QCD phase diagram and CEP

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QCD@Work, Matera, Jun.25-28, 2018

Content

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II. Searching for the QCD CEP

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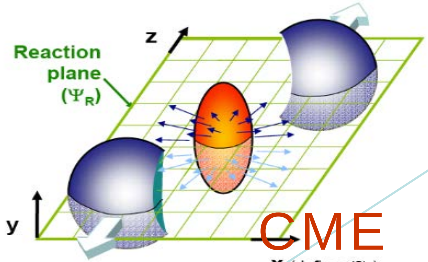
Explored QCD phase diagram now

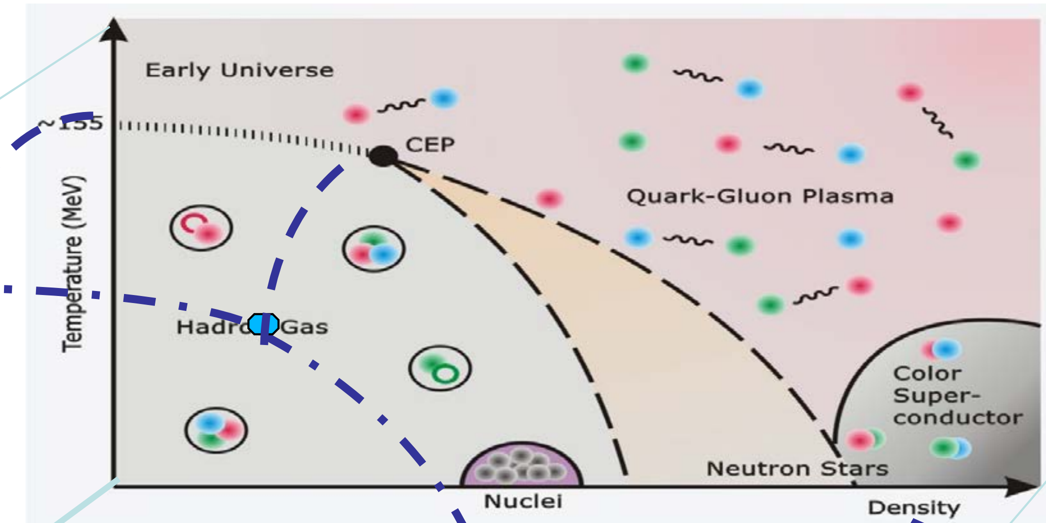
by theorists



CME

CVE

Inverse Magnetic Catalysis

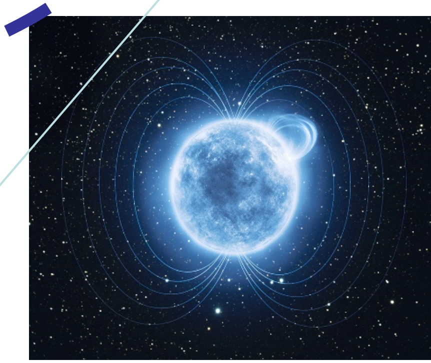


Charged rho condensation

Neutral/charged pion condensation

(Inverse) Magnetic Catalysis

Magnetar

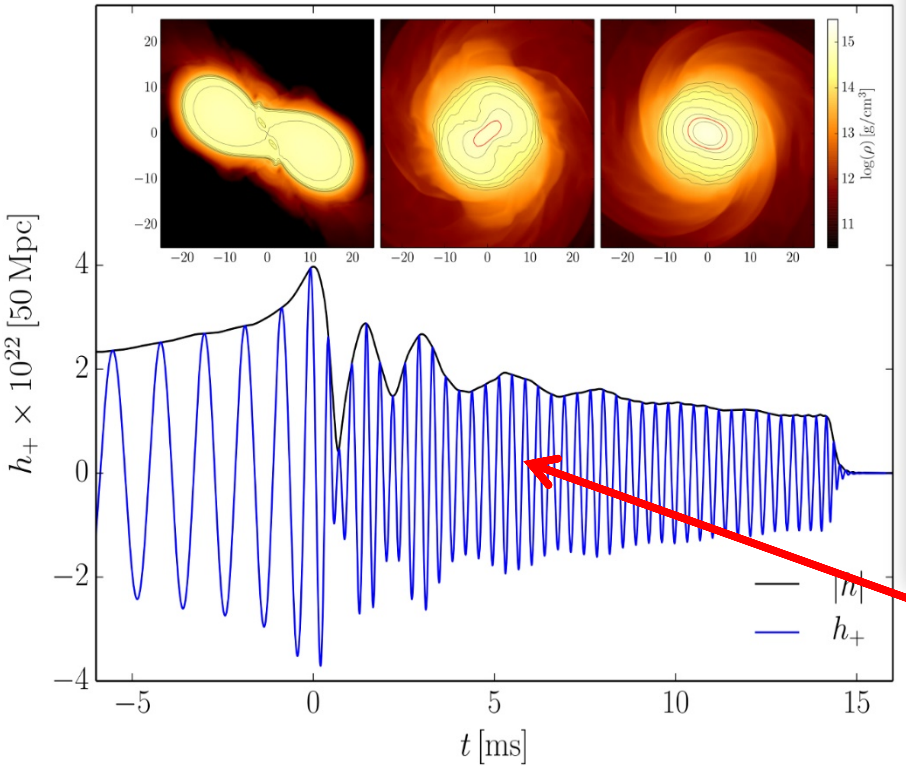


$$\mathbf{B}, \mathbf{E}\cdot\mathbf{B}, \omega, \mu_I$$

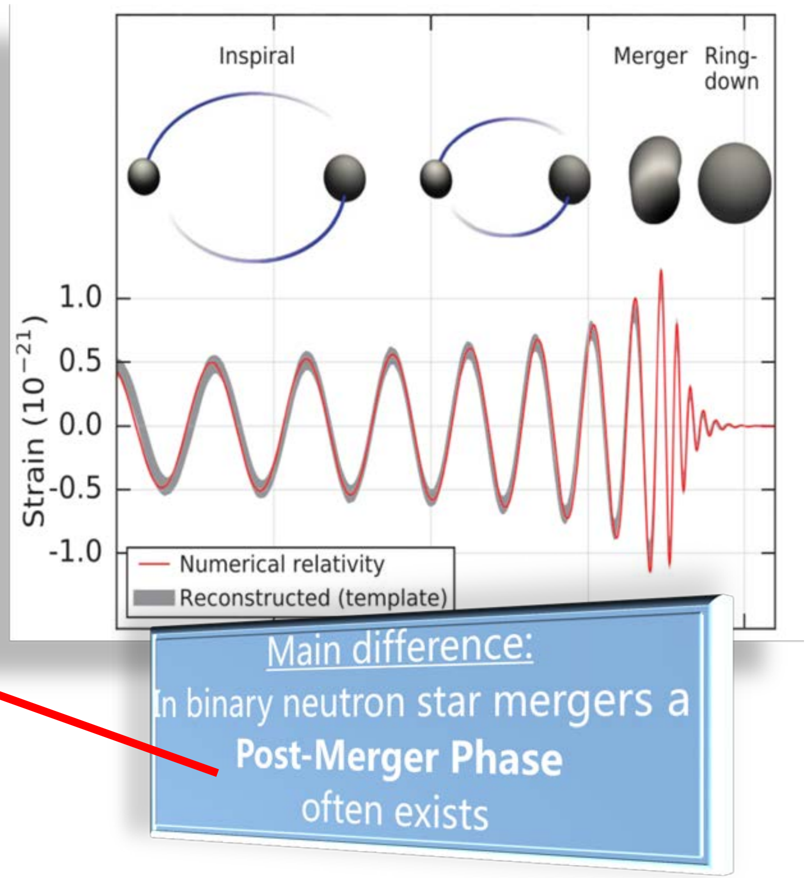
Gravitational Waves from Neutron Star Mergers

GW170817

Neutron Star Collision (Simulation)



Collision of two Black Holes

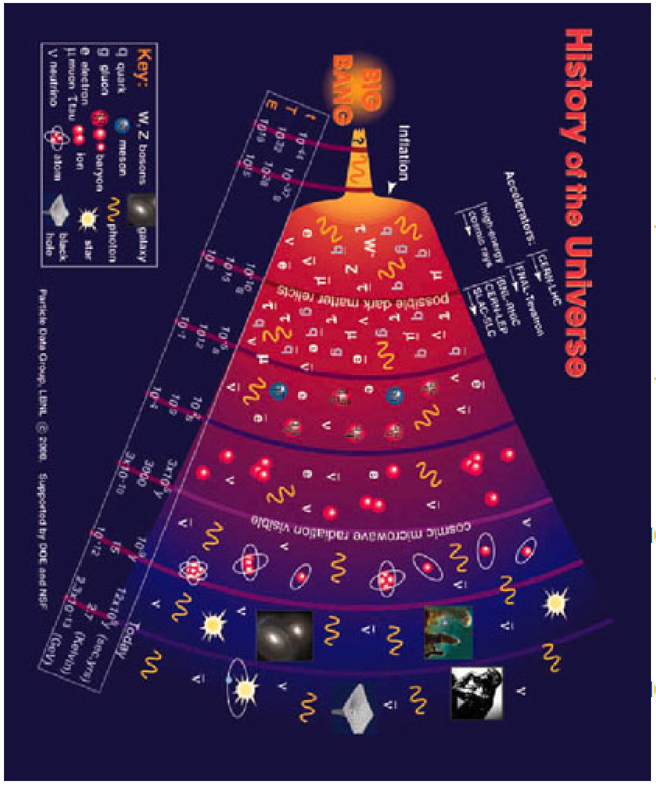


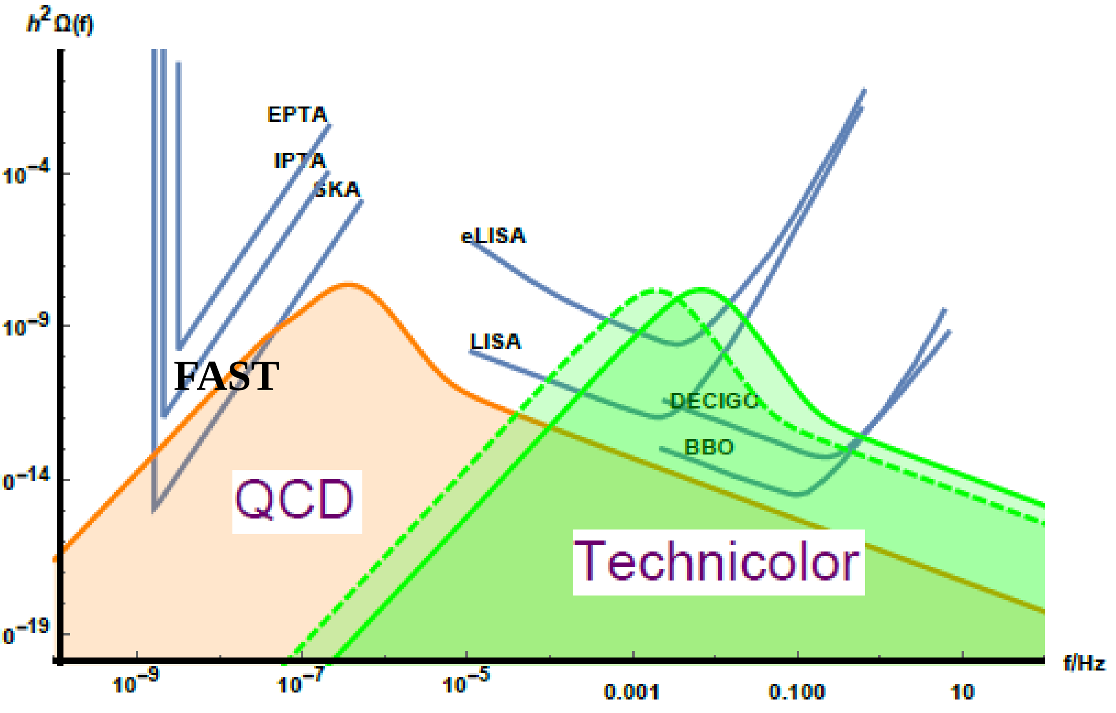
M. Hanauske@Frankfurt Uni., 2017

Gravitation wave from QCD & electroweak phase transitions in the early universe

1^{st} order phase transition for pure gluon system!

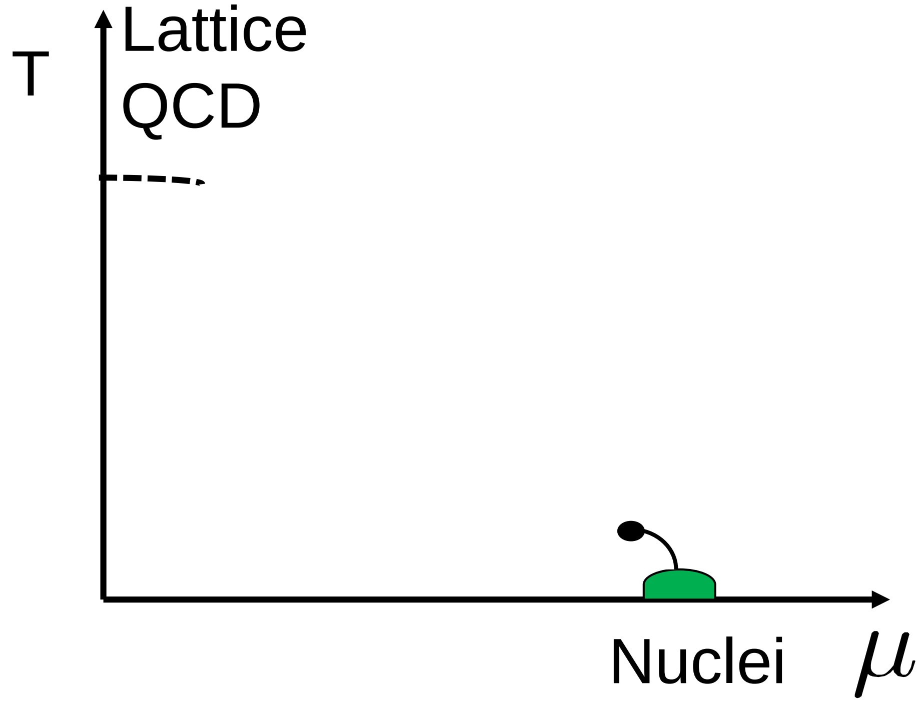
Yidian Chen, Mei Huang, Qishu Yan,
arXiv:1712.03470, JHEP05(2018)178





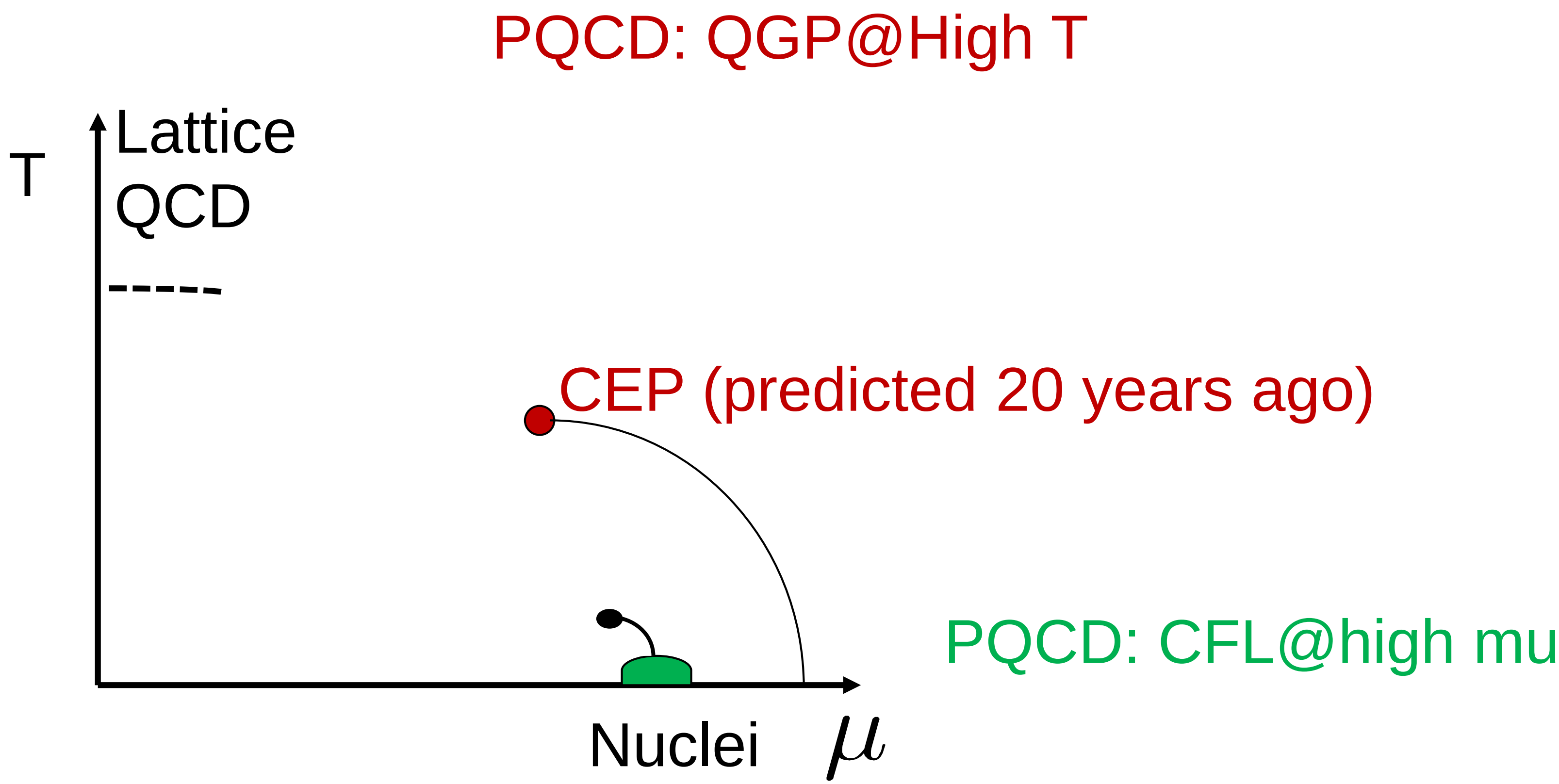
Confirmed QCD phase diagram

PQCD: QGP@High T



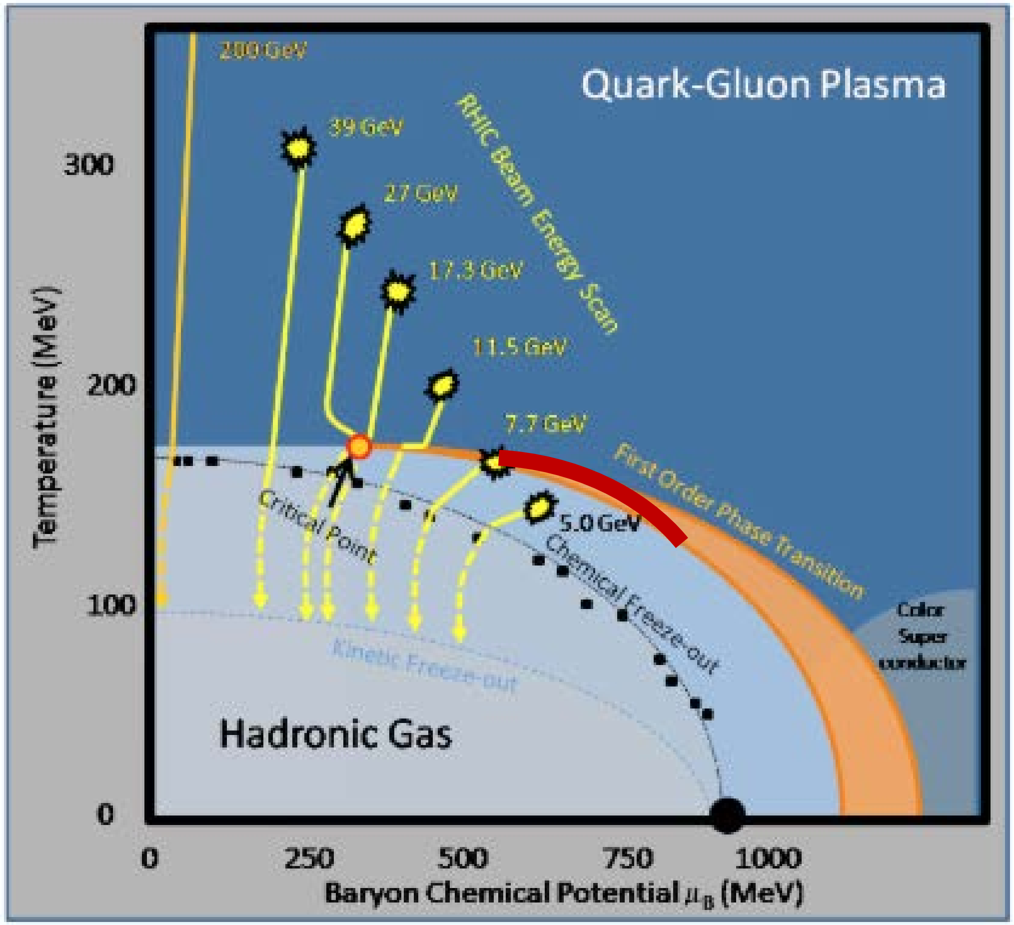
PQCD: CFL@high mu

Searching for the QCD CEP



Locating CEP is essential for the QCD phase diagram!

Locating the QCD CEP



- ❑ BES @ RHIC
- ❑ NICA @Dubna
- ❑ CBM@FAIR
- ❑ HIAF@IMP

Chiral and deconfinement phase transitions

CEP is for chiral phase transition!

Chiral phase transition:

quark-antiquark condensate (for m=0)

Chiral symmetry breaking: $\langle\bar{\psi}\psi\rangle \neq 0$

Chiral symmetry restoration: $\langle\bar{\psi}\psi\rangle = 0$

Deconfinement phase transition:

referring to the “permanent confinement”

Polyakov loop (for m= infinity)

$$L(\vec{x}) = \frac{1}{N_c}\mathrm{tr}\,\mathcal{P}(\vec{x}) \text{ with } \mathcal{P}(\vec{x}) = \mathrm{P}\,e^{ig\int_0^\beta dt\, A_0(t,\vec{x})}$$

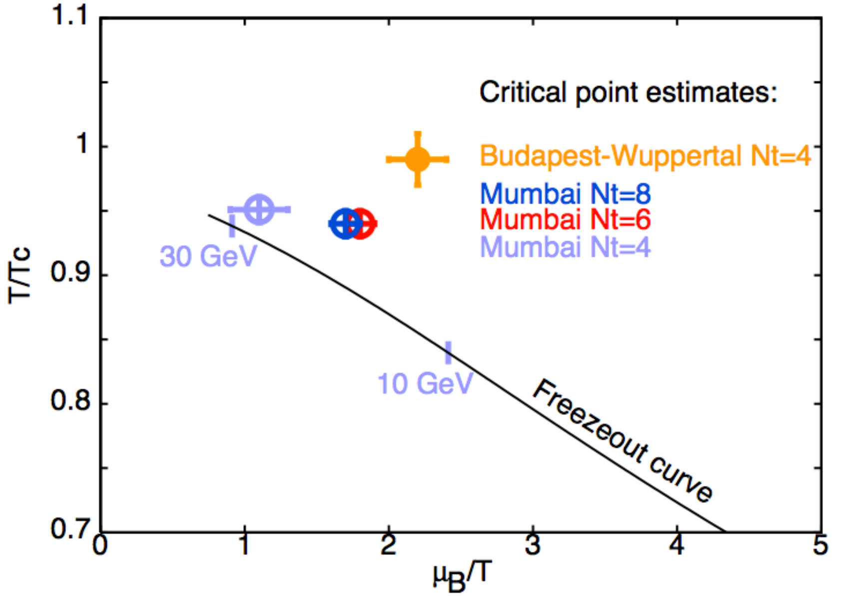
$$\langle L(\vec{x})\rangle \sim \exp(-\beta F_q)$$

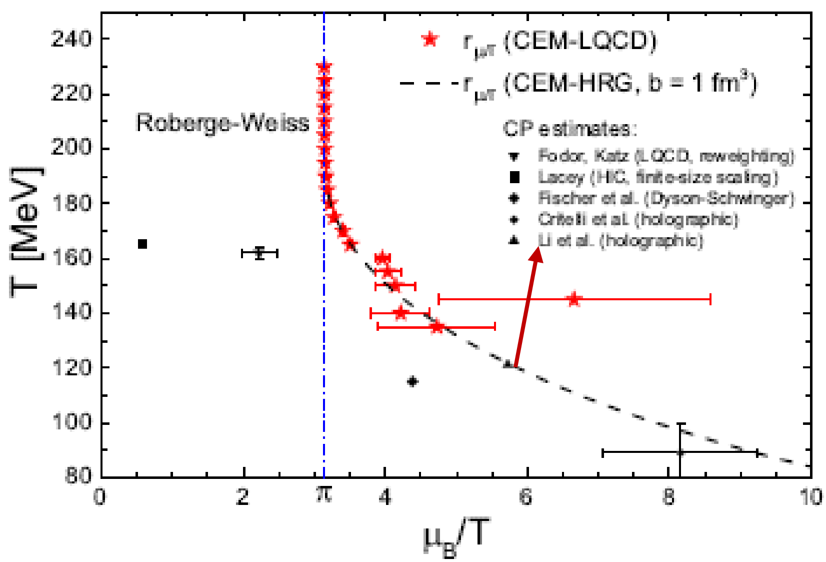
Confinement: center symmetric $\langle L\rangle = 0 \quad F_q \to \infty$

Deconfinement: center symmetry breaking $\langle L\rangle \neq 0 \quad F_q < \infty$

monopole (DI GIACOMO)

Location of CEP from Lattice QCD





1) Fodor&Katz, JHEP 0404,050 (2004).

$(\mu^E_B, T_E) = (360, 162)$ MeV

2) Gavai&Gupta, NPA 904, 883c (2013)

$(\mu^E_B, T_E) = (279, 155)$ MeV

3) F. Karsch (CPOD2016)

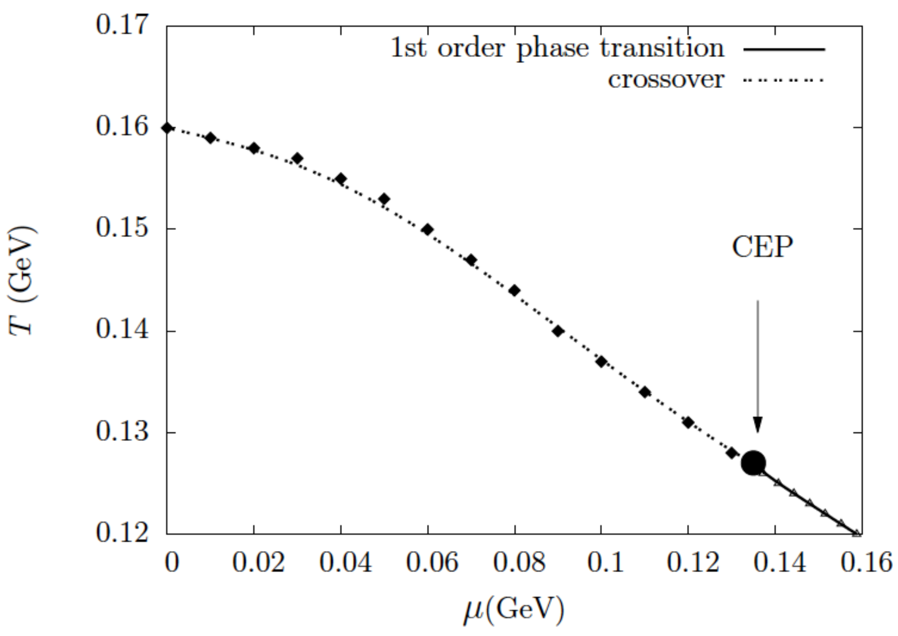
$\mu^E_B / T_E > 2$

4) V. Vovchenko, J. Steinheimer, O. Philipsen, H.Stoecker, arXiv:1711.01261

$$\mu_B^E / T_E > \pi$$

Latest lattice calculation shows that small baryon number density region for CEP is ruled out!

Location of CEP from DSE



1): Y. X. Liu, et al., PRD90, 076006 (2014).

$(\mu^E_B, T^E) = (372, 129)$ MeV

2): Hong-shi Zong et al., JHEP 07, 014 (2014).

$(\mu^E_B, T_E) = (405, 127)$ MeV

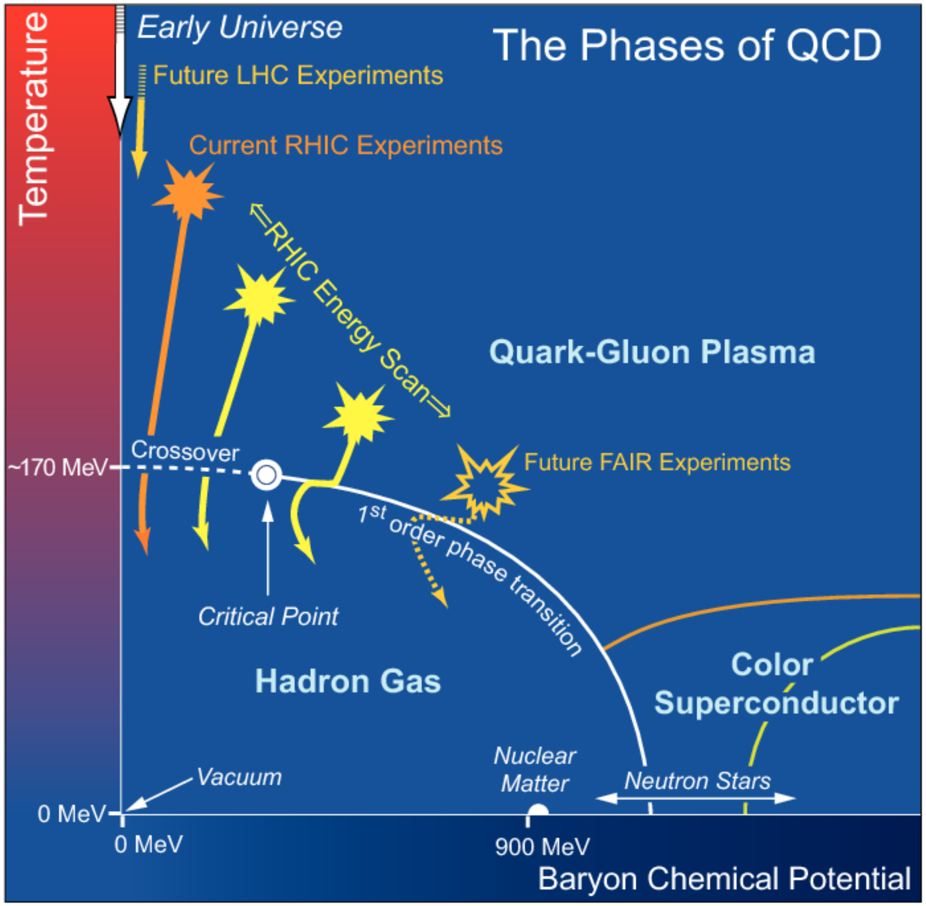
3): C. S. Fischer et al., PRD90, 034022 (2014).

$(\mu^E_B, T^E) = (504, 115)$ MeV

$$\mu_B = 3\mu_q$$

baryon number density region 300-500 MeV

Searching for the QCD CEP



BES Phase-I

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	$^*\mu_B$ (MeV)	$^*T_{CH}$ (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140

Higher Order Fluctuations of Conserved Quantities

$$\chi_n^B = \frac{\partial^n [P/T^4]}{\partial [\mu_B/T]^n}$$

$$B \rightarrow Q, s$$

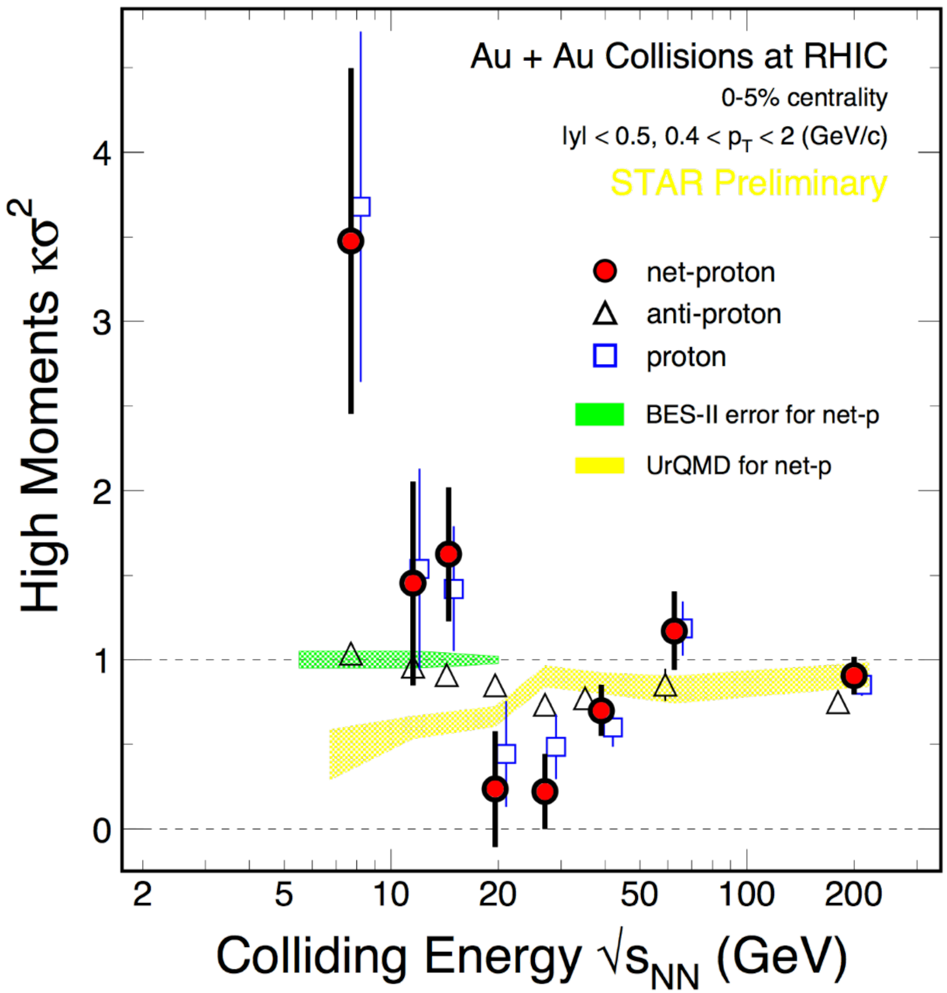
$$C_n^B = VT^3 \chi_n^B$$

$$\frac{\sigma^2}{M} = \frac{C_2^B}{C_1^B} = \frac{\chi_2^B}{\chi_1^B}, \quad S\sigma = \frac{C_3^B}{C_2^B} = \frac{\chi_3^B}{\chi_2^B},$$

$$\frac{S\sigma^3}{M} = \frac{C_3^B}{C_1^B} = \frac{\chi_3^B}{\chi_1^B}, \quad \kappa\sigma^2 = \frac{C_4^B}{C_2^B} = \frac{\chi_4^B}{\chi_2^B}.$$

S. Ejiri et al,Phys.Lett. B 633 (2006) 275. Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694. F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12)
S. Borsanyi et al., PRL111, 062005(13), P. Alba et al., arXiv:1403.4903

Measurement of Higher Order Fluctuations of Conserved Quantities



Non-monotonic trend is observed for the 0-5% most central Au+Au collisions. Dip structure is observed around 19.6 GeV.

What information about CEP can be read from experimental measurement?

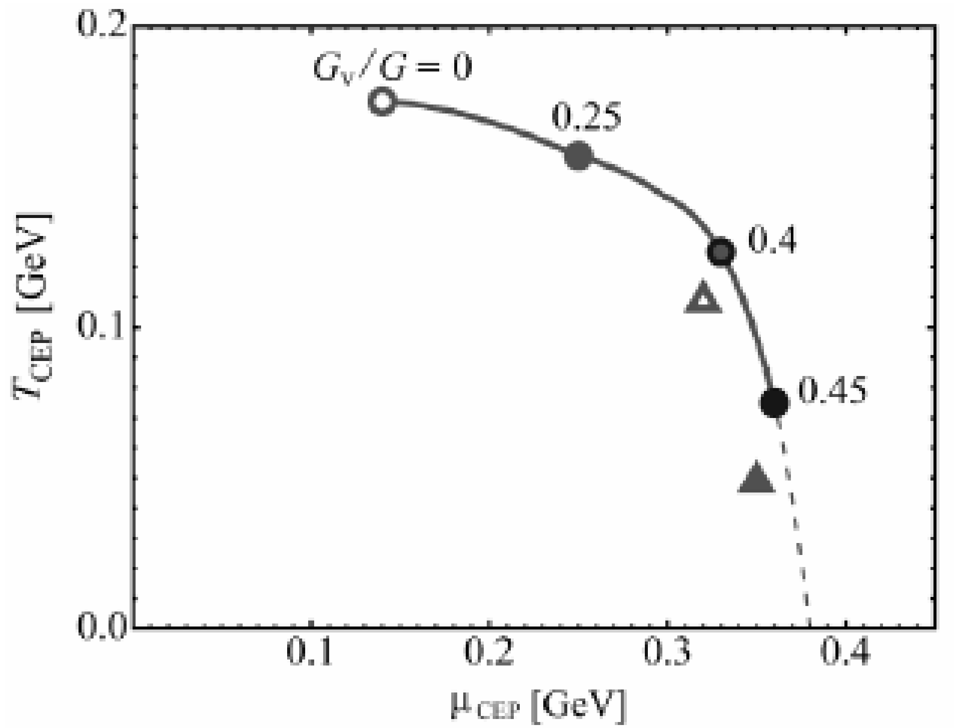
STAR: **PRL112**, 32302(14); **PRL113**,092301(14);
X.F.Luo, N.Xu, arXiv:1701.02105

CEP from PNJL-like models

Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215

Location of CEP: NJL

NJL, PNJL, Nonlocal NJL, ……



Hell, Kashiwa, Weise

Journal of Modern Physics, 2013, 4, 644-650

P.F Zhuang,M.Huang,
Y.X.Liu,W.J.Fu, Z.Zhang
H.S.Zong, X.Luo, G.Y.Shao…..
J.Deng, J.W.Chen,G.Q.Cao,
X.G.Huang……

Weise,
Klevansky,
Hatsuda,Kunihiro,
Fukushima,
Redlich,Sasaki,
Ratti,
……

$$\mu_B = 3\mu_q$$

from small to high baryon number density region ……

NJL model

$$\mathcal{L}_{NJL} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi + G_S[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2] - G_V(\bar{\psi}\gamma_\mu\psi)^2$$

Shift the location of CEP

PNJL model K.Fukushima

$$\frac{\mathcal{U}(\Phi,\bar{\Phi},T)}{T^4} = -\frac{a(T)}{2}\bar{\Phi}\Phi + b(T)\ln[1 - 6\bar{\Phi}\Phi + 4(\bar{\Phi}^3 + \Phi^3) - 3(\bar{\Phi}\Phi)^2]$$

Mimic gluodynamics

$$a(T) = a_0 + a_1\left(\frac{T_0}{T}\right) + a_2\left(\frac{T_0}{T}\right)^2 \quad b(T) = b_3\left(\frac{T_0}{T}\right)^3$$

muPNJL model

$$T_0(N_f,\mu_i) = T_\tau e^{-\frac{1}{\alpha_0 f(N_f,\mu_i)}}$$

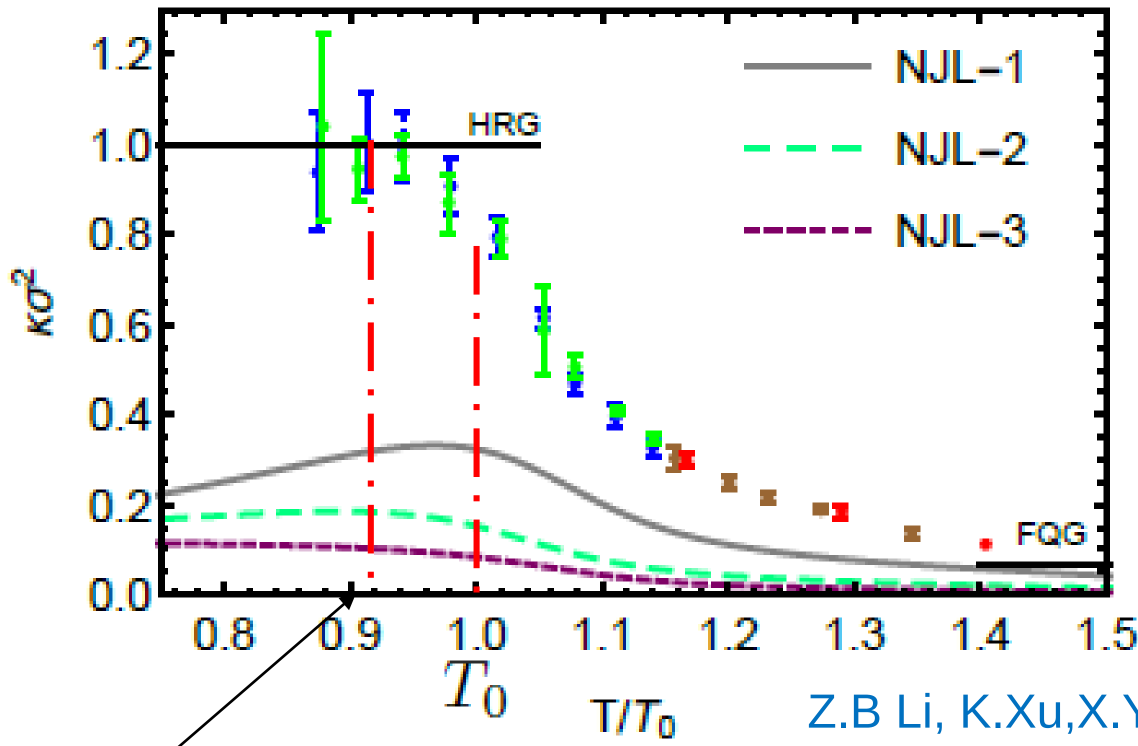
$$f(N_f,\mu_i) = \frac{11N_c - 2N_f}{6\pi} - \kappa\frac{16N_f}{\pi}\frac{\mu^2}{T_\tau^2}$$

Observation from lattice result: 0.8 of BNF at chiral phase transition, 1 at hadron-QGP transition

Unexpected results: Dominant contribution (80-90%) from gluodynamics to baryon number fluctuation!!!

Lattice result: A. Bazavov et al Phys. Rev. D95 no. 5, (2017) 054504

$\mu = 0$



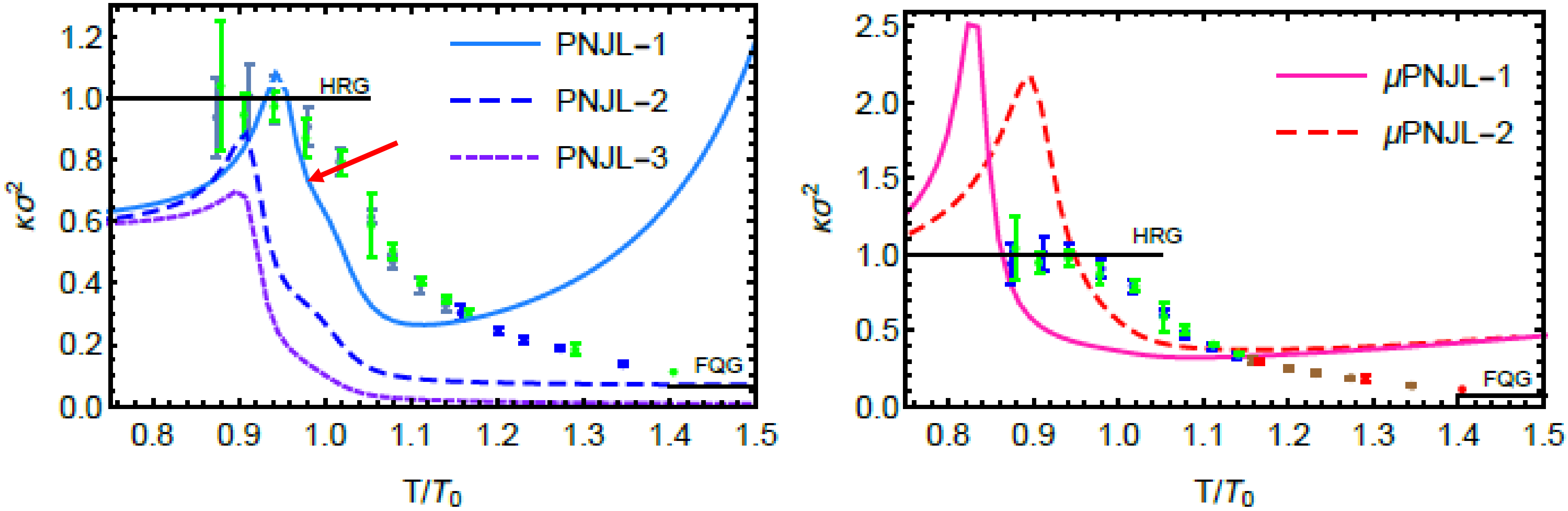
T_0

Z.B Li, K.Xu,X.Y.Wang, M.Huang arXiv:1801.09215

$T_0^{dec} \simeq 140\text{MeV}$

a physical "confinement-deconfinement" transition

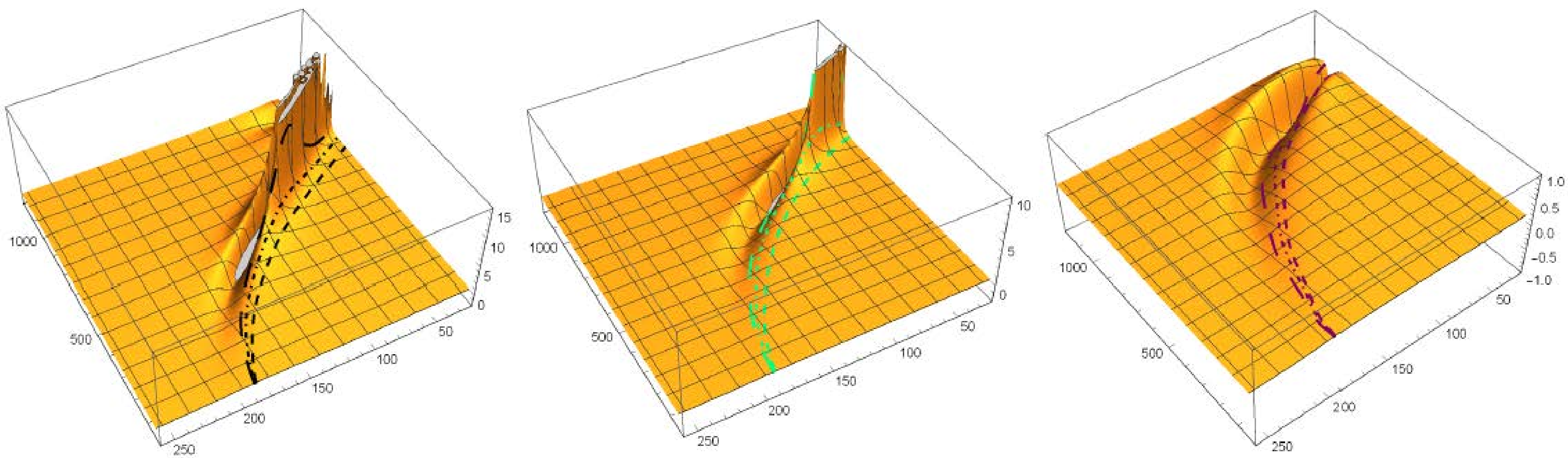
Lattice results for BNF at mu=0 can constrain models



Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215

Shifting the location of CEP in the NJL model

$G_V = -0.5 G_S$ $G_V = 0$ $G_V = 0.67 G_S$

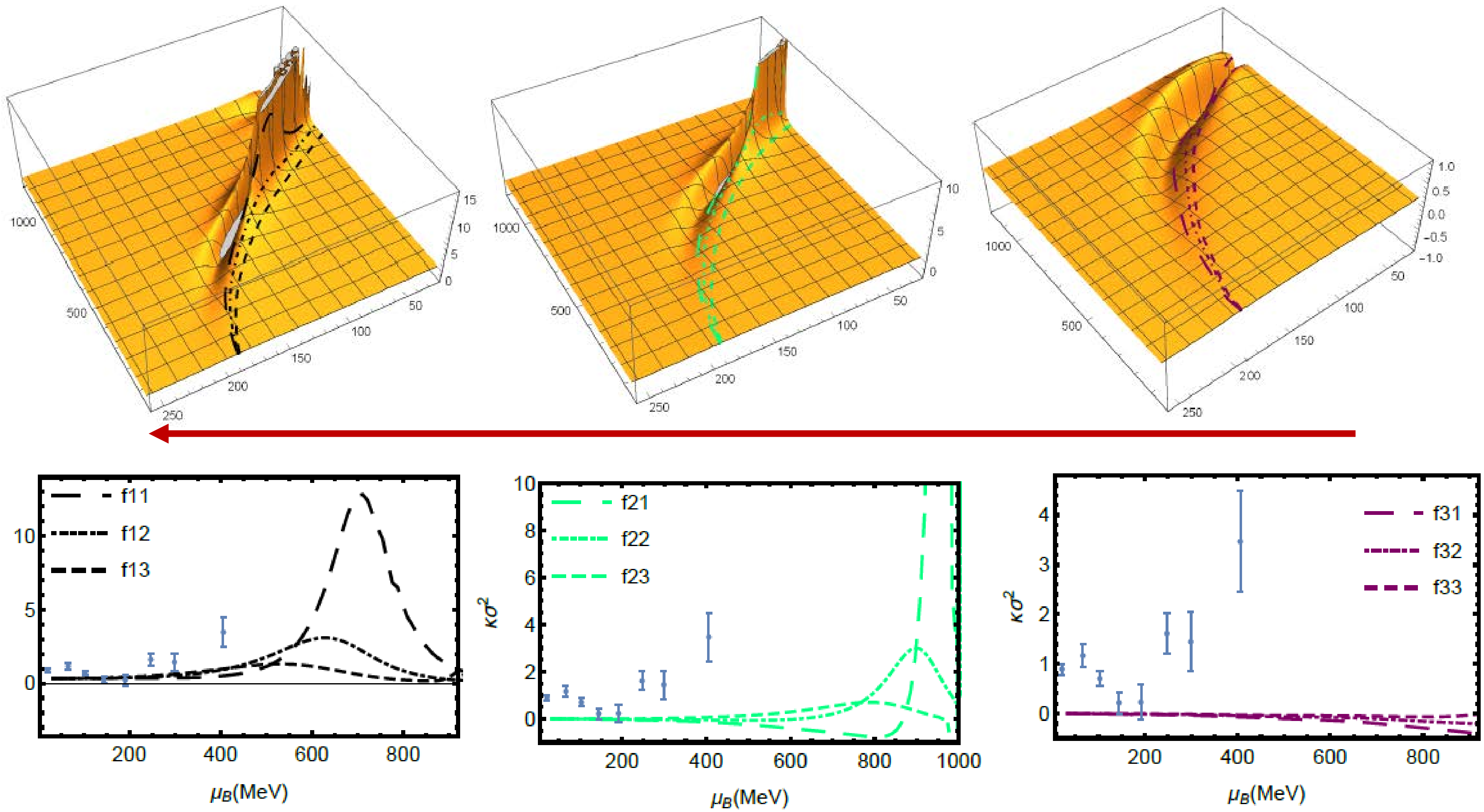


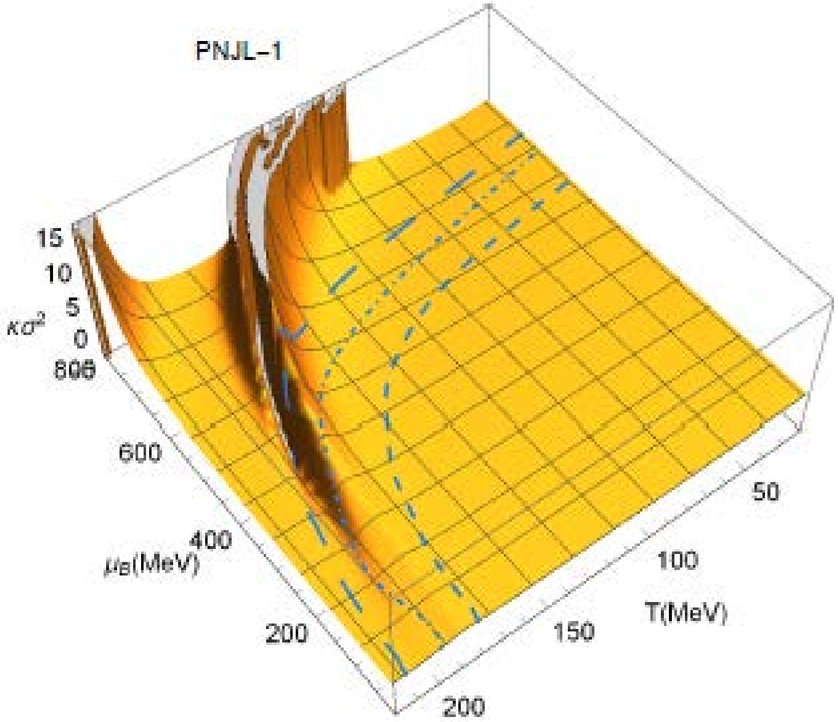
NJL-1 NJL-2 NJL-3

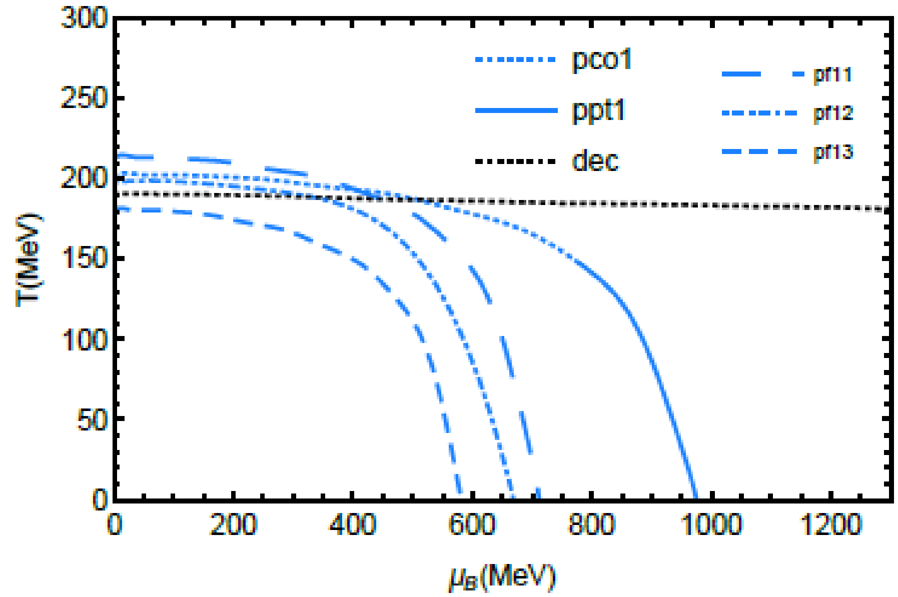
Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215

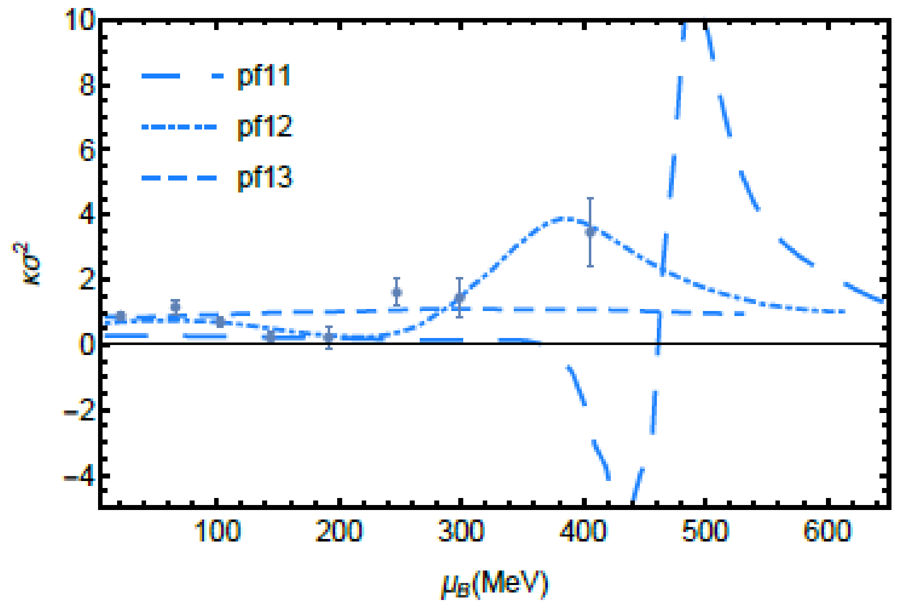
Results from NJL model

1. Location of CEP peak determines the location of the peak for BNF along freeze-out line;
2. If no CEP, no structure for BNF along freeze-out line.







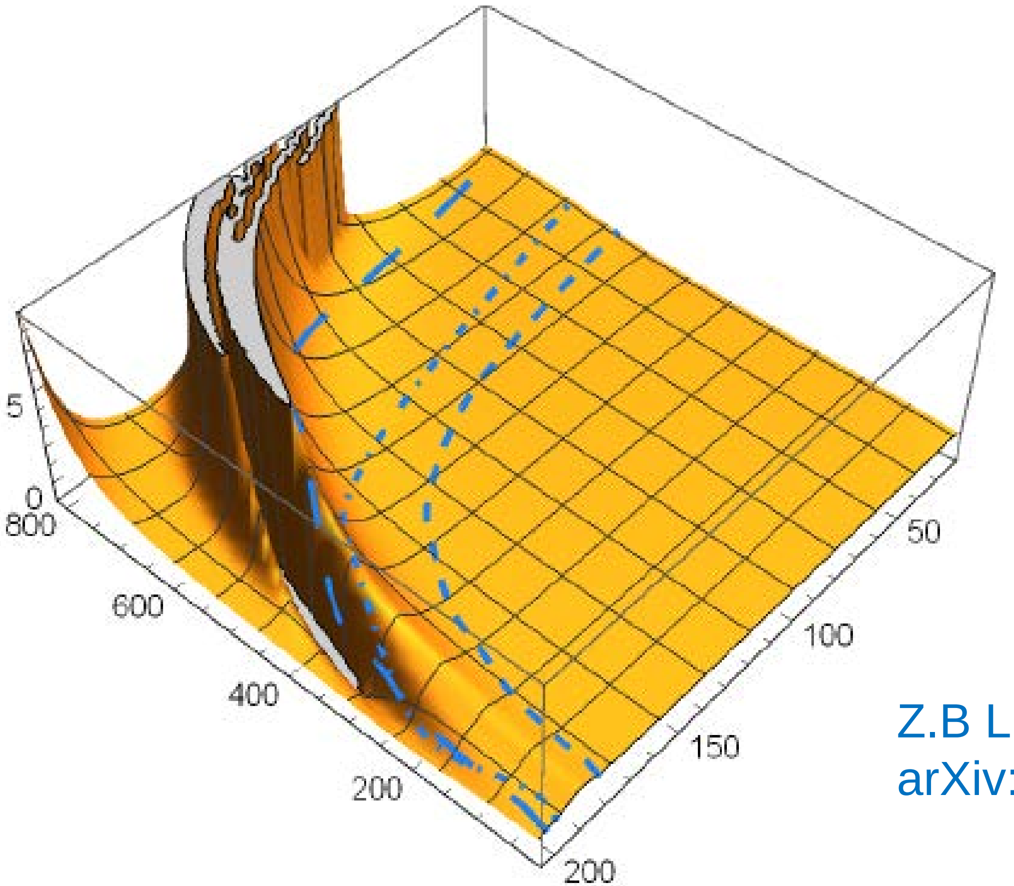


Freeze-out starts from back-ridge of the phase boundary, ➔
forming the dip structure

Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215

Freeze-out line crosses the foot of CEP mountain
====> forming the peak structure

Peak structure is a clean signature for CEP!!!



Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215

A realistic PNJL model

A. Bhattacharyya, S. K. Ghosh, S. Maity, S. Raha,
B. R. Ray, K. Saha and S. Upadhaya, arXiv:1609.07882.

NJL part:

$$\Omega = g_S \sum_f \sigma_f^2 - \frac{g_D}{2}\sigma_u\sigma_d\sigma_s + 3\frac{g_1}{2}(\sum_f \sigma_f^2)^2 + 3g_2\sum_f \sigma_f^4 - 6\sum_f \int \frac{d^3p}{(2\pi)^3} E_f \Theta(\Lambda - |\vec{p}|)$$
$$- 2T\sum_f \int \frac{d^3p}{(2\pi)^3} \ln[1 + 3(\Phi + \bar{\Phi}e^{-(E_f-\mu_f)/T})e^{-(E_f-\mu_f)/T} + e^{-3(E_f-\mu_f)/T}]$$
$$- 2T\sum_f \int \frac{d^3p}{(2\pi)^3} \ln[1 + 3(\Phi + \bar{\Phi}e^{-(E_f+\mu_f)/T})e^{-(E_f+\mu_f)/T} + e^{-3(E_f+\mu_f)/T}]$$
$$+ U'(\Phi, \bar{\Phi}, T)$$

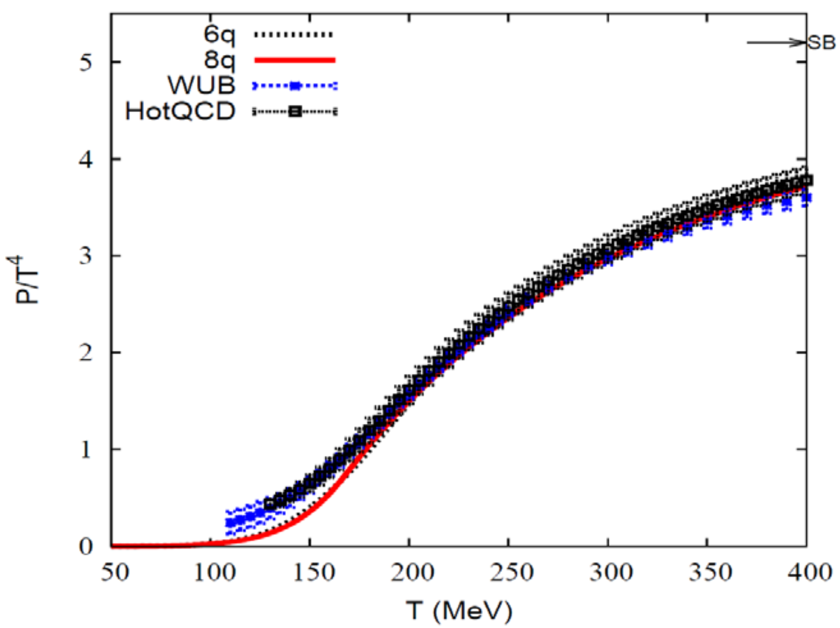
Polyakov Loop:

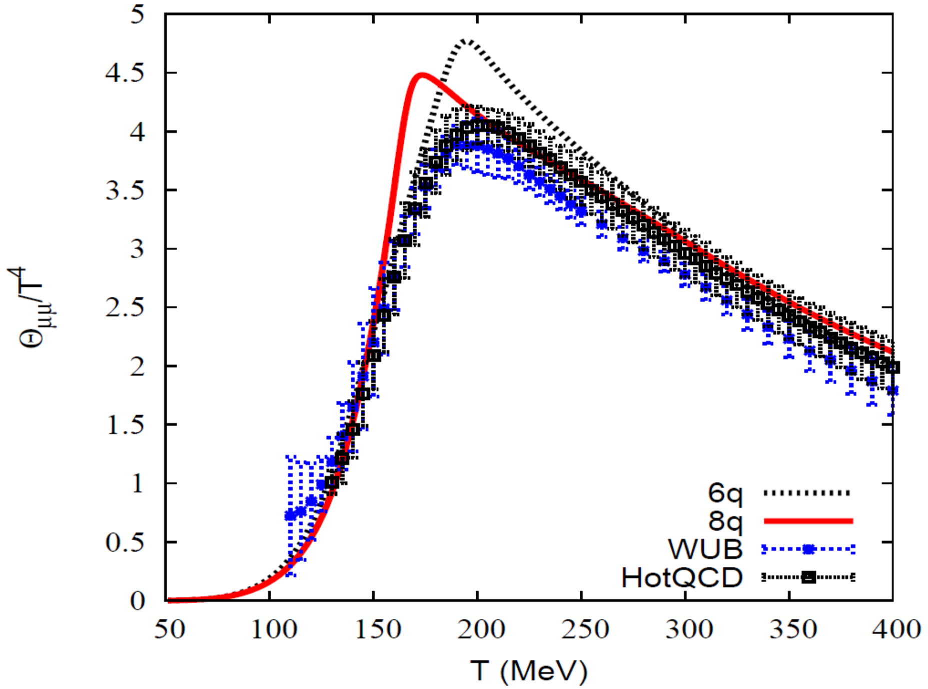
$$\frac{U'}{T^4} = \frac{U}{T^4} - \kappa \ln[J(\Phi, \bar{\Phi})] \qquad \frac{U}{T^4} = -\frac{b_2(T)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}(\Phi^3 + \bar{\Phi}^3) + \frac{b_4}{4}(\Phi\bar{\Phi})^2$$

$$J = (\frac{27}{24\pi^2})(1 - 6\Phi\bar{\Phi} + 4(\Phi^3 + \bar{\Phi}^3) - 3(\Phi\bar{\Phi})^2)$$

$$b_2(T) = a_0 + a_1\frac{T_0}{T}\exp(-a_2\frac{T}{T_0})$$

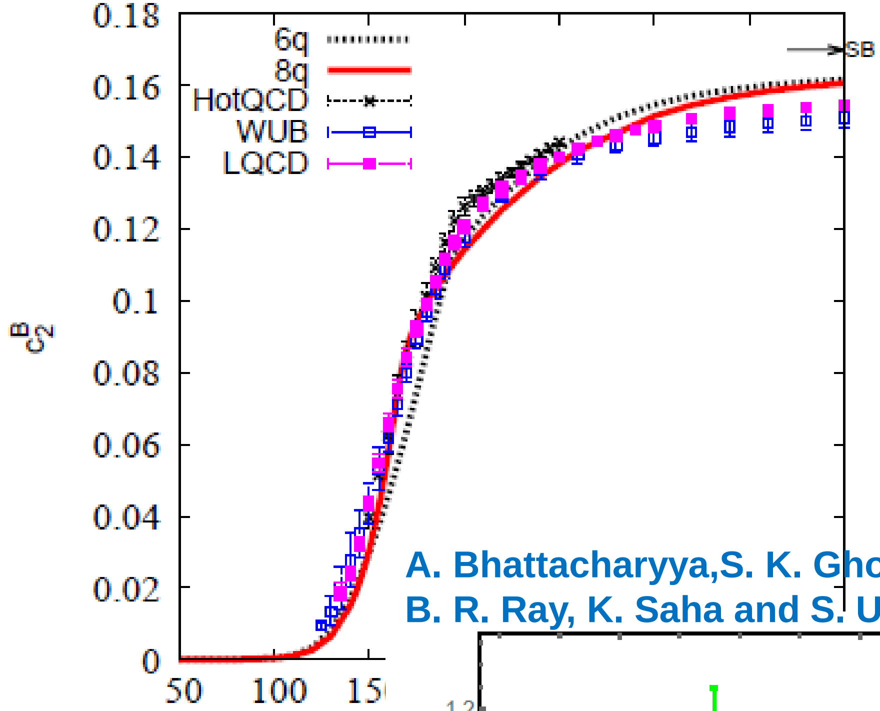
A. Bhattacharyya,S. K. Ghosh, S. Maity, S. Raha,
B. R. Ray, K. Saha and S. Upadhaya,arXiv:1609.07882.

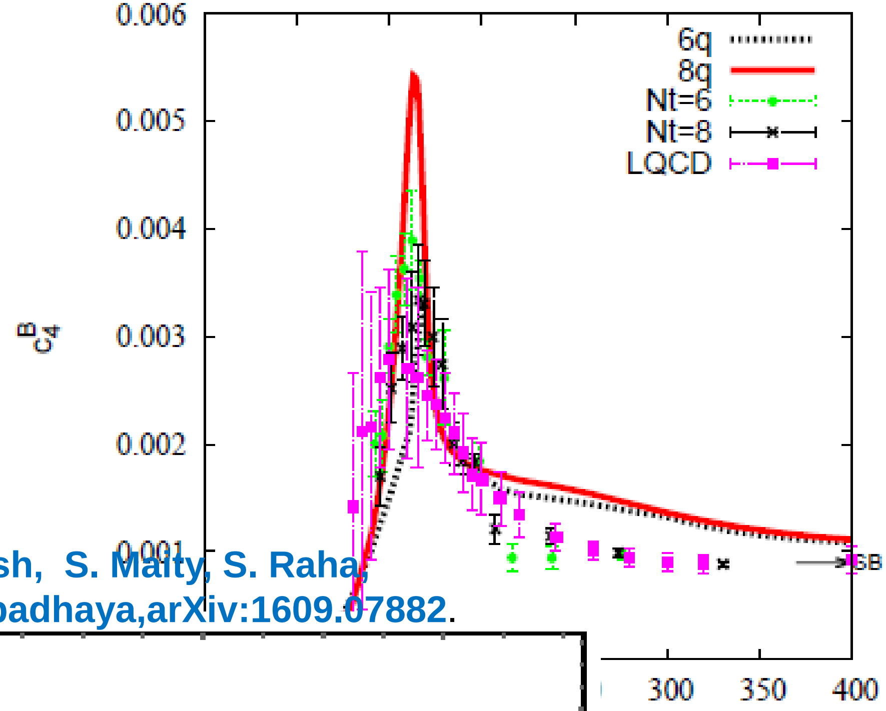




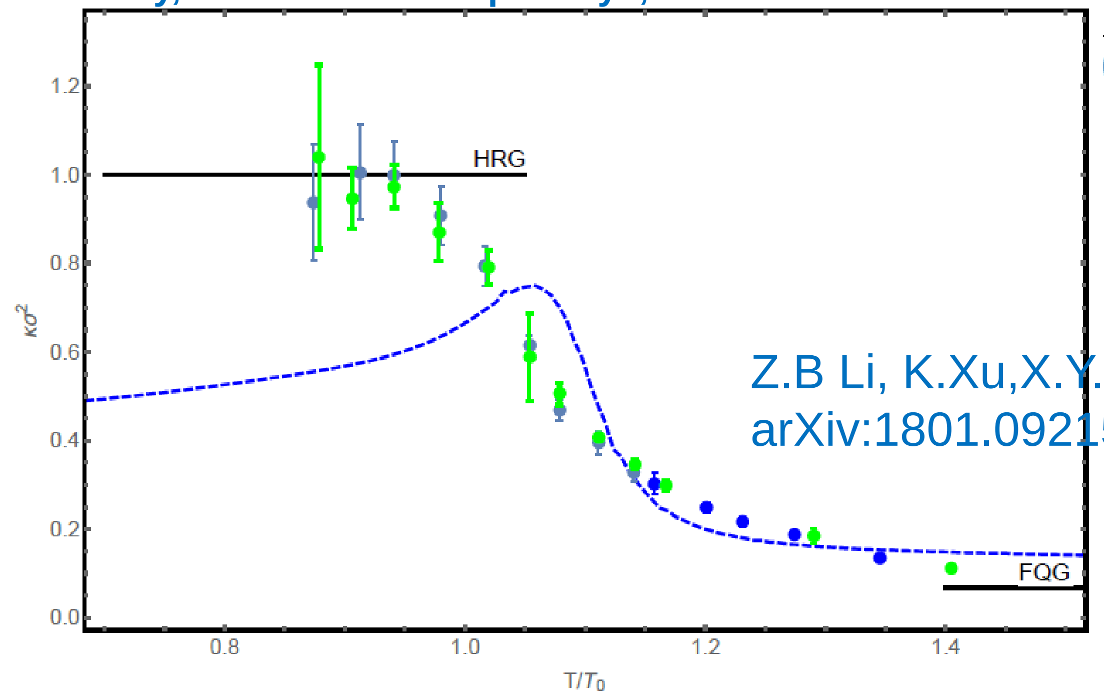
Parameters are fitted to pressure density lattice result at zero baryon chemical potential,

1) **Tc=154 MeV;**
2) **EOS: p,e,s, trace anomaly;**
3) **Baryon number fluctuations**



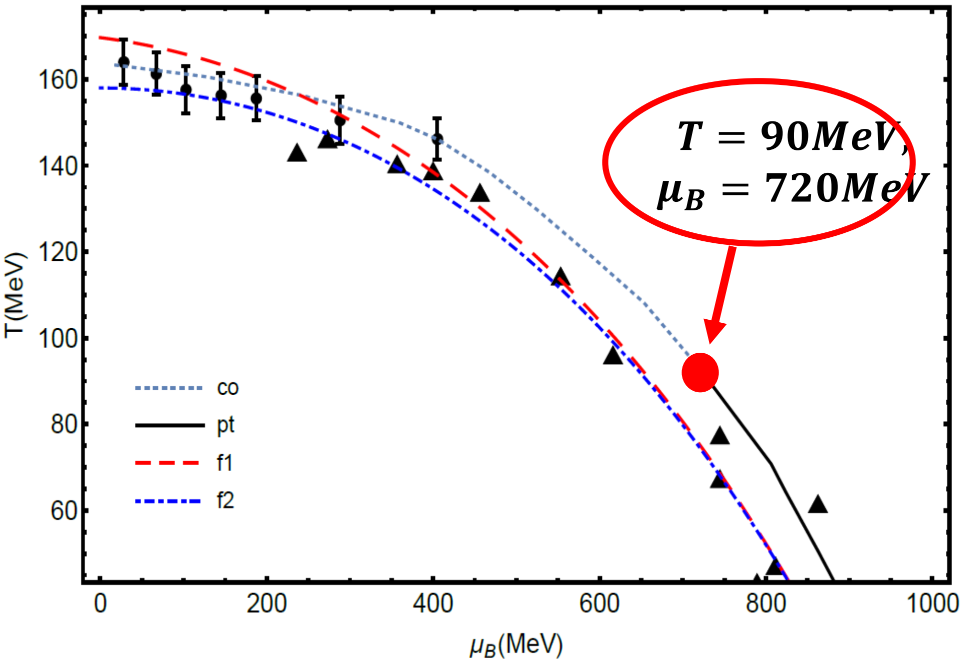


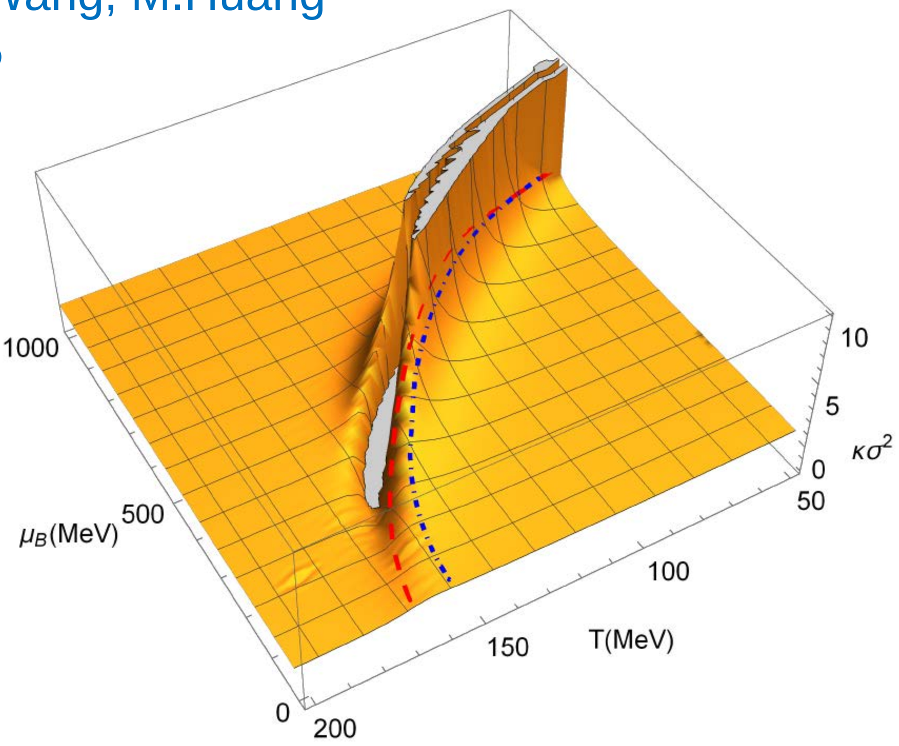
A. Bhattacharyya, S. K. Ghosh, S. Maity, S. Raha, B. R. Ray, K. Saha and S. Upadhaya, arXiv:1609.07882.



Z.B Li, K.Xu, X.Y.Wang, M.Huang
arXiv:1801.09215

Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215





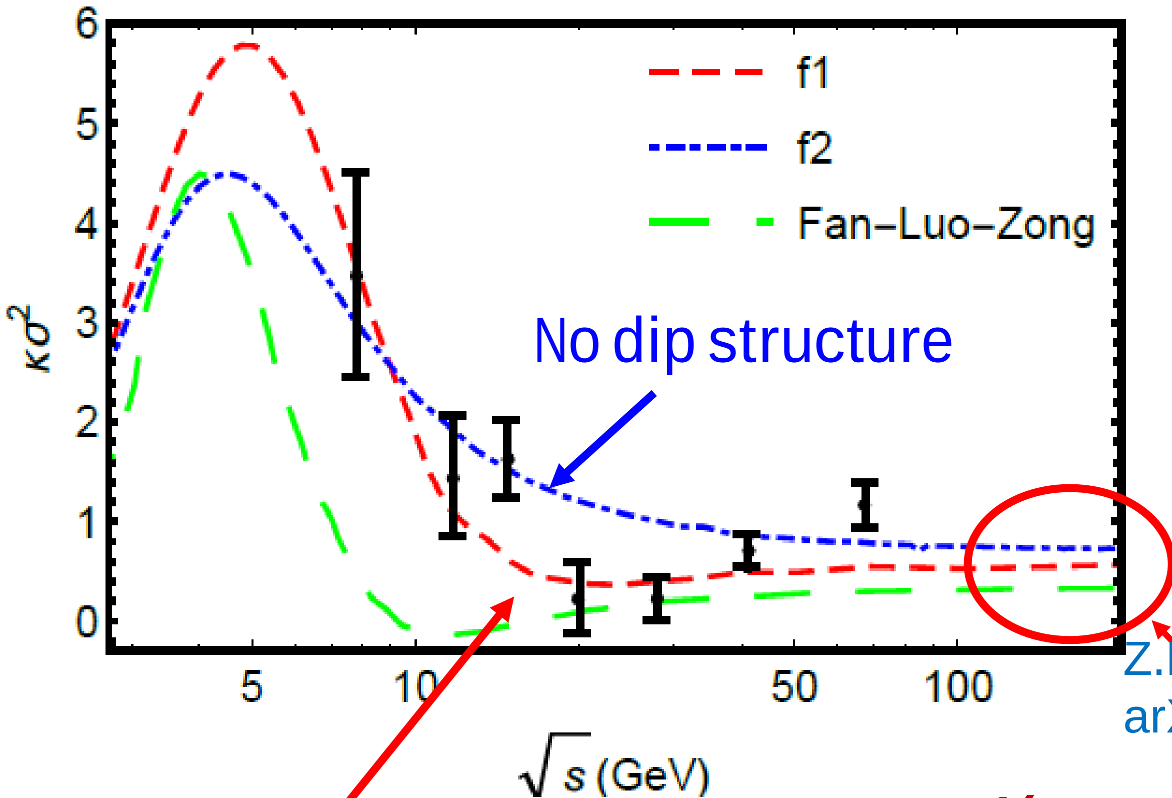
Freeze-out data: BES-I data and other experimental data

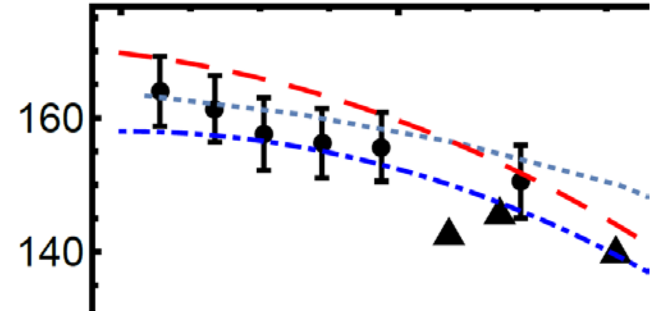
Two freeze-out lines:

f1: $T(\mu) = 0.158 - 0.14\mu^2 - 0.04\mu^4 - 0.013(0.948 - \mu)^2$

f2: $T(\mu) = 0.158 - 0.14\mu^2 - 0.04\mu^4$

Kurtosis along freeze-out lines





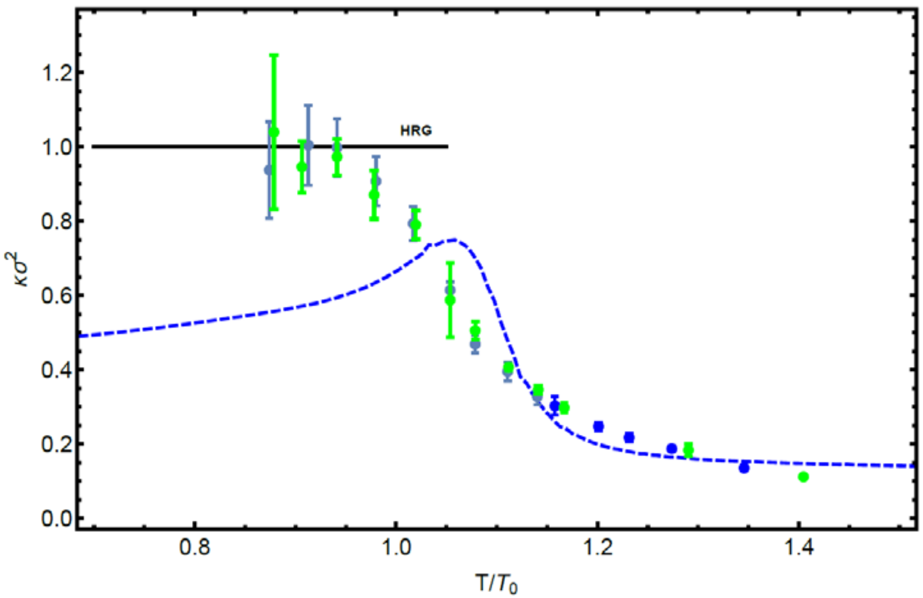
f1 cross the phase boundary while f2 not!

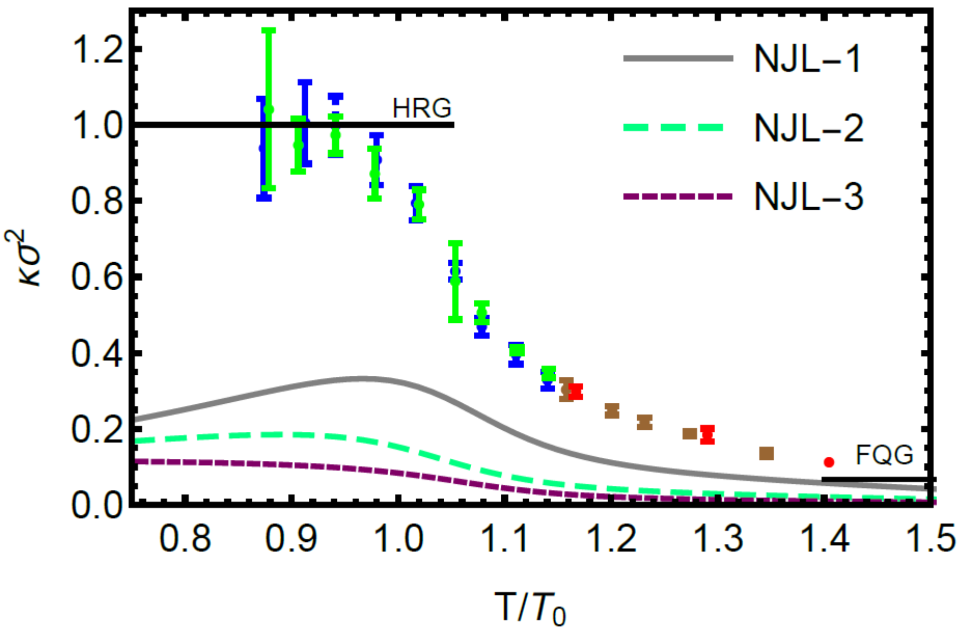
Z.B Li, K.Xu,X.Y.Wang, M.Huang
arXiv:1801.09215

Dip structure

1(experimental data)>PNJL>NJL

1. Agree well with BES-I data! --->equilibrium result can describe the experimental data!!!
2. The dip structure is sensitive to the relation between the freeze-out line and the phase boundary





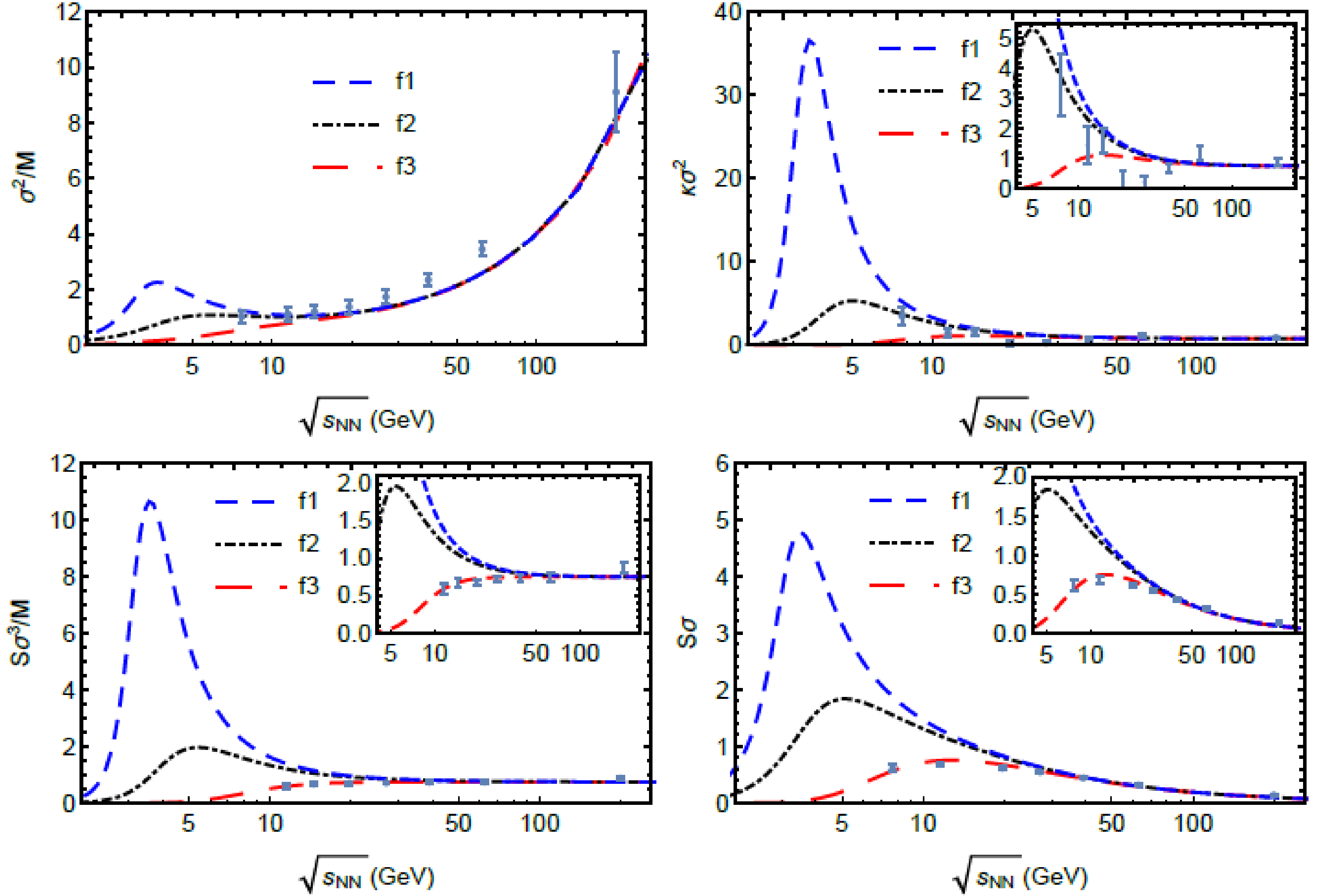
PNJL model

NJL model

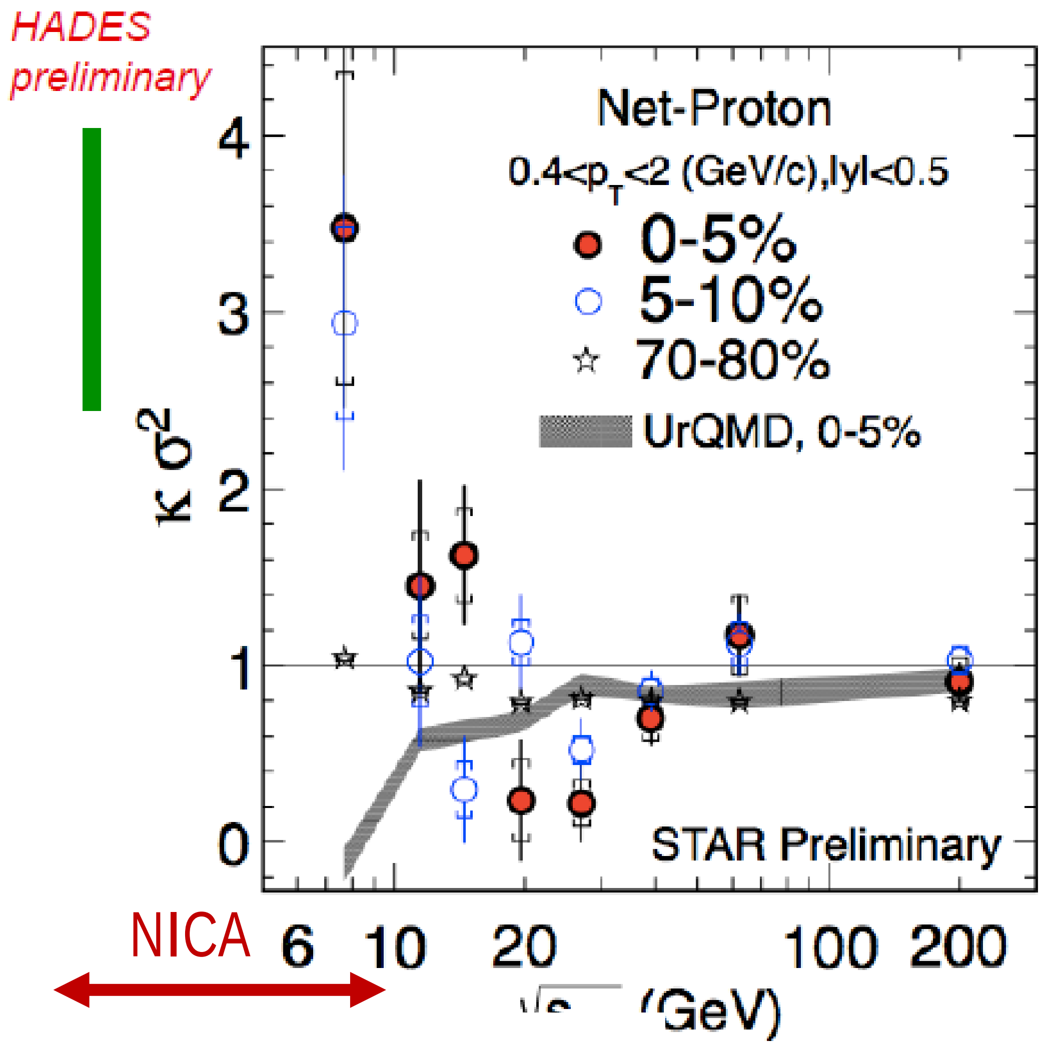
- ❑ **Contribution from gluon plays a important role!**
- ❑ **The difference of BNF between PNJL model and lattice data below Tc is due to the fact of no real confinement in the PNJL model! (To be improved in the future!)**

BES Phase-I measurement meets with HQCD model

Zhibin Li, Yidian Chen, Danning Li, M.H., arXiv:1706.02238



Peak structure is solely determined by CEP!!! A clean signature for CEP!!! From BES-I and HADES, peak structure is expected to show up in the collision energy of 5-6 GeV!!!

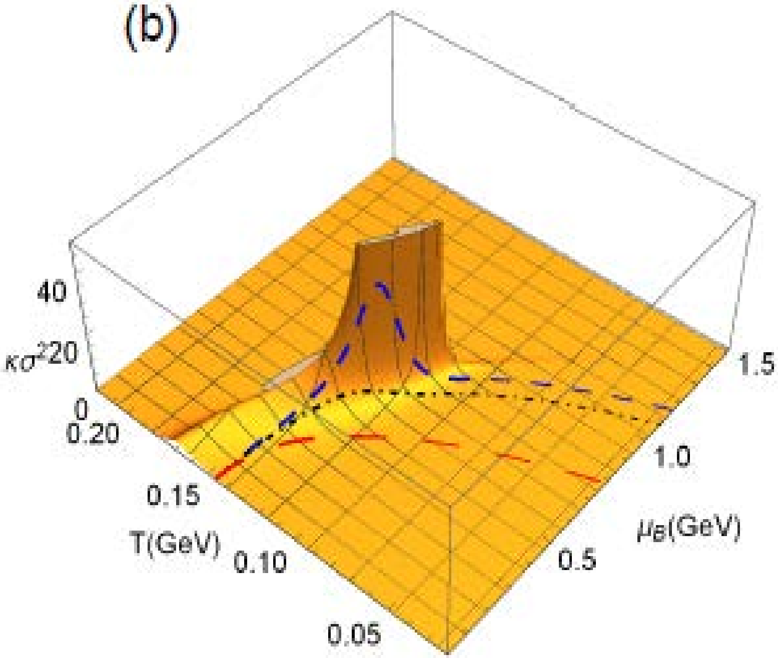


NICA: $\sqrt{s_{NN}}$ = 4 -11 GeV

Warning: The precise location of the CEP measured might not be the same as real QCD predicted

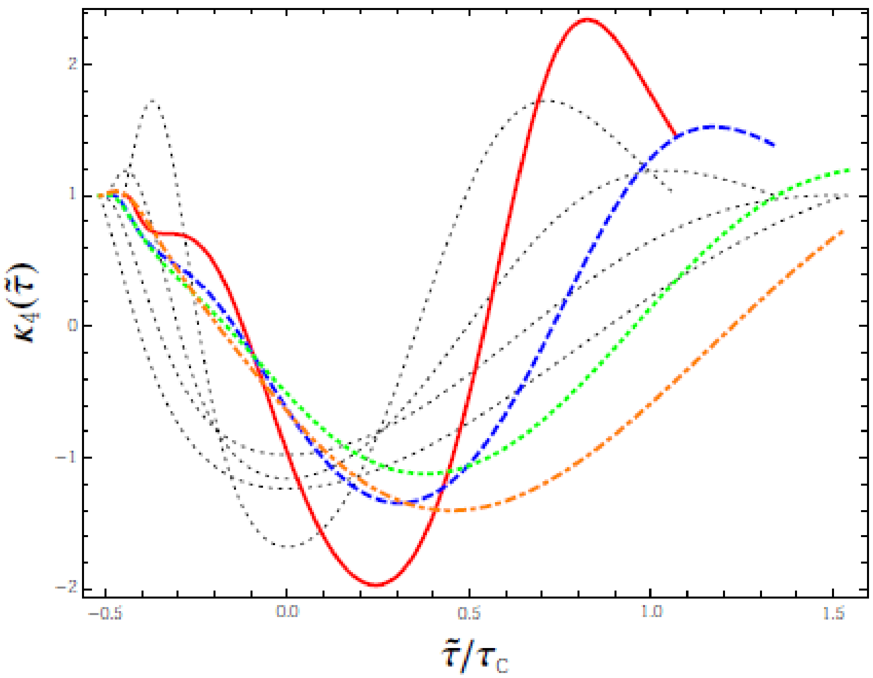
Finite size effect, freeze out, evolution of the system ……

these effects may shift the location of CEP,



Out-of equilibrium, without the constraint of stability condition

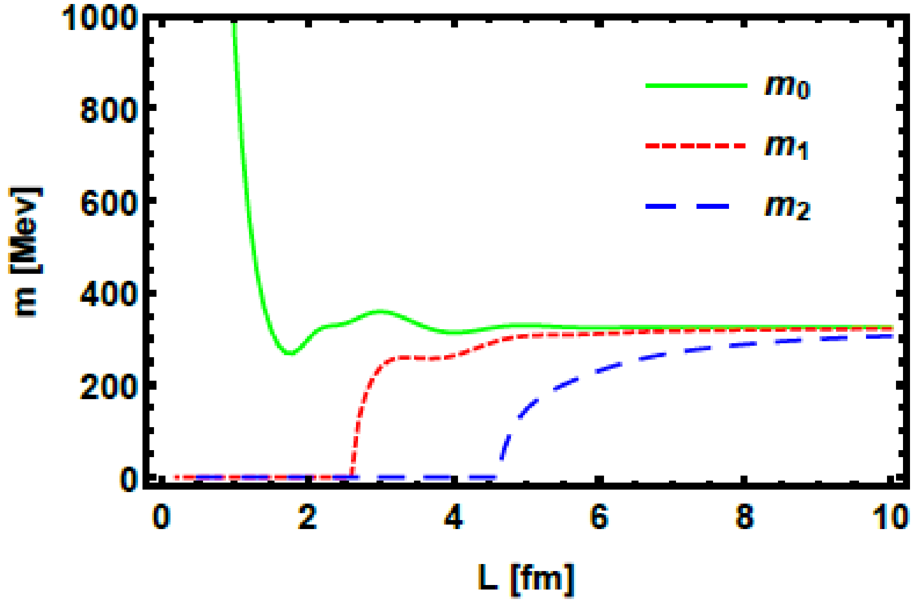
-> Sign change ?



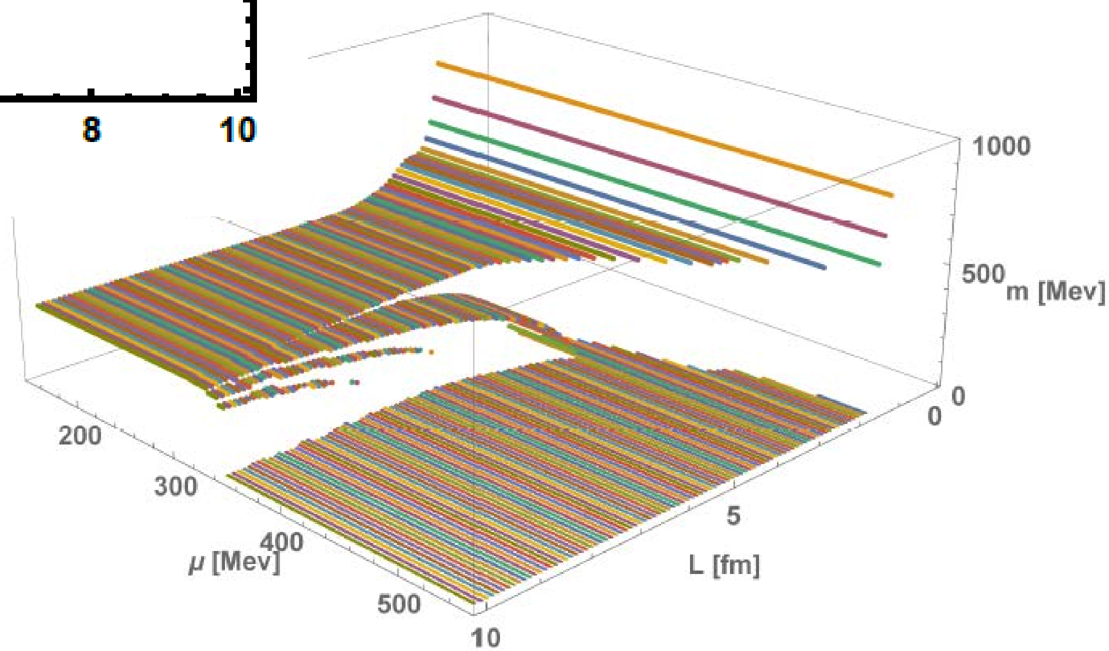
The sign and magnitude at freeze-out is most important!

S.Mukherjee, R.Venugopalan, Y.Yin, Phys.Rev.Lett. 117 (2016) no.22, 222301

L>5fm: Finite size effect is negligible
L<3 fm: Finite size effect is significant!



K.Xu, M.Huang, to appear



III. Conclusion and Outlook

- Contribution from gluodynamics is dominant for BNF;
- The peak of BNF along freeze-out line is solely related to the CEP;
- The BES-I measurement of BNF can be described by a realistic PNJL model in equilibrium;
- CEP at small baryon number densities are ruled out both from lattice results and BES-I measurement!

Thanks for your attention!