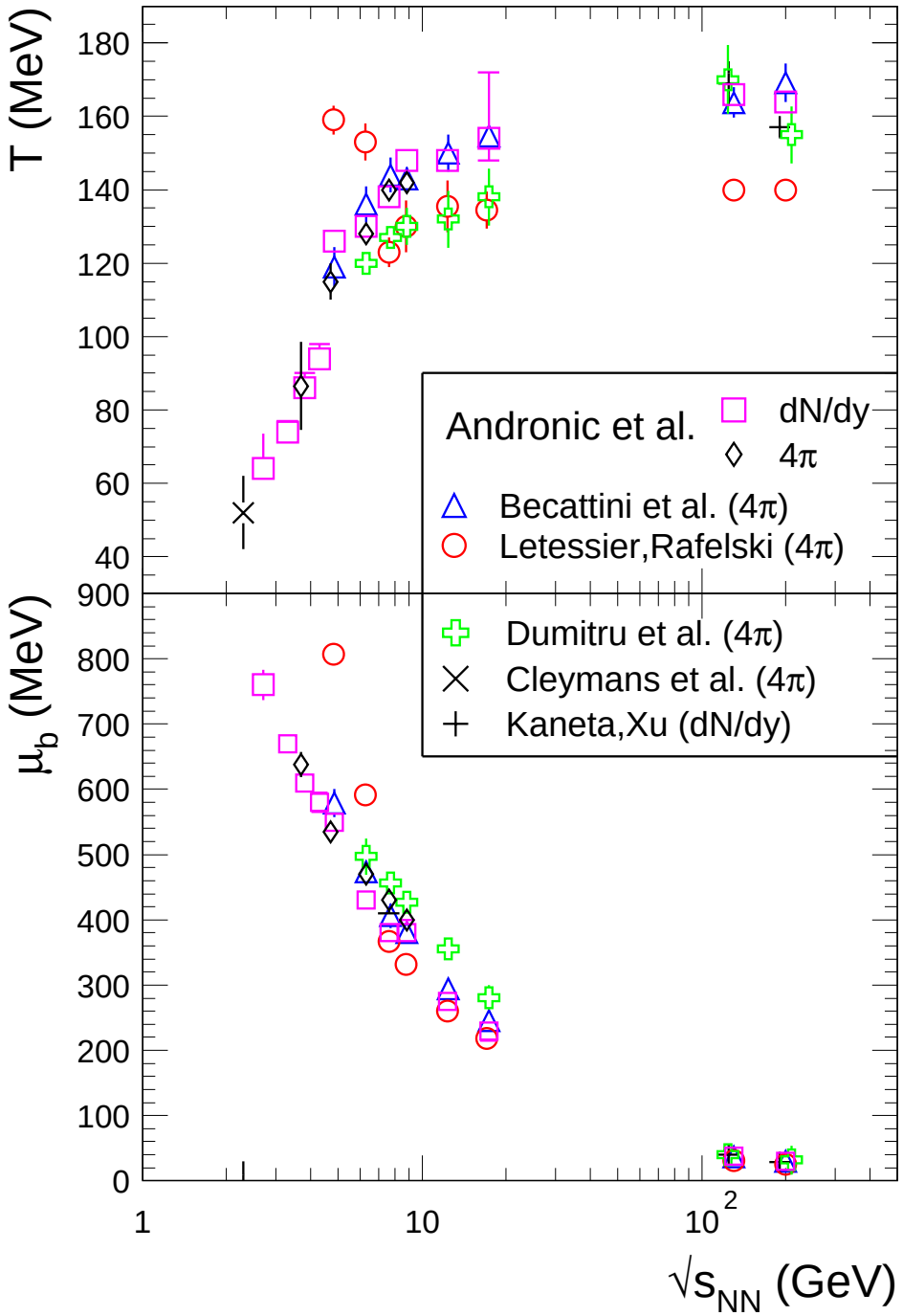
V_{HBT}:

CERES, PRL, 90 (2003) 022301

($\lambda_f \simeq$1 fm)

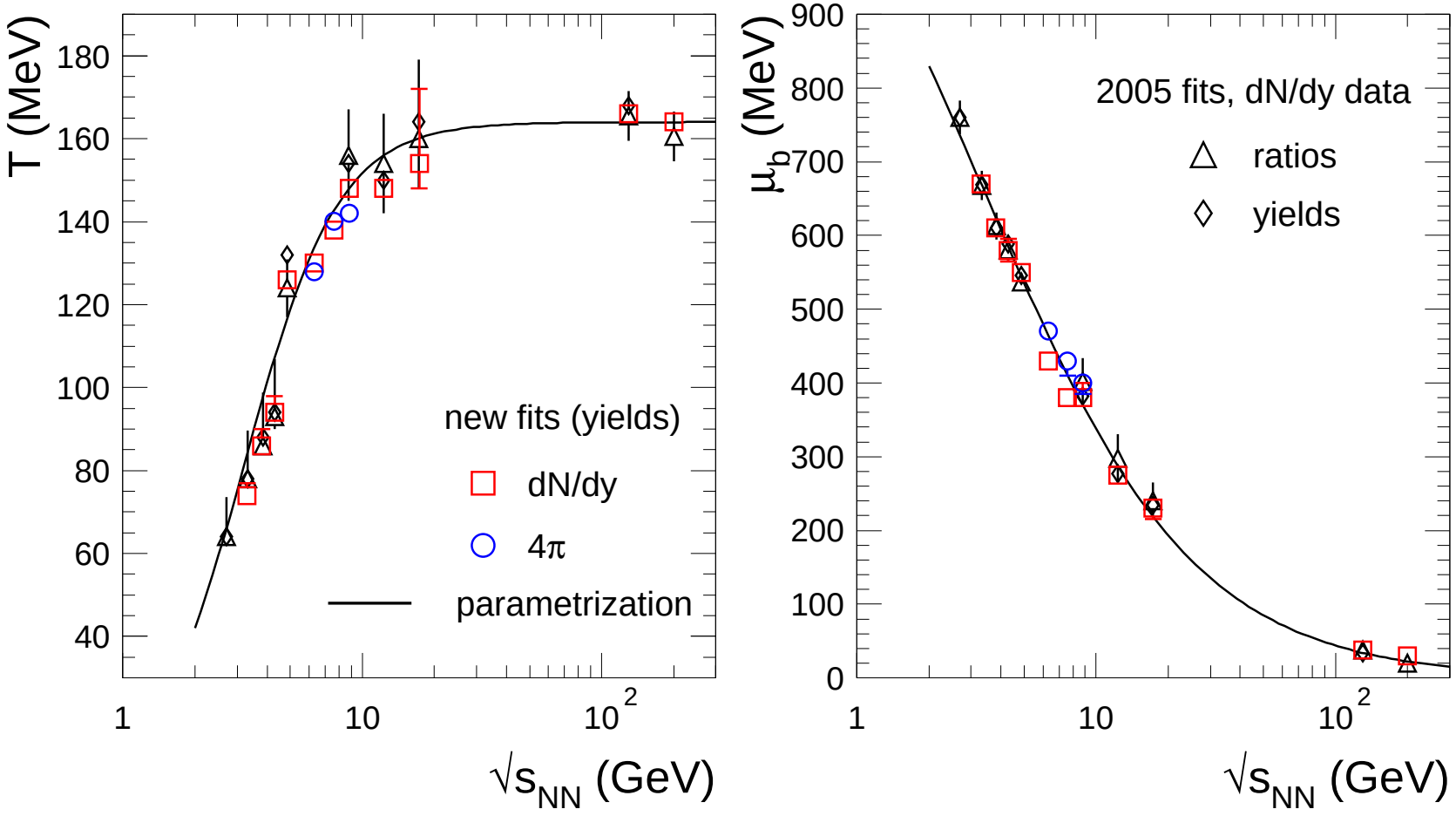
not fully understood dependen

Energy dependence of the thermal parameters



- Becattini et al.: $+\gamma_S$ - hep-ph/0511092,0806.4100
- Rafelski et al.: $+\gamma_{S,q}$, λ_{q,S,I_3} - nucl-th/0504028
  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, $\delta\mu_B$) - nucl-th/0511084

Energy dependence of T, μ_b (parametrizations)

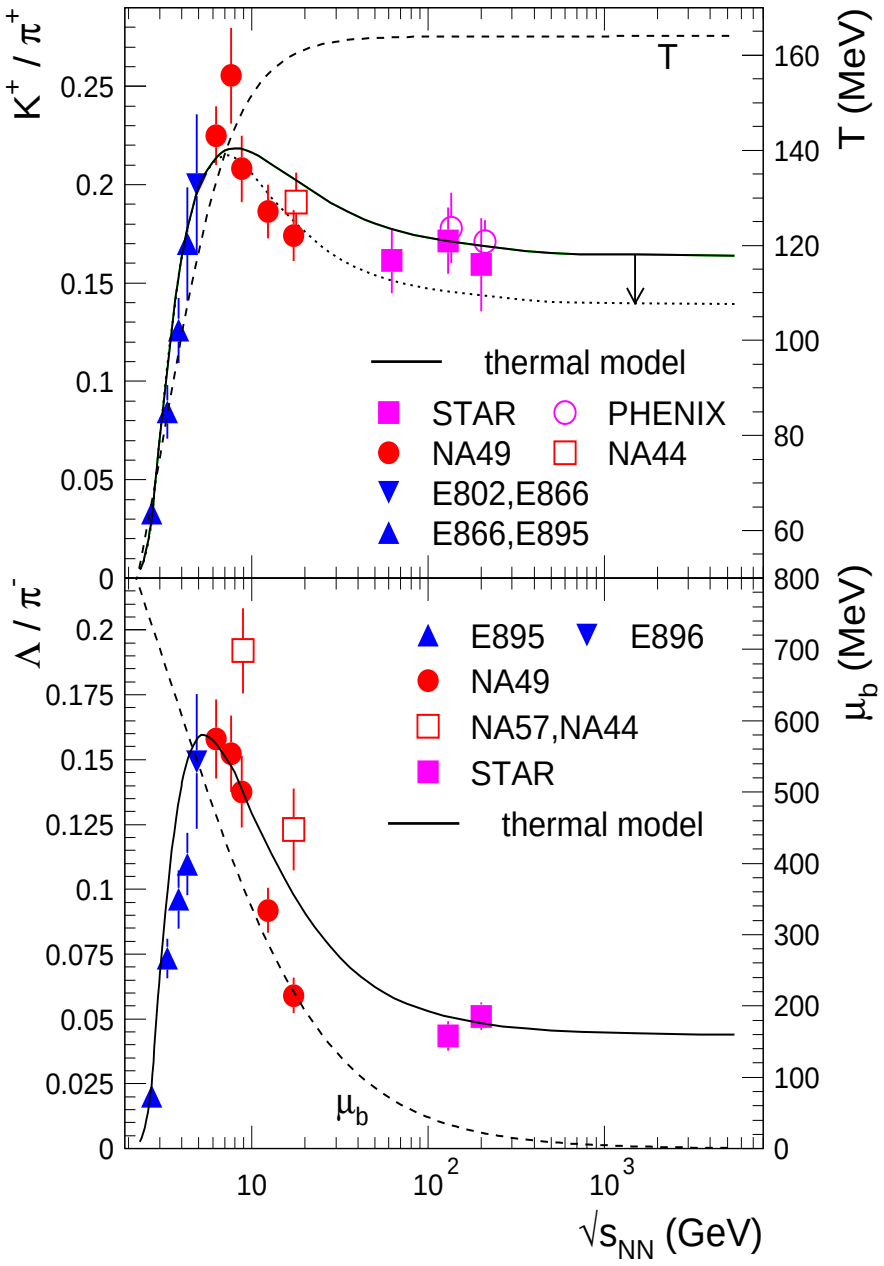


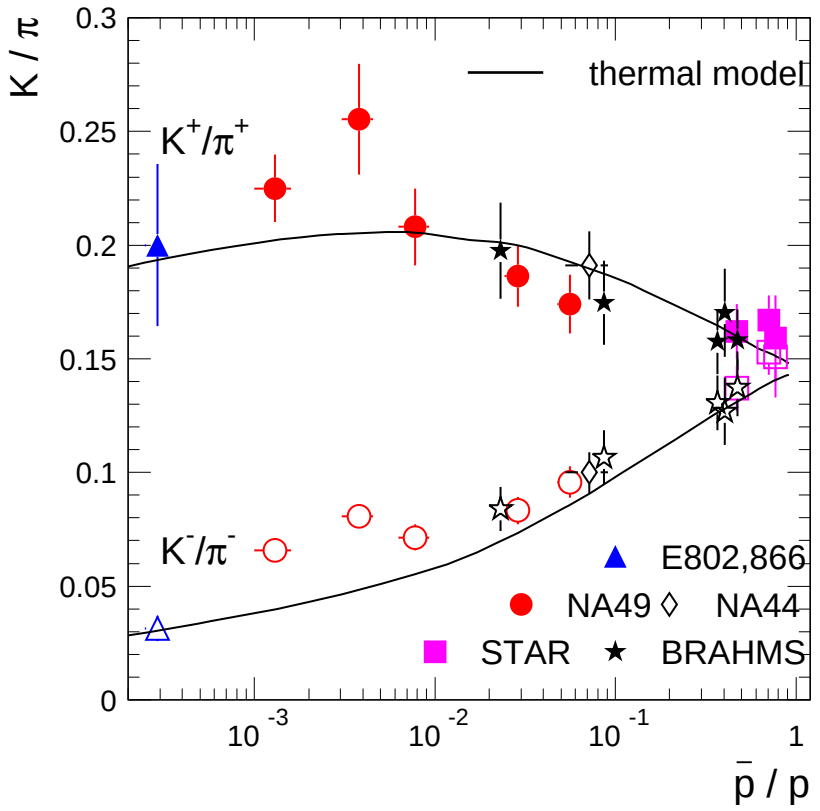
thermal fits exhibit a limiting temperature: $T_{lim} = 164 \pm 4$ MeV

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

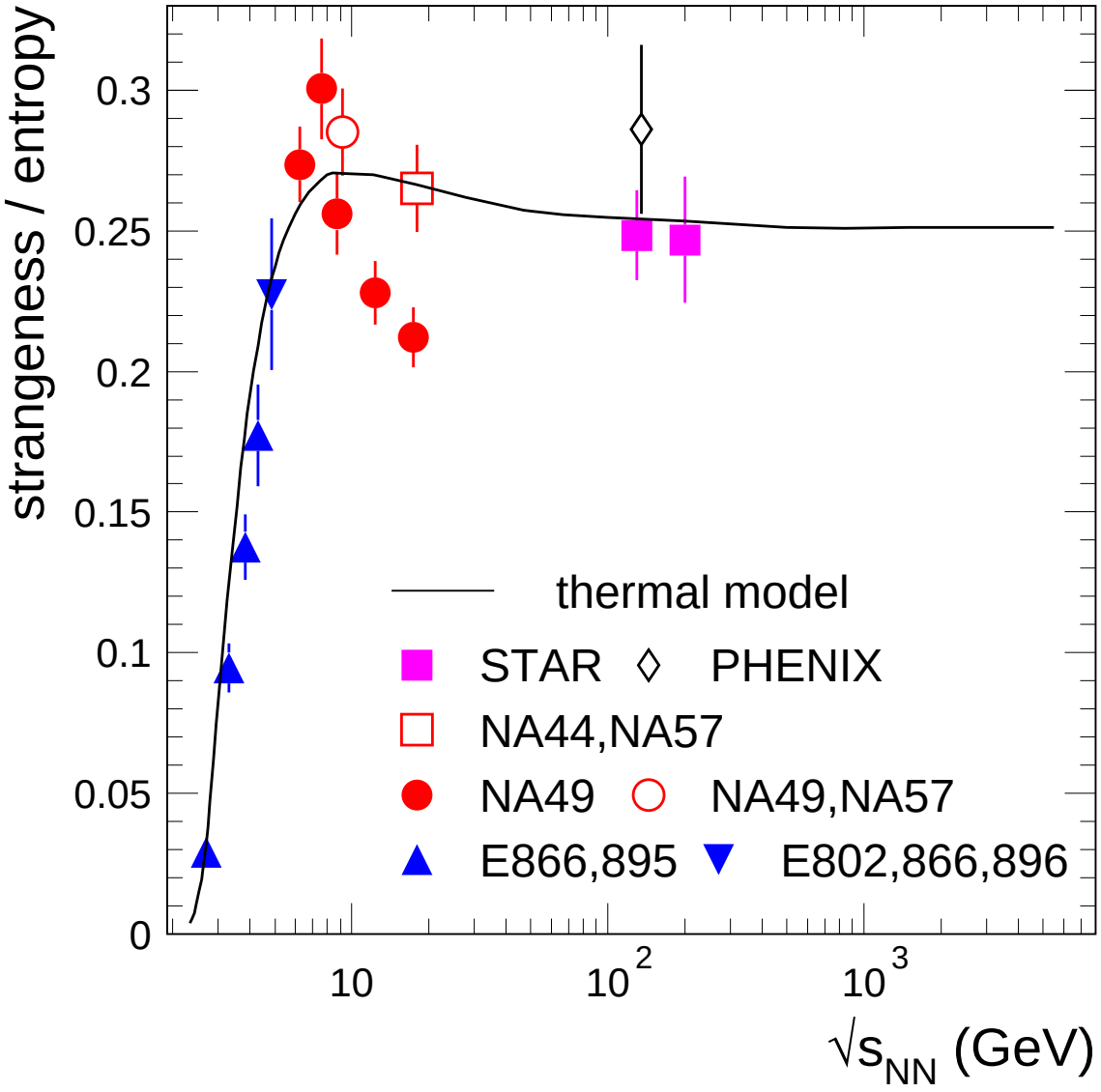
use param. to check energy dep. of the thermal character of hadron abundanc

Particle ratios: the horn





A global ratio: strangeness/entropy



"strangeness":
$2 \times (K^+ + K^-) + 1.54 \times (\Lambda +$

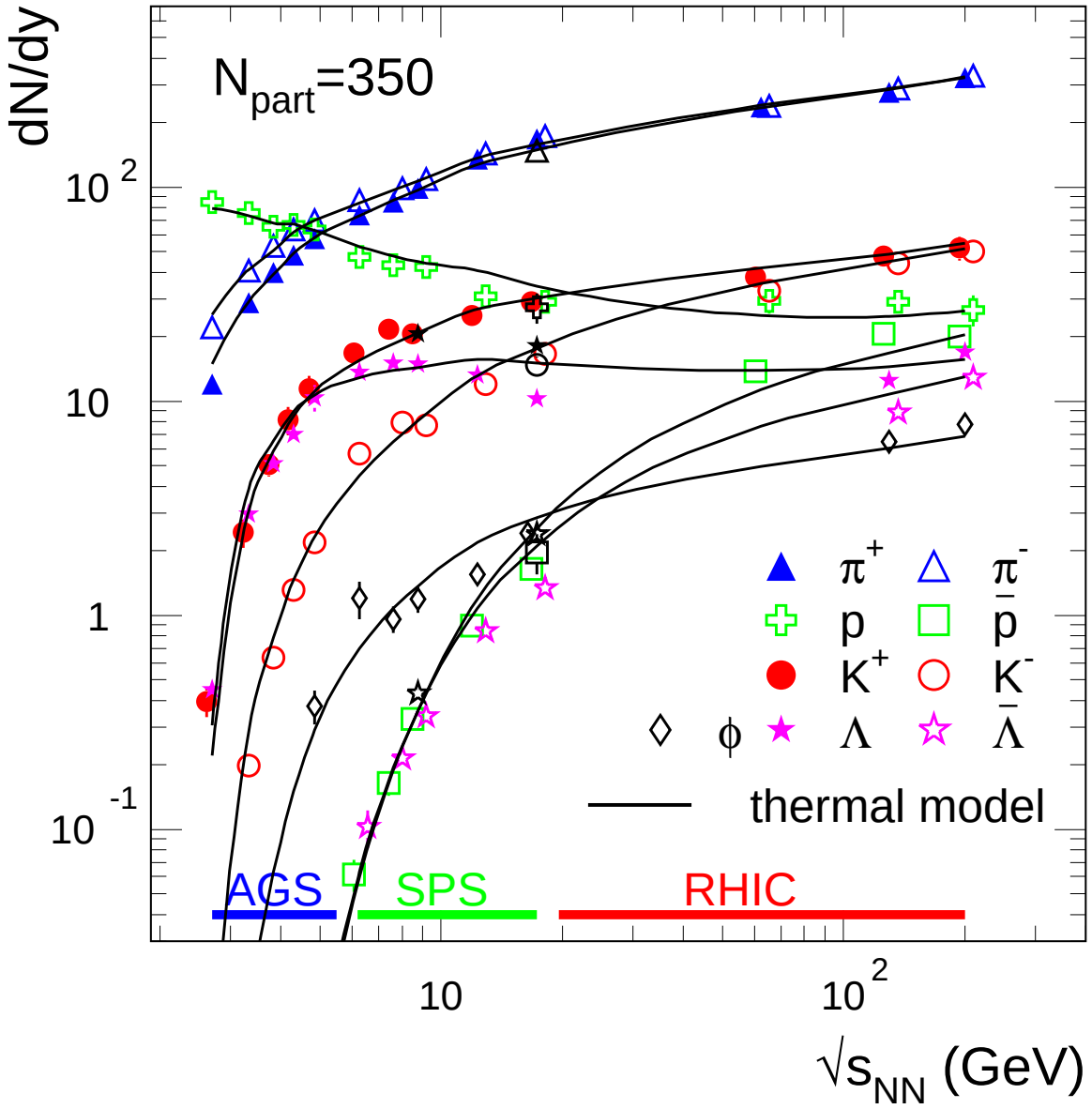
"entropy":
$1.5 \times (\pi^+ + \pi^-) + 2 \times \bar{p}$

anything beyond therma

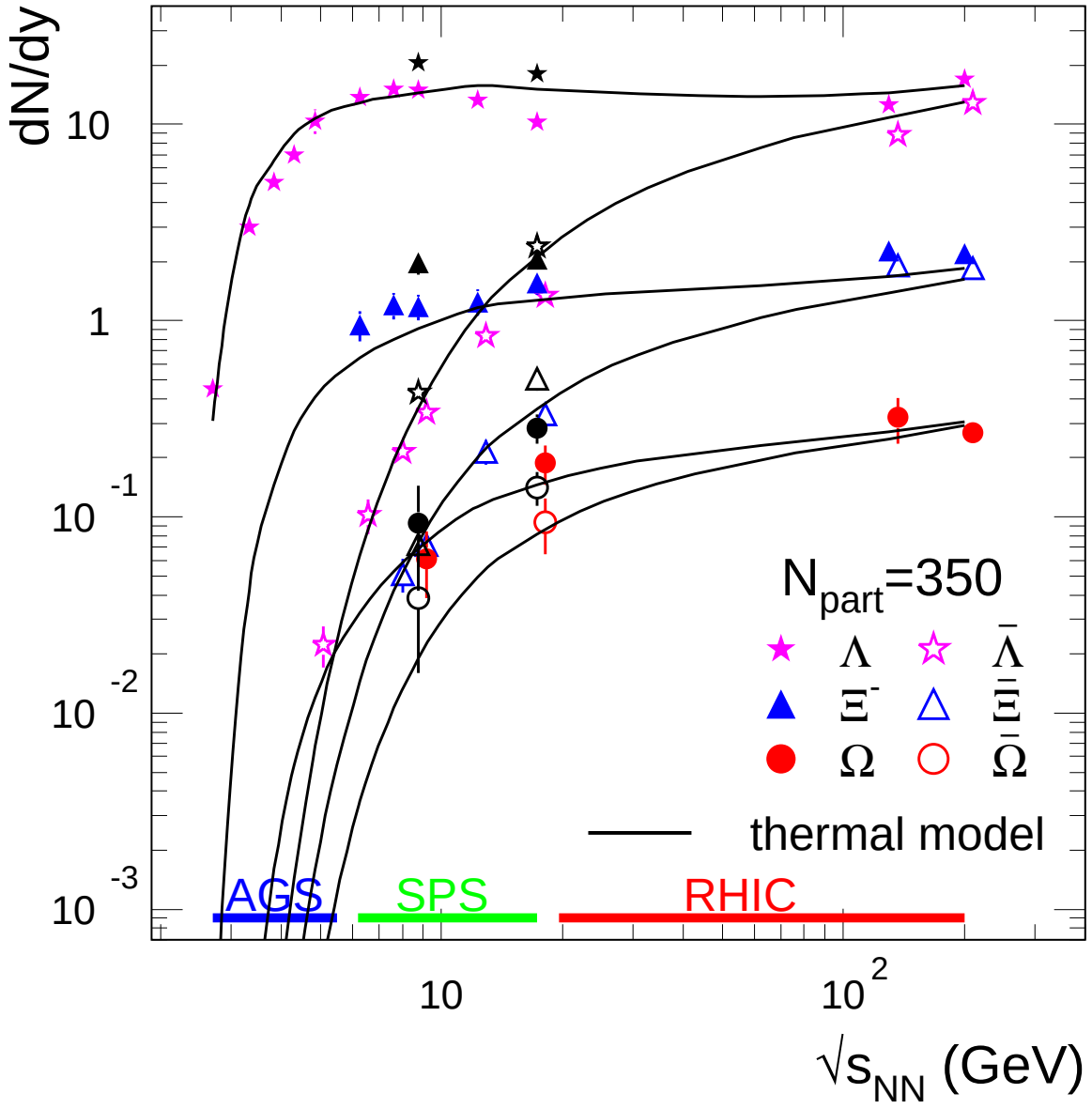
yes, in NA49 data...

...but hard to argue over

Yields at mid-rapidity



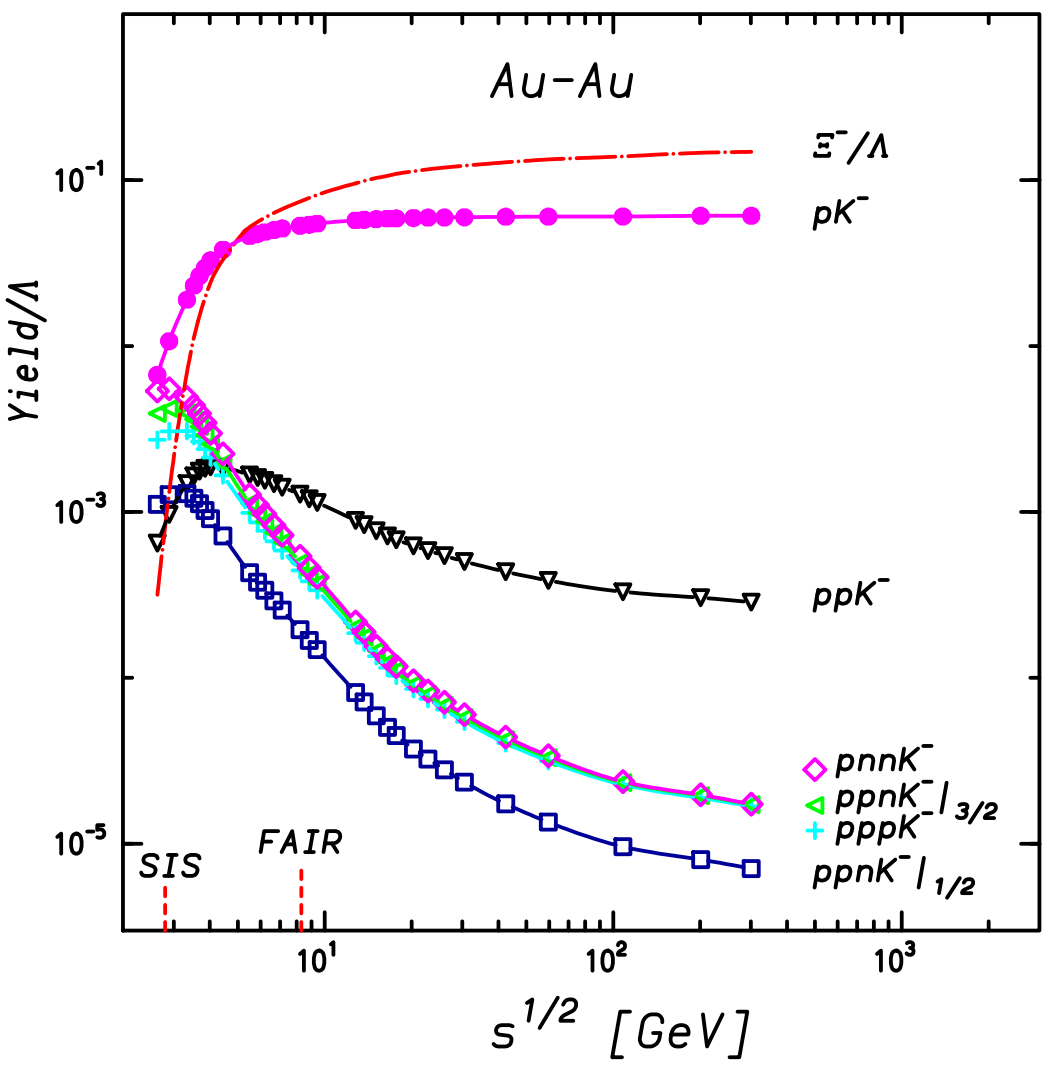
Yields at mid-rapidity: hyperons

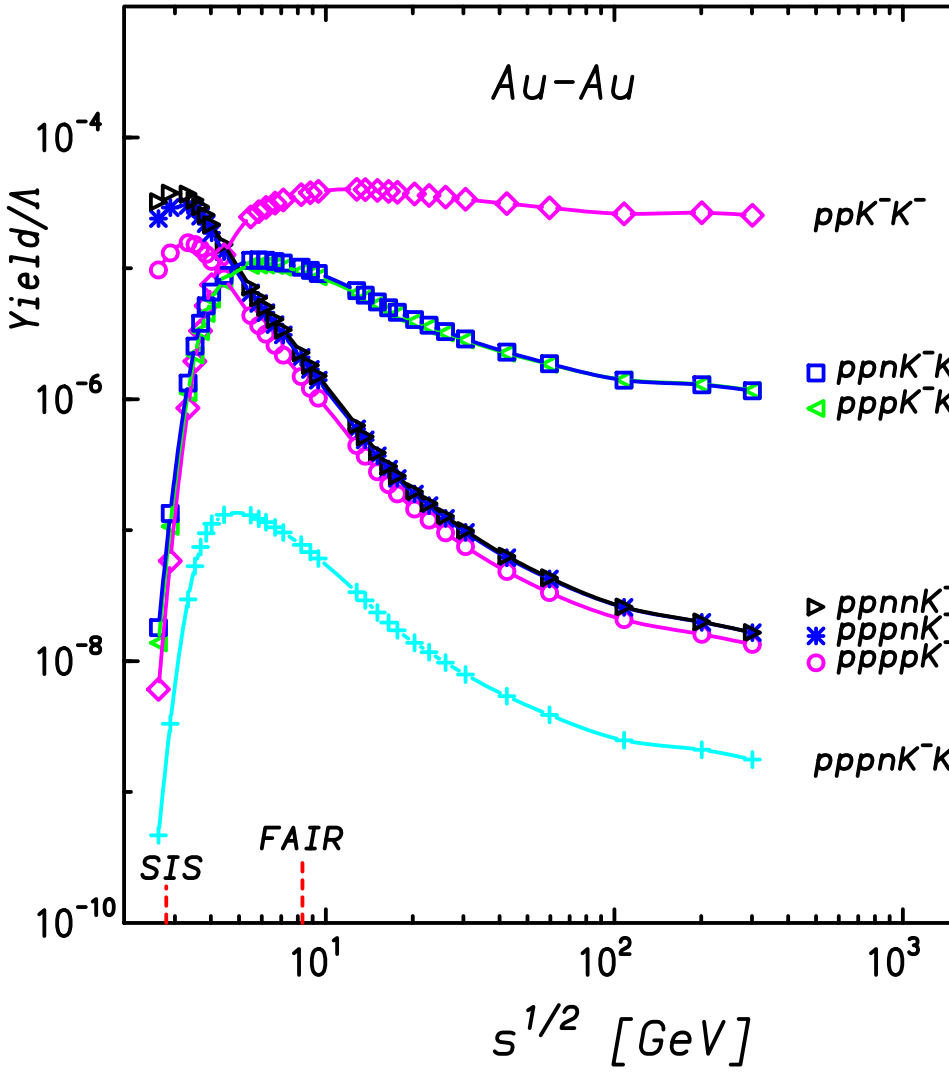


production (dN/dy) at 8 AG

Λ: 9.0	$\bar{\Lambda}$: $1.4{\cdot}10^{-3}$
Ξ: 0.27	$\bar{\Xi}$: $3.2{\cdot}10^{-4}$
Ω: $5.4{\cdot}10^{-3}$	$\bar{\Omega}$: $5.4{\cdot}10^{-5}$

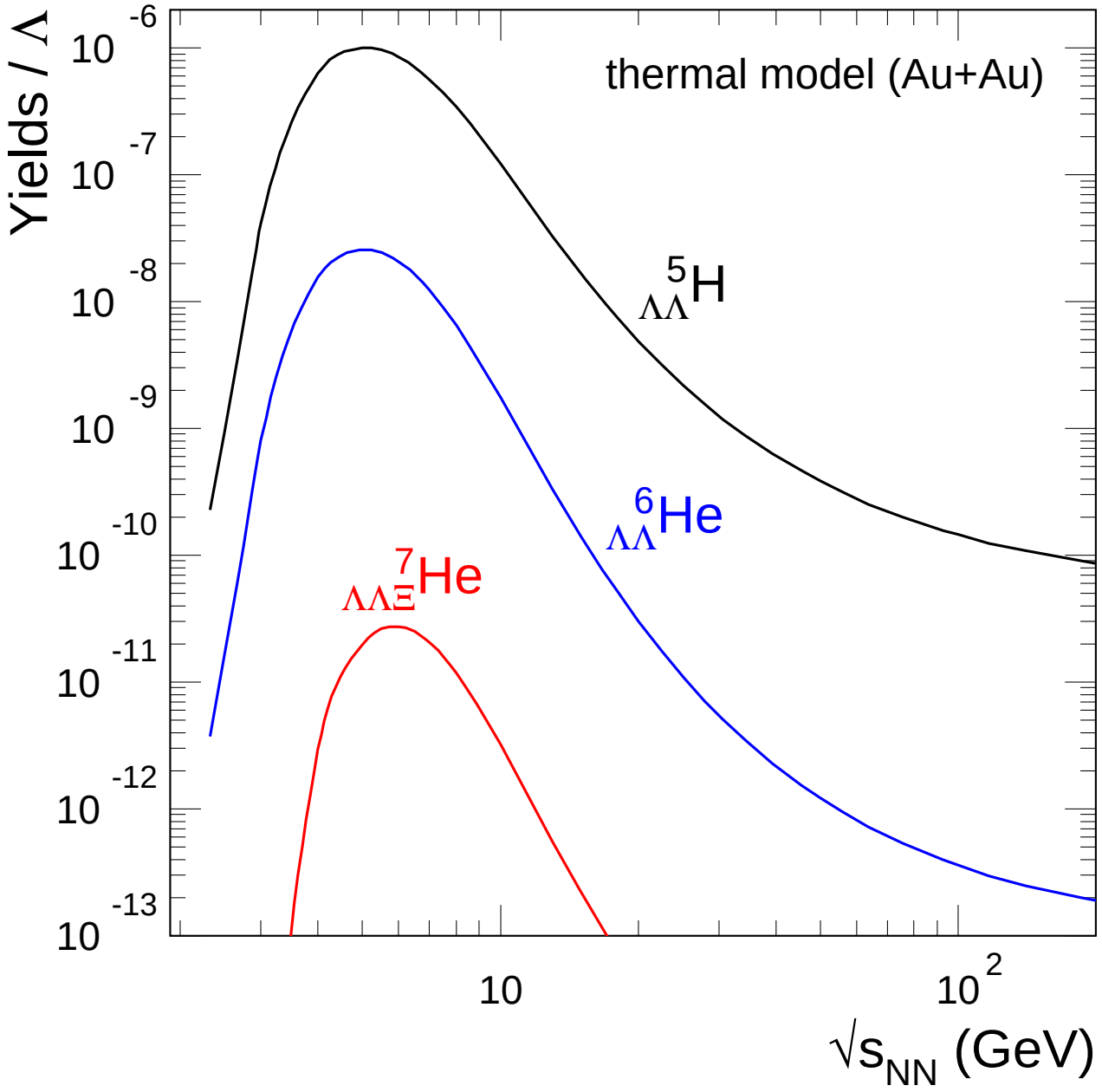
Exotica: FAIR (SIS100) is ideal





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

More Exotica: FAIR (SIS100) remains ideal



Summary

- thermal fits work remarkably well (AGS-RHIC) $\Rightarrow$ (T,μ_b,V)
- limiting temperature $\Rightarrow$ phase boundary (LQCD)
  $\longrightarrow$ for the skeptics... *LHC case will be decisive* ("bigger,...")
- indications (bad fits) for the critical point? ...maybe, at SPS...
  ...but not a strong case due to disagreements between experiments

indications for strangeness non-equilibrium (γ_S) in central collisions?
NOT (others: not at SIS and RHIC, *some* at AGS-SPS, *some* at RHIC)

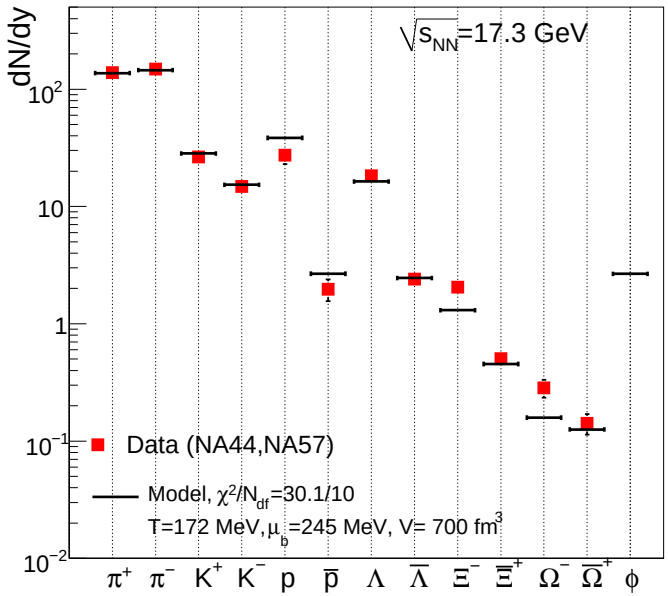
SIS100 "mission":

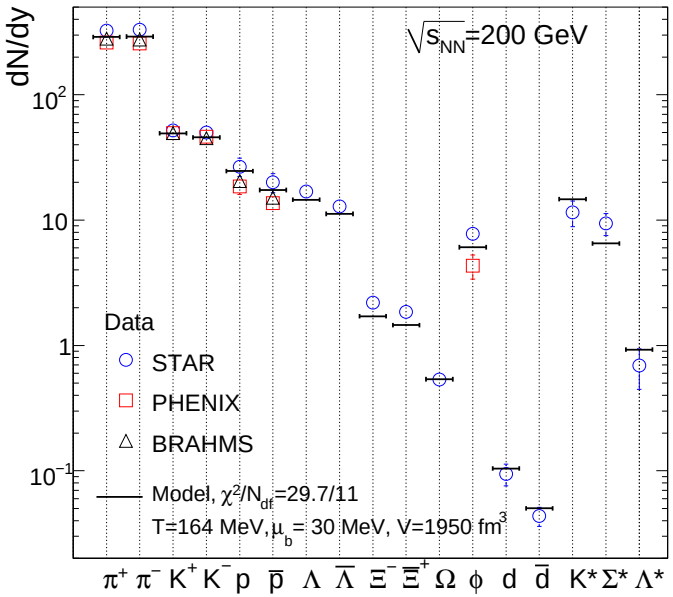
measure the freeze-out line (or phase boundary?) at high μ_b

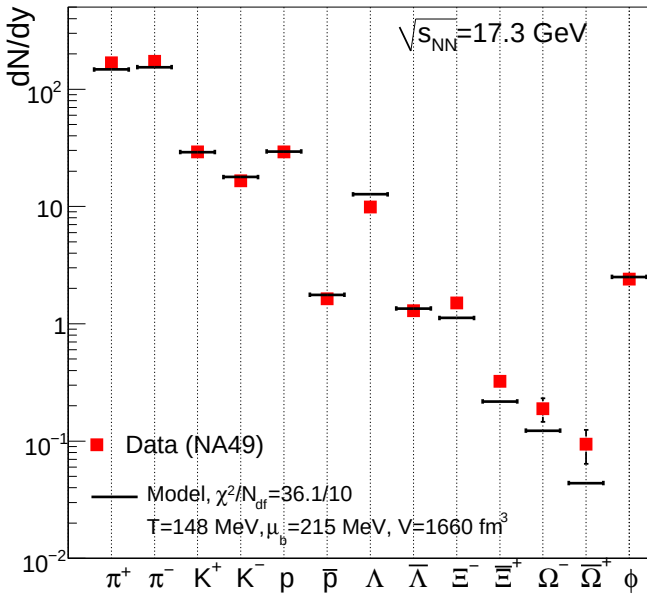
CBM = "Chemically-frozen" baryonic matter

(or Collisionally Broadened Matter ?:)

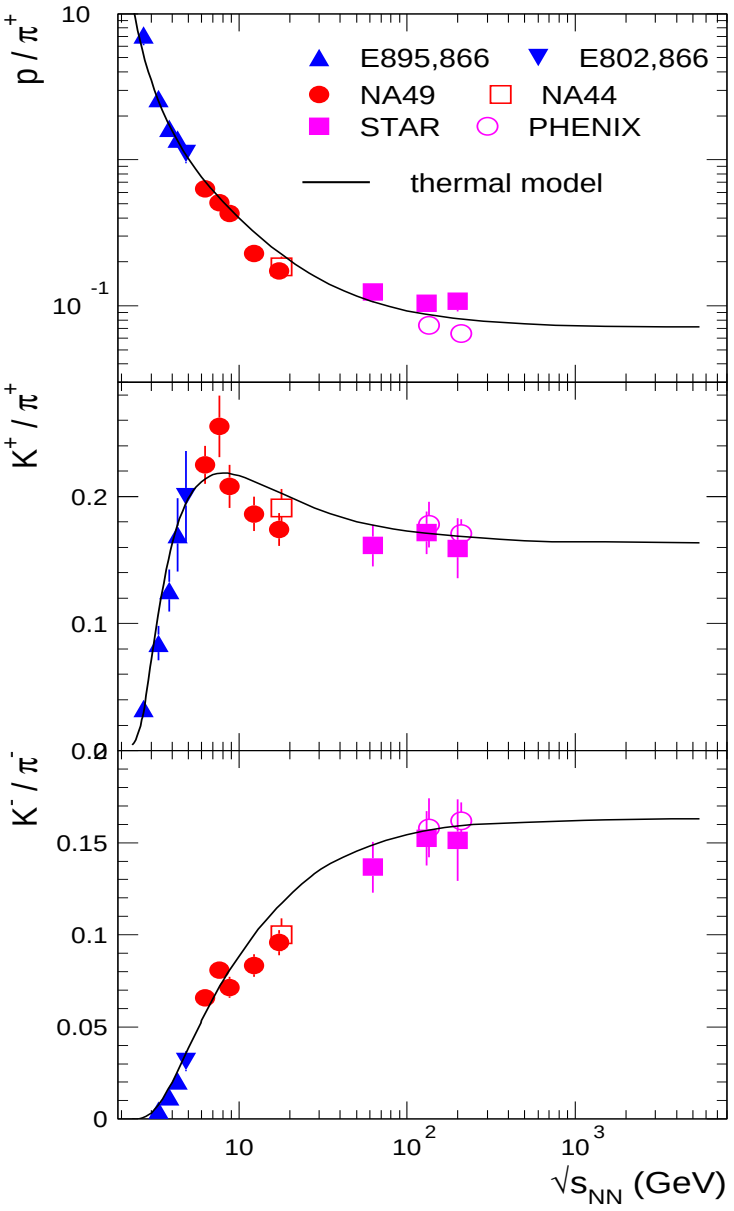
SPS, 158 AGeV

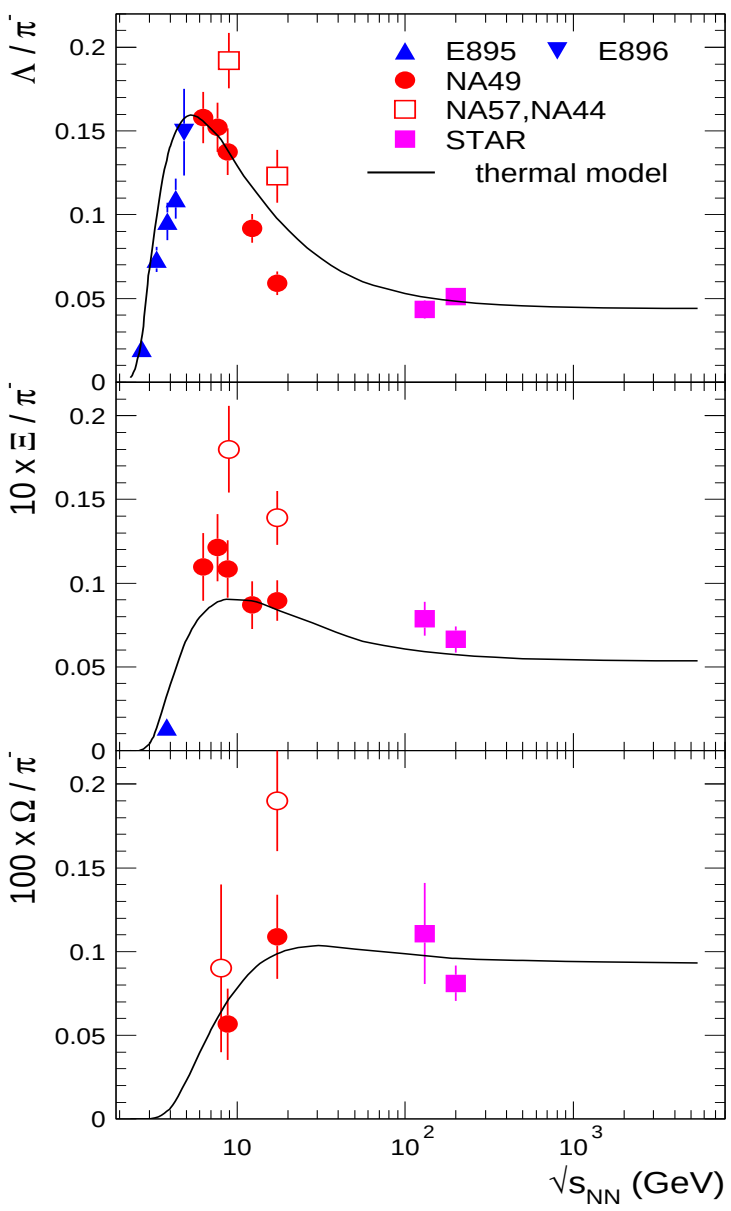

dN/dy
$\sqrt{s_{NN}}$=17.3 GeV
Data (NA44,NA57)
Model, χ^2/N_{df}=30.1/10
T=172 MeV, μ_b=245 MeV, V= 700 fm^3
π^+ π^- K^+ K^- p $\bar{p}$ Λ $\bar{\Lambda}$ Ξ^- $\bar{\Xi}^+$ Ω^- $\bar{\Omega}^+$ ϕ


dN/dy
$\sqrt{s_{NN}}$=200 GeV
Data
STAR
PHENIX
BRAHMS
Model, χ^2/N_{df}=29.7/11
T=164 MeV, μ_b= 30 MeV, V=1950 fm^3
π^+ π^- K^+ K^- p $\bar{p}$ Λ $\bar{\Lambda}$ Ξ^- $\bar{\Xi}^+$ Ω ϕ d $\bar{d}$ K*Σ* Λ*

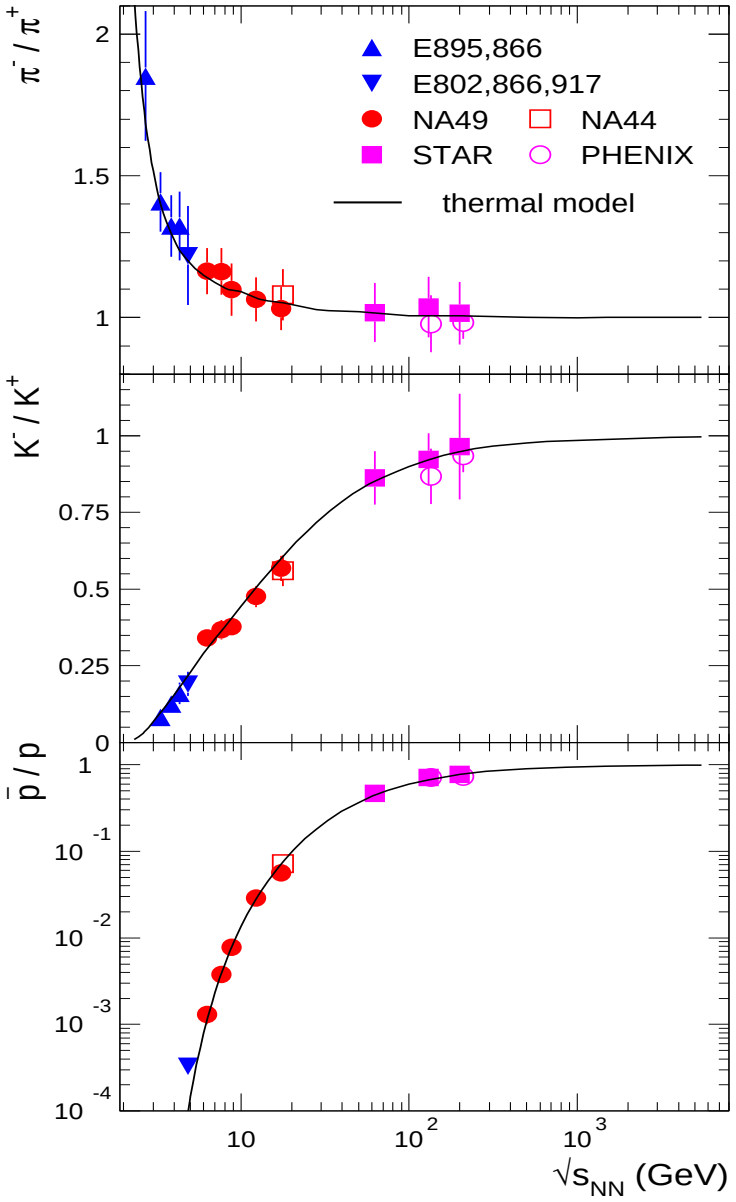

dN/dy
$\sqrt{s_{NN}}$=17.3 GeV
Data (NA49)
Model, χ^2/N_{df}=36.1/10
T=148 MeV, μ_b=215 MeV, V=1660 fm^3
π^+ π^- K^+ K^- p $\bar{p}$ Λ $\bar{\Lambda}$ Ξ^- $\bar{\Xi}^+$ Ω^- $\bar{\Omega}^+$ ϕ

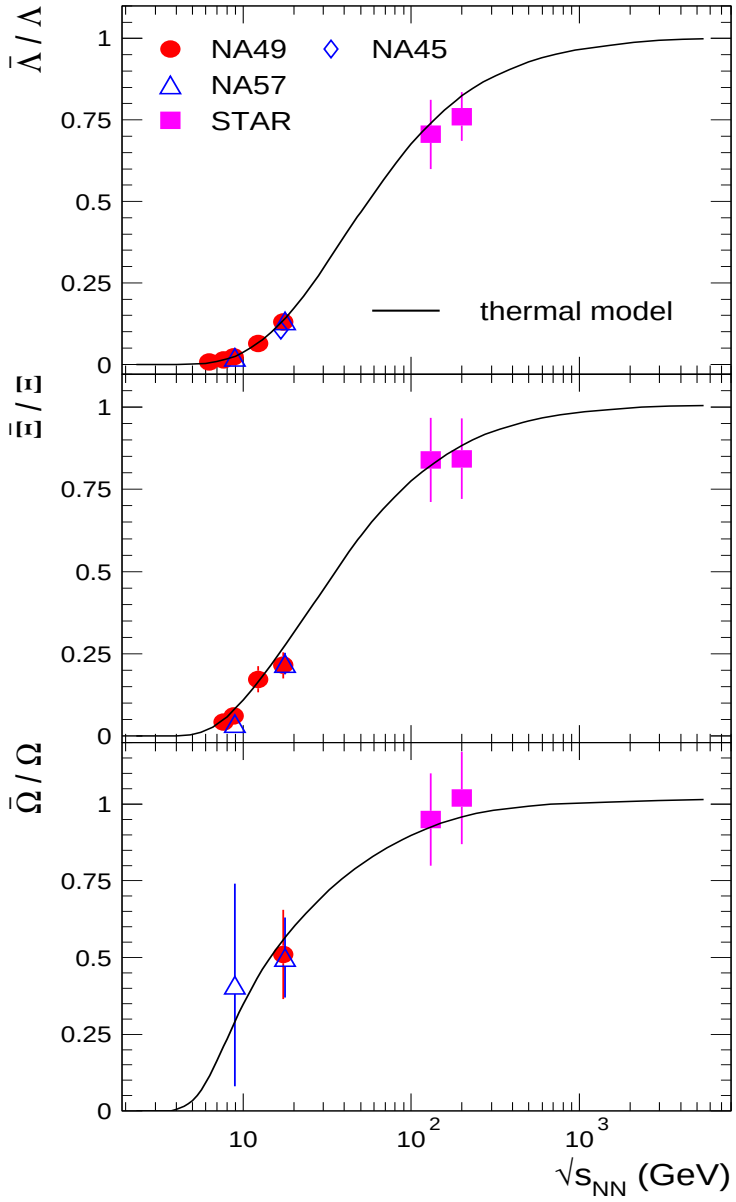
More particle ratios



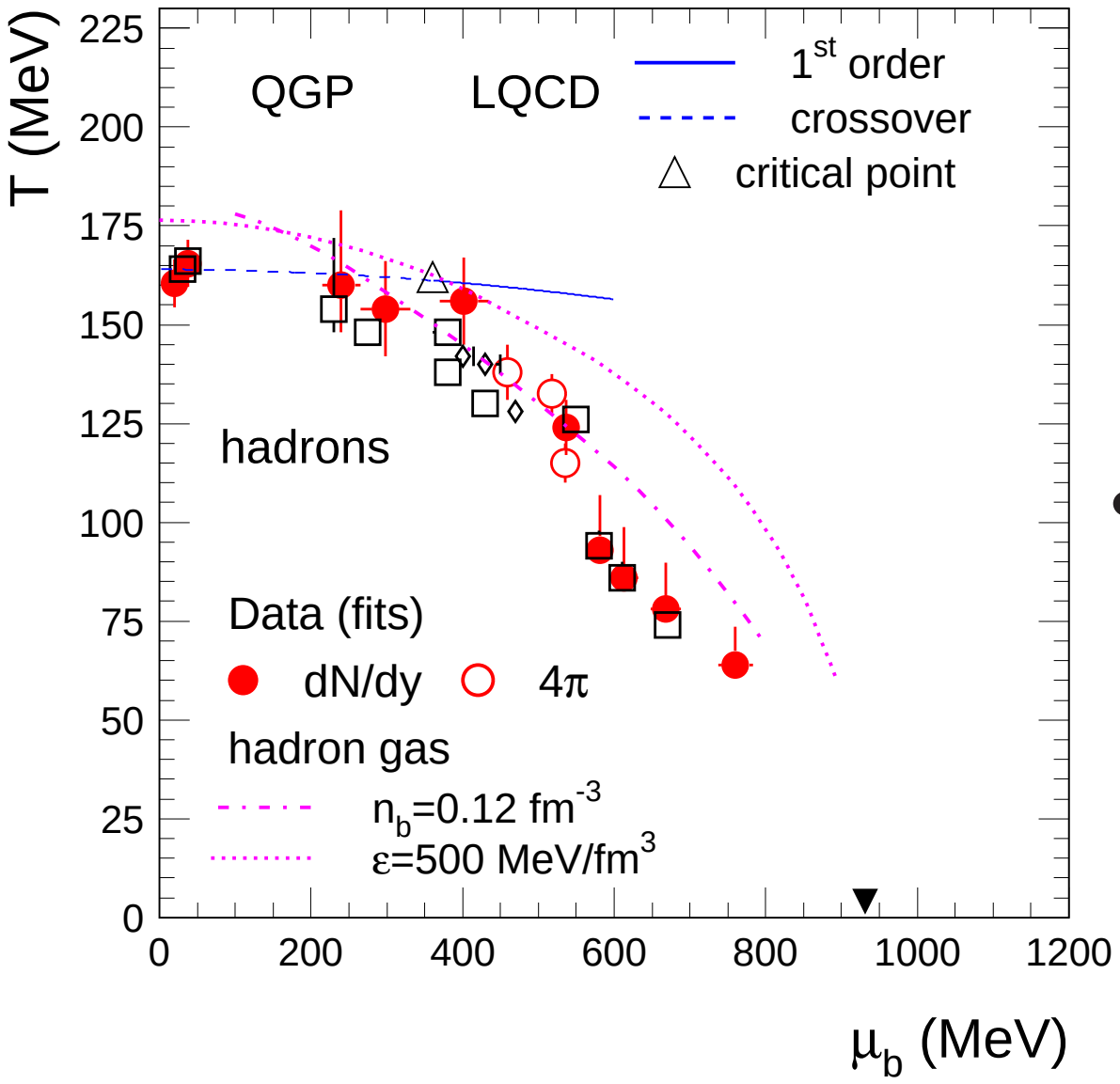


More particle ratios





The phase diagram of QCD (2009 vs. 2005)



- similar features