Onset of deconfinement in nucleus-nucleus collisions

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THE PROBLEM

- Strongly interacting matter:
  phases and transitions

AND ITS SOLUTIONS:

PAST (this talk)

- Observation of the onset of deconfinement

AND FUTURE (CPOD, next week)

- Search for the critical point

THE PROBLEM

- Strongly interacting matter:
  phases and transitions

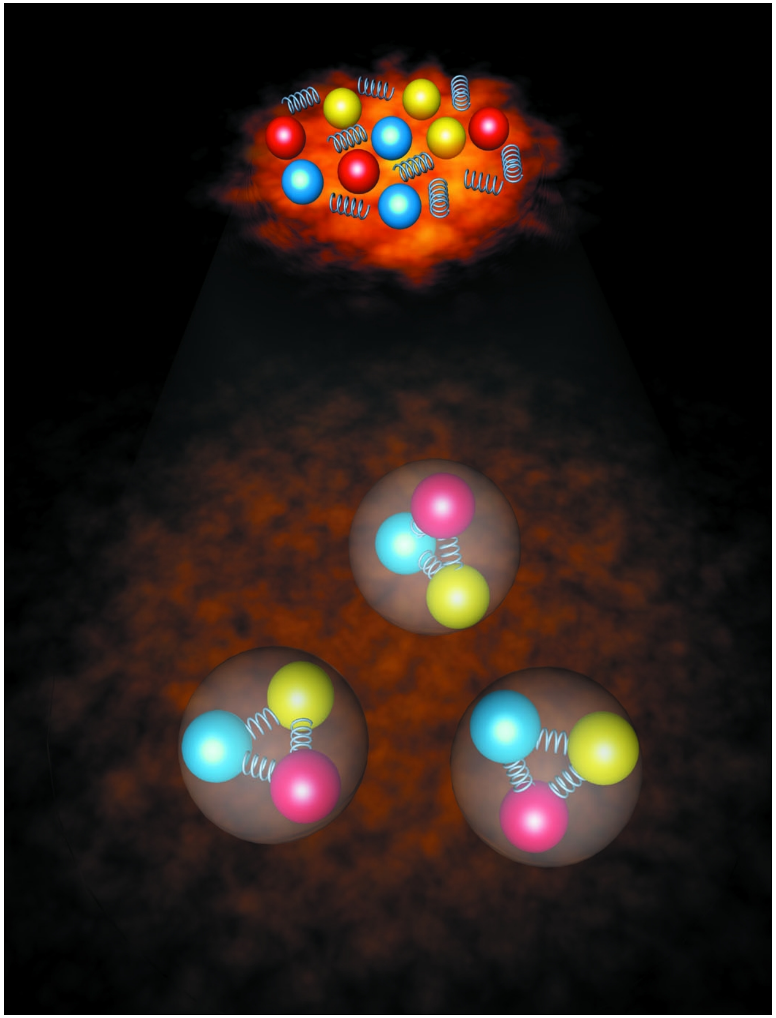
What are the phases of strongly interacting matter?

How do the transitions between them look like?

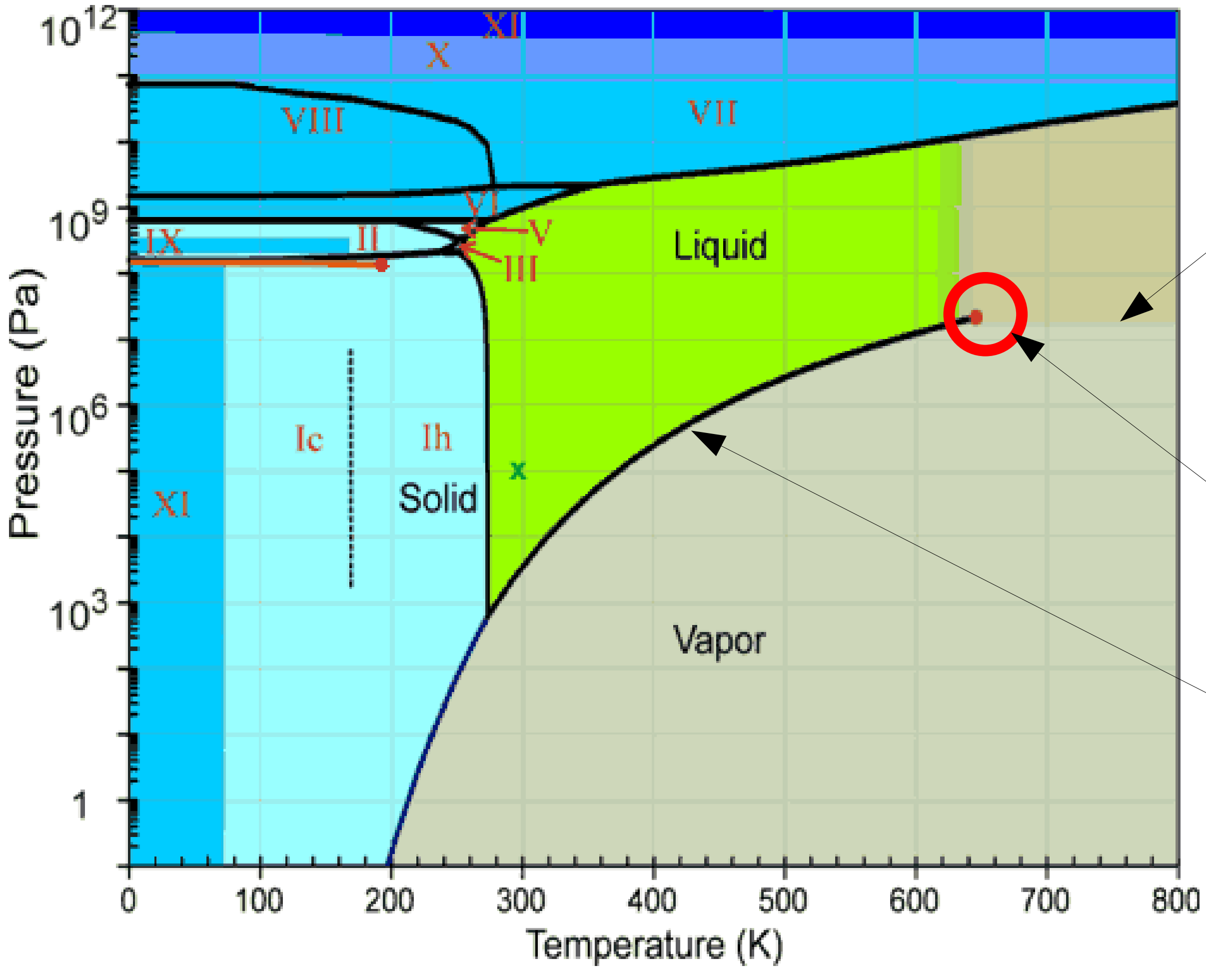
?

Phases of water

Phases of strongly interacting matter



Phase diagram of water



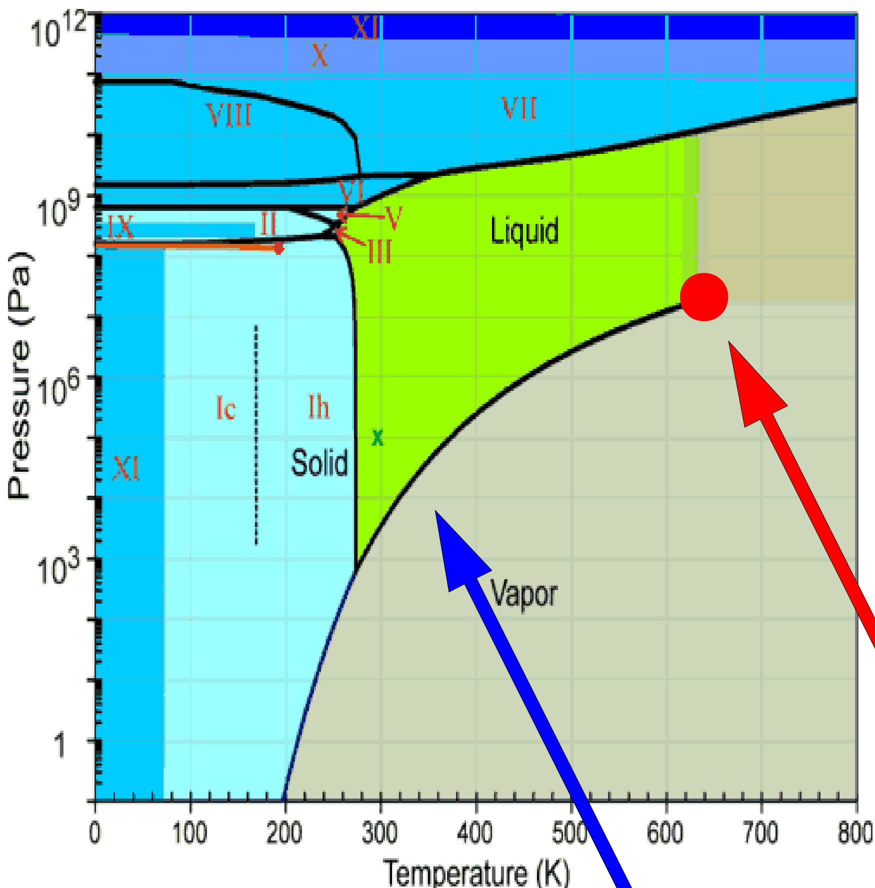
cross-over

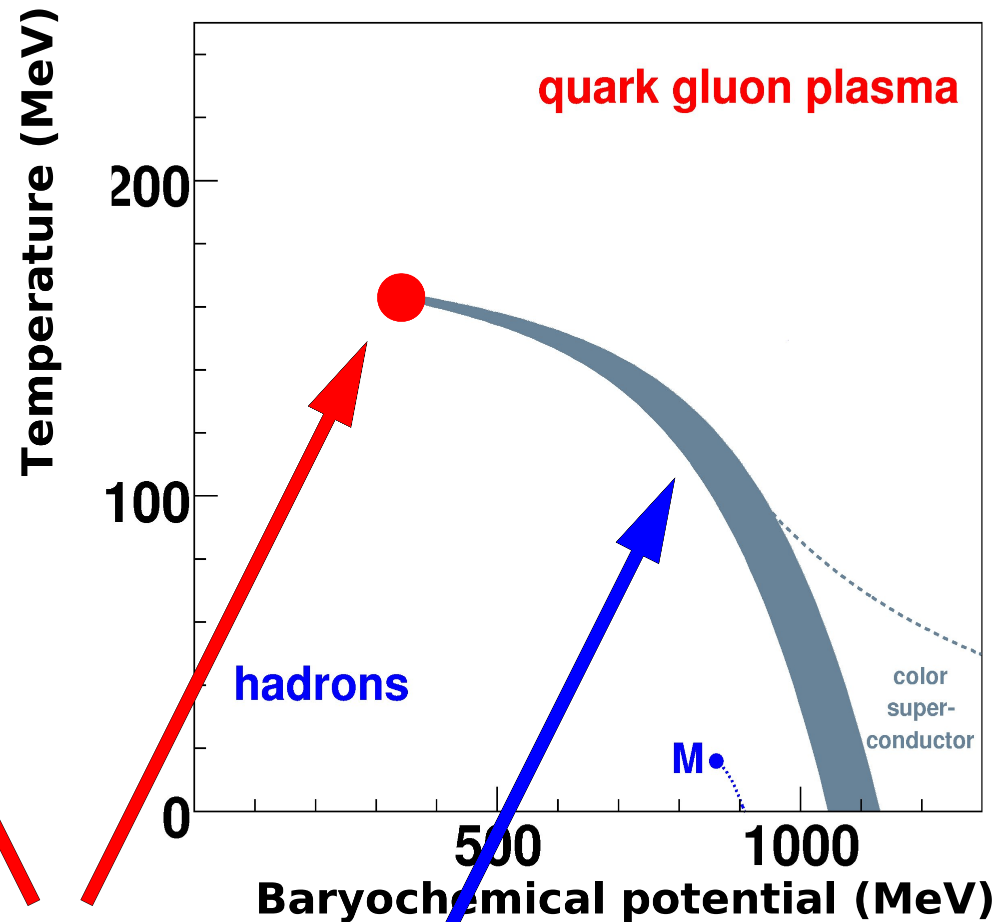
critical point

1st order phase transition

The phase diagram of water is well established

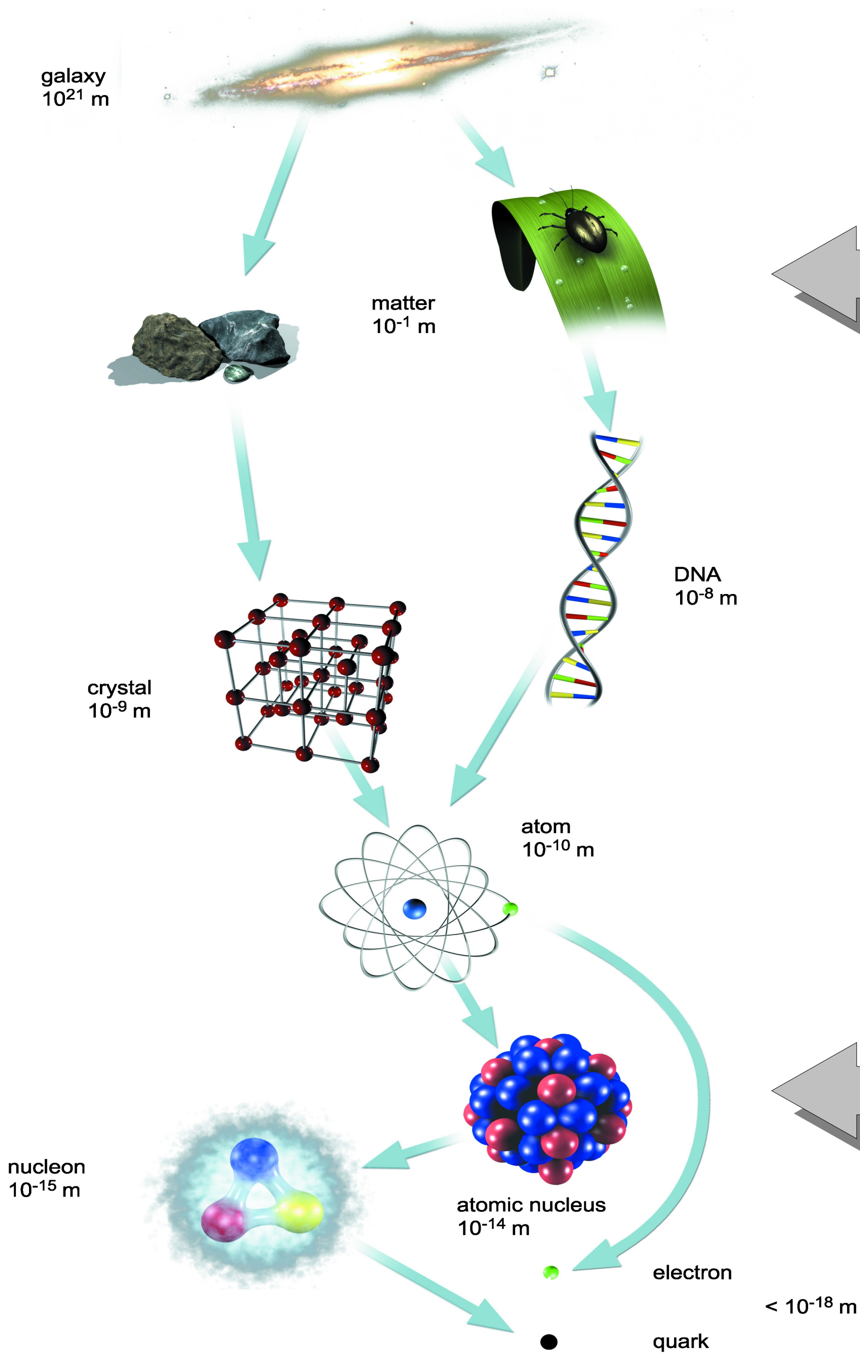
The phase diagram of strongly interacting matter is under study





critical point

1st order phase transition



In our daily life ...

droplets of water

10^{-12}

droplets of strongly interacting matter

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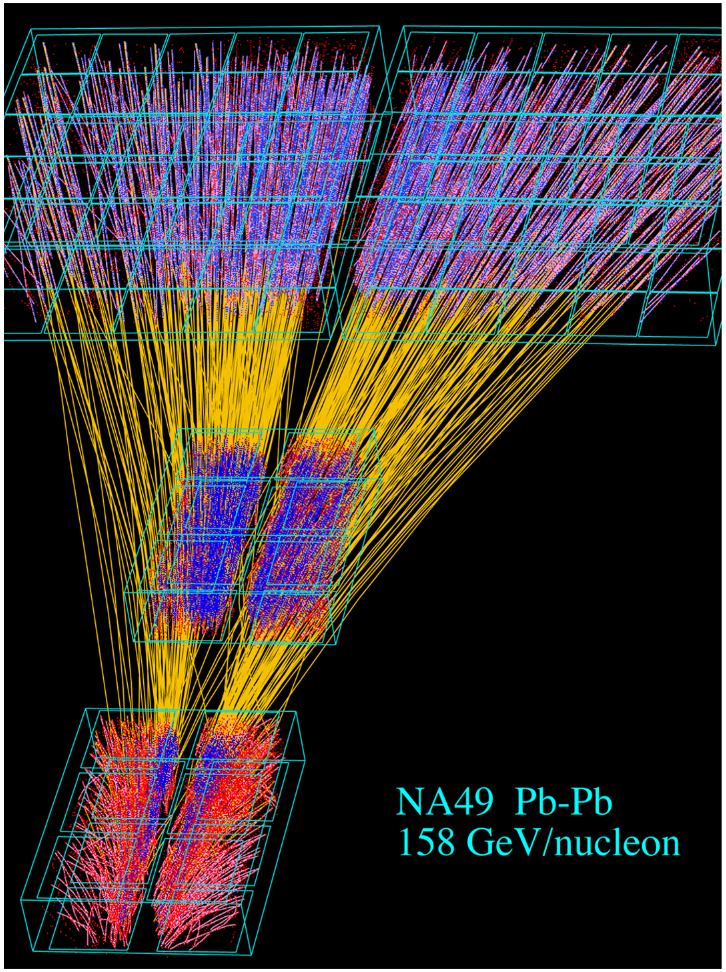
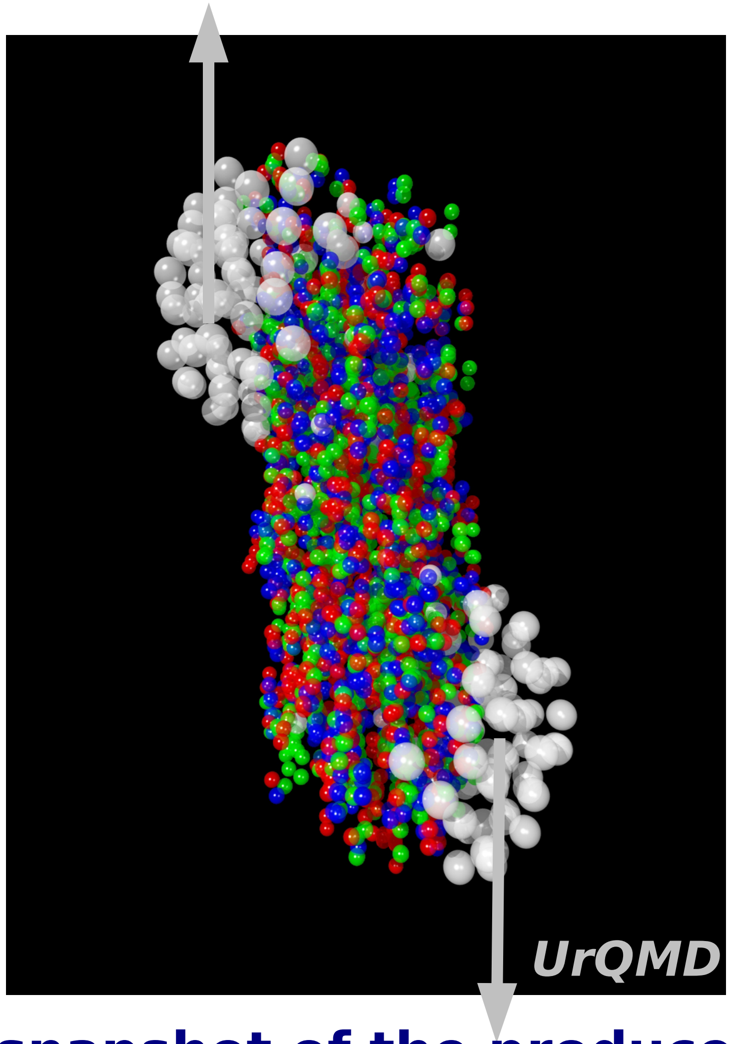
the properties of strongly interacting matter can be studied only in collisions of heavy nuclei

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)

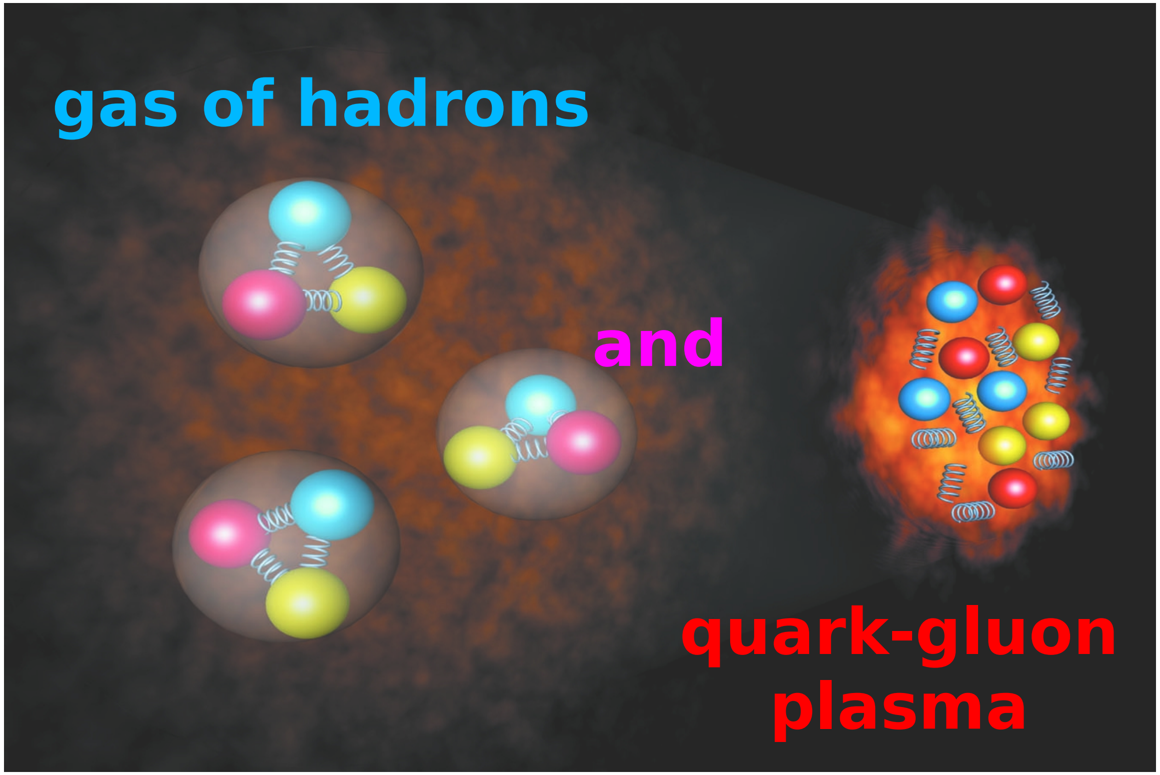


snapshot of the produced matter after the collision (scale 10^{-14} m)

Two basic states of strongly interacting matter are expected

Hadron gas at low densities

Quark-gluon plasma at high densities



... Shuryak ...

Superdense Matter: Neutrons or Asymptotically Free Quarks?

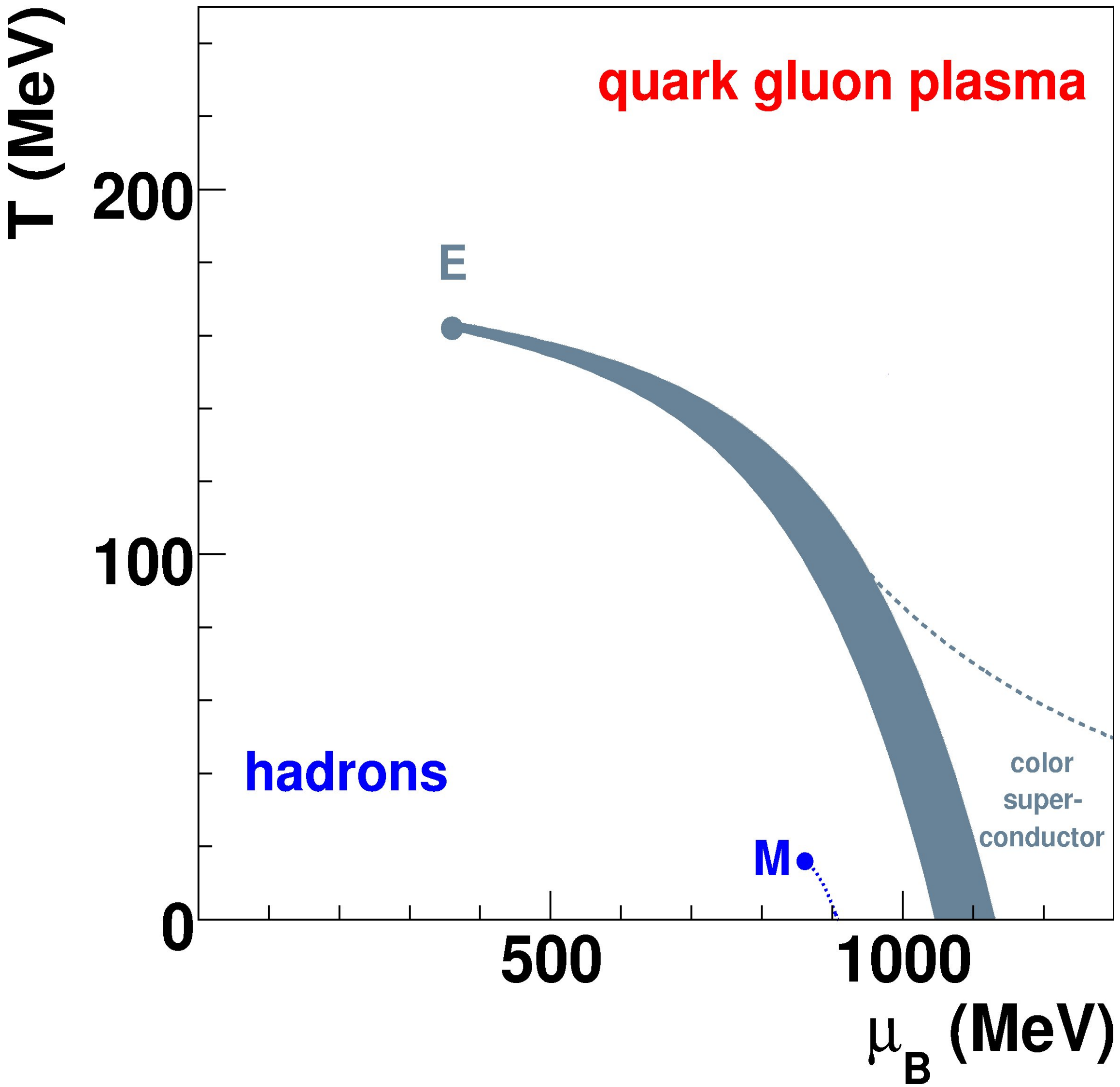
J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

We first give arguments leading to this idea. It is commonly believed that hadrons consist of quarks[5-7] despite the apparent nonexistence of free quarks.[8] There are two main reasons for this belief. First, a quark model explains[5,6] many properties of the hadron spectrum, and of strong-interaction decays. Secondly we have Bjorken scaling[7] in the deep inelastic scattering of leptons by nucleons. Basically, this indicates that hadrons consist of pointlike objects (partons) which interact weakly with each other when close together. Analysis of the data indicates that partons are the fractionally charged spin-$\frac{1}{2}$ Gell-Mann–Zweig quarks. Since free quarks are not observed,[8] it is assumed that they are permanently bound in hadrons[9] by a mechanism as yet unknown, but much speculated on.

A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

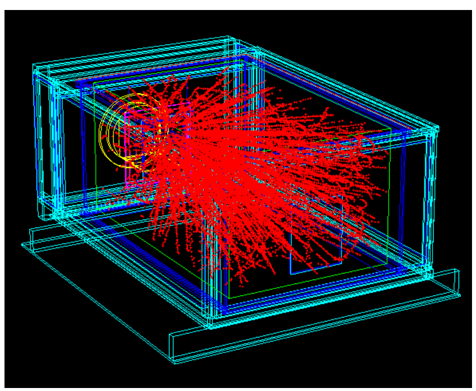
Hypothetical phase diagram of strongly interacting matter



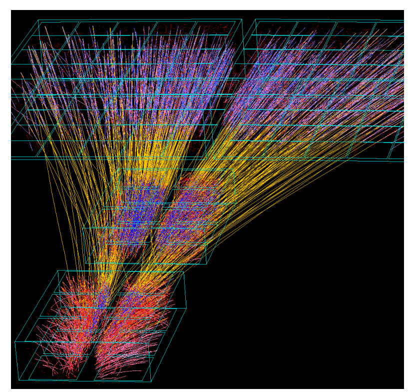
- Observation of the onset of deconfinement

- Brief history of the CERN SPS ion programs and NA49
- Observation of the onset of deconfinement

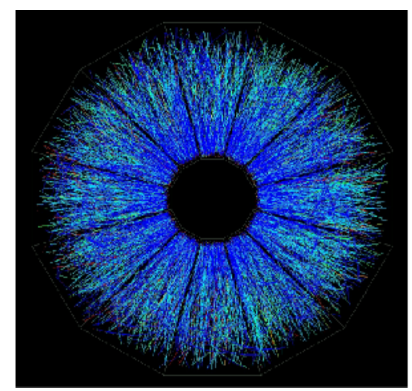
BNL AGS → CERN SPS → BNL RHIC



E895



NA49



STAR

Brief history of the CERN SPS ion programs and NA49

Rafelski, Muller
Matsui, Satz

1986-1991: Pioneering study with O and S beams

Strangeness enhancement and J/ψ suppression

⇒ Simple superposition models do not work

↓

1994-2000: Pb+Pb collisions at the top SPS energy

anomalous J/ψ suppression, statistical properties of hadron production, direct photons

⇒ Is a new state of matter created?

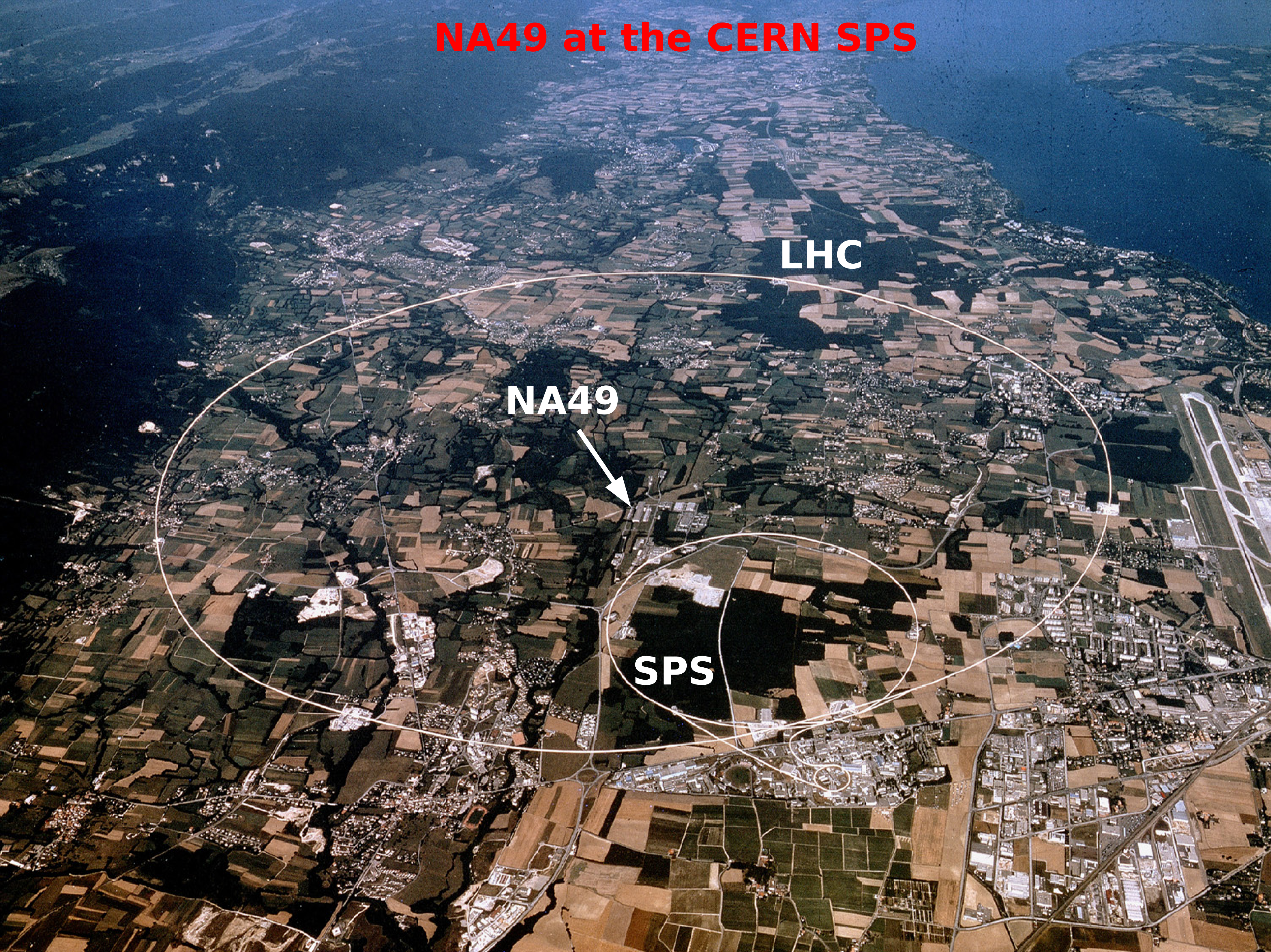
M.G., Gorenstein

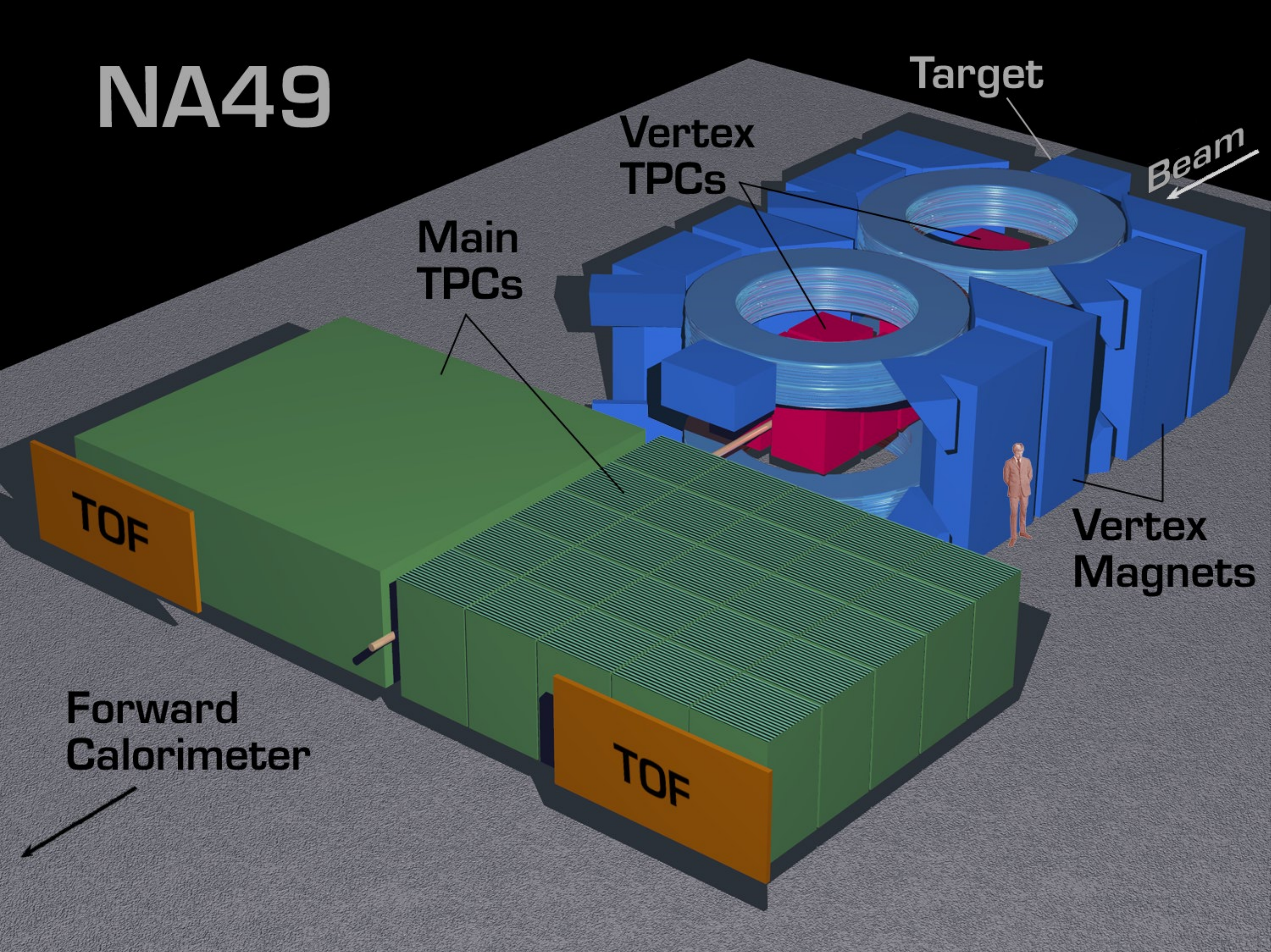
↓

1998-2002: Pb+Pb collisions at low SPS energies
(NA49 energy scan program at the CERN SPS)

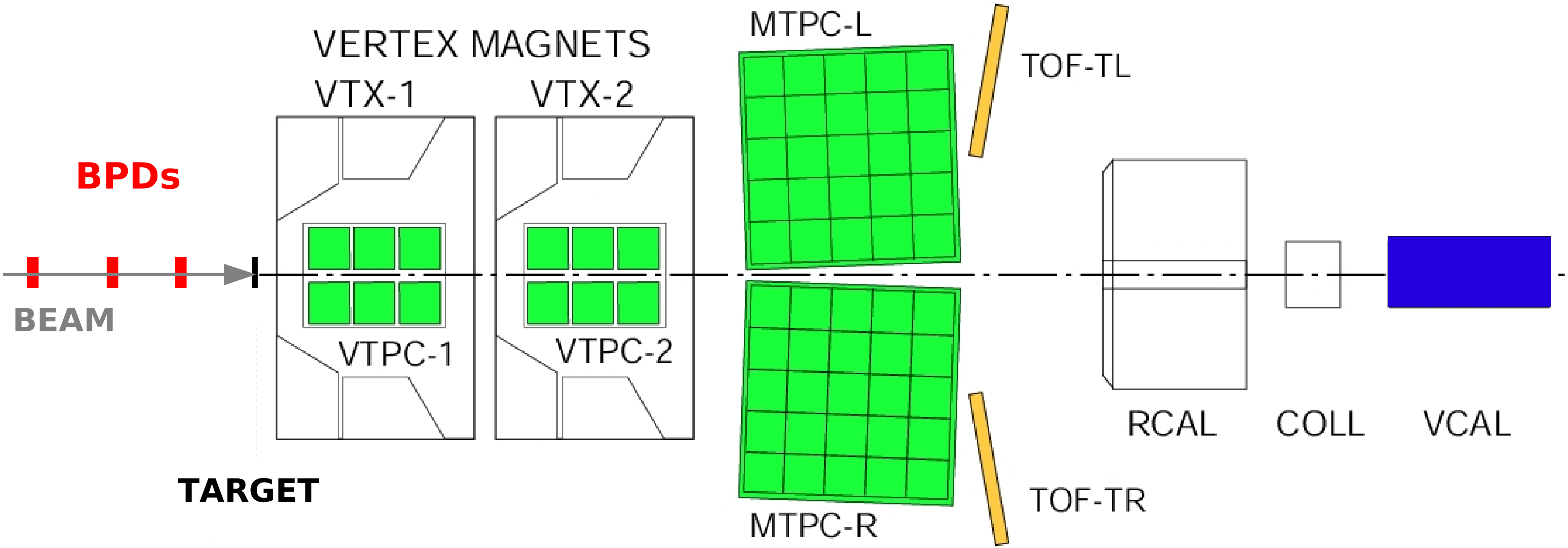
Anomalies in energy dependence of hadron production

⇒ Observation of the onset of deconfinement


NA49 at the CERN SPS
LHC
NA49
SPS


NA49
Target
Vertex
TPCs
Beam
Main
TPCs
TOF
Vertex
Magnets
TOF
Forward
Calorimeter

NA49 at CERN SPS

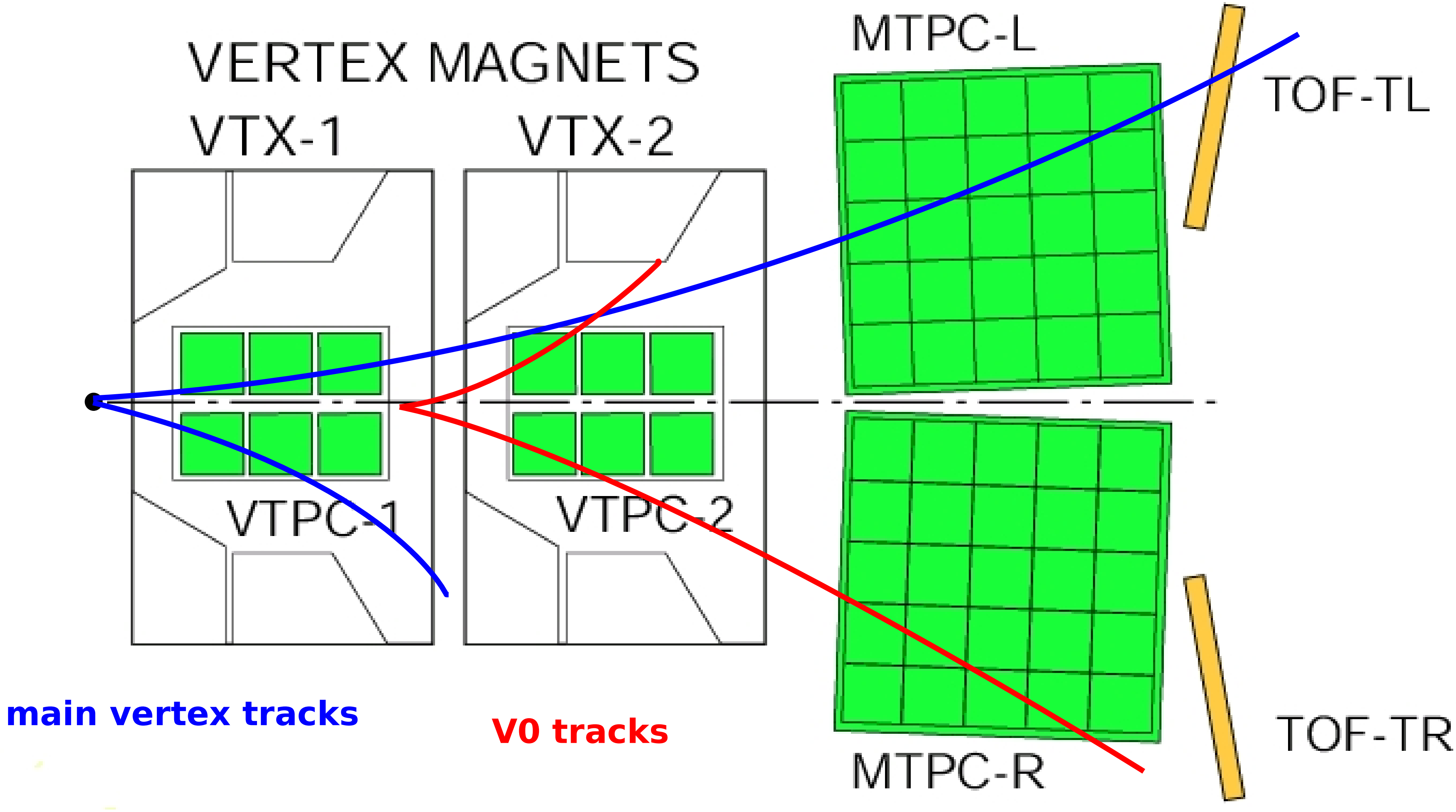


BPDs:
coordinates of the beam particle
+ *z-TARGET:* coordinates of the interaction point (x,y,z)

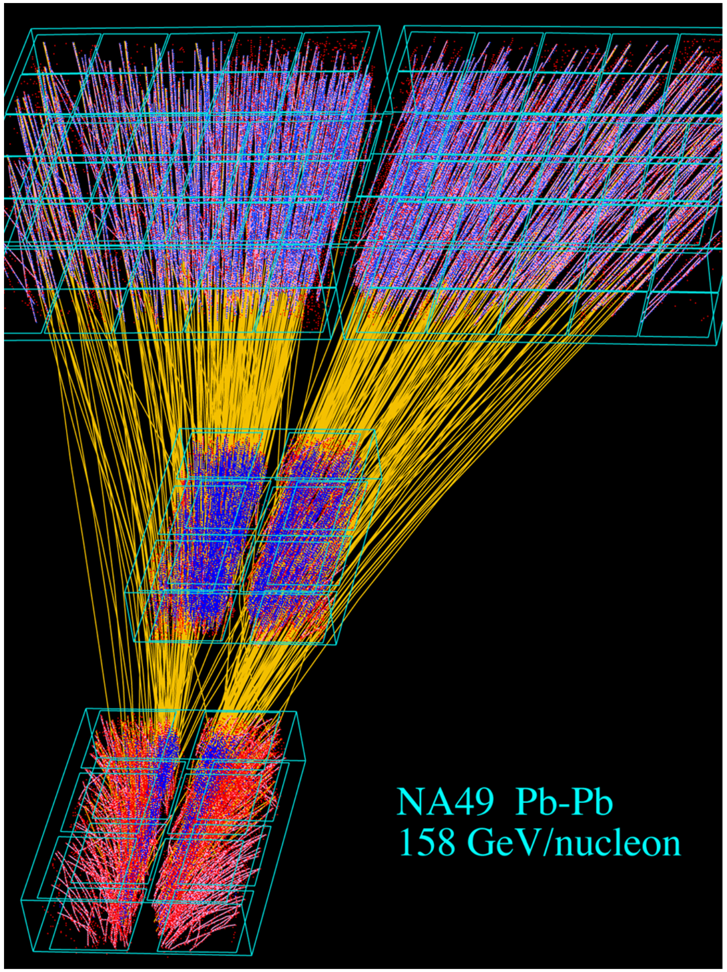
TPCs:
for each track:
electric charge, momentum, mass (dE/dx),
for more than one track:
common origin point (coordinates of main or secondary vertex)

TOFs:
mass (tof)

VCAL:
energy of projectile spectators (centrality of the collision)


VERTEX MAGNETS
VTX-1
VTX-2
MTPC-L
TOF-TL
VTPC-1
VTPC-2
TOF-TR
MTPC-R
main vertex tracks
V0 tracks

NA49 at the CERN SPS



→ A large acceptance: ≈50%

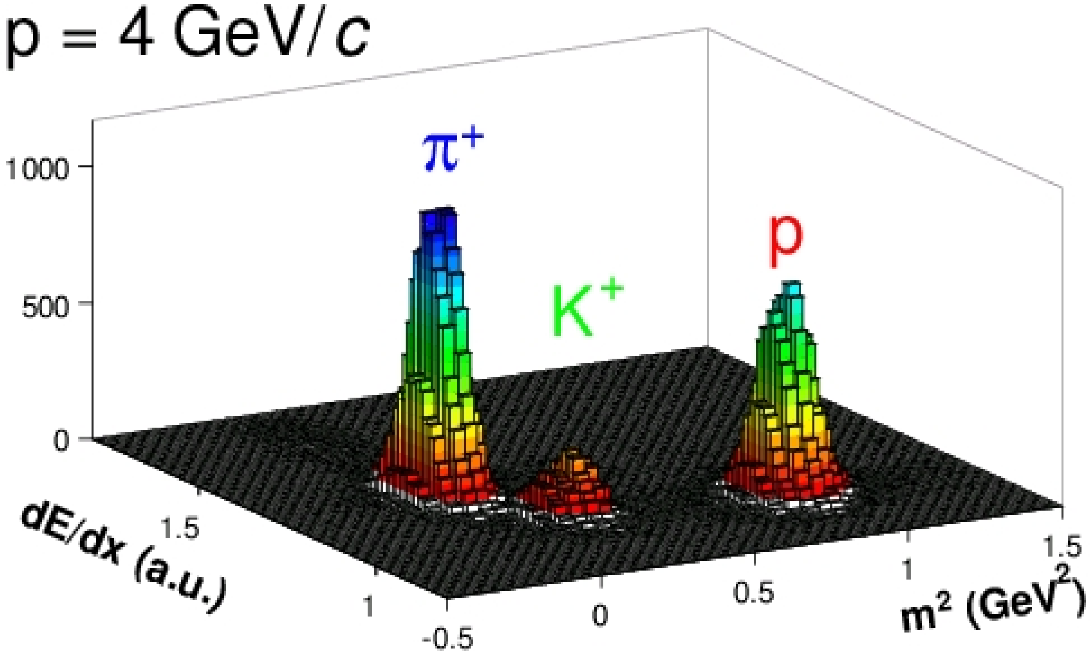
→ A high momentum resolution:

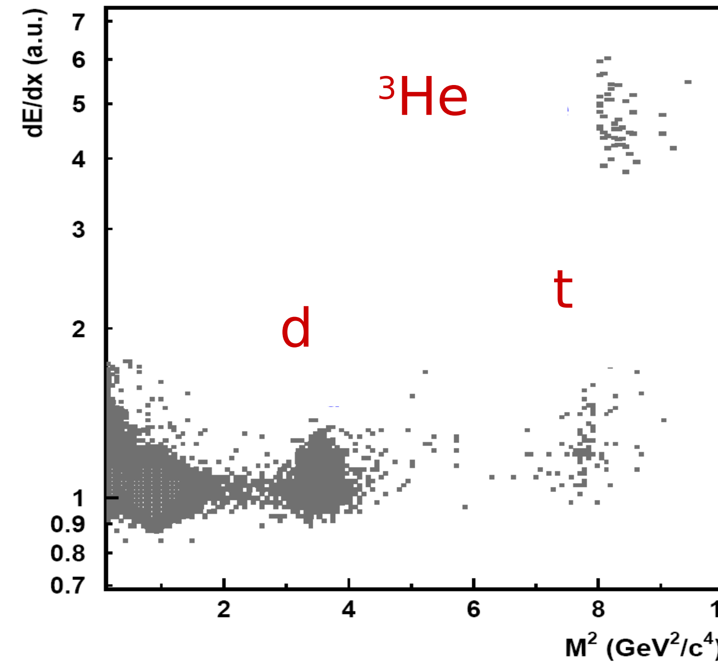
$$\sigma(p)/p^2 \approx 10^{-4} \quad ((GeV/c)^{-1})$$

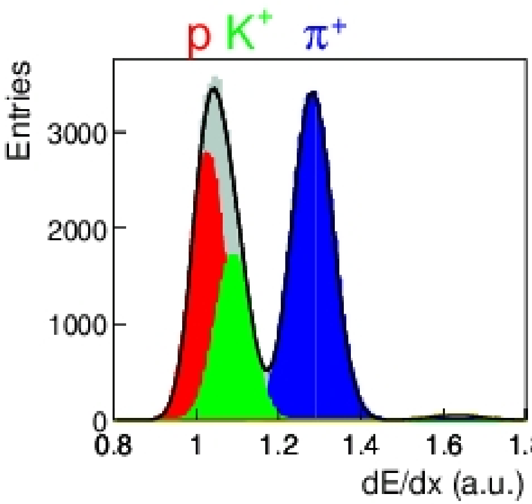
→ A good particle identification:

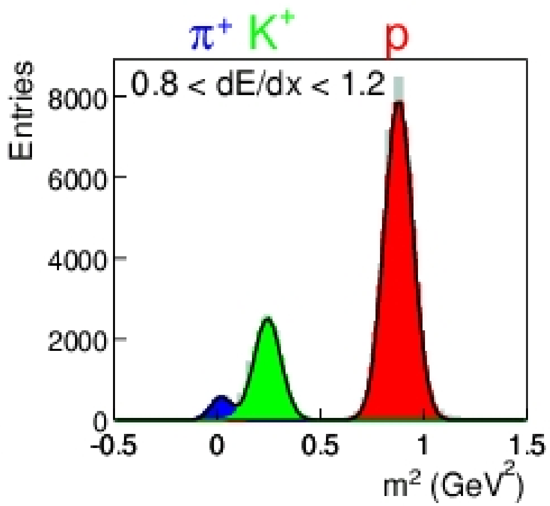
$$\sigma(TOF) \approx 60\,ps,$$
$$\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04,$$
$$\sigma(m_{inv}) \approx 5\,MeV$$

Mass measurements via dE/dx + tof



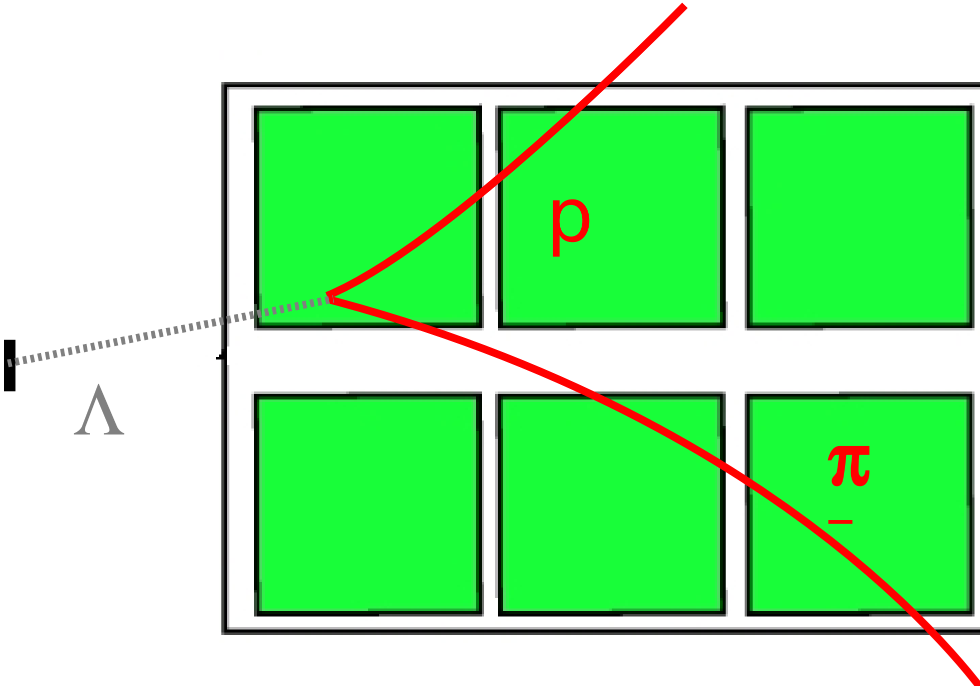


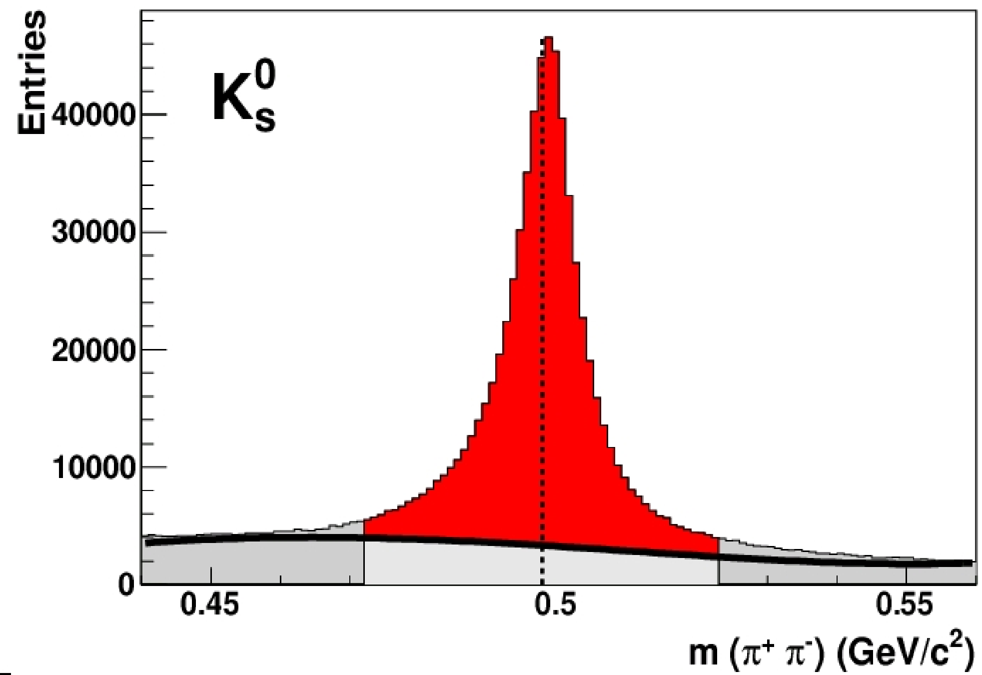


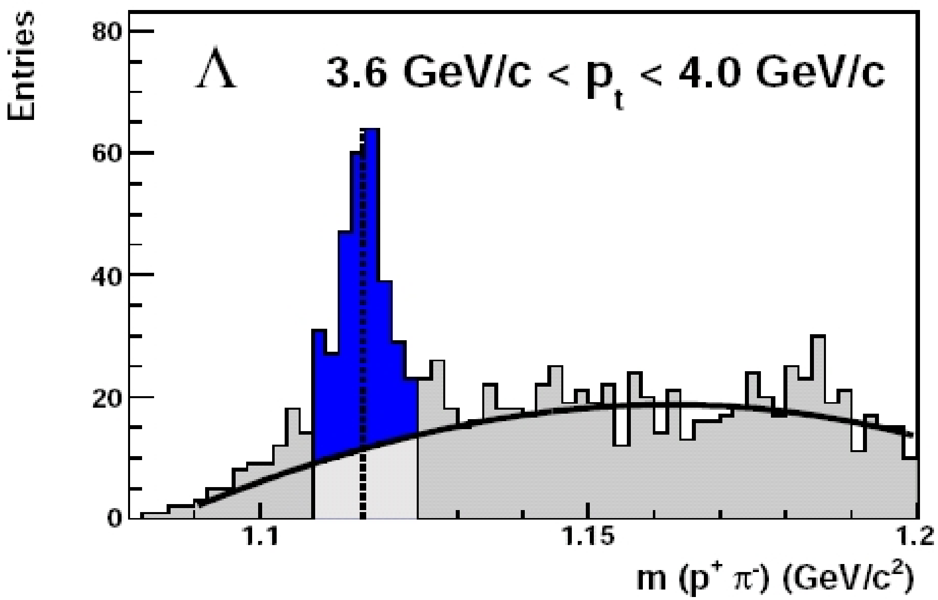


$$\sigma(TOF) \approx 60\,ps\,,$$
$$\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04$$

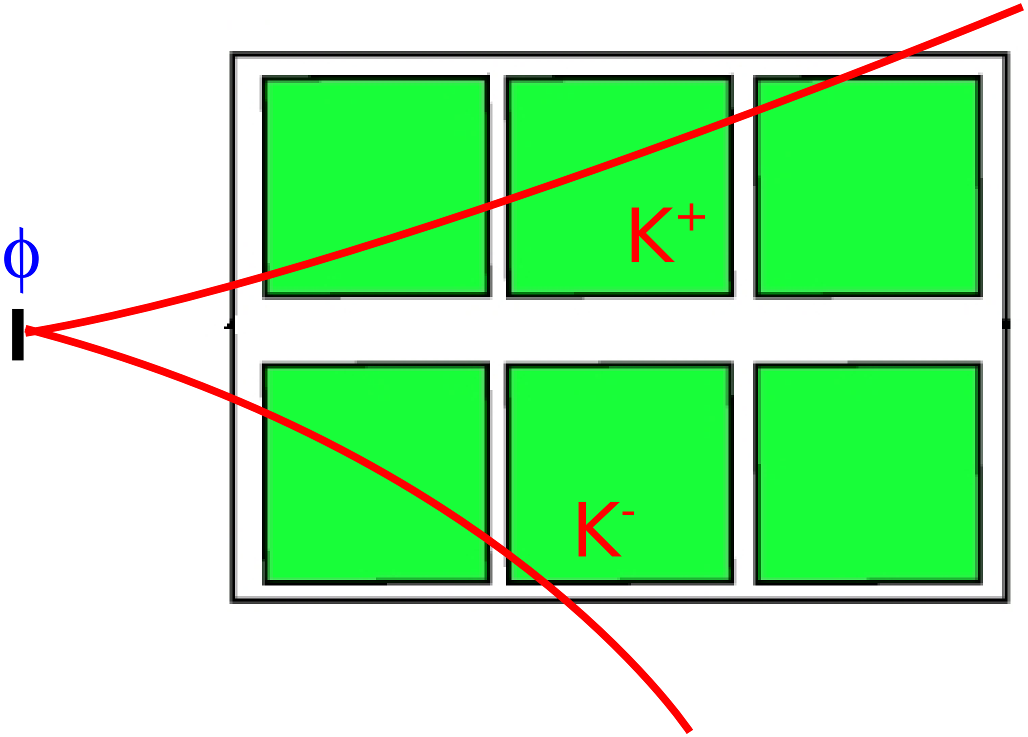
PID via decay topology and invariant mass

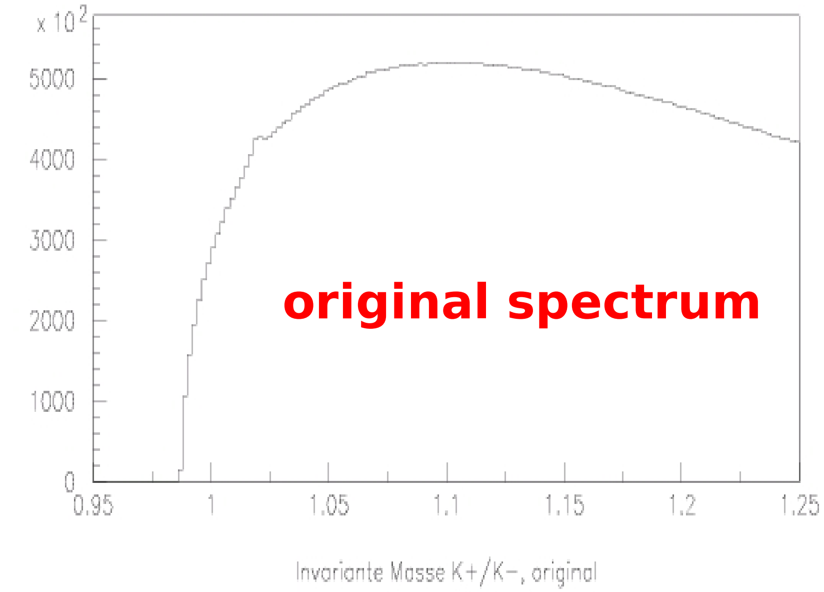


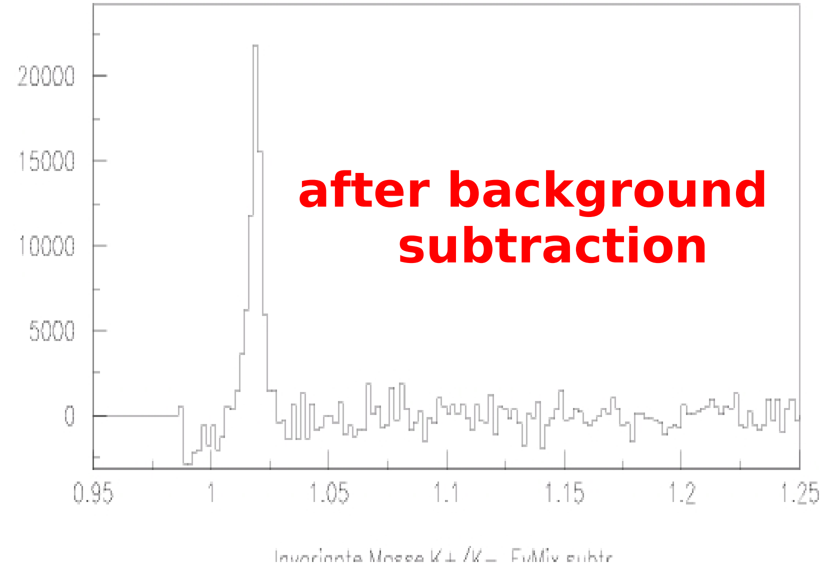




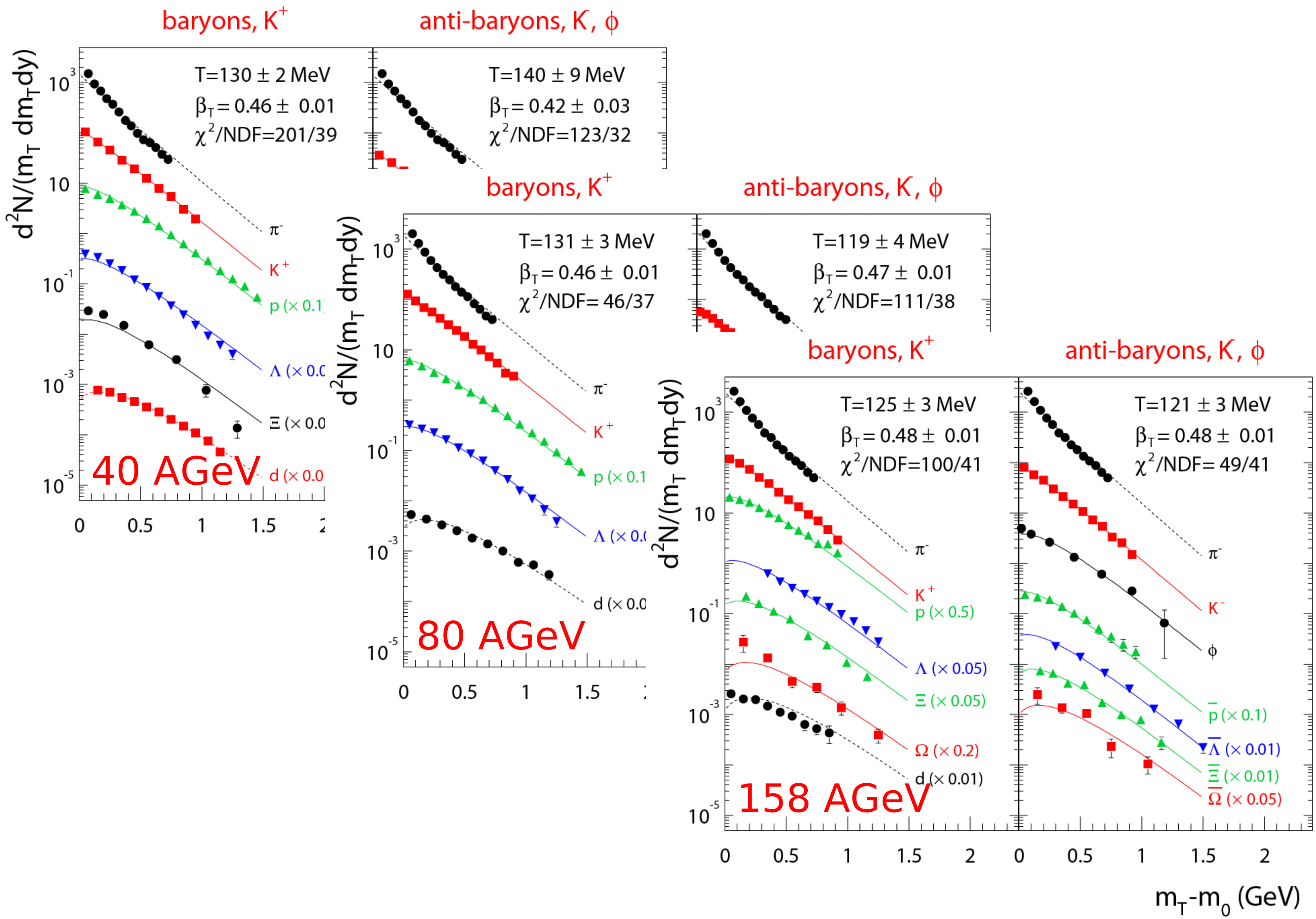
PID via invariant mass



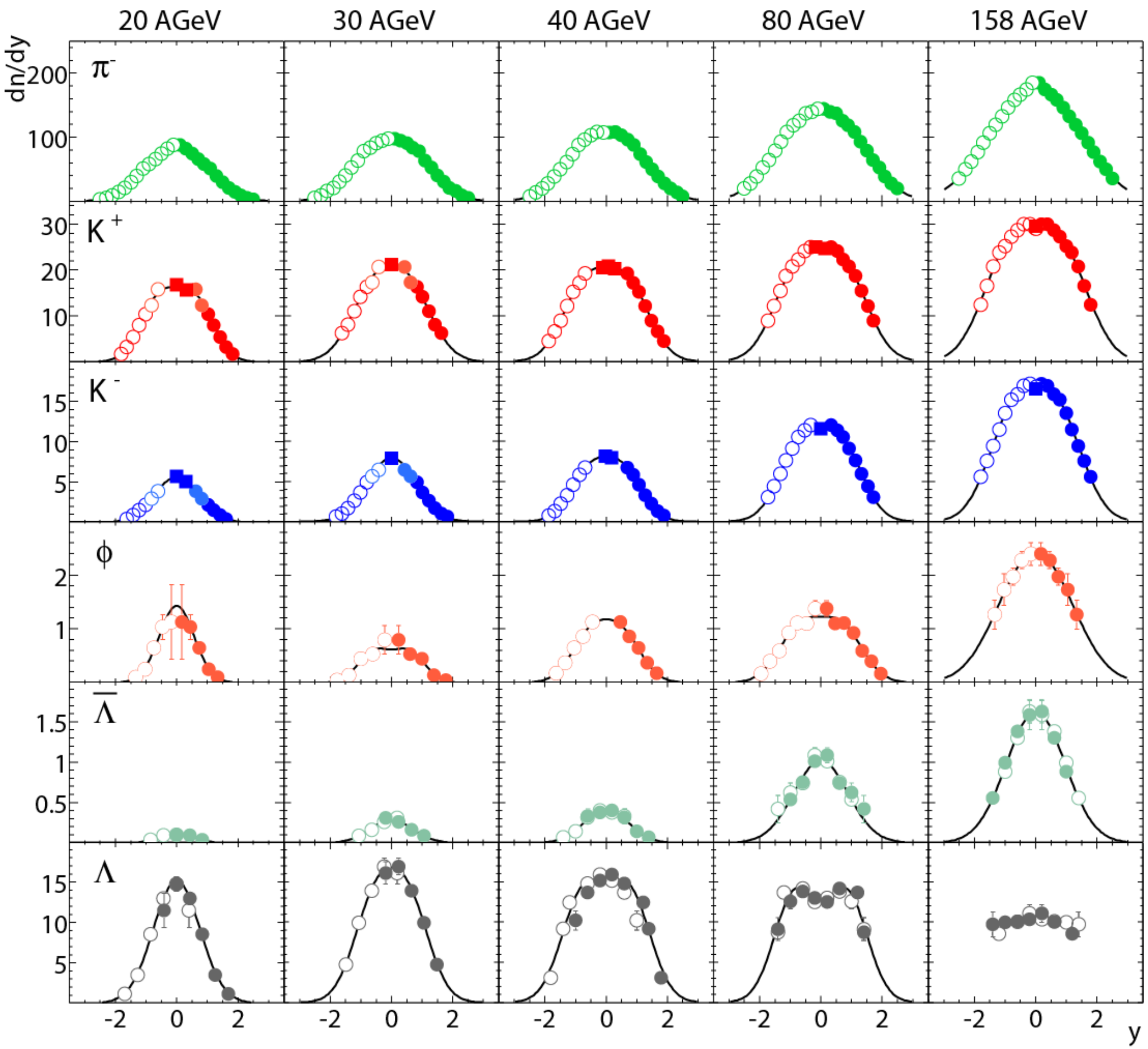




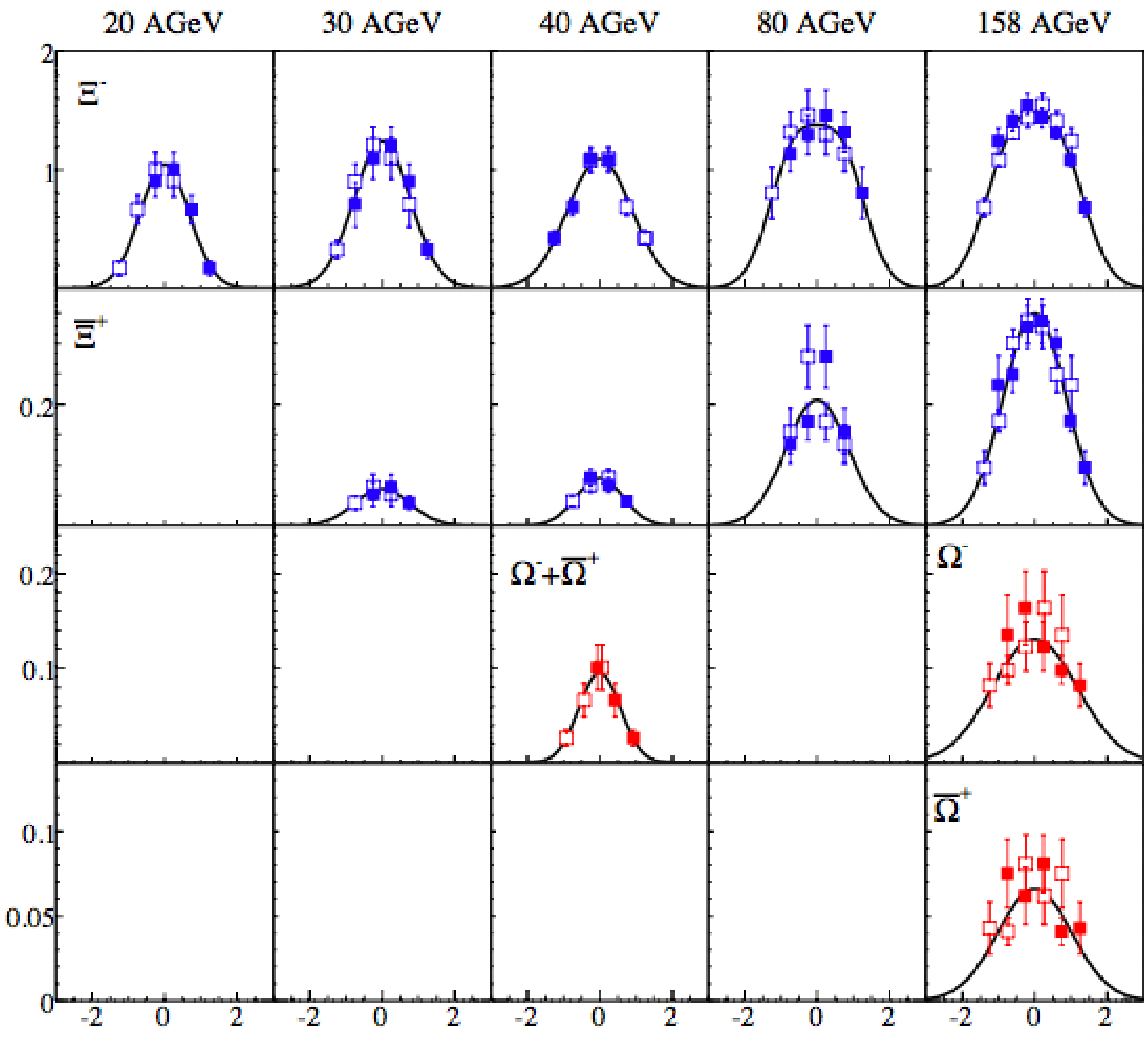
central Pb+Pb collisions at the SPS energies



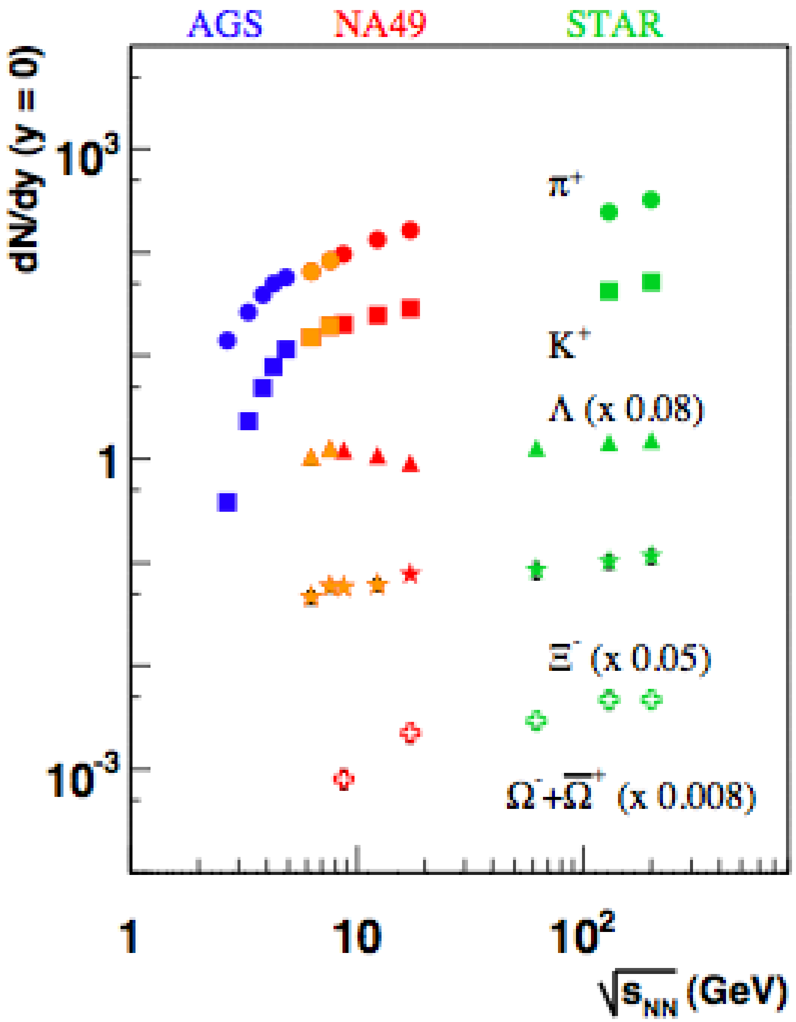
central Pb+Pb collisions at the SPS energies

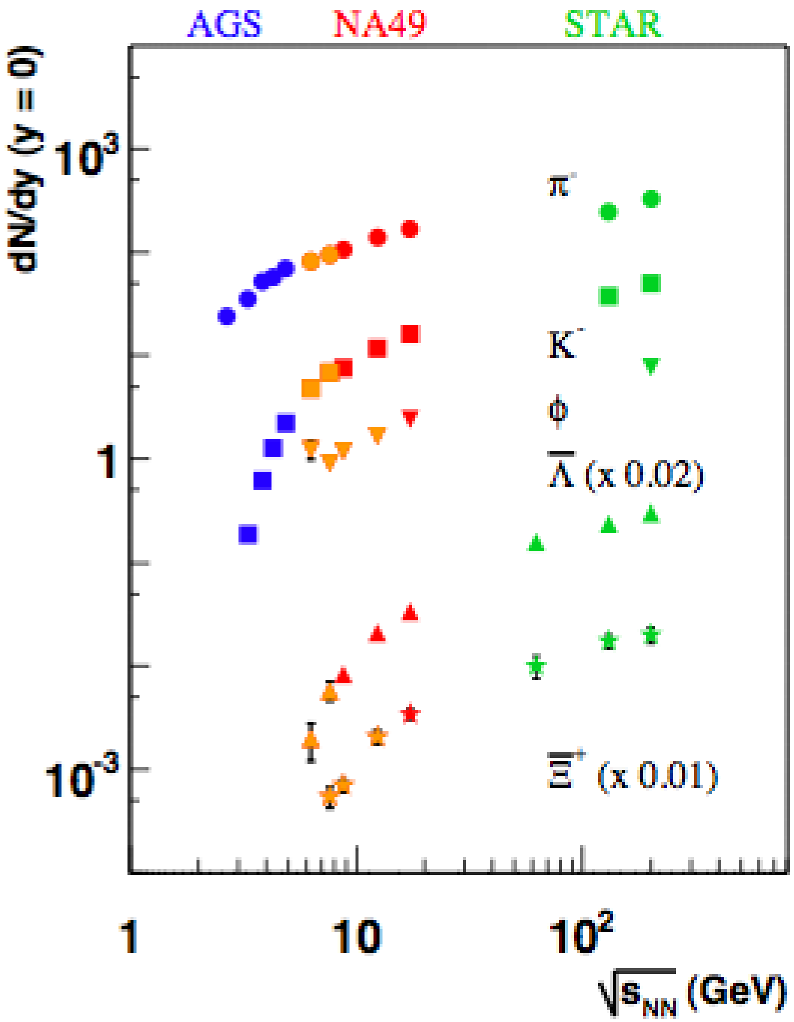


central Pb+Pb collisions at the SPS energies

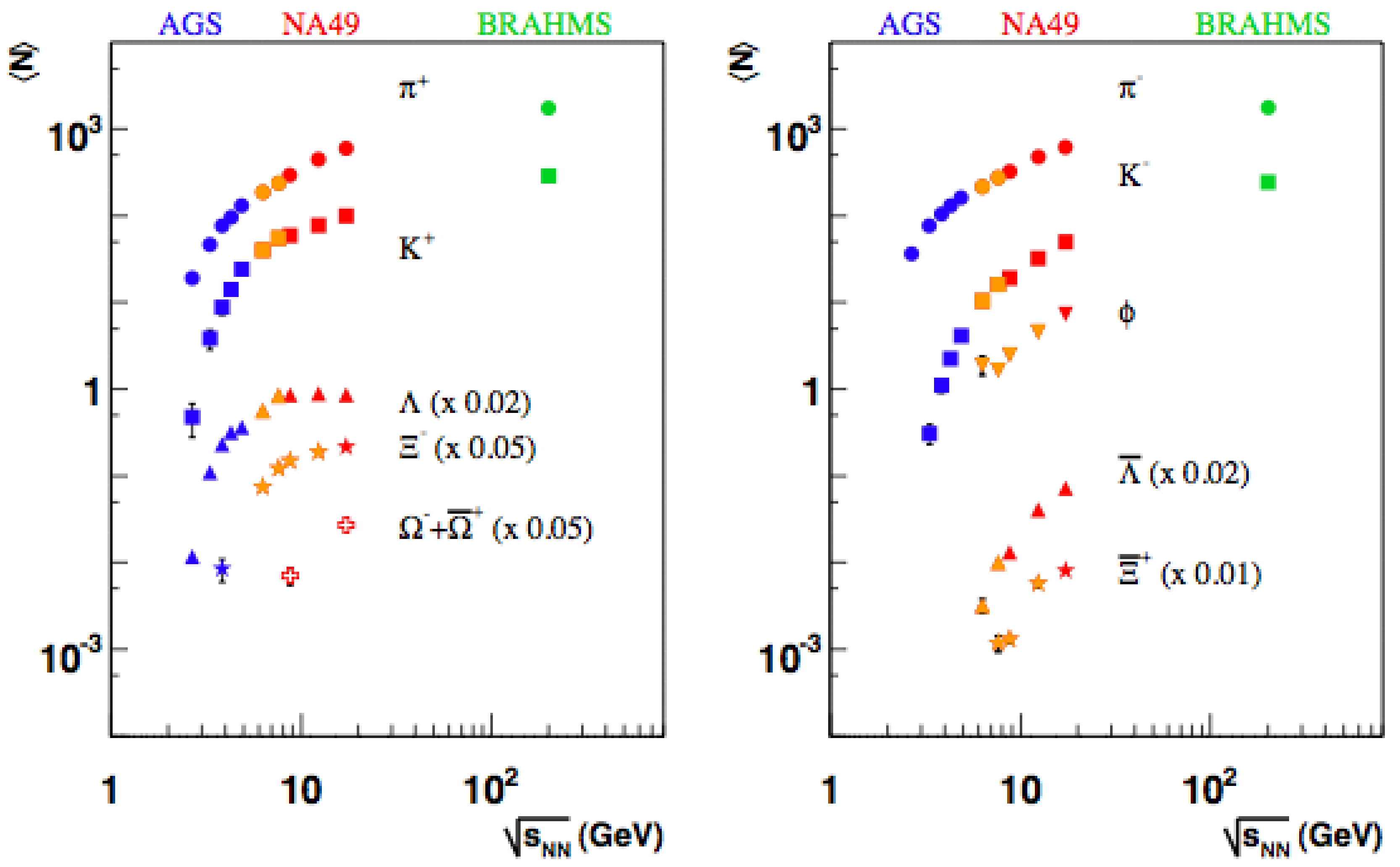


central Pb+Pb (Au+Au) collisions



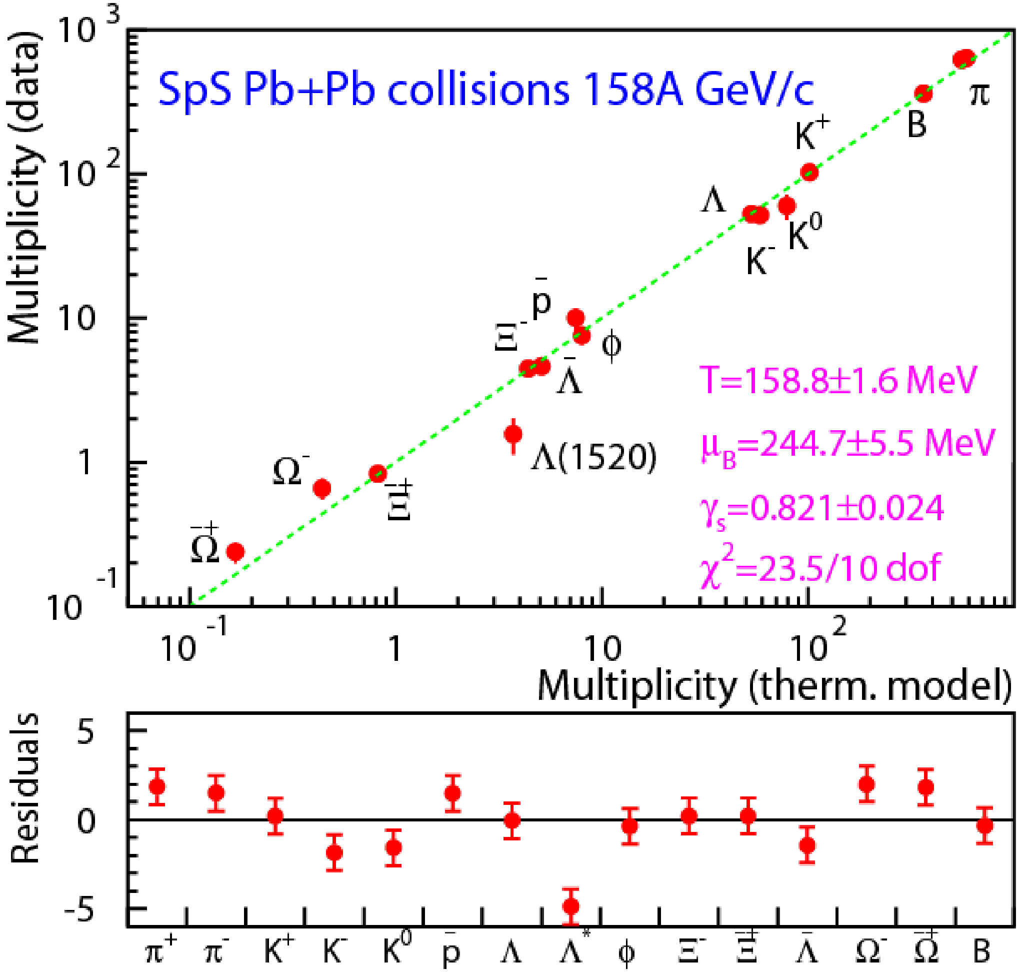


central Pb+Pb (Au+Au) collisions



Hadron gas model analysis

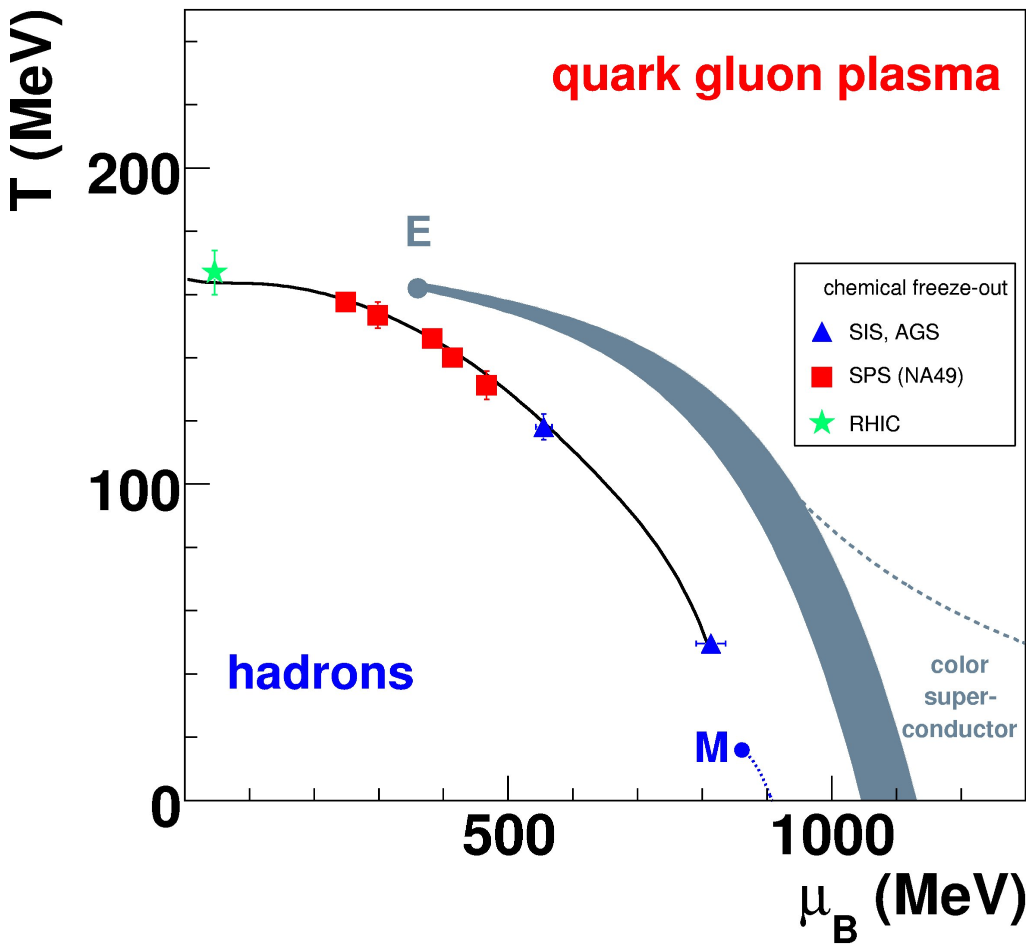
$$\langle n_i \rangle = \frac{(2J_i+1)\,V}{(2\pi)^3}\int d^3p\,\frac{1}{\gamma_s^{-S_i}\,exp[(E_i-(\mu_B+\mu_S+\mu_Q))/T]\pm 1}$$



fit parameters

↓

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



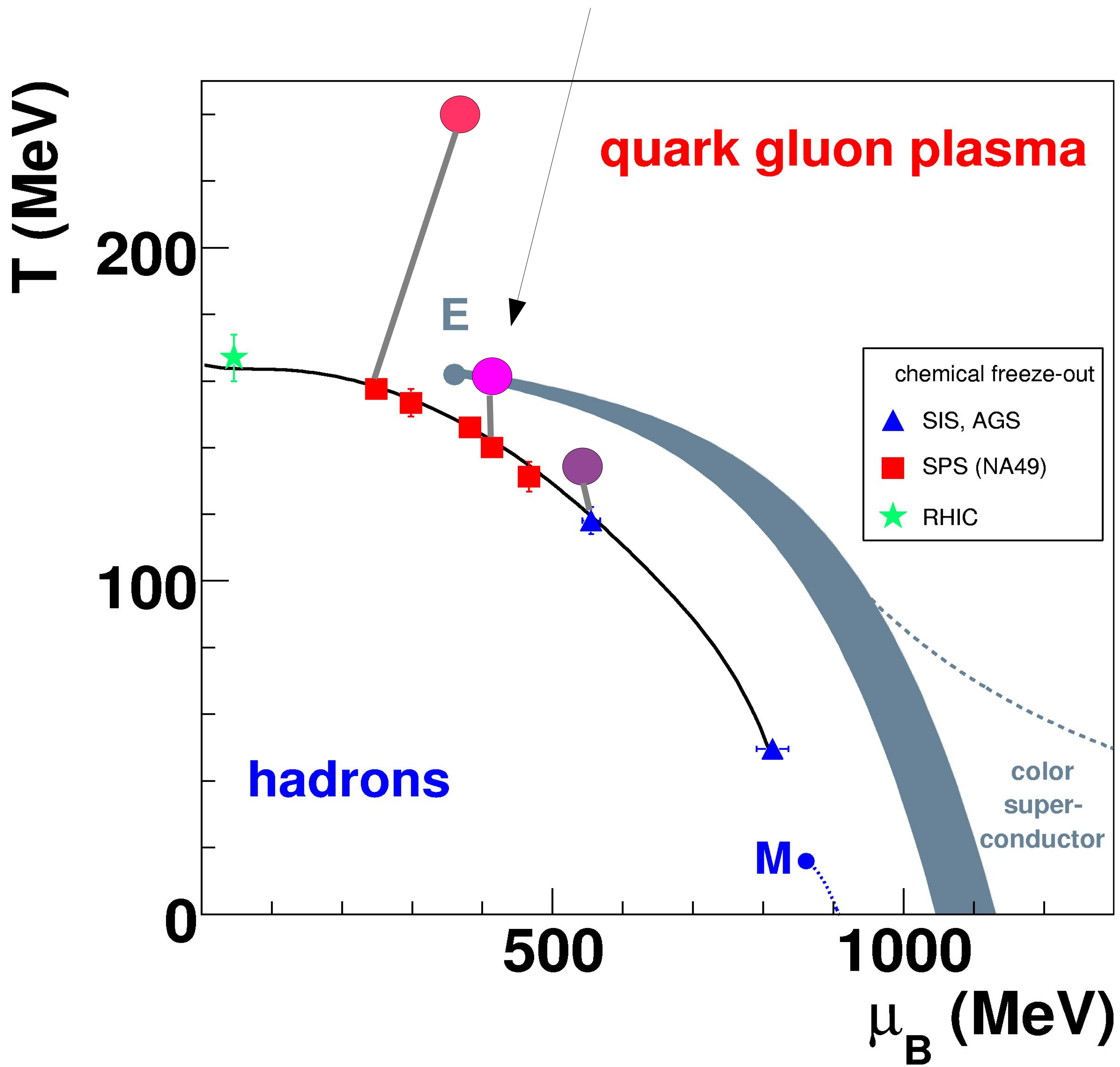
Freeze-out points of central heavy ion collisions at SPS are close to the phase boundary

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

HG fits: Becattini et al.,
Cleymans, Redlich et al.

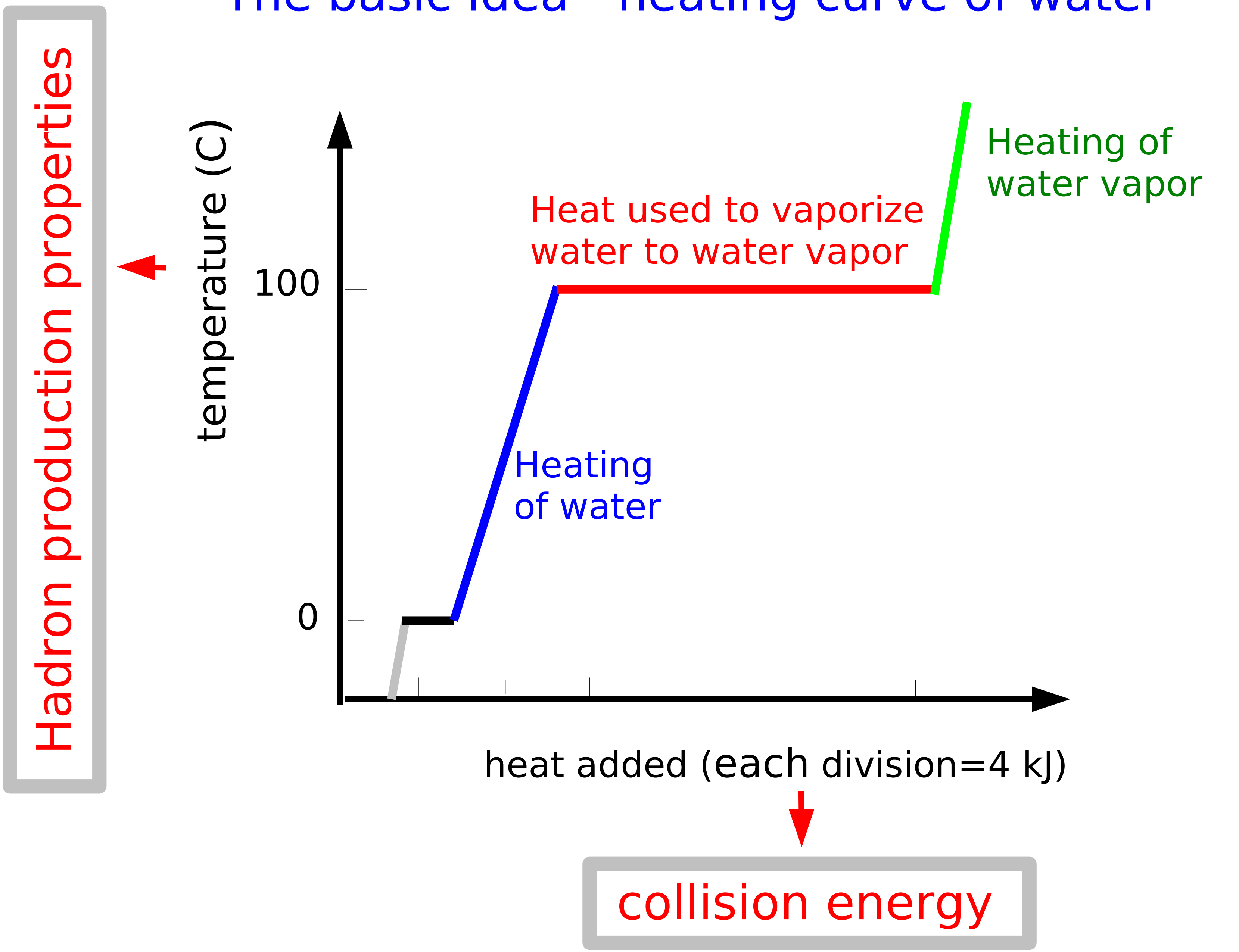
CP: Fodor, Katz

Onset of deconfinement: the early stage hits the transition line



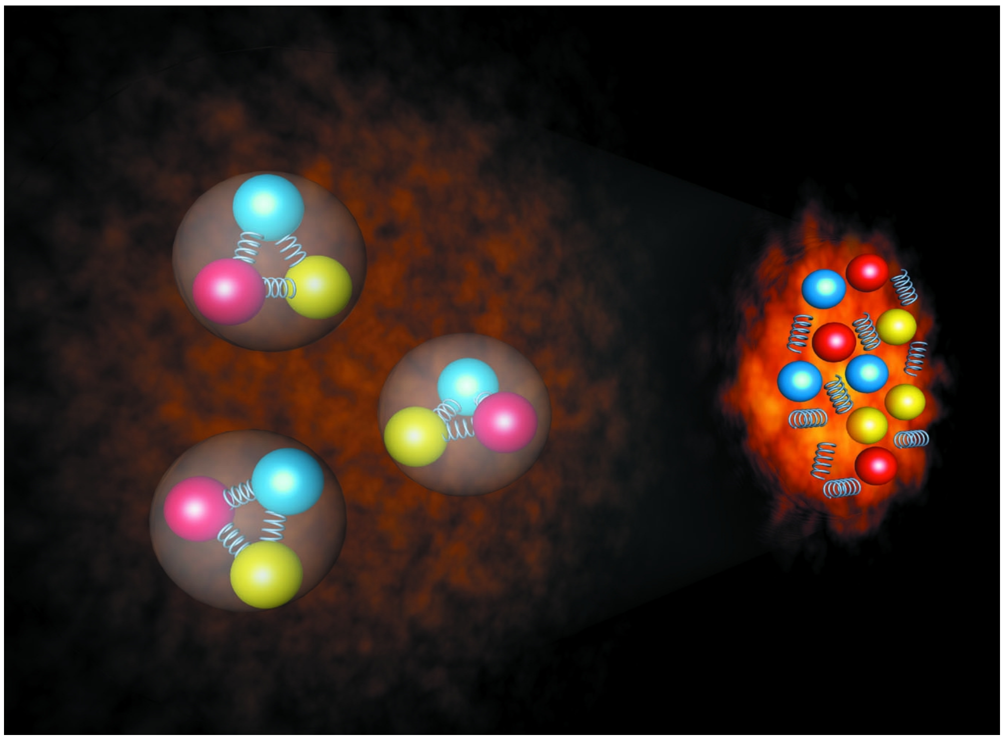
Onset of deconfinement at the CERN SPS

The basic idea - heating curve of water



Heating curves of strongly interacting matter

hadrons **mixed** **QGP**

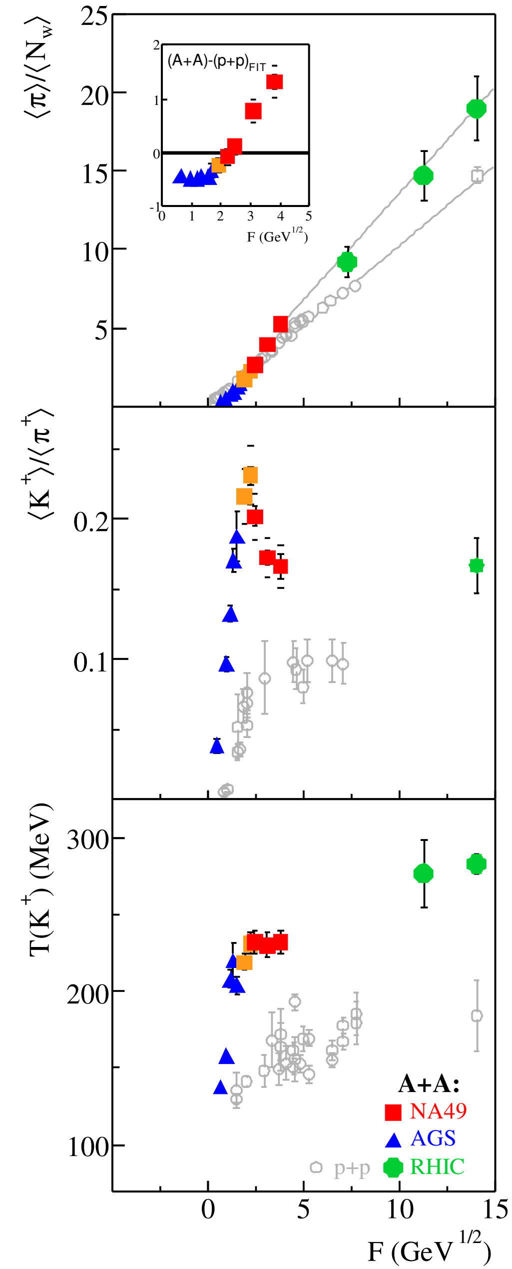


AGS **SPS** **RHIC**

collision energy

AGS **SPS** **RHIC**

hadronic observables



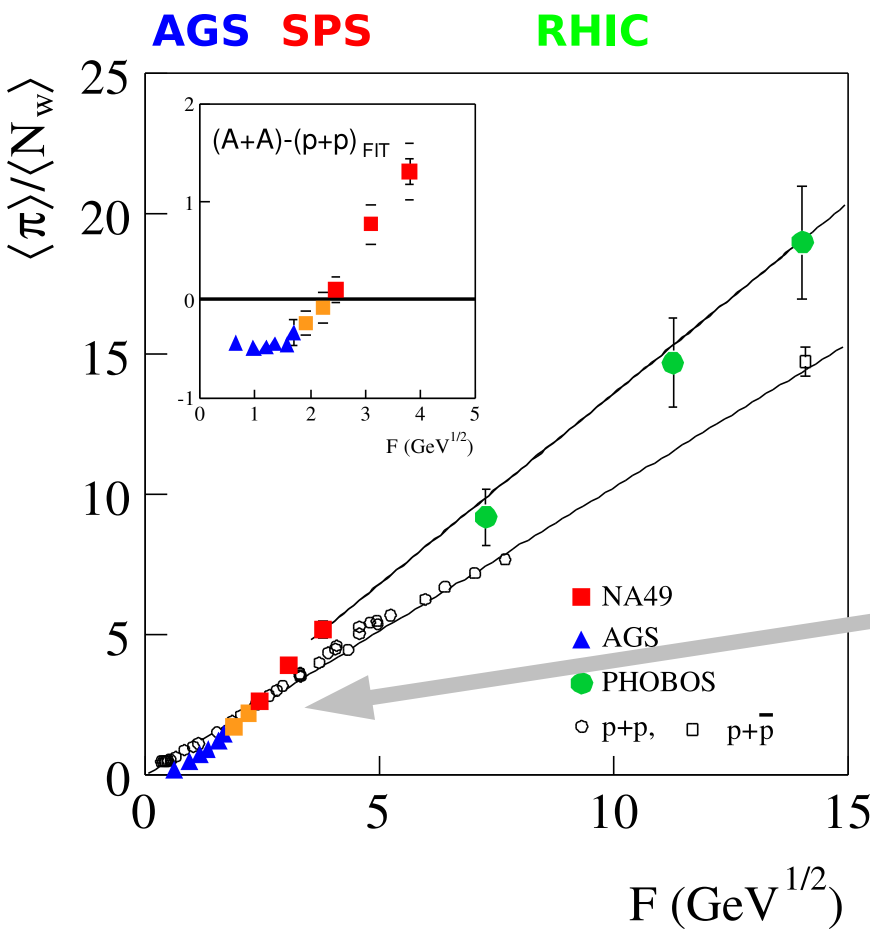
Kink

Horn

Step

collision energy

The kink in pion multiplicity



Deconfinement

↓

Increased entropy production

↓

Steepening of the increase of pion production

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

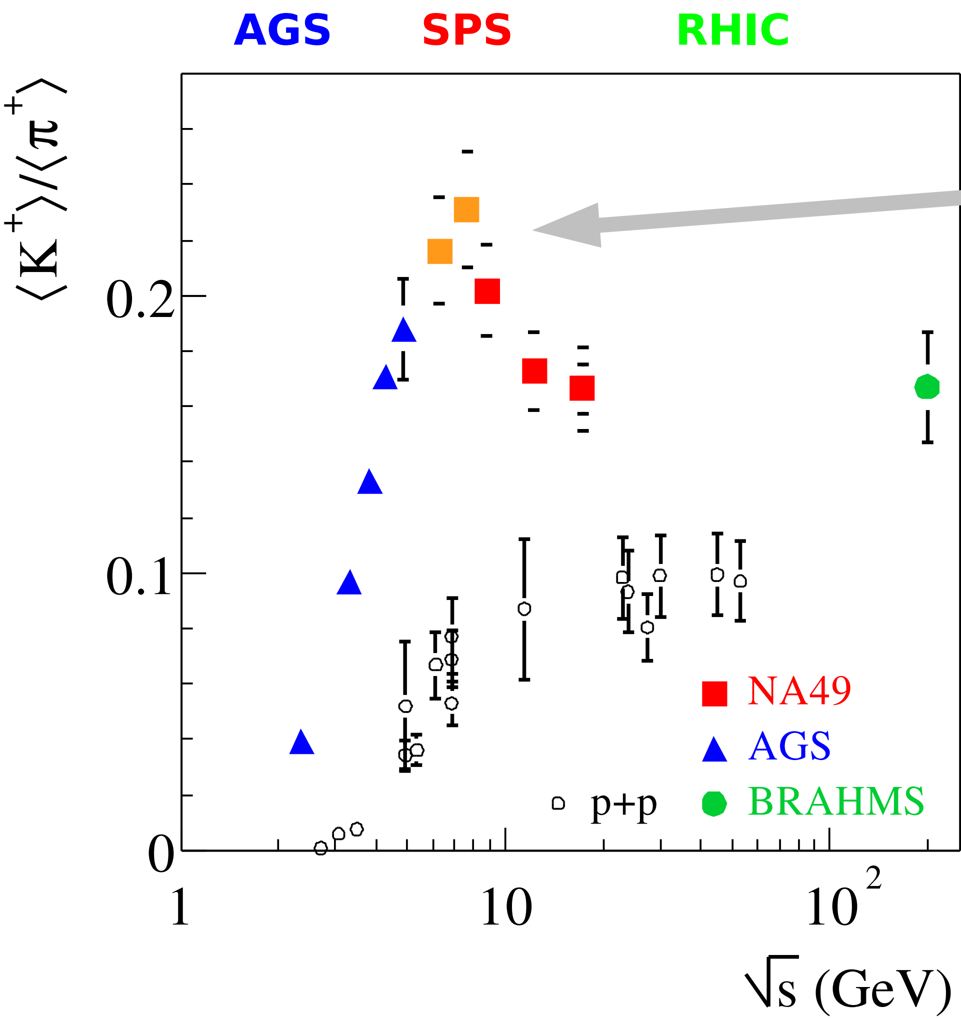
$F \approx \sqrt{\sqrt{s_{NN}}}$

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

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

M.G., Gorenstein

The horn in strangeness yield



Deconfinement

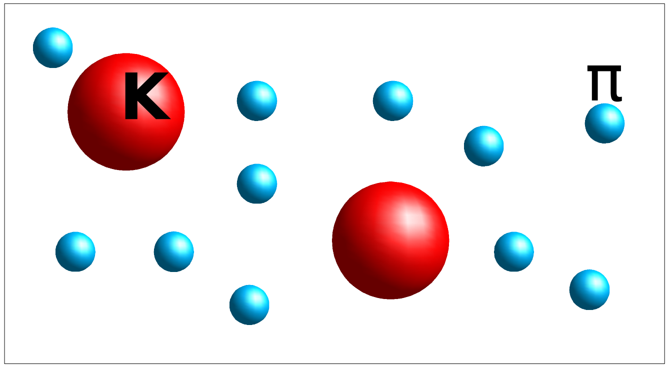
Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom

A sharp maximum in the strangeness to pion ratio

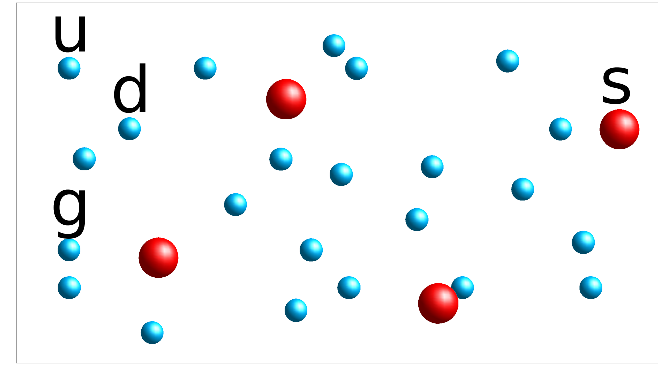
M.G., Gorenstein

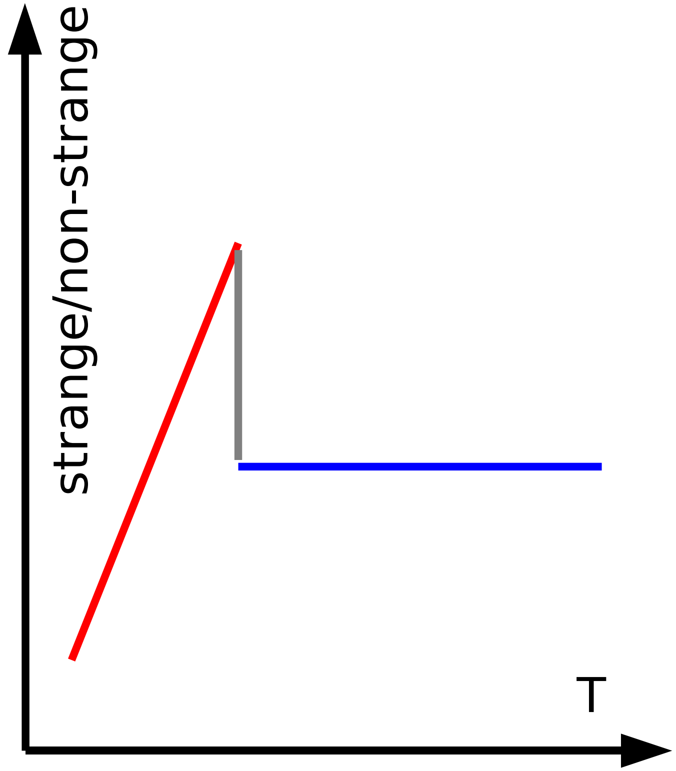
A toy model of the horn

hadron gas



quark-gluon plasma





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

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

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

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

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

main strangeness carriers

$\bar{s}$ = s (strangeness conservation)

$K^+ \approx K^0$ (isospin symmetry)

$K^- \approx \bar{K}^0$ (isospin symmetry)

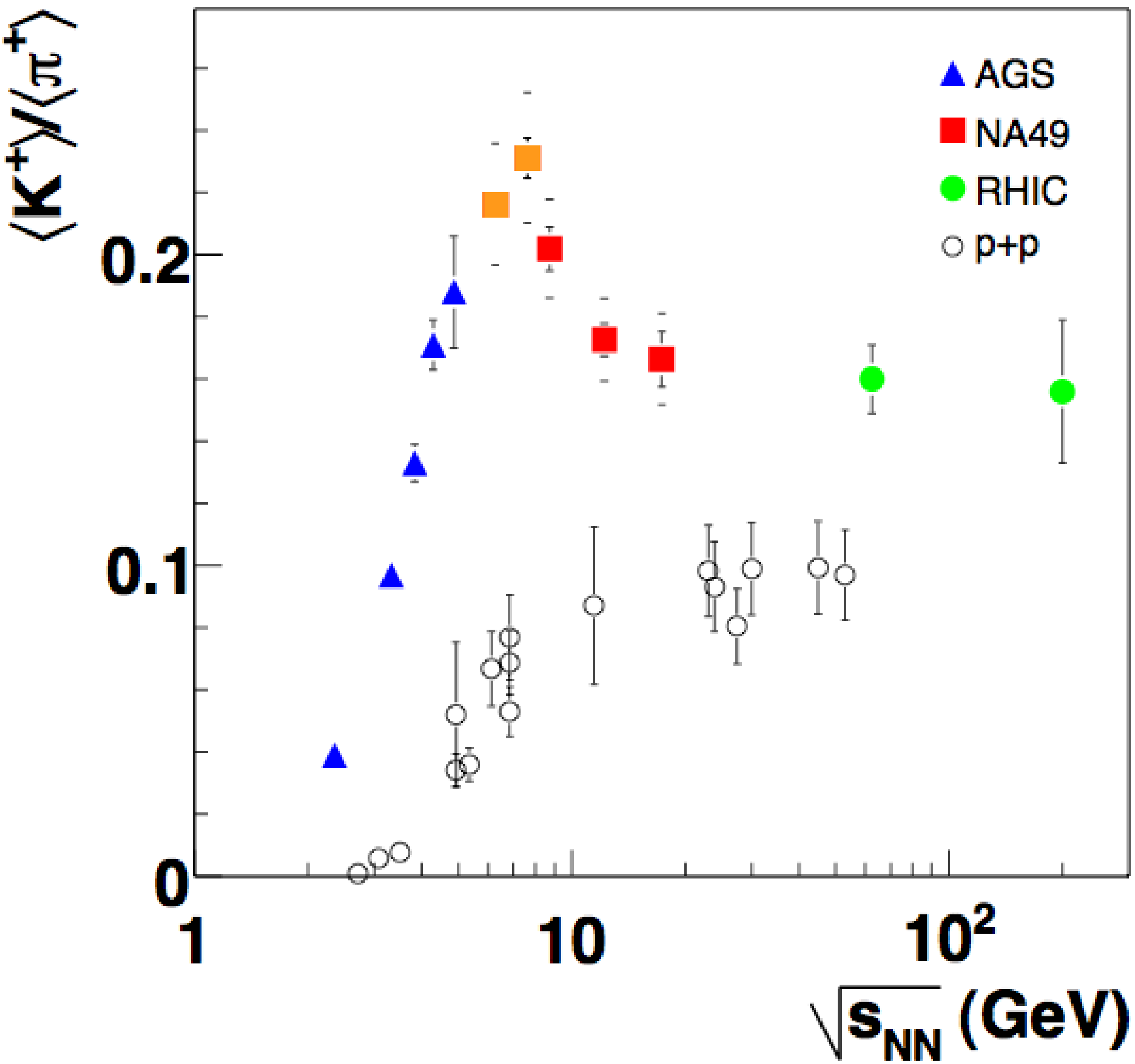
$K^+ \gg \bar{\Lambda}$

$K^- \approx \Lambda$

$\bar{\Lambda} << \Lambda$ (high baryon density)

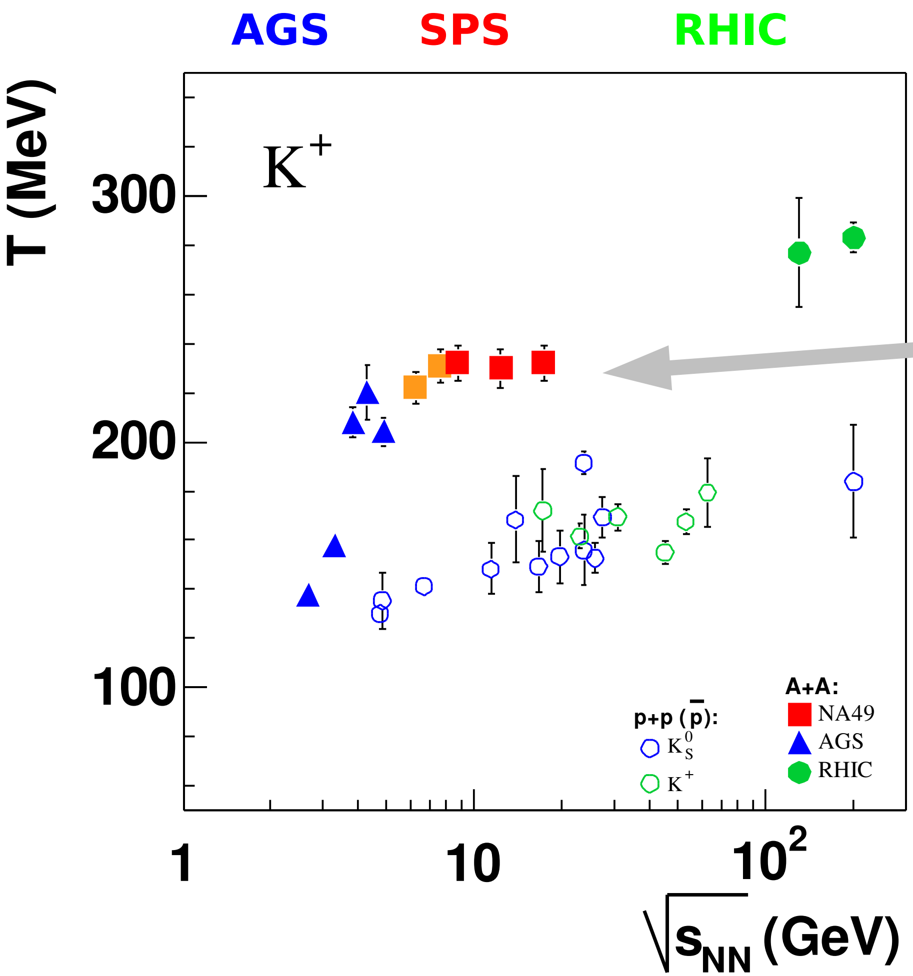
sensitive to strangeness content only

sensitive to strangeness content and baryon density



⟨K+⟩/⟨π+⟩
0.2
0.1
0
1
10
10^2
√sNN (GeV)
AGS
NA49
RHIC
p+p

The step in m_T slopes



Deconfinement

↓

Constant temperature and pressure in the mixed phase region

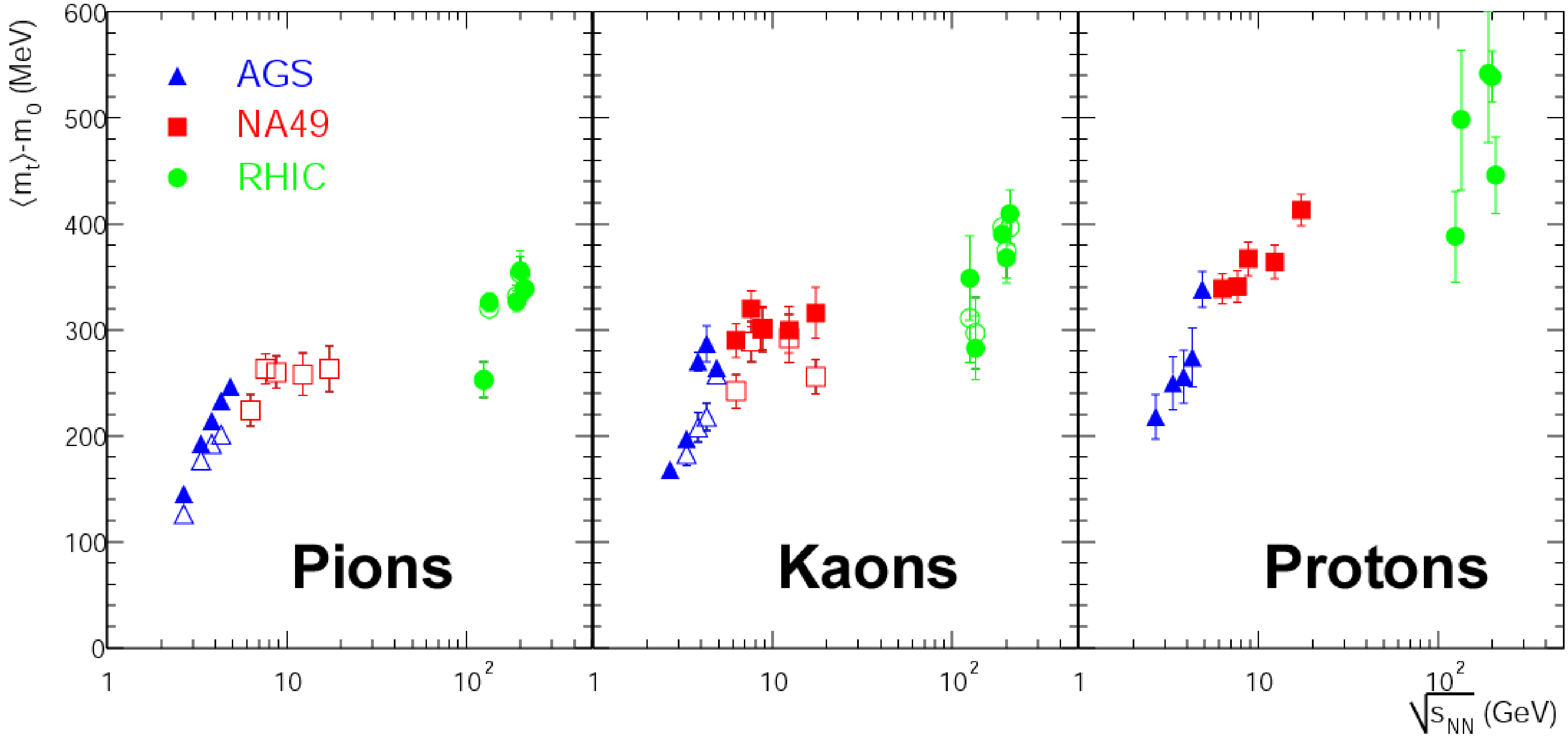
↓

Weaker transverse expansion and thus weaker energy dependence of T

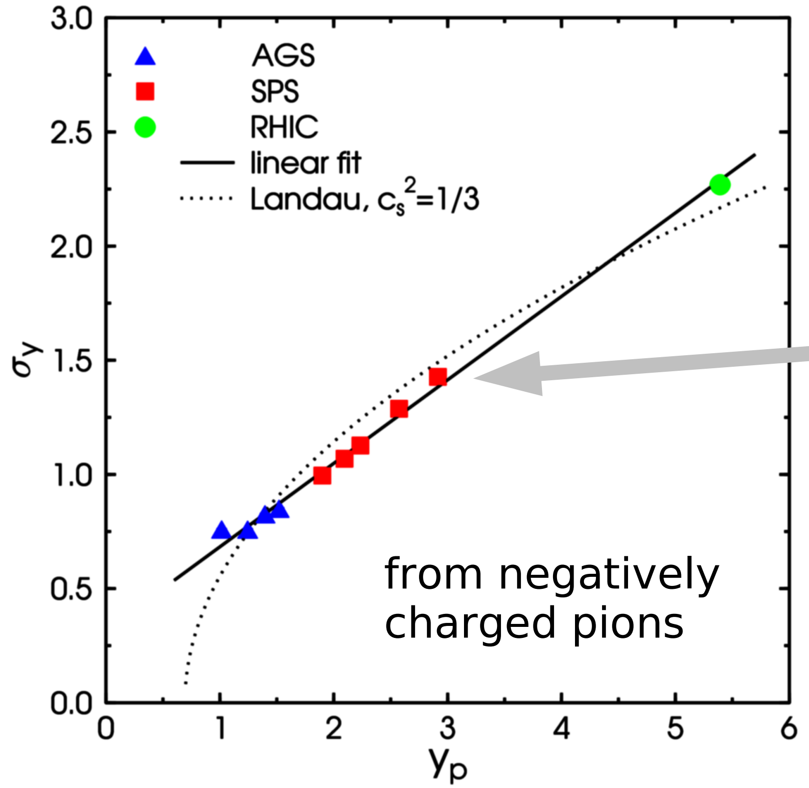
T – inverse slope parameter of transverse mass spectra

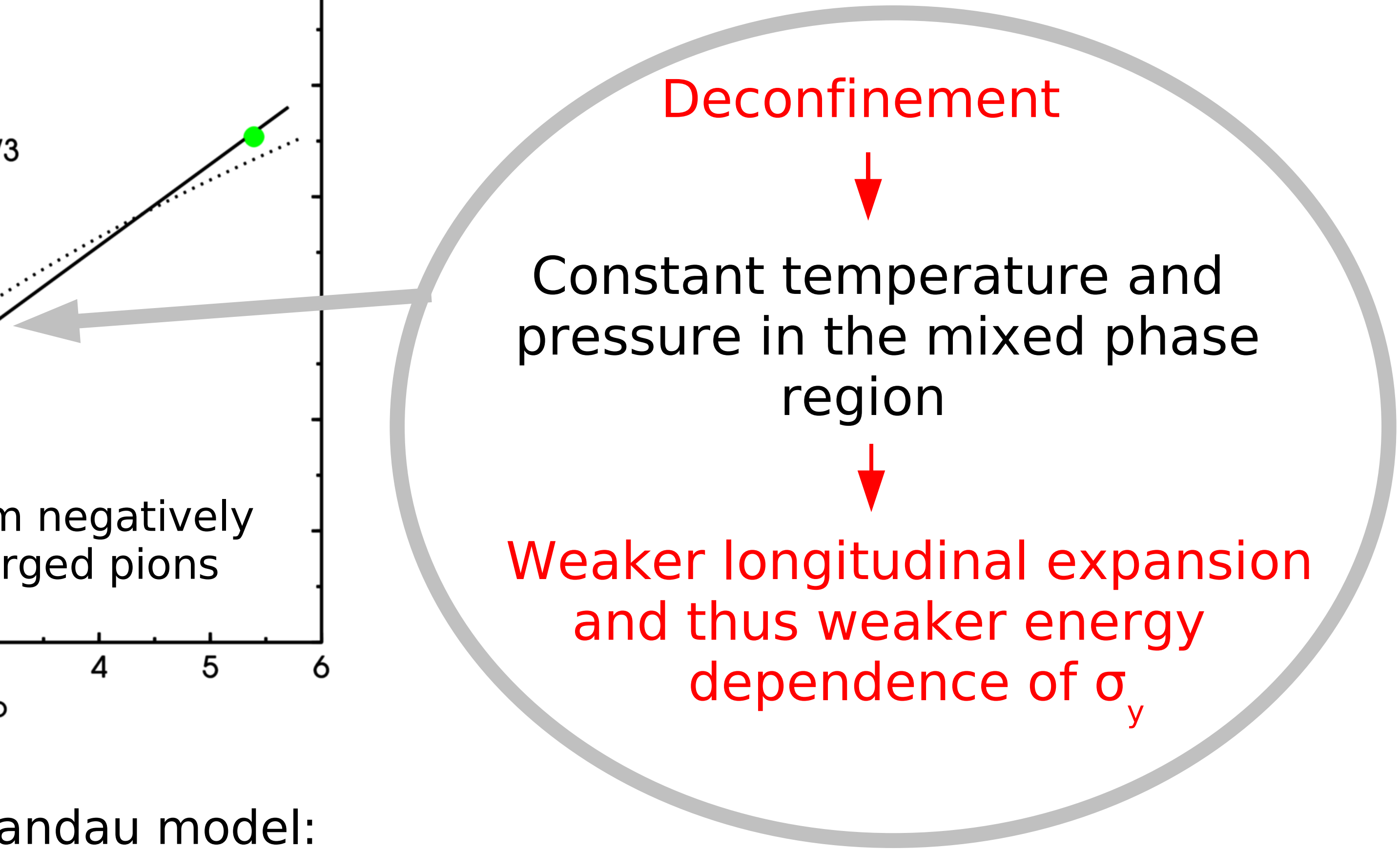
Gorenstein, M.G., Bugaev (Shuryak, van Hove)

... and in <m_T> of various hadrons



The weakening of longitudinal expansion ...



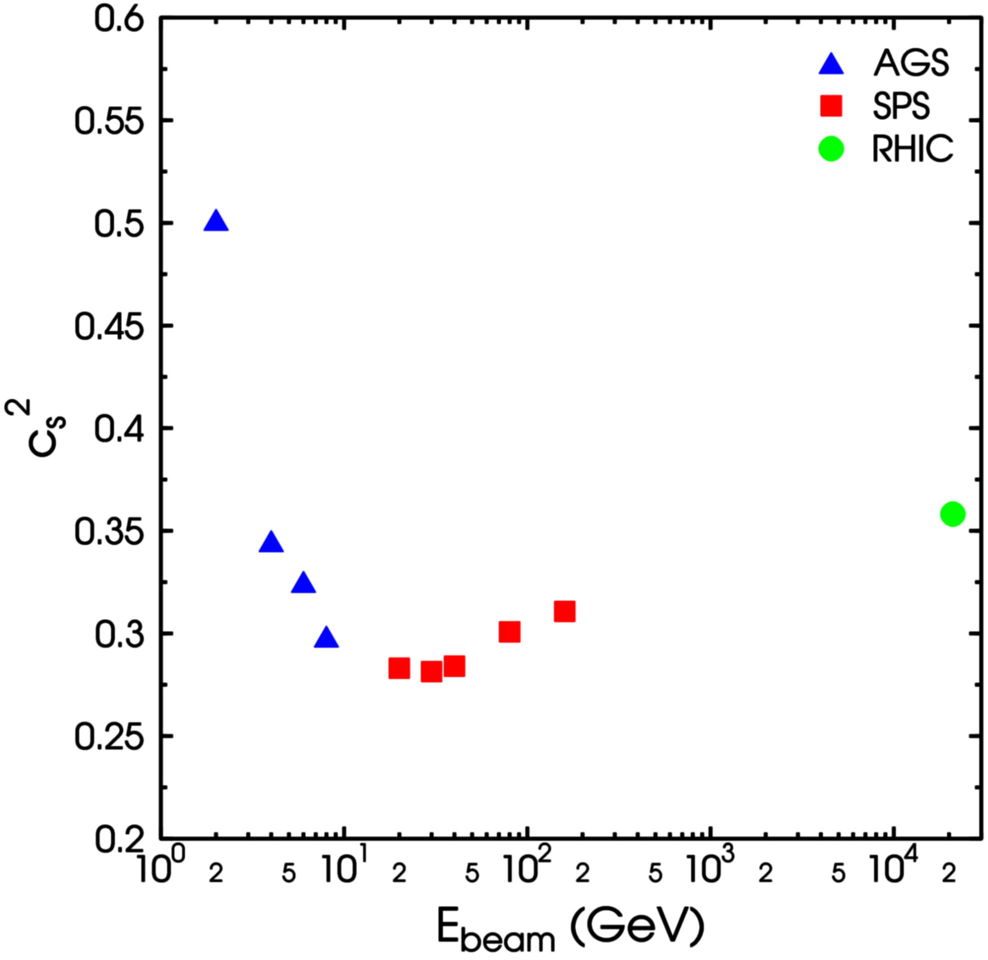


Hydrodynamical Landau model:
*(E.Shuryak,Yad.Fiz.**16**, 395 (1972))*

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

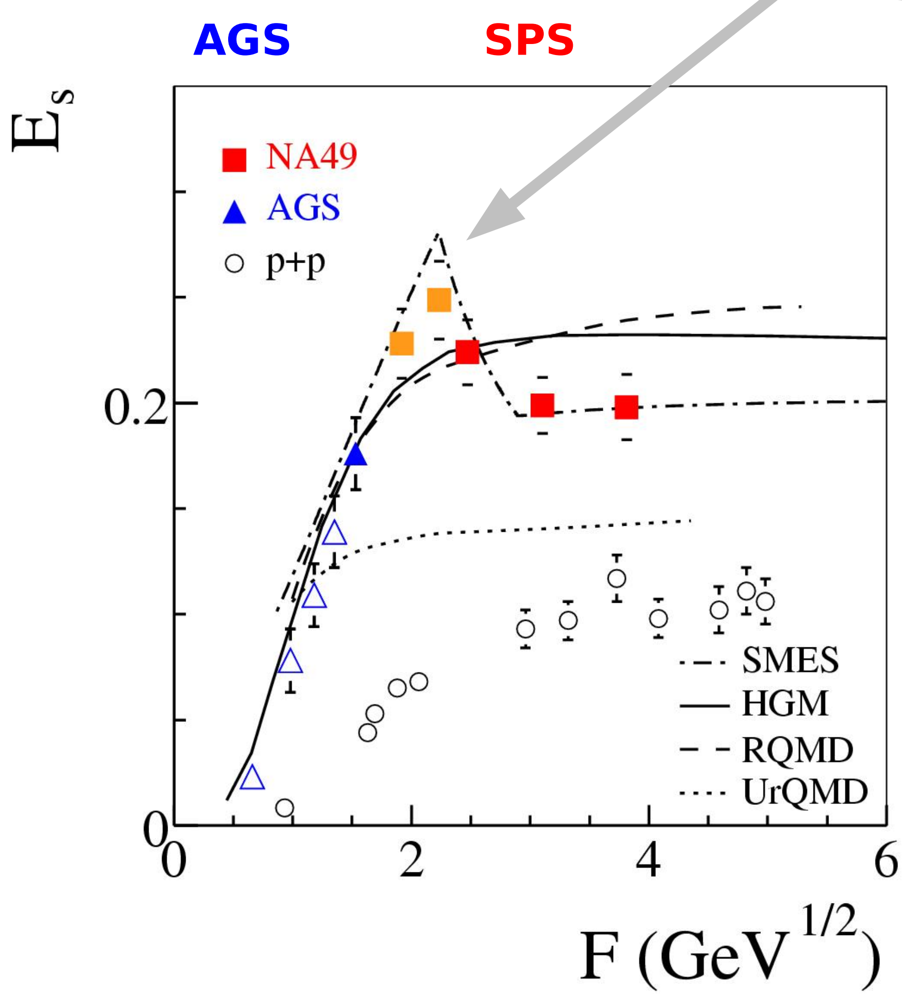
Bleicher

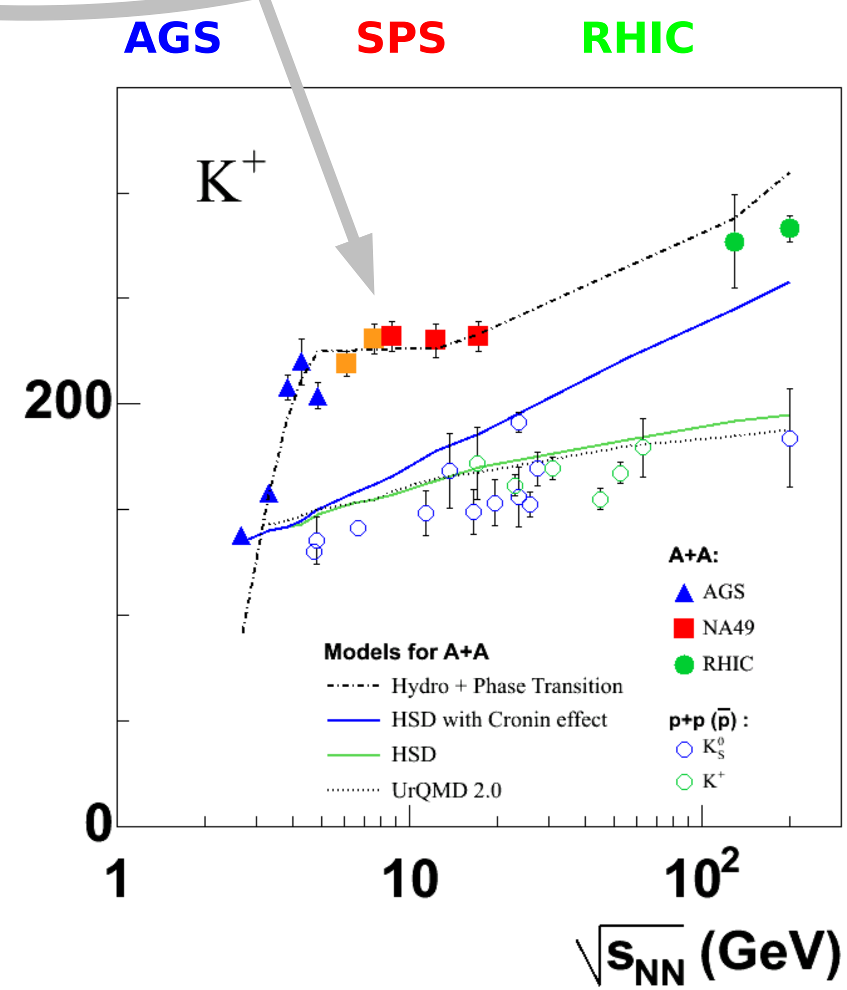
... and the dale in sound velocity



The models

Models with the
1^{st} order phase transition
reproduce the data

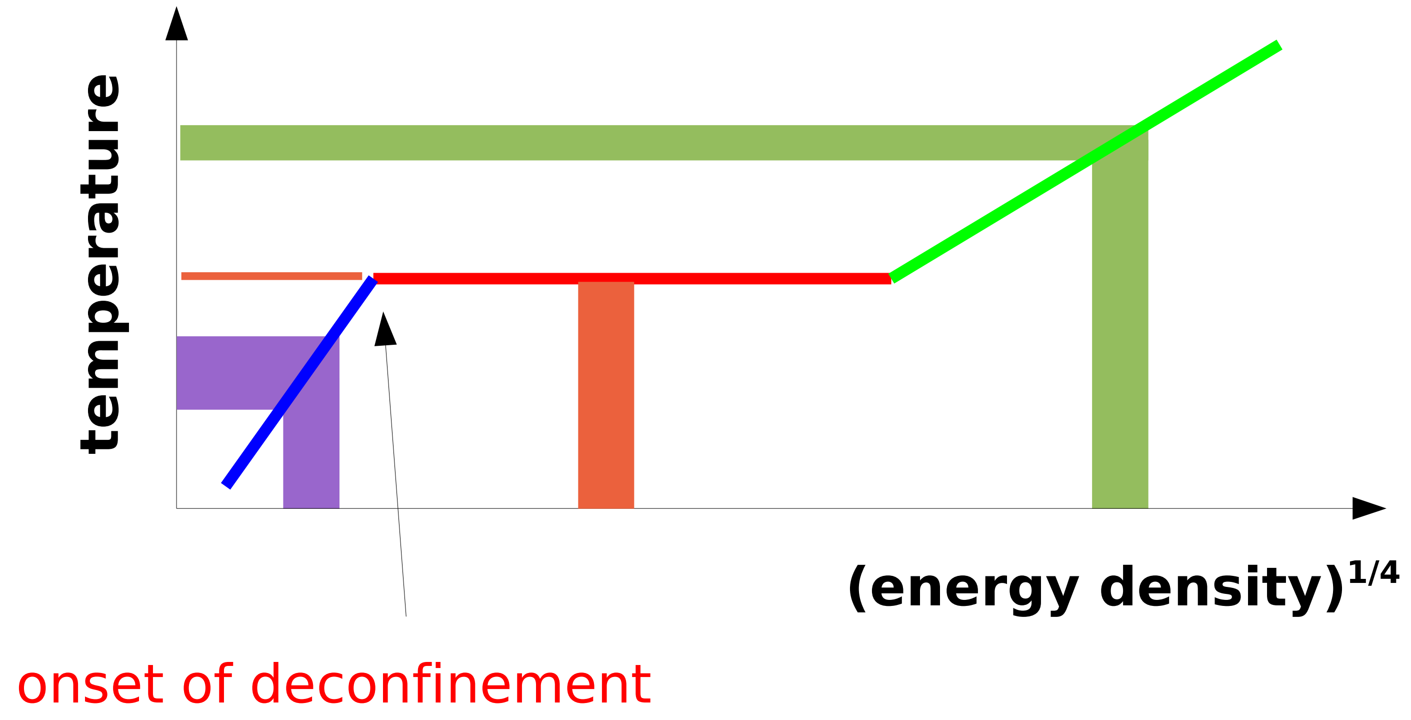




$$E_S = (\langle \Lambda \rangle + \langle K + \bar{K} \rangle) / \langle \pi \rangle$$

Strangeness fluctuations and deconfinement

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



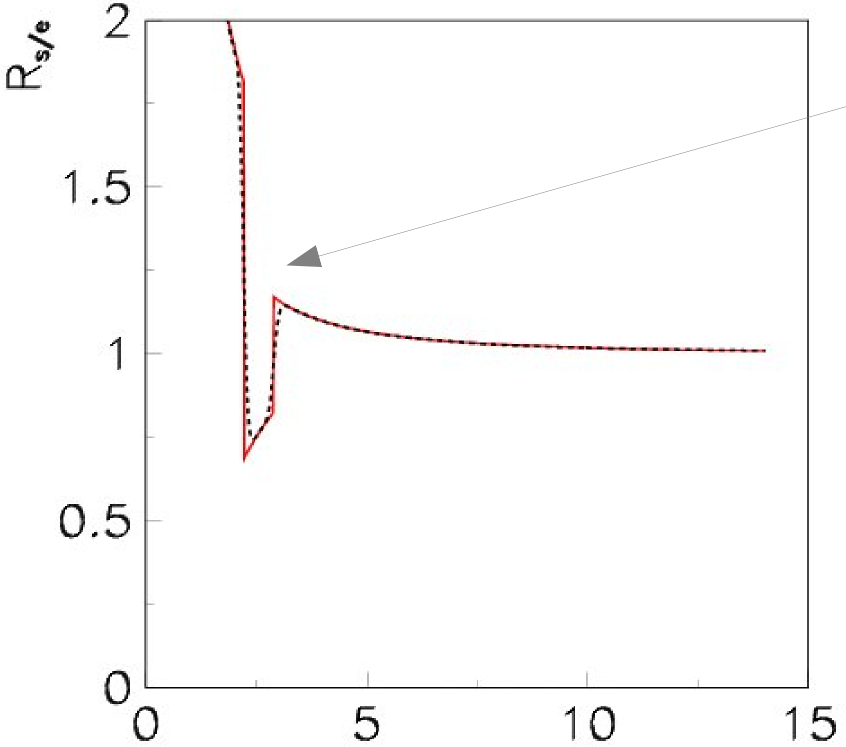
Gorenstein, M.G., Zozulya, PL B585:237, 2004

... and the energy dependence of dynamical strangeness fluctuations

The onset of deconfinement is signaled by a rapid change of the energy dependence

AGS **SPS** **RHIC**

dynamical strangeness fluctuations

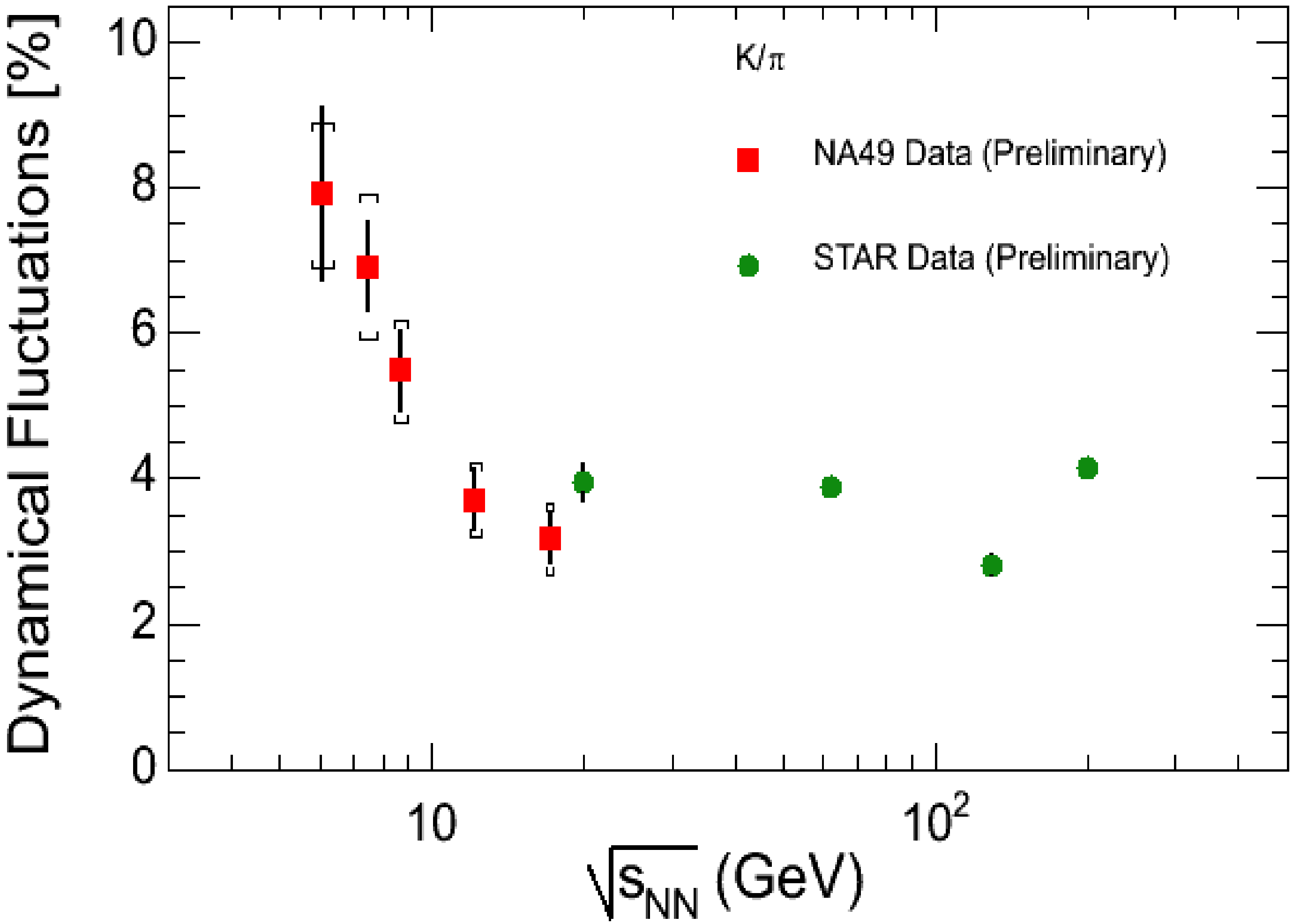


$F \approx \sqrt{\sqrt{s_{NN}}}$

collision energy

Kaon/pion fluctuations

NA49 STAR



Is this the first fluctuation signal of the onset of deconfinement?

Summary

I Several anomalies in hadron production are observed at low SPS energies

II The onset of observed anomalies is located at about 30*A* GeV

III The anomalies cannot be reproduced by the models without phase transition

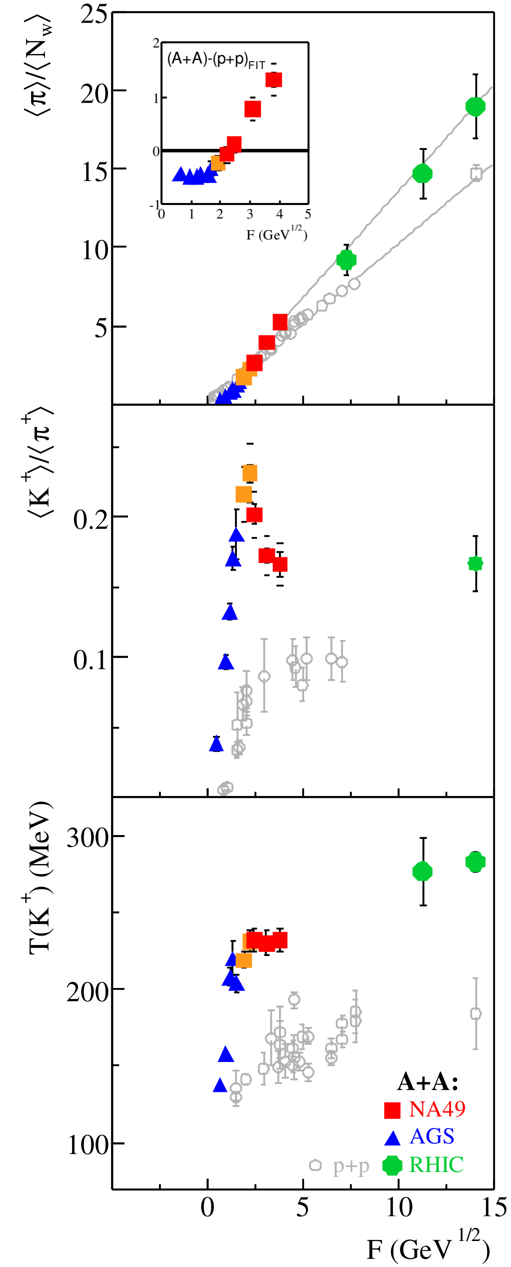
IIII Measured rapid changes are consistent with models assuming 1st order PT

↓

FUTURE

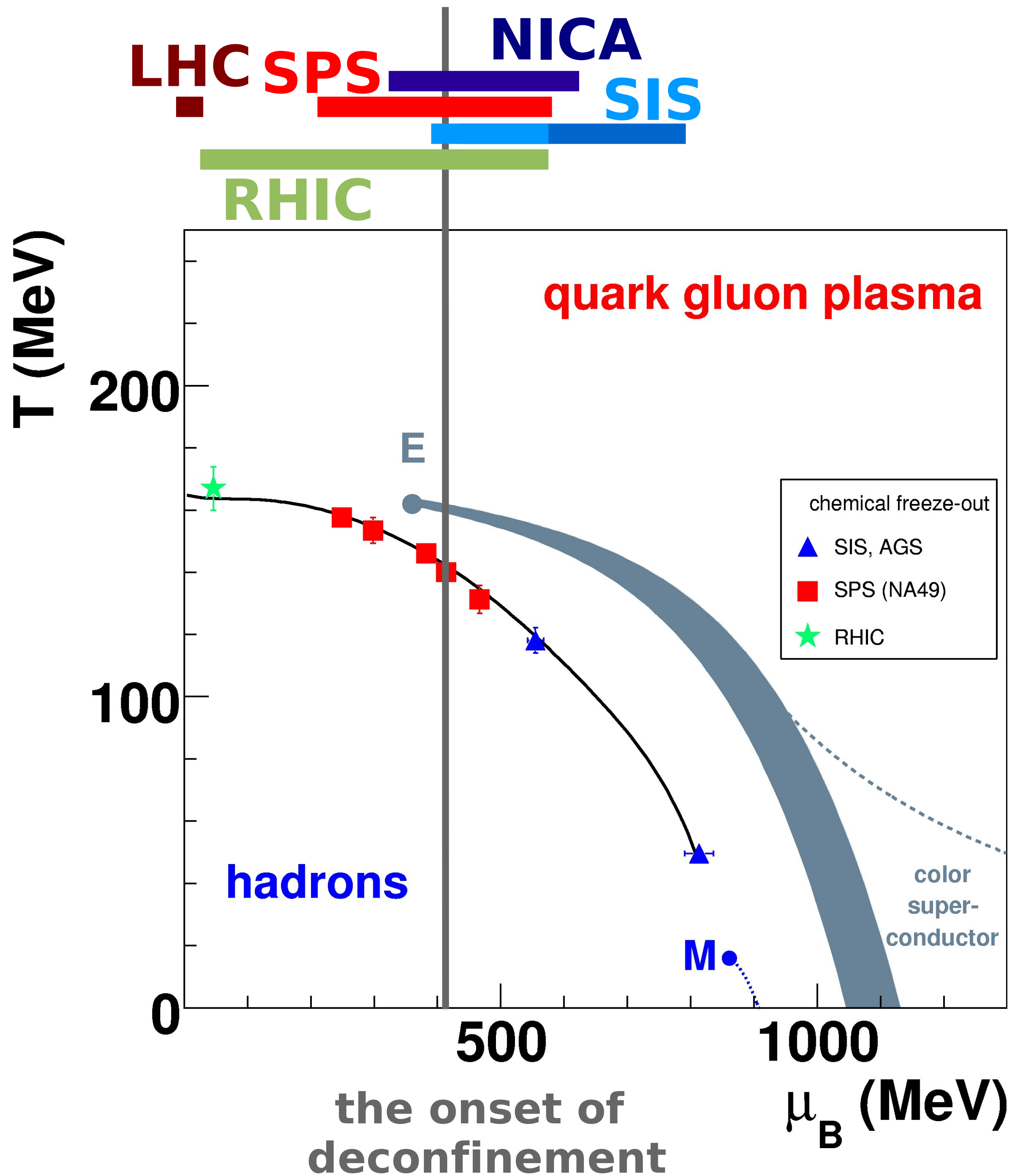
AGS SPS RHIC

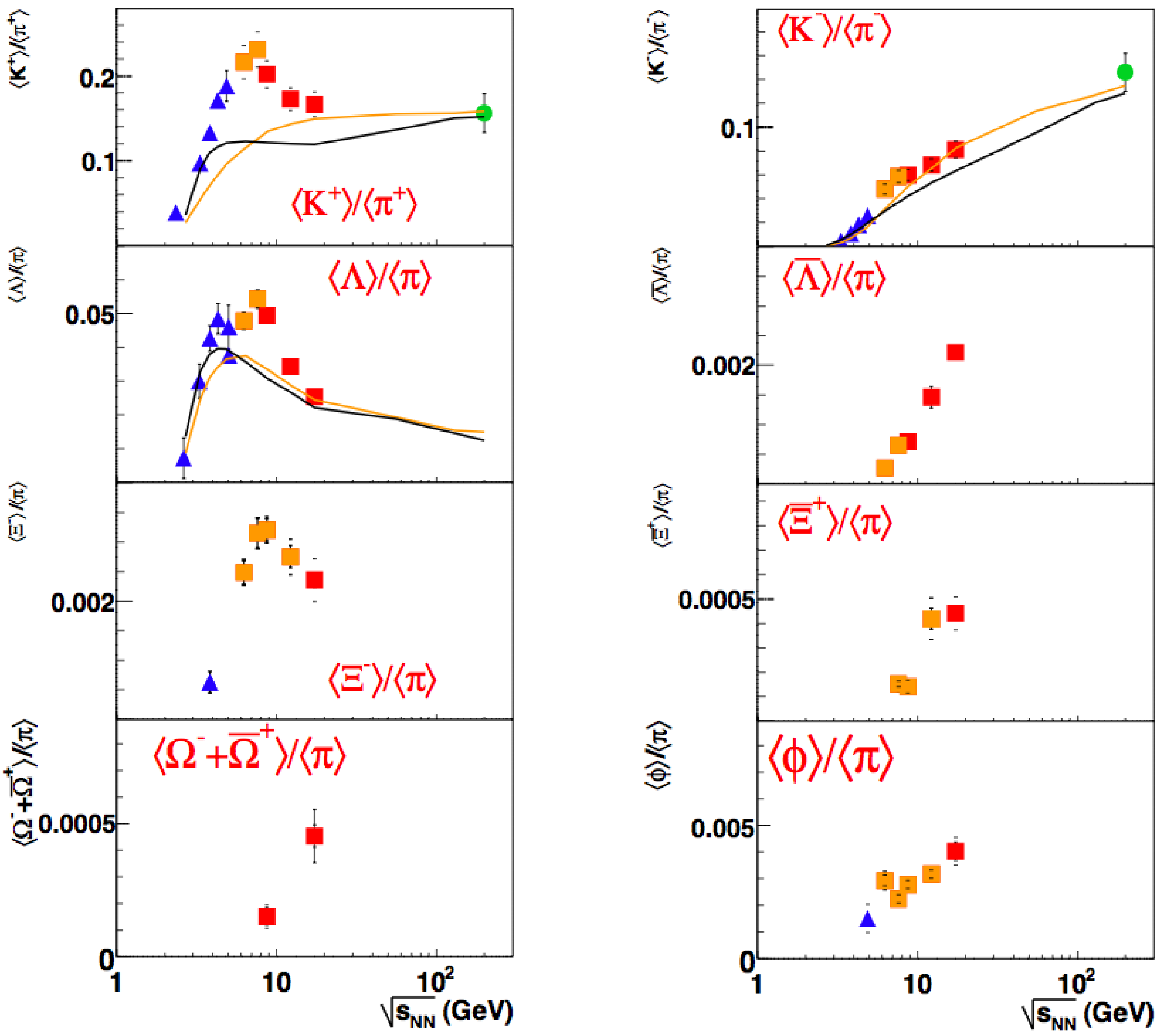
hadronic observables

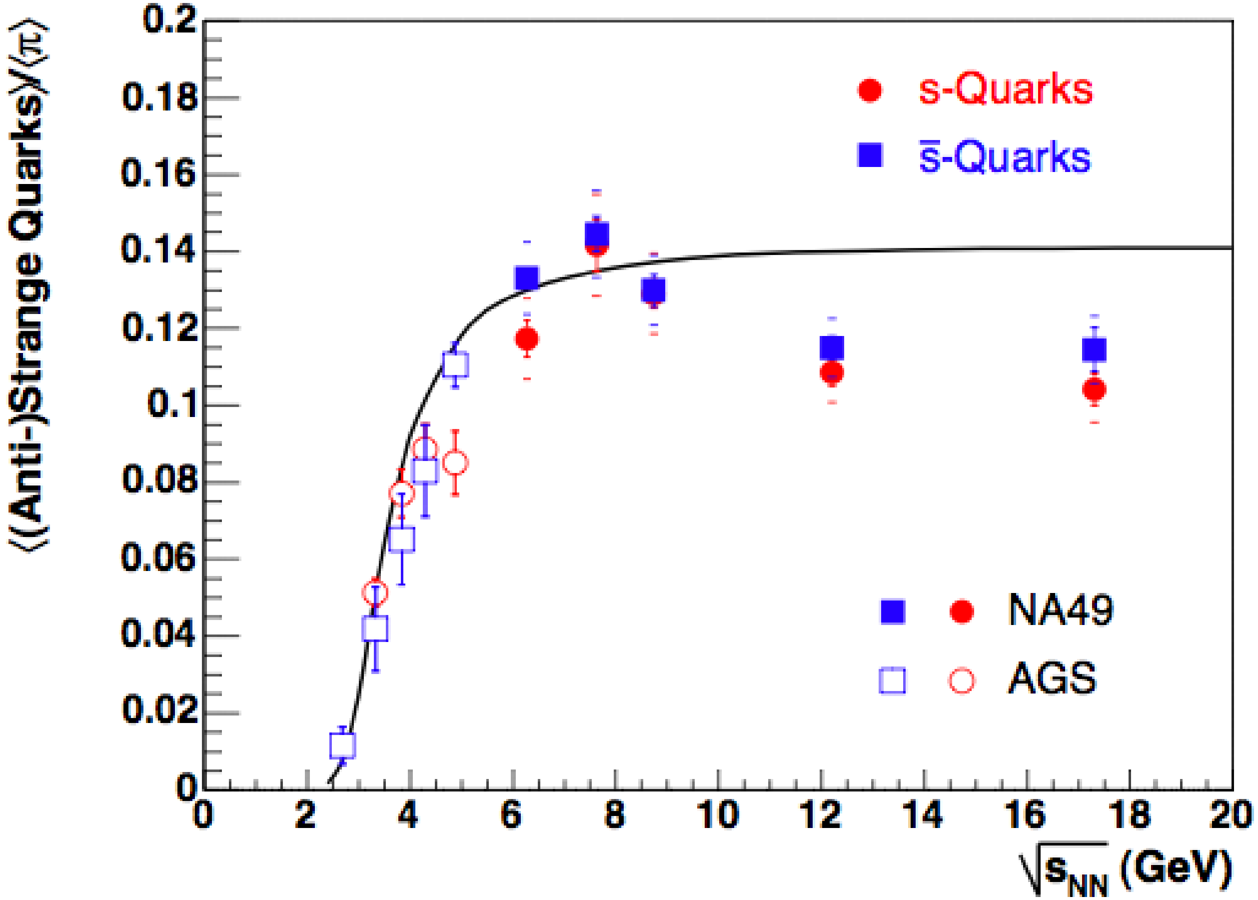


collision energy

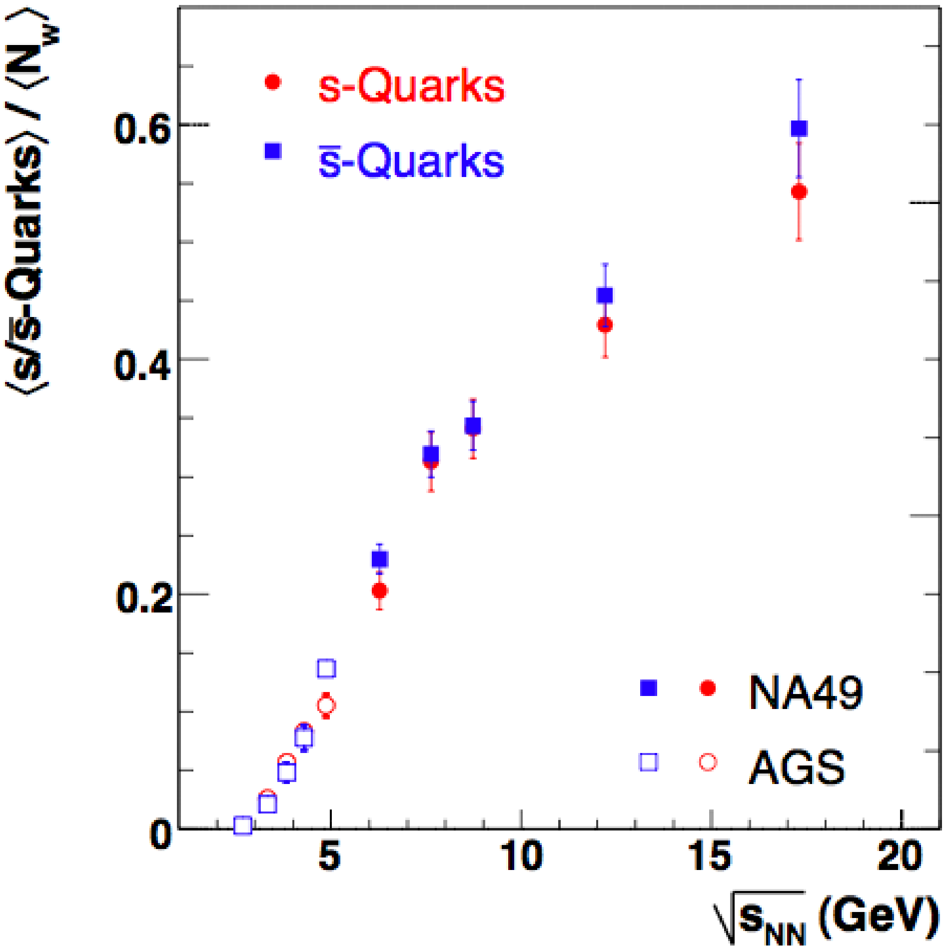
Additional slides


LHC
SPS
NICA
SIS
RHIC
T (MeV)
200
100
0
500
1000
μ_B (MeV)
quark gluon plasma
E
chemical freeze-out
SIS, AGS
SPS (NA49)
RHIC
hadrons
M
color
super-
conductor
the onset of
deconfinement

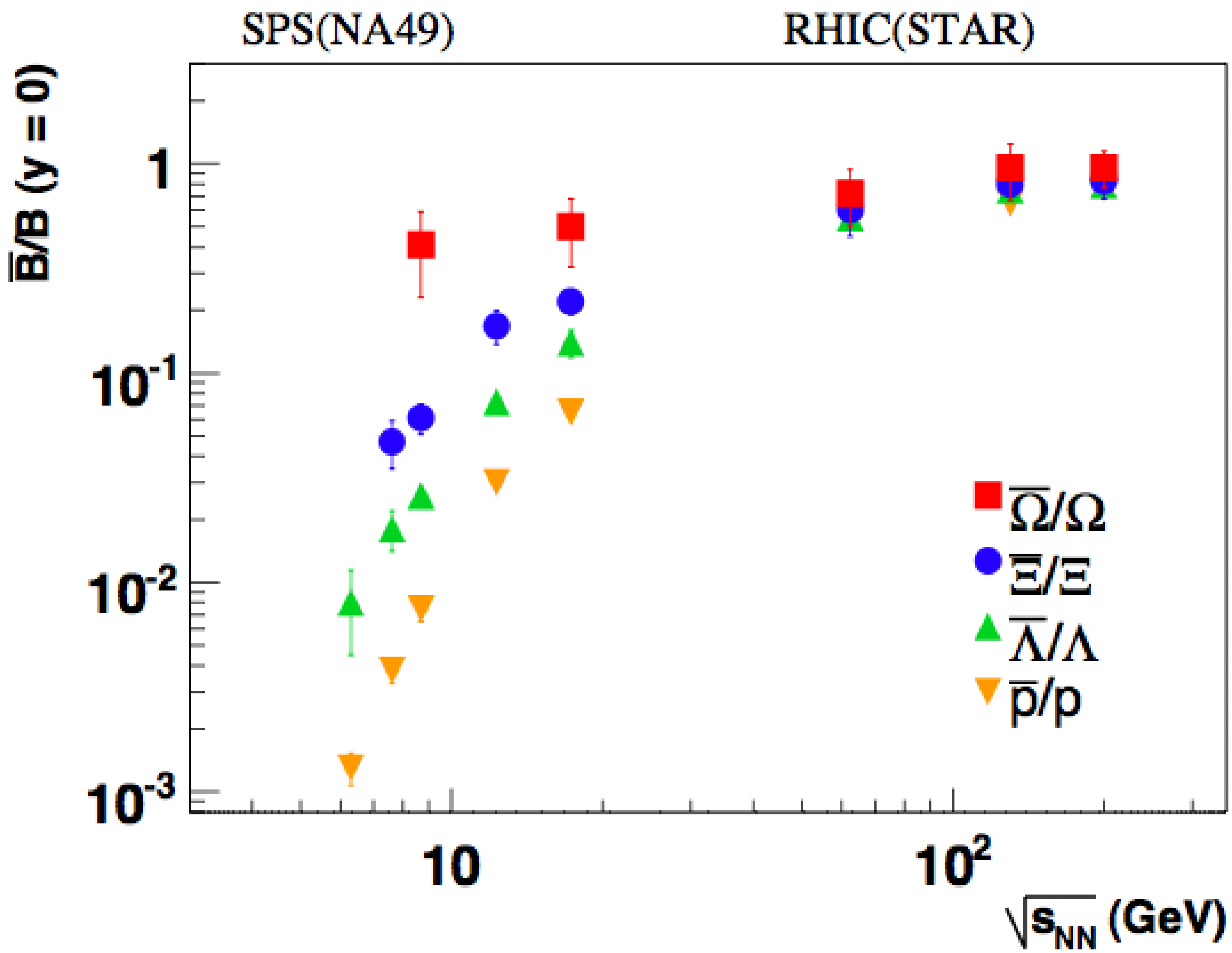

⟨K⁺⟩/⟨π⁺⟩
0.2
0.1
⟨K⁻⟩/⟨π⁻⟩
0.1
⟨Λ⟩/⟨π⟩
0.05
⟨Λ̄⟩/⟨π⟩
0.002
⟨Ξ⁻⟩/⟨π⟩
0.002
⟨Ξ̄⁺⟩/⟨π⟩
0.0005
⟨Ω⁻+Ω̄⁺⟩/⟨π⟩
0.0005
0
⟨φ⟩/⟨π⟩
0.005
0
1
10
10²
√sNN (GeV)



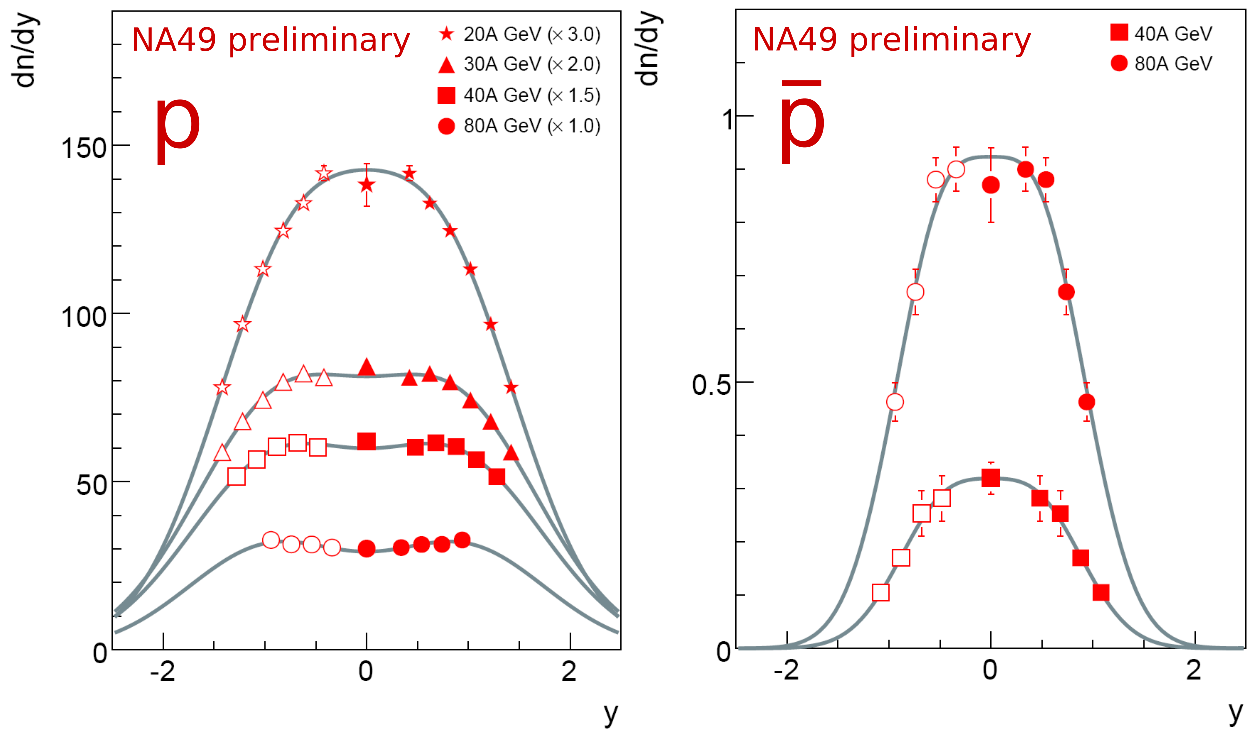
⟨(Anti-)Strange Quarks⟩/⟨π⟩
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
18
20
√s_NN (GeV)
s-Quarks
s̄-Quarks
NA49
AGS



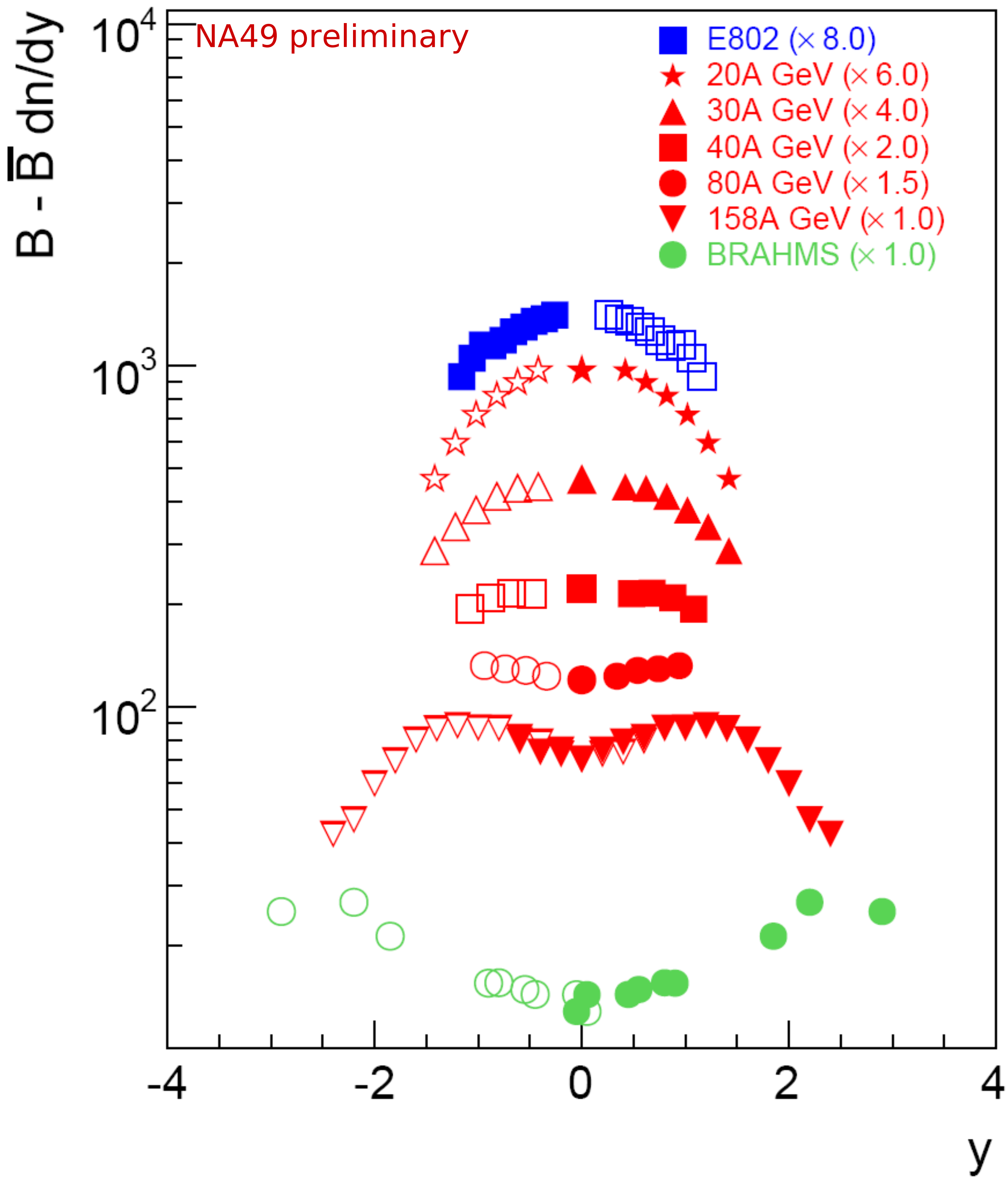
s-Quarks
s̄-Quarks
NA49
AGS
0.6
0.4
0.2
0
5
10
15
20
⟨s/s̄-Quarks⟩ / ⟨N_w⟩
√s_NN (GeV)



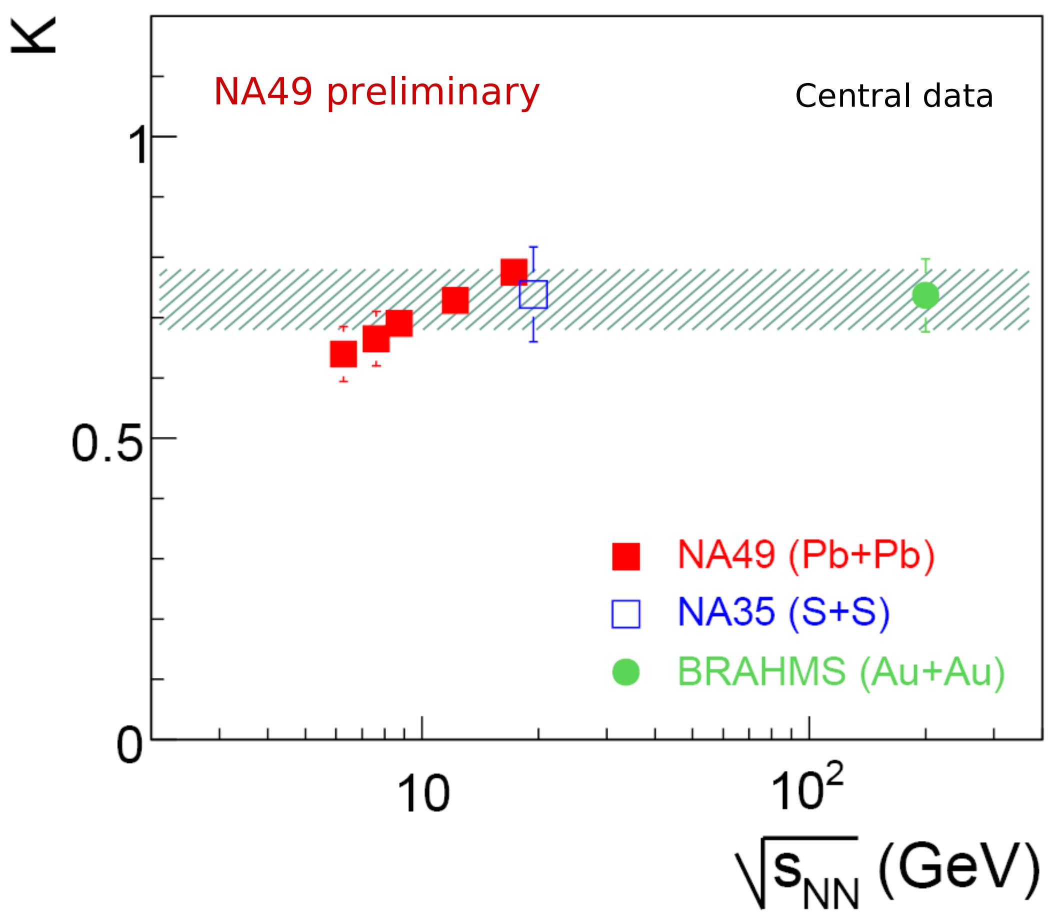
SPS(NA49)
RHIC(STAR)
$\bar{B}/B$ (y = 0)
1
10^{-1}
10^{-2}
10^{-3}
10
10^2
$\sqrt{s_{NN}}$ (GeV)
$\bar{\Omega}/\Omega$
$\bar{\Xi}/\Xi$
$\bar{\Lambda}/\Lambda$
$\bar{p}/p$

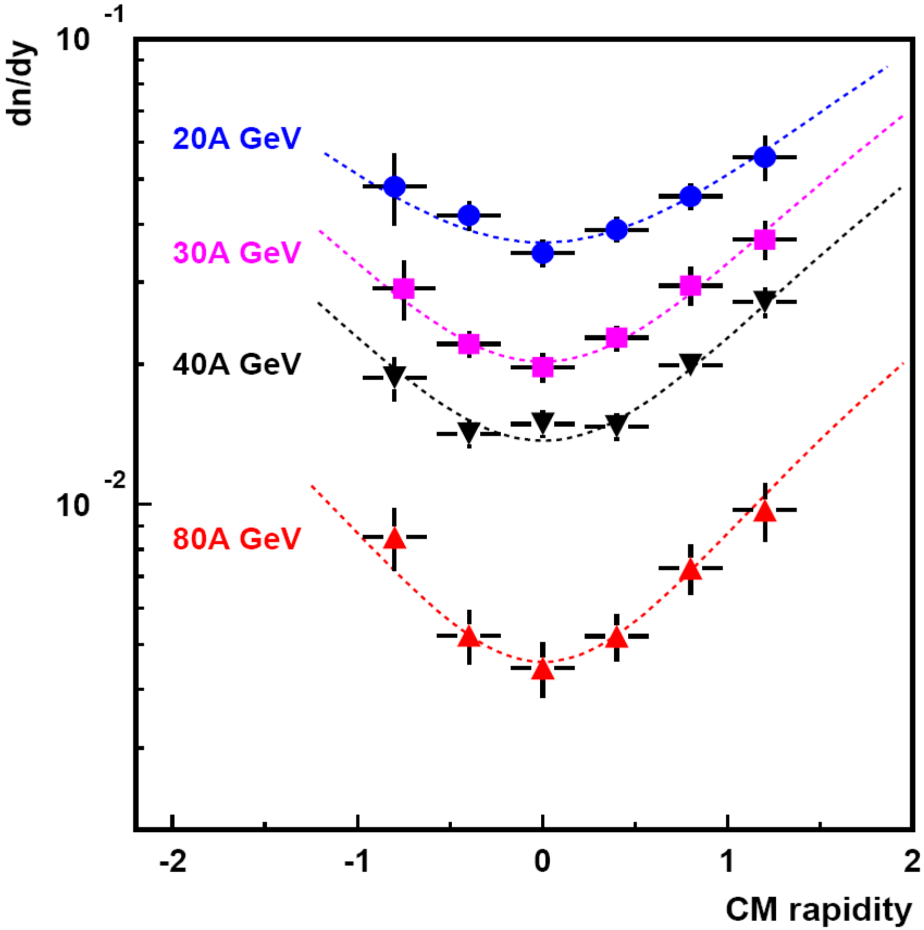


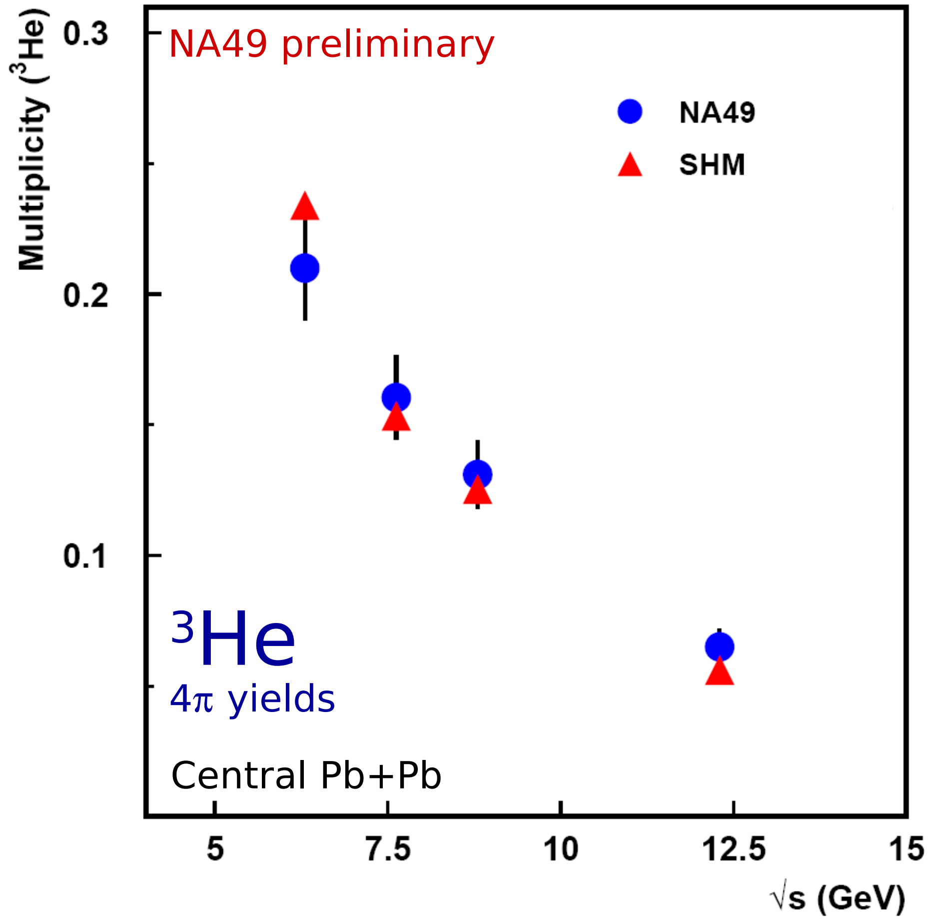
NA49 preliminary
p
20A GeV (× 3.0)
30A GeV (× 2.0)
40A GeV (× 1.5)
80A GeV (× 1.0)
dn/dy
150
100
50
0
-2
0
2
y
NA49 preliminary
p̄
40A GeV
80A GeV
dn/dy
1
0.5
0
-2
0
2
y



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)


dn/dy
10^{-1}
10^{-2}
20A GeV
30A GeV
40A GeV
80A GeV
-2
-1
0
1
2
CM rapidity


NA49 preliminary
NA49
SHM
Multiplicity (^{3}He)
0.3
0.2
0.1
^{3}He
4π yields
Central Pb+Pb
5
7.5
10
12.5
15
√s (GeV)