RHICにおけるビームエネルギースキャン実験での陽子数揺らぎに関する熱力学的解釈

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科研費
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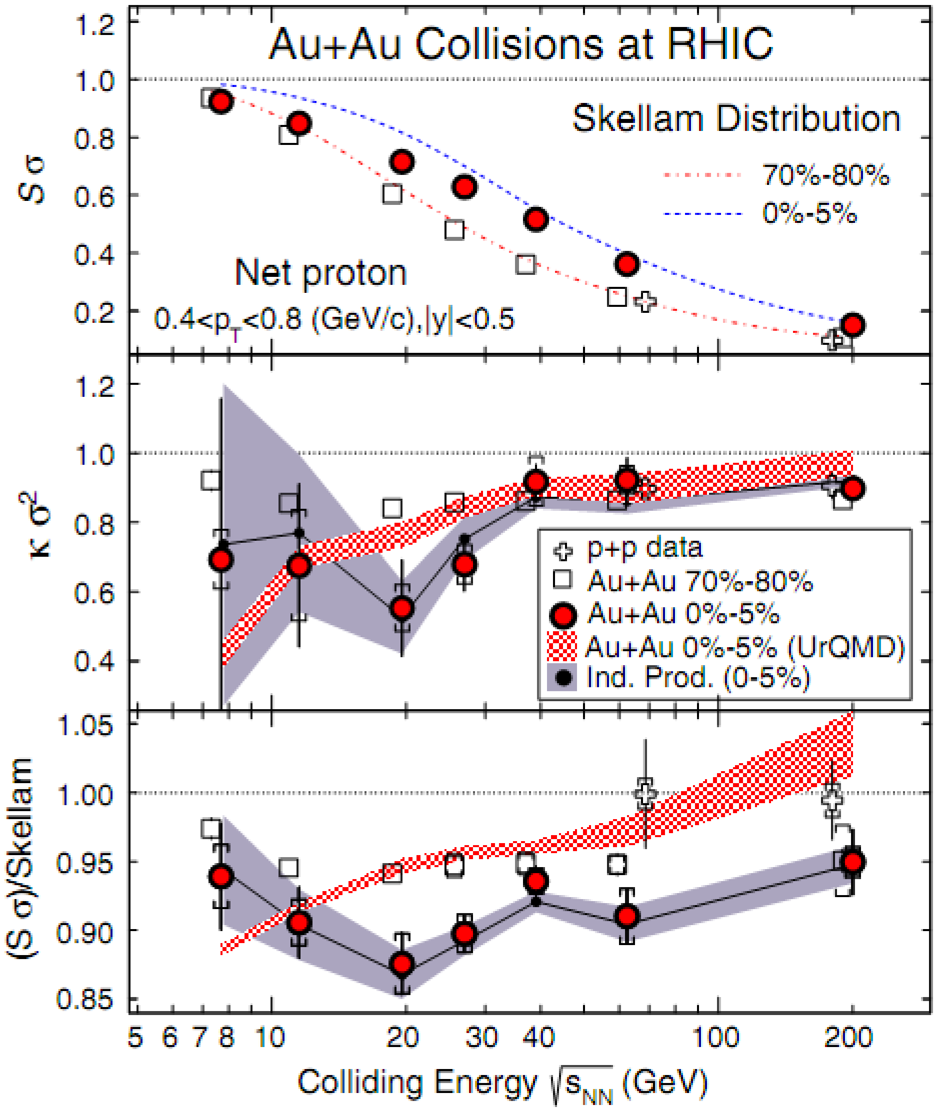
Introduction



STAR Collaboration, PRL **112**, 032302 (2014)

Skewness and Kurtosis of net proton distribution

Deviate from the Skellam distribution.

- Partonic matter ?
- Phase transition ?

What is the good baseline ?

Introduction

Skewness and Kurtosis

n-th order cumulant of the distribution

$C_2 = \sigma^2$, $C_3 = S\sigma^3$, $C_4 = \kappa\sigma^4$ …

(σ: Deviation, S: Skewness, κ: Kurtosis)

These are related to the correlation length ξ of matter

Skellam distribution

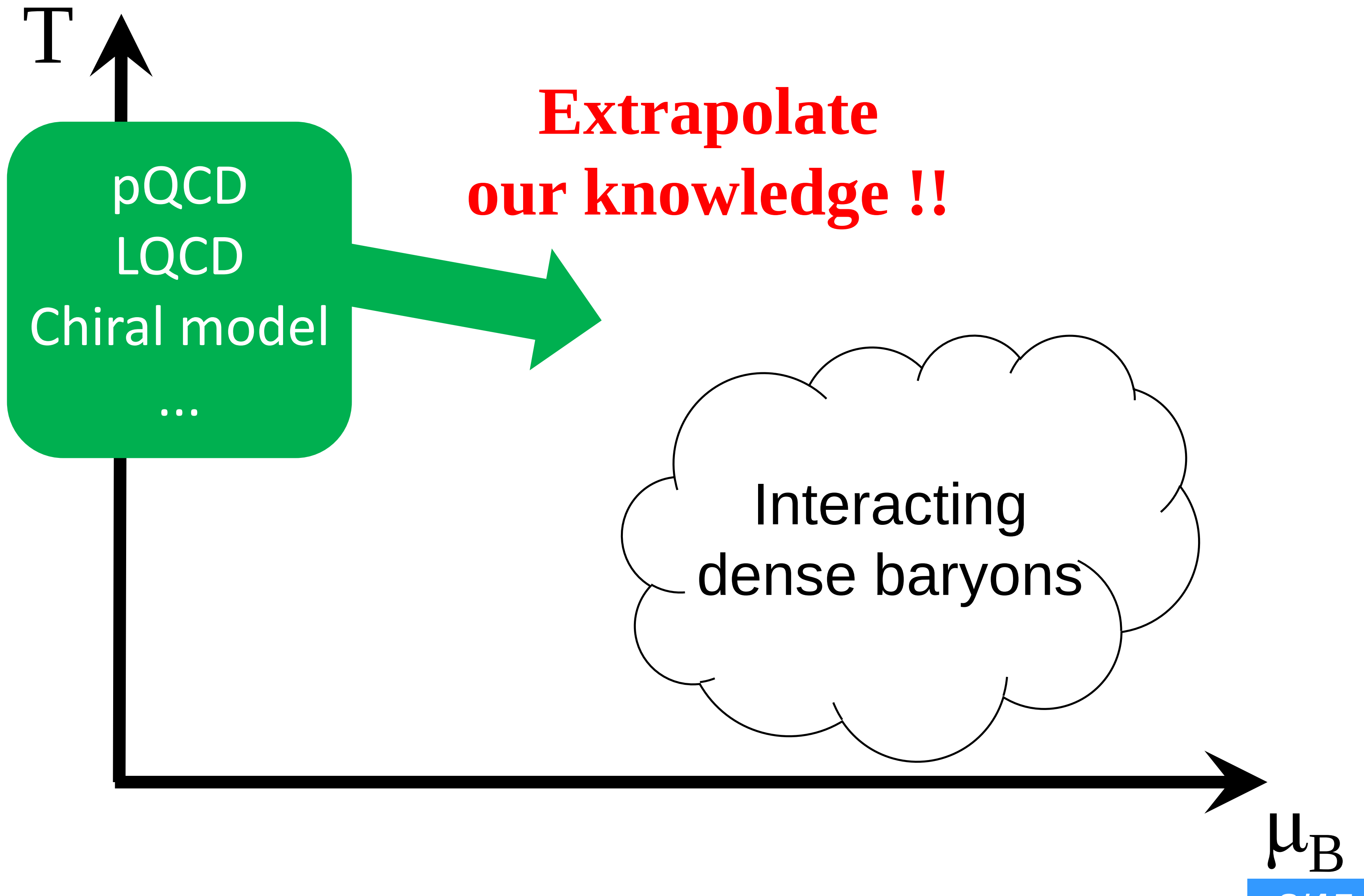
Difference of two Poisson distribution

Boltzmann distribution

➡ The "Skellam" corresponds to classical proton and antiproton gas

How large the quantum effect ?

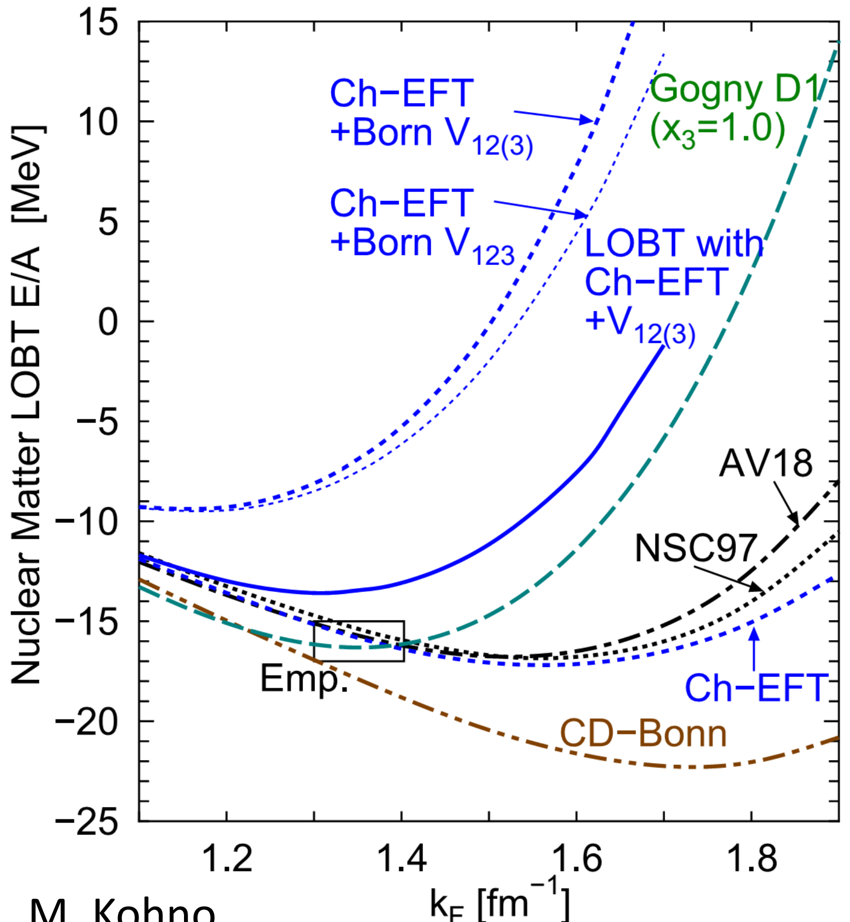
Introduction



Introduction

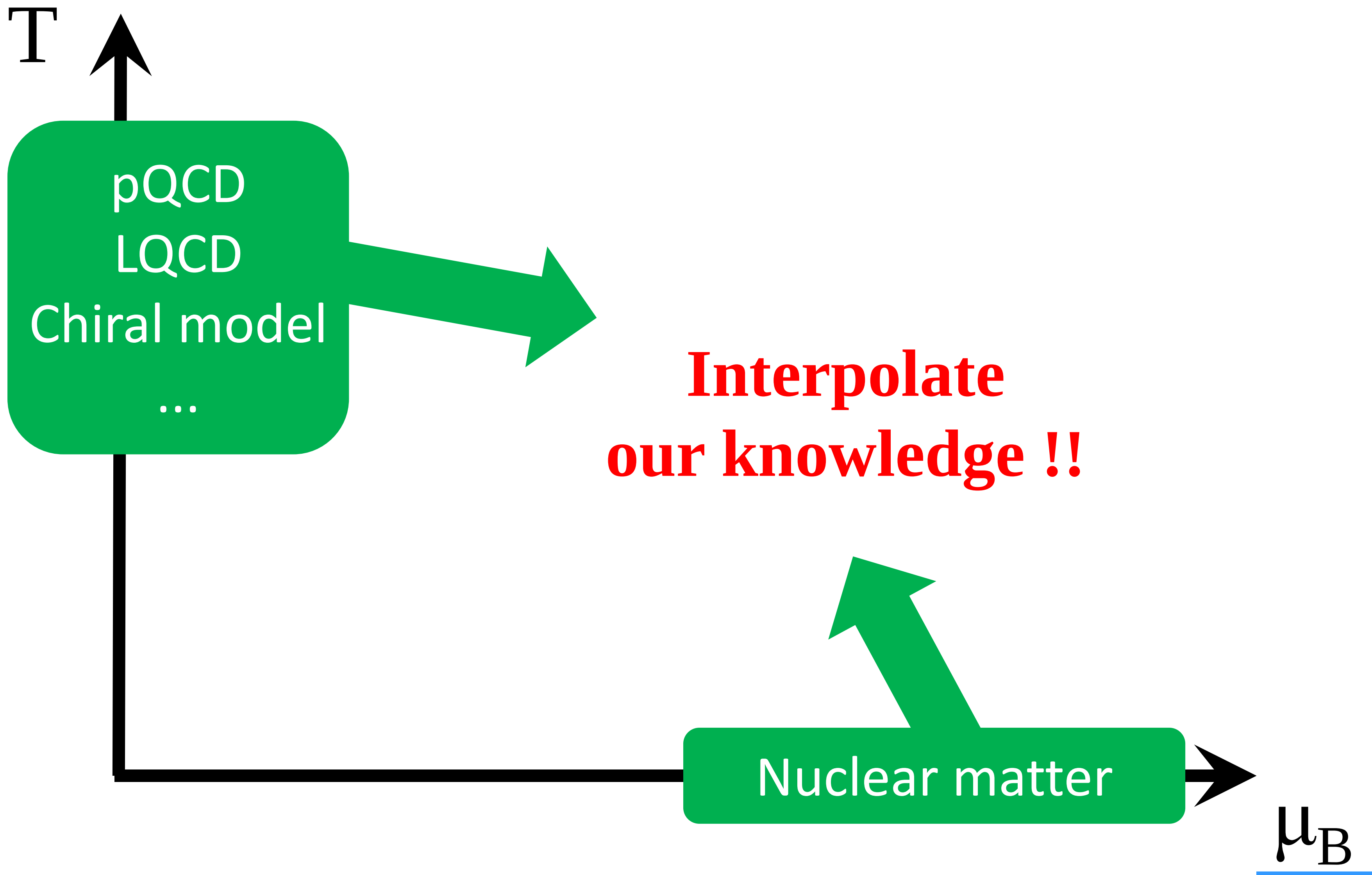
We know about interacting nucleon as nuclear matter

- Liquid-Gas transition
- Saturation of nuclear matter
- Empirical value of saturation properties (E/A, ρ_0, K, ...)



M. Kohno, Phys. Rev. C **86**, 061301(R) (2012)

Introduction



This work

We investigate the following effects to the fluctuations for large chemical potential.

- Fermi statistics
  (Free Proton gas)

- Interacting hadron
  (nuclear matter model)

Free Fermi gas

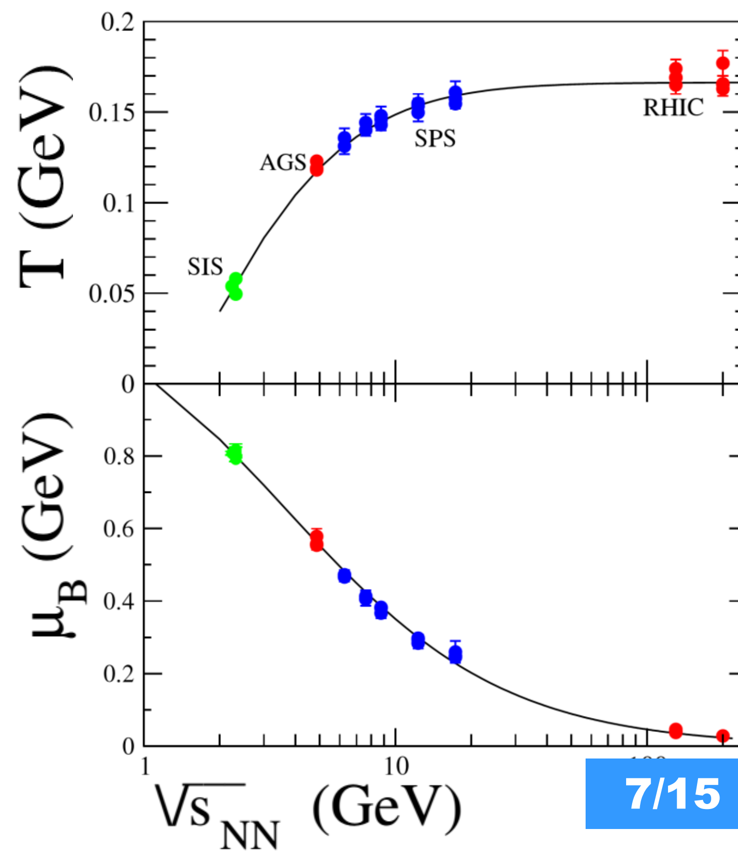
$$p = 2T \int \frac{d^3p}{(2\pi)^3} \left[\ln(1+e^{-(\varepsilon_p-\mu)/T}) + \ln(1+e^{-(\varepsilon_p+\mu)/T}) \right]$$

Collision energy and (μ_B, T)

$$T(\mu_B) = a - b\mu_B^2 - c\mu_B^4$$

$$\mu_B(\sqrt{s}) = \frac{d}{1+e\sqrt{s}}$$

J. Cleymans, H. Oeschler, K. Redlich,
and S. Wheaton, Phys. Rev. C **73**, 034905 (2006).



Free Fermi gas

Dimensionless fluctuations

$$\chi_B^{(n)} = \frac{\partial^n}{\partial(\mu/T)^n} \frac{p}{T^4}$$

$$S\sigma = \chi_{\mathrm{B}}^{(3)}/\chi_{\mathrm{B}}^{(2)} \ , \quad \kappa\sigma^2 = \chi_{\mathrm{B}}^{(4)}/\chi_{\mathrm{B}}^{(2)}$$

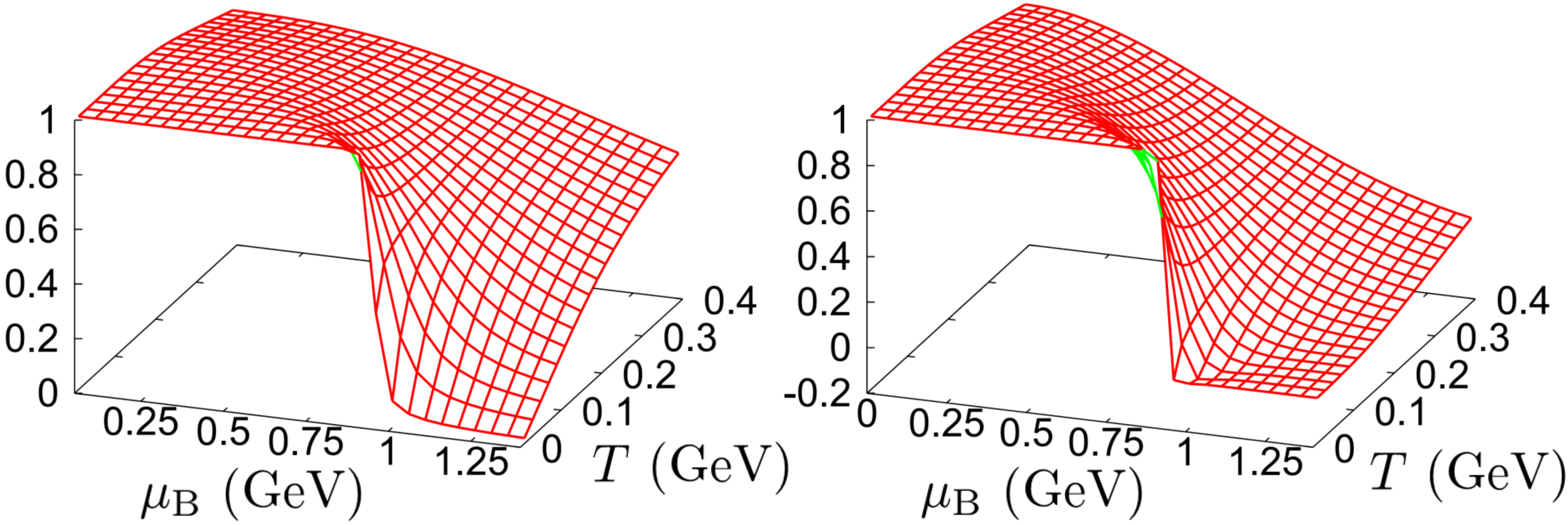
Classical limit

$$n_p = \frac{1}{1 + e^{(\varepsilon_p - \mu)/T}} \quad \Rightarrow \quad n_p = e^{-(\varepsilon_p - \mu)/T}$$

$$S\sigma = \tanh\left(\mu/T\right) \ , \quad \kappa\sigma^2 = 1$$

Free Fermi gas

$S\sigma/\text{Skellam}$ $\kappa\sigma^2$



Simple Fermi statistics can be seen
in high density region.

Interacting hadron

Walecka model with nonlinear self potential

$$\mathcal{L} = \underline{\bar{\psi}(i\gamma_\mu \partial^\mu + \mu_{\mathrm{B}} - g_\omega \gamma_\mu \omega^\mu - M_{\mathrm{N}} + g_\sigma \hat{\sigma})\psi}$$

Nucleon

$$+\underline{\frac{1}{2}\partial_\mu \hat{\sigma} \partial^\mu \hat{\sigma} - U(\hat{\sigma})} - \underline{\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu}$$

Scalar Boson   Vector Boson

$$\omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \;\; U(\hat{\sigma}) = \frac{1}{2}m_\sigma \hat{\sigma}^2 + \frac{1}{3}b\hat{\sigma}^3 + \frac{1}{4}c\hat{\sigma}^4$$

Interaction effects → One-body potential represented by the mean-field variables

D. Walecka, Ann. Phys. **83**, 491 (1974).

J. Boguta and A. R. Bodmer, Nucl. Phys. A **83**, 413 (1977).

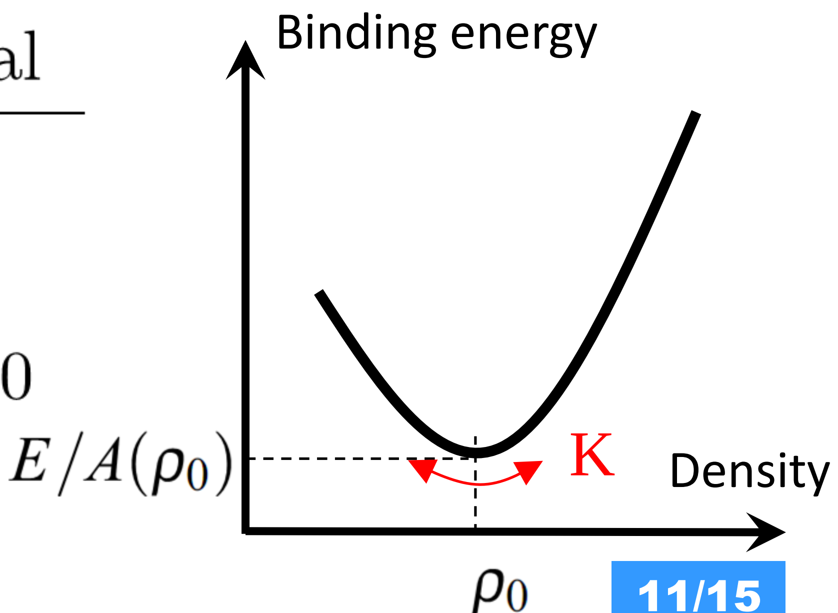
Interacting hadron

$$\frac{\Omega}{V} = -2 \cdot 2T \int \frac{d^3p}{(2\pi)^3} \left\{ \ln\left[1 + e^{-\beta(\varepsilon_p - \mu_B^*)}\right] + \ln\left[1 + e^{-\beta(\varepsilon_p + \mu_B^*)}\right] \right\} + U(\bar{\sigma}) - \frac{1}{2} m_\omega^2 (\bar{\omega}_0)^2$$

$$\varepsilon_p = \sqrt{p^2 + (M_N^*)^2}\,, \quad M_N^* = M_N - g_\sigma \bar{\sigma}\,, \quad \mu_B^* = \mu_B - g_\omega \bar{\omega}_0$$

Saturation properties

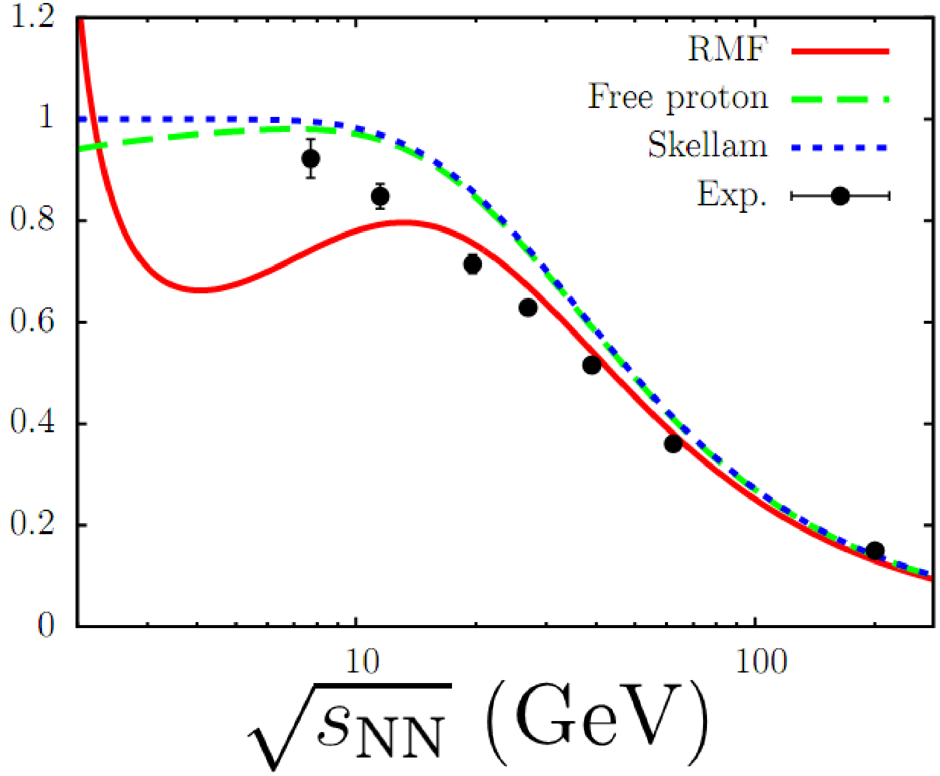
	Model	Empirical
ρ_0 (fm^{-3})	0.15	0.17
E/A (MeV)	-16	-16
K (MeV)	210	210 - 250



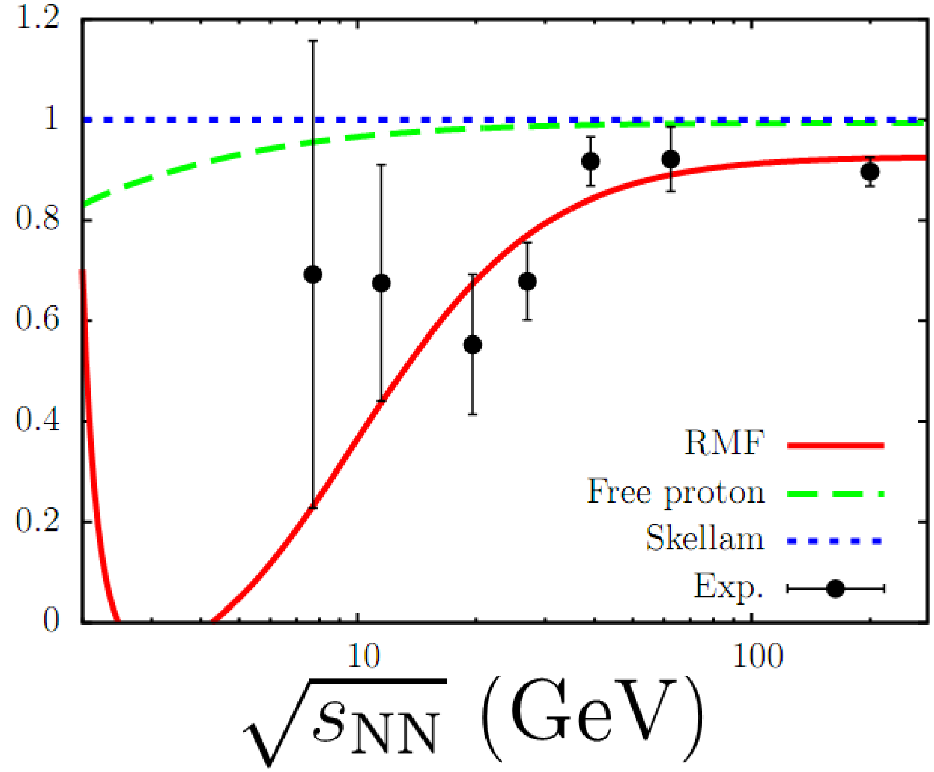
B. M. Walfhauser, J. A. Maruhn, H. Stoecker, and W. Greiner, Phys. Rev. C **38**, 1003 (1988).

Interacting hadron

$S\sigma$



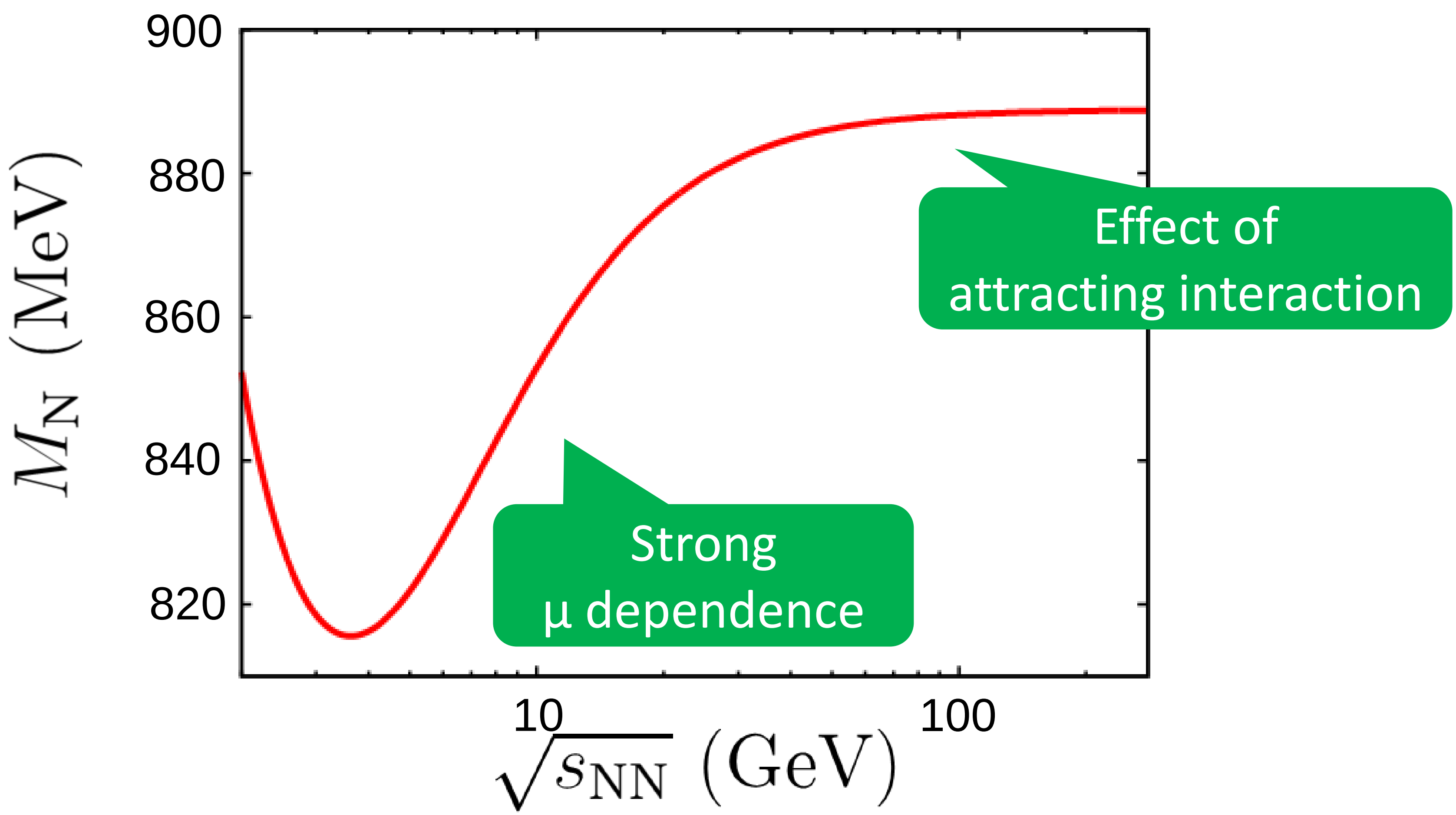
$\kappa\sigma^2$



Nuclear matter model (RMF) well reproduce the experimental data.

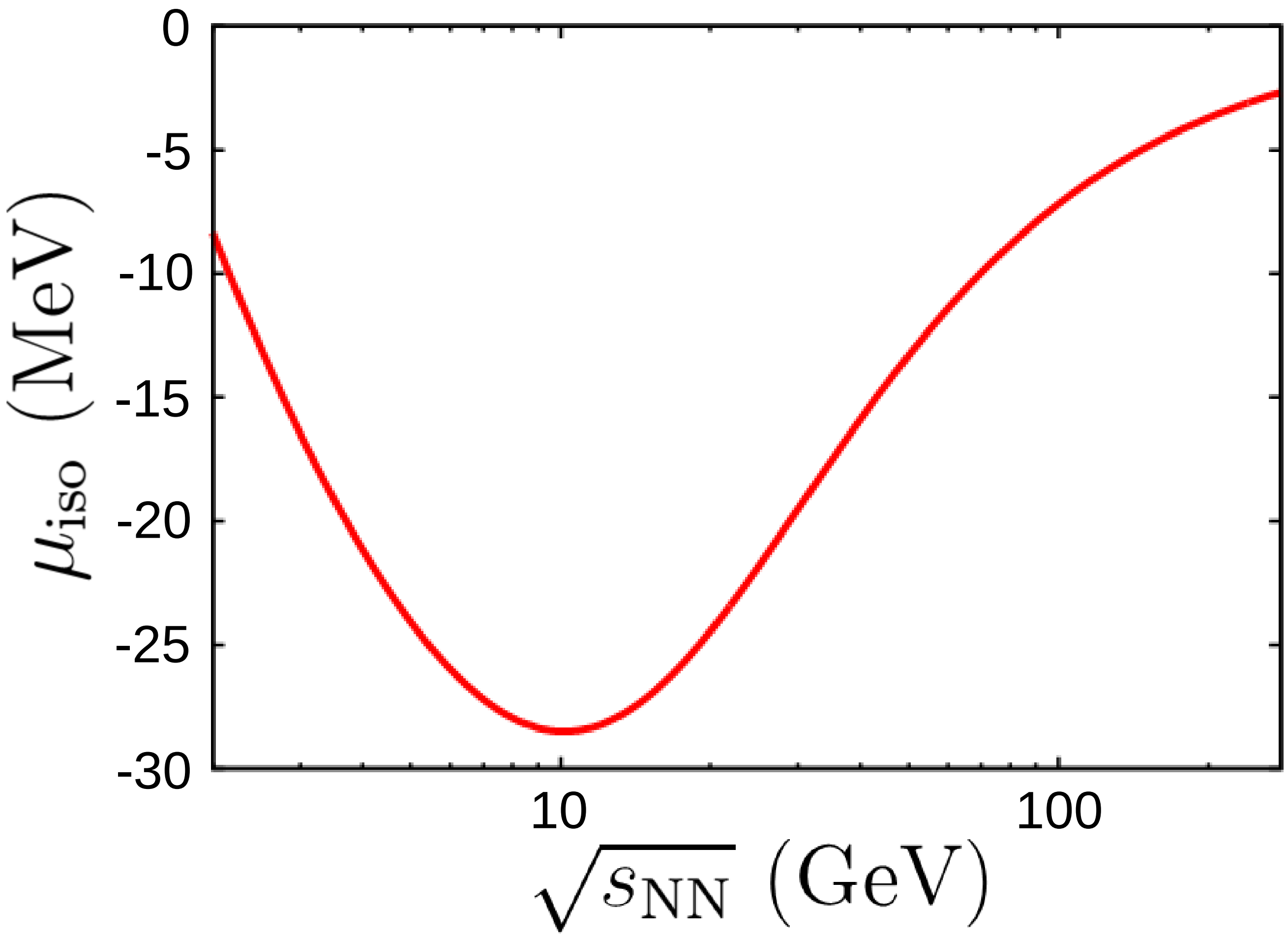
Experiment: STAR Collaboration, PRL **112**, 032302 (2014)

Interacting hadron



Effective nucleon mass depends on μ_B,
and it affect to the fluctuations.

Interacting hadron



$\mu_{\rm iso} \equiv (\mu_{\rm p} - \mu_{\rm n})/2$

For each μ_B

$n_p : n_n$

$= 79 : 118$

(Au nucleus)

Assuming symmetric matter is not so bad.

Summary

We investigate the proton number fluctuations in higher density region.

- Fermi-statistics affect to the fluctuations.
- Relativistic mean-field model (i.e. interacting hadron) reproduces the experimental result.

Further discussions

- Signal of QCD transition
- Validity of RMF model for higher temperature
- etc ...