# Transition from Baryonic to Mesonic Freeze-Out.

J. Cleymans

12 August 2005
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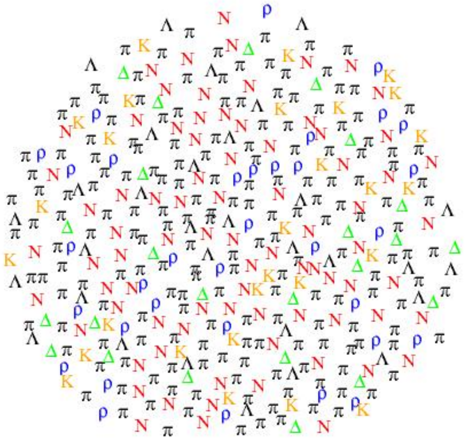
# Outline

# Hadronic Gas before Chemical Freeze-Out



The number of particles of type $i$ is determined by:

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int d\sigma_\mu p^\mu \exp\left(-\frac{p^\mu u_\mu}{T} + \frac{\mu_i}{T}\right)$$

Integrating this over all momenta

$$N_i = \frac{g_i}{(2\pi)^3}\int d\sigma_\mu \int \frac{d^3p}{E} p^\mu \exp\left(-\frac{p^\mu u_\mu}{T} + \frac{\mu_i}{T}\right)$$

or

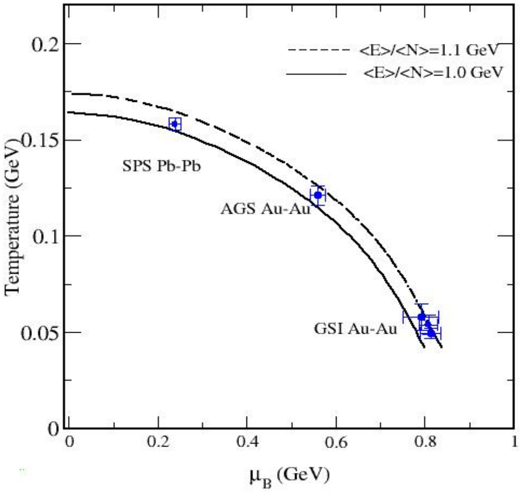
$$N_i = \int d\sigma_\mu u^\mu n_i(T,\mu)$$

If the temperature and chemical potential are unique along the freeze-out curve

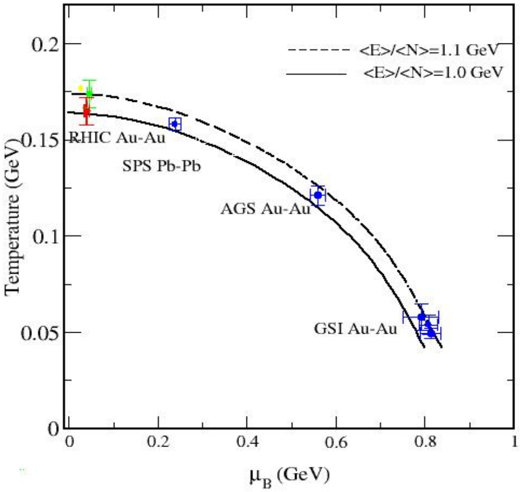
$$N_i = n_i(T,\mu)\int d\sigma_\mu u^\mu$$

i.e. integrated ($4\pi$) multiplicities are the same as for a single fireball at rest (apart from the volume).

# E/N in 1999

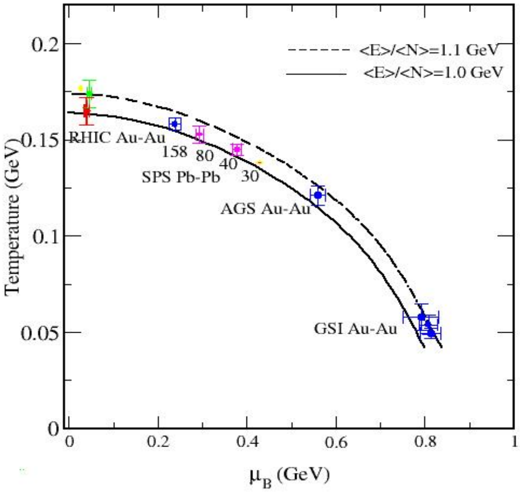

<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
μB (GeV)

# E/N in 2000

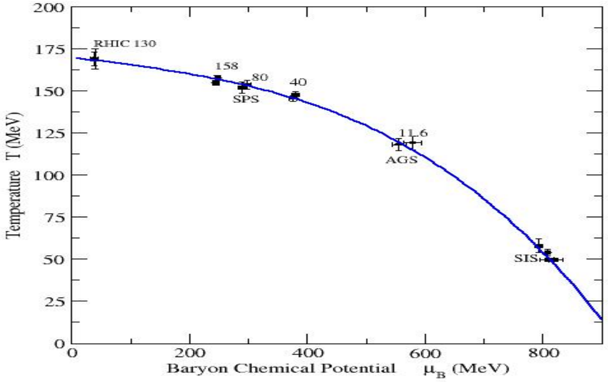


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
μB (GeV)
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1

# E/N in 2005

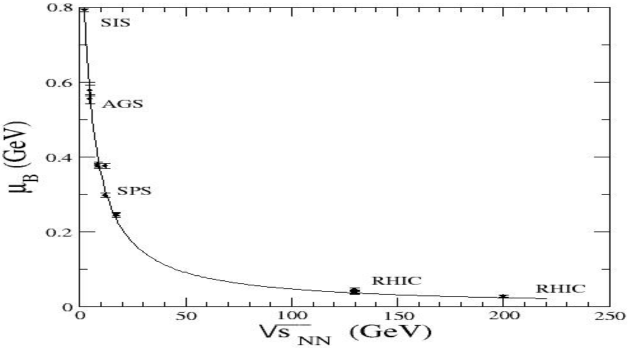


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
μB (GeV)



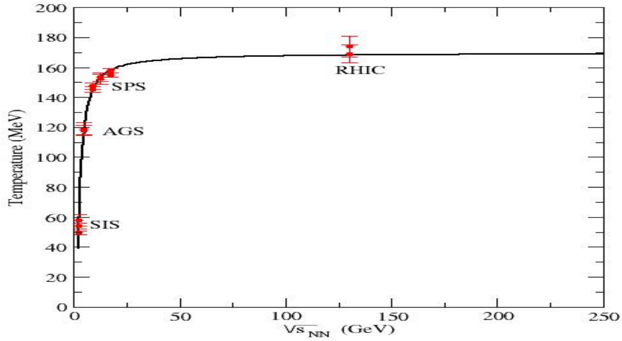

$$T(\mu_B) = 0.16446 - 0.11196\,\mu_B^2 - 0.139139\,\mu_B^4 + 0.0684637\,\mu_B^6$$

# $\mu_B$ as a function of $\sqrt{s_{NN}}$



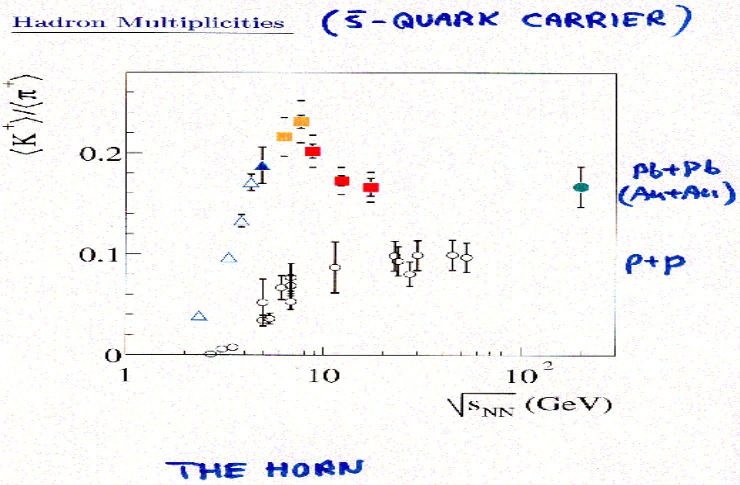

$$\mu_B = 1.27347/(1.0 + 0.25767 * \sqrt{s_{NN}})$$

# $T$ as a function of $\sqrt{s_{NN}}$



The NA49 Collaboration has recently performed a series of measurements of Pb-Pb collisions at 20, 30, 40, 80 and 158 AGeV beam energies . When these results are combined with measurements at lower beam energies from the AGS they reveal an unusually sharp variation with beam energy in the $\Lambda/\langle\pi\rangle$, with $\langle\pi\rangle \equiv 3/2(\pi^+ + \pi^-)$, and $K^+/\pi^+$ ratios. Such a strong variation with energy does not occur in pp collisions and therefore indicates a major difference in heavy-ion collisions. This transition has been referred as the “horn”.

# NA49: Horn



Hadron Multiplicities
( s̄ - QUARK CARRIER )
⟨K+⟩/⟨π+⟩
0.2
0.1
0
1
10
10 2
√sNN (GeV)
Pb+Pb
(Au+Au)
p+p
THE HORN

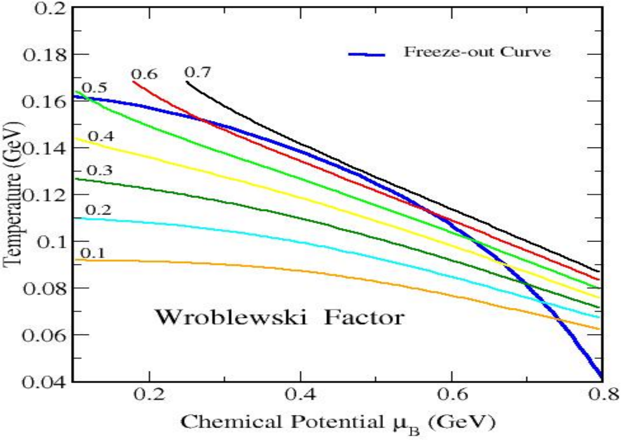
## Strangeness in Heavy Ion Collisions
vs
## Strangeness in pp - collisions

Use the Wroblewski factor

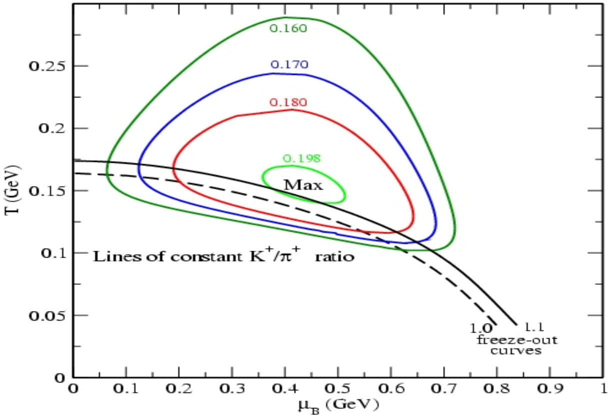
$$\lambda_s = \frac{2\,\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

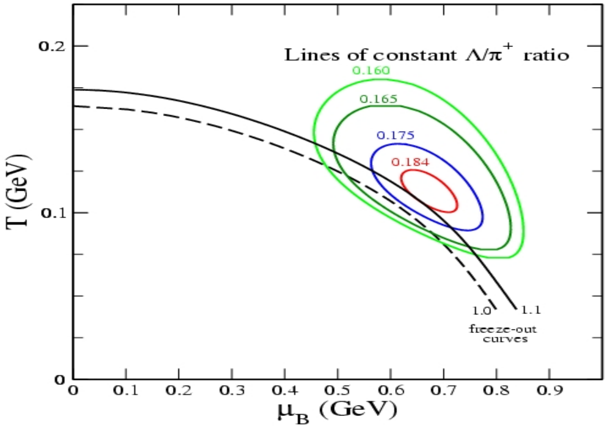
This is determined by the number of **newly** created quark – anti-quark pairs and **before** strong decays, i.e. before $\rho$'s and $\Delta$'s decay.

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



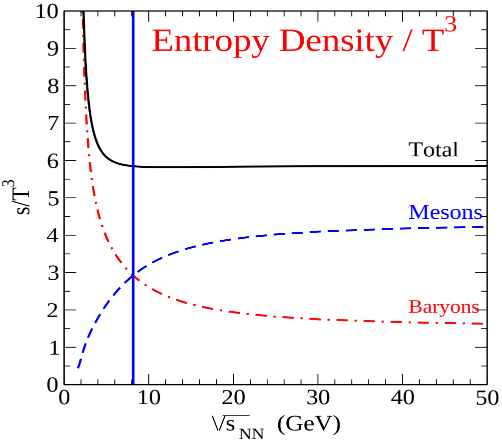
Freeze-out Curve
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Wroblewski Factor
Temperature (GeV)
Chemical Potential μB (GeV)

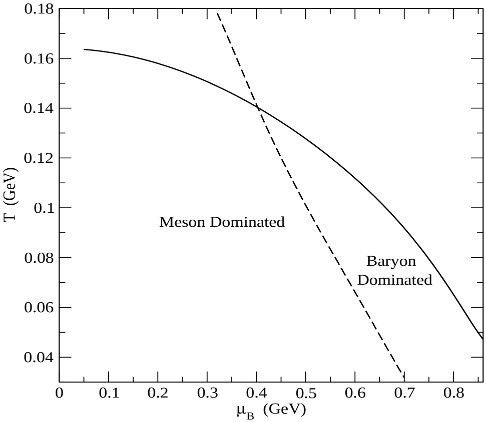

0.160
0.170
0.180
0.198
Max
Lines of constant K+/π+ ratio
1.0
1.1
freeze-out
curves
T (GeV)
μB (GeV)
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

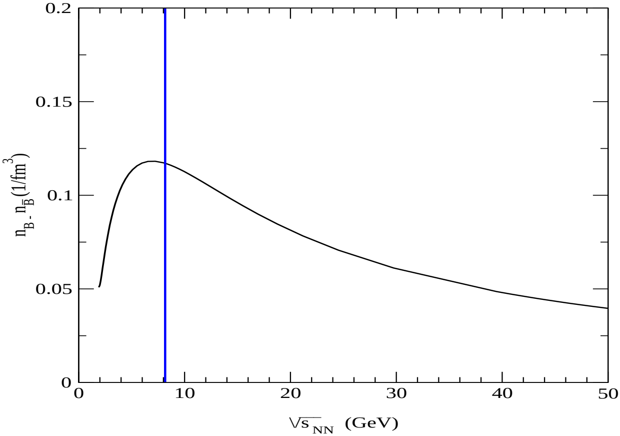

Lines of constant Λ/π+ ratio
0.160
0.165
0.175
0.184
1.0
1.1
freeze-out curves
T (GeV)
μB (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

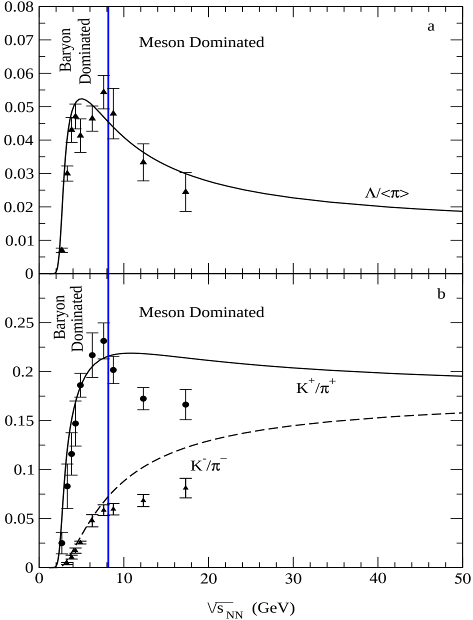
# J.C., H. Oeschler, K. Redlich, S. Wheaton, Phys. Lett. B 2005

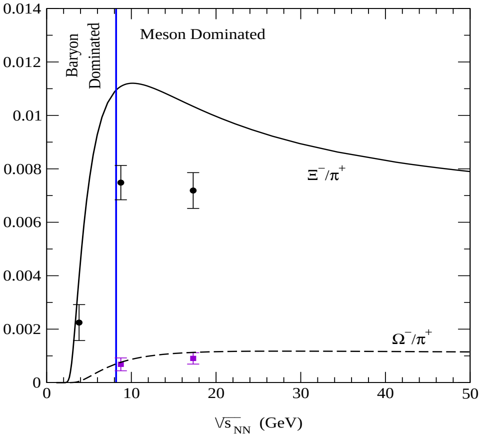
In the statistical model a rapid change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The transition occurs at a temperature $T$ = 140 MeV and baryon chemical potential $\mu_B$ = 410 MeV corresponding to an incident energy of $\sqrt{s_{NN}}$ = 8.2 GeV.


Entropy Density / T3
Total
Mesons
Baryons
s/T3
√s NN (GeV)
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10


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


0.2
0.15
0.1
0.05
0
$n_B - n_{\bar{B}}$ (1/fm$^3$)
0
10
20
30
40
50
$\sqrt{s}_{NN}$ (GeV)


a
Meson Dominated
Baryon Dominated
Λ/<π>
b
Meson Dominated
Baryon Dominated
K+/π+
K-/π-
√s_NN (GeV)


0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
10
20
30
40
50
Baryon Dominated
Meson Dominated
$\Xi^-/\pi^+$
$\Omega^-/\pi^+$
$\sqrt{s}_{NN}$ (GeV)

It is to be expected that if these maxima do not all occur at the same temperature, i.e. at the same beam energy, then the case for a phase transition is not very strong. The observed behavior seems to be governed by properties of the hadron gas. More detailed experimental studies of multi-strange hadrons will allow the verification or disproval of the trends shown in this paper. It should be clear that the $\Omega^-/\pi^+$ ratio is very broad and shallow and it will be difficult to find a maximum experimentally.

**Maxima in Particle Ratios predicted by the Thermal Model.**

| Ratio | Maximum at $\sqrt{s_{NN}}$ (GeV) | Maximum Value |
|---|---|---|
| $\Lambda/\langle\pi\rangle$ | 5.1 | 0.052 |
| $\Xi^-/\pi^+$ | 10.2 | 0.011 |
| $K^+/\pi^+$ | 10.8 | 0.22 |
| $\Omega^-/\pi^+$ | 27 | 0.0012 |

In conclusion, while the statistical model cannot explain the sharpness of the peak in the $K^+/\pi^+$ ratio, its position corresponds precisely to a transition from a baryon-dominated to a meson-dominated hadronic gas. This transition occurs at a

- temperature $T = 140$ MeV,
- baryon chemical potential $\mu_B = 410$ MeV,
- energy $\sqrt{s_{NN}} = 8.2$ GeV.

In the statistical model this transition leads to a sharp peak in the $\Lambda/\langle\pi\rangle$ ratio, and to moderate peaks in the $K^+/\pi^+$, $\Xi^-/\pi^+$ and $\Omega^-/\pi^+$ ratios. Furthermore, these peaks are at different energies in the statistical model. The statistical model predicts that the maxima in the $\Lambda/\langle\pi\rangle$, $\Xi^-/\pi^+$ and $\Omega^-/\pi^+$ occur at increasing beam energies.

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