Probing the Thermal Nature of Matter formed at RHIC via Fluctuations

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Outline:

- Introduction and Motivation
- Model and Methodology
- Results
- Summary

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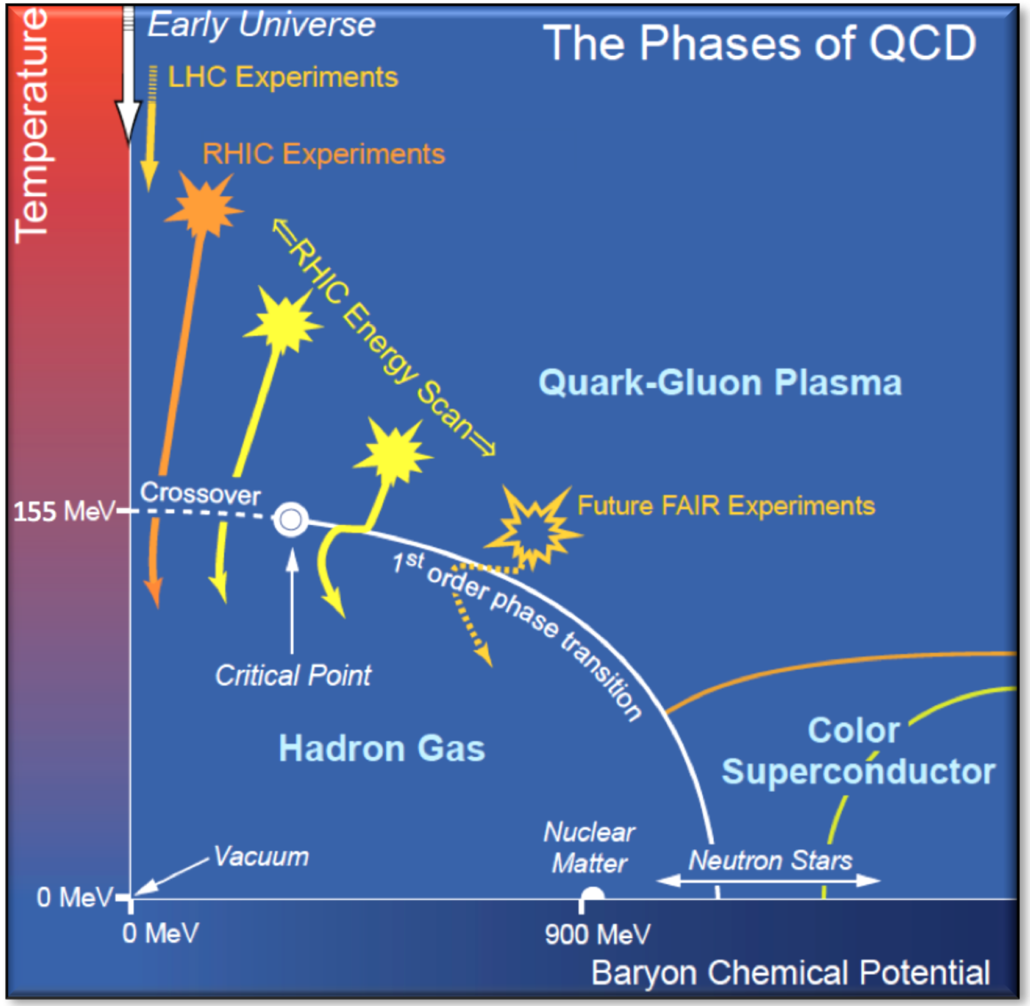
Introduction

- ❑ At $\mu_B = 0$, transition is a Cross-over.
- ❑ At finite μ_B , 1st order phase transition.
- ❑ Possible Critical point at the end of 1st order line.

Y.Aoki et al., Nature 443 (2006) 675–678

Transition temperature, $T_C = 155 \pm 9$ MeV: Lattice QCD

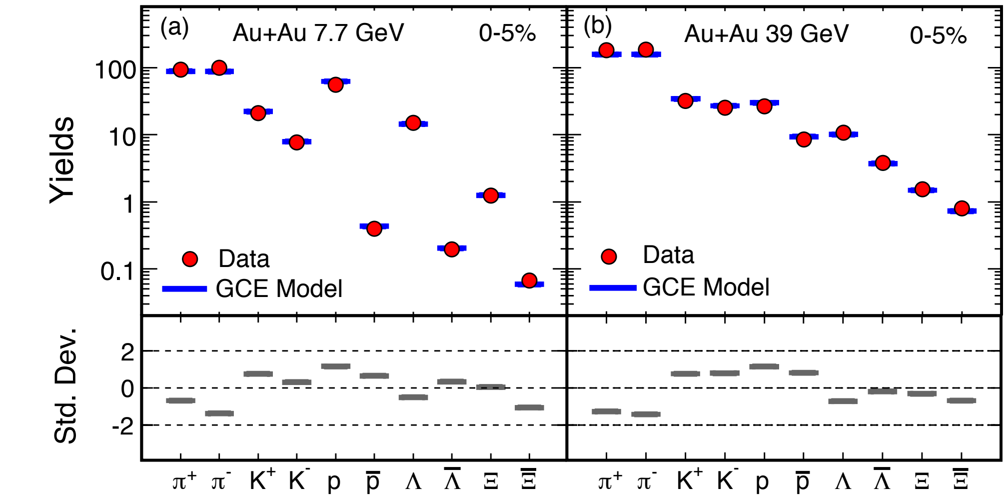
- ❖ Theory calculations performed in thermal / near-thermal equilibrium scenarios.
- ❖ Experiments (e.g. at RHIC) study the property of this system at various collision energies to map the QCD phase diagram.
- ❖ To establish creation of Quark-Gluon Plasma, one looks for thermal signatures of de-confined states of matter.



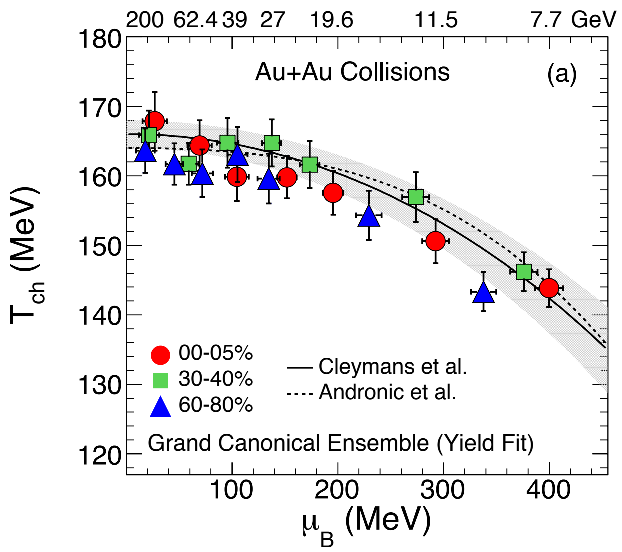
The Hot QCD White Paper (2015): arXiv:1502.02730

✓ To explore the QCD phase diagram, the assumption of thermal equilibrium is utilized.

Current Status



STAR: Phys.Rev.C 96, 044904

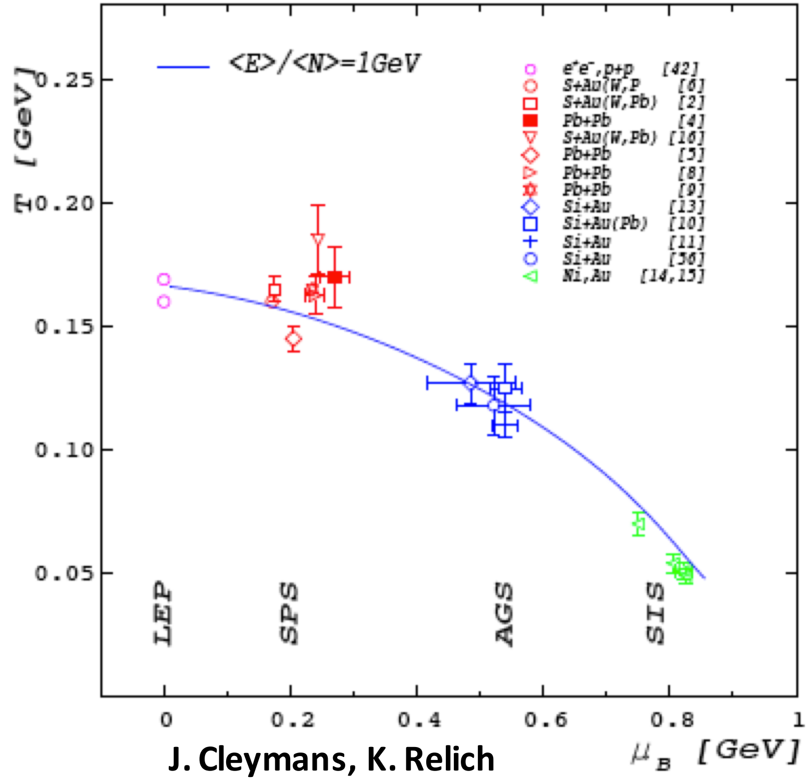


Particle yields and their ratios are explained quite well by Thermal Models.

- ❖ Hadronic yields in most central Au+Au collisions explained by thermal model for $\gamma_S = 1$.

Could this be an unique and sufficient test ?

Thermal model also fits the data from e+e-, p+p collisions.



J. Cleymans, K. Relich
Phys.Rev.C60:054908,1999

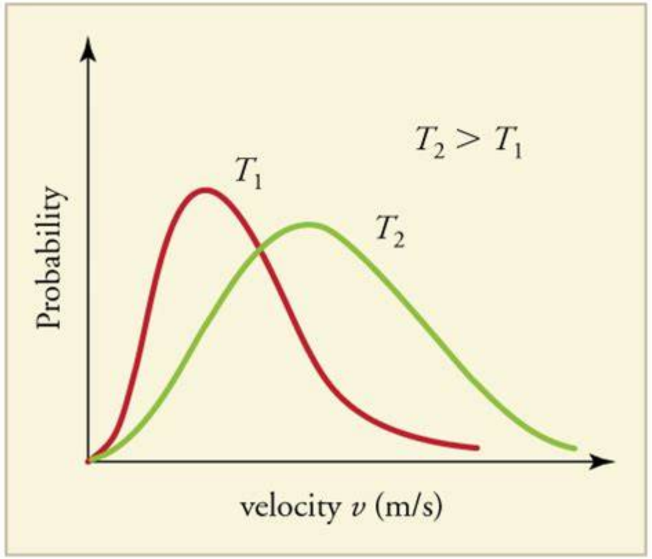
- ✓ We need more observable to probe finer into the thermal nature of the system.
- ✓ Higher order fluctuations of conserved charges could act as those probes.

Motivation

Distribution uniquely defined by its all order moments

System in thermal equilibrium <==> All order moments of the distribution should yield similar thermodynamic conditions

M.B. velocity distribution



In a static thermal model of hadrons and resonances, given the thermodynamic parameters, all orders of number susceptibility can be calculated.

System: Au + Au collisions at RHIC for $\sqrt{s_{NN}}$ = 7.7 to 200 GeV

Observables: Moments of conserved charge distributions

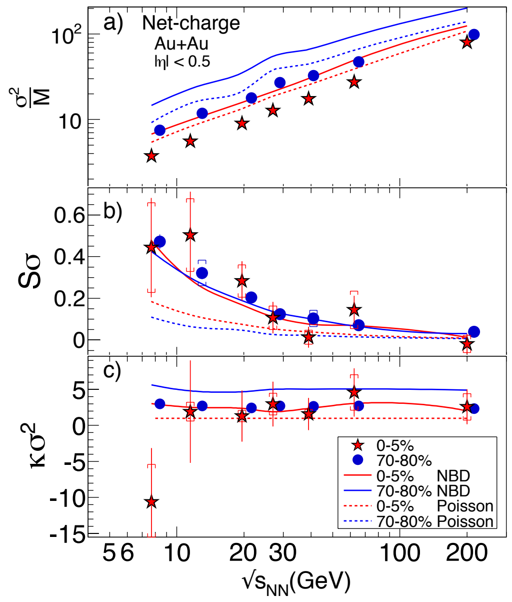
Challenges with the system formed in experiments:

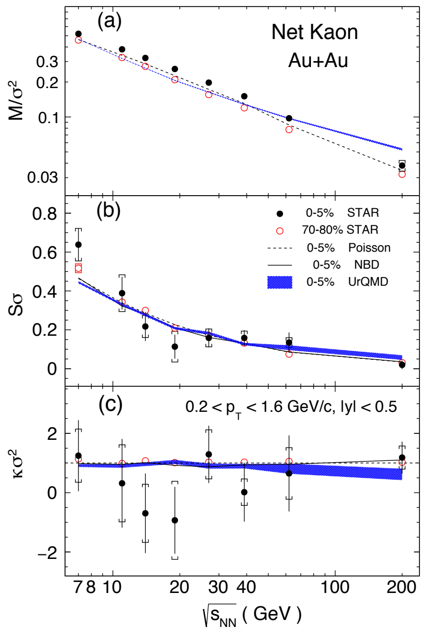
a) Small and Evolving system
b) Different parts of the distribution may evolve differently due to different *relaxation times.

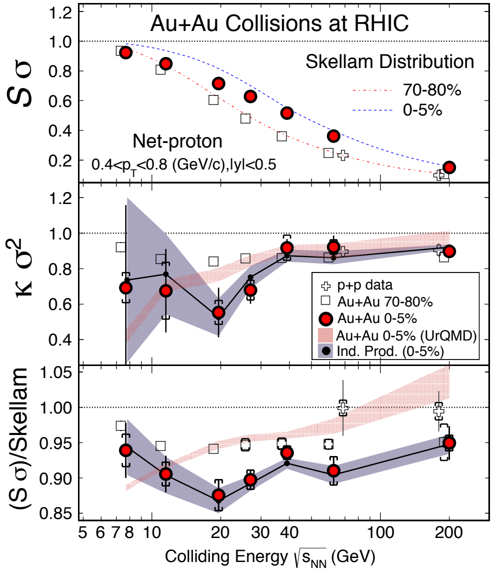
*Relaxation time depend on detail of microscopic interaction

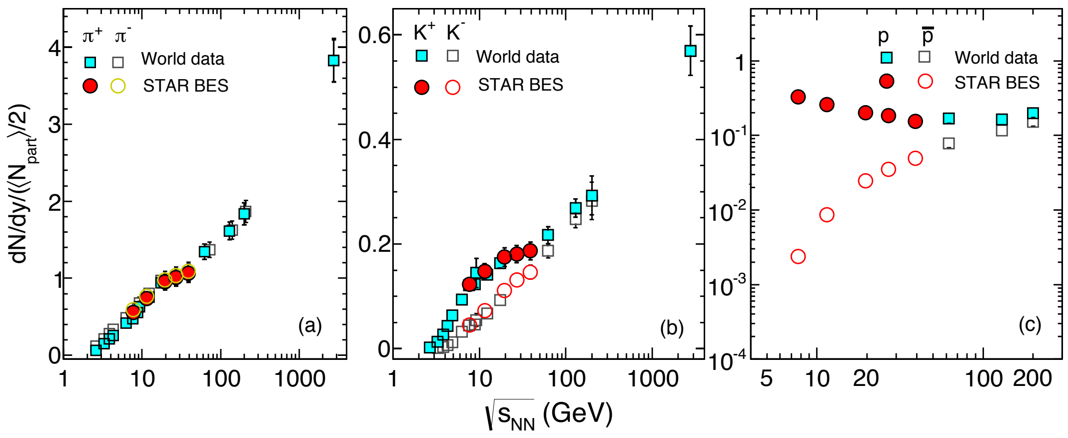
Experimental Data from STAR

STAR: Phys.Rev.C 96, 044904 (2017)









STAR: Phys. Rev. Lett. 113, 092301 (2014)
STAR: Phys. Rev. Lett. 112, 032302 (2014)
STAR: Phys. Lett. B785, 551 (2018)

STAR data: Au + Au Collisions (0 – 5%) at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV

Order	Observables
First	M_π, M_K, M_P : 6 - Observables
Second	$\frac{\sigma^2}{M}(NC)$, $\frac{\sigma^2}{M}(NK)$, $\frac{\sigma^2}{M}(NP)$: 3 - Observables
Third	$S\sigma(NC)$, $S\sigma(NK)$, $S\sigma(NP)$: 3 - Observables

Thermal Model

Grand Canonical - Average conservation of B, S, and Q

Partition Function :

$$\ln Z_i(T,\mu_i,V) = a\frac{Vg_i}{2\pi^2}\int d^3p \ln\left(1 + a\exp\left(\frac{\mu_i - E}{T}\right)\right)$$

"a" is +1 (-1) for baryons (mesons) .

Pressure : $P(T,\mu) = \sum_i \frac{T}{V}\ln Z_i(T,\mu_i,V)$

The nth order generalized susceptibilities for any species x : $\chi_x^n = \frac{d^n\left[\frac{P(T,\mu)}{T^4}\right]}{d\left(\frac{\mu_x}{T}\right)^n}$

Relationship Between Thermodynamic Susceptibility and Cumulants:

$$C_X^n = \left(\frac{V}{T}\right)T^n\chi_X^{(n)}(T,\mu_B)$$

C_n^X s are the cumulants of the distribution of conserved charges.

- Susceptibility ratios are calculated employing proper kinematical acceptances as used in experiment
- Particles listed in PDG with mass up to 2.5 GeV are included in the model
- All particles obey free particle dispersion relation

Methodology

Extract Freeze-out Parameters: $\mathbf{T}$, $\boldsymbol{\mu_B}$, $\boldsymbol{\mu_S}$, $\boldsymbol{\mu_Q}$ at each $\sqrt{s_{NN}}$

Chi - squared Minimization: $\chi^2 = \sum \left(\frac{R_i^{exp} - R_i^{Model}}{E_i^{exp}} \right)^2$

$\frac{\sigma^2}{M}$ of net-proton and net-charge are not properly explained.

Mishra, D.K et al., Phys. Rev. C94, 014905 (2016)
Nahrgang, M. et al., Eur. Phys. C75, 573 (2015)
Alba, P. et al., Phys. Lett. B738, 305 (2014)

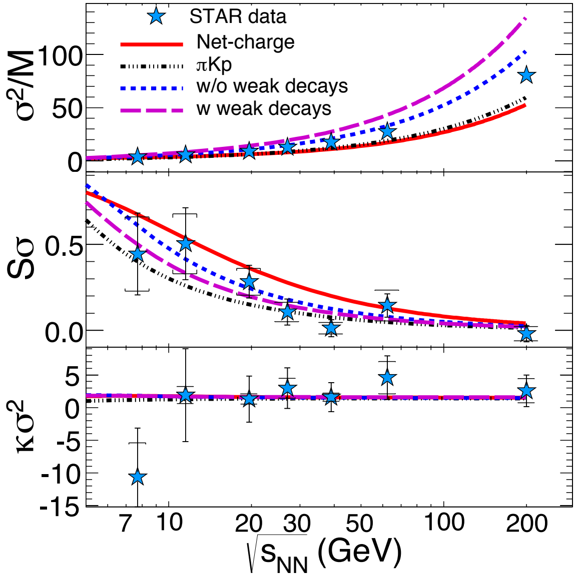
Reason: acceptance limitation in the measurements to handle decay kinematics.

Final 10 Observables:

M_π , M_K , M_P

$\frac{\sigma^2}{M}$(NK)

$S\sigma$(NC) , $S\sigma$(NK) , $S\sigma$(NP)

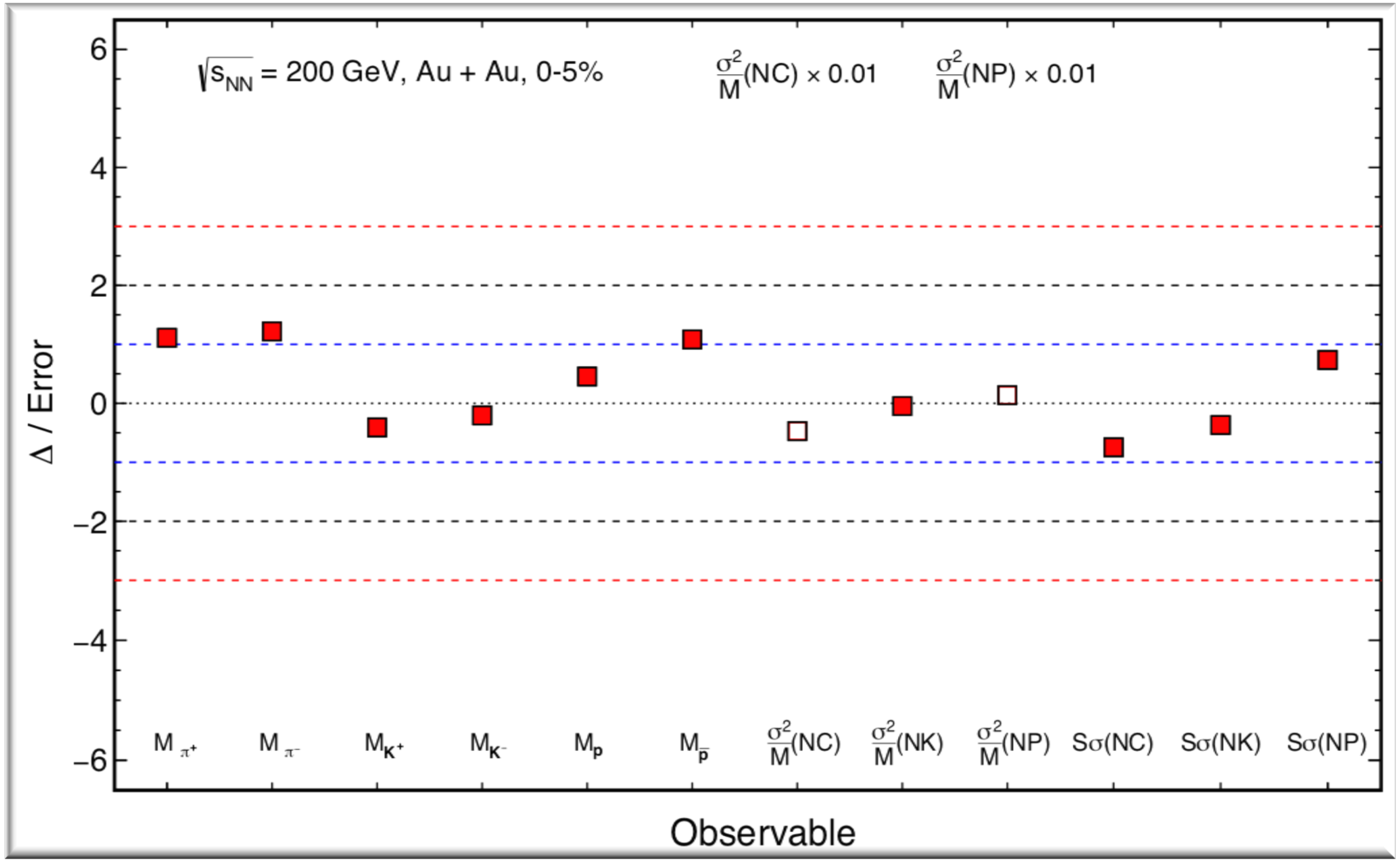


Few references from literature on comparison of HRG/Lattice to data:

Alba, P. et al., Phys. Lett. B738, 305 (2014)
Nahrgang, M. et al., Eur. Phys. C75, 573 (2015)
Bazavov, A. et al., Phys. Rev. Lett. 109, 192302 (2012)
Gupta, S. et al., Science 332, 1525 (2011)

Methodology

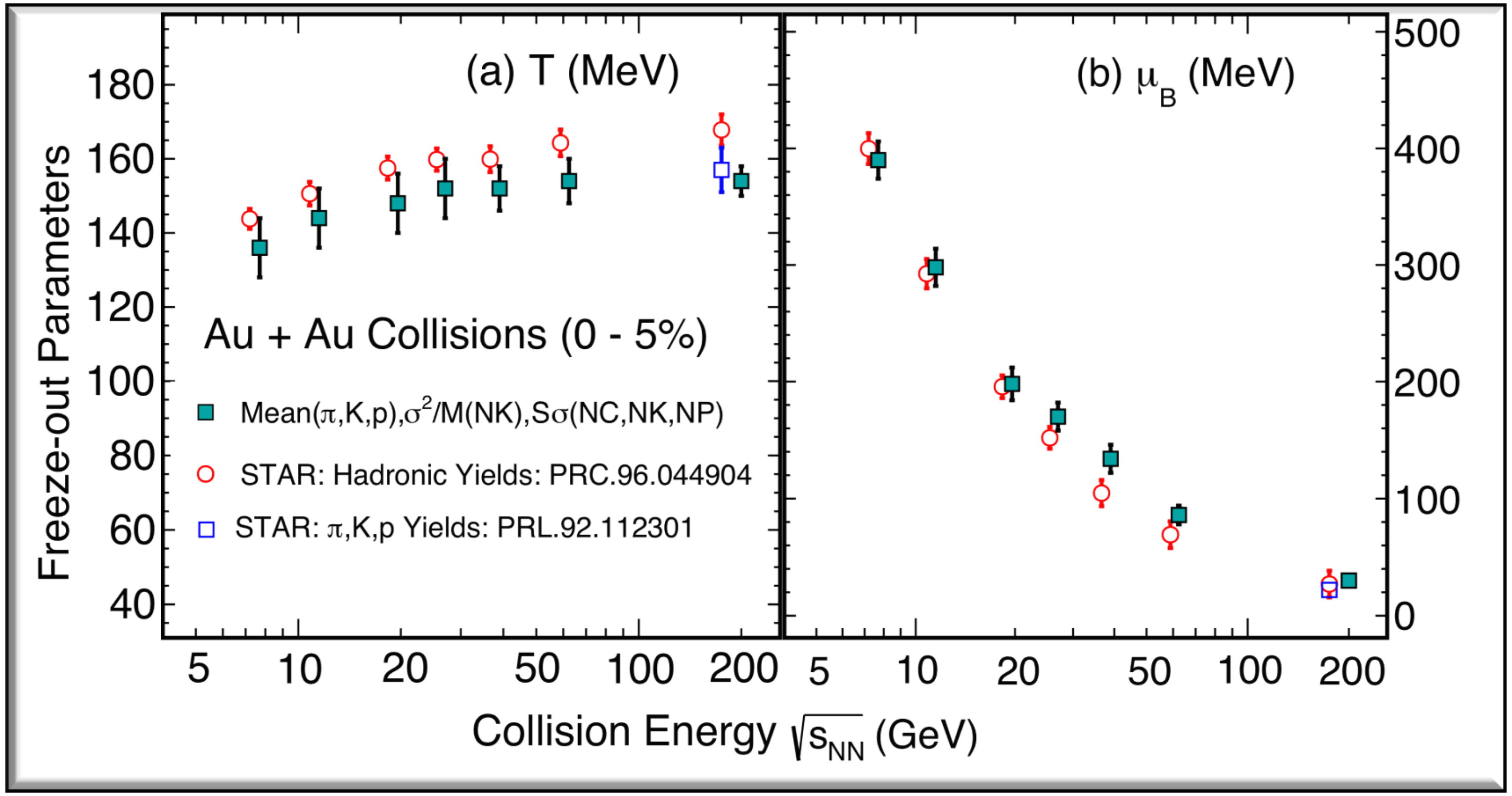
Difference between the Measurement and Model: $\mathbf{\Delta = R^{exp} - R^{Model}}$



- Good agreement between data and Model for 10 observables $\chi^2/ndf \sim O(1)$
- $\frac{\sigma^2}{M}$(NC) and $\frac{\sigma^2}{M}$(NP) do not agree with the model

Freeze-out Conditions

Extracted Freeze-out conditions at collision energy.

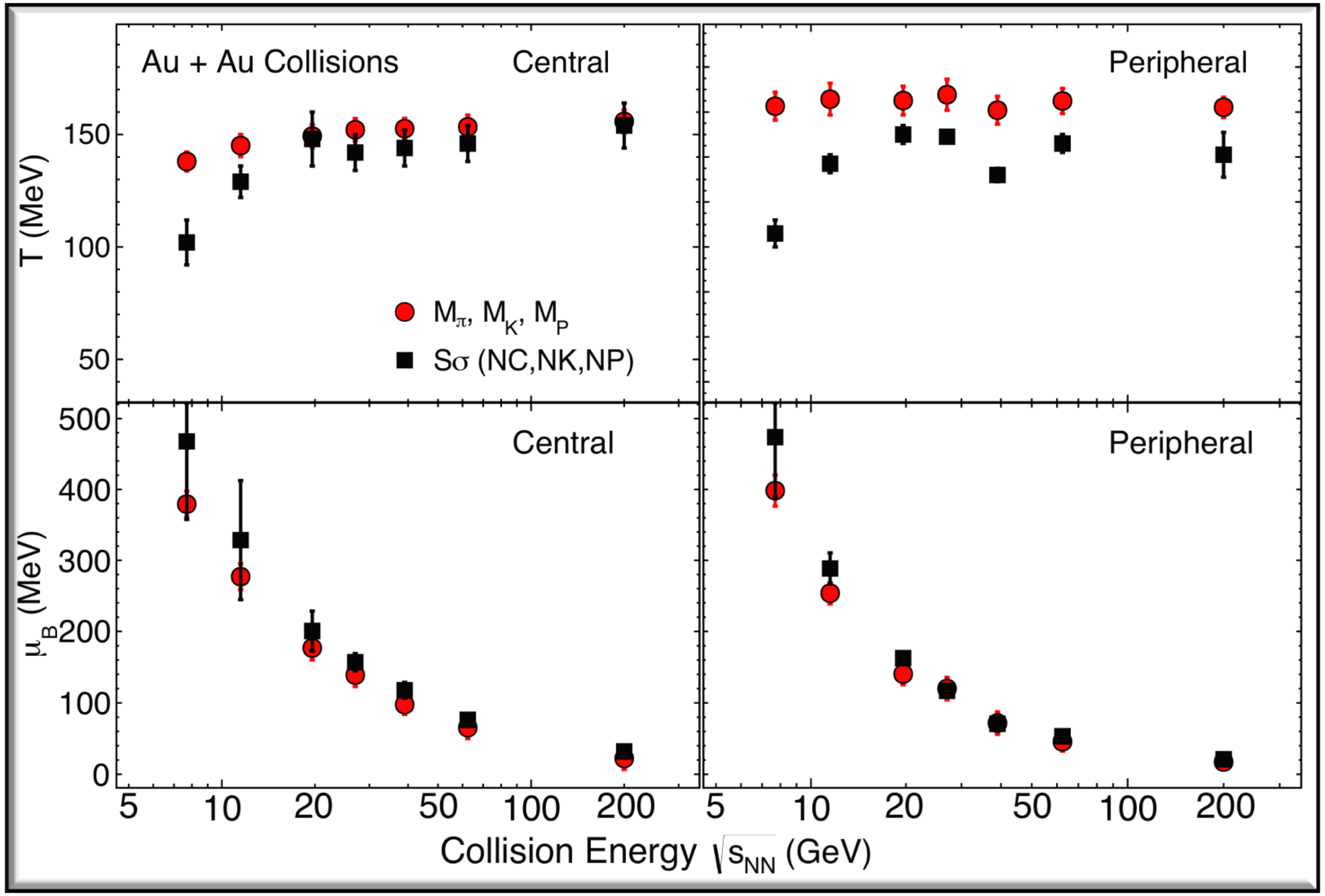


- T shows good agreement with that from the fit of hadronic yields from the STAR
- Slight difference in T value from STAR due to inclusion of multi-strange hadrons

Consistency of Freeze-out Parameters

Agreement of freeze-out conditions from different orders.

Varying parameters : T, μ_B.
μ_S from STAR(yield), μ_Q = 0.



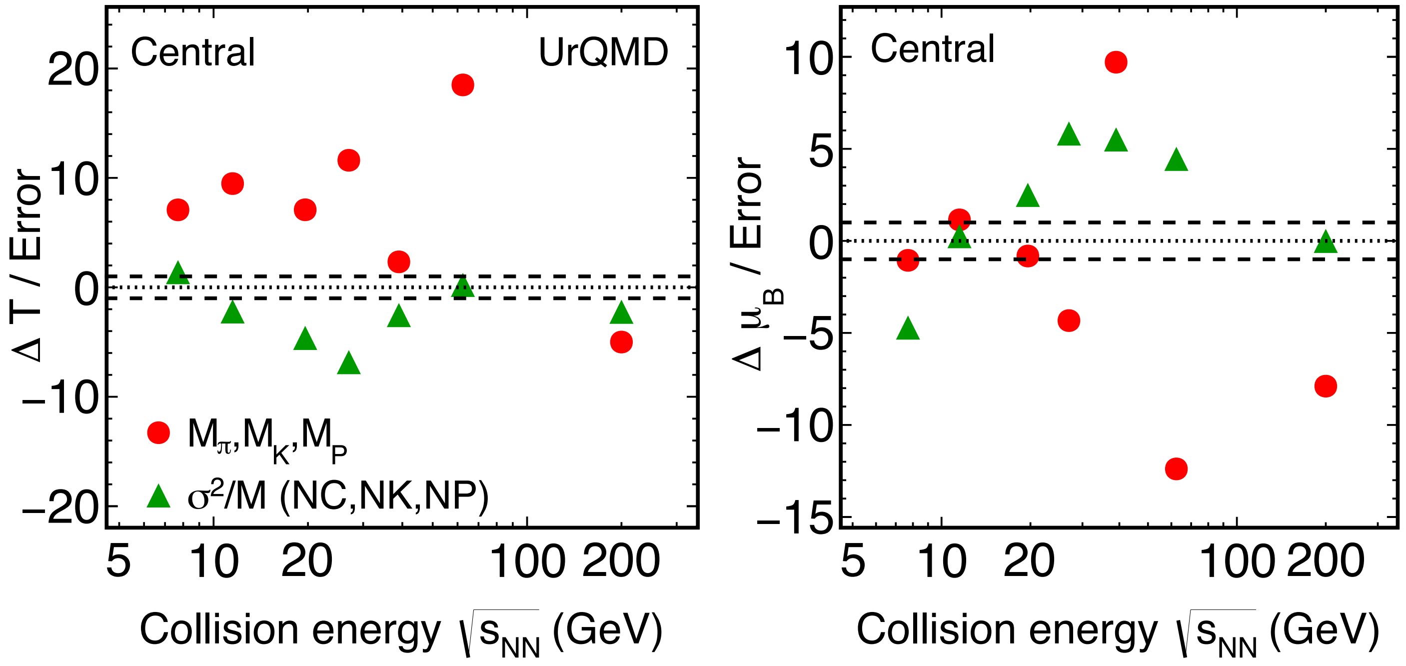
- In central collisions for $\sqrt{s_{NN}} \geq 19.6$ GeV, freeze-out parameters agree with each other
- In peripheral collisions different observables give different freeze-out conditions
- This consistency implies towards a "thermal" system

Test with Non-thermal Model

UrQMD model: Most central Au+Au collisions

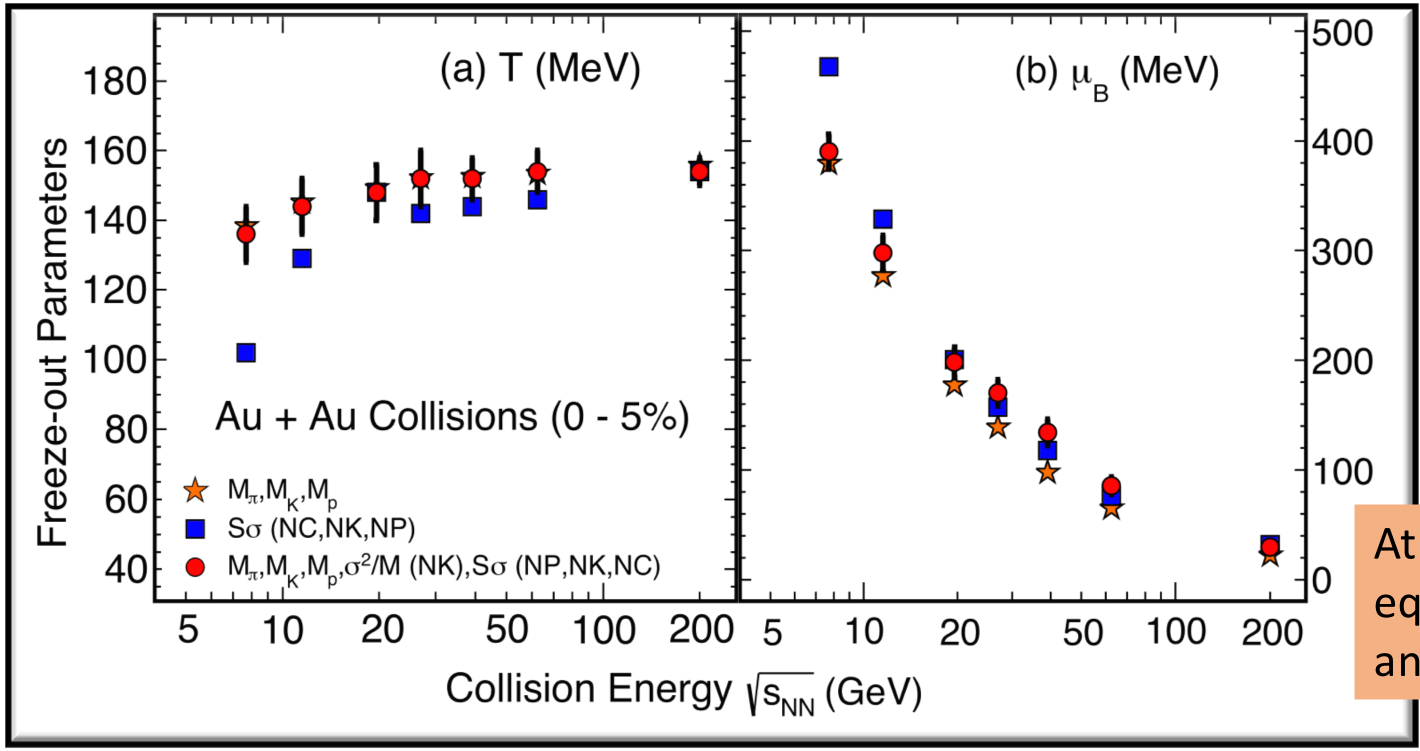
For 10-Observables: It gives $\chi^2/\mathrm{ndf} \sim O(100 - 10000)$.

ΔT is difference of Temperature obtained for an observable to that obtained from $S\sigma$(NC,NK,NP)



- URQMD results cannot be fitted with thermal model
- Agreement of HRG model with data is NOT accidental

Energy Dependence of Freeze-out Conditions

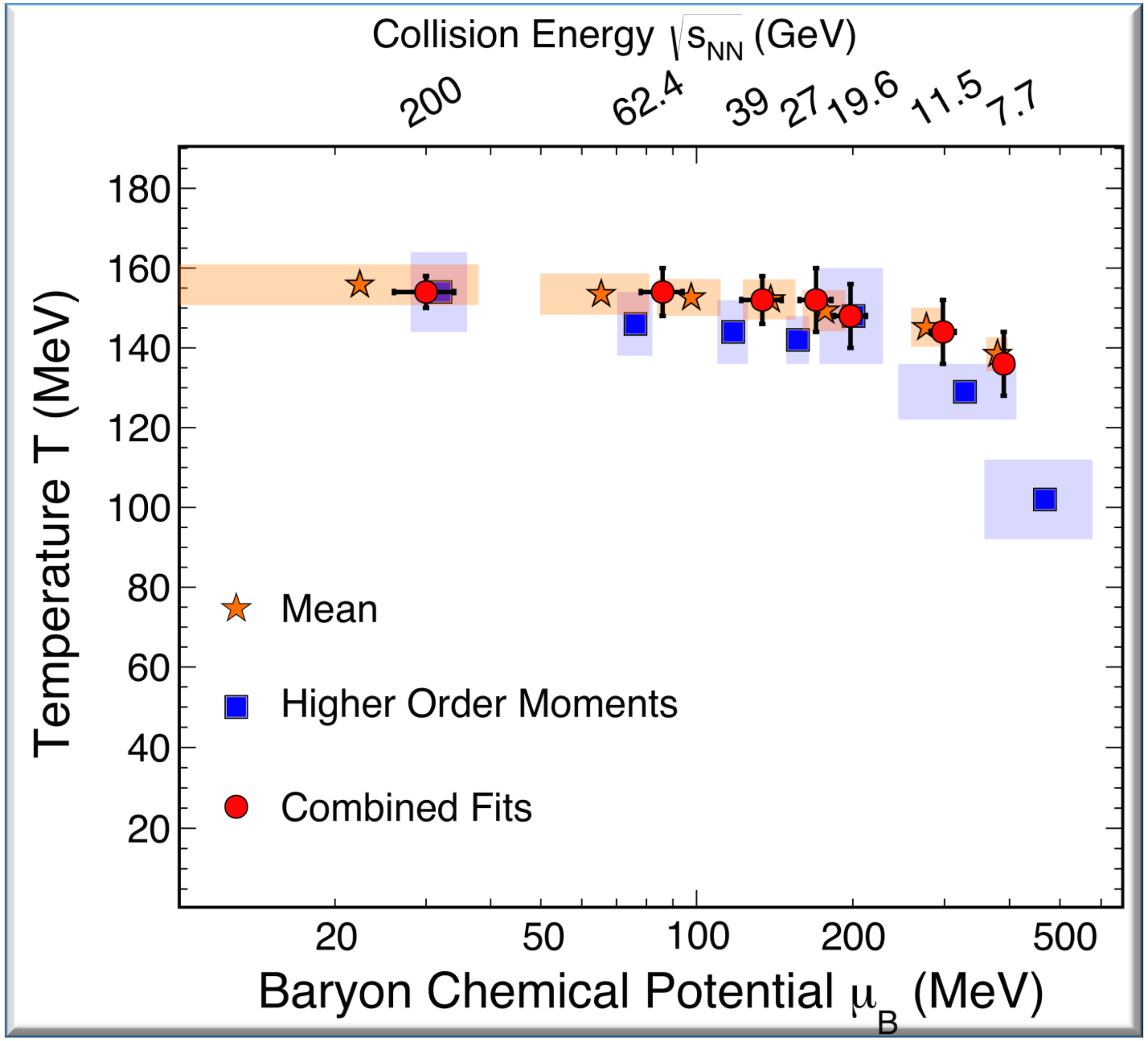


- In central collisions for $\sqrt{s_{\rm NN}} \geq 19.6$ GeV, T and μ_B show good agreement.
- At lower energies, deviation of freeze-out conditions of different moments from each other hints for departure from thermal equilibrium.

At low $\sqrt{s_{\rm NN}}$ fireballs being too dilute to ever come to equilibrium ?
and/Or different relaxation times for different moments ?

The agreement of various moments of conserved charge distributions in most central Au+Au collisions with thermal model shows the system at freeze-out is thermalized

Freeze-out Surface



The agreement of freeze-out conditions for various moments of conserved charge distributions in most central Au+Au collisions with thermal model shows the system at freeze-out is thermalized

Summary

- For the first time, we presented a study of thermalization at the last scattering surface of matter created at RHIC via simultaneous fit of moments up to the third order of the conserved charge distributions using a thermal model.

- Consistency between the freeze-out conditions from different order of moments hints that not only the region near the peak of the distribution, but also some part of the tail begins to approach a thermal distribution in most central Au+Au collisions (0-5%) for $\sqrt{s_{\mathrm{NN}}} \geq 19.6$ GeV.

- This also shows the relaxation time scales for the system are comparable to or smaller than the life time of the fireball.

- This is a clear indication of the system formed in most central Au+Au collisions at RHIC is thermalized unlike the case in synthetic data and peripheral collisions.

- We observe the disagreement of freeze-out conditions from different order of moments which suggest departure from thermal equilibrium for collisions at the two lowest $\sqrt{s_{\mathrm{NN}}}$.

It will be interesting to further check for the reasons for possible departure from thermal equilibrium at lower $\sqrt{s_{\mathrm{NN}}}$.

Thank you for your time