Delineating the QCD Phase Diagram with Data from Different Accelerators.

Jean Cleymans
University of Cape Town, South Africa

Accelerators Revealing the QCD Secrets
Thessaloniki, Greece
3 - 5 September, 2016

Thermal equilibration and expansion in nucleus-nucleus collisions at the AGS
P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu.
Published in Phys.Lett. B344 (1995) 43-48
Detailed record - Cited by 508 records TopCite

Chemical equilibration in Pb + Pb collisions at the SPS
P. Braun-Munzinger, I. Heppe, J. Stachel.
Published in Phys.Lett. B465 (1999) 15-20
Detailed record - Cited by 555 records TopCite

Hadron production in Au - Au collisions at RHIC
P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel.
Published in Phys.Lett. B518 (2001) 41-46
Detailed record - Cited by 606 records TopCite

Hadron production in central nucleus-nucleus collisions at chemical freeze-out
A. Andronic, P. Braun-Munzinger, J. Stachel.
Published in Nucl.Phys. A772 (2006) 167-199
Detailed record - Cited by 504 records TopCite

ELSEVIER

26 January 1995

PHYSICS LETTERS B

Physics Letters B 344 (1995) 43–48

Thermal equilibration and expansion in nucleus-nucleus collisions at the AGS

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu [1]

Department of Physics, State University of New York at Stony Brook, Stony Brook, NY 11794-3800, USA

Received 20 October 1994; revised manuscript received 14 November 1994
Editor: G.F. Bertsch

Abstract

The rather complete data set of hadron yields from central Si + A collisions at the Brookhaven AGS is used to test whether the system at freeze-out is in thermal and hadro-chemical equilibrium. Rapidity and transverse momentum distributions are discussed with regards to the information they provide on hydrodynamic flow.

The goal of the ultra-relativistic heavy-ion program at the BNL AGS and CERN SPS is to study highly excited and dense nuclear matter and possibly the transition from hot and dense hadronic matter to deconfined quark-matter with restored chiral symmetry. While future collider experiments will probe a hot quark-gluon plasma with low net baryon density, present fixed target experiments create matter, possibly quark-matter, at very high baryon density and moderate temperature.

The present paper is following up on an earlier suggestion by some of us [1], based on the first AGS and SPS data, that a high degree of thermalization is

net baryon density at freeze-out, the baryon chemical potential. The relatively large freeze-out temperature thus determined implies that even higher temperatures are reached earlier in the collision. In order to reach the freeze-out stage, the system has to expand considerably. Longitudinal and transverse spectra and, in particular, their mass dependence can yield information on the expansion velocity. This discussion forms the second part of this paper.

The present study starts on the following background:

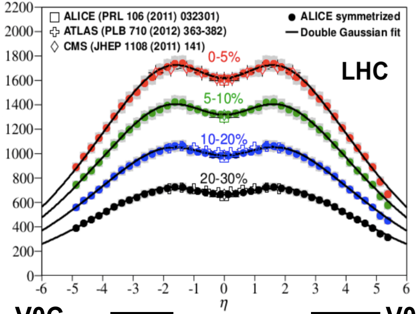
i) Production of transverse energy and the proton ra-

Particle Multiplicity in Heavy Ion Collisions

Acceptance for charged particles

ALICE

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



Now:
(T0 now shown)

V0C — **V0A**
SPD (outer layer)
FMDC — **FMDA**

After LS2:

T0C+ (ext) — **T0A+** (but not hermetic: 80%)
V0A+ (ext)
MFT — **ITS IB (middle layer)**

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

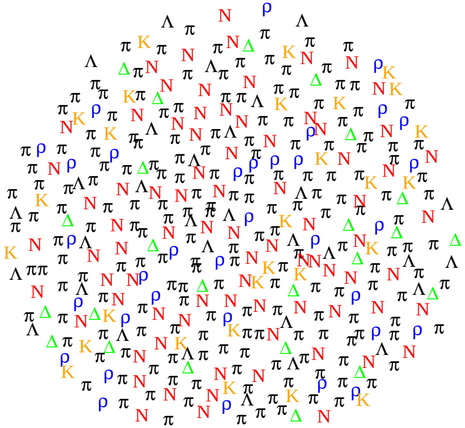
Particle Multiplicity in Heavy Ion Collisions

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 m_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 $\pi R^2 \tau$!

Uncertainties in the Thermal Model

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

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

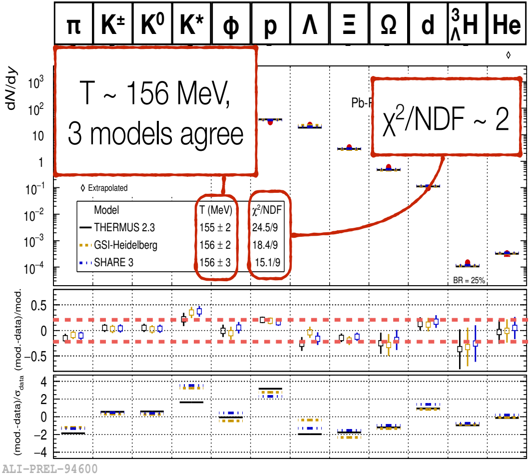
Hence one must know how hadronic resonances decay.

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

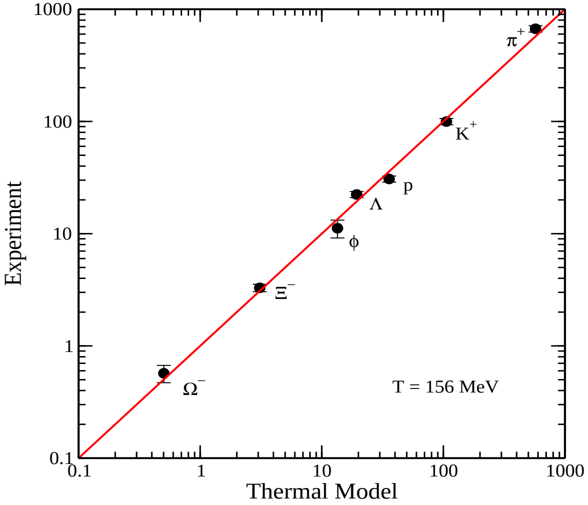


N.B.
RHIC (STAR)
$\sqrt{s}$ = 200 GeV
χ^2/NDF~1

Better fit in
60-80%,

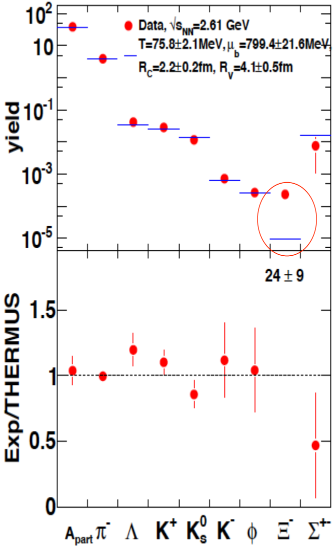
Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

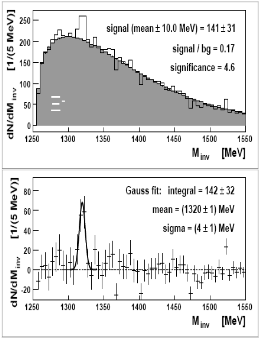
ALICE



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

Hadrons in Ar+KCl@1.76A GeV





Strong excess of the Ξ^-

NN-threshold:

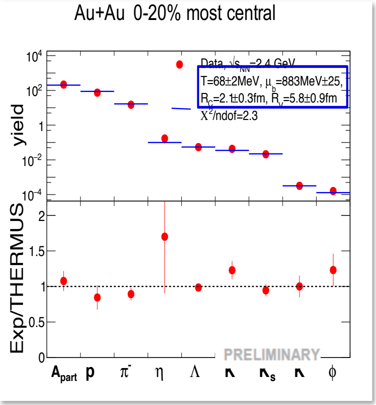
E_{beam}= 3.74GeV $\rightarrow \sqrt{s}-\sqrt{s_{th}}$=-630MeV!

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

Comparing Au+Au data with a statistical model

Macroscopic description based on:

- Grand canonical ensemble
  (T, $\mu = \mu_B\ \mu_S\ \mu_Q$, V and sometimes γ_S, usually μ_s and μ_Q are constrained)
- Strangeness canonical ensemble
  (T, $\mu = \mu_B\ \mu_Q$, $R_c = R_v$)
- Strangeness canonically suppressed at low temperatures, but not enough to explain data → needs additional parameter: $R_c < R_v$
- ϕ meson (hidden strangeness) not suppressed by R_c but strongly by γ_S



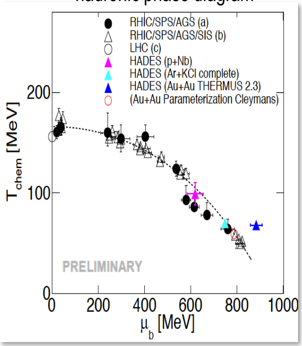
Implementation: THERMUS V2.3
Wheaton & Cleymans Comp. Phys. Com. 180 (2009)

Hadron yields described by T, μ_B, R_v, and R_c

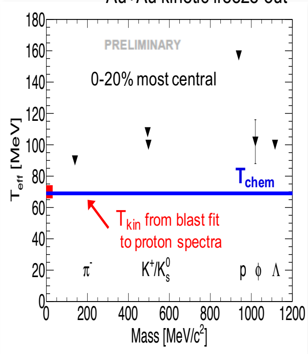
→ rather large values for **T** and **μ_B**
→ γ_s instead of R_c delivers similar results, but undershoots the ϕ yield

HADES in the phase diagram

hadronic phase diagram



Au+Au kinetic freeze-out



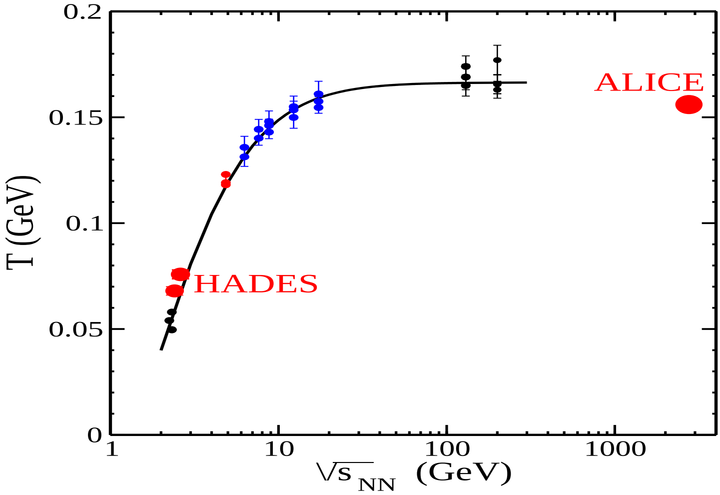
T and μ_b higher than expected from parameterization and universal freeze-out line (E/B=1GeV)

We find $T_{kin} \approx T_{chem} = 68$ MeV

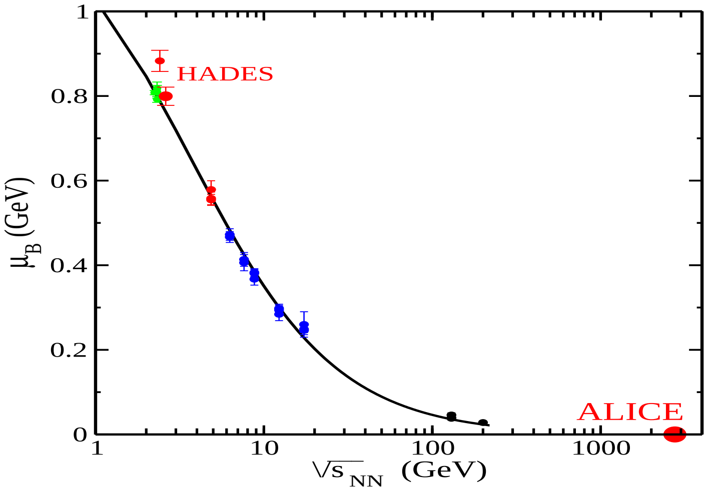
Todo: add fragments (d,t,He) to further constrain T_{kin}

Systematics of freeze-out points:
Andronic, PBM, J. Stachel, NPA 772 (2006)
Cleymans, Oeschler et al., PRC 73 (2006)
Parameterization of T and μ_b:
Cleymans, Oeschler et al., PRC 73 (2006)

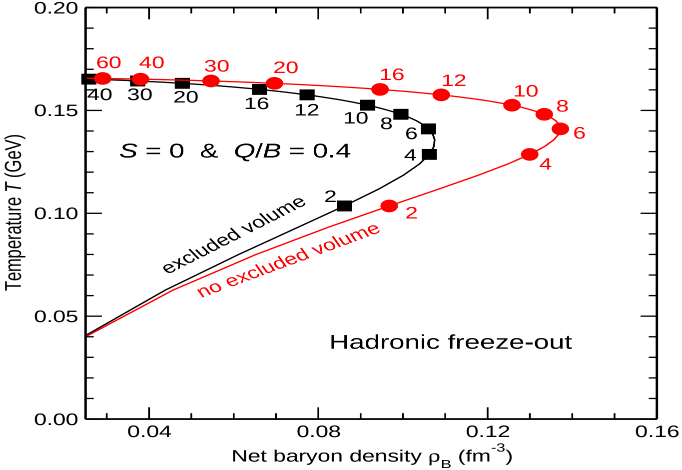
Chemical Freeze-Out Temperature



Chemical Freeze-Out μ_B

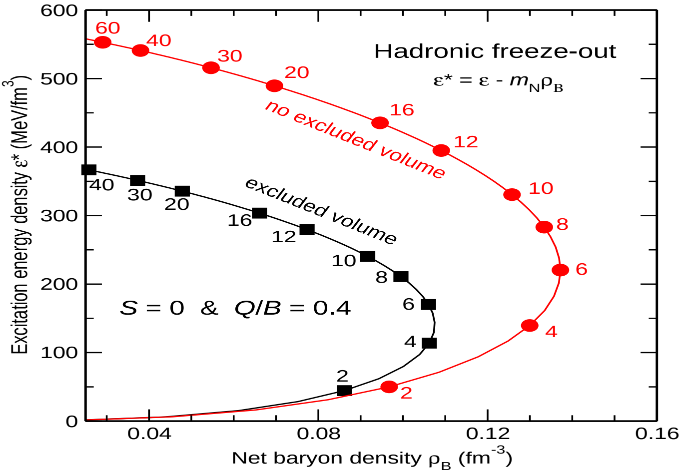


Unexpected Results



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

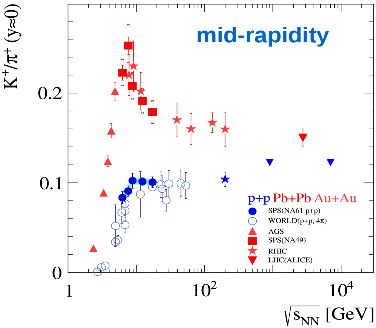
Unexpected Results

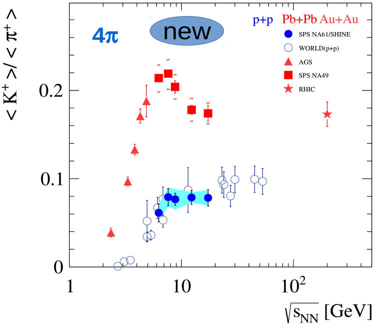


J. Randrup and J.C. Eur. Phys. J. A **52** (2016) 218.

Unexpected Results

K. Grebieszkow (NA61/SHINE) talk at CPOD2016:
Maximum in the K^+/π^+ ratio disappears in small systems





To analyze the particle ratios use:

- the Wroblewski factor
- $s/T^3 = 7$ describes chemical freeze-out

Strangeness in Heavy Ion Collisions
vs
Strangeness in pp - collisions

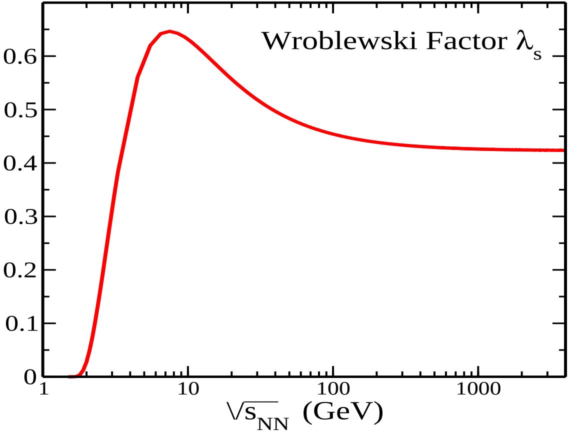
Use the Wroblewski factor

$$\lambda_s = \frac{2\,\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

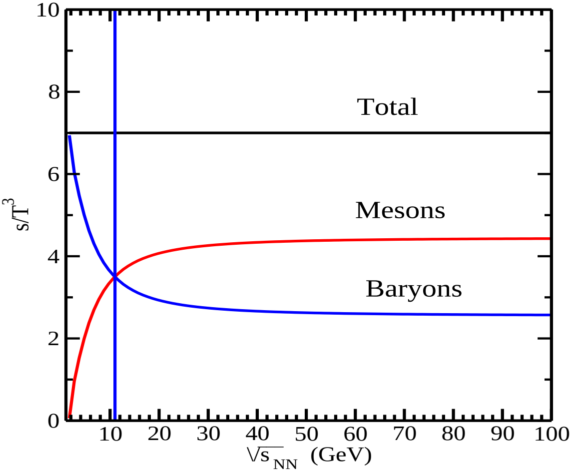
This is determined by the number of **newly** created quark – anti-quark pairs and **before** strong decays, i.e. before ρ's and Δ's decay.

Limiting values :
$\lambda_s = 1$ all quark pairs are equally abundant, SU(3) symmetry.
$\lambda_s = 0$ no strange quark pairs.

Wroblewski Factor



s/T^3



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

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.

In this region the interplay between temperature and baryon chemical potential leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios **which occur at different beam energies.**

P. Braun-Munzinger, J.C., H. Oeschler, K. Redlich, Nucl. Phys. A697 (2002) 902.

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.

In this region the interplay between temperature and baryon chemical potential leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios **which occur at different beam energies.**

P. Braun-Munzinger, J.C., H. Oeschler, K. Redlich, Nucl. Phys. A697 (2002) 902.

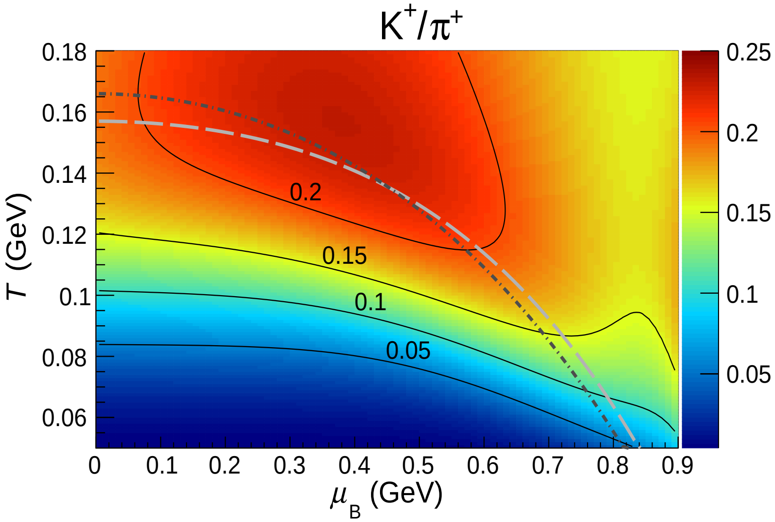
J.C., H. Oeschler, K. Redlich, S. Wheaton, Phys. Lett. B615 (2005) 50-54

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.

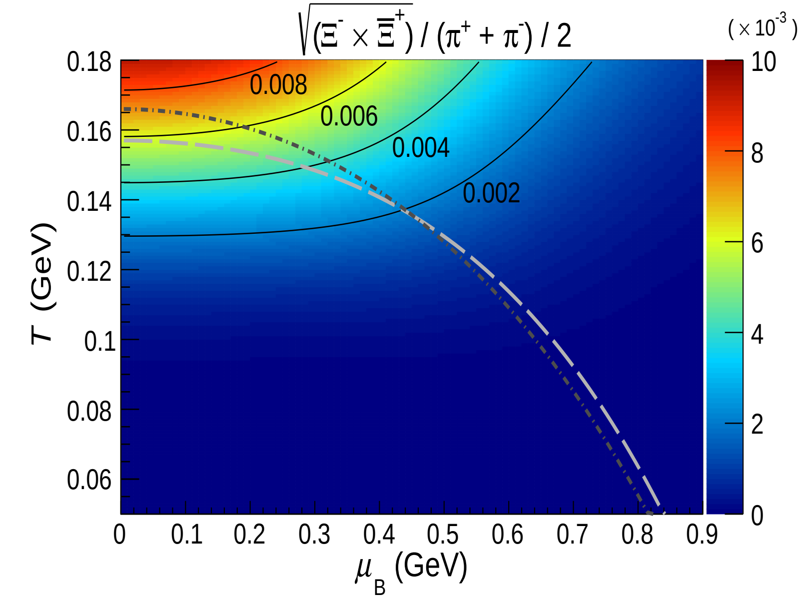
In this region the interplay between temperature and baryon chemical potential leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios **which occur at different beam energies.**

P. Braun-Munzinger, J.C., H. Oeschler, K. Redlich, Nucl. Phys. A697 (2002) 902.

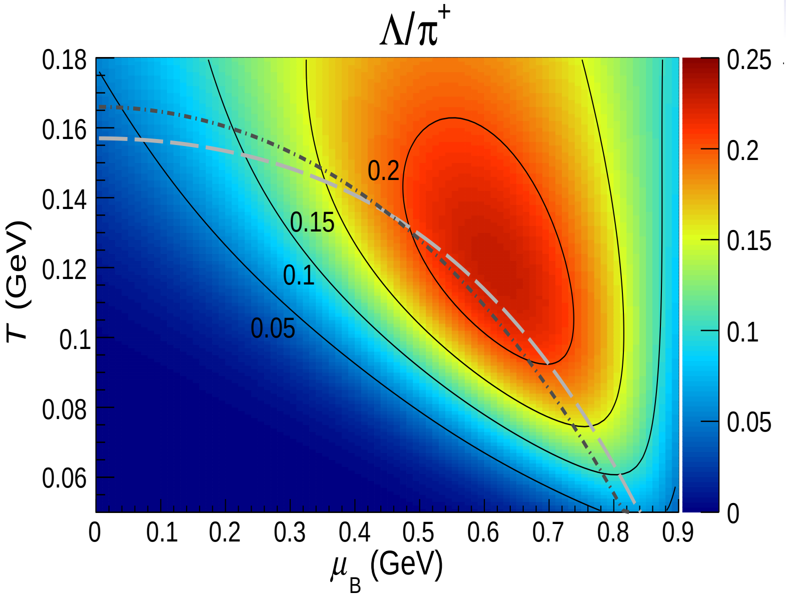


J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553

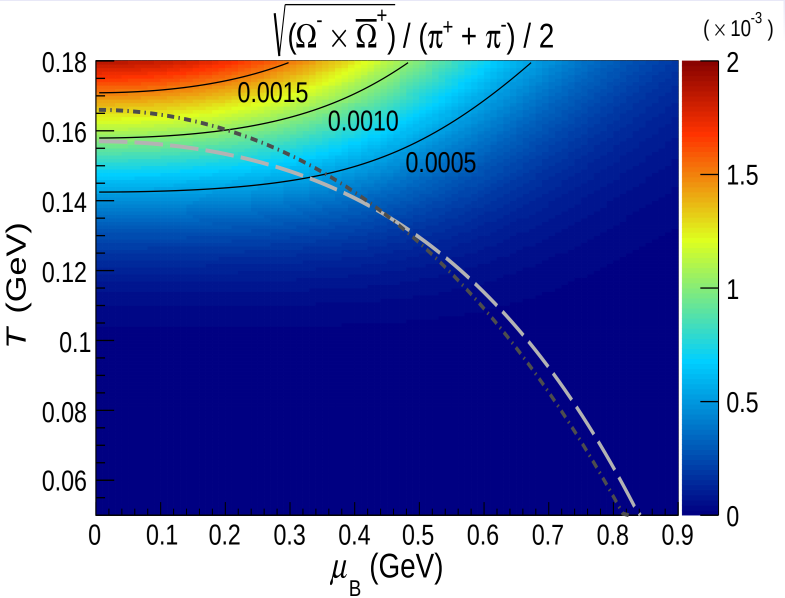
V. Vovchenko, V.V. Begun, M.I. Gorenstein, arXiv:1512.08025[nucl-th]



J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553



J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553



J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553

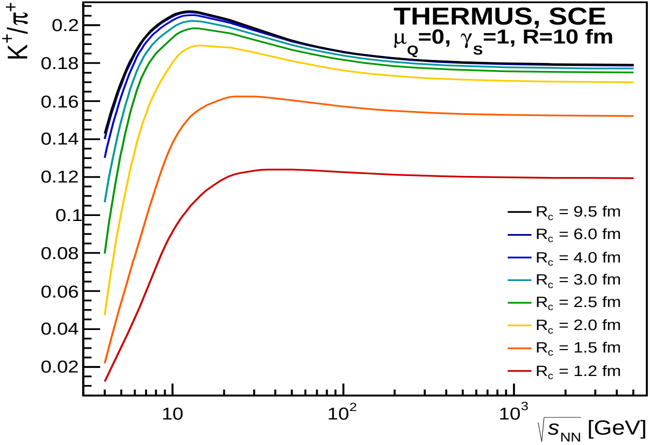
Small systems.

- Use the canonical ensemble with strangeness conservation.
- Introduce two volumes: global volume and a strangeness correlation volume .
- Reduce the strangeness correlation volume to describe small systems.

J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553

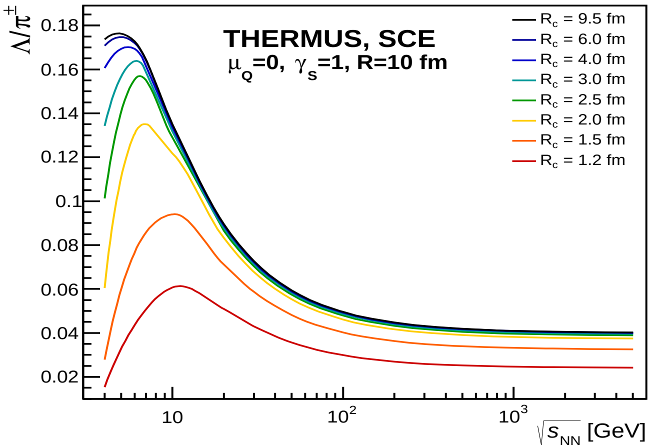
S. Hamieh, K. Redlich and A. Tounsi, Phys. Lett. B486 (2000) 61

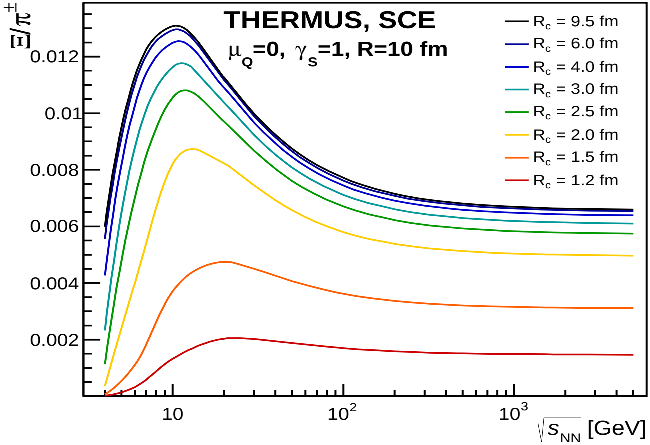
Maximum in K^+/π^+ ratio disappears

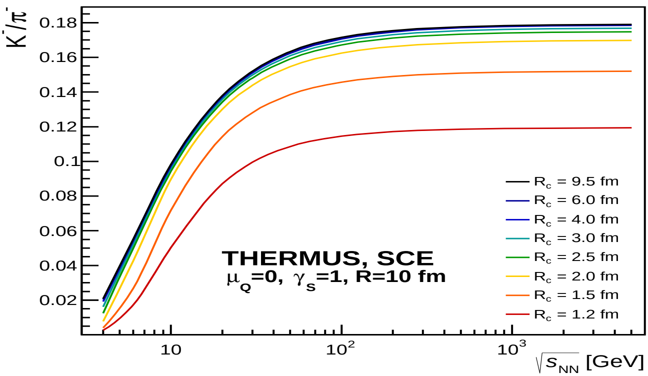


J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553

Maximum in Λ/π^+ ratio survives




THERMUS, SCE
μ_Q=0, γ_s=1, R=10 fm
R_c = 9.5 fm
R_c = 6.0 fm
R_c = 4.0 fm
R_c = 3.0 fm
R_c = 2.5 fm
R_c = 2.0 fm
R_c = 1.5 fm
R_c = 1.2 fm
Ξ/π^±
0.012
0.01
0.008
0.006
0.004
0.002
10
10^2
10^3
√s_NN [GeV]



K^-/π^-
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
10
10^2
10^3
$\sqrt{s_{NN}}$ [GeV]
THERMUS, SCE
μ_Q=0, γ_s=1, R=10 fm
R_c = 9.5 fm
R_c = 6.0 fm
R_c = 4.0 fm
R_c = 3.0 fm
R_c = 2.5 fm
R_c = 2.0 fm
R_c = 1.5 fm
R_c = 1.2 fm

Conclusions

- Maximum in K^+/π^+ ratio disappears for small systems,
- A small maximum in Λ/π ratio SURVIVES for small systems,

If this is confirmed experimentally then a hadronic scenario explains the behaviour seen in the hadronic ratios and there is no need for other mechanisms.

Conclusions

- Maximum in K^+/π^+ ratio disappears for small systems,
- A small maximum in Λ/π ratio SURVIVES for small systems,

If this is confirmed experimentally then a hadronic scenario explains the behaviour seen in the hadronic ratios and there is no need for other mechanisms.

Peter, many happy returns.