The Search for the Quark-Gluon Plasma - II

Jean Cleymans
University of Cape Town, South Africa

International Workshop on Hot and Dense Nuclear and Astrophysical Matter,
Stellenbosch, South Africa
26 November - 2 December 2017

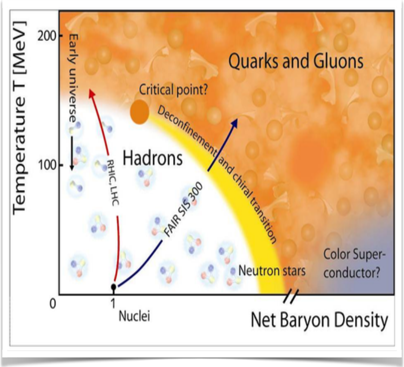
Outline


RHIC
BOOSTER
LINAC
AGS
HTB
TANDEMS
HITL

Heavy-Ion Physics "Standard Model"

QCD predicts **deconfined medium** at high temperature, the **Quark-Gluon Plasma** ($T_c \simeq 155$ MeV)

Heavy Ions: study the **QCD phase diagram** in the laboratory, create and **characterize the QGP**



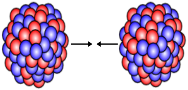
Basic idea:

- Collision of Pb-Pb nuclei creates the conditions for the phase transition
- The system gets close to thermal equilibrium and expands collectively
- Expansion ⇒ cool-down: transition to hadrons

Current research

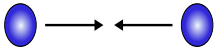
- Precise measurement of macroscopic properties
- Understanding microscopic fabric of QGP

The Paradigm



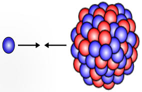
Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

- Core business: create and characterize the QGP



pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

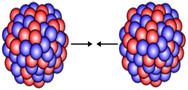
- Reference data



p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

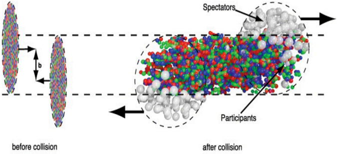
- Control experiment
- “Cold nuclear matter” effects (e.g. modifications to PDF)

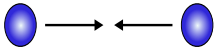
The Paradigm



Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

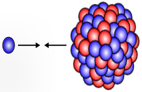
- Core business: create and characterize the QGP
- Centrality





pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

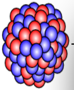
- Reference data



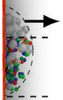
p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

- Control experiment
- “Cold nuclear matter” effects (e.g. modifications to PDF)

The Paradigm



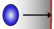
e QGP

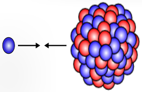


Towards a paradigm shift!

Striking **similarities** between pp/p–Pb/Pb–Pb
Phenomena considered **hallmarks of heavy-ions**
seen **in smaller systems**
(discovered in high multiplicity events,
seem to be relevant also for minimum-bias events)

⇒ Important consequences for the
interpretation of all hadronic collisions!





p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

- Control experiment
- "Cold nuclear matter" effects
  (e.g. modifications to PDF)

Kinematic Variables Used in Heavy-Ion Collisions

Transverse Mass

$$p^\mu = (E, p_x, p_y, p_z)$$
$$m_T^2 \equiv p_x^2 + p_y^2 + m^2$$

so that

$$E^2 = m_T^2 + p_z^2$$

Kinematic Variables Used in Heavy-Ion Collisions

Rapidity

$$p^\mu \equiv (m_T \cosh y, p_x, p_y, m_T \sinh y)$$

since

$$\begin{aligned} p^2 &= m_T^2 \cosh^2 y - p_x^2 - p_y^2 - m_T^2 \sinh^2 y \\ &= m_T^2 - p_x^2 - p_y^2 = m^2 \end{aligned}$$

$$\begin{aligned} m_T e^y &= E + p_z \\ m_T e^{-y} &= E - p_z \end{aligned} \qquad (1)$$

$$\begin{aligned} e^{2y} &= \frac{E + p_z}{E - p_z} \\ y &= \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \end{aligned}$$

Kinematic Variables Used in Heavy-Ion Collisions

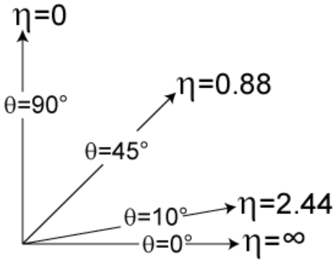
Pseudorapidity

If one doesn't know the mass of the particle, or if the mass can be neglected:

$$\begin{aligned} \eta &= \frac{1}{2}\ln\frac{p(1+\cos\theta)}{p(1-\cos\theta)} \\ &= \frac{1}{2}\ln\frac{\cos^2(\theta/2)}{\sin^2(\theta/2)} \\ \eta &= -\ln\tan(\theta/2) \qquad (2) \end{aligned}$$

Easy to measure.

A quick reminder about pseudorapidity

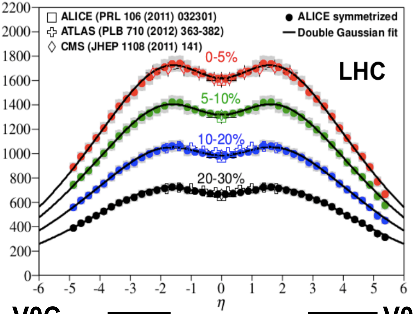


$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Particle Multiplicity in Heavy Ion Collisions

Acceptance for charged particles

η coverages for z_{vtx}=0 (shown at last AW)



Now:
(T0 now shown)

V0C — V0A
SPD (outer layer)
FMDC — FMDA
T0C+ (ext) — T0A+ (but not hermetic: 80%)

After LS2:

V0A+ (ext)
MFT — ITS IB (middle layer)

This is (-3.6,-2.5), i.e. the MFT+MUON acc.

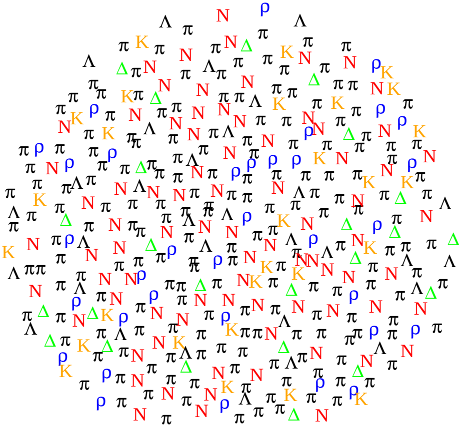
Particle Multiplicity in Heavy Ion Collisions

About 24 000 particles are produced in a heavy ion collision at the LHC.

Hence: Use Concepts from Statistical Mechanics to analyze the final state
e.g. use Energy Density, Particle Density, Pressure, Temperature, Chemical Composition, ...

These concepts turn out to be useful at all energies, RHIC, SPS, GSI ...

Hadronic Gas before Chemical Freeze-Out



J.C. and H. Satz, Z. fuer Physik C57, 135, 1993.

The Theoretical Basis for the Thermal Model

Bjorken scaling + Transverse expansion

After integration over p_T (and ONLY! after integration over p_T)

$$\frac{dN_i/dy}{dN_j/dy} = \frac{N_i^0}{N_j^0}$$

where N_i^0 is the particle yield
as calculated in a fireball **AT REST!**

Effects of hydrodynamic flow cancel out in ratios.
The volume is given by $\pi R^2 \tau$!

The Theoretical Basis for the Thermal Model

In general

If hydrodynamics is the basic underlying mechanism, then, after integration over p_T and y

$$\frac{N_i}{N_j} = \frac{N_i^0}{N_j^0}$$

where N_i^0 is the particle yield as calculated in a fireball **AT REST!**

This is because N_i is a Lorentz invariant quantity unaffected by boosts and flows. This needs the freeze-out temperature to be the same for all particles which may not be the case always.

Uncertainties in the Thermal Model

Uncertainties are related to the information in the Particle Data Booklet.
Particle yields are determined from:

$$N_i = \sum_j N_j Br(j \to i).$$

Hence one must know how hadronic resonances decay.

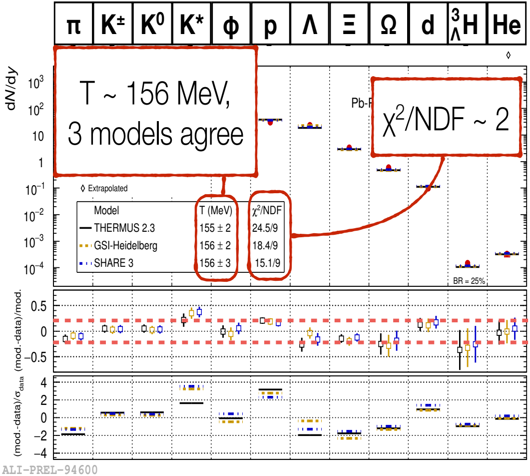
As an example, the final yield of π^+'s is given by

$$N_{\pi^+} = N_{\pi^+}(\mathrm{thermal}) + N_{\pi^+}(\mathrm{resonance\ decays})$$

depending on the temperature, over 80% of observed pions are due to resonance decays

Equilibrium SHM Fits in Central Pb-Pb

AL

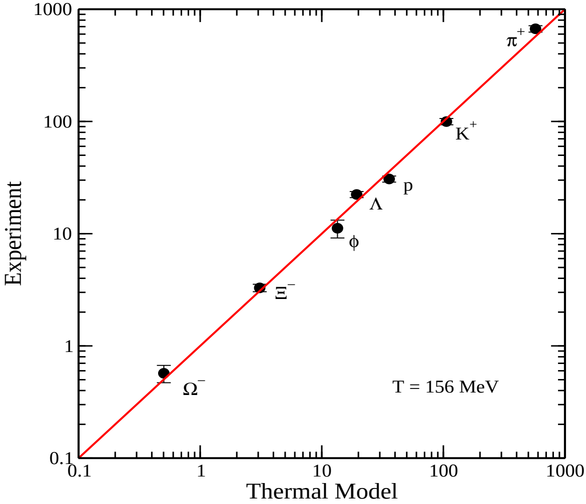


N.B.
RHIC (STAR)
$\sqrt{s}$ = 200 GeV
χ^2/NDF~1

Better fit in
60-80%,

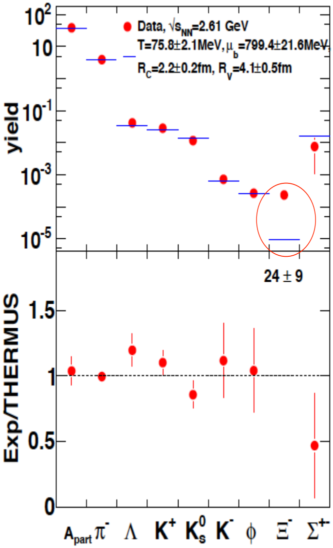
Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

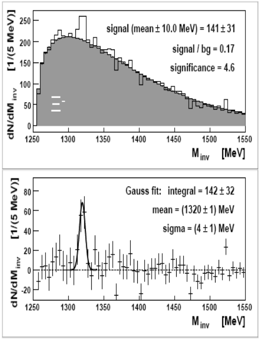
ALICE



1000
100
10
1
0.1
Experiment
0.1
1
10
100
1000
Thermal Model
π+
K+
p
Λ
ϕ
Ξ−
Ω−
T = 156 MeV

Hadrons in Ar+KCl@1.76A GeV





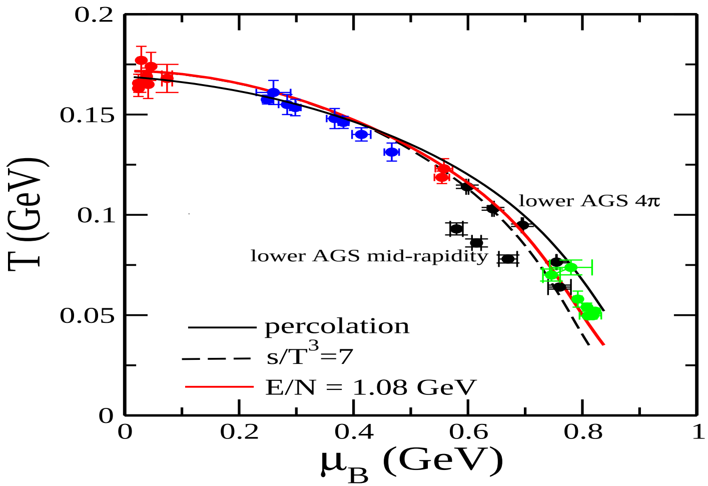
Strong excess of the Ξ^-

NN-threshold:

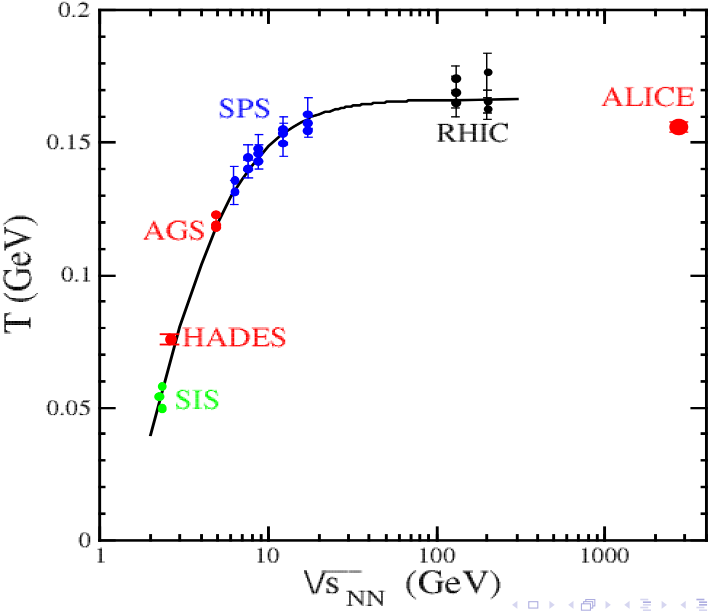
E_{beam}= 3.74GeV $\rightarrow\sqrt{s}-\sqrt{s_{th}}$=-630MeV!

THERMUS: S. Wheaton, J.Cleymans: Comput.Phys.Commun.180:84-106,2009

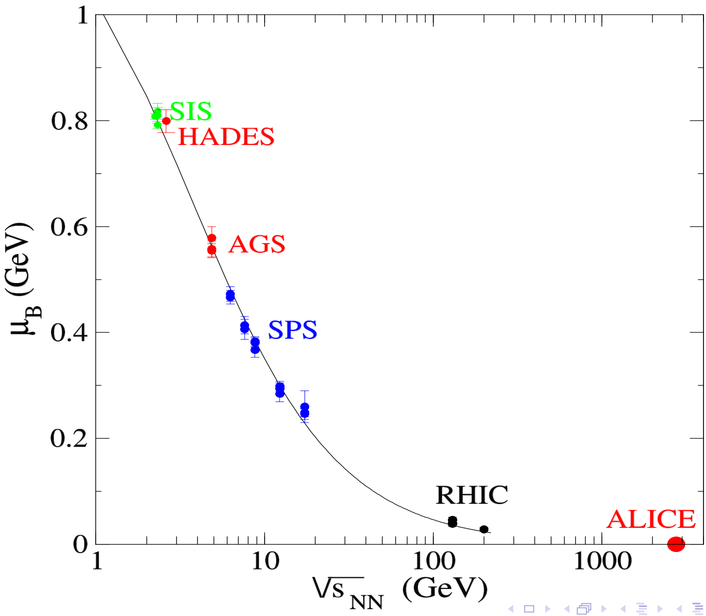
Chemical Freeze-Out: Criteria



Chemical Freeze-Out Temperature



Chemical Freeze-Out μ_B

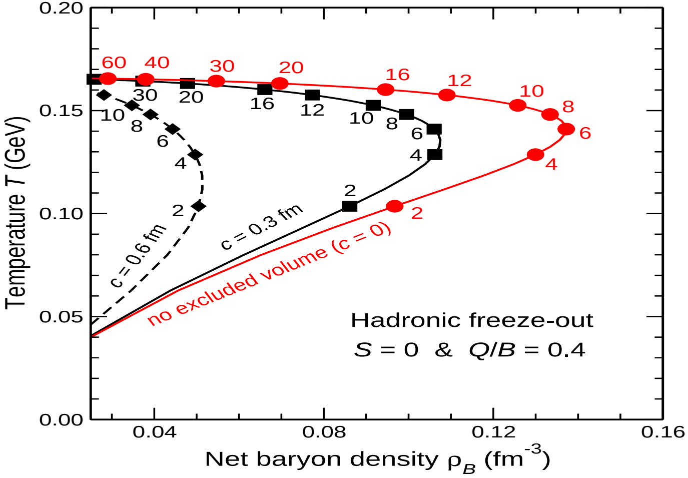


μ_B as a function of $\sqrt{s_{NN}}$

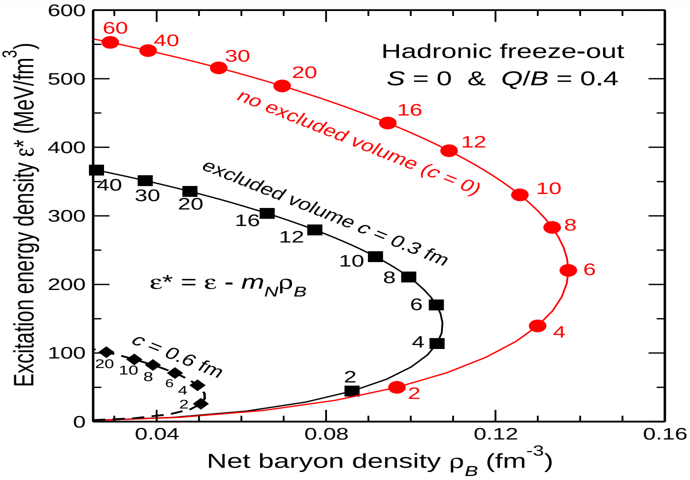
$$\mu_B(\sqrt{s}) = \frac{1.308 \text{ GeV}}{1 + 0.273 \text{ GeV}^{-1}\sqrt{s}}.$$

This predicts at LHC $\mu_B \approx 1$ MeV.

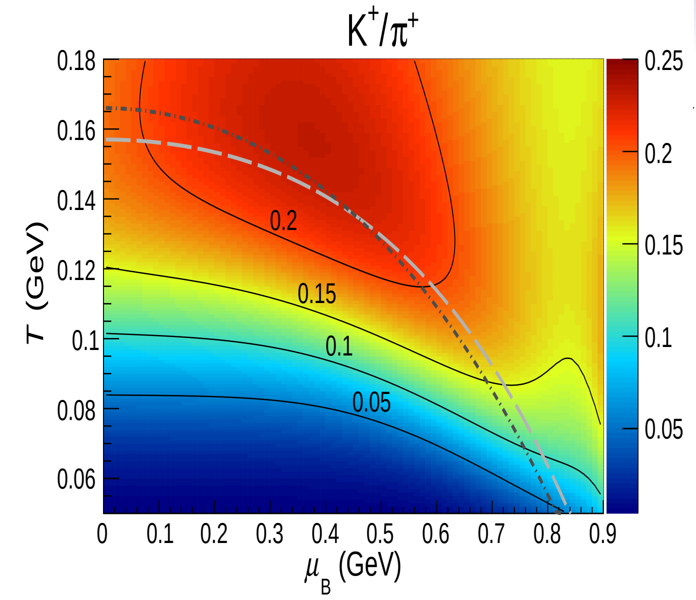
J. C., H. Oeschler, K. Redlich, S. Wheaton
Phys. Rev. C73 034905 (2006)



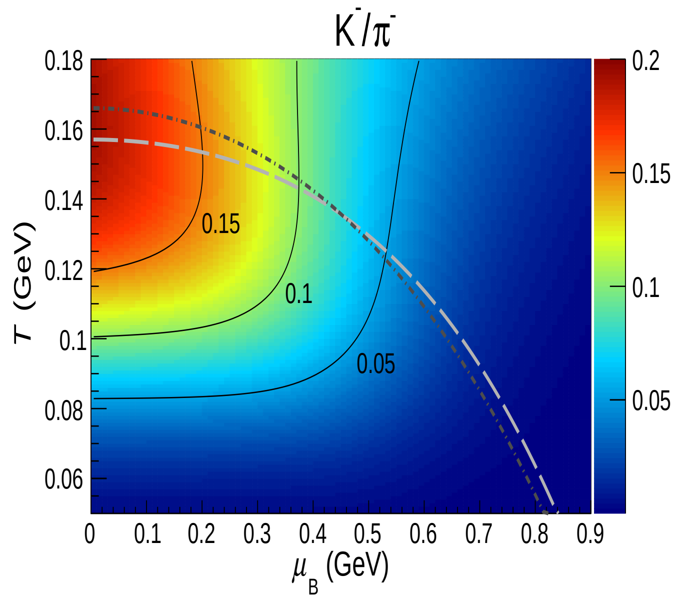
J. Randrup and J.C., Eur. Phys. J. A **52** (2016) 218.



J. Randrup and J.C., Eur. Phys. J. A **52** (2016) 218.

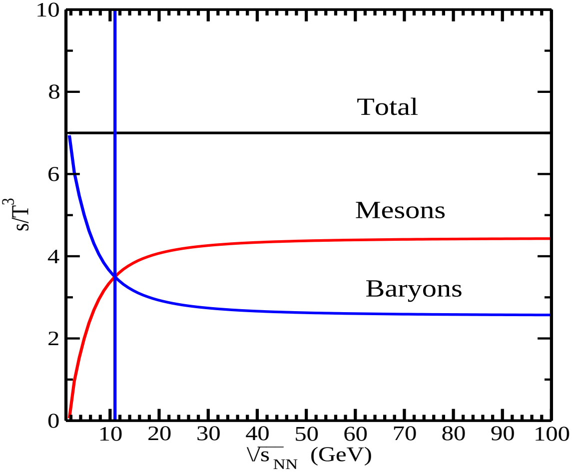


H. Oeschler, J.C., B. Hippolyte, K. Redlich and N. Sharma



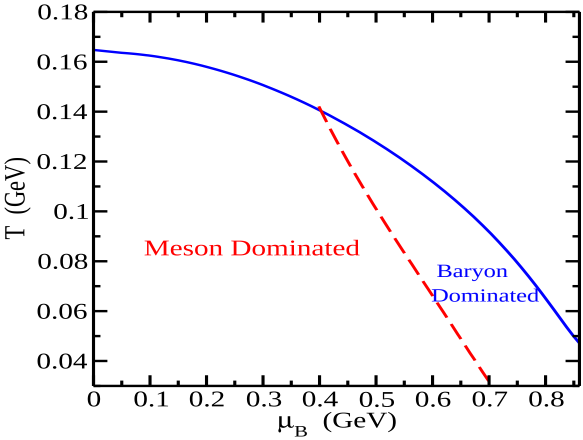
H. Oeschler, J.C., B. Hippolyte, K. Redlich and N. Sharma

s/T^3



J. C., H. Oeschler, K. Redlich and S. Wheaton, Physics Letters B615 (2005) 50-54.

Transition


0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
T (GeV)
Meson Dominated
Baryon
Dominated
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
μB (GeV)

J.C., H. Oeschler, K. Redlich, S. Wheaton, Phys. Lett. B615 (2005) 50-54

In the statistical model a rapid change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The transition occurs at a

- temperature $T = 151$ MeV,
- baryon chemical potential $\mu_B = 327$ MeV,
- energy $\sqrt{s_{NN}} = 11$ GeV.

However,
the sharpness of the peak in the K^+/π^+ ratio suggests that something more is happening.
Also, in the thermal model this transition leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios which occur at different beam energies.

J.C., H. Oeschler, K. Redlich, S. Wheaton, Phys. Lett. B615 (2005) 50-54

In the statistical model a rapid change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The transition occurs at a

- temperature $T = 151$ MeV,
- baryon chemical potential $\mu_B = 327$ MeV,
- energy $\sqrt{s_{NN}} = 11$ GeV.

However,
the sharpness of the peak in the K^+/π^+ ratio suggests that something more is happening.
Also, in the thermal model this transition leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios which occur at different beam energies.

J.C., H. Oeschler, K. Redlich, S. Wheaton, Phys. Lett. B615 (2005) 50-54

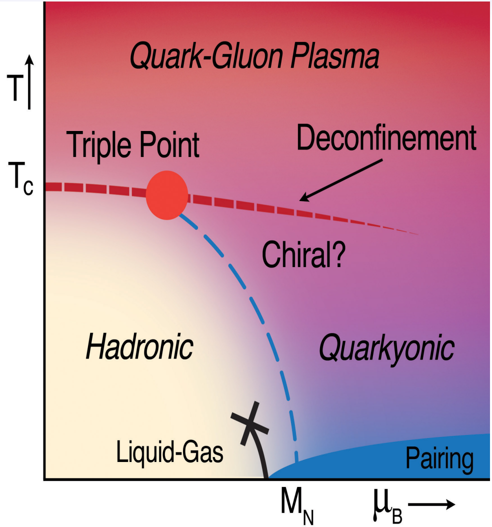
In the statistical model a rapid change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The transition occurs at a

- temperature $T = 151$ MeV,
- baryon chemical potential $\mu_B = 327$ MeV,
- energy $\sqrt{s_{NN}} = 11$ GeV.

However,

the sharpness of the peak in the K^+/π^+ ratio suggests that something more is happening.

Also, in the thermal model this transition leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios which occur at different beam energies.



R. Pisarski and L. McLerran

Conclusions

- Maximum in K^+/π^+ ratio is in the FAIR/NICA energy region,
- Maximum in Λ/π ratio is in the FAIR/NICA energy region,
- Maximum in the net baryon density is in the FAIR/NICA energy region,
- Transition from a Baryon dominated system to a Meson dominated one happens in the FAIR/NICA energy region.

Conclusions

- Maximum in K^+/π^+ ratio is in the FAIR/NICA energy region,
- Maximum in Λ/π ratio is in the FAIR/NICA energy region,
- Maximum in the net baryon density is in the FAIR/NICA energy region,
- Transition from a Baryon dominated system to a Meson dominated one happens in the FAIR/NICA energy region.

Conclusions

- Maximum in K^+/π^+ ratio is in the FAIR/NICA energy region,
- Maximum in Λ/π ratio is in the FAIR/NICA energy region,
- Maximum in the net baryon density is in the FAIR/NICA energy region,
- Transition from a Baryon dominated system to a Meson dominated one happens in the FAIR/NICA energy region.

Conclusions

- Maximum in K^+/π^+ ratio is in the FAIR/NICA energy region,
- Maximum in Λ/π ratio is in the FAIR/NICA energy region,
- Maximum in the net baryon density is in the FAIR/NICA energy region,
- Transition from a Baryon dominated system to a Meson dominated one happens in the FAIR/NICA energy region.