Study of Hadron Behavior in finite Density at J-PARC and NICA

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in collaboration with
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REIMEI Workshop, Feb. 21-23, 2022

Messages in this talk

- J-PARC and NIKA are an ideal place to study finite density QCD.

Don't forget FAIR and BES-II !

- Lattice QCD can be a useful tool here. (We can avoid from Sign problem.)
  - We can calculate even hadron masses at finite density.

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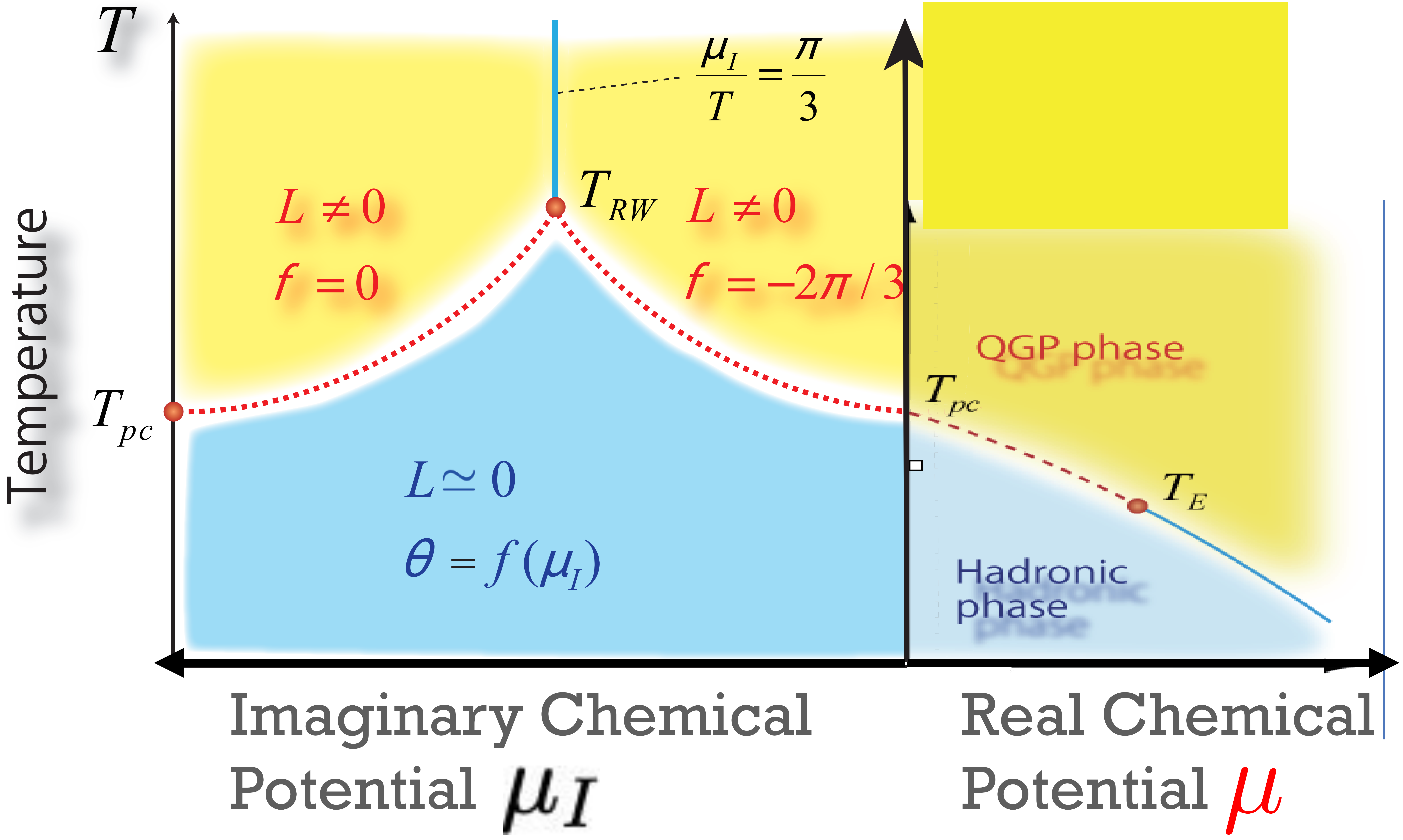


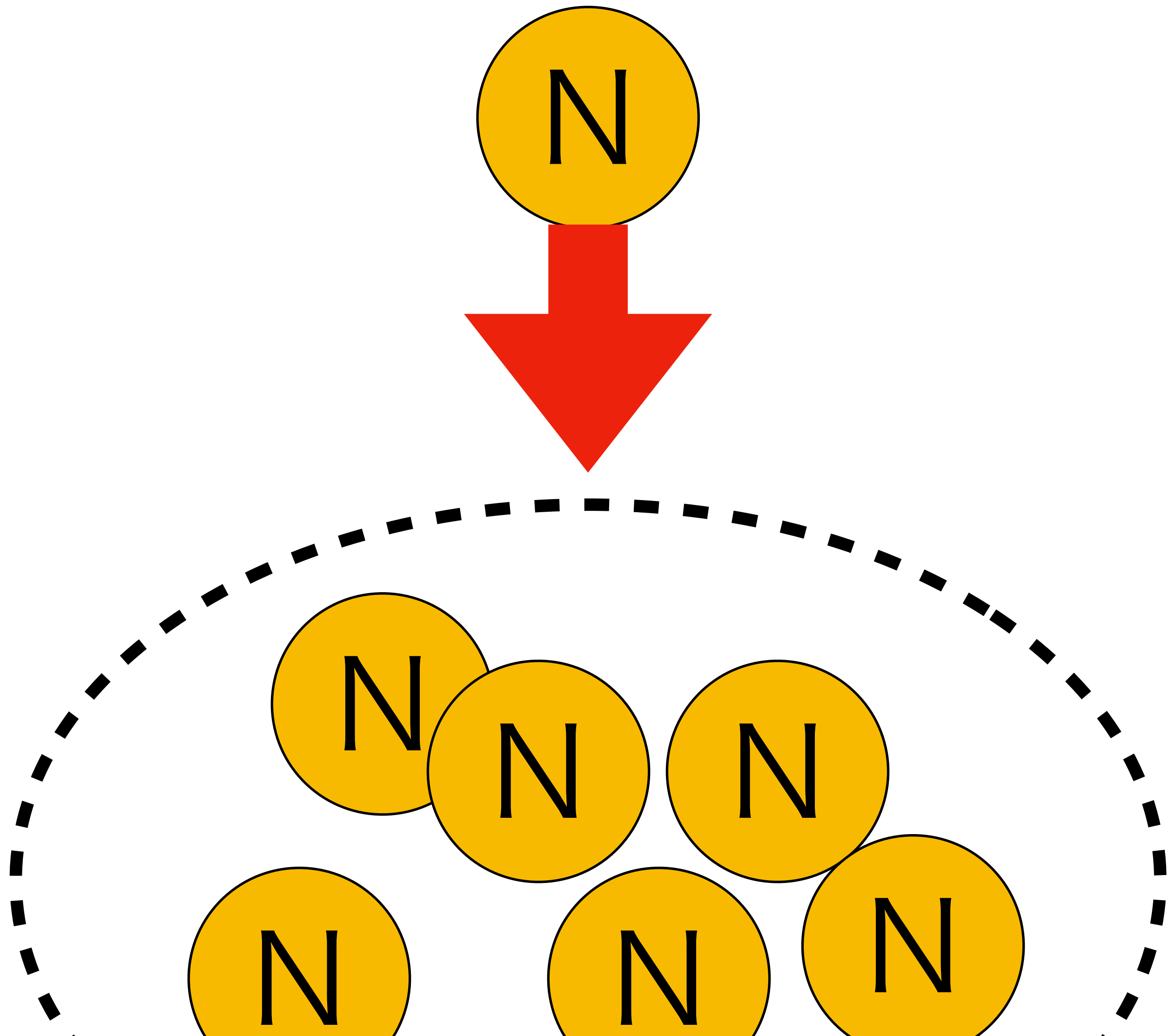
T
Temperature
T_{pc}
$\frac{\mu_I}{T} = \frac{\pi}{3}$
T_{RW}
$L \neq 0$
$f = 0$
$L \neq 0$
$f = -2\pi/3$
$L \simeq 0$
$\theta = f(\mu_I)$
QGP phase
T_{pc}
T_E
Hadronic phase
Imaginary Chemical Potential μ_I
Real Chemical Potential μ

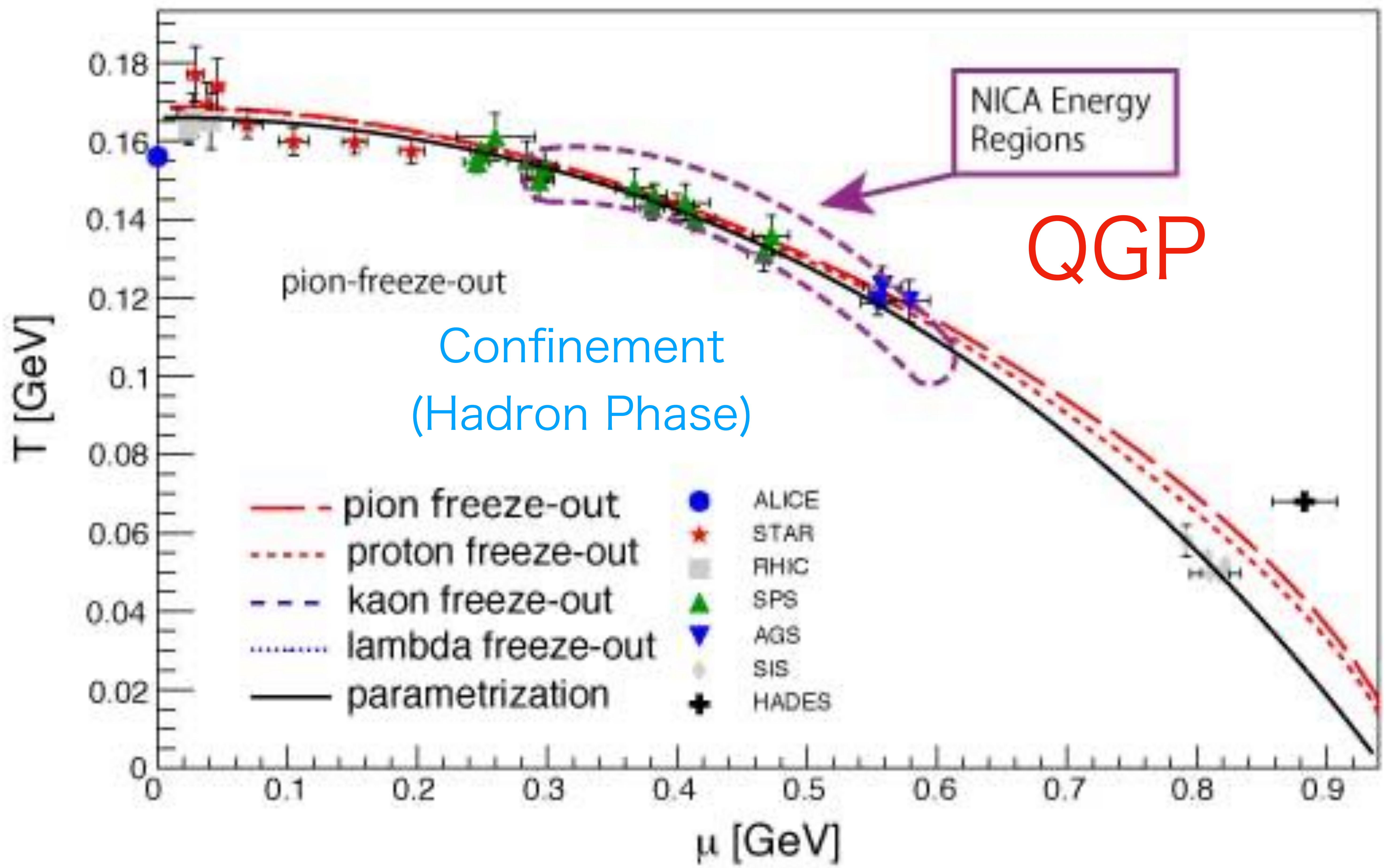
Intuitive meaning of Chemical Potential μ

$$Z(\mu, T) = \mathrm{Tr}\, e^{-(H-\mu\hat{N})/T}$$
$$= e^{-F/T}$$

$$\frac{e^{-(H-\mu(\hat{N}+1))/T}}{e^{-(H-\mu\hat{N})/T}} = e^{-\Delta F/T}$$

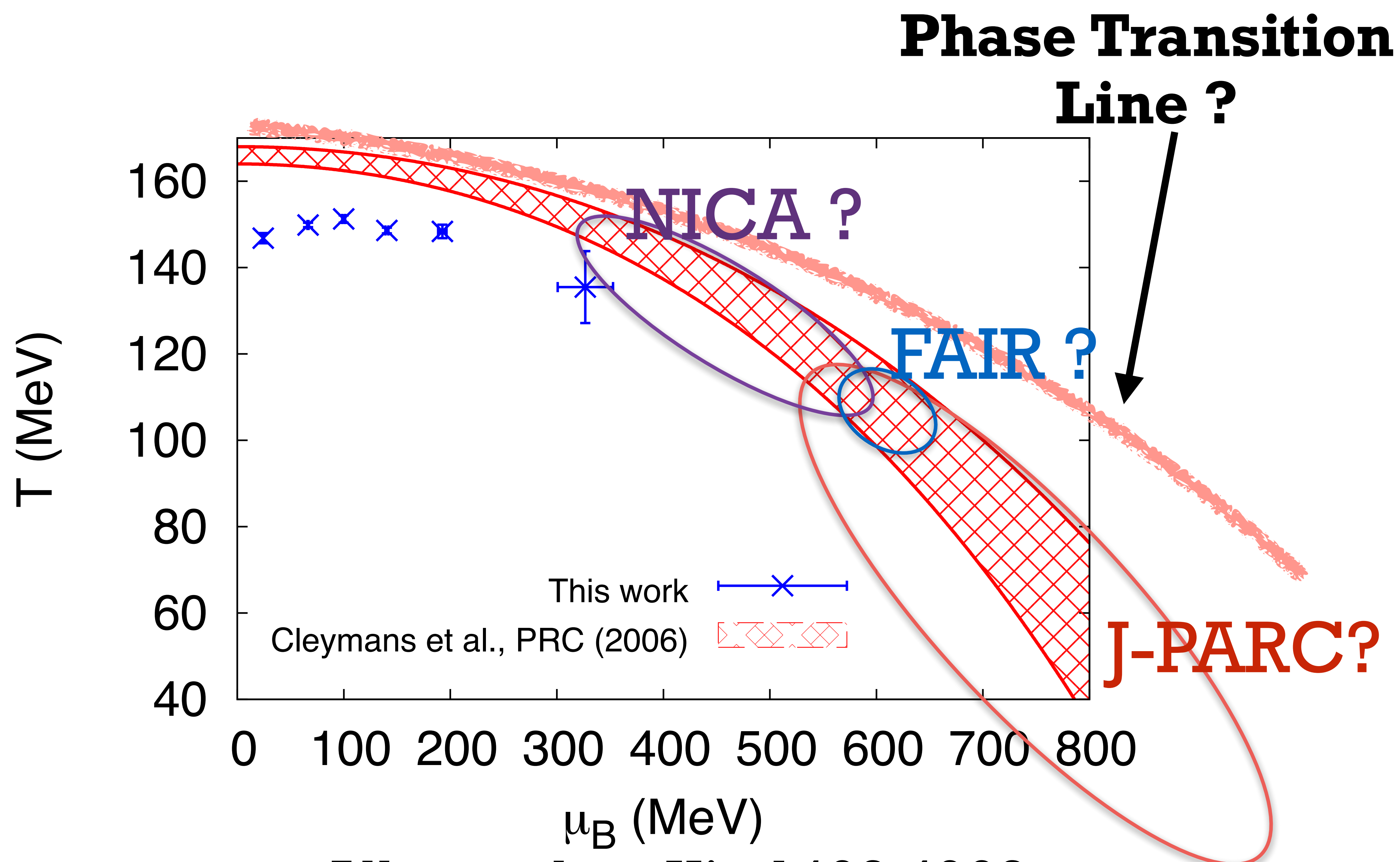
Energy for adding one more particle



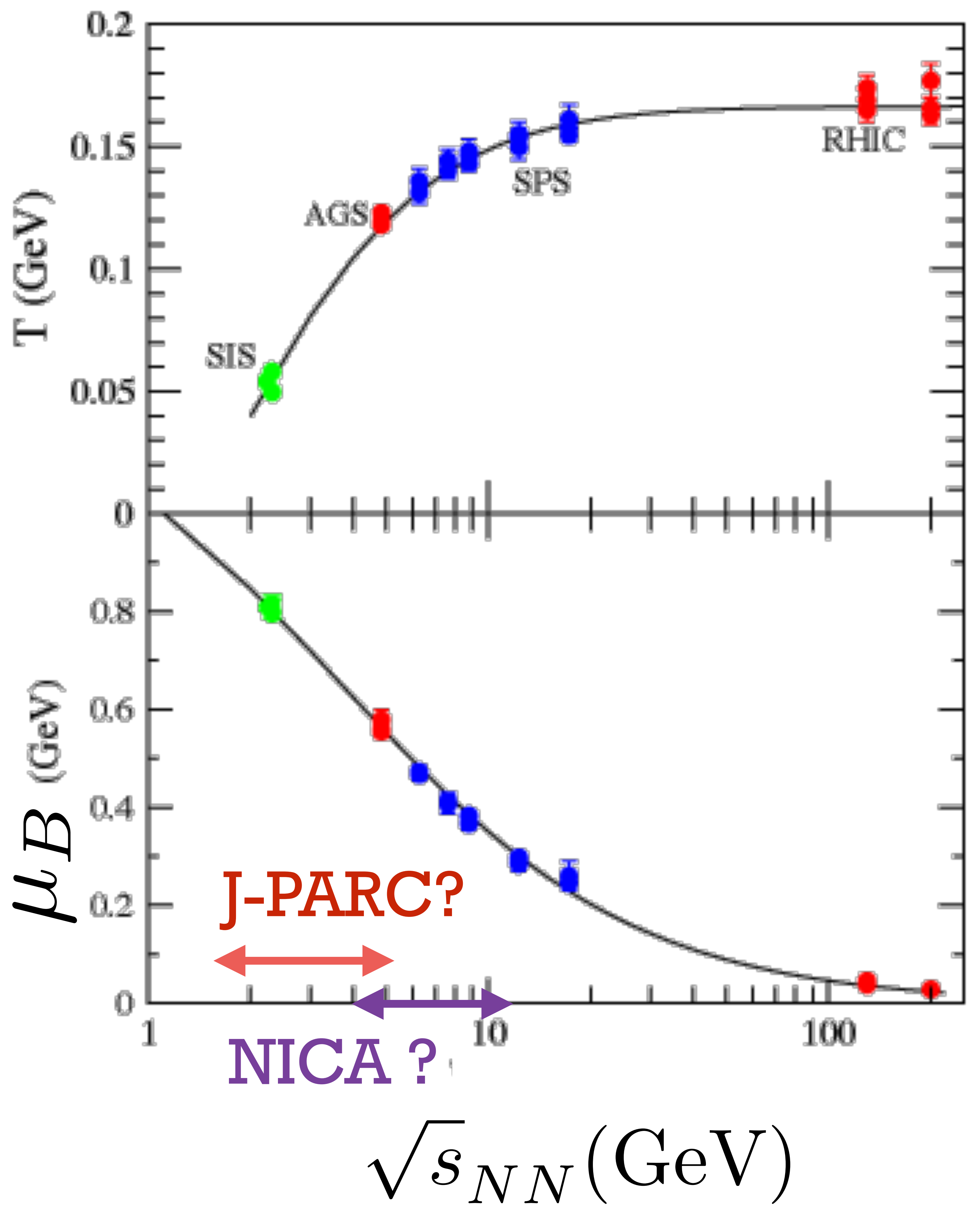


μ :Chemical Potential

D. Blaschke, J. Jankowski, and M. Naskręt
arXiv:1705.00169



Alba et al., arXiv:1403.4903

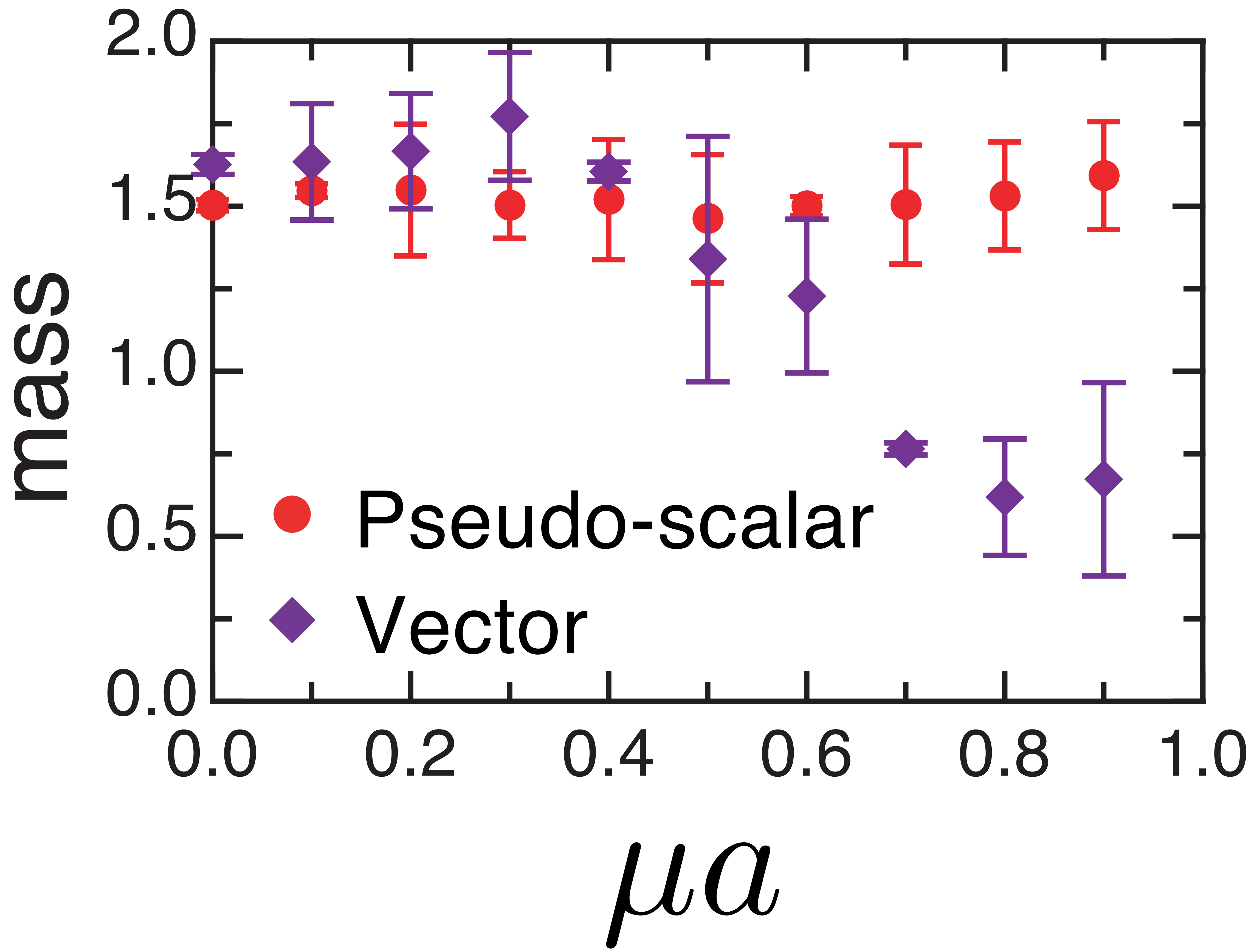


J.Cleymans et al.,
Phys. Rev. C73, (2006) 034905.

Muroya, Nakamura and Nonaka

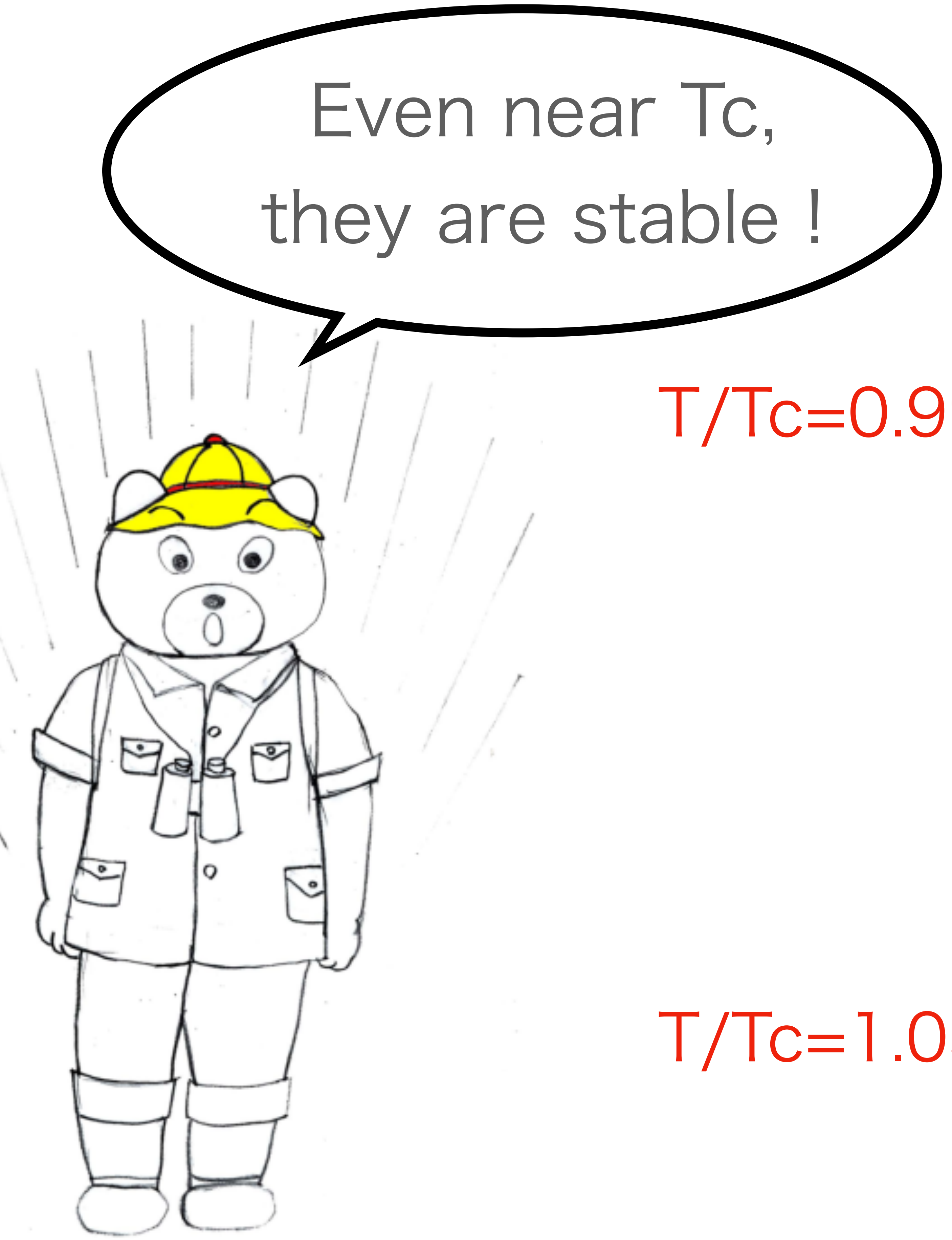
arXiv 0211010 Phys. Lett. B551,(2003) pp305-310

$\kappa = 0.160$ 4^3x8 SU(2)



Vector meson mass drops !

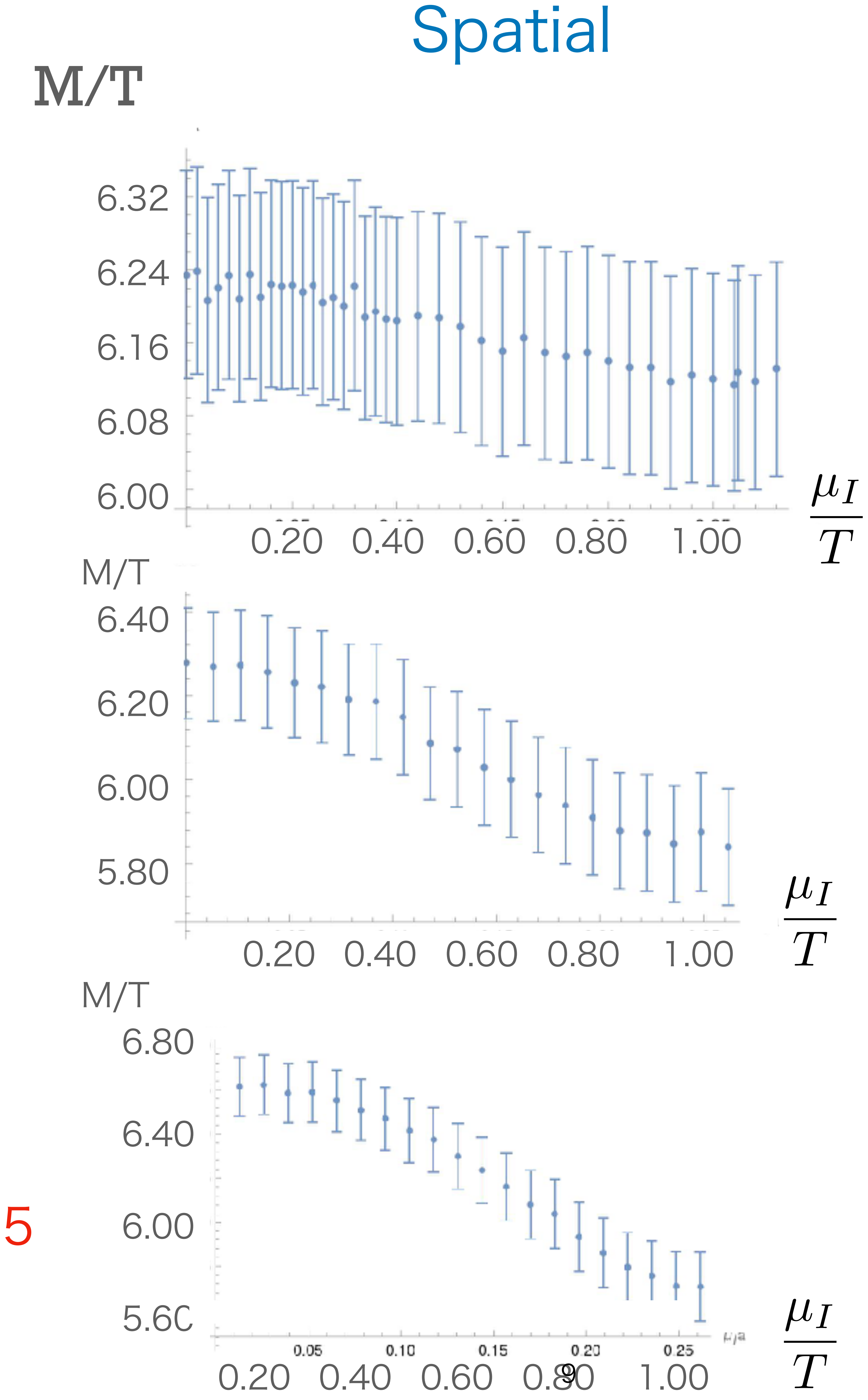
pion mass by Goy

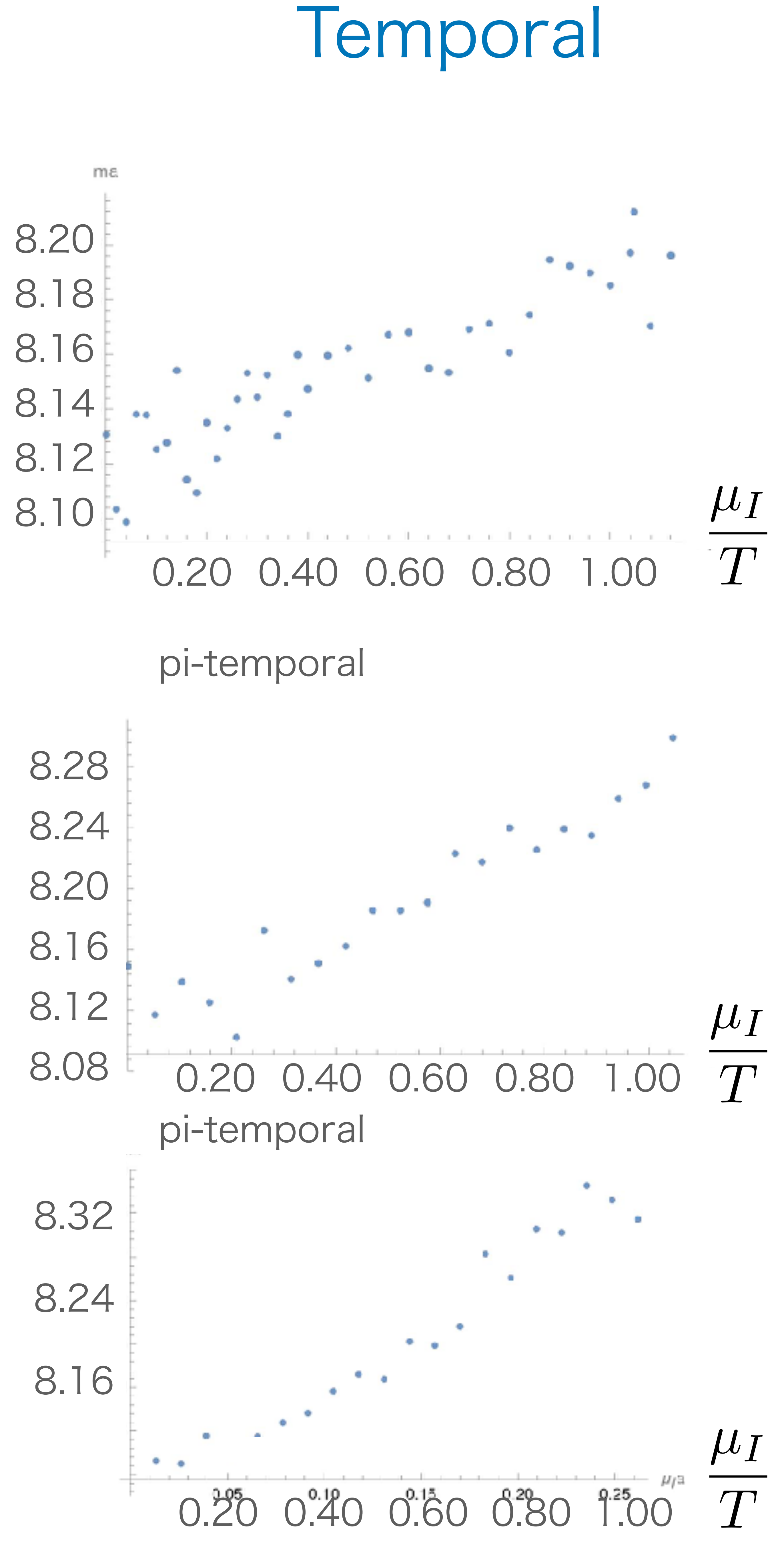


T/Tc=0.93

T/Tc=0.99

T/Tc=1.035



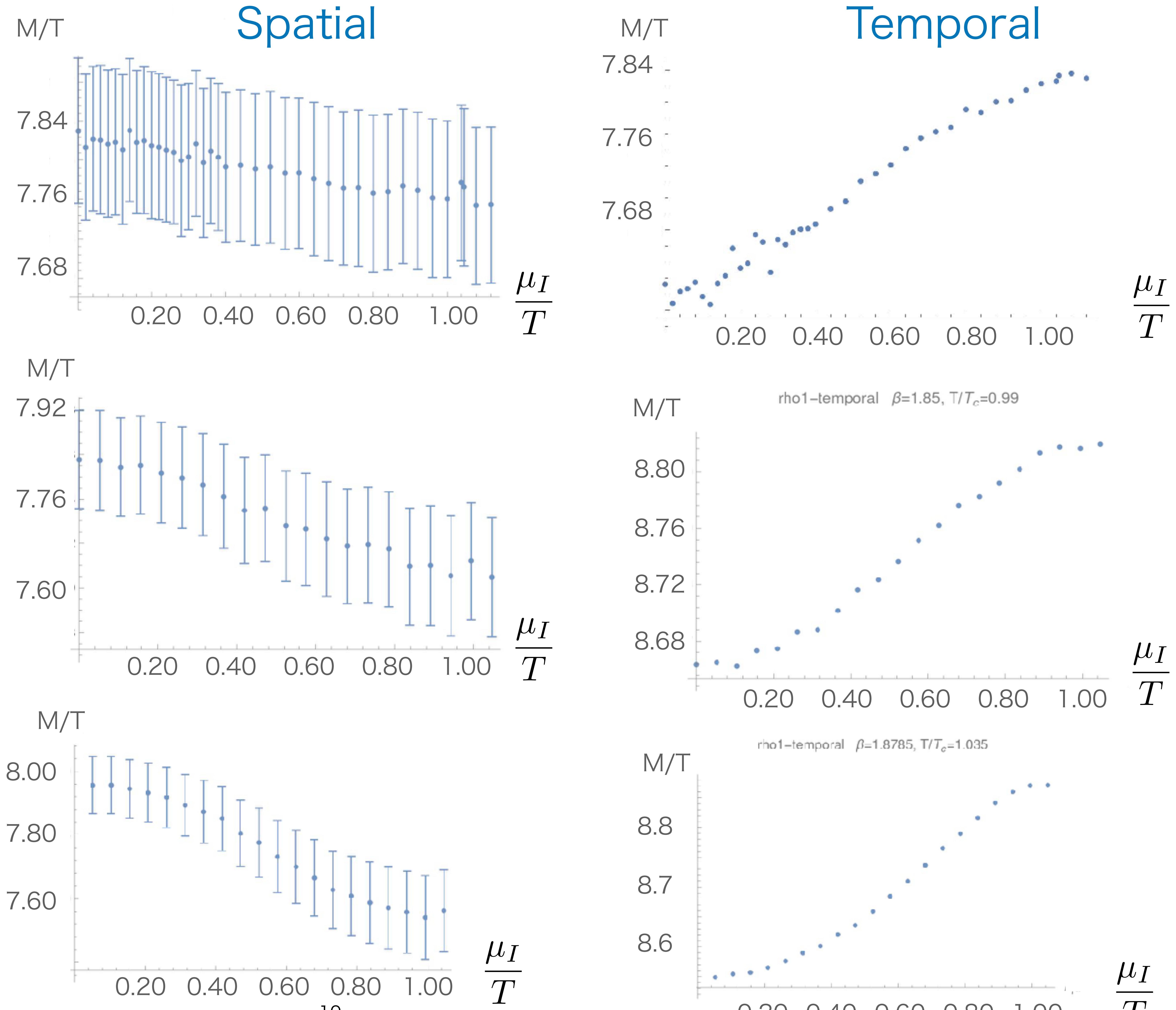


rho meson mass by Goy

T/Tc=0.93

T/Tc=0.99

T/Tc=1.035



Phase Structure in pure imaginary μ

$$(\det \Delta(\mu))^* = \det \Delta(\mu)^\dagger = \det \Delta(-\mu^*)$$

$\mu = i\mu_I$ ➡ $\det \Delta$: Real !

Comparison of obtained ξ

$$\xi \equiv e^{\mu/T}$$

$\sqrt{s_{NN}}$ GeV	Cleymans(06)	Aba(14)	Our
11.5	8.04	11.1	7.48
19.6	3.62	3.65	3.21
27	2.62	2.58	2.43
39	1.98	1.93	1.88
62.4	1.55	1.53	1.53
200	1.18	1.18	1.18

Why imaginary μ ?
In our world, μ is real !

Oni: Japanese demon

How to obtain the information at real μ

1. Continuation by Fugacity Expansion
   (—> Next slide)

2. Taylor expansion：

$$\frac{M(\mu)}{T} = \frac{M}{T}\,|_{\mu=0} + \left(\frac{\mu}{T}\right)\frac{\partial M}{\partial \mu}\,|_{\mu=0} + \left(\frac{\mu}{T}\right)^2 \frac{1}{2}\frac{\partial^2 M}{\partial \mu^2}\,|_{\mu=0} + \cdots$$

Fugacity Expansion

$$Z(\mu, T) = \sum_n z_n(T)(e^{\mu/T})^n$$

$Z(\mu, T)$: Grand Canonical Partition Function

$z_n(T)$: Canonical Partition Function

Inverse transformation:

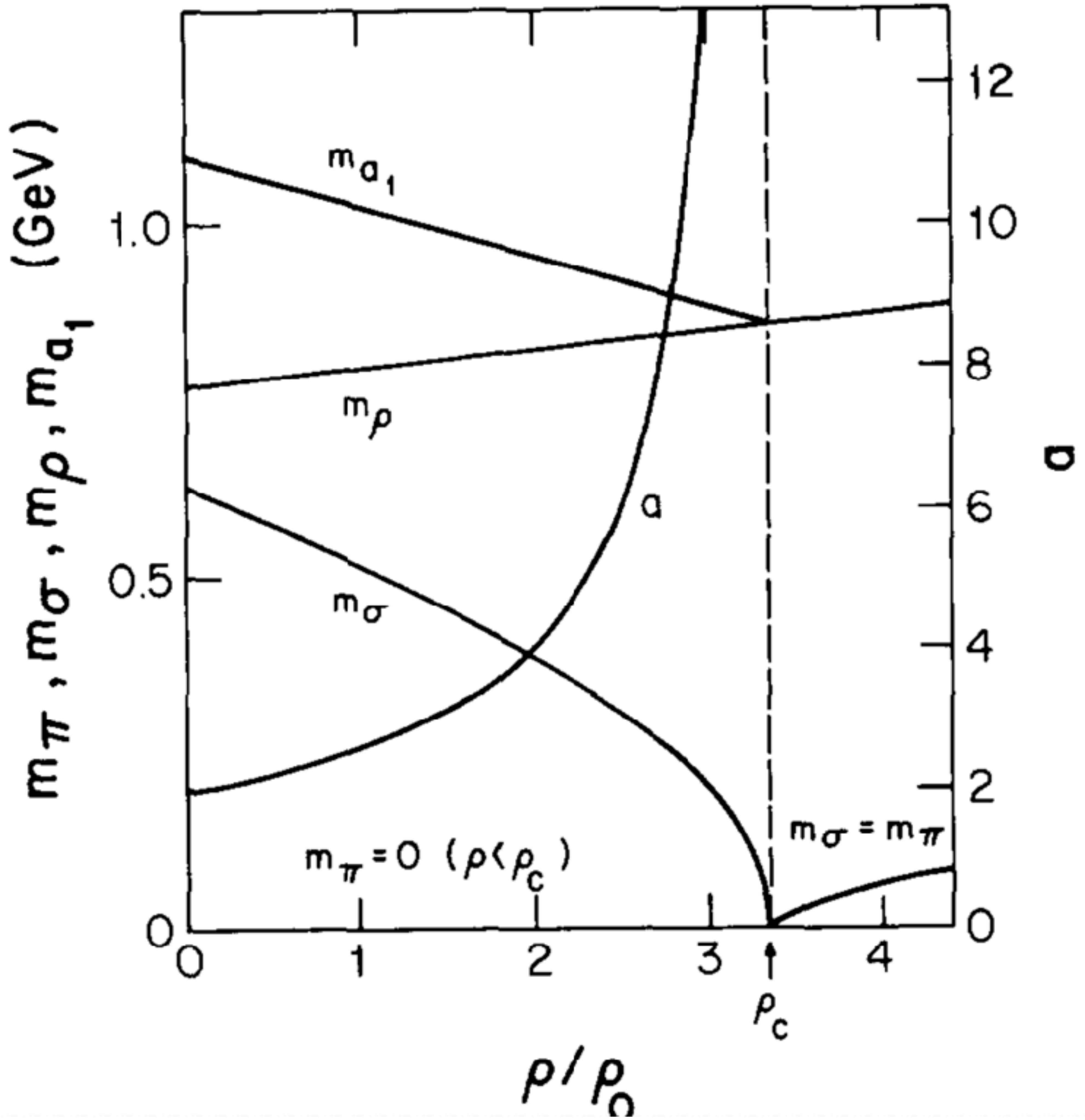
$$z_n = \int \frac{d\theta}{2\pi} e^{i\theta n} Z_{GC}(\theta \equiv \frac{\mathrm{Im}\mu}{T}, T)$$

A.Hasenfratz and Toussaint (1992)

z_n can be determined in imaginary μ regions.

Effective model study + Lattice
(Under consideration)

- Effective models:
  - Hosaka, Phys. Lett. B244, 363 (1990), "Meson properties at finite density in an extended Nambu-Jona-Lasinio model"
  - Ishii, Miyahara, Kouno and Yahiro, Phys. Rev. D **99**, 2019, "Extrapolation for meson screening masses from imaginary to real chemical potential"
- We compare Results of Lattice and Effective model and Effective model can give Results at real μ



Summary

- At J-PARC and NIKA, high density hadron states are realized

  High intensity beam and fixed targets at J-PARC is good for non-simple measurement.

- Lattice simulations can study at imaginary chemical potential regions.

- We can study the high density hadron world (i.e., real chemical potential regions) from the information at imaginary chemical potential data.

- This is a preparatory study on a small lattice (Nt=4). We will go to more realistic one (Nt=6).

Backup Slides

QCD-TARO Pushkina et al.

Physics Letters B
Volume 609, Issues 3–4, 10 March 2005, Pages 265-270

Properties of hadron screening masses at small baryonic density

QCD-TARO Collaboration, Irina Pushkina [a], Philippe de Forcrand [b, c], Margarita Garcia Perez [d], Seyong Kim [e, f], Hideo Matsufuru [g], Atsushi Nakamura [h], Ion-Olimpiu Stamatescu [i, j], Tetsuya Takaishi [k], Takashi Umeda [l]

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https://doi.org/10.1016/j.physletb.2005.01.006

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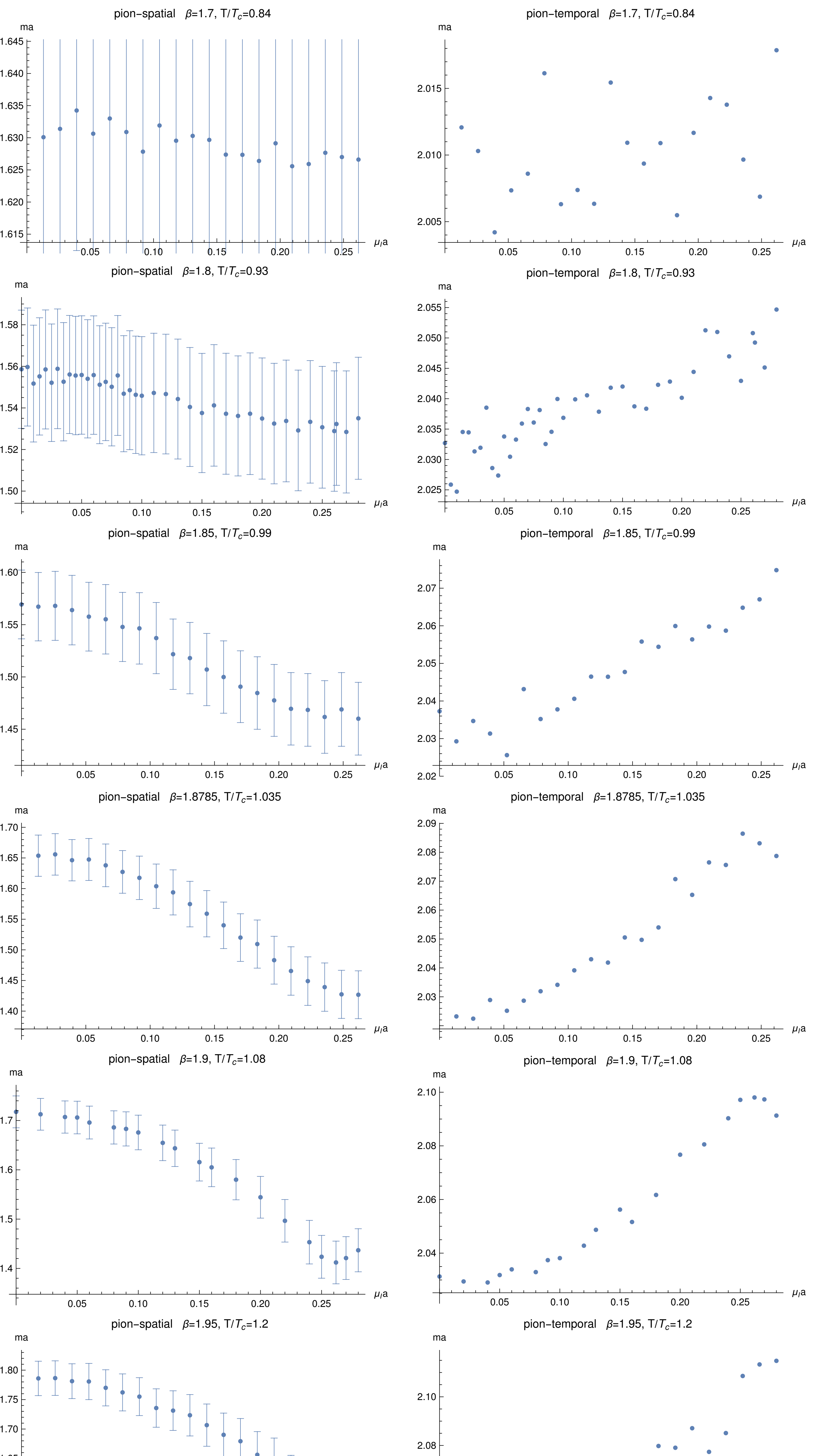
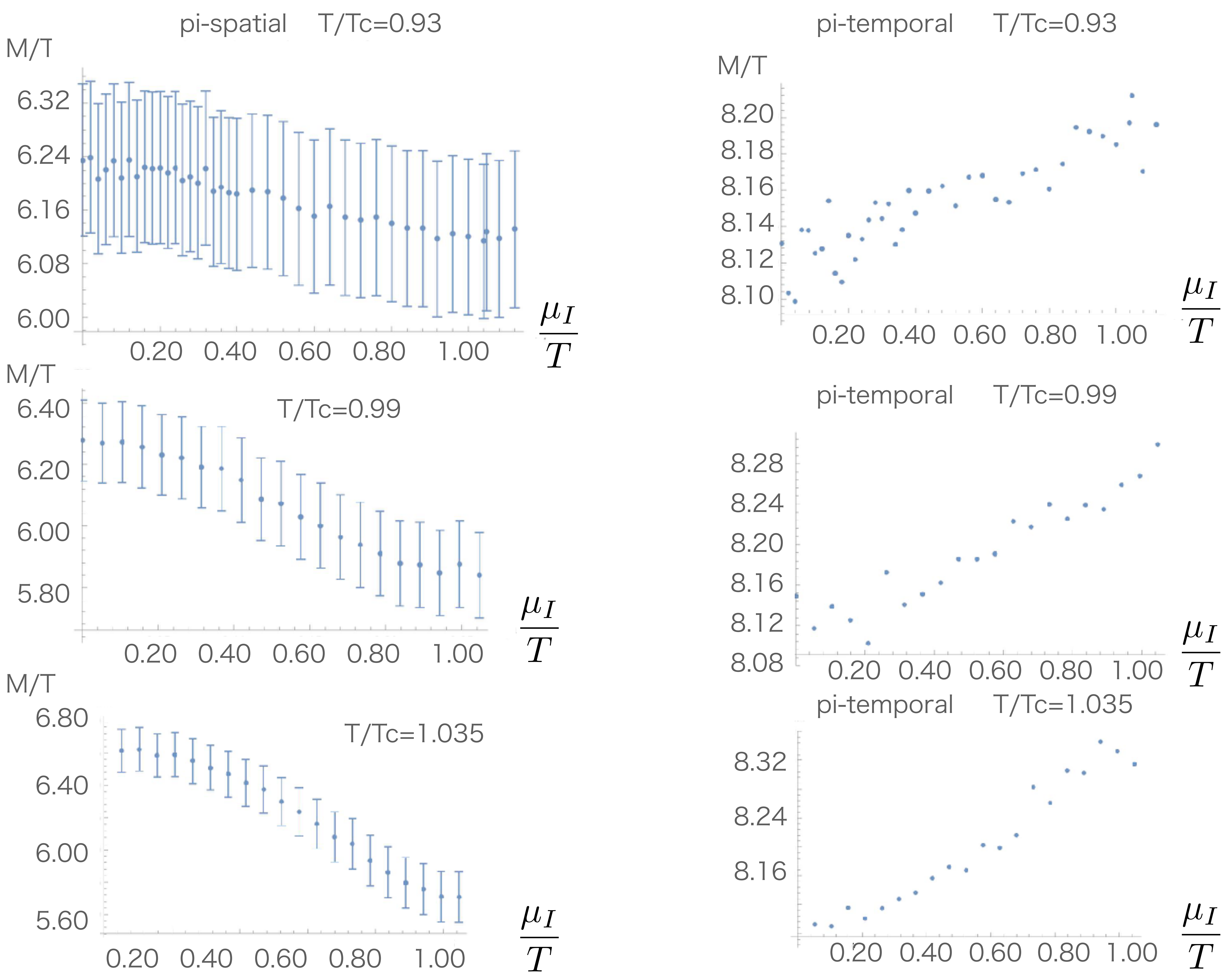
Abstract

The properties of hadron screening masses around the


pion-spatial β=1.7, T/T_c=0.84
pion-temporal β=1.7, T/T_c=0.84
pion-spatial β=1.8, T/T_c=0.93
pion-temporal β=1.8, T/T_c=0.93
pion-spatial β=1.85, T/T_c=0.99
pion-temporal β=1.85, T/T_c=0.99
pion-spatial β=1.8785, T/T_c=1.035
pion-temporal β=1.8785, T/T_c=1.035
pion-spatial β=1.9, T/T_c=1.08
pion-temporal β=1.9, T/T_c=1.08
pion-spatial β=1.95, T/T_c=1.2
pion-temporal β=1.95, T/T_c=1.2
ma
μ_I a


pi-spatial T/Tc=0.93
M/T
6.32
6.24
6.16
6.08
6.00
0.20 0.40 0.60 0.80 1.00
$\frac{\mu_I}{T}$
M/T
6.40
T/Tc=0.99
6.20
6.00
5.80
0.20 0.40 0.60 0.80 1.00
$\frac{\mu_I}{T}$
M/T
6.80
T/Tc=1.035
6.40
6.00
5.60
0.20 0.40 0.60 0.80 1.00
$\frac{\mu_I}{T}$
pi-temporal T/Tc=0.93
M/T
8.20
8.18
8.16
8.14
8.12
8.10
0.20 0.40 0.60 0.80 1.00
$\frac{\mu_I}{T}$
pi-temporal T/Tc=0.99
8.28
8.24
8.20
8.16
8.12
8.08
0.20 0.40 0.60 0.80 1.00
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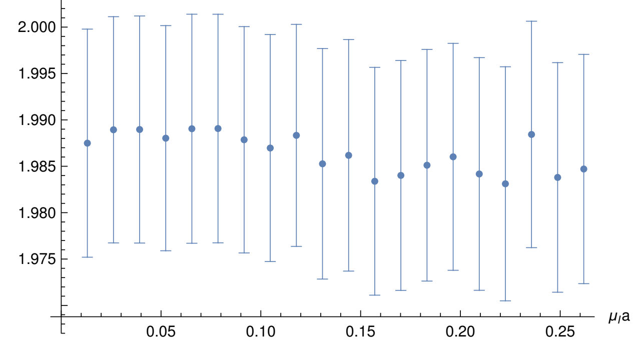
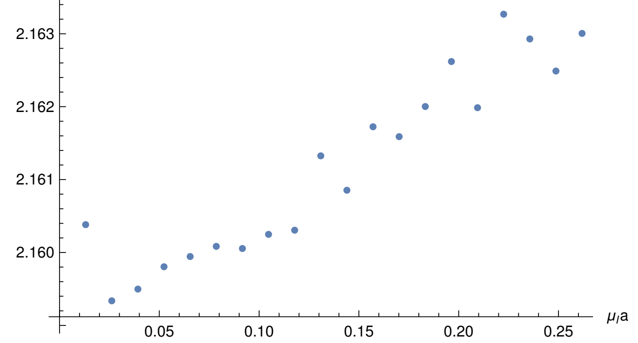
8.24
8.16
0.20 0.40 0.60 0.80 1.00
$\frac{\mu_I}{T}$





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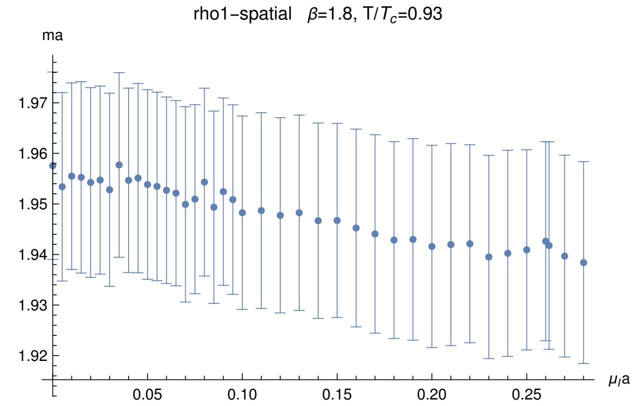
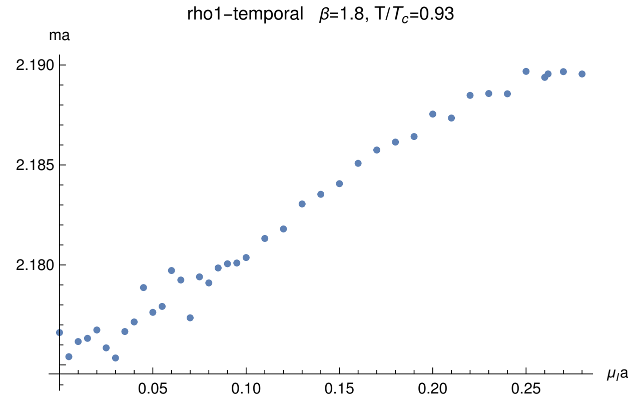
rho1-temporal β=1.8, T/T_c=0.93





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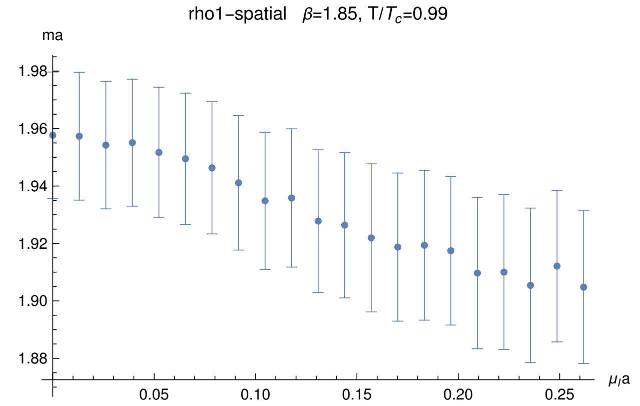
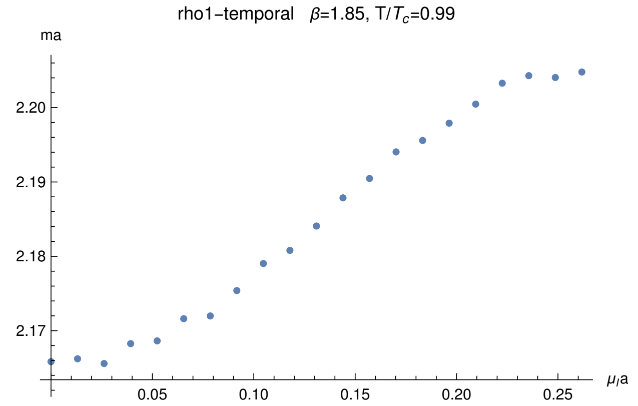
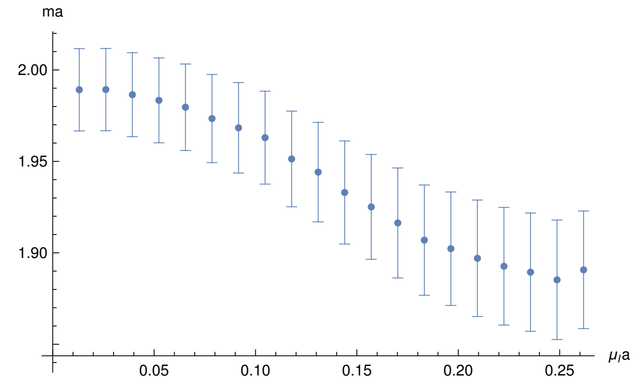
rho1-temporal β=1.85, T/T_c=0.99

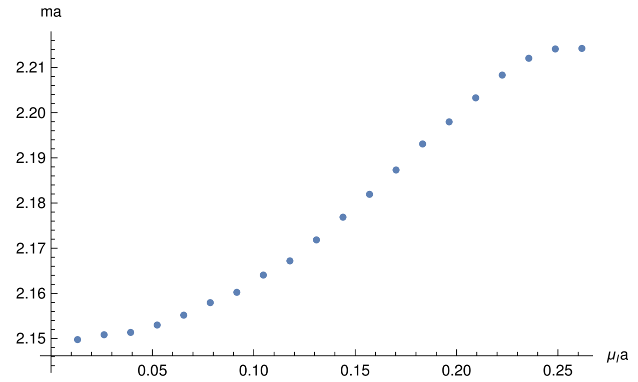




rho1-spatial β=1.8785, T/T_c=1.035

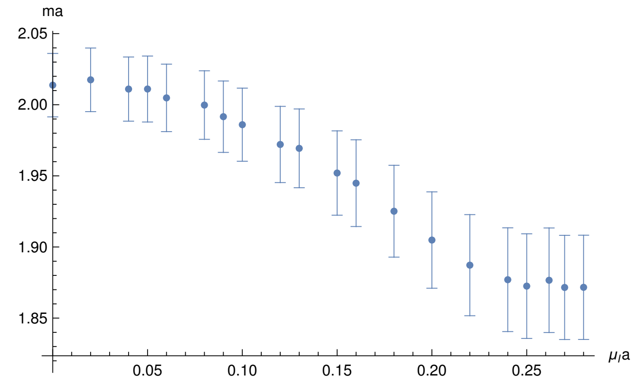
rho1-temporal β=1.8785, T/T_c=1.035

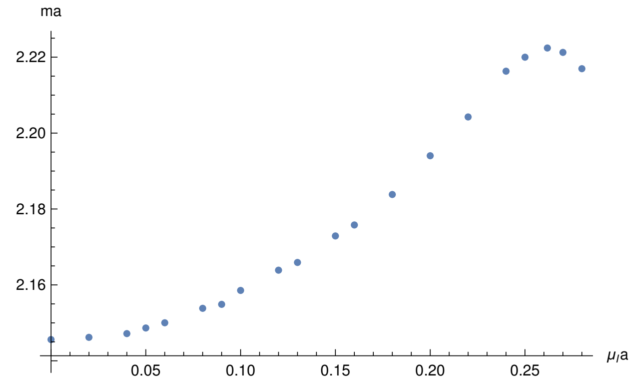




rho1-spatial β=1.9, T/T_c=1.08

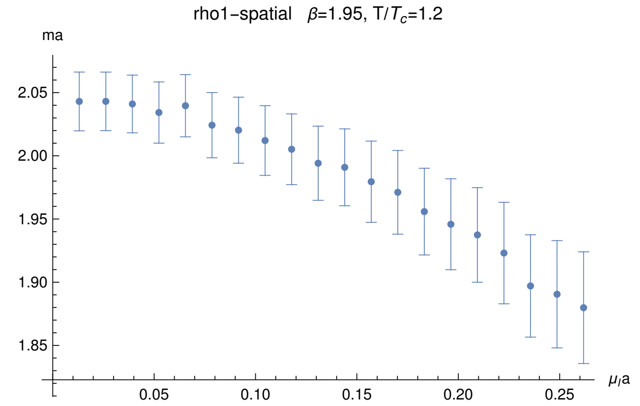
rho1-temporal β=1.9, T/T_c=1.08

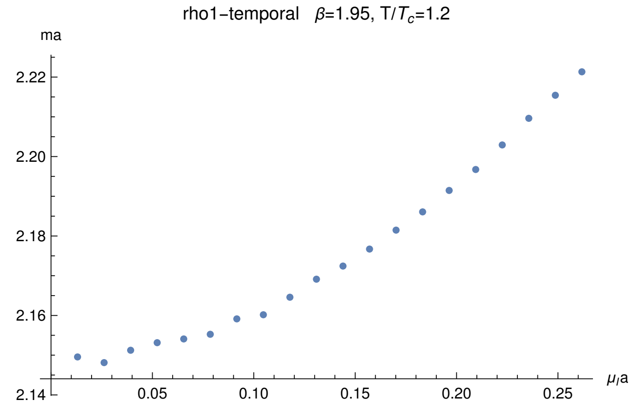




rho1-spatial β=1.95, T/T_c=1.2

rho1-temporal β=1.95, T/T_c=1.2





rho1-spatial β=2., T/T_c=1.35

rho1-temporal β=2., T/T_c=1.35