High energy density physics and relativistic nucleus-nucleus collisions

M.I. Gorenstein (BITP, KieV)

1. Matter from elementary particles 1950

2a. Quark Model
2b. Limiting Temperature of Fireballs 1965

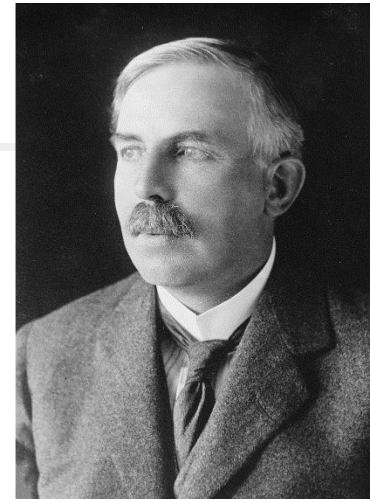
3. Phase Transitions in the Gas of Bags 1980

4. Onset of Deconfinement 2000

5. QCD critical point 2015

Summary

I. Matter from Elementary Particles



Ernest Rutherford
1871-1937

p proton="first", Rutherford ,1920

n Chadwick, 1932 (Nobel Prize 1935)

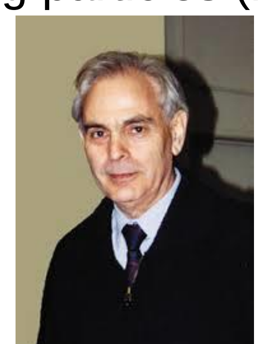
π^+, π^-, π^o Powell, 1947, cosmic rays;
Yukawa (NP 1949), Powell (NP 1950)

K, Λ strange hadrons, cosmic rays, 1947

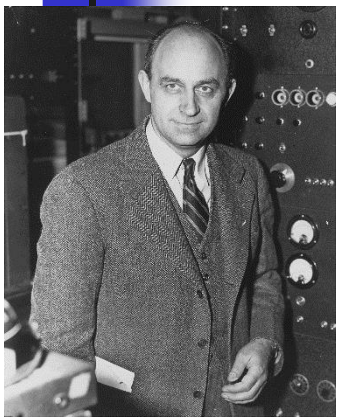
$\overline{p}$ antiproton predicted by Dirac in his 1933 NP lecture,
discovered by Serge and Chamberlain in 1955 (NP in 1959)

In 1960 about of several tens of strongly interacting particles (hadrons) were known

HADRONS Lev Okun 1962



Multiparticle Production in proton-proton collisions



1950, Fermi – Statistical Model
Progr. Theor. Phys. (1950)

1953, Landau – Hydrodynamical Model
Izv. Akad. Nauk (1953)

$$p = \frac{1}{3}\varepsilon , \qquad \varepsilon = \sigma T^4$$

1. Ideal Gas 2. $m \ll T$

Units: $\hbar = c = k = 1$ 1fm=10^{-13}cm, 1fm/c=10^{-23}sec

$m_\pi = 140$ MeV, $m_p = 940$ MeV, $1\text{fm} \simeq \frac{1}{200\ \text{MeV}}$

Interacting hadrons = (non-interacting) Hadrons + Resonances

E. Beth and G.E. Uhlenbeck, Physica (1937), calculated the level density for interacting particles. They derived an expression for this density which describes the interaction by the scattering phase shifts.

S.Z. Belenkij, Nucl. Phys. (1956), proposed to treat hadronic resonances exactly like stable particles in phase space calculations.

R. Dashen, S. Ma, and H.J. Bernstein, Phys. Rev. (1969), S-matrix formulation of statistical mechanics.

II. Limiting Temperature

Relativistic, Ideal, Boltzmann, Multi-Component, Gas

$$Z(T,V;m) = \sum_{N=0}^{\infty} \frac{V^N}{N!} \int_0^{\infty} \frac{k_1^2 dk_1}{2\pi^2} \exp\left(-\frac{\sqrt{k_1^2 + m^2}}{T} \right) \ldots$$

$$\ldots \int_0^{\infty} \frac{k_N^2 dk_N}{2\pi^2} \exp\left(-\frac{\sqrt{k_N^2 + m^2}}{T} \right) = \exp\left(\frac{V \; m^2 T \; K_2(m/T)}{2\pi^2} \right)$$

$$= \exp\left(\bar{N}(T,m) \right) ,$$

$$Z(T,V;m_1,\ldots,m_L) = \prod_{j=1}^{L} Z(T,V;m_j) = \exp\left[\bar{N}(T,m_1) \right] \times \ldots$$

$$\times \exp\left[\bar{N}(T,m_L) \right] = \exp\left[\sum_{j=1}^{L} \bar{N}(T,m_j) \right] = \exp\left[\int_0^{\infty} dm \rho(m) \; \bar{N}(T,m) \right]$$

$$Z(T,V) = \exp\left[\int_0^\infty dm\, \rho(m)\ \frac{V}{2\pi^2}\ m^2 T\ K_2\left(\frac{m}{T}\right)\right]$$

$$\rho(m) = C\ m^{-a}\ \exp\left(\frac{m}{T_H}\right)$$

$$p(T) = \frac{T \ln Z}{V} = T\int_{M_0}^\infty dm\ \rho(m)\ \left(\frac{mT}{2\pi}\right)^{3/2} \exp\left(-\frac{m}{T}\right) \propto\ (T_H - T)^{a-5/2}$$

$$\varepsilon(T) = T\frac{dp}{dT} - p\ \propto\ (T_H - T)^{a-7/2}$$

At $T \to T_H$: $\quad p,\ \varepsilon \to \infty,$ for $a\ \le\ \frac{5}{2}$

$p \to const,\ \varepsilon \to \infty,$ for $\frac{5}{2} < a \le \frac{7}{2}$

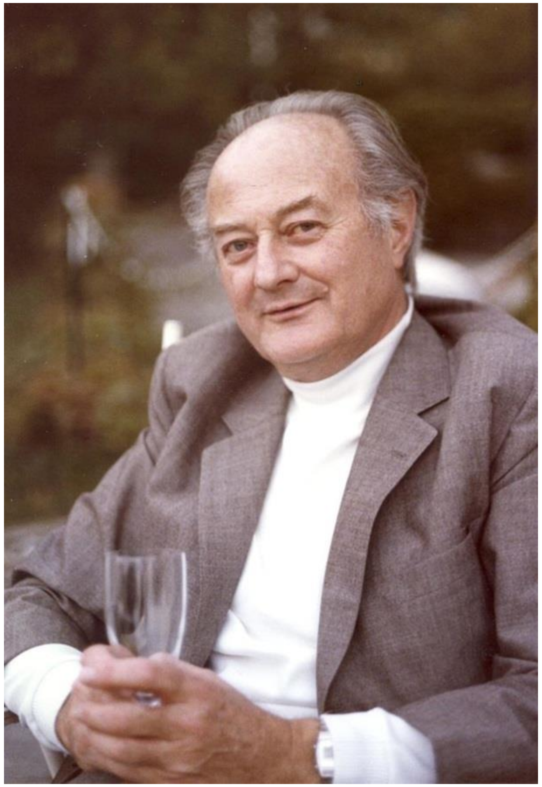
$p \to const,\ \varepsilon \to const,$ for $a > \frac{7}{2}$

Transverse momentum spectra

T_H must govern the transverse momentum spectra of outgoing final particles in high energy collisions:

$$\frac{dN}{dp_T} \propto \exp\left(- \frac{\sqrt{p_T^2 + m^2}}{T_H} \right)$$

$$T_H = 158 \pm 3 \text{ MeV}$$



$$T_H = 160 \pm 5 \text{ MeV} \approx 1.7 \times 10^{12} \ {}^0K$$

this estimate was used in further publications

T_H=158 MeV R. Hagedorn (1965)

p_T spectra

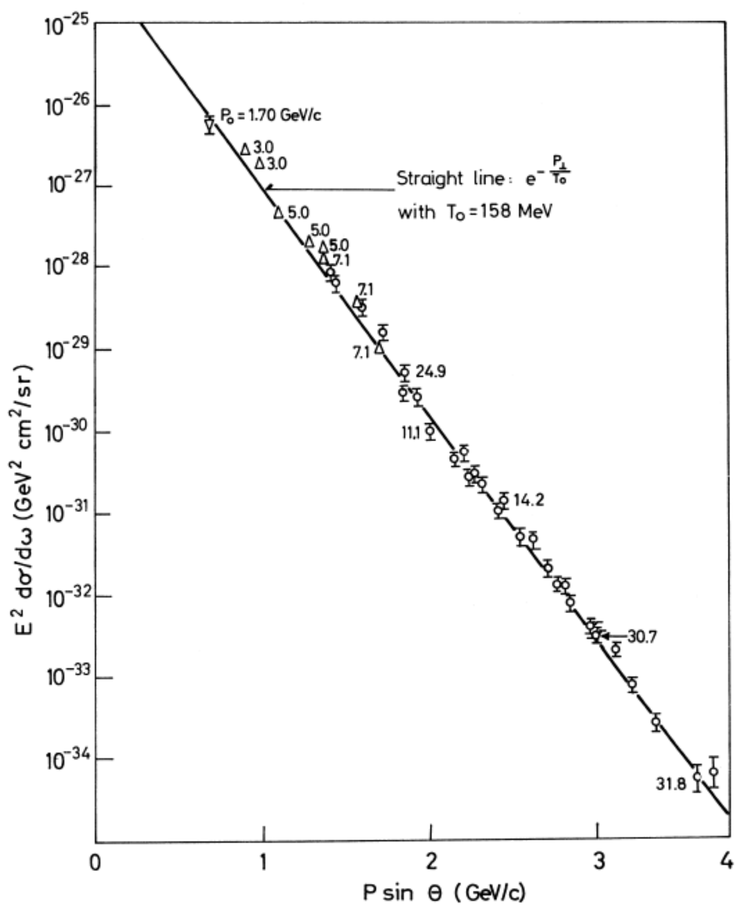


FIG. 1 $[E^2 d\sigma_{el}/d\omega]_{pp}$ as a function of the transverse momentum [taken from ref. 14)]

$\rho(m)$ versus m

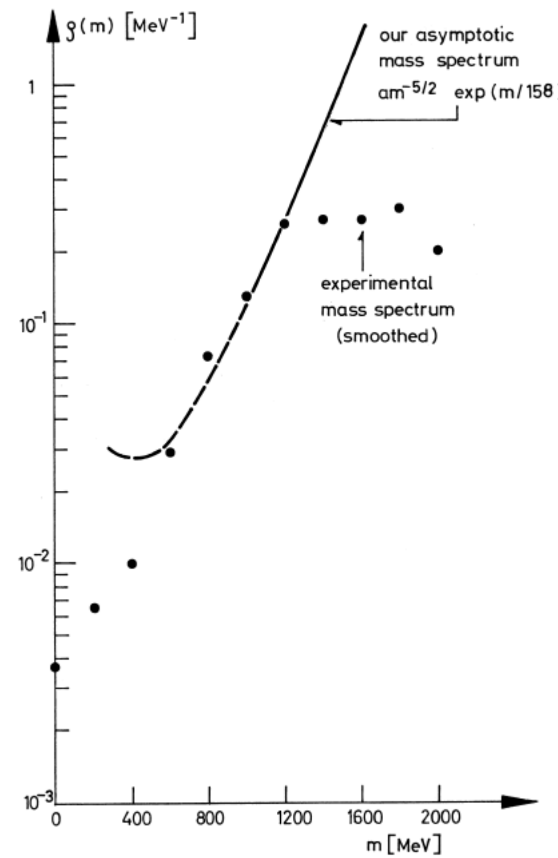


FIG. 2 The experimental mass spectrum[10] (smoothed) compared to our asymptotic $\rho(m)$; one-parameter fit with $a \approx 6.5 \times 10^3$ [MeV$^{3/2}$]

R. Hagedorn and J. Ranft, Suppl. Nuovo Cim. (1968);
R. Hagedorn, Suppl. Nuovo Cim. (1968), Nuovo Cim. (1967, 1968).

R. Hagedorn, "Remarks on the Thermodynamical Model of Strong Interactions", Nucl. Phys. B (1970).

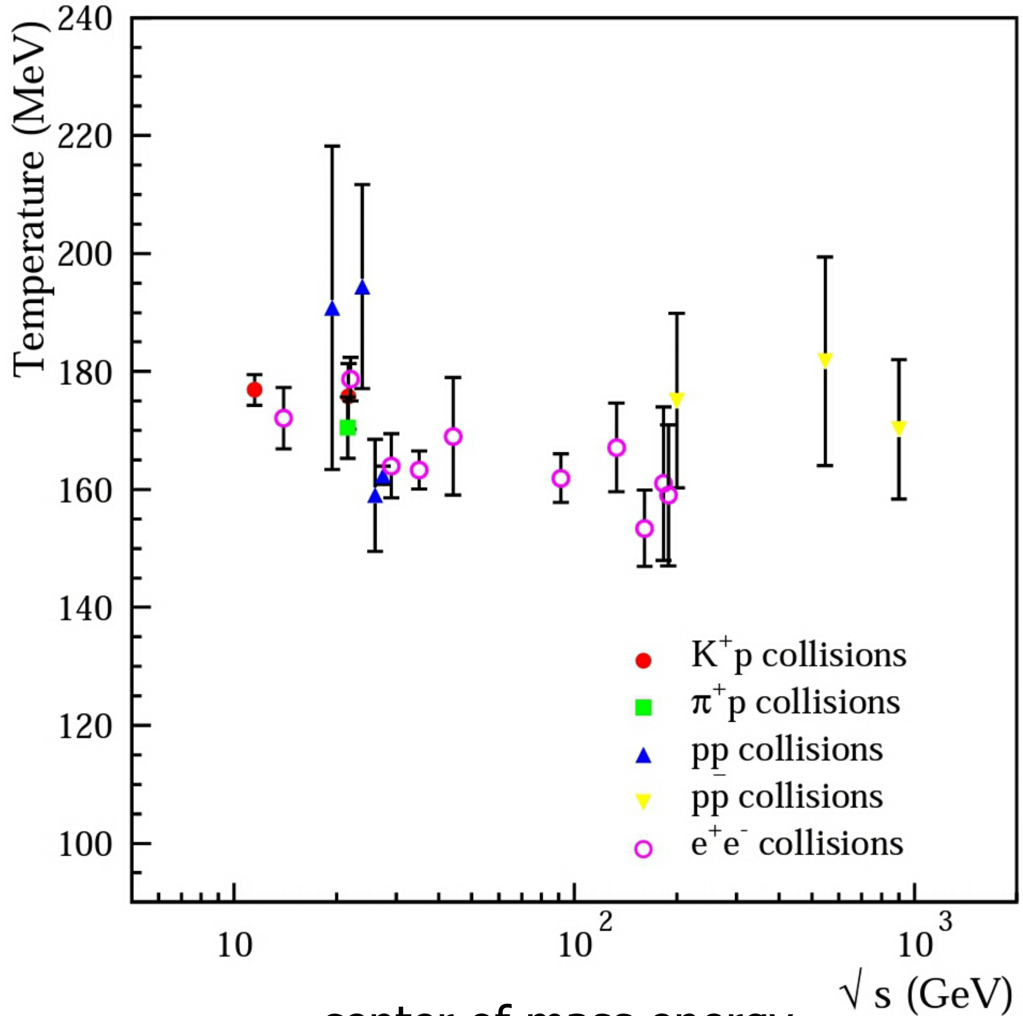
A firebal is
a statistical equilibrium of undetermined numbers of fireballs, each of which, in turn, is considered to be …

New philosophy: If quarks exist as real free particles then the hadron mass contains states with non-integer charge and baryon number; if they do not exist as free particles, then the hadron spectrum does not contains such states. In both cases quarks need not be considered more elementary than other hadrons, they are just members of the family

G. Veneziano, Nuovo Cim. (1968), dual resonance model (Veneziano model), Exponentially increasing mass spectrum, Strings (1020 citations)

Fireballs=Strings

T_H is a limiting temperature in the Hadron World

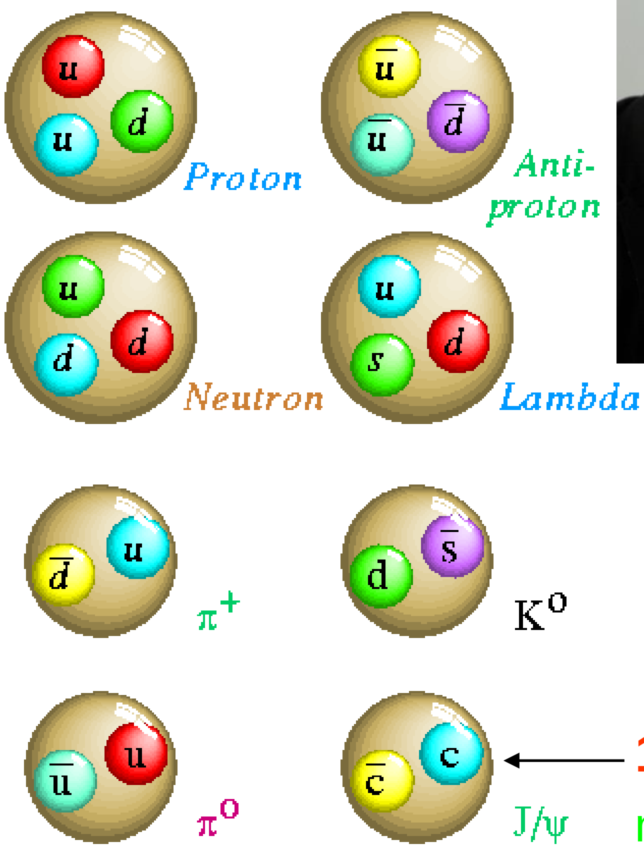


center of mass energy

From fitting the data on hadron multiplicities within statistical model,
Becattini
arXiv:0901.3643 [hep-ph]

QUARKS

1963, Gell-Mann and Zweig (u,d,s)



Gell-Mann
(NP, 1969)

1974
m=3.1 GeV
(NP, 1976)

$\Upsilon(b\bar{b}), \quad m = 9.46\ \mathrm{GeV}$

1977

Mesons:

$\pi^\pm, \ \pi^0, \ \eta, \ \rho, \ \omega, \ \phi(s\bar{s}), \ \ldots$

$K^+(u\bar{s}), \ K^0(d\bar{s}), \ \overline{K^0}(\bar{d}s), \ K^-(\bar{u}s)$

$c\bar{c} \quad \eta_c, J/\psi, \xi_c, h_c, \psi(2S), \ \ldots$

$D^+(c\bar{d}), \ D^0(c\bar{u}), \ \overline{D^0}(\bar{c}u), \ D^-(\bar{c}d)$

$D_s^+(c\bar{s}), \ D_s^-(\bar{c}s)$

$b\bar{b} \qquad \Upsilon, \xi_b, h_b, \ldots,$

$u\bar{b}, d\bar{b}, \bar{d}b, \bar{u}b,$

$s\bar{b}, \bar{s}b, \ c\bar{b}, \bar{c}, b$

Baryons:

uud, udd, uuu, ddd

uds, uus, uds, dds, uss, dss, sss

udc, uuc, ddc, usc, dsc, ssc

udb, usb, dsb, ssb

Bogolyubov Institute for Theoretical Physics
National Academy of Sciences of Ukraine

May 16-17, 2013, Kiev

COLOR OF QUARKS

Workshop in memory of Boris V. STRUMINSKY
(14.08.1939 – 18.01.2003)

Topics:

- Quark model of structure and hadron interaction
- Quantum chromodynamics and standard model of elementary particles
- Collective properties of nuclear matter

Relatives, friends, and colleagues are welcome!

For further information, please contact:

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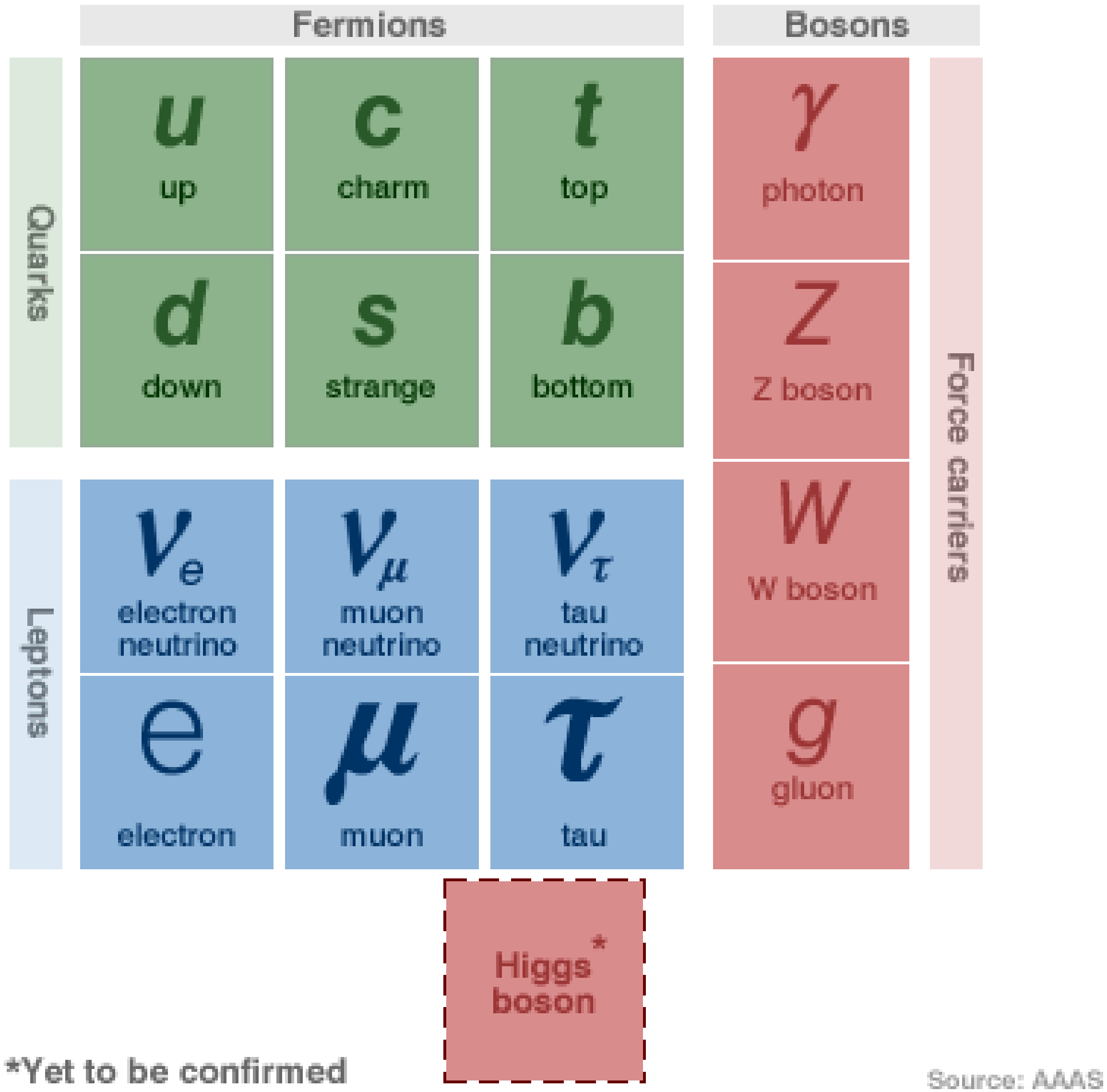
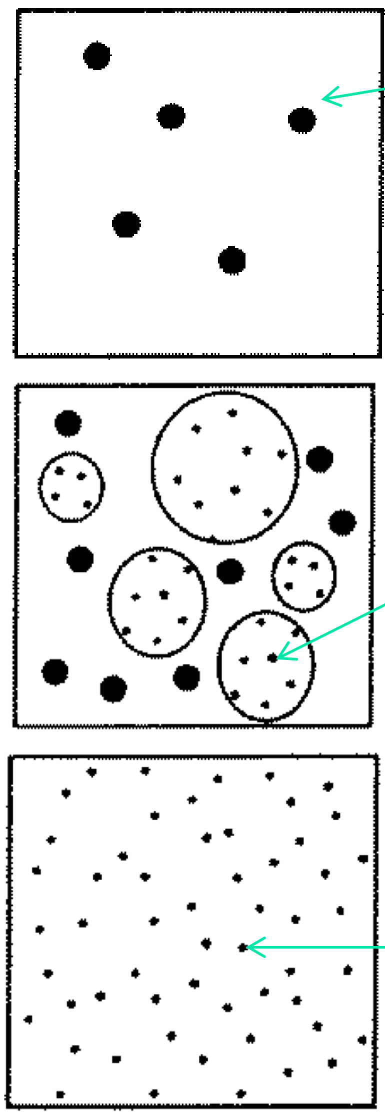
Fax: (+38044) 5265998

THE STANDARD MODEL



III. Phase Transitions in the Gas of Bags



m

$$\rho(m) = C \; m^{-a} \; \exp\left(\frac{m}{T_H}\right)$$

(m, v) M.I.G., Petrov, and Zinovjev, Phys. Lett. B (1981)

$$\rho(m,v) = C v^{\gamma} (m - Bv)^{\delta} \exp\left[\frac{4}{3}\sigma^{1/4} v^{1/4} (m - Bv)^{3/4}\right]$$

Quark Gluon Plasma

Phase Transition in the Gas Bags

$$\hat{Z}(T,s) = \int_0^\infty dV \exp(-sV)\, Z(T,V) = \frac{1}{s - f(T,s)}$$

$$f(T,s) \equiv \left(\frac{T}{2\pi}\right)^{3/2} \int dm dv\; m^{3/2} \rho(m,v) \exp\left(-\frac{m}{T}\right) \exp(-sv)$$

$$p(T) = Ts^*(T) = T \max\{s_H(T), s_Q(T)\}$$

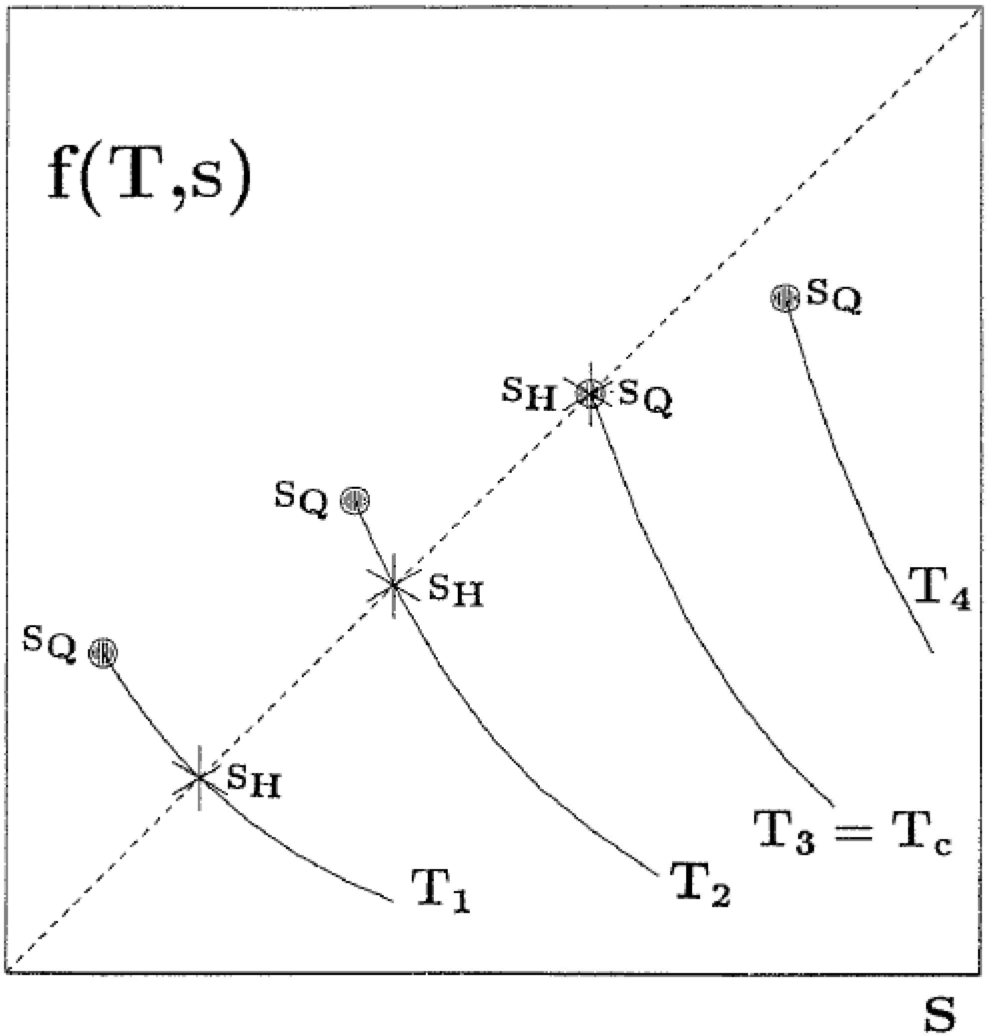
$$Z(T,V) = \exp\left[\frac{p(T)\, V}{T}\right]$$

s^* is the farthest-right singularity of $\hat{Z}(T,s)$: $p(T) = Ts^*(T)$

$s_H = f(T, s_H)$, $f(T, s_Q)$

$\gamma + \delta < -3, \quad \delta < -7/4$ conditions for the PTs

$$p(T) = Ts_Q(T) = \frac{\sigma}{3}T^4 - B$$



HG → QGP

M.I.G., Zinovjev, Petrov, and Shelest,
Teor. Mat. Fiz. (1982)
M.I.G. Yad. Fiz. (1984)

1st order PT

M.I.G., W. Greiner, and
Shin Nan Yang, J. Phys. G (1998)

2nd order PT

M.I.G., Gazdzicki, and
W. Greiner, Phys. Rev. C (2005)

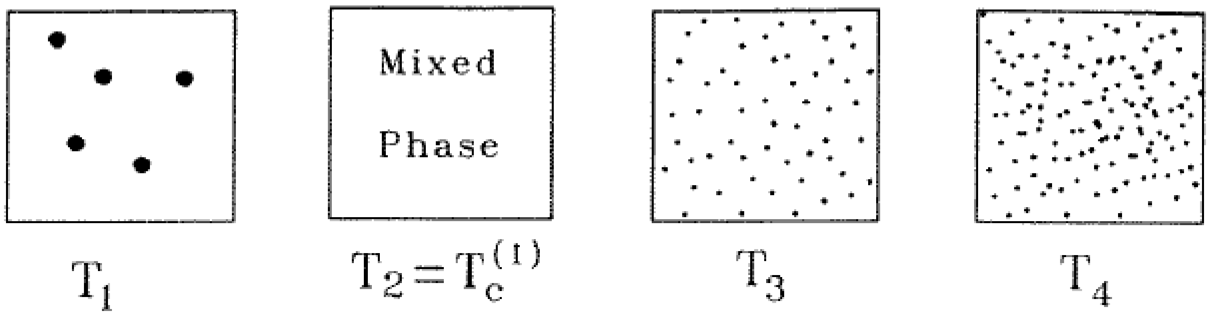
Higher order PTs

Hadron-Resonance-Bag Gas

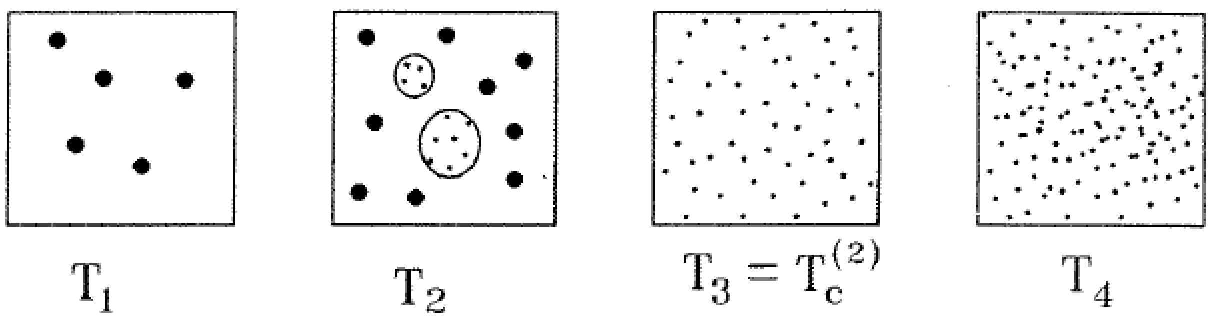
Quark Gluon Plasma

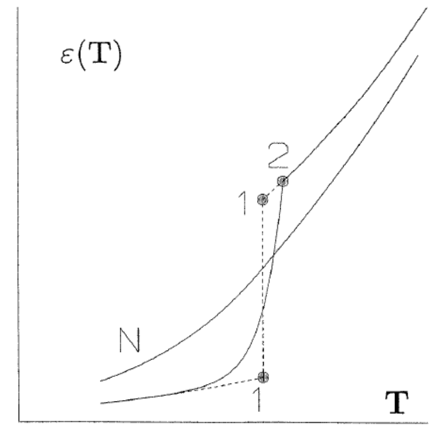
1^{st} order PT, 2^{nd} order PT, …, Cross-over

hadrons=small bags 1^{st} order PT QGP=infinitely large bag



2^{nd} order PT





Nucleus-Nucleus Collisions

	E (GeV)	$S^{1/2}$ (GeV)
AGS BNL Au+Au 1980 – 1990	2 ÷ 11	2.3 ÷ 4.7
SPS CERN Pb+Pb 1990 – 2000 2000 2002 2003 2010-…	160 40, 80 30 20 10 ÷160	17.4 8.3, 12.3 7.6 6.3
RHIC BNL Au+Au 2000 –…		200 8 ÷ 200
LHC CERN Pb+Pb 2010 -- …		2760

Alternative Gradient Synchrotron

Super Gradient Synchrotron

NA 49

NA 61

Relativistic Heavy Ion Collider

2000-2010

2010- …, STAR

ALICE

Large Hadron Collider

QGP discovery 2000

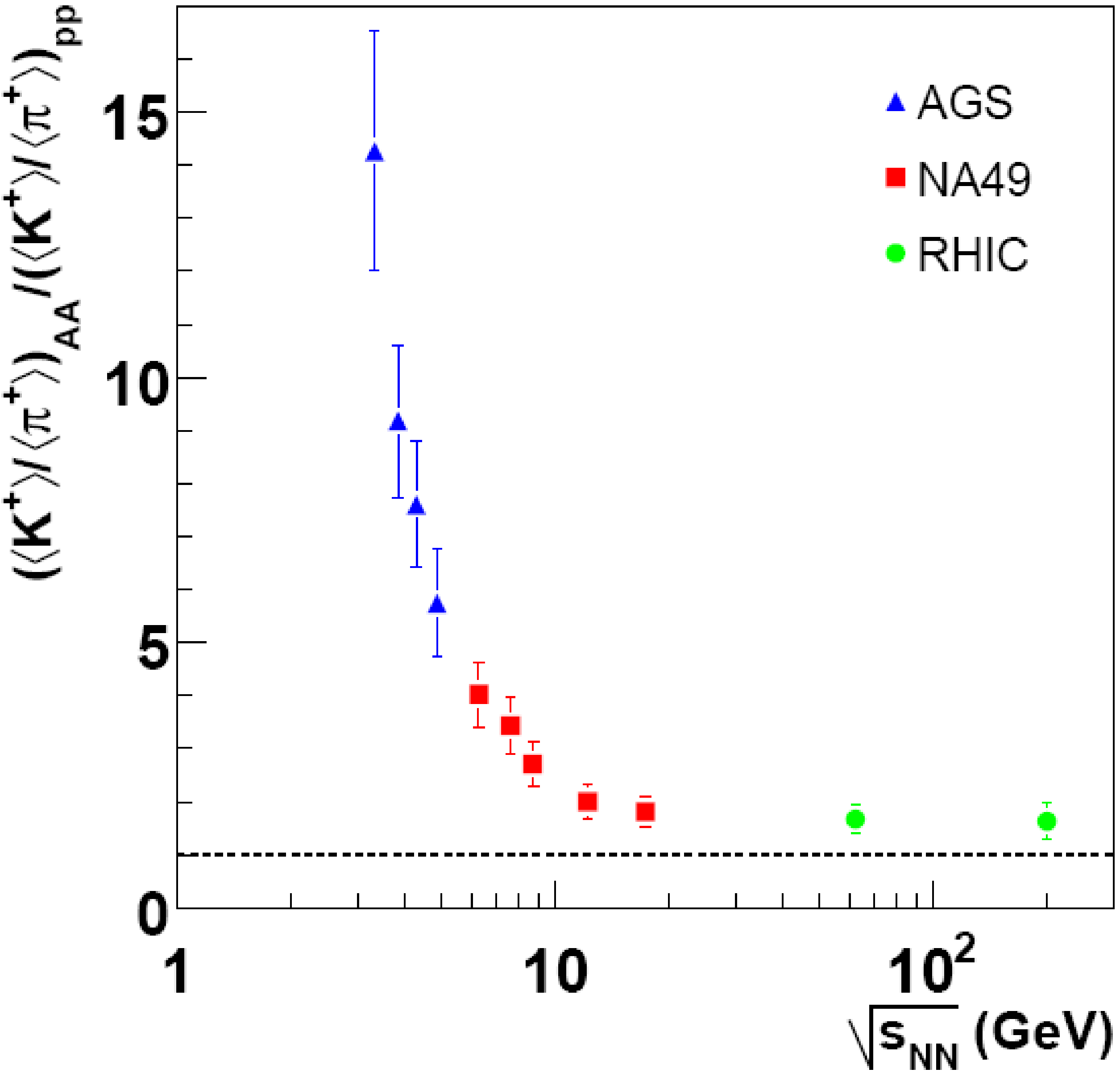
- 1). J/psi Suppression - Matsui, Satz (1986)

$$\left[\frac{N_{J/\psi}}{N^{DY}_{e^+e^-}}\right]_{AA} < \left[\frac{N_{J/\psi}}{N^{DY}_{e^+e^-}}\right]_{pp}$$

- 2). Strangeness Enhancement - Koch, Muller, Rafelsky (1986) .

$$\left[\frac{N_K}{N_\pi}\right]_{AA} > \left[\frac{N_K}{N_\pi}\right]_{pp}$$

3). Photon and Lepton Thermal Production   4)……

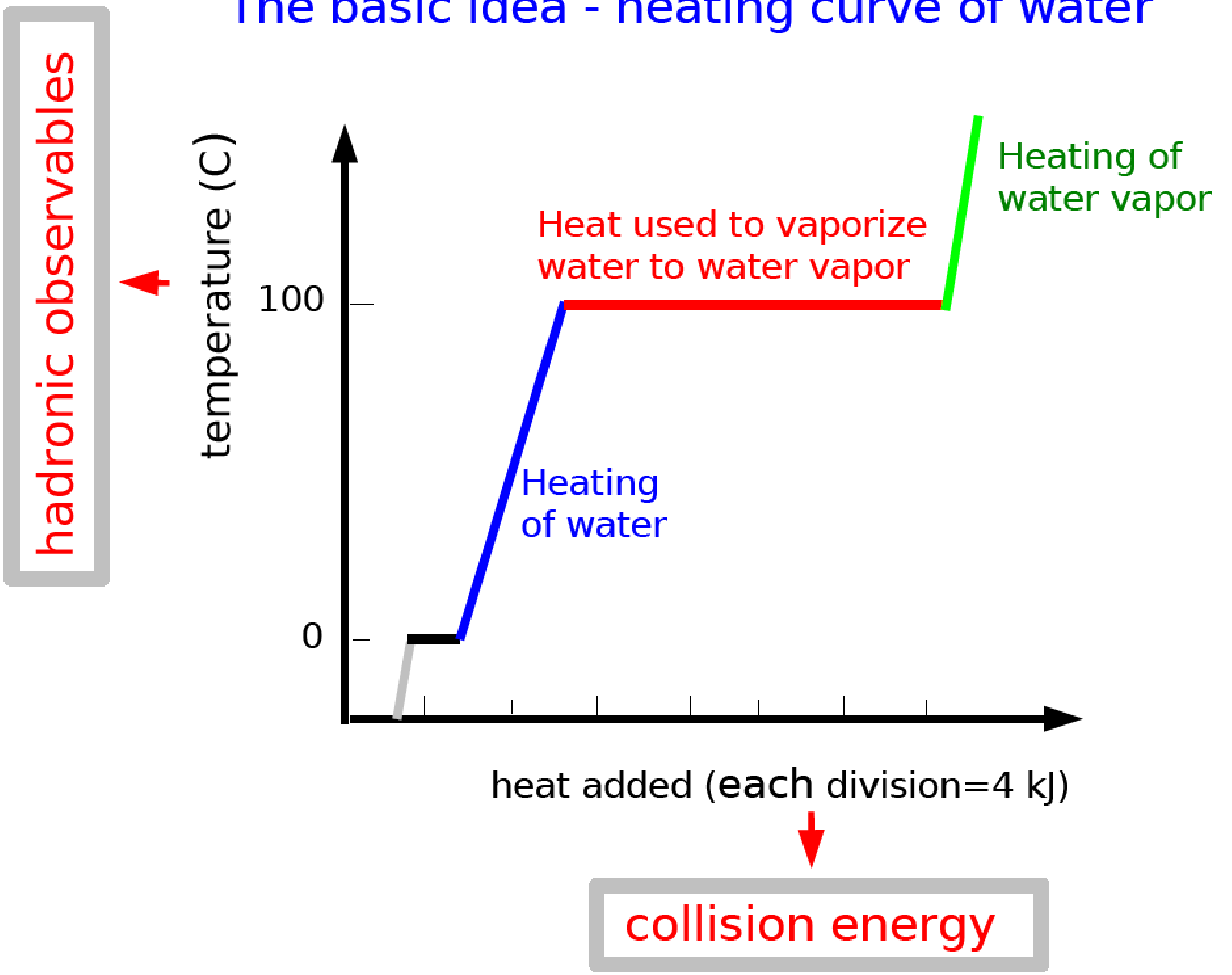


Strangeness Enhancement

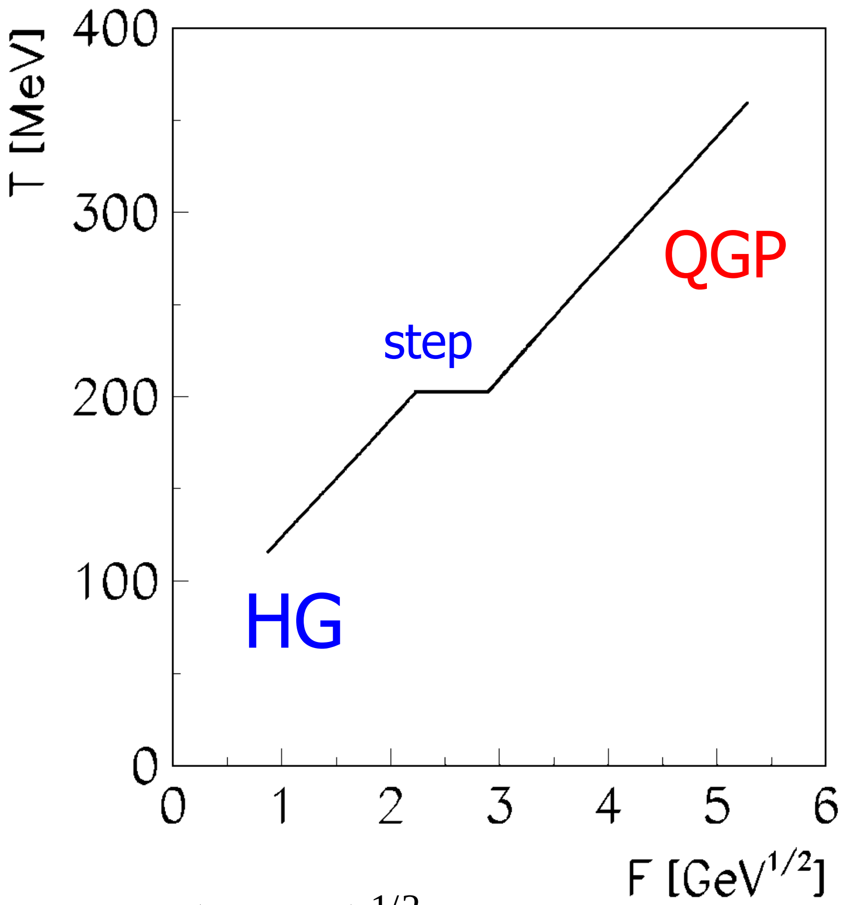
IV. Onset of Deconfinement

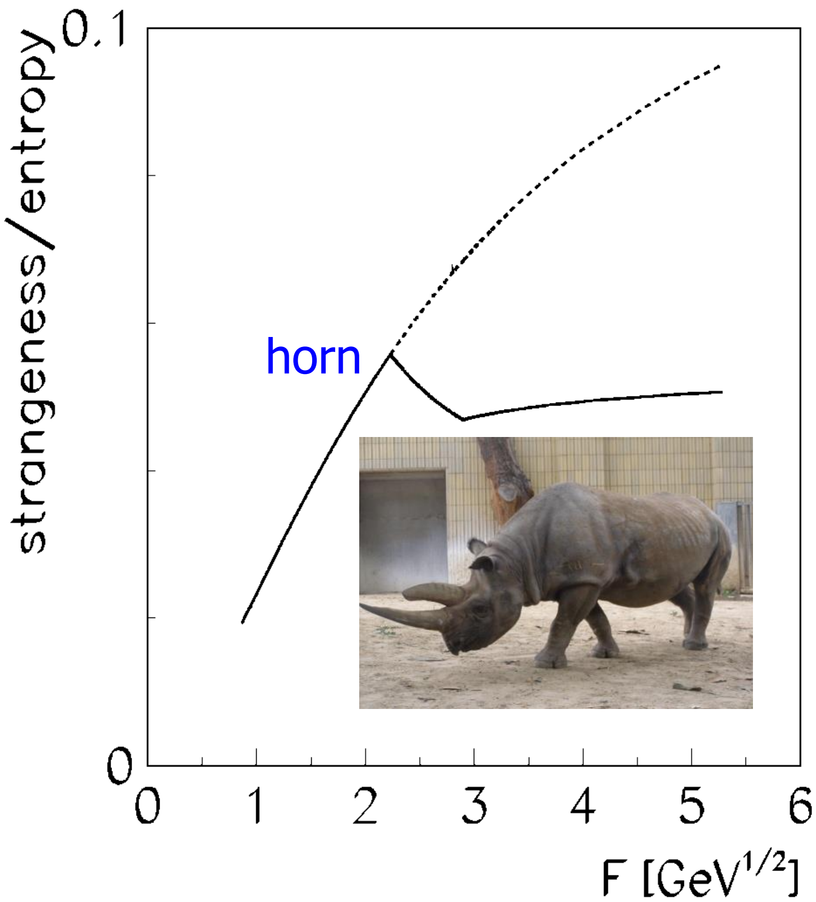
Onset of deconfinement at the CERN SPS

The basic idea - heating curve of water



Statistical Model of Early Stage



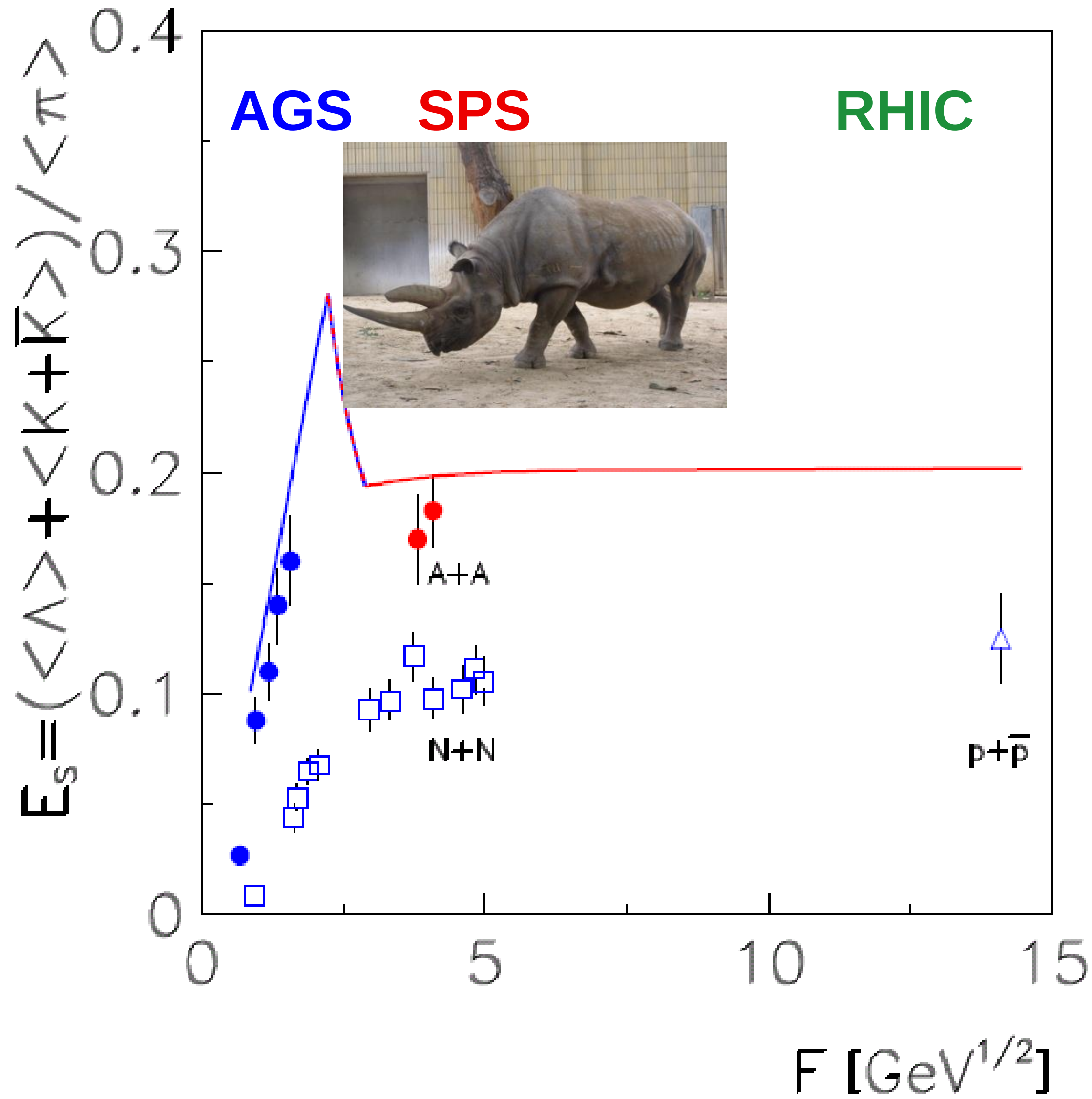


$$F \cong \left(\sqrt{s_{NN}}\right)^{1/2}$$

Gazdzicki and M.I.G., Acta Phys. Pol. (1998)

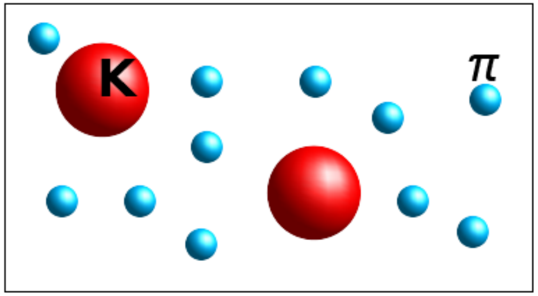
Experimental Data in 1998

$$\frac{\text{strangeness}}{\text{entropy}}$$

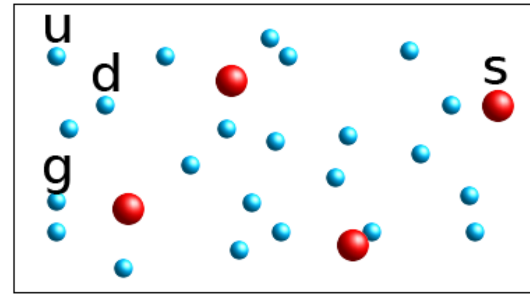


A toy model of the horn

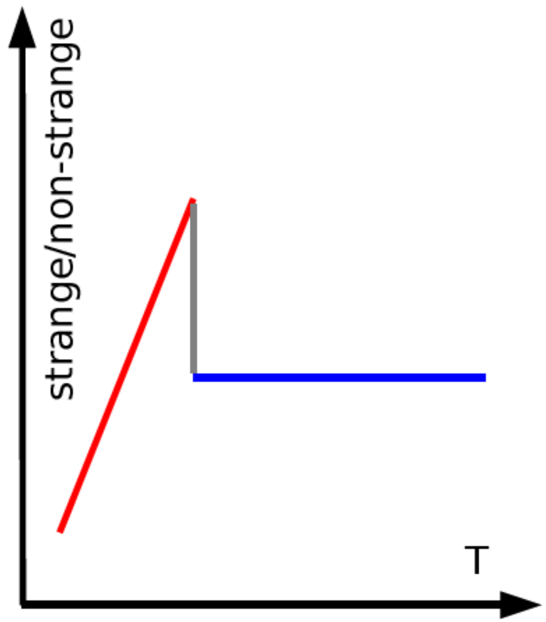
hadron gas



quark-gluon plasma



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



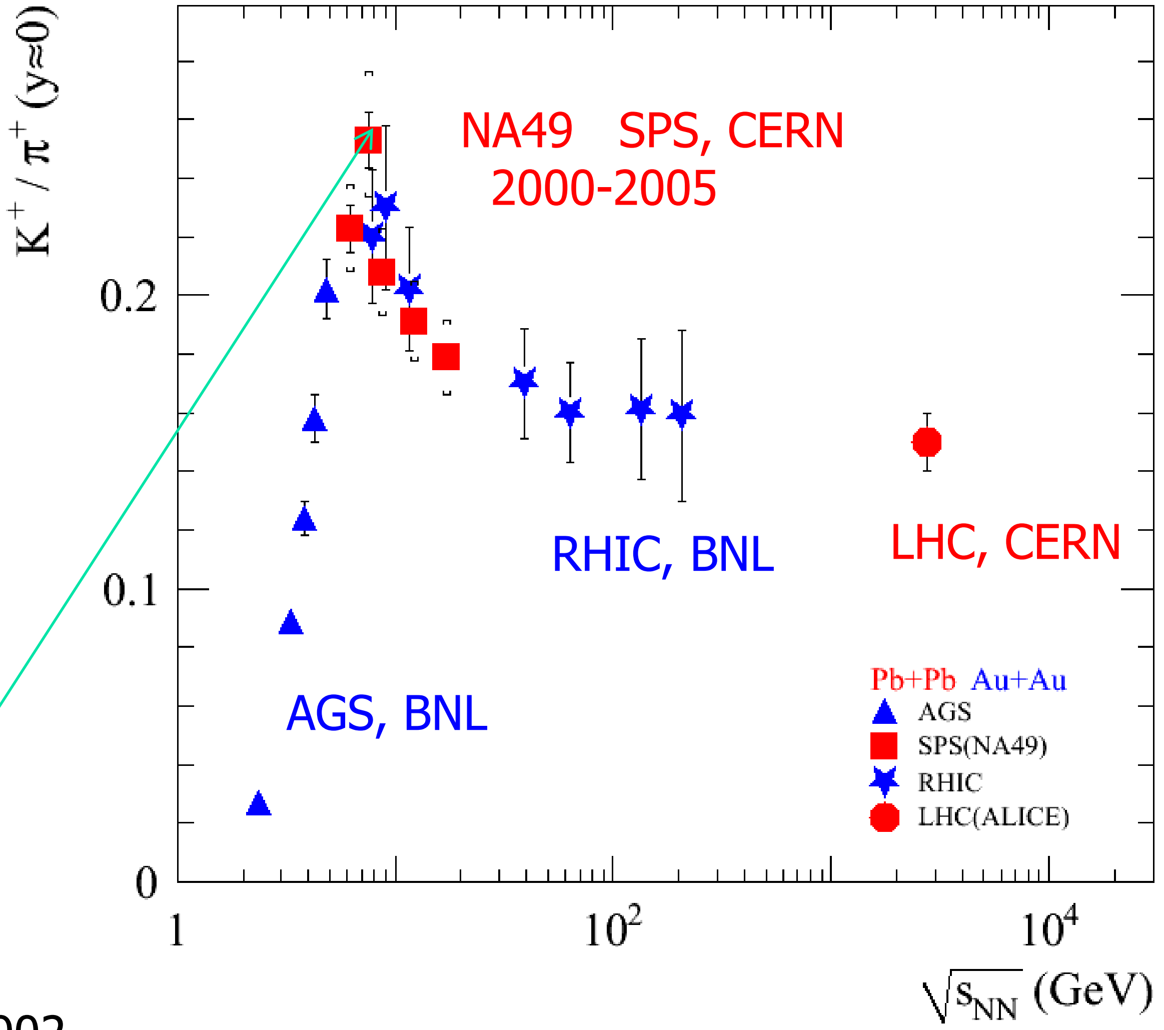
$$\frac{\langle s \rangle}{\langle u+d+g \rangle} \propto \frac{T^3}{T^3} = const(T)$$

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

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

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

The Horn: Pb+Pb



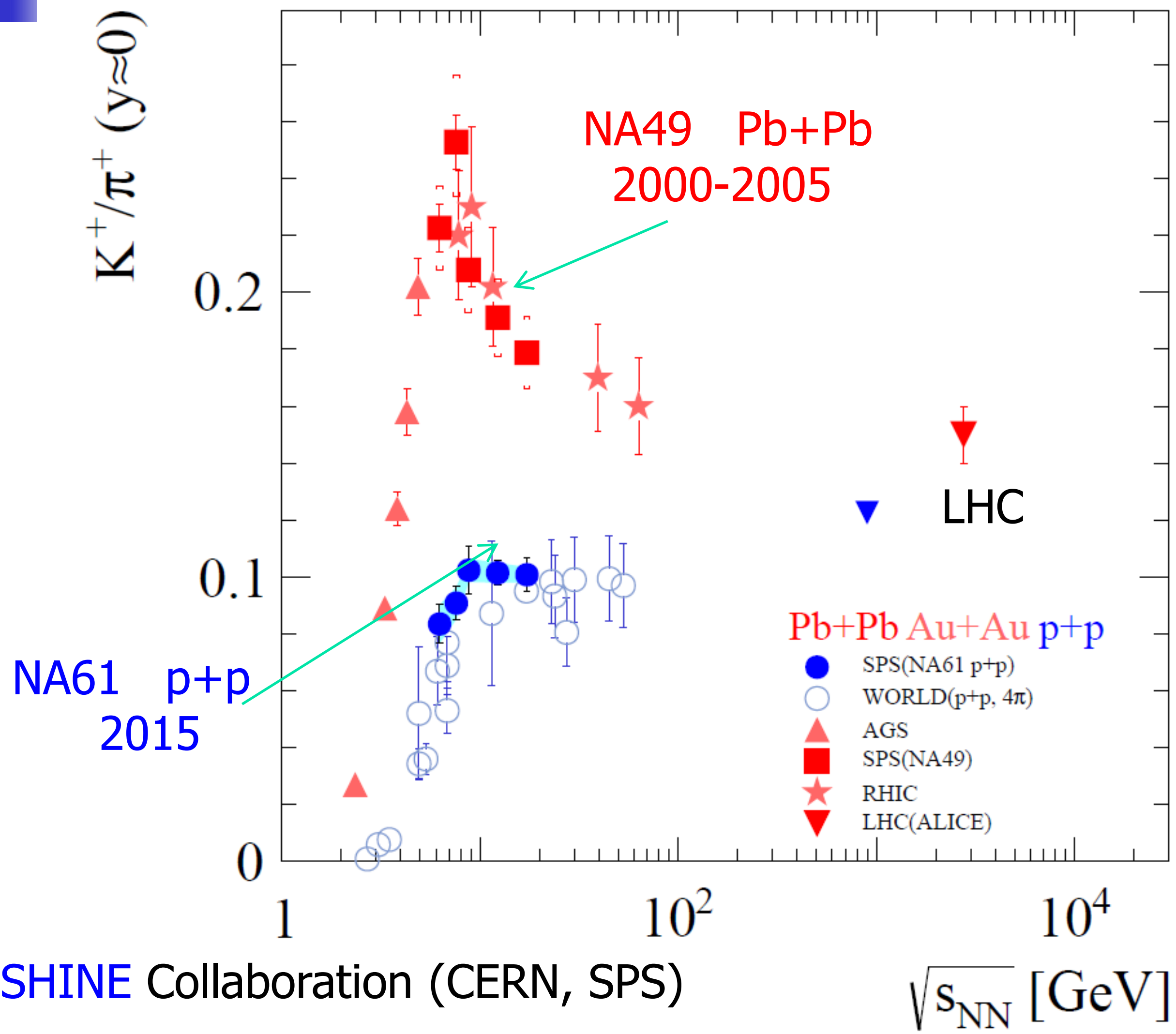
$$\frac{\text{strangeness}}{\text{entropy}}$$

NA49 Collaboration
(CERN SPS)

Phys.Rev. C66 (2002) 054902

Phys.Rev. C77 (2008) 024903

The Horn: Pb+Pb vs p+p

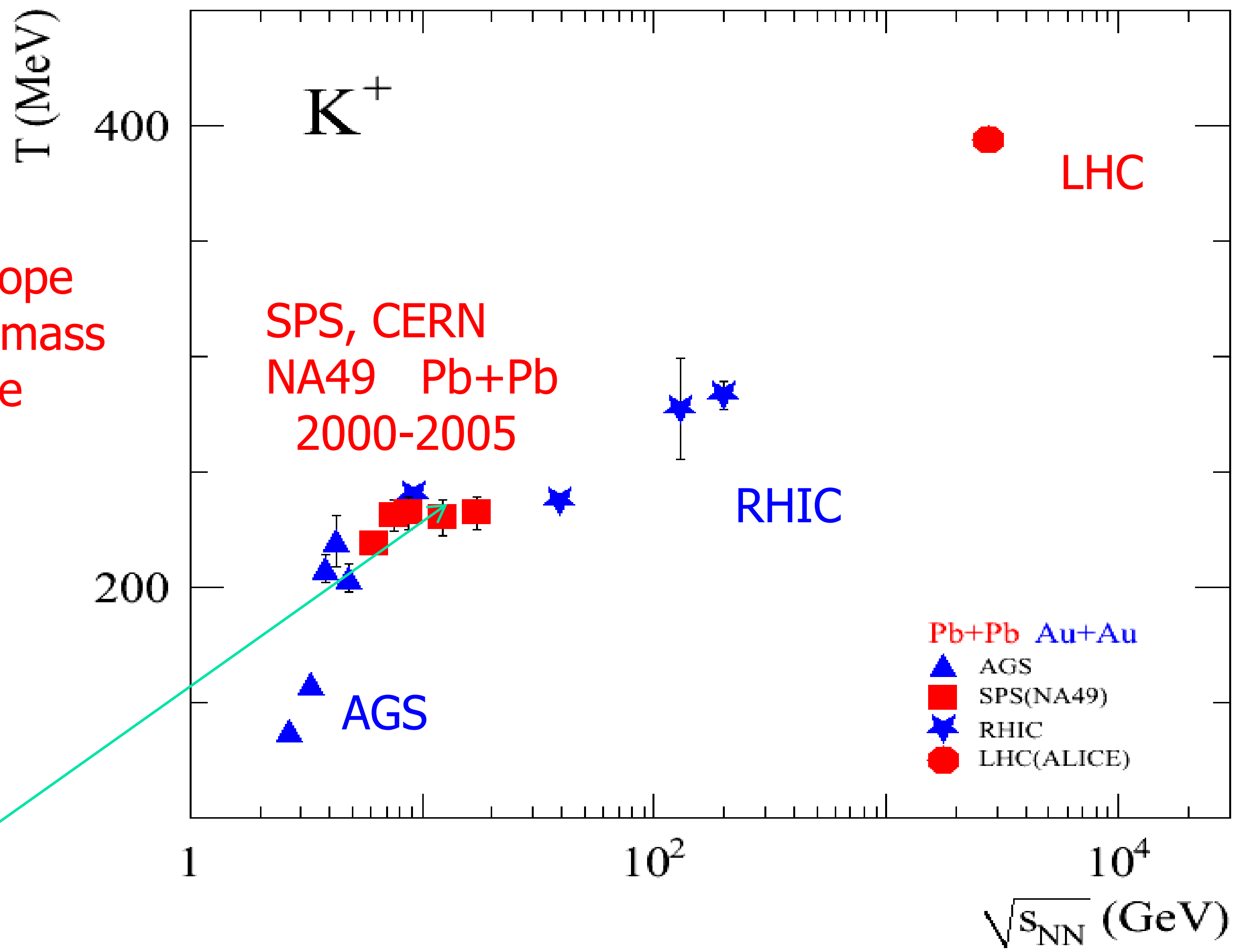


NA61/SHINE Collaboration (CERN, SPS)

arXiv:1502.07916 [nucl-ex]

The Step: Pb+Pb

T is the inverse slope of the transverse mass spectra = effective temperature.



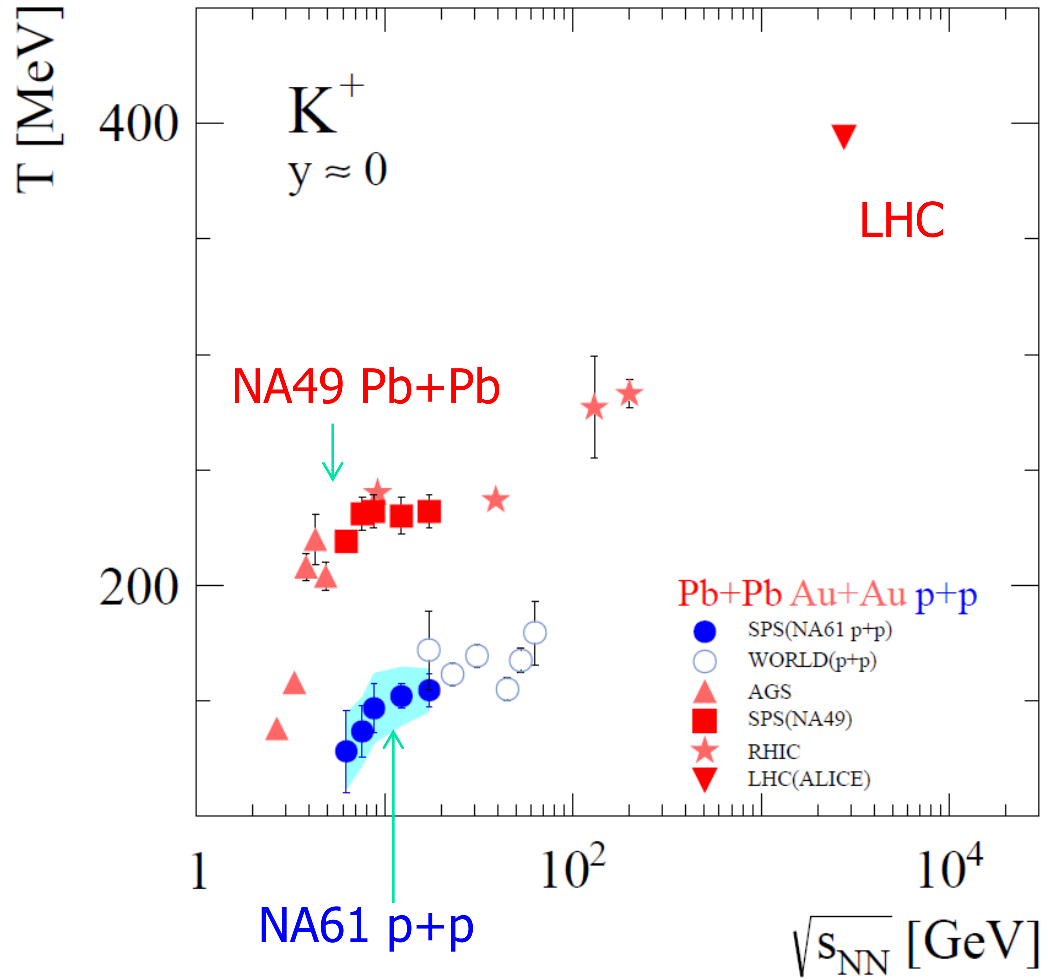
NA49

Phys.Rev. C66 (2002) 054902

Phys.Rev. C77 (2008) 024903

The Step: Pb+Pb vs p+p

K^+

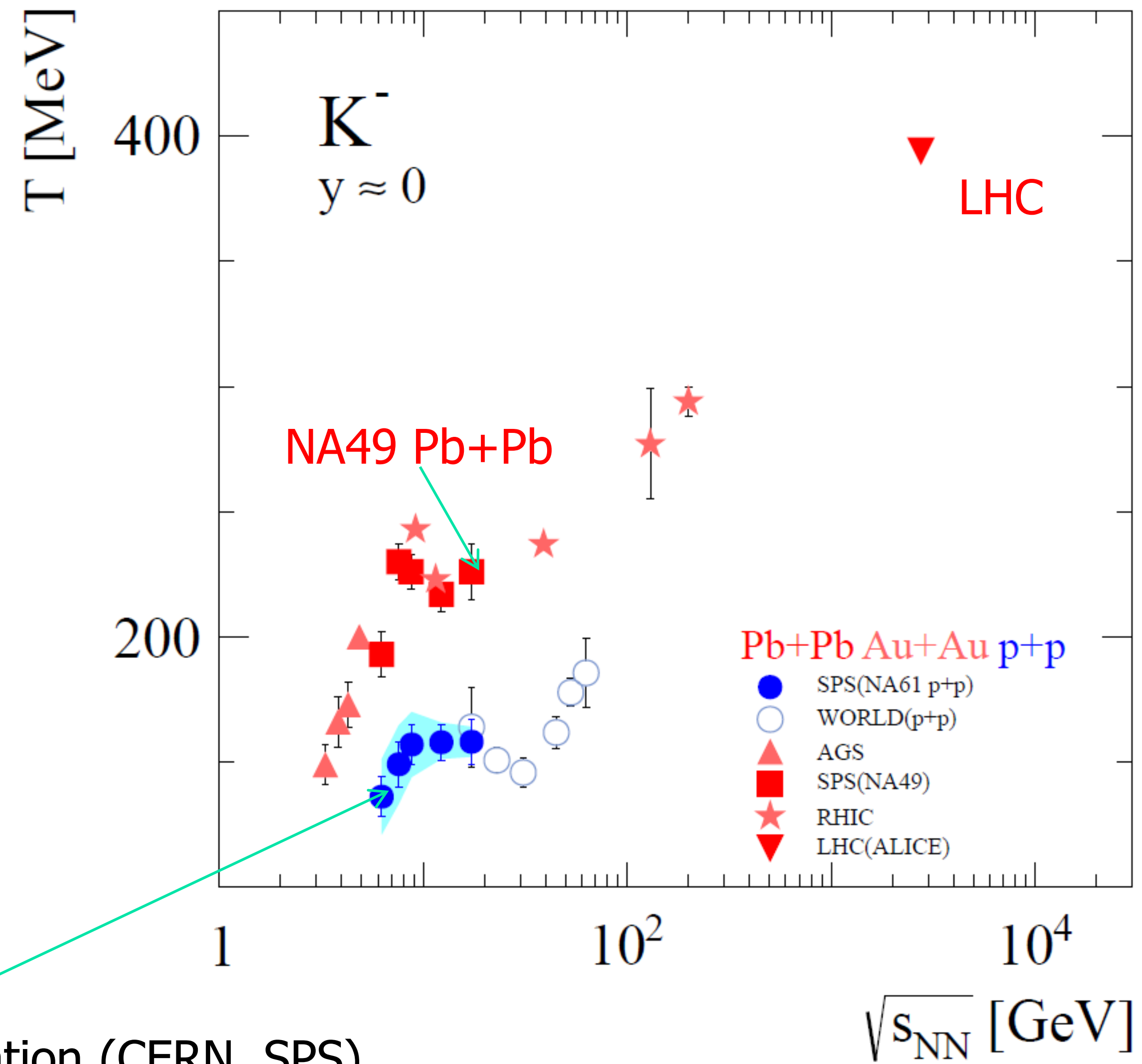


NA61/SHINE Collaboration (CERN, SPS)

arXiv:1502.07916 [nucl-ex]

The Step: Pb+Pb vs p+p

K^-



NA61/SHINE Collaboration (CERN, SPS)

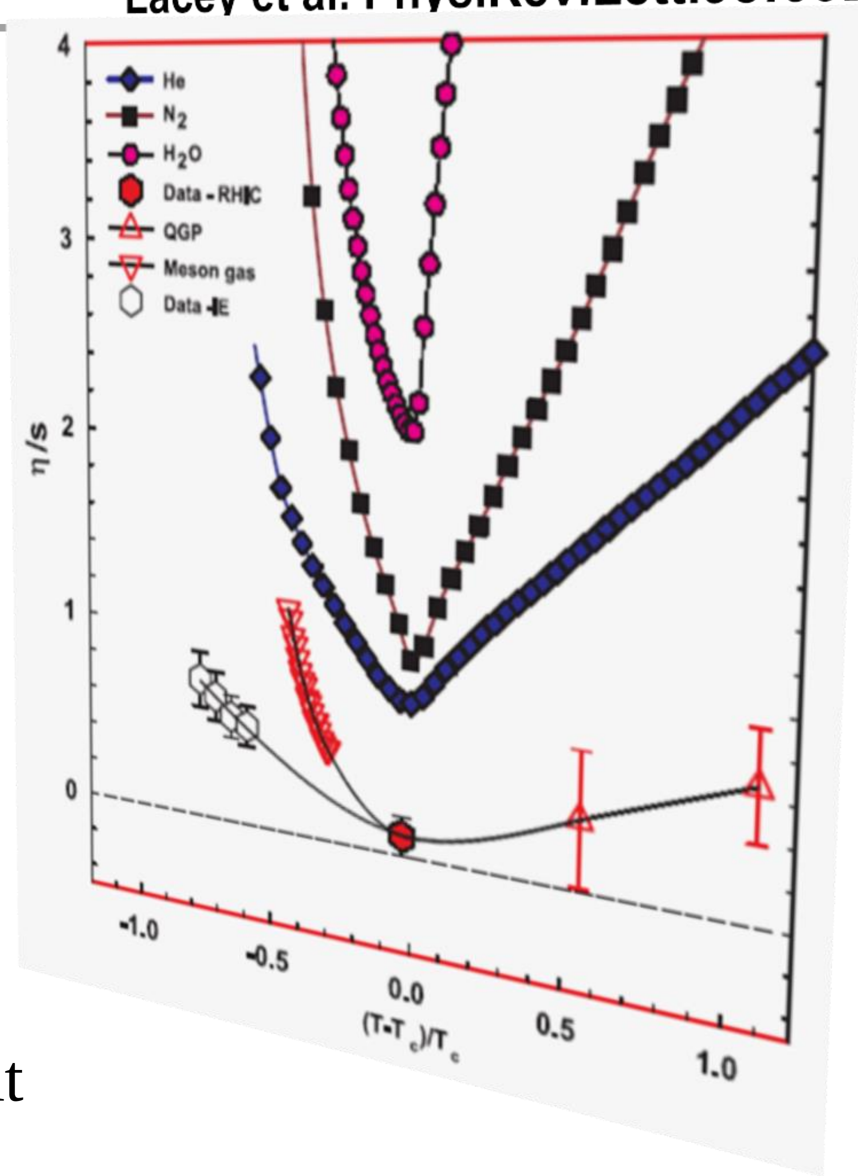
arXiv:1502.07916 [nucl-ex]

RHIC discovery

Au+Au

$$\sqrt{s_{NN}} = 200 \text{ GeV}$$

Lacey et al. Phys.Rev.Lett.98:092301



QGP = Ideal Liquid

(almost)

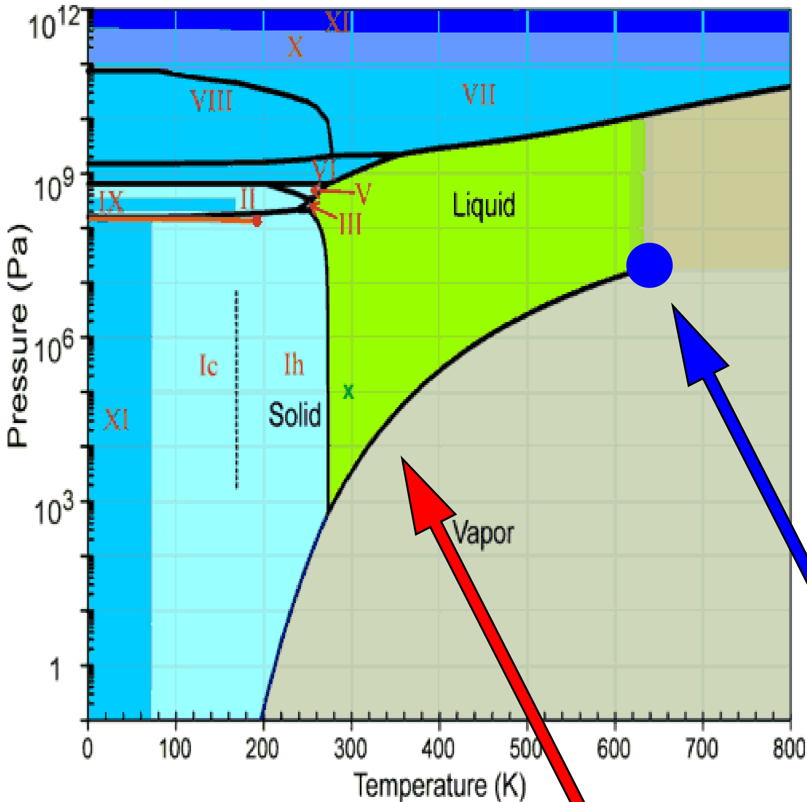
shear viscosity

$$\frac{\eta}{s} \simeq 0.1 \geq \frac{1}{4\pi}$$ the lowest limit

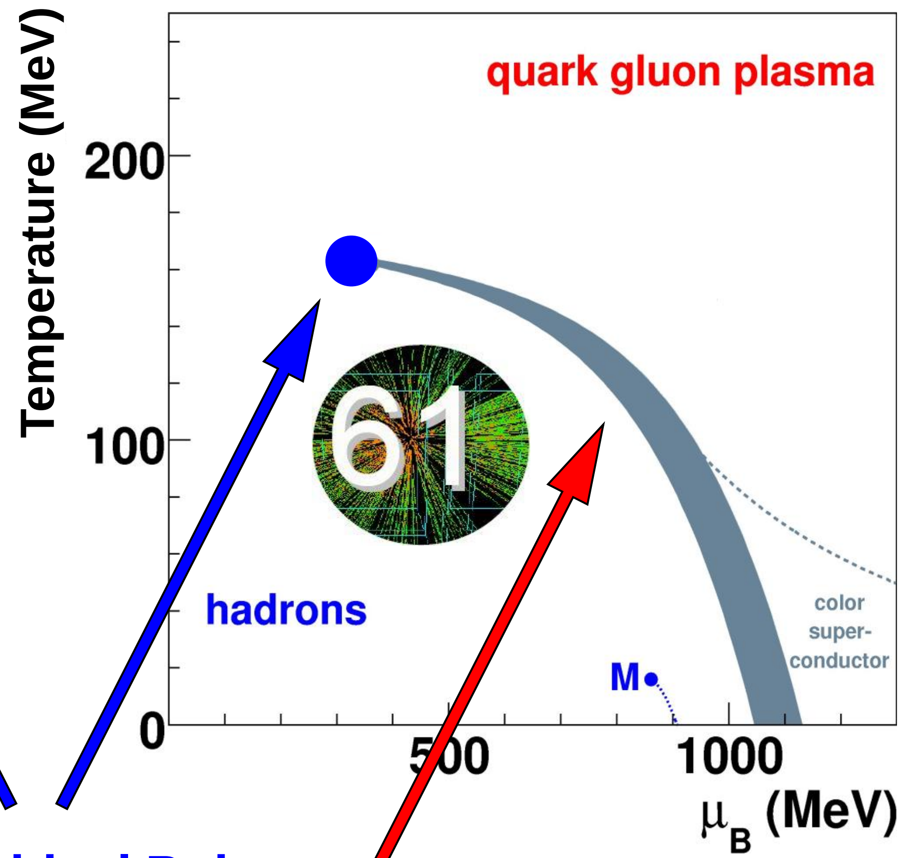
entropy density

V. QCD Critical Point

Water



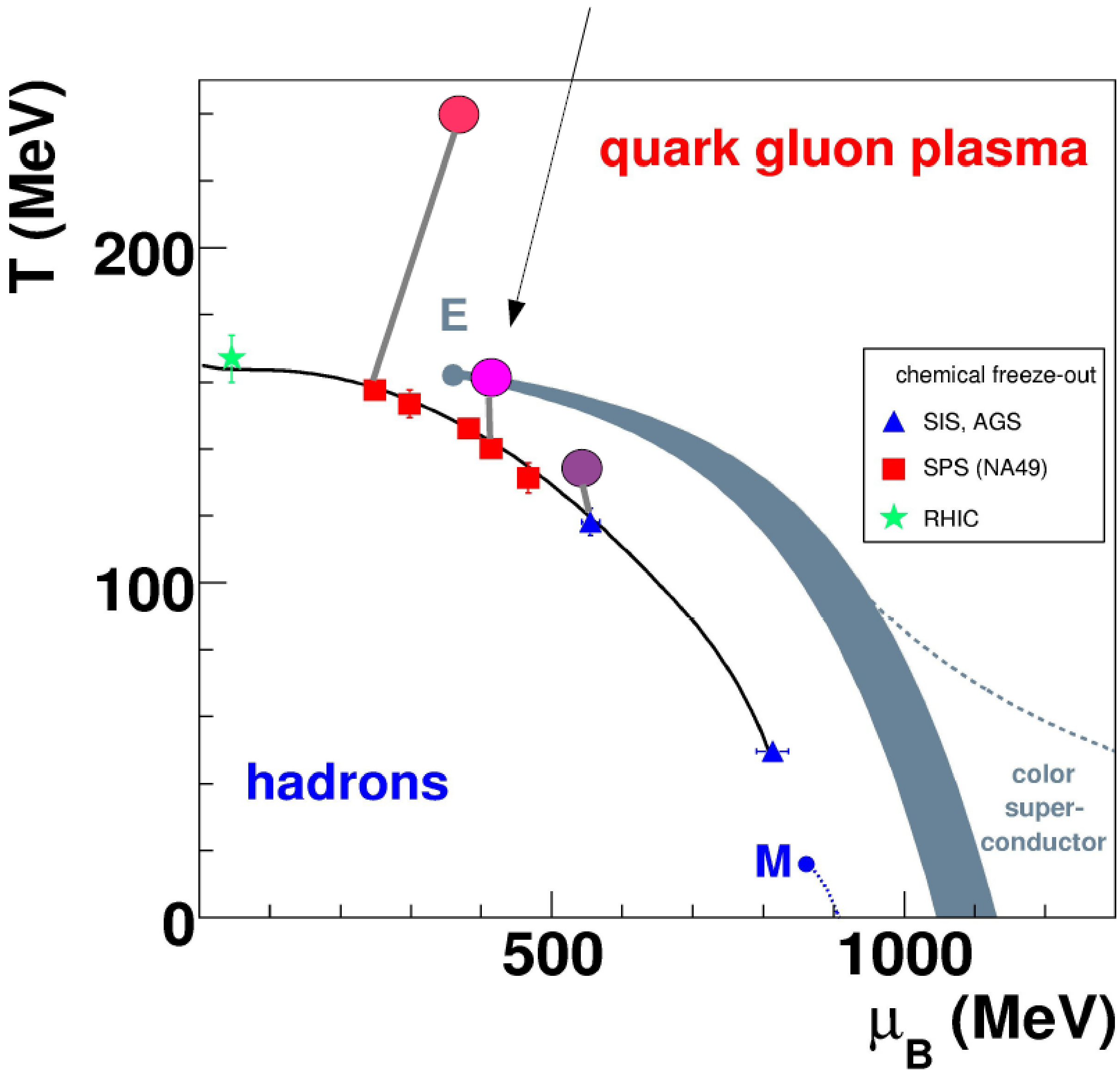
Strongly Interacting Matter



QCD Critical Point

1st Order Phase Transition

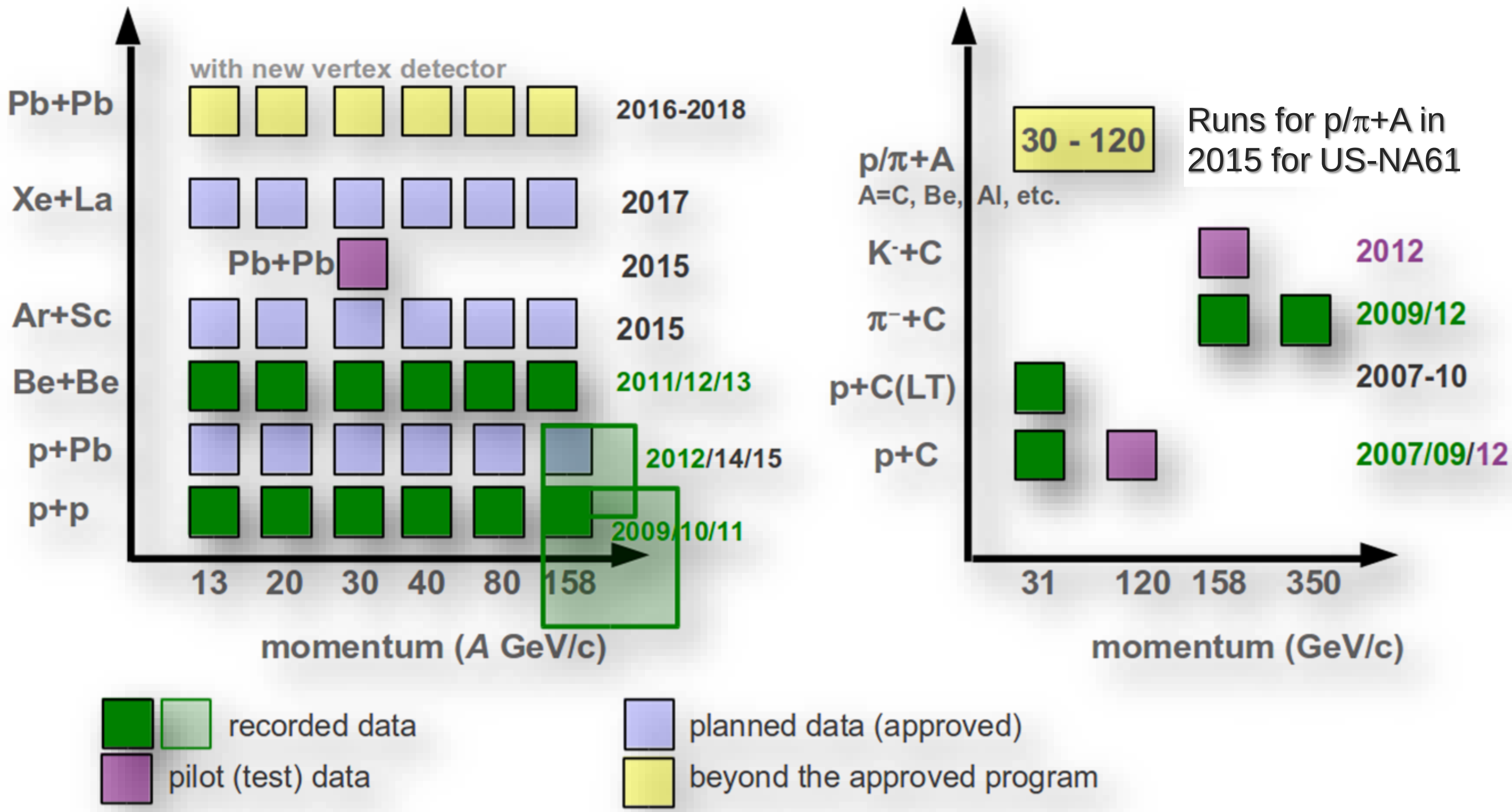
Onset of deconfinement: the early stage hits the transition line

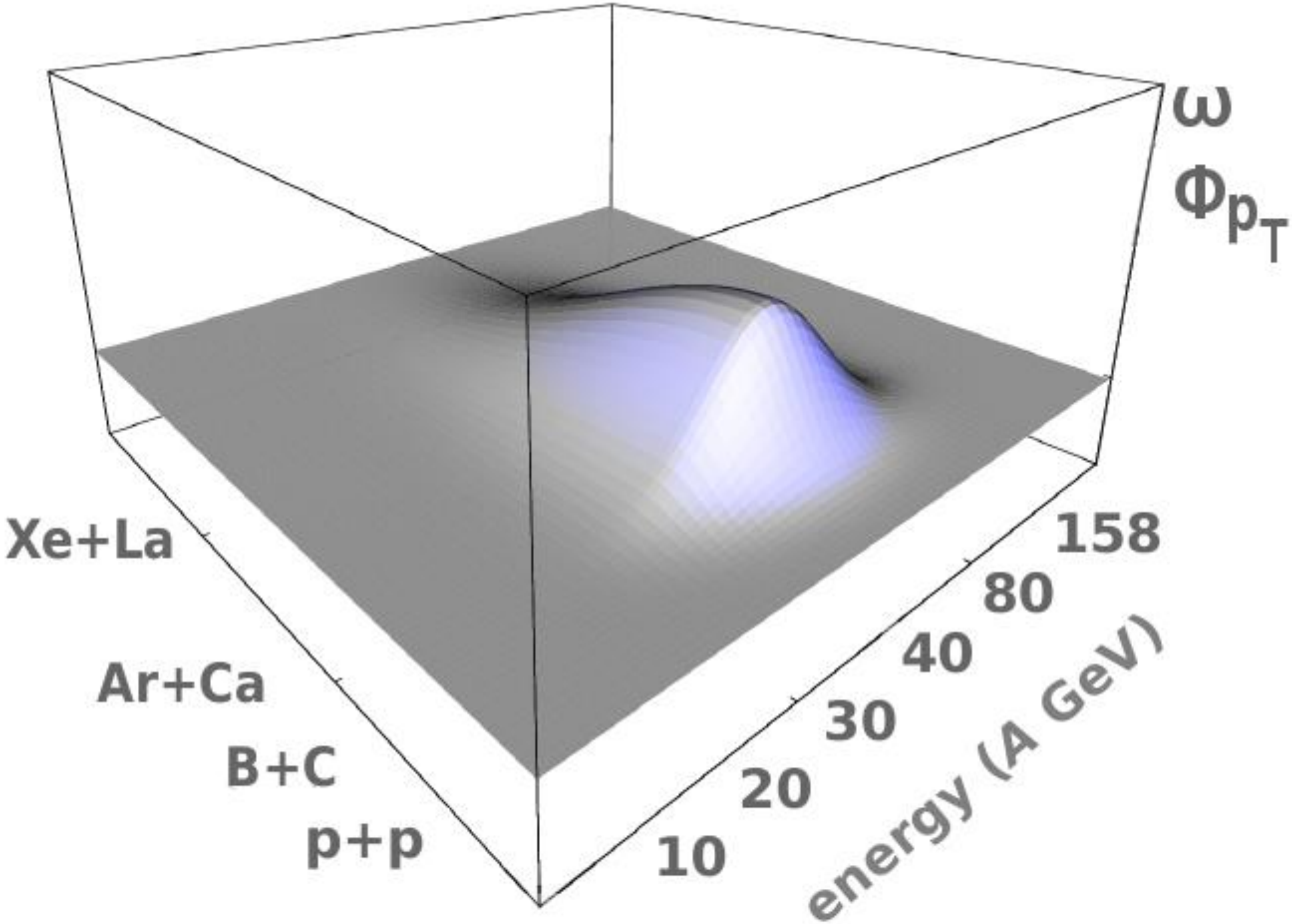


SPS CERN, NA61/SHINE: the data taking plan

Strong interactions program

Neutrino and CR programs

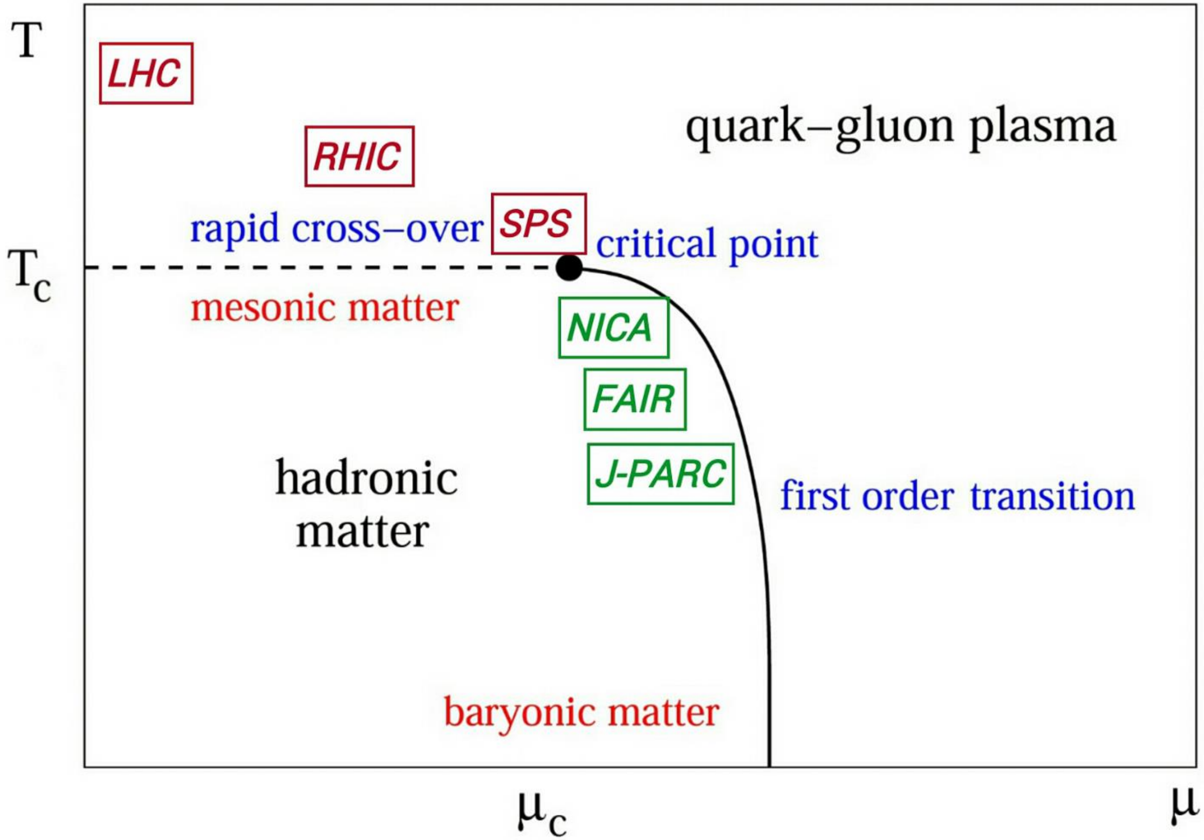




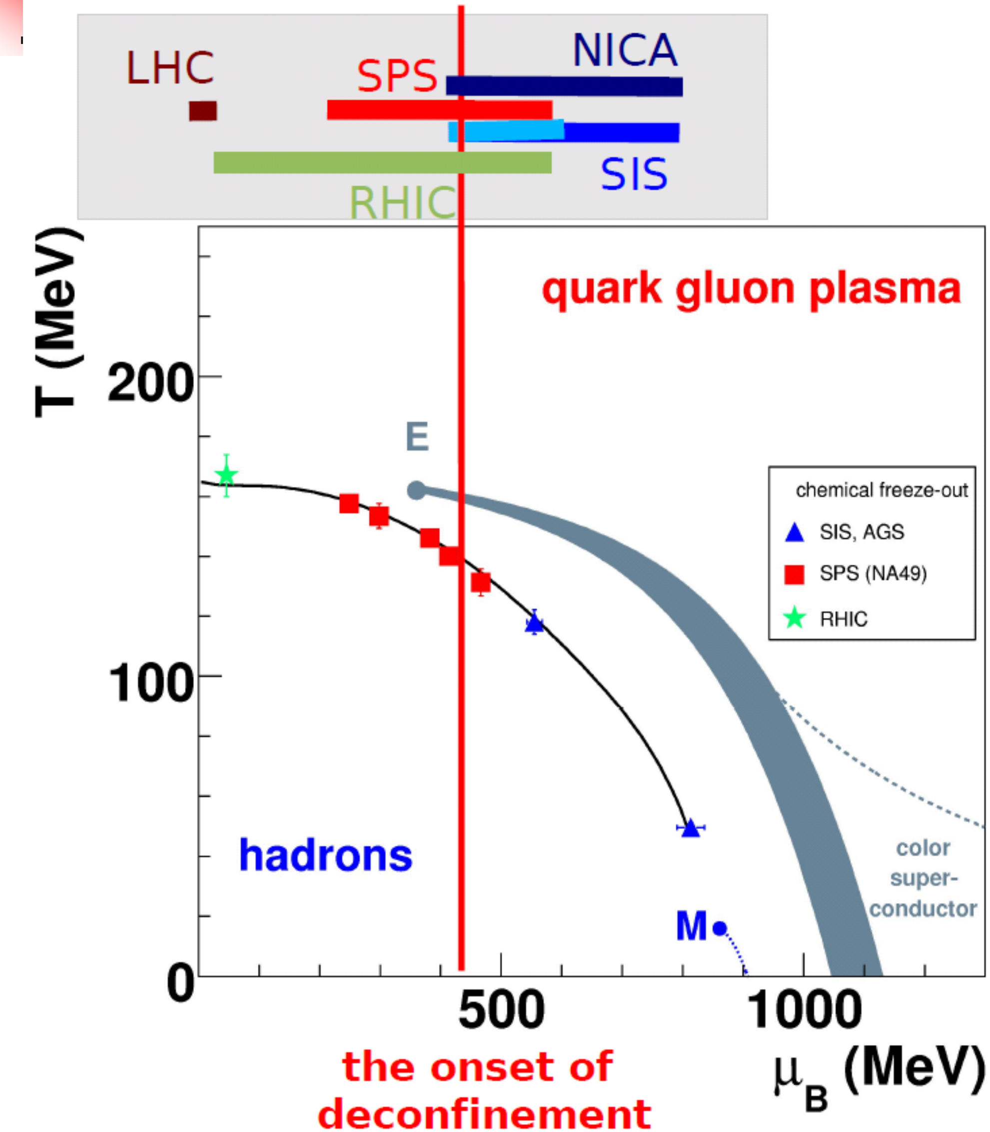
ω
Φ_{p_T}
Xe+La
Ar+Ca
B+C
p+p
158
80
40
30
20
10
energy (A GeV)

Summary

$$\text{Hadron Gas} \quad T_0 \rightarrow \begin{cases} 1^{st} \text{ order PT} & (\text{large } \mu) \\ \text{Cross-over} & (\text{small } \mu) \end{cases} \rightarrow \text{Quark Gluon Plasma}$$



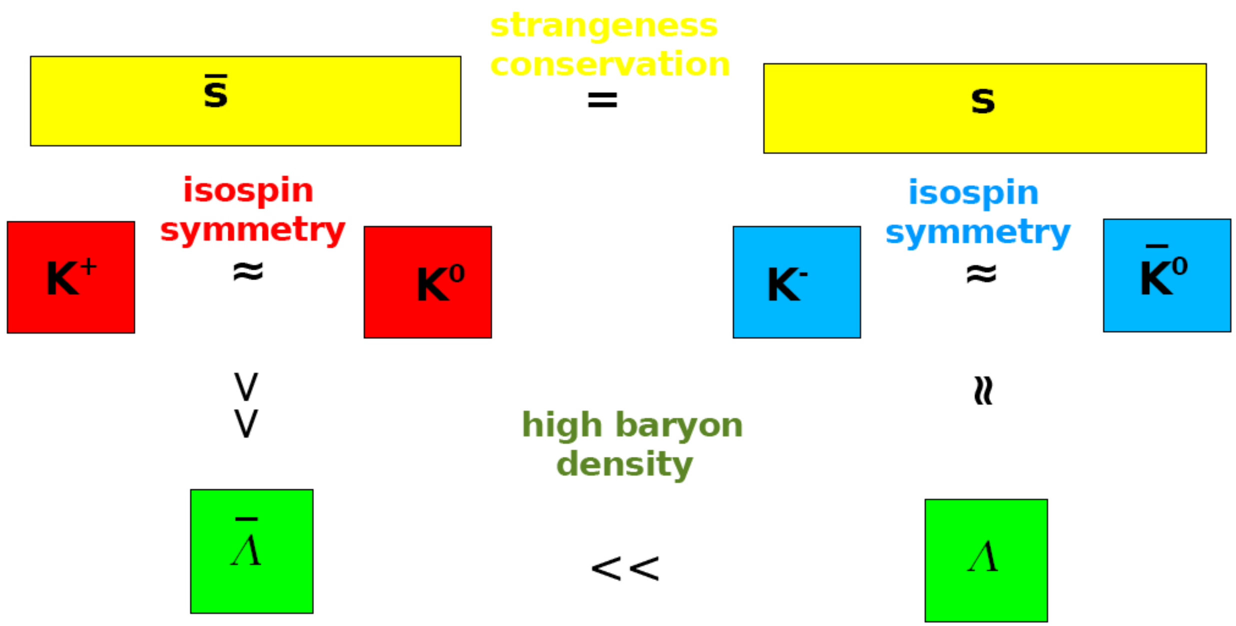
Experiments:



NICA, Dubna	2020
SIS, GSI	2020
SPS, CERN NA61/SHINE	2009
RHIC, BNL STAR	2010

Thank You !

main strangeness carriers



sensitive to strangeness content only

sensitive to strangeness content and baryon density

QGP discovery 2000

- 1). J/psi Suppression - Matsui, Satz (1986)

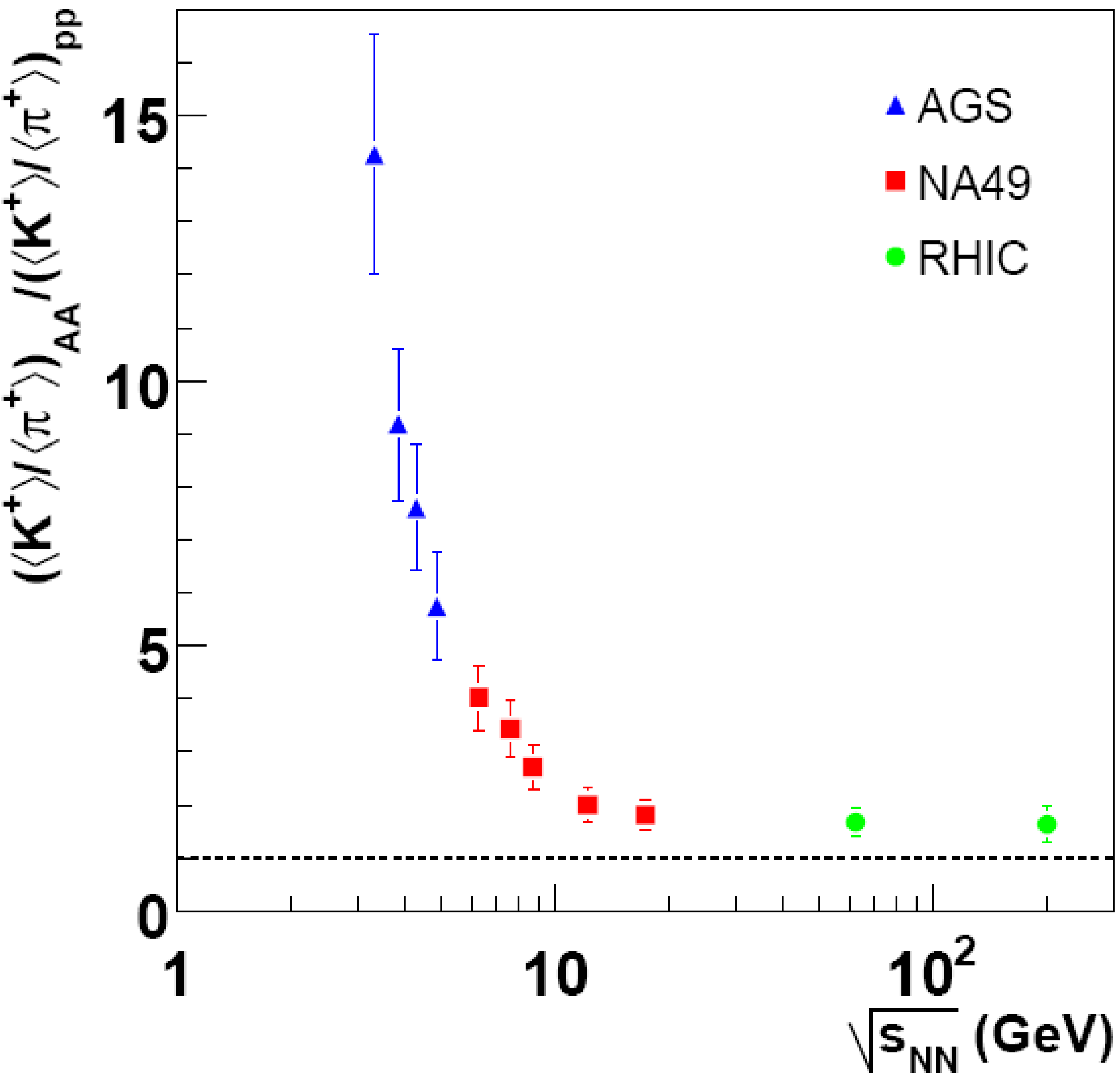
$$\left[\frac{N_{J/\psi}}{N^{DY}_{e^+e^-}}\right]_{AA} < \left[\frac{N_{J/\psi}}{N^{DY}_{e^+e^-}}\right]_{pp}$$

- 2). Strangeness Enhancement - Koch, Muller, Rafelsky (1986) .

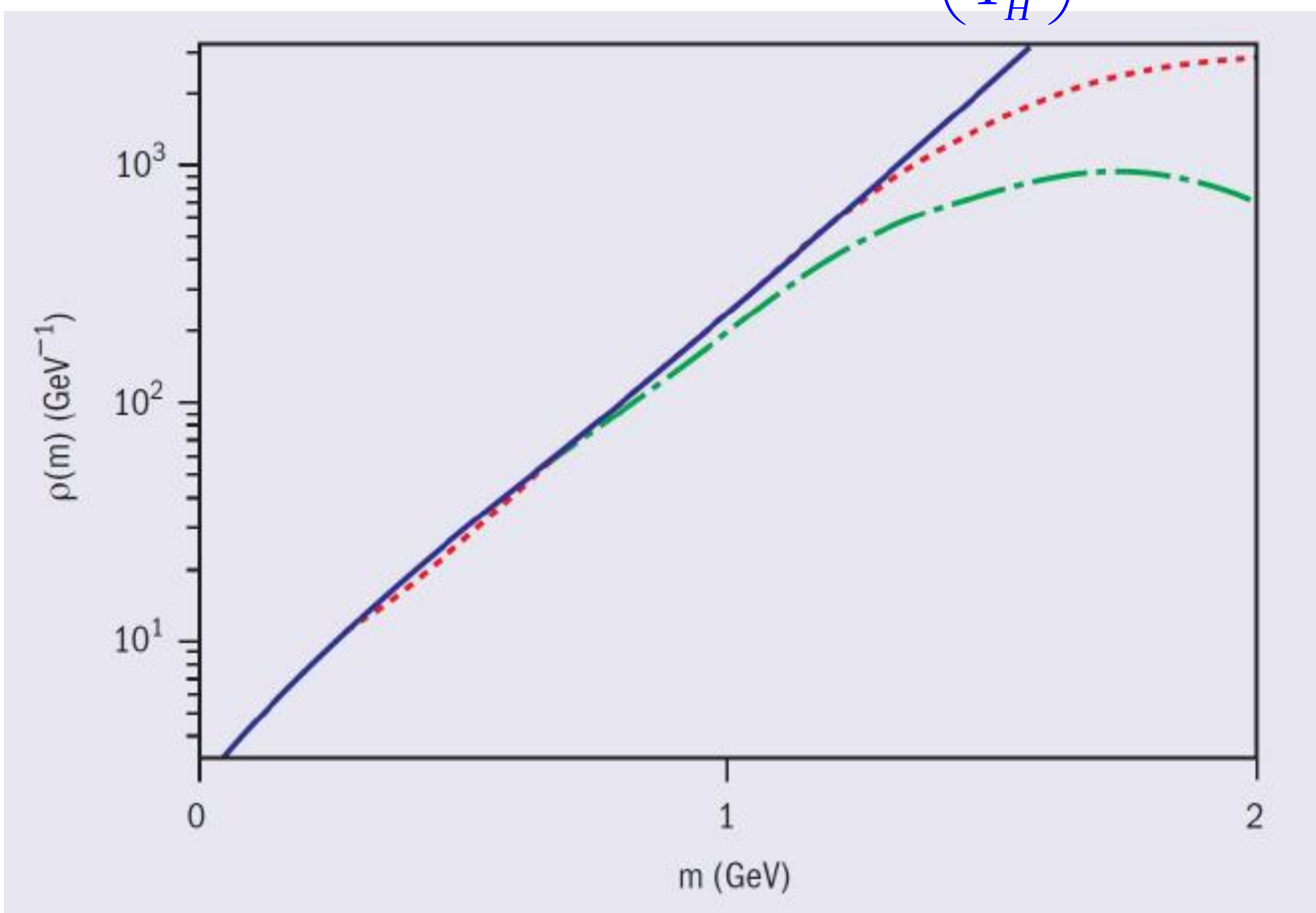
$$\left[\frac{N_K}{N_\pi}\right]_{AA} > \left[\frac{N_K}{N_\pi}\right]_{pp}$$

3). Photon and Lepton Thermal Production 4)......

Strangeness Enhancement



$$\exp\left(\frac{m}{T_H}\right)$$



4627 states
2000

1411 states
1967

Limiting Temperature (short summary)

$$\rho(m) = C \; m^{-a} \exp\left(\frac{m}{T_H}\right) \qquad \text{for} \qquad m \to \infty$$

$$p(T) = T \int_{M_0}^{\infty} dm \; \rho(m) \left(\frac{mT}{2\pi}\right)^{3/2} \exp\left(-\frac{m}{T}\right) \propto \left(T_H - T\right)^{a-5/2}$$

$$\varepsilon(T) = T\frac{dp}{dT} - p \propto \left(T_H - T\right)^{a-7/2}$$

$$\text{At } T \to T_H : \quad p,\ \varepsilon \to \infty, \ \text{for } a \le \frac{5}{2}$$

$$p \to const,\ \varepsilon \to \infty, \ \text{for } \frac{5}{2} < a \le \frac{7}{2}$$

$$p \to const,\ \varepsilon \to const, \ \text{for } a > \frac{7}{2}$$

$$Z(T,V)=\sum_{N=0}^{\infty}\left(\frac{V}{2\pi^2}\int_{M_0}^{\infty}dm\int_0^{\infty}k^2dk\;\rho(m)\exp\left(-\sqrt{k^2+m^2}\right)/T\right)^N\frac{1}{N!}$$

$$=\;\exp[\;\frac{VT}{2\pi^2}\int_{M_o}^{\infty}dm\;\rho(m)\;m^2\;K_2(m/T)\;]$$

$$V\rightarrow\left(V-\sum_{i=1}^{N}v_i\right)$$

$$\rho(m)\rightarrow\rho(m,v)=\rho_0+Cv^{\gamma}(m-Bv)^{\delta}\exp\left[\frac{4}{3}\sigma^{1/4}v^{1/4}(m-Bv)^{3/4}\right]$$

$$Z(T,V)=\sum_{N=0}^{\infty}\frac{1}{N!}\left(\prod_{i=1}^{N}\int_{M_0}^{\infty}dm_i\int_{V_0}^{\infty}dv_i\;\;(V-v_1-...-v_N)\rho(m_i,v_i)K_2\left(\frac{m_i}{T}\right)\right)$$