Status of Chemical Equilibrium in Heavy Ion Collisions.

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in collaboration with

I. Kraus, H. Oeschler, K. Redlich, S. Wheaton

ISMD 2010,
September 24, 2010

Outline

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

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 and temperature.

The Role of Resonances: Important

Example: ρ's

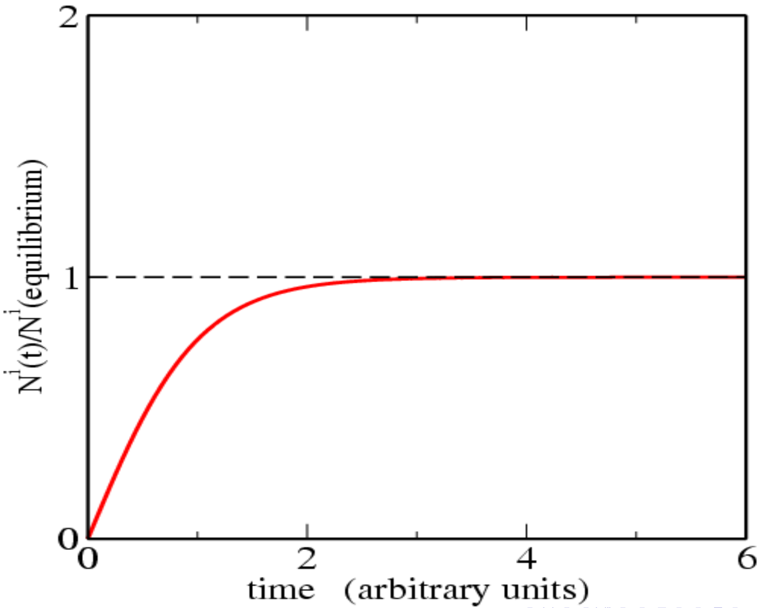
$$\rho \to \pi^+ \pi^-$$

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 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: 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$^+/\pi^+$	0.003±0.00075
π^-/π^+	2.05±0.51
η/π^0	0.018±0.007

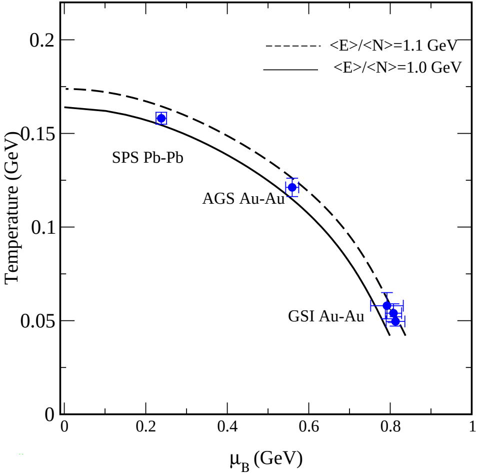
SIS data.

SIS: Freeze-Out Parameters:

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

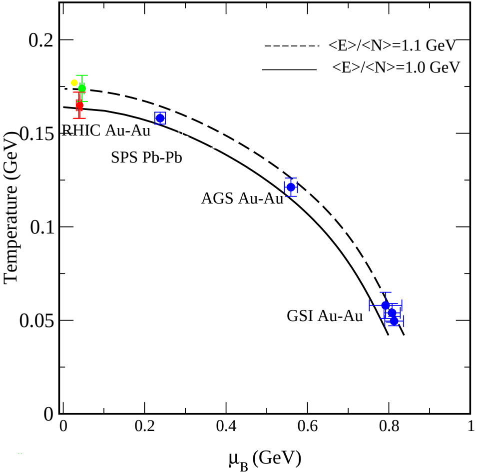
J. C., H. Oeschler, K. Redlich
Physical Review C59, (1999) 1663.

E/N in 1999



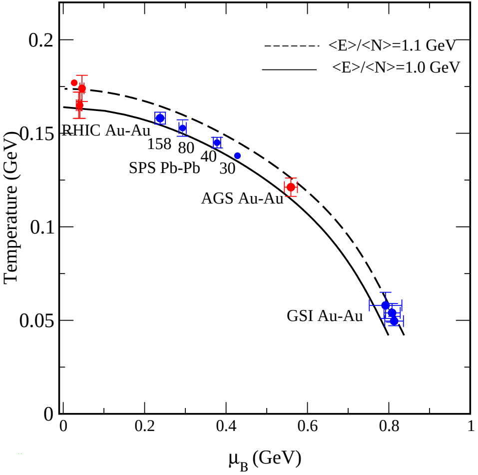
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
Temperature (GeV)
0.2
0.15
0.1
0.05
0
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
0
0.2
0.4
0.6
0.8
1
μB (GeV)

E/N in 2000



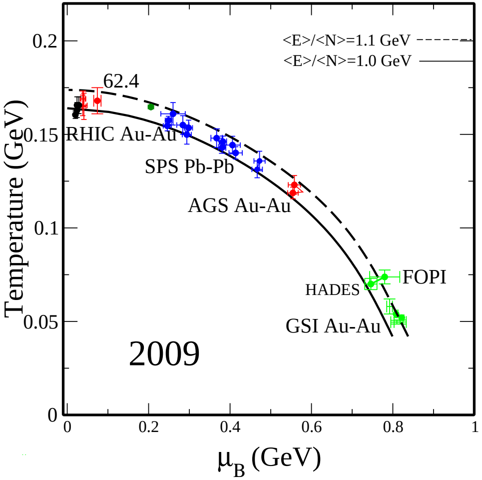
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1
μB (GeV)

E/N in 2005



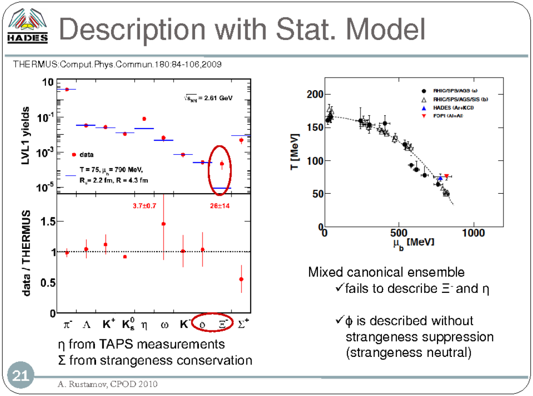
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1
μB (GeV)

E/N in 2009



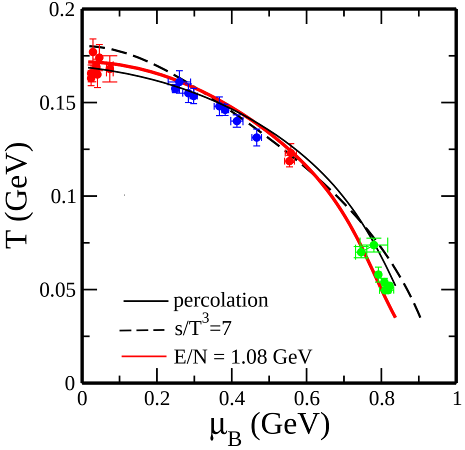
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772, 167, 2006
J. Manninen, F. Becattini, M, Gazdzicki, Phys. Rev. C73 044905, 2006
R. Picha, U of Davis, Ph.D. thesis 2002
J. Takahashi, SQM2008

2010

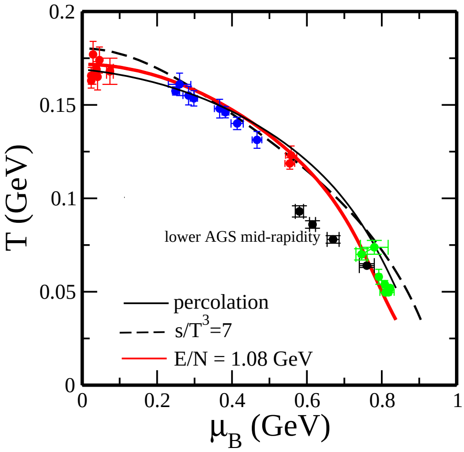


Rustamov, CPOD 2010, Dubna.

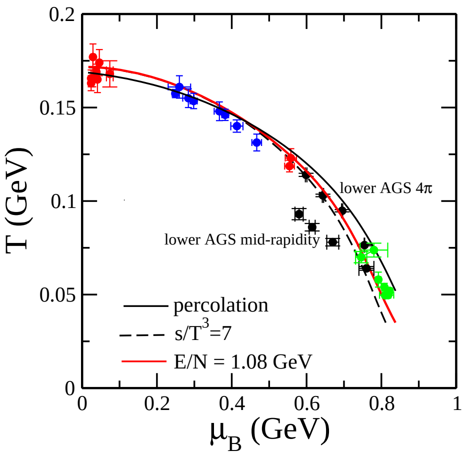
Chemical Freeze-Out: Criteria



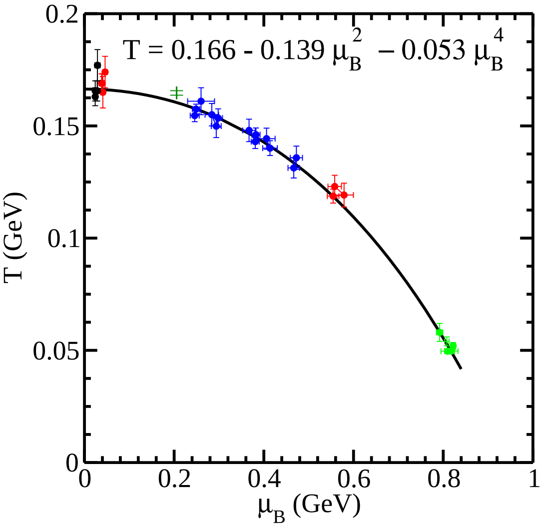
Chemical Freeze-Out: Criteria



Chemical Freeze-Out: Criteria

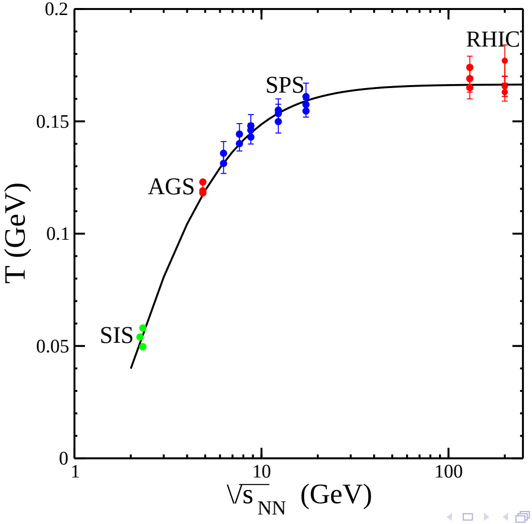


Chemical Freeze-Out

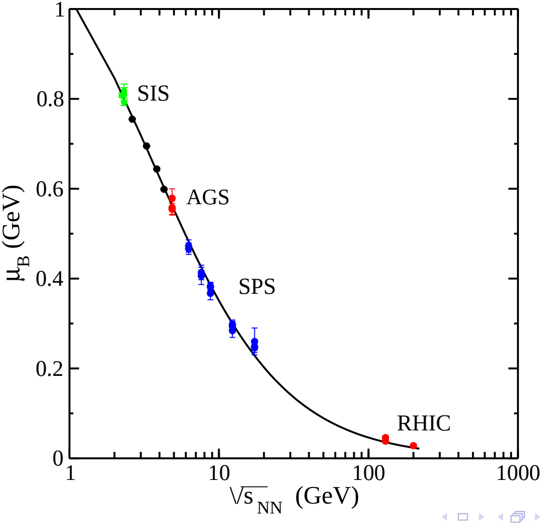


J.C., H. Oeschler, K. Redlich, S. Wheaton hep-ph/0511094

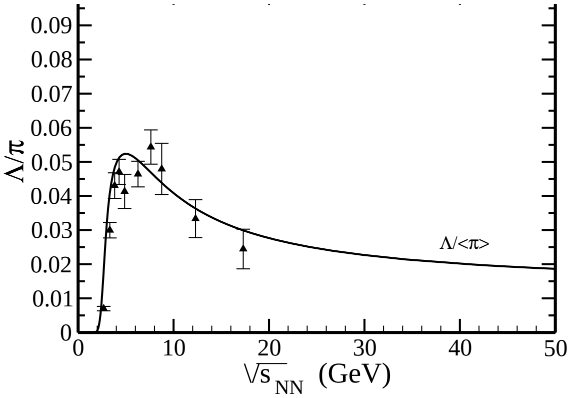
Chemical Freeze-Out Temperature



Chemical Freeze-Out μ_B



Λ/π Ratio

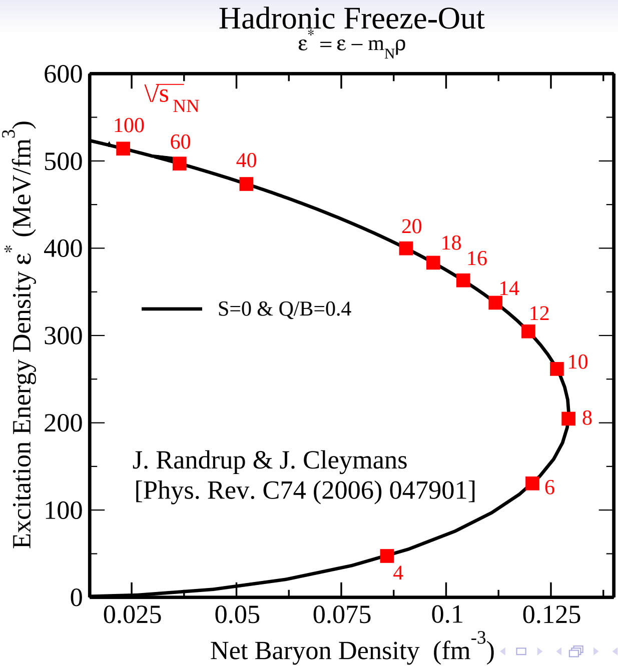


μ_B as a function of $\sqrt{s_{NN}}$

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

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
ε* = ε − m_N ρ
√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/fm³)
Net Baryon Density (fm⁻³)
0
100
200
300
400
500
600
0.025
0.05
0.075
0.1
0.125

Strangeness in Heavy Ion Collisions
vs
Strangeness in pp - collisions

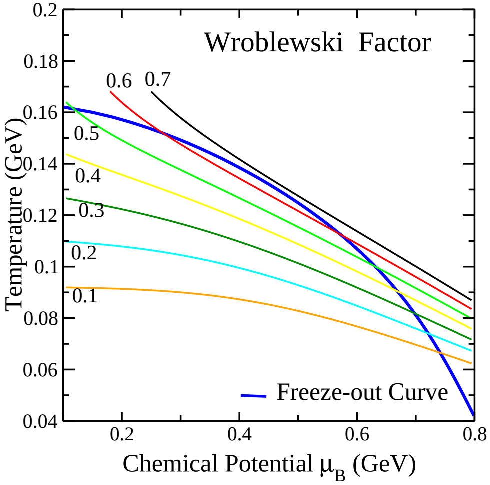
Use the Wroblewski factor

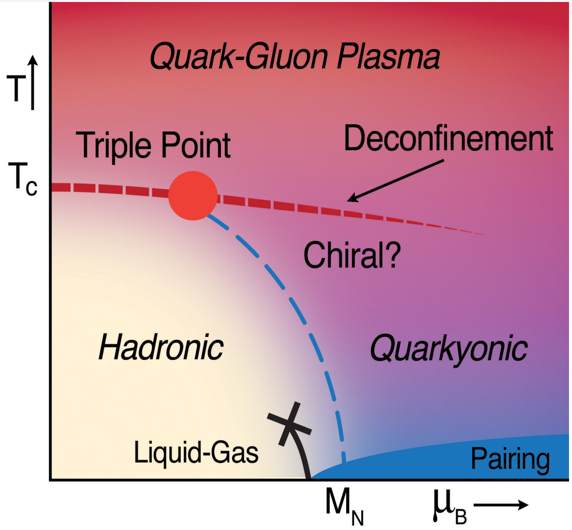
$$\lambda_s = \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

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^+





R. Pisarski and L. McLerran

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

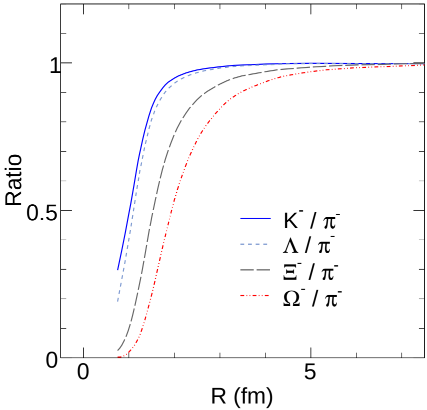
In the statistical model a rapid change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The transition occurs at a temperature T = 151 MeV and baryon chemical potential μ_B = 327 MeV corresponding to an incident energy of $\sqrt{s_{NN}}$ = 11 GeV.

Predictions for p-p LHC

I. Kraus, J.C., H. Oeschler, K. Redlich,
Phys. Rev. C79 (2009) 014901; arXiv:0808.0611

I. Kraus, J.C., H. Oeschler, K. Redlich,
J. Phys. G37 (2010) 094021; arXiv:1001.4354

F. Becattini, P. Castorina, A. Milov, H. Satz, arXiv:912.2855



I. Kraus, J.C., H. Oeschler, K. Redlich, Phys. Rev. C79 (2009) 014901; arXiv:0808.0611
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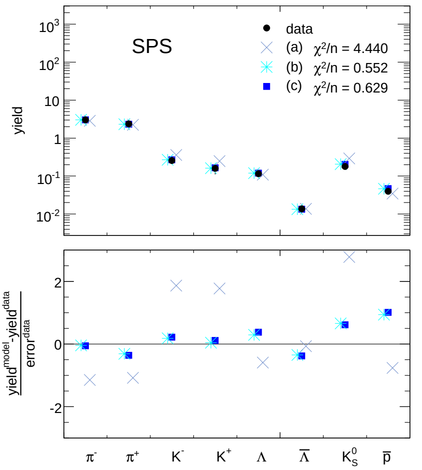

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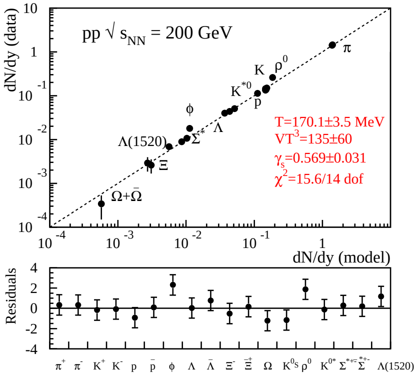
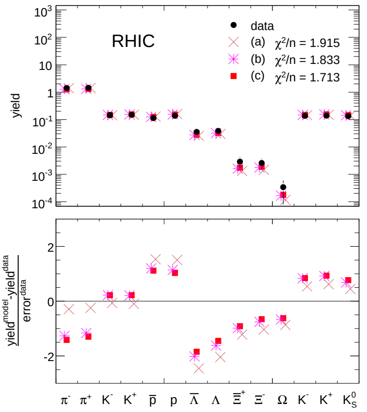
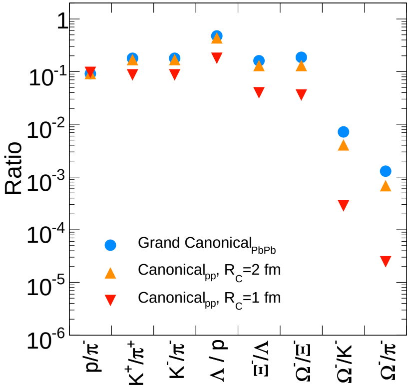


F. Becattini, P. Castorina, A. Milov, H. Satz; arXiv:0911.3026



I. Kraus, J.C., H. Oeschler, K. Redlich, Phys. Rev. C79 (2009) 014901; arXiv:0808.0611
I. Kraus, J.C., H. Oeschler, K. Redlich, J. Phys. G37 (2010) 094021; arXiv:1001.4354



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I. Kraus, J.C., H. Oeschler, K. Redlich, J. Phys. G37 (2010) 094021; arXiv:1001.4354

In conclusion,

- The evidence for chemical equilibrium is very strong.
- Clear evidence for deviations but the global picture stands firm.
- First results at LHC seem to confirm chemical equilibrium.