

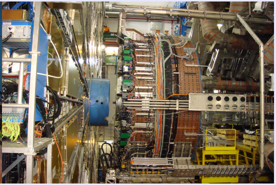

Foundations of Nuclear and Particle Physics.

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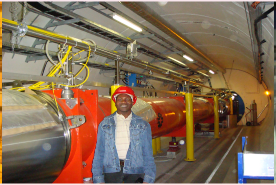
University of Cape Town, South Africa

2/3 August 2010 / Stellenbosch, South Africa


Outline

A vast subject which can easily cover a whole lecture series.
I will focus on the high energy physics aspects of nuclear and particle physics covered at CERN in Europe and at the Brookhaven National Lab in USA.

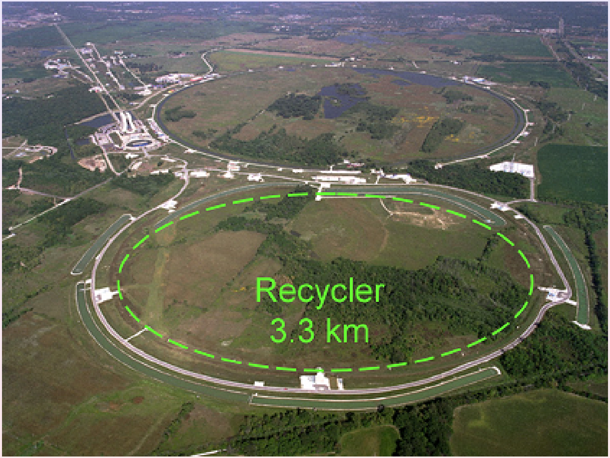
I will emphasize the difference between high energy particle physics and high energy nuclear physics.
Some aspects of quantum chromodynamics can only be unraveled in heavy ion collisions.

CERN

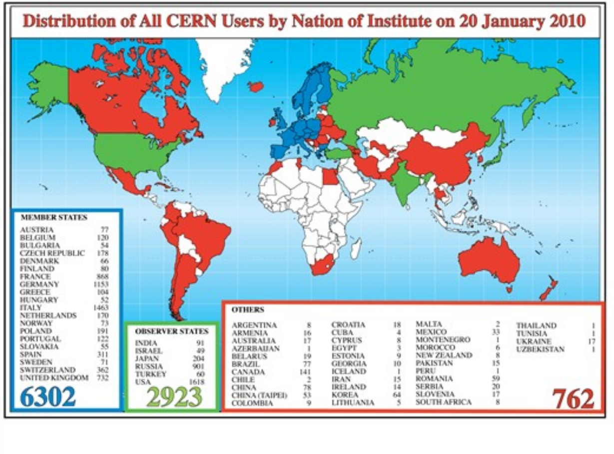
CERN

BNL-RHIC

FermiLab



CERN



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GEORGIA 10
ICELAND 1
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PERU 1
ROMANIA 59
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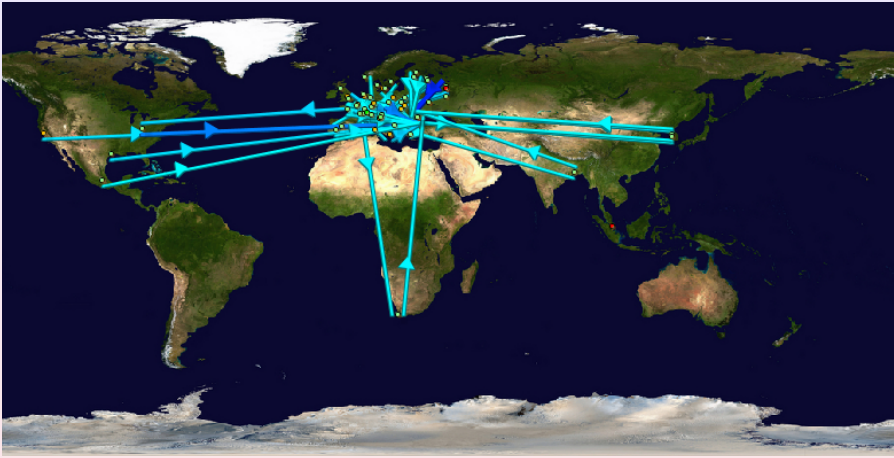
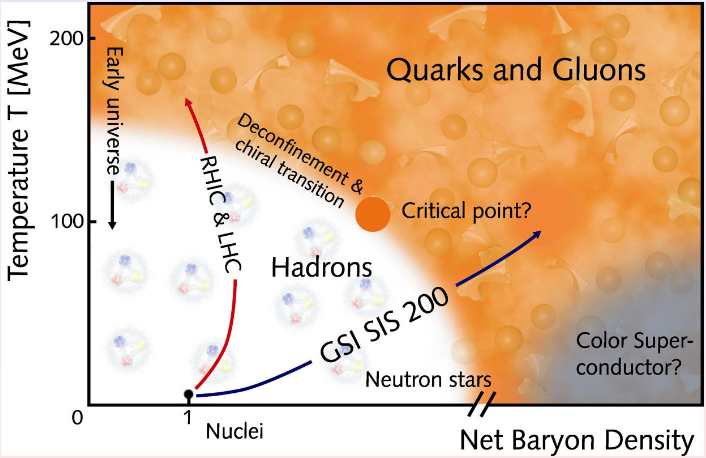
SOUTH AFRICA 8
THAILAND 1
TUNISIA 1
UKRAINE 17
UZBEKISTAN 1
762

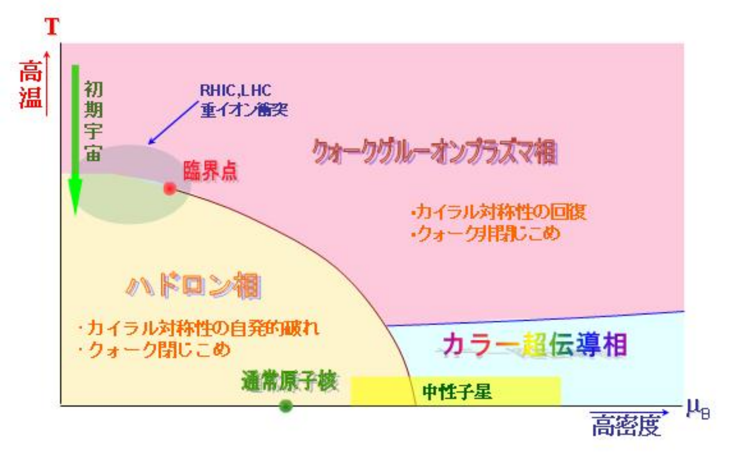
Grid Computing



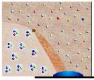
Phase Diagramme



Phase Diagramme



Phase Diagramme



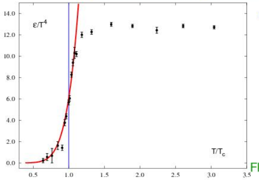
Critical behaviour in dense matter
Hagedorn's Resonance Gas

R. Hagedorn, Nuovo Cimento 35 (1965) 395

strong interactions $\Rightarrow$ exponentially rising spectrum of resonances

$$\textbf{Hagedorn spectrum}: \ \rho(m_H) \sim c\, m_H^a\, \mathrm{e}^{m_H/T_H}$$

$$Z(T,\mu_B) \;=\; \int \mathrm{d}m_H\, \rho(m_H)\, \mathrm{e}^{-m_H/T}$$



$\Rightarrow$ critical behaviour: $T_c \equiv T_H$
(end of hadronic physics)

resonance gas (adjusted mass spectrum):
$\sim$ 1000 resonance d.o.f.

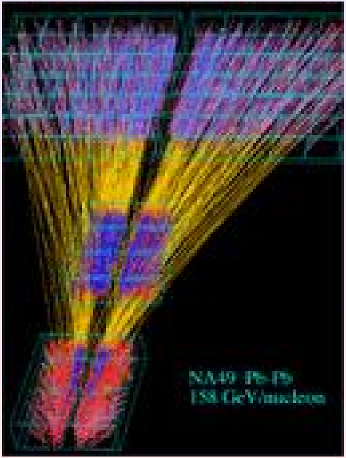
lattice calculation:
(2+1)-flavor QCD, $m_q/T = 0.4$, $\mu_B = 0$

continuous transition at T_c

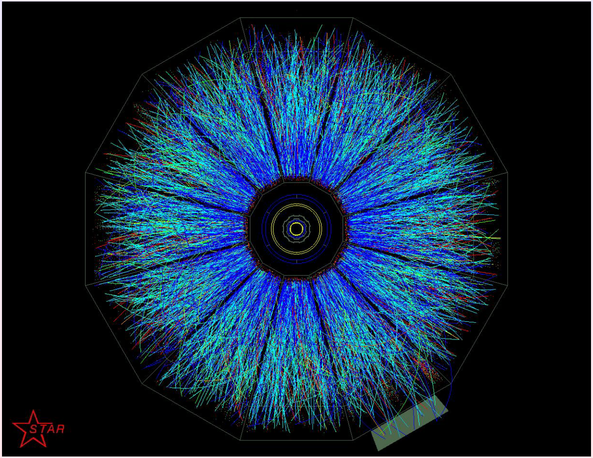
FK, K. Redlich, A. Tawfik, hep-ph/0303108

F. Karsch, Strange Quark Matter 2004 – p.25/35

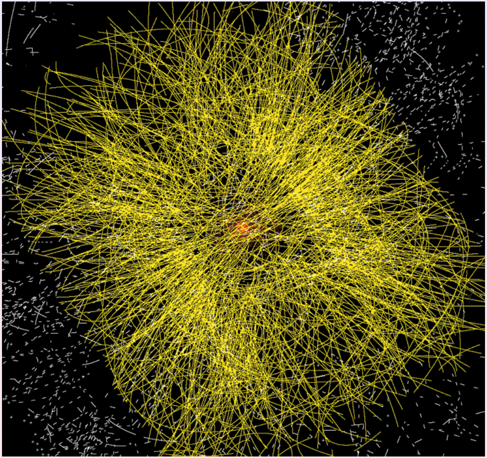
Event Simulation Pb-Pb at the SPS.



RHIC, Brookhaven



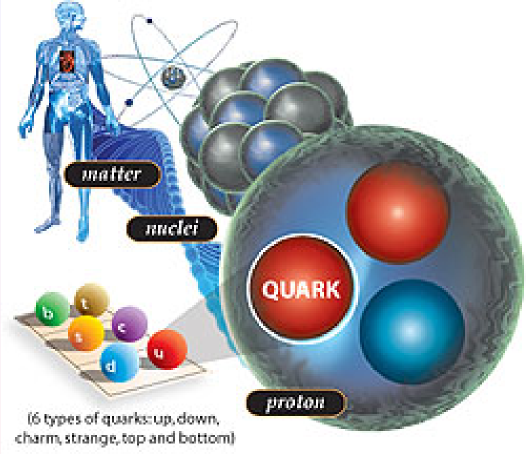
Event Simulation Pb-Pb at the LHC.



What are all those tracks?

g_i	m_i	stat	S_i	B_i	Q_i	Particle i
1	0.140	boson	0	0	1.	π^+
1	0.140	boson	0	0	-1.	π^-
2	0.938	fermion	0	1	1.	proton
2	0.938	fermion	0	-1	-1.	anti-proton
1	0.494	boson	1	0	1.	K^+
1	0.494	boson	-1	0	-1.	K^-

RHIC


matter
nuclei
QUARK
proton
b
t
c
s
u
d
(6 types of quarks: up, down, charm, strange, top and bottom)

In terms of quarks (and anti-quarks):
u-quark : charge +2/3
d-quark : charge -1/3
s-quark : charge -1/3

g_i	m_i	stat	S_i	B_i	Q_i	Particle i	
1	0.140	boson	0	0	1.	π^+	$u\bar{d}$
1	0.140	boson	0	0	-1.	π^-	$d\bar{u}$
2	0.938	fermion	0	1	1.	proton	uud
2	0.938	fermion	0	-1	-1.	anti-proton	$\bar{u}\bar{u}\bar{d}$
1	0.494	boson	1	0	1.	K^+	$u\bar{s}$
1	0.494	boson	-1	0	-1.	K^-	$s\bar{u}$

Natural Units

$$c = \hbar = 1 \tag{1}$$

$$c \equiv 299792458\ \frac{m}{s} \qquad \text{exact}$$

$$\hbar c \approx 197\ \ \mathrm{MeV} \cdot \mathrm{fm} \tag{2}$$

As an example:

$$\begin{aligned} 140\ \mathrm{MeV} &= 140\ \mathrm{MeV} \frac{1}{197\ \mathrm{MeV} \cdot \mathrm{fm}} \\ &= 0.71 \mathrm{fm}^{-1} \end{aligned} \tag{3}$$

Natural Units for Temperature

Boltzmann's constant

$$\begin{aligned} k_B &= 1 \\ k_B &= 8.6173 \times 10^{-14}\ \mathrm{GeV}/{}^\circ\mathrm{K} \end{aligned} \tag{4}$$

As an example:

$$1\ \mathrm{eV} = 1.16 \times 10^5\ {}^\circ\mathrm{K} \tag{5}$$

Kinematic variables

$$\begin{aligned} E^2 &= |\vec{p}|^2 + m^2 \\ &= p_x^2 + p_y^2 + p_z^2 + m^2 \\ &= p_T^2 + p_z^2 + m^2 \end{aligned} \tag{6}$$

$p_T^2 + m^2 \equiv m_T^2$ is called the **transverse mass.**
Hence

$$E^2 = p_z^2 + m_T^2 \tag{7}$$

$$\begin{aligned} E &= m_T \cosh y \\ p_z &= m_T \sinh y \end{aligned}$$

y is called the rapidity.

Rapidity

$$
\begin{aligned}
E &= m_T \cosh y = m_T \frac{1}{2}\left(e^{y} + e^{-y}\right) \\
p_z &= m_T \sinh y = m_T \frac{1}{2}\left(e^{y} - e^{-y}\right)
\end{aligned}
$$

$$
\begin{aligned}
m_T e^{y} &= E + p_z \\
m_T e^{-y} &= E - p_z
\end{aligned}
\tag{8}
$$

and

$$
\boxed{y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}}
$$

Tutorial 1: calculate the maximum value of the rapidity y at the highest beam energy at CERN $E = 7000$ GeV and at BNL $E = 200$ GeV. What is the corresponding γ factor?

Tutorial 2 : Show that $\frac{d^3p}{E}$ is invariant under Lorentz transformations.

Tutorial 3 : What is the temperature of the sun expressed in eV?

Rapidity

d^3p/E is invariant under Lorentz transformations.

$$\begin{aligned} \frac{d^3p}{E} &= p_T \; dp_T \; d\phi \frac{dp_z}{E} \\ &= m_T \; dm_T \; d\phi \frac{m_T \cosh y dy}{m_T \cosh y} \\ &= m_T \; dm_T \; d\phi \; dy \end{aligned} \quad (9)$$

Pseudo-Rapidity

Disadvantage of rapidity: need to know mass *m* of particle.

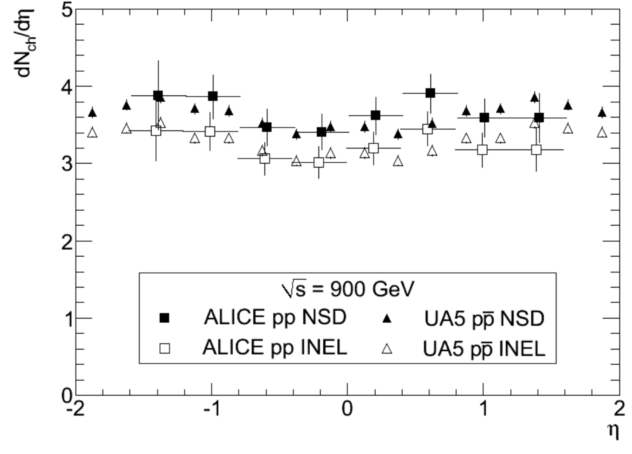
Pseudo-rapidity

$$\boxed{\eta = \tfrac{1}{2}\ln\tfrac{|\vec{p}|+p_z}{|\vec{p}|-p_z}}$$

$$\begin{aligned}
\eta &= \frac{1}{2}\ln\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z} \\
&= \frac{1}{2}\ln\frac{|\vec{p}|+|\vec{p}|\cos\theta}{|\vec{p}|-|\vec{p}|\cos\theta} \\
&= \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} \\
&= \frac{1}{2}\ln\frac{\cos^2(\theta/2)}{\sin^2(\theta/2)} \\
&= \ln\cot(\theta/2) \\
&= -\ln\tan(\theta/2)
\end{aligned} \tag{10}$$

Hence one only needs to know the angle.

Pseudorapidity at the LHC



Conclusion: at 900 GeV p-p collisons at the LHC there is NOTHING NEW!!!
(This will not be true for heavy-ion collisions in November 2010.)

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

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

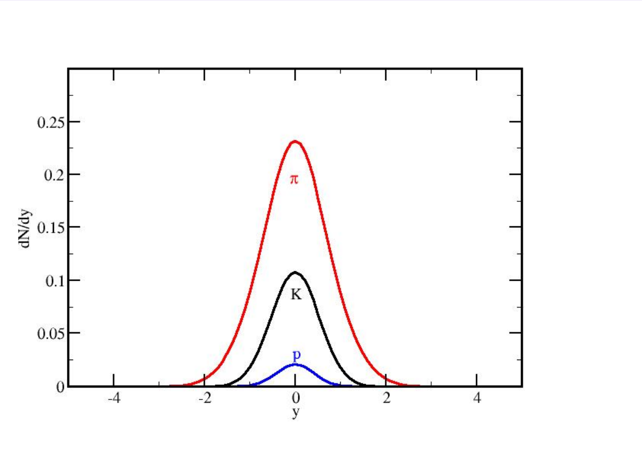
$$\frac{dN_i}{dy} = \frac{g_i V}{2\pi^2}\left[\frac{2T^3}{\cosh^2 y} + \frac{2mT^2}{\cosh y} + m^2 T\right] e^{\frac{\mu_i}{T}}$$

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

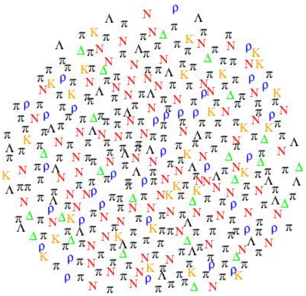
Narrow Distribution in Rapidity

Approximately Gaussian

Rapidity Distribution in the Thermal Model



Hadronic Gas



Thermal Equilibrium

In thermal equilibrium

$$Z = \text{Tr}\; e^{-\frac{H}{T} + \frac{\mu N}{T}}$$

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

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

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

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

Thermal Equilibrium

Average Energy

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

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

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

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

$$E_1 + E_2 + \cdots = E_3 + E_4 + E_5 + \cdots \tag{11}$$

for the chemical potentials

$$\mu_1 + \mu_2 + \cdots = \mu_3 + \mu_4 + \mu_5 + \cdots \tag{12}$$

As an example

$$\pi^0 + p \leftrightarrow \pi^0 + p + \pi^0 \tag{13}$$

leads to

$$\mu_{\pi^0} + \mu_p = \mu_{\pi^0} + \mu_p + \mu_{\pi^0} \tag{14}$$

which leads to

$$\mu_{\pi^0} = 0 \tag{15}$$

Chemical Equilibrium

In equilibrium

$$B + B \leftrightarrow B + B + B + \bar{B} \tag{16}$$

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

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

$$dE = (\mu_B + \mu_{\bar{B}}) dN_B = 0 \tag{17}$$

$$\mu_B = -\mu_{\bar{B}} \tag{18}$$

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:

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

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

$$\mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S + C_i\mu_C + .. \tag{19}$$

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

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

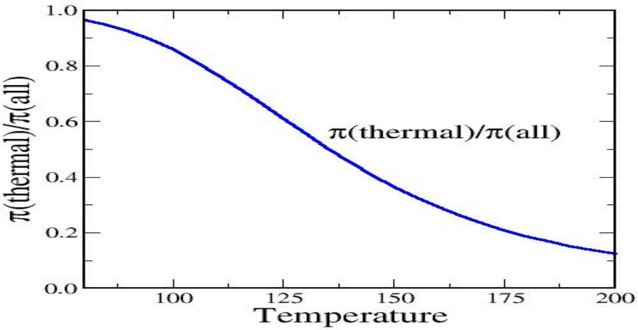
Final, observed, number of π^+ is given by

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

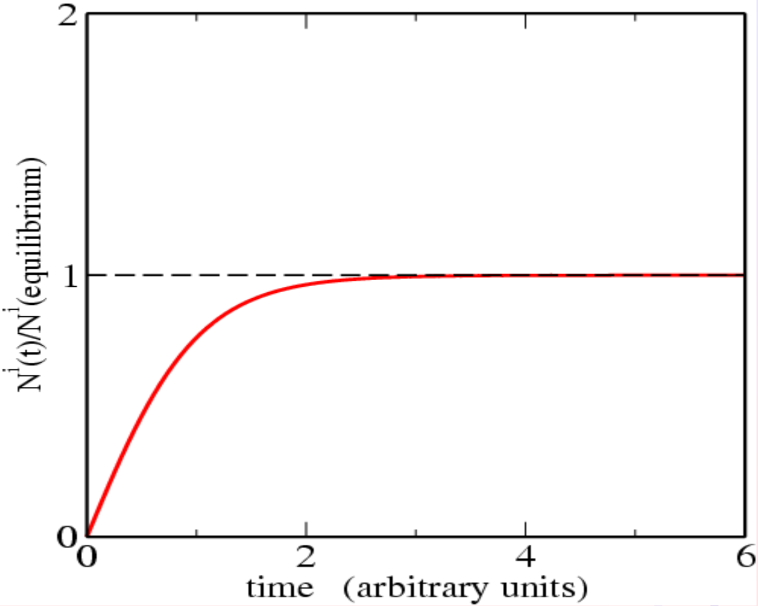
depending on the temperature, over 80% of observed pions are due to resonance decays

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.

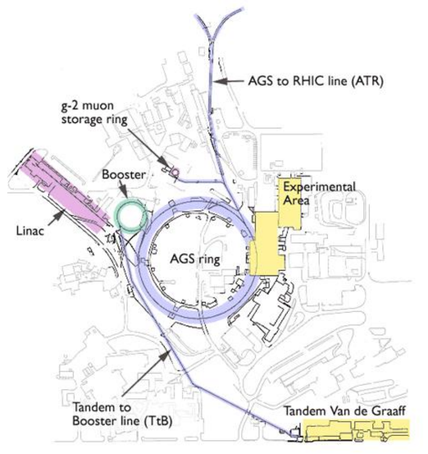
	Measurement
Pb–Pb 158*A* GeV	
$(\pi^+ + \pi^-)/2.$	600±30
K^+	95 ±10
K^-	50 ±5
K^0_S	60 ±12
p	140±12
$\bar{p}$	10 ±1.7
ϕ	7.6±1.1
Ξ^-	4.42±0.31
$\overline{\Xi^-}$	0.74±0.04
$\overline{\Lambda}/\Lambda$	0.2±0.04

SPS data.

SPS: Chemical Freeze-Out Parameters:

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

AGS


AGS to RHIC line (ATR)
g-2 muon
storage ring
Booster
Experimental
Area
Linac
AGS ring
Tandem to
Booster line (TtB)
Tandem Van de Graaff

AGS data.

	Measurement
Au–Au 11.6*A* 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:

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

SIS data.

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

SIS data.

SIS: Chemical Freeze-Out Parameters:

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

RHIC data.

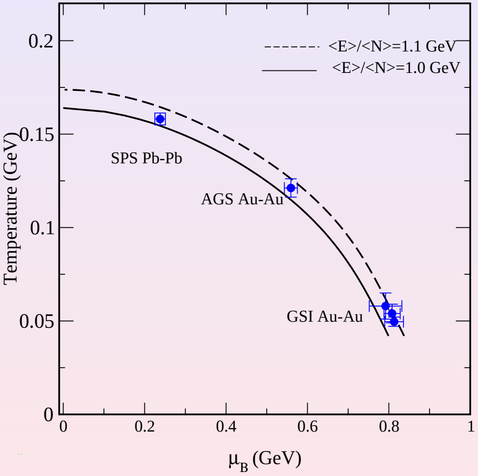
Ratio	Experiment	Central	Mid-Central	Peripheral
$\pi^-_{(2)}/\pi^+_{(2)}$	BRAHMS	0.990±0.100		
	PHENIX	0.960±0.177	0.920±0.170	0.933±0.172
	PHOBOS	1.000±0.022		
	STAR	1.000±0.073	1.000±0.073	1.000 ± 0.073
$K^+_{(2)}/K^-_{(2)}$	PHENIX	1.152±0.240	1.292±0.268	1.322±0.284
	PHOBOS	1.099±0.111		
	STAR	1.109±0.022	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
$\Omega^-/\pi^-_{(2)}$	STAR	0.0014±0.0004		

RHIC data.

RHIC: Chemical Freeze-Out Parameters:

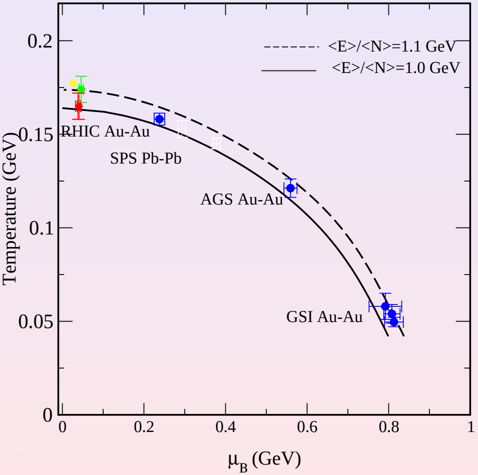
$$\begin{aligned} T &= 169 \pm 4.2\mathrm{MeV} \\ \mu_B &= 39.6 \pm 6\mathrm{MeV} \\ \gamma_s &= 0.9 \pm 0.1 \end{aligned}$$

E/N in 1999



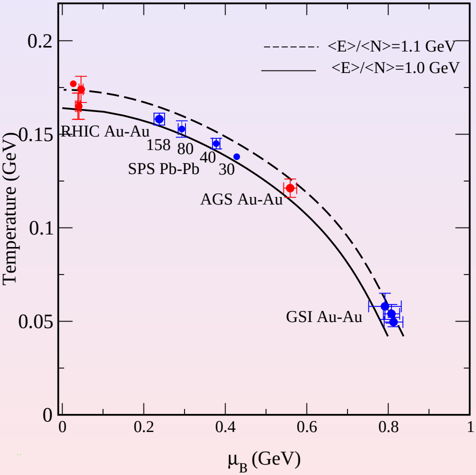
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1
μ_B (GeV)

E/N in 2000



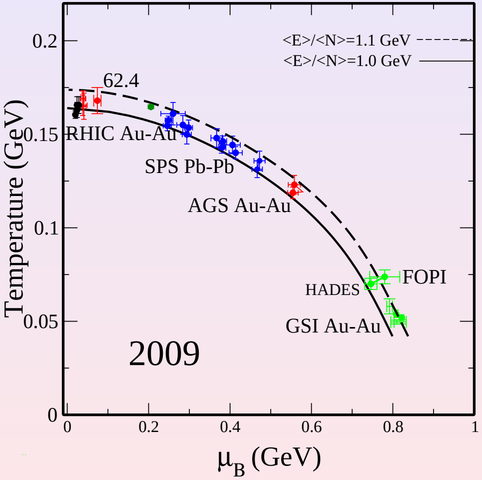
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
μ_B (GeV)

E/N in 2005



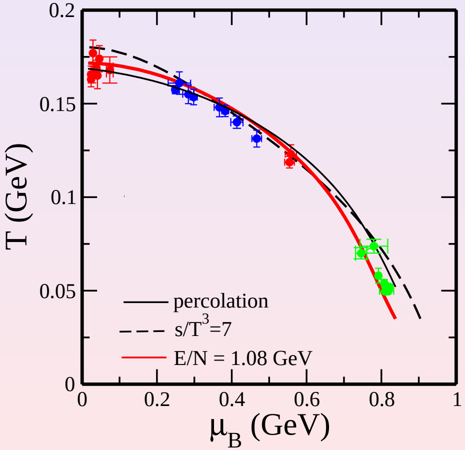
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1
μ_B (GeV)

E/N in 2009

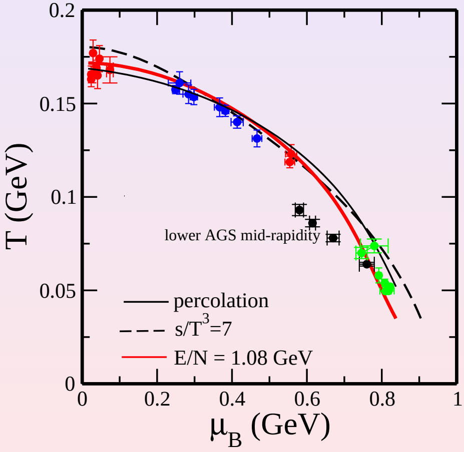


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
62.4
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
HADES
FOPI
GSI Au-Au
2009
Temperature (GeV)
μ_B (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1

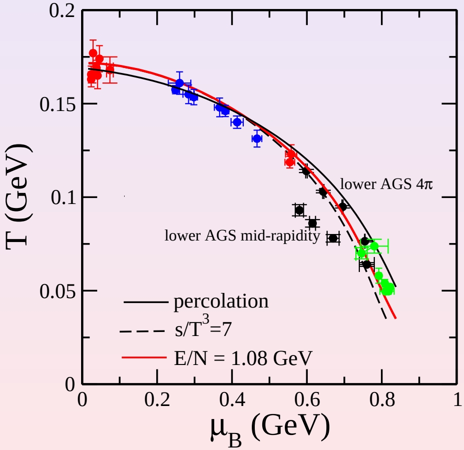
Chemical Freeze-Out: Criteria



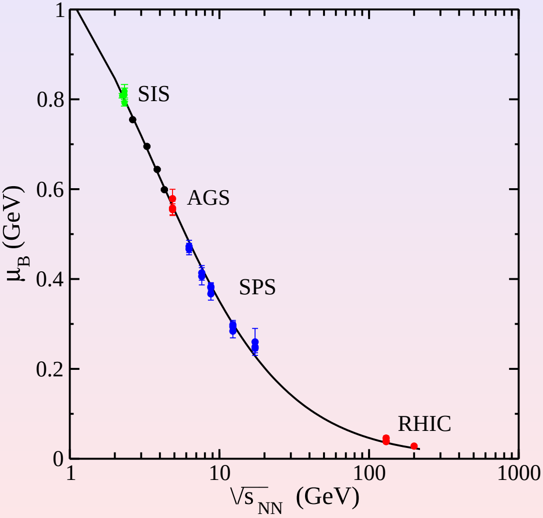
Chemical Freeze-Out: Criteria



Chemical Freeze-Out: Status in 2010



μ_B as a function of $\sqrt{s_{NN}}$

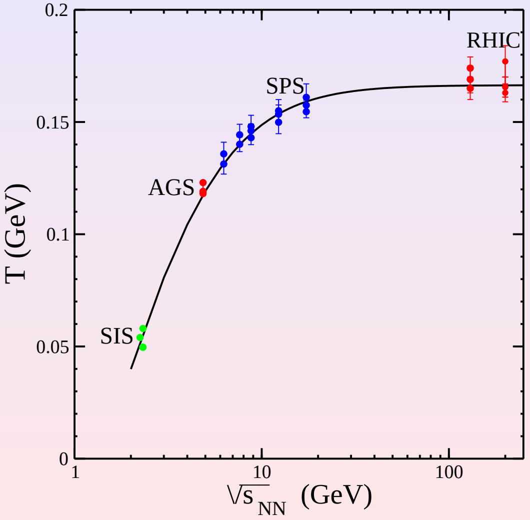


μ_B as a function of $\sqrt{s_{NN}}$

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

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

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



ALICE: presentations at 72 conferences in 2010!

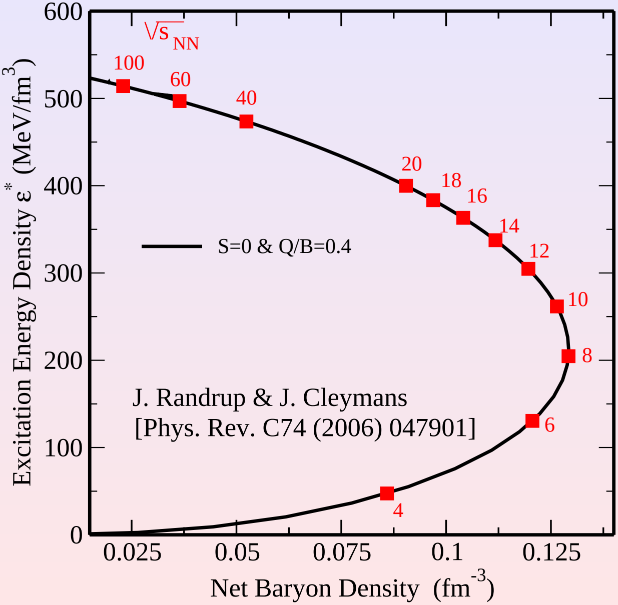
Publications

- "*First proton-proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at $\sqrt{s}$ = 900 GeV.*"
  European Physics Journal C65 (2010) 111-125
- "*Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s}$ = 0.9 and 2.36 TeV with ALICE and LHC.*"
  European Physics Journal C68 (2010) 89-108
- "*Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s}$ = 7 TeV with ALICE and LHC.*"
  European Physics Journal (submitted)
- "*Midrapidity antiproton-to-proton ratio in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV measured by the ALICE experiment.*"
  Physical Review Letters (accepted for publication)

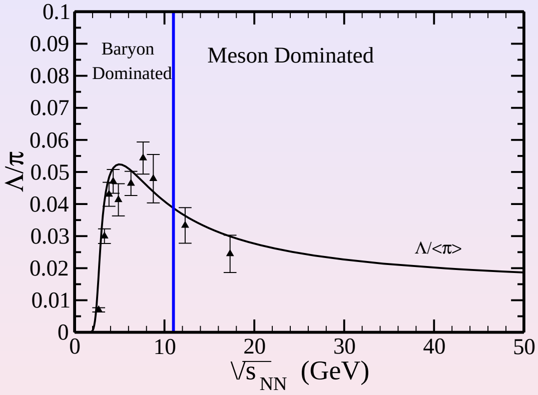
- "*Two-pion Bose-Einstein correlations in pp collisions at* $\sqrt{s}$ *= 900 GeV.*"
- "*Transverse momentum spectra of charged particles in proton-proton collisions at* $\sqrt{s}$ *= 900 GeV with ALICE and LHC.*"

Hadronic Freeze-Out

$\varepsilon^* = \varepsilon - m_N \rho$



Roller-coaster Λ/π Ratio

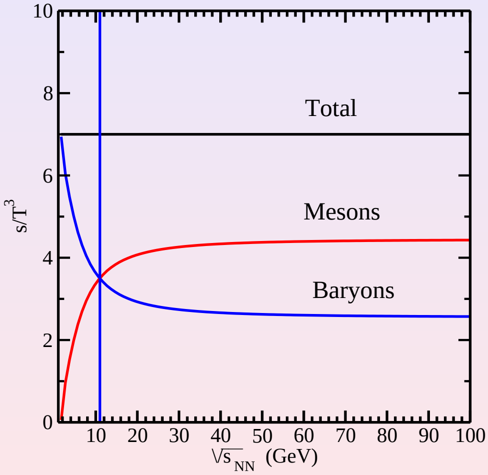


THERMUS

S. Wheaton, J. Cleymans, M. Hauer

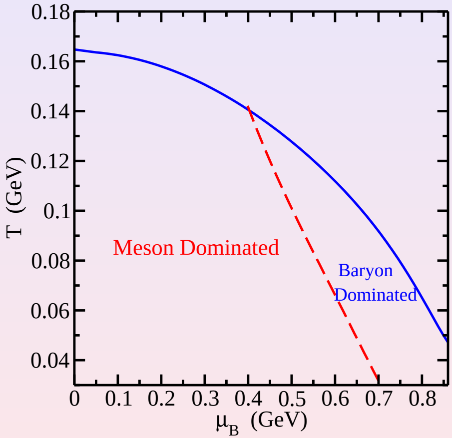
Comp. Phys. Comm. 180 (2009) 84-106

s/T^3



Total
Mesons
Baryons
s/T^3
√s_NN (GeV)
0
2
4
6
8
10
10 20 30 40 50 60 70 80 90 100

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
μ_B (GeV)
Meson Dominated
Baryon
Dominated

Strangeness in Heavy Ion Collisions
vs
Strangeness in pp - collisions

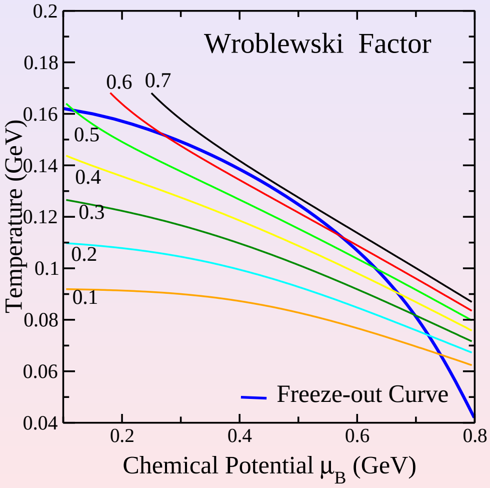
Use the Wroblewski factor

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

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^+



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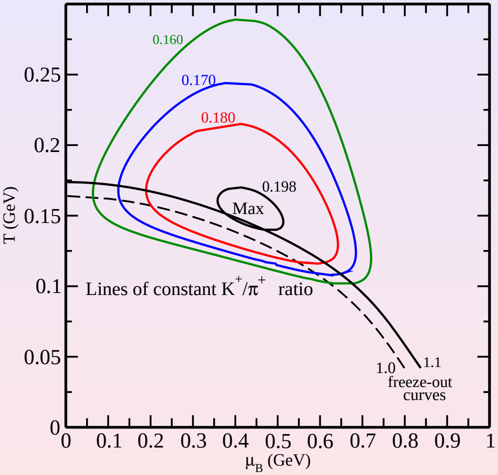
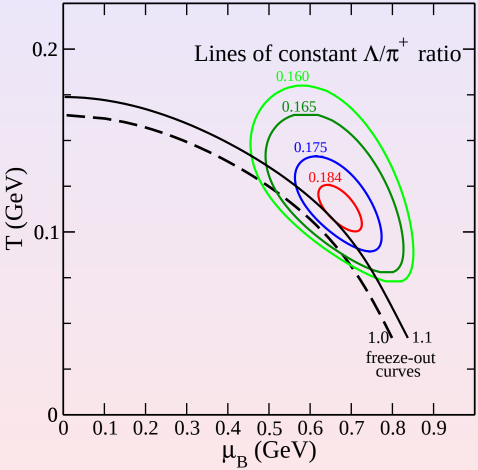
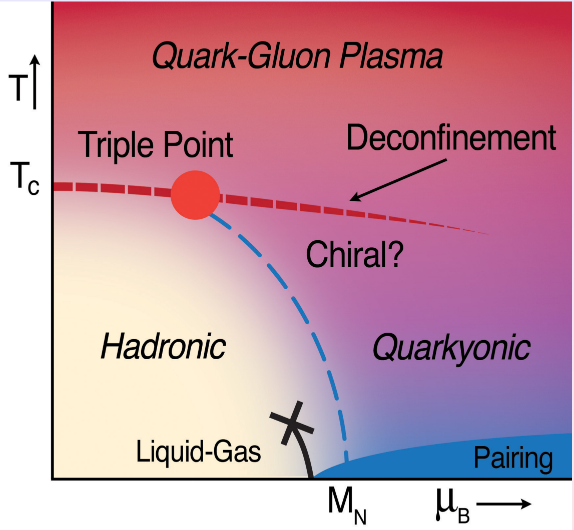


Maxima in particle ratios : K^+/π^+





R. Pisarski and L. McLerran

RHIC

In conclusion, the roller-coaster seen in the particle ratios corresponds to a transition from a baryon-dominated to a meson-dominated hadronic gas. This transition occurs at a

- temperature $T = 151$ MeV,
- baryon chemical potential $\mu_B = 327$ MeV,
- energy $\sqrt{s_{NN}} = 11$ GeV.

In the statistical model this transition leads to peaks in the $\Lambda / \langle \pi \rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios.

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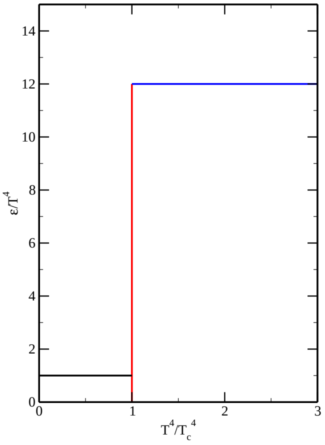
Hadronic sector : Massless Pions

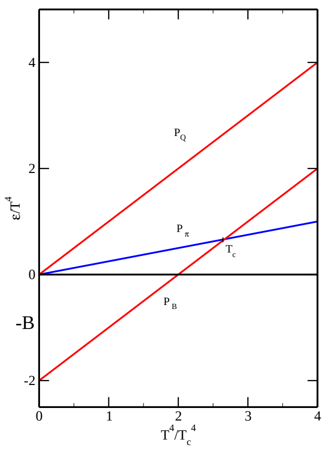
$$P_\pi / T^4 = \pi^2/30 \approx 1/3$$
$$\epsilon_p i / T^4 = \pi^2/10 \approx 1$$

QGP sector : Massless Quarks and Gluons

$$P_Q / T^4 = (37\pi^2/90) \approx 4$$
$$\epsilon_p i / T^4 = (37\pi^2/30) \approx 12$$



14
12
10
8
6
4
2
0
ε/T^4
0
1
2
3
T^4/T_c^4



4
2
0
-2
-B
ε/T^4
P_Q
P_π
T_c
P_B
0
1
2
3
4
T^4/T_c^4