Freexe-out and Expansion Dynamics in AGS and SPS Heavy Ion Collisions

- Hadron Yields
- Hadron Spectra
- Two-Particle Correlations

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RHIC Winter Workshop at LBNL
January 9, 1999

CERN SPS Data and Thermal Model

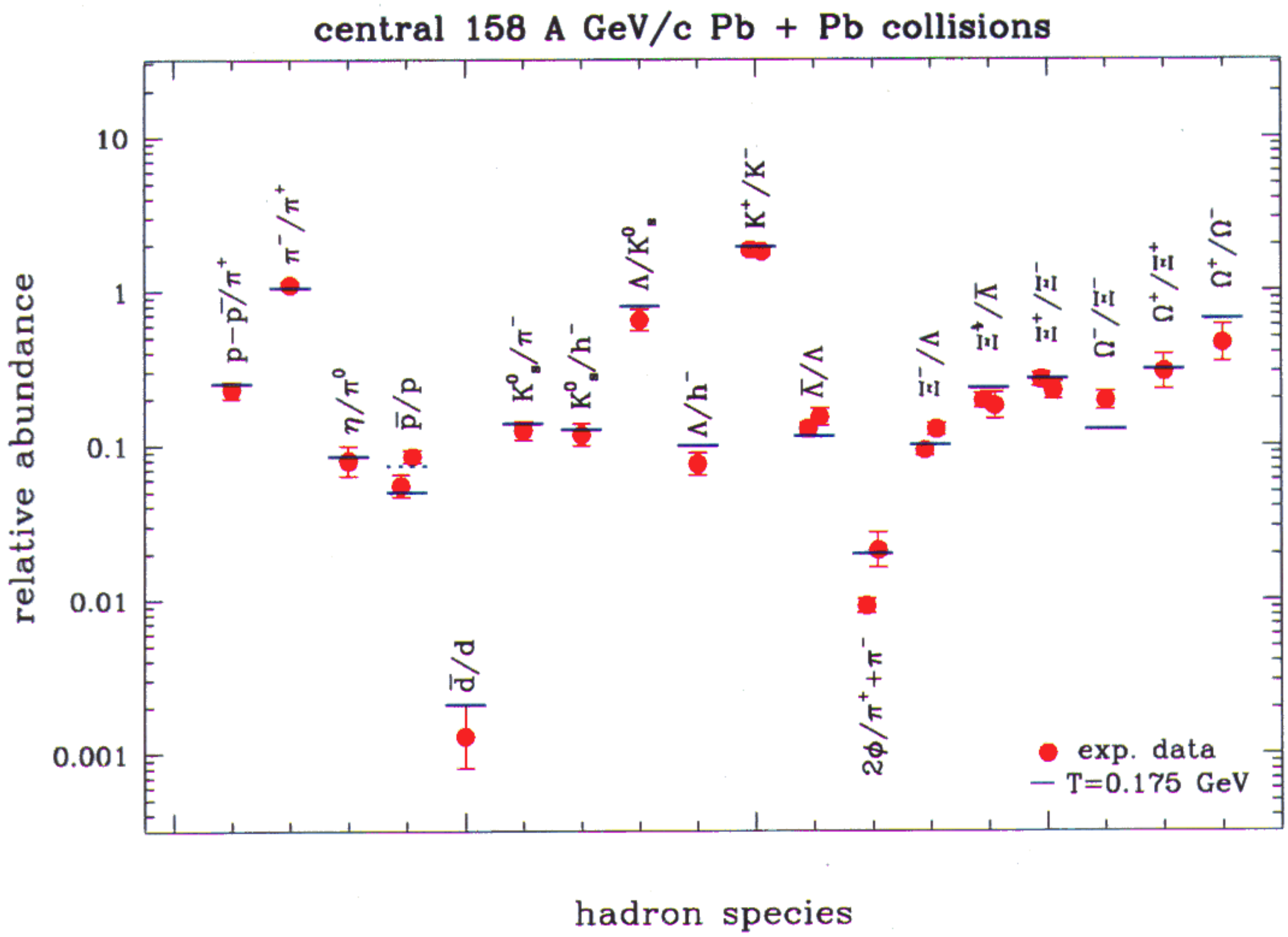
P.Braun-Munzinger, I. Heppe, J.Stachel 1998

$T = 0.170 - 0.175$ GeV driven by $K_s^0/\bar{\Lambda}$, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, Ξ^+/Ξ^-

$\mu_b = 0.27 - 0.28$ GeV driven by p/π

$\mu_s = 0.078$ GeV *from* $\Delta S = 0$ $\gamma_s = 1.0$

$\mu_{I_3} = 0.006$ GeV *from* $\Delta Q = 0$



Statistical model for particle yields

- grand canonical ensemble

$$\rho_i = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_b B_i - \mu_s S_i - \mu_{I_3} I_3^i)/T] \pm 1}$$

- use conservation laws

• baryon number $V(\sum_i n_i B_i) = Z + N$

• strangeness $\sum_i n_i S_i = 0$

• charge $V \sum_i n_i I_3^i = \frac{Z-N}{2}$

➡ leaves only μ_b and T as free parameters

- excluded volume correction à la Rischke, Gorenstein et al.

$p^{excl}(T,\mu) = p^{igas}(T,\hat{\mu})$ with

$\hat{\mu} = \mu - V_{eigen}\, p^{excl}(T,\mu)$

recursive ...

but : different choice of eigenvolume relevant distance where interaction becomes repulsive ! order 0.3 fm

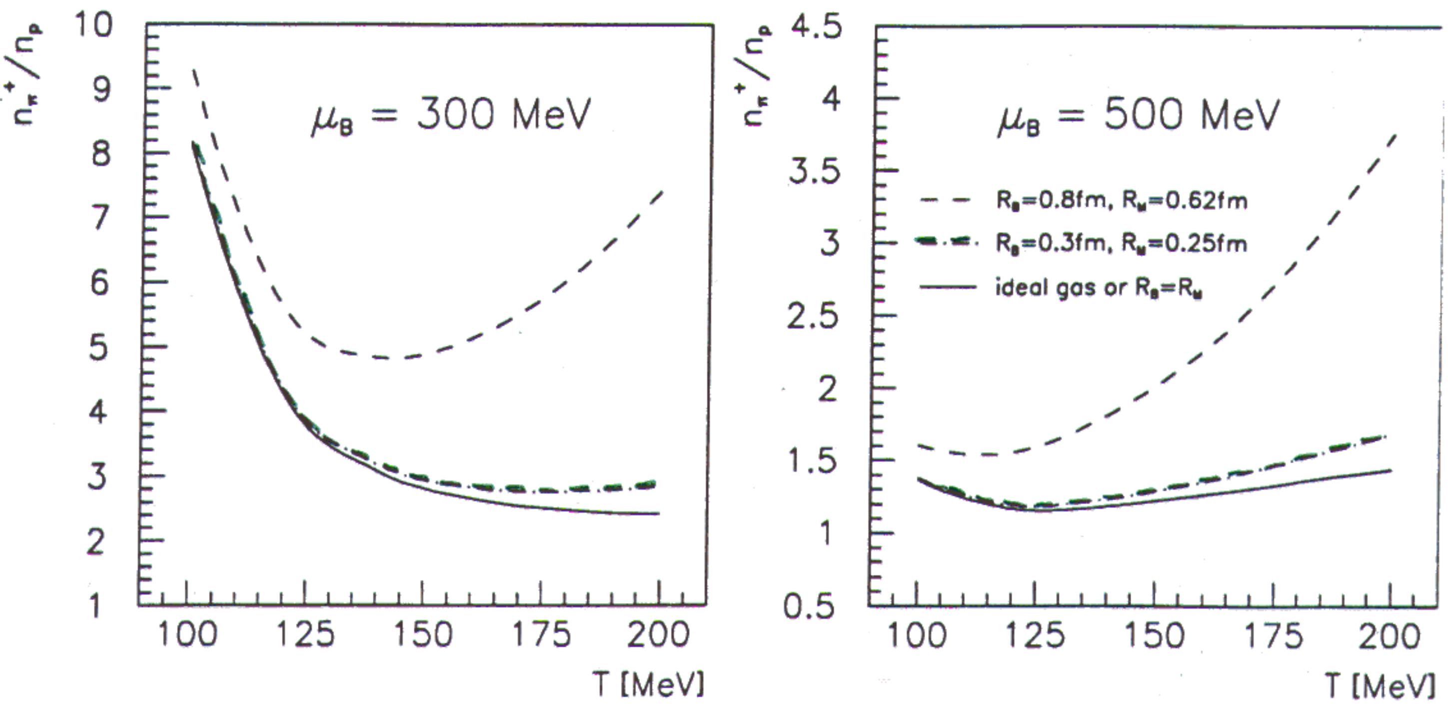
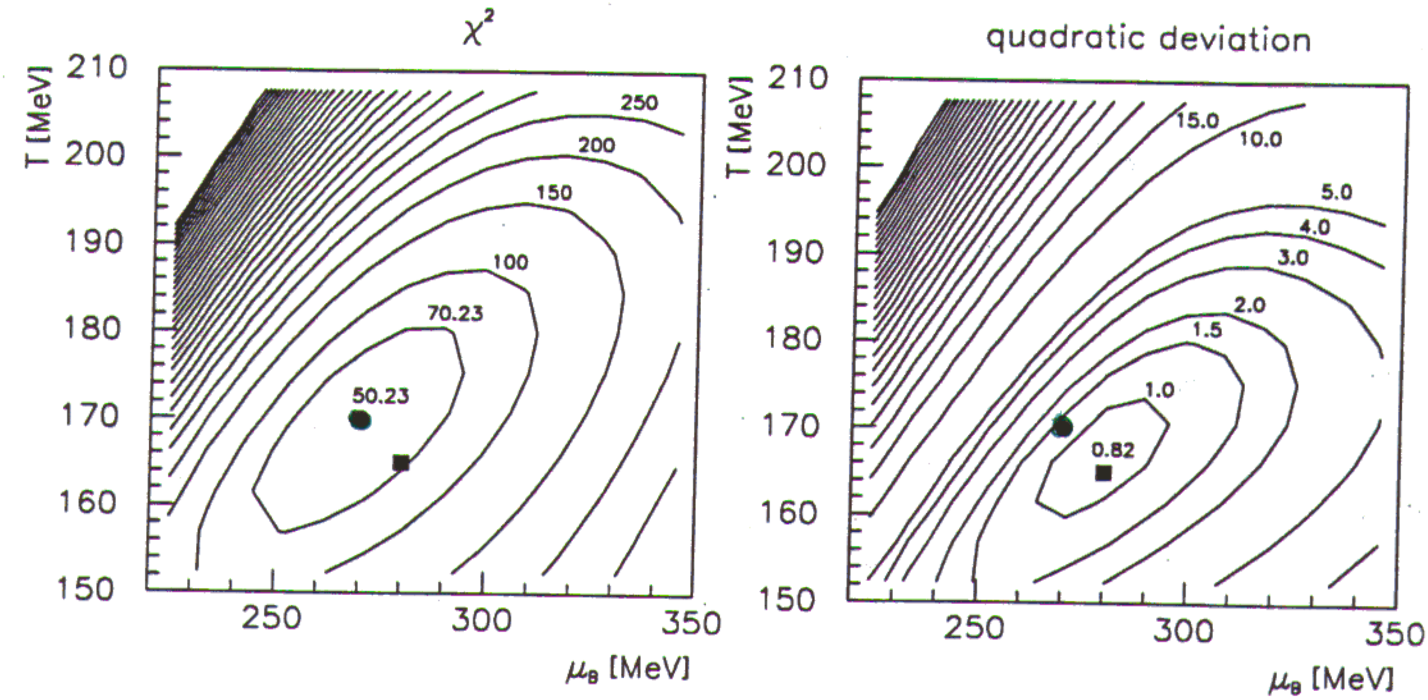


Figure 1: The influence of different excluded volumes for baryons und mesons on the π^+/p ratio as example.

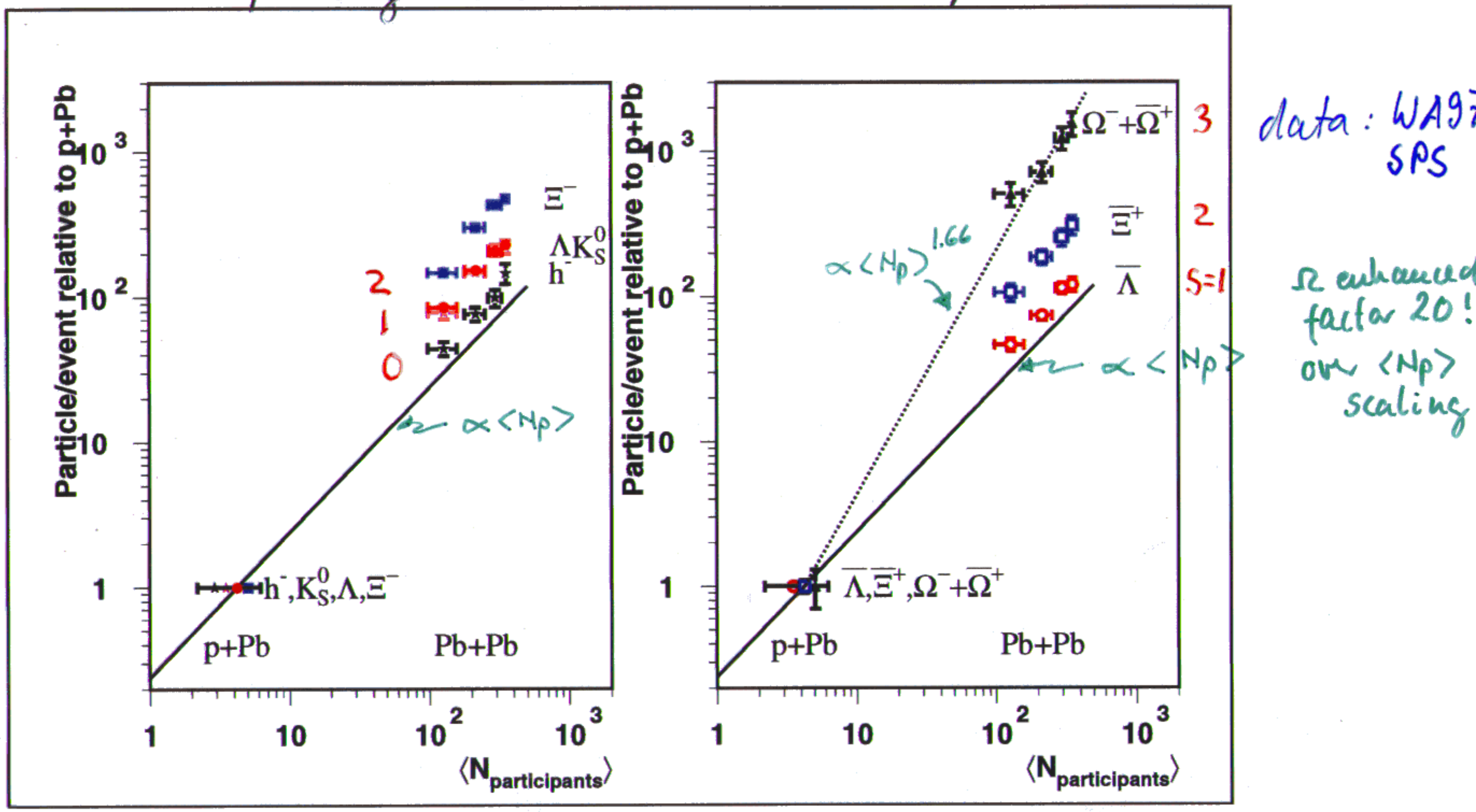
- for nucleon-nucleon interaction know that potential becomes strongly repulsive at $r = 0.3$ fm
- choose same for all particles

$$\sum_i \frac{(R^i_{exp} - R^i_{calc})^2}{\sigma^{i\,2}_{exp}} \qquad \sum_i \frac{(R^i_{exp} - R^i_{calc})^2}{R^{i\,2}_{exp}}$$



22 deg of freedom
statistical errors only!

➡ Yield of (multiply) strange hadrons rises more than linearly w. number of participating nucleons between pA and AA

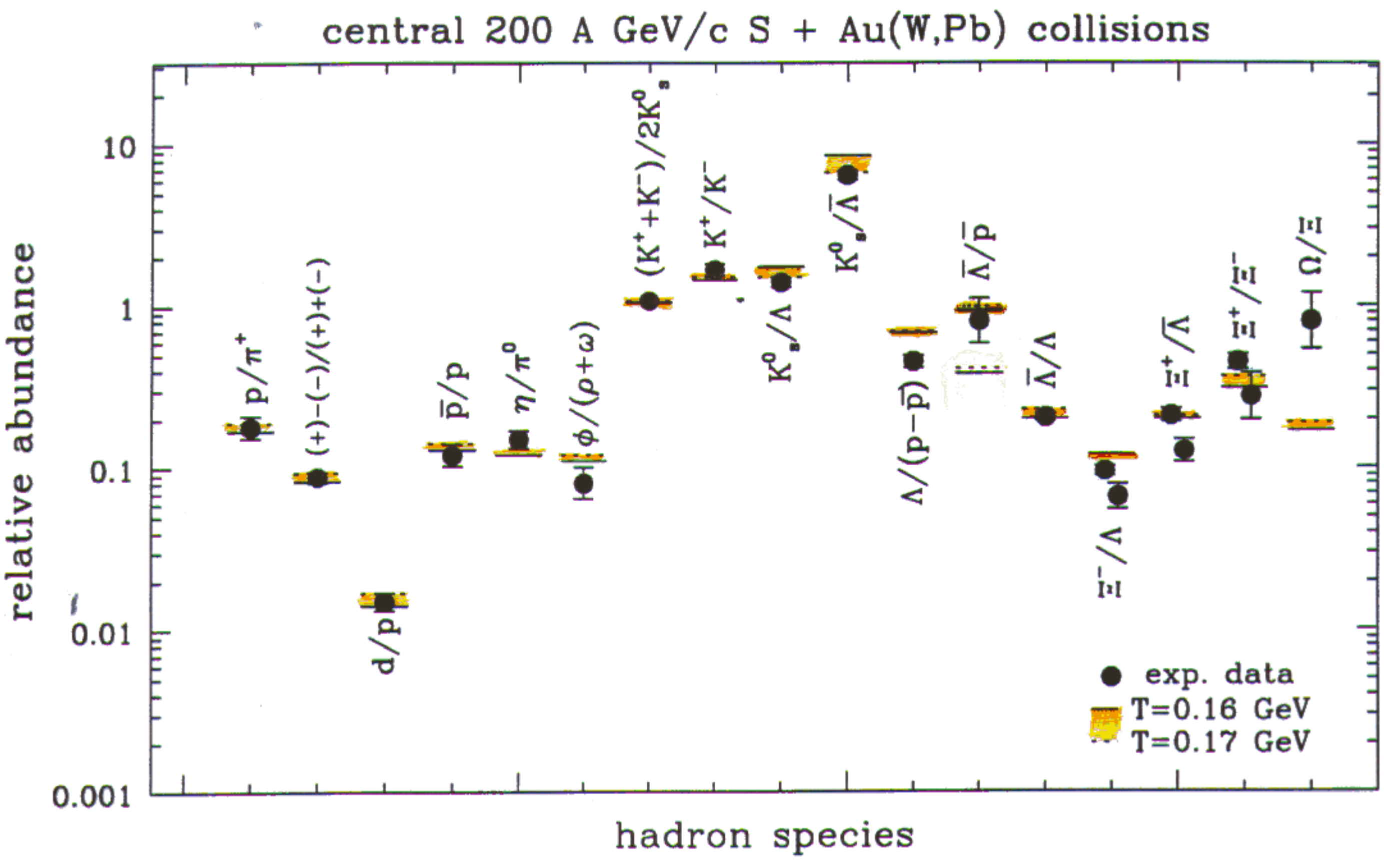


CERN SPS Data and Thermal Model

P.Braun-Munzinger, J.Stachel, J.P.Wessels, N.Xu, Phys.Lett.B365(1996)1

$T = 0.16 - 0.17$ GeV driven by $K^0_s/\bar{\Lambda}$, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, Ξ^+/Ξ^-

$\mu_b = 0.17 - 0.18$ GeV driven by p/π $\mu_s = 0.038 - 0.047$ GeV from $\Delta S = 0$



Note: $\mu_{s-quark} = \frac{1}{3}\mu_b - \mu_s \approx 0$ (10 MeV) in perfectly hadronic scenario

- data not 4π yet
- need PbPb

AGS Data and Thermal Model

P.Braun-Munzinger, J.Stachel, J.P.Wessels, N.Xu, Phys.Lett.B344(1995)43

grand canonical

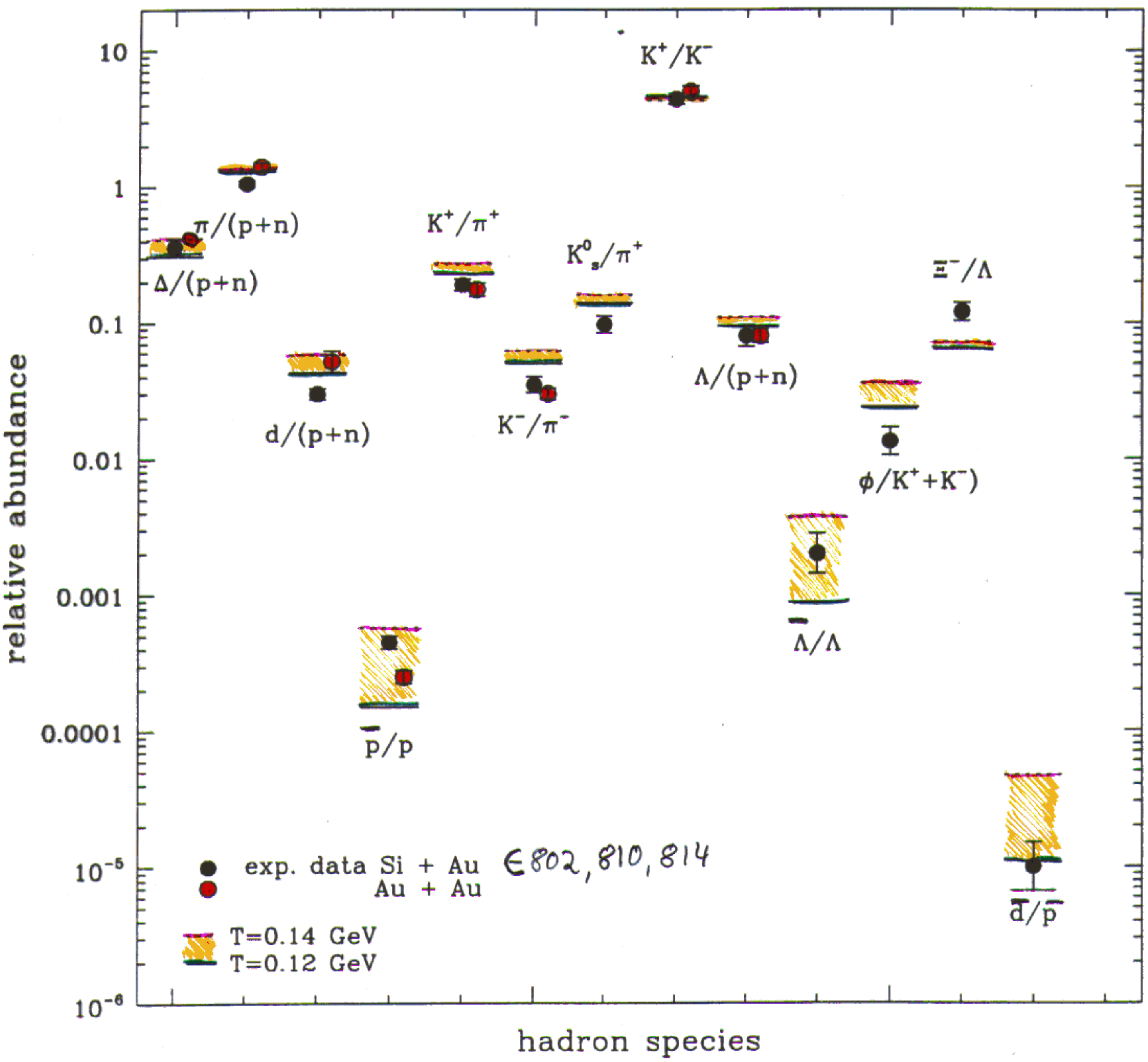
$$\rho_i^0 = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_b B_i - \mu_s S_i)/T] \pm 1}$$

$T = 0.12 - 0.14$ GeV from $\Delta/(p+n)$ $\quad \mu_b = 0.54$ GeV from $\pi/(p+n)$

$\mu_s = 0.108 - 0.135$ GeV from $\Delta S = 0$

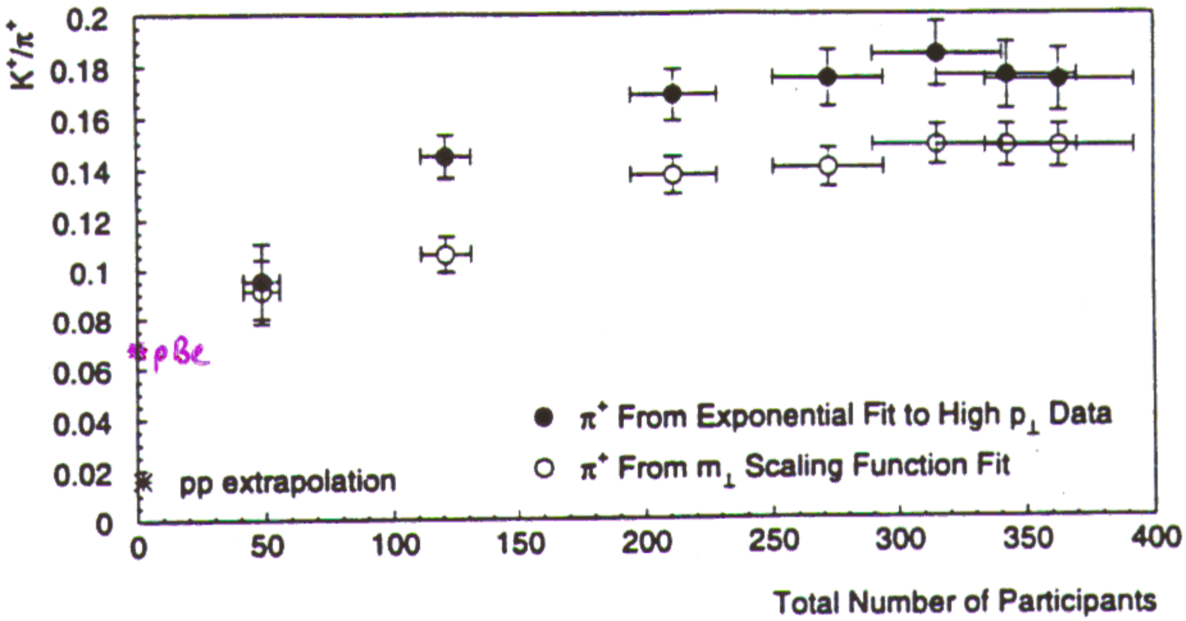
use integrated data (y, p_t)

central Si(Au) + Au collisions at the AGS



central Au + Au collisions at 11.6 A GeV/c

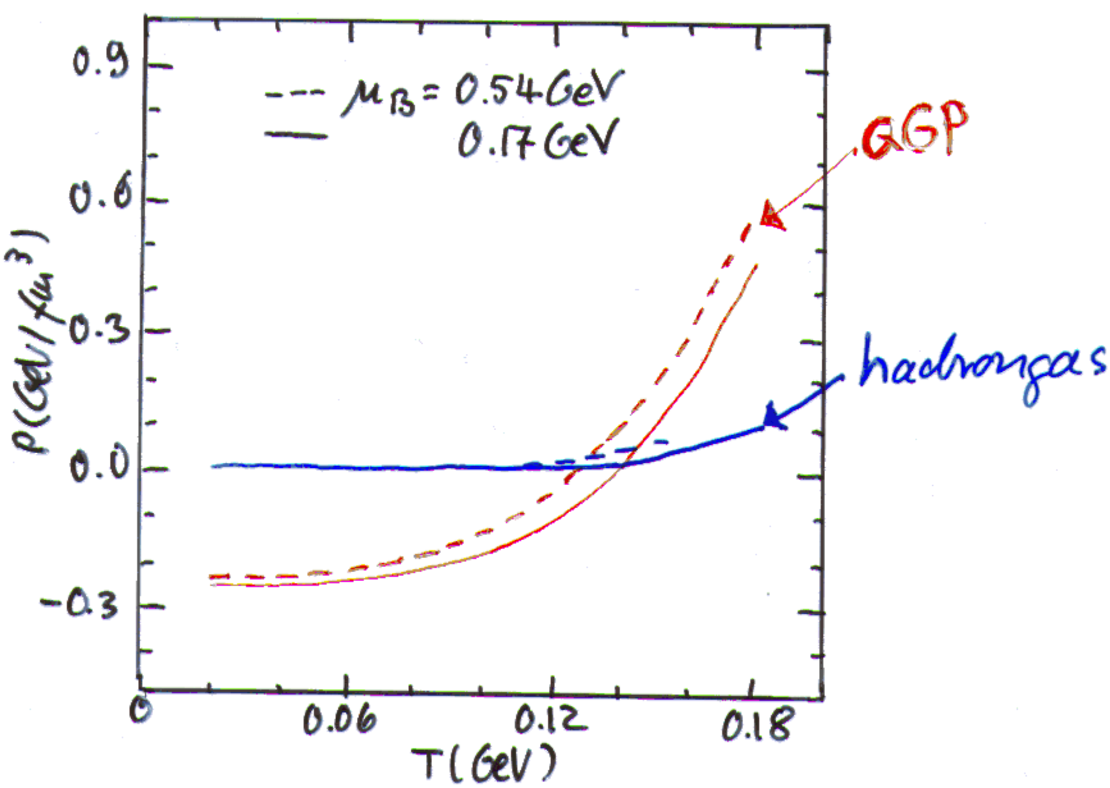
F. Wang, E866 coll.



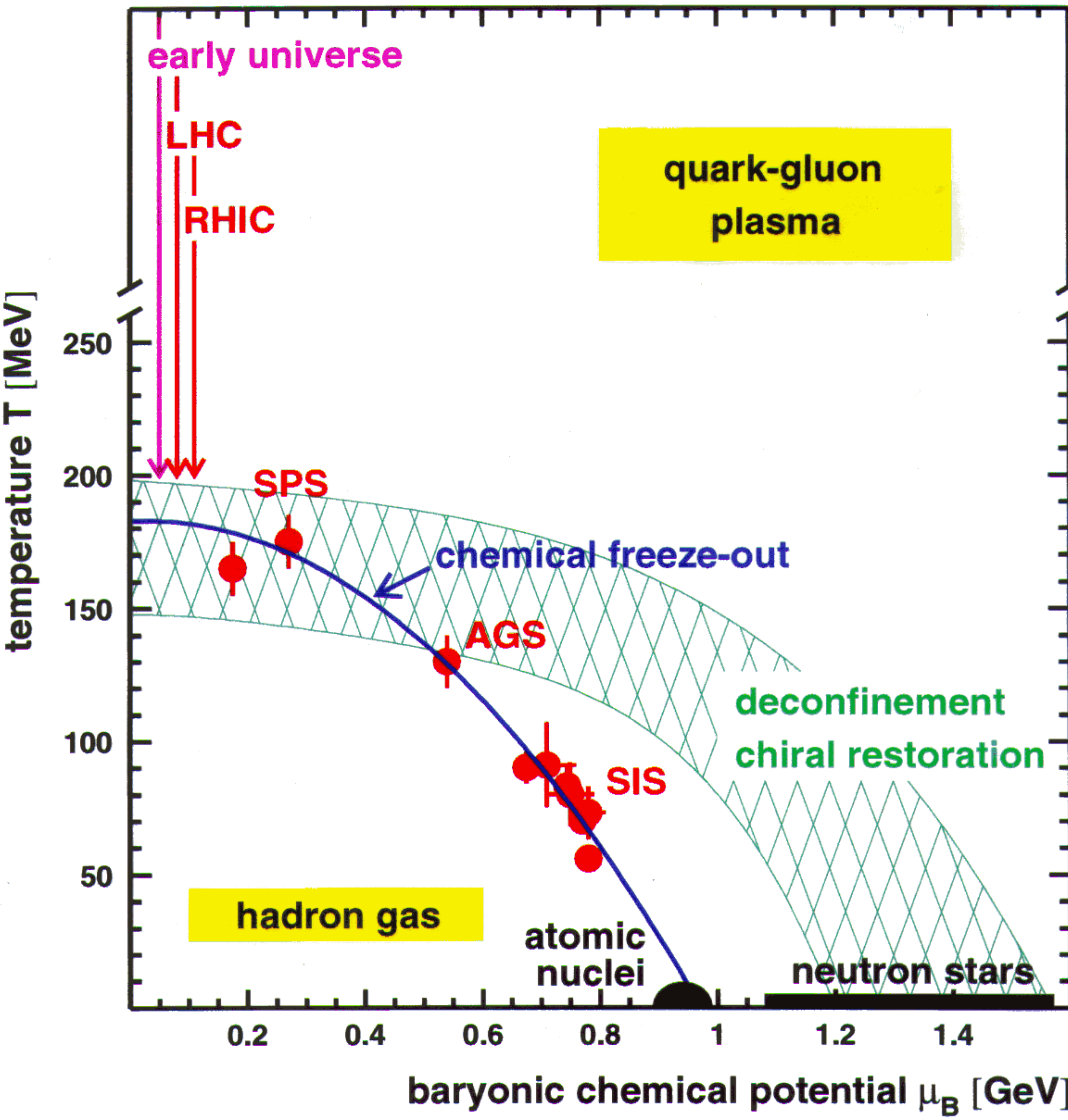
Constructing the Phase Transition

- Hadron gas containing all known states up to 2 GeV
- ideal gas of quarks and gluons
  u, d massless ; s 150 MeV
- fix bag constant to reproduce lattice result at $\mu_B = 0$ ⤳ $B = 262$ MeV/fm^3

⇨ calculate $p(\mu_B, T)$ pressure & μ_B continuous
⤳ T_c

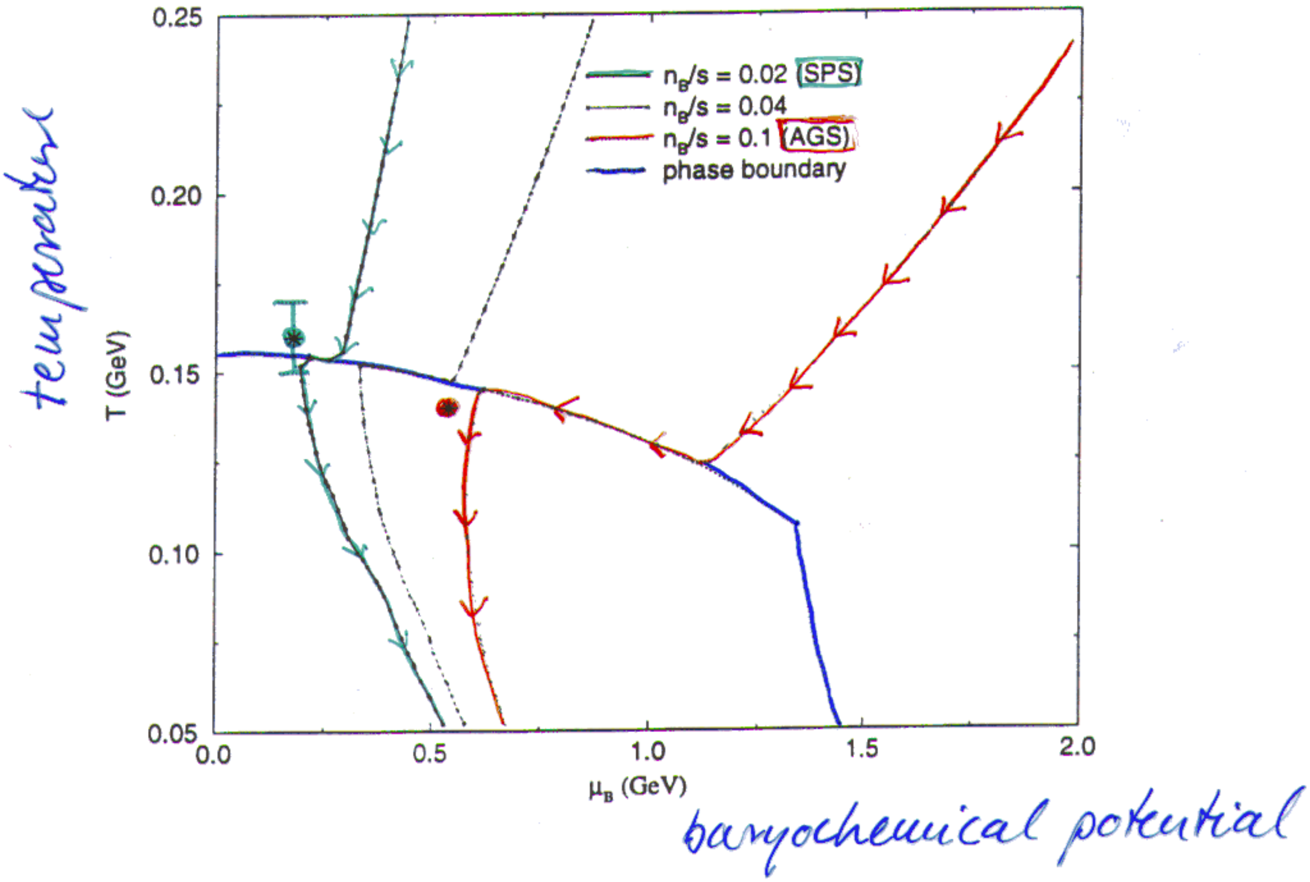


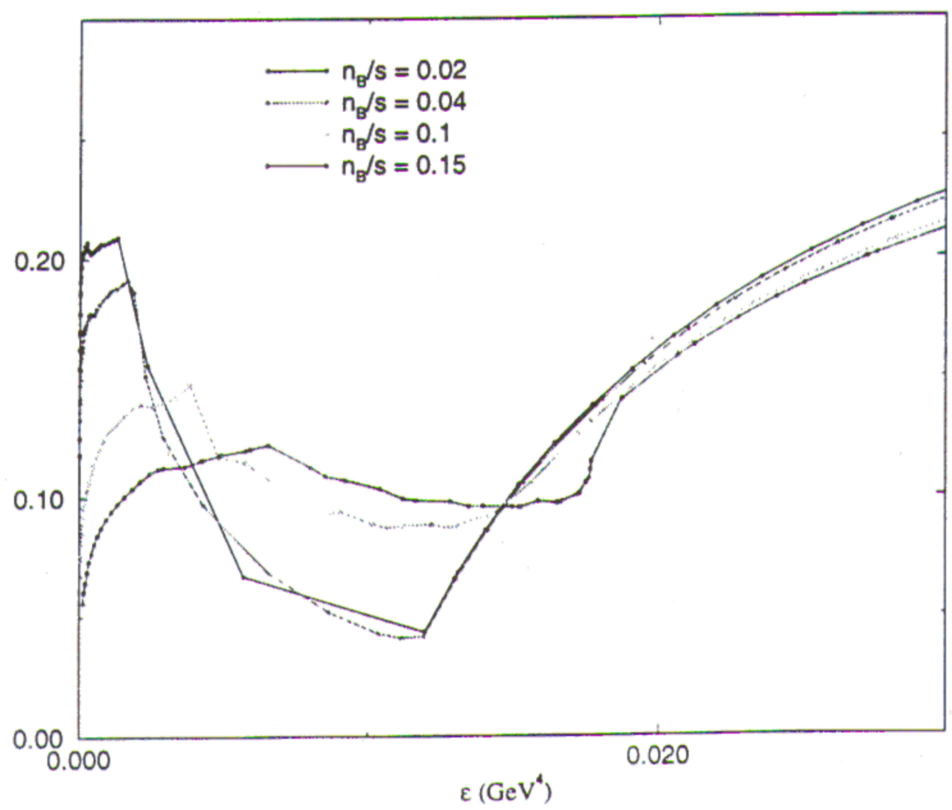
P. Braun-Munzinger & J. Stachel, Nucl. Phys. A606 (1996) 320



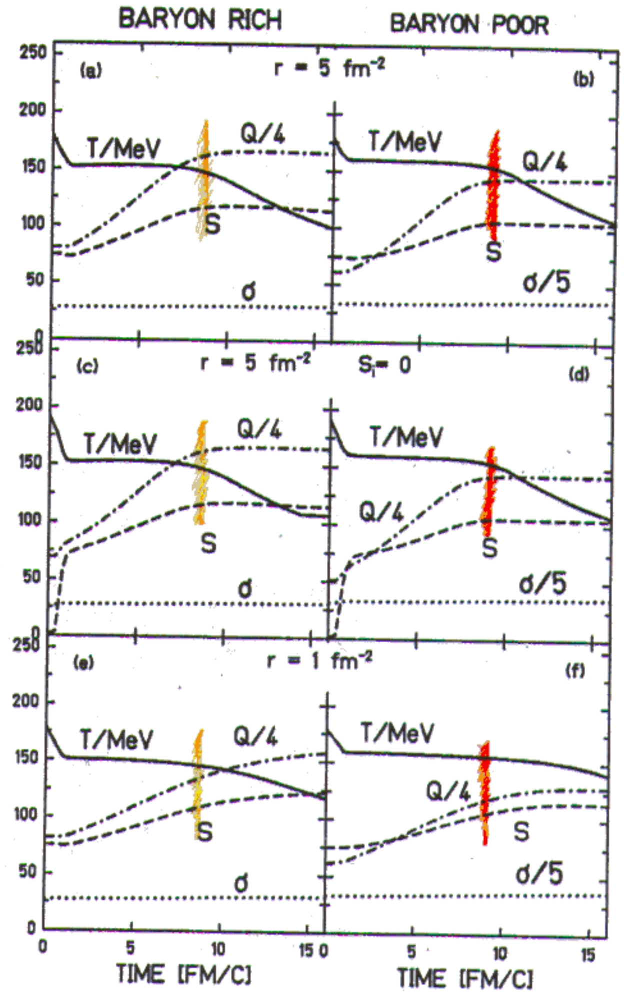
early universe
LHC
RHIC
quark-gluon plasma
SPS
chemical freeze-out
AGS
deconfinement
chiral restoration
SIS
hadron gas
atomic nuclei
neutron stars
temperature T [MeV]
250
200
150
100
50
0.2
0.4
0.6
0.8
1
1.2
1.4
baryonic chemical potential μ_B [GeV]

Phase Diagram and Hydrodynamic Evolution (E.V. Shuryak, Hirschegg 1997)

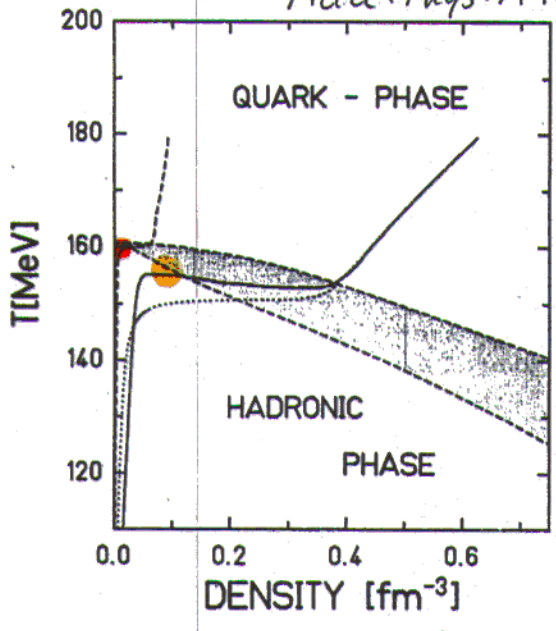




Barz, Friman, Knoll, Schulz 1988/89



Nucl. Phys. A 484, 661 (1988)



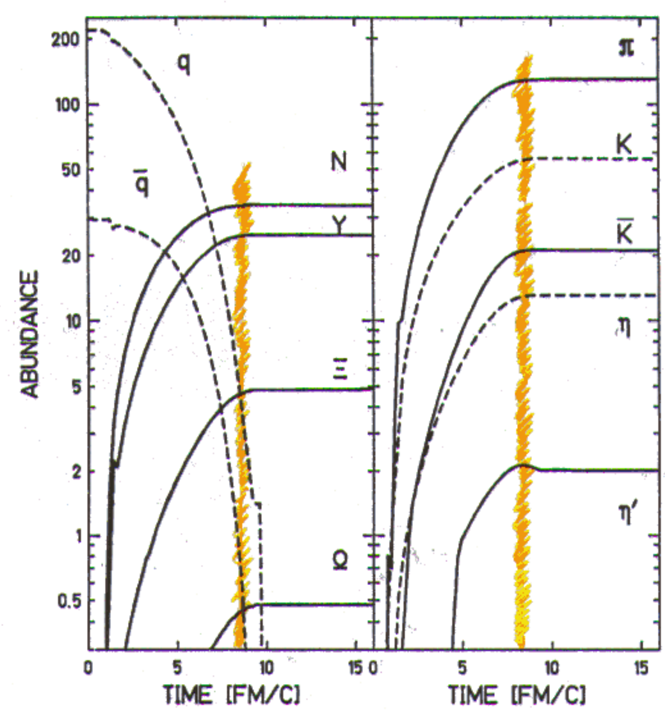
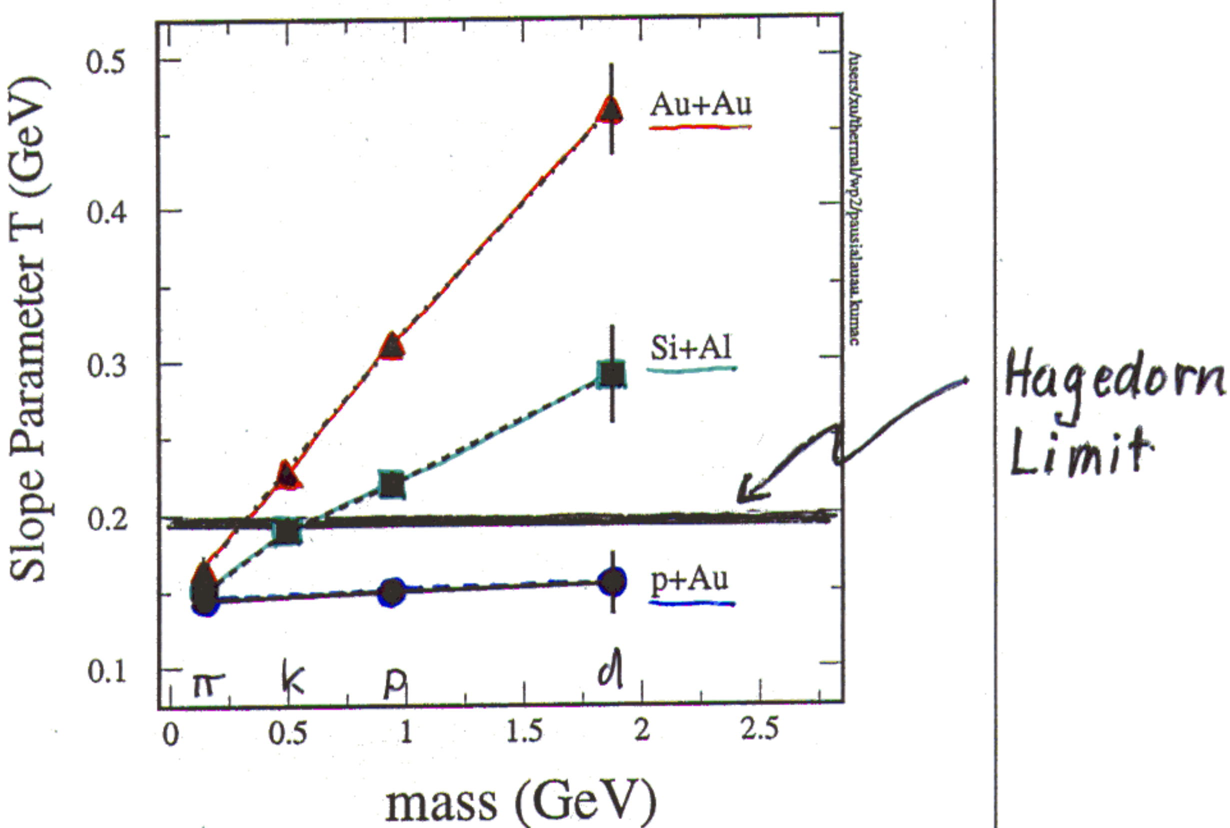


Fig. 4. Time evolution of the number of unbound quarks q, unbound antiquarks q̄, mesons and baryons of an initial plasma of volume $V_0 = 100\ \mathrm{fm}^3$, baryon number density $0.63\ \mathrm{fm}^{-3}$ and temperature $T =$

Dependence of Slope Parameters on Particle Mass

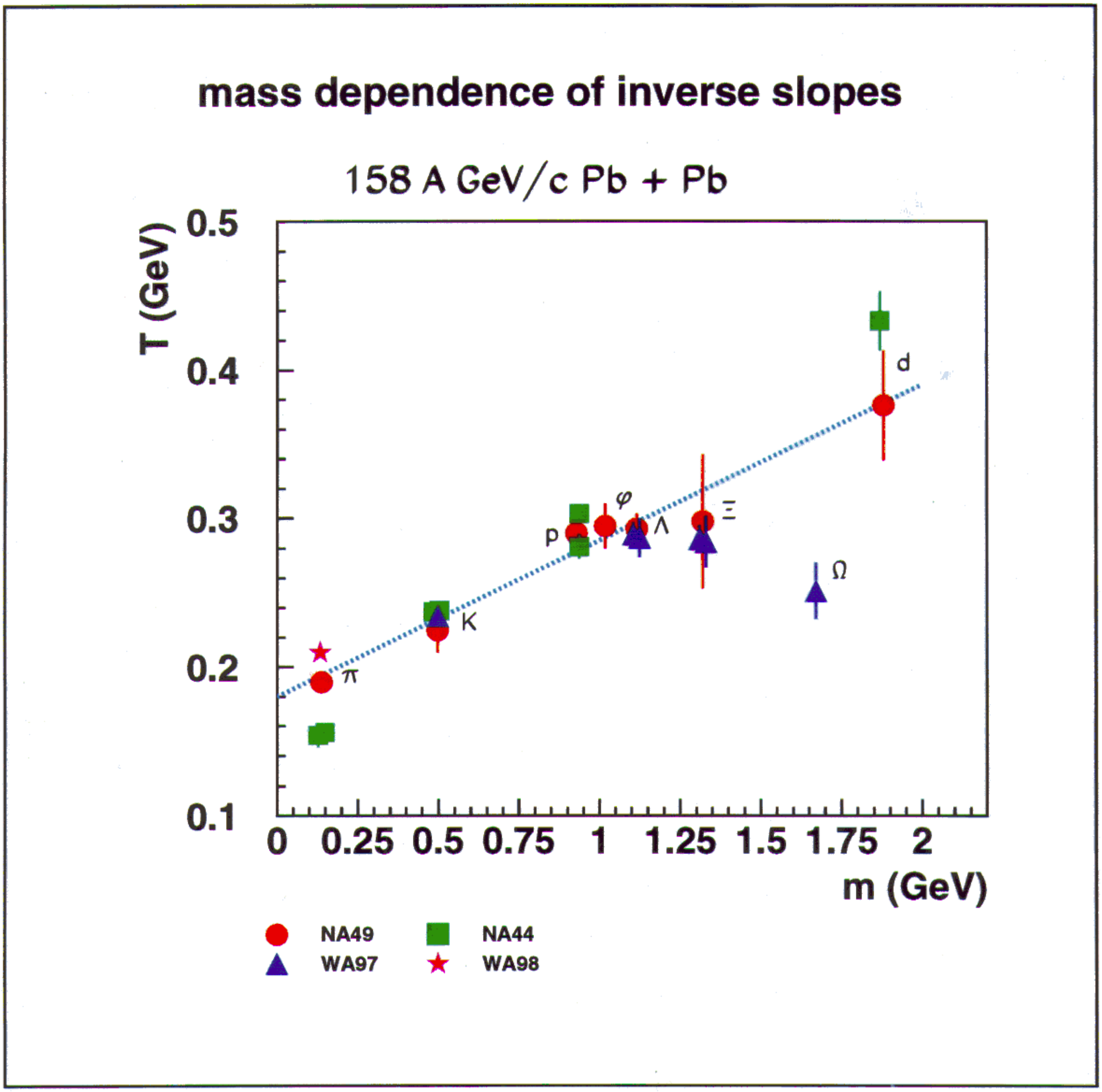


AGS { p+Au 14.6AGeV/c
Si+Al 14.6AGeV/c
Au+Au 11.6AGeV/c

Z.Chen for E802/E859/E866 Preliminary

$$T_{eff} = T \oplus \text{const.} \times m \cdot \beta^2$$

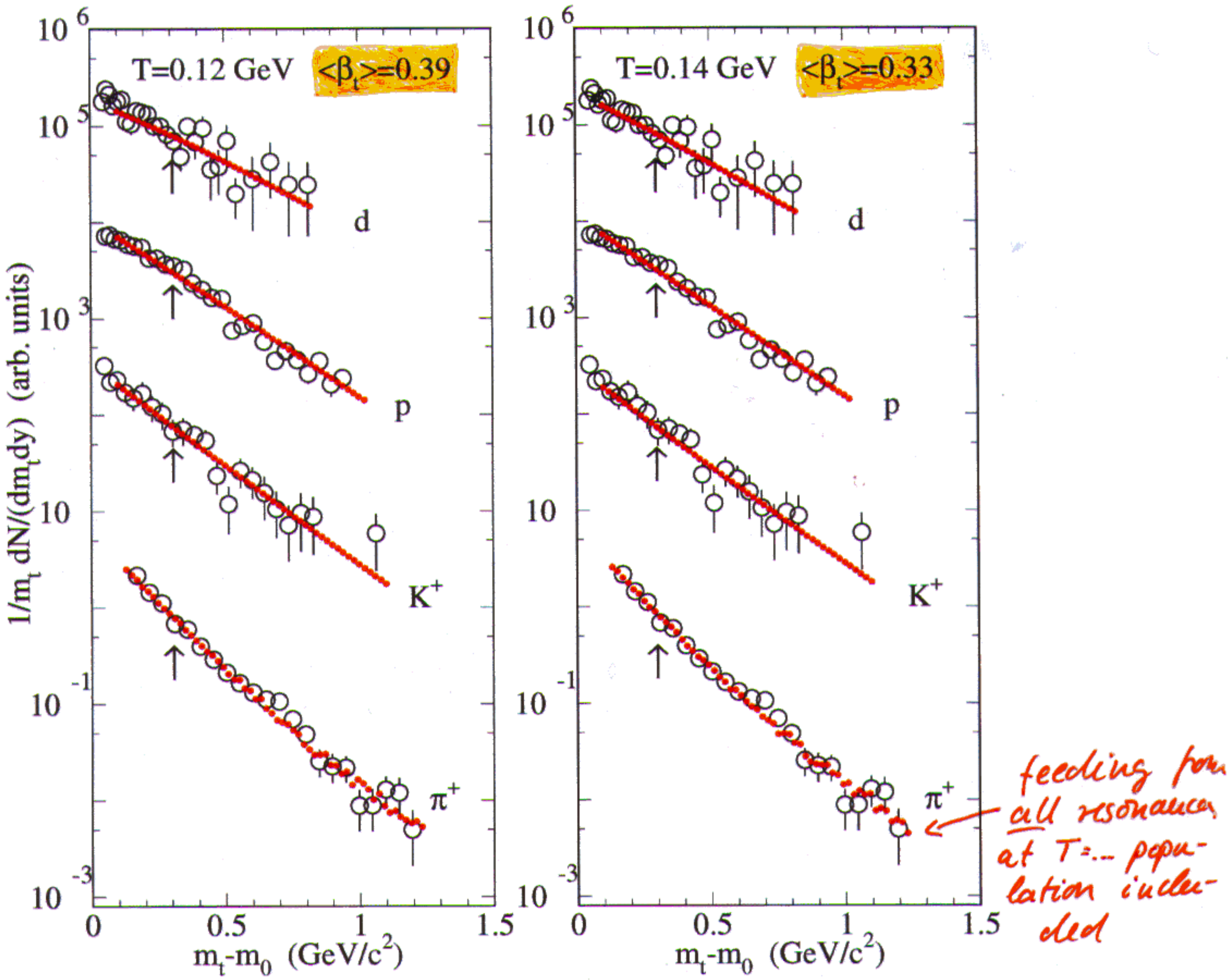
'collective expansion'



mass dependence of inverse slopes
158 A GeV/c Pb + Pb
T (GeV)
0.1
0.2
0.3
0.4
0.5
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
m (GeV)
π
K
p
φ
Λ
Ξ
Ω
d
NA49
NA44
WA97
WA98

Transverse Mass Spectra from Si+Au at Midrapidity

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, **PLB 344** (95) 43
Data from E802

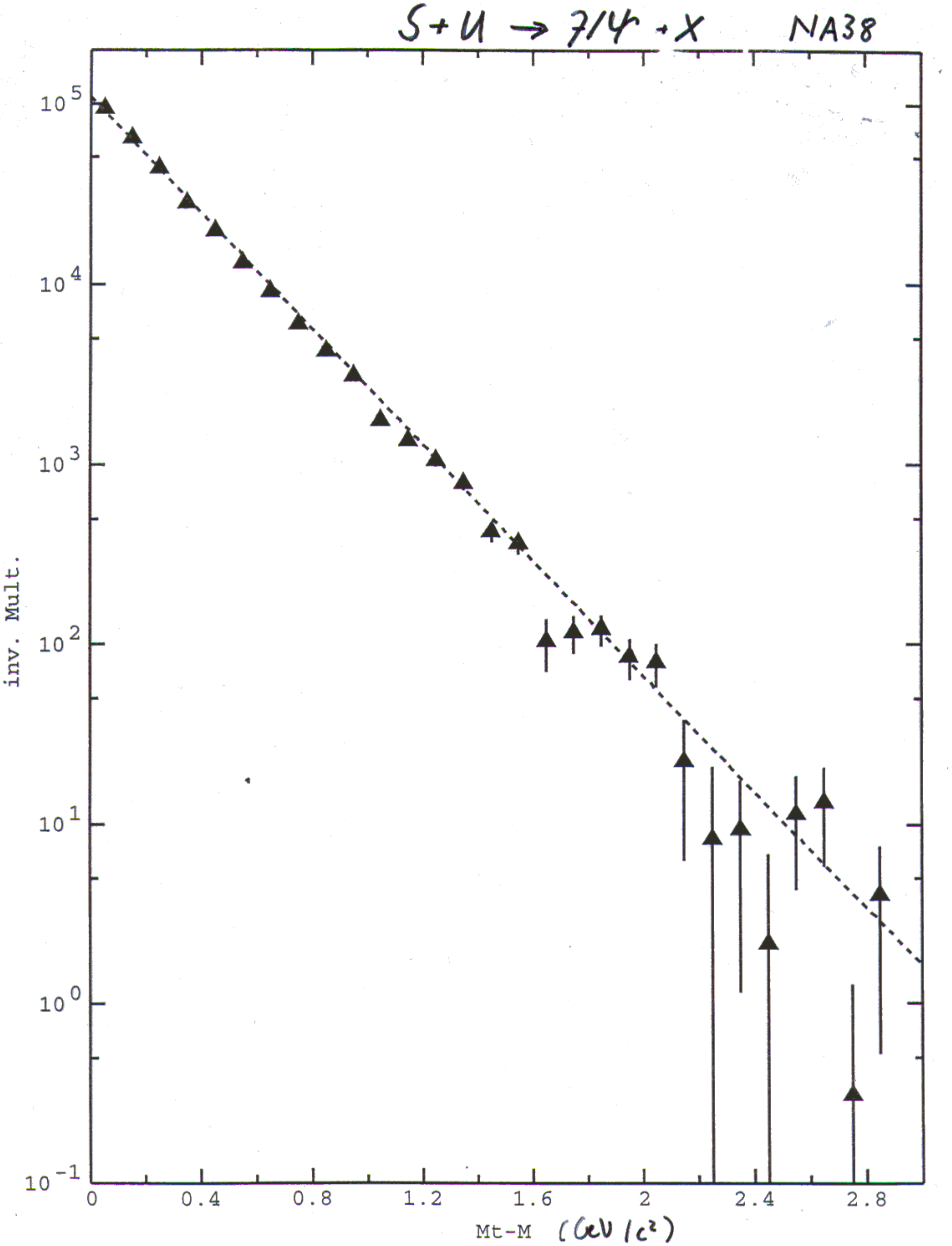


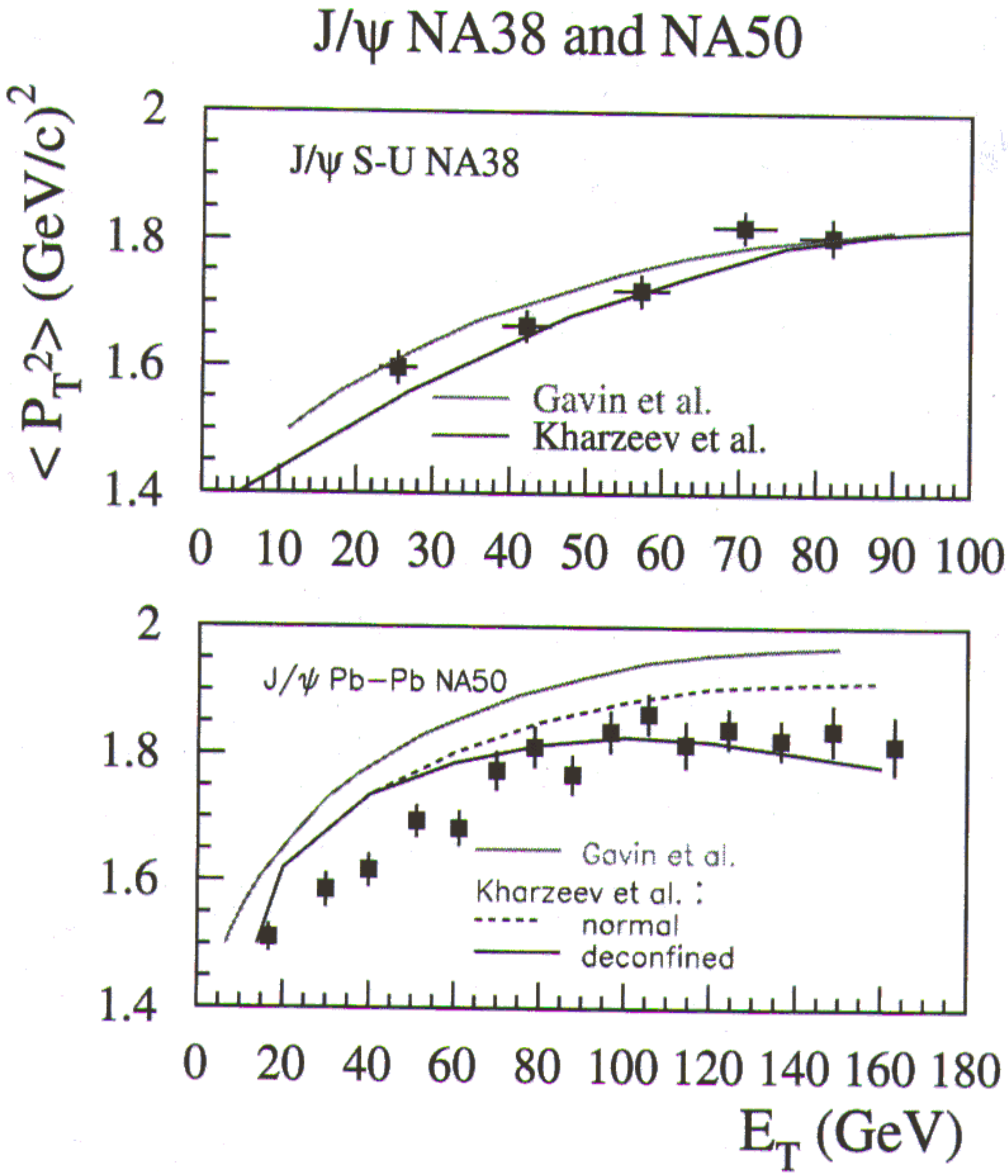
$$\frac{dN}{m_t dm_t} \propto \int_0^R r dr\, m_t I_0\left(\frac{p_t \sinh(\varrho)}{T}\right) K_1\left(\frac{m_t \cosh(\varrho)}{T}\right)$$

$$\varrho = \tanh^{-1}(\beta_t) \qquad \beta_t(r) = \beta_t^{max}(r/R)$$

E. Schnedermann, J. Sollfrank, U. Heinz, **PRC50** (94) 1675

$T_B = 240$ MeV Boltzmann distr.
$T_0 = 270$ MeV m_t exp.



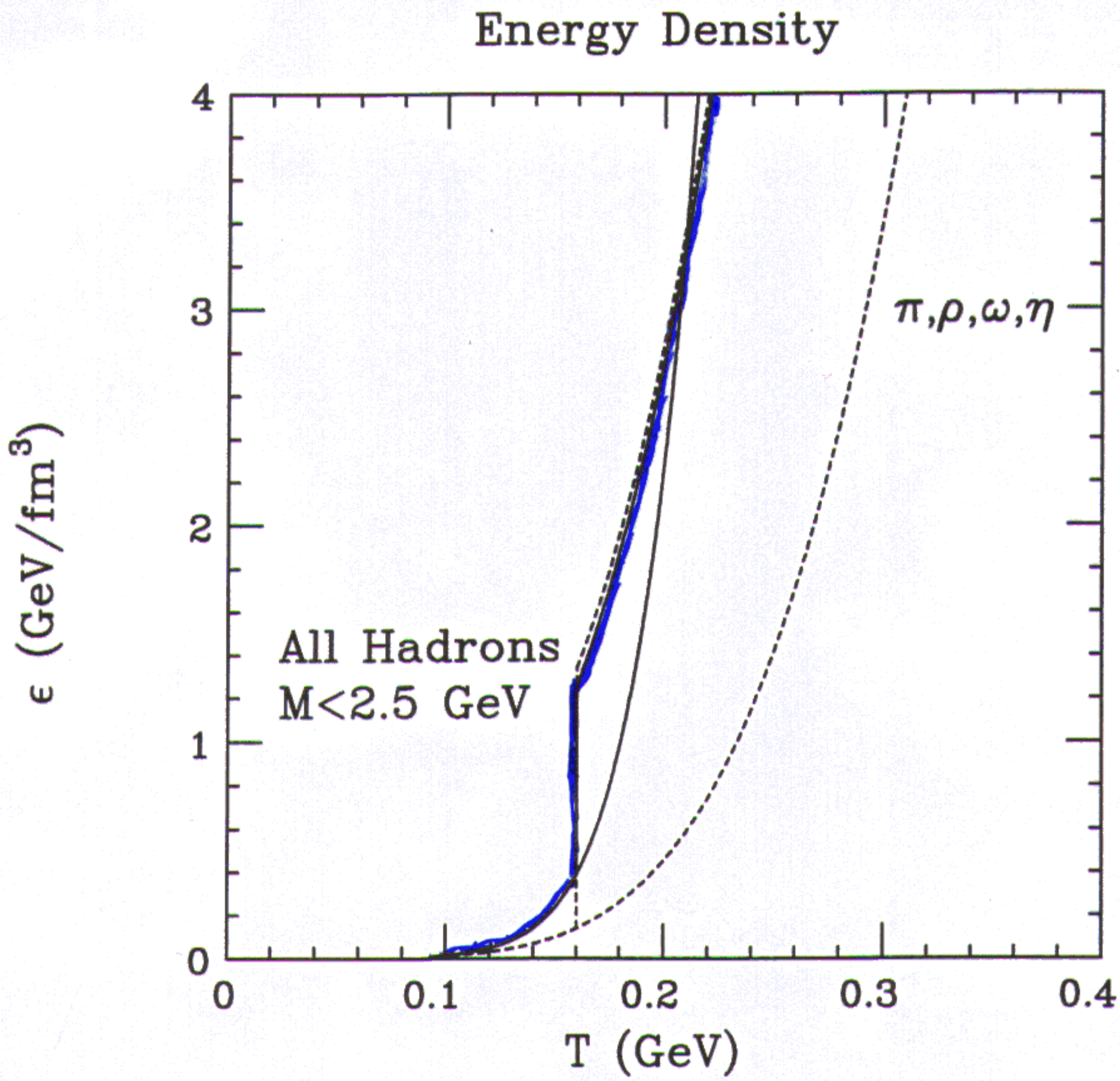


Gavin et al.: hep–ph/9610432

Kharzeev et al.: BI–TP 97/02

NA50

Cleymans, Redlich, Srivastava
nucl-th/9611047 Phys. Rev. C55 (1997) 1431



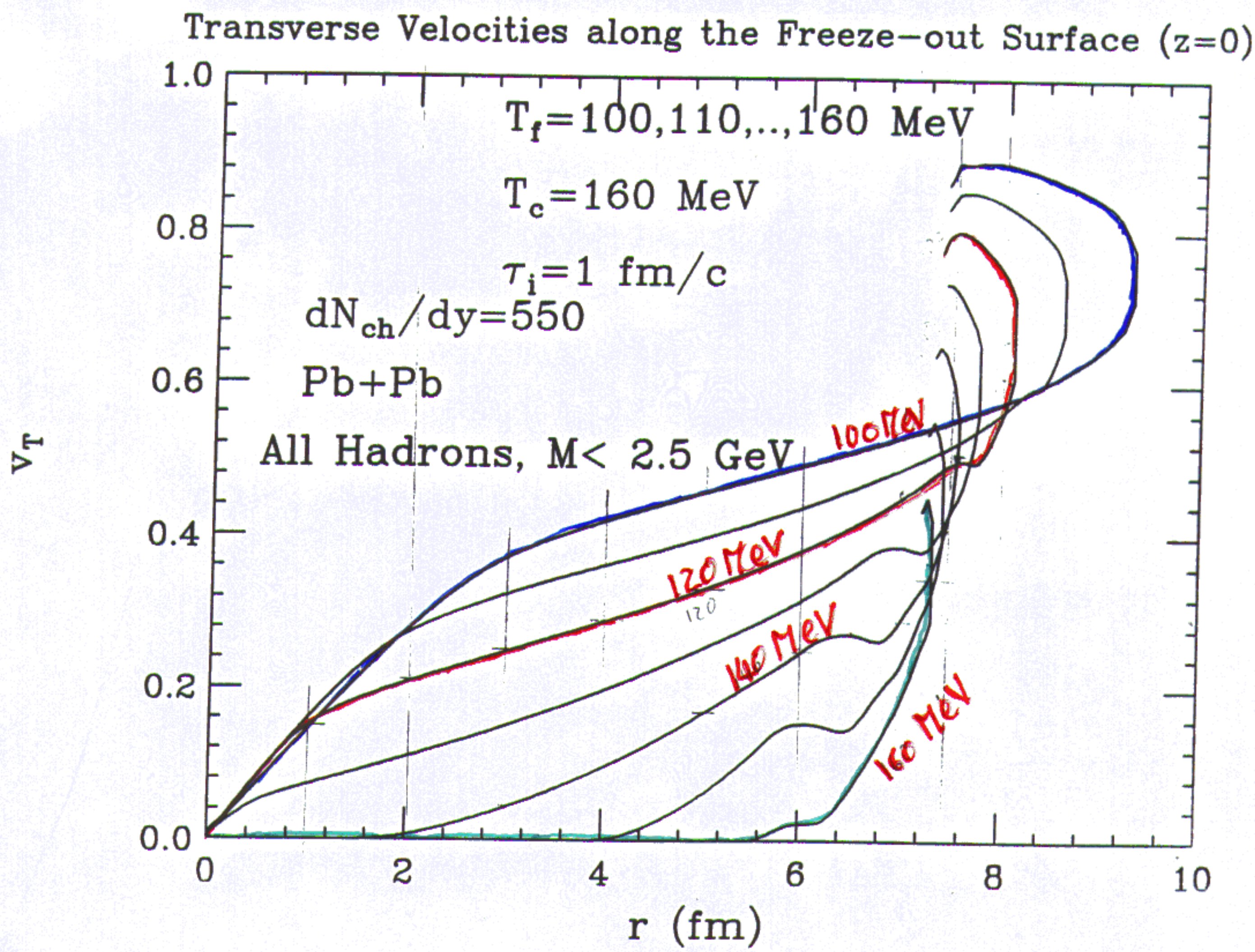
Hydrodynamic Evolution of System

Cleymans, Redlich, Srivastava, nucl-th/9611047

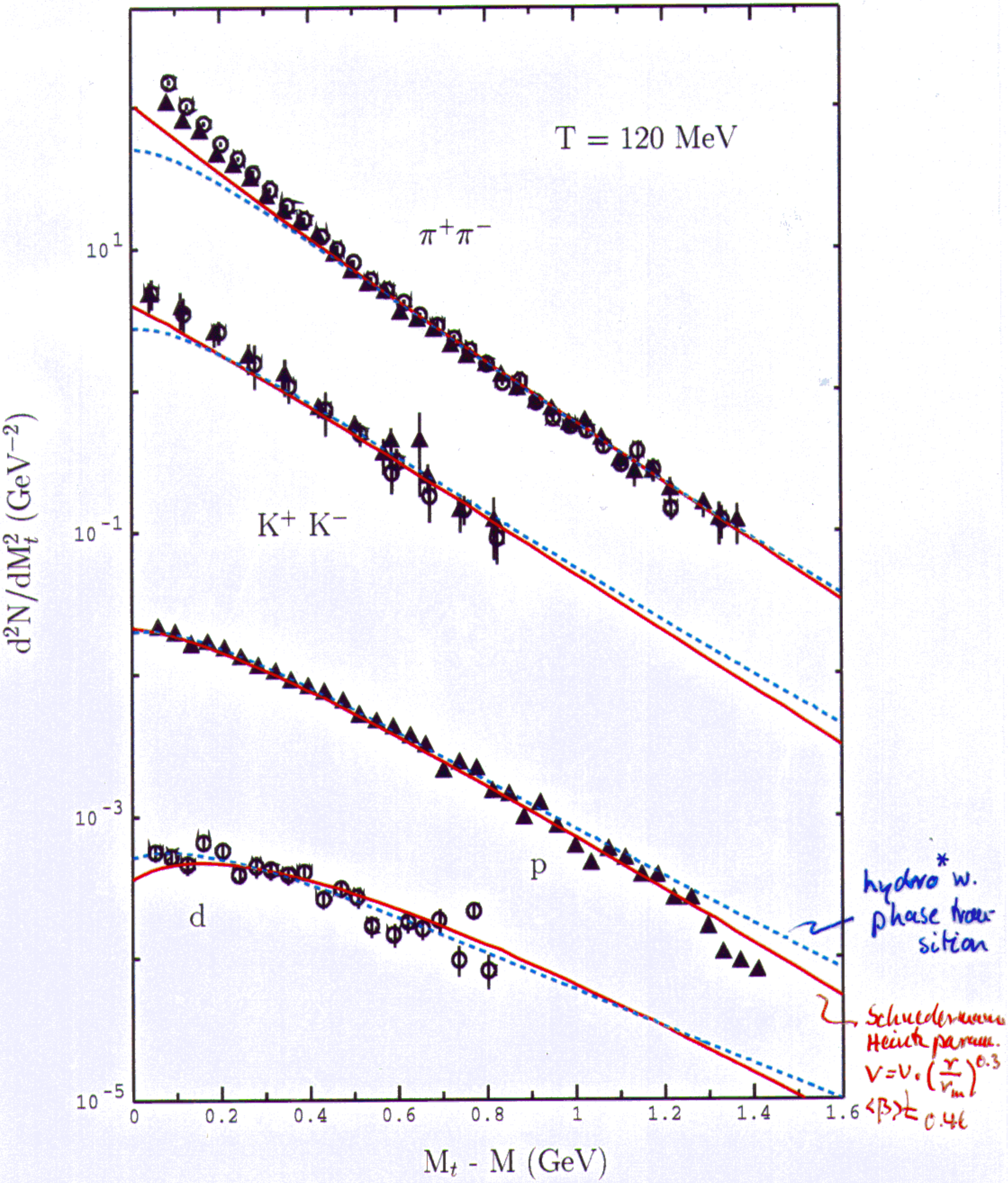
v^t Phys. Rev C55 (1997) 1431

transverse expansion velocity vs radius (time)

system undergoes first order phase transition at T_c = 160 MeV

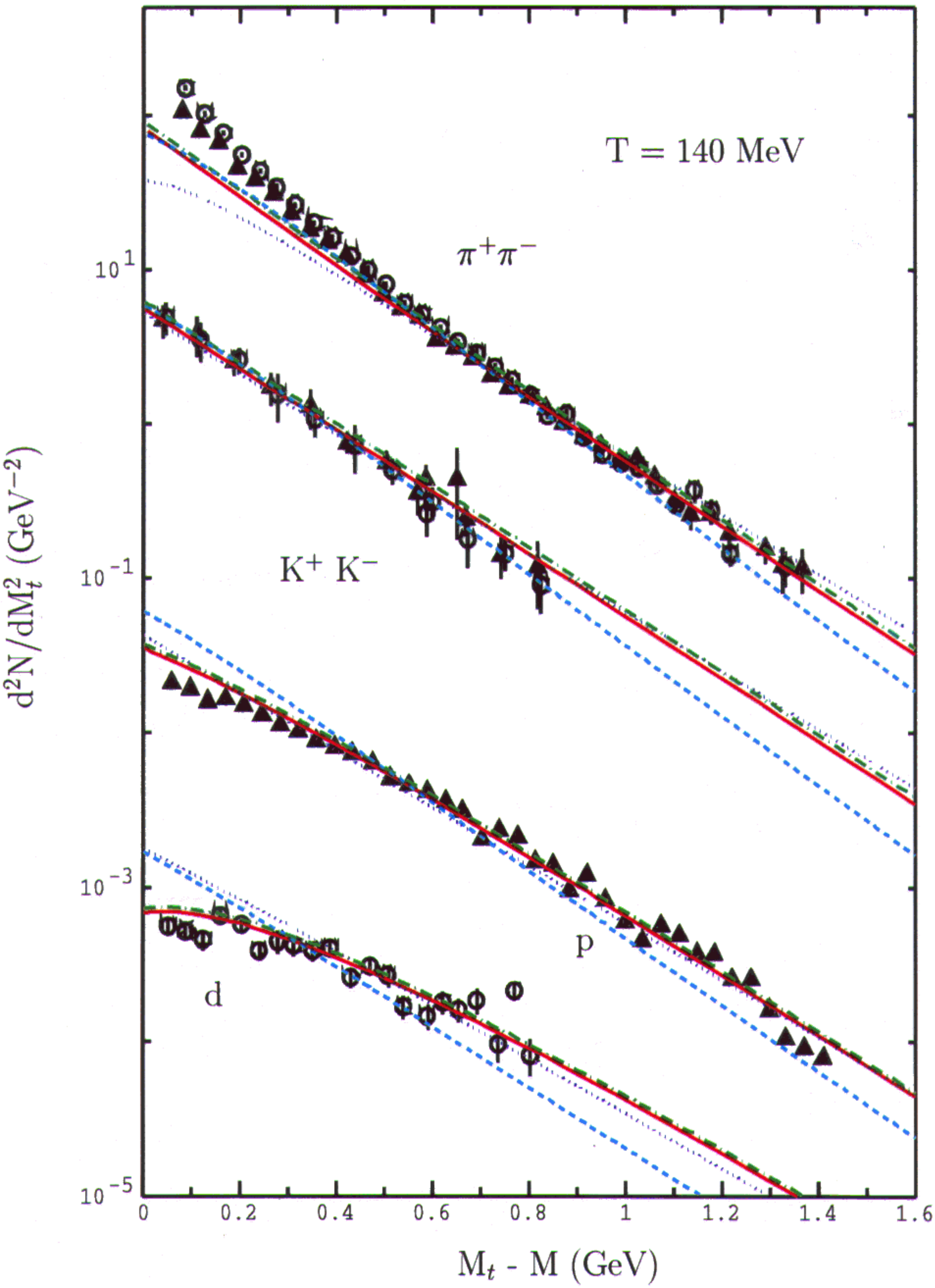


central 11 A GeV/c Au+Au at AGS



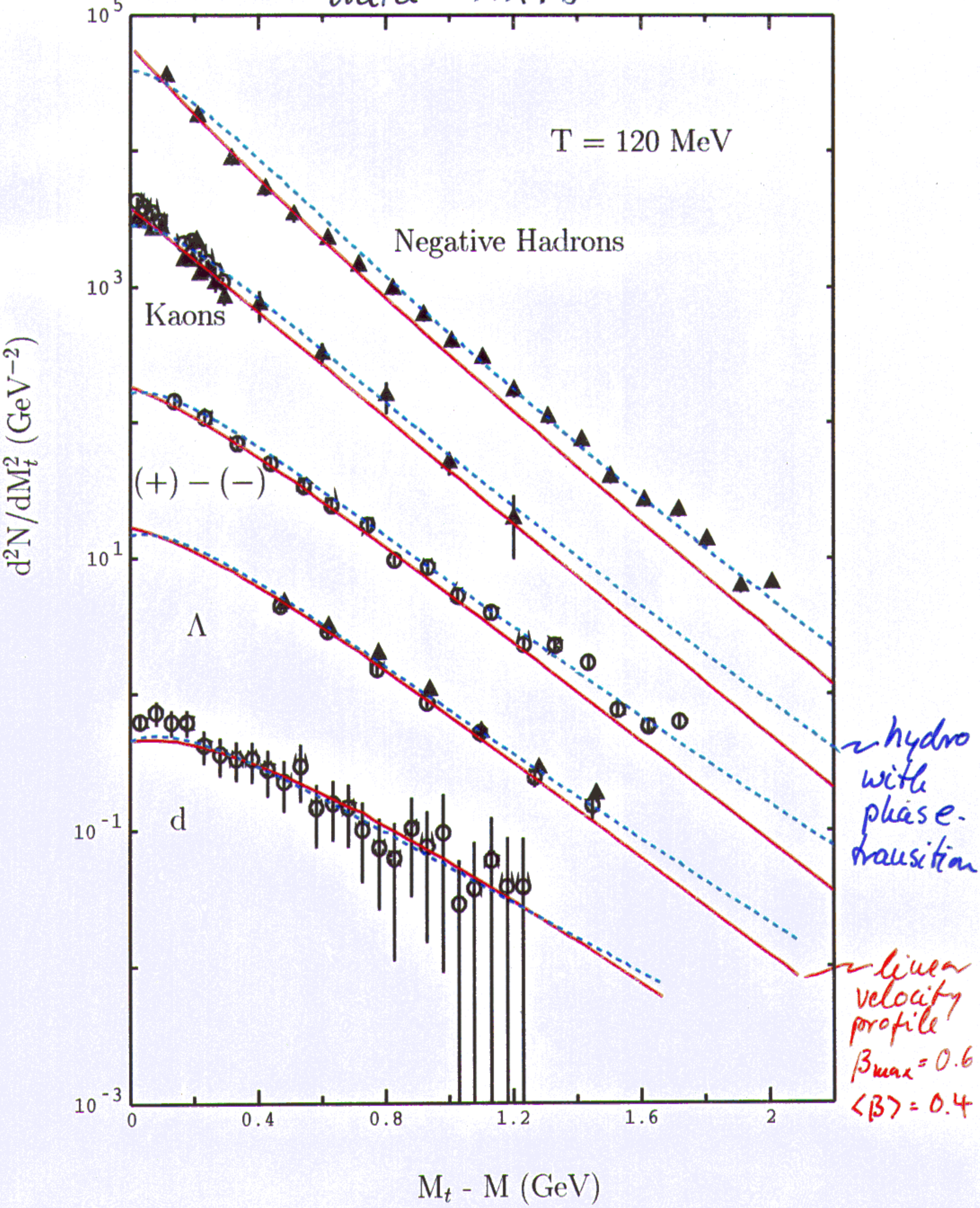
* velocity profile from Cleymans, Redlich, Srivastava Phys. Rev C58 (1997) 1431

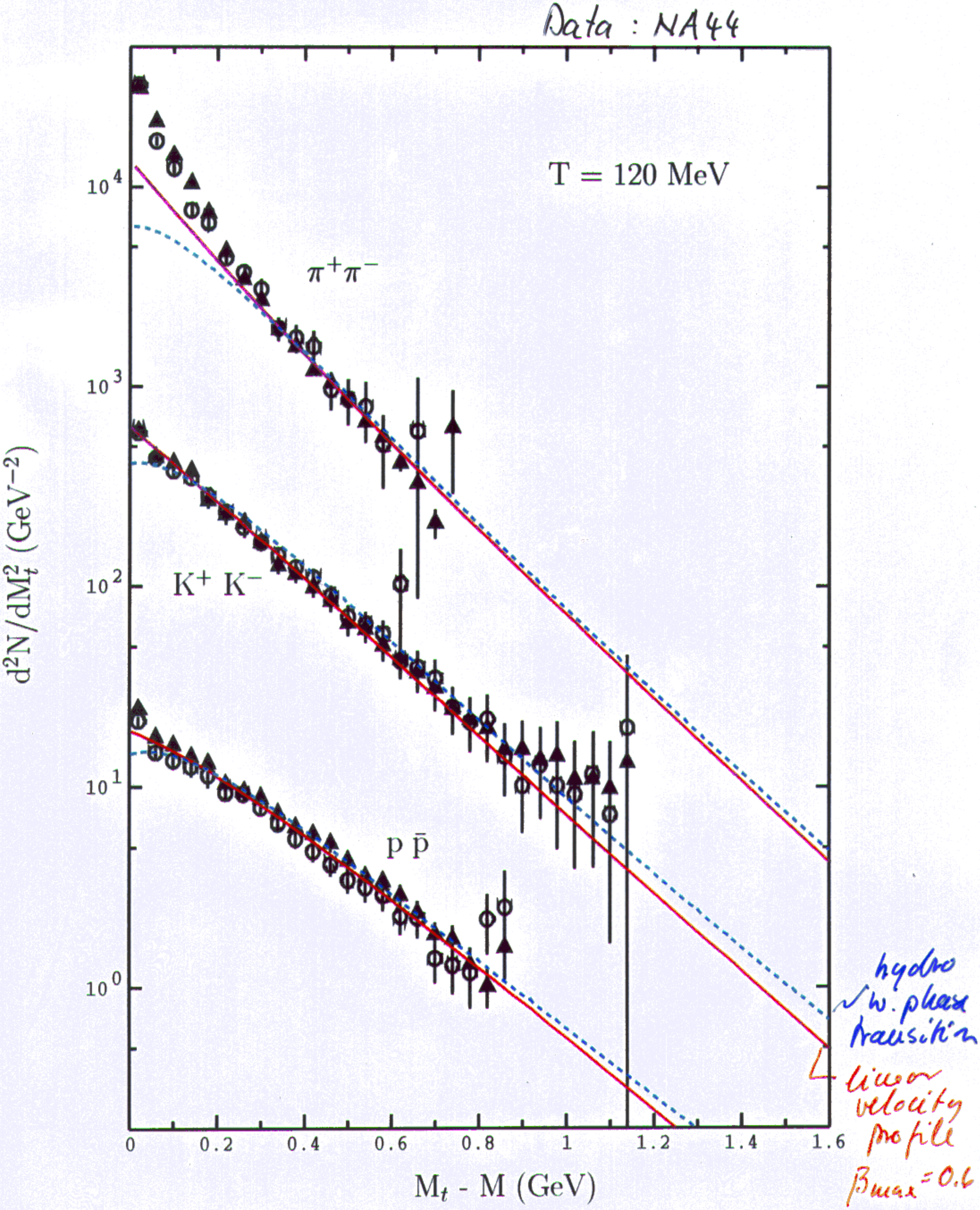
central 11 A GeV/c Au + Au AGS



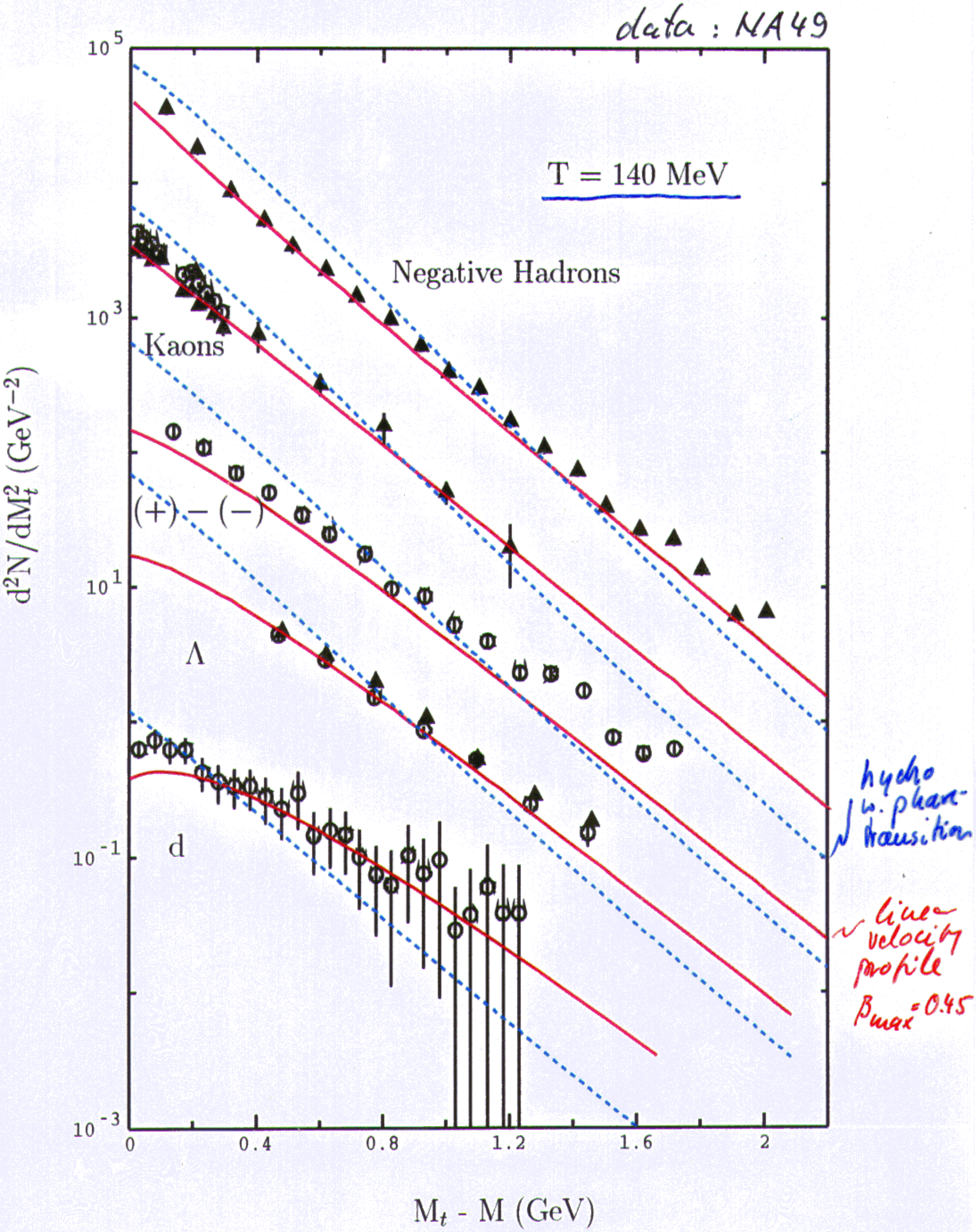
central 158 A GeV/c Pb+Pb at SPS

data : NA49



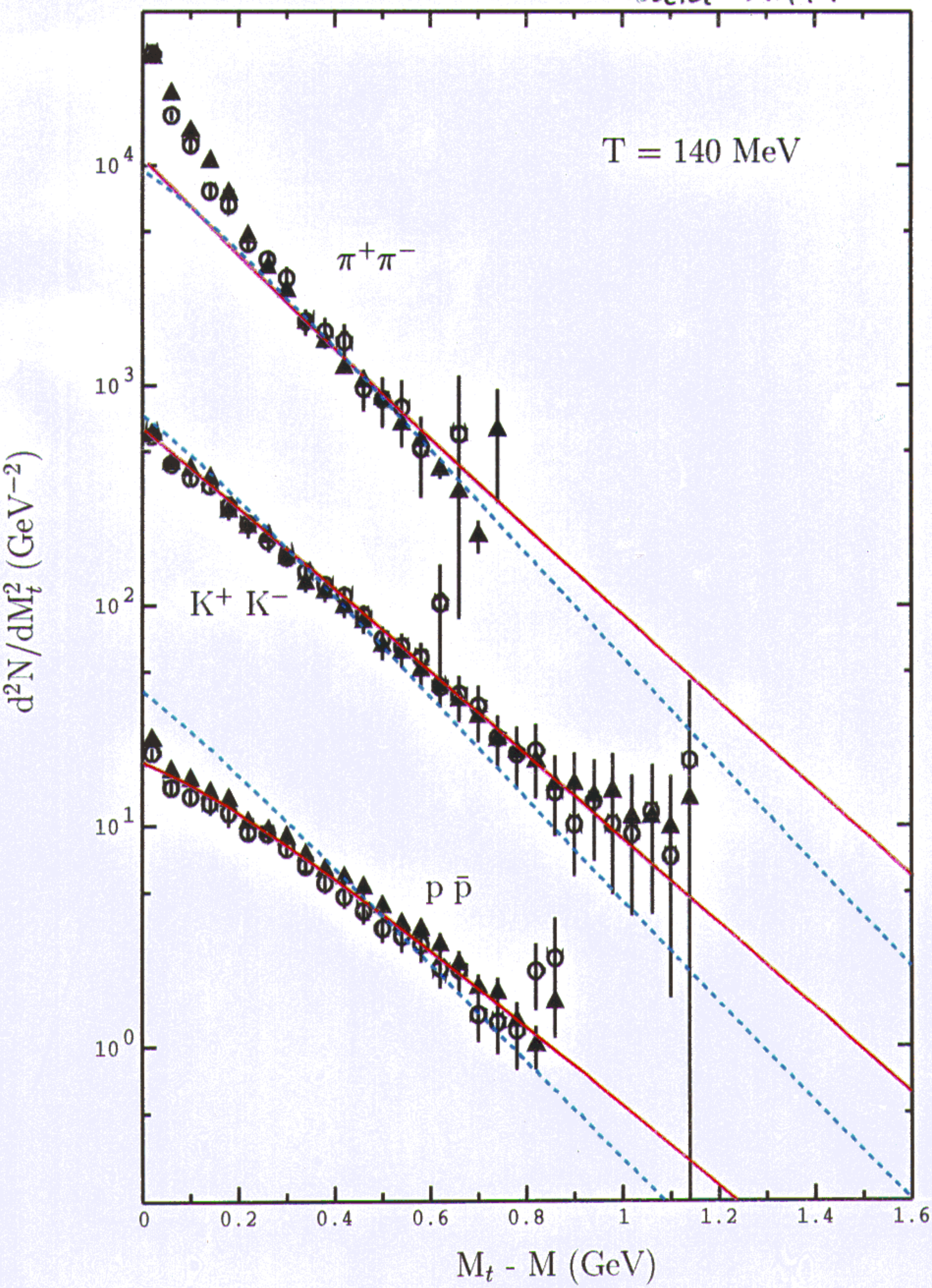


Data : NA44
T = 120 MeV
π⁺π⁻
K⁺ K⁻
p p̄
d²N/dM²ₜ (GeV⁻²)
Mₜ - M (GeV)
hydro w. phase transition
linear velocity profile βmax = 0.6

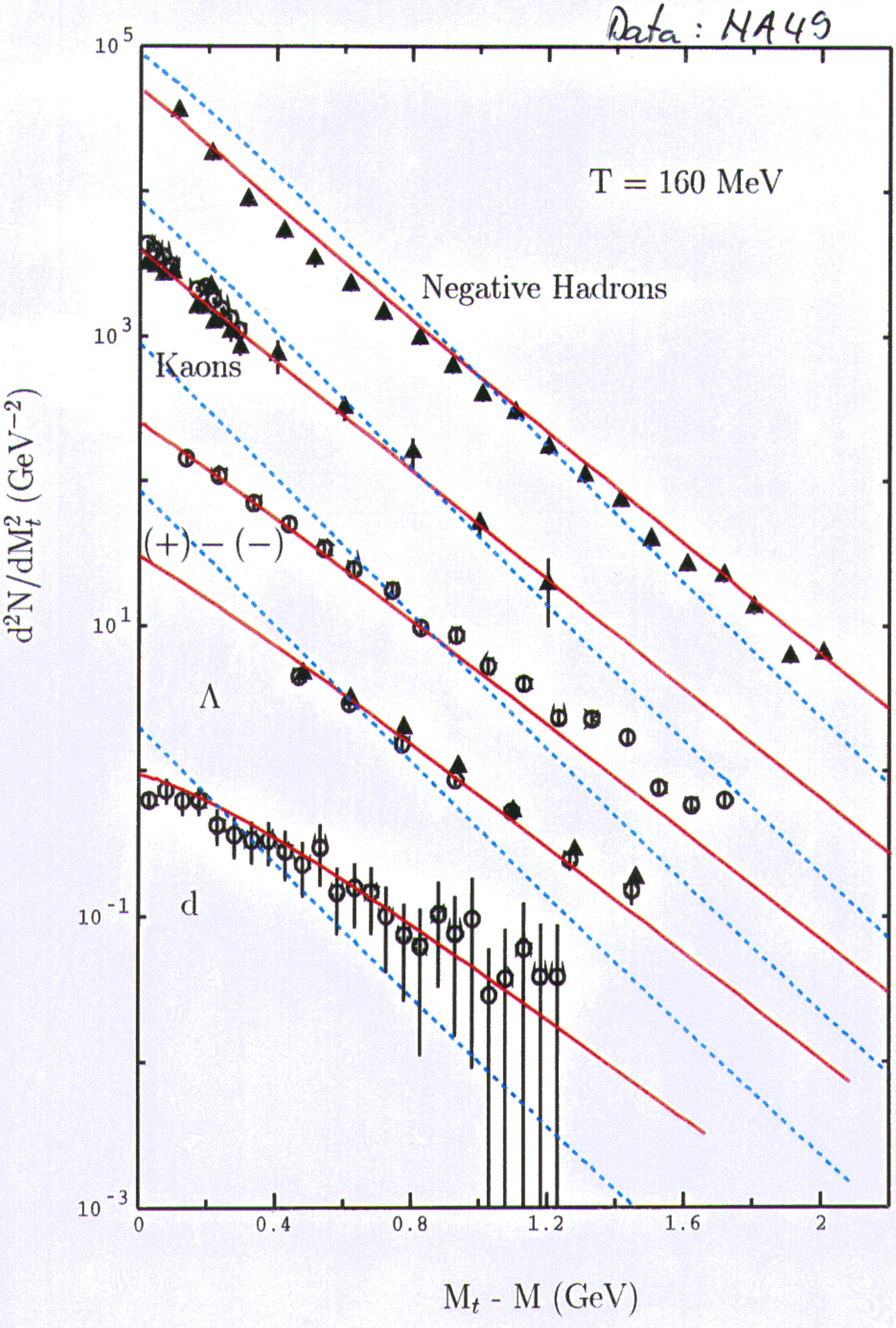


data : NA49
T = 140 MeV
Negative Hadrons
Kaons
(+) − (−)
Λ
d
d^2N/dM_t^2 (GeV^{-2})
M_t - M (GeV)
hydro w. phase-transition
linear velocity profile $\beta_{max}=0.45$

Data : NA44

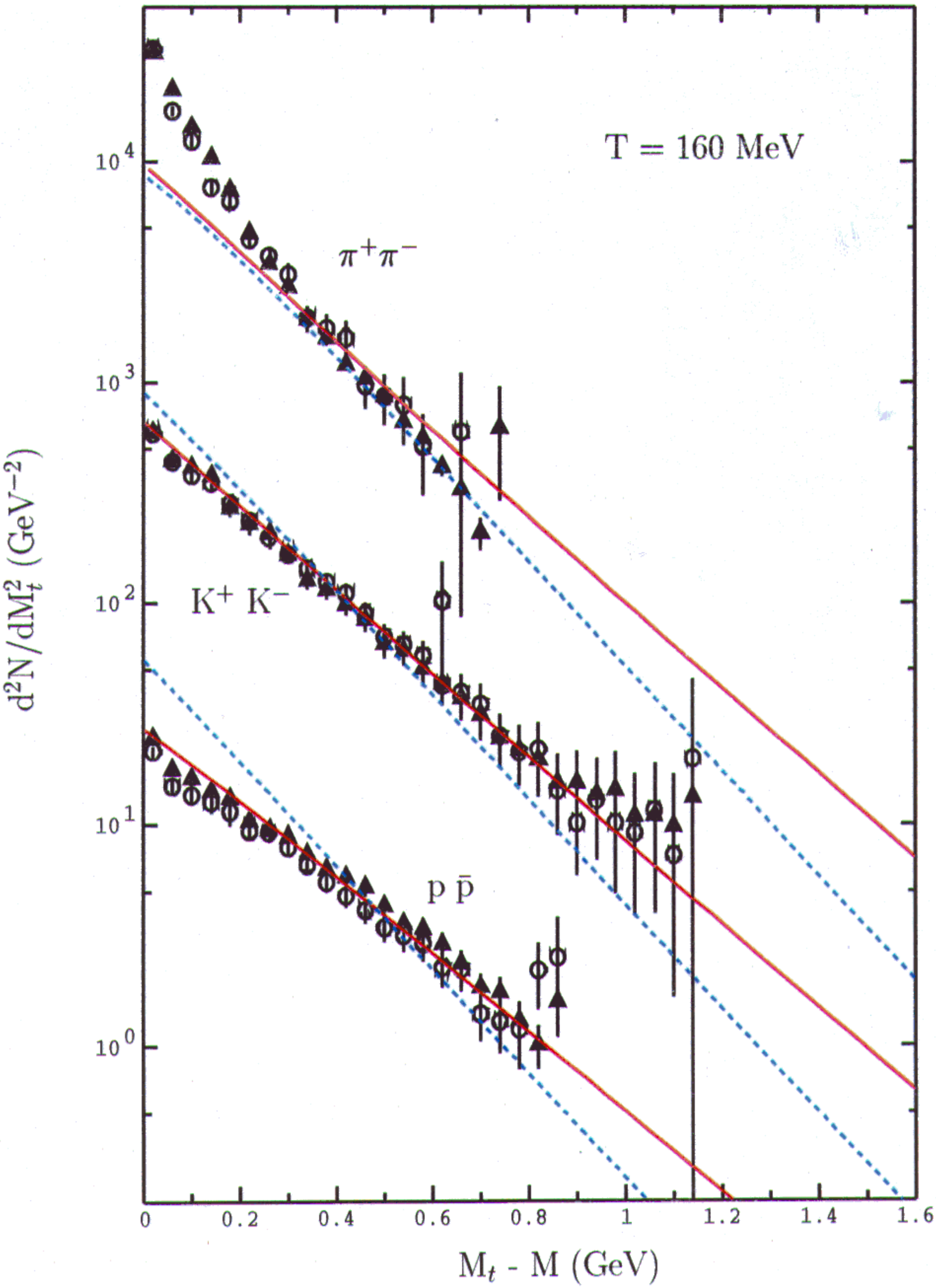


T = 140 MeV
$\pi^+\pi^-$
$K^+ K^-$
$p\ \bar{p}$
10^4
10^3
10^2
10^1
10^0
d^2N/dM_t^2 (GeV^{-2})
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
M_t - M (GeV)

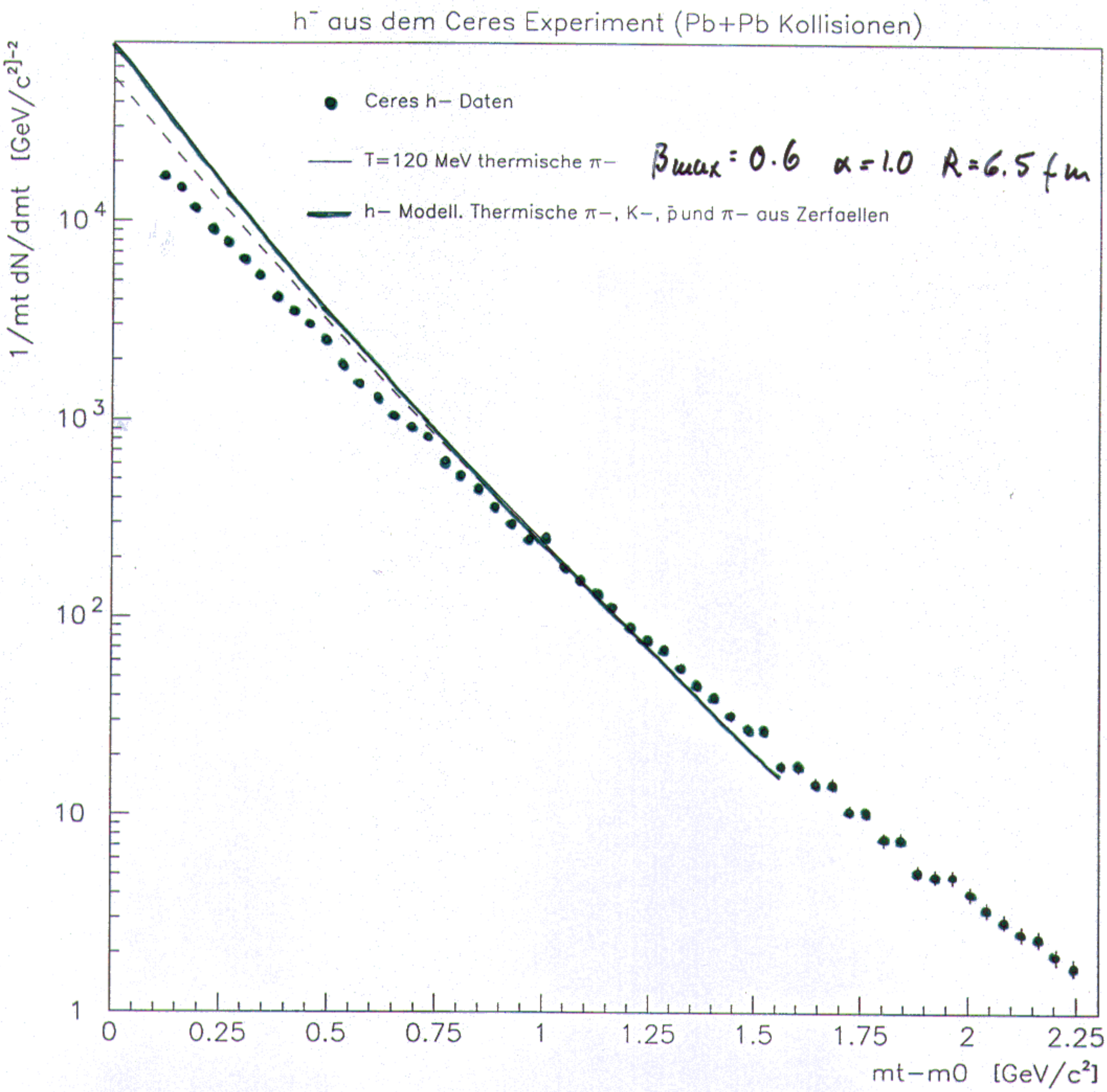


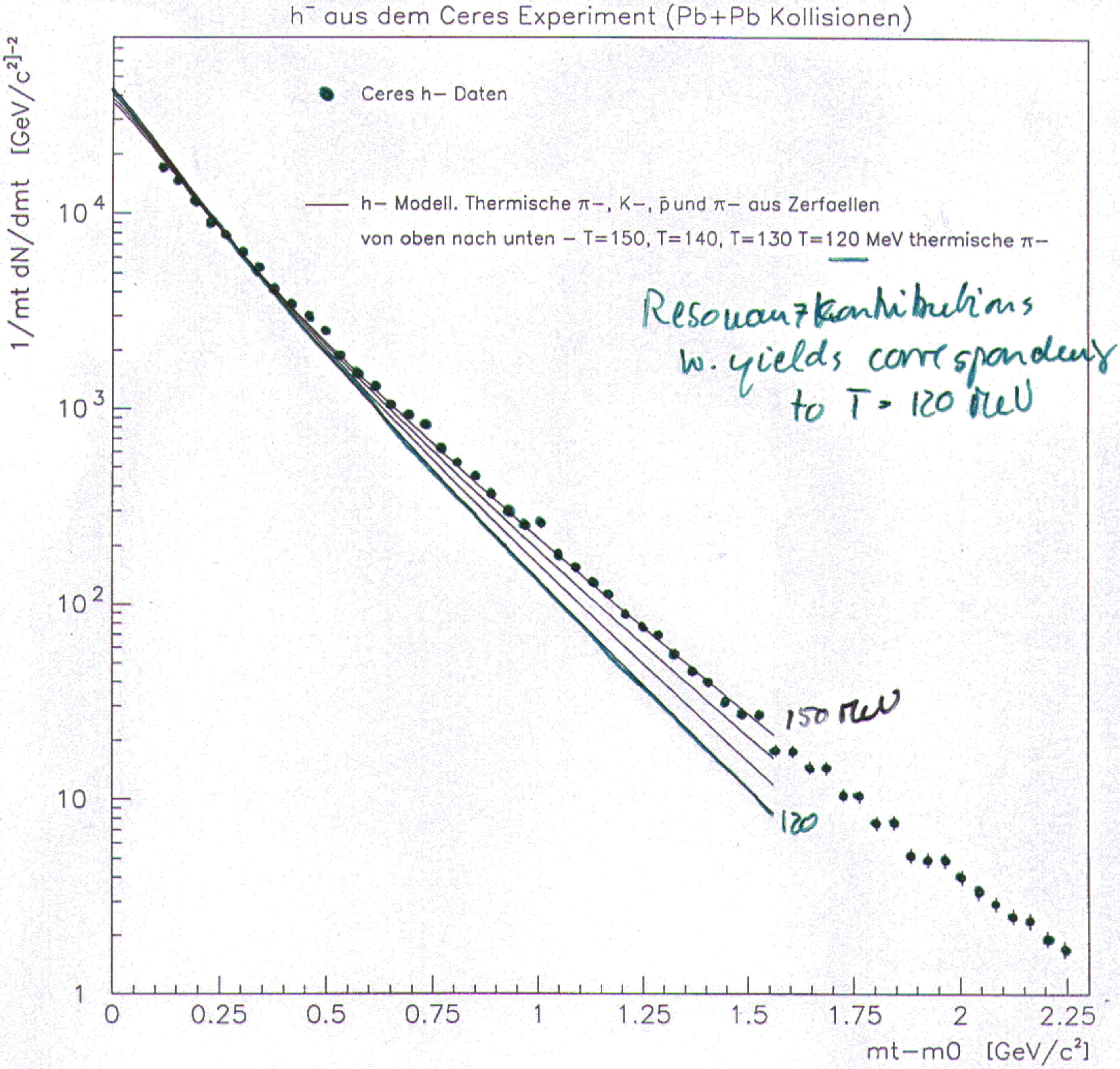
Data : NA49
T = 160 MeV
Negative Hadrons
Kaons
(+) − (−)
Λ
d
d²N/dM²_t (GeV⁻²)
M_t - M (GeV)
10^5
10^3
10^1
10^-1
10^-3
0
0.4
0.8
1.2
1.6
2

Data : NA44

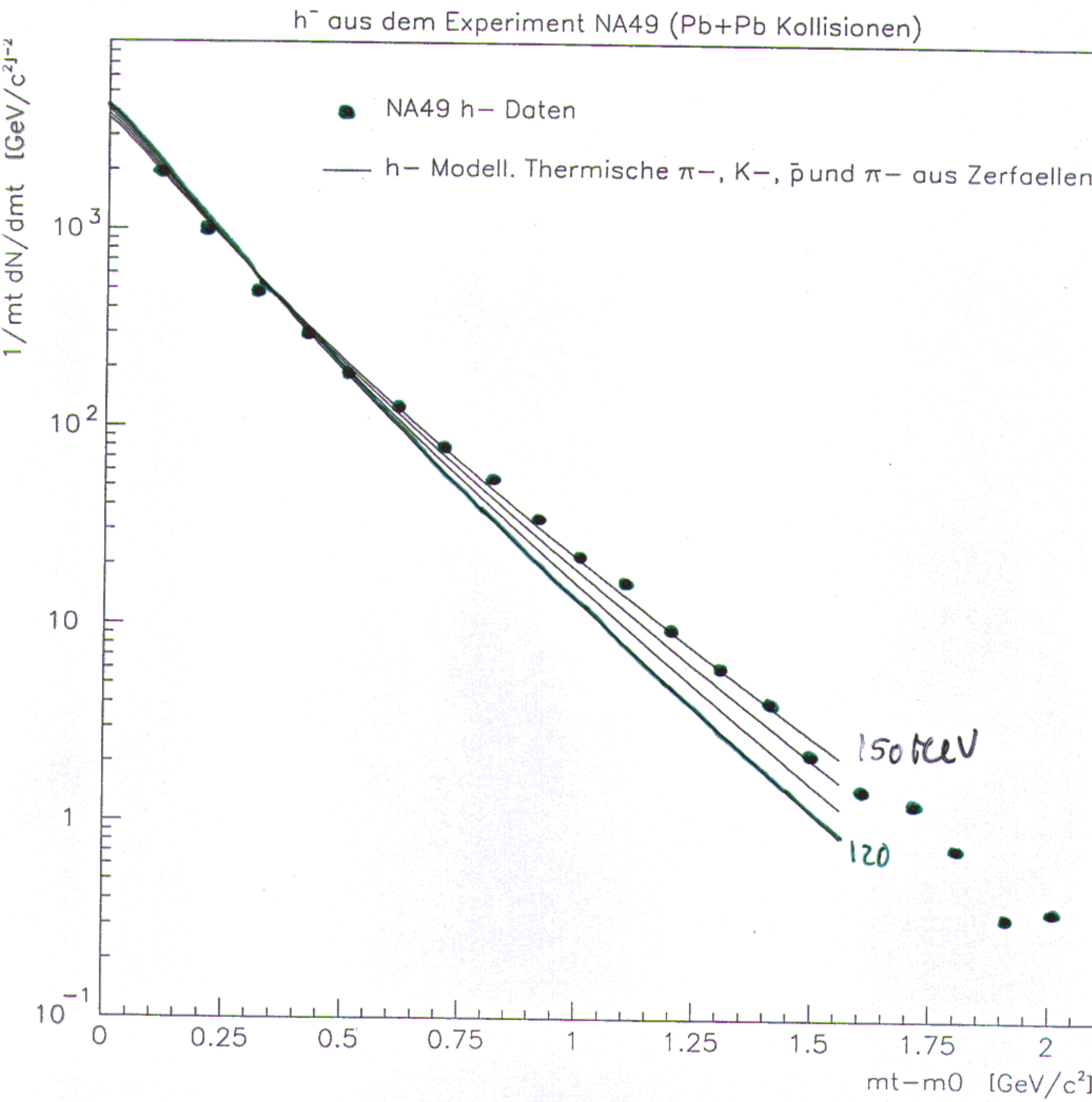


T = 160 MeV
$\pi^+\pi^-$
$K^+ K^-$
$p\ \bar{p}$
d^2N/dM_t^2 (GeV^{-2})
M_t - M (GeV)
10^4
10^3
10^2
10^1
10^0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6


h⁻ aus dem Ceres Experiment (Pb+Pb Kollisionen)
Ceres h− Daten
T=120 MeV thermische π−
h− Modell. Thermische π−, K−, p̄ und π− aus Zerfaellen
βmax = 0.6 α = 1.0 R = 6.5 fm
1/mt dN/dmt [GeV/c²]⁻²
mt−m0 [GeV/c²]
10⁴
10³
10²
10
1
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25

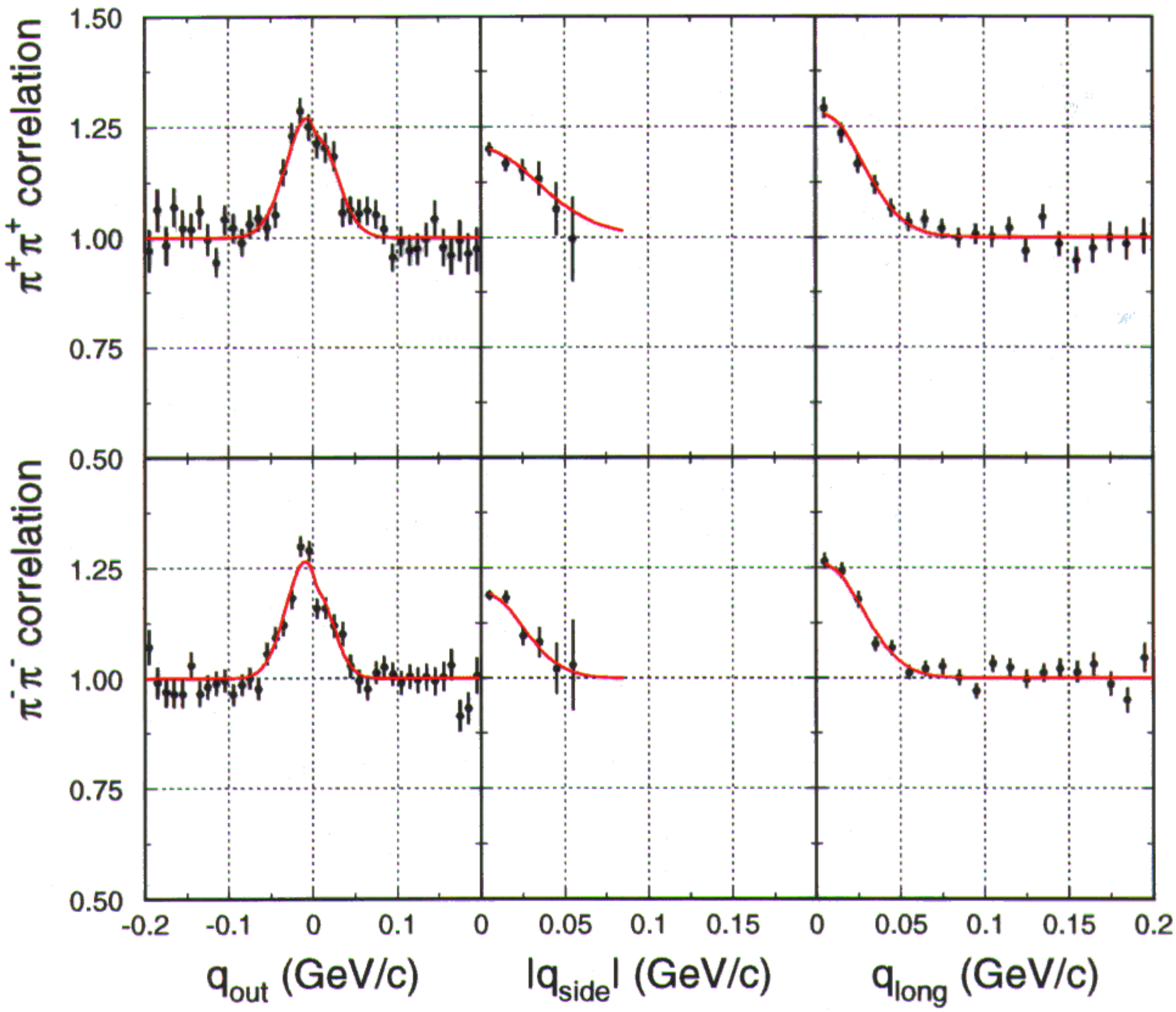


h⁻ aus dem Ceres Experiment (Pb+Pb Kollisionen)
Ceres h− Daten
h− Modell. Thermische π−, K−, p̄ und π− aus Zerfaellen
von oben nach unten − T=150, T=140, T=130 T=120 MeV thermische π−
Resonanzkontributions w. yields corresponding to T = 120 MeV
150 MeV
120
1/mt dN/dmt [GeV/c²]⁻²
mt−m0 [GeV/c²]


h⁻ aus dem Experiment NA49 (Pb+Pb Kollisionen)
NA49 h− Daten
h− Modell. Thermische π−, K−, p̄ und π− aus Zerfaellen
1/mt dN/dmt [GeV/c²]⁻²
mt−m0 [GeV/c²]
150 GeV
120

Two-pion correlations from Au+Au at 10.8 A GeV/c (E877)

PRL 78(1997)2916

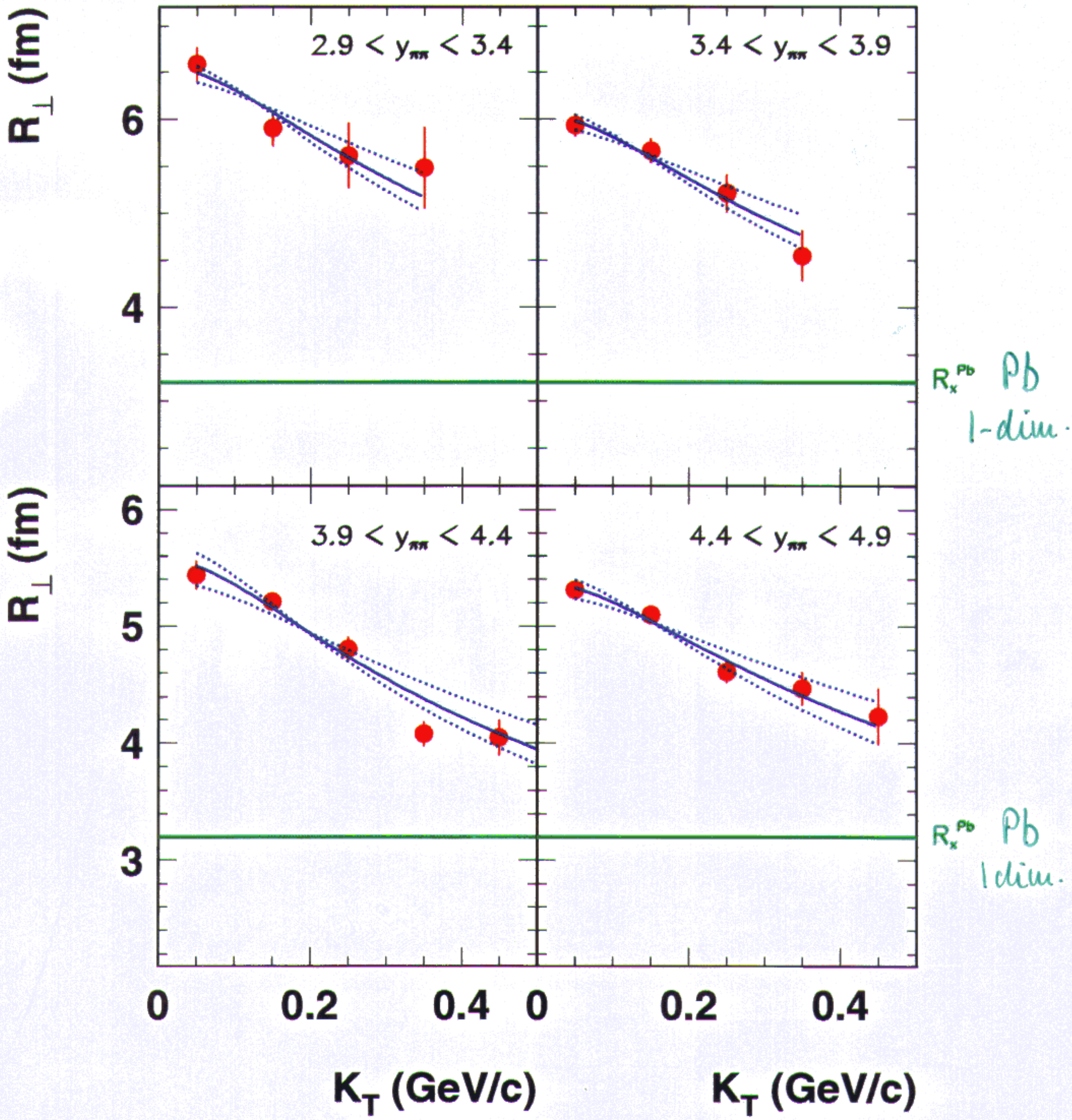


$$C(q_o, q_s, q_l) = 1 + \lambda \exp(-R_o{}^2 q_o{}^2 - R_s{}^2 q_s{}^2 - R_l{}^2 q_l{}^2 - 2|R_{ol}|R_{ol} q_o q_l)$$

	λ	R_o(fm)	R_s(fm)	R_l(fm)	R_{ol}(fm)
$\pi^+\pi^+$	0.62±0.06	5.8±0.5	3.9±0.8	5.5±0.4	2.4±0.7
$\pi^-\pi^-$	0.62±0.05	6.5±0.5	5.6±0.7	5.8±0.4	3.7±0.8

lower limit estimate for volume: $V \gtrsim 2600\ fm^3 \hat{=} 1.5 \times V_{Au-nuc.}$

$\rho_n \simeq \rho_\pi \leq 0.12 / fm^3$



┄ fits w. $R_\perp = \sigma_x \left(1 + M_T \beta^2 / T \cosh(y_{YKP} - y_{\pi\pi})\right)^{-1/2}$

(U. Heinz et al.) $\quad M_T = \sqrt{m_\pi^2 + K_T^2}$

● NA49, Eur. Phys. J C2 (1998) 661

➡ $\beta \approx 0.5 \quad T \simeq 120$ MeV $\quad \sigma_x = 8.2$ fm at y_{mid}

$\hat{=} \; \rho_\pi \simeq 0.12 / fm^3$

- P. Braun-Munzinger, J. Stachel: Nucl.Phys.A 606(1996)320 → Phase Diagram
- P. Braun-Munzinger et al.: Phys. Lett. B 365(1996)1 → SPS
- I. Heppe, P.Braun-Munzinger, J. Stachel: 1998 → SPS
- P. Braun-Munzinger at el.: Phys. Lett. B 344(1995)43 → AGS
- R. Averbeck: nucl-ex/9803001 → SIS