Freeze-Out in HI Collisions.

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November , 2006 / Quark Matter 2006, Shanghai, China

Outline

Thermal Model

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 (4π) multiplicities are the same as for a single fireball at rest (apart from the volume).

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, K. Redlich, E. Suhonen
Physical Review C64 (2001) 024901.

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, K. Redlich, E. Suhonen
Physical Review C64 (2001) 024901.

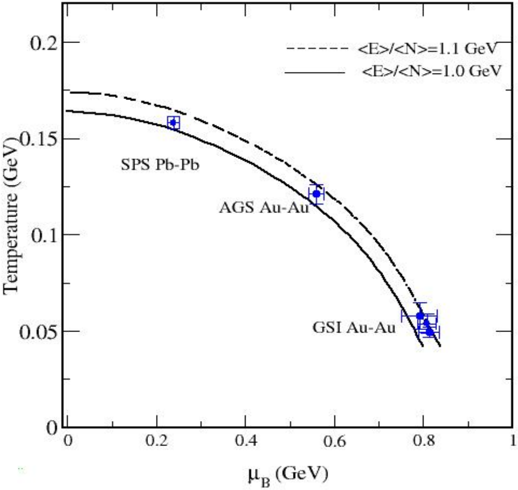
RHIC data.

RHIC: Chemical Freeze-Out Parameters:

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

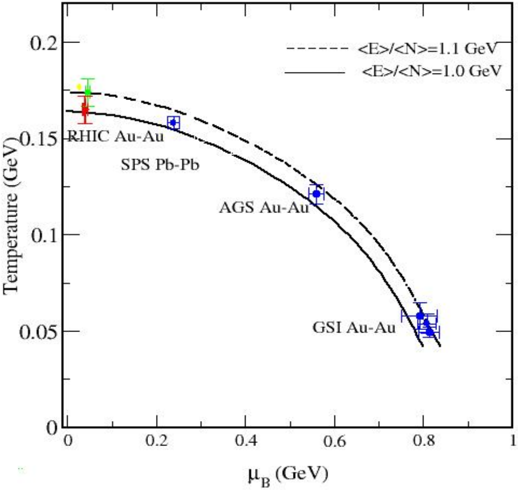
J. C., B. Kämpfer, M. Kaneta, S. Wheaton, N. Xu
Phys. Rev. C71, 0409071 (2005)

E/N in 1999

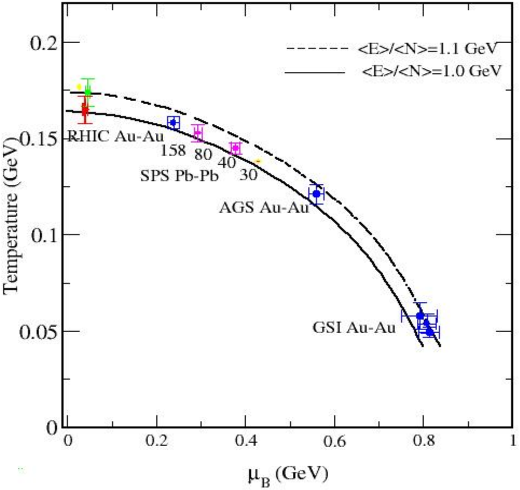


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
μ_B (GeV)
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1

E/N in 2000

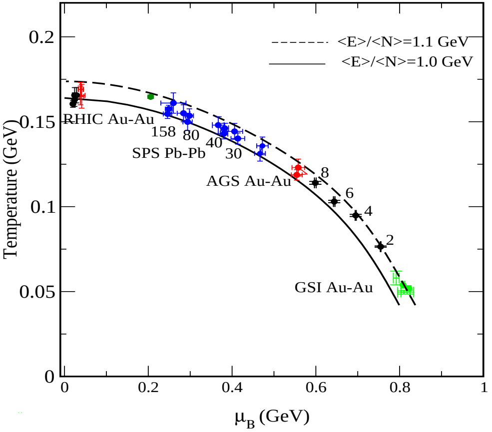

0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
Temperature (GeV)
μ_B (GeV)
<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
GSI Au-Au

E/N in 2005

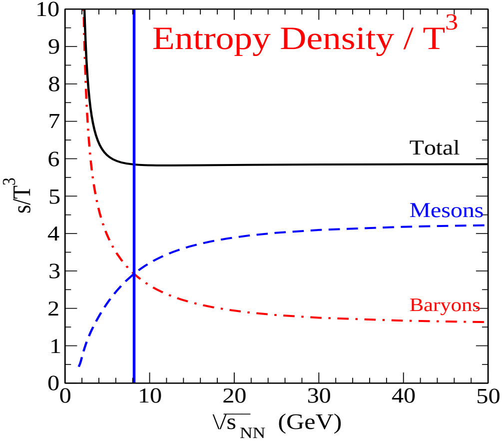


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
μB (GeV)

E/N in 2006



J. Manninen, F. Becattini, M, Gazdzicki hep-ph/0511092
R. Picha, U of Davis, Ph.D. thesis 2002
AGS data based on D. Cebra, U of Davis
A. Andronic, P. Braun-Munzinger, J. Stachel hep-ph/0511074



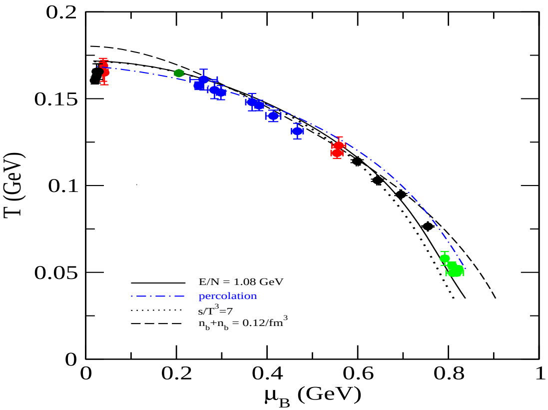
J. C., H. Oeschler, K. Redlich and S. Wheaton, Physics Letters B615 (2005) 50-54.
A. Tawfik, J. Phys. G Nucl. Part. Phys. G31 S1105 (2005).

Percolation Model

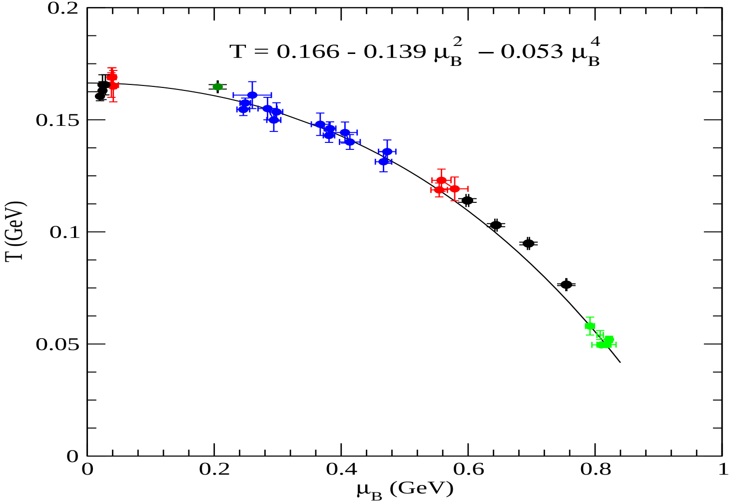
V. Magas and H. Satz, Eur. Phys. J. **C32** 115 (2003).

$$n(T,\mu) = \frac{1.24}{V_h}\left[1 - \frac{n_B(T,\mu)}{n(T,\mu)}\right] + \frac{0.34}{V_h}\left[\frac{n_B(T,\mu)}{n(T,\mu)}\right].$$

Chemical Freeze-Out: Status in 2006

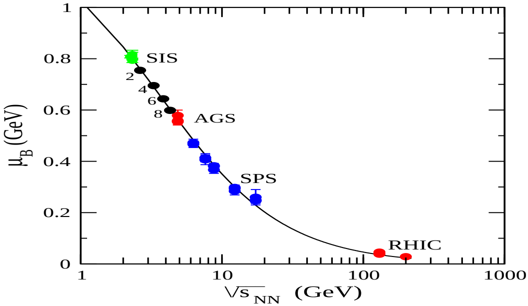


Chemical Freeze-Out: Status in 2006



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

μ_B as a function of $\sqrt{s_{NN}}$

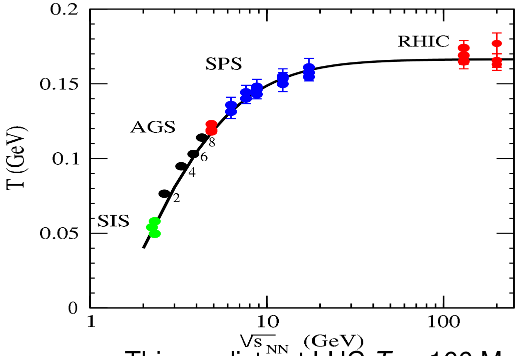


$$\mu_B(\sqrt{s}) = \frac{1.308 \text{ GeV}}{1 + 0.273 \text{ GeV}^{-1}\sqrt{s}}.$$

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

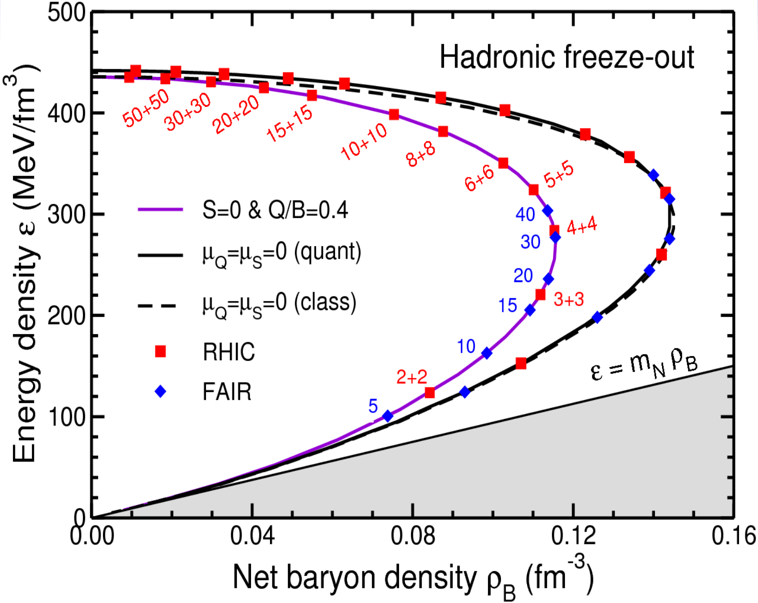
J. C., H. Oeschler, K. Redlich, S. Wheaton
Phys. Rev. C73 034905 (2006)

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



This predicts at LHC $T \approx 166$ MeV.

J. C., H. Oeschler, K. Redlich, S. Wheaton
Phys. Rev. C73 034905 (2006)
Detailed predictions for LHC energies: I. Kraus et al.
Phys. Rev. C74 034903 (2006)



J. Randrup, J.C., Phys. Rev. C74 047901 (2006)

Rapidity Distribution in the Thermal Model

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

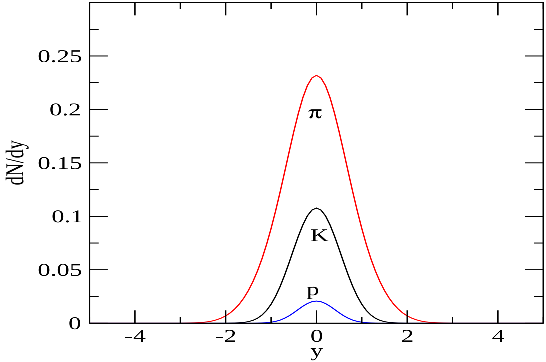
$$\frac{dN_i}{dy} = \frac{g_i V}{2\pi^2}\left[\frac{2T^3}{\cosh^2 y} + \frac{2mT^2}{\cosh y} + m^2 T\right] e^{\frac{\mu_i}{T}}$$

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

Narrow Distribution in Rapidity

Approximately Gaussian

Rapidity Distribution in the Thermal Model



Deducing particle abundancies from mid-rapidity values might give misleading results.

Superposition of Fireballs - 1.

$$\frac{dN_i}{dy} = \int_{-\infty}^{\infty} dY\ \rho(Y)\frac{dN_i^0}{dy}(y-Y)$$

where

$$\frac{dN_i^0}{dy} = \frac{g_i V}{2\pi^2}\left[\frac{2T^3}{\cosh^2(y-Y)} + \frac{2mT^2}{\cosh(y-Y)} + m^2 T\right] e^{\frac{\mu_i}{T}}$$

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

Superposition of Fireballs.

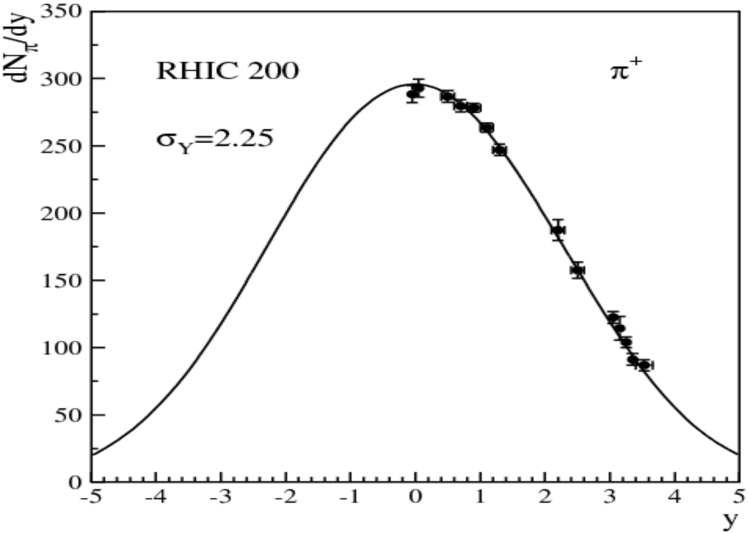
$$\rho(Y) = \frac{1}{\sqrt{2}\pi\sigma} \exp\left(-\frac{Y^2}{2\sigma_Y^2}\right)$$

At RHIC

$$\sigma_Y = 2.25$$

At SPS

$$\sigma_Y = 1.7$$

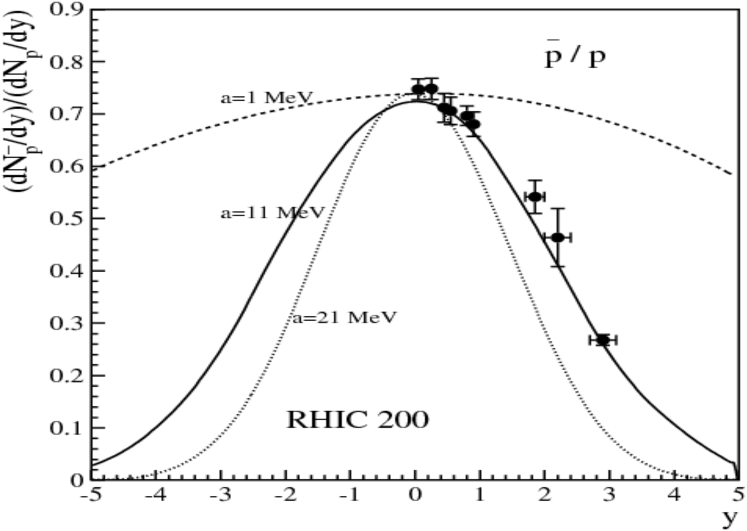


RHIC 200
σ_Y=2.25
π^+
dN_π/dy
y

Dependence of μ_B on Rapidity

$$\mu_B = \mu_B^0 + a * Y^2$$

Laura Siles and Michael Murray nucl-ex/0601039
Dieter Roehrich, Florence, Italy, July 2006
B. Biedroh and W. Broniowski nucl-th/0610083
F. Becattini, J. C., Berkeley & Davis, January 2006, Florence, Italy, July 2006



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Dependence of μ_B on Rapidity

$$\mu_B = \mu_B^0 + 0.011 * Y^2$$

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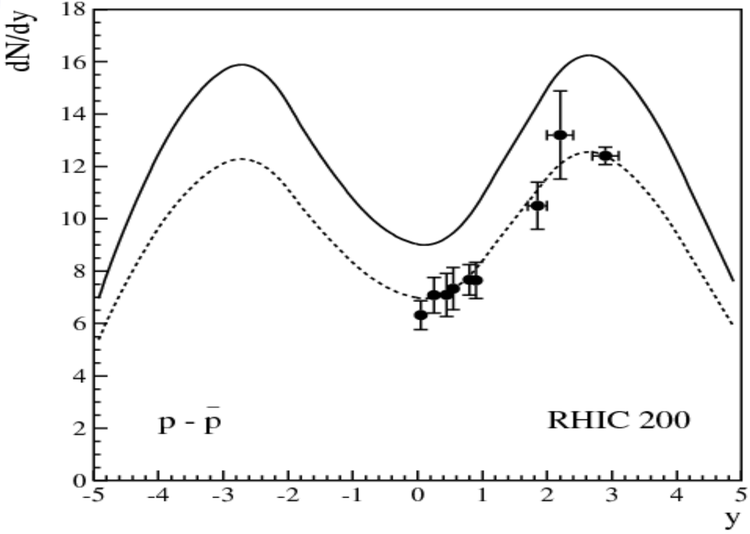
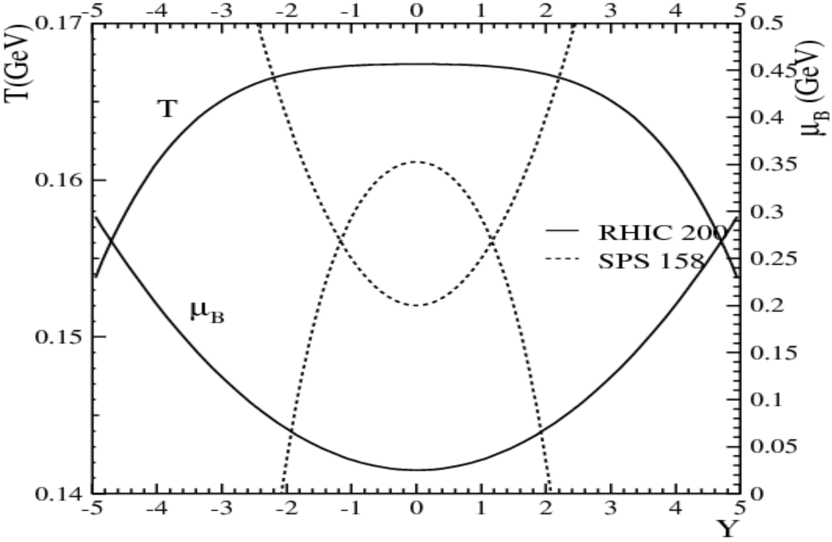


F. Becattini, J. C..



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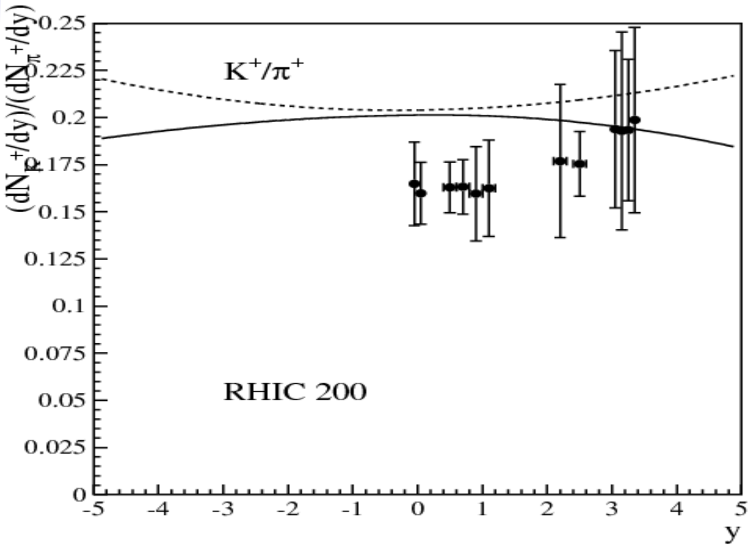

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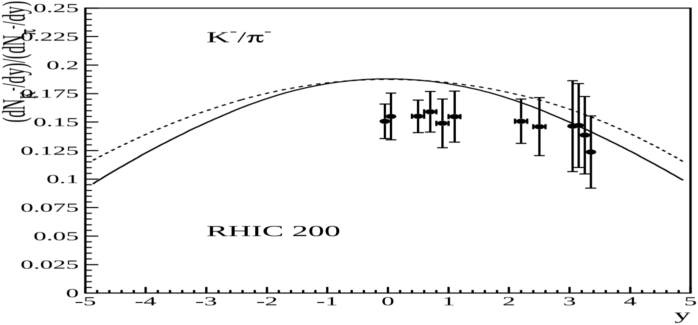
Dependence of μ_B on Rapidity



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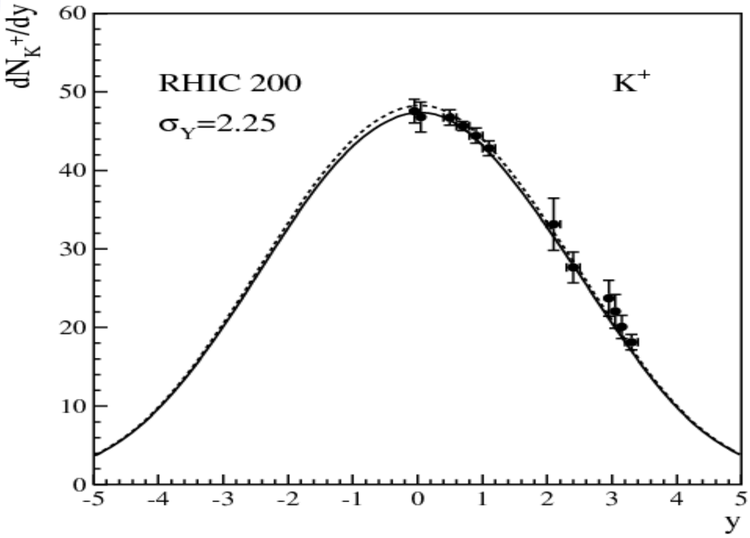

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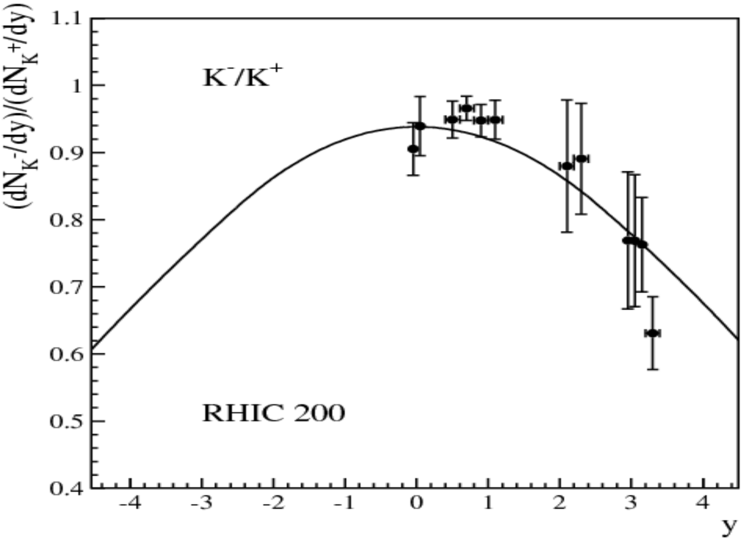

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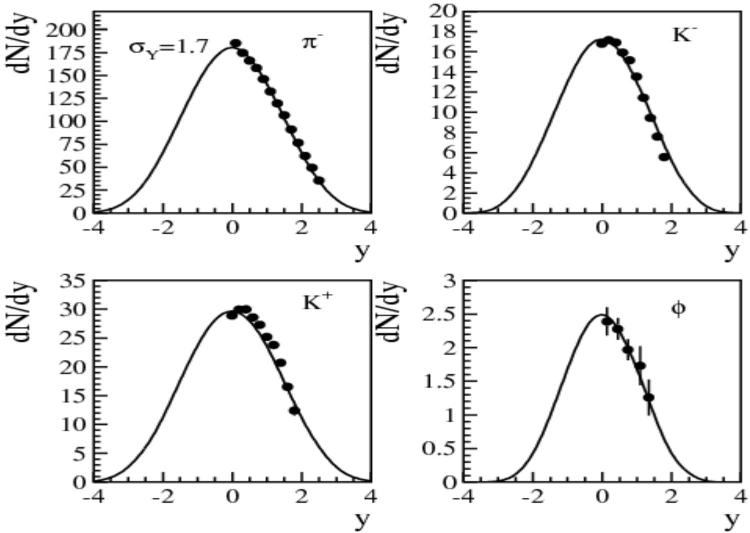
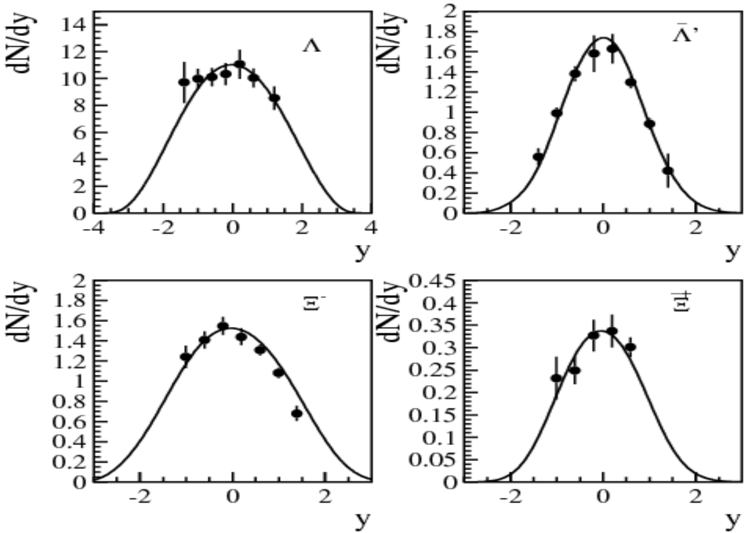
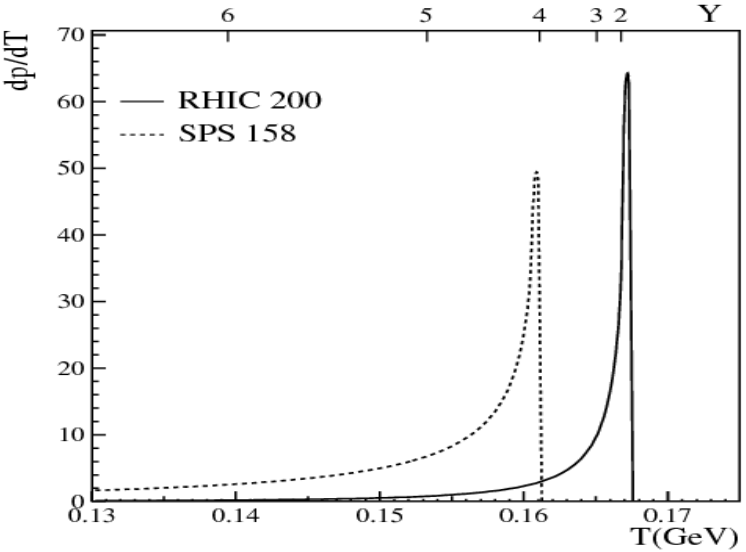
Rapidity Gaussian Distribution




dN/dy
y
Λ
Λ̄'
Ξ⁻
Ξ̄⁺



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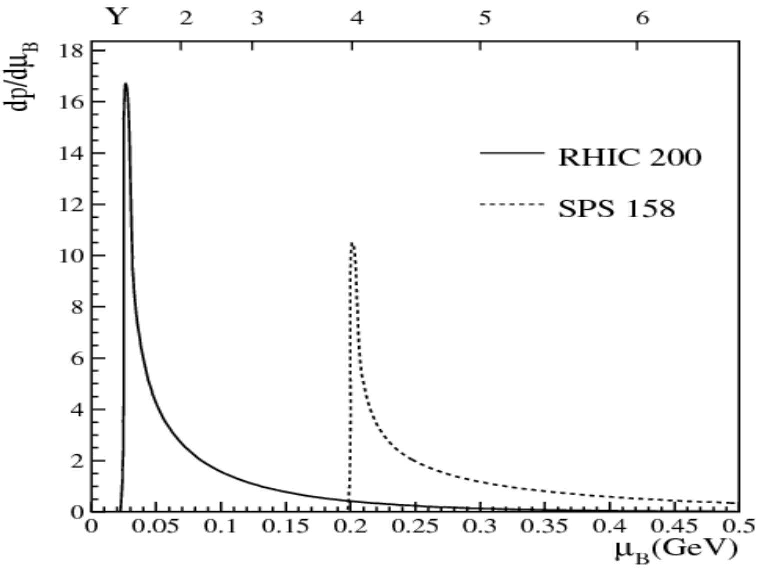

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Conclusions:

- The evidence for chemical equilibrium is OVERWHELMING.
- Thermal-Statistical Models are very good for particle ratios, multiplicities,