QCD phase structure and inhomogeneous instabilities at finite temperature and densities

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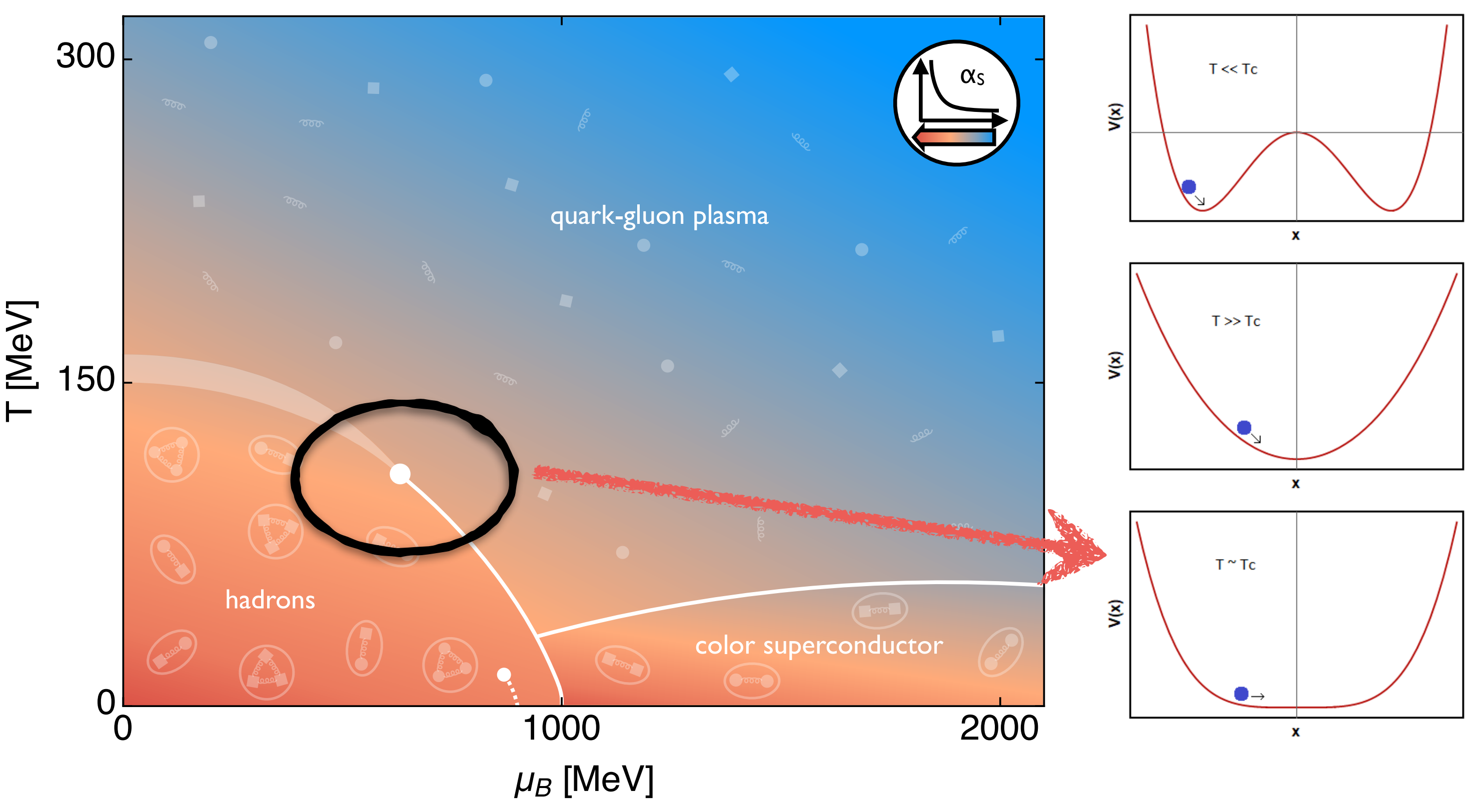
Critical end point and fluctuations

QCD phase diagram



However, former analysis showed

$$\chi_n^B = \xi^{\frac{n}{2}(5-\eta)-3}$$

$\eta \ll 1$

$$\chi_2^B \sim \xi^2, \qquad \chi_3^B \sim \xi^{4.5}, \qquad \chi_4^B \sim \xi^7$$
$$\chi_5^B \sim \xi^{9.5}, \qquad \chi_6^B \sim \xi^{12}$$

Stephanov, *PRL* 102 (2009) 032301

Scaling analysis of fluctuations

Baryon number fluctuations of the n-th order:

$$\chi_n^B = \frac{\partial^n}{\partial(\mu_B/T)^n}\frac{p}{T^4}$$

pressure

$$p \sim \xi^{-d}$$

when $\mu_B \to \mu_{B_c}$

$$\mu_B \sim \xi^{-1/\nu}$$

which leads us to

$$\chi_n^B \sim \xi^{\frac{n}{\nu}-d} \quad (\mu_B \neq 0)$$

For $d = 3$ and the $O(4)$ symmetry

$$\nu = 0.75$$

one has

$$\chi_2^B \sim \xi^{-0.33}, \qquad \chi_3^B \sim \xi^{1.00}, \qquad \chi_4^B \sim \xi^{2.33}$$
$$\chi_5^B \sim \xi^{3.67}, \qquad \chi_6^B \sim \xi^{5.00}$$

For the $Z(2)$ symmetry

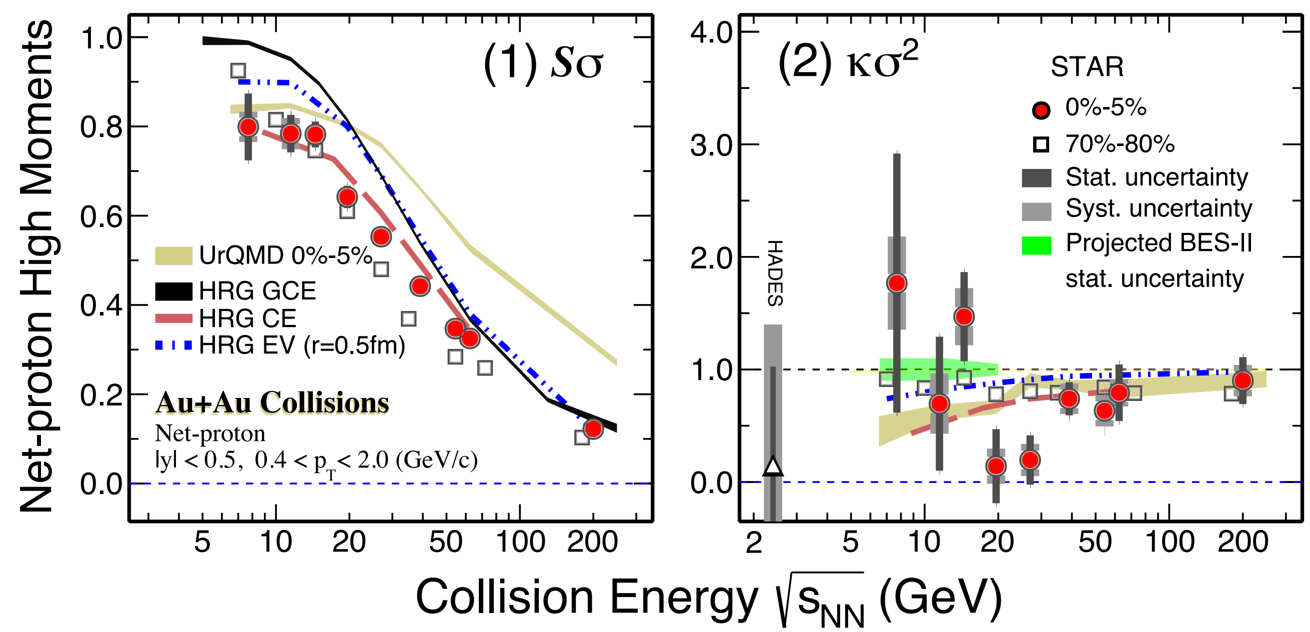
$$\nu = 0.63$$

then one has

$$\chi_2^B \sim \xi^{0.17}, \qquad \chi_3^B \sim \xi^{1.76}, \qquad \chi_4^B \sim \xi^{3.35}$$
$$\chi_5^B \sim \xi^{4.93}, \qquad \chi_6^B \sim \xi^{6.52}$$

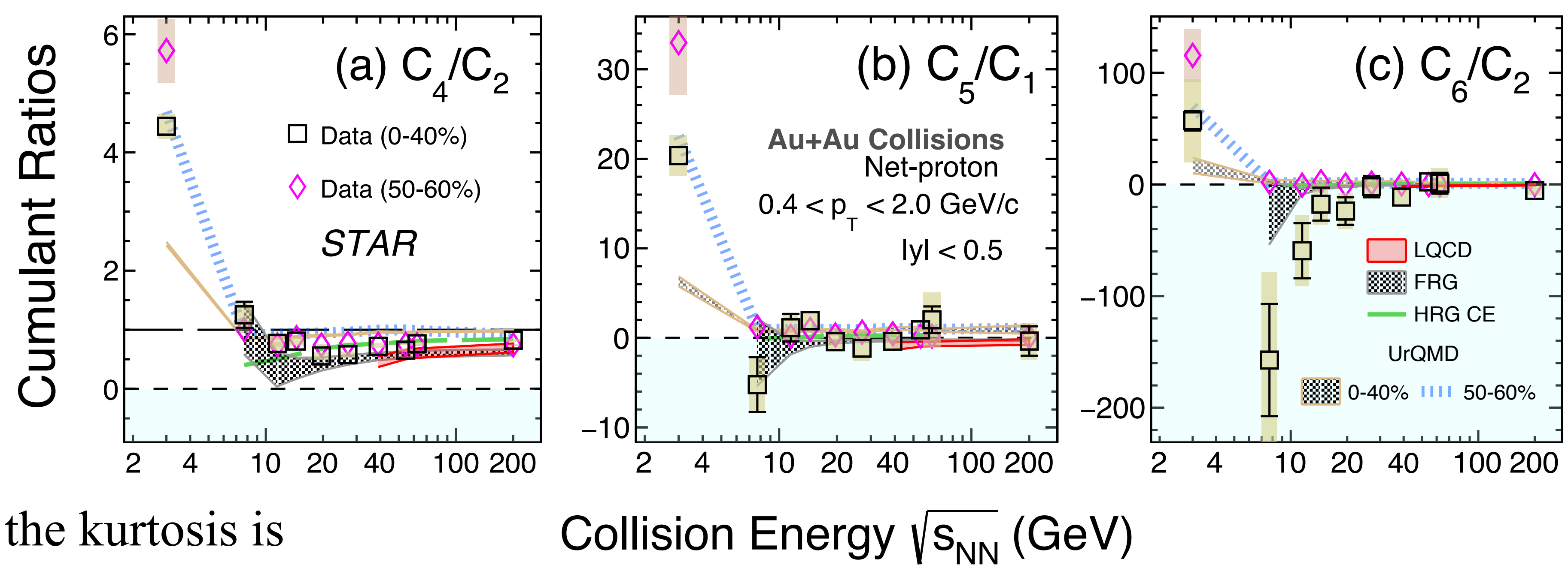
Fluctuation measurements at RHIC

Skewness and kurtosis of net-proton distributions



J. Adam *et al.* (STAR), *PRL* 126 (2021) 092301

Hyper-order net-proton fluctuations at RHIC



- The non-monotonicity of the kurtosis is observed with 3.1σ significance.
- Hyper-order fluctuations are increasingly negative.
- Is CEP not far away?

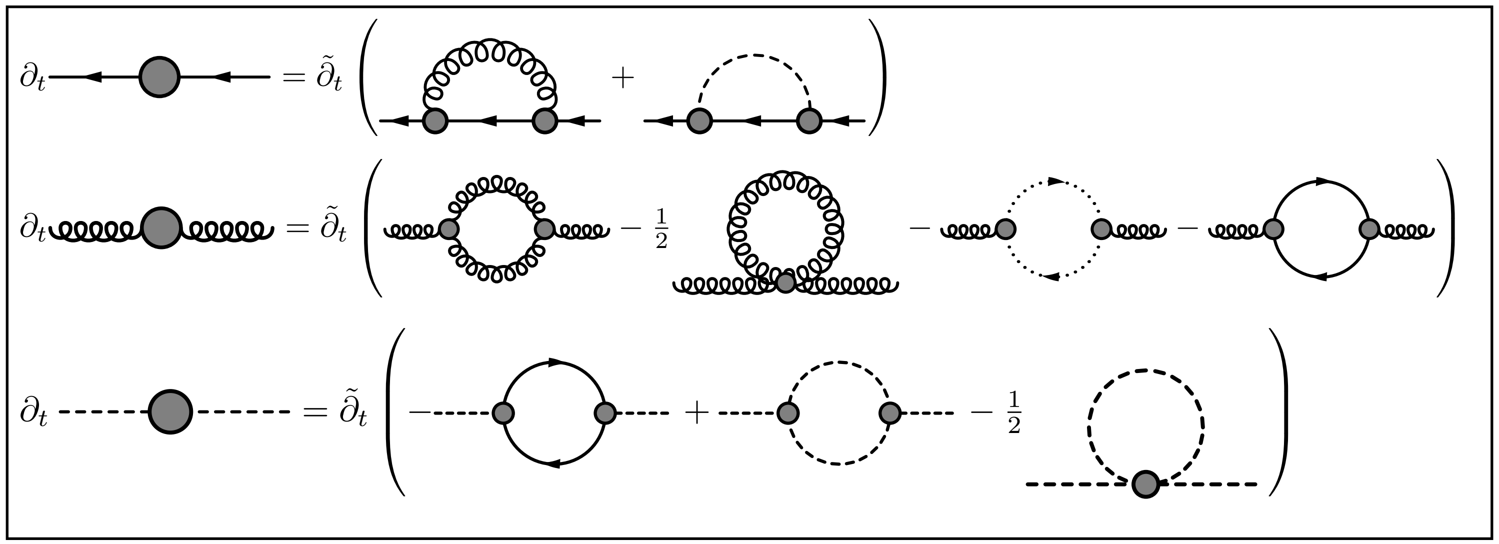
STAR: The STAR Collaboration, arXiv:2207.09837
LQCD: A. Bazavov *et al.*, *PRD* 101 (2020) 074502
fRG: WF, Luo, Pawlowski, Rennecke, Wen, Yin, *PRD* 104 (2021) 094047
HRG CE: P. Braun-Munzinger *et al.*, *NPA* 1008 (2021) 122141

Outline

- Introduction
- fRG approach to QCD
- QCD phase structure from fRG
- Inhomogeneous instabilities
- Summary

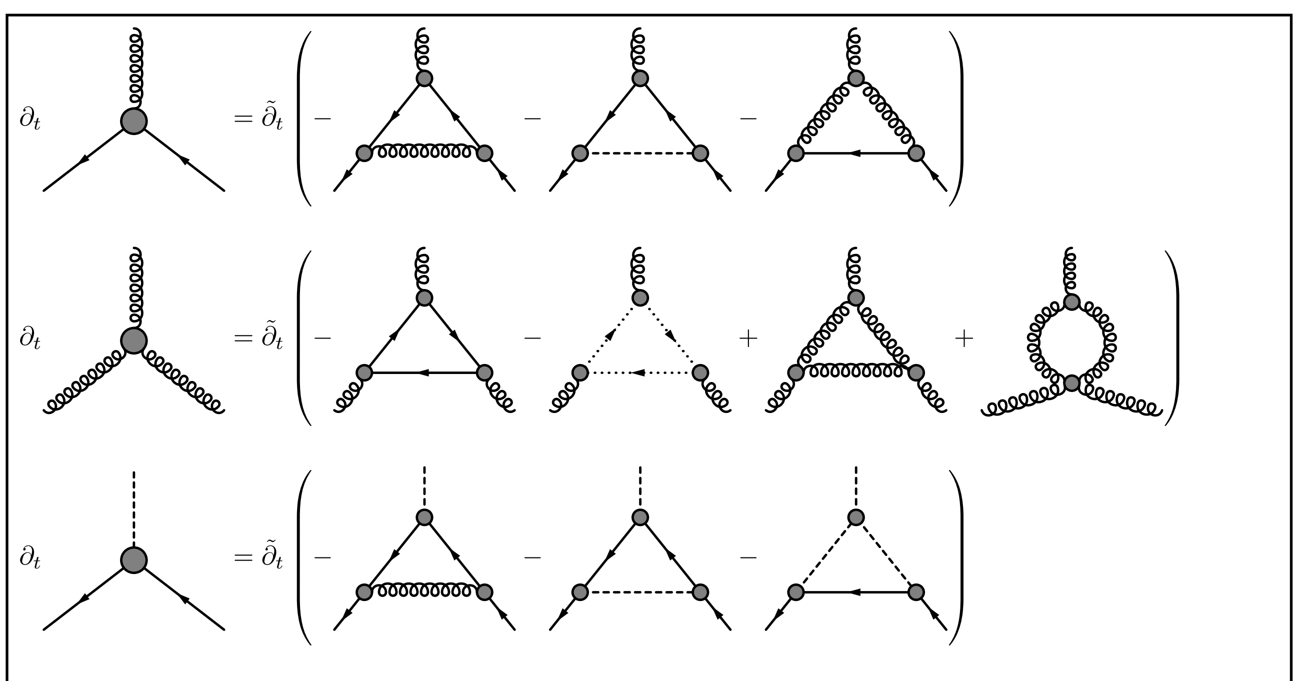
Functional renormalization group to QCD

Propagators:

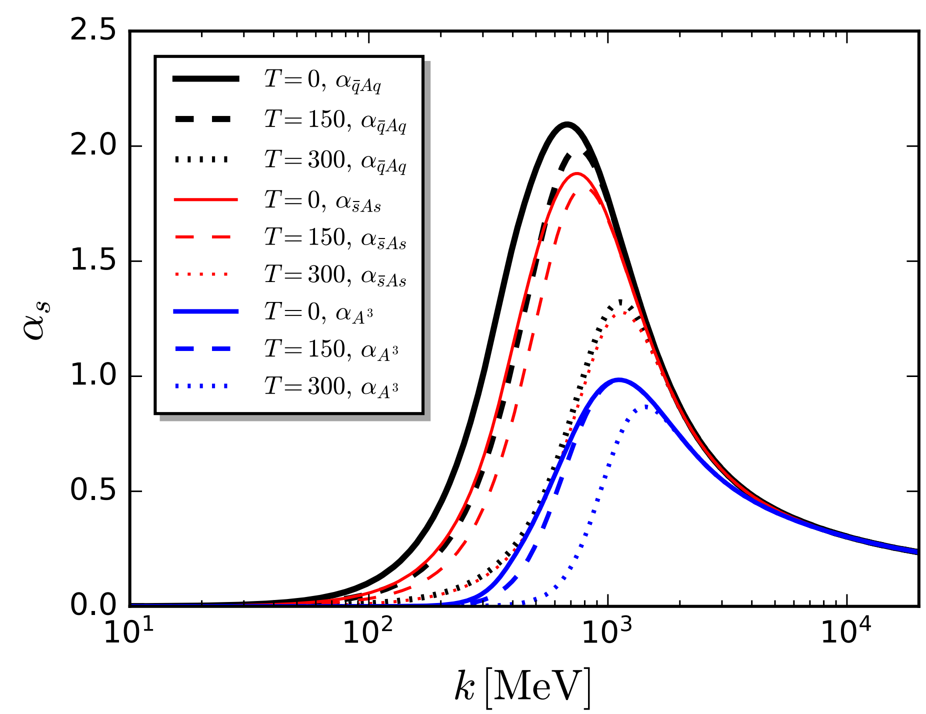


- Vertex expansion: apparent convergence.
- Expansion around $N_f = 2$ gluon propagator in vacuum QCD.
- Effective mesonic potential of $N_f = 2$, improved to the full potential of $N_f = 2+1$ recently.

Three-point functions:

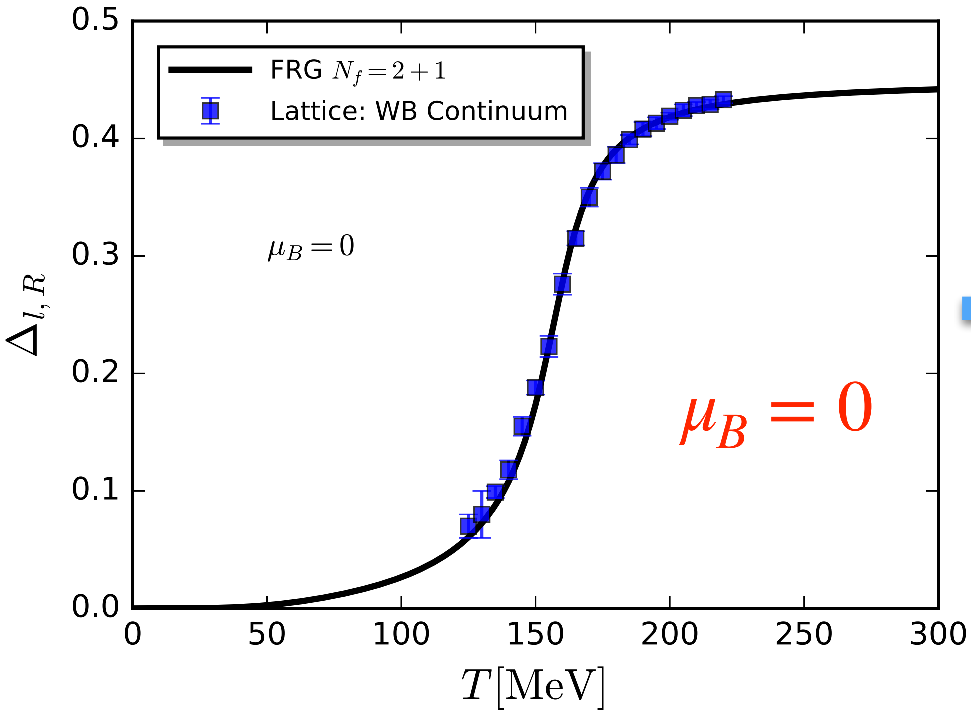


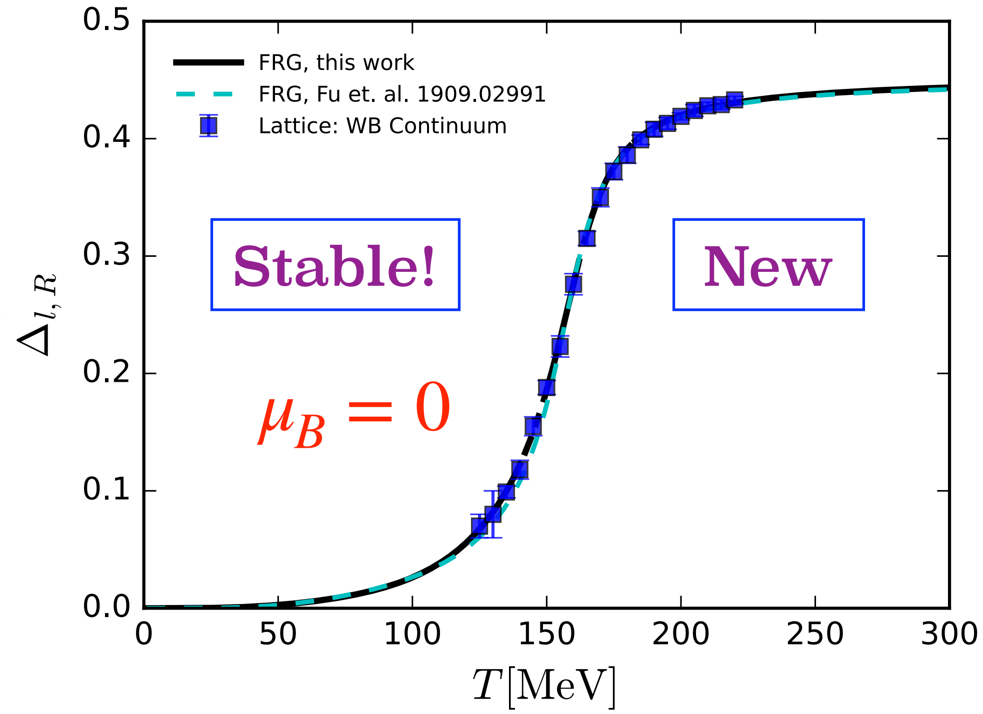
Strong couplings:



WF, Pawlowski, Rennecke, *PRD* 101 (2020) 054032

Renormalized light quark condensate



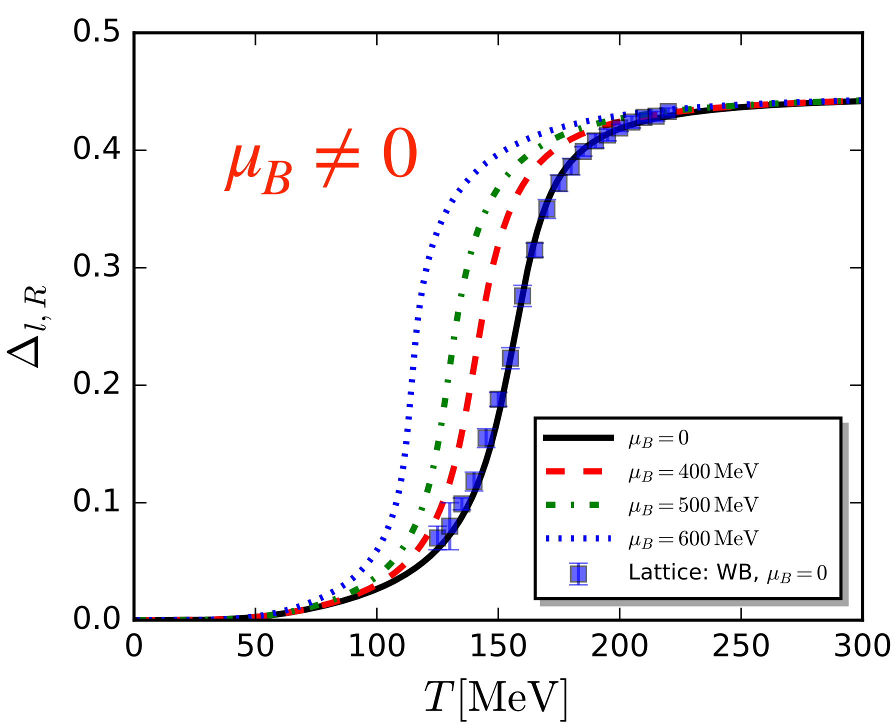


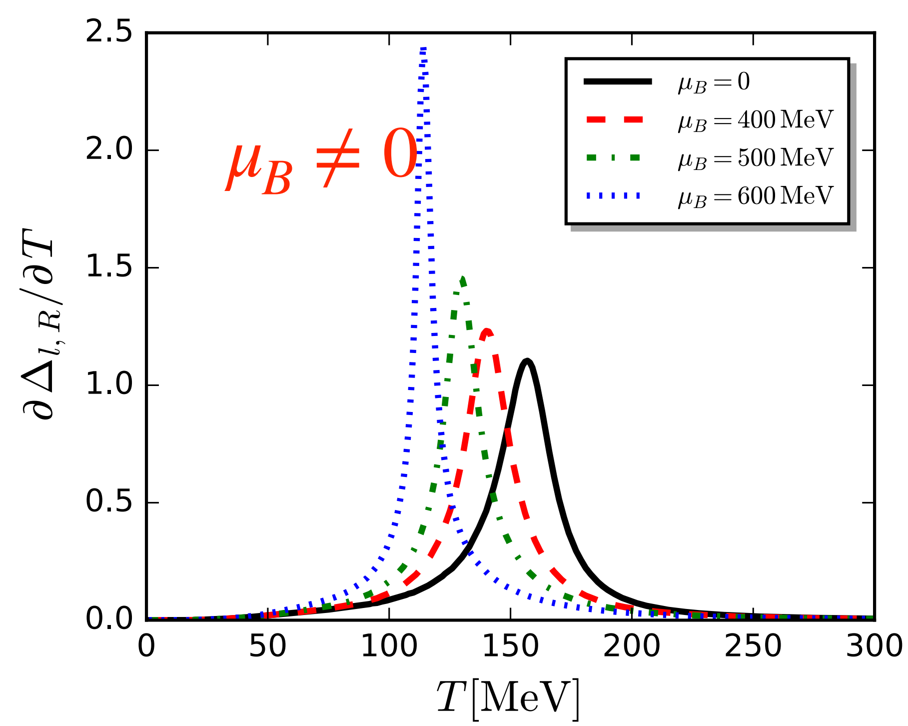
improved truncations for the sector of s quark and the full mesonic potential of N_f = 2+1.

Lattice: Borsanyi *et al.* (WB), *JHEP* 09 (2010) 073

fRG: WF, Pawlowski, Rennecke, *PRD* 101 (2020) 054032

fRG: WF, Pawlowski, Rennecke, Wen, Yin, (2022) in preparation



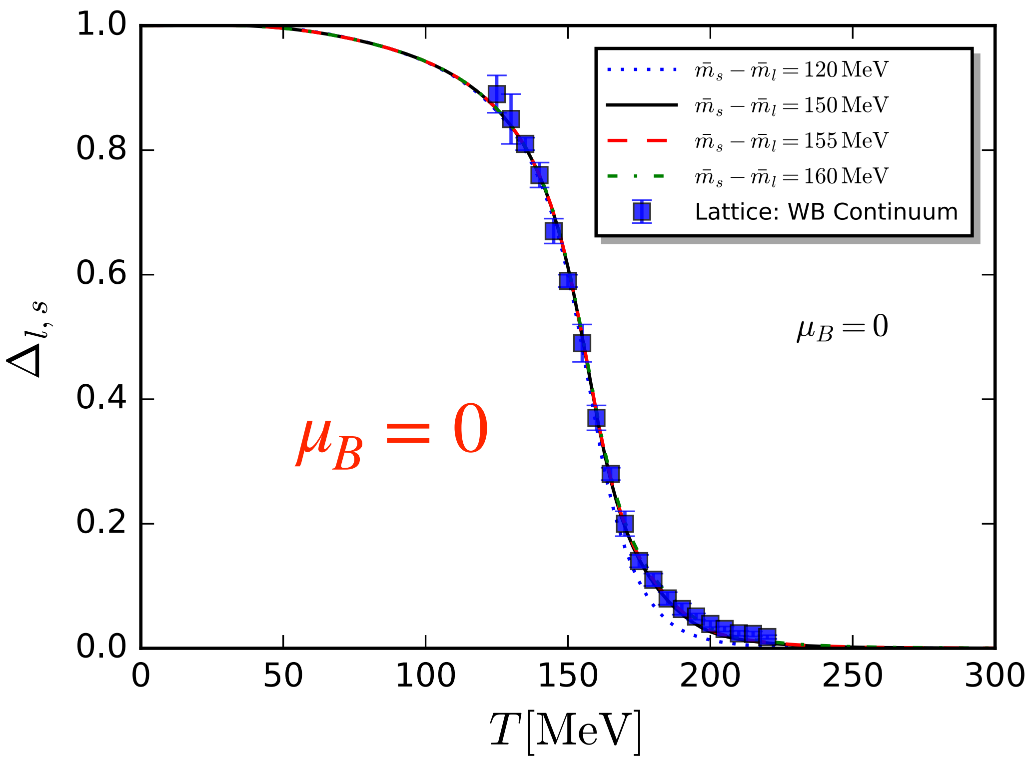


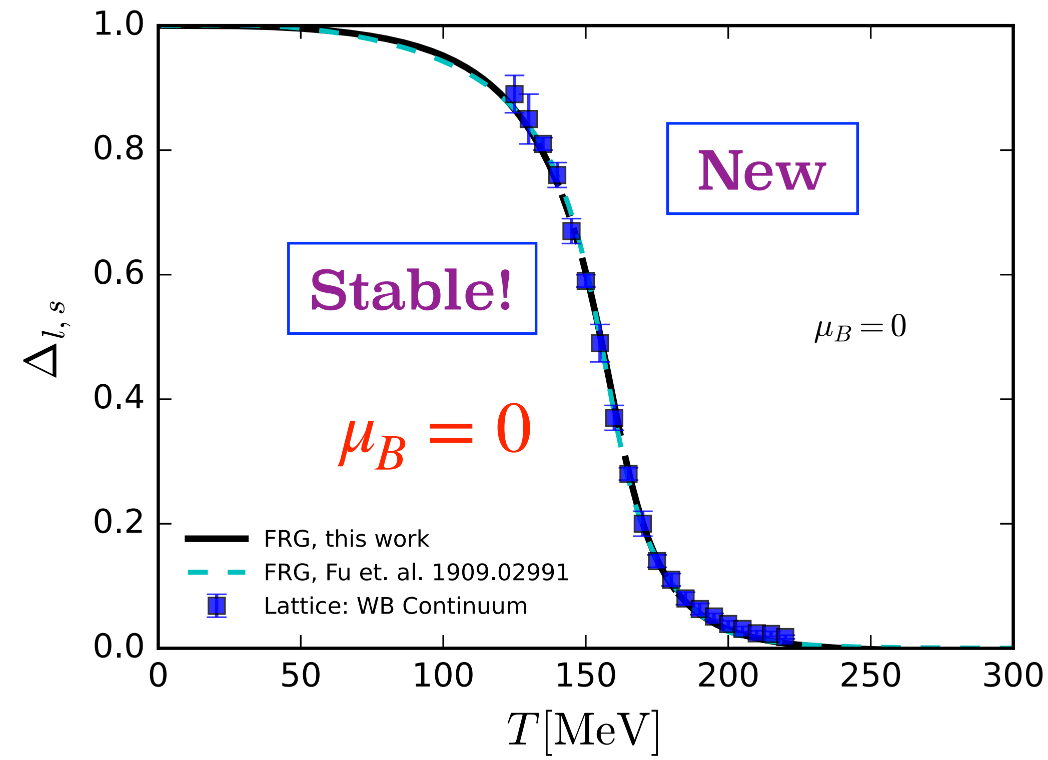
quark condensate:

$$\Delta_{q_i} \simeq -m^0_{q_i} T \sum_{n\in\mathbb{Z}} \int \frac{d^3q}{(2\pi)^3} \mathrm{tr}\, G_{q_i\bar{q}_i}(q)\,,$$

$$\Delta_{q_i,R} = \frac{1}{\mathcal{N}_R}\left[\Delta_{q_i}(T,\mu_q) - \Delta_{q_i}(0,0)\right]\,.$$

Other fermionic observables





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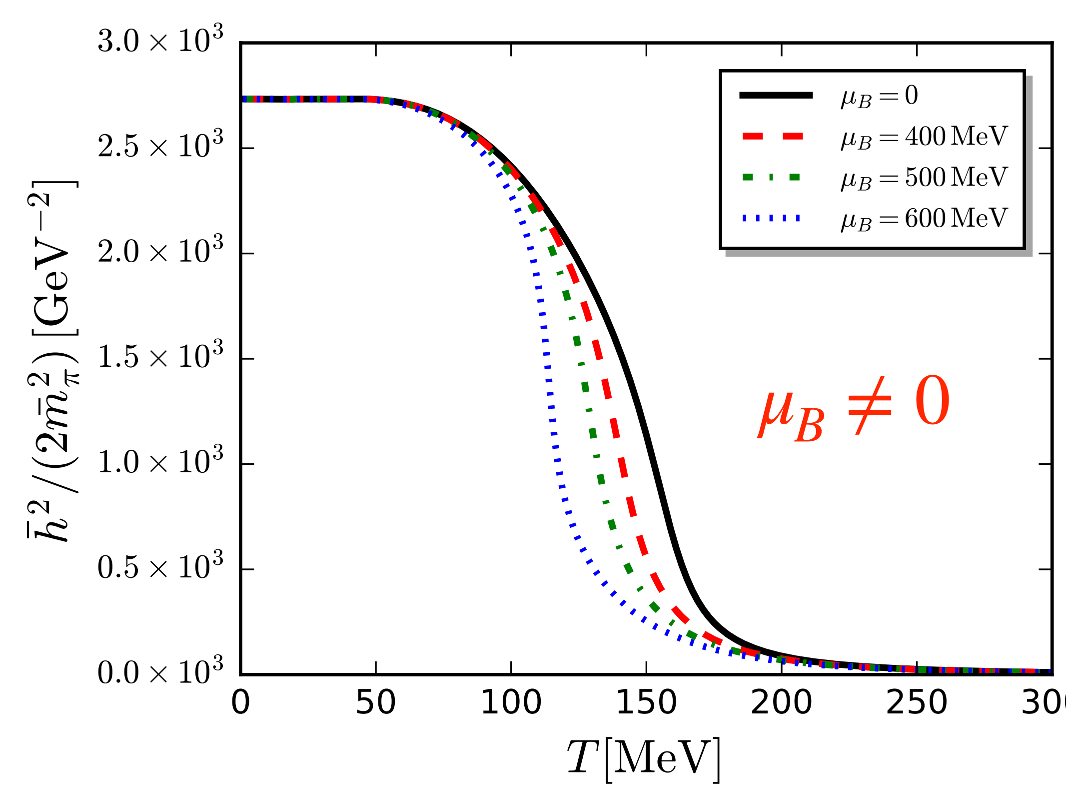
fRG: WF, Pawlowski, Rennecke, *PRD* 101 (2020) 054032

fRG: WF, Pawlowski, Rennecke, Wen, Yin, (2022) in preparation

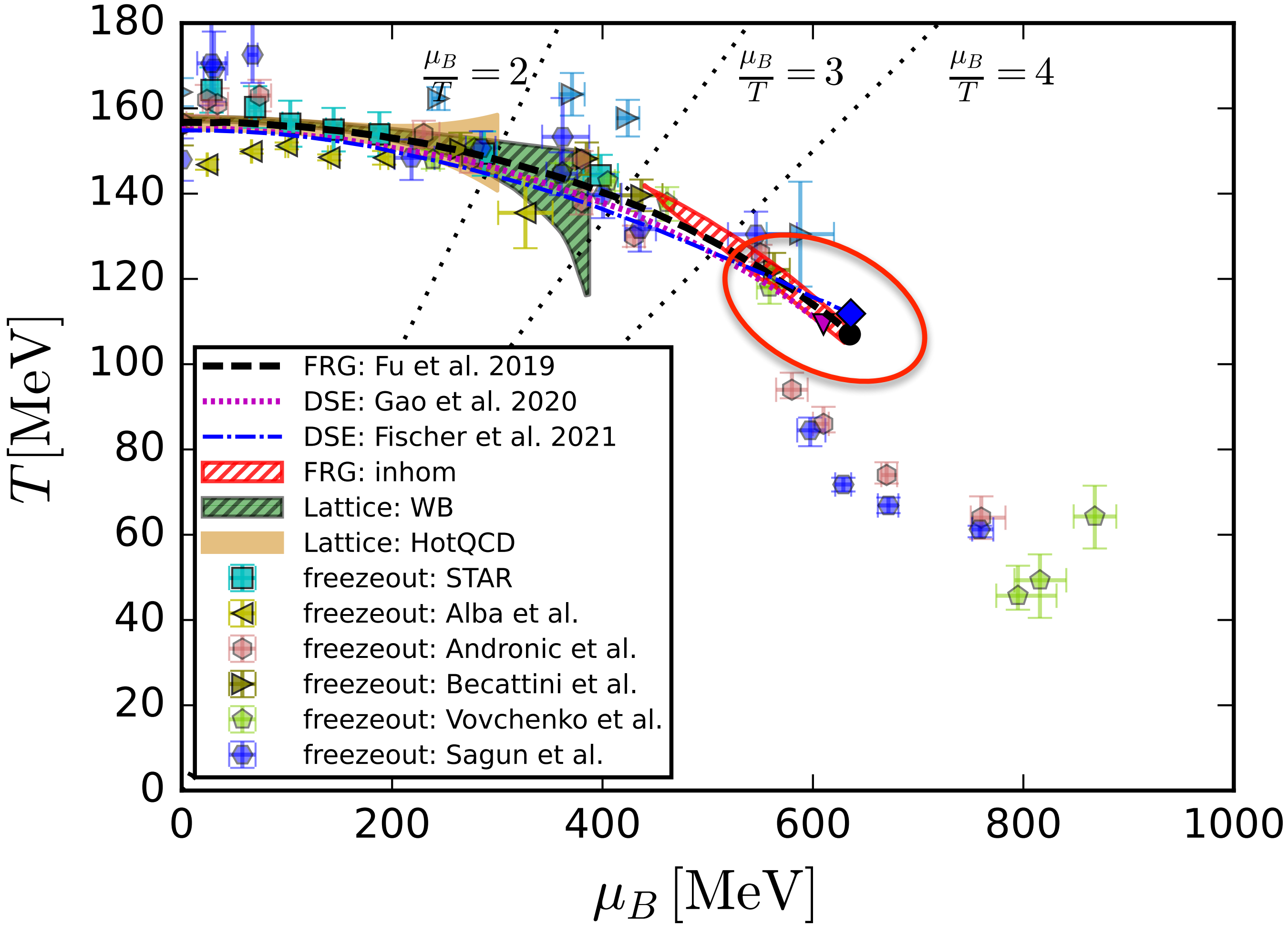
Reduced condensate:

$$\Delta_{l,s}(T,\mu_q) = \frac{\Delta_l(T,\mu_q) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(T,\mu_q)}{\Delta_l(0,0) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(0,0)}$$

Effective four-quark coupling:



CEP from functional QCD



- No CEP observed in $\mu_B/T \lesssim 2 \sim 3$ from lattice QCD. Karsch, *PoS* CORFU2018 (2019)163
- Recent studies of QCD phase structure from both fRG and DSE have shown convergent estimate for the location of CEP.
- Considering relatively larger errors when $\mu_B/T \gtrsim 4$, one arrives at a reasonable estimation : 450 MeV $\lesssim \mu_{B_{\rm CEP}} \lesssim 650$ MeV.

Prediction of location of CEP from functional QCD in literature

fRG:

● $(T,\mu_B)_{\rm CEP} = (107, 635)$**MeV**

fRG: WF, Pawlowski, Rennecke, *PRD* 101 (2020), 054032

DSE:

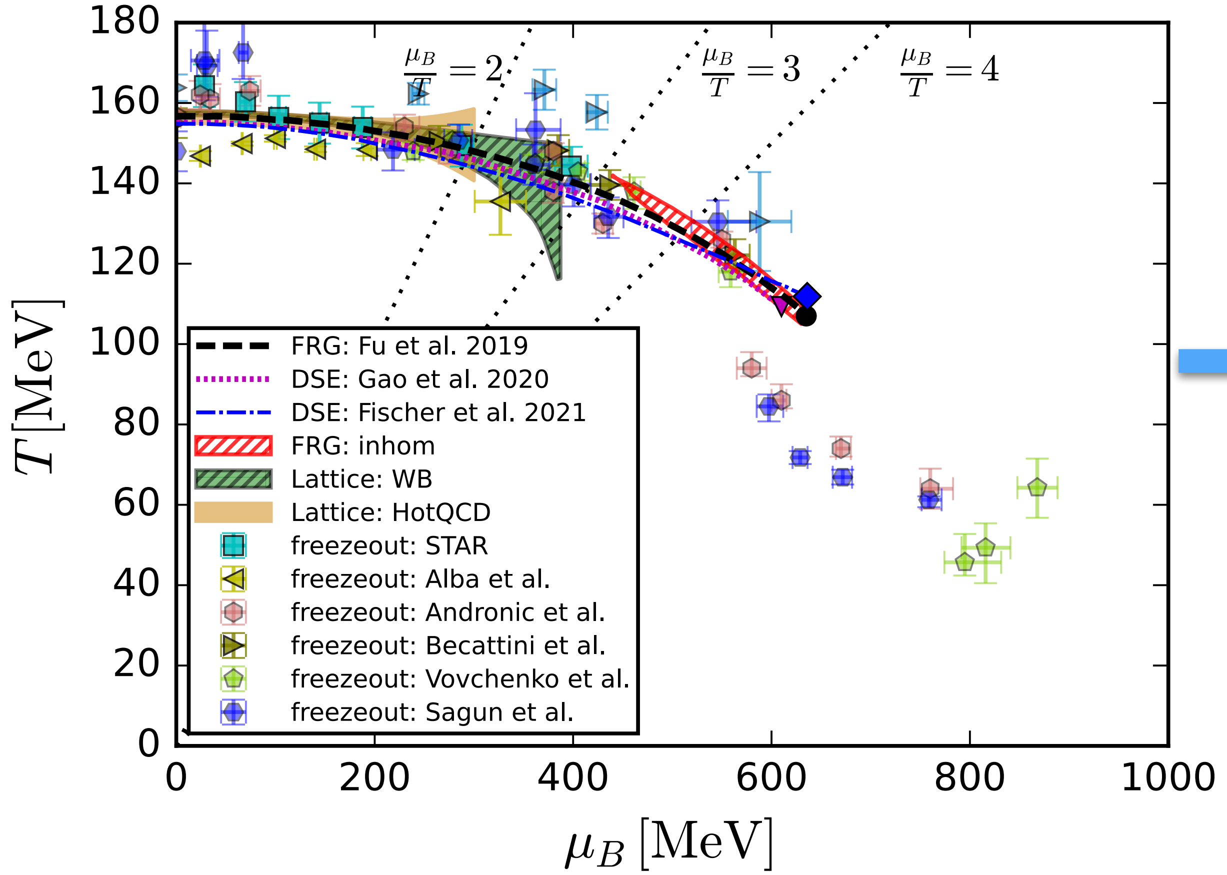
▼ $(T,\mu_B)_{\rm CEP} = (109, 610)$**MeV**

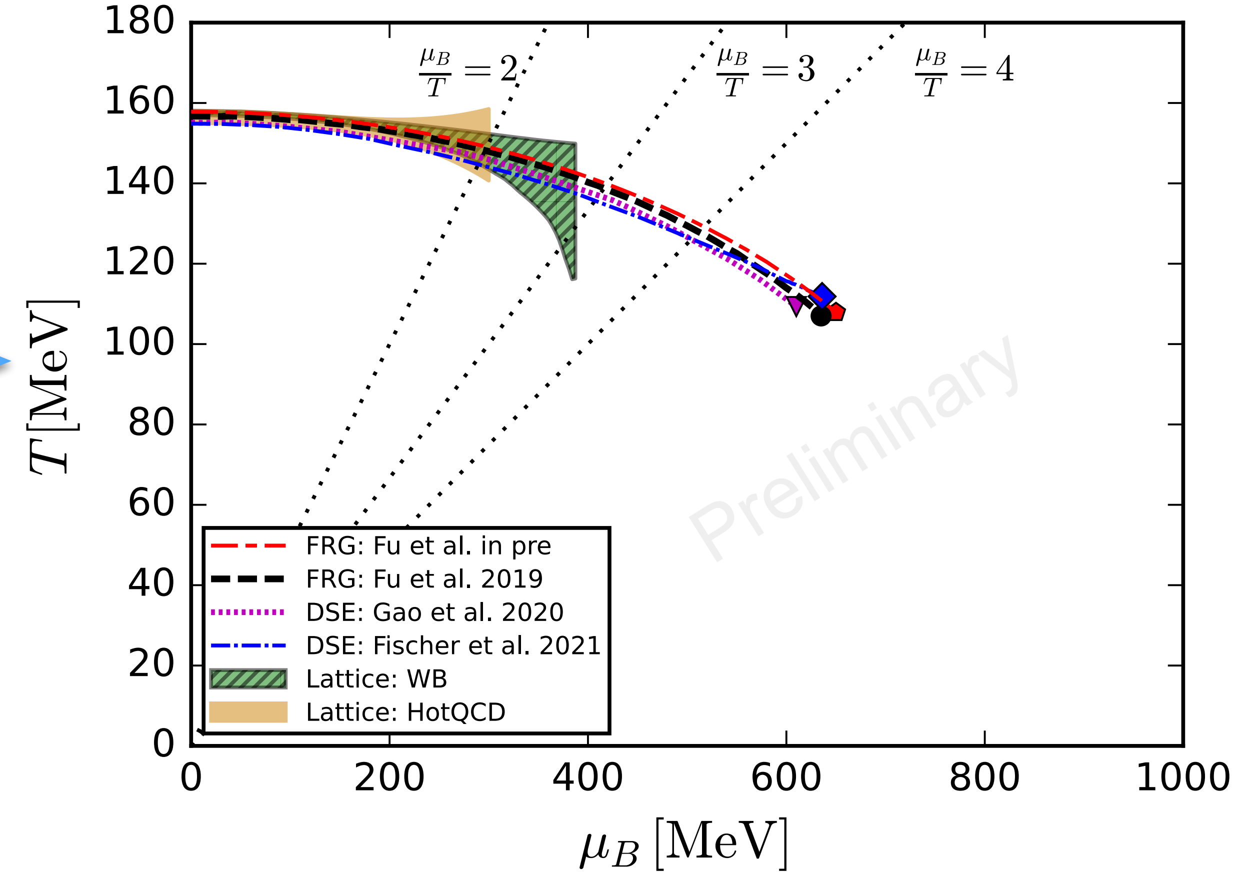
DSE (fRG): Gao, Pawlowski, *PLB* 820 (2021) 136584

◆ $(T,\mu_B)_{\rm CEP} = (112, 636)$**MeV**

DSE: Gunkel, Fischer, *PRD* 104 (2021) 5, 054022

Update: CEP from fRG





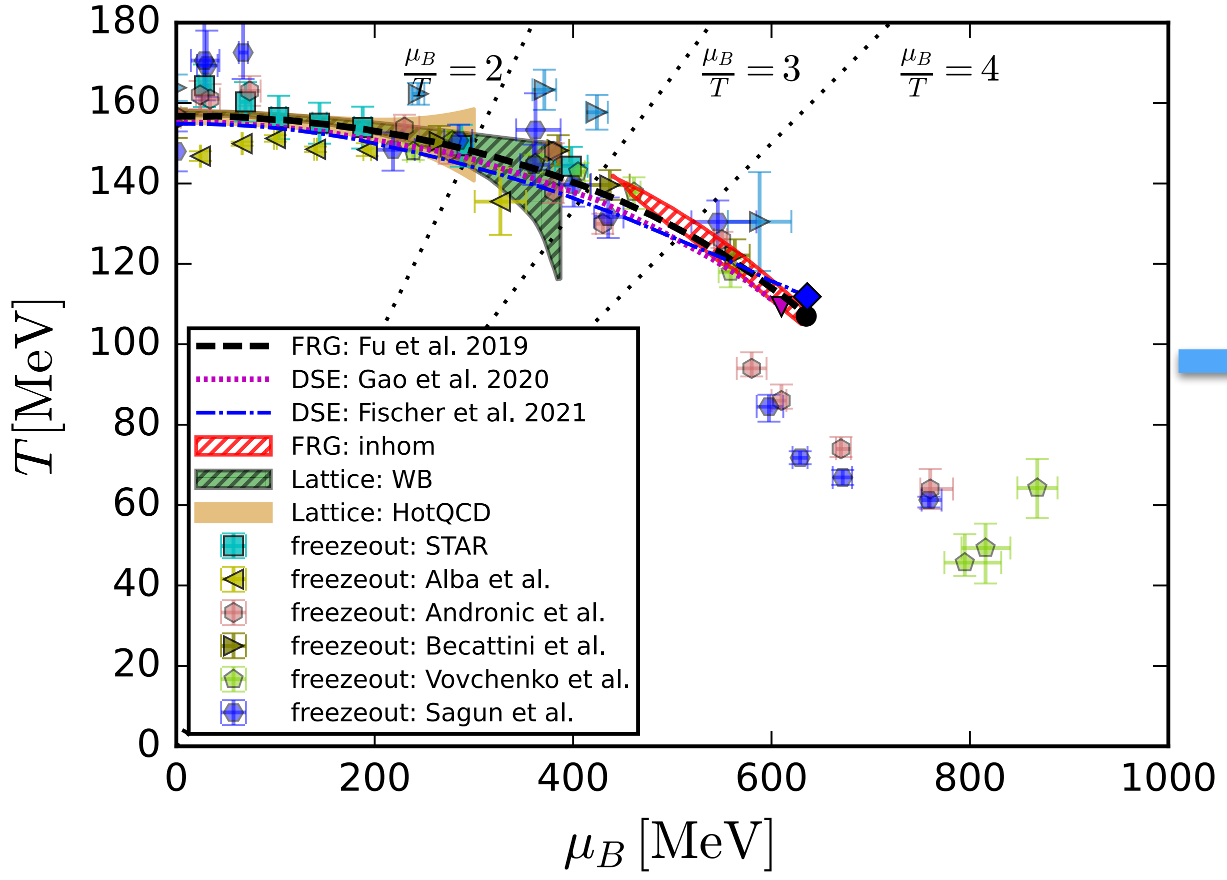
fRG:

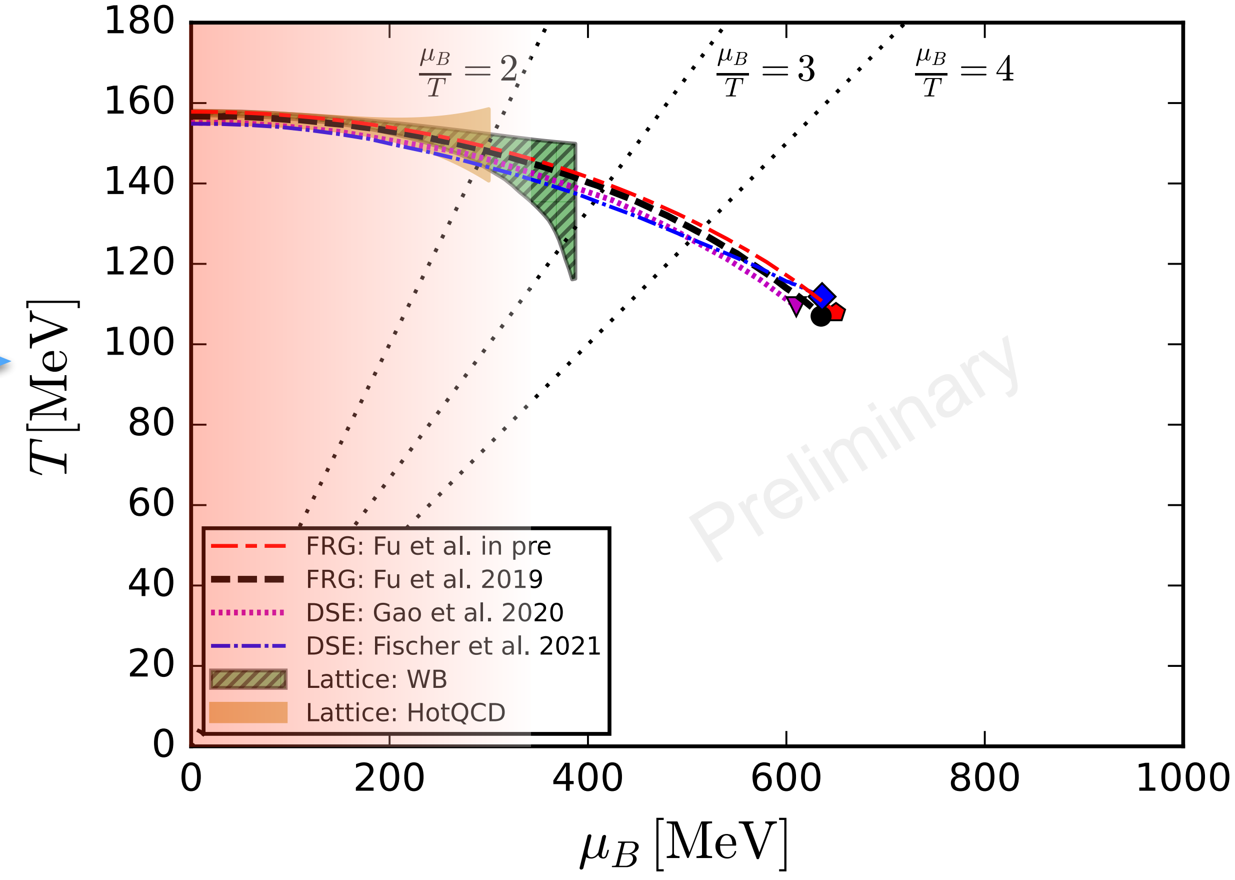
⬠ $(T,\mu_B)_{\mathrm{CEP}} = (108, 650)\,\mathbf{MeV}$

improved truncations for the sector of *s* quark and the full mesonic potential of $N_f = 2+1$.

fRG: WF, Pawlowski, Rennecke, Wen, Yin, (2022) in preparation

Update: CEP from fRG





fRG:

⬟ $(T,\mu_B)_{\mathrm{CEP}} = (108, 650)\,\mathbf{MeV}$

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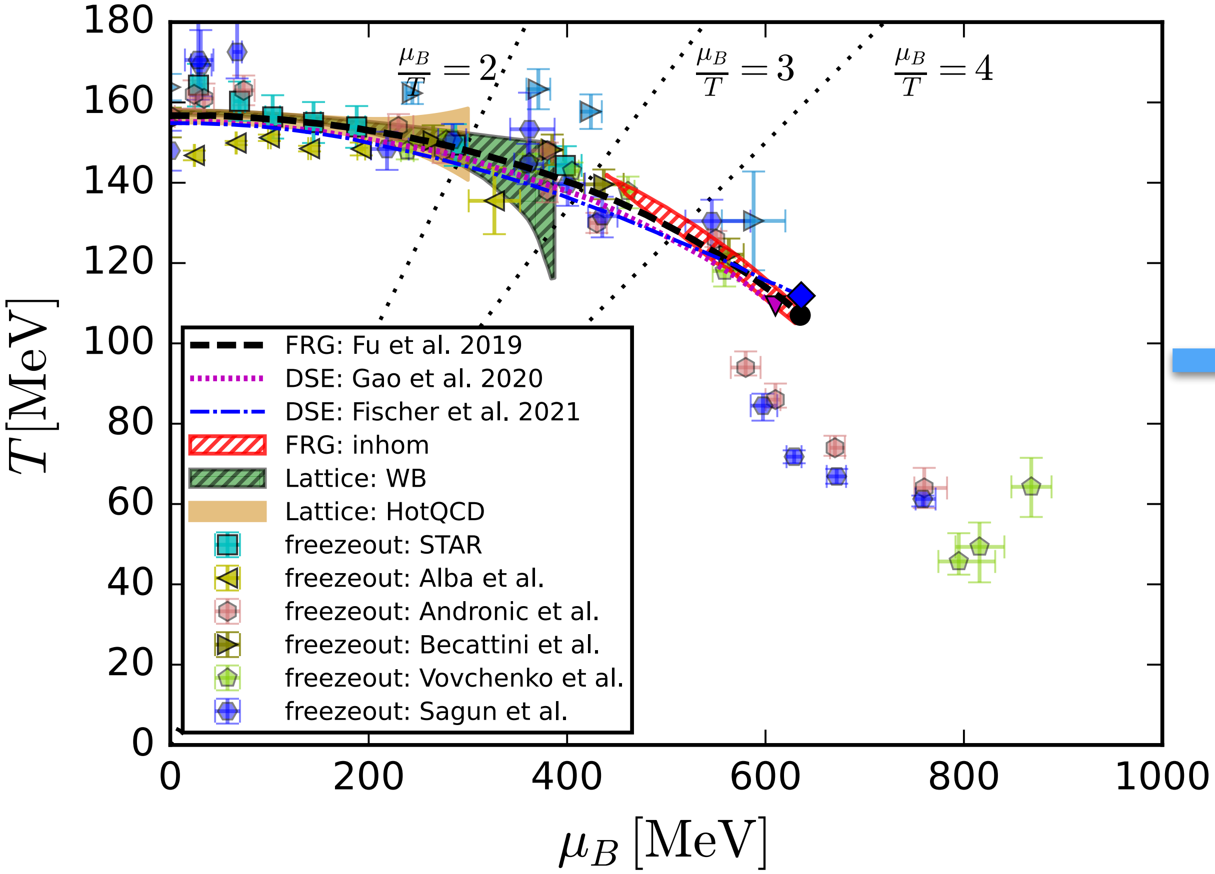
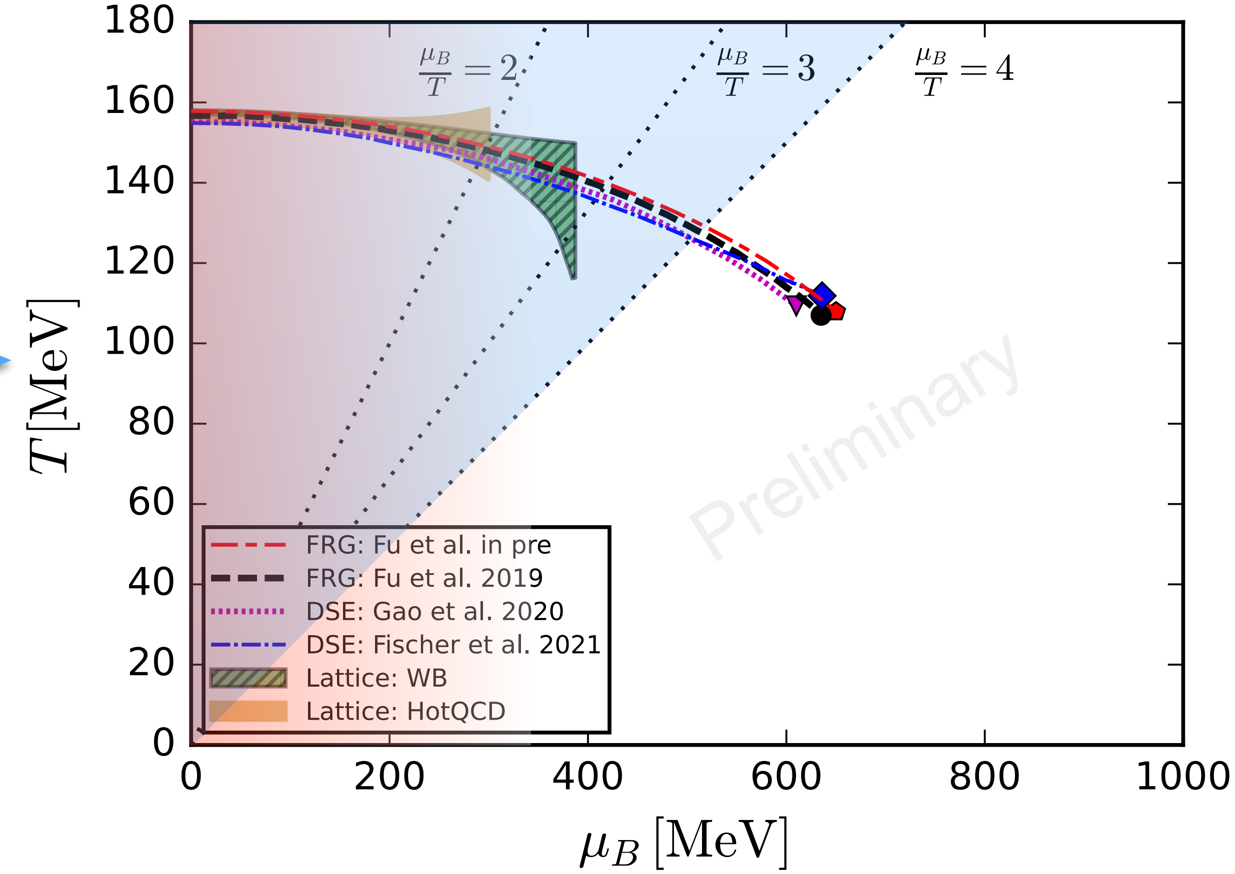
Passing lattice benchmark tests at vanishing μ_B.

fRG: WF, Pawlowski, Rennecke, Wen, Yin, (2022) in preparation

Update: CEP from fRG





fRG:

$$(T, \mu_B)_{\text{CEP}} = (108, 650)\,\textbf{MeV}$$

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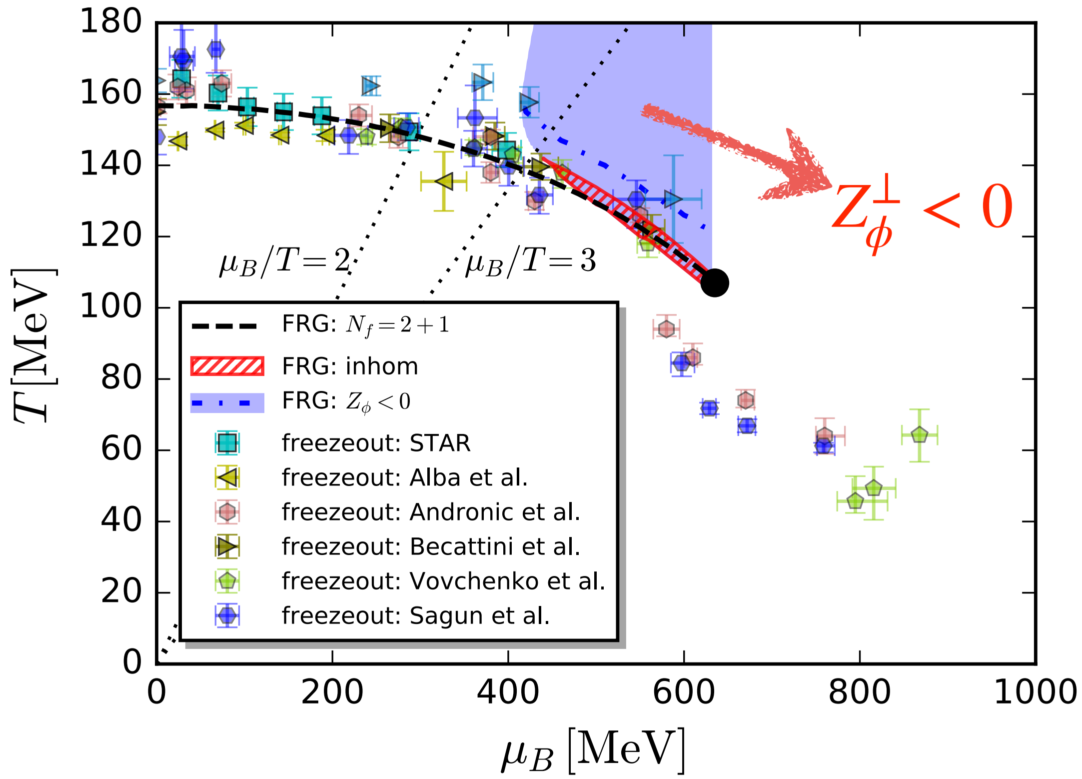
fRG: WF, Pawlowski, Rennecke, Wen, Yin, (2022) in preparation

Passing lattice benchmark tests at vanishing μ_B.

Regime of reliability of current best truncation.

Inhomogeneous instabilities in QCD phase diagam



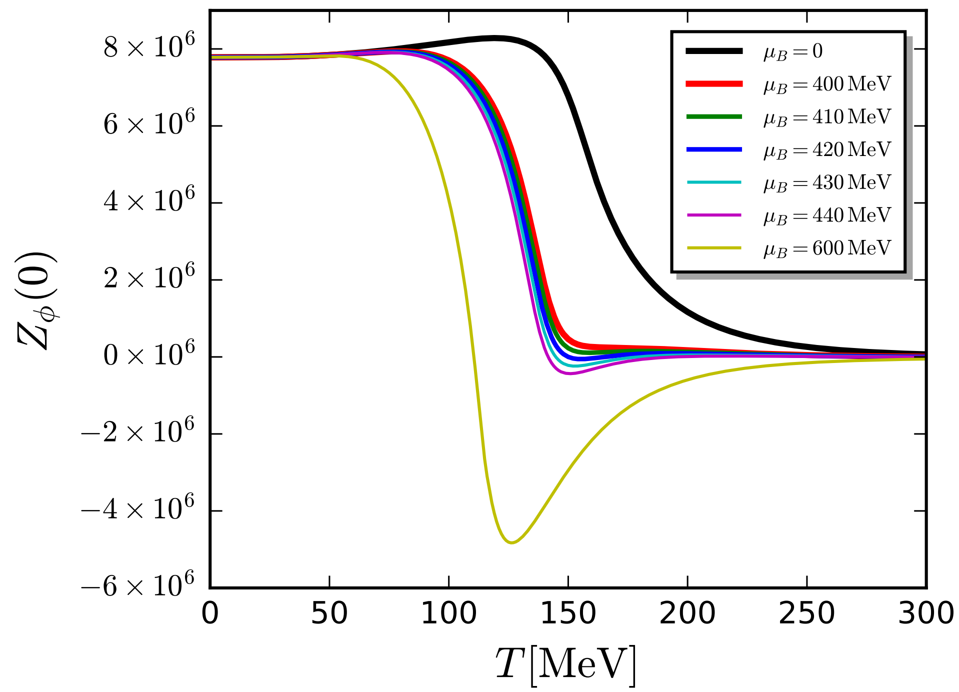
Mesonic two-point correlation function:

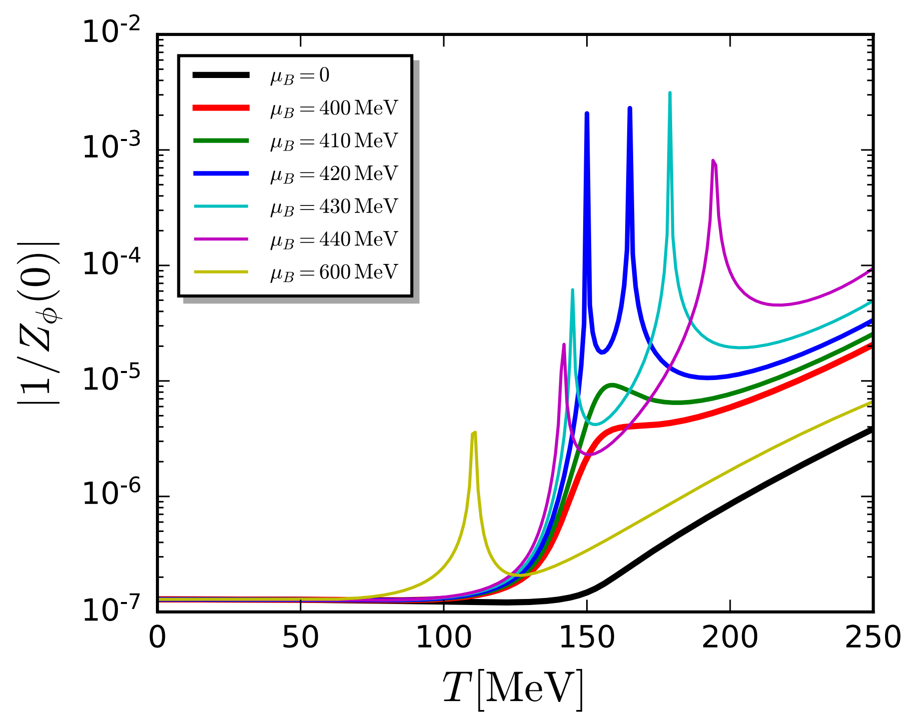
$$\Gamma^{(2)}_{\phi\phi}(p) = \left[Z^{\parallel}_{\phi}(p_0, \mathbf{p})\, p_0^2 + Z^{\perp}_{\phi}(p_0, \mathbf{p})\, \mathbf{p}^2\right] + m_\phi^2$$

with

$$\Gamma^{(2)}_{\phi\phi,k} = \left.\frac{\delta^2 \Gamma_k[\Phi]}{\delta\phi\delta\phi}\right|_{\Phi=\Phi_{\mathrm{EoM}}}$$

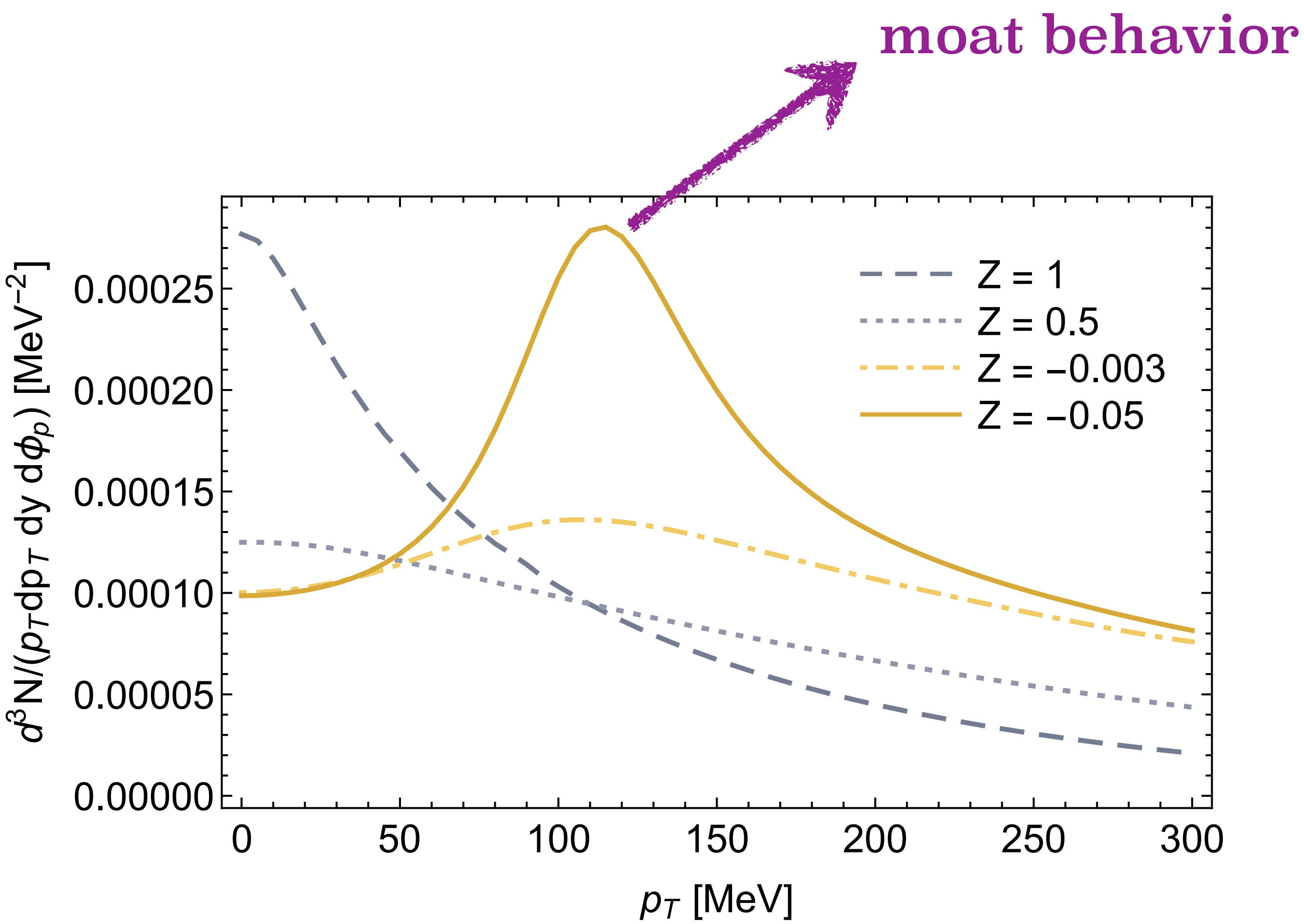
WF, Pawlowski, Rennecke, *PRD* 101 (2020) 054032





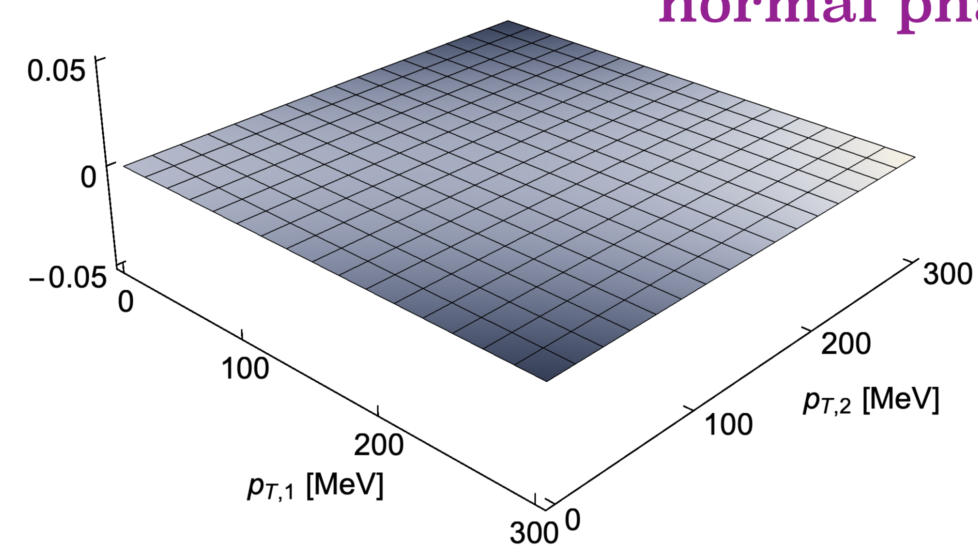
Signature of inhomogeneous instability in heavy-ion collisions—-"moat" spectrum

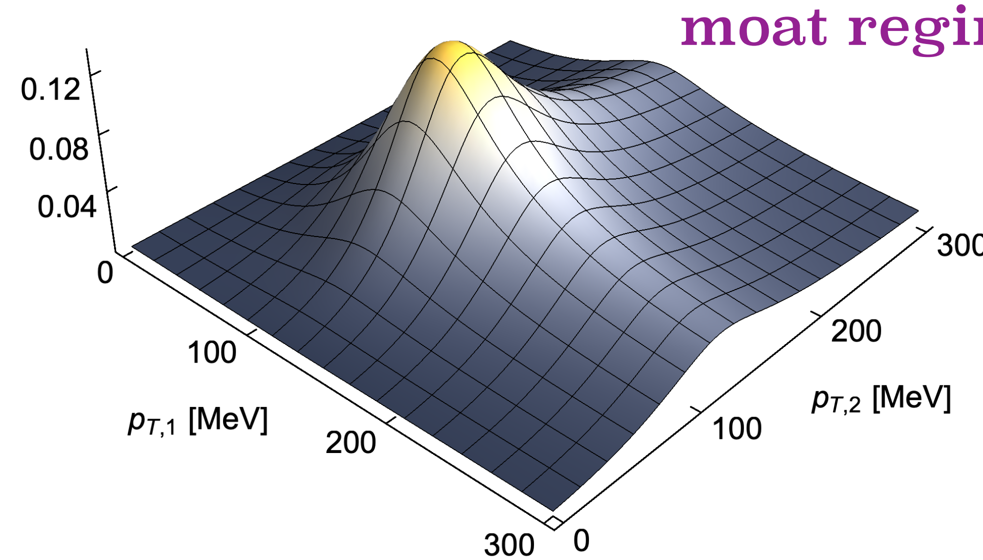
- **transverse momentum spectrum of one particle:**



Pisarski, Rennecke, *PRL* 127 (2021) 152302;
Rennecke, Pisarski, arXiv:2110.02625

- **two-particle correlation:**

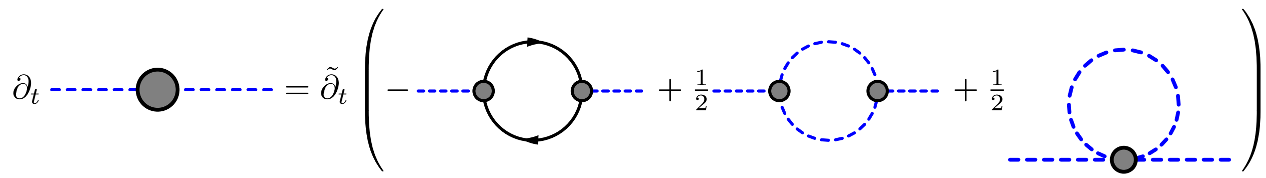


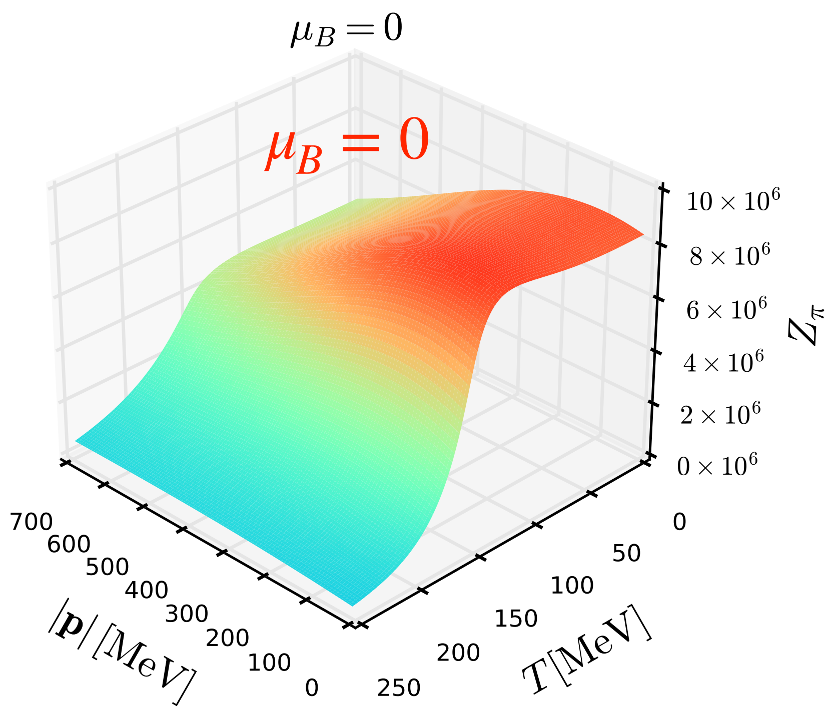


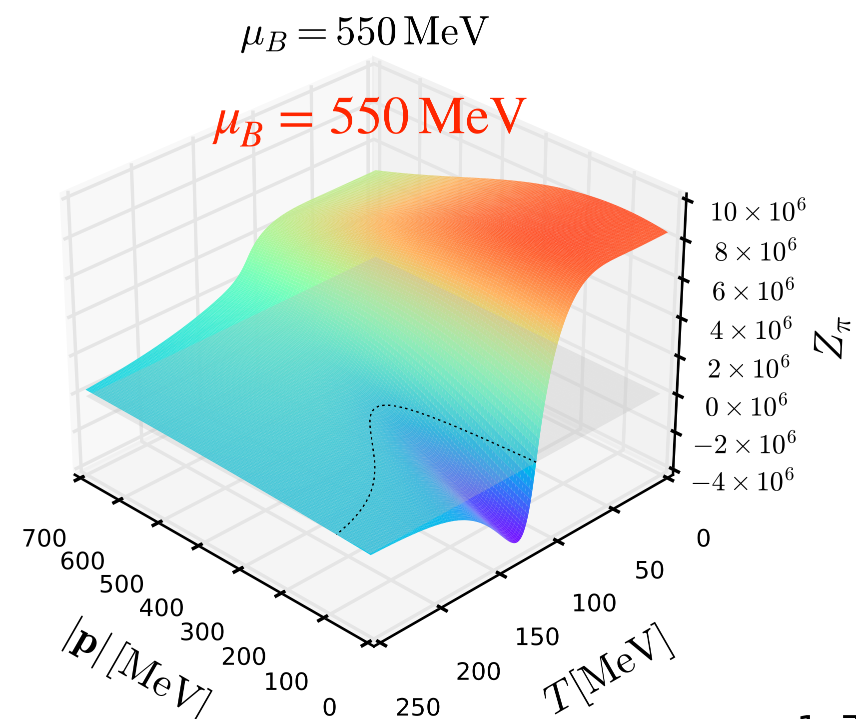
$$\Delta n_{12} = \left\langle \left(\frac{d^3N}{d\mathbf{p}^3}\right)^2 \right\rangle_c \Big/ \left\langle \frac{d^3N}{d\mathbf{p}^3} \right\rangle^2$$

Momentum-dependent mesonic wave function

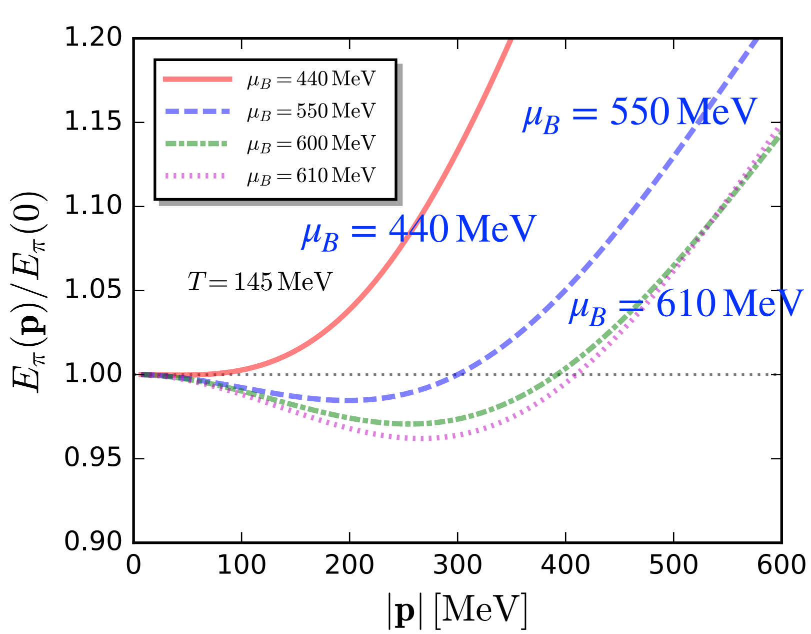
Flow equation for mesonic two-point functions:







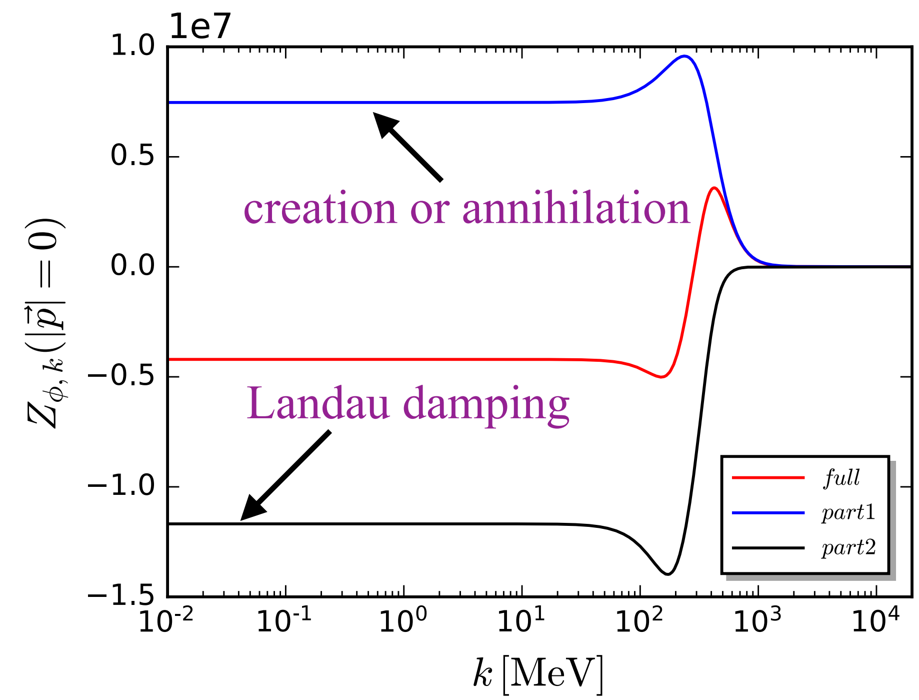
- Inhomogeneous instability is resulted from Landau damping of two quarks in thermal bath in the regime of large baryon chemical potential.



Dispersion relation:

$$E_\phi(\mathbf{p}) = \left[Z_\phi^\perp(\mathbf{p})\, \mathbf{p}^2 + m_\phi^2 \right]^{1/2}$$

WF, Pawlowski, Pisarski, Rennecke, Wen, Yin, in preparation.

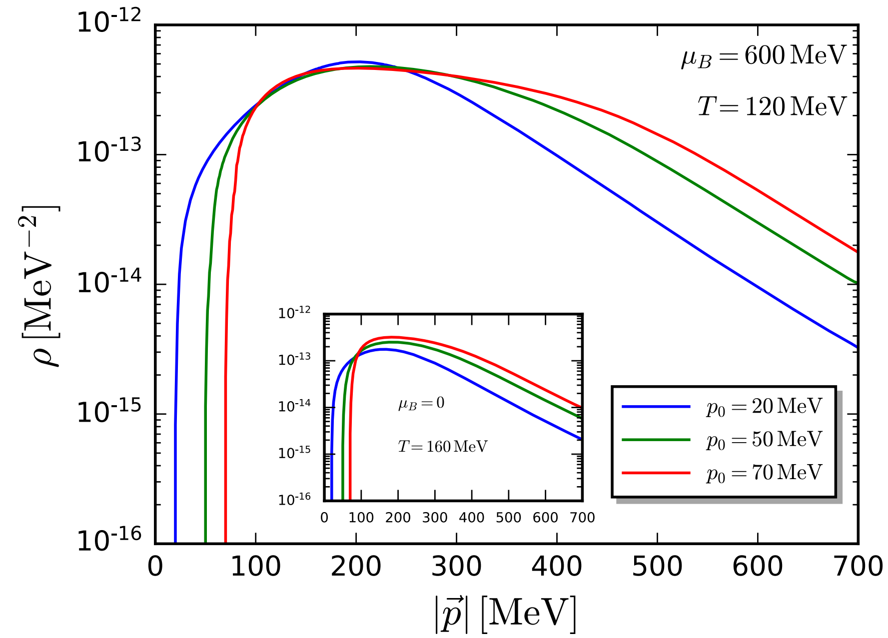


Real-time mesonic two-point functions

Analytic continuation on the flow equation:

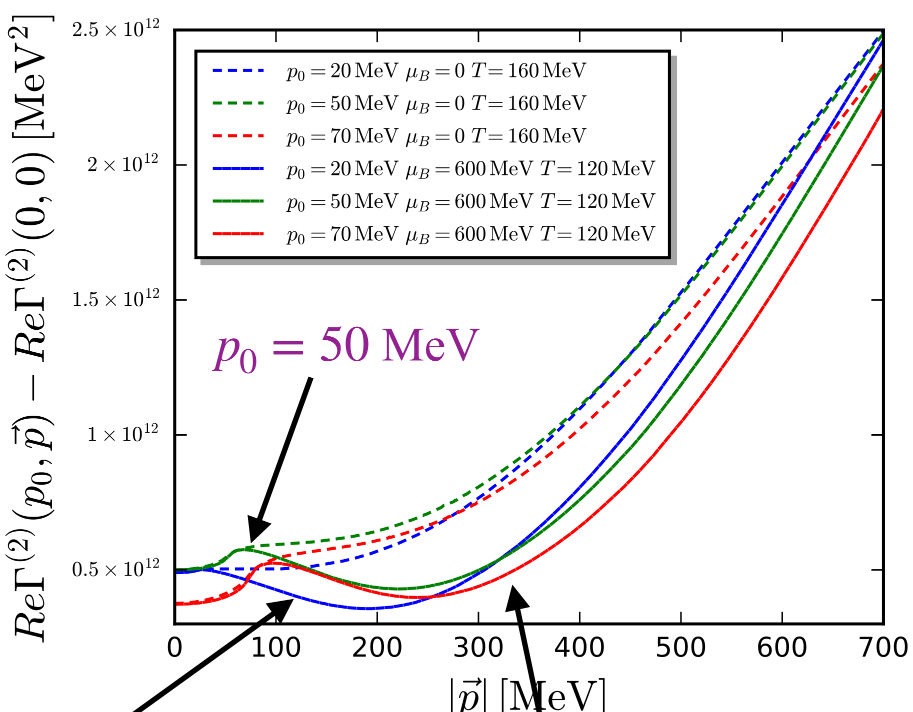
$$\Gamma^{(2)}_{\phi\phi,\mathrm{R}}(\omega,\mathbf{p}) = \lim_{\epsilon\to 0^+} \Gamma^{(2)}_{\phi\phi}\big(-\mathrm{i}(\omega+\mathrm{i}\epsilon),\mathbf{p}\big)$$

Note: not on data!



Spectral function

Real part of $\Gamma^{(2)}_{\phi\phi,\mathrm{R}}(p_0,\mathbf{p})$:

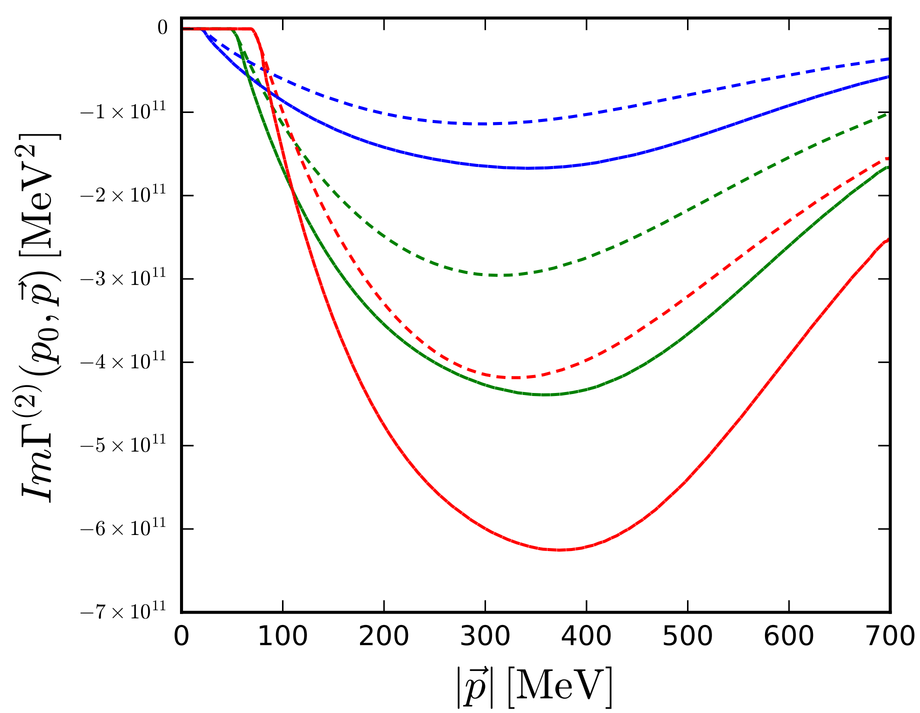


$p_0 = 50$ MeV

$p_0 = 20$ MeV

$p_0 = 70$ MeV

Imaginary part of $\Gamma^{(2)}_{\phi\phi,\mathrm{R}}(p_0,\mathbf{p})$:



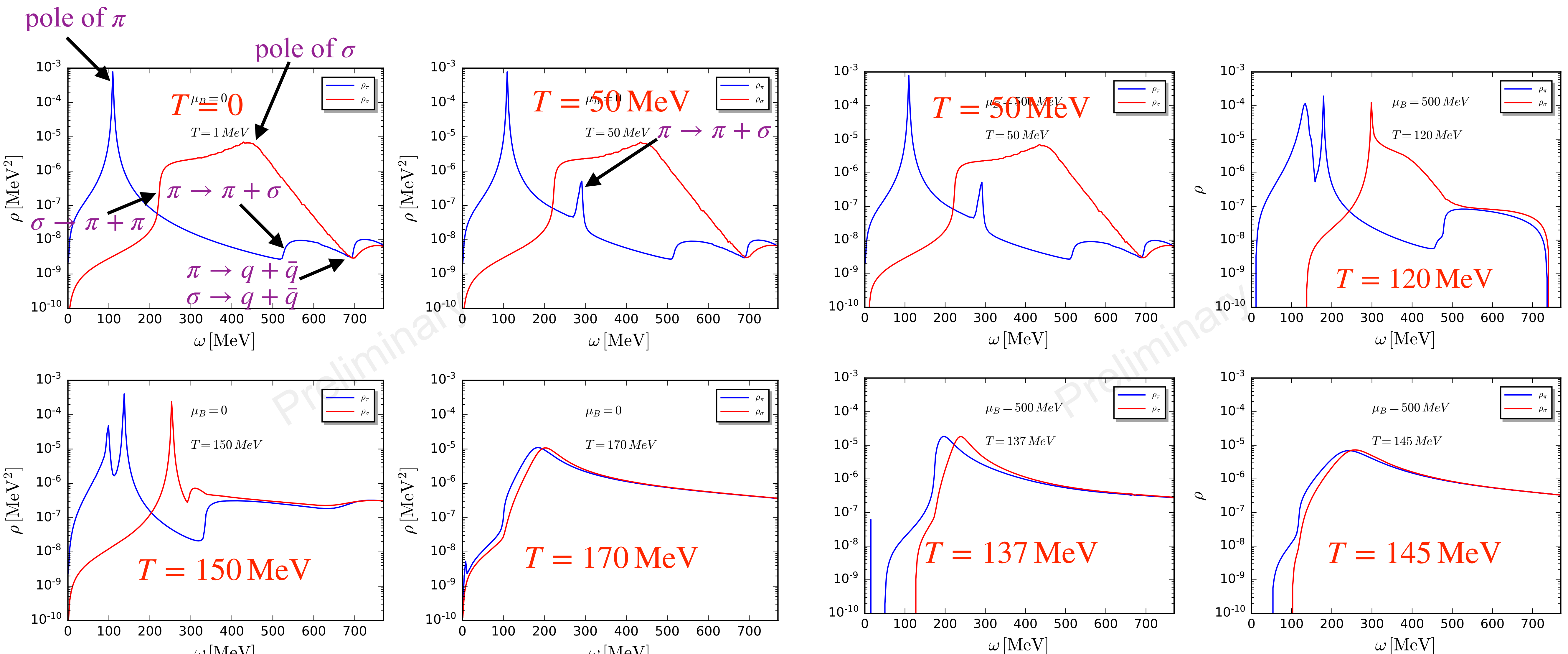
- Imaginary part of the mesonic two-point functions and spectral function are enhanced by the Landau damping effect

WF, Pawlowski, Pisarski, Rennecke, Wen, Yin, in preparation.

Spectral functions for mesons

- spectral function:

$$\rho(\omega, \vec{p}) = -\frac{1}{\pi} \frac{\mathrm{Im}\Gamma^{(2),R}(\omega, \vec{p})}{(\mathrm{Re}\Gamma^{(2),R}(\omega, \vec{p}))^2 + (\mathrm{Im}\Gamma^{(2),R}(\omega, \vec{p}))^2}$$



$\mu_B = 0$ $\mu_B = 500$ MeV

WF, Pawlowski, Pisarski, Rennecke, Wen, Yin, in preparation

Summary

- ★ Estimates for the location of the CEP or the onset of new physics from fRG and Dyson-Schwinger Equations converge in a rather small region at baryon chemical potentials of about 600 MeV.

- ★ It is found that inhomogeneous instabilities in the regime of large baryon chemical potential arise from the Landau damping.

Summary

★ Estimates for the location of the CEP or the onset of new physics from fRG and Dyson-Schwinger Equations converge in a rather small region at baryon chemical potentials of about 600 MeV.

★ It is found that inhomogeneous instabilities in the regime of large baryon chemical potential arise from the Landau damping.

Thank you very much for your attentions!