Evidence for the onset of deconfinement at 8 GeV and the softest point at 12 GeV (in central Pb+Pb/Au+Au collisions)

Zakopane, June 2014

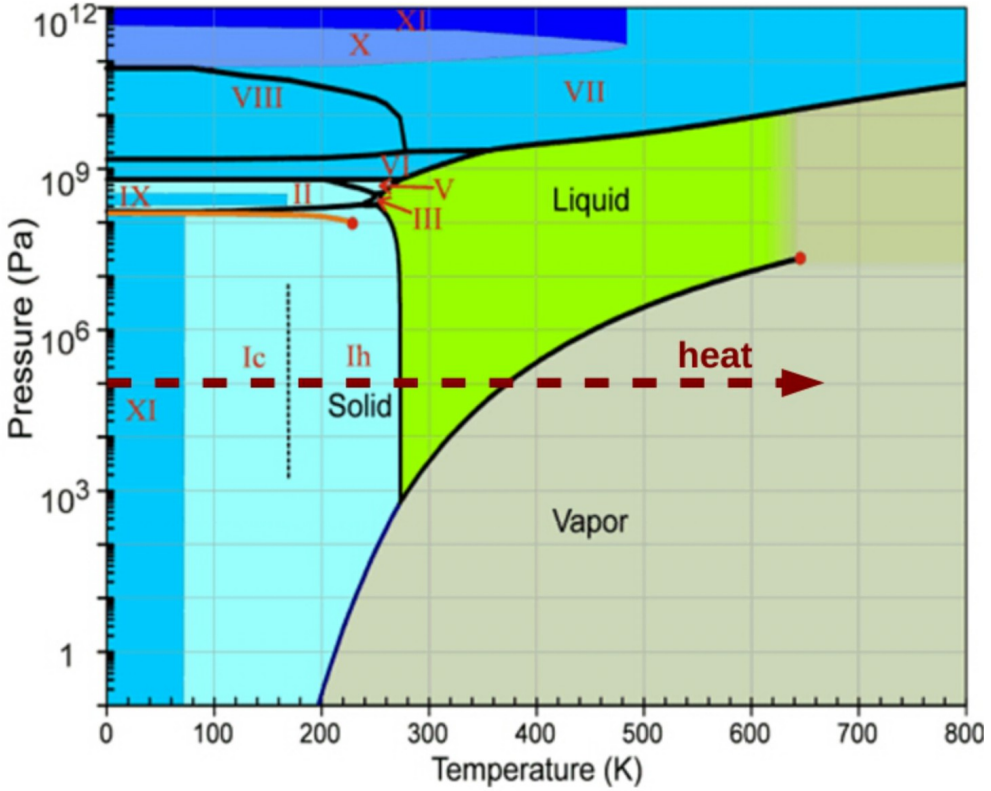
1 Basic idea

2 Experimental evidence

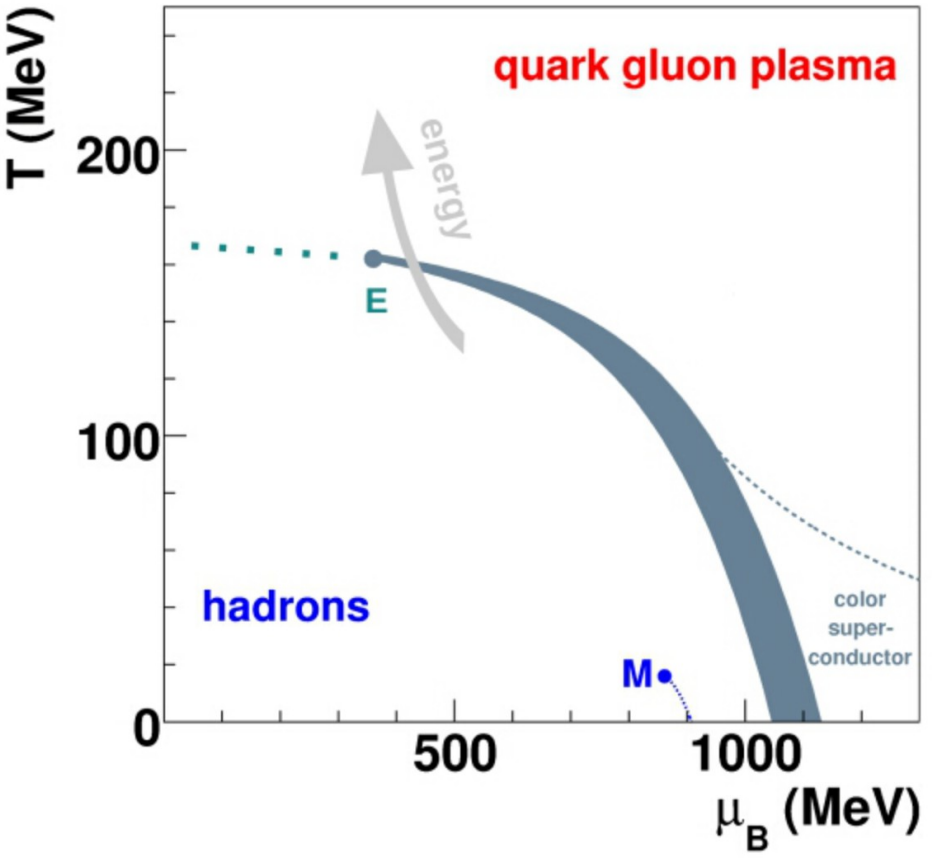
3 Present and future measurements

M. Gazdzicki, Frankfurt, Kielce

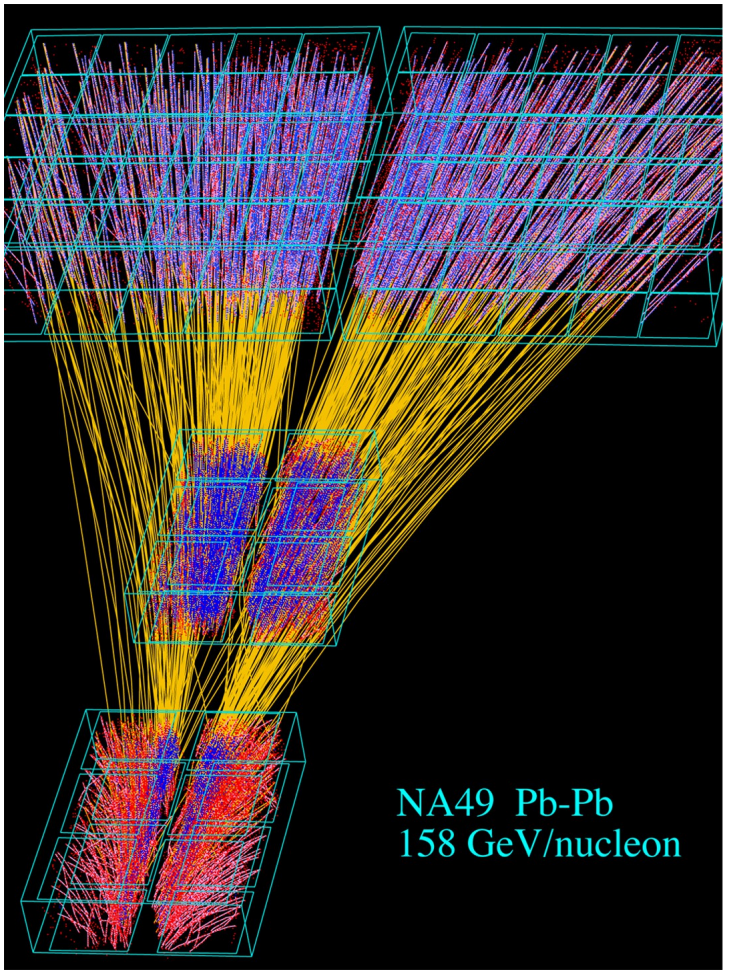
Water



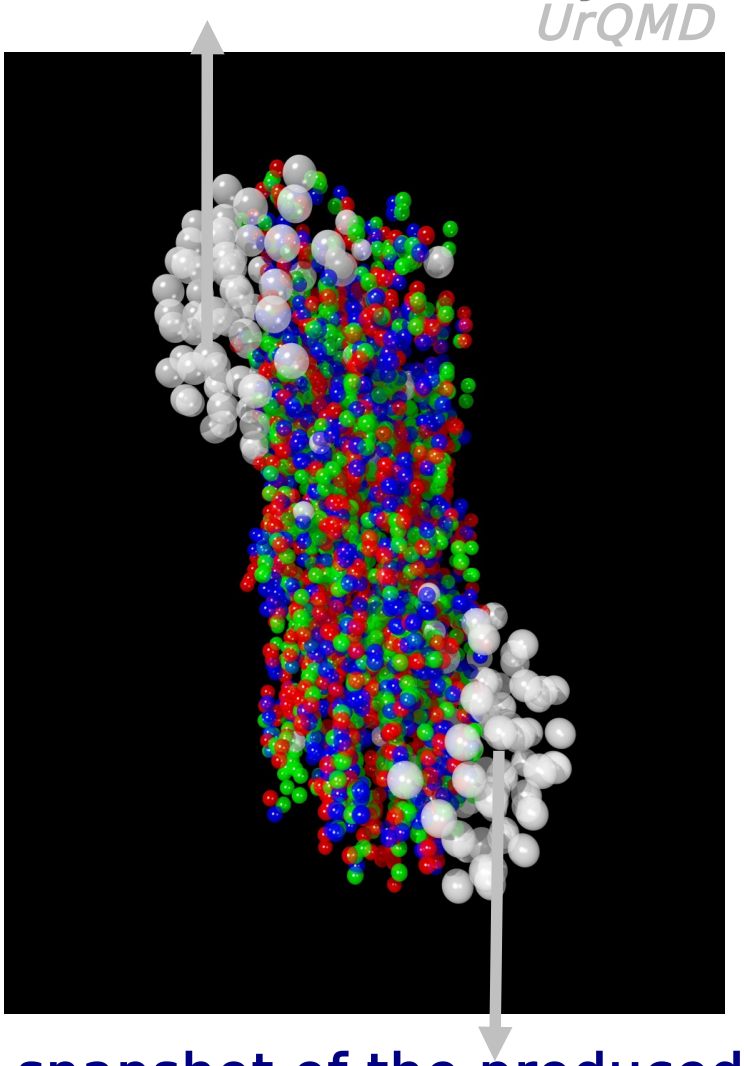
Strongly interacting matter



COLLISIONS OF TWO NUCLEI
-the only tool to study properties of strongly interacting matter in the laboratory

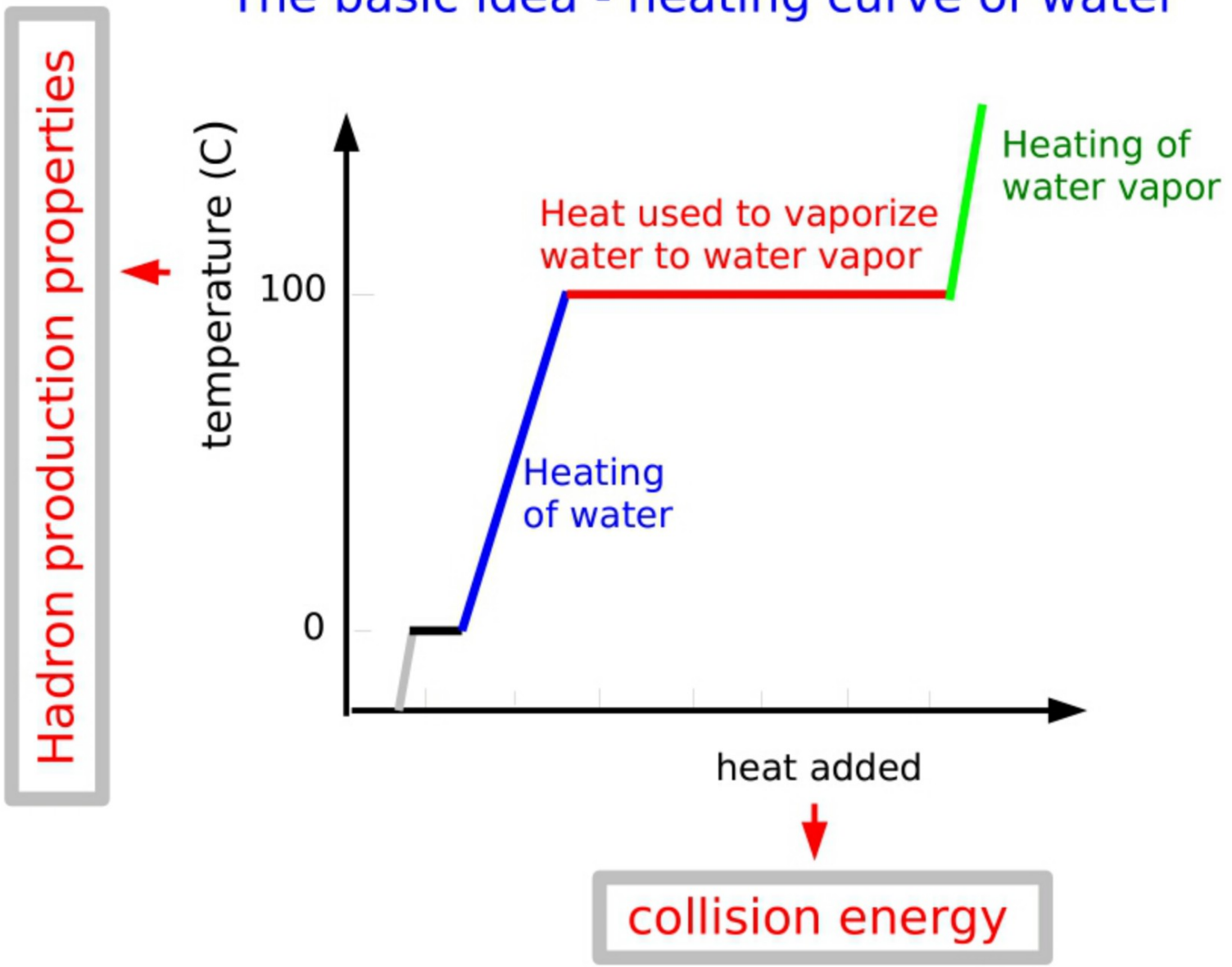


produced particles measured in the NA49 apparatus (scale 10 m)



snapshot of the produced matter after the collision (scale 10^{-14} m)

The basic idea - heating curve of water



(Generalized) Landau model

ASSUMPTIONS:

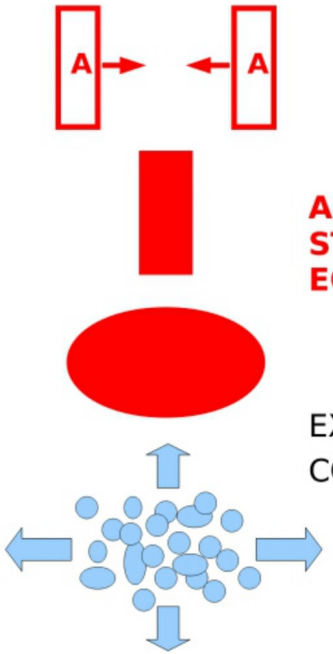
GENERAL PICTURE:

INITIAL STATE:

EARLY STAGE:

EXPANSION:

FREEZE-OUT:



ALL POSSIBLE MICROSCOPIC STATES OF THE SYSTEM ARE EQUALLY PROBABLY

EXPANSION AND FREEZE-OUT CONSERVE ENTROPY and s, $\bar{s}$

ε

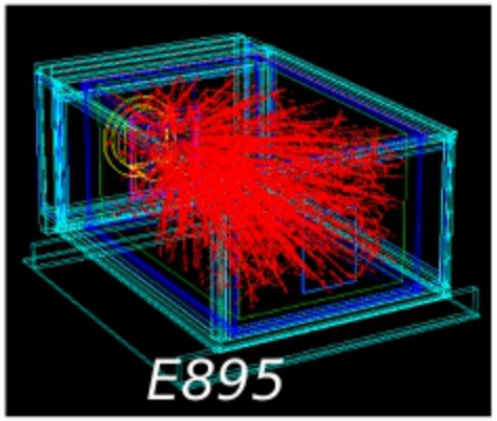
$$E = \eta \cdot (\sqrt{S_{NN}} - 2m_N) \cdot A_p$$

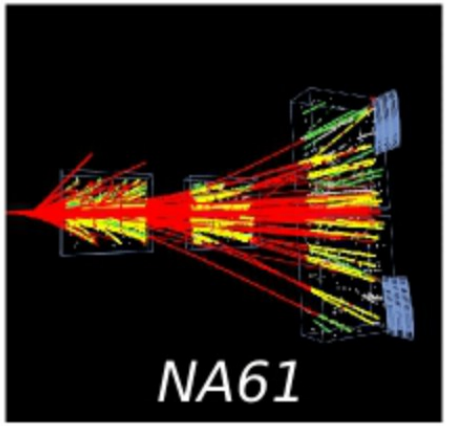
$$V = \frac{V_0}{\gamma} = \frac{A_p/\rho_0}{\sqrt{S_{NN}}/(2m_N)}$$

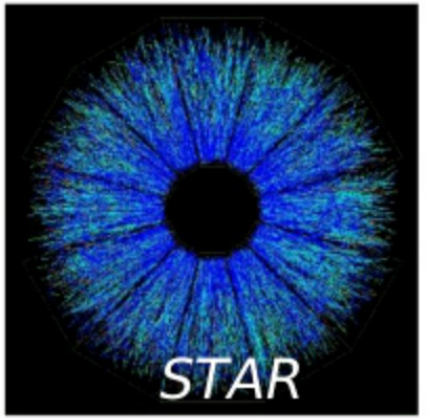
$$\varepsilon \equiv \frac{E}{V} = \frac{\eta \cdot \rho_0 (\sqrt{S_{NN}} - 2m_N) \cdot \sqrt{S_{NN}}}{2m_N}$$

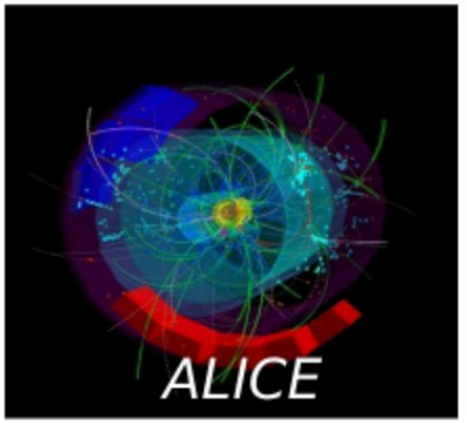
$$\varepsilon \sim \sqrt{s_{NN}}^2$$

BNL AGS → CERN SPS → BNL RHIC → CERN LHC





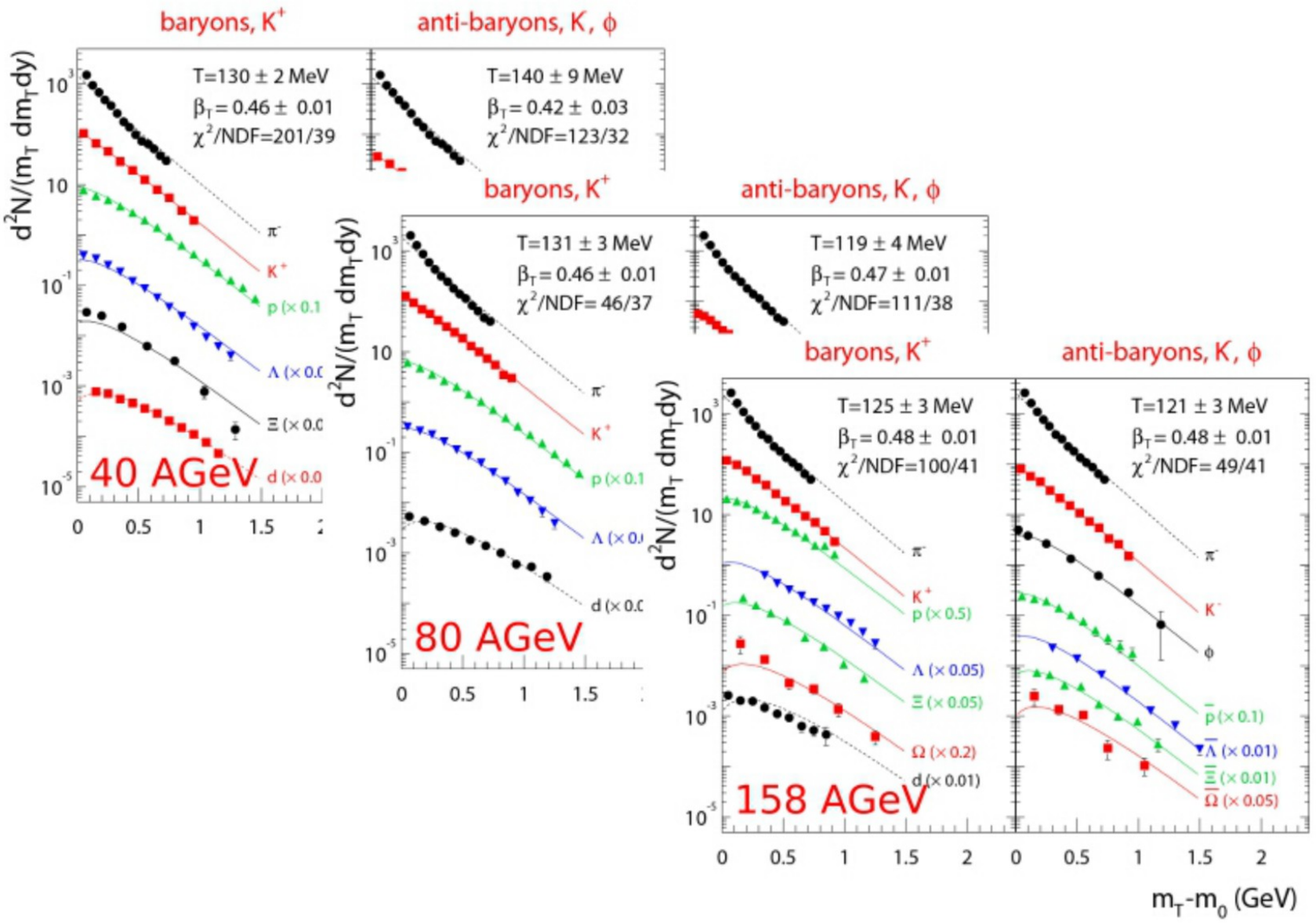




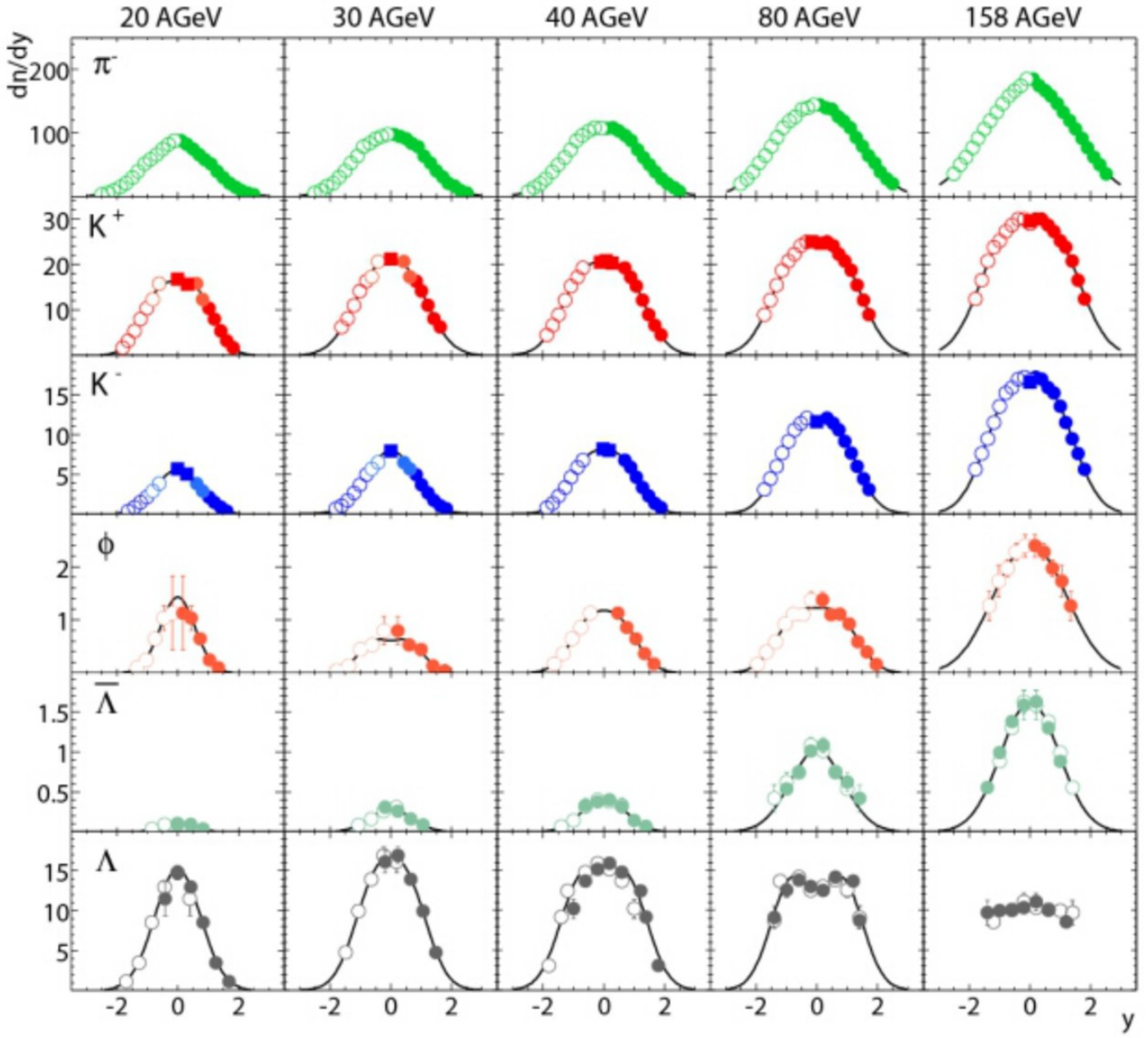
After more than 40 years of experimental effort we have now rich experimental data on single particle spectra of popular hadrons in Pb+Pb and p+p interactions from several GeV to several TeV.

Global Beam Energy Scan is well advanced !

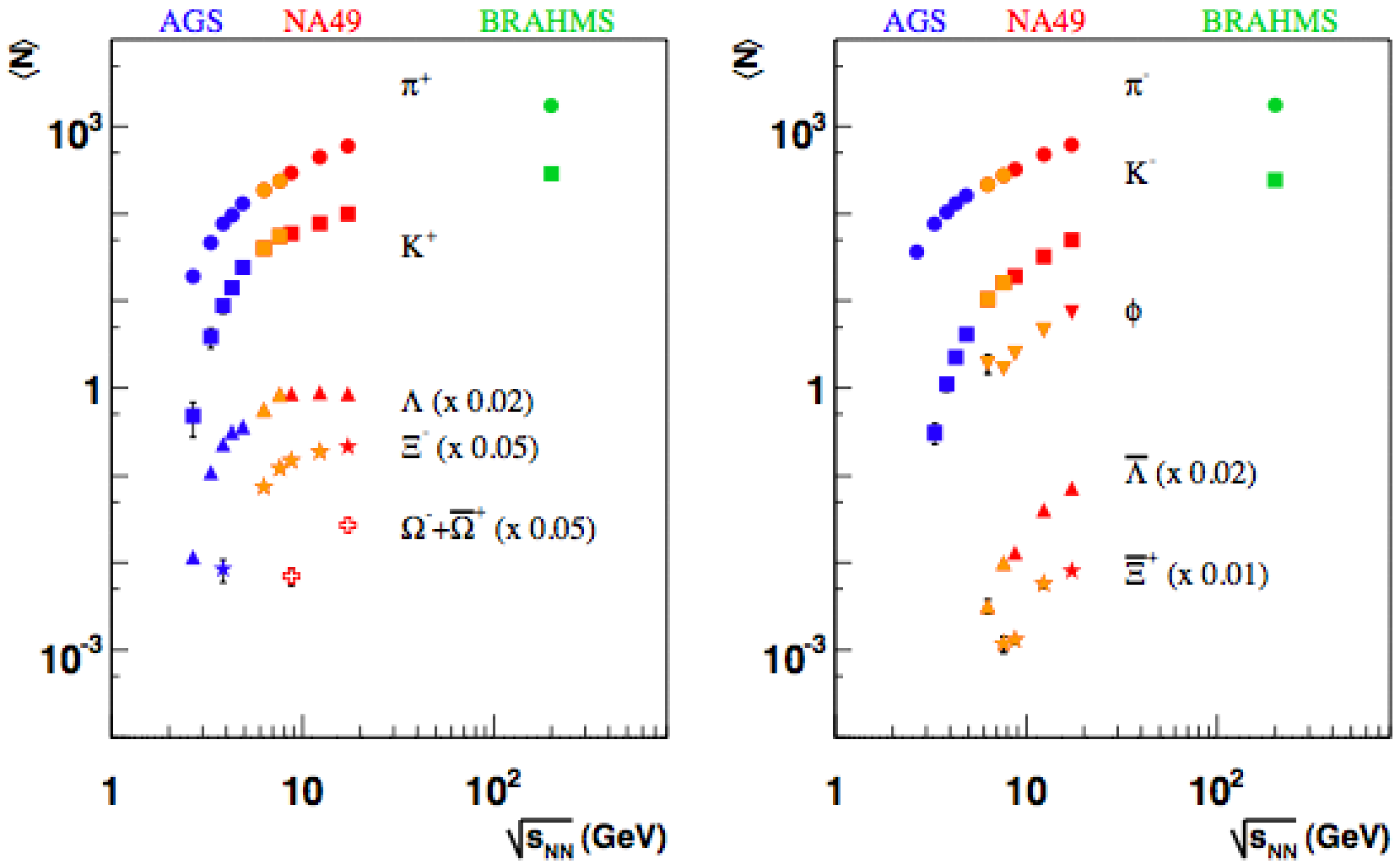
central Pb+Pb collisions at the SPS energies



central Pb+Pb collisions at the SPS energies

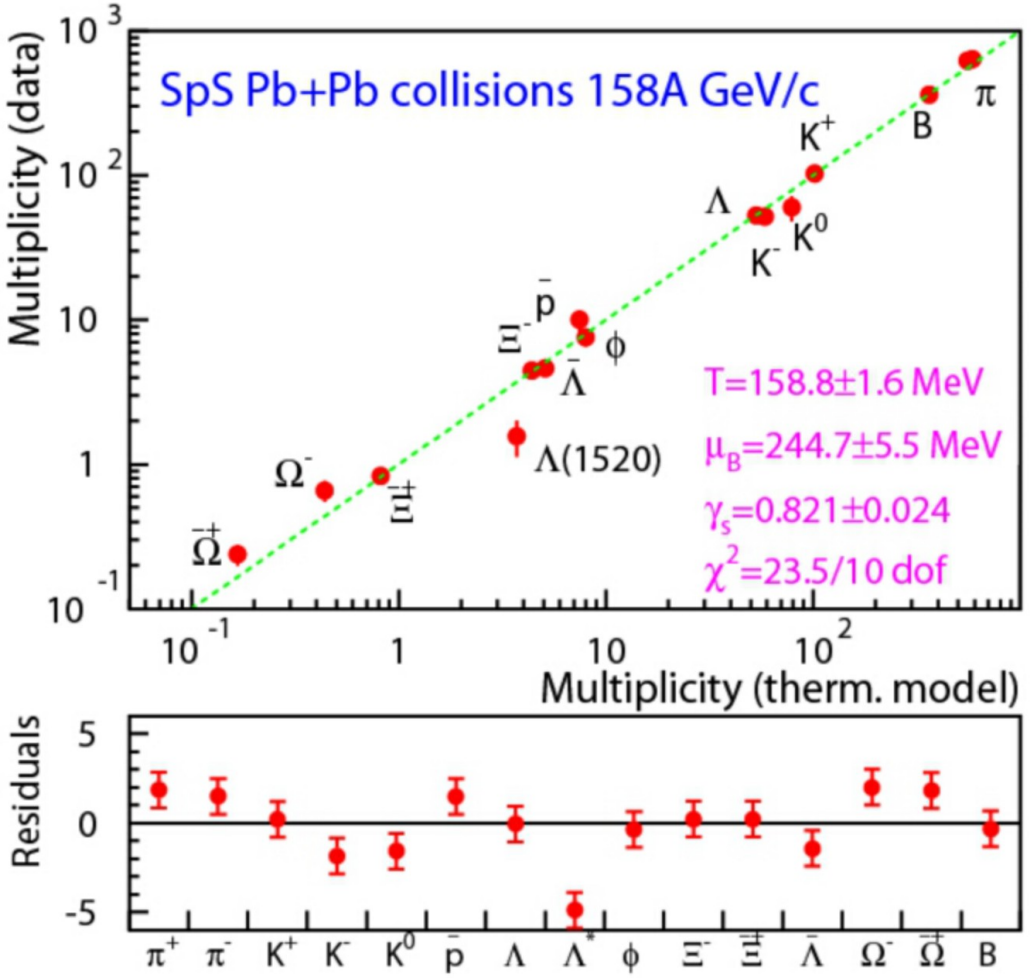


central Pb+Pb (Au+Au) collisions



Hadron gas model analysis

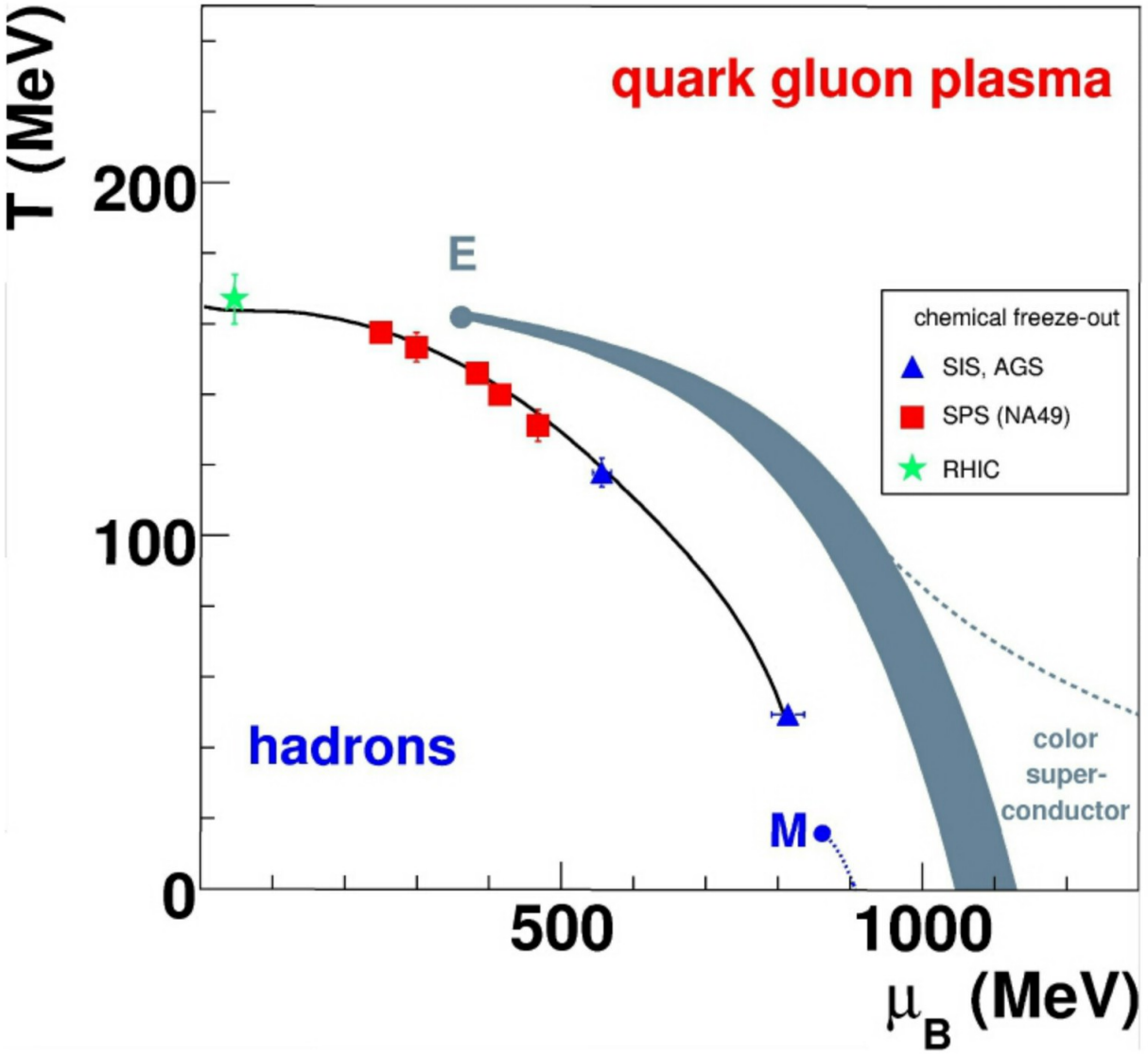
$$\langle n_i \rangle = \frac{(2J_i+1)\,V}{(2\pi)^3} \int d^3p \, \frac{1}{\gamma_s^{-S_i} exp[(E_i - (\mu_B + \mu_S + \mu_Q))/T] \pm 1}$$



fit parameters

↓

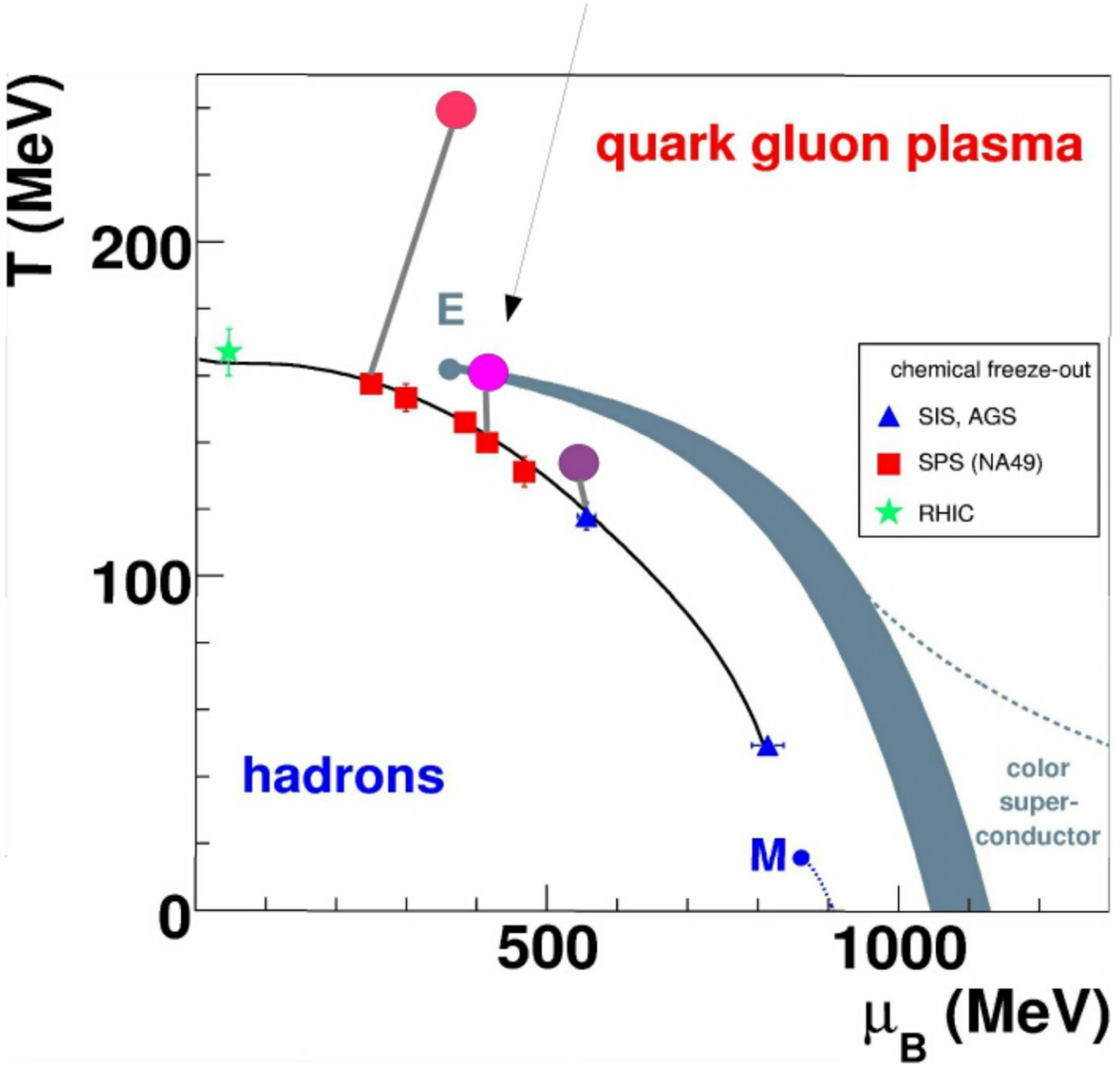
chemical freeze-out of matter created in A+A collisions

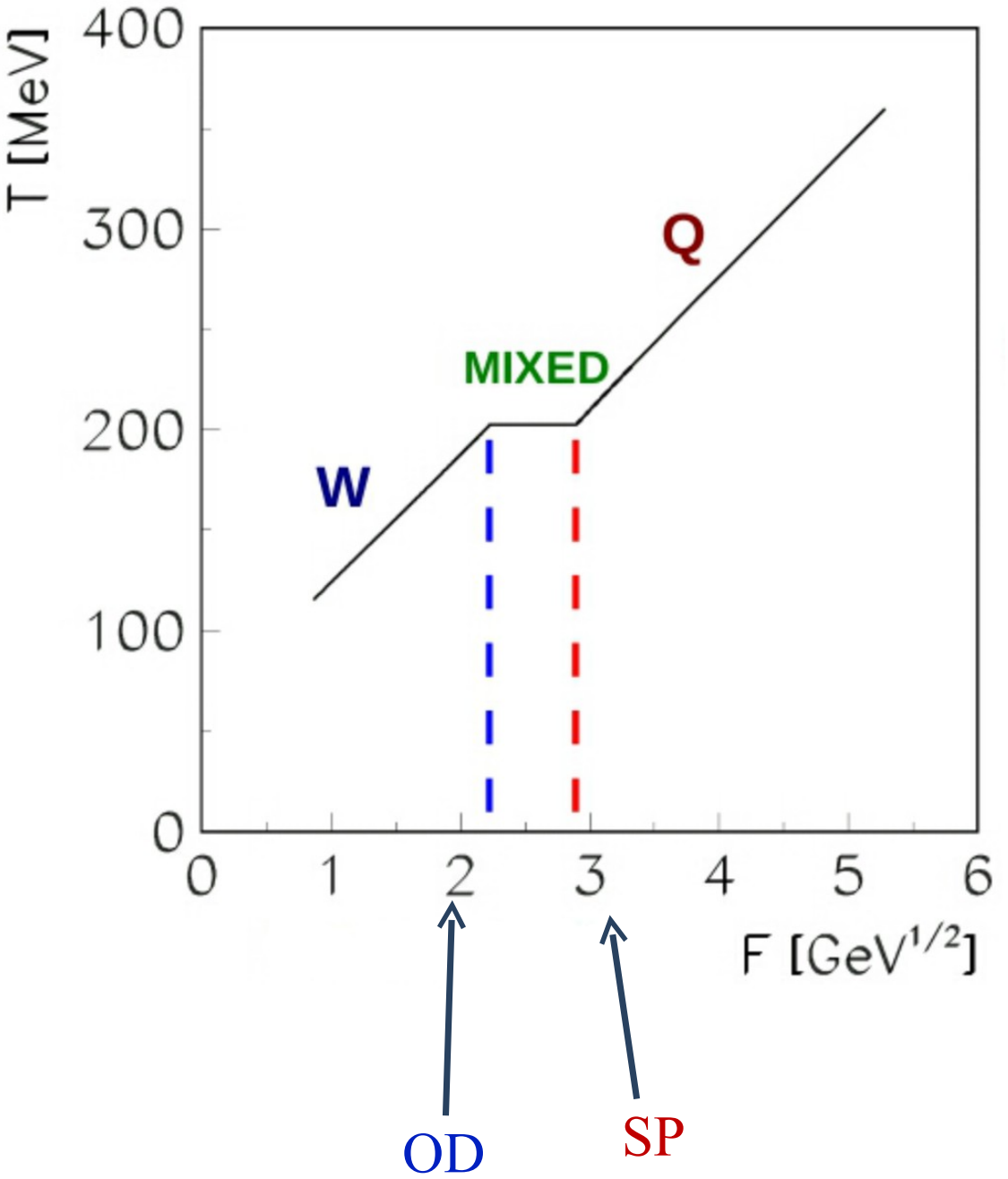


Freeze-out points of central heavy ion collisions at SPS are close to the phase boundary

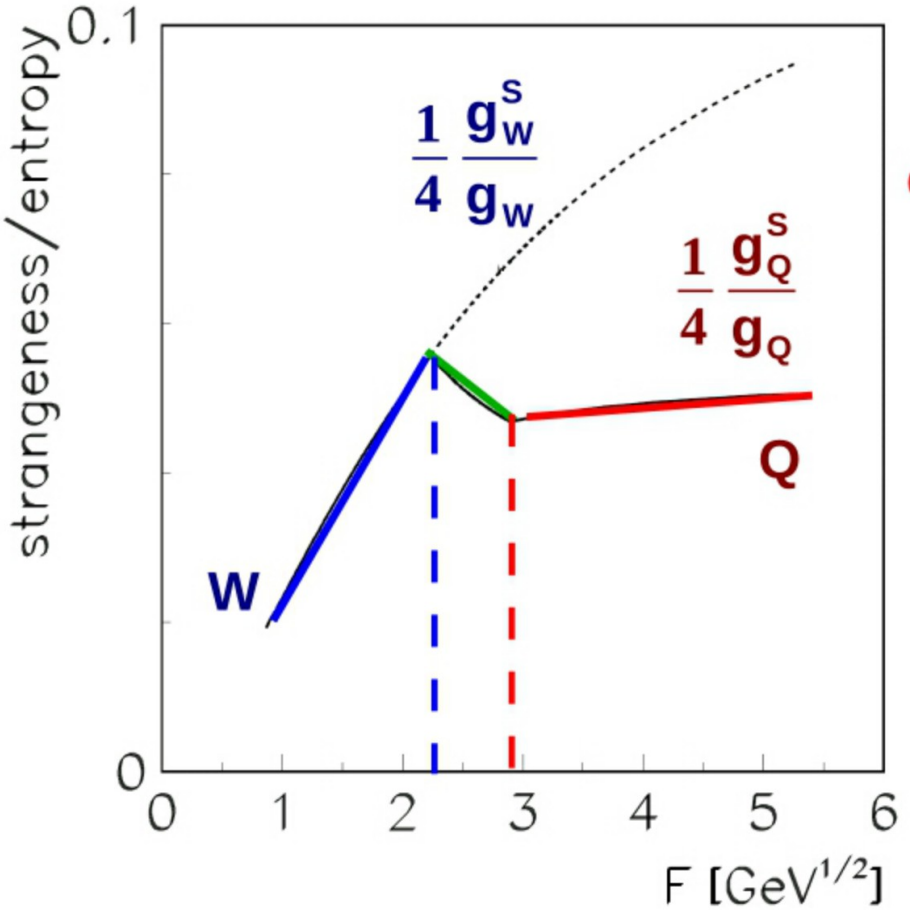
Its possible that the early stage crosses the phase boundary at SPS energies (onset of deconfinement)

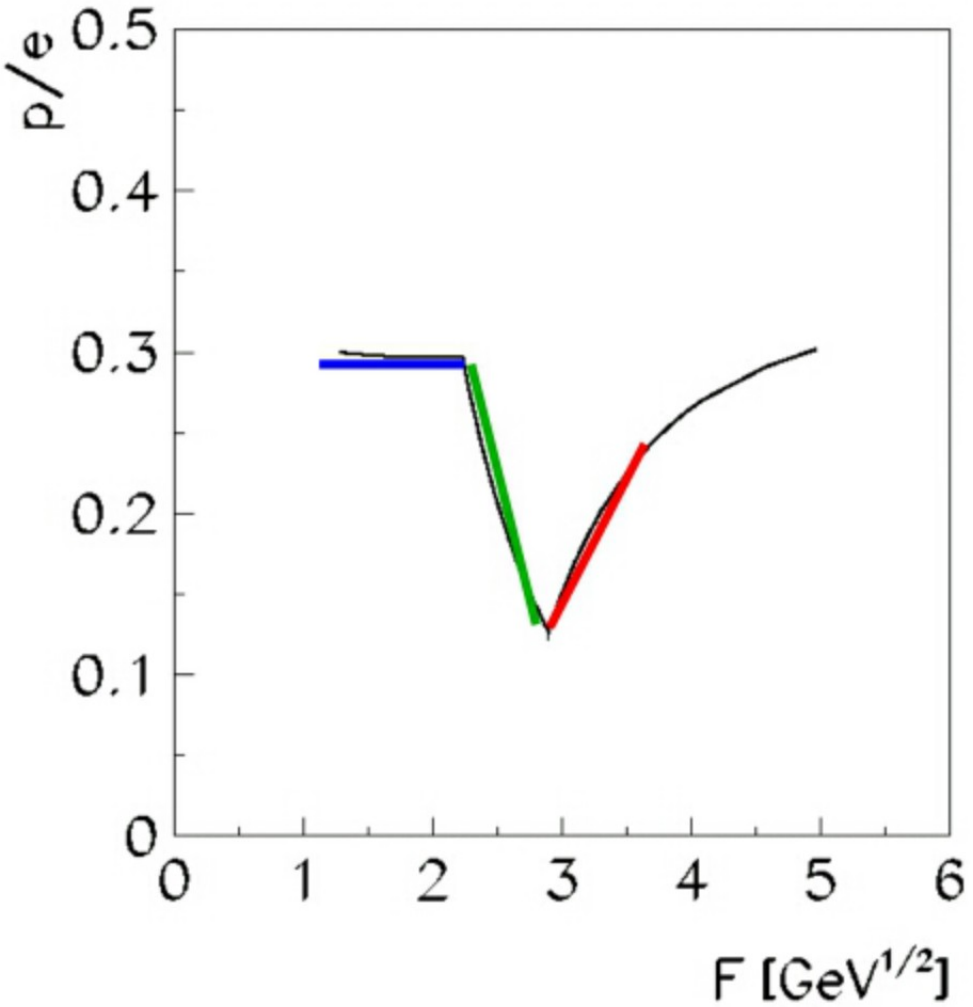
Onset of deconfinement: the early stage hits the transition line



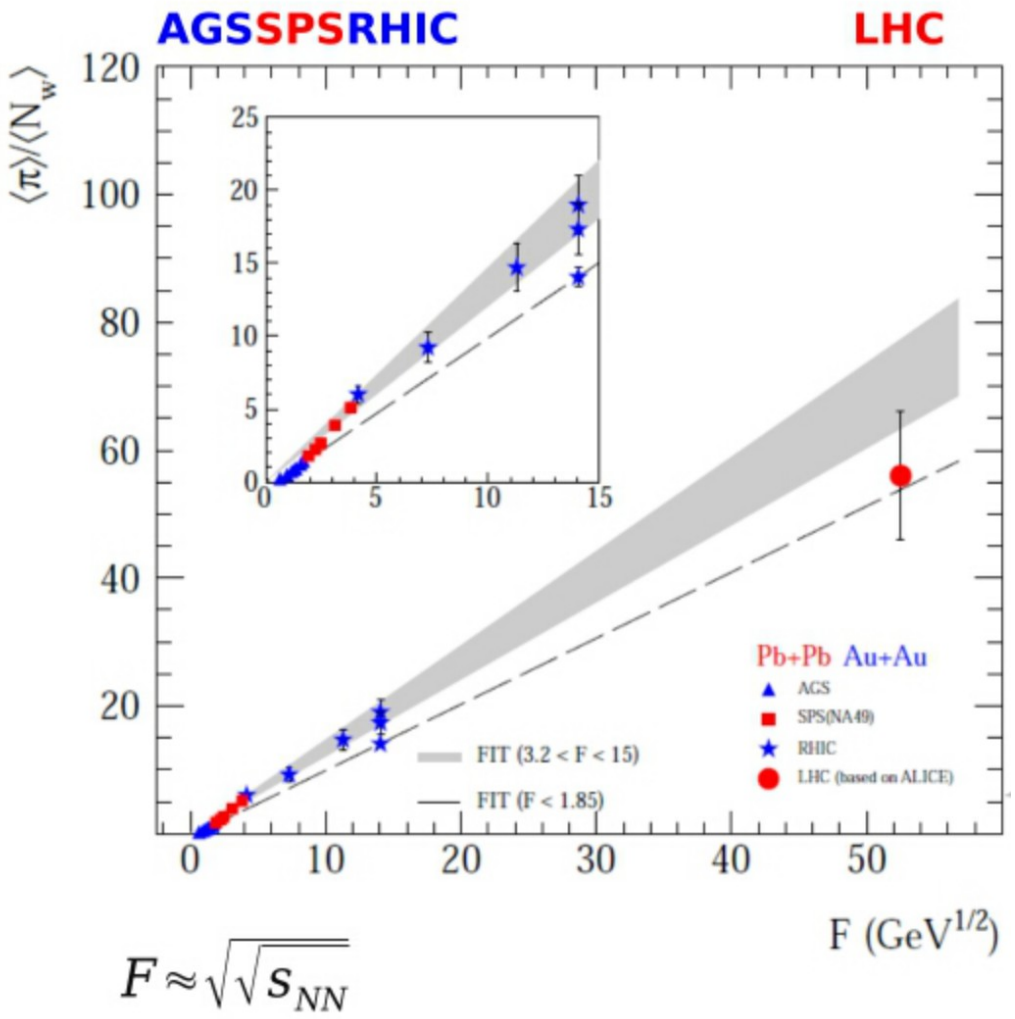


$$F \simeq \sqrt{\sqrt{s_{NN}}}$$


strangeness/entropy
0.1
0
0
1
2
3
4
5
6
F [GeV^1/2]
1/4 g_W^s/g_W
1/4 g_Q^s/g_Q
W
Q


p/e
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
F [GeV^1/2]

The kink in pion multiplicity



$$F \approx \sqrt{\sqrt{s_{NN}}}$$

Deconfinement

↓

Increased entropy production

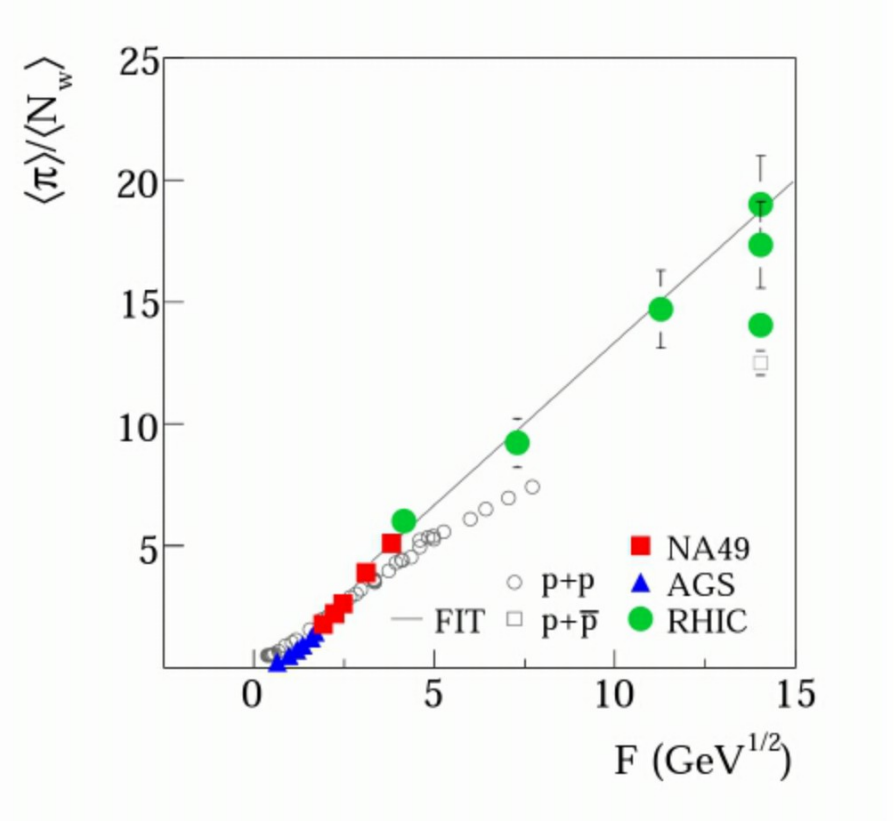
↓

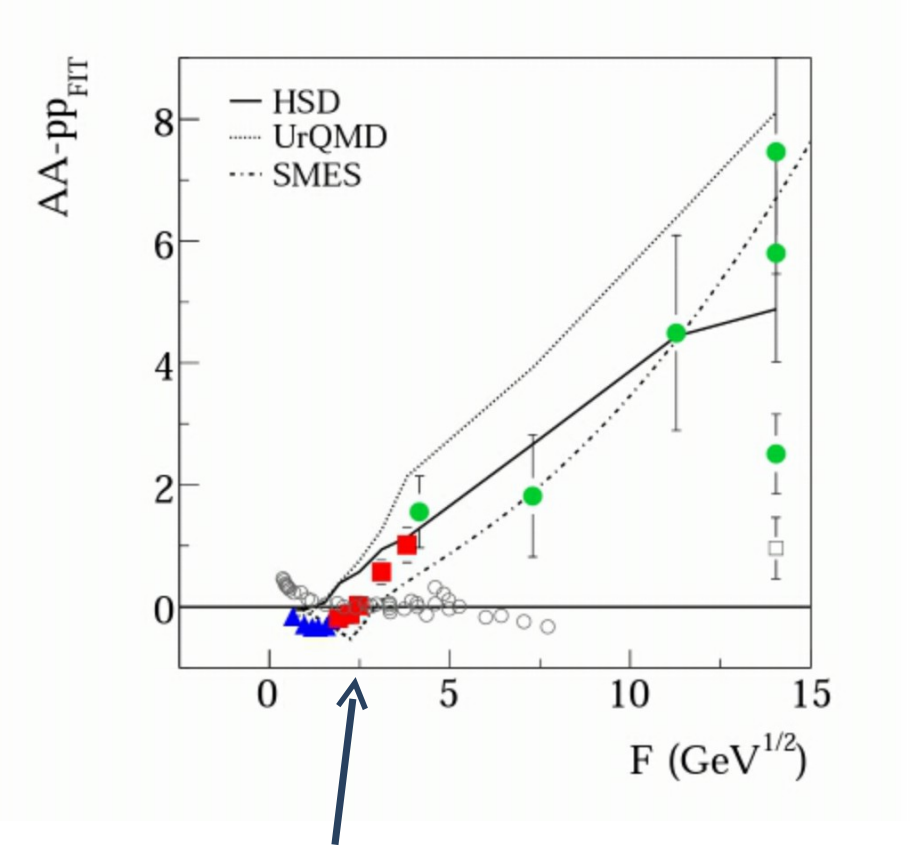
Steepening of the increase of pion production

$$\langle\pi\rangle \sim g^{1/4} F - \epsilon$$

$\langle\pi\rangle$ - total pion multiplicity

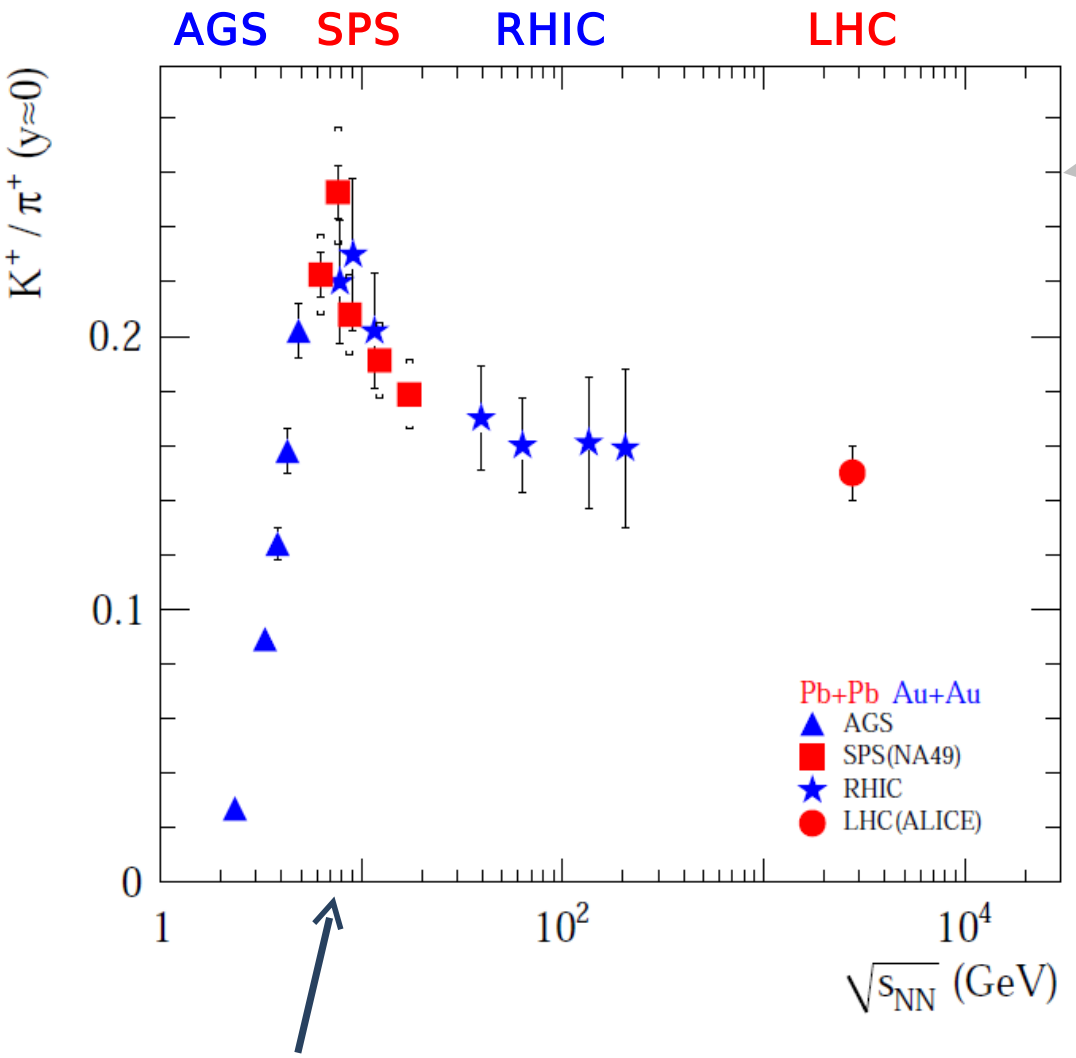
$\langle N_W\rangle$ - number of interacting nucleons





Kink: OD 8 GeV, SP ?

The horn in strangeness yield



Deconfinement

↓

Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom

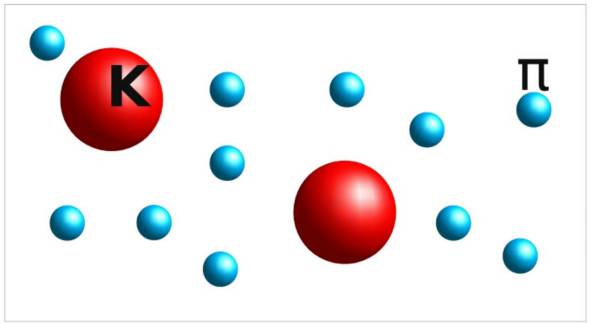
↓

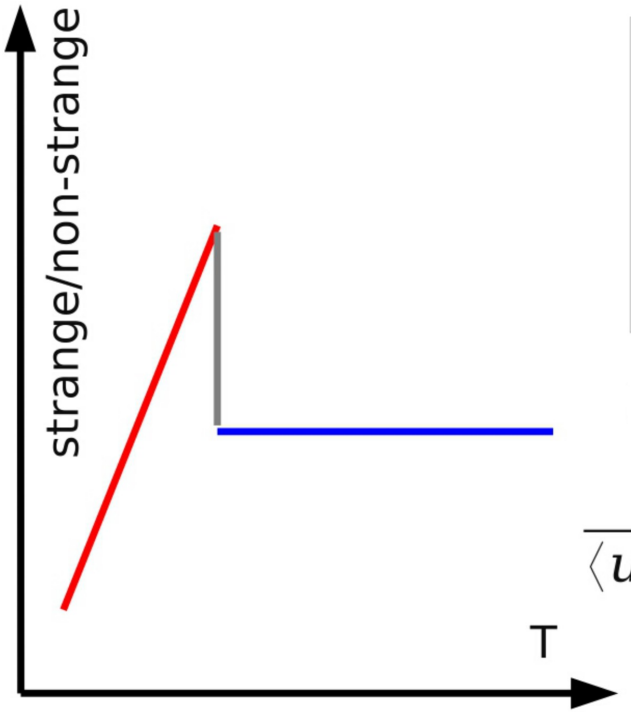
A sharp maximum in the strangeness to pion ratio

M.G., Gorenstein

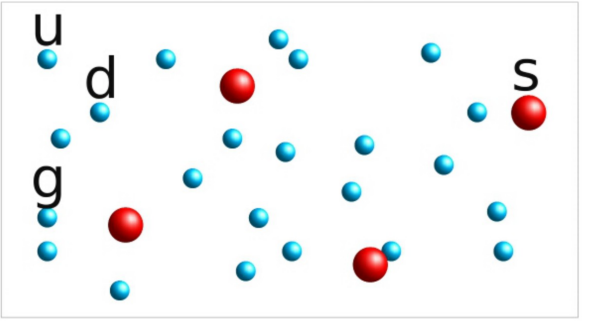
A toy model of the horn

hadron gas





quark-gluon plasma



$$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{M T^{3/2}}{T^3} \cdot e^{-M/T}$$

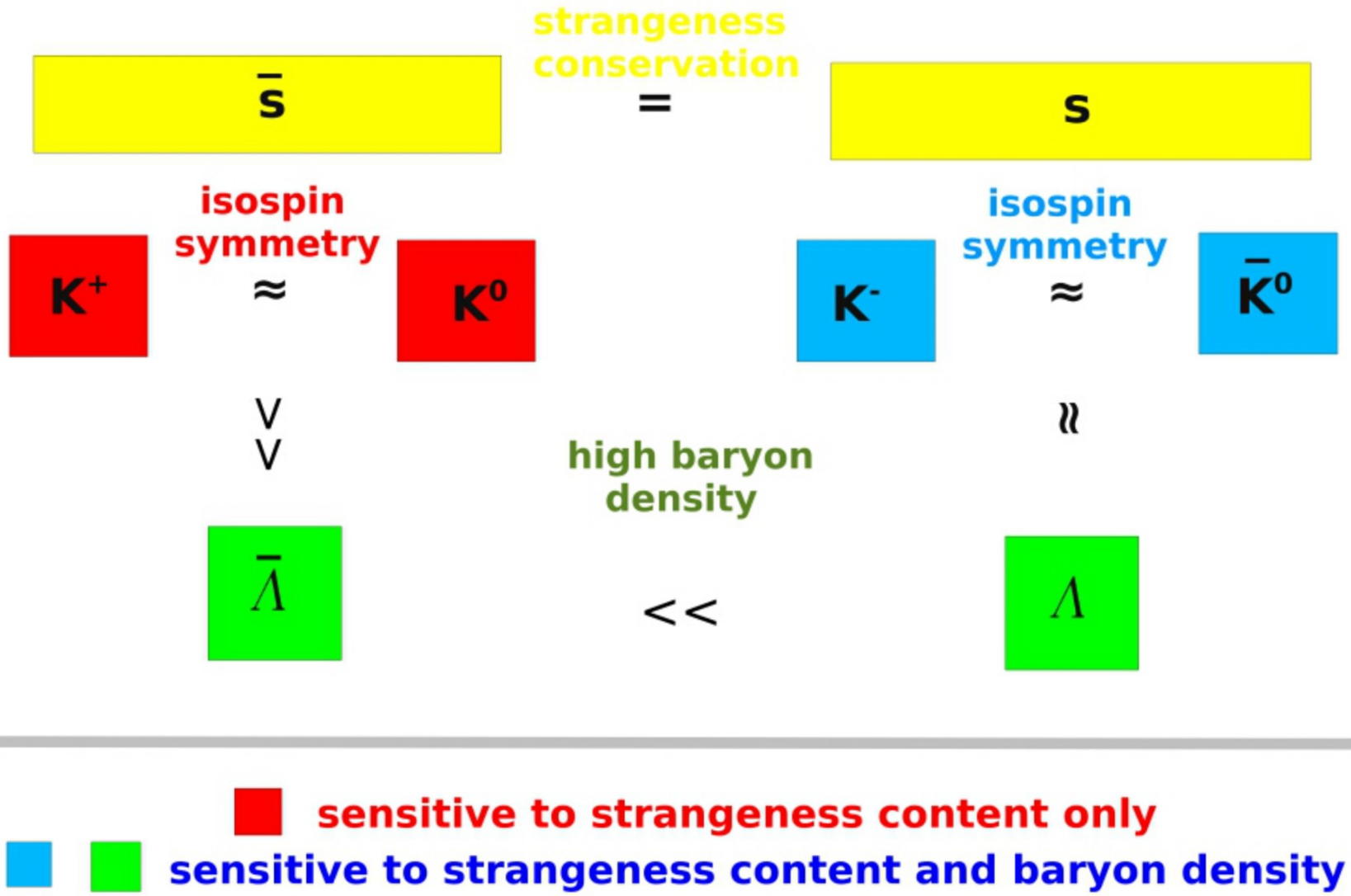
$$\frac{\langle s \rangle}{\langle u+d+g \rangle} \propto \frac{T^3}{T^3} = const(T)$$

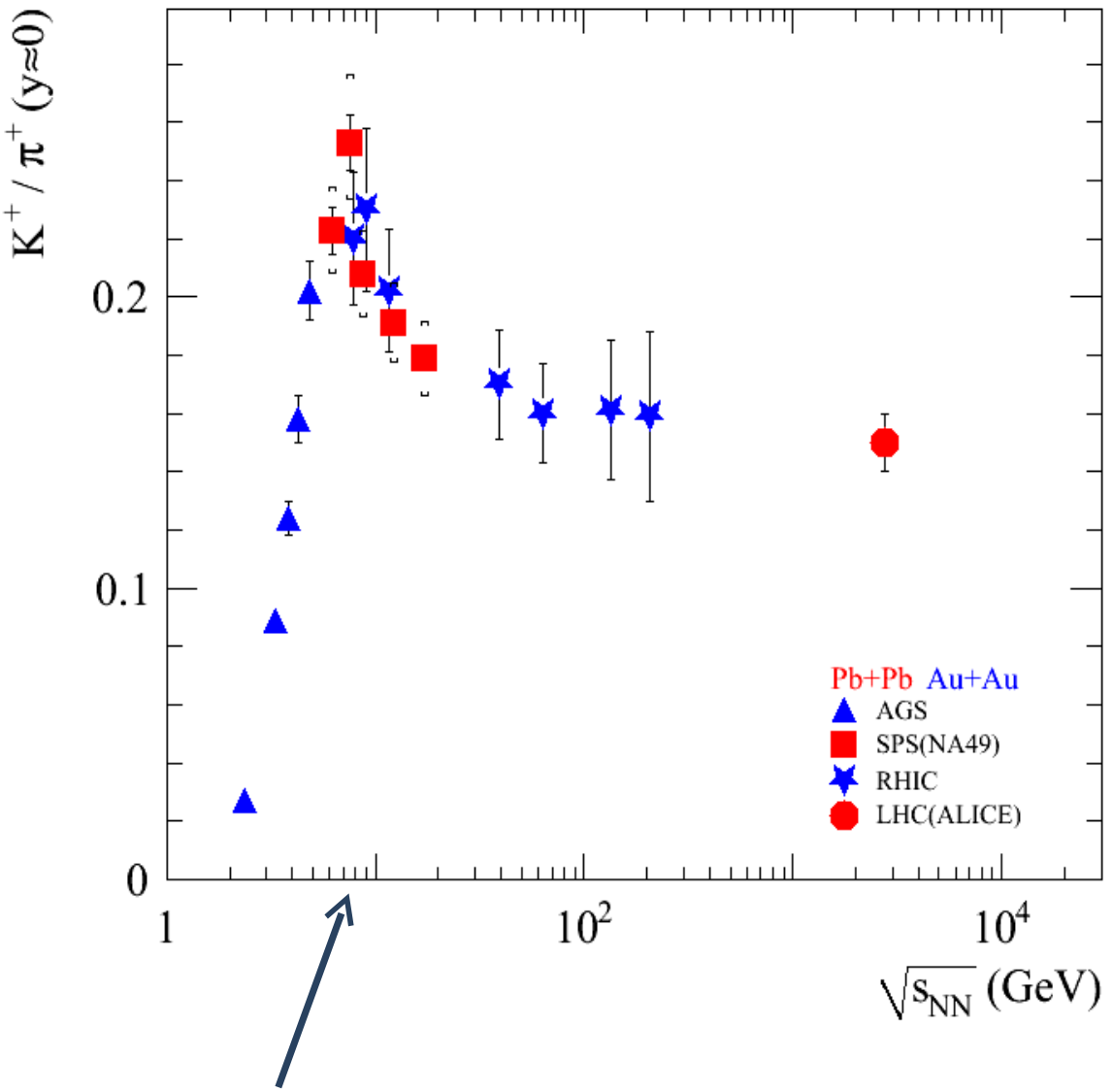
$$\langle n \rangle = \frac{gV}{(2\pi)^3} \int d^3p \; \frac{1}{e^{E/T} \pm 1}$$

$$\approx gV \; \frac{2\pi^2}{4 \cdot 45} \; T^3 \qquad \text{for light particles}$$

$$\approx gV \; \left(\frac{MT}{2\pi}\right)^{3/2} \; e^{-M/T} \qquad \text{for heavy particles}$$

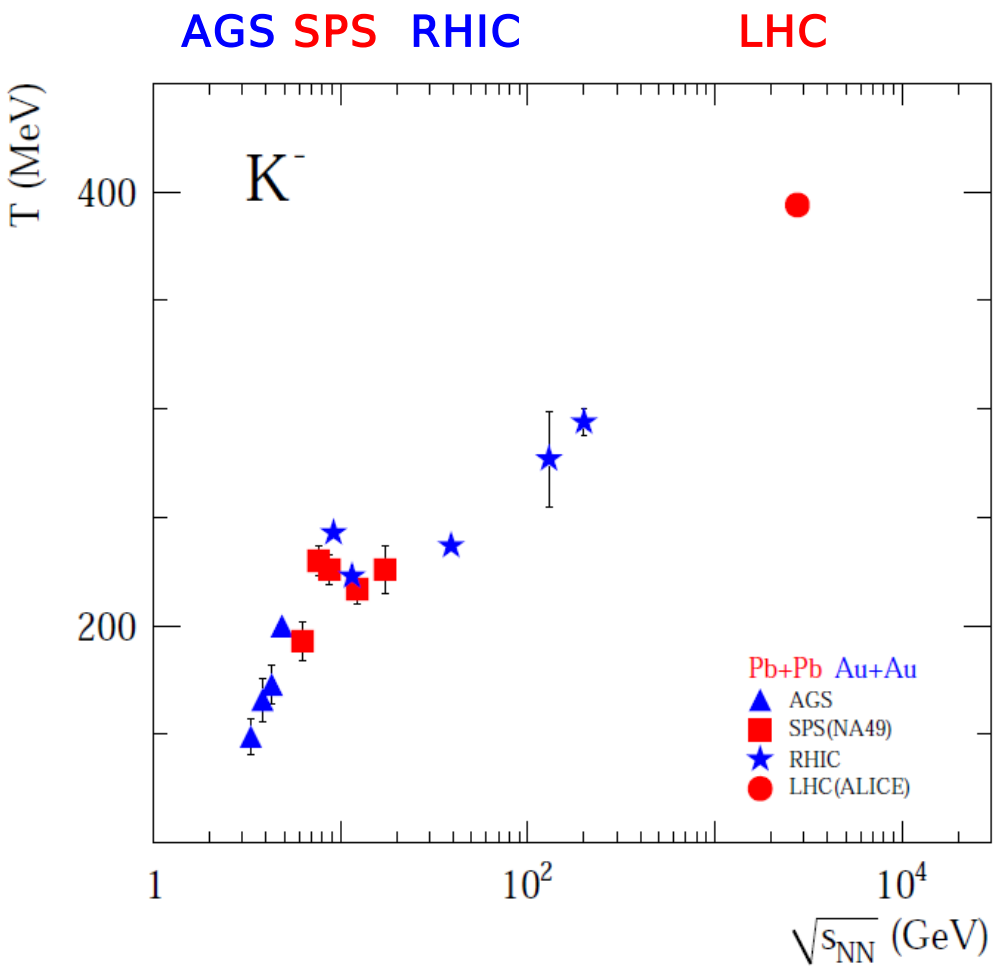
main strangeness carriers





Horn: OD 8 GeV, SP ?

The step in m_T slopes



Deconfinement

↓

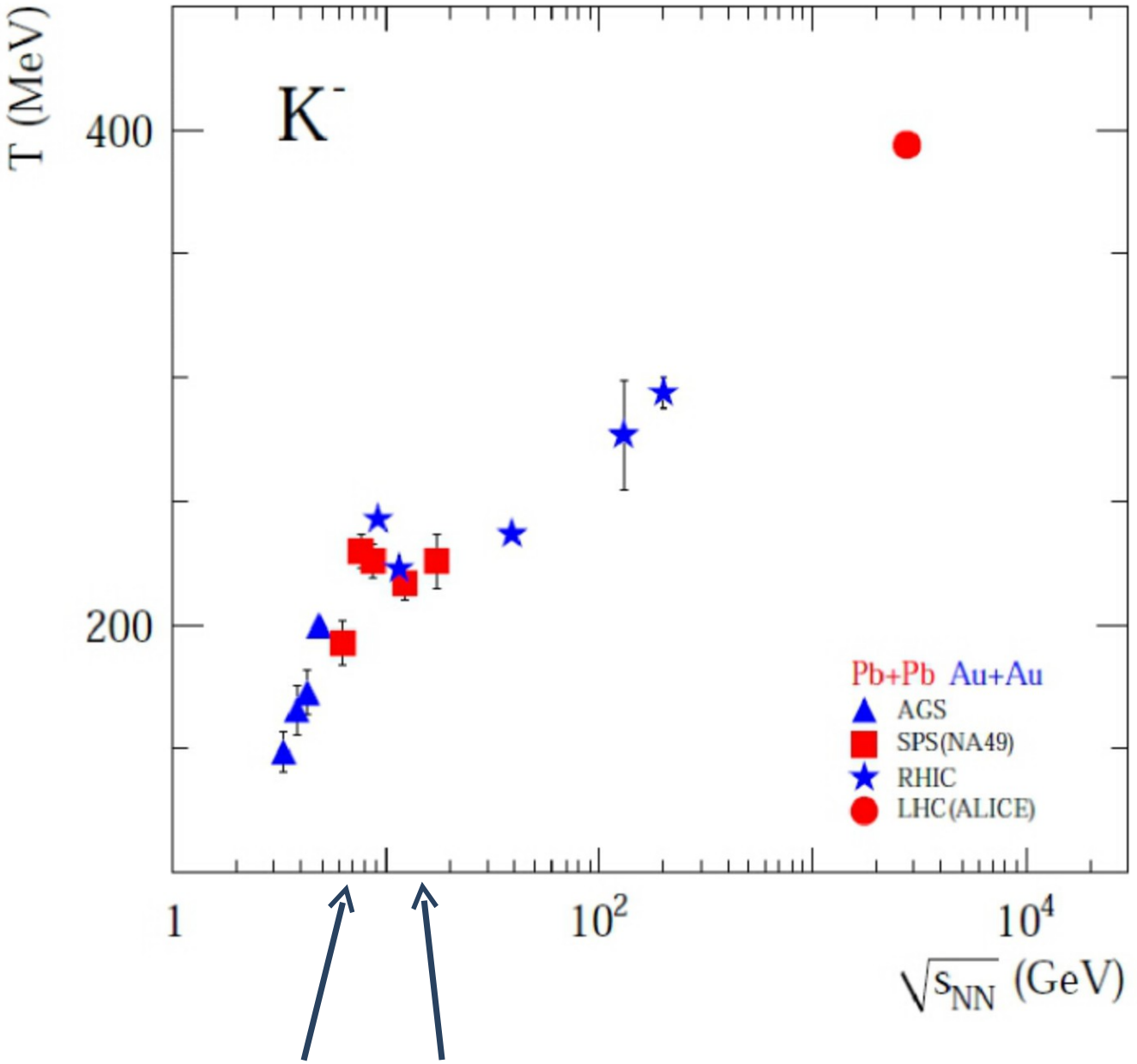
Constant temperature and pressure in the mixed phase region

↓

Weaker transverse expansion and thus weaker energy dependence of T

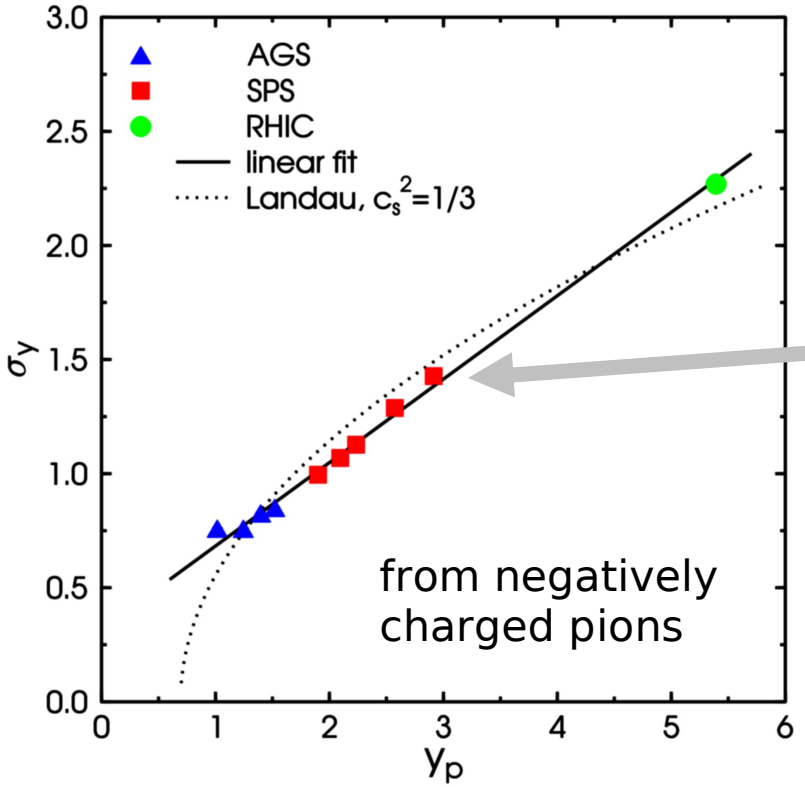
T – inverse slope parameter of transverse mass spectra

Gorenstein, M.G., Bugaev (Shuryak, van Hove)



Step: OD 8 GeV, SP 12 GeV

... and the rapidity dale ...



Deconfinement

↓

Constant temperature and pressure in the mixed phase region

↓

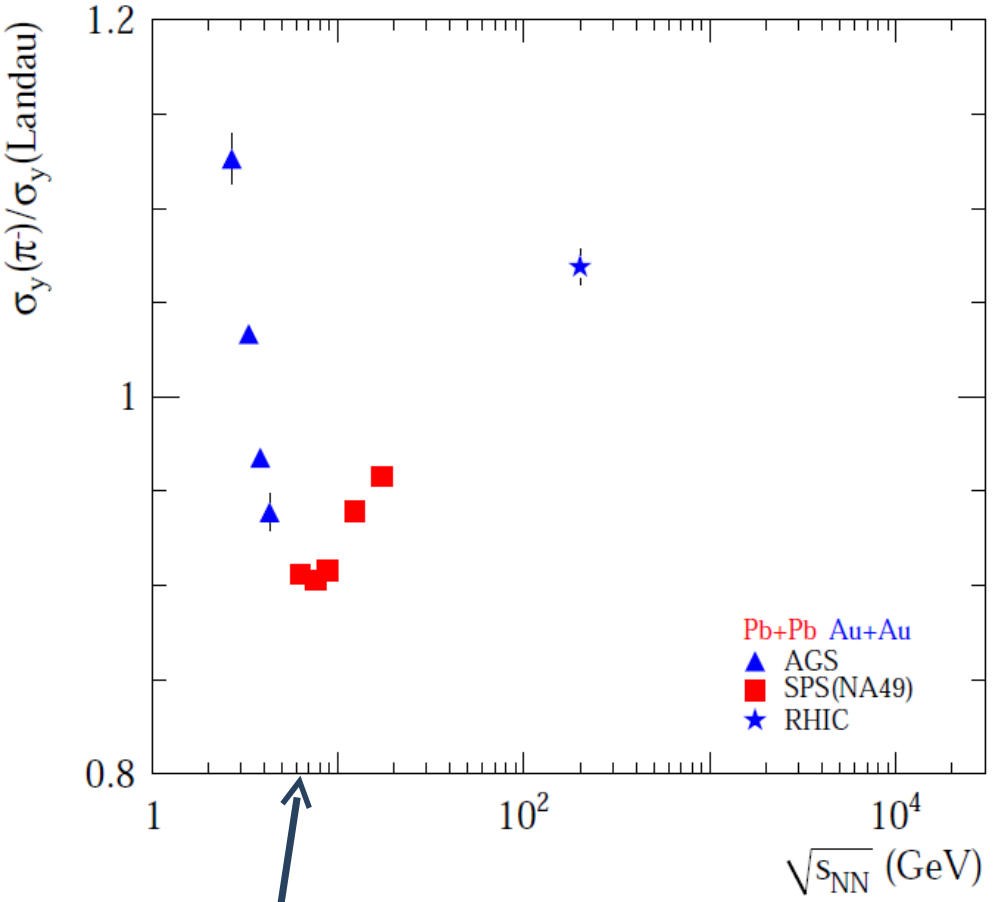
Weaker longitudinal expansion and thus weaker energy dependence of σ_y

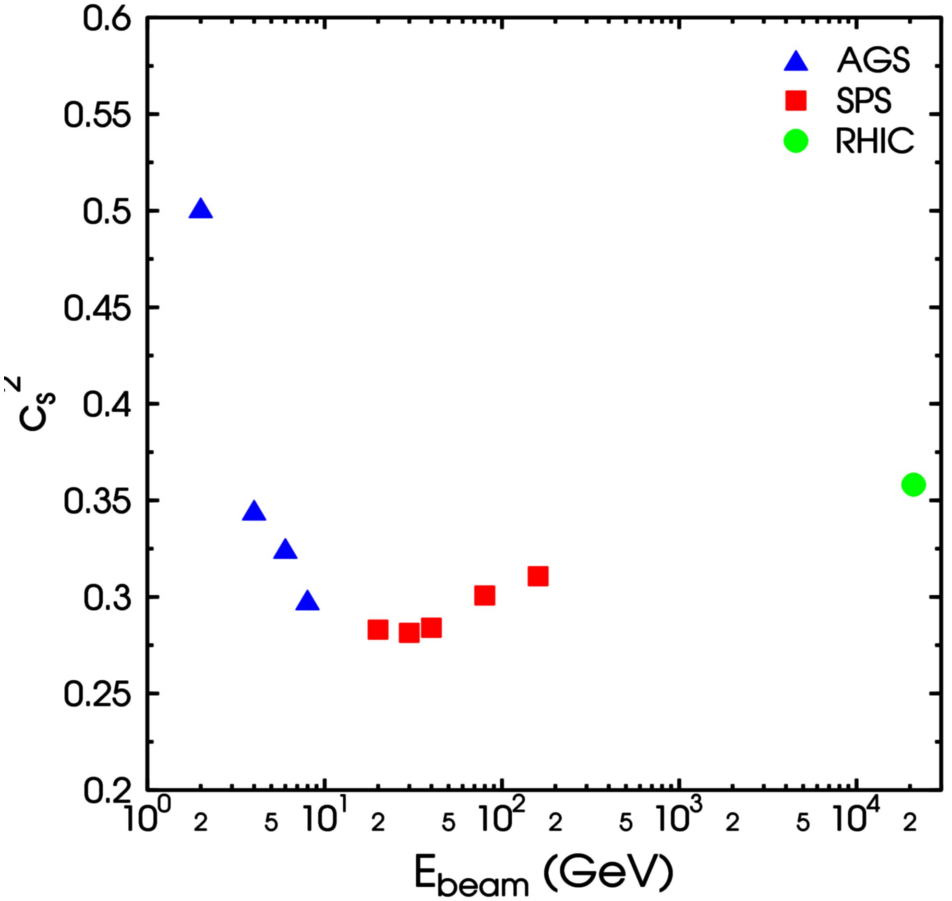
Hydrodynamical Landau model:
*(E.Shuryak,Yad.Fiz.**16**, 395 (1972))*

$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln(\sqrt{s_{NN}}/2m_p)$$

Bleicher

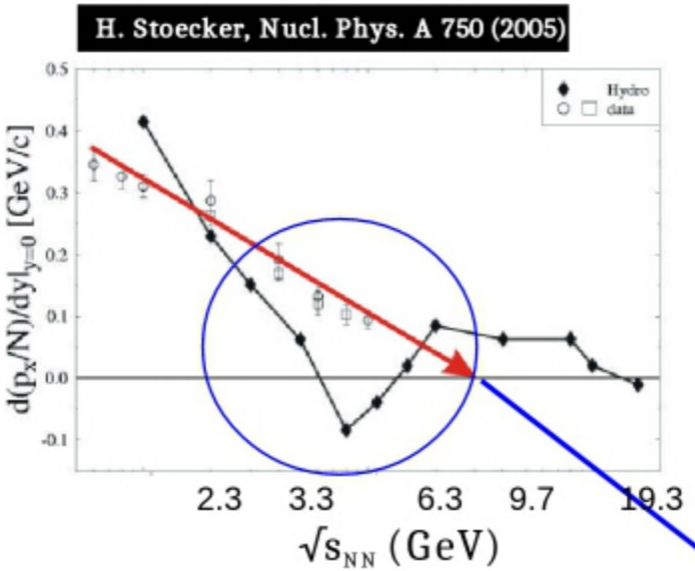
… and the rapidity dale …

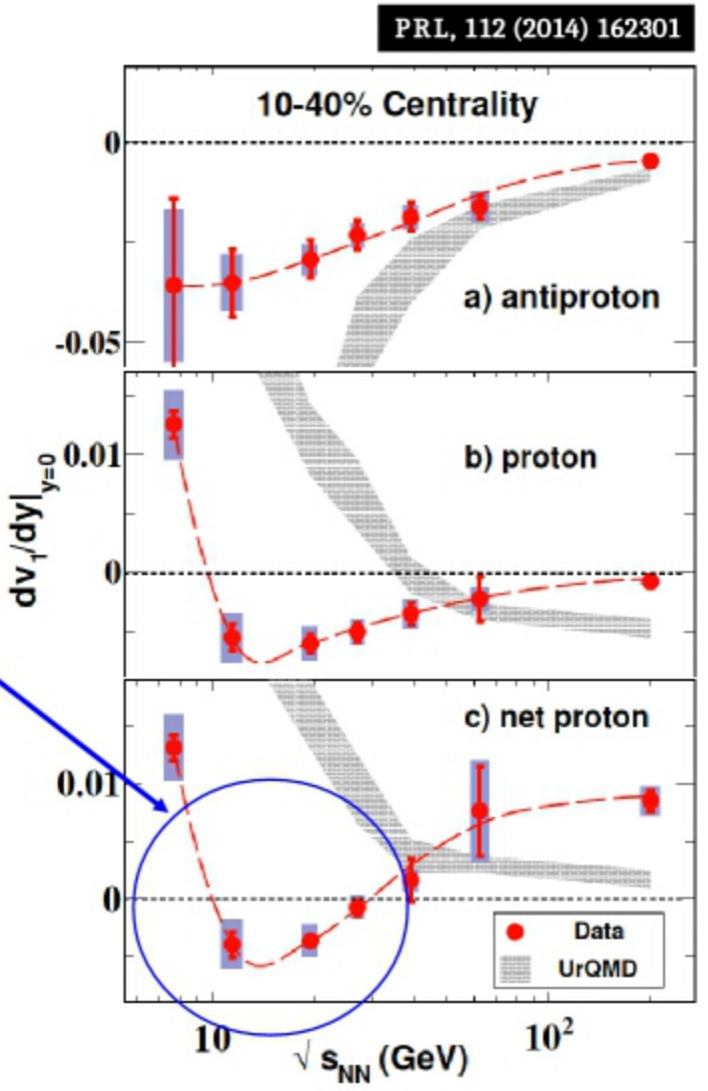




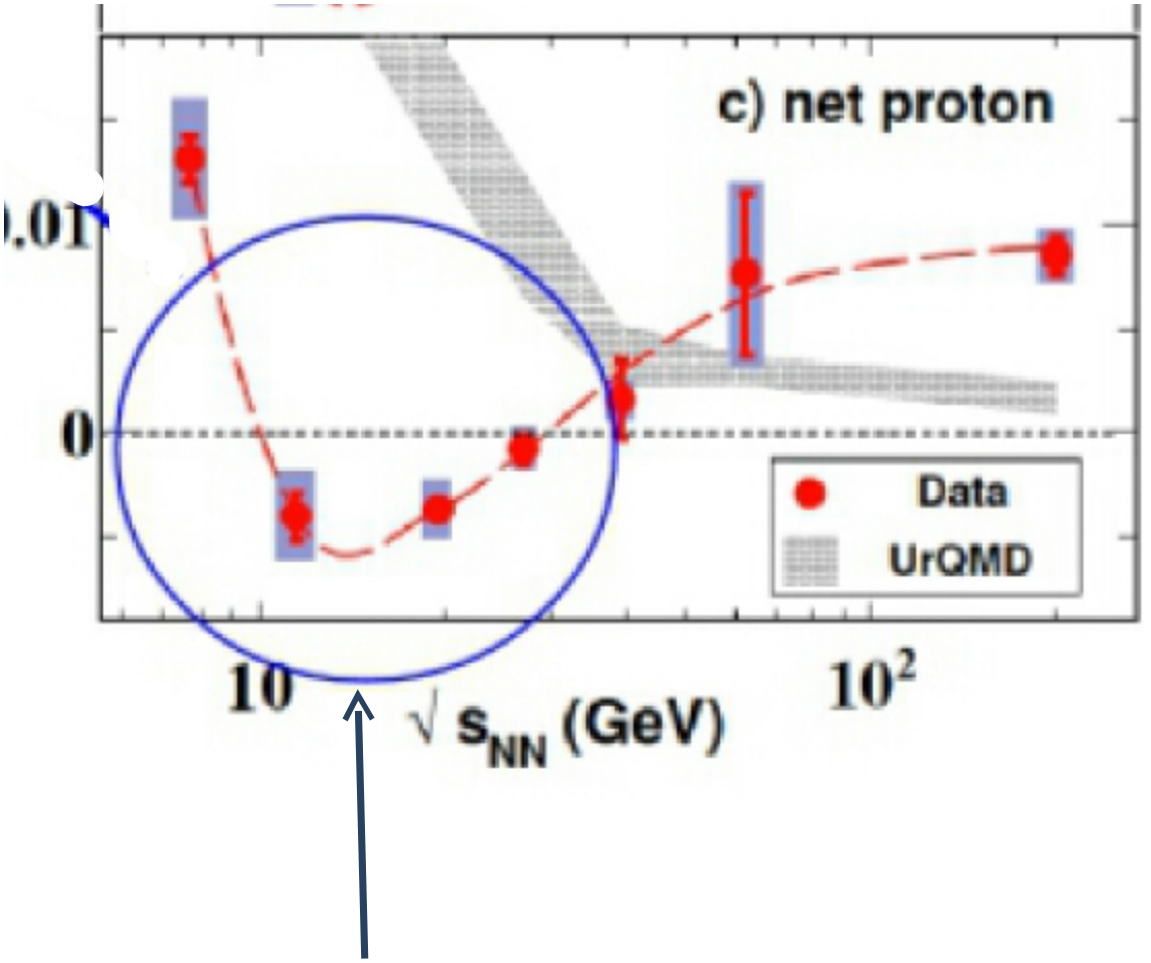
Dale: OD ?, SP 8 GeV

... and the v_1 dip...





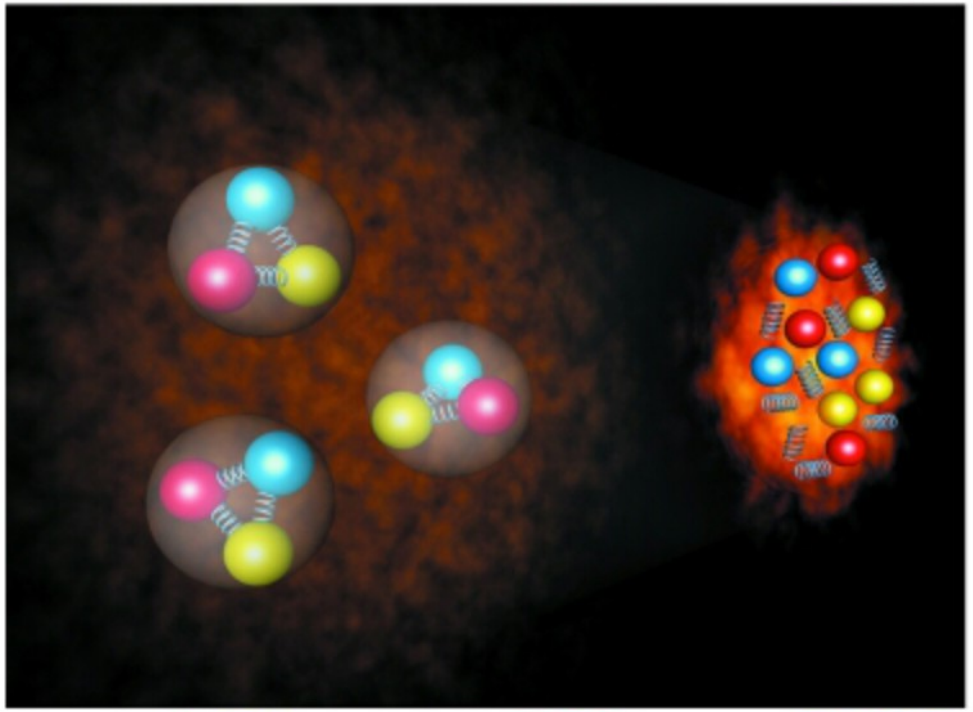
Dip in v1(y) slope at y = 0
agrees with expectations for
the softening of EoS at
the first order phase transition



Dip: OD ?, SP 12 GeV

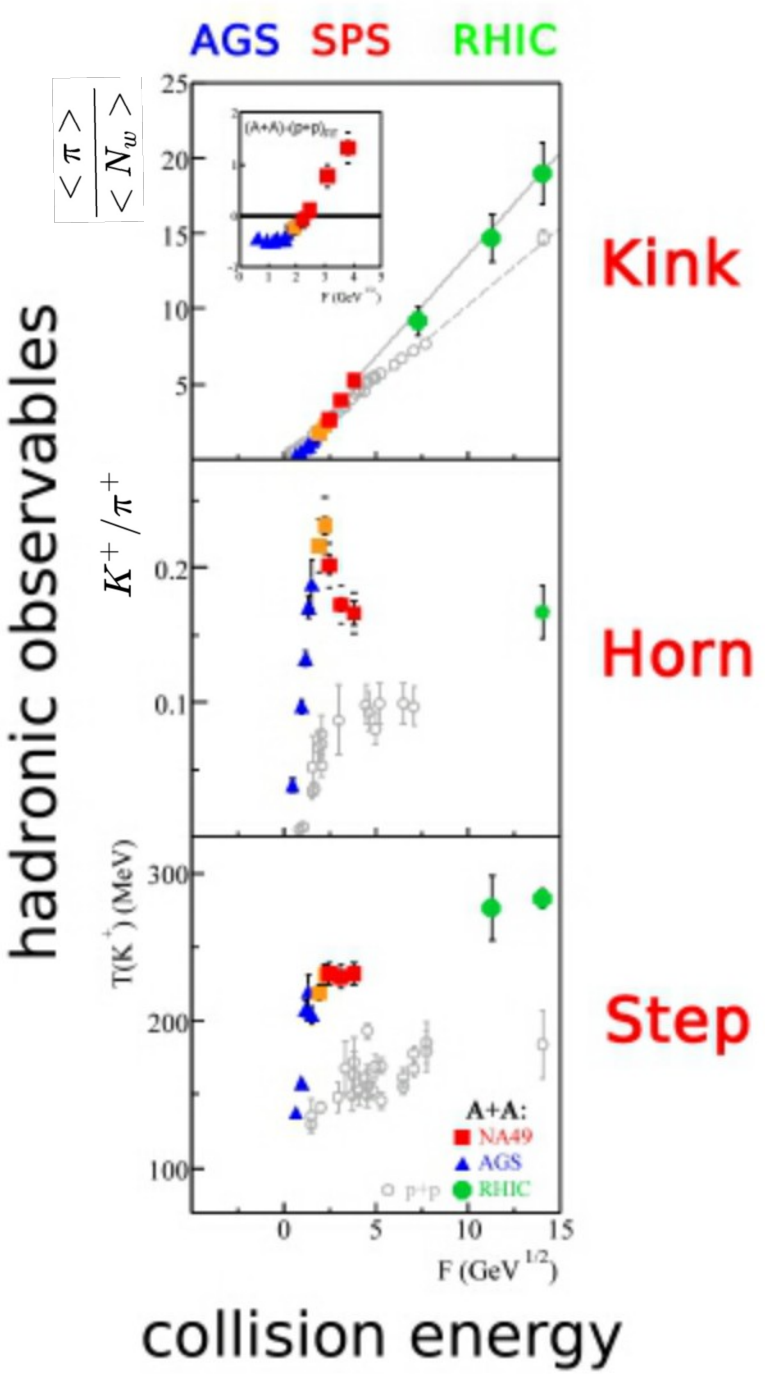
Heating curves of strongly interacting matter

hadrons mixed QGP

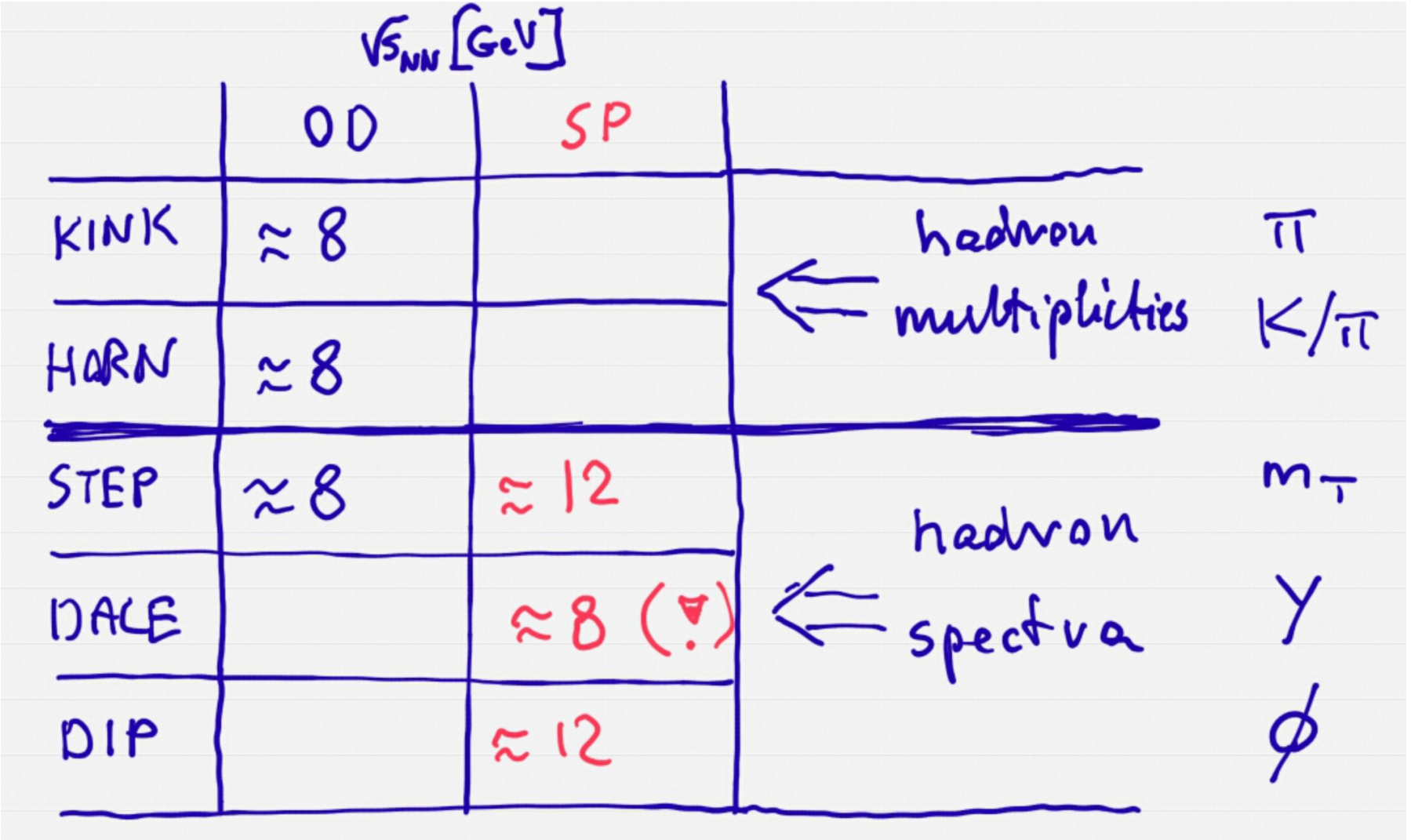


AGS SPS RHIC

collision energy



Evidence for the onset of deconfinement and the softest point in central Pb+Pb collisions at 8 GeV and 12 GeV



ROLF HAGEDORN 1994:

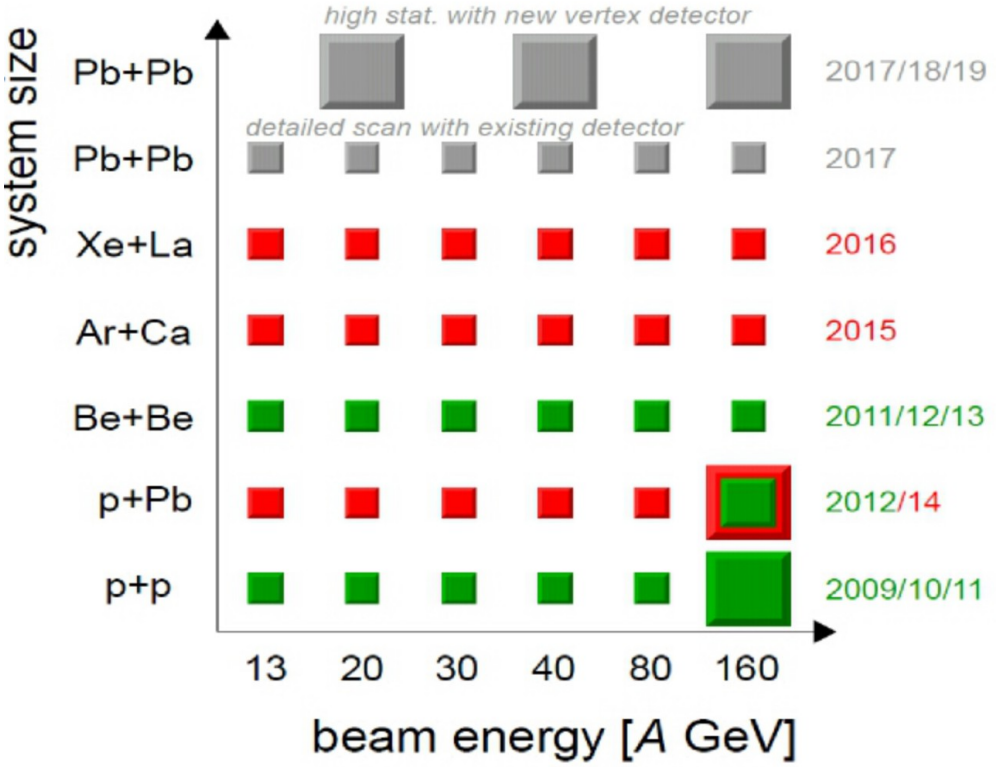
Dear Dr. Gaździcki,

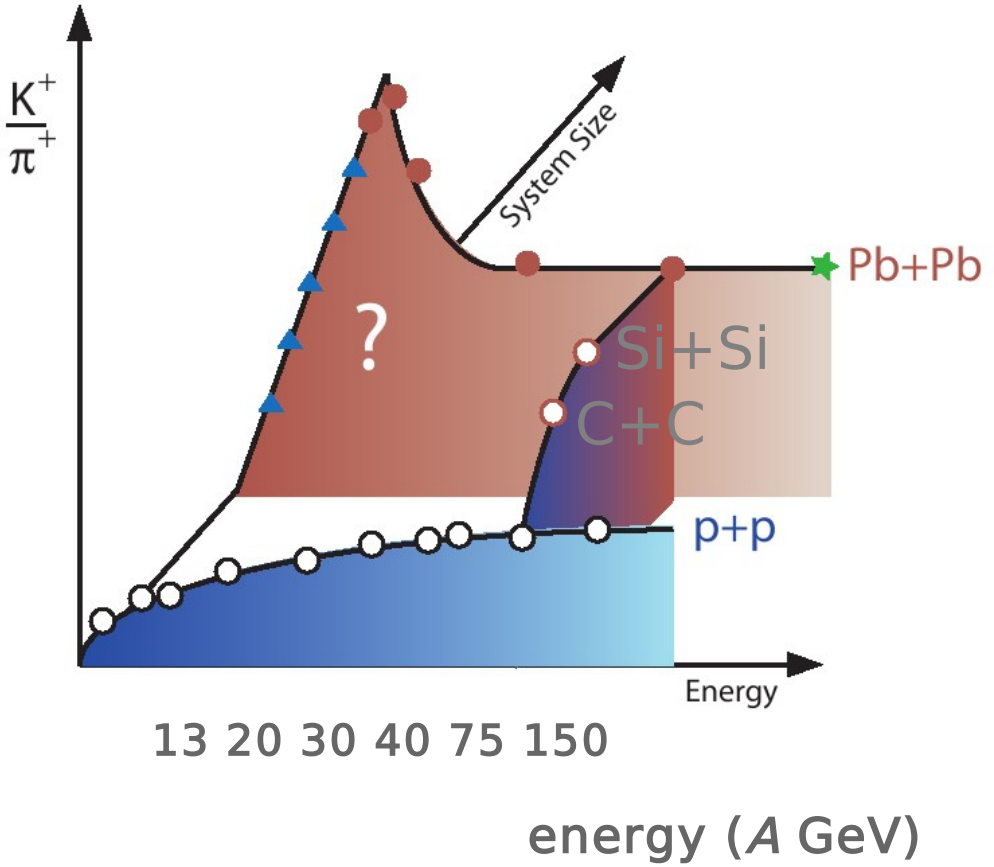
it was a pleasure to listen to your presentation of entropy production in nuclear collisions. It would be interesting to see your interpretation of the overproduction in S+S collisions at 200 GeV/c/A confirmed by future data and by independent theoretical estimates of the change of entropy at the phase transition. A lot of work remains to be done before we know there is a (one, maybe two?) phase transition and what are the details. Good luck for the future!

Yours Rolf Hagedorn

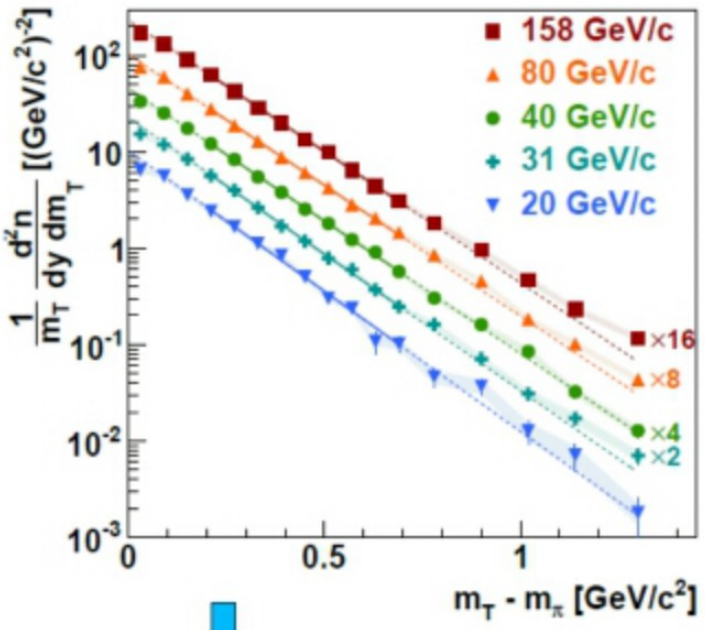
CERN 2003:
ROLF HAGEDORN WHO INTRODUCED THE CONCEPT THAT HADRONIC MATTER HAS A MELTING POINT, DIED ON MARCH 9 2003

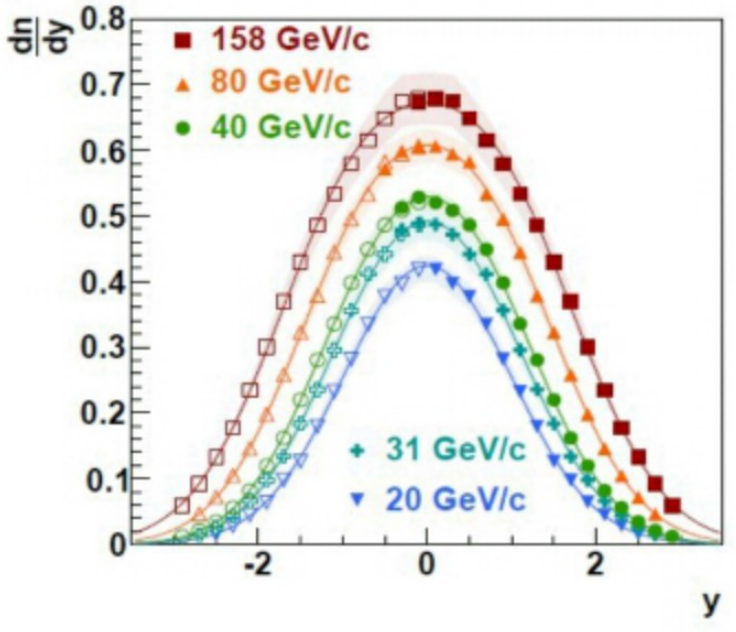
NA61/SHINE at the CERN SPS studies system size dependence of the onset signals





Energy dependence of hadron production in p+p interactions

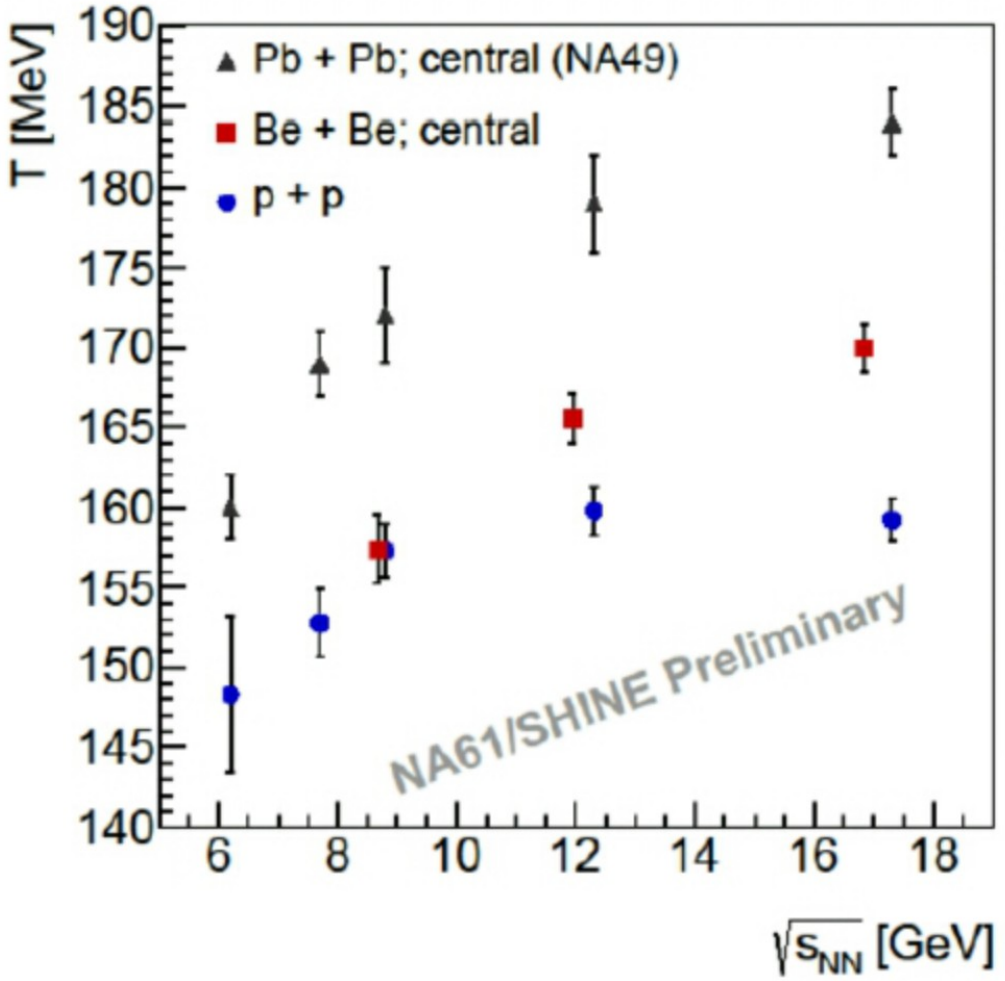




… and their projections/slices

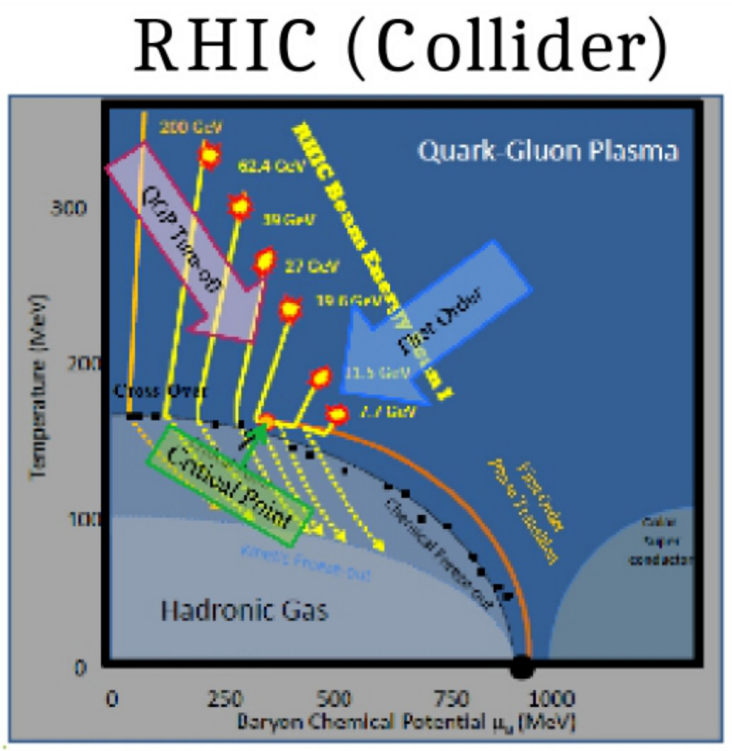
inverse slope parameter of transverse mass spectra, T

Preliminary results on Be+Be collisions: inverse slope parameter of transverse mass spectra



Onset of collectivity in central Be+Be collisions at about 75*A* GeV/c

RHIC Beam Energy Scan



$\sqrt{s_{NN}}$ (GeV)	*MB Events in 10^6
7.7	4.3
11.5	11.7
14.5	24**
19.6	35.8
27	70.4
39	130.4
62.4	67.3

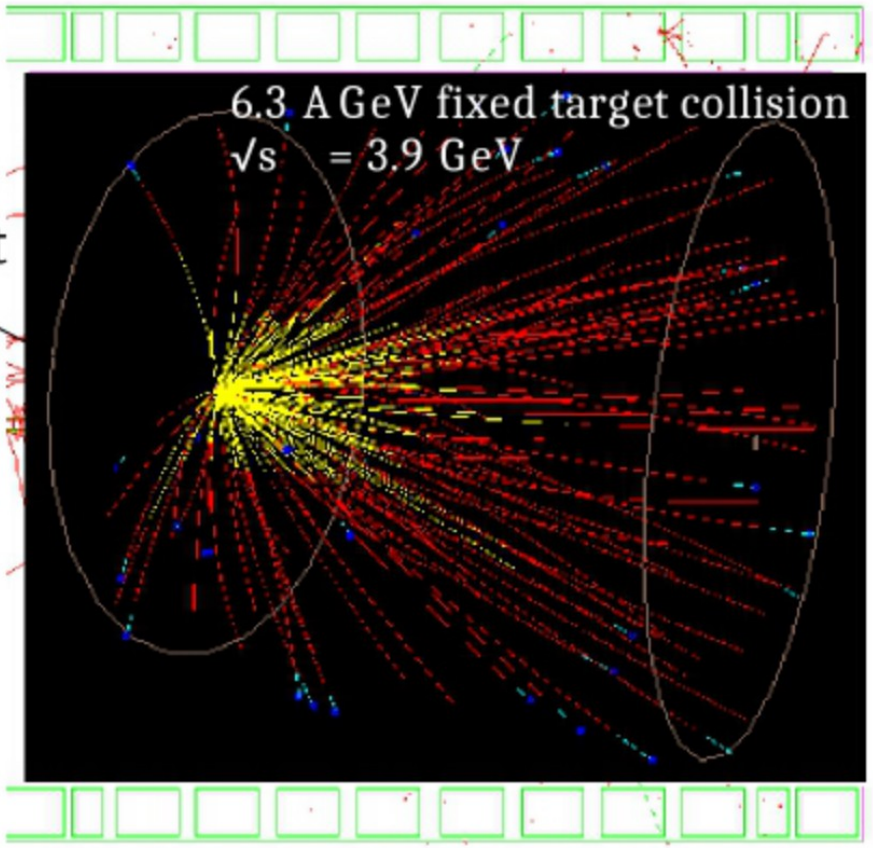
Phase I: Analysis of already recorded data

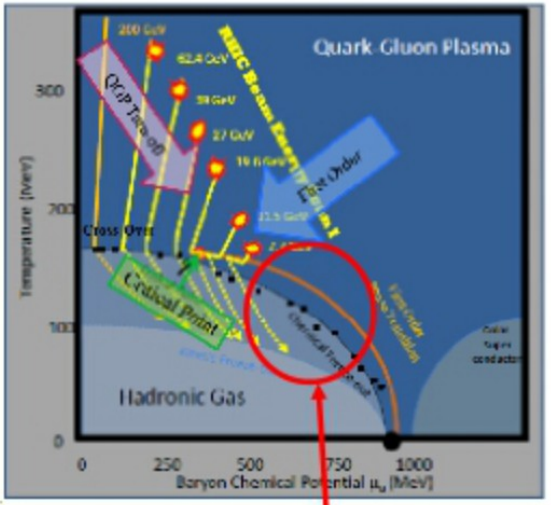
Phase II: Significantly higher Statistics with upgraded detectors

and ...

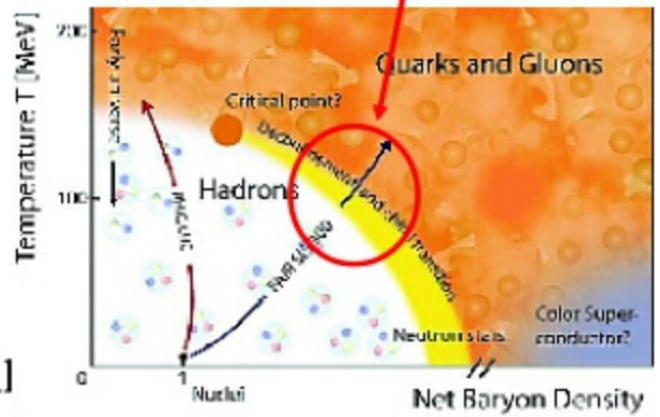
Fixed Target Program for BES II

Brooke Haag, poster





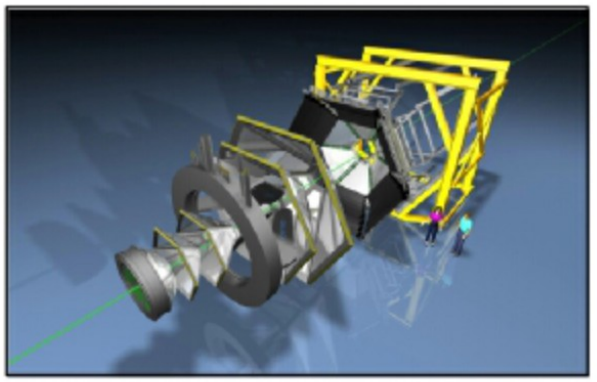
Access to low T, high μ_B



- Fixed target program extends STAR's physics reach to region of compressed baryonic matter
- Simultaneous run with collider mode (ions from the hal **but** much lower luminosity compared to CBM!

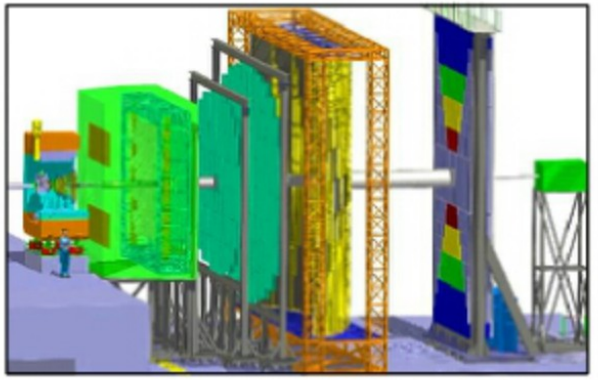
Future Experiments at High Baryon Densities

HADES@FAIR



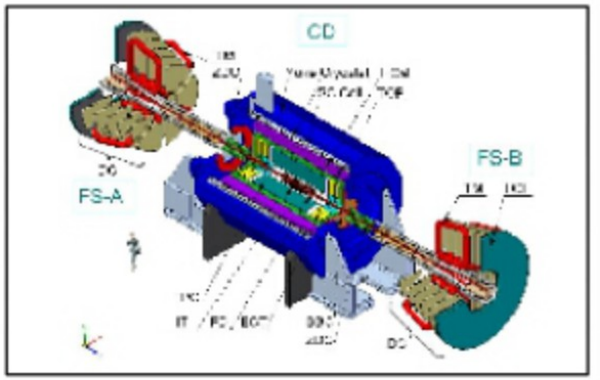
- Fixed target experiment
- SIS18/SIS100
- → $\sqrt{s_{NN}}$ = 2-3 GeV
- Di-leptons + multi-strange hadrons
- EMCAL upgrade for π^0 and η
- But: limited by occupancy, data rate and acceptance at higher energies
- → CBM

CBM@FAIR



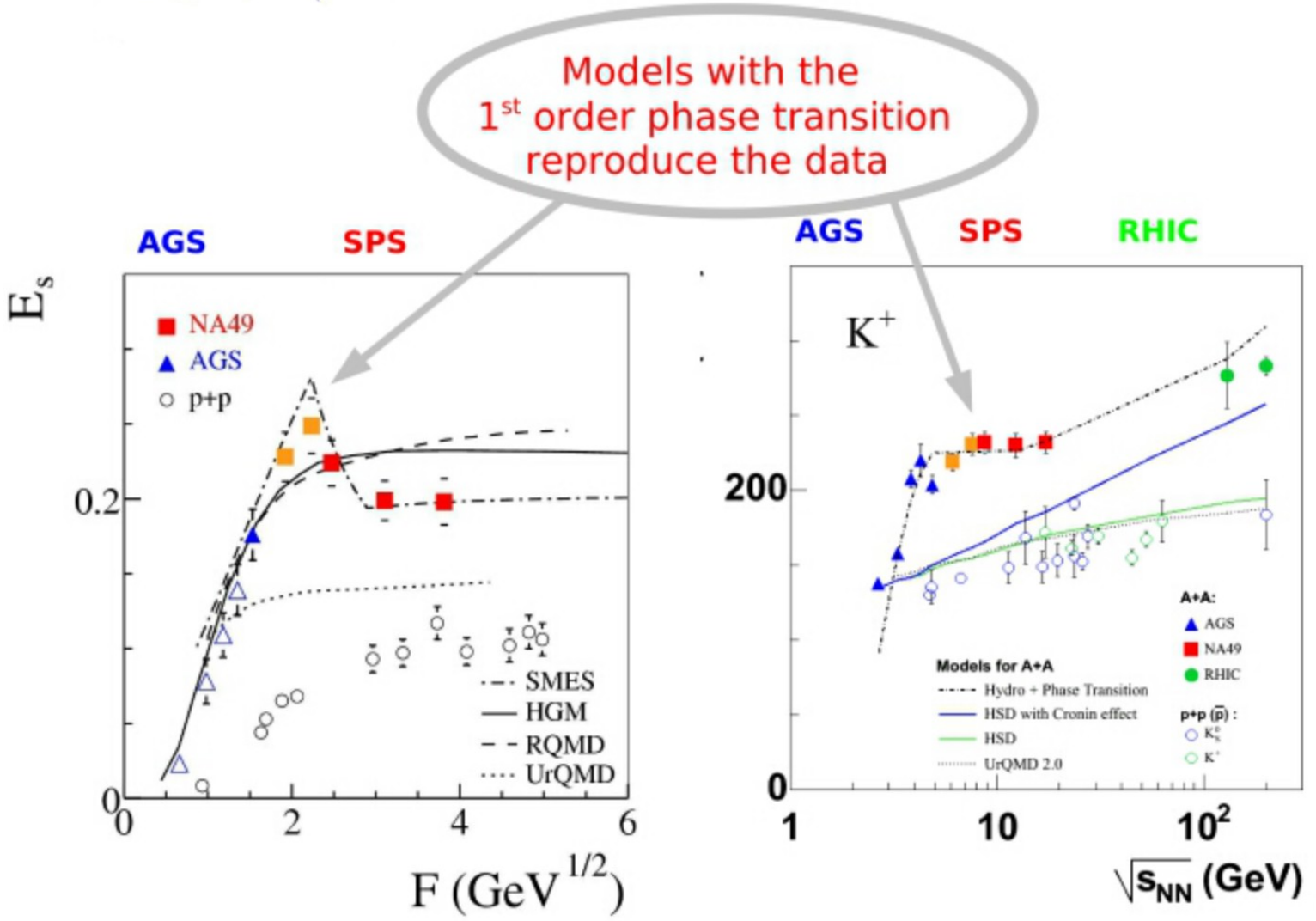
- Fixed target experiment
- SIS100/SIS300
- → $\sqrt{s_{NN}}$ = 2-8 GeV
- Differential measurements of rare probes (Ξ, J/ψ, D^0,...)
- Phase transition to quarkyonic and partonic matter
- Charm production, hypernuclei,...
- SIS 100 ready: 2019

MPD@NICA



- Collider experiment
- $\sqrt{s_{NN}}$ = 4-11 GeV
- Study of in-medium properties of hadrons
- Nuclear EoS
- Phase transition, critical point search

The models



$$E_S = (\langle \Lambda \rangle + \langle K + \overline{K} \rangle) / \langle \pi \rangle$$

ROLF HAGEDORN 1994:

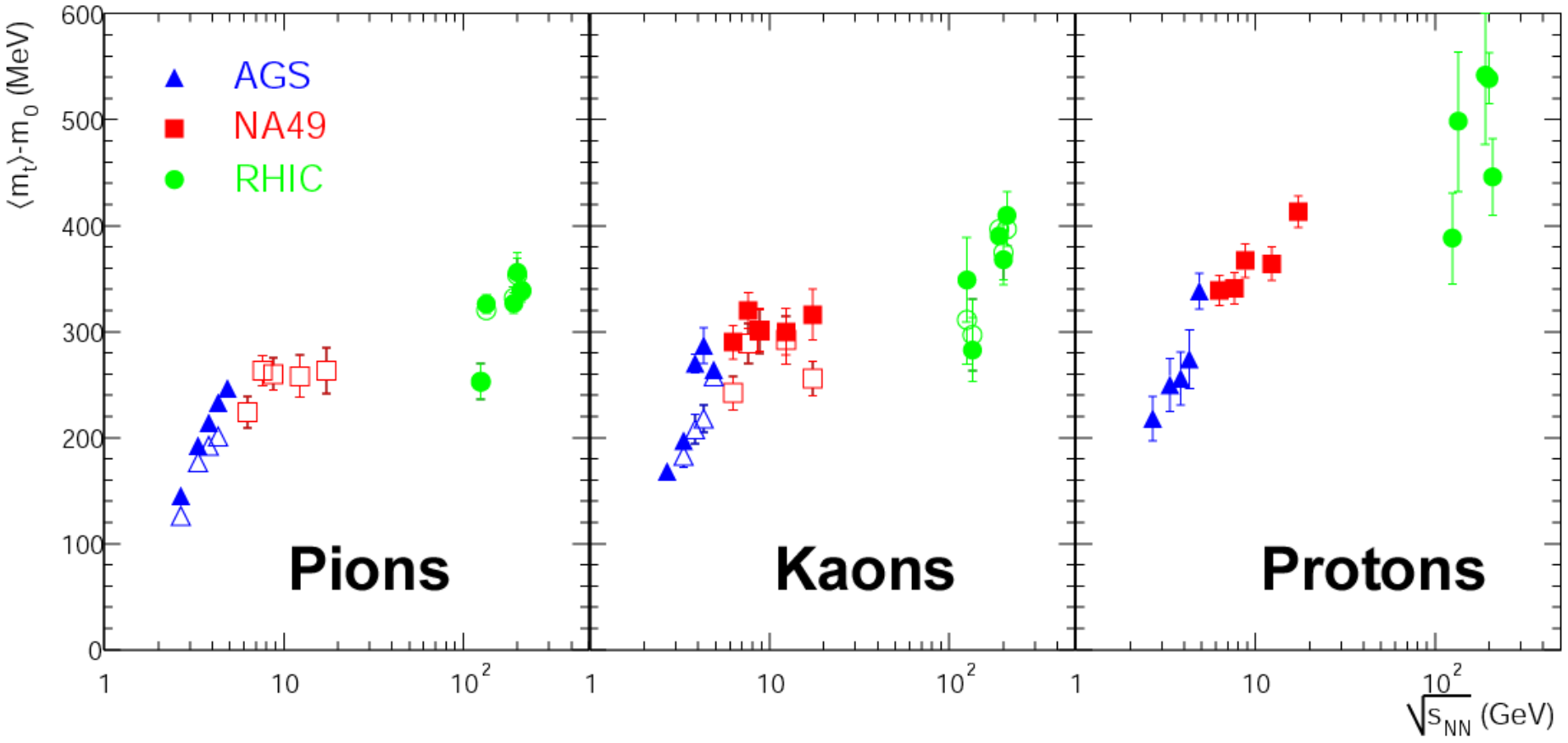
Dear Dr. Gaździcki,

it was a pleasure to listen to your presentation of entropy production in nuclear collisions. It would be interesting to see your interpretation of the overproduction in S+S collisions at 200 GeV/c/A confirmed by future data and by independent theoretical estimates of the change of entropy at the phase transition. A lot of work remains to be done before we know there is a (one, maybe two?) phase transition and what are the details. Good luck for the future!

Yours Rolf Hagedorn

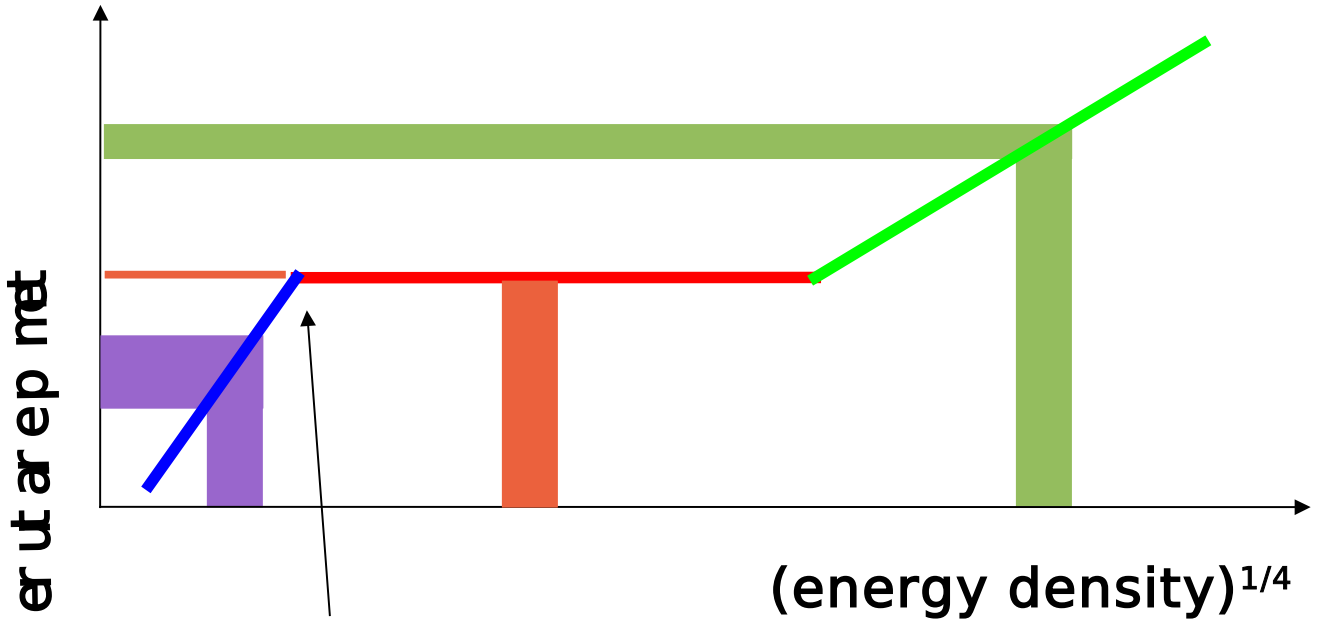
CERN 2003:
ROLF HAGEDORN WHO INTRODUCED THE CONCEPT THAT HADRONIC MATTER HAS A MELTING POINT, DIED ON MARCH 9 2003

... and in $\langle m_T \rangle$ of various hadrons



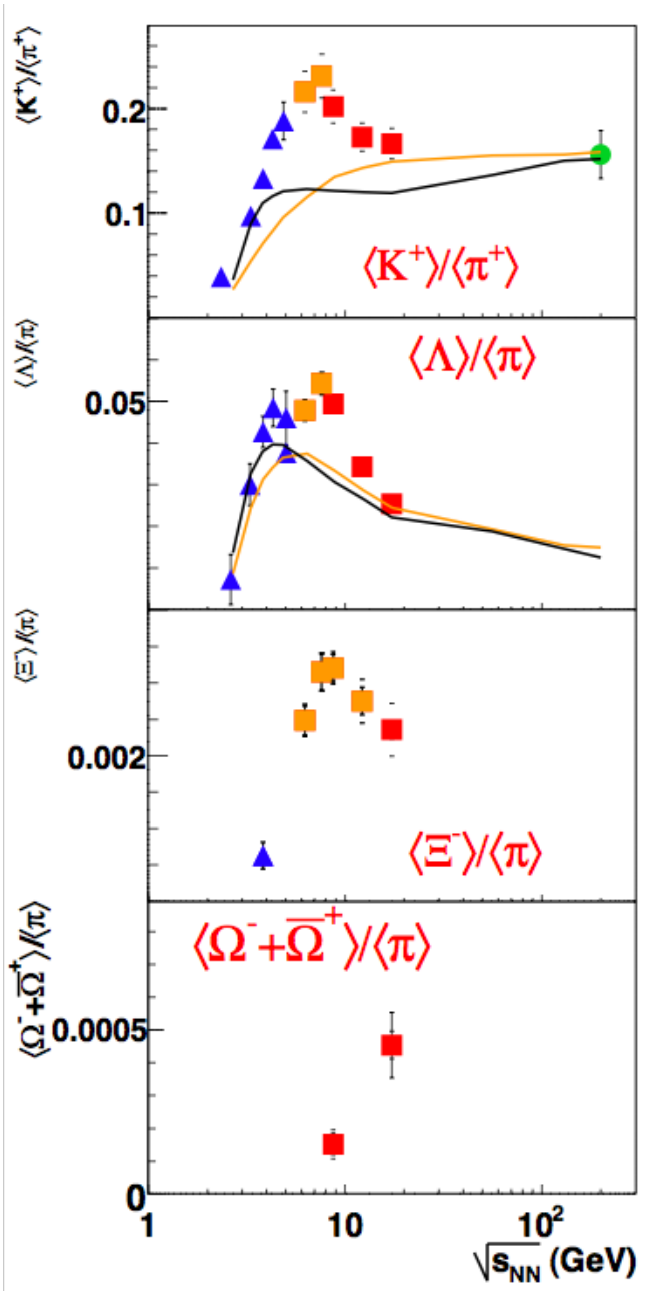
Strangeness fluctuations and deconfinement

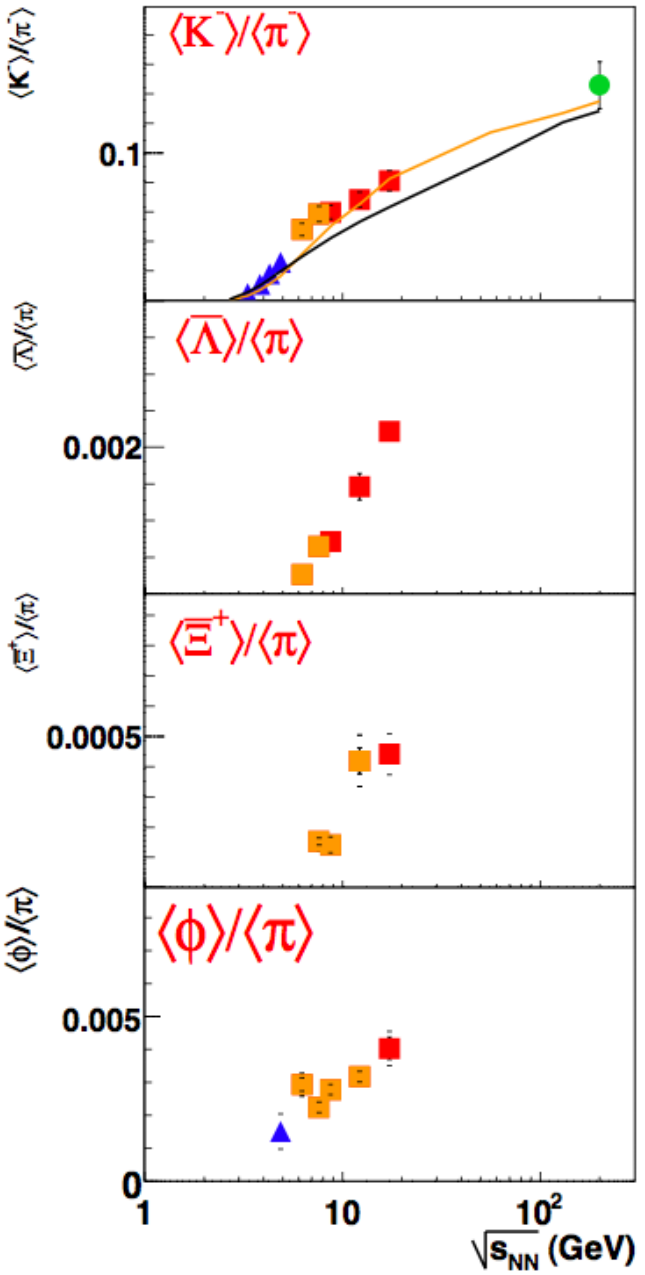
Response to the initial energy density fluctuations depends on the Equation of State at the early stage of the collisions

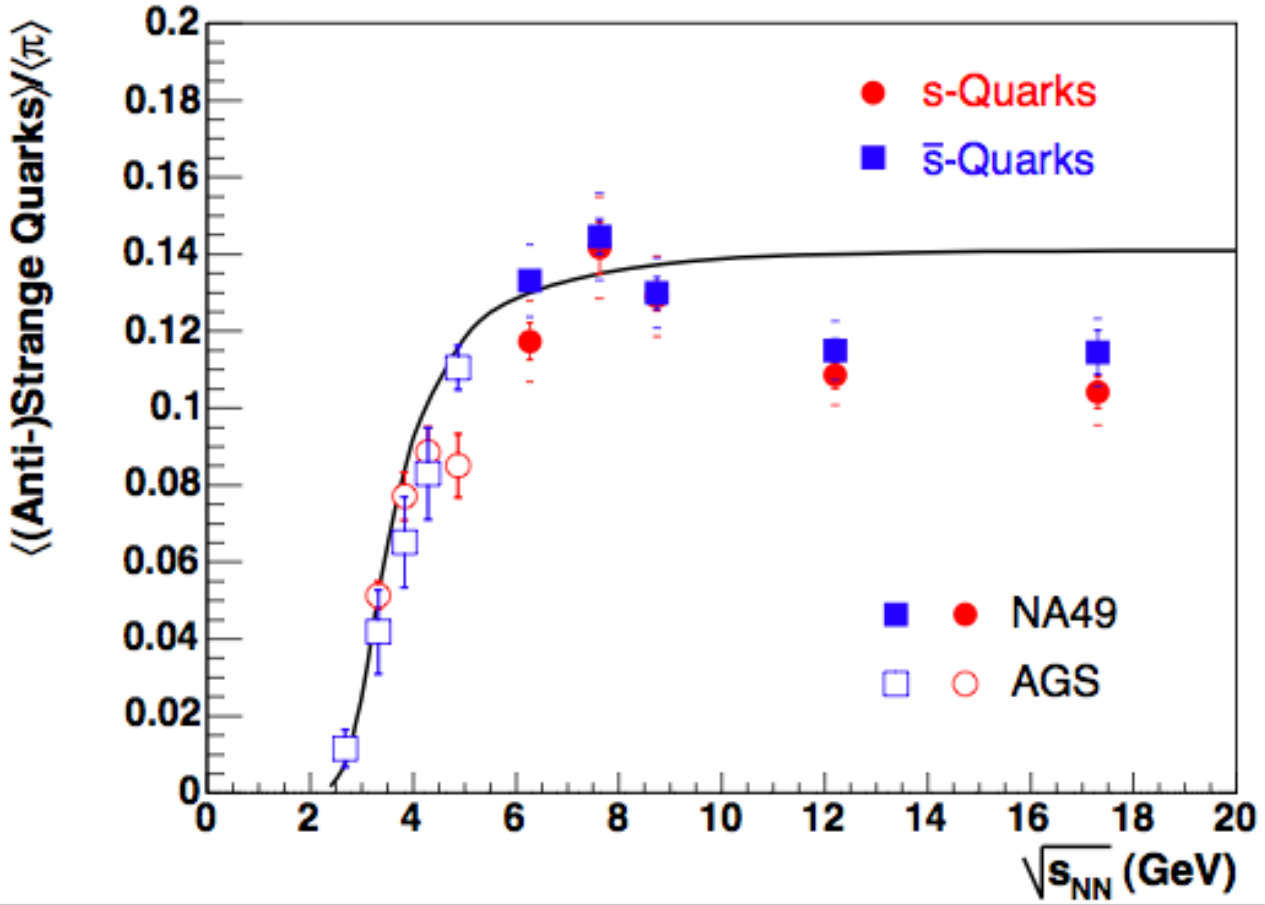


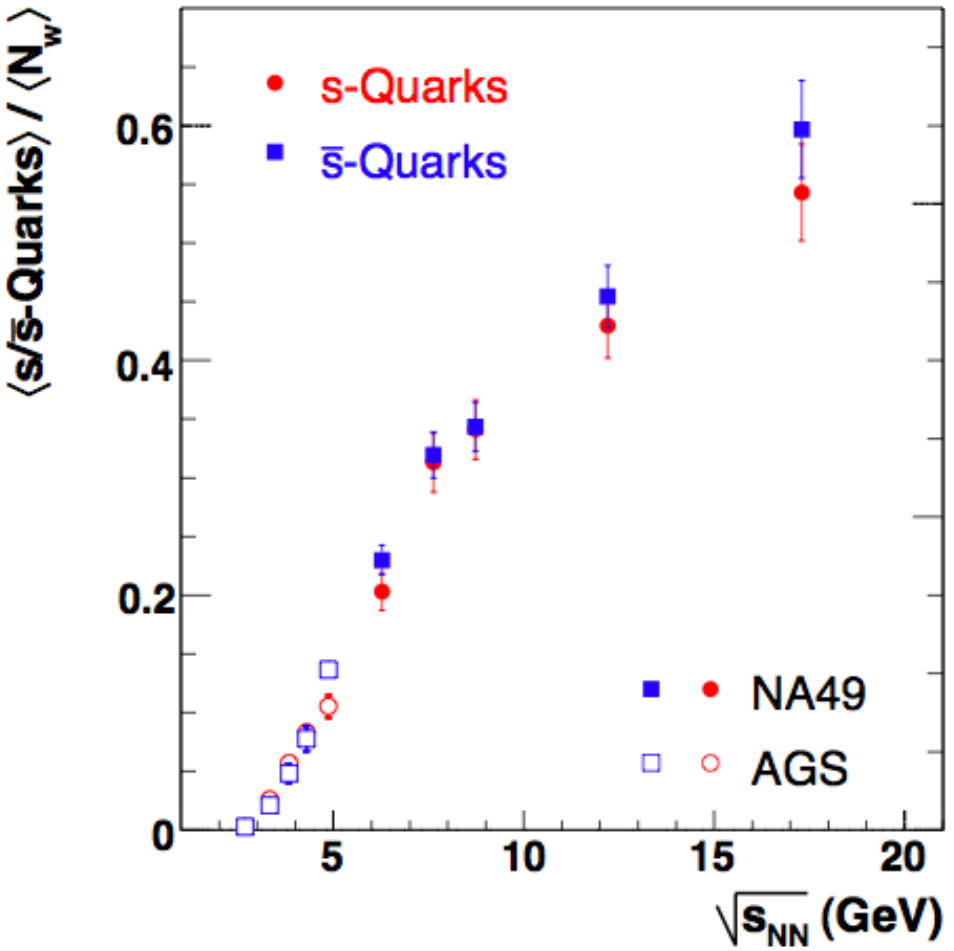
onset of deconfinement

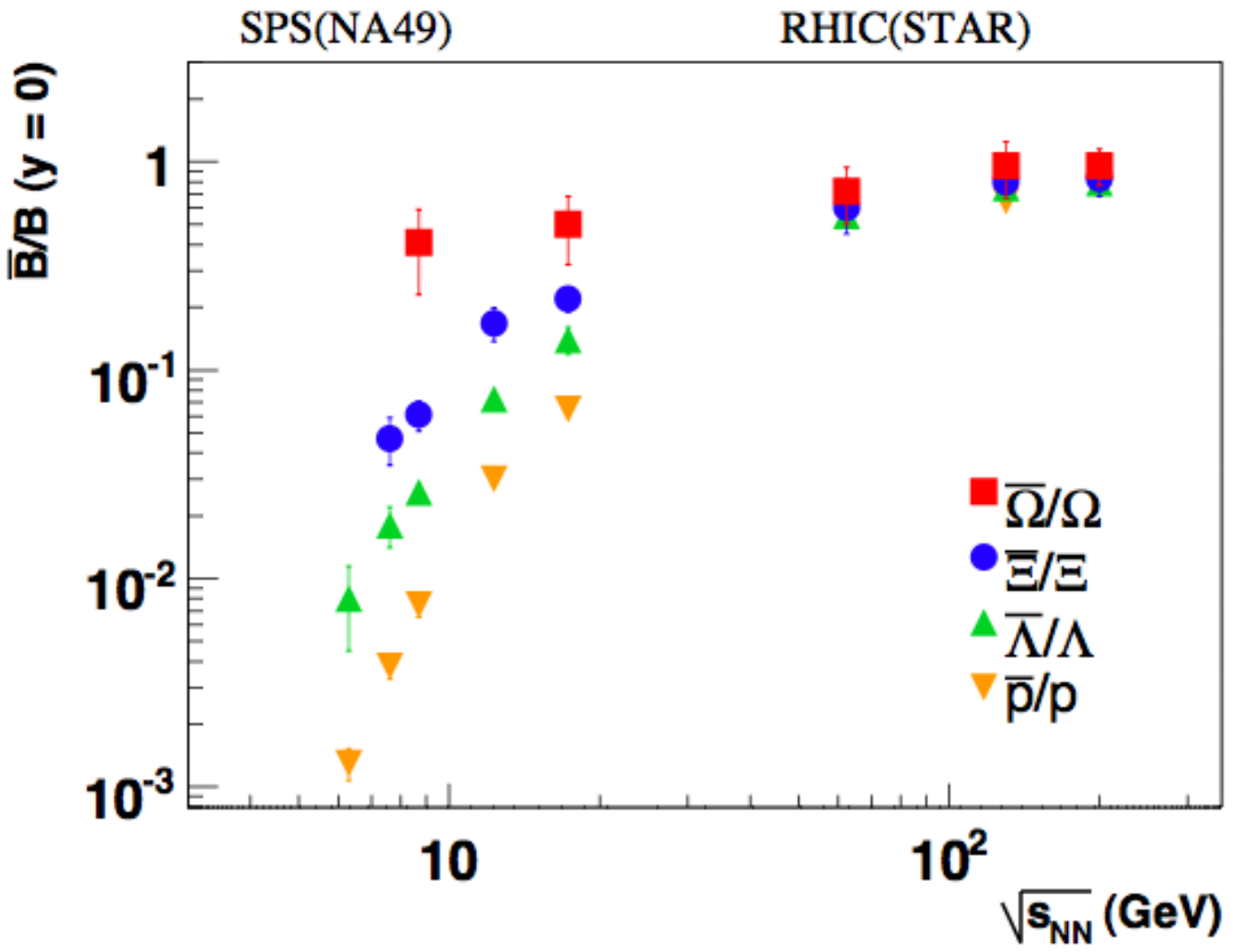
Gorenstein, M.G., Zozulya, PL B585:237, 2004

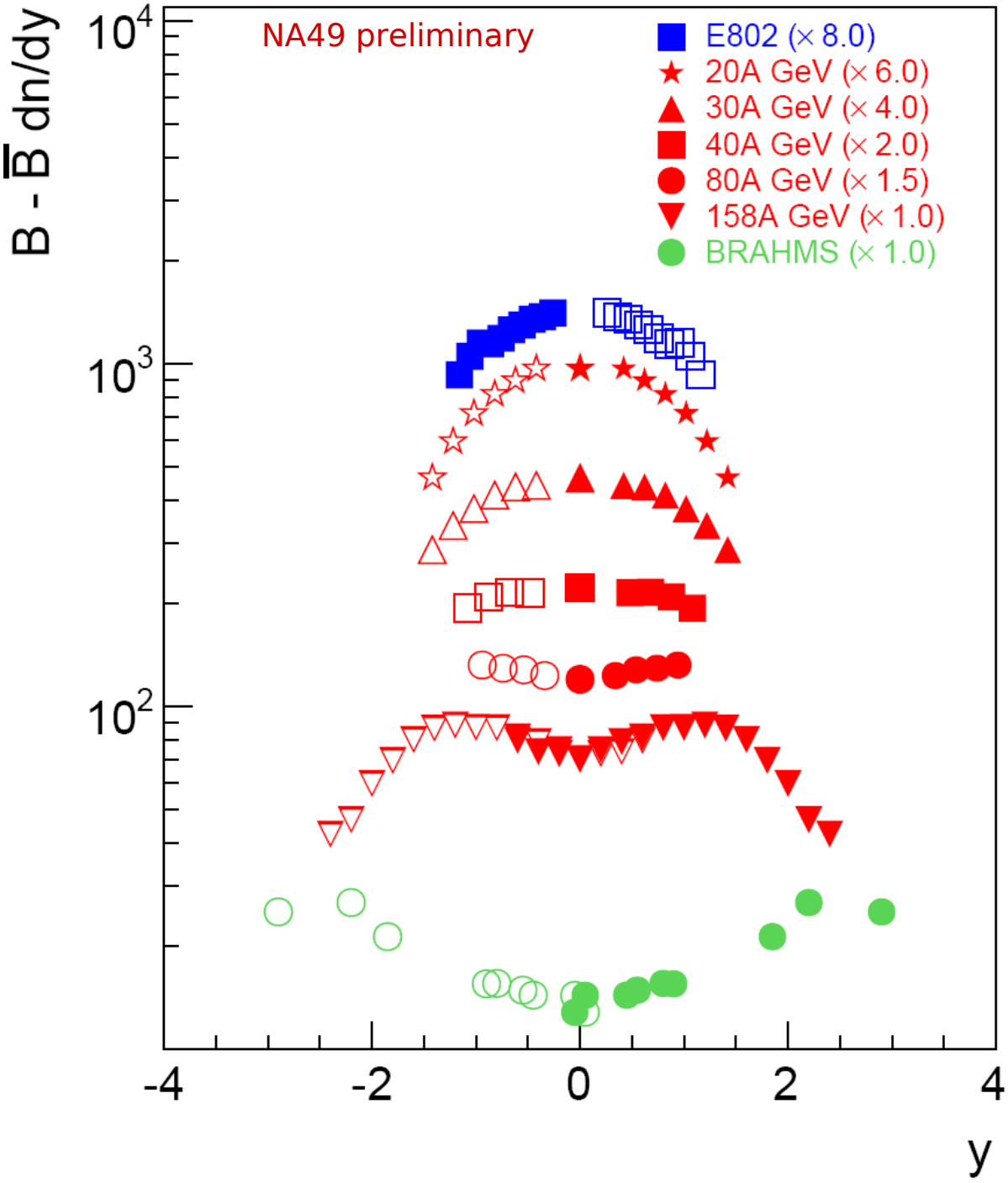

⟨K⁺⟩/⟨π⁺⟩
⟨Λ⟩/⟨π⟩
⟨Ξ⁻⟩/⟨π⟩
⟨Ω⁻+Ω̄⁺⟩/⟨π⟩
0.2
0.1
0.05
0.002
0.0005
0
1
10
10²
√sNN (GeV)

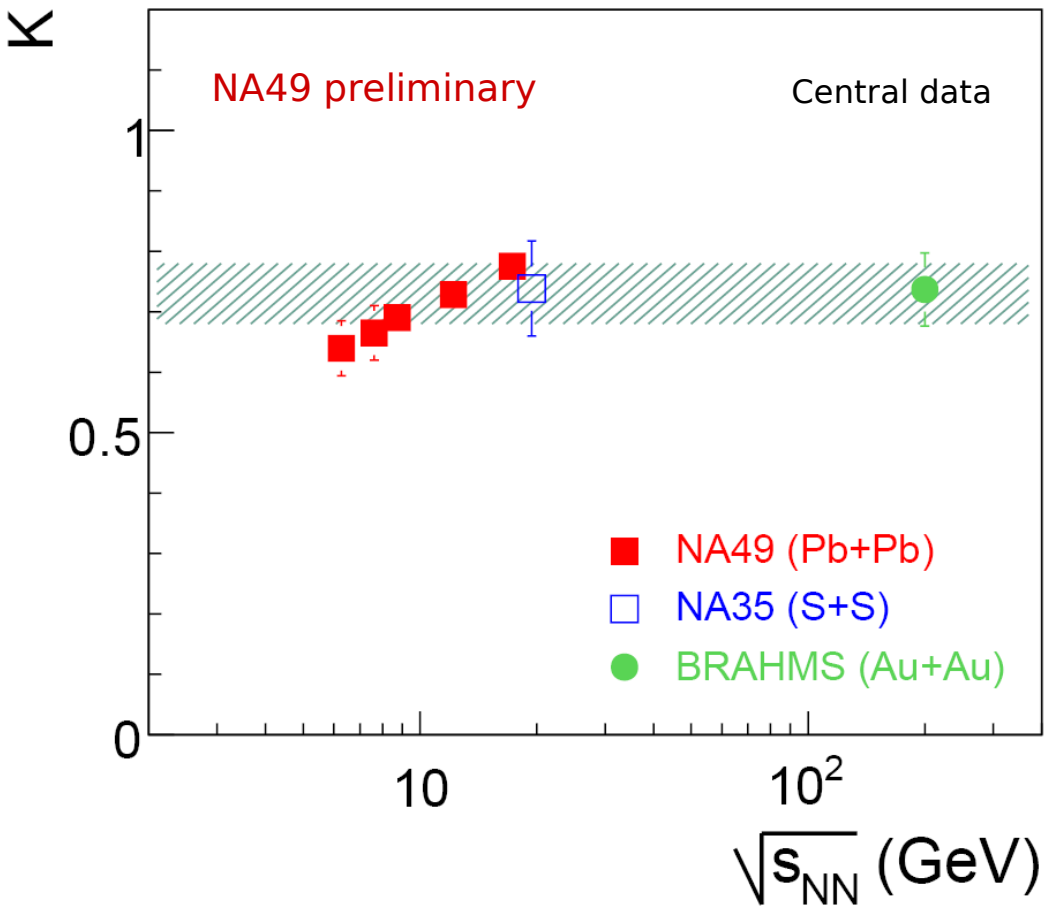

⟨K⁻⟩/⟨π⁻⟩
⟨Λ̄⟩/⟨π⟩
⟨Ξ̄⁺⟩/⟨π⟩
⟨ϕ⟩/⟨π⟩
0.1
0.002
0.0005
0.005
0
1
10
10²
√sNN (GeV)


⟨(Anti-)Strange Quarks⟩/⟨π⟩
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
18
20
√sNN (GeV)
s-Quarks
s̄-Quarks
NA49
AGS


⟨s/s̄-Quarks⟩ / ⟨N_w⟩
s-Quarks
s̄-Quarks
NA49
AGS
0
0.2
0.4
0.6
5
10
15
20
√s_NN (GeV)


SPS(NA49)
RHIC(STAR)
$\bar{B}/B$ (y = 0)
1
10^{-1}
10^{-2}
10^{-3}
10
10^2
$\sqrt{s_{NN}}$ (GeV)
$\bar{\Omega}/\Omega$
$\bar{\Xi}/\Xi$
$\bar{\Lambda}/\Lambda$
$\bar{p}/p$


NA49 preliminary
E802 (× 8.0)
20A GeV (× 6.0)
30A GeV (× 4.0)
40A GeV (× 2.0)
80A GeV (× 1.5)
158A GeV (× 1.0)
BRAHMS (× 1.0)
B - B̄ dn/dy
10^4
10^3
10^2
-4
-2
0
2
4
y


K
NA49 preliminary
Central data
1
0.5
0
10
10^2
$\sqrt{s_{NN}}$ (GeV)
NA49 (Pb+Pb)
NA35 (S+S)
BRAHMS (Au+Au)