QCD phase diagram and CEP

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Workshop on iHIC2018, Tsinghua Uni., Apr.8-11,2018

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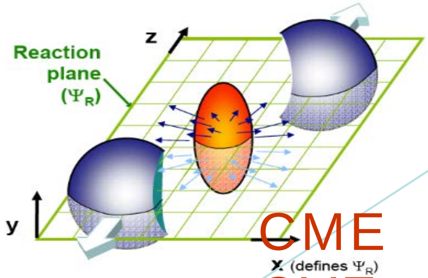
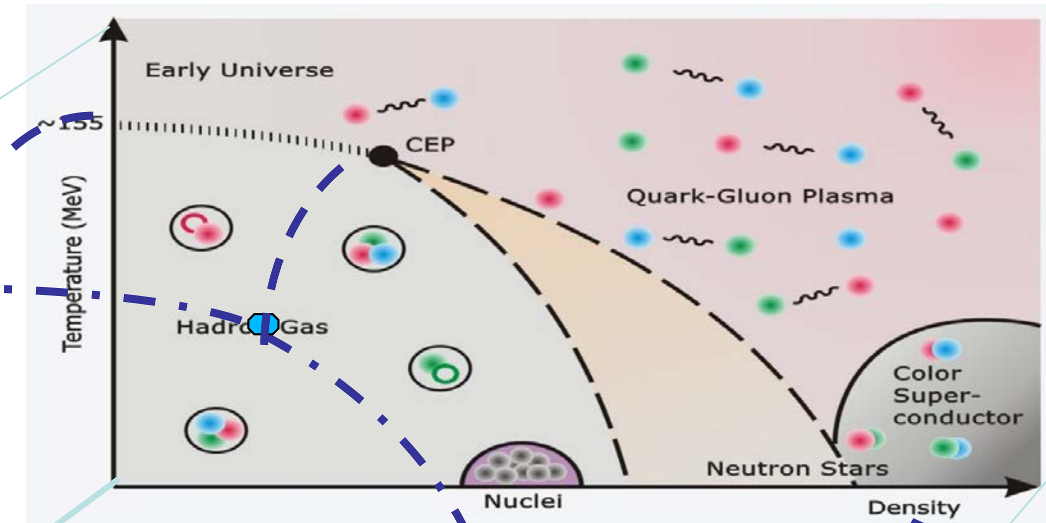
Explored QCD phase diagram now

by theorists





CME

CVE

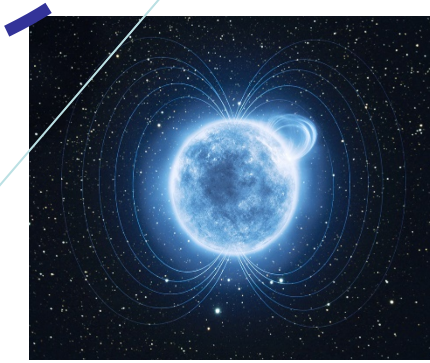
Inverse Magnetic Catalysis

Charged rho condensation

Neutral/charged pion condensation

(Inverse) Magnetic Catalysis

Magnetar

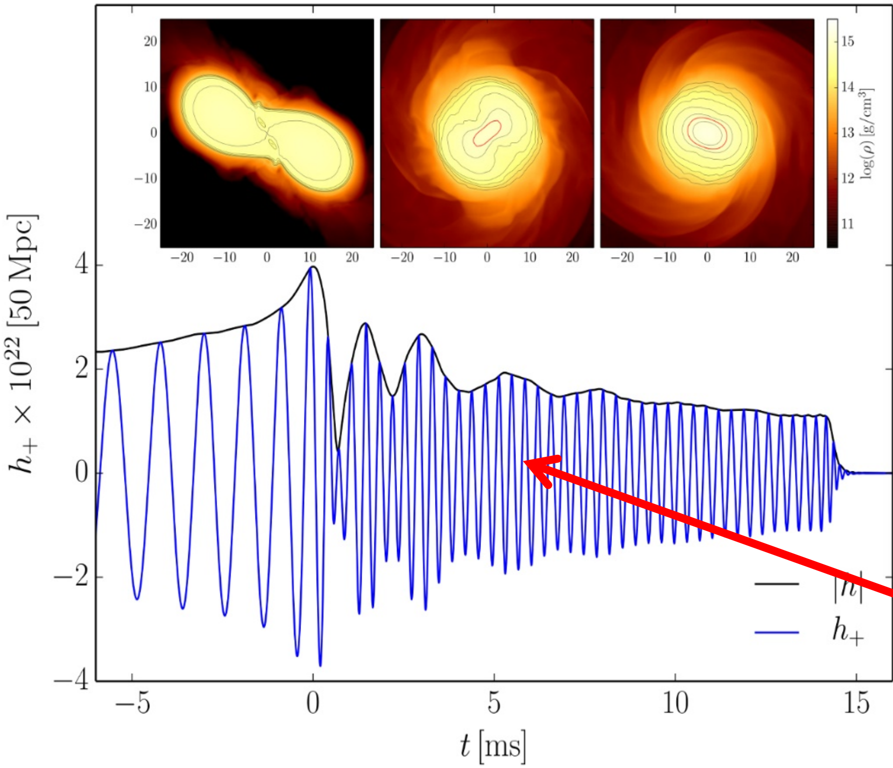


$$\mathbf{B}, \mathbf{E}\cdot\mathbf{B}, \omega, \mu_I$$

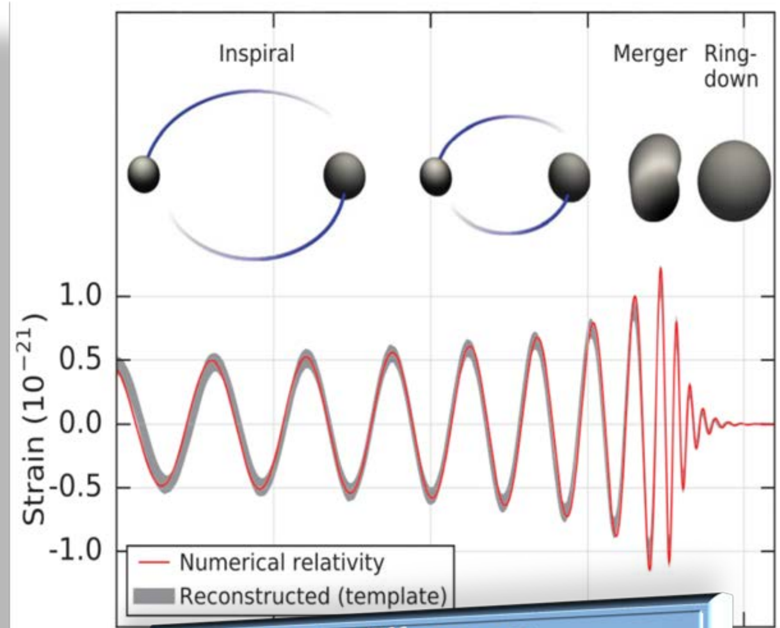
Gravitational Waves from Neutron Star Mergers

GW170817

Neutron Star Collision (Simulation)



Collision of two Black Holes



Main difference:

In binary neutron star mergers a **Post-Merger Phase** often exists

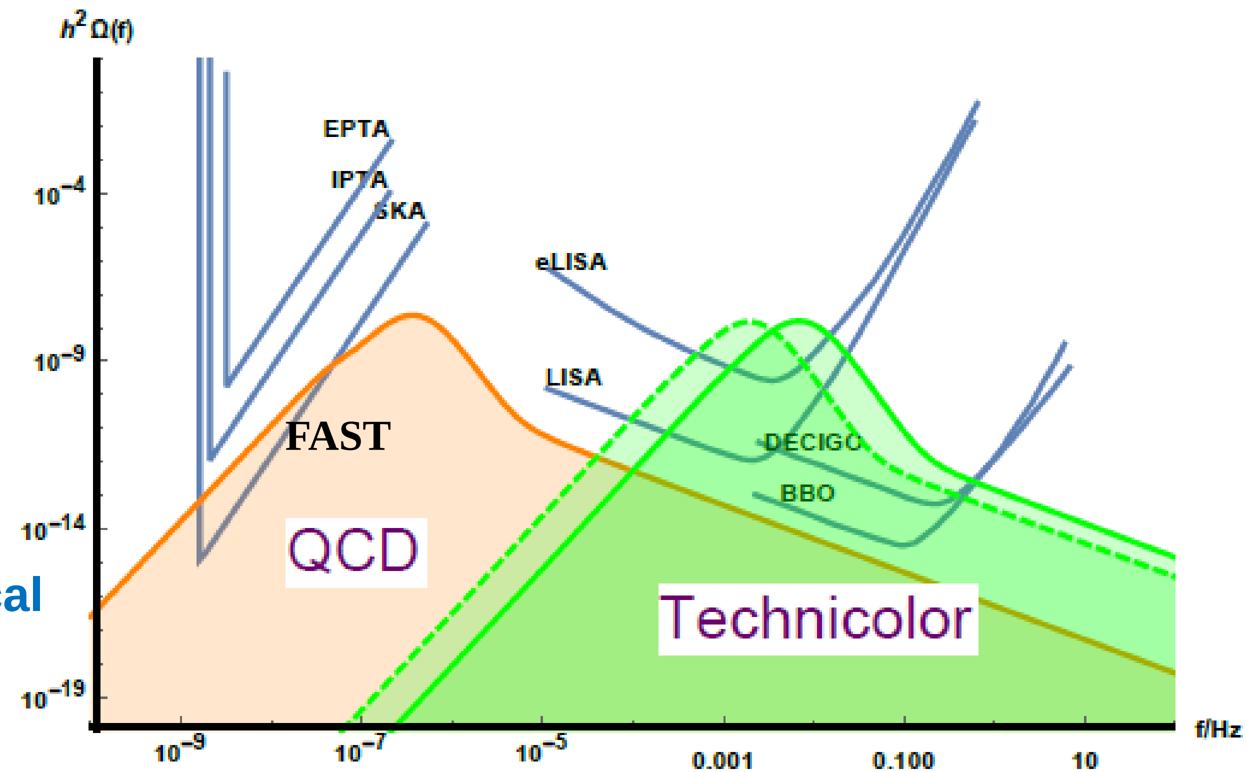
M. Hanauske@Frankfurt Uni., 2017

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

1st order phase transition for pure gluon system!

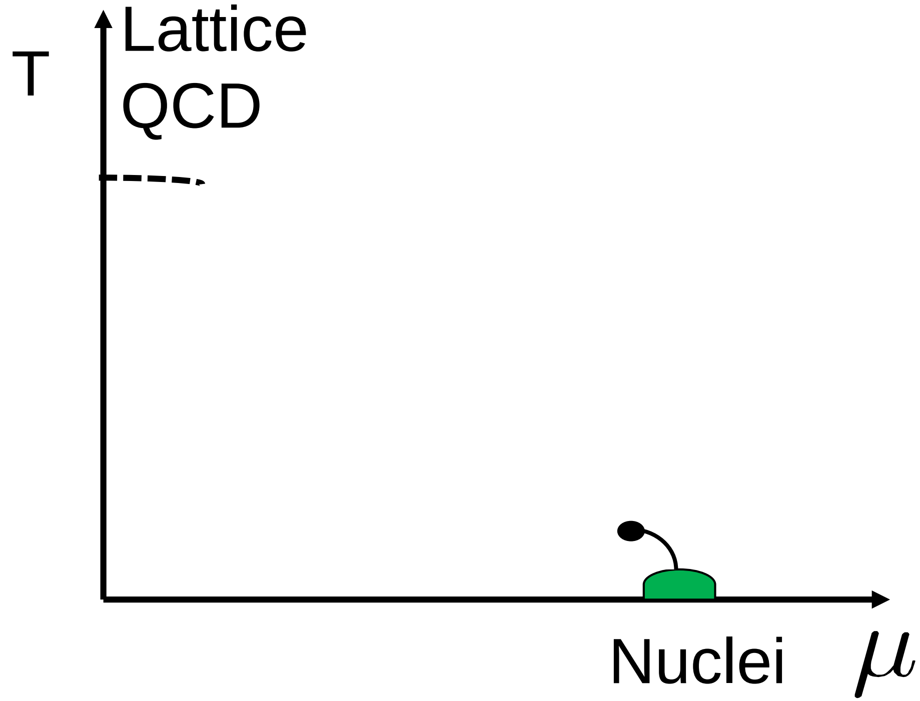
Yidian Chen, Mei Huang, Qishu Yan, arXiv:1712.03470

FAST(Five hundred meters Aperture Spherical Radio Telescope)



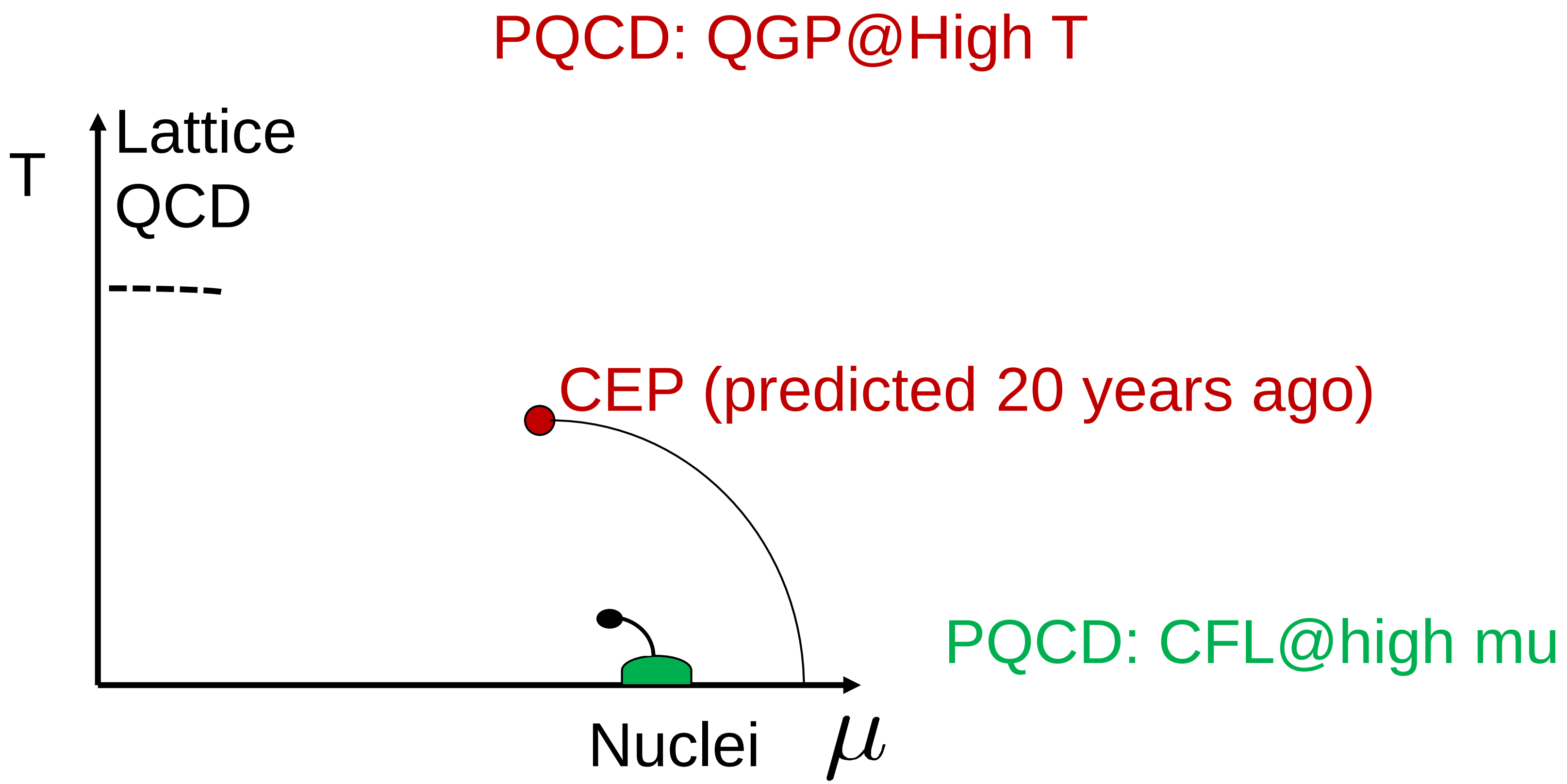
Confirmed QCD phase diagram

PQCD: QGP@High T



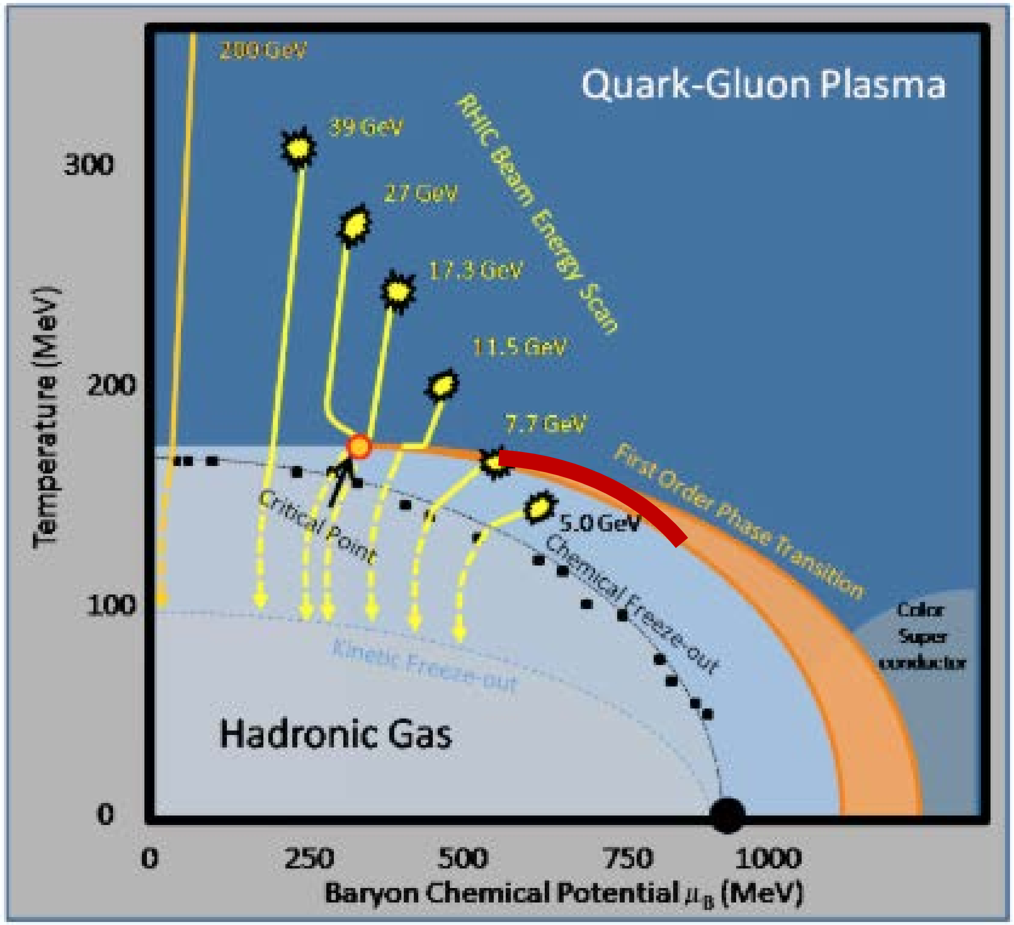
PQCD: CFL@high mu

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)

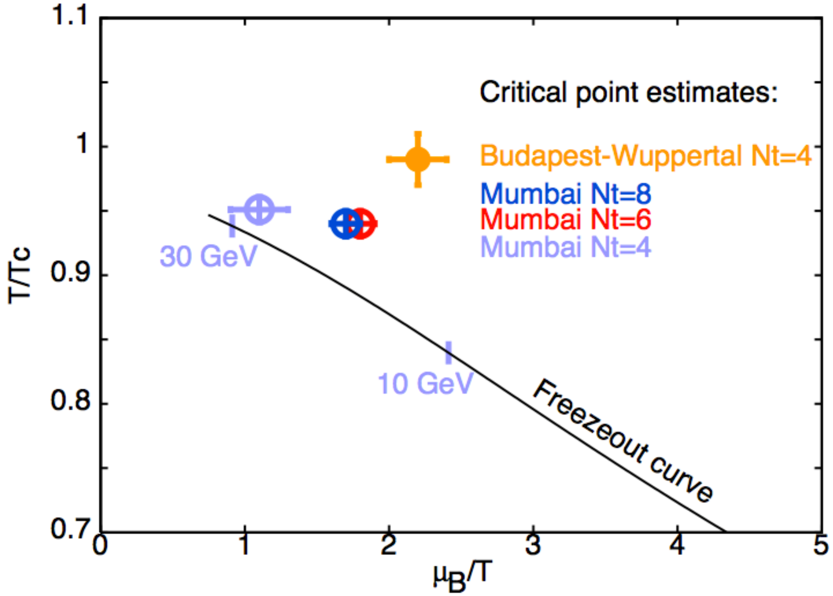
$$L(\vec{x}) = \frac{1}{N_c}\mathrm{tr}\,\mathcal{P}(\vec{x}) \text{ with } \mathcal{P}(\vec{x}) = \mathrm{P}\,\mathrm{e}^{ig\int_0^\beta dt\, A_0(t,\vec{x})}$$

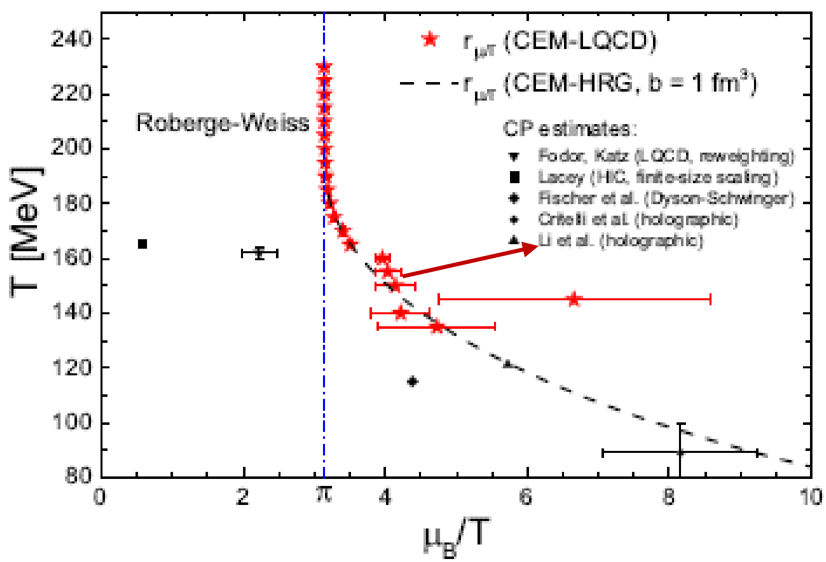
$$\langle L(\vec{x})\rangle \sim \exp(-\beta F_q)$$

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

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

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)

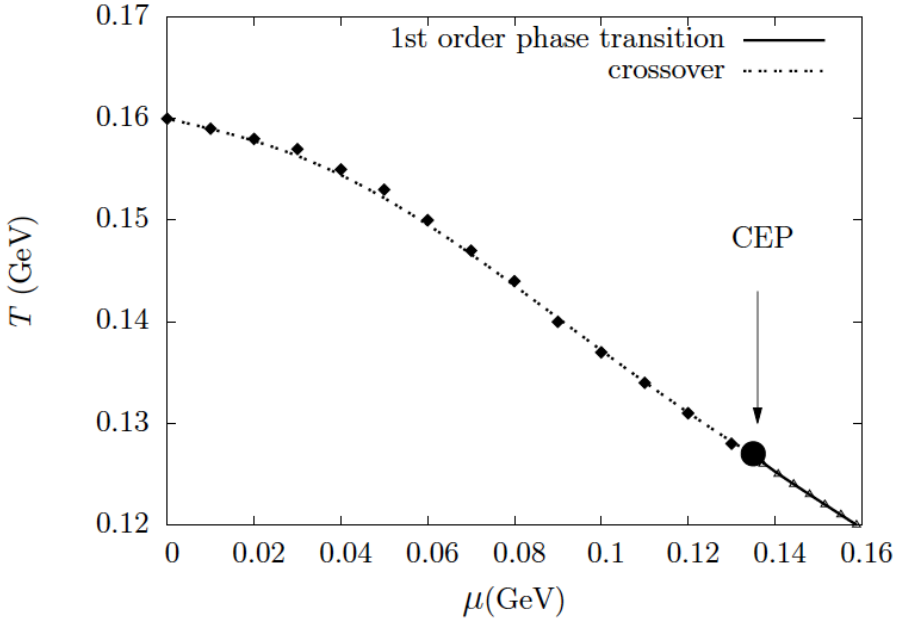
$\mu^E_B / T_E > 2$

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

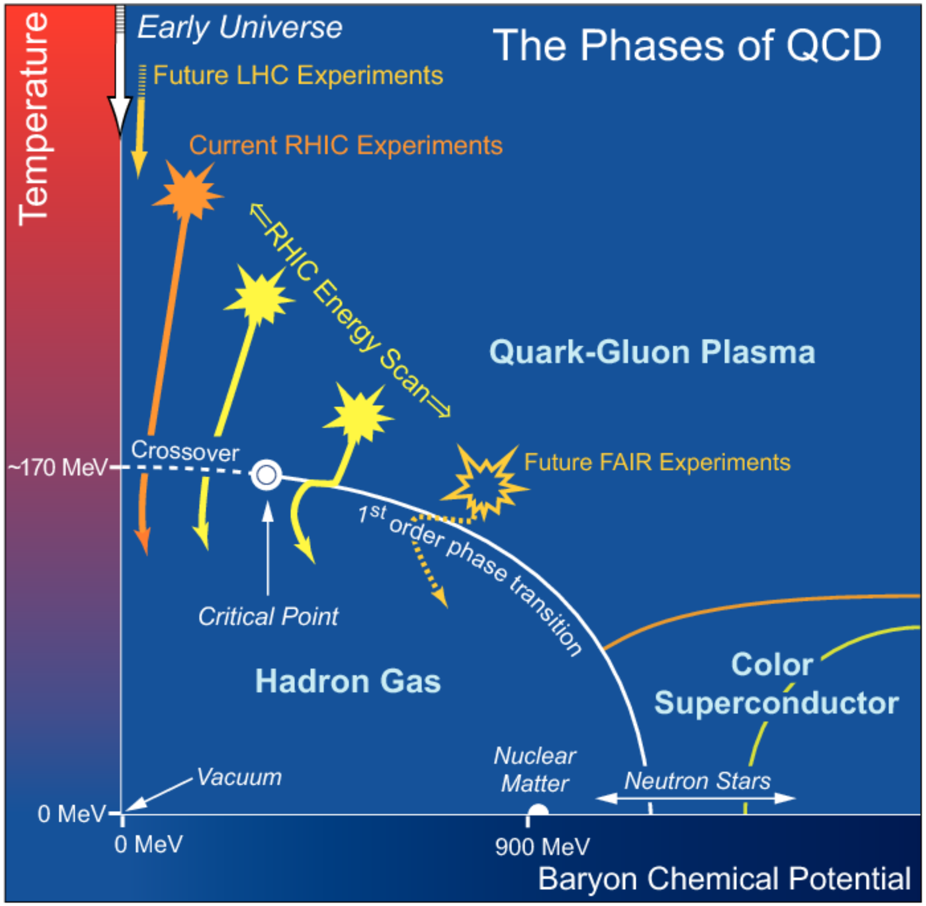
3): C. S. Fischer et al., PRD90, 034022 (2014).

$(\mu^E_B, T^E) = (504, 115)$ 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	*μ_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

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

$$B \rightarrow Q, s$$

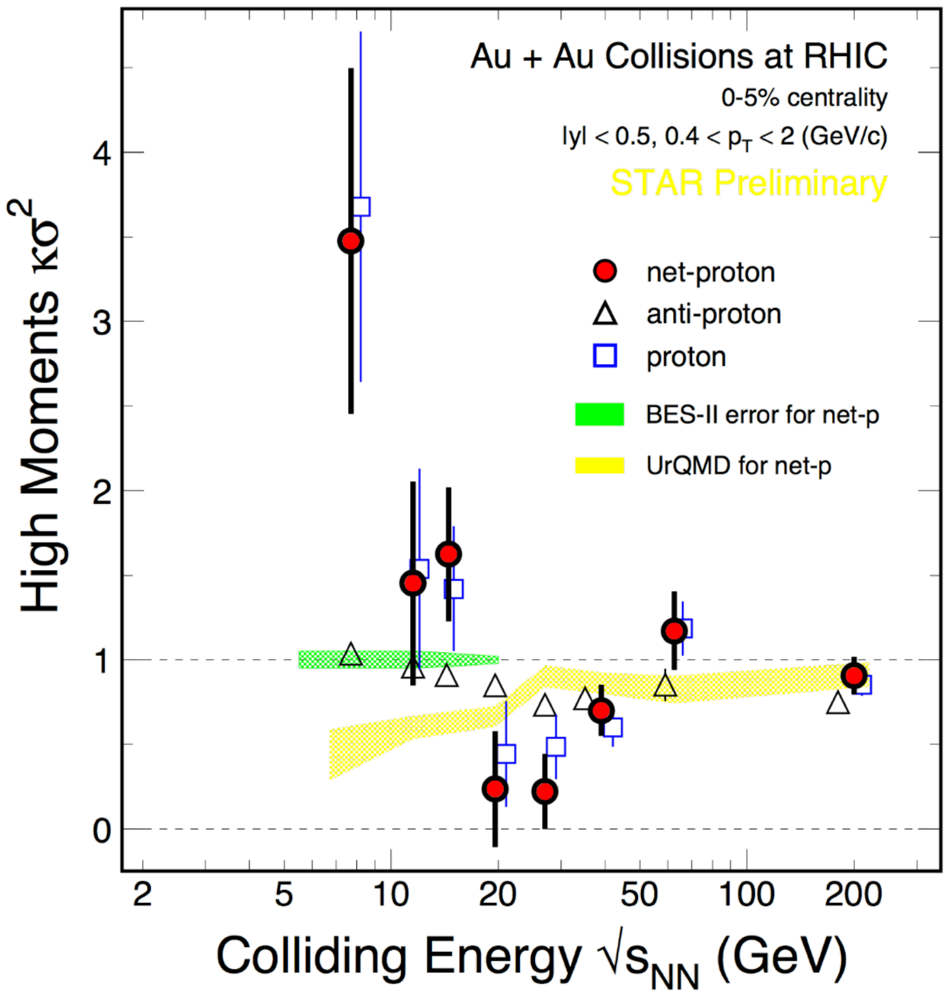
$$C_n^B = VT^3 \chi_n^B$$

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

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

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

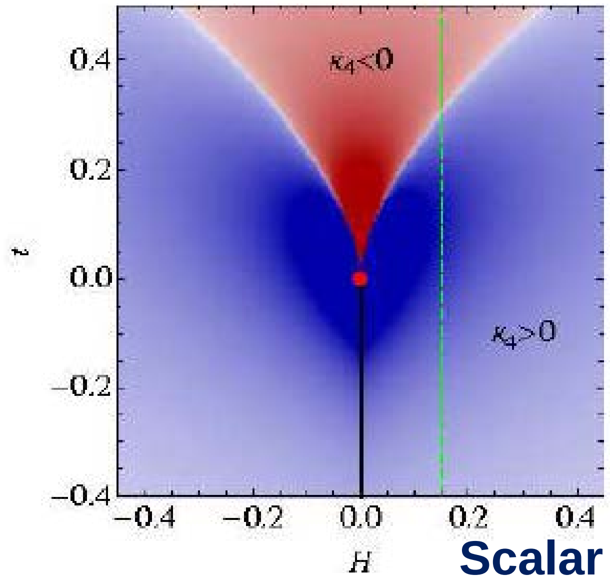
Measurement of Higher Order Fluctuations of Conserved Quantities



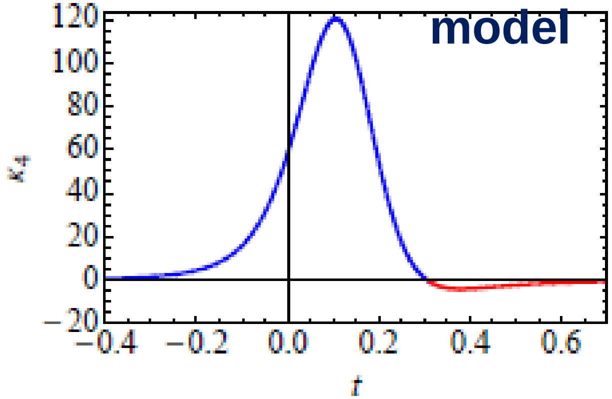
Non-monotonic trend is observed for the 0-5% most central Au+Au collisions. Dip structure is observed around 19.6 GeV.

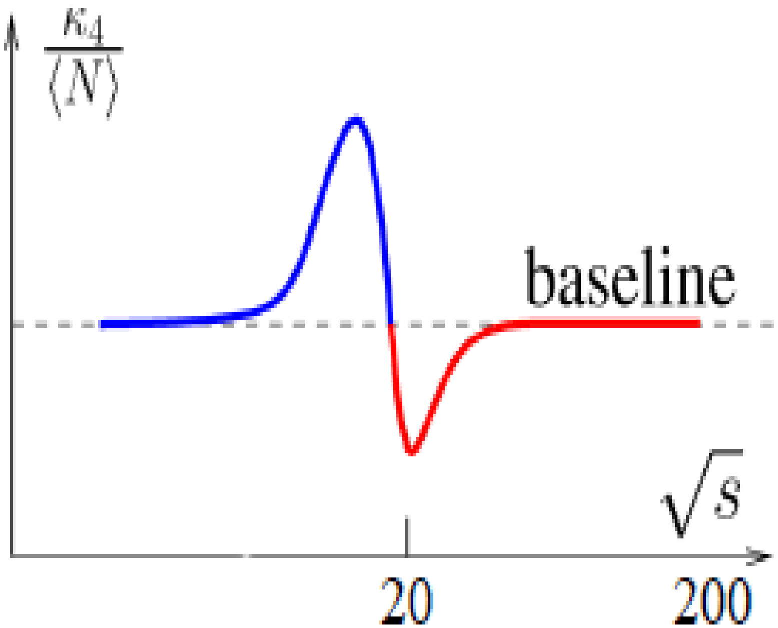
STAR: **PRL112**, 32302(14); **PRL113**,092301(14);
X.F.Luo, N.Xu, arXiv:1701.02105

How to determine the location of CEP?



Scalar model





Dip Structure & Peak Structure

⇓

Positive/negative ?

- M. Stephanov, *PRL107*, 052301(2011)

What we are not going to answer:

Predict the location of CEP from theory

Different models give different locations of CEP, even the same model with different parameters give different locations of CEP.

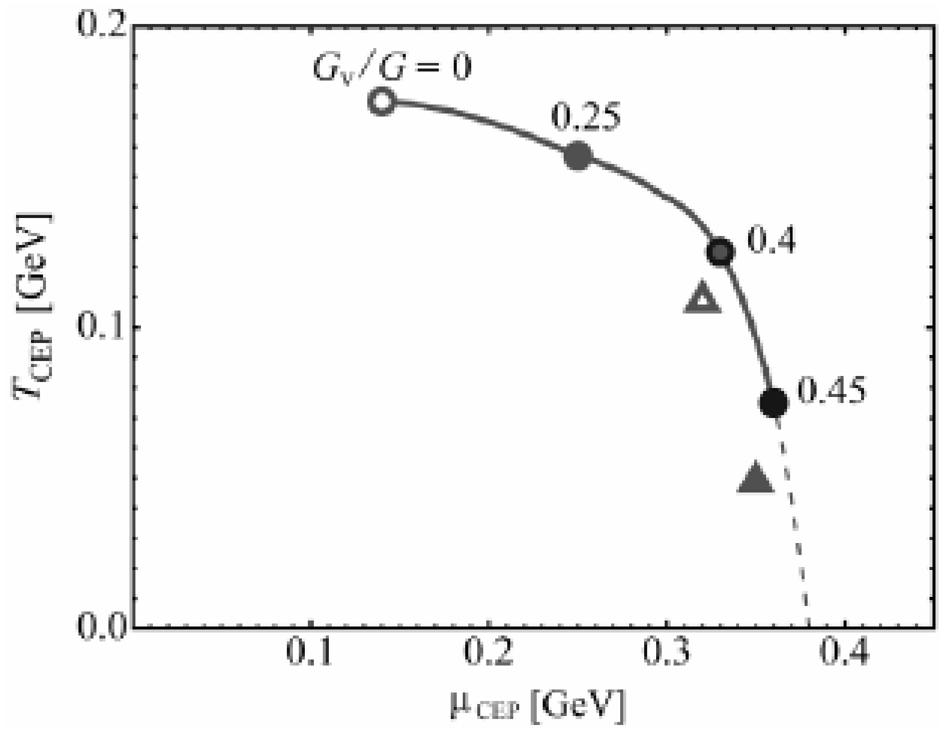
What we are willing to answer:

1. **What's the universal feature of CEP?**
2. **What information of the CEP can be read from experimental measurement?**
3. **Understand the formation of the dip and peak structures**

CEP from NJL-like models

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 ……

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

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

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

Mimic gluodynamics

muPNJL model

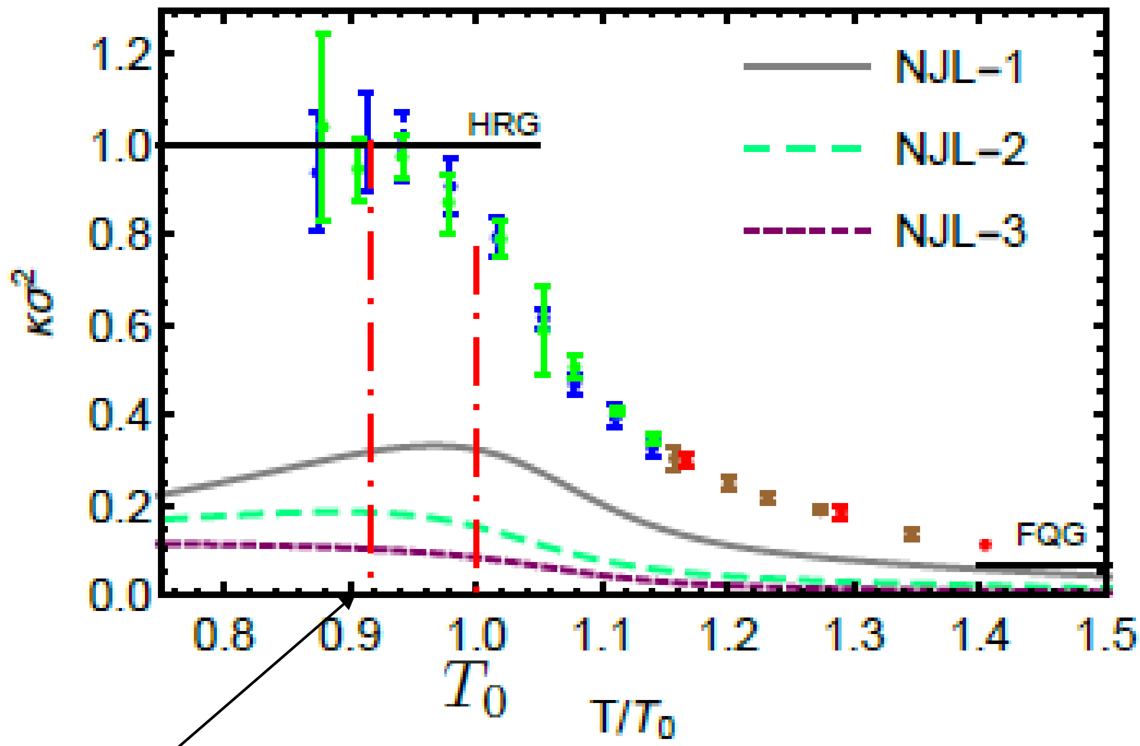
$$T_0(N_f,\mu_i) = T_\tau e^{-\frac{1}{\alpha_0 f(N_f,\mu_i)}}$$

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

Observation from lattice result: 0.8 of BNF at chiral phase transition, 1 at hadron-QGP transition
Unexpected results: Dominant contribution (80-90%) from gludynamics to baryon number fluctuation!!!

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

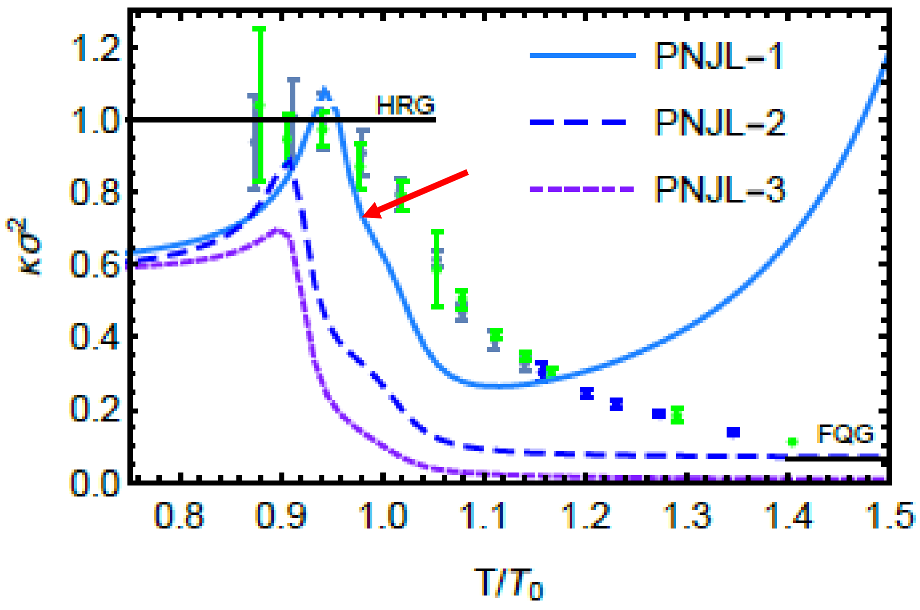
$\mu = 0$

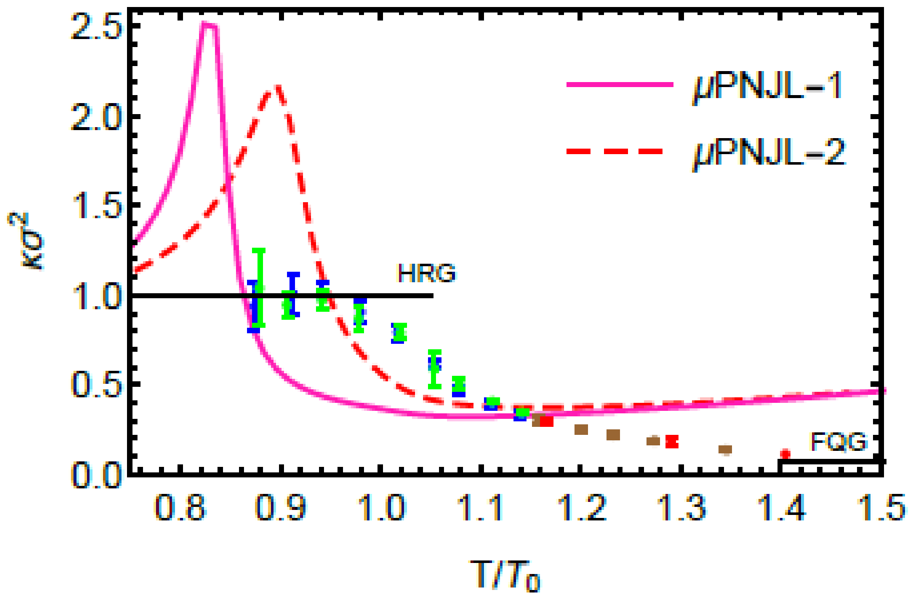


$T_0^{dec} \simeq 140\mathrm{MeV}$

a physical "confinement-deconfinement" transition

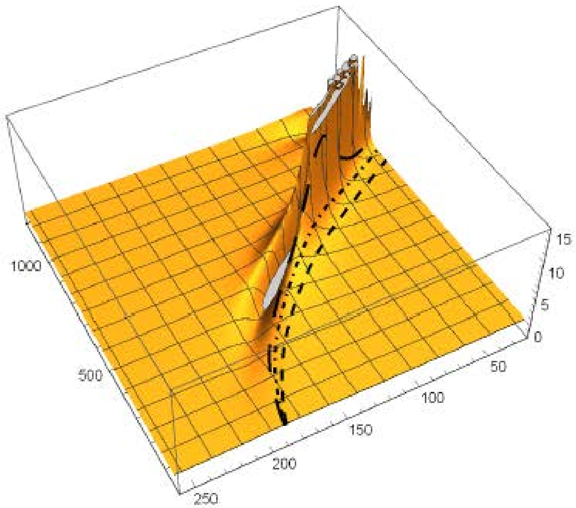
Lattice results for BNF at mu=0 can constrain models



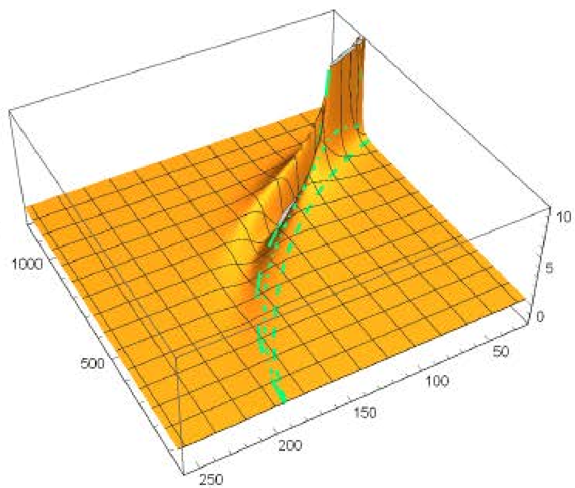


Shifting the location of CEP in the NJL model

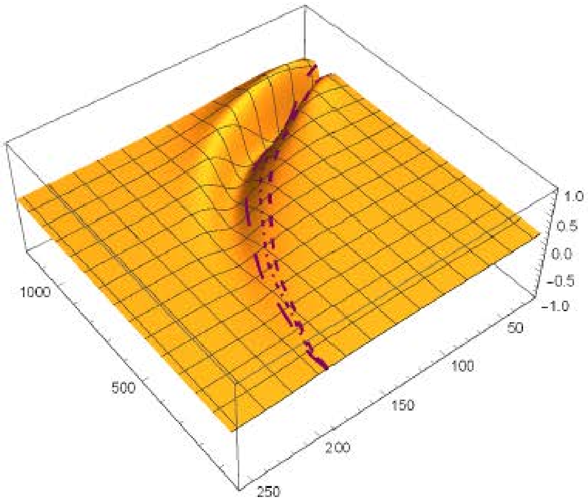
$G_V = -0.5G_S$



$G_V = 0$



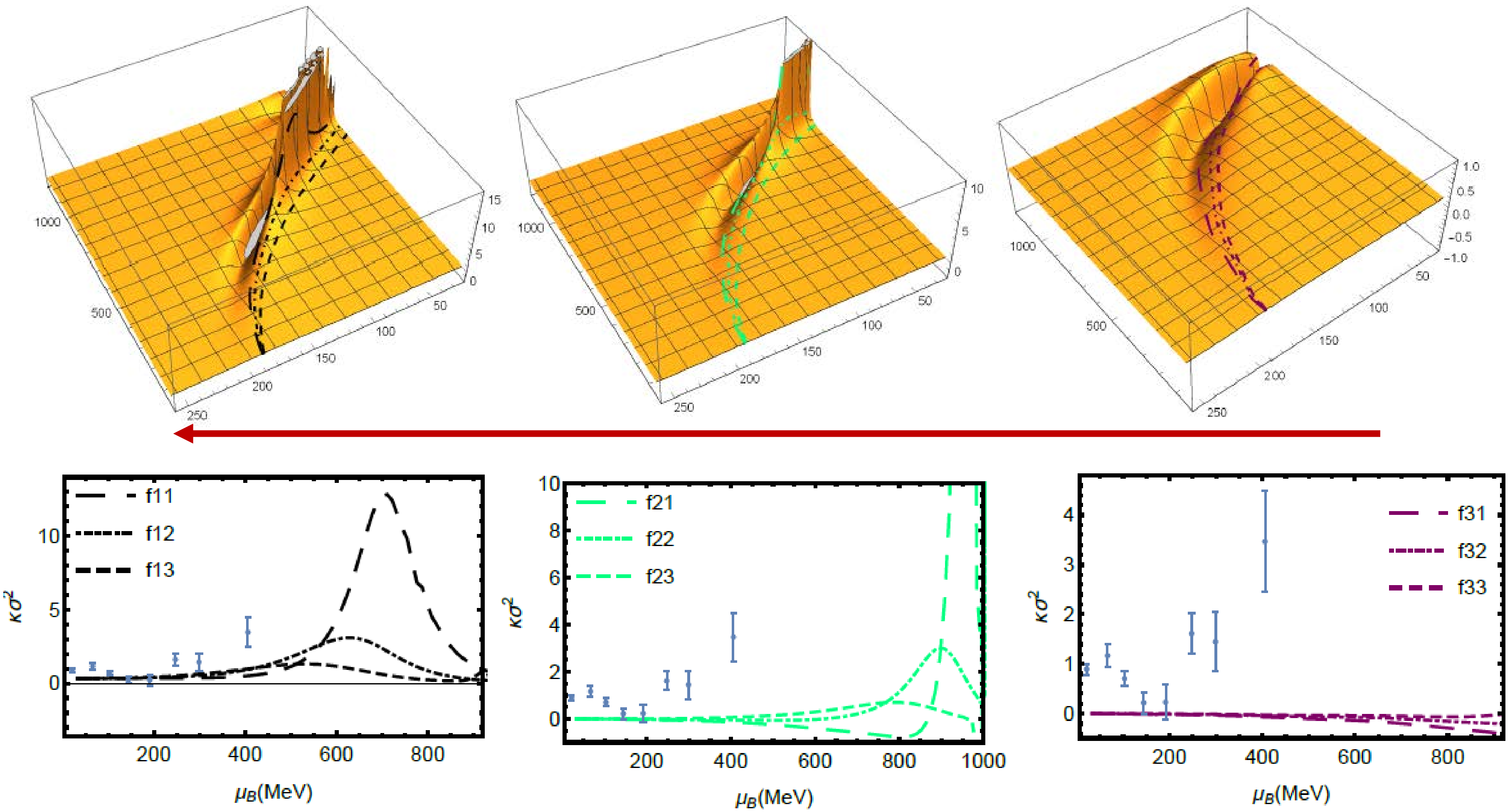
$G_V = 0.67G_S$

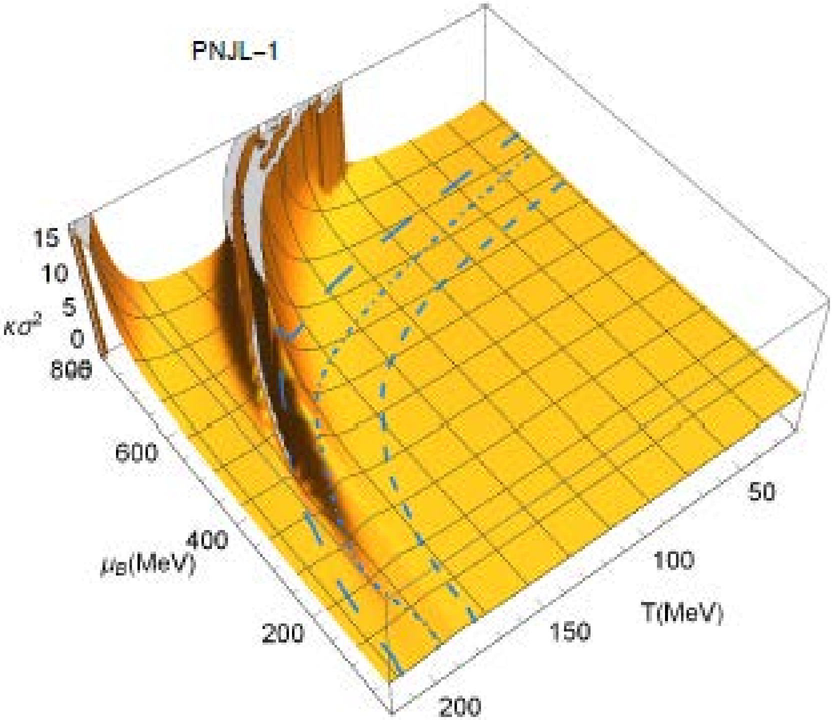


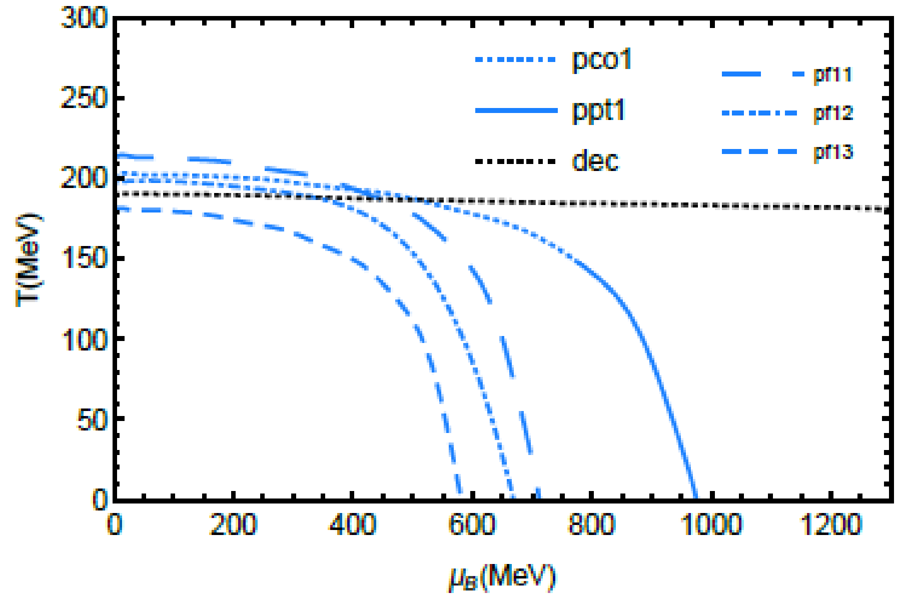
NJL-1 NJL-2 NJL-3

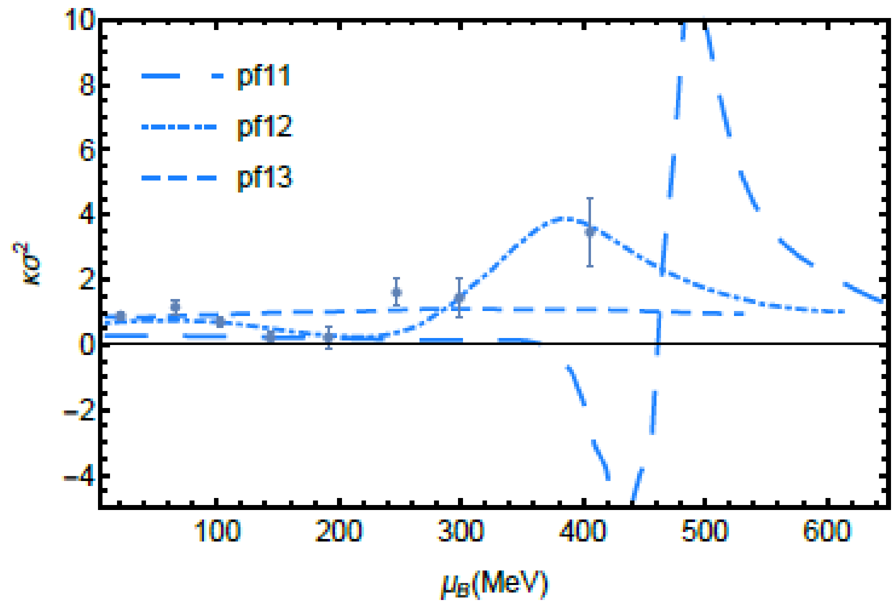
Results from NJL model

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.





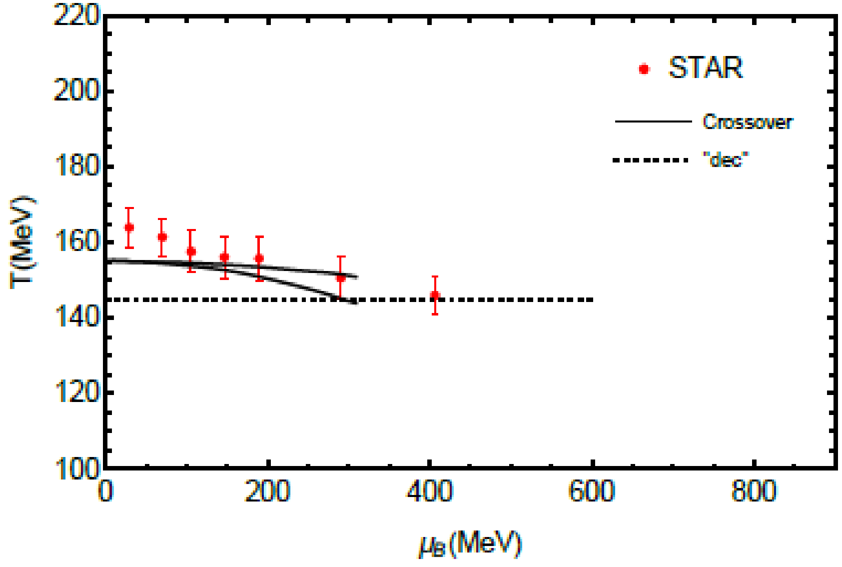


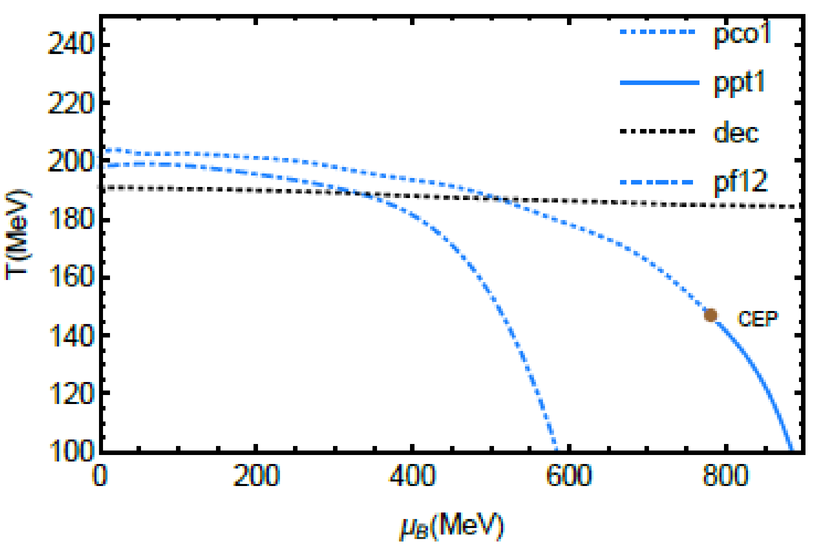


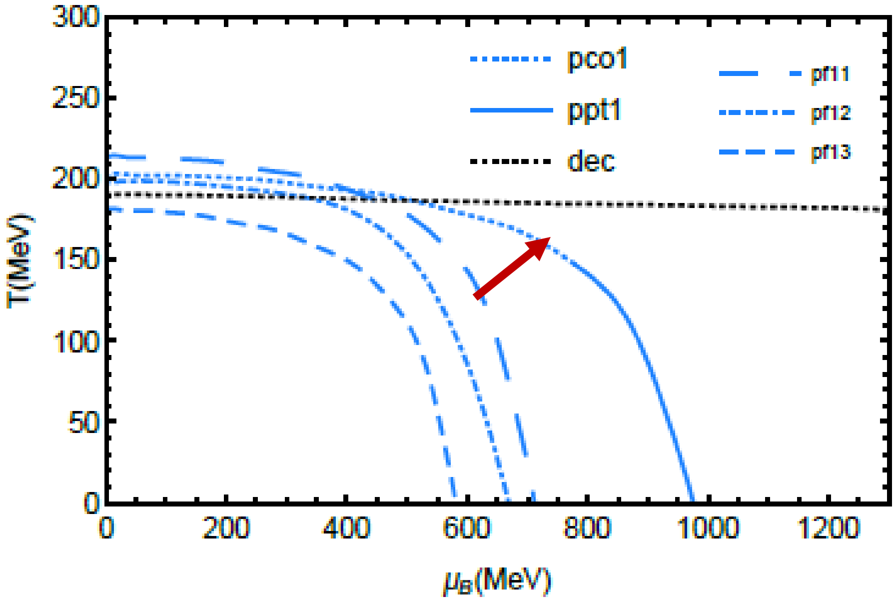
Freeze-out starts from back-ridge of the deconfinement phase boundary, ➔
forming the dip structure

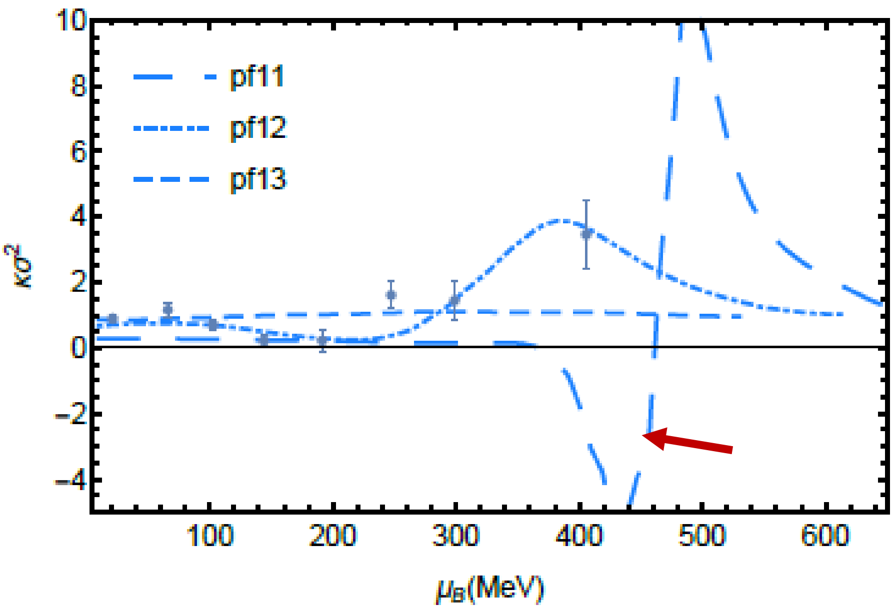
Freeze-out starts from back-ridge of the "deconfinement" phase boundary

====> forming the dip structure







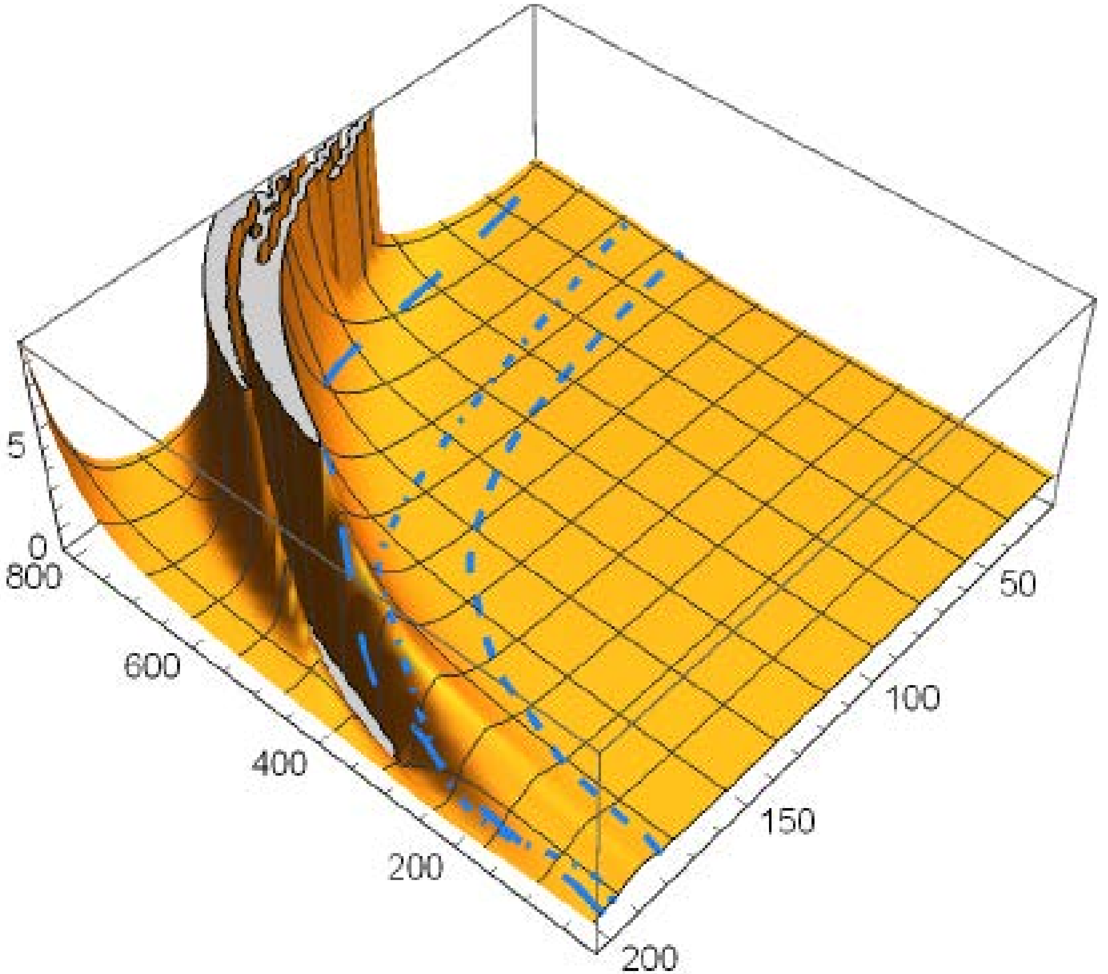


If BNF is negative at the dip ➔freeze out line crosses the negative region thus is close to the CEP.

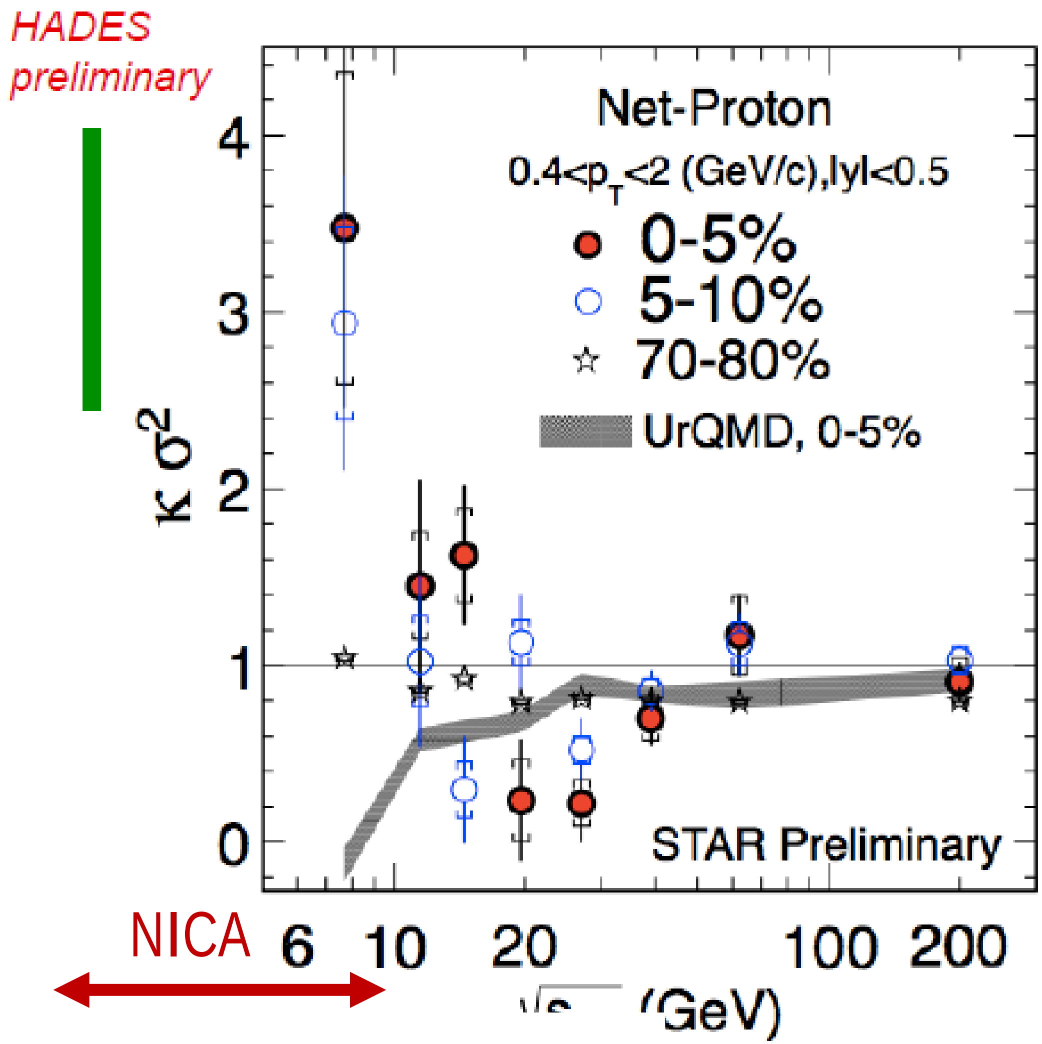
Dip but positive➔ Freeze-out line is not very close to the CEP

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

Peak structure is a clean signature for CEP!!!



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!!!

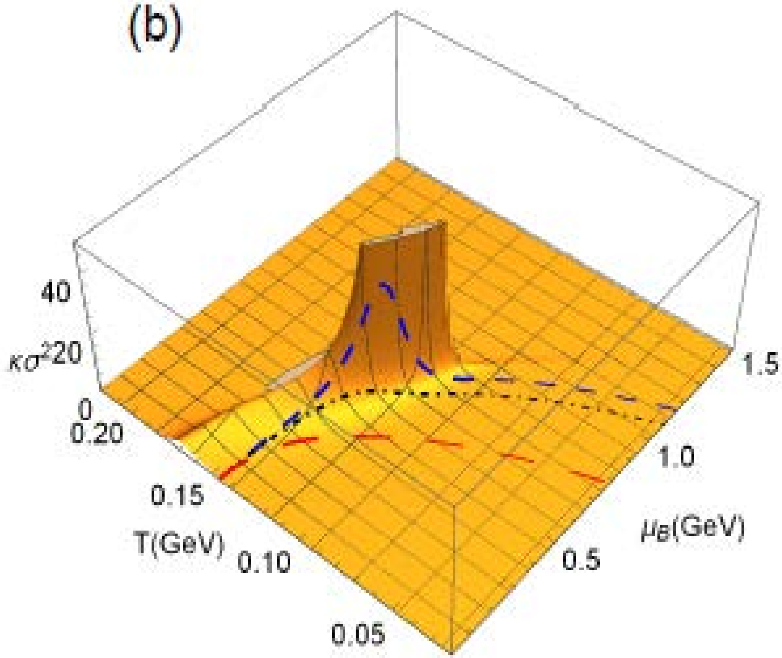


NICA: $\sqrt{s_{NN}}$ = 4 -11 GeV

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

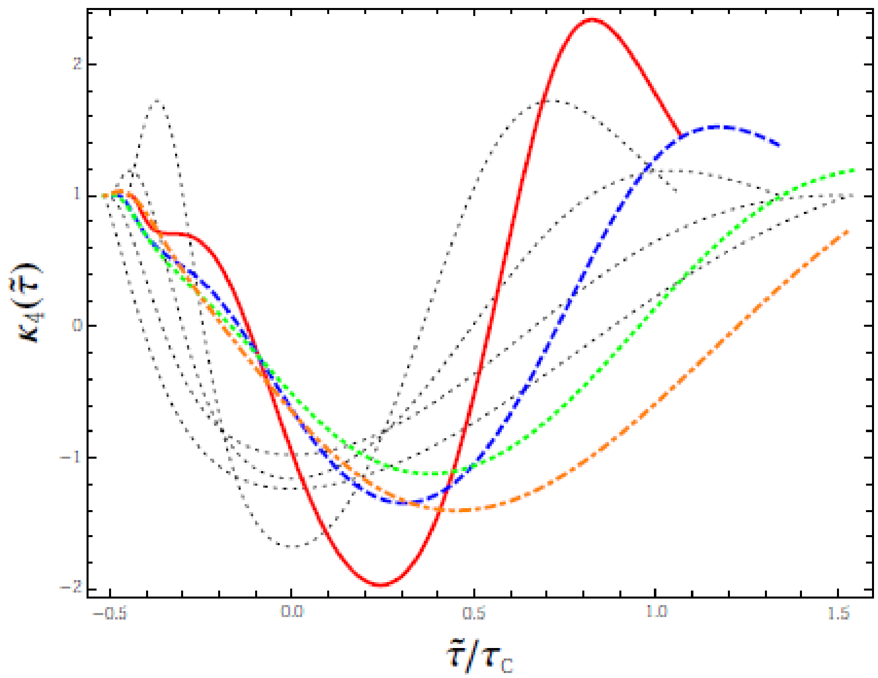
Finite size effect, freeze out, evolution of the system ……

these effects may shift the location of CEP,



Out-of equilibrium, without the constraint of stability condition

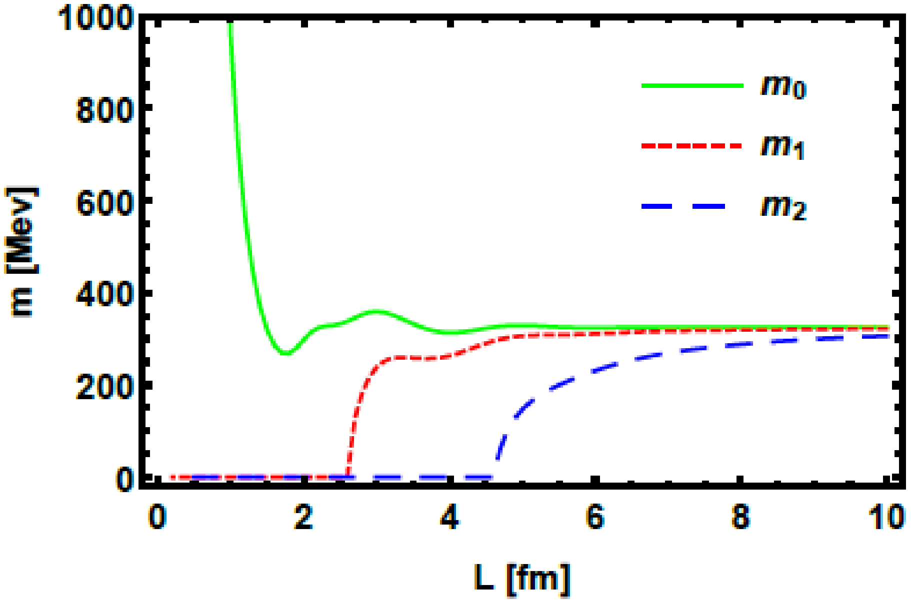
-> Sign change ?



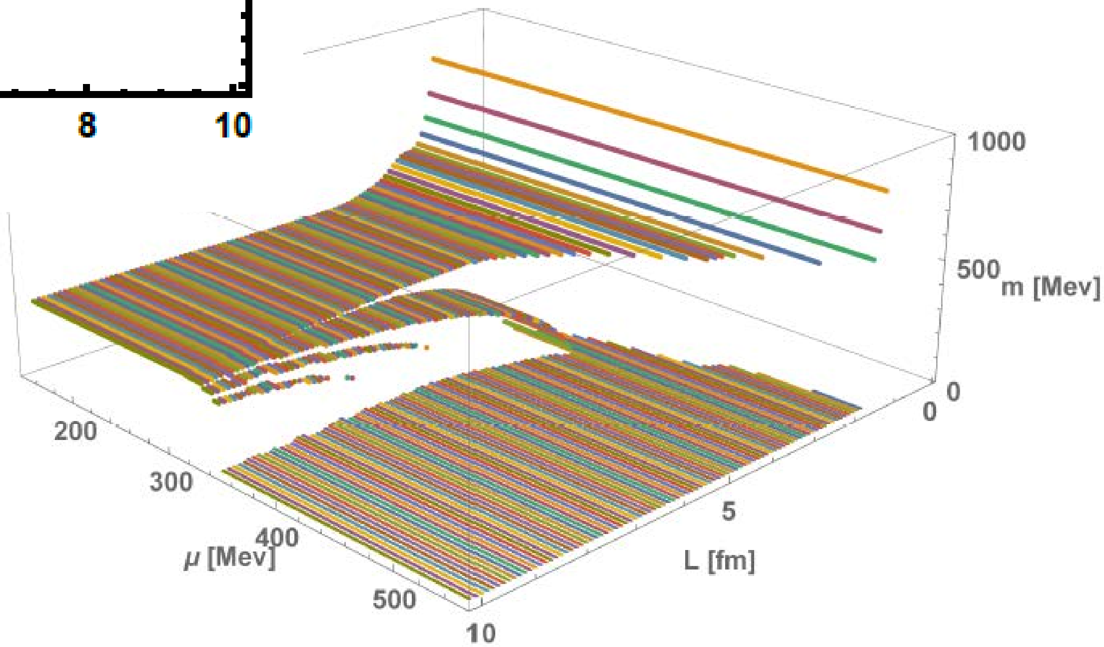
The sign and magnitude at freeze-out is most important!

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
arXiv:1804.xxxxx



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;
- CEP at small baryon number densities are ruled out both from lattice results and BES-I measurement!

Thanks for your attention!