Statistical Model for the QCD Phase Diagram.

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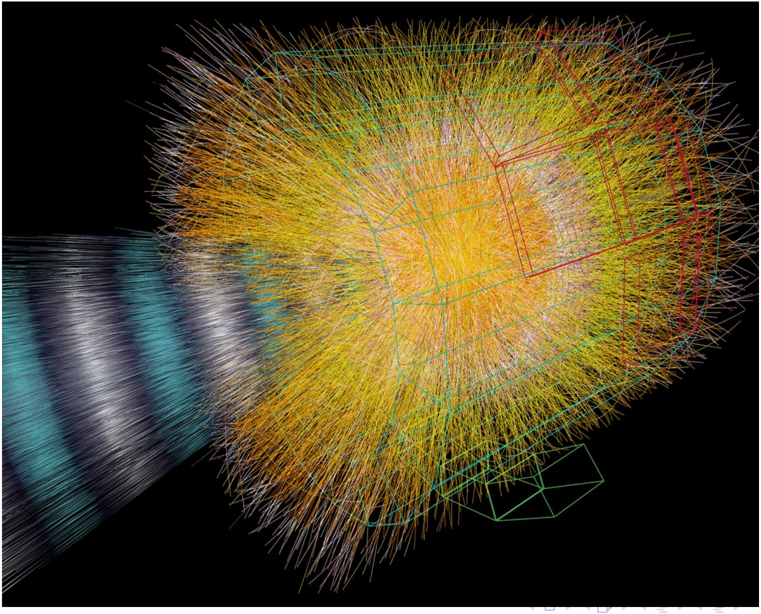
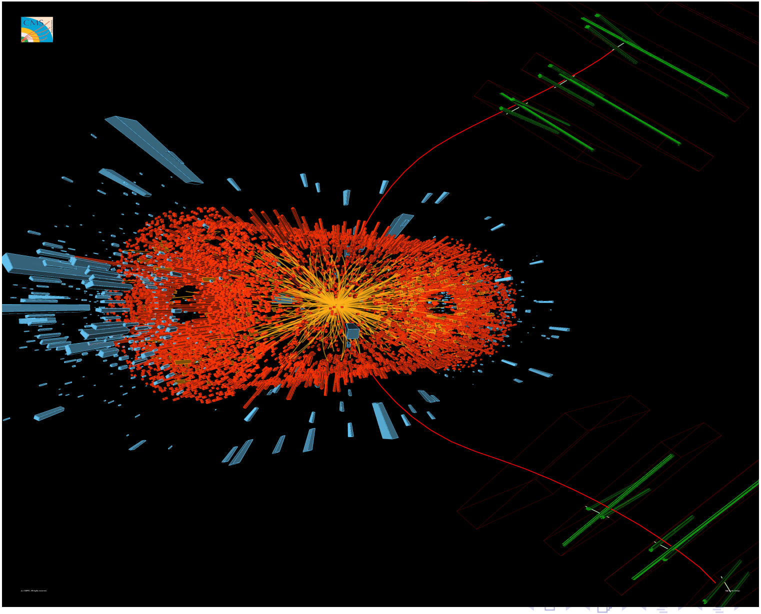
Outline

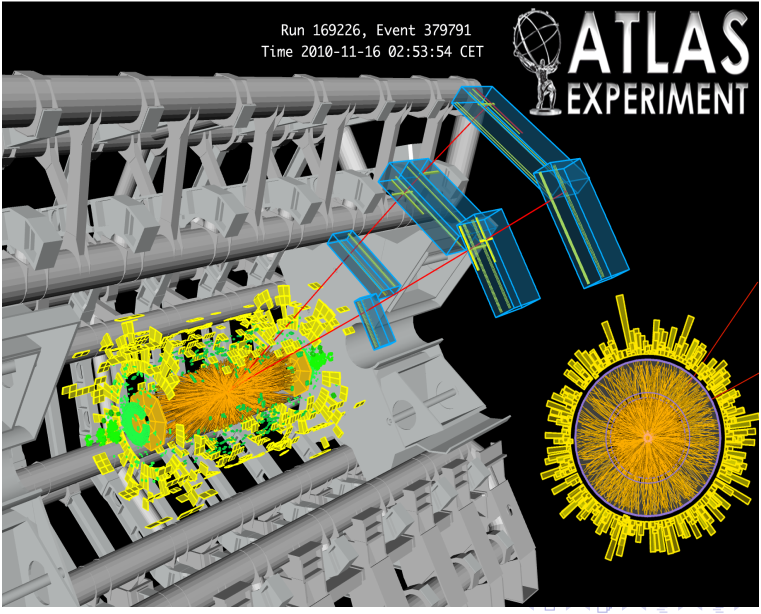
Heavy Ion Collisions in ALICE



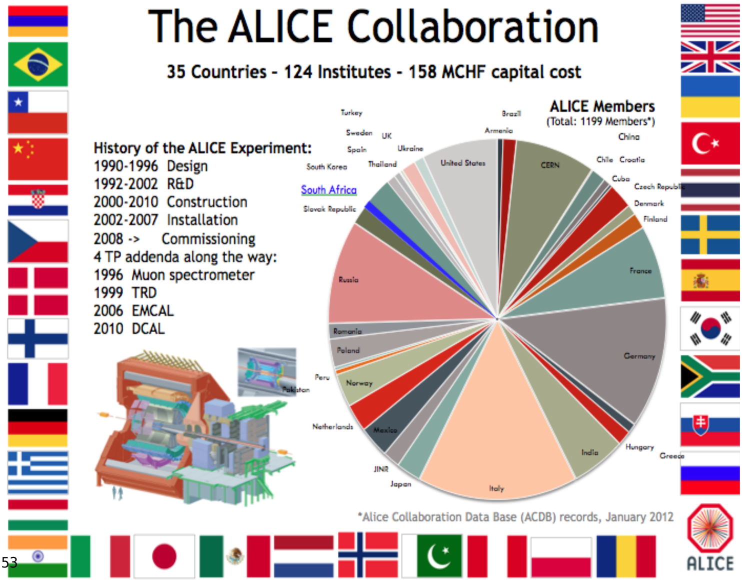
Heavy Ion Collisions in CMS



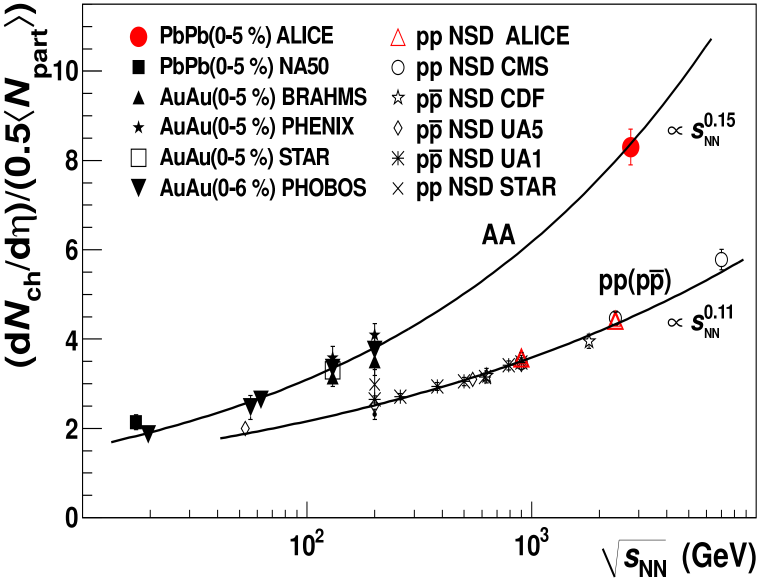
Heavy Ion Collisions in ATLAS



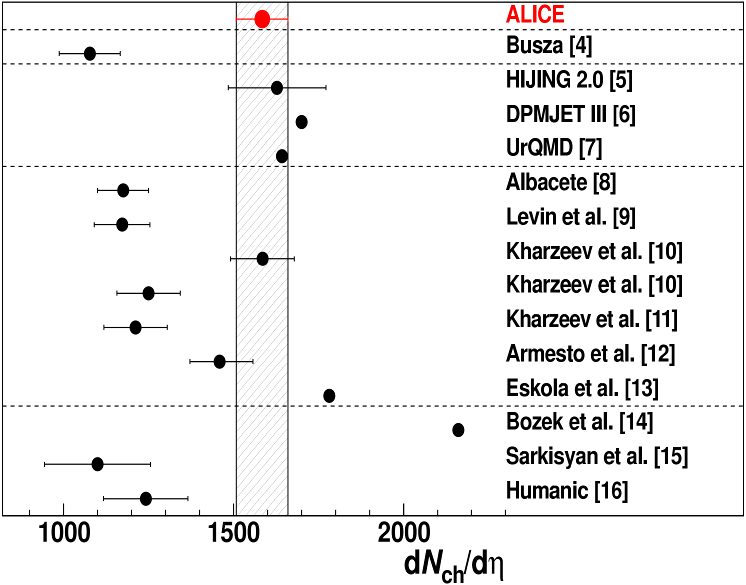
South Africa



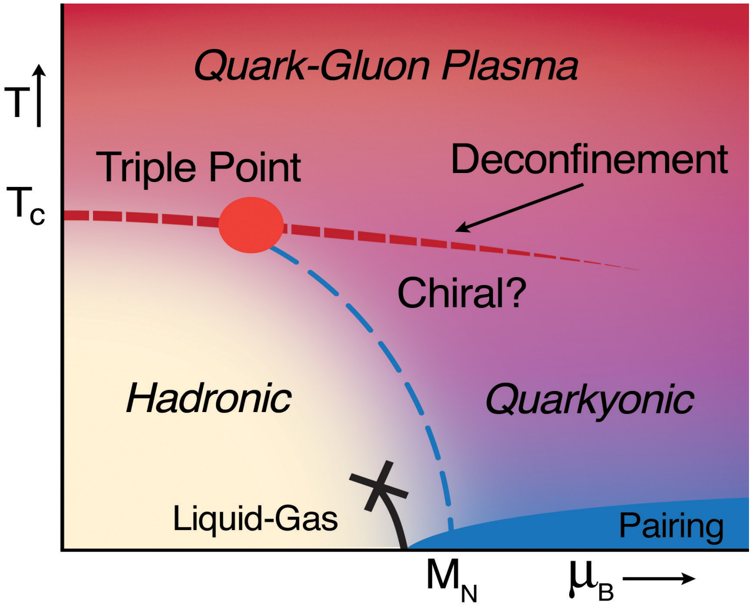
Particle Multiplicity in Heavy Ion Collisions



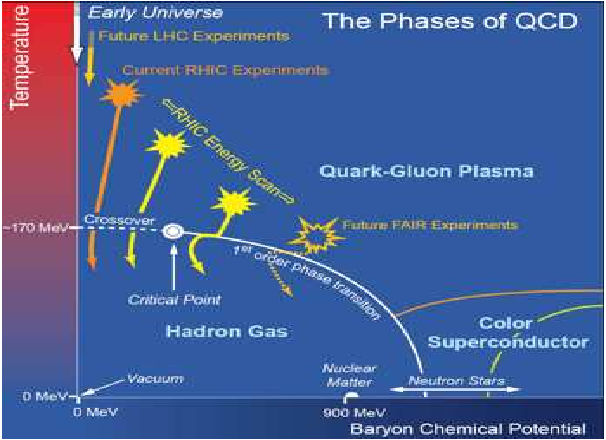
Particle Multiplicity in Heavy Ion Collisions



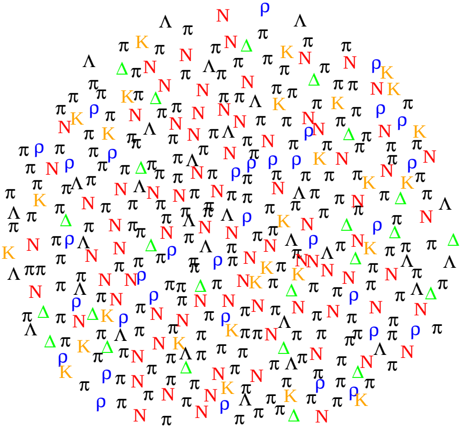
Phase Diagram



Phase Diagram



Hadronic Gas before Chemical Freeze-Out



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

Thermal Equilibrium

In thermal equilibrium

$$Z = \mathrm{Tr}\, e^{-\dfrac{H}{T} + \dfrac{\mu N}{T}}$$

$$\langle N \rangle = \frac{\mathrm{Tr}\, N e^{-\dfrac{H}{T} + \dfrac{\mu N}{T}}}{\mathrm{Tr}\, e^{-\dfrac{H}{T} + \dfrac{\mu N}{T}}}$$

$$\langle E \rangle = \frac{\mathrm{Tr}\, E e^{\frac{-H}{T} + \frac{\mu N}{T}}}{\mathrm{Tr}\, e^{\frac{-H}{T} + \frac{\mu N}{T}}}$$

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.

Thermal Equilibrium

Particle Number

$$
\begin{aligned}
\langle N \rangle &= \frac{\mathrm{Tr}\, N e^{-\frac{H}{T} + \frac{\mu N}{T}}}{\mathrm{Tr}\, e^{-\frac{H}{T} + \frac{\mu N}{T}}} \\
&= \frac{T}{Z} \frac{\partial}{\partial \mu} \mathrm{Tr}\, e^{\frac{-H}{T} + \frac{\mu N}{T}} \\
&= T \frac{1}{Z} \frac{\partial Z}{\partial \mu} \\
&= T \frac{\partial}{\partial \mu} \ln Z
\end{aligned}
$$

Thermal Equilibrium

Average Energy

$$\langle E \rangle = \frac{\text{Tr}\, H\, e^{\frac{-H}{T} + \frac{\mu N}{T}}}{\text{Tr}\, e^{\frac{-H}{T} + \frac{\mu N}{T}}}$$

$$= -\frac{1}{Z}\frac{\partial Z}{\partial \beta} + \mu \langle N \rangle$$

$$= T^2 \frac{\partial}{\partial T} \ln Z + \mu \langle N \rangle$$

Thermal Equilibrium

$$\begin{aligned} N_i &= g_i\, V \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E}{T}\right) e^{\frac{\mu_i}{T}} \\ &= g_i\, V \frac{4\pi}{(2\pi)^3} \int p^2\, dp \exp\left(-\frac{\sqrt{p^2+m_i^2}}{T}\right) e^{\frac{\mu_i}{T}} \\ &= g_i\, V \frac{4\pi}{(2\pi)^3} T^3 \int x^2\, dx \exp\left(-\sqrt{x^2+m_i^2/T^2}\right) e^{\frac{\mu_i}{T}} \\ &= g_i\, V \frac{1}{2\pi^2} T m_i^2 K_2\left(\frac{m_i}{T}\right) e^{\frac{\mu_i}{T}} \end{aligned}$$

Thermal Equilibrium

$$
\begin{aligned}
n_i &= g_i \frac{1}{2\pi^2} T m_i^2 K_2\left(\frac{m_i}{T}\right) e^{\frac{\mu_i}{T}} \\
\epsilon_i &= g_i \frac{1}{2\pi^2} T m_i^3 \left[K_1\left(\frac{m_i}{T}\right) + 3\frac{T}{m} K_2\left(\frac{m_i}{T}\right)\right] e^{\frac{\mu_i}{T}} \\
s_i &= g_i \frac{1}{2\pi^2} m_i^3 \left[K_1\left(\frac{m_i}{T}\right) + \frac{4T}{m} K_2\left(\frac{m_i}{T}\right) - \frac{\mu_i}{m} K_2\left(\frac{m_i}{T}\right)\right] e^{\frac{\mu_i}{T}} \\
P_i &= g_i \frac{1}{2\pi^2} T^2 m_i^2 K_2\left(\frac{m_i}{T}\right) e^{\frac{\mu_i}{T}}
\end{aligned}
$$

Chemical Equilibrium

In equilibrium

$$E_1 + E_2 + \cdots = E_3 + E_4 + E_5 + \cdots \tag{1}$$

for the chemical potentials

$$\mu_1 + \mu_2 + \cdots = \mu_3 + \mu_4 + \mu_5 + \cdots \tag{2}$$

As an example

$$\pi^0 + p \leftrightarrow \pi_0 + p + \pi^0 \tag{3}$$

leads to

$$\mu_{\pi^0} + \mu_p = \mu_{\pi^0} + \mu_p + \mu_{\pi^0} \tag{4}$$

which leads to

$$\mu_{\pi^0} = 0 \tag{5}$$

Chemical Equilibrium

In equilibrium

$$B + B \leftrightarrow B + B + B + \bar{B} \tag{6}$$

$$dE = -pdV + TdS + \mu_B dN_B + \mu_{\bar{B}} dN_{\bar{B}}$$

Due to baryon number conservation one has

$$N_B - N_{\bar{B}} = \text{constant}$$

and

$$dN_B = dN_{\bar{B}}$$

The energy is a minimum for

$$dE = (\mu_B + \mu_{\bar{B}}) dN_B = 0 \tag{7}$$

$$\mu_B = -\mu_{\bar{B}} \tag{8}$$

Chemical Equilibrium

In equilibrium

$$N_B = g\ V \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E}{T} + \frac{\mu_B}{T}\right)$$

$$N_{\bar{B}} = g\ V \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E}{T} - \frac{\mu_B}{T}\right)$$

$$\begin{aligned} N_B &= N_{\bar{B}} \rightarrow \mu_B = 0 \\ N_B &\geq N_{\bar{B}} \rightarrow \mu_B \geq 0 \\ N_B &\leq N_{\bar{B}} \rightarrow \mu_B \leq 0 \end{aligned}$$

	Chemical Equilibrium	No Chem. Equil.
π	$\exp\left[-\frac{E_\pi}{T}\right]$	$\exp\left[-\frac{E_\pi}{T}+\frac{\mu_\pi}{T}\right]$
N	$\exp\left[-\frac{E_N}{T}+\frac{\mu_B}{T}\right]$	$\exp\left[-\frac{E_N}{T}+\frac{\mu_N}{T}\right]$
$\overline{N}$	$\exp\left[-\frac{E_N}{T}-\frac{\mu_B}{T}\right]$	$\exp\left[-\frac{E_N}{T}+\frac{\mu_{\overline{N}}}{T}\right]$
Λ	$\exp\left[-\frac{E_\Lambda}{T}+\frac{\mu_B}{T}-\frac{\mu_S}{T}\right]$	$\exp\left[-\frac{E_\Lambda}{T}+\frac{\mu_\Lambda}{T}\right]$
$\overline{\Lambda}$	$\exp\left[-\frac{E_\Lambda}{T}-\frac{\mu_B}{T}+\frac{\mu_S}{T}\right]$	$\exp\left[-\frac{E_\Lambda}{T}+\frac{\mu_{\overline{\Lambda}}}{T}\right]$
K	$\exp\left[-\frac{E_K}{T}+\frac{\mu_S}{T}\right]$	$\exp\left[-\frac{E_K}{T}+\frac{\mu_K}{T}\right]$
$\overline{K}$	$\exp\left[-\frac{E_K}{T}-\frac{\mu_S}{T}\right]$	$\exp\left[-\frac{E_K}{T}+\frac{\mu_{\overline{K}}}{T}\right]$

The number of particles of type i is determined by:

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

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

Only conserved quantum numbers matter for chemical equilibrium: In equilibrium

$$\mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S + C_i\mu_C + .. \tag{9}$$

g_i	m_i	stat	S_i	B_i	Q_i	Particle i
1	0.140	-1	0	0	1.	π^+
1	0.135	-1	0	0	0.	π^0
1	0.140	-1	0	0	-1.	π^-
1	0.547	-1	0	0	0.	η
3	0.770	-1	0	0	1.	ρ^+
3	0.770	-1	0	0	0.	ρ^0
3	0.770	-1	0	0	-1.	ρ^-
3	0.782	-1	0	0	0.	ω
1	0.958	-1	0	0	0.	η'
1	0.980	-1	0	0	0.	f_0
1	0.982	-1	0	0	1.	a_0^+
1	0.982	-1	0	0	0.	a_0^0
1	0.982	-1	0	0	-1.	a_0^-
3	1.019	-1	0	0	0.	ϕ
3	1.170	-1	0	0	0.	
3	1.230	-1	0	0	1.	
3	1.230	-1	0	0	0.	
3	1.230	-1	0	0	-1.	
3	1.229	-1	0	0	1.	
3	1.229	-1	0	0	0.	
3	1.229	-1	0	0	-1.	
5	1.275	-1	0	0	0.	
3	1.282	-1	0	0	0.	
1	1.297	-1	0	0	0.	
1	1.300	-1	0	0	1.	
1	1.300	-1	0	0	0.	

The Role of Resonances

Example: ρ's

$$\rho \rightarrow \pi^+\pi^-$$

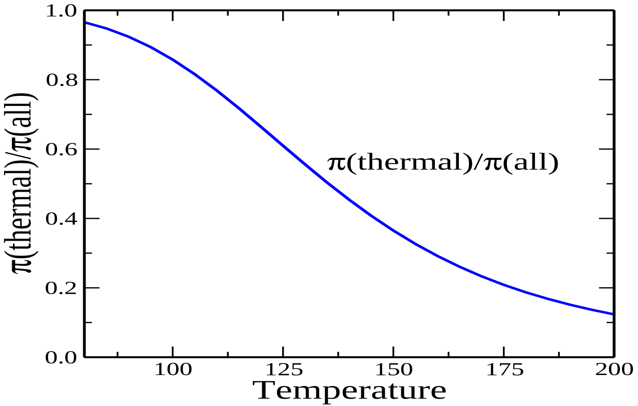
Final, observed, number of π^+ is given by

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

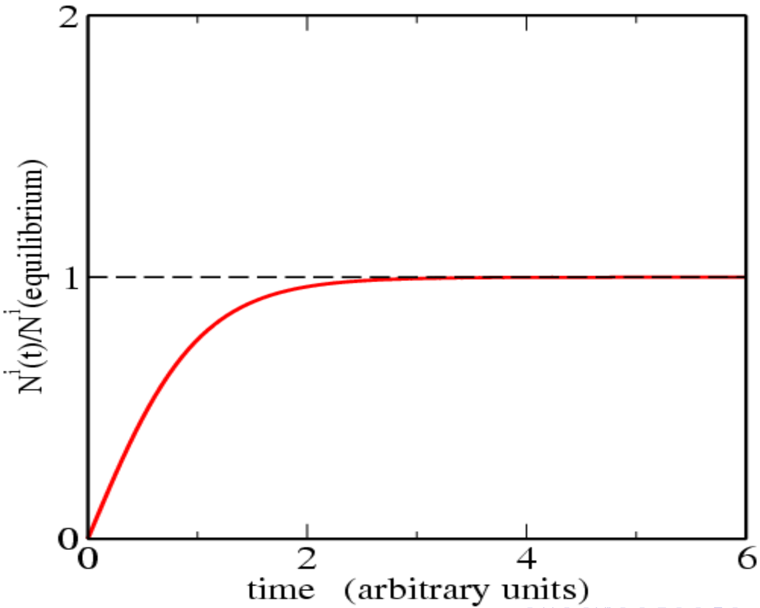
depending on the temperature, over 80% of observed pions are due to resonance decays

g_i	m_i	stat	S_i	B_i	Q_i	BR$\rightarrow \pi^+$	Particle i
1	0.140	-1	0	0	1.	1.000	π^+
1	0.135	-1	0	0	0.	0.000	π^0
1	0.140	-1	0	0	-1.	0.000	π^-
1	0.547	-1	0	0	0.	0.285	η
3	0.770	-1	0	0	1.	1.000	ρ^+
3	0.770	-1	0	0	0.	1.000	ρ^0
3	0.770	-1	0	0	-1.	0.000	ρ^-
3	0.782	-1	0	0	0.	0.910	ω
1	0.958	-1	0	0	0.	0.965	η'
1	0.980	-1	0	0	0.	0.521	f_0
1	0.982	-1	0	0	1.	1.285	a_0^+
1	0.982	-1	0	0	0.	0.285	a_0^0
1	0.982	-1	0	0	-1.	0.285	a_0^-
3	1.019	-1	0	0	0.	0.155	ϕ
3	1.170	-1	0	0	0.	1.000	h_1
3	1.230	-1	0	0	1.	1.500	
3	1.230	-1	0	0	0.	0.50	
3	1.230	-1	0	0	-1.	0.50	
3	1.229	-1	0	0	1.	1.91	
3	1.229	-1	0	0	0.	0.91	
3	1.229	-1	0	0	-1.	0.91	
5	1.275	-1	0	0	0.	0.69	
3	1.282	-1	0	0	0.	1.00	
1	1.297	-1	0	0	0.	1.11	
1	1.300	-1	0	0	1.	2.00	
1	1.300	-1	0	0	0.	1.50	

Importance of Resonances.



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

$\gamma_s = 1$ strangeness in chemical equilibrium

$\gamma_s > 1$ 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
$\overline{\Lambda}/\Lambda$	0.2±0.04

SPS data.

SPS: Chemical 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: Chemical 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$\pm$0.013
K$^+/\pi^+$	0.003$\pm$0.00075
π^-/π^+	2.05$\pm$0.51
η/π^0	0.018$\pm$0.007

SIS data.

SIS: Chemical Freeze-Out Parameters:

$$
\begin{aligned}
T &= 49.7 \pm 1.1\mathrm{MeV} \\
\mu_B &= 818 \pm 15\mathrm{MeV} \\
\gamma_s &= 1 \text{ (fixed)}
\end{aligned}
$$

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

RHIC data.

J. C., B. Kämpfer, M. Kaneta, S. Wheaton, N. Xu, Phys. Rev. C71, 0409071 (2005)

Ratio	Experiment	Central	Mid-Central	Peripheral
$\pi^-_{(2)}/\pi^+_{(2)}$	BRAHMS	0.990±0.100		
	PHENIX	0.960±0.177	0.920±0.170	0.933±0.172
	PHOBOS	1.000±0.022		
	STAR	1.000±0.073	1.000±0.073	1.000 ± 0.073
$K^+_{(2)}/K^-_{(2)}$	PHENIX	1.152±0.240	1.292±0.268	1.322±0.284
	PHOBOS	1.099±0.111		
	STAR	1.109±0.022	1.105±0.036	1.120±0.040
$\bar{p}_{(1)}/p_{(1)}$	PHENIX	0.680±0.149	0.671±0.142	0.717±0.157
$\bar{p}_{(2)}/p_{(2)}$	BRAHMS	0.650±0.092		
	PHOBOS	0.600±0.072		
	STAR	0.714±0.050	0.724±0.050	0.764±0.053
$\bar{\Lambda}_{(1)}/\Lambda_{(1)}$	PHENIX	0.750±0.180	0.798±0.197	0.795±0.197
$\bar{\Lambda}_{(2)}/\Lambda_{(2)}$	STAR	0.719±0.090	0.739±0.092	0.744±0.100
$\bar{\Xi}^+_{(2)}/\Xi^-_{(2)}$	STAR	0.840±0.053	0.822±0.114	0.815±0.096
$\bar{\Omega}^+/\Omega^-$	STAR	1.062±0.410		
$K^-_{(2)}/\pi^-_{(2)}$	PHENIX	0.151±0.030	0.134±0.027	0.116±0.023
	STAR	0.151±0.022	0.147±0.022	0.130±0.019
$K^0_S/\pi^-_{(2)}$	STAR	0.134±0.022	0.131±0.022	0.108±0.018
$\bar{p}_{(1)}/\pi^-_{(2)}$	PHENIX	0.049±0.010	0.047±0.010	0.045±0.009
$\bar{p}_{(2)}/\pi^-_{(2)}$	STAR	0.069±0.019	0.067±0.019	0.067±0.019
$\Lambda_{(1)}/\pi^-_{(2)}$	STAR	0.043±0.008	0.043±0.008	0.039±0.007
$\Lambda_{(2)}/\pi^-_{(2)}$	PHENIX	0.072±0.017	0.068±0.016	0.074±0.017
$< K^{*0} > /\pi^-_{(2)}$	STAR	0.039±0.011		
$\phi/\pi^-_{(2)}$	STAR	0.022±0.003	0.021±0.004	0.022±0.004
$\Xi^-_{(2)}/\pi^-_{(2)}$	STAR	0.0093±0.0012	0.0072±0.0011	0.0060±0.0008

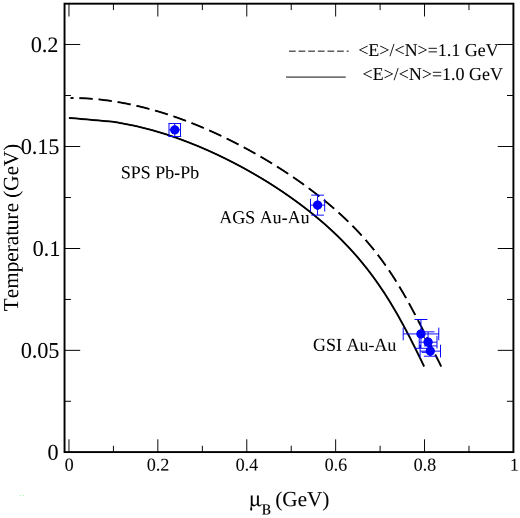
RHIC data.

RHIC: Chemical Freeze-Out Parameters:

$$
\begin{aligned}
T &= 169 \pm 4.2\mathrm{MeV} \\
\mu_B &= 39.6 \pm 6\mathrm{MeV} \\
\gamma_s &= 0.9 \pm 0.1
\end{aligned}
$$

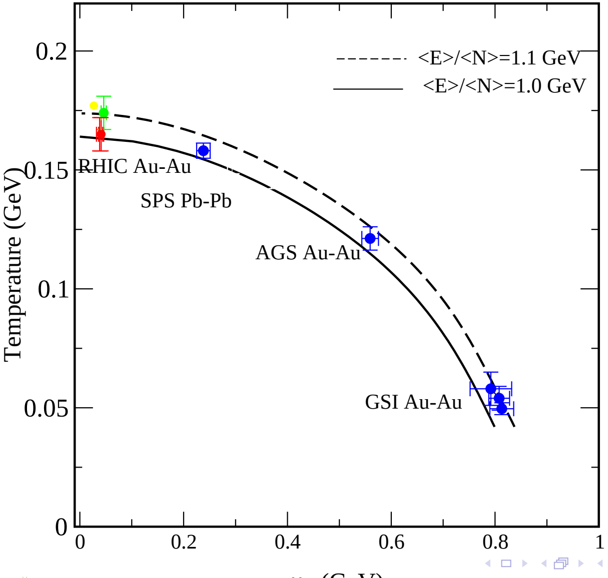
J. C., B. Kämpfer, M. Kaneta, S. Wheaton, N. Xu
Phys. Rev. C71, 0409071 (2005)

E/N in 1999

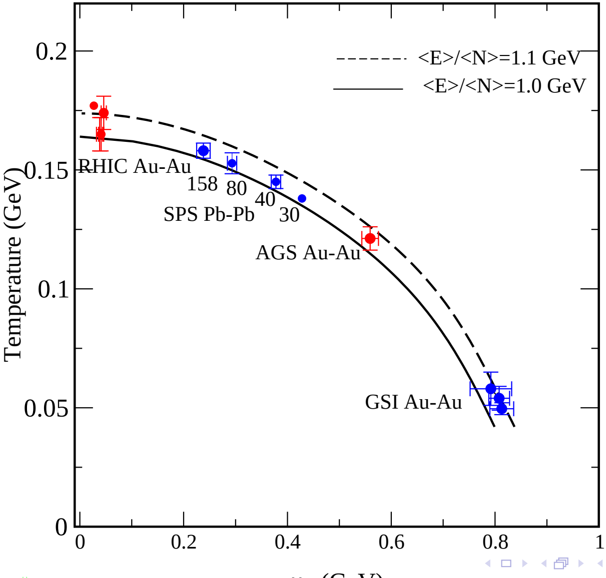


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1
μB (GeV)

E/N in 2000

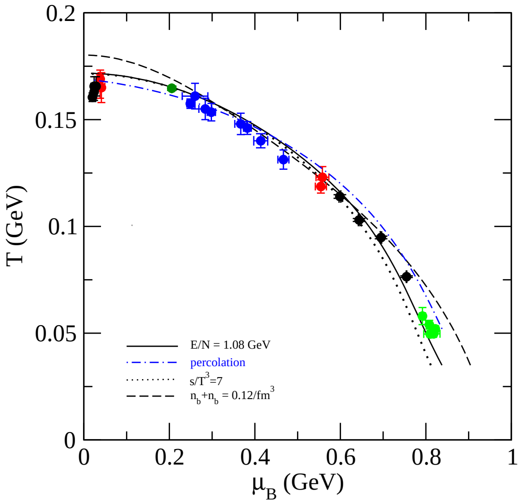

<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1

E/N in 2005

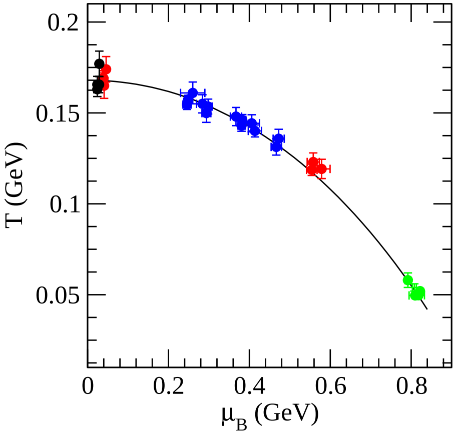


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1

Chemical Freeze-Out: Status in 2005



Chemical Freeze-Out: Status in 2005

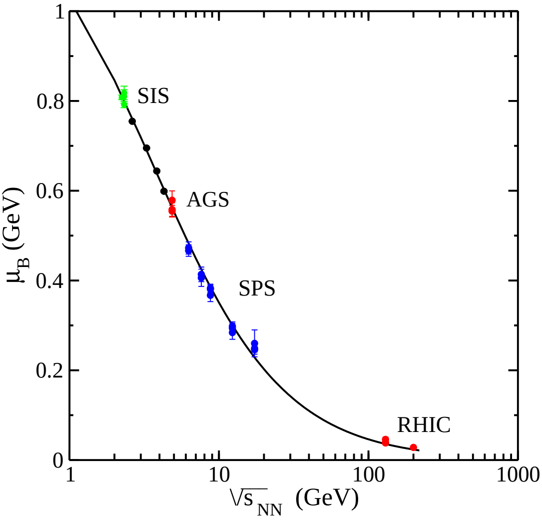


$$T = 0.166 - 0.139\,\mu_B^2 - 0.053\,\mu_B^4$$

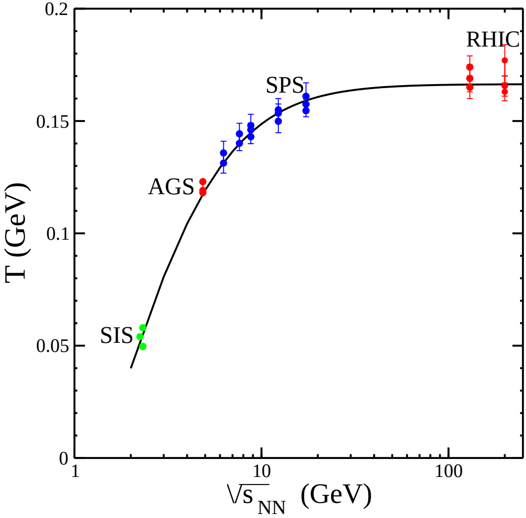
J.C., H. Oeschler, K. Redlich, S. Wheaton,

PR C73, 034905 (2006)

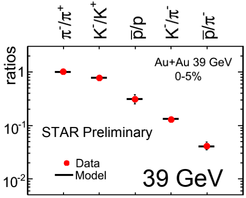
μ_B as a function of $\sqrt{s_{NN}}$

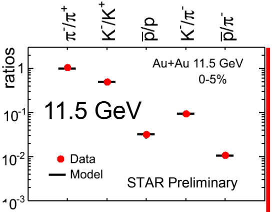


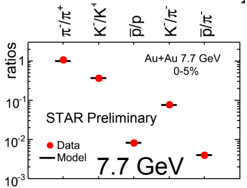
T as a function of $\sqrt{s_{NN}}$



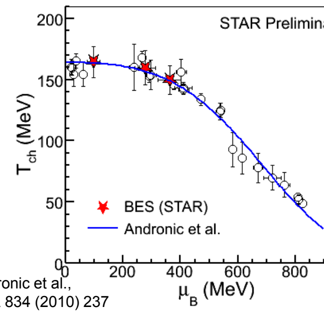
Freeze-out Conditions



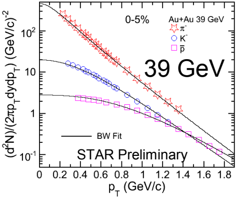


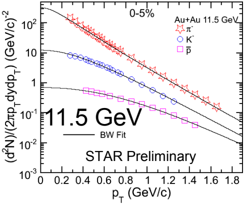


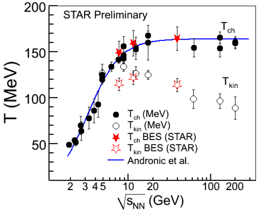
Chemical freeze-out:
Particle ratios

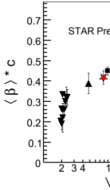


Andronic et al.,
NPA 834 (2010) 237



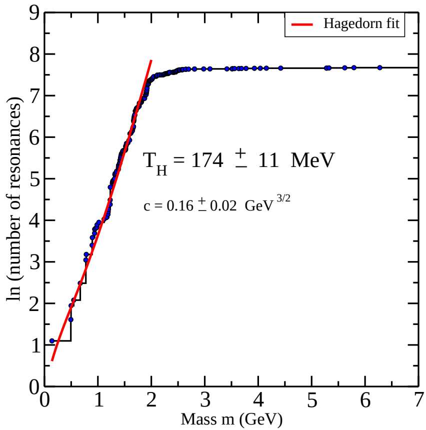






Kinetic freeze-out : Momentum distributions

THE HAGEDORN TEMPERATURE.



Keep on adding the number of hadronic resonances.

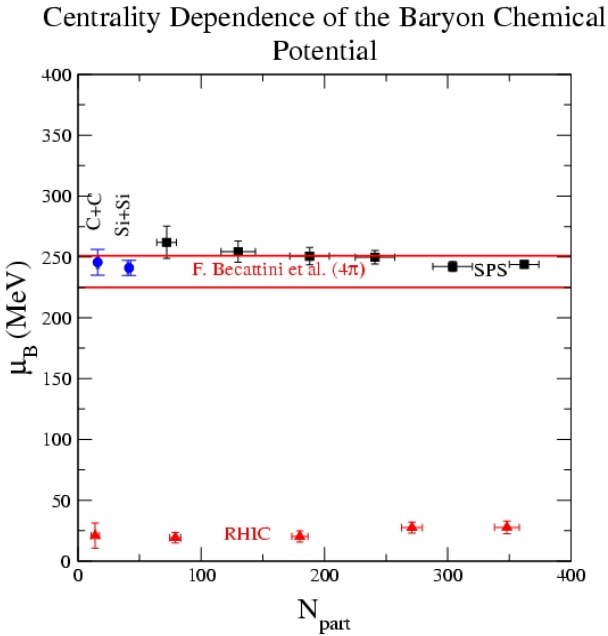
J.C. and Dawit Worku, Mod. Phys. Lett. A26 (2011) 1197; arXiv: 1103.1463

HADRONS DO NOT EXIST ABOVE THE HAGEDORN TEMPERATURE.

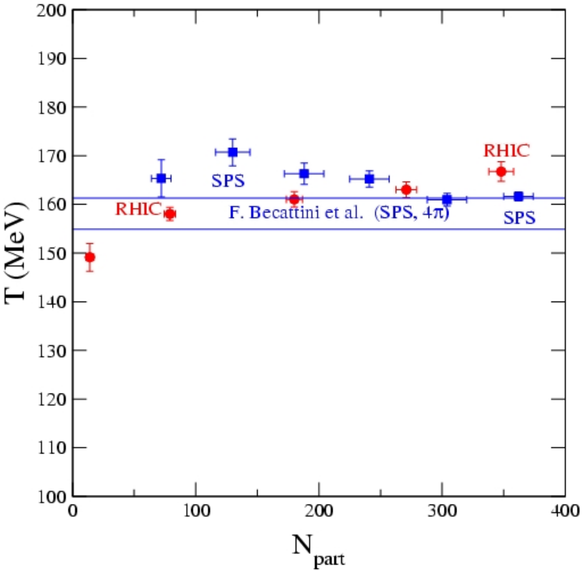
Thermodynamic quantities like particle density, energy density, pressure ,... all involve a summation over hadron species:

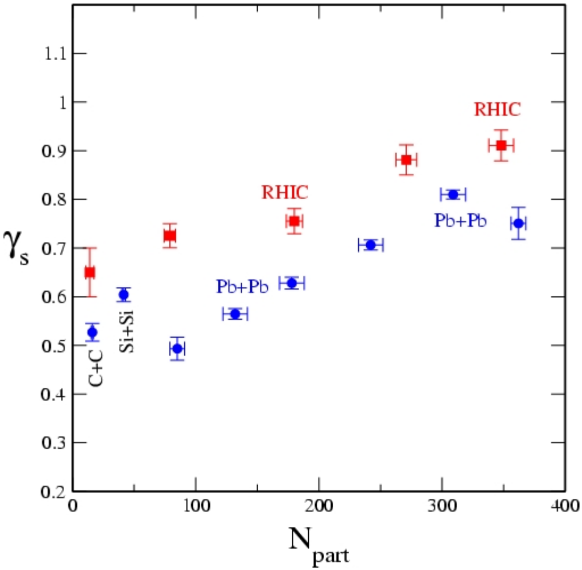
$$\sum_i \exp -\frac{E_i}{T}$$

and the sum becomes (too) large due to the number of resonances.


Centrality Dependence of the Baryon Chemical Potential
C+C
Si+Si
F. Becattini et al. (4π)
SPS
RHIC
μB (MeV)
Npart
0
50
100
150
200
250
300
350
400
0
100
200
300
400

Centrality Dependence of the Chemical Freeze-out Temperature





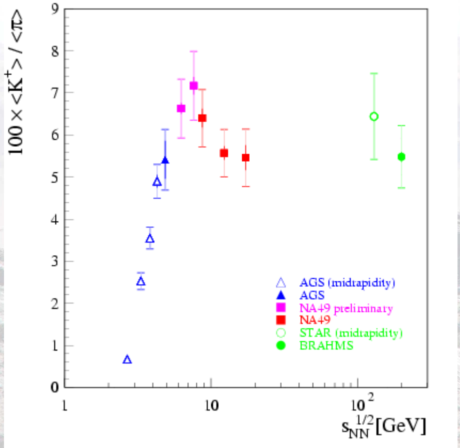
RHIC
RHIC
Pb+Pb
Pb+Pb
C+C
Si+Si
γ_s
N_{part}
0
100
200
300
400
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

The NA49 Collaboration has 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^+/π^+ 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”.

The Elephant in the Room

Friese
Dinkelaker
Blume
Speltz



Difficult to avoid, Hard to Model

→ But no unambiguous corroborating evidence

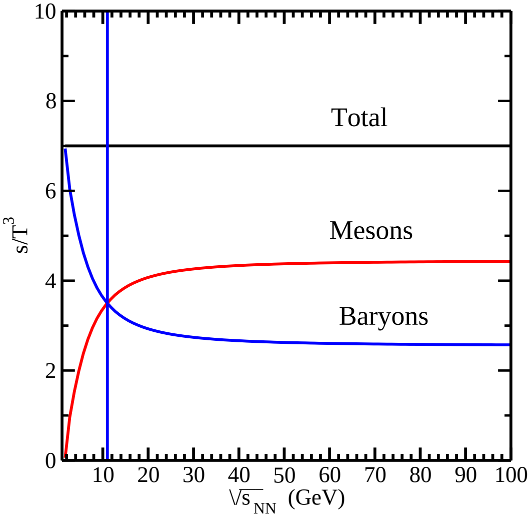
Strangeness in Heavy Ion Collisions
vs
Strangeness in pp - collisions

Use the Wroblewski factor

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

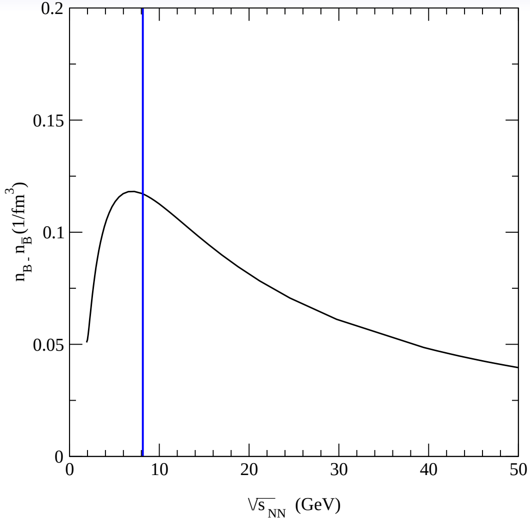
This is determined by the number of **newly** created quark – anti-quark pairs and **before** strong decays, i.e. before ρ's and Δ's decay.

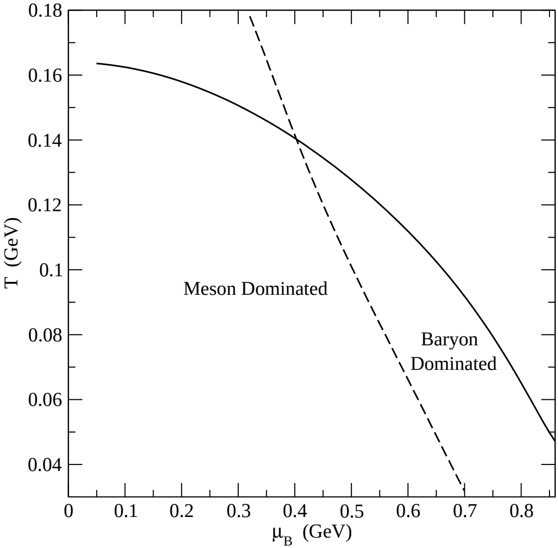
Limiting values :
$\lambda_s = 1$ all quark pairs are equally abundant, SU(3) symmetry.
$\lambda_s = 0$ no strange quark pairs.

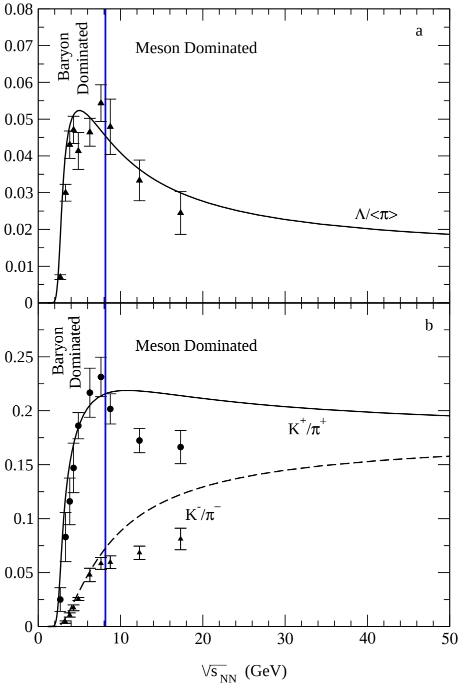

Total
Mesons
Baryons
s/T3
√s NN (GeV)
0
2
4
6
8
10
10 20 30 40 50 60 70 80 90 100

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

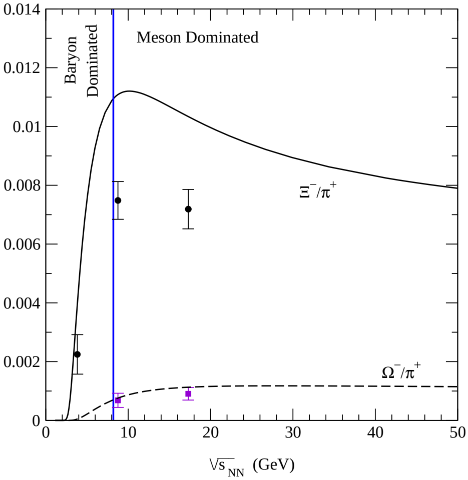
In the statistical model a rapid change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The transition occurs at a temperature T = 151 MeV and baryon chemical potential μ_B = 327 MeV corresponding to an incident energy of $\sqrt{s_{NN}}$ = 11 GeV.


0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
n_B - n_B̄ (1/fm^3)
√s_NN (GeV)


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



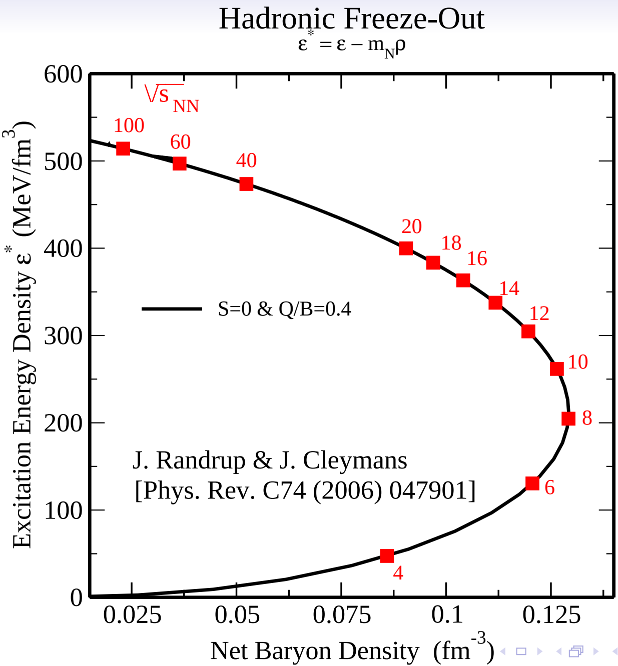
a
Baryon Dominated
Meson Dominated
Λ/<π>
b
Baryon Dominated
Meson Dominated
K+/π+
K-/π-
√s_NN (GeV)


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
Ξ^-/π^+
Ω^-/π^+
$\sqrt{s}_{NN}$ (GeV)

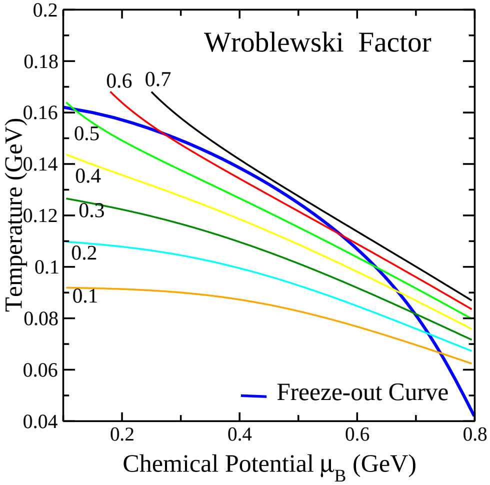
Maxima in Particle Ratios predicted by the Thermal Model.

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

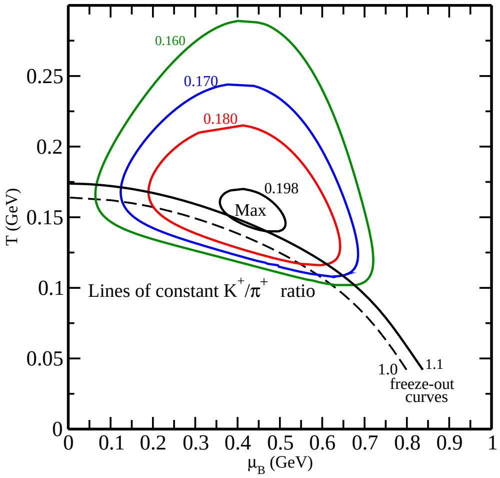
J. C., H. Oeschler, K. Redlich and S. Wheaton, Physics Letters B615 (2005) 50-54.


Hadronic Freeze-Out
$\varepsilon^* = \varepsilon - m_N \rho$
$\sqrt{s}_{NN}$
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]
Excitation Energy Density ε^* (MeV/fm^3)
600
500
400
300
200
100
0
0.025
0.05
0.075
0.1
0.125
Net Baryon Density (fm^{-3})

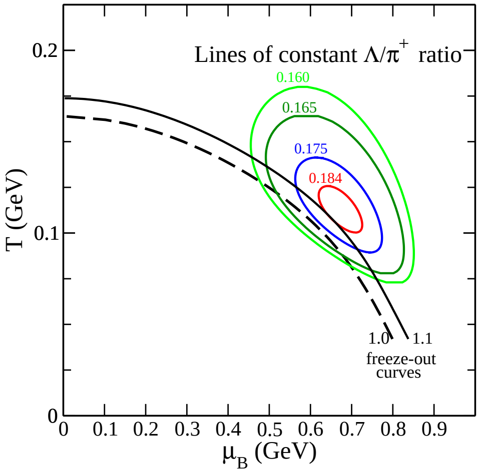
Maxima in particle ratios : K^+/π^+



Maxima in particle ratios : K^+/π^+



Maxima in particle ratios : K^+/π^+



GOOD NEWS FOR NICA.

Main goals of the project

1a) Heavy ion colliding beams $^{197}Au^{79+}$ x $^{197}Au^{79+}$ at

$\sqrt{s_{NN}} = 4 \div 11$ GeV (1 ÷ 4.5 GeV/u ion kinetic energy)

at

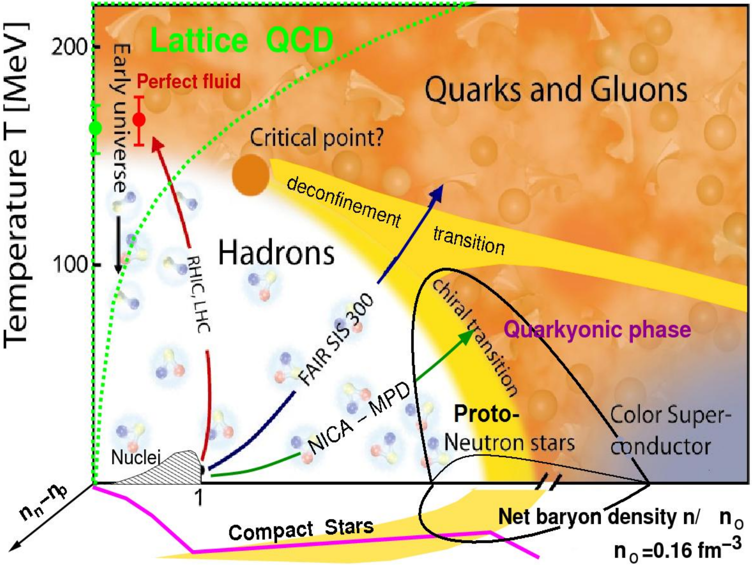
$L_{average} = 10^{27}$ $cm^{-2} \cdot s^{-1}$ (at $\sqrt{s_{NN}} = 9$ GeV)

1b) Light-Heavy ion colliding beams of the same energy range and luminosity

2) Polarized beams of protons and deuterons:

p↑p↑ $\sqrt{s_{NN}} = 12 \div 25$ GeV (5 ÷ 12.6 GeV kinetic energy)

d↑d↑ $\sqrt{s_{NN}} = 4 \div 13.8$ GeV (2 ÷ 5.9 GeV/u ion kinetic energy)


Lattice QCD
Temperature T [MeV]
200
100
Early universe
Perfect fluid
Quarks and Gluons
Critical point?
deconfinement
transition
Hadrons
RHIC, LHC
FAIR SIS 300
NICA – MPD
chiral transition
Quarkyonic phase
Proto-
Neutron stars
Color Super-
conductor
Nuclei
1
$n_n - n_p$
Compact Stars
Net baryon density n/ n_0
n_0=0.16 fm^{-3}

GOOD LUCK NICA.