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Exploring the phase transition of strongly interacting matter with density fluctuations

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Outline:

I. Introduction

II. Phase structure and density fluctuations

- Chiral transition including the instable and metastable phase
- Nuclear LG transition and beyond

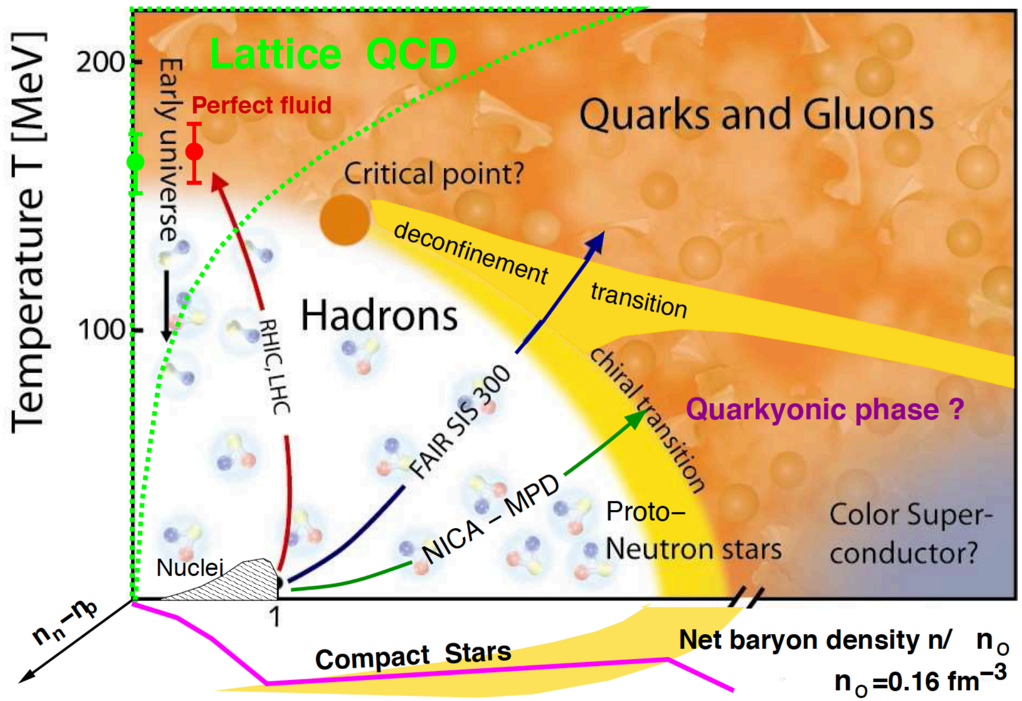
III. Magnetized quark matter

IV. Summary

Based on PRD 100, 104020 (2019), EPJC 78, 138 (2018) & work in progress

I. Introduction

■ QCD phase diagram？



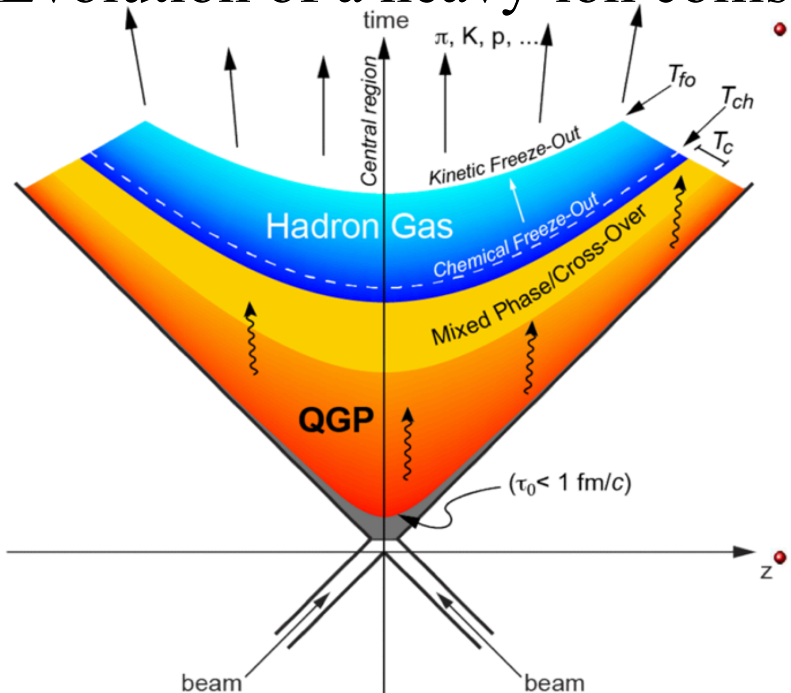
- Lattice QCD
- DSE
- FRG
- Hadron-quark two phase model
- Effective quark model： e.g., PNJL, QMC

□ Key issues:

- Location of the critical end point of chiral phase transition?
- *Boundaries* of the first-order transition?
- Phases of QCD at high density?

■ Exploring the phase structure with heavy-ion collisions

□ Evolution of a heavy-ion collision



- Deconfinement
- Hadronization
- Chemical freeze-out

  inelastic collisions cease, chemical composition is fixed (ratios and fluctuations)
- Kinetic freeze-out:

  elastic collisions cease (spectra and correlation crease)

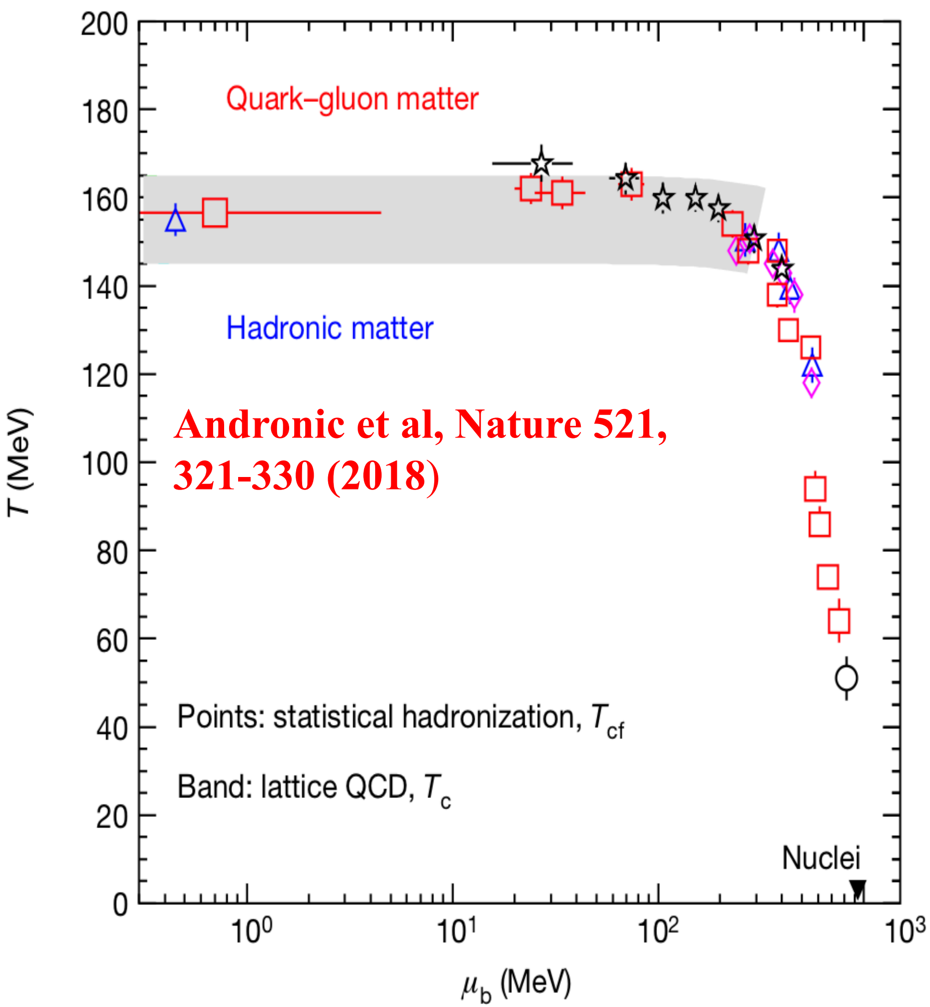
□ Chemical freeze-out conditions

Statistical thermal model (HRG model): hypothesis of hadron abundance in equilibrium

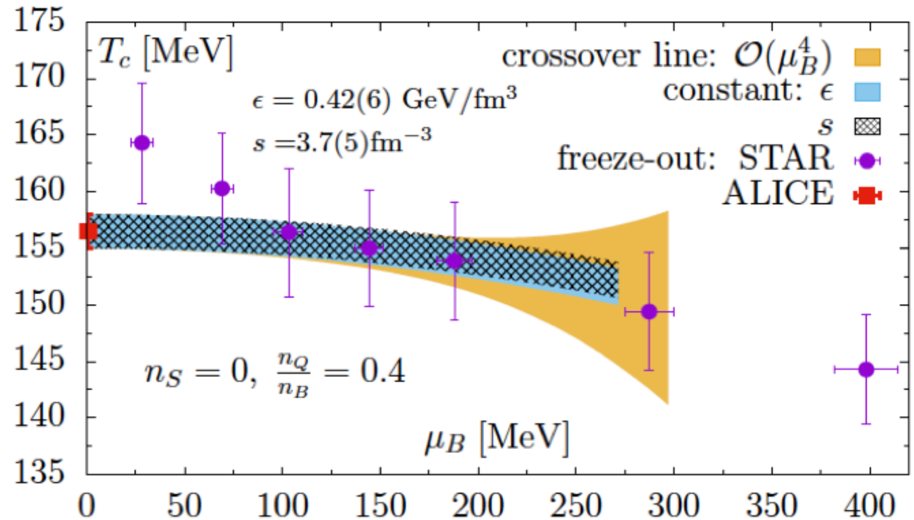
$$N_i = -T\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i V}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

- Particle counting (average of many events)
- Fit to hadron yields (parameters T, μ,V)
- Fit to hadron ratios (cancels out V)

◻ Mapping the chemical freeze-out curve



Andronic et al, Nature 521, 321-330 (2018)



Bazavov et al (Hot QCD) arXiv:1812.08235

- Changing collision energy, different chemical freeze-out conditions can be reached

☐ Fluctuations at chemical freeze-out

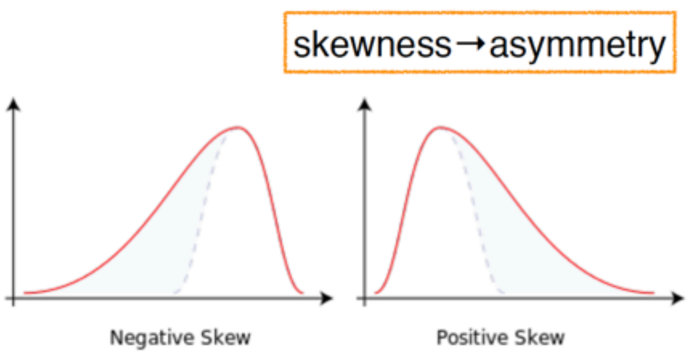
- Fluctuations of conserved quantities are sensitive observables to study a phase transition, in particular the critical phenomenon

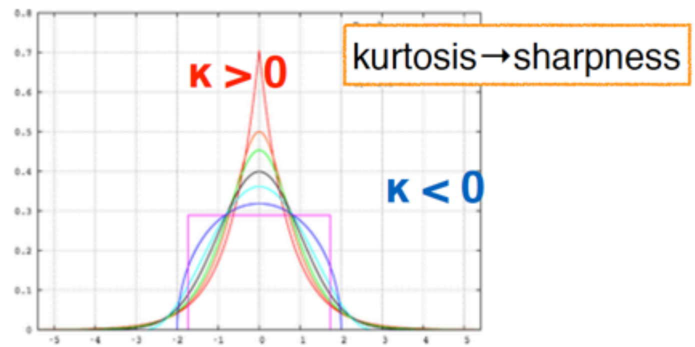
- Drastic fluctuations in the critical region
- Can we observe signals of criticality and/or the chiral first-order transition in HICs?

Critical opalescence in CO_2
J.V. Sengers, A.L Sengers, Chem. Eng. News, June 10, 104–118, 1968

✦ **Moments and cumulants are mathematical measures of "shape" of a distribution which probe the fluctuation of observables.**

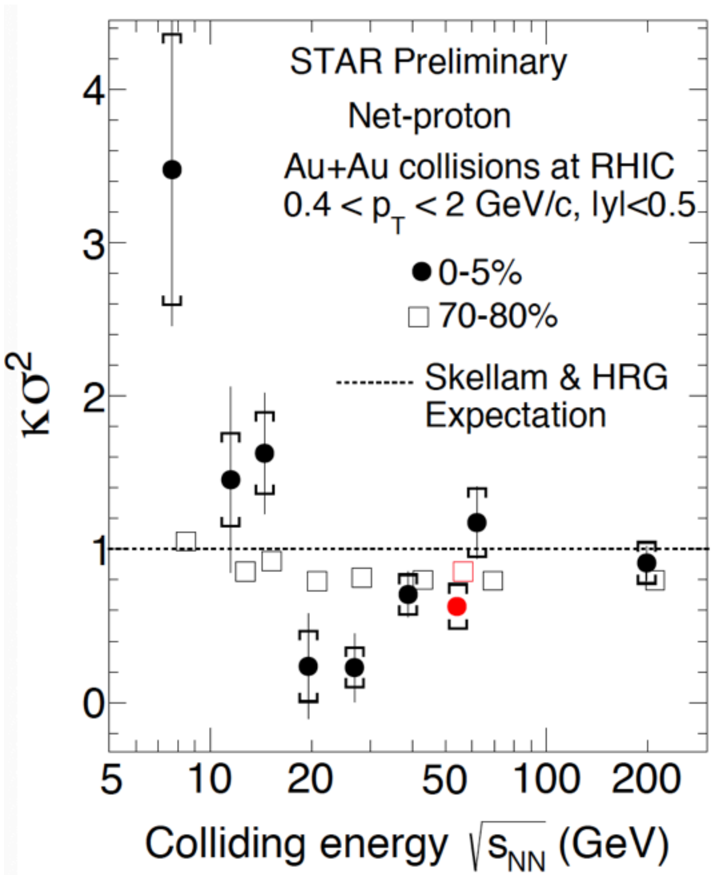
✓ **Moments: mean (*M*), standard deviation (*σ*), skewness (*S*) and kurtosis (κ).**
✓ ***S and κ are non-gaussian* fluctuations.**





- "shape" of distribution along CFL curve reflecting the phase transition

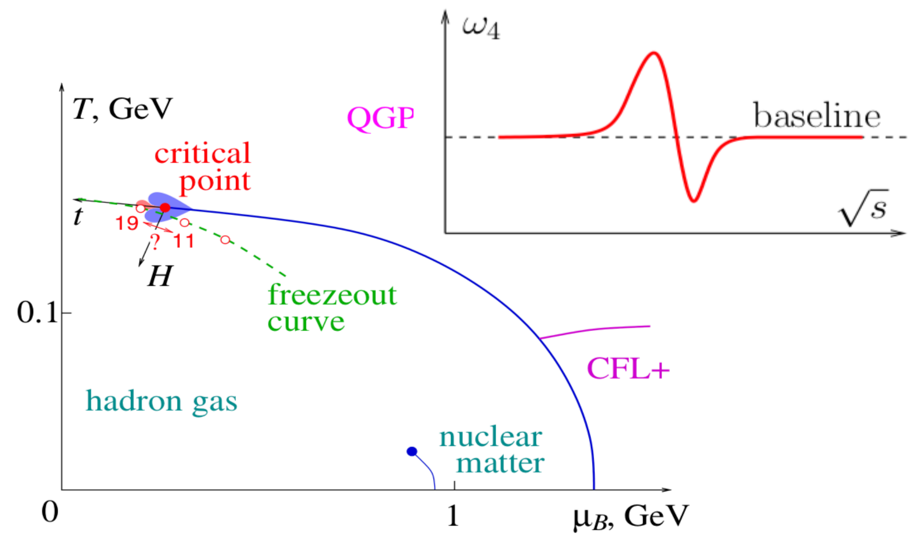
II. QCD phase structure and density fluctuations



STAR Preliminary result of the net-proton kurtosis

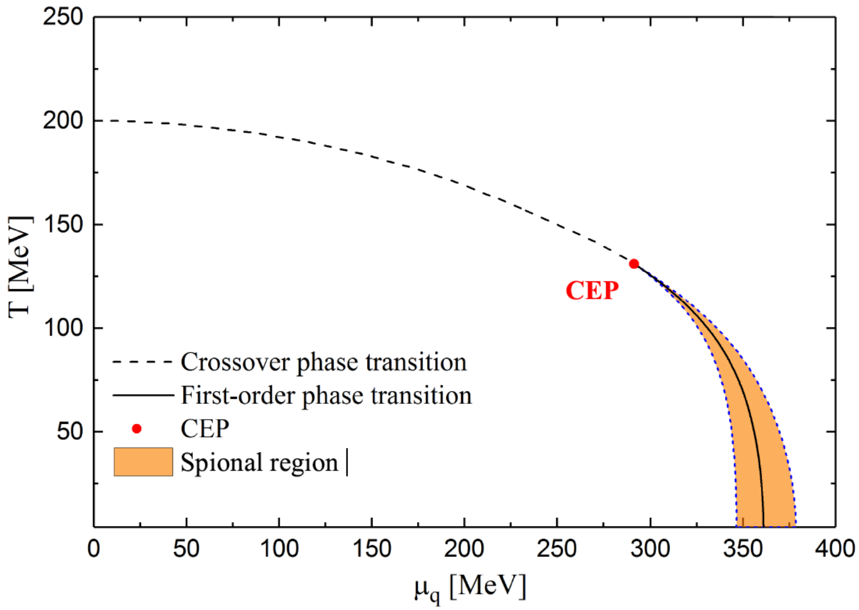
- Non-monotonic energy dependence below 39 GeV
- Large deviation from the baseline

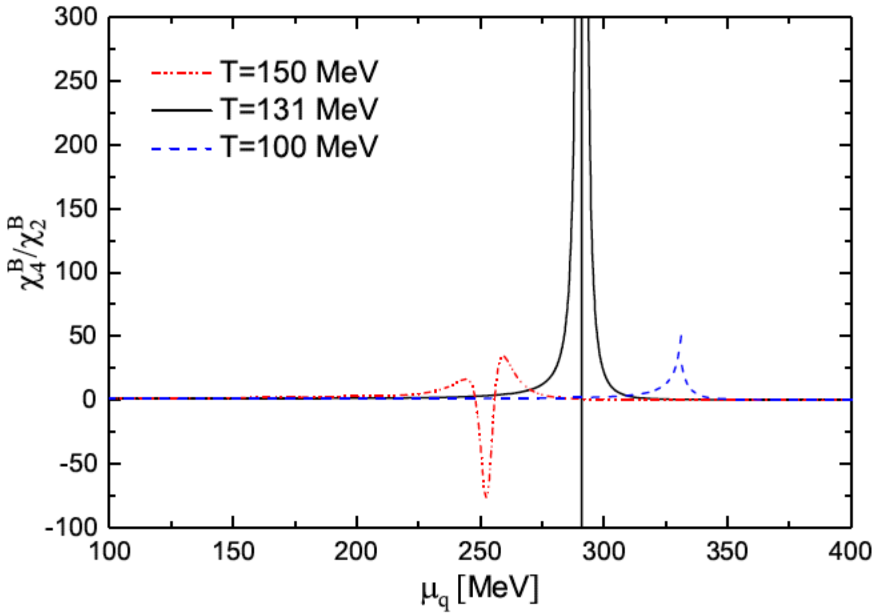
✓ **Consistent with the prediction of first order transition with a CEP**



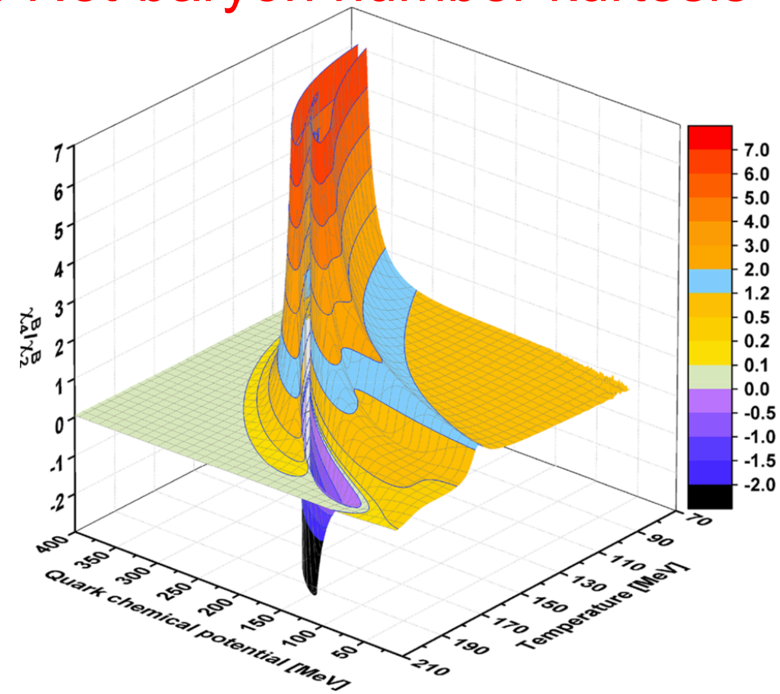
M. Stephanov, PRL107, 052301(2011); J. Phys. G: 38, 124147 (2011).

Phase structure and net-baryon number fluctuations in the PNJL model





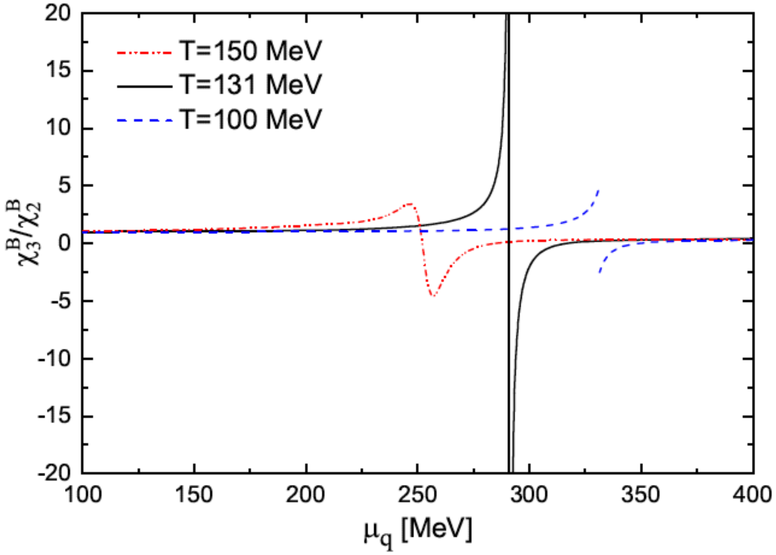
Net-baryon number kurtosis

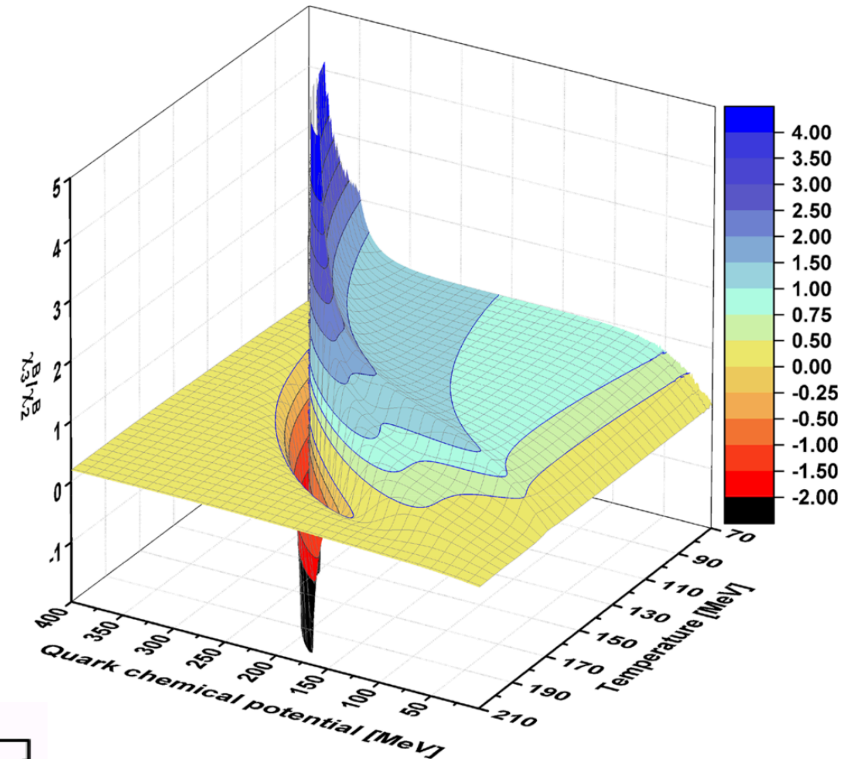


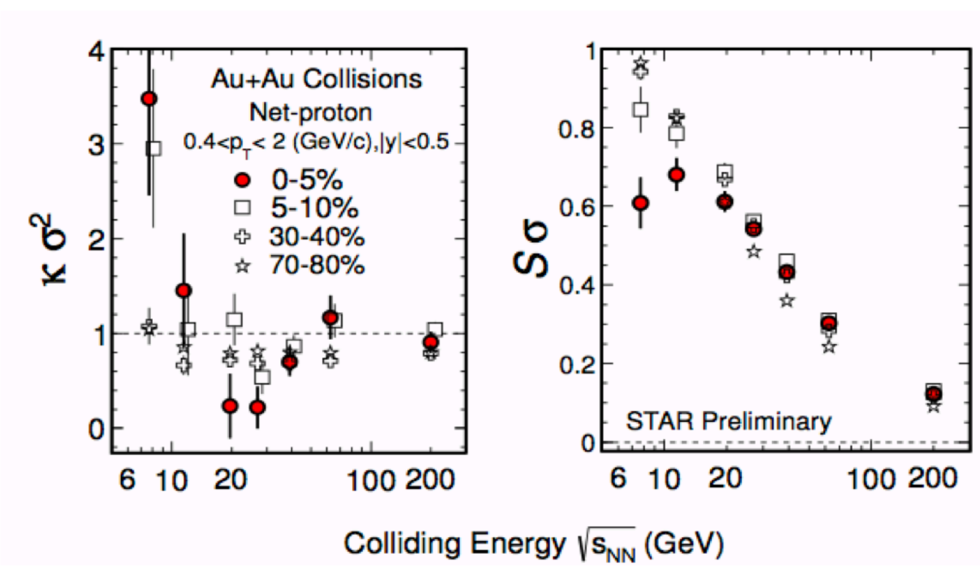
- Divergence at the CEP
- Finite for the first-order phase transition
- Minus value along the crossover line in the vicinity of CEP

G.Y. SHAO et al, EPJC 78, 138 (2018)

Net-baryon number skewness







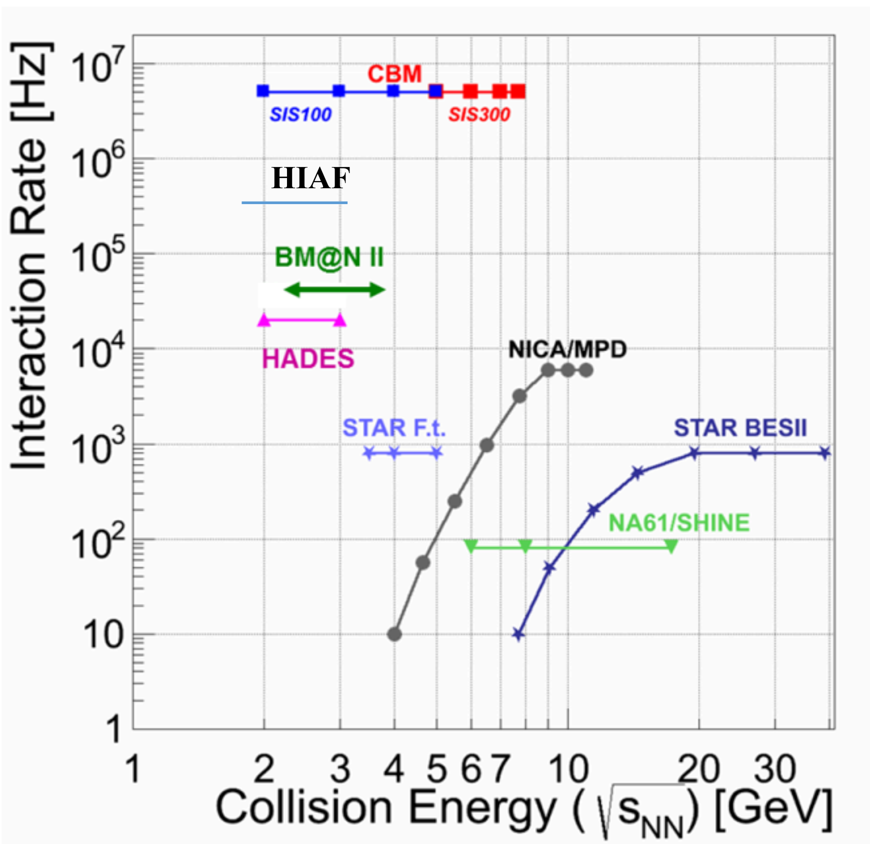
- Signals with the decrease of collision energy?

X.Luo (STAR), PoS CPOD2014, 019 (2014)

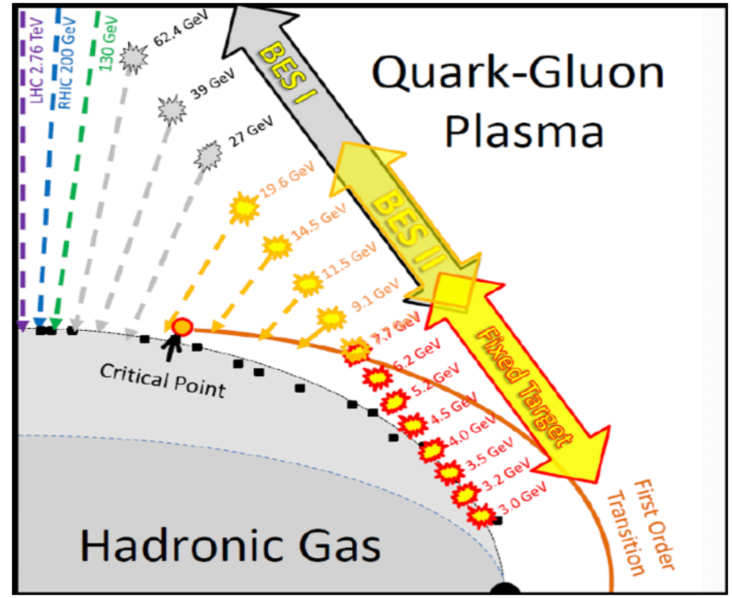
BES II & Fixed Target experiments

- Locating the CEP
- First-order phase transition
- Turn-off of QGP signatures

Other planned experiments



Nucl. Phys. A 967, 808 (2017)



Compilation by D. Cebra

Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2017	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed target	Fixed target Lighter ion collisions	Collider Fixed target	Fixed target	Fixed target

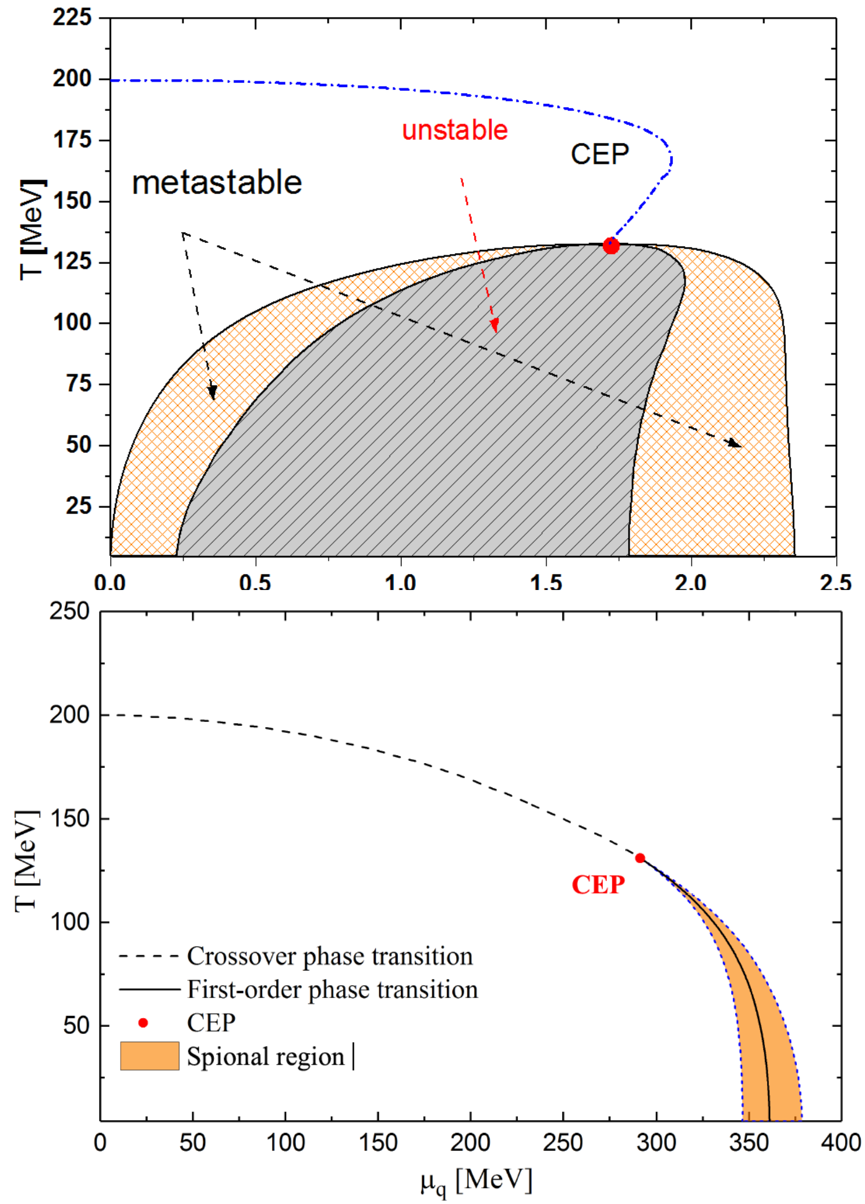
CP=Critical Point OD= Onset of Deconfinement DHM=Dense Hadronic Matter

- **The nonequilibrium effect of the chiral first-order transition in an expanding system**

- **Spinodal instability maybe trigged** ***(Steinheimer, Randrup, V. Koch Phys. Rev. Lett. 109, 212301 (2012) Phys. Rev. C. 96, 034907(2017).***

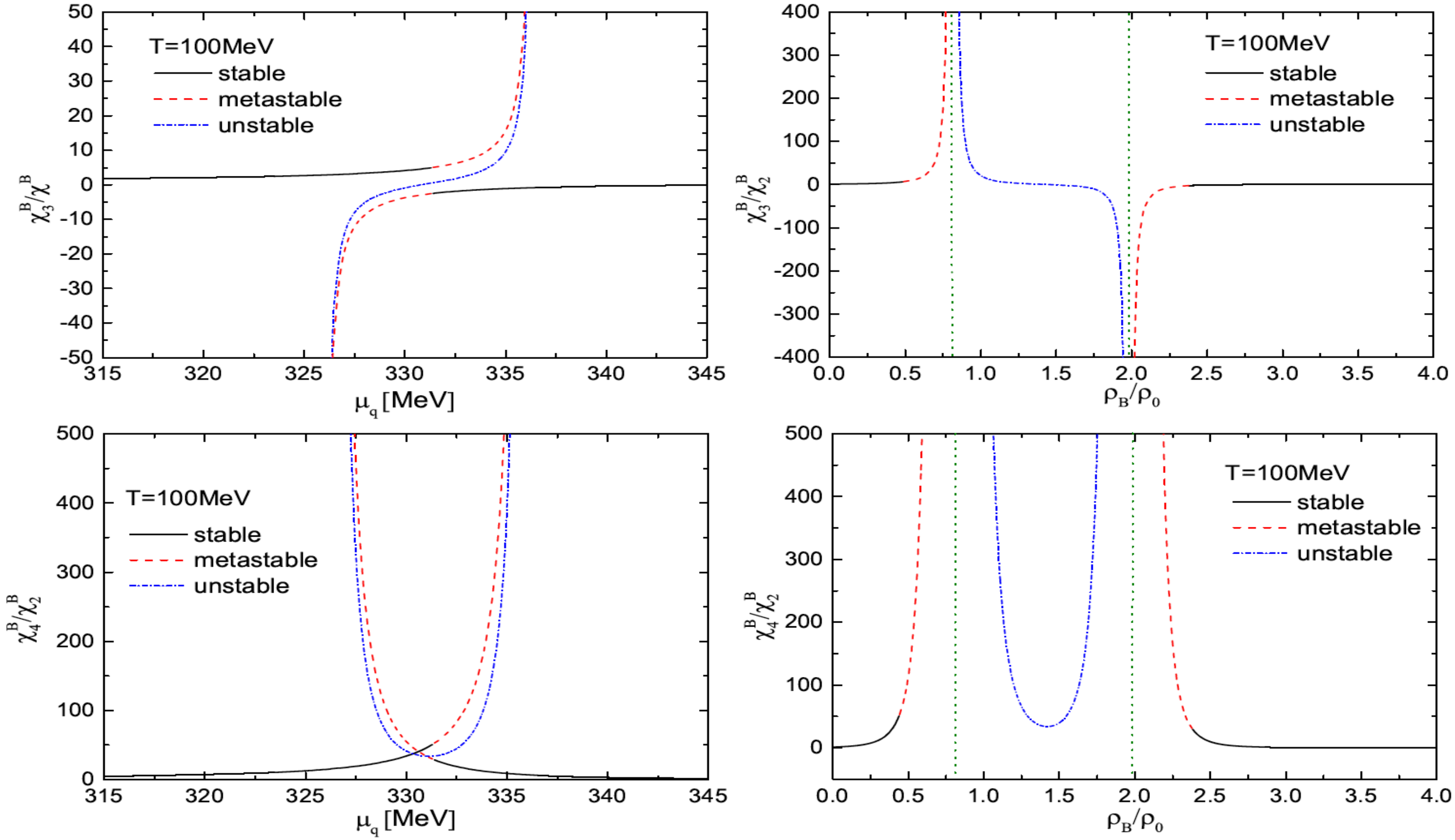
- **Fluctuations in the metastable and unstable phase?**

- **Final signals in observation?**



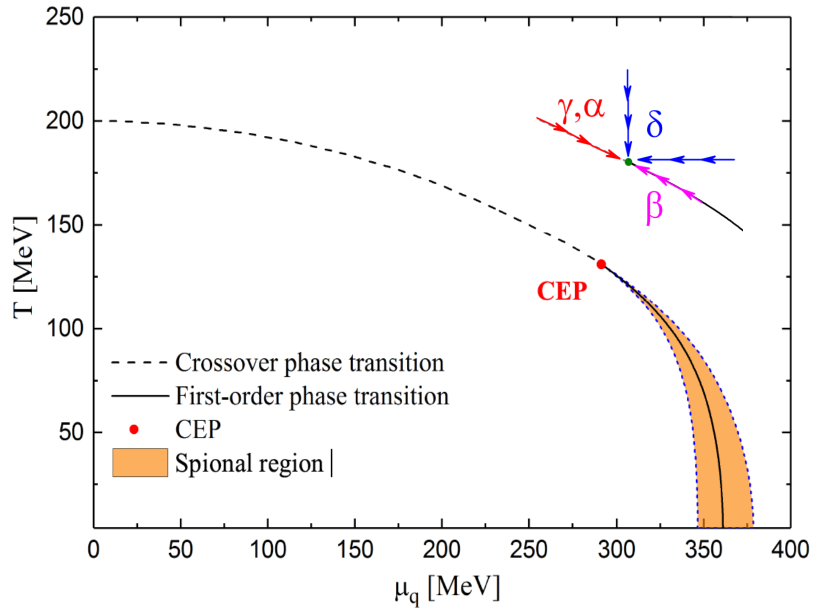
Spinodal structure of the first order transition

Skewness and kurtosis



Critical exponents at the CEP and spinodal line at mean field level

Critical exponents at the CEP



- Four standard thermodynamical critical exponents

$$C_\rho \sim |T - T_c|^{-\alpha} \quad \chi_2 \sim (T - T_c)^{-\gamma}$$

$$\Delta\rho \sim (T_c - T)^{\beta} \quad \rho - \rho_c \sim (\mu - \mu_c)^{\frac{1}{\delta}}$$

- We also calcualte

$$\chi_2 \sim |\mu - \mu_c|^{-\nu} \quad S\sigma \sim |\mu - \mu_c|^{-\zeta}$$

$$\kappa\sigma^2 \sim |\mu - \mu_c|^{-\eta}$$

α	β	γ	δ	ν	ζ	η
0.02	0.50	1.03	3.02	0.70	1.03	2.08

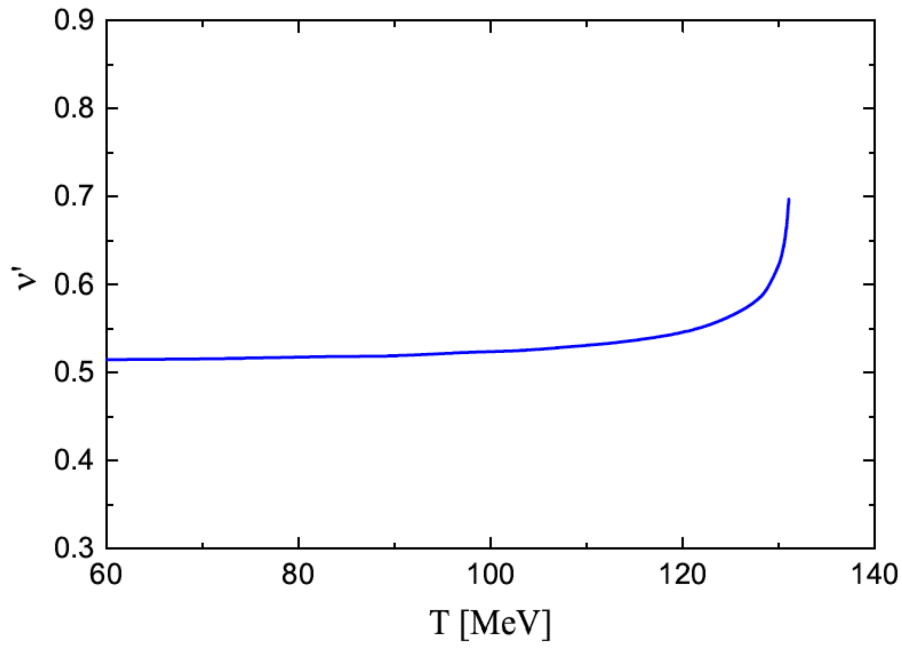
- $\alpha, \beta, \gamma, \delta$ are consistent with the Landau-Ginzburg theory in the mean field
- $\zeta \simeq 1 < \eta \simeq 2$, kutosis is more sensitive than skewness

Critical exponents along the spinodal line

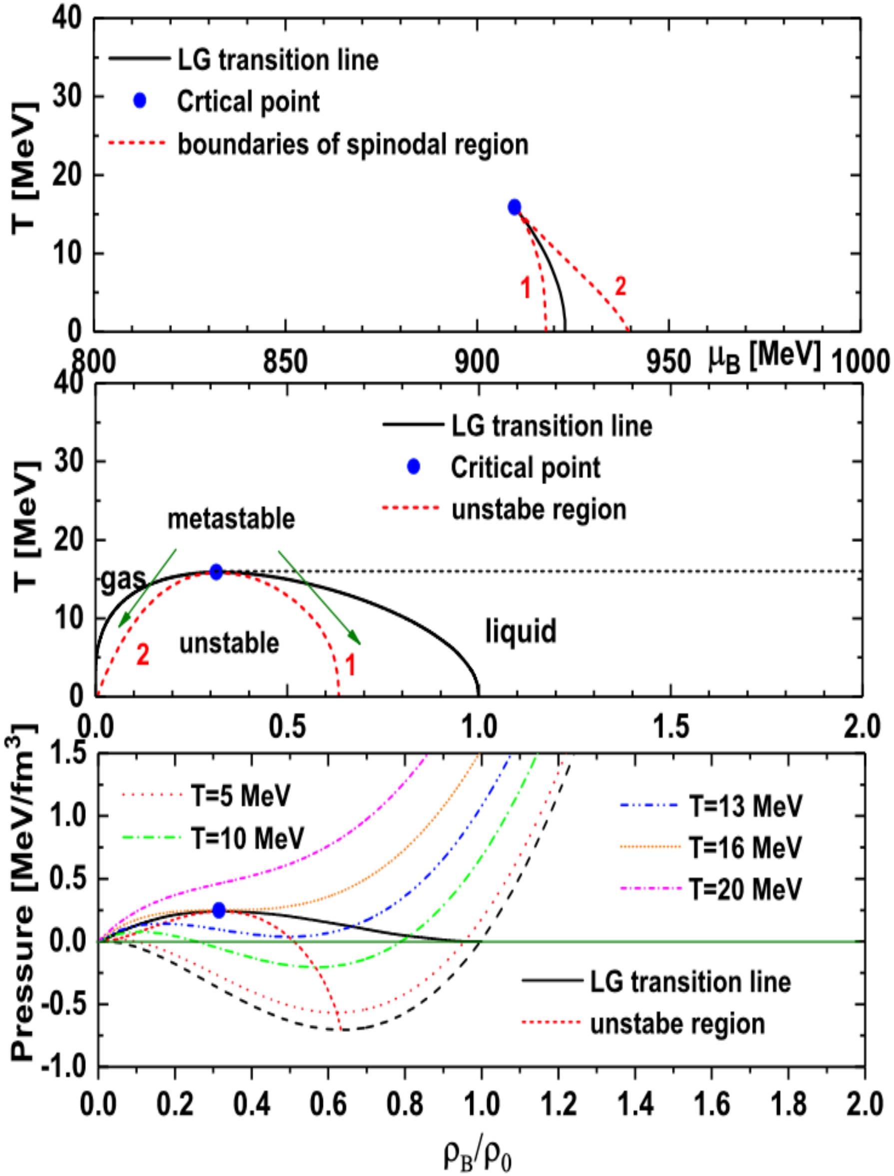
$$\chi_2 \sim |\mu - \mu_0|^{-\nu'} \qquad S\sigma \sim |\mu - \mu_0|^{-\zeta'} \qquad \kappa\sigma^2 \sim |\mu - \mu_0|^{-\eta'}$$

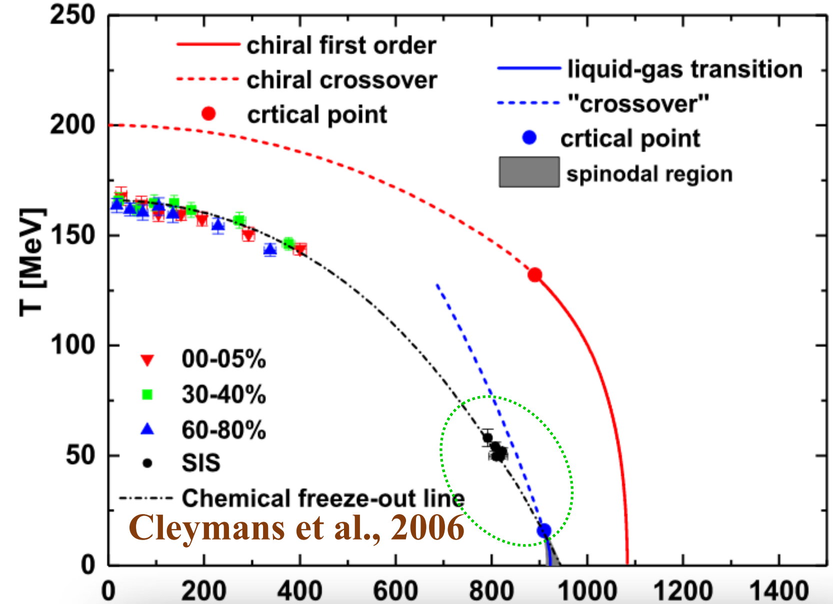
- $\zeta' = 1.02 \pm 0.02$ and $\eta' = 2.08 \pm 0.02$, keeping constants along the spinodal line
- The same divergence as at CEP

- $\nu' = 0.52 \pm 0.01$ for $T < 110\,\mathrm{MeV}$. A rapid increase only occurs near the critical region, and $\nu' = 0.7$ at the CEP.



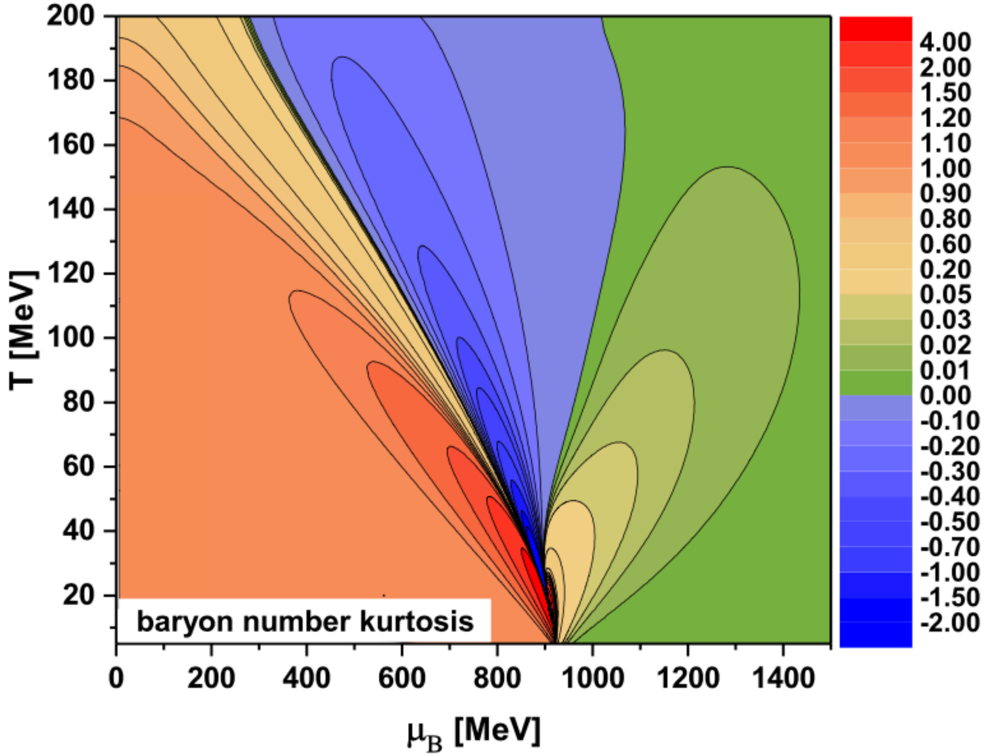
■ Nuclear liquid-gas transition and beyond

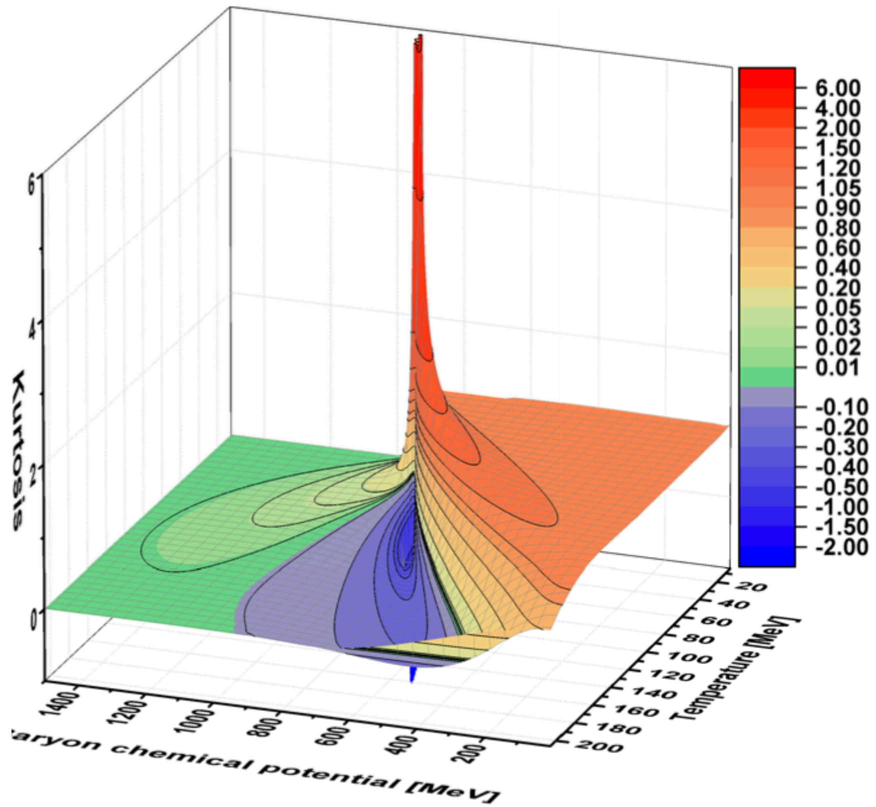




Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721
5.0	2.5	1.6	0.82	774

net-baryon number kurtosis

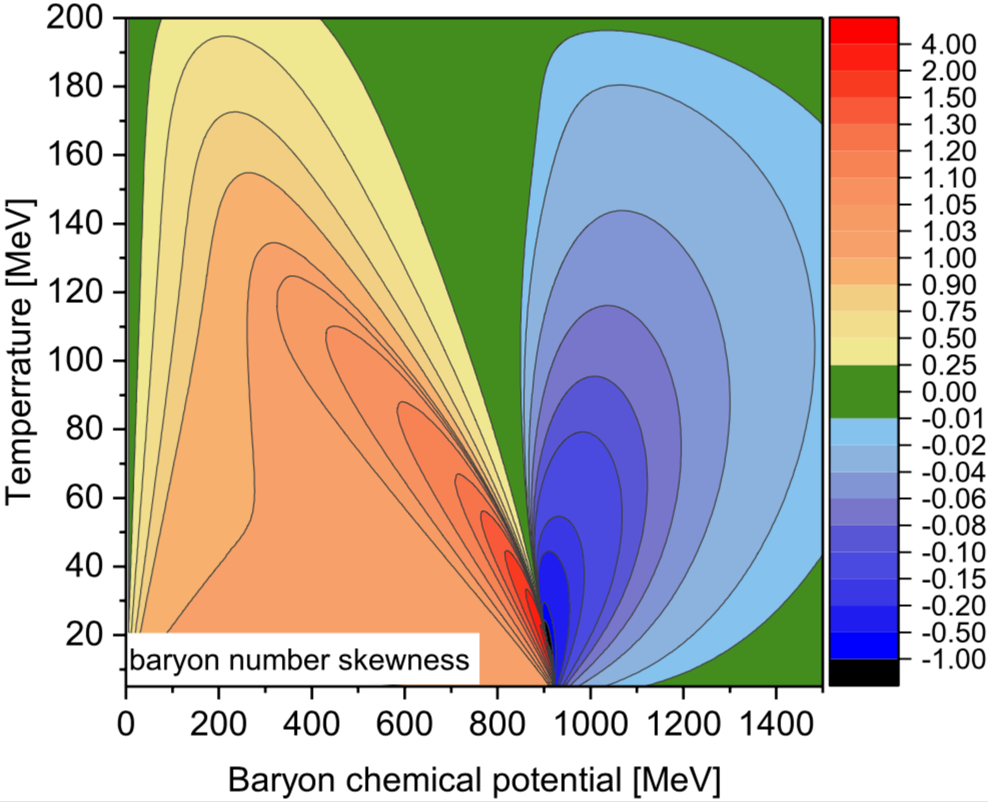


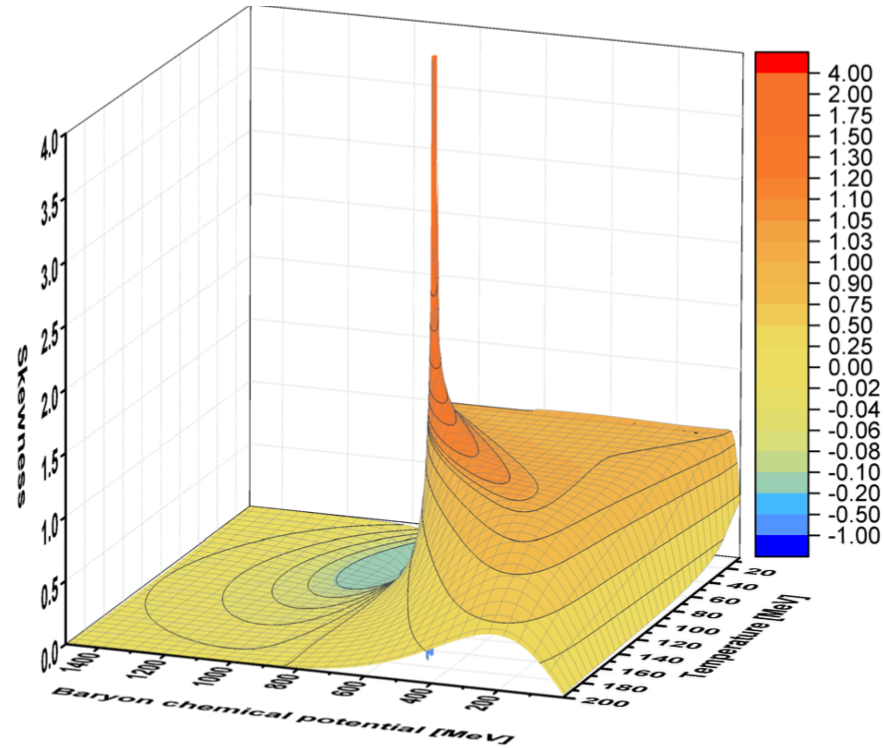


- Negative in the blue area
- Positive in the rest region
- Diverges at the CEP

- Similar structure to the chiral first-order transition
- But at much lower density

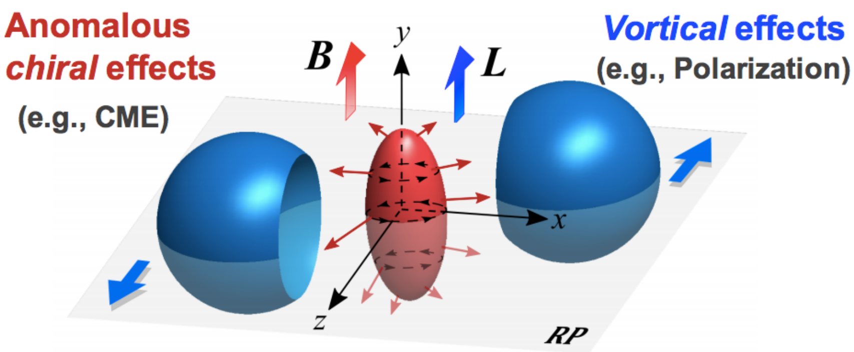
◻ net-baryon number skewness

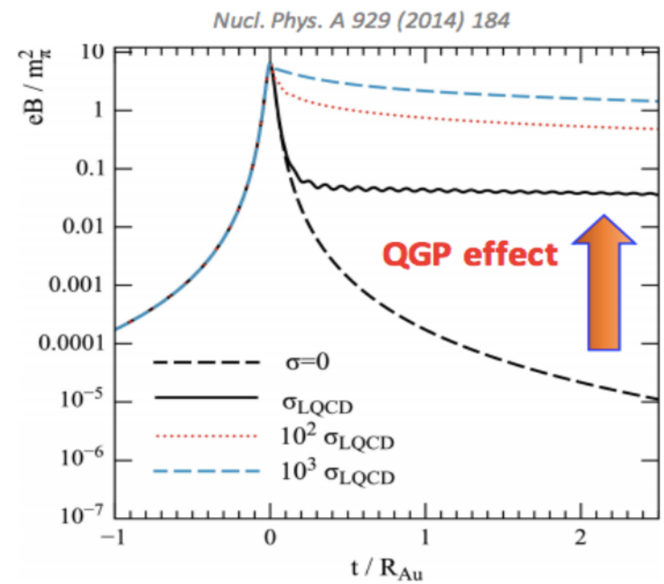




III. Magnetized quark matter:

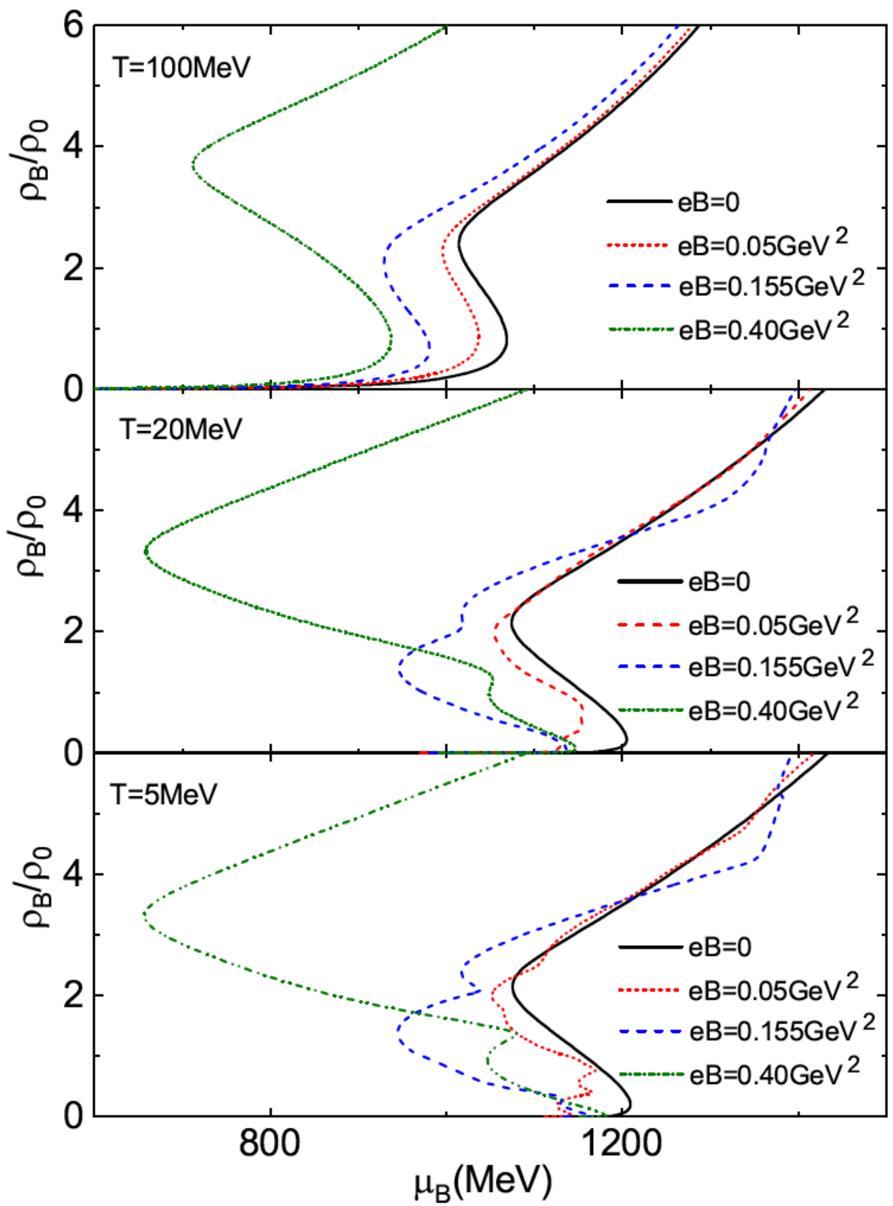
Deformed QCD phase structure in the presence of a magnetic field





- Chiral magnetic effect
- Chiral separation effect
- Electrical conductivity of the QGP medium
- ……
- (Inverse) Magnetic catalysis of chiral condensate
- ✓ Deformation of the phase structure with a magnetic field?

First-order phase transition with a magnetic field



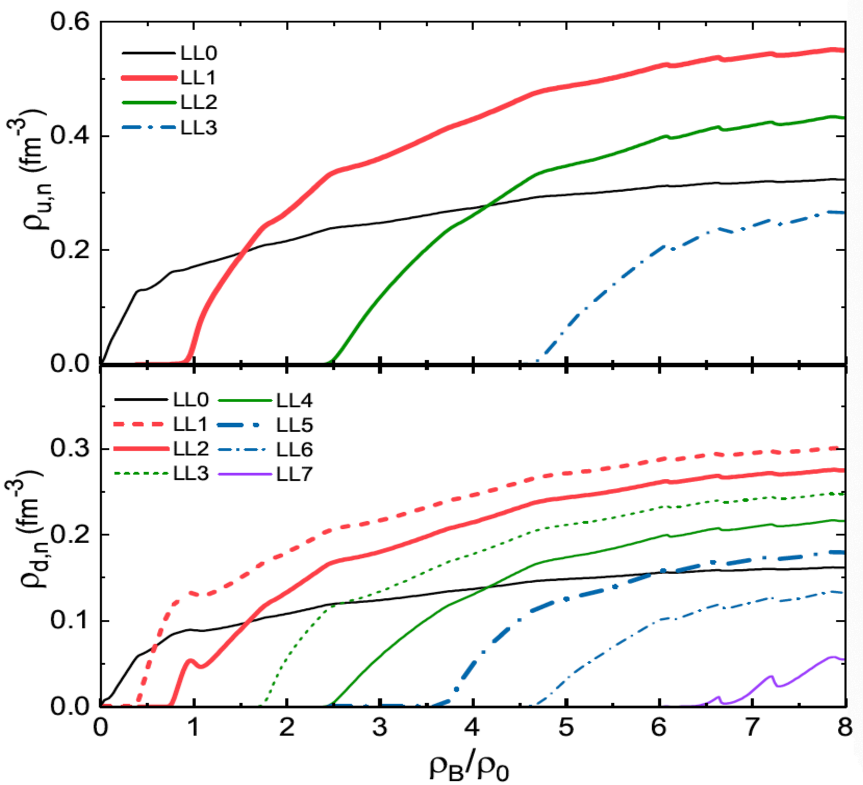
G.Y. SHAO et al, PRD 100, 104020 (2019)

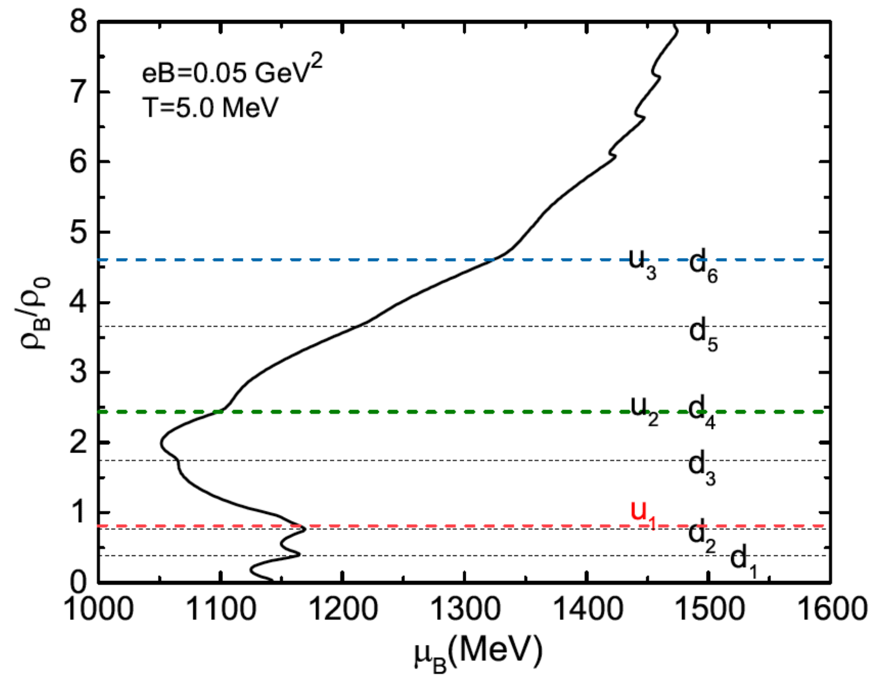
- First order-phase transition at different temperatures
  - Becoming complicated with the decrease of temperature
  - In particular, zigzag behavior for some magnetic field strength possibly reachable at RHIC

- **Why the zigzag shape?**

Landau quantization

$$E_{f,n} = (2n|q_f|B + p_z^2 + M_f^2)^{1/2}$$

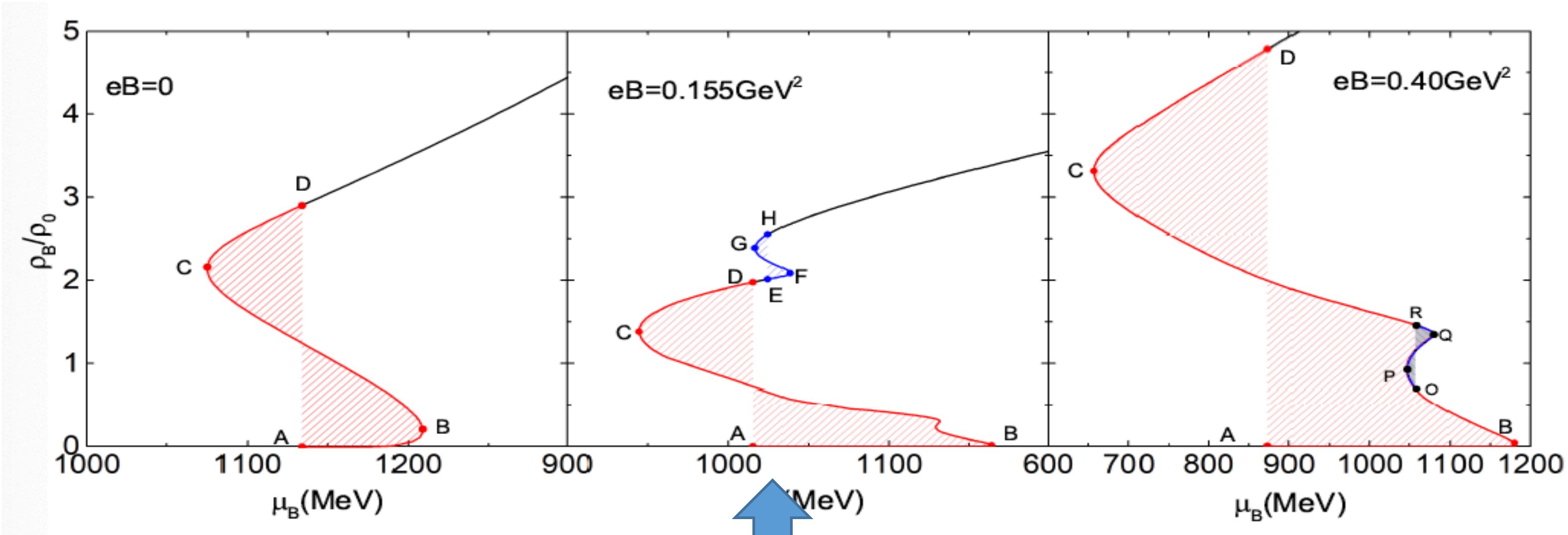




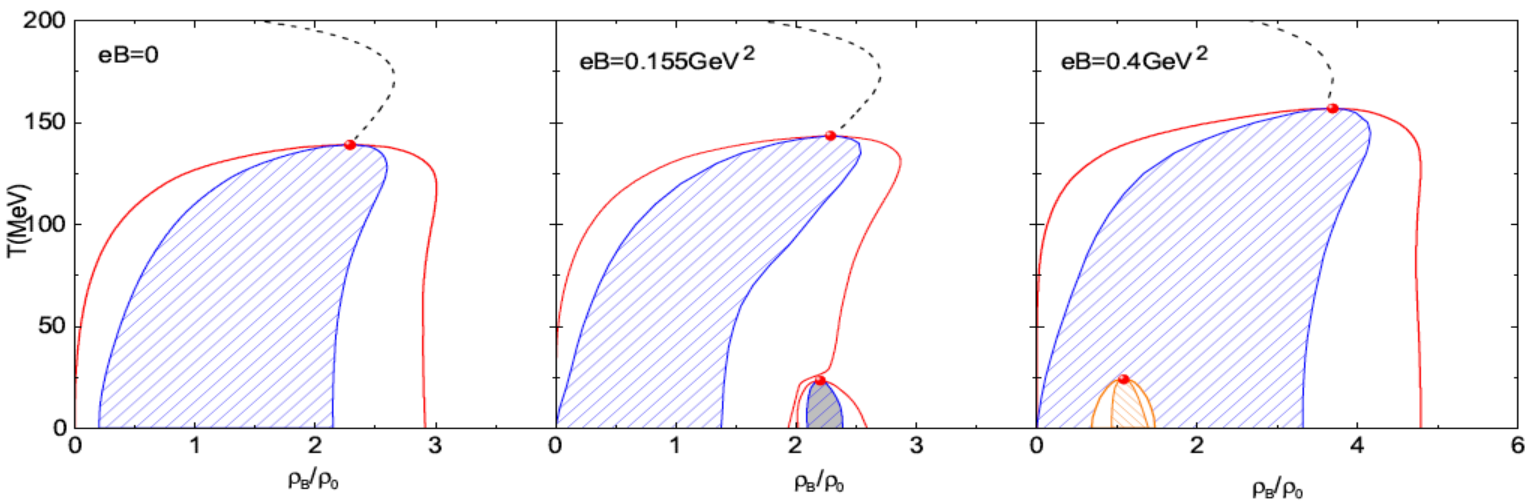
- Contribution from different Landau levels
- More Landau levels of *d* quark being filled than *u* quark due to different electric charges

- A twist appearing when quarks occupy a new Landau level
- More Landau levels being filled for smaller *eB*, responsible for the complicated phase structure

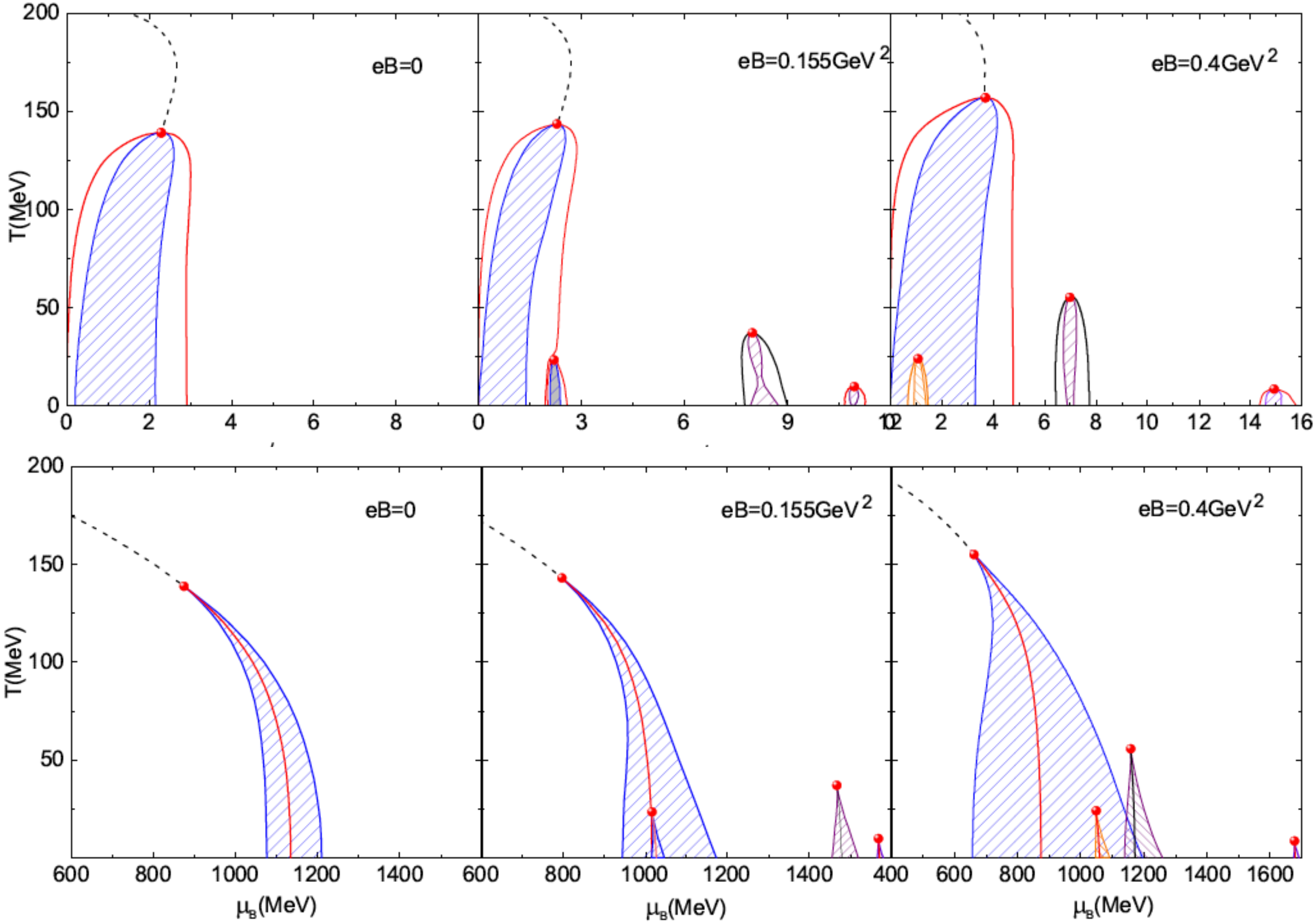
◻ Phase transition under different magnetic fields (T=5MeV)



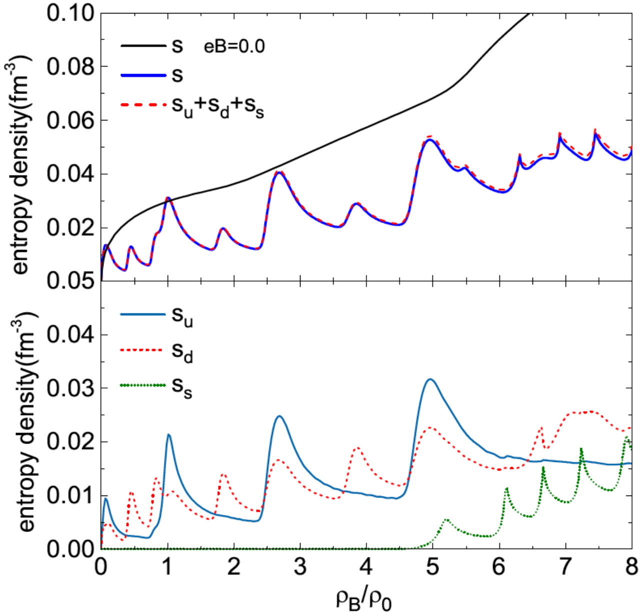
two first-order transitions

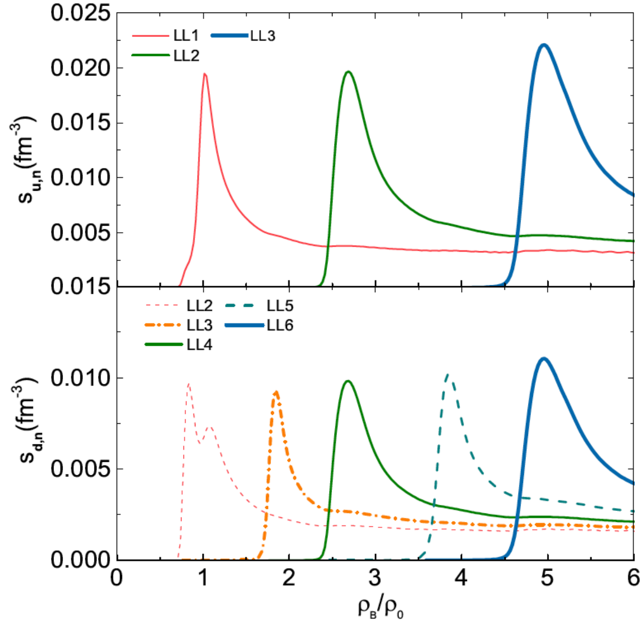


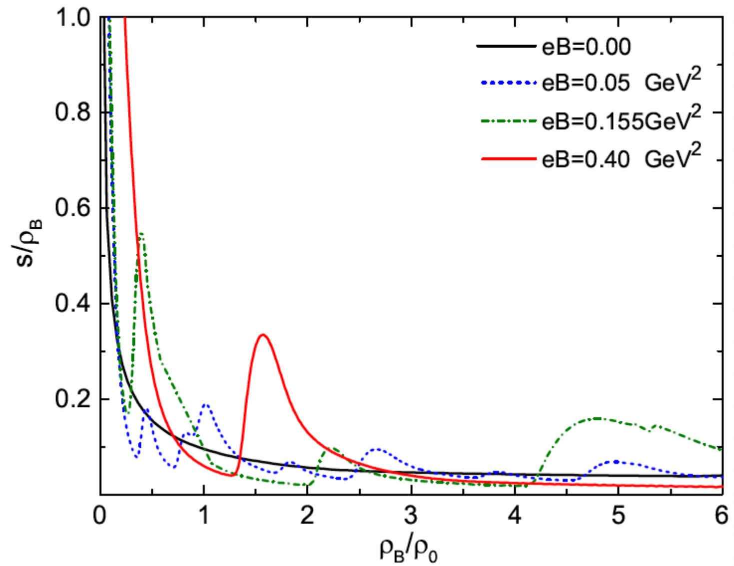
Deformed phase diagram under different magnetic fields



Entropy oscillation







IV. Summary

- ✧ Net-baryon number fluctuations can be used to explore the QCD phase structure
- ✧ In the first-order transition region, fluctuations from the metastable and unstable region possibly affect the final statistical distributions. More simulations are needed to predict the signals of the first-order transition and the energy dependence.
- ✧ The contribution from nuclear LG transition at low temperature may be important with lower collision energies
- ✧ The magnetic field will deform the phase structure and the corresponding particle fluctuation distributions in the non-central collision
- ✧ More investigations are needed to connect theory with future HIC experiments

Thank you!