Locating the CEP

Mei Huang

Theoretical Physics Division

Institute of High Energy Physics, CAS

Phases of Quantum Chromodynamics (QCD) and Beam Energy Scan Program with Heavy Ion Collisions , Aug.15-18, 2017, Fudan Uni.

Content

I. Introduction

II. The QCD CEP

III. Locating the CEP

IV. Conclusion and discussion

Zhibin Li

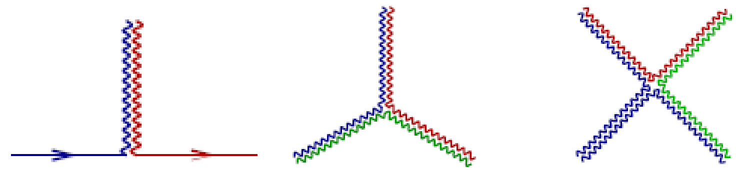
Danning Li

Yidian Chen

I. Introduction

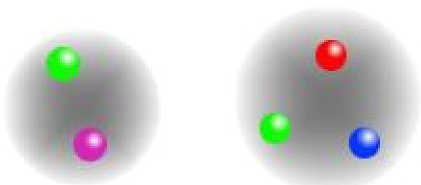
QCD

Strong coupling

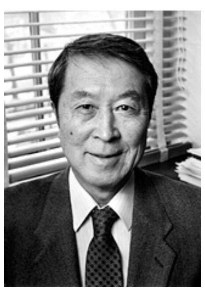


- Confinement

- Spontaneous chiral symmetry breaking

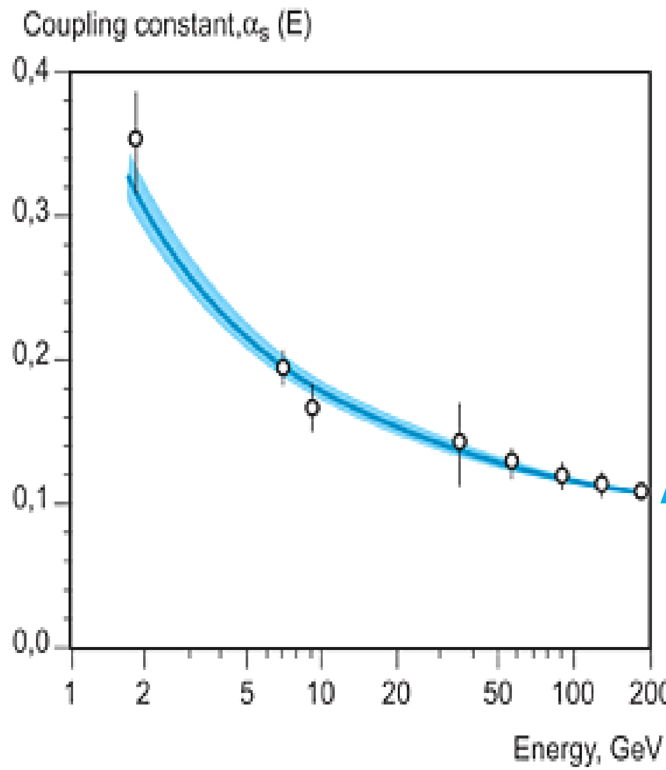


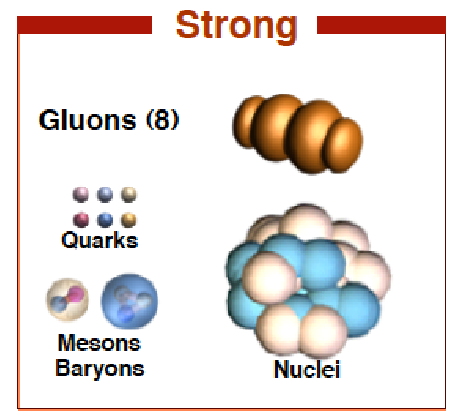
99.9% origin of mass for visible universe



"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Nobel prize 2008



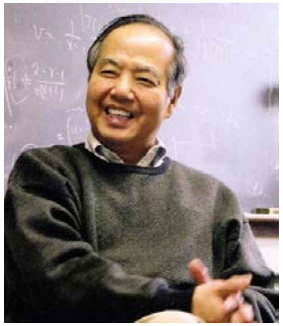


Weak coupling

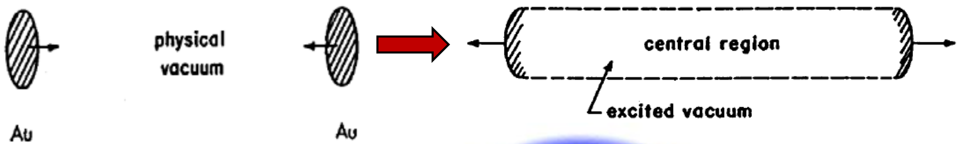
Asymptotic Freedom

Nobel Prize 2004

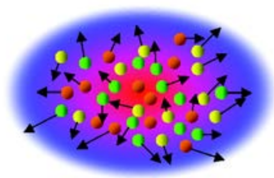
Explore QCD phase structure by HIC



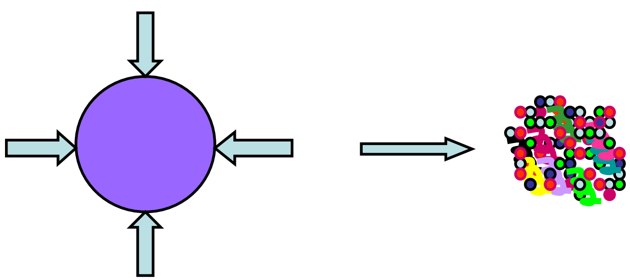
excite QCD vacuum



QGP



squeeze matter

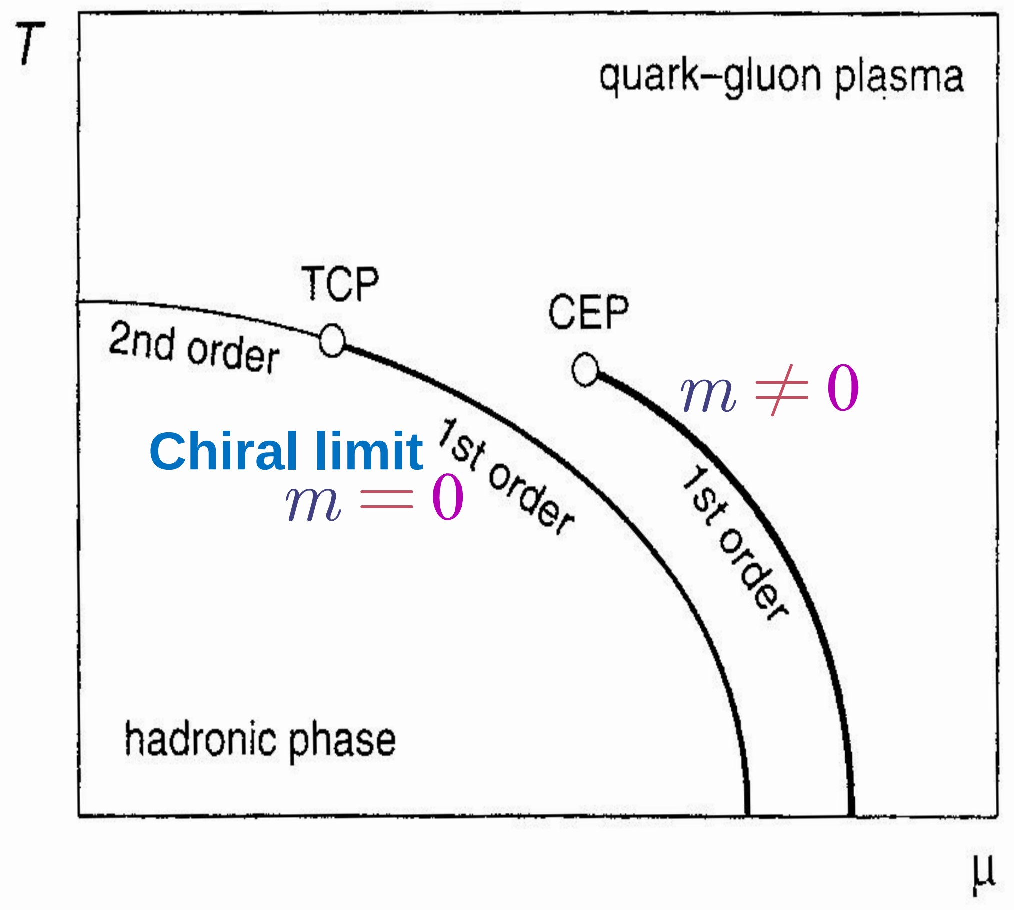


HIC（High T & High mu）：

RHIC@BNL ALICE@CERN FAIR@GSI
NICA@DUBNA，CSR@IMPCAS，HIAF@IMPCAS

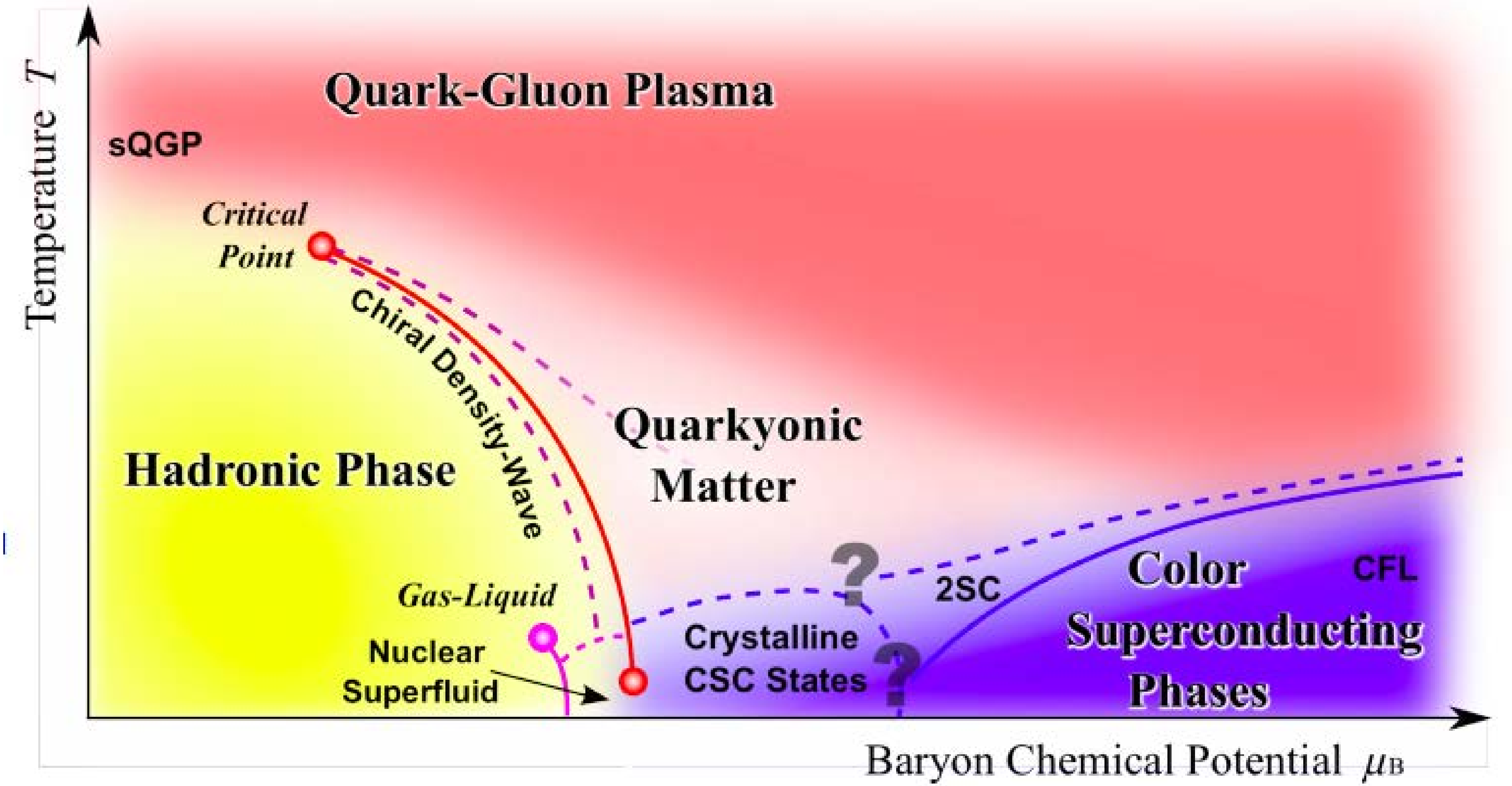
Explored QCD phase diagram 20 years ago

by theorists



Mainly based on chiral phase transition

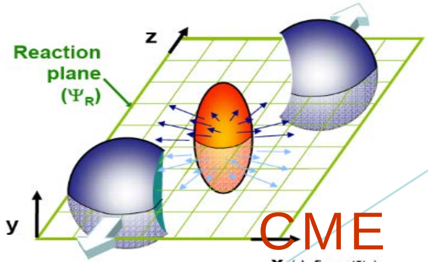
Explored QCD phase diagram 10 years ago
by theorists



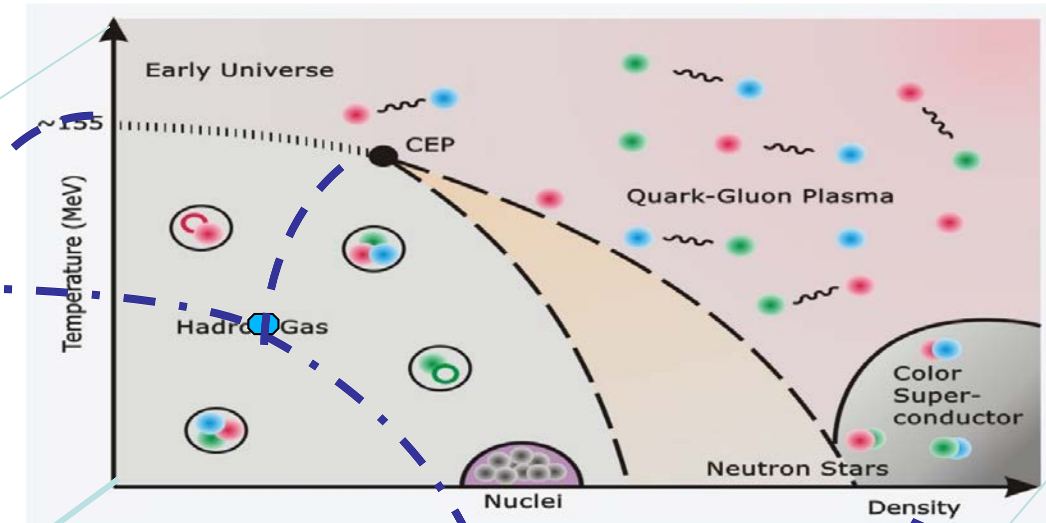
K. Fukushima and T. Hatsuda, Rept. Prog. Phys. ***74****, 014001(2011); arXiv: 1005.4814*

Explored QCD phase diagram now

by theorists



CME
CVE
Inverse Magnetic Catalysis

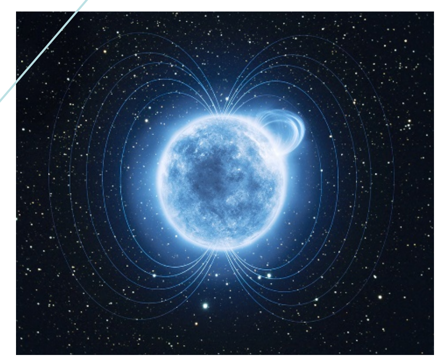


Vacuum superconductor

(Inverse) Magnetic Catalysis

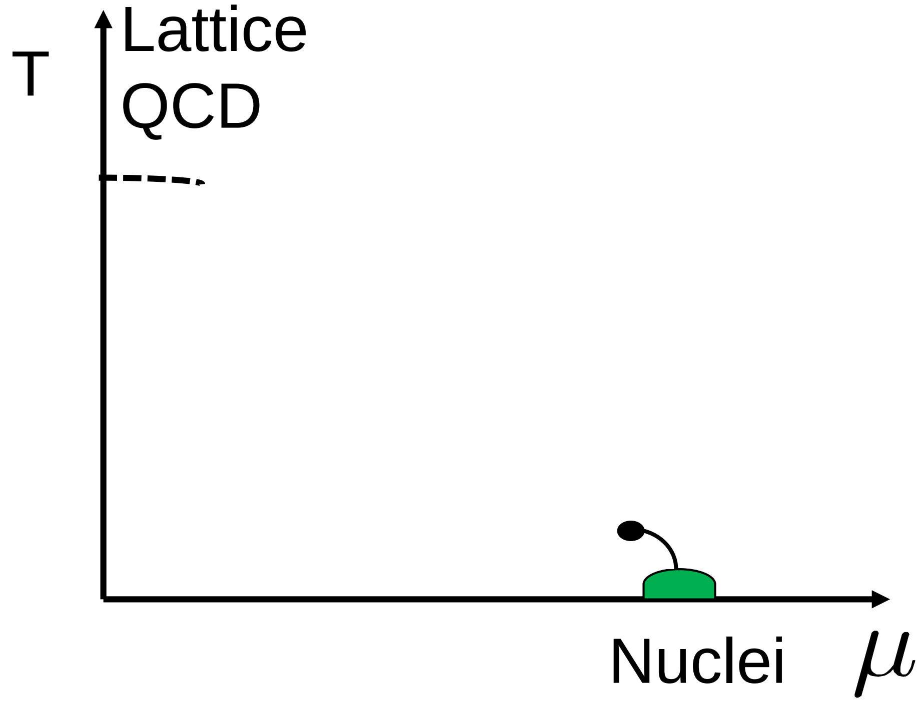
B

Magnetar



Confirmed QCD phase diagram

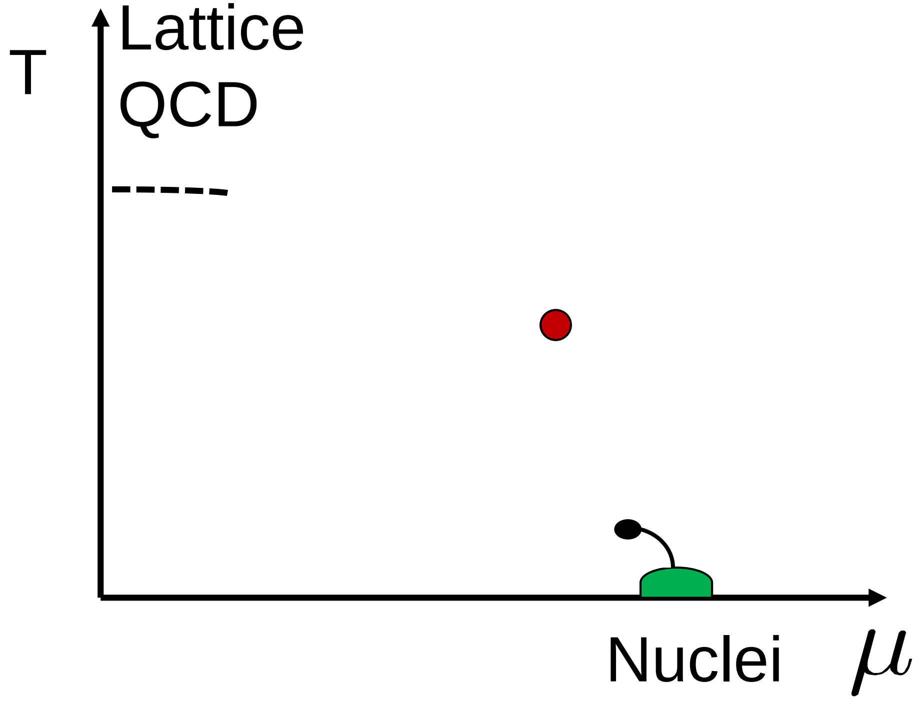
PQCD: QGP@High T



PQCD: CFL@high mu

Searching for the QCD CEP

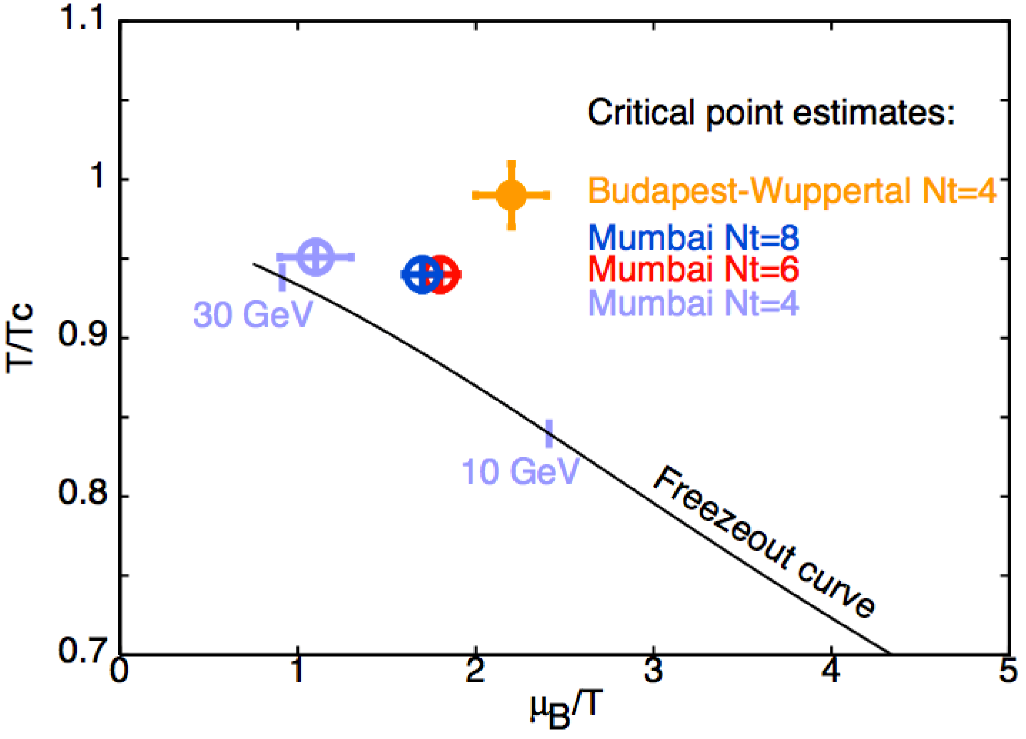
PQCD: QGP@High T



PQCD: CFL@high mu

II. The QCD CEP

Location of CEP: Lattice QCD



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

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

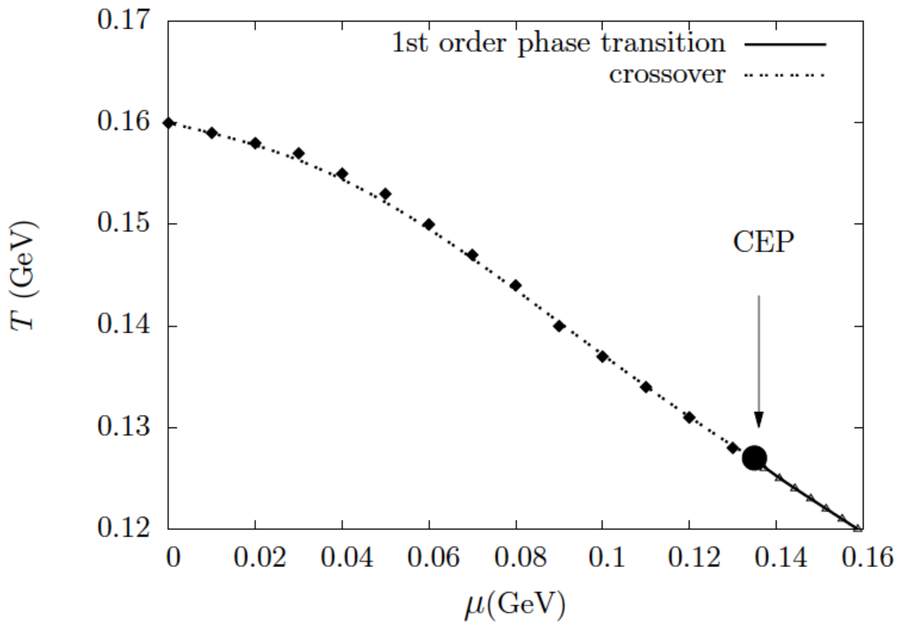
2): Gavai&Gupta, NPA 904, 883c (2013)

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

3): F. Karsch ($\mu^E_B / T_E > 2$, CPOD2016)

Small baryon number density region

Location of CEP: 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).

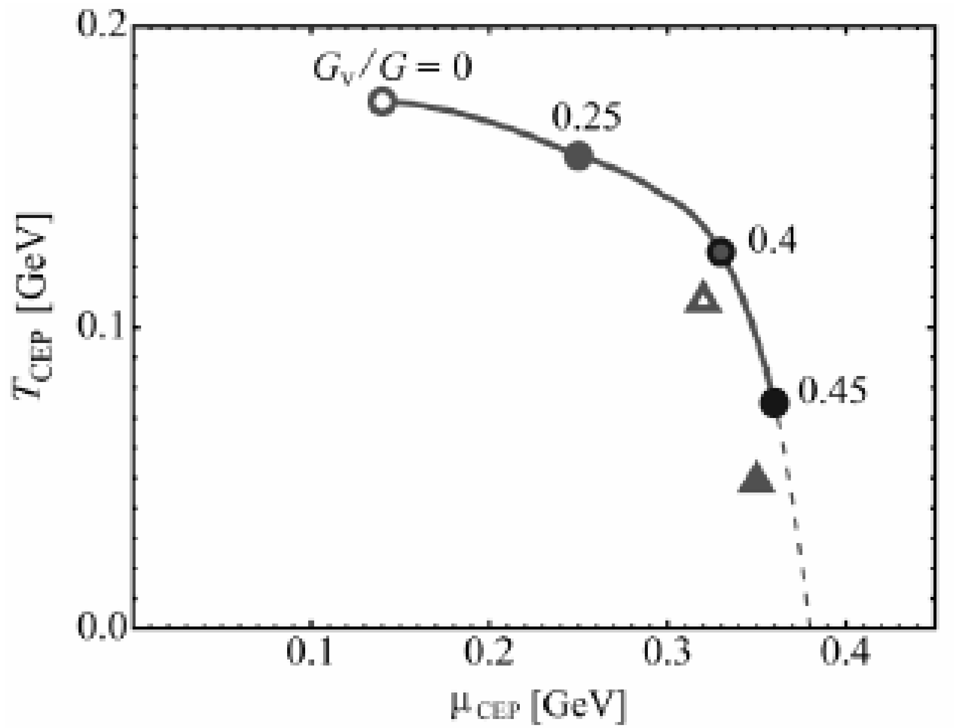
$(\mu^E_B, T^E) = (504, 115)$ MeV

$$\mu_B = 3\mu_q$$

Rather small baryon number density region

Location of CEP: NJL

NJL, PNJL, Nonlocal NJL, ……



Hell, Kashiwa, Weise

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

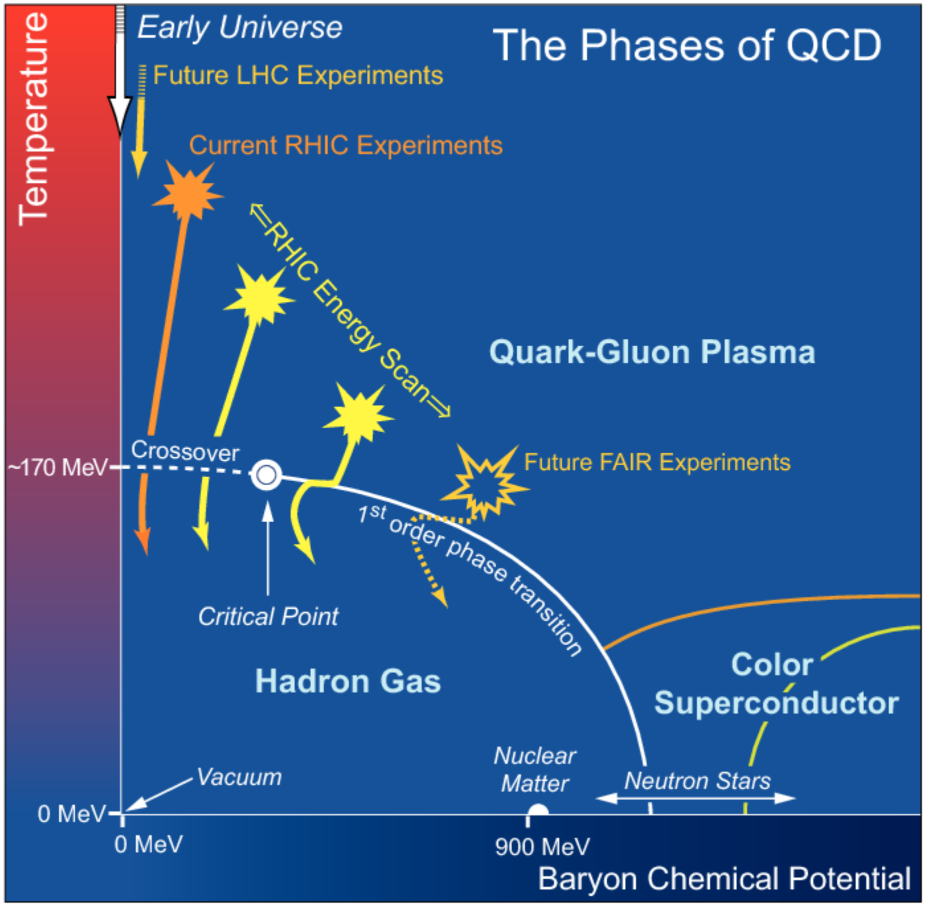
P.F Zhuang,M.Huang,
Y.X.Liu,W.J.Fu, Z.Zhang
H.S.Zong, X.Luo, G.Y.Shao…..
J.Deng, J.W.Chen,……

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

$$\mu_B = 3\mu_q$$

from small to high baryon number density region ……

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

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

$$B \rightarrow Q, s$$

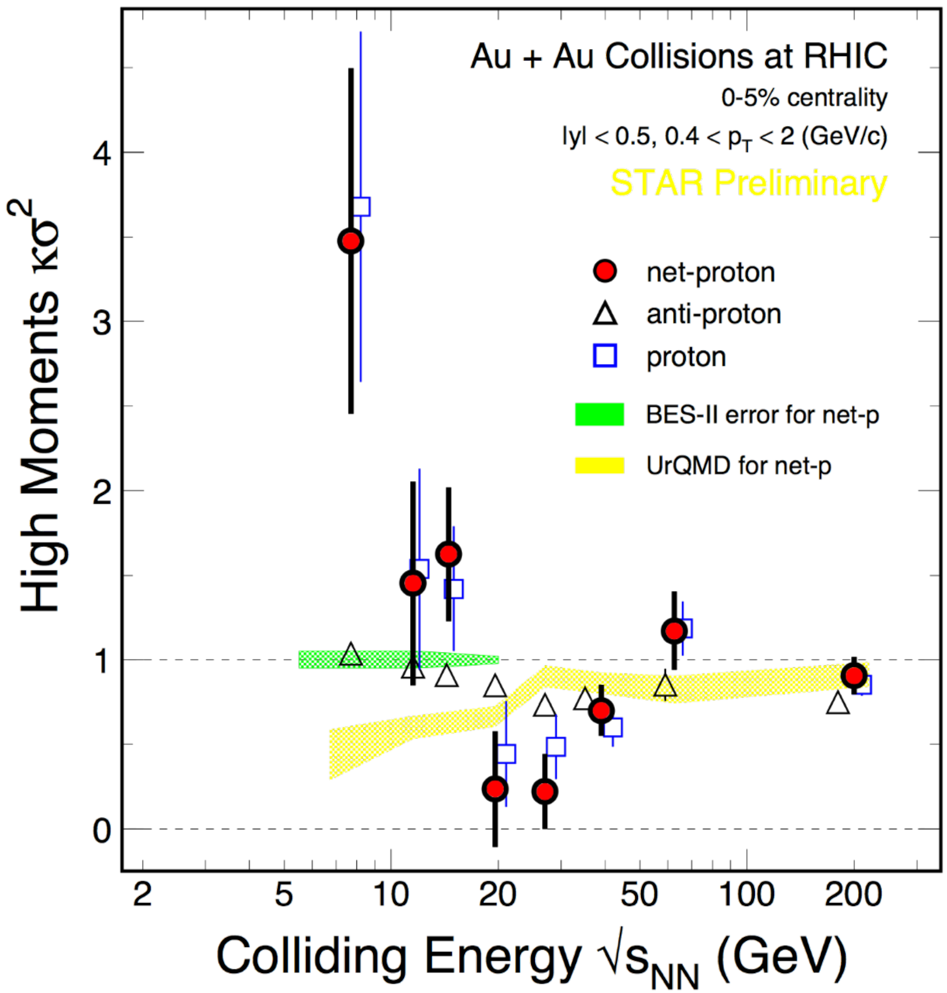
$$C_n^B = VT^3\chi_n^B$$

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

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

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

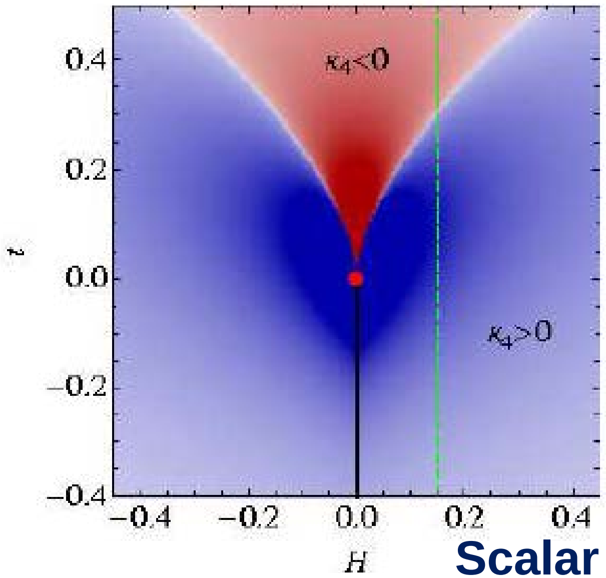
Measurement of Higher Order Fluctuations of Conserved Quantities



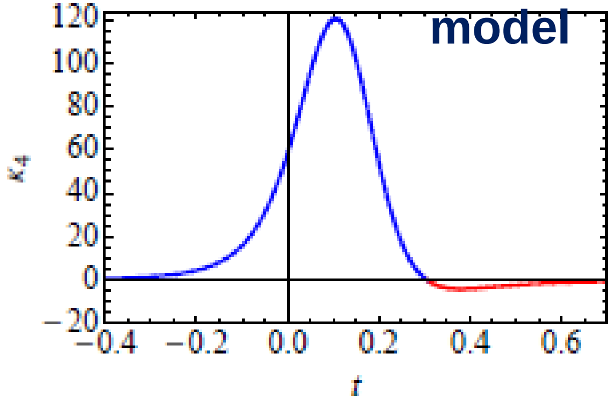
Non-monotonic trend is observed for the 0-5% most central Au+Au collisions. Dip structure is observed around 19.6 GeV.

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

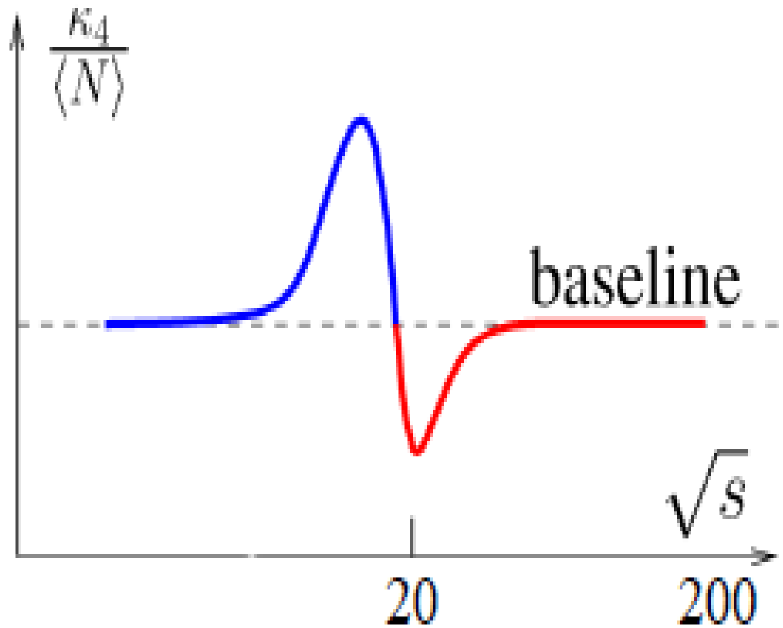
How to determine the location of CEP?



Scalar model



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



- Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

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.

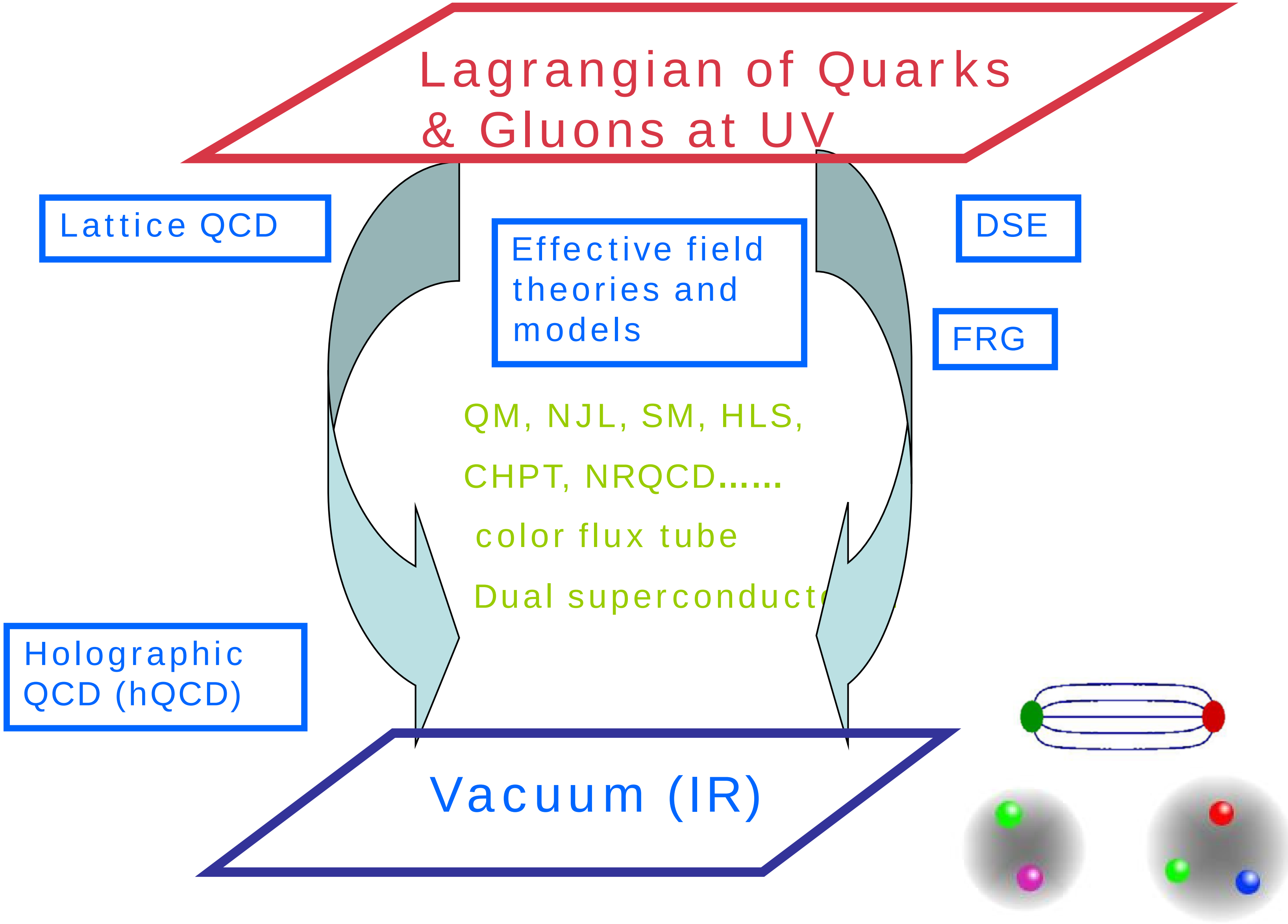
What we are willing to answer:

1. **What’s the universal feature of CEP?**
2. **What information of the CEP can be read from experimental measurement?**

III. Locating the CEP

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

Strong QCD


Lagrangian of Quarks
& Gluons at UV
Lattice QCD
Effective field theories and models
DSE
FRG
QM, NJL, SM, HLS,
CHPT, NRQCD......
color flux tube
Dual superconduct
Holographic QCD (hQCD)
Vacuum (IR)

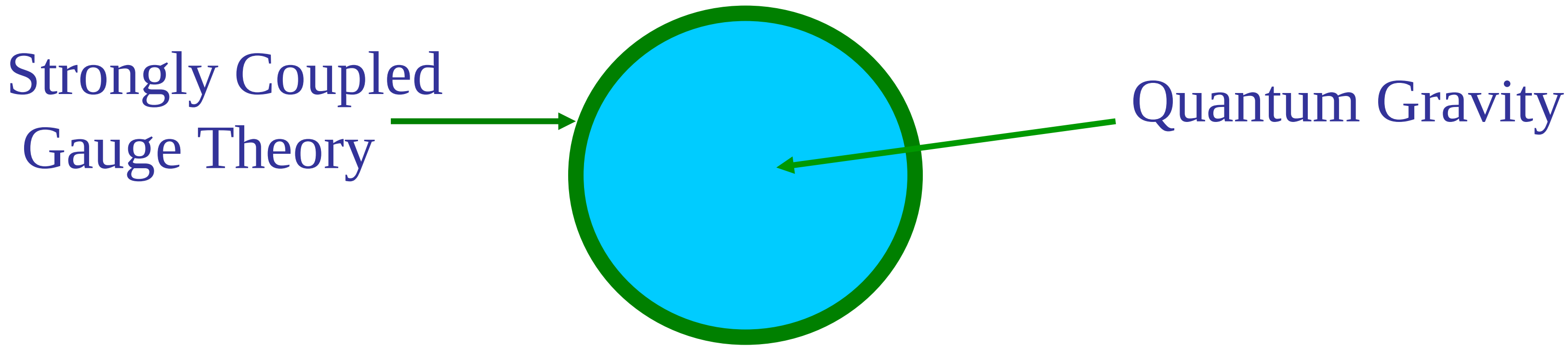
Holographic Duality: Gravity/QFT

AdS/CFT : Original discovery of duality

J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998)

Supersymmetry and conformality are required for AdS/CFT.

Holographic Duality: (d+1)-Gravity/ (d)-QFT

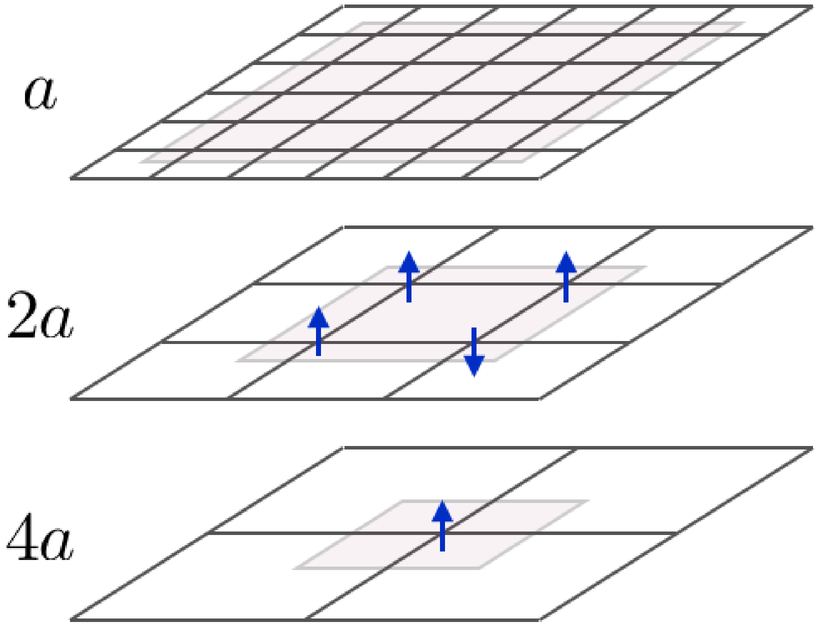


Holographic Duality & RG flow

Coarse graining spins on a lattice: Kadanoff and Wilson

$$H = \sum_{x,i} J_i(x) \mathcal{O}^i(x)$$

J(x): coupling constant or source for the operator



$$H = \sum_i J_i(x, a)\, \mathcal{O}^i(x)$$

$$H = \sum_i J_i(x, 2a)\, \mathcal{O}^i(x)$$

$$H = \sum_i J_i(x, 4a)\, \mathcal{O}^i(x)$$

$$u \frac{\partial}{\partial u} J_i(x, u) = \beta_i(J_j(x, u), u)$$

arXiv:1205.5180

Holographic Duality & RG flow

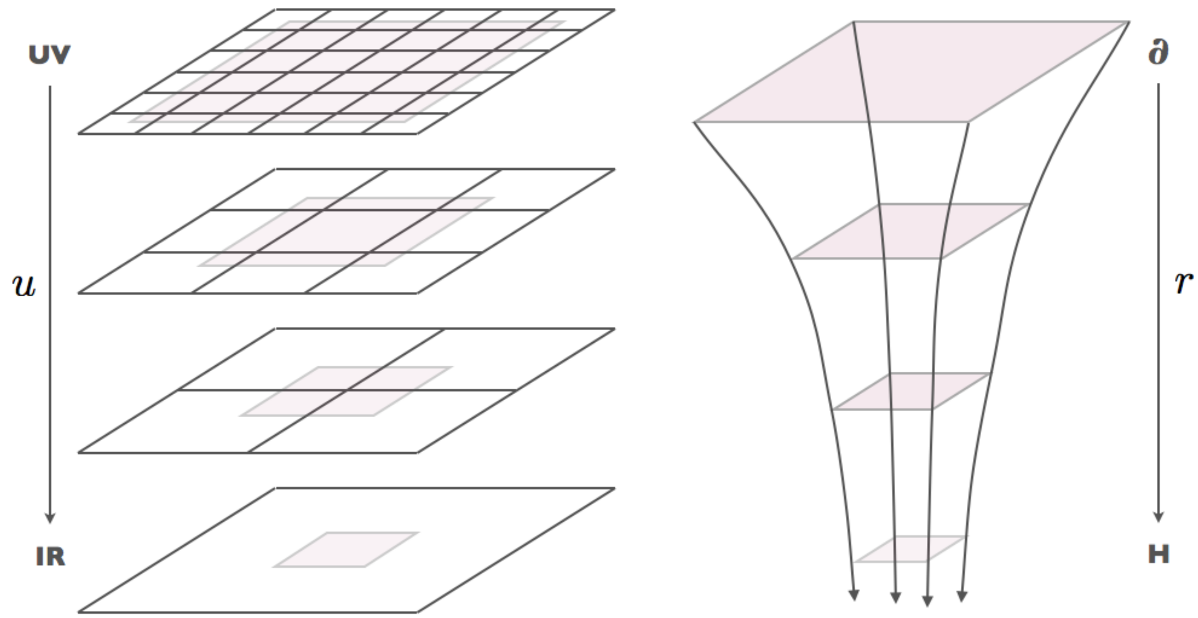
QFT on lattice equivalent to GR problem from Gravity

RG scale -> an extra spatial dimension

Coupling constant -> dynamical filed

arXiv:1205.5180

$$J_i\big|_{UV} = \Phi_i\big|_{\partial}$$



The extra dimension plays the role of energy scale in QFT, with motion along the extra dimension representing a change of scale, or renormalization group (RG) flow.

A systematic framework: Graviton-dilaton system

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R_s + 4\partial_M\Phi\partial^M\Phi - V_G^s(\Phi)\right)$$

N=4 Super YM

conformal

AdS$_5$

$$ds^2 = \frac{L^2}{z^2}\left(dt^2 + d\vec{x}^2 + dz^2\right)$$

$$V_E(\phi) = -\frac{12}{L^2}$$

QCD

nonconformal

deformed AdS$_5$

$$ds^2 = \frac{h(z)L^2}{z^2}\left(dt^2 + d\vec{x}^2 + dz^2\right)$$

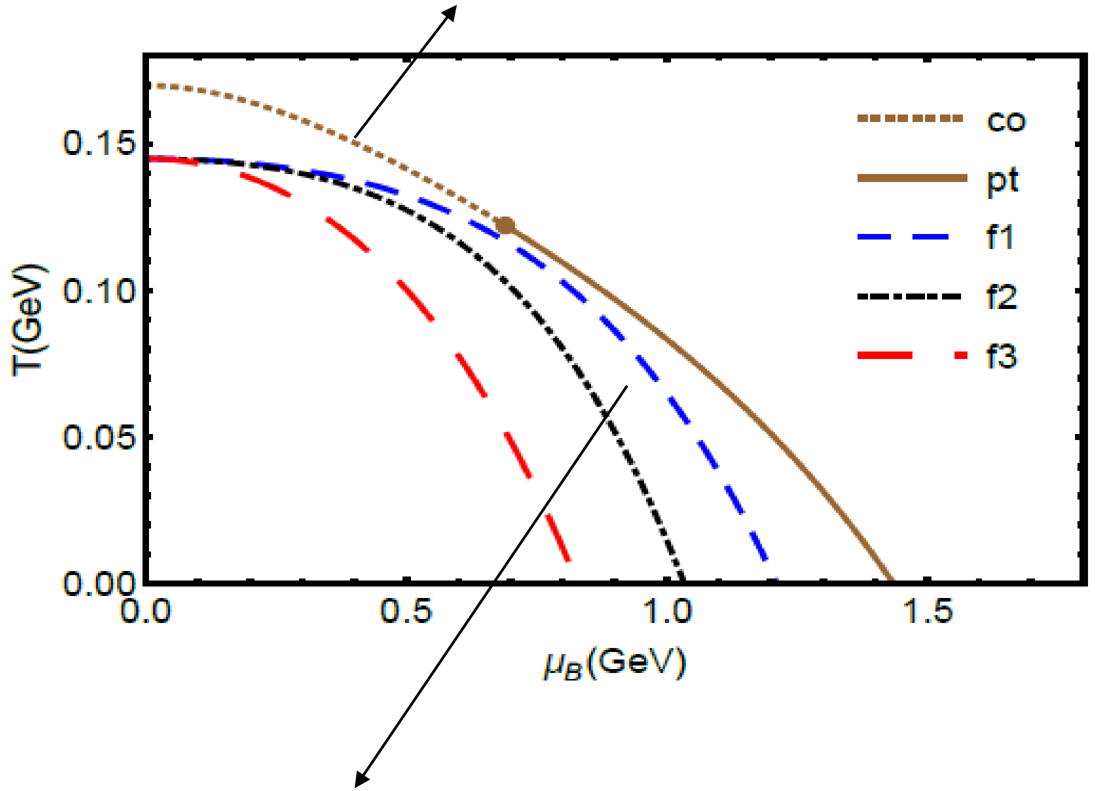
Dilaton field breaks conformal symmetry

Input: QCD dynamics (gluon condensate & chiral condensate) at IR

Solve: Metric structure, dilaton potential

CEP: $(T^c, \mu_B^c) = (0.121\mathrm{GeV}, 0.693\mathrm{GeV})$

Phase transition line



Three chemical freezeout lines

Higher Order Fluctuations of baryon number

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

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

Experiment measurement of baryon number fluctuations is along freeze-out line

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

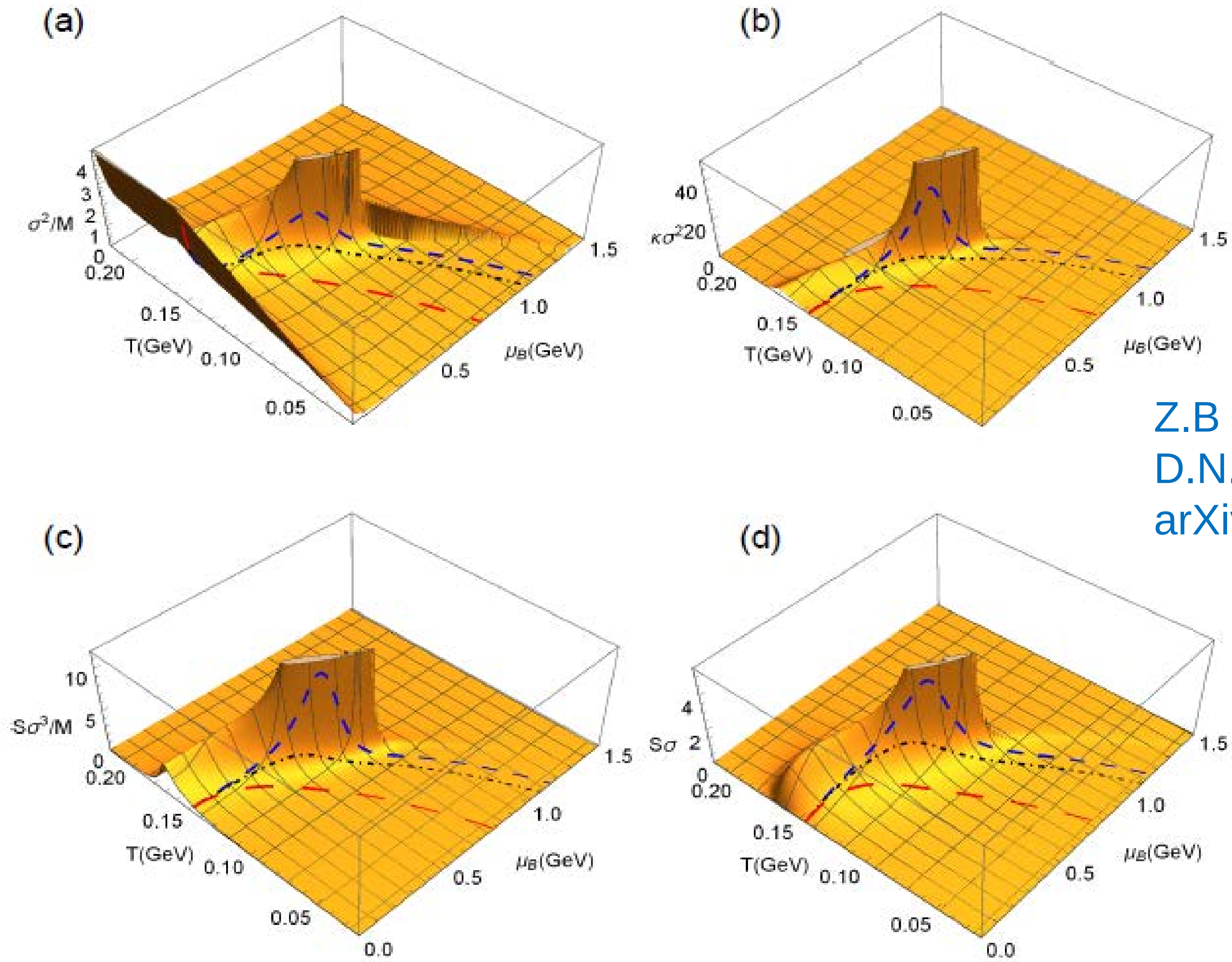
$$\frac{S\sigma^3}{M} = \frac{C_3^B}{C_1^B} = \frac{\chi_3^B}{\chi_1^B}, \quad \kappa\sigma^2 = \frac{C_4^B}{C_2^B} = \frac{\chi_4^B}{\chi_2^B}.$$

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

Universal feature:

Phase transition: Ridge + hallow sword shape mountain at CEP

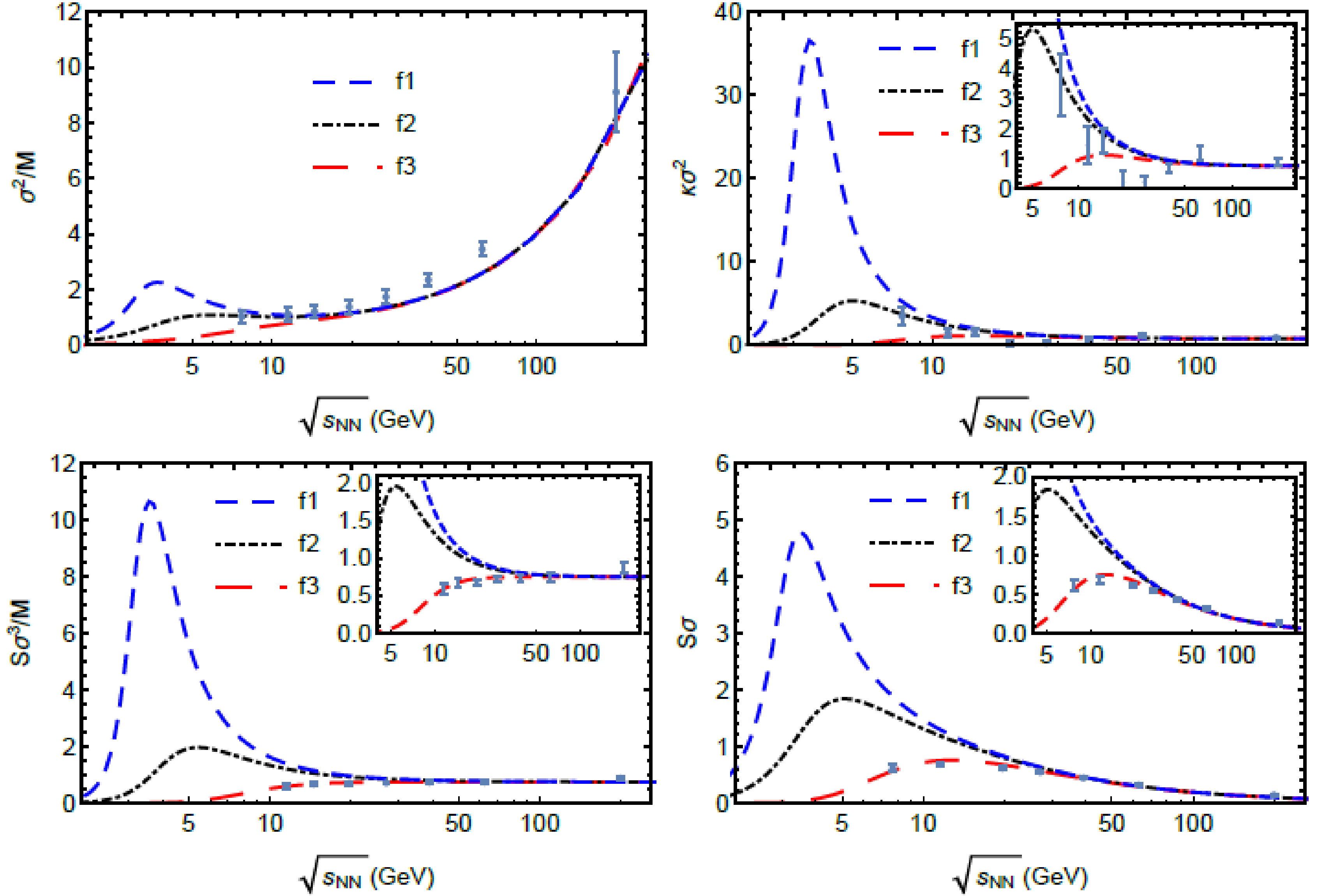
Freezeout: foot of the mountain



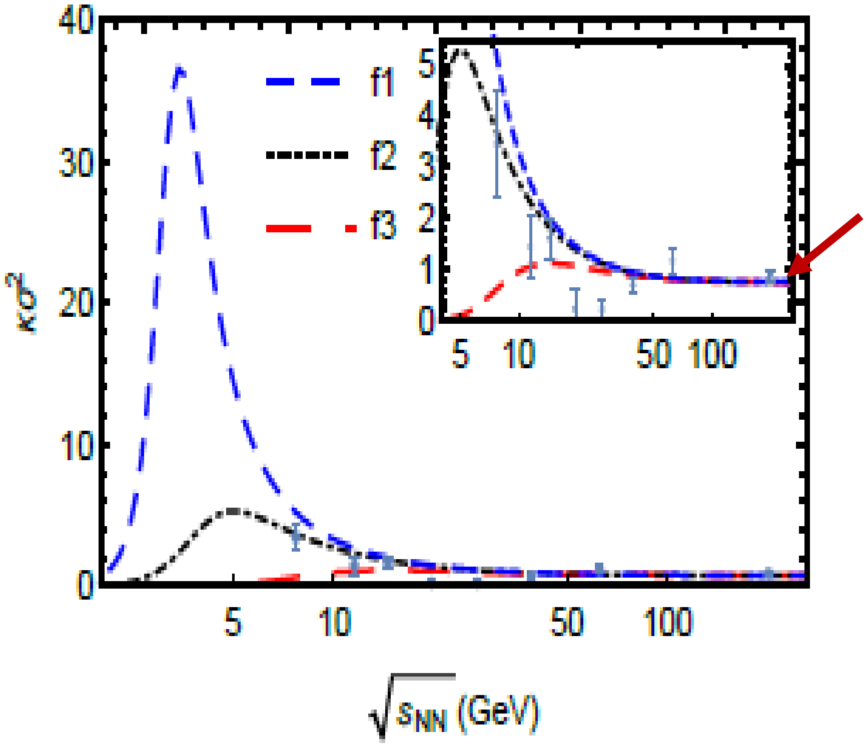
Z.B Li, Y.D. Chen, D.N. Li, M.H., arXiv:1706.02238

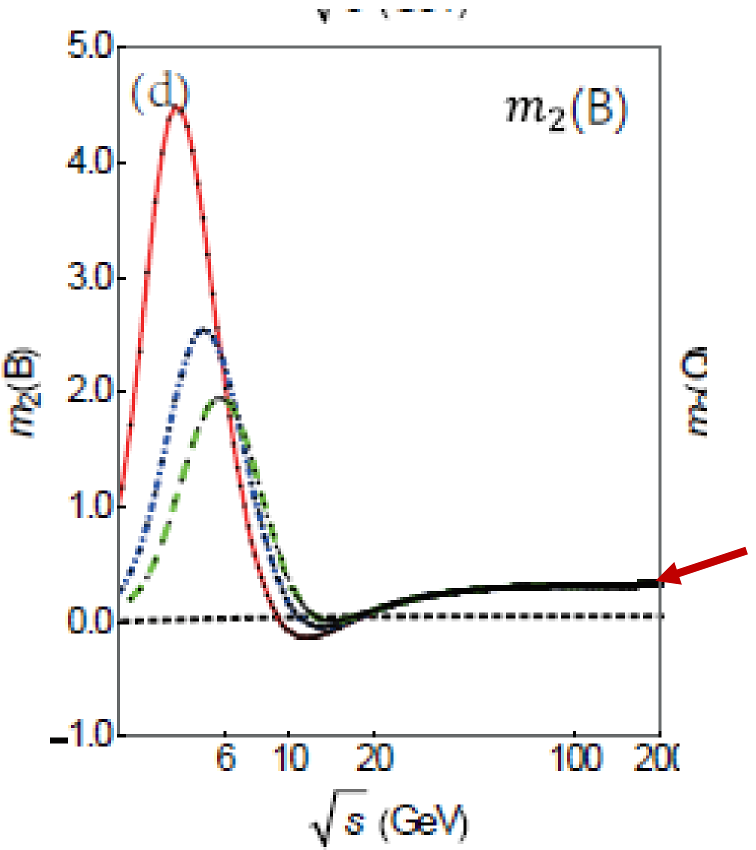
BES Phase-I measurement indicates a peak may show up around 5 GeV, CEP is located around 3GeV

Z.B Li, Y.D. Chen, D.N. Li, M.H., arXiv:1706.02238



Comparing with NJL model





Z.B Li, Y.D. Chen, D.N. Li, M.H., arXiv:1706.02238

W.K.Fan, X.F.Luo, H.S.Zong, arXiv:1608.07903

Dominant contribution from gluon-dynamics at low baryon density?

V. Conclusion and Outlook

Which results are model dependent?

- The location of the CEP

Which results are model independent?

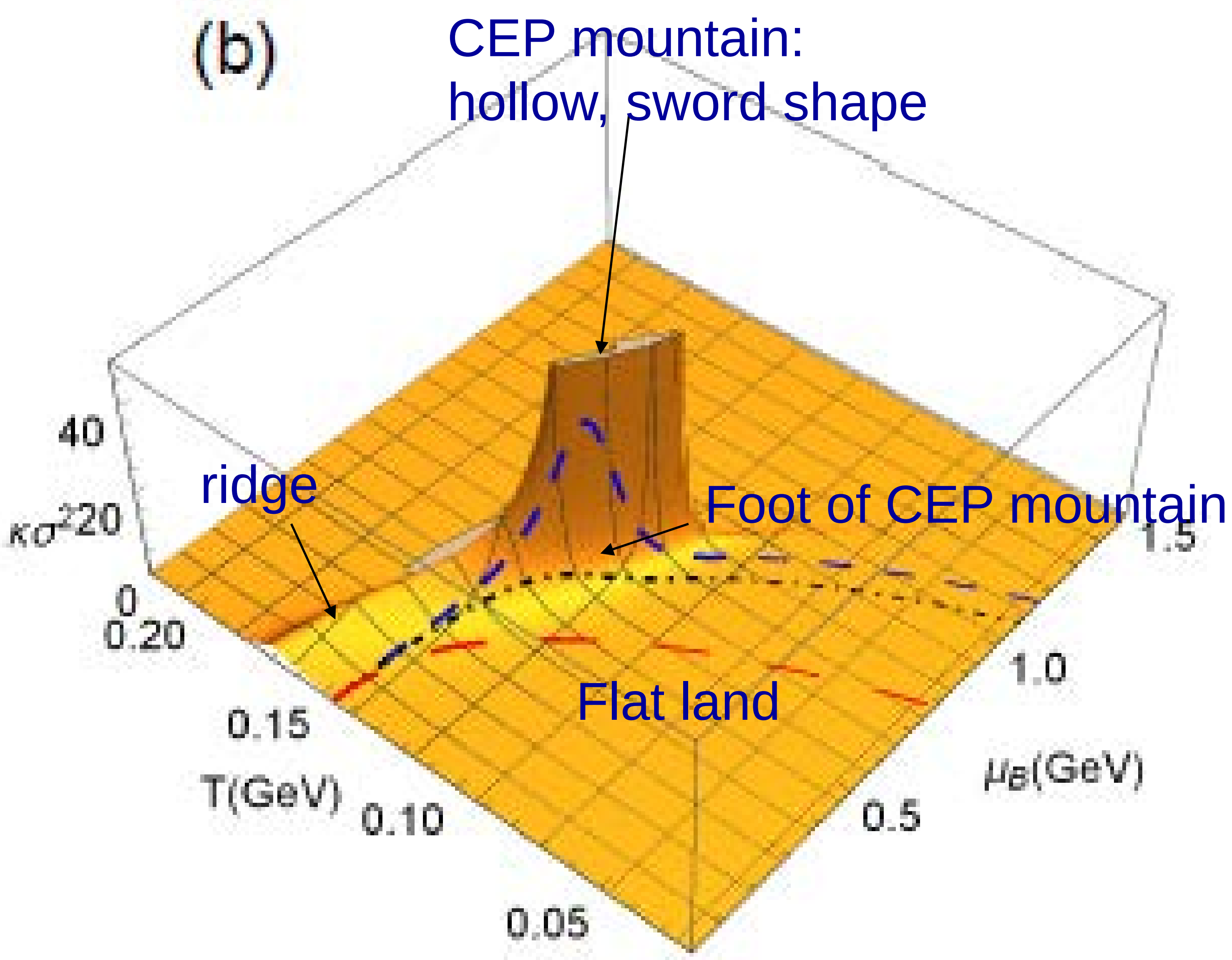
- Universal feature along phase transition with CEP

Phase transition:

- ❑ Ridge
- ❑ Sword shape mountain at CEP
- ❑ Hollow inside the CEP mountain

Freezeout:

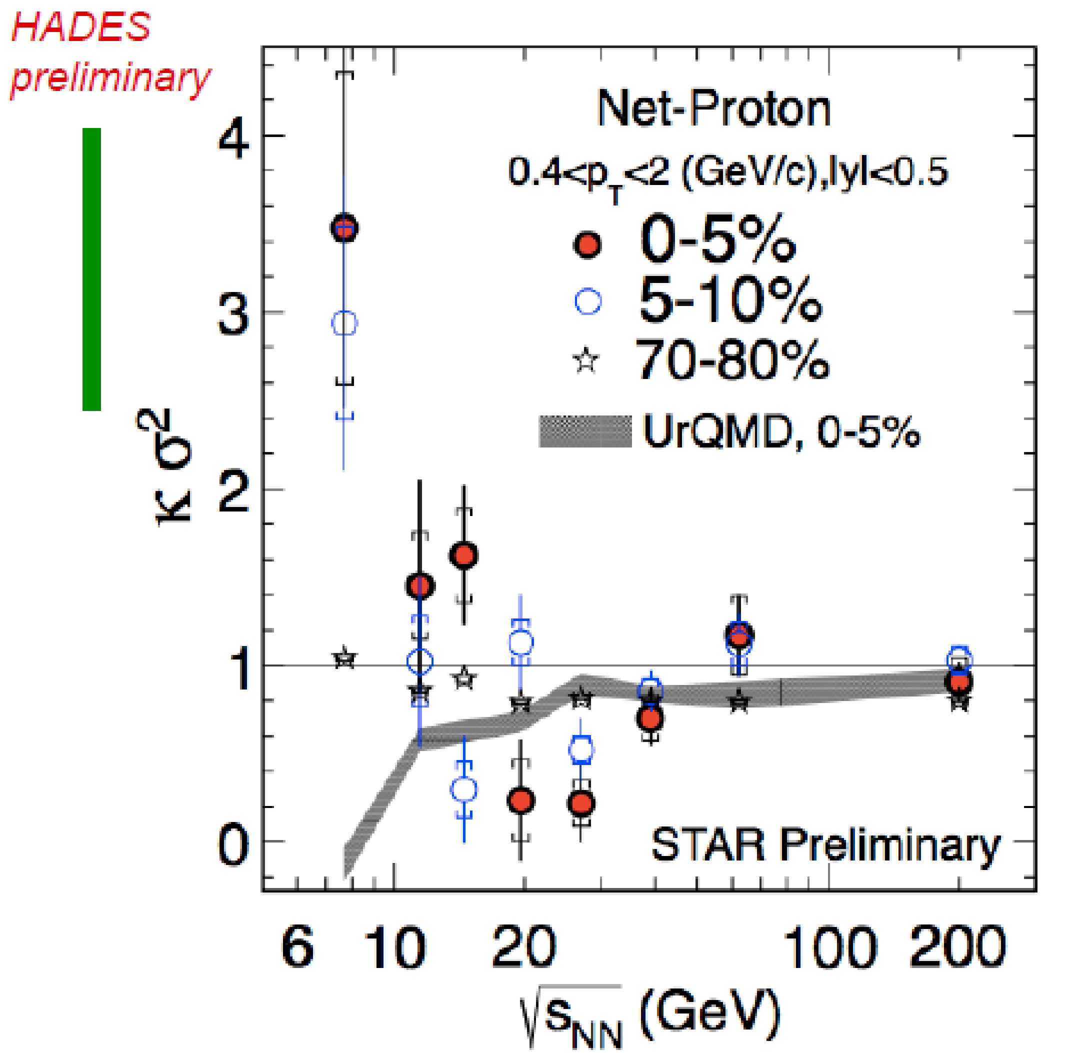
- ❑ crosses the foot of the mountain or the flat land


(b)
CEP mountain:
hollow, sword shape
40
ridge
κσ²20
Foot of CEP mountain
1.5
0
0.20
1.0
Flat land
0.15
μB(GeV)
T(GeV)
0.10
0.5
0.05

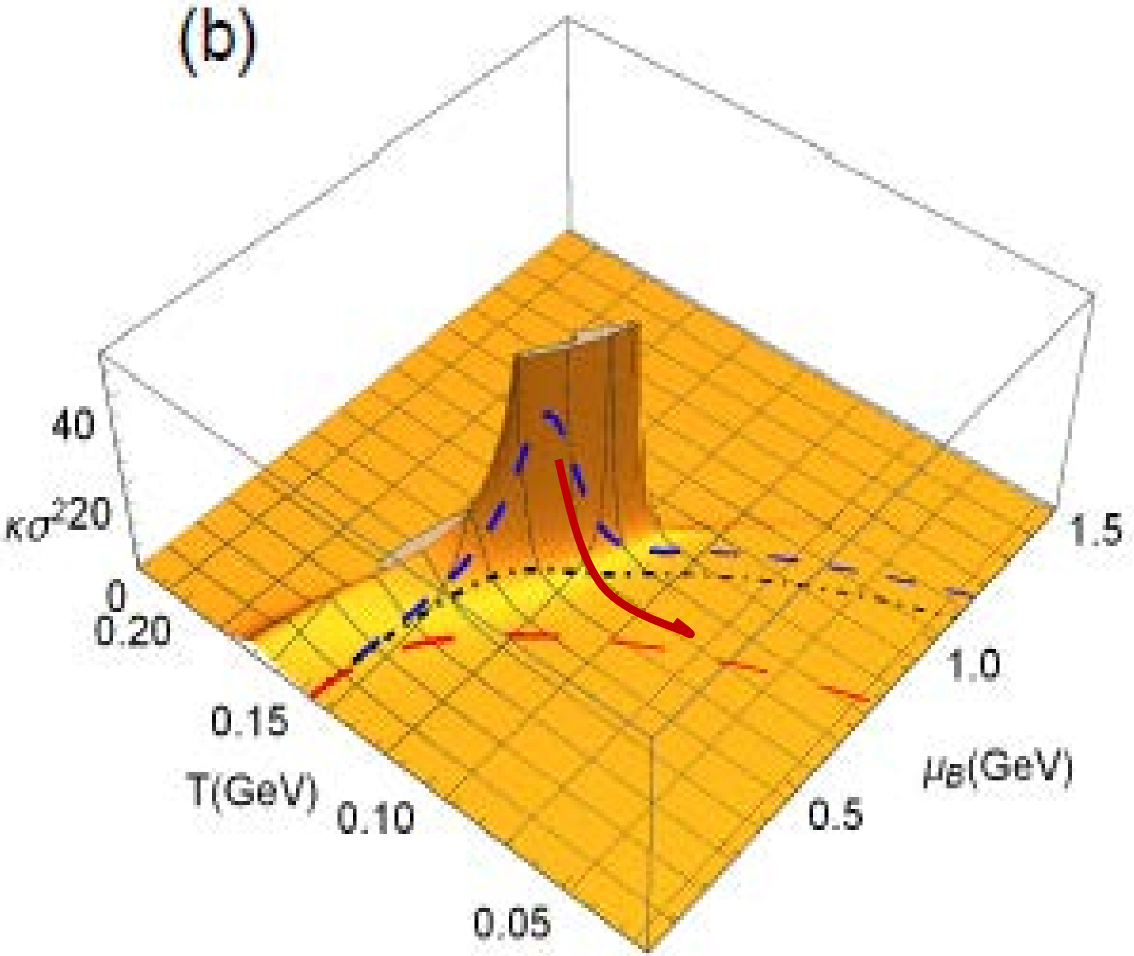
Which results can we conclude from Exp.?

- Measurement of higher order baryon number fluctuations is along the freezeout line, which is below the phase transition line;
- The measurement of higher order baryon number fluctuations can tell us how far the freezeout line is away from the phase transition line;
- The measurement tells us that CEP is not located at small baryon number density region;
- The show-up of a peak of higher order baryon number fluctuations along freezeout line is due to the existence of the CEP mountain nearby **(Lucky!!!).**

BES Phase-I measurement indicates a peak may show up around 5 GeV, then CEP is located around

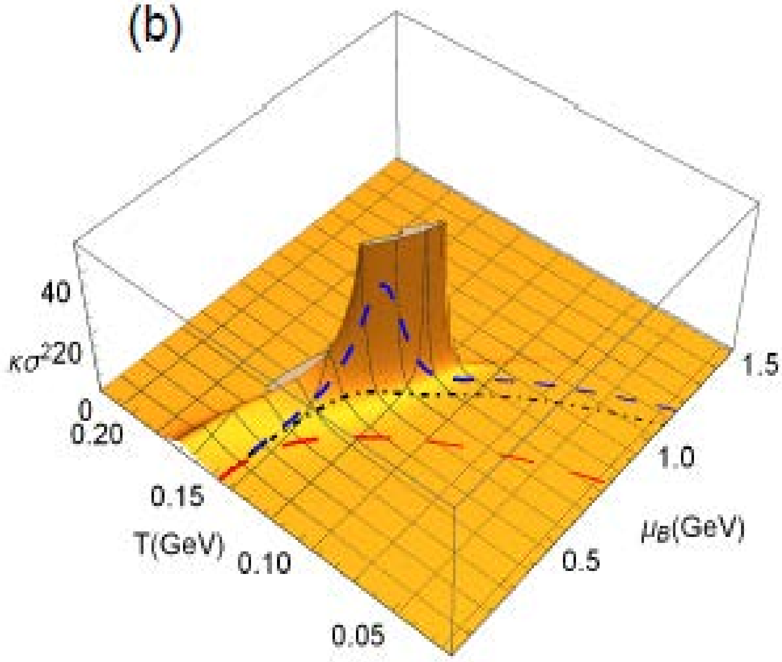


How does the system evolve from phase transition line to the freeze-out line ?



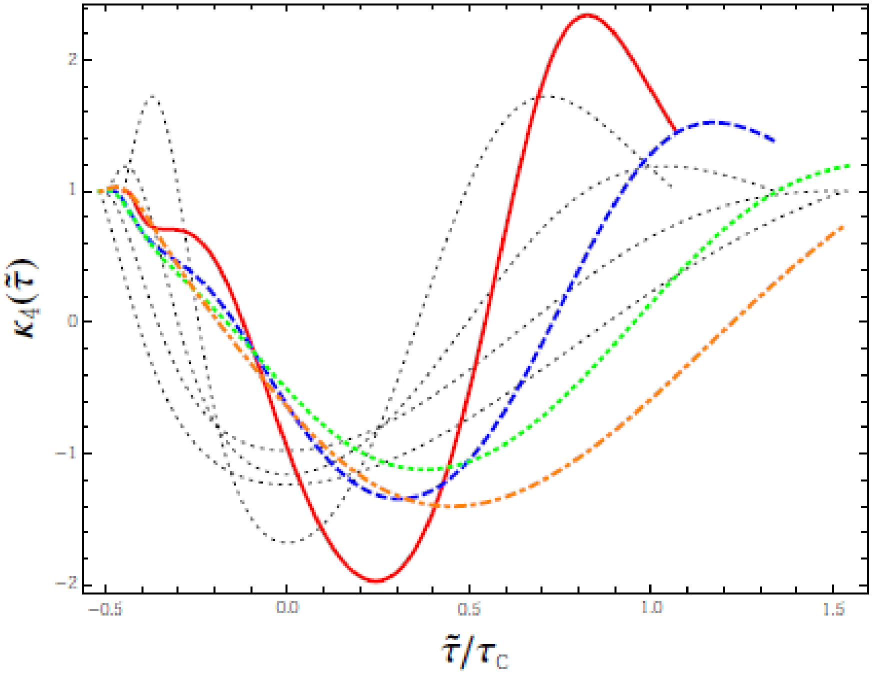
I. Along the surface of the mountain, which is determined by stability condition

-> No sign change



II. 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

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

Finite size effect, freeze out, …… these effects may shift the location of CEP, but the CEP mountain might be broadened (more chances for Exp.)

Thanks for your attention!