NICA Physics - theory

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The First Collaboration Meeting of the MPD and BM@N
Experiments at the NICA Facility,
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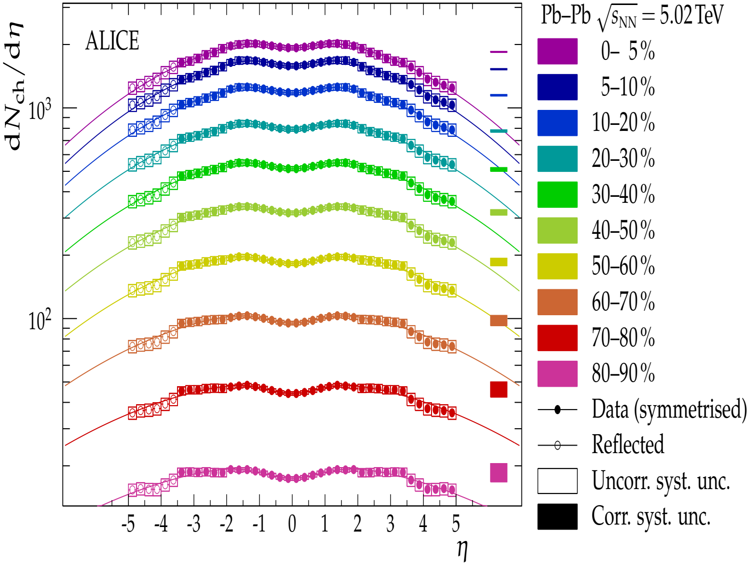
Outline

Particle Multiplicity in Heavy Ion Collisions



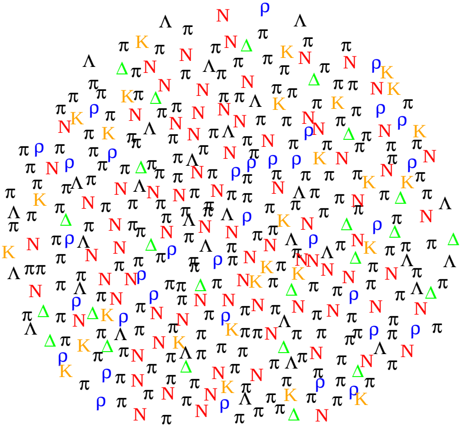
Particle Multiplicity in Heavy Ion Collisions

About 30 000 particles are produced in a heavy ion collision at the LHC.

Hence: Use Concepts from Statistical Mechanics to analyze the final state
e.g. use Energy Density, Particle Density, Pressure, Temperature, Chemical Composition, ...

These concepts turn out to be useful at all energies, RHIC, SPS, GSI ...

Hadronic Gas before Chemical Freeze-Out



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

The Theoretical Basis for the Thermal Model

Bjorken scaling + Transverse expansion

After integration over p_T (and ONLY! after integration over p_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.
The volume is given by $\pi R^2 \tau$!

The Theoretical Basis for the Thermal Model

The number of particles of type *i* is determined by:

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int d\sigma_\lambda p^\lambda \exp\left(-\frac{p^\mu u_\mu}{T}+\frac{\mu_i}{T}\right)$$

Integrating this over all momenta

$$N_i = \frac{g_i}{(2\pi)^3}\int d\sigma_\lambda \boxed{\int \frac{d^3p}{E}p^\lambda \exp\left(-\frac{p^\mu u_\mu}{T}+\frac{\mu_i}{T}\right)}$$

box must be a four-vector, only u^λ is available as a four-vector

$$\boxed{N_i = \int d\sigma_\lambda u^\lambda N_i^0(T,\mu)}$$

If the temperature and chemical potential are unique along the freeze-out curve

$$N_i = N_i^0(T,\mu)\int d\sigma_\lambda u^\lambda$$

The Theoretical Basis for the Thermal Model

In general

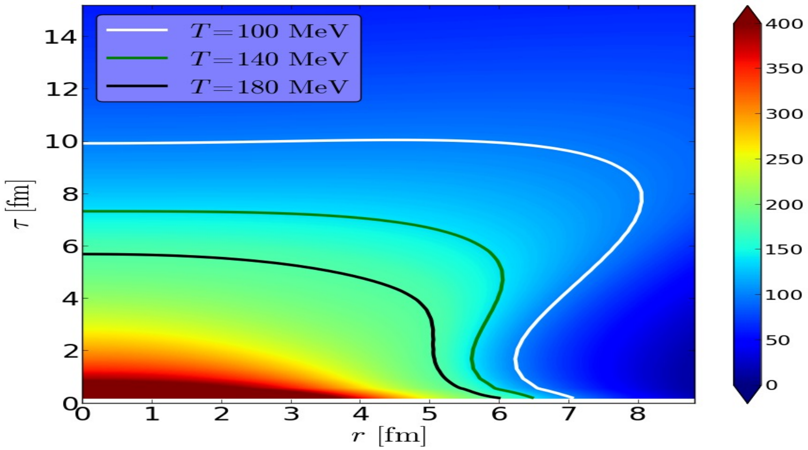
If hydrodynamics is the basic underlying mechanism, then,
after integration over p_T and y

$$\boxed{\frac{N_i}{N_j} = \frac{N_i^0}{N_j^0}}$$

where N_i^0 is the particle yield
as calculated in a fireball **AT REST!**

This is because N_i is a Lorentz invariant quantity unaffected by boosts and flows. This needs the freeze-out temperature to be the same for all particles which may not be the case always.

This does NOT mean that the freeze-out has to be instantaneous. The only requirement is that the freeze-out temperature has to be the same along the freeze-out curve.



H. Niemi and G.S. Denicol arxiv 1404.7327

Uncertainties in the Thermal Model

Uncertainties are related to the information in the Particle Data Booklet.
Particle yields are determined from:

$$N_i = \sum_j N_j Br(j \rightarrow i).$$

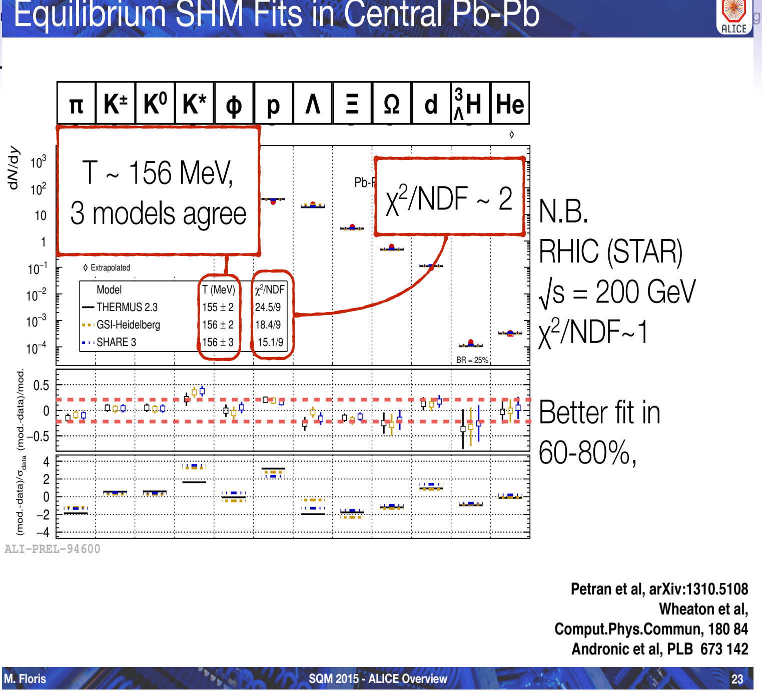
Hence one must know how hadronic resonances decay.

As an example, the final yield of π^+'s is given by

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

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

AL



Equilibrium SHM Fits in Central Pb-Pb

Model	T (MeV)	χ^2/NDF
THERMUS 2.3	155 ± 2	24.5/9
GSI-Heidelberg	156 ± 2	18.4/9
SHARE 3	156 ± 3	15.1/9

T ~ 156 MeV,
3 models agree

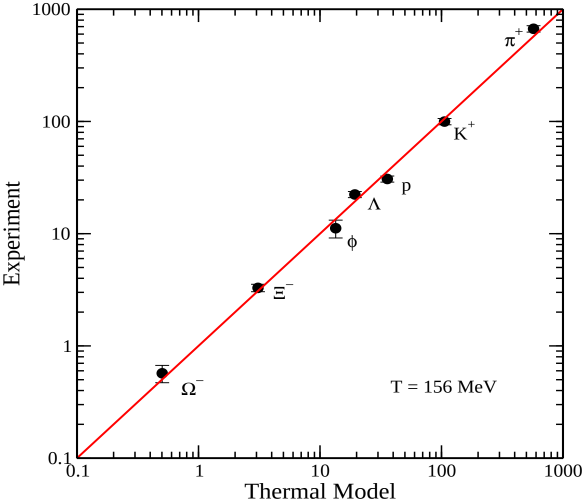
χ^2/NDF ~ 2

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

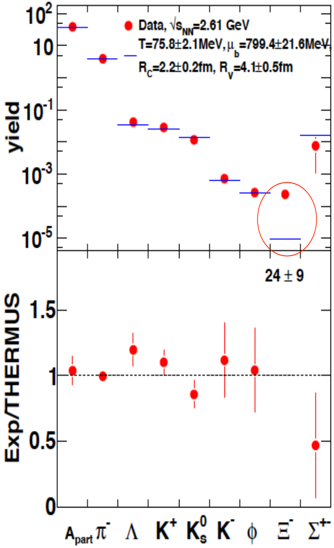
Better fit in
60-80%,

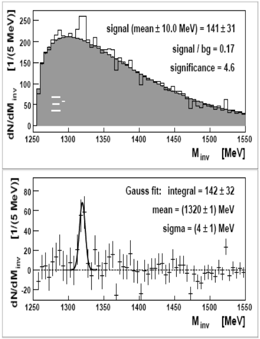
Petran et al, arXiv:1310.5108
Wheaton et al,
Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

ALICE


1000
100
10
1
0.1
Experiment
0.1
1
10
100
1000
Thermal Model
π^+
K^+
p
Λ
ϕ
Ξ^-
Ω^-
T = 156 MeV

Hadrons in Ar+KCl@1.76A GeV



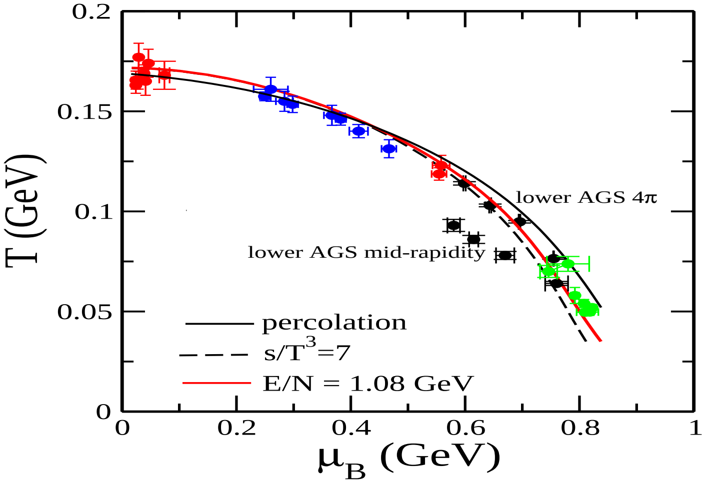


Strong excess of the Ξ^-

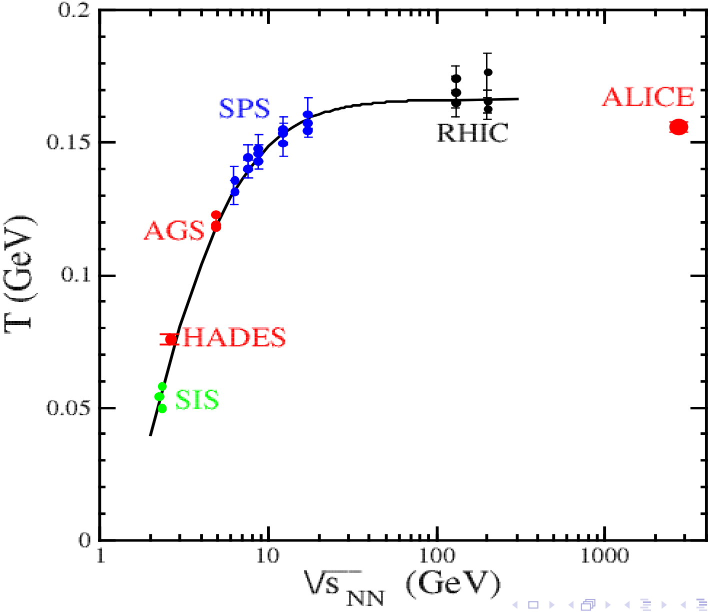
NN-threshold:
E_{beam}= 3.74GeV →$\sqrt{s}$-$\sqrt{s_{th}}$=-630MeV!

THERMUS: S. Wheaton, J.Cleymans: Comput.Phys.Commun.180:84-106,2009

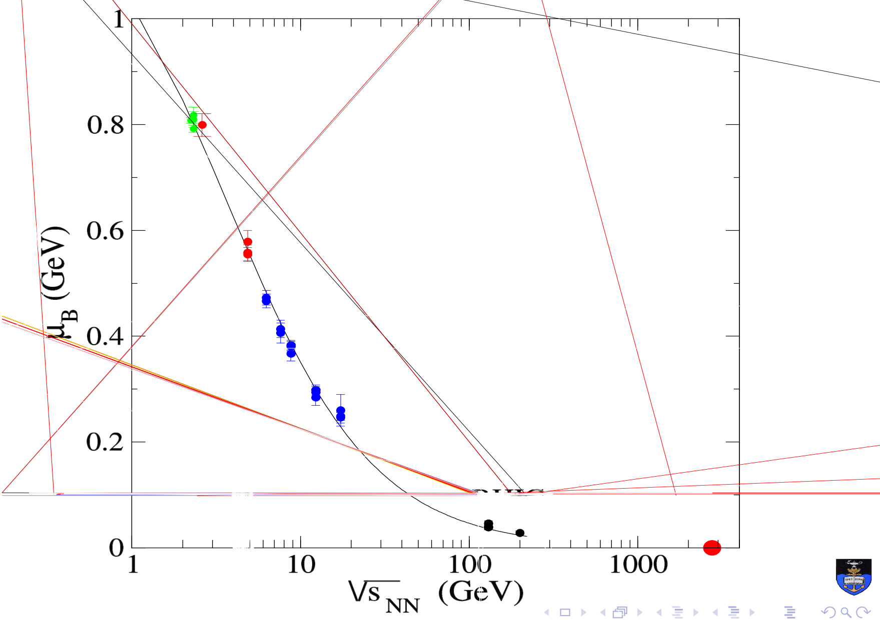
Chemical Freeze-Out: Criteria



Chemical Freeze-Out Temperature



Chemical Freeze-Out μ_B

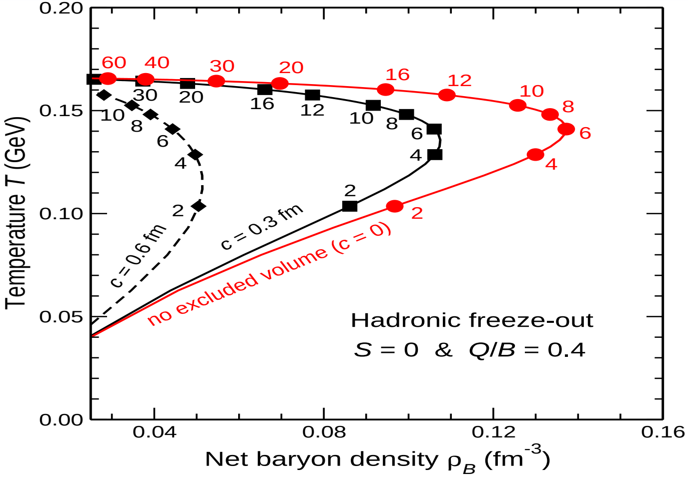


μ_B as a function of $\sqrt{s_{NN}}$

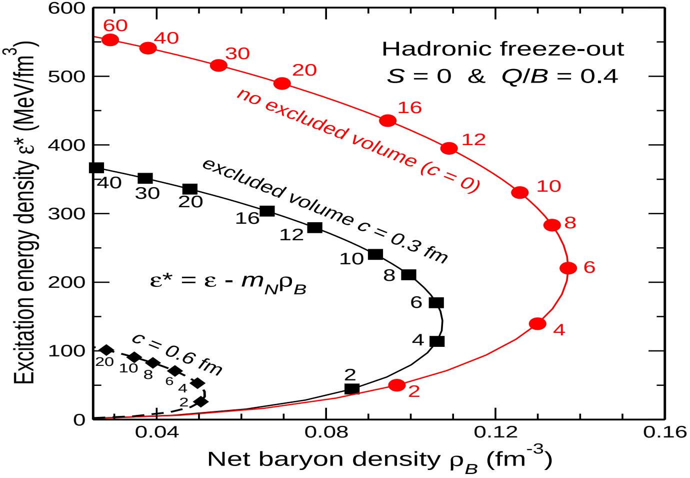
$$\mu_B(\sqrt{s}) = \frac{1.308\ \mathrm{GeV}}{1 + 0.273\ \mathrm{GeV}^{-1}\sqrt{s}}.$$

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

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



J. Randrup and J.C., Eur. Phys. J. A **52** (2016) 218.



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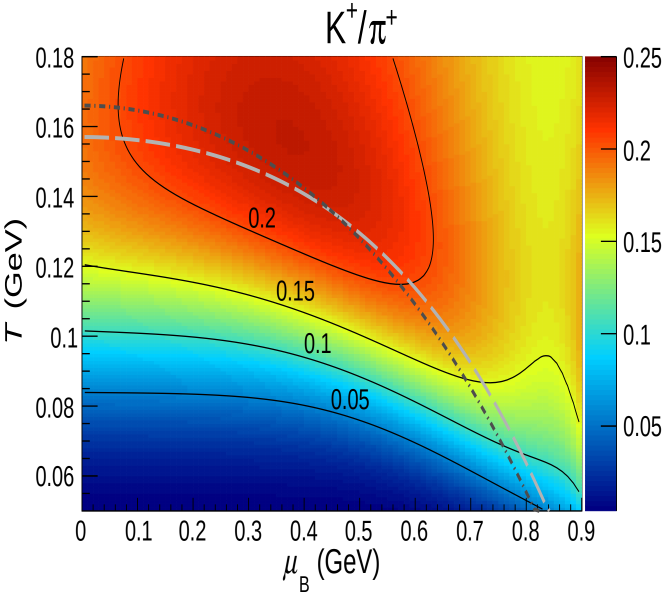
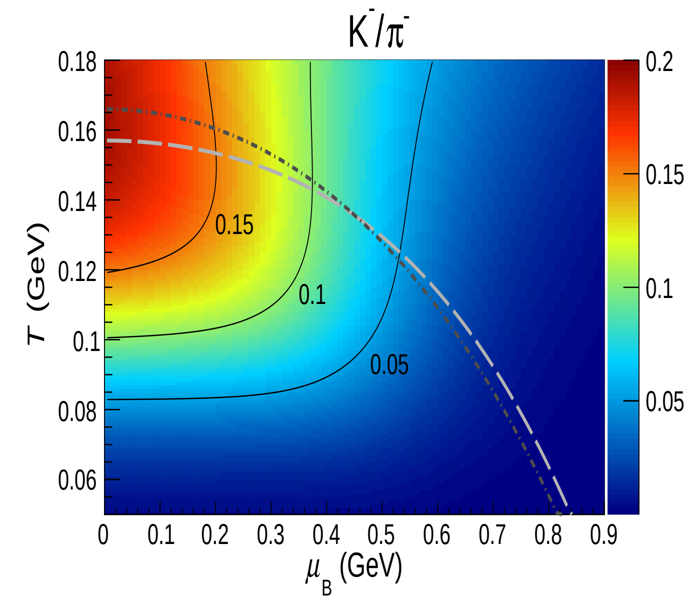


H. Oeschler, J.C., B. Hippolyte, K. Redlich and N. Sharma



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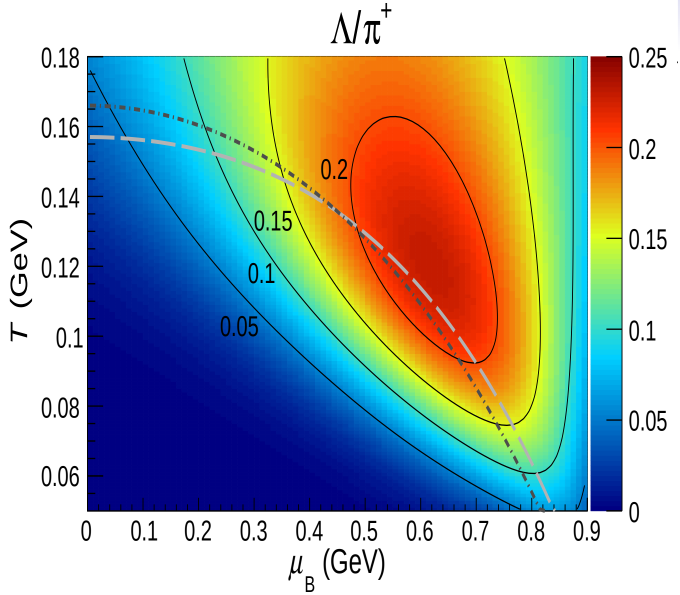
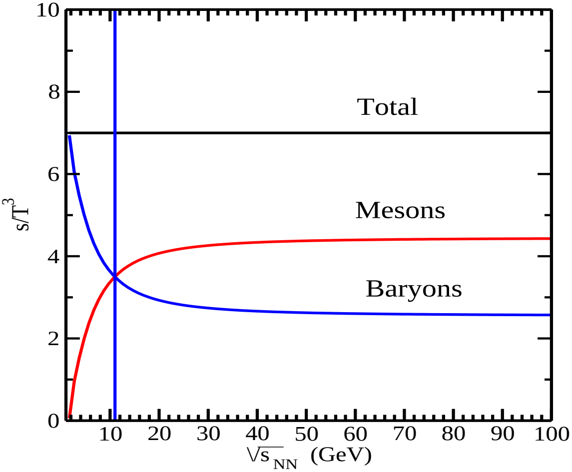
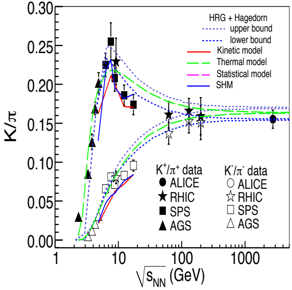

Λ/π^+
0.18
0.16
0.14
0.12
0.1
0.08
0.06
T (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
μ_B (GeV)
0.05
0.1
0.15
0.2
0.25
0.2
0.15
0.1
0.05
0

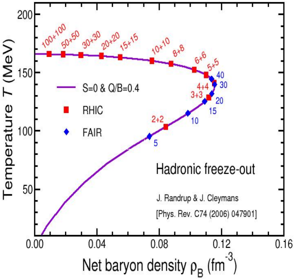
s/T^3



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

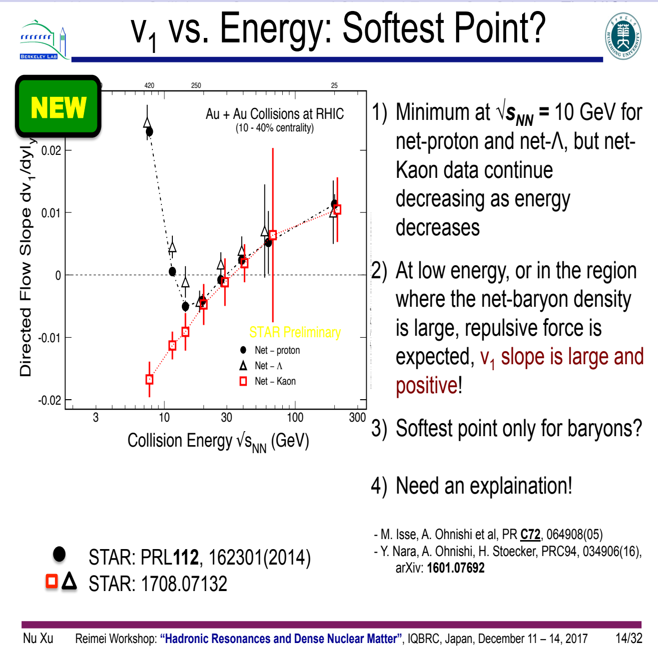
K/π Ratios and Baryon Density





1) The $\mathbf{K^+/\pi}$ ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV,
   $\mathbf{K^-/\pi}$ ratio merges with $\mathbf{K^+/\pi}$ at higher collision energy
2) Model: Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV
3) At **$\sqrt{s_{NN}}$ > 8 GeV, pair production becomes important**

STAR: 1701.07065; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)



v_1 vs. Energy: Softest Point?

1) Minimum at $\sqrt{s_{NN}}$ = 10 GeV for net-proton and net-Λ, but net-Kaon data continue decreasing as energy decreases

2) At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive!

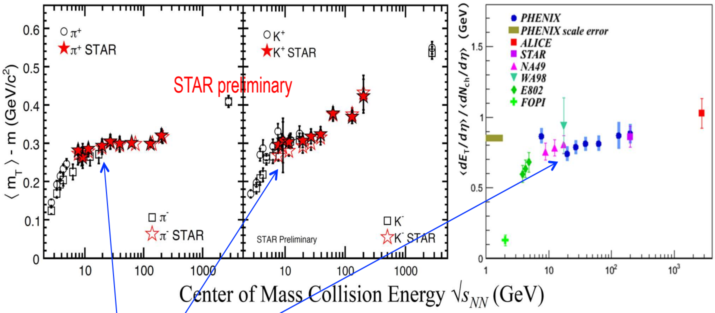
3) Softest point only for baryons?

4) Need an explaination!

● STAR: PRL**112**, 162301(2014)
🟥 △ STAR: 1708.07132

- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)
- Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16), arXiv: **1601.07692**

plateau in $<m_T>$



- $<m_T>$ - m is a measure of the thermal excitation, i.e. temperature
- observed plateau in $<m_T>$ is characteristic of a 1st order phase transition
- dN/dy ~ $\ln(\sqrt{s_{NN}})$ may represent the entropy
- E_T includes mass and is assocaited with the energy density

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

However,

the sharpness of the peak in the K^+/π^+ ratio suggests that something more is happening.

Also, in the thermal model this transition leads to peaks in the $\Lambda/\langle\pi\rangle$, K^+/π^+, Ξ^-/π^+ and Ω^-/π^+ ratios which occur at different beam energies.

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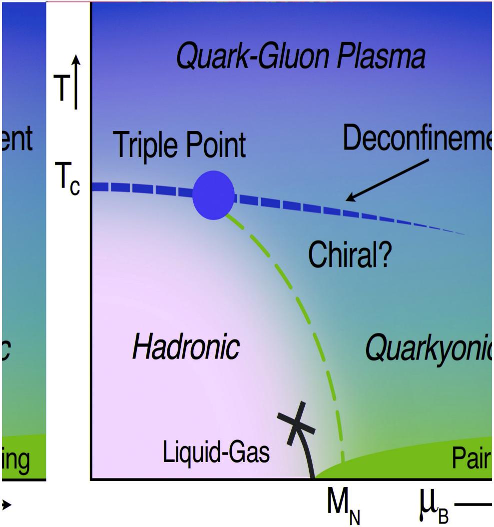

R. Pisarski and L. McLerran

Conclusions

- Maximum in K^+/π^+ ratio is in the NICA energy region,
- Maximum in Λ/π ratio is in the NICA energy region,
- Maximum in the net baryon density is in the NICA energy region,
- Transition from a Baryon dominated system to a Meson dominated one happens in the NICA energy region.

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Good Luck NICA, MPD and BM@N