The Thermal Model

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DISCOVERY PHYSICS AT THE LHC

1 - 6 December 2014

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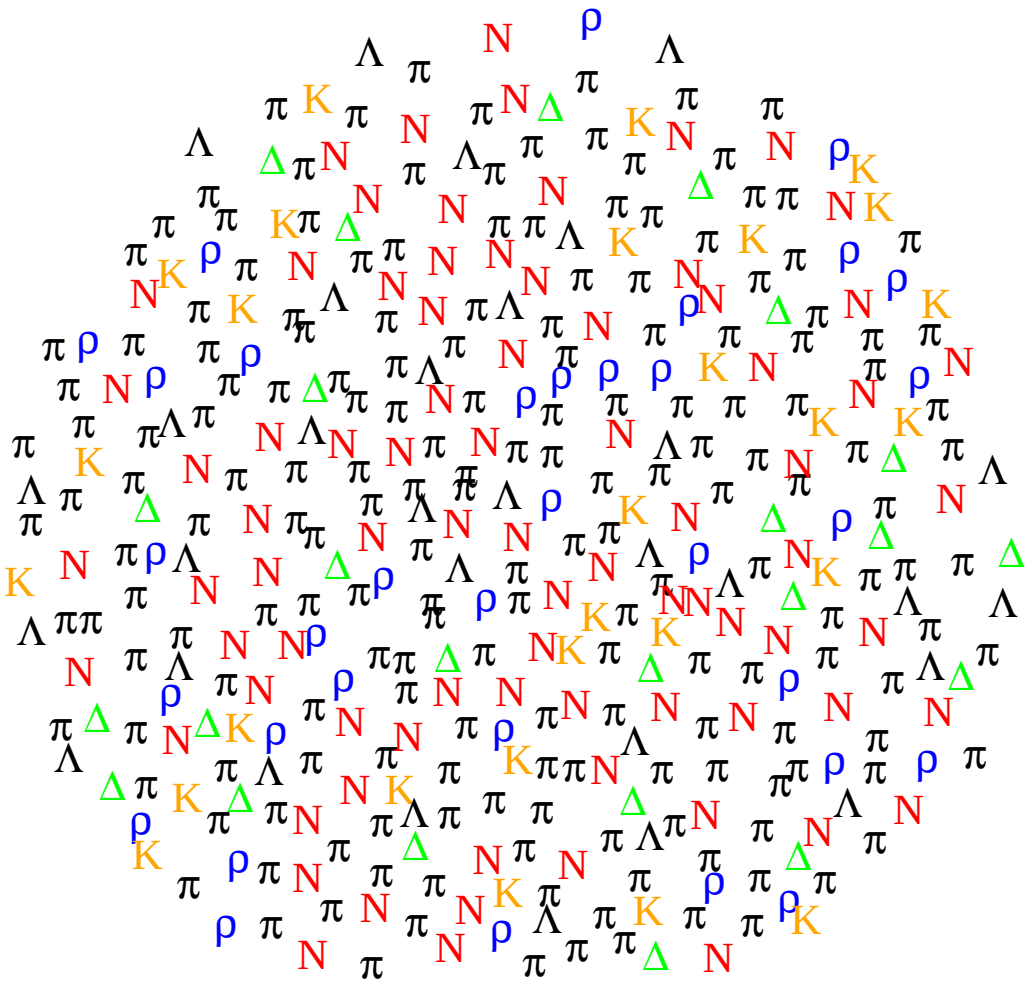
Outline

Work done in collaboration with:
Francesco Becattini,
Antti Keränen,
Ingrid Kraus,
Helmut Oeschler,
Jörg Randrup,
Krzysztof Redlich,
Helmut Satz,
Natasha Sharma,
Esko Suhonen,
Spencer Wheaton.

Hadronic Gas



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

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

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

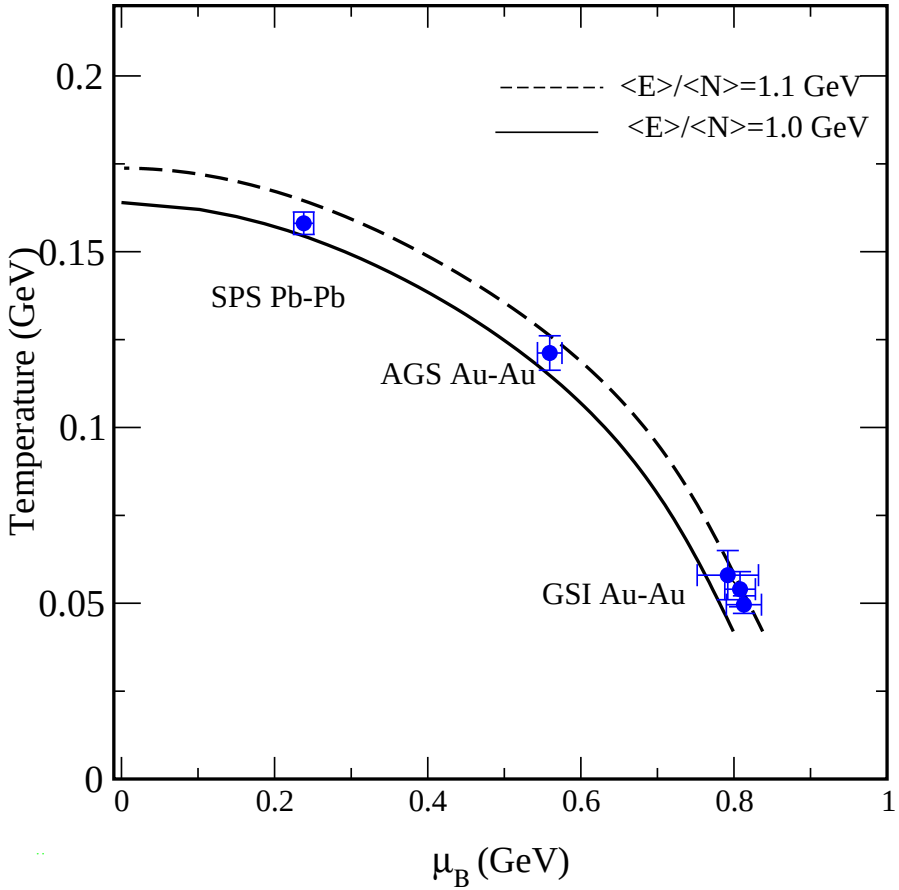
SPS data.

SPS: Freeze-Out Parameters:

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

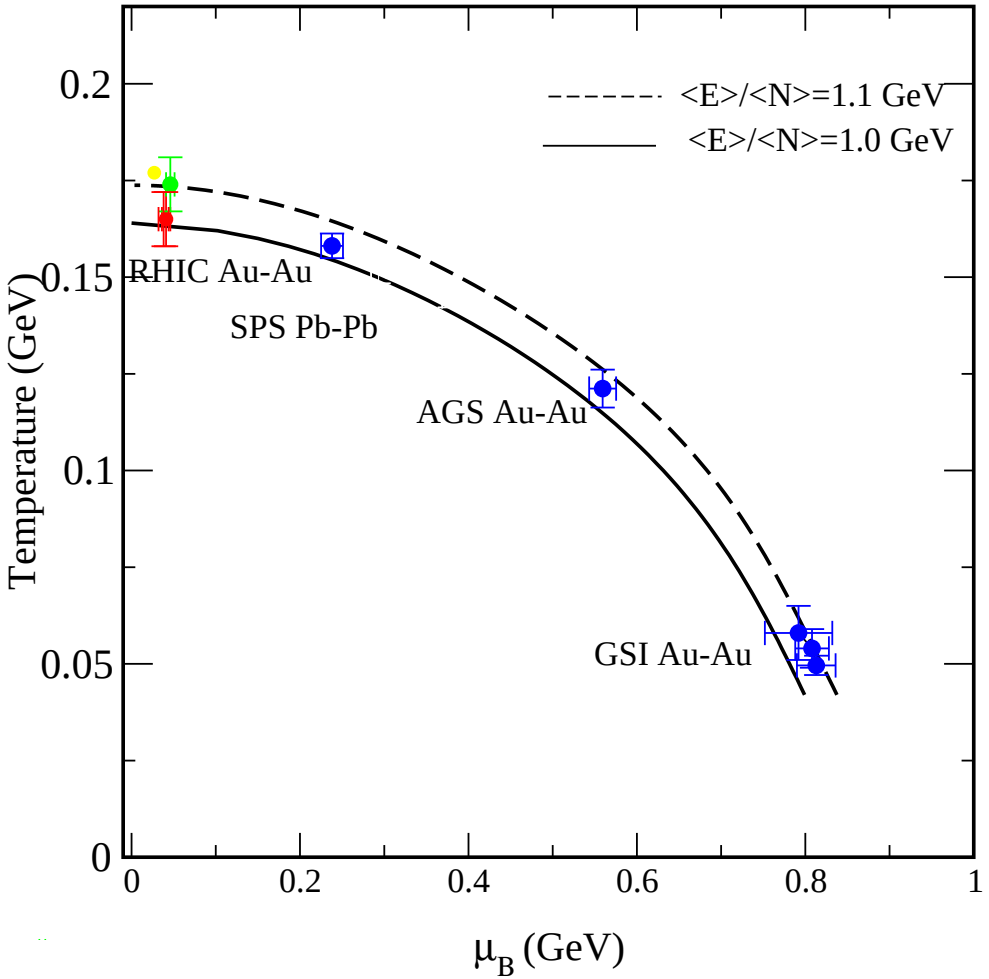
F. Becattini, J.C., A. Keränen, E. Suhonen and K. Redlich
Physical Review C64 (2001) 024901.

E/N in 1999

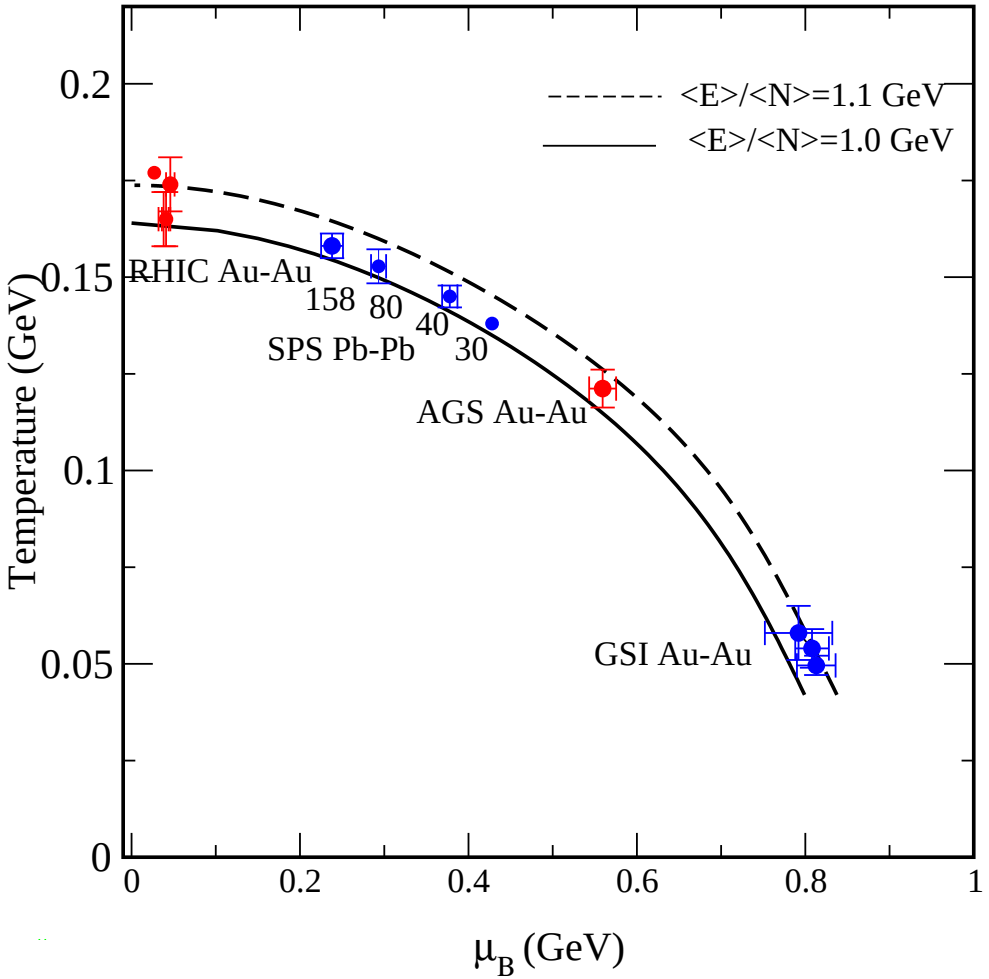


J. C., K. Redlich, PRL 24 (1998) 5284.

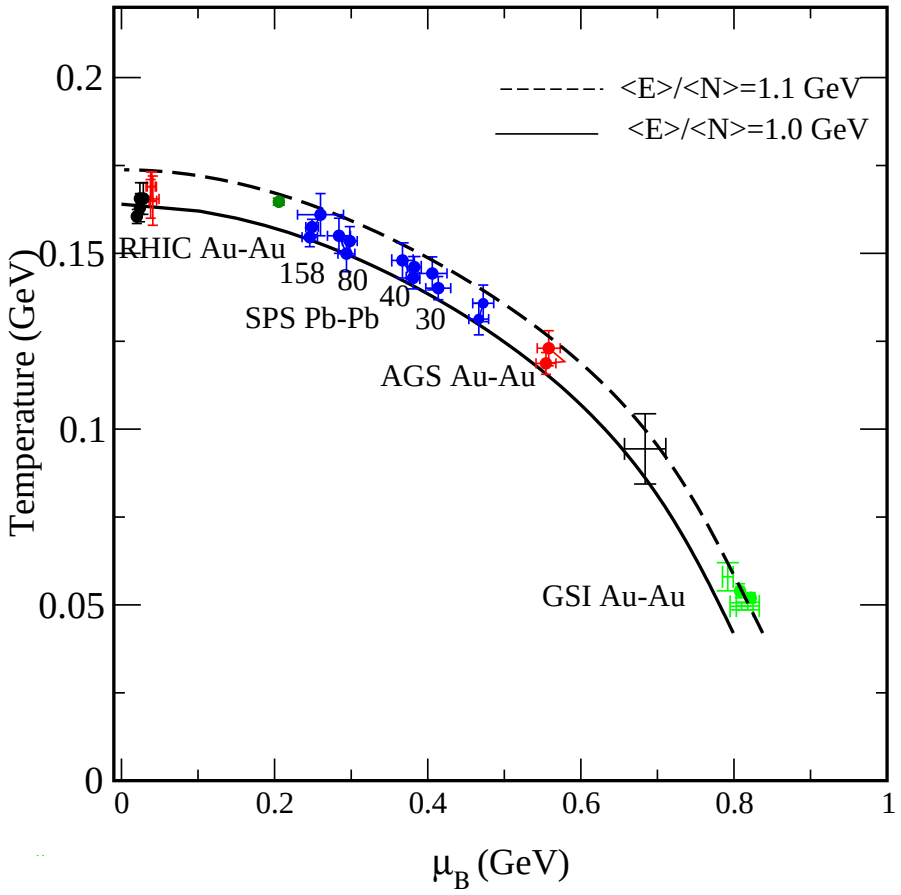
E/N in 2000


<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

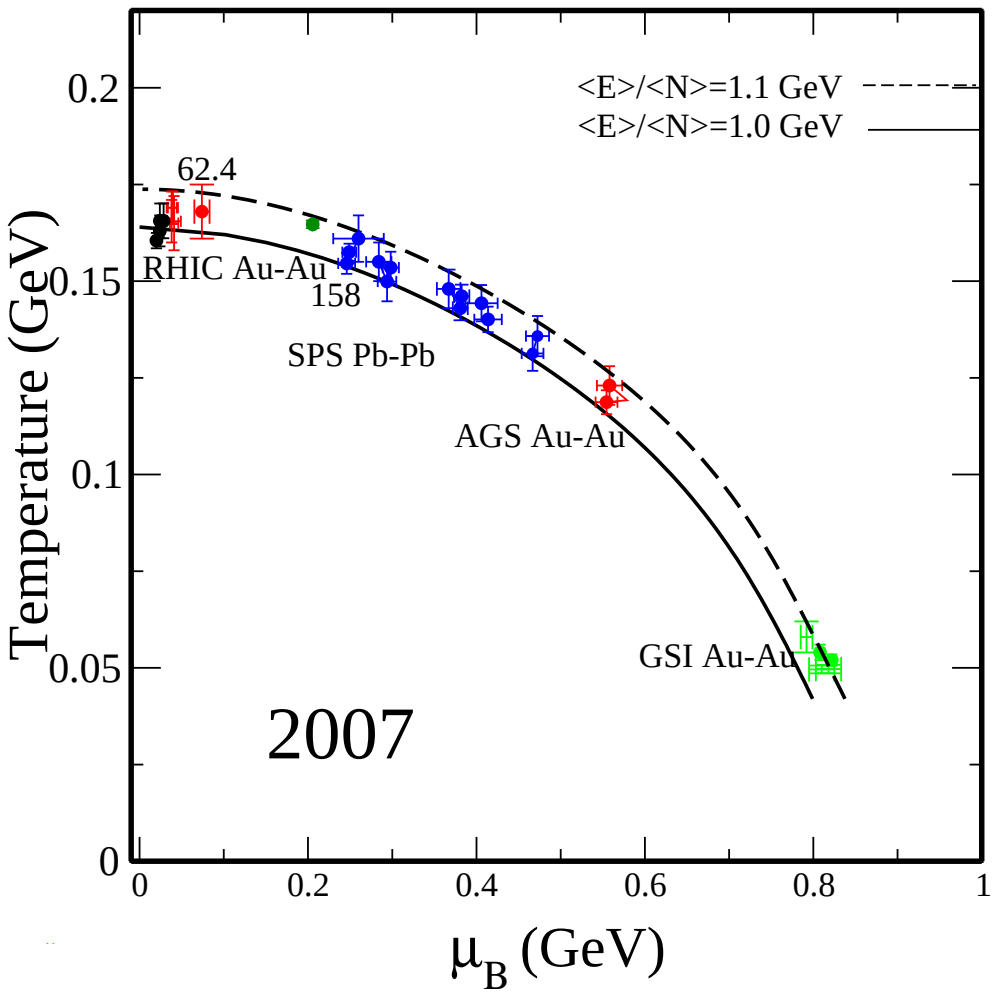

<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
RHIC Au-Au
158
80
40
30
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
Temperature (GeV)
μ_B (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1

E/N in 2006

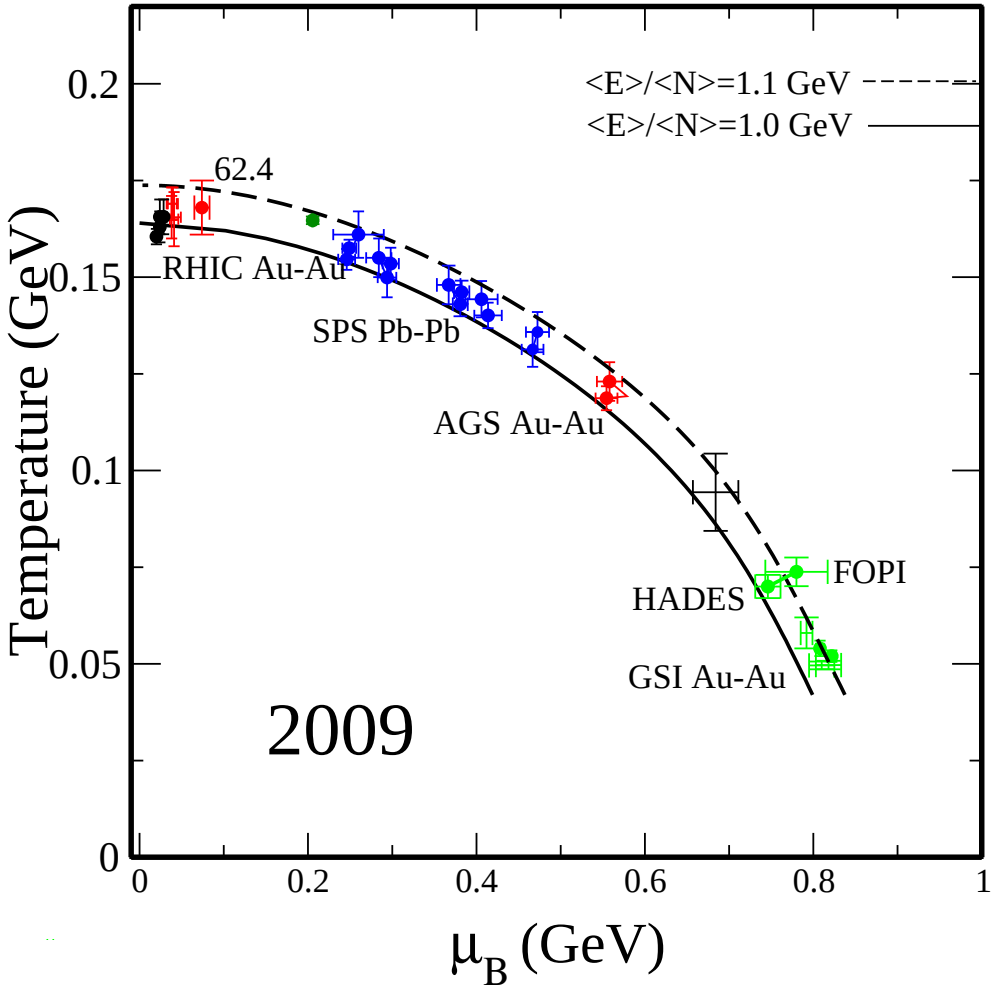


A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772, 167, 2006
J. Manninen, F. Becattini, M, Gazdzicki, Phys. Rev. **C73** 044905, 2006
J.C., K. Redlich, H. Oeschler, S. Wheaton, Phys. Rev. **C 73**, 034905 (2006).

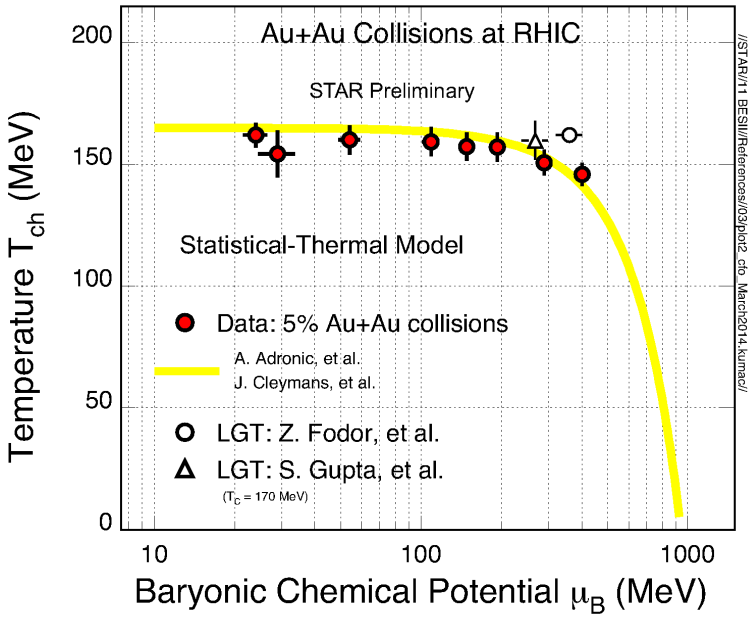
E/N in 2007


<E>/<N>=1.1 GeV
<E>/<N>=1.0 GeV
62.4
RHIC Au-Au
158
SPS Pb-Pb
AGS Au-Au
GSI Au-Au
2007
Temperature (GeV)
μB (GeV)
0
0.05
0.1
0.15
0.2
0
0.2
0.4
0.6
0.8
1

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

Beam Energy Scan at RHIC



BES-I

Year 2014

$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39
μ_B (MeV)	420	315	260	205	155	115

Observables:

Phase boundary

Charge separation;
v_2 - NCQ scaling

1st order phase transition

Directed flow v_1

Critical point

Fluctuations

Chiral symmetry restoration

Di-lepton production

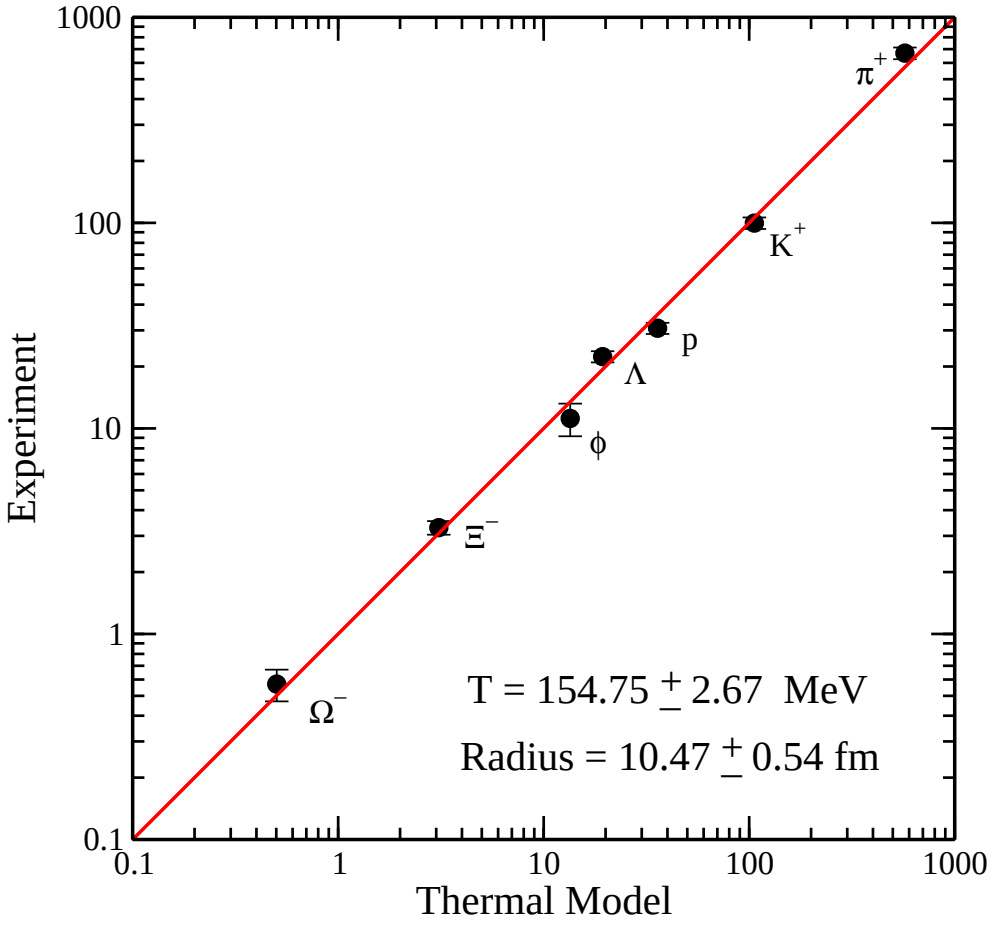
Study QCD Phase Structure!

Daniel McDonald: July 29 [FAIR workshop]

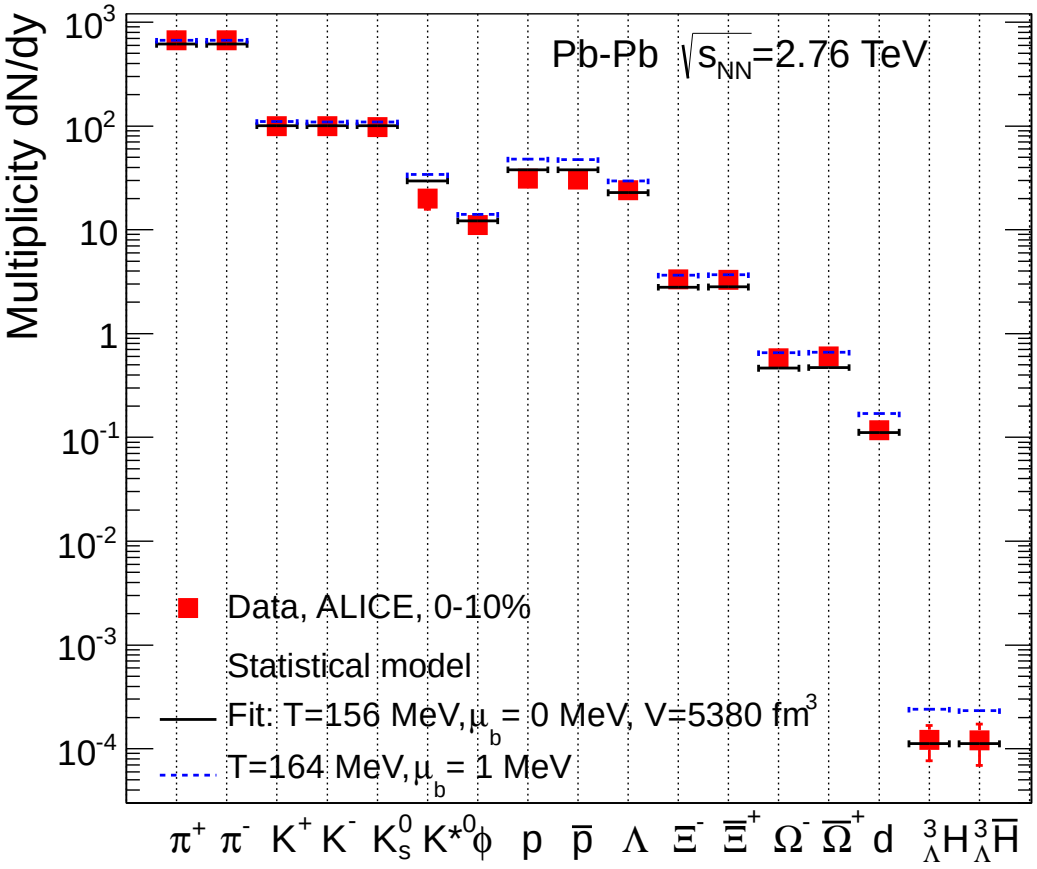
Shusu Shi (for the STAR Collaboration) ICNFP2014
J.C., K. Redlich, H. Oeschler, S. Wheaton, Phys. Rev. **C 73**, 034905 (2006)

A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. **A772**, 167, 2006

ALICE 2013


1000
100
10
1
0.1
Experiment
0.1
1
10
100
1000
Thermal Model
π+
K+
p
Λ
ϕ
Ξ−
Ω−
T = 154.75 ± 2.67 MeV
Radius = 10.47 ± 0.54 fm

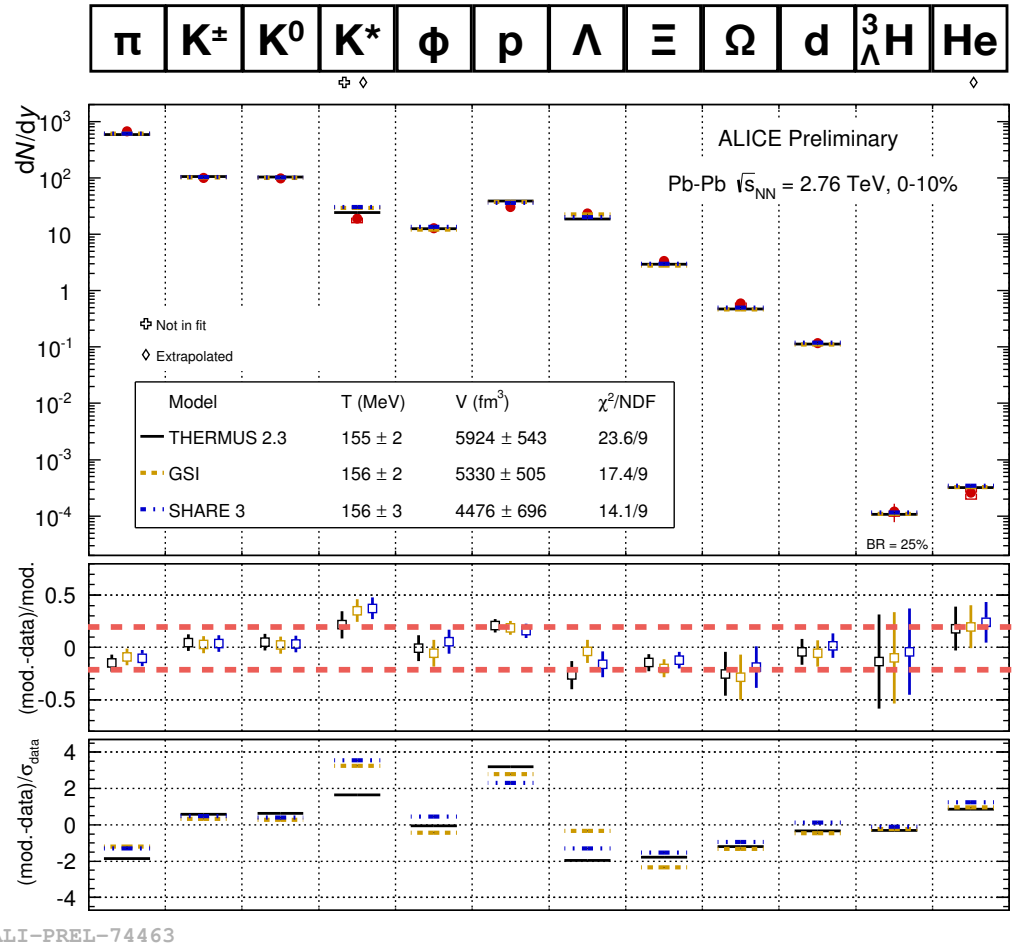
ALICE 2013



J. Stachel, A. Andronic, P. Braun-Munzinger, K. Redlich, SQM2013, J. Phys. Conf. Series 509 (2014) 012019

2014

Equilibrium SHM Fits



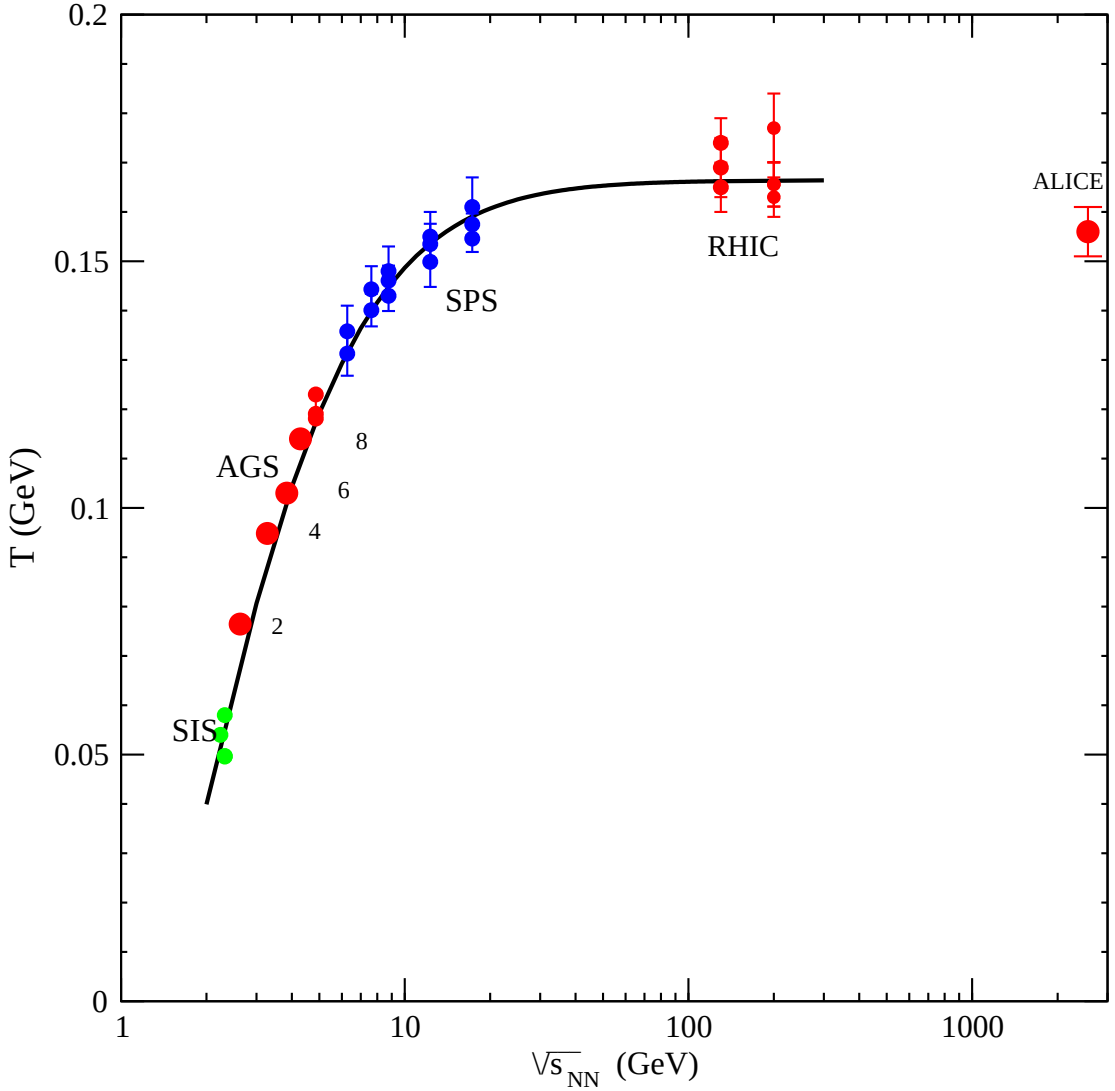
N.B.
RHIC
$\sqrt{s}$ = 200 STAR
χ^2/NDF~1

Better fit in
60-80%,
(feel free to ask about it)

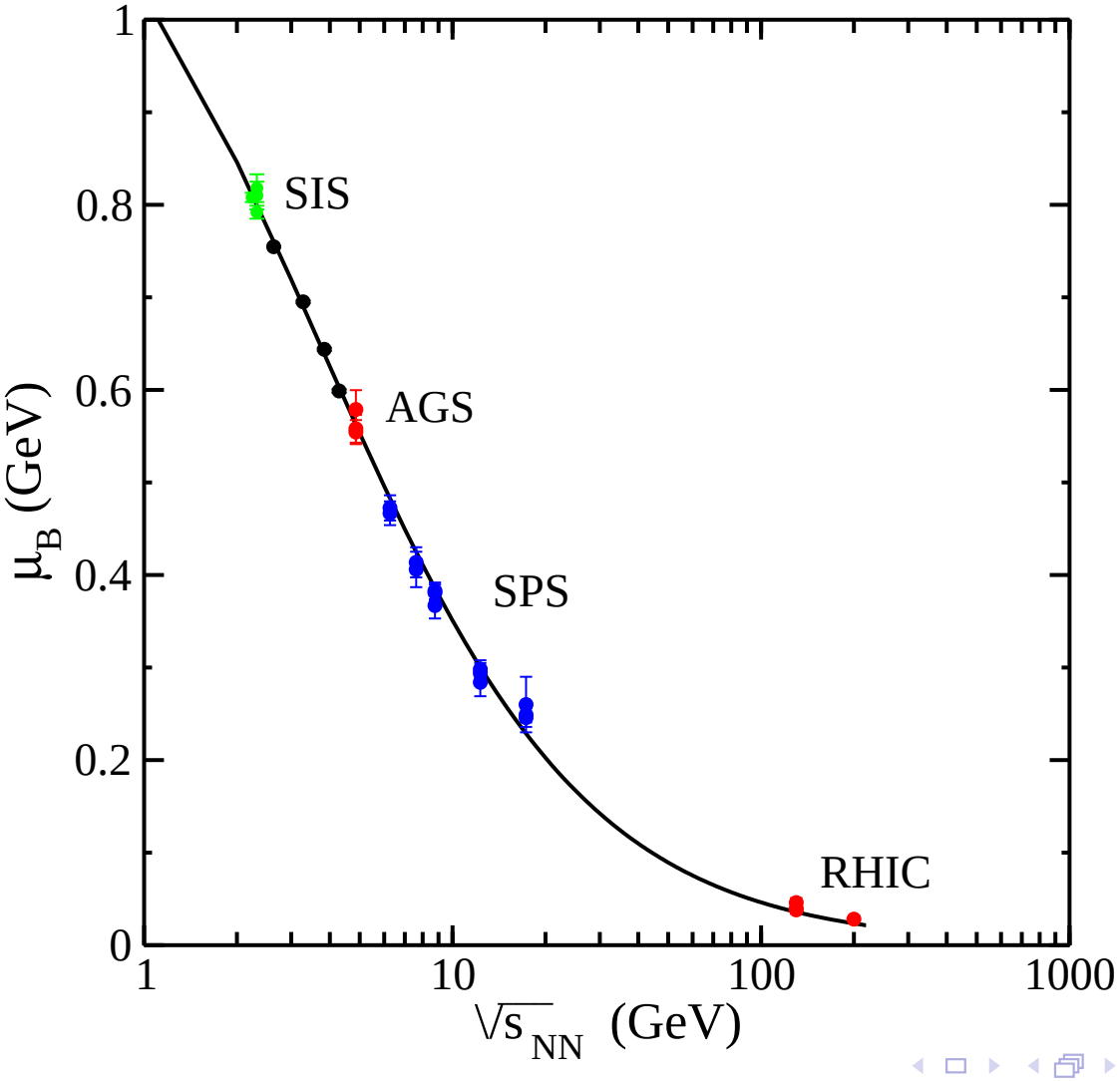
Petran et al, arXiv:1310.5108
Wheaton et al,
Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

M. Floris, QM2014

Chemical Freeze-Out Temperature

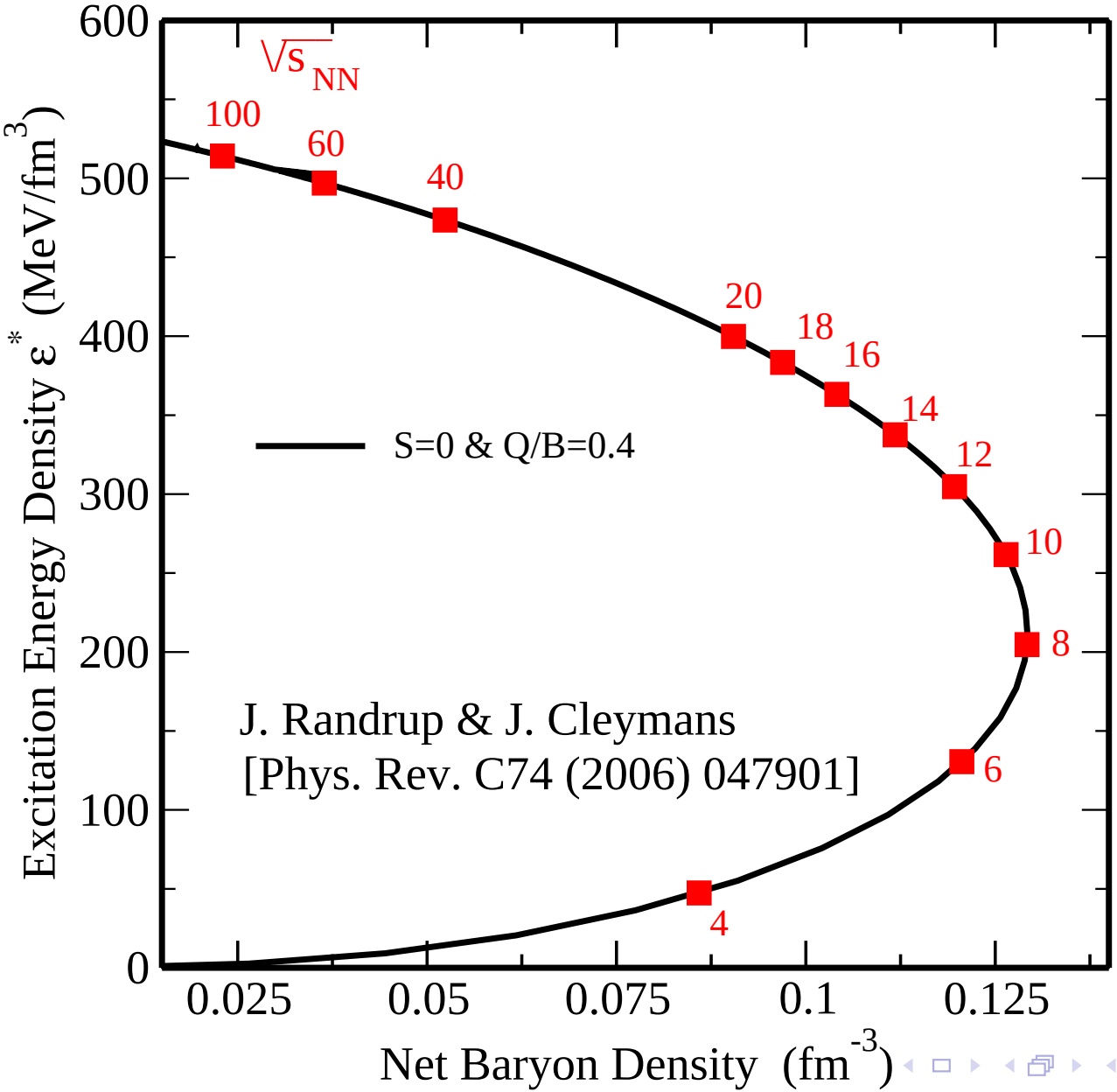


Chemical Freeze-Out μ_B

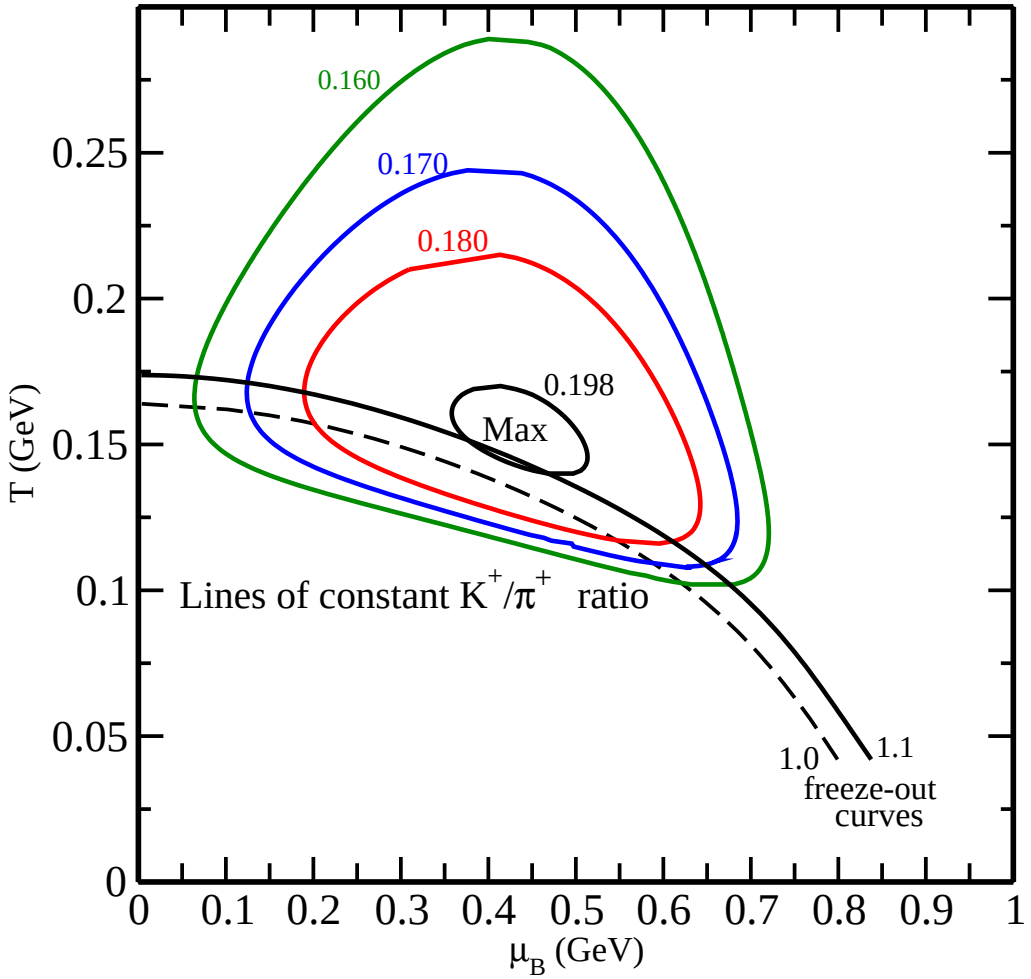


Hadronic Freeze-Out

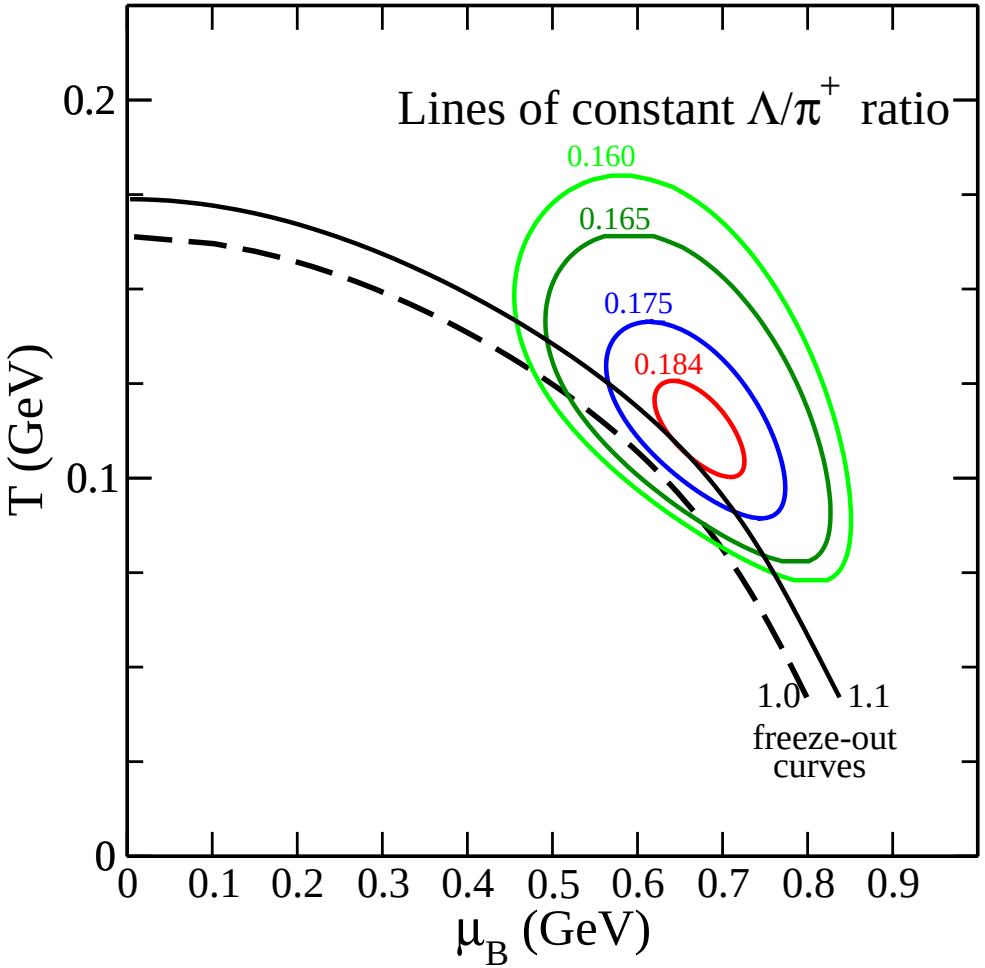
$\varepsilon^* = \varepsilon - m_N \rho$



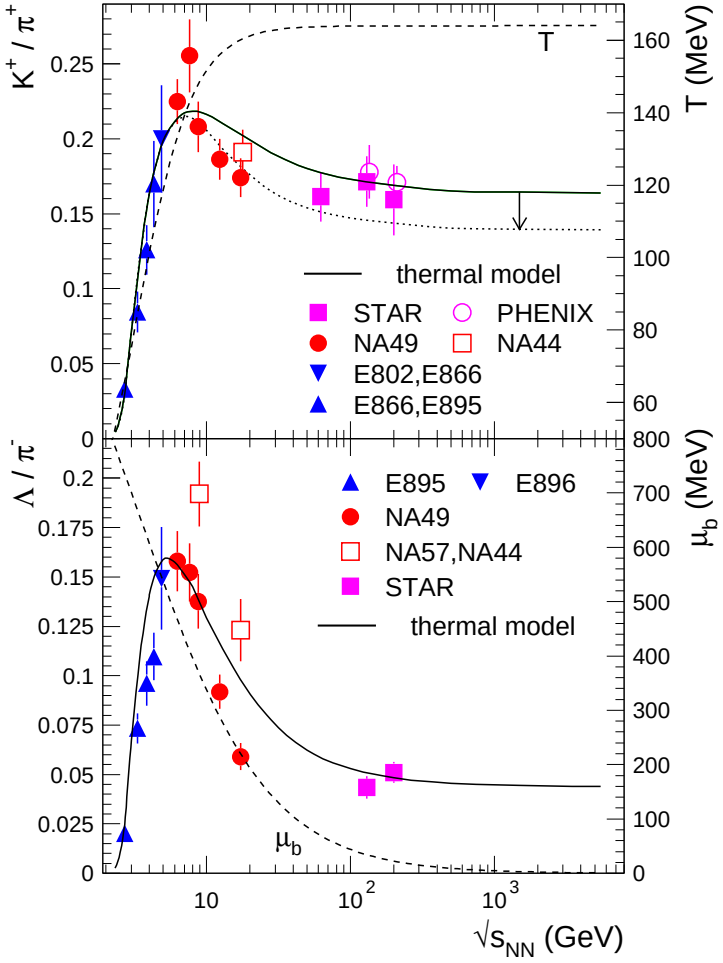
Maxima in particle ratios : K^+/π^+



Maxima in particle ratios : Λ/π^+



Maxima in particle ratios



A. Andronic, P. Braun-Munzinger, J. Stachel, Phys. Lett. B673 (2009) 142.

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

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, each one at a different beam energy!

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