Antimatter Production in p-p and heavy Ion Collisions at Ultrarelativistic Energies.

J. Cleymans, S. Kabana I. Kraus, H. Oeschler, K. Redlich, N. Sharma

Kruger 2010,
December 8, 2010

Outline

1. Chemical Equilibrium
2. Comparison of Chemical Freeze-Out Criteria
3. If everything is smooth why is there such a roller-coaster in the particle ratios?
4. Production of antibaryons
5. Antimatter
6. Production of nuclei, antinuclei, hypernuclei and antihypernuclei


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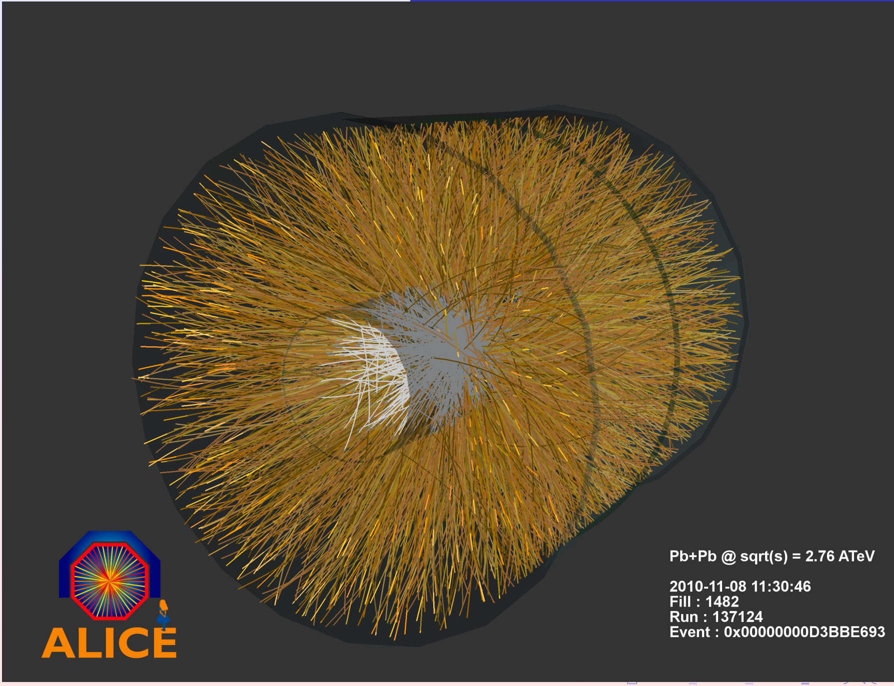
ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
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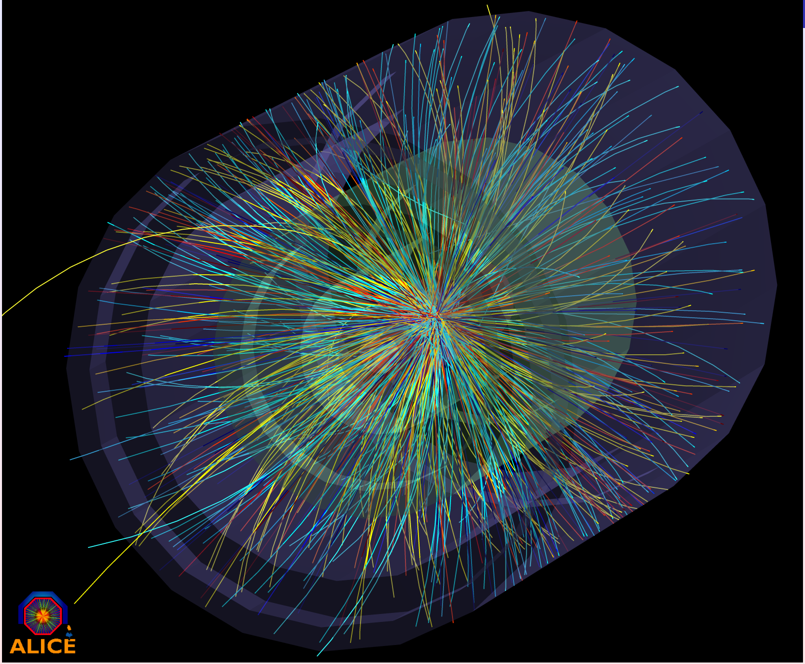
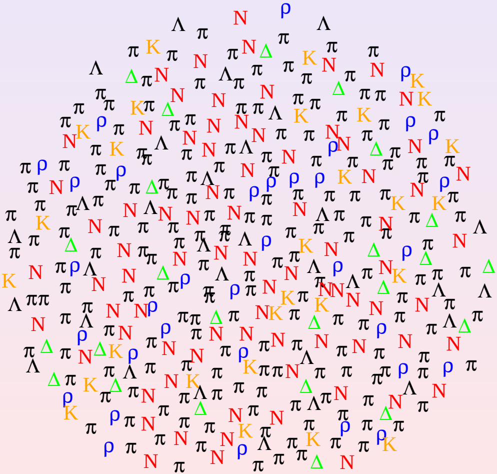

ALICE



The energy is

$$\sqrt{s} = 2760.0 \ \mathrm{AGeV}$$

yet the temperature seen in the particle ratios is only

$$T \approx 0.17 \ \mathrm{GeV}$$

What is the story behind this?

Temperature

The temperature can be obtained from:

- Mass spectrum of hadrons: simply adding up the number of hadronic resonances (Hagedorn, Ranft) (Hagedorn temperature)
- Transverse momentum spectra (kinetic or thermal freeze-out temperature),
- Hadronic ratios (chemical freeze-out temperature),
- Lattice QCD at finite temperature (phase transition temperature).

Are they all the same?

Sizable production of Deuterons, Antideuterons, Helium 3, ...

Observation of hypertritons, ${}^{3}_{\Lambda}\mathrm{H}$, and antihypertritons, ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$. by the STAR collaboration.

Chemical Equilibrium

	Equilibrium
π^0	$\exp\left[-\frac{E_\pi}{T}\right]$
π^+	$\exp\left[-\frac{E_\pi}{T}+\frac{\mu_Q}{T}\right]$
p	$\exp\left[-\frac{E_N}{T}+\frac{\mu_B}{T}+\frac{\mu_Q}{T}\right]$
$\bar{p}$	$\exp\left[-\frac{E_N}{T}-\frac{\mu_B}{T}-\frac{\mu_Q}{T}\right]$
Λ	$\exp\left[-\frac{E_\Lambda}{T}+\frac{\mu_B}{T}-\frac{\mu_S}{T}\right]$
$\bar{\Lambda}$	$\exp\left[-\frac{E_\Lambda}{T}-\frac{\mu_B}{T}+\frac{\mu_S}{T}\right]$

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

$$N_i = V\,g_i \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

For bosons:

$$N_i = V\,g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left(\frac{E_i}{T} - \frac{\mu_i}{T}\right) - 1}$$

For fermions:

$$N_i = V\,g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left(\frac{E_i}{T} - \frac{\mu_i}{T}\right) + 1}$$

Chemical Equilibrium: Parameters

In equilibrium

$$\frac{\text{number of protons}}{\text{number of neutrons}} = e^{\mu_Q/T}$$

Hence $\mu_Q = 0$ if $N_p = N_n$.

Determine μ_Q from $B/2Q$.

$B/2Q > 1$ $\mu_Q < 0$ (small) and negative (e.g. gold and lead)
$B/2Q = 1$ $\mu_Q = 0$ (sulfur, ...)
$B/2Q < 1$ $\mu_Q > 0$ (small) and postive.

Determine μ_S from overall strangeness neutrality.
Remaining parameters: volume, temperature, baryon chemical potential.

The Role of Resonances

Example: ρ's

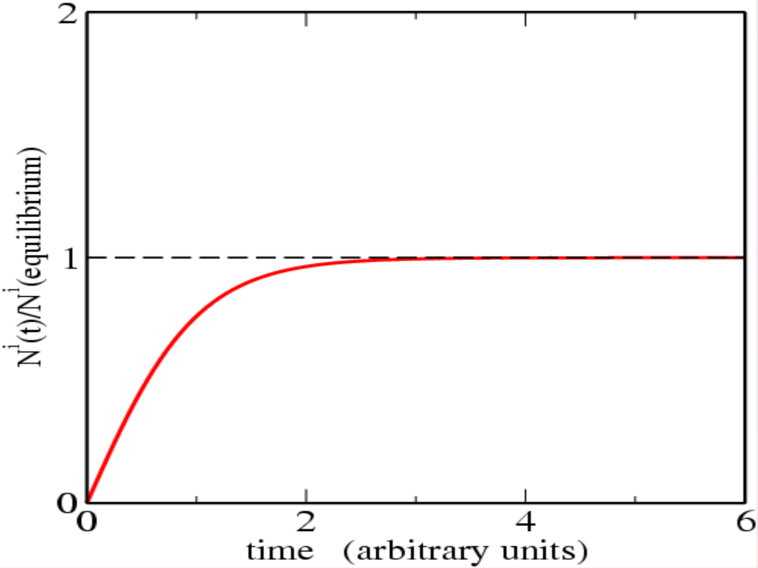
$$\rho \to \pi^+ \pi^-$$

Final, observed, number of π^+ is given by

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

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

Strangeness saturation?



Strangeness saturation?

$$N_i = \boxed{\gamma_s^{|S|}} V\, g_i \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

with

$\gamma_s < 1$ strangeness under-saturation (p - p collisions)
$\gamma_s = 1$ strangeness in chemical equilibrium ($\approx$ heavy ion collisions)
$\gamma_s > 1$ strangeness over-saturation

SPS data.

	Measurement
Pb–Pb 158A GeV	
$(\pi^+ + \pi^-)/2.$	600±30
K^+	95 ±10
K^-	50 ±5
K^0_S	60 ±12
p	140±12
$\bar{p}$	10 ±1.7
ϕ	7.6±1.1
Ξ^-	4.42±0.31
$\overline{\Xi^-}$	0.74±0.04
$\bar{\Lambda}/\Lambda$	0.2±0.04

SPS data.

SPS: Freeze-Out Parameters:

$$\begin{aligned} T &= 156.0 \pm 2.4\mathrm{MeV} \\ \mu_B &= 239 \pm 12\mathrm{MeV} \\ \gamma_s &= 0.862 \pm 0.036 \end{aligned}$$

F. Becattini, J.C., A. Keränen, E. Suhonen and K. Redlich
Physical Review C64 (2001) 024901.

AGS data.

	Measurement
Au–Au 11.6A GeV	
Participants	363±10
K^+	23.7±2.9
K^-	3.76±0.47
π^+	133.7±9.9
Λ	20.34±2.74
p/π^+	1.234±0.126
$\bar{p}$	$>$0.0185±0.0018

AGS data.

AGS: Freeze-Out Parameters:

$$
\begin{aligned}
T &= 130.6 \pm 5.5\mathrm{MeV} \\
\mu_B &= 594 \pm 26\mathrm{MeV} \\
\gamma_s &= 0.883 \pm 0.124
\end{aligned}
$$

F. Becattini, J.C., A. Keränen, E. Suhonen and K. Redlich
Physical Review C64 (2001) 024901.

SIS data.

	Measurement
Au–Au 1.7*A* GeV	
π^+/p	0.052±0.013
K^+/π^+	0.003±0.00075
π^-/π^+	2.05±0.51
η/π^0	0.018±0.007

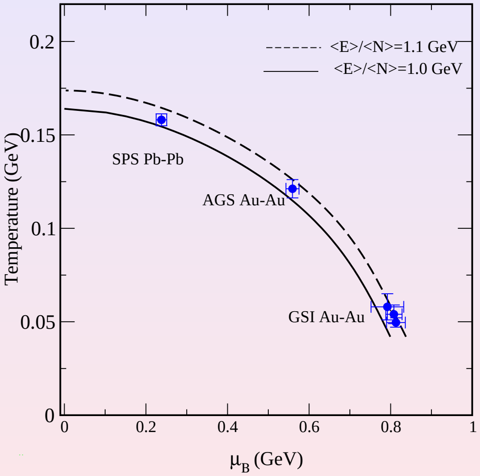
SIS data.

SIS: Freeze-Out Parameters:

$$
\begin{aligned}
T &= 49.7 \pm 1.1 \mathrm{MeV} \\
\mu_B &= 818 \pm 15 \mathrm{MeV}
\end{aligned}
$$

J. C., H. Oeschler, K. Redlich
Physical Review C59, (1999) 1663.

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
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1
μB (GeV)

Momentum Distribution in a Thermal Model

$$N_i = g_i \; V \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

$$E_i \frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3} V E_i \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

Momentum Distribution in a Thermal Model

$$\frac{dN_i}{dy\ m_T dm_T} = \frac{g_i}{(2\pi)^2} V m_T \cosh y\ e^{-\frac{m_T}{T}\cosh y + \frac{\mu_i}{T}}$$

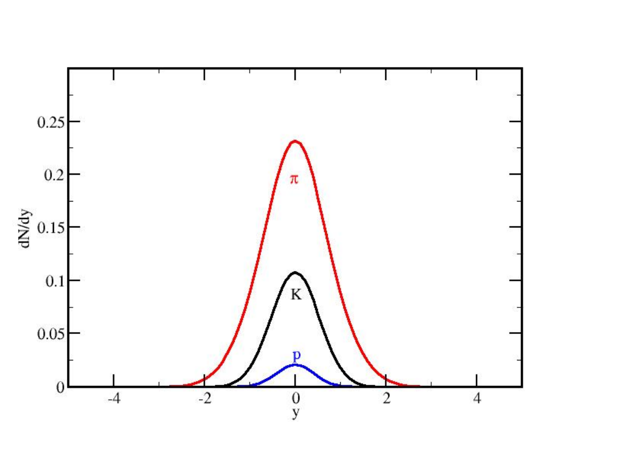
$$\frac{dN_i}{dy} = \frac{g_i V}{2\pi^2}\left[\frac{2T^3}{\cosh^2 y} + \frac{2mT^2}{\cosh y} + m^2 T\right] e^{\frac{\mu_i}{T}}$$

$$e^{-\frac{m}{T}\cosh y}$$

Narrow Distribution in Rapidity

Approximately Gaussian

Rapidity Distribution in the Thermal Model



Full Hydrodynamic Flow

Bjorken scaling + Transverse expansion

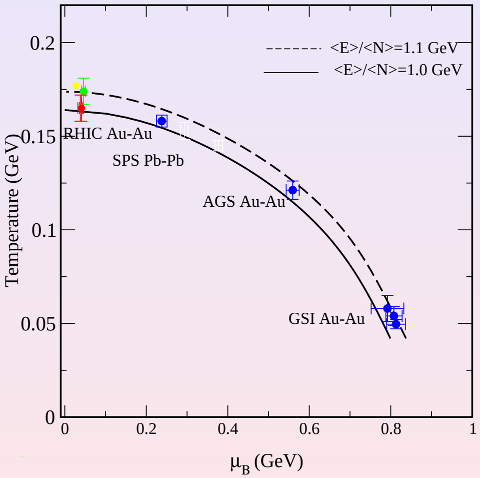
After integration over m_T

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

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

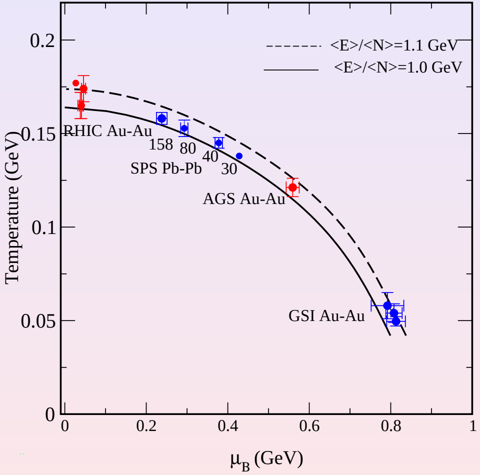
Effects of hydrodynamic flow cancel out in ratios.

E/N in 2000



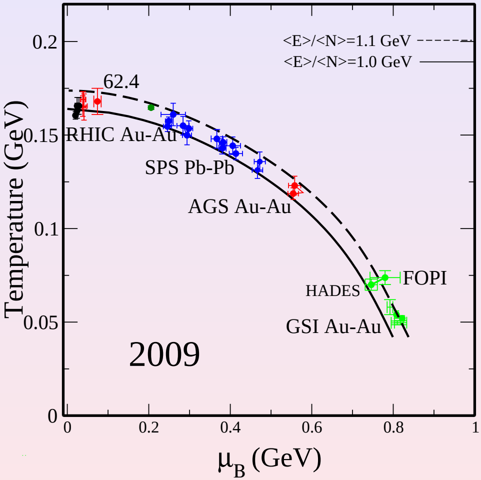
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
μB (GeV)

E/N in 2005



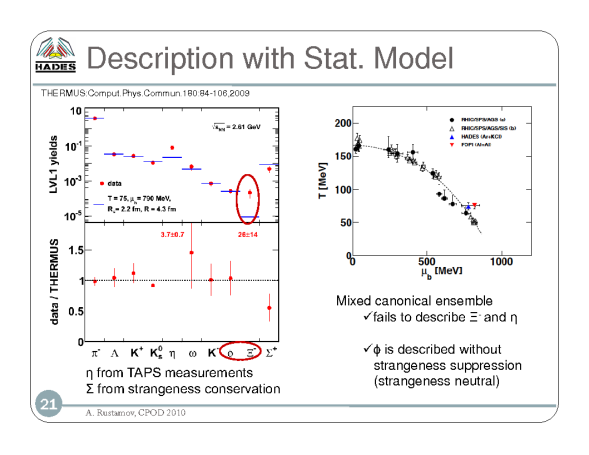
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
μ_B (GeV)

E/N in 2009



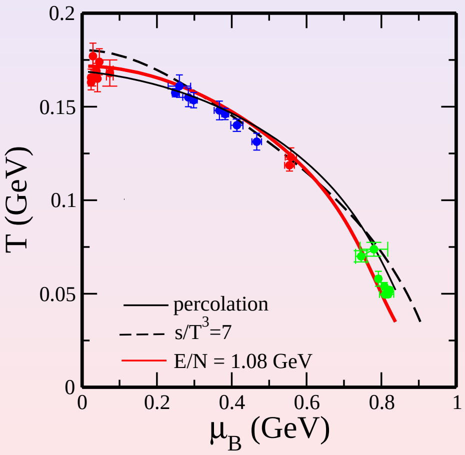
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772, 167, 2006
J. Manninen, F. Becattini, M, Gazdzicki, Phys. Rev. C73 044905, 2006

2010

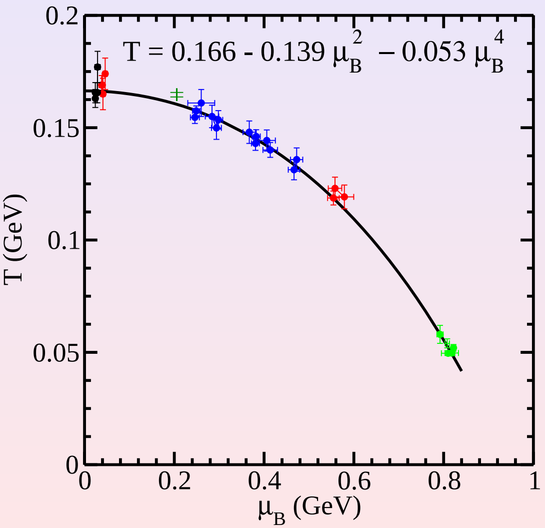


Rustamov, CPOD 2010, Dubna.

Chemical Freeze-Out: Criteria

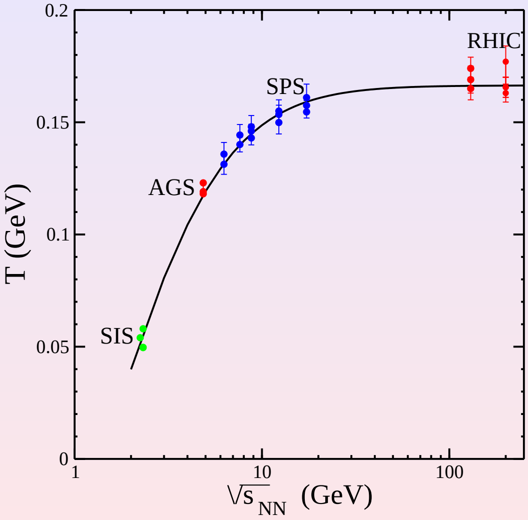


Chemical Freeze-Out

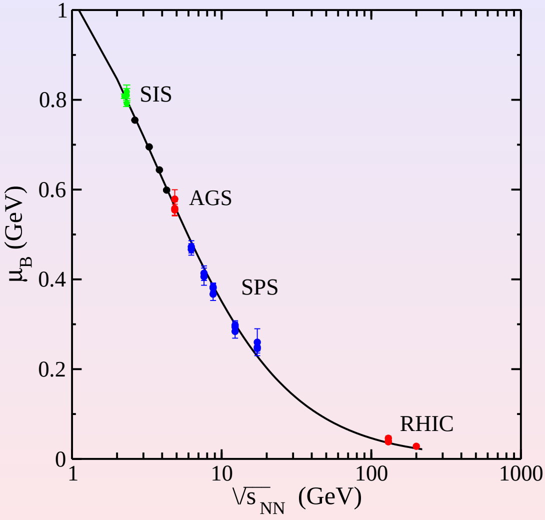


J.C., H. Oeschler, K. Redlich, S. Wheaton hep-ph/0511094

Chemical Freeze-Out Temperature



Chemical Freeze-Out μ_B

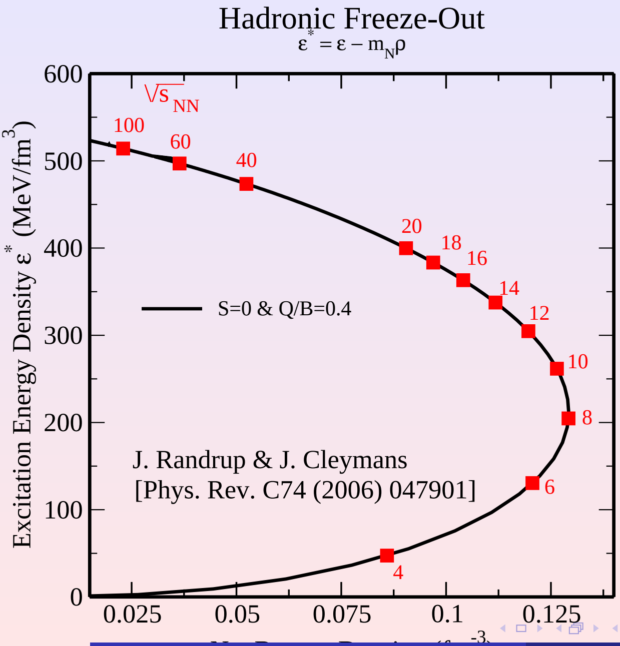


μ_B as a function of $\sqrt{s_{NN}}$

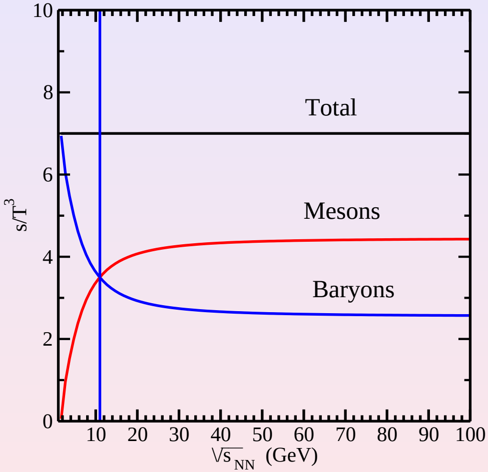
$$\mu_B(\sqrt{s}) = \frac{1.308\ \mathrm{GeV}}{1 + 0.273\ \mathrm{GeV}^{-1}\sqrt{s}}.$$

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

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

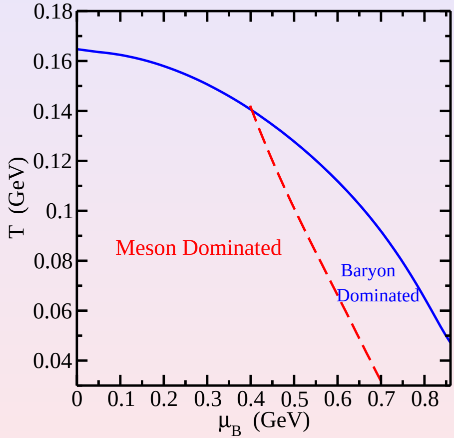

Hadronic Freeze-Out
$\varepsilon^* = \varepsilon - m_N \rho$
Excitation Energy Density ε^* (MeV/fm^3)
$\sqrt{s}_{NN}$
100
60
40
20
18
16
14
12
10
8
6
4
S=0 & Q/B=0.4
J. Randrup & J. Cleymans
[Phys. Rev. C74 (2006) 047901]
0
100
200
300
400
500
600
0.025
0.05
0.075
0.1
0.125

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)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
μB (GeV)
Meson Dominated
Baryon
Dominated

Strangeness in Heavy Ion Collisions

vs

Strangeness in pp - collisions

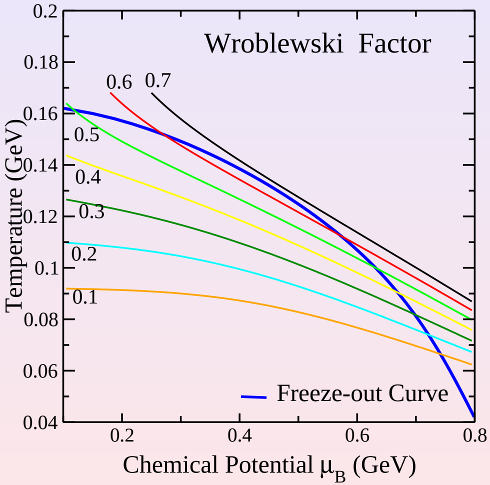
Use the Wroblewski factor

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

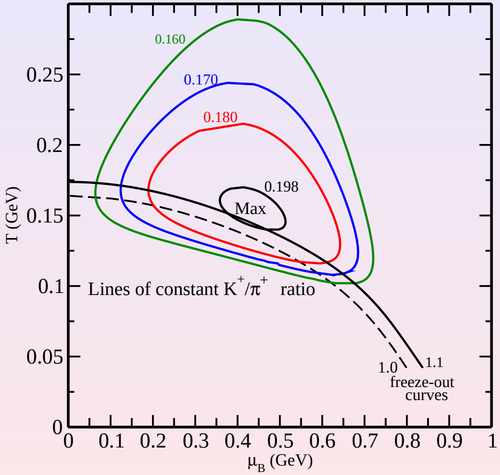
This is determined by the number of **newly** created quark – anti-quark pairs and **before** strong decays, i.e. before ρ's and Δ's decay.

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

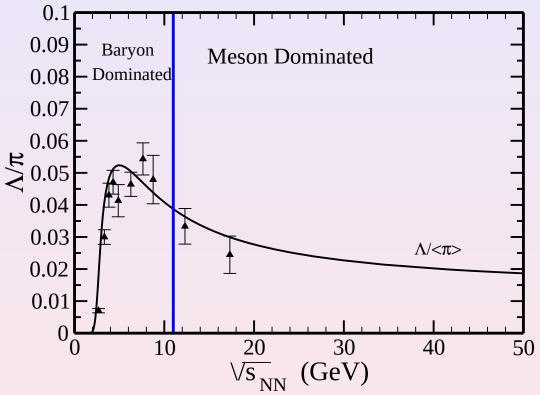
Maxima in particle ratios : K^+/π^+



Maxima in particle ratios : K^+/π^+



Λ/π Ratio

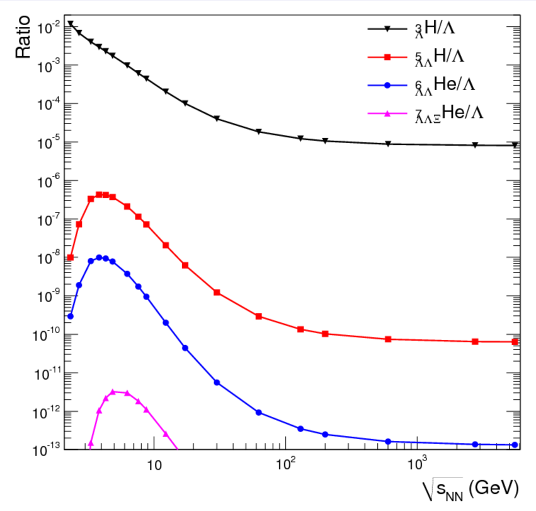


THERMUS

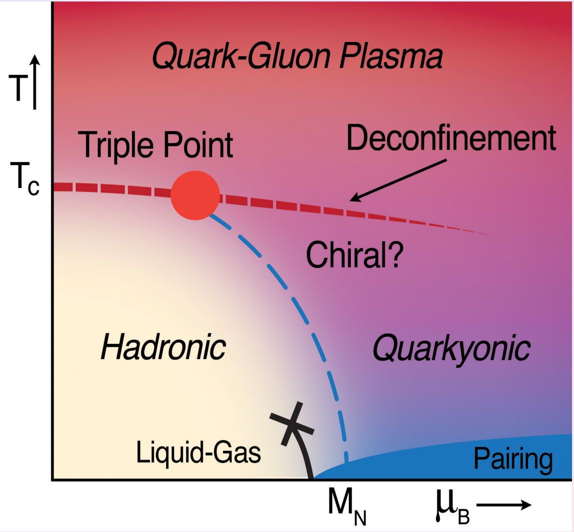
S. Wheaton, J. Cleymans, M. Hauer

Comp. Phys. Comm. 180 (2009) 84-106

Roller-Coa



A. Andronic, P.Braun-Munzinger, J. Stachel, arXiv:1010.2995 [nucl-th]



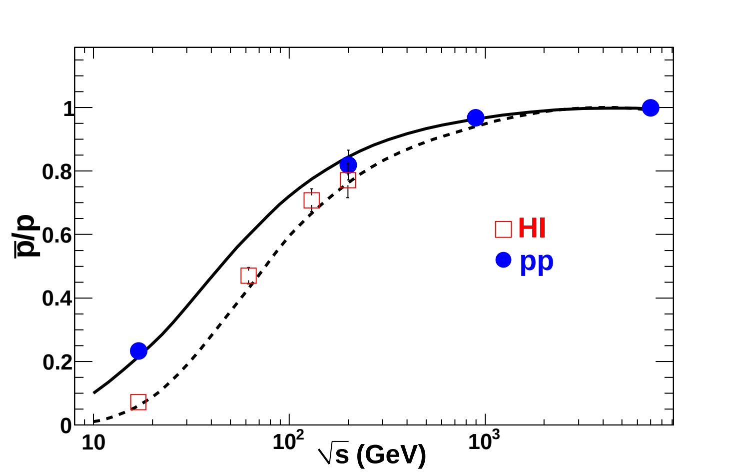
R. Pisarski and L. McLerran

In conclusion,

The evidence for chemical equilibrium is very strong.

Antimatter

One of the striking features of particle production at the Large Hadron Collider (LHC) is the near equal abundance of matter and antimatter in the central rapidity region.



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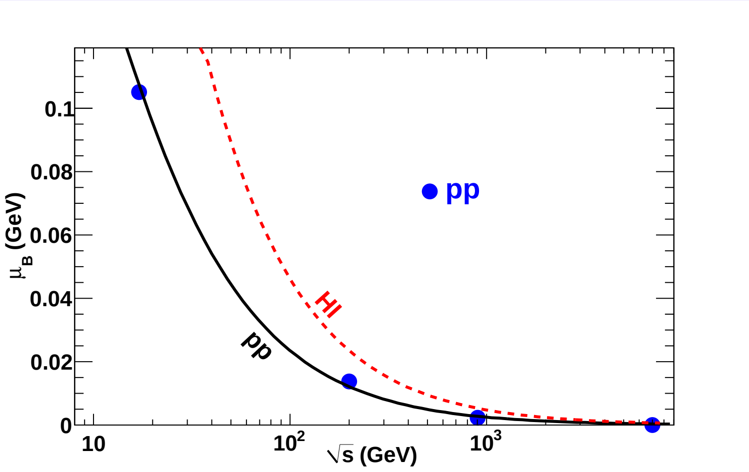
It is important to note that μ_B is always lower in pp collisions than in heavy ion collisions, e.g. the freeze-out chemical potential follows a different pattern, due to the lower stopping power in pp collisions.



Variation of the baryon chemical potential μ_B as a function of $\sqrt{s}$. The dashed line describes heavy ion collisions while the solid line is new parametrization for pp collisions.

The relation between the $\overline{\mathrm{p}}/\mathrm{p}$ ratio and μ_B can be shown easily within the statistical concept using Boltzmann statistics. In the model calculation, the appropriate statistics and also feed down from strong decays are taken into account. The density of particle i is then given by

$$n_i = \frac{d_i}{2\pi^2} K_2\left(\frac{m_i}{T}\right) e^{(N_B\mu_B + N_S\mu_S)/T} \tag{1}$$

with N_B and N_S being the baryon and strangeness quantum numbers of particle i.

This leads to a $\overline{\mathrm{p}}/\mathrm{p}$ ratio of (excluding feed-down from heavier resonances):

$$\frac{n_{\overline{\mathrm{p}}}}{n_{\mathrm{p}}} = e^{-(2\mu_B)/T} \tag{2}$$

The ratio of strange antibaryons/ baryons is then given by

$$\frac{n_{\overline{\mathrm{B}}}}{n_{\mathrm{B}}} = e^{-(2\mu_B - N_S\mu_S)/T} \tag{3}$$

As μ_S is always smaller than μ_B, the ratios appear ordered with the strangeness quantum number, i.e. the higher N_S, the smaller the difference between antibaryon and baryon. The agreement between the model results and the data is very good.

Deuterium has an additional neutron and the antideuterium to deuterium ratio is given by the square of the antiproton to proton ratio:

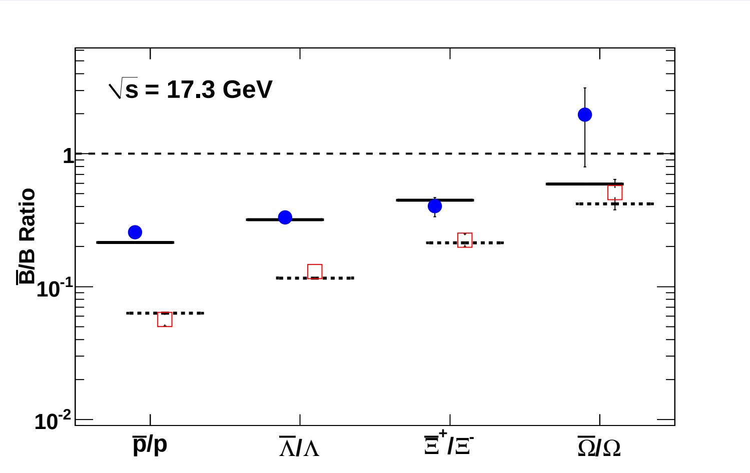
$$\frac{n_{\overline{\mathrm{d}}}}{n_{\mathrm{d}}} = e^{-(4\mu_B)/T}$$

Helium 3 has 3 nucleons and the corresponding anti-Helium 3 to helium 3 ratio is given by:

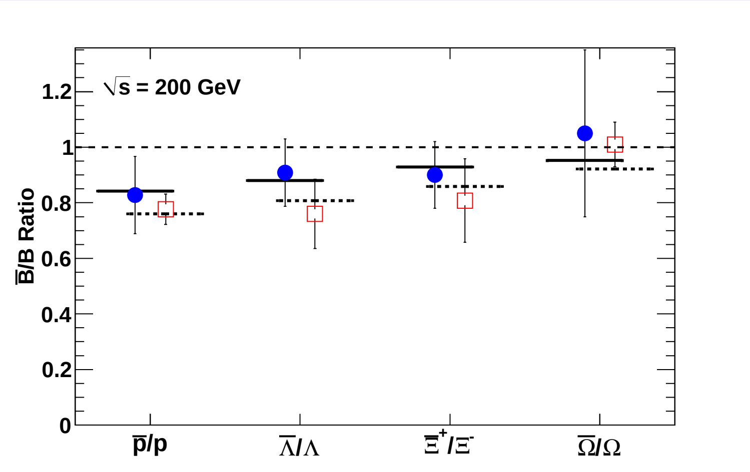
$$\frac{n_{{}^3\overline{\mathrm{He}}}}{n_{{}^3\mathrm{He}}} = e^{-(6\mu_B)/T}$$

If the nucleus carries strangeness this leads to an extra factor of μ_S

$$\frac{n_{{}^3_{\sim}\overline{\mathrm{H}}}}{n_{{}^3_{\sim}\mathrm{H}}} = e^{-(6\mu_B-2\mu_S)/T}$$



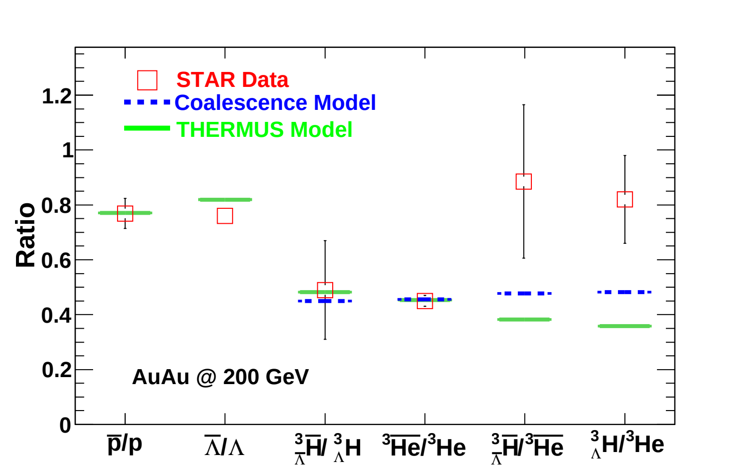
Antibaryon to baryon ratios at the SPS according to strangeness content. Circles refer to p-p collisions, squares to heavy ion collisions.



Antibaryon to baryon ratios at STAR according to strangeness content. Circles refer to p-p collisions, squares to heavy ion collisions.

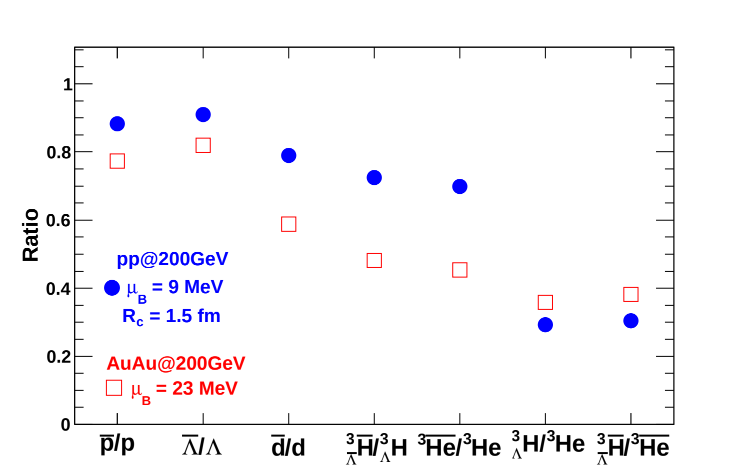
Comparison to data from RHIC

The production of light nuclei including hypertritons (${}^{3}_{\Lambda}$H) and antihypertritons (${}^{3}_{\Lambda}\overline{\mathrm{H}}$) was recently observed by the STAR collaboration. The abundances of such light nuclei and antinuclei follows a consistent pattern in the thermal model. The temperature remains the same as before but an extra factor of μ_B is picked up each time one the baryon number is increased. Each proton or neutron thus simply adds a factor of μ_B to the Boltzmann factor. The production of nuclear fragments is therefore very sensitive to the precise value of the baryon chemical potential and could thus lead to a precise determination of μ_B.

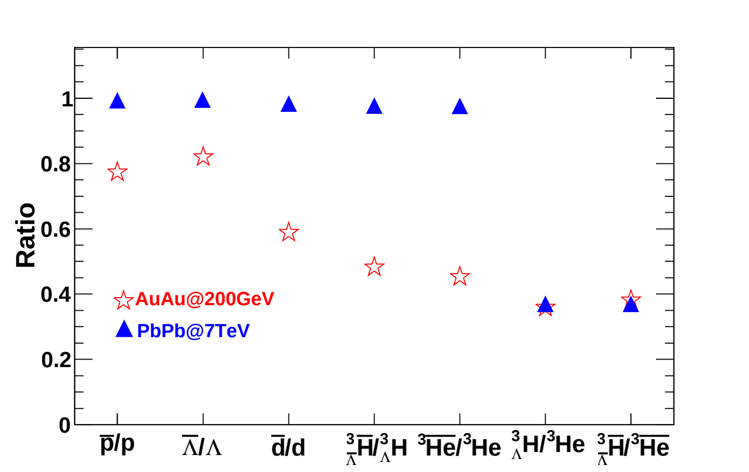


Comparison of results from the STAR collaboration both with the statistical model and the coalescence model.

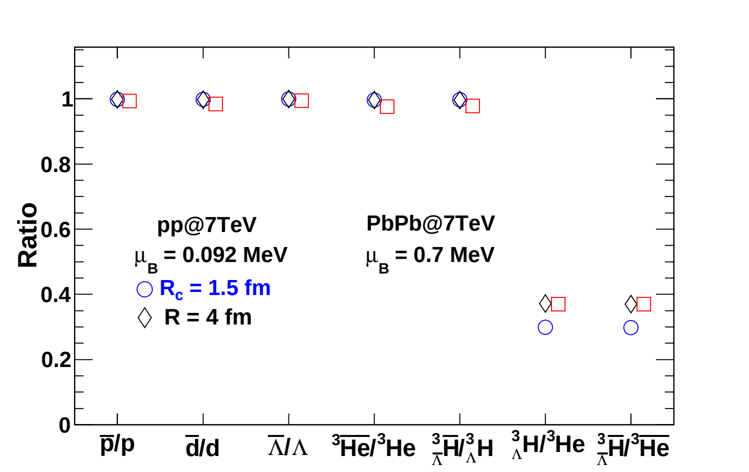
Predictions for RHIC and LHC



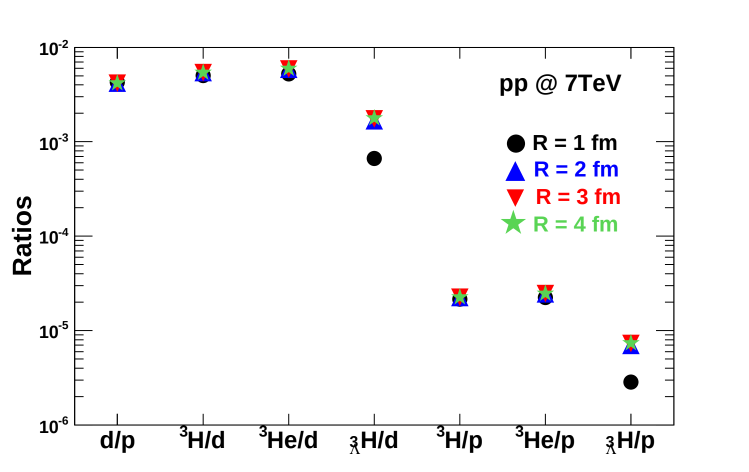
Comparison of pp and heavy ion collisions at $\sqrt{s}$= 200 GeV evidencing the influence of different values of $\mu_B$and of the canonical suppression.



Comparison of two different collision energies for heavy ion collisions.



Prediction for $\sqrt{s} = 7$ TeV both for pp and PbPb collision.



Ratios of yields for different masses.

In conclusion,

- The evidence for chemical equilibrium is very strong.
- First results at LHC seem to confirm chemical equilibrium.
- Deuterium, hypernuclei are highly sensitive to thermal model parameters μ_B.