HIC:
Status of Chemical Equilibrium in Heavy Ion Collisions.

Jean Cleymans
University of Cape Town, South Africa

ULtra-RelativIstCH HEavy IoNZ 2016,
CERN
18 - 20 July, 2016

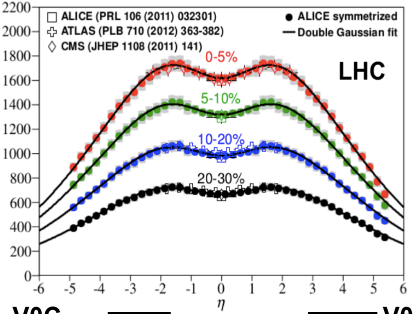
Outline

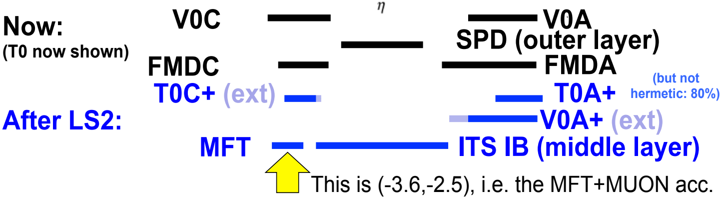
Particle Multiplicity in Heavy Ion Collisions

Acceptance for charged particles

ALICE

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





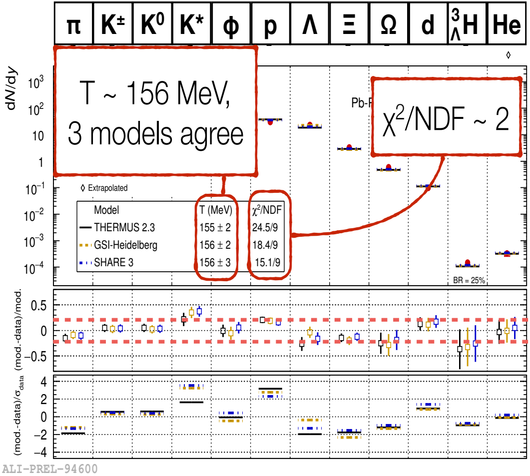
Particle Multiplicity in Heavy Ion Collisions

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 ...

Equilibrium SHM Fits in Central Pb-Pb

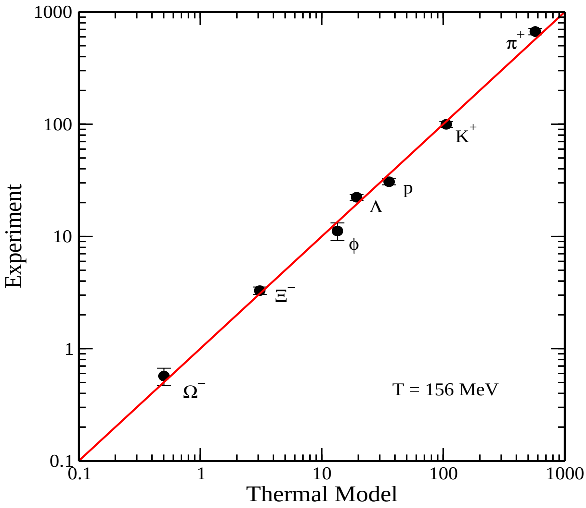


N.B.
RHIC (STAR)
$\sqrt{s}$ = 200 GeV
χ^2/NDF~1

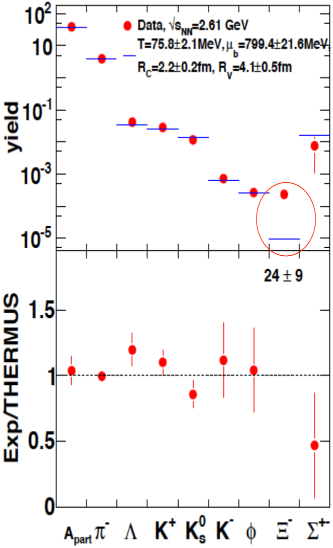
Better fit in
60-80%,

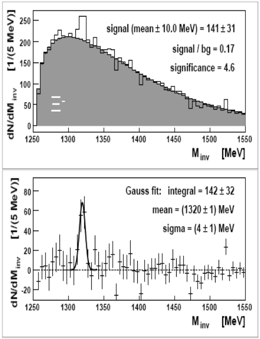
Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

ALICE


1000
100
10
1
0.1
0.1
1
10
100
1000
Experiment
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:

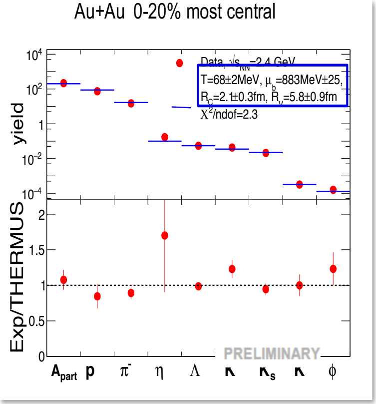
E_{beam} = 3.74GeV $\rightarrow \sqrt{s}-\sqrt{s_{th}}$=-630MeV!

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

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



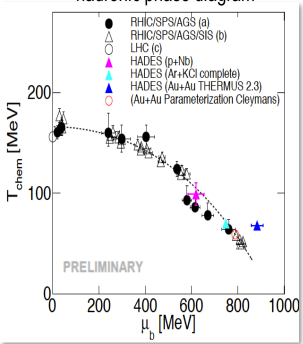
Implementation: THERMUS V2.3
Wheaton & Cleymans Comp. Phys. Com. 180 (2009)

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

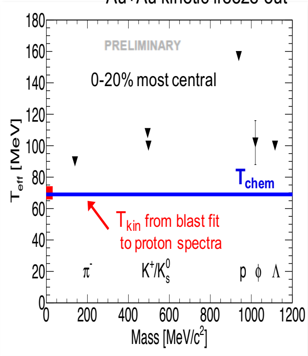
hadronic phase diagram



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

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)

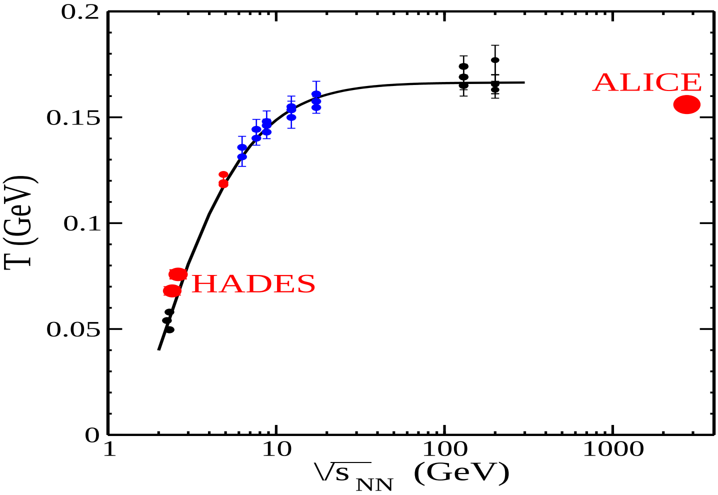
Au+Au kinetic freeze-out



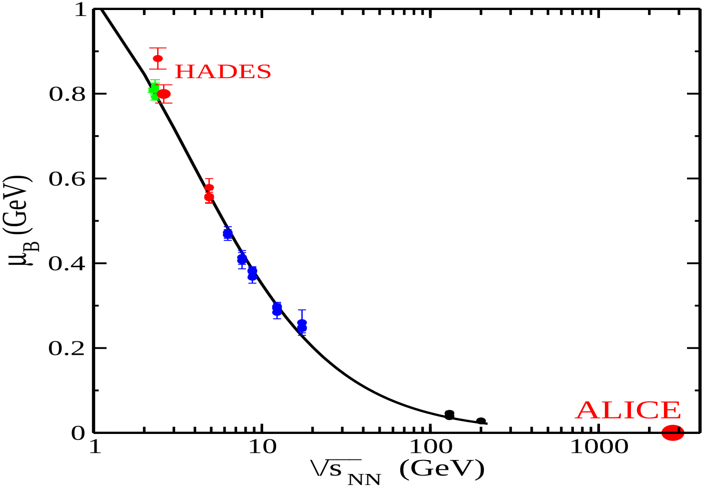
We find $T_{kin} \approx T_{chem} = 68$ MeV

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

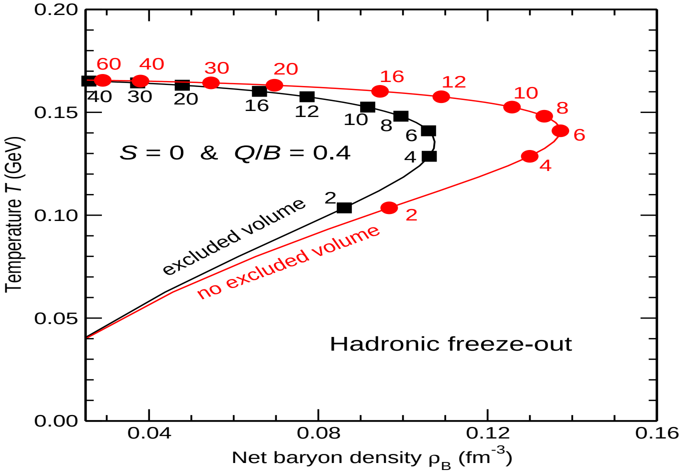
Chemical Freeze-Out Temperature



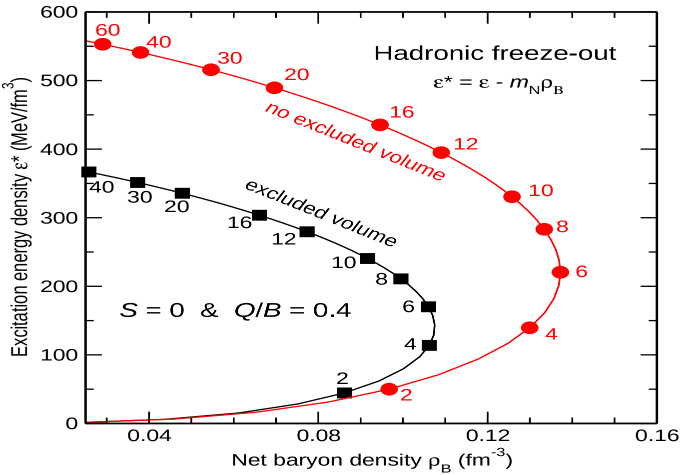
Chemical Freeze-Out μ_B



Unexpected Results

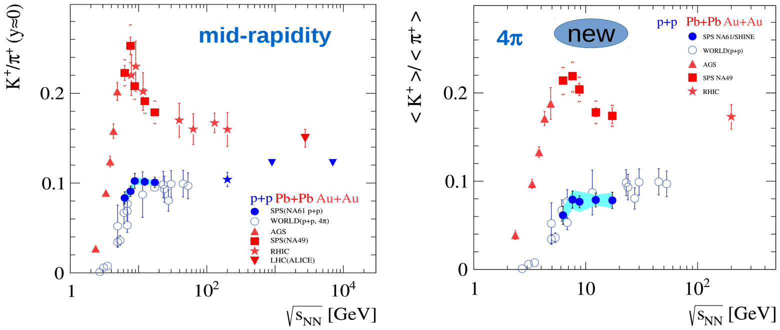


Unexpected Results



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

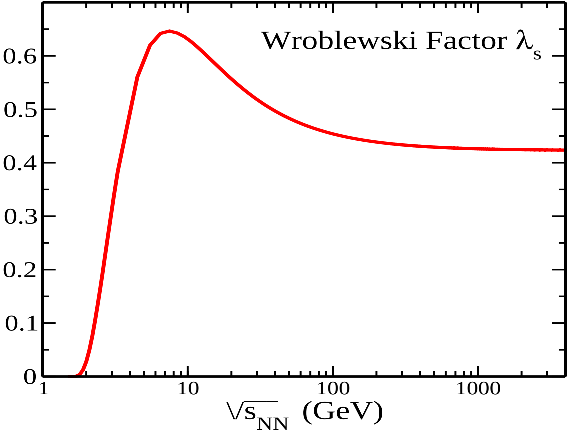
Use the Wroblewski factor

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

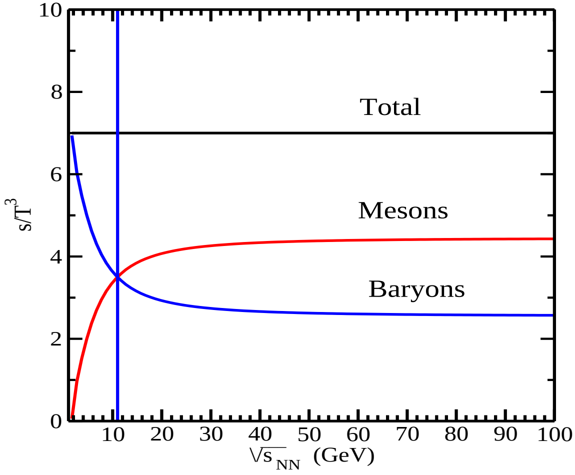
This is determined by the number of **newly** created quark – anti-quark pairs and **before** strong decays, i.e. before ρ's and Δ's decay.

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.

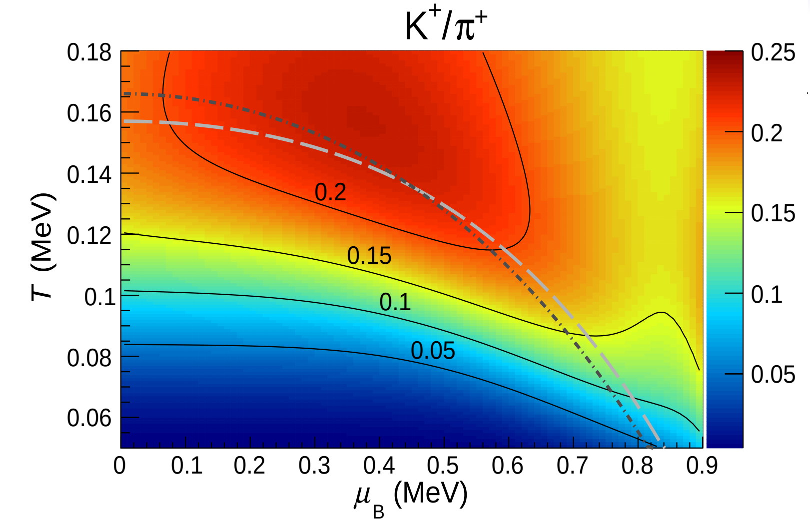
J.C., H. Oeschler, K. Redlich, S. Wheaton, Phys. Lett. B615 (2005) 50-54

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.

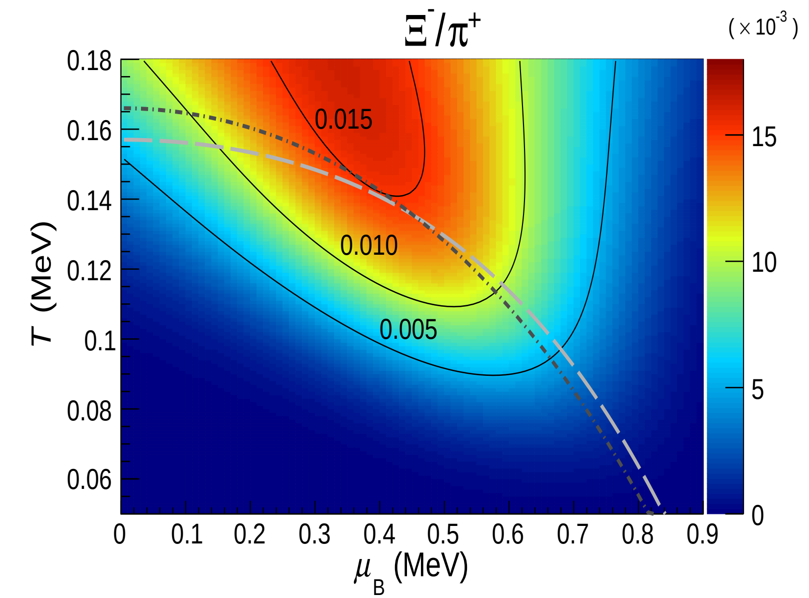
In this region the interplay between temperature and baryon chemical potential leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios **which occur at different beam energies.**

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

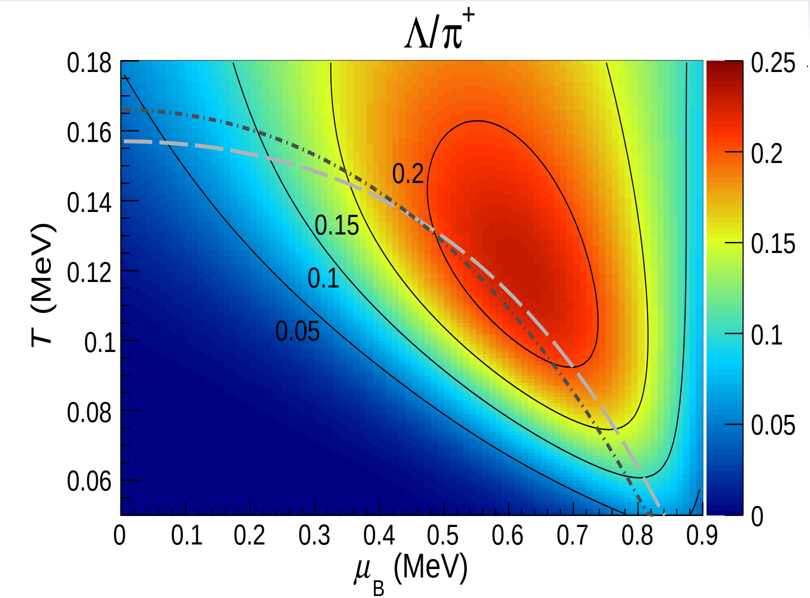


J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553

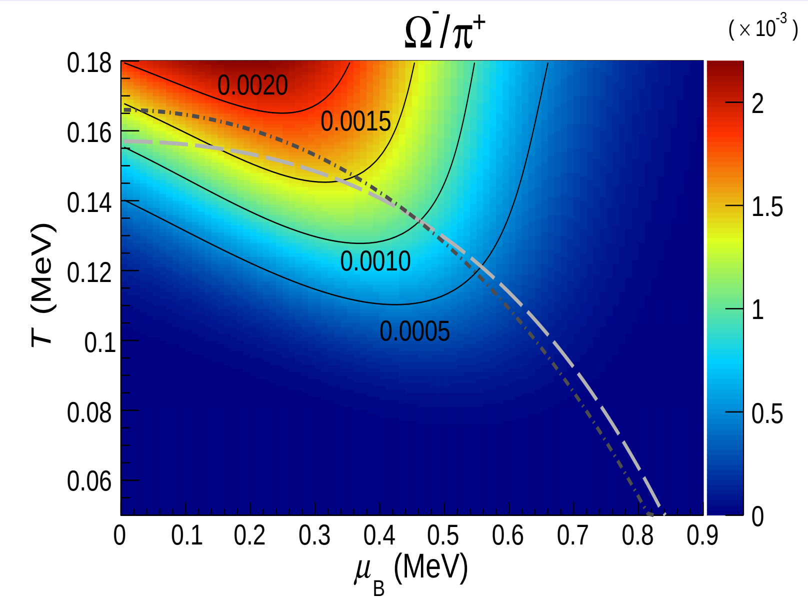
V. Vovchenko, V.V. Begun, M.I. Gorenstein, arXiv:1512.08025[nucl-th]



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

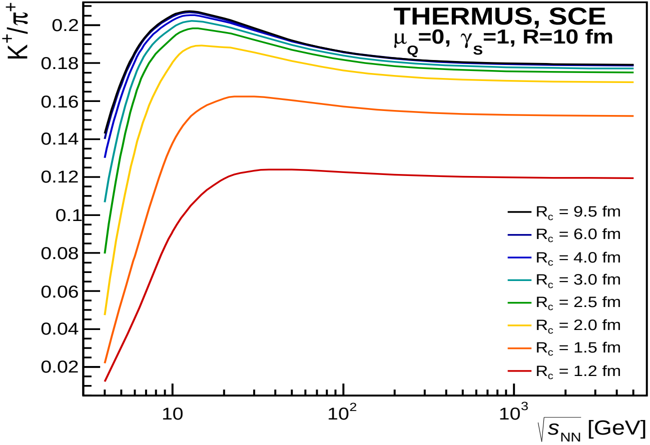
Small systems.

- 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

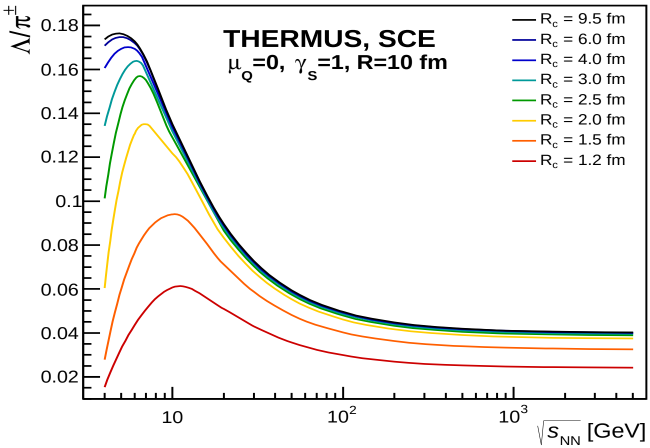
S. Hamieh, K. Redlich and A. Tounsi, Phys. Lett. B486 (2000) 61

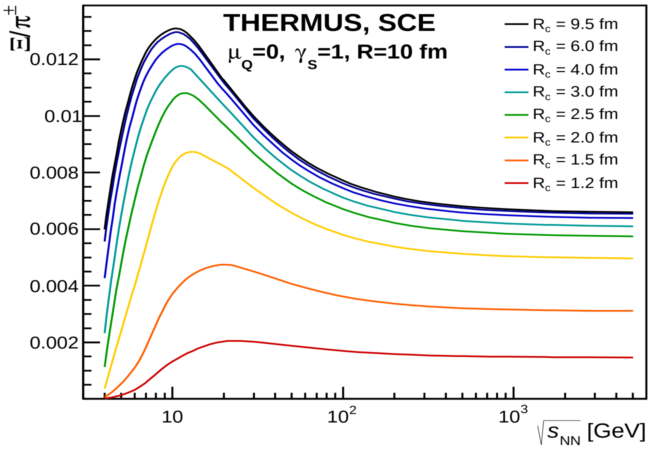
Maximum in K^+/π^+ ratio disappears

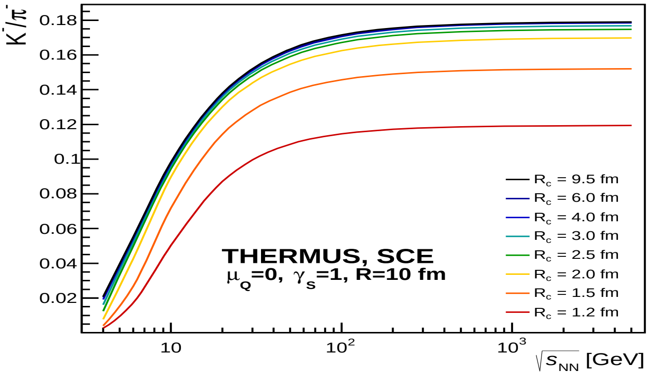


J.C., B. Hippolyte, H. Oeschler, K. Redlich, N. Sharma arXiv:1603.09553

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.

Uli, many happy returns.