

The QCD phase structure at finite density: Facts & Fiction

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Wuhan, October 16th 2025



fqcd-collaboration.github.io



STRUCTURES
CLUSTER OF
EXCELLENCE



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Experimental & Theoretical Landscape

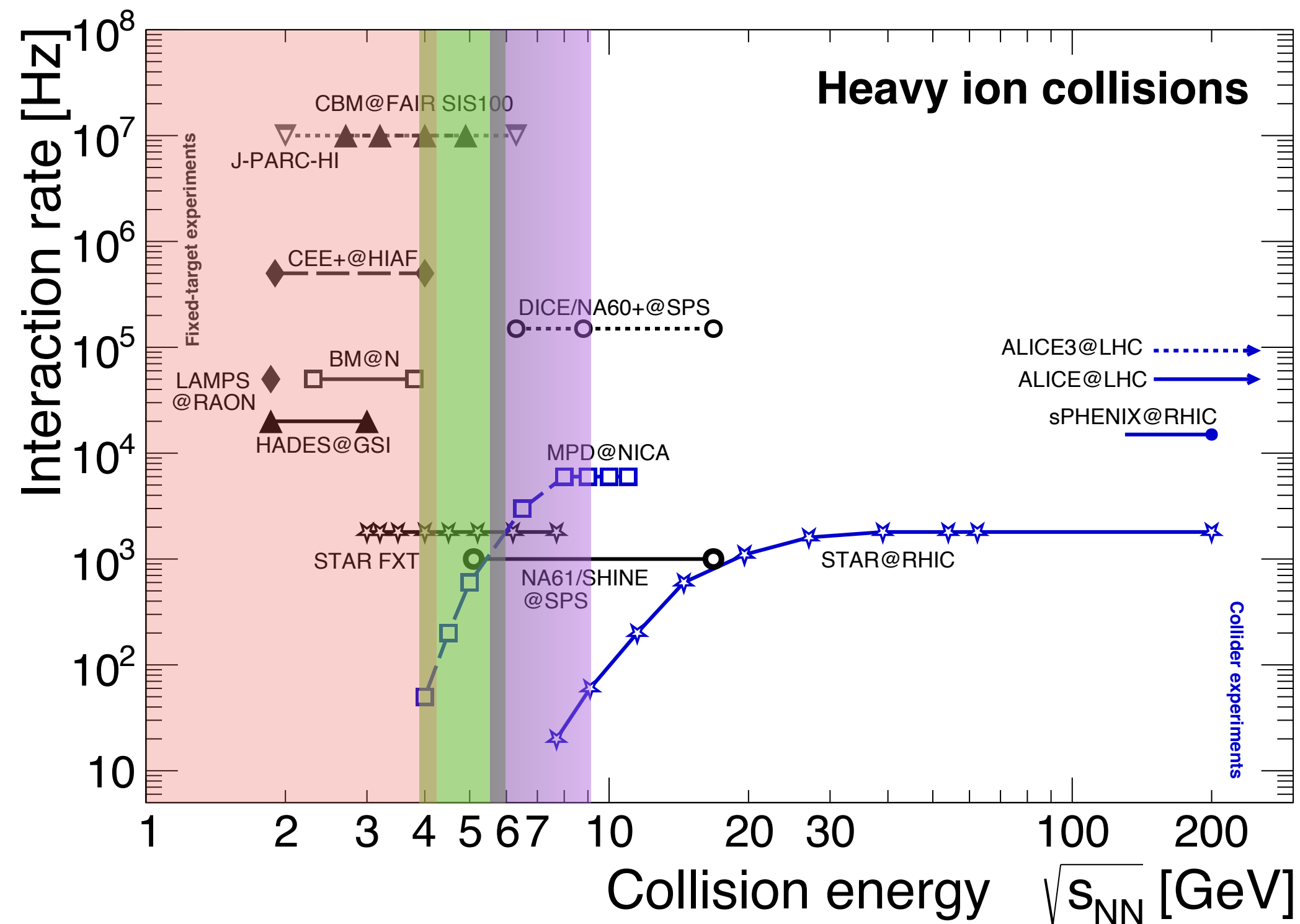
Experimental landscape

Theoretical landscape

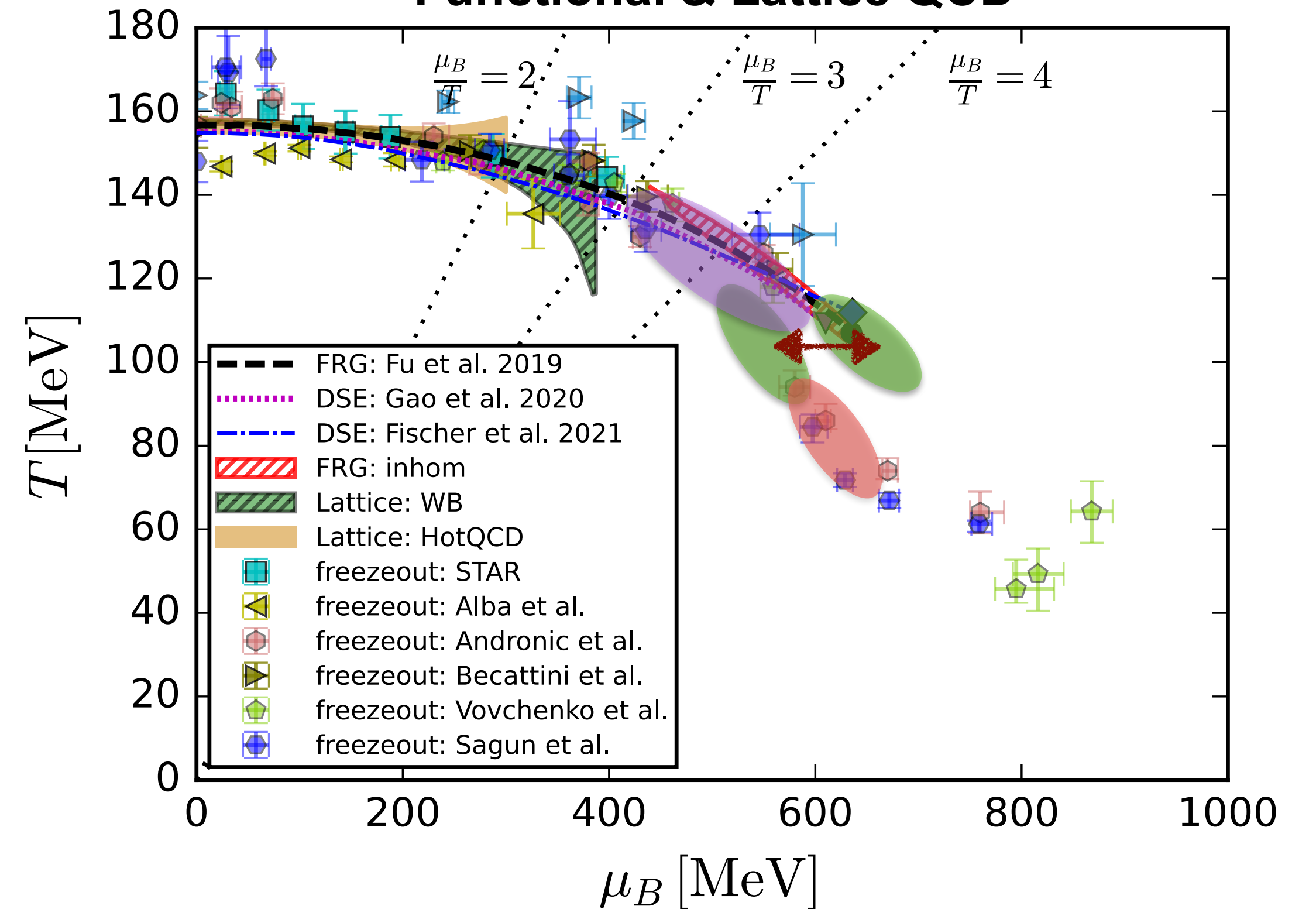
Onset of new phases on the chiral transition line (CEP)

New phases

Transition regime



Functional & Lattice QCD



Peak of kurtosis on the freeze-out line

Galatyuk, A982 (2019) update 2025; CBM, EPJA 53 3 (2017) 60

QCD phase structure at finite density: Facts & Fiction

Facts

Fiction

$$\mu_B = 0$$

- Chiral crossover at about

$$T_\chi \approx 155 \text{ MeV}$$

- Strongly correlated phase for temperatures

$$T_\chi \lesssim T \lesssim 2T_\chi$$

- Physical QCD is in the chiral scaling regime

$$\text{Chiral scaling regimes are very small } m_\pi \lesssim 10 \text{ MeV}$$

Soft modes are commonplace

- Confinement crossover is at XXX

$$T_\chi \lesssim T_{\text{conf}} \lesssim 2T_\chi$$

$$\mu_B \neq 0$$

- No chiral critical end point for

$$\mu_B \lesssim 600 \text{ MeV}$$

- No chiral crossover for

$$\mu_B \gtrsim 700 \text{ MeV}$$

- There is a CEP

$$\text{Onset of new phases } 600 \text{ MeV} \lesssim \mu_B^{\text{onset}} \lesssim 700 \text{ MeV}$$

- Scaling regime (Ising) of the CEP is humongous

No, it is not!

Most likely: too small to be measured

QCD phase structure at finite density: Facts & Fiction

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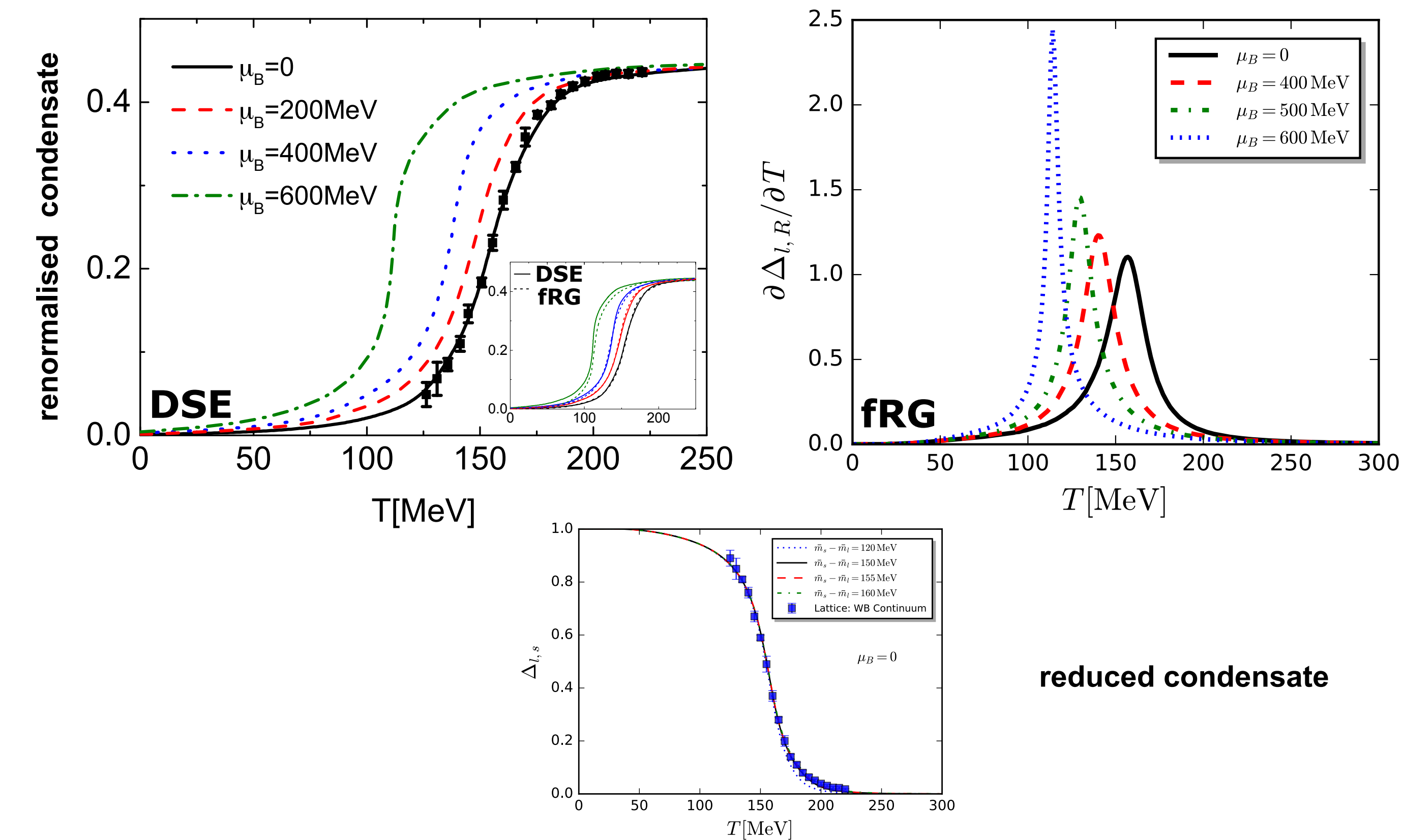
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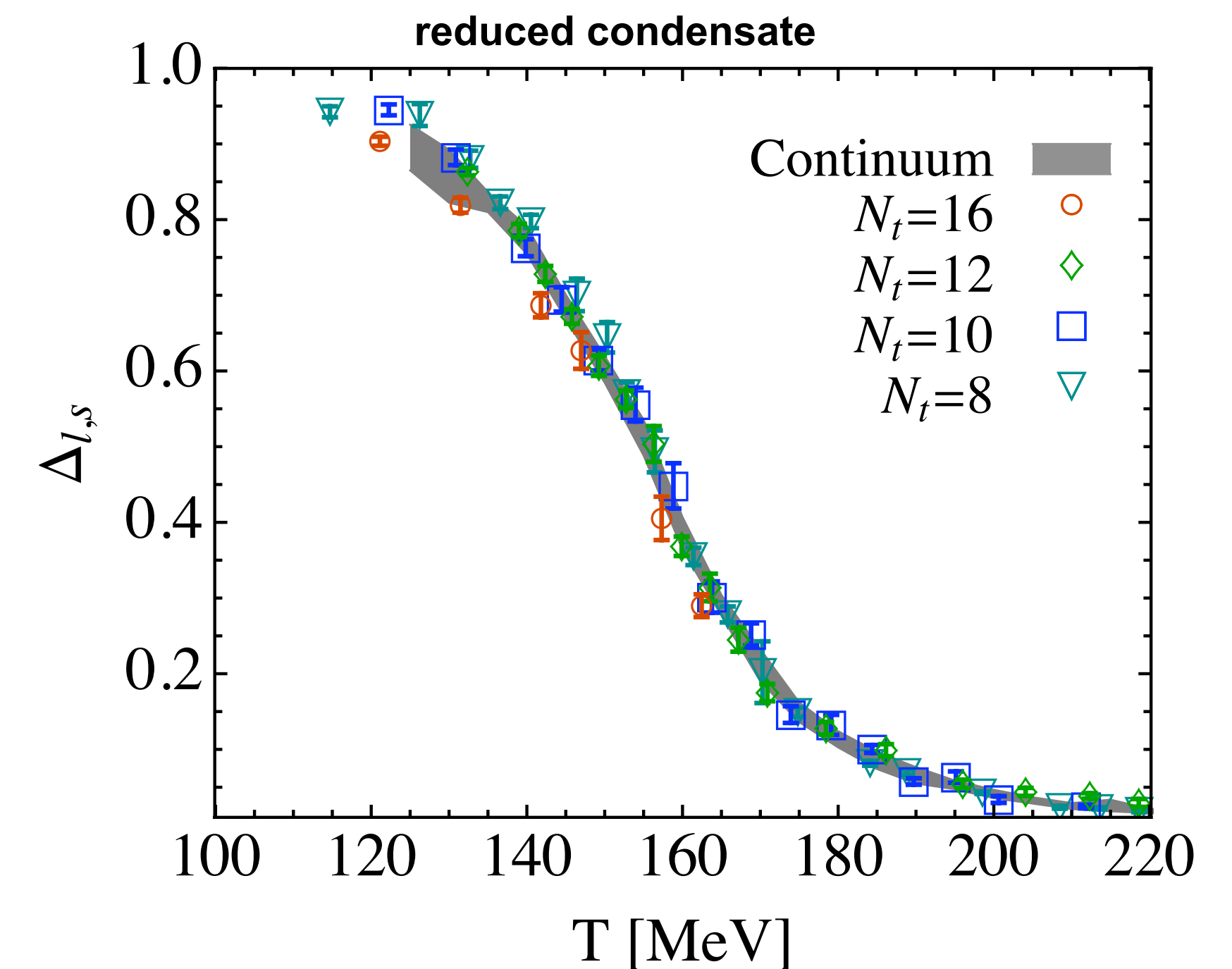
QCD phase structure at finite density: Facts & Fiction

Chiral crossover at about $T_\chi \approx 155 \text{ MeV}$

Functional QCD



Lattice QCD



DSE: Fischer, Luecker, Welzbacher, PRD 90 (2014) 034022

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

fRG: Fu, JMP, Rennecke, PRD 101 (2020) 054032

Borsányi, Fodor, Hoelbling, Katz, Krieg, Ratti, Szabo, JHEP 09, 073 (2010)

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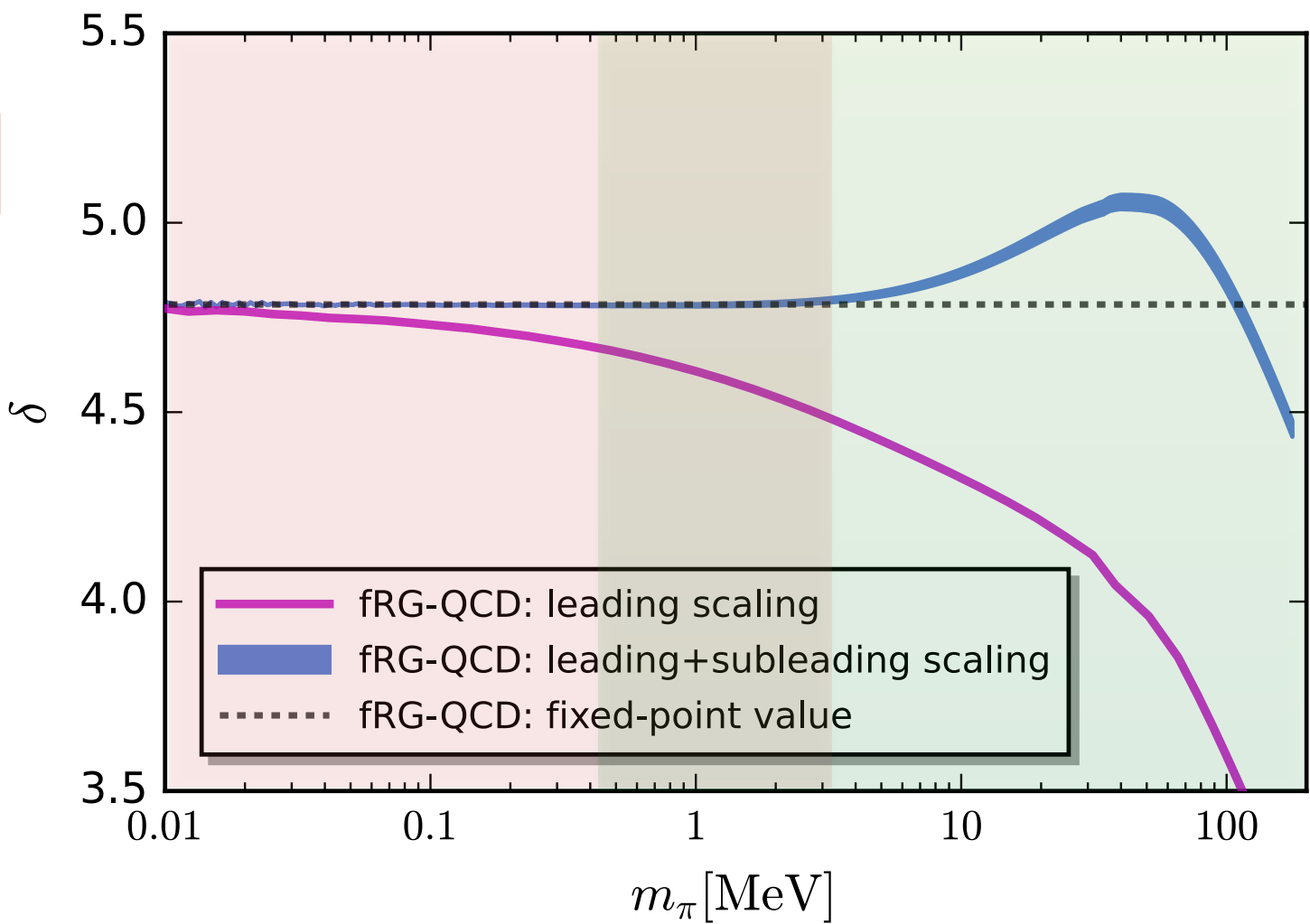
Chiral scaling regimes are very small $m_\pi \lesssim 10 \text{ MeV}$

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$$\mu_B = 0$$

Chiral dynamics & quasi-massless modes in the chiral limit

Scaling coefficient as function of the pion mass



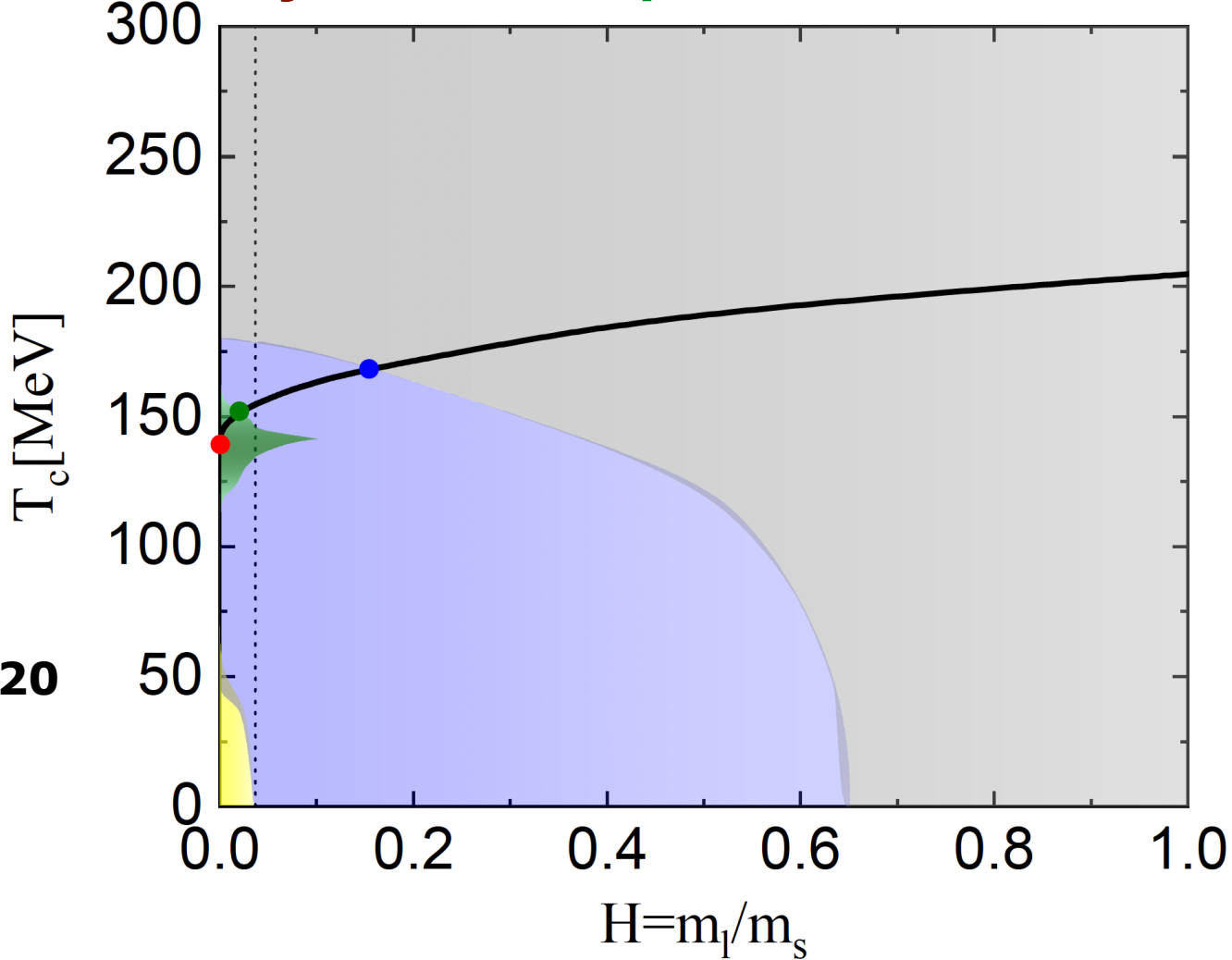
Critical O(4) scaling

‘chiral scaling’
Trivial $\Delta_l^{1+\delta}$ scaling

$$\Delta_l(m_\pi) \propto m_\pi^{2/\delta} [1 + a_m m_\pi^{2\theta_H} + \dots]$$

Small chiral scaling regime

Chiral dynamics & quasi-massless modes



Critical scaling

Gao, JMP, PRD 105 (2022) 094020

‘Non-critical chiral scaling’

Far away from the critical regime for $m_\pi \gtrsim 1$ MeV

$$\Delta_l(T, H) \approx \Delta_{l,\chi}(0) \left(c_0 + c_{\frac{1}{5}} H^{\frac{1}{5}} + c_{\frac{1}{3}} H^{\frac{1}{3}} + c_1 H \right)$$

$$V_\chi(\Delta_l) \propto \begin{matrix} \updownarrow & \updownarrow & \updownarrow \\ \Delta_l^6 & \Delta_l^4 & \Delta_l^2 \end{matrix}$$

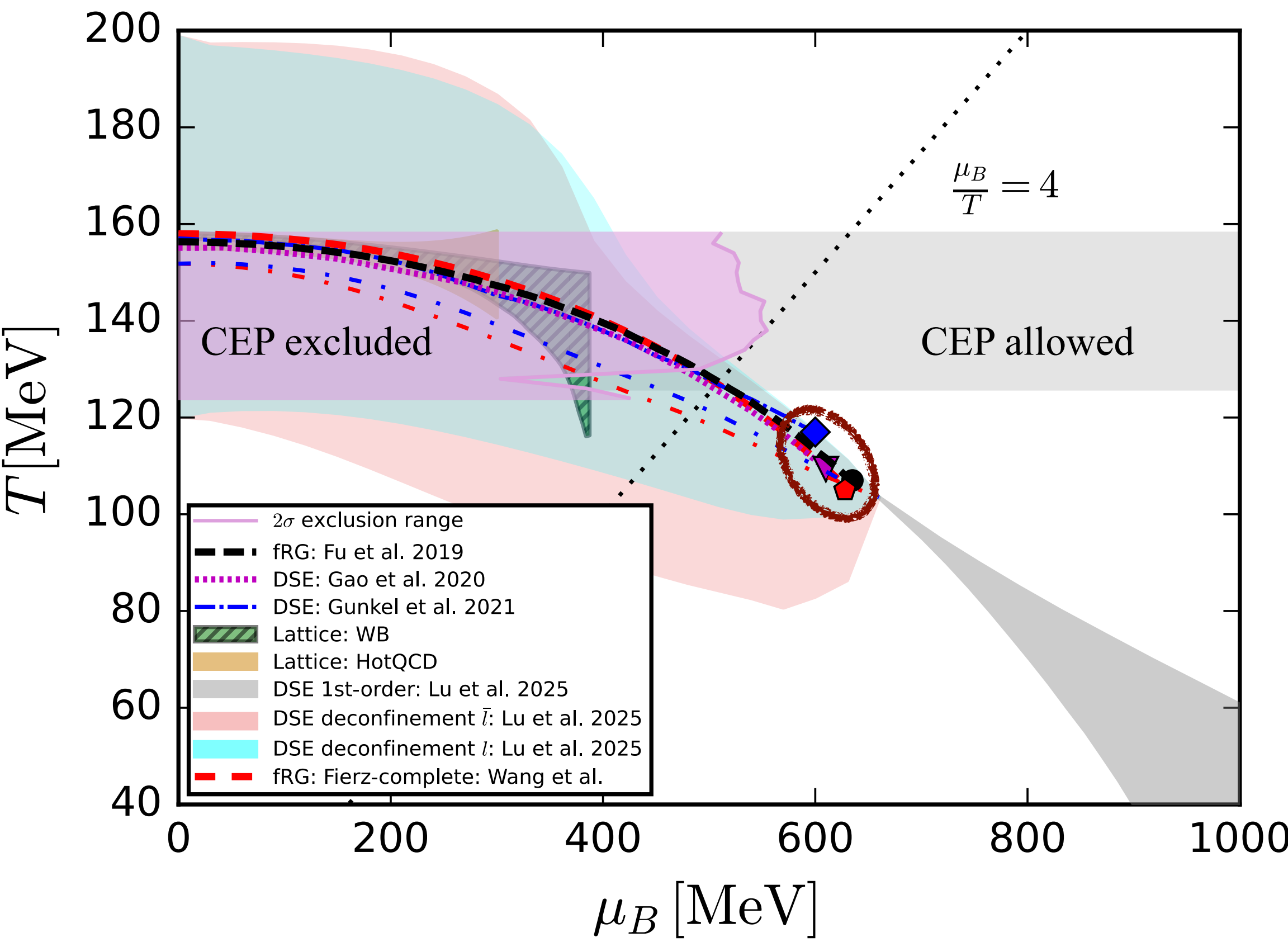
Criticality & quasi-massless modes around the CEP



Fu, JMP, Rennecke, PRD 101 (2020) 054032
 Wang, Zhou, Huang, Wen, Yin, Fu, in preparation

Small scaling regime around potential CEP

!!Great News!!
 Location of CEP/New phase accessible via combination
 of precision measurements & computations



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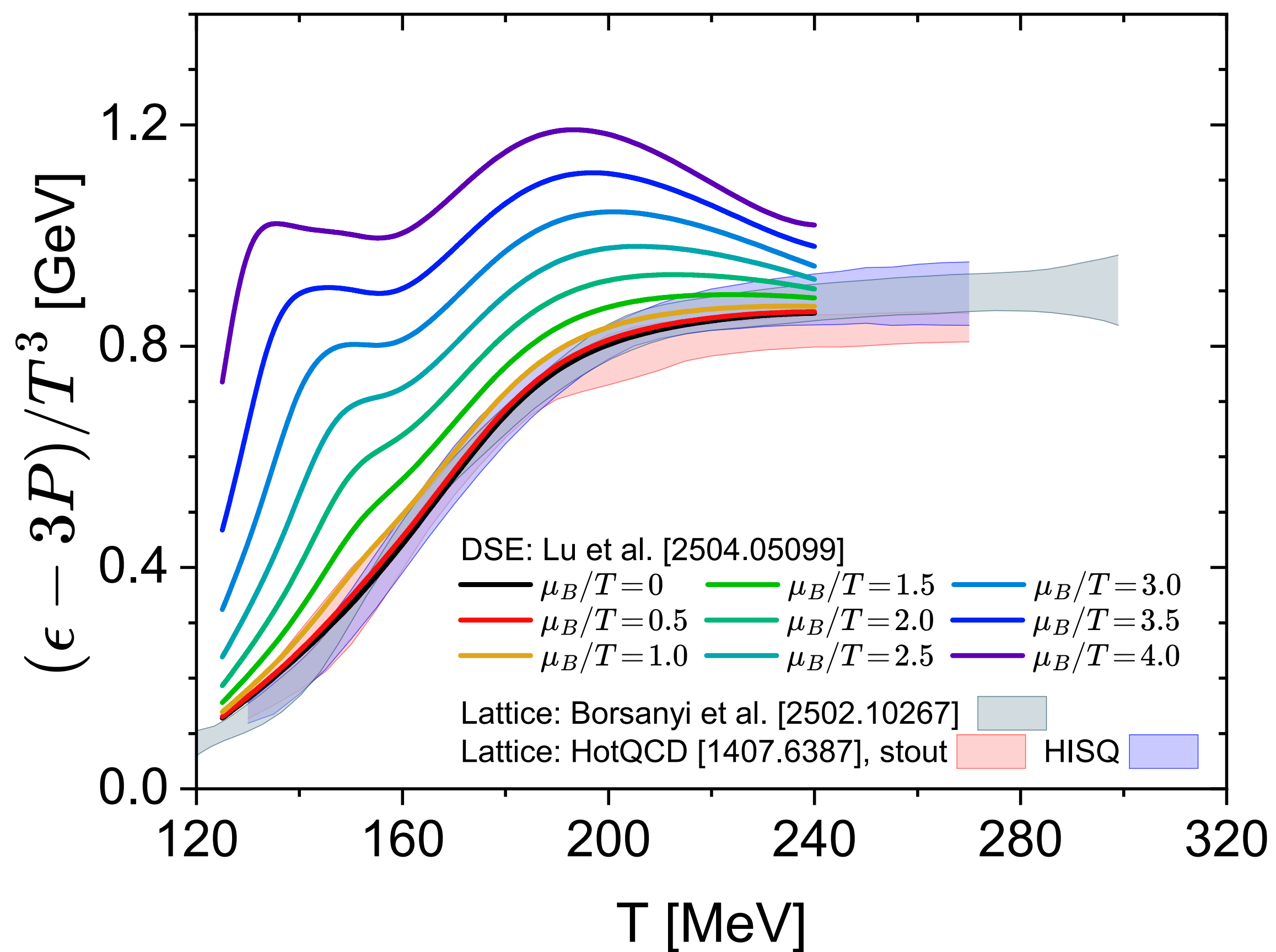
$$\mu_B = 0$$

QCD phase structure at finite density: Facts & Fiction

Strongly correlated phase for temperatures $T_\chi \lesssim T \lesssim 2T_\chi$

Functional QCD

Lattice QCD

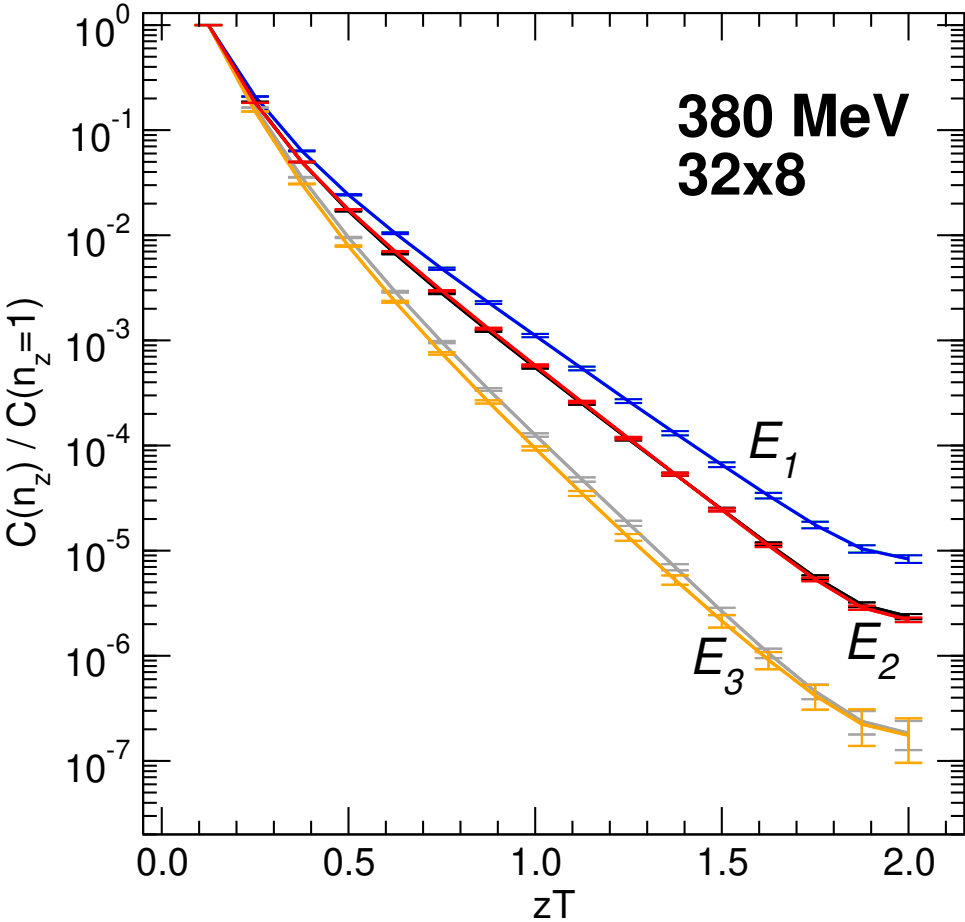
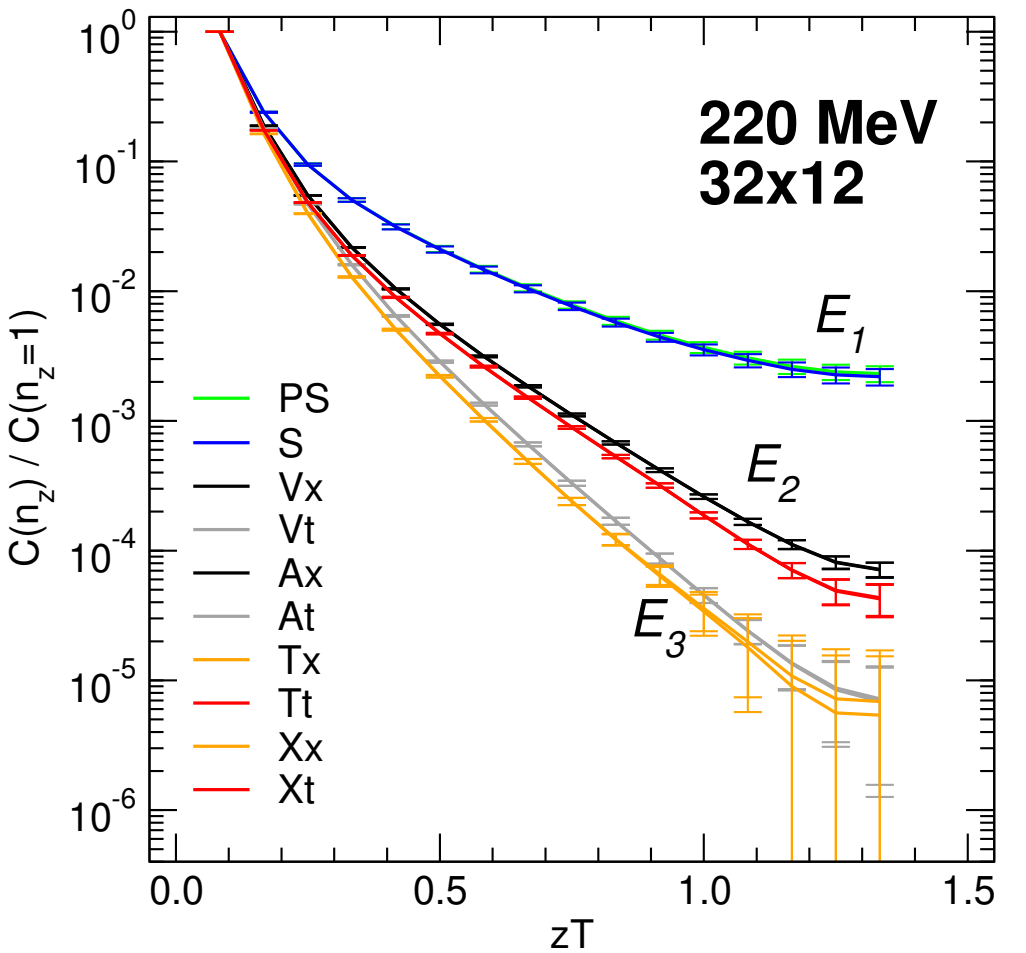


QCD phase structure at finite density: Facts & Fiction

Chiral spin symmetry for $T_\chi \lesssim T \lesssim 2T_\chi$

Functional QCD

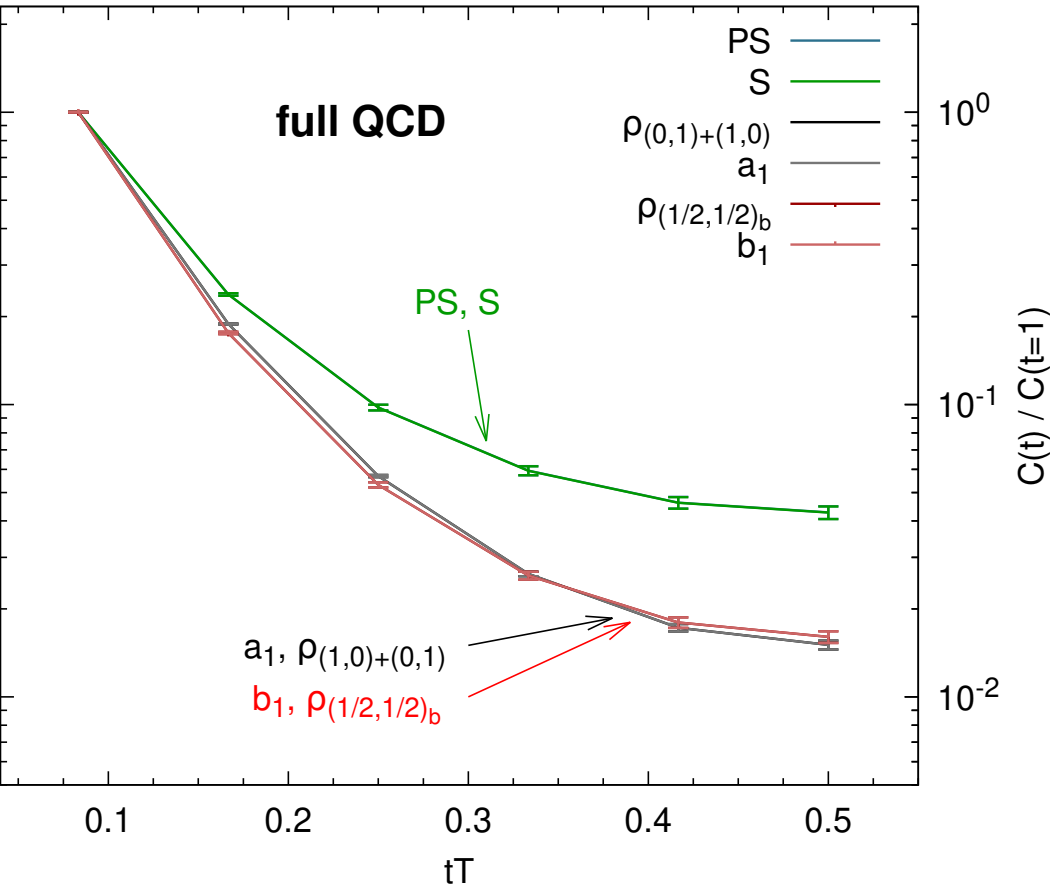
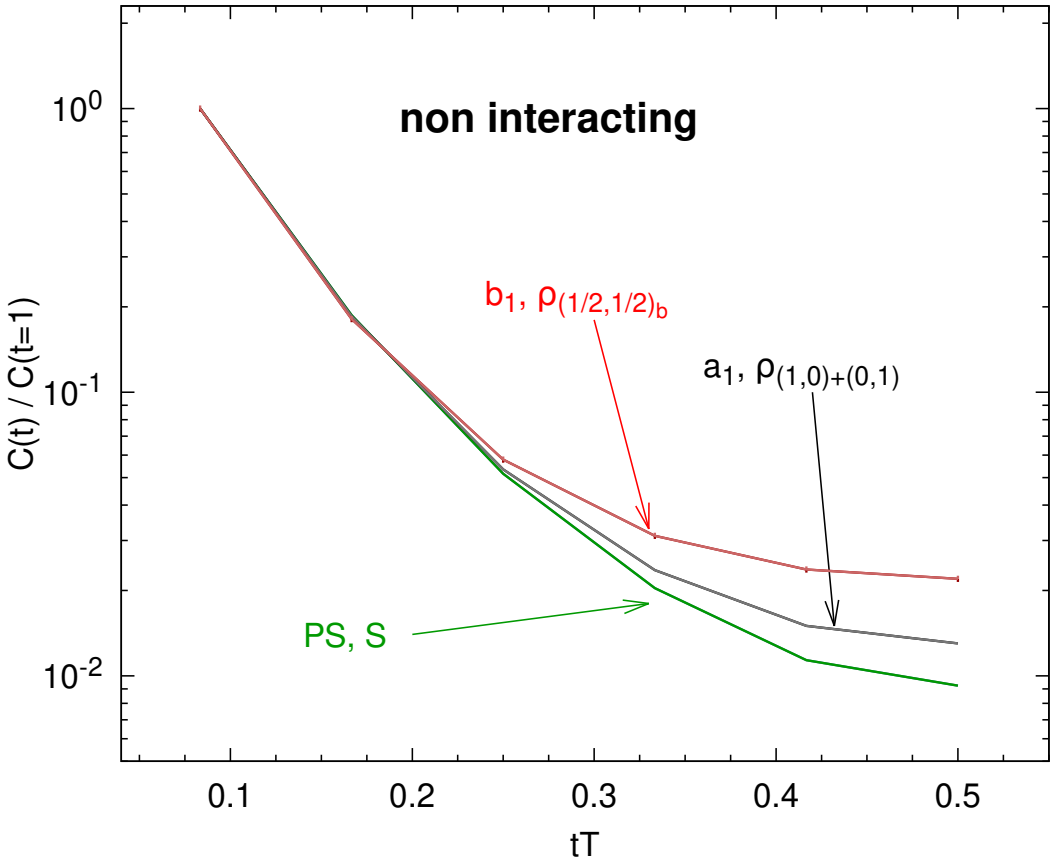
not yet



⋮
Rohrhofer, Aoki, Cossu, Fukaya, Glozman, Hashimoto,
Lang, Prelovsek, PRD 96 (2017) 094501
⋮

Rohrhofer, Aoki, Glozman, Hashimoto, PLB 802 (2020) 135245
⋮

Lattice QCD



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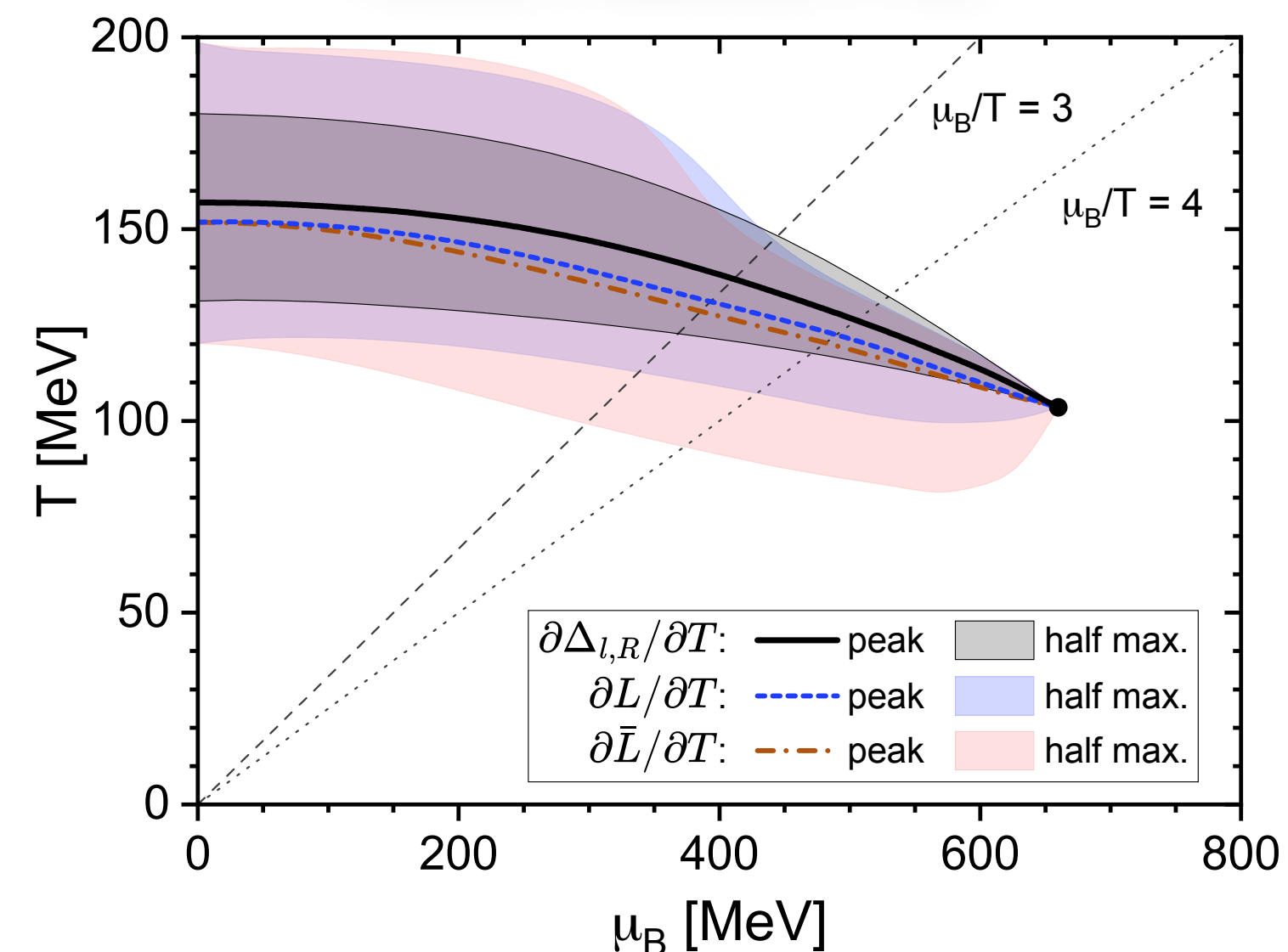
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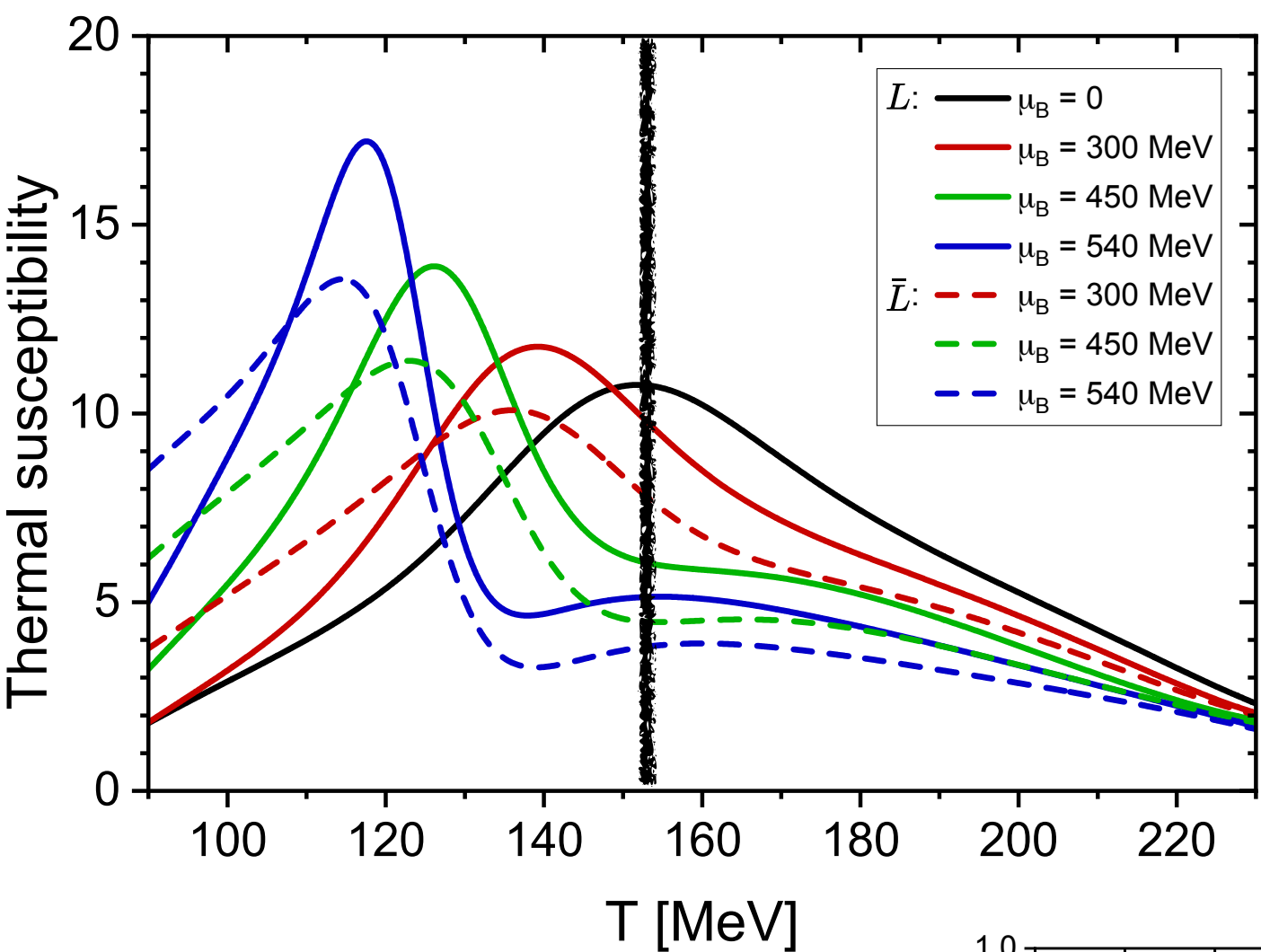
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Strongly correlated physics

‘Confinement’ related crossovers at $T_\chi \lesssim T_{\text{conf}} \lesssim 2 T_\chi$

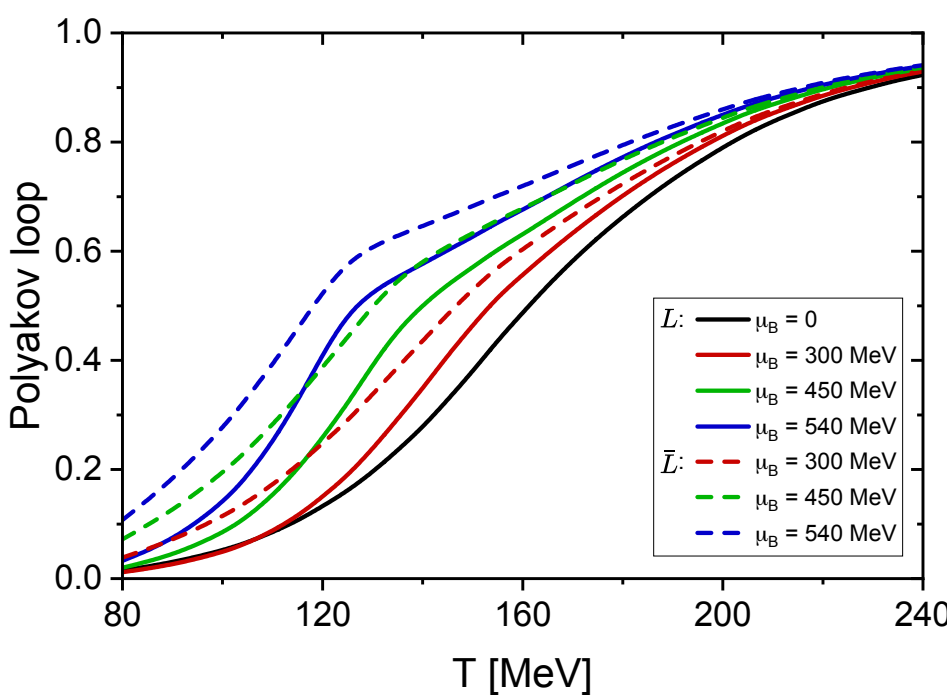
Functional QCD



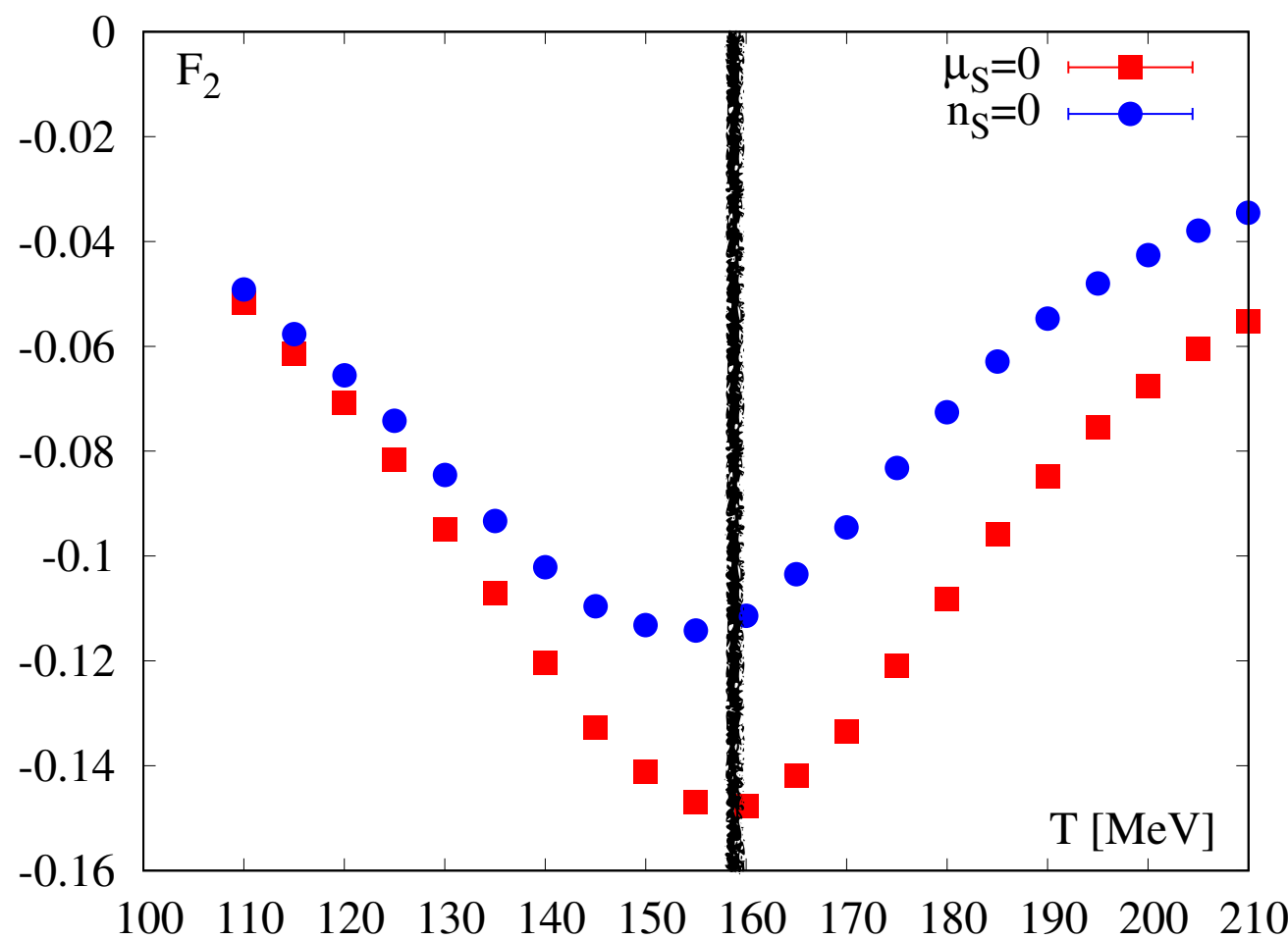
Variants of the
traced Polyakov loop

$$P = \frac{1}{N_c} \text{tr} e^{2\pi i \varphi}$$

$$\propto P(\langle \text{ev}(\varphi) \rangle)$$

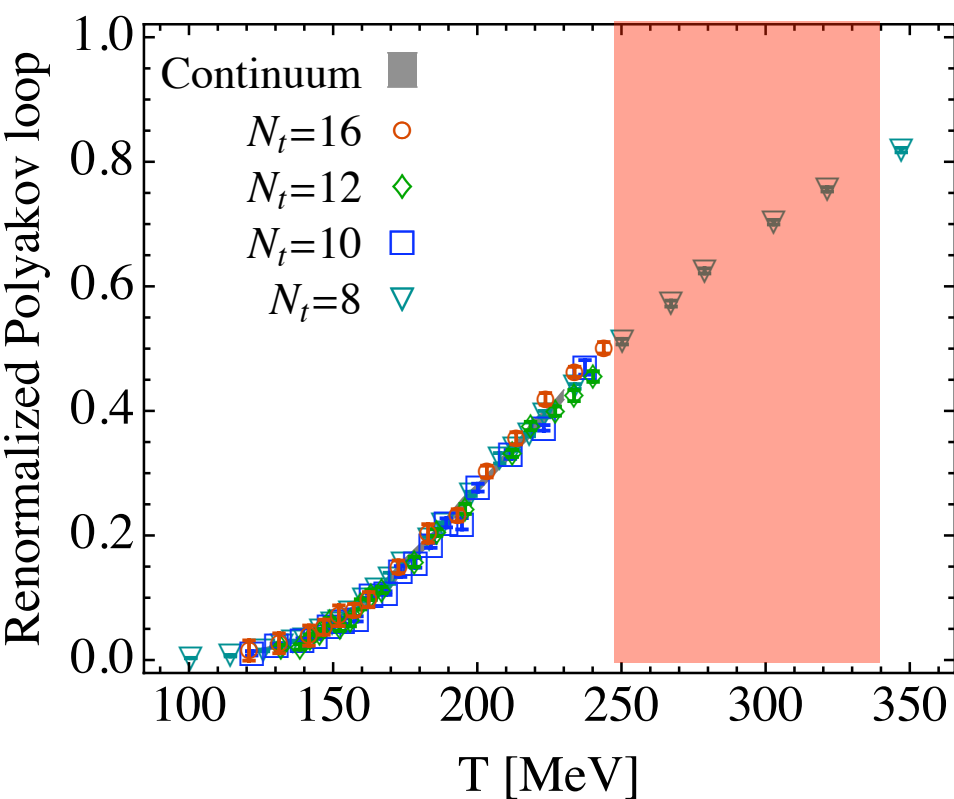


Lattice QCD



$$\propto T \frac{\partial^2 \log |\langle P \rangle|}{(\partial \mu_B / T)^2}$$

$$\propto \langle P \rangle$$



Braun, Gies, JMP, PLB 684 (2010) 262-267

Borsanyi, Fodor, Hoelbling, Katz, Krieg, Ratti, Szabo, JHEP 09, 073 (2010)

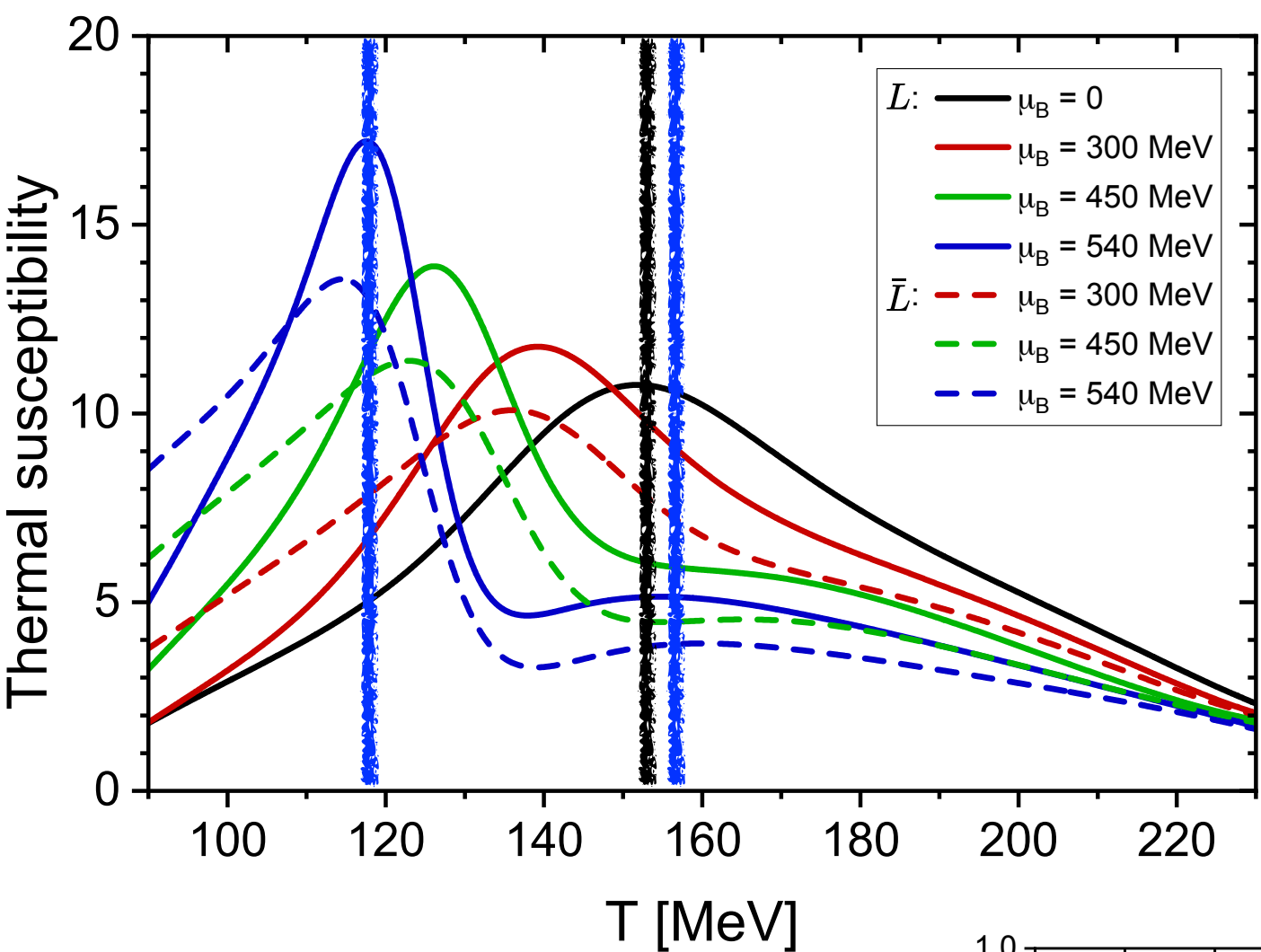
Lu, Gao, Liu, JMP, arxiv:2504.05099

Borsányi, Fodor, Guenther, Kara, Paolo Parotto, Pásztor, Pirelli, Wong, PRD 110 (2024) 114507

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‘Confinement’ related crossovers at $T_\chi \lesssim T_{\text{conf}} \lesssim 2 T_\chi$

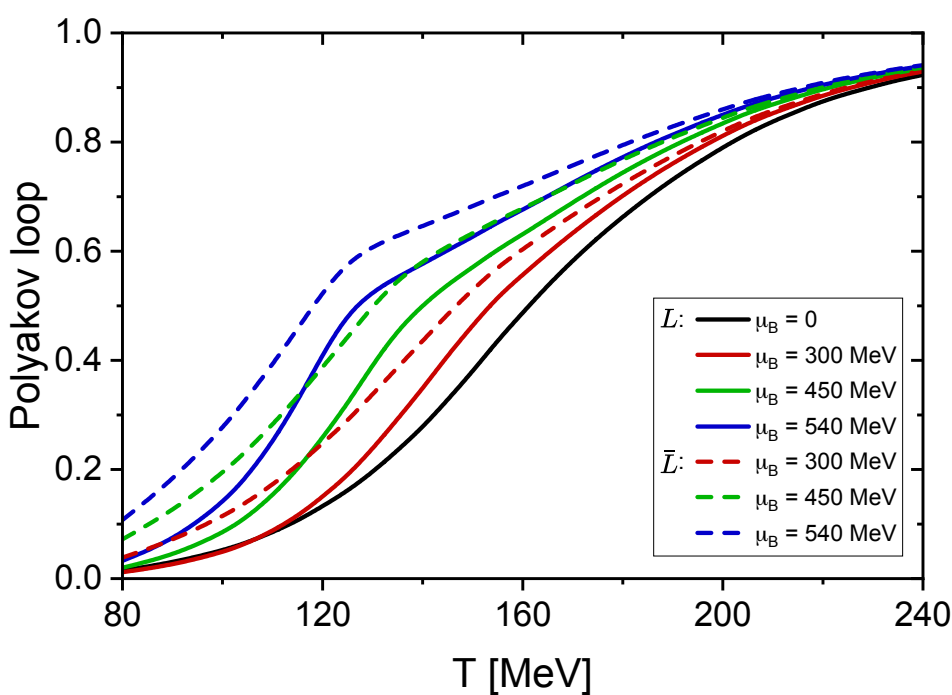
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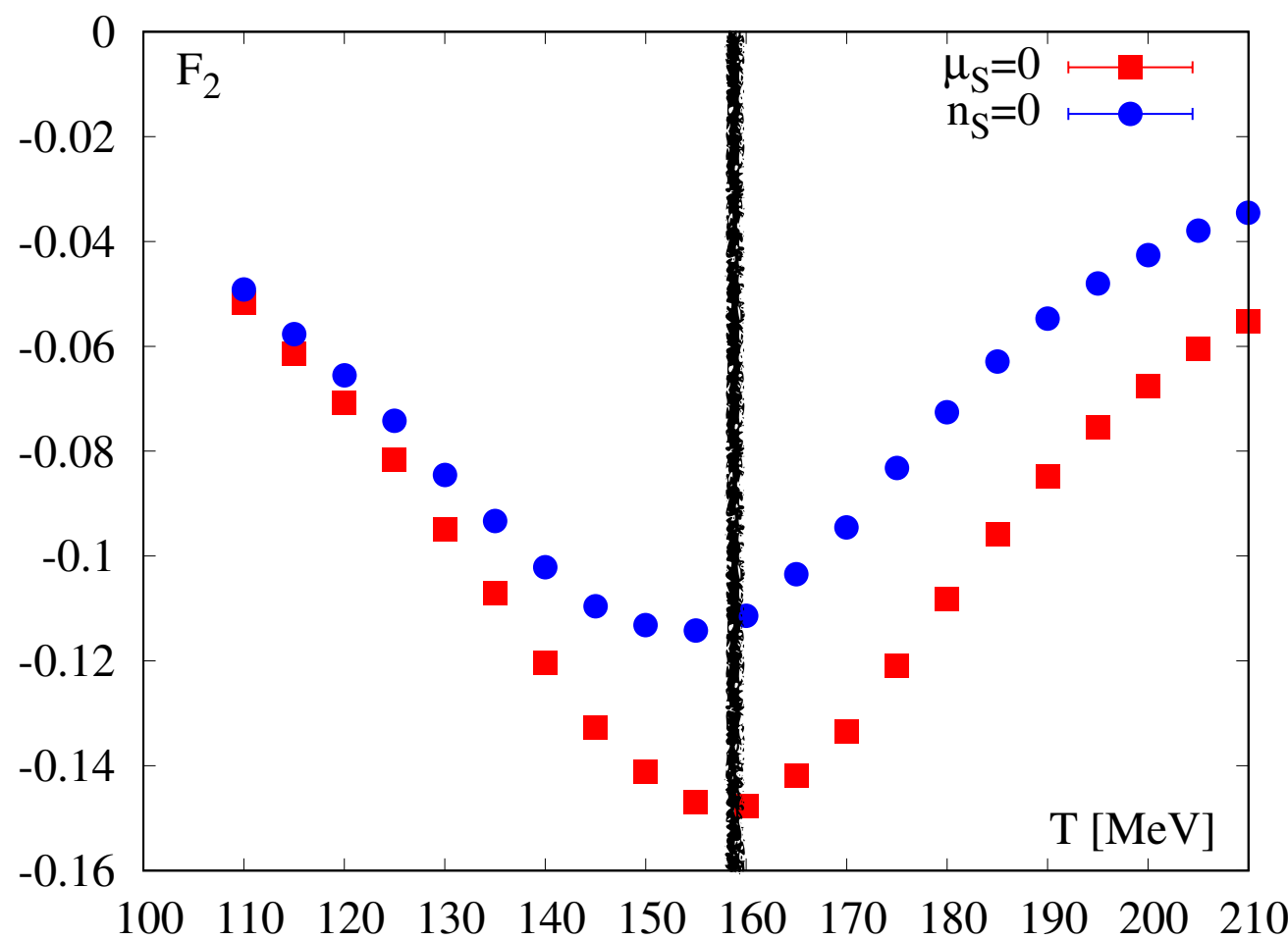
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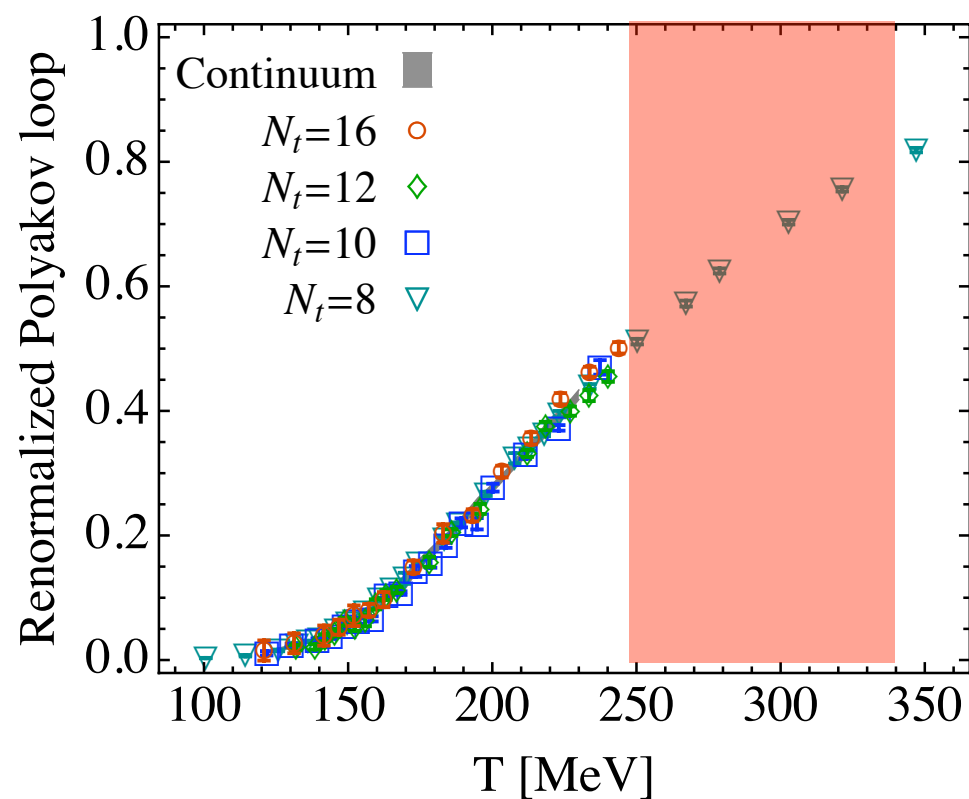


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$$\mu_B \neq 0$$

- No **chiral** critical end point for

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chiral: driven by scalar-pseudo scalar fluctuations

QCD phase structure at finite density: Facts & Fiction

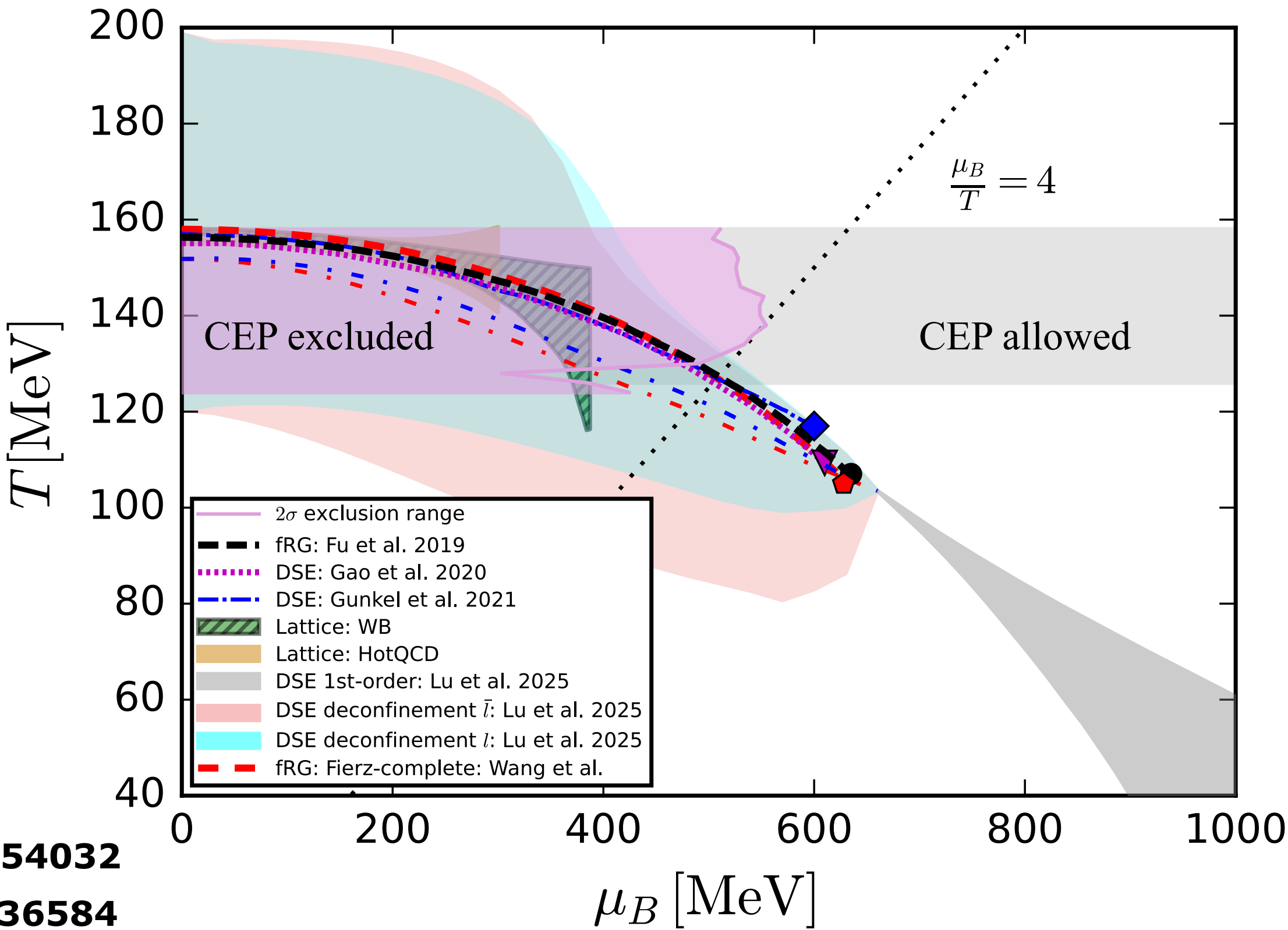
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Functional QCD

Functional QCD CEP+ lattice QCD exclusion plot

Lattice QCD

$\mu_B \lesssim 450 \text{ MeV}$



Fu, JMP, Rennecke, PRD 101 (2020) 054032

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

Lu, Gao, Liu, JMP, arXiv:2504.05099

Lu, Gao, Liu, arXiv:2509.02974

Wang et al, in preparation

Borsanyi, Fodor, Guenther, Parotto, Pasztor,
Ratti, Vovchenko, Wong, arxiv: 2502.10267

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- Onset of new phases and their physics

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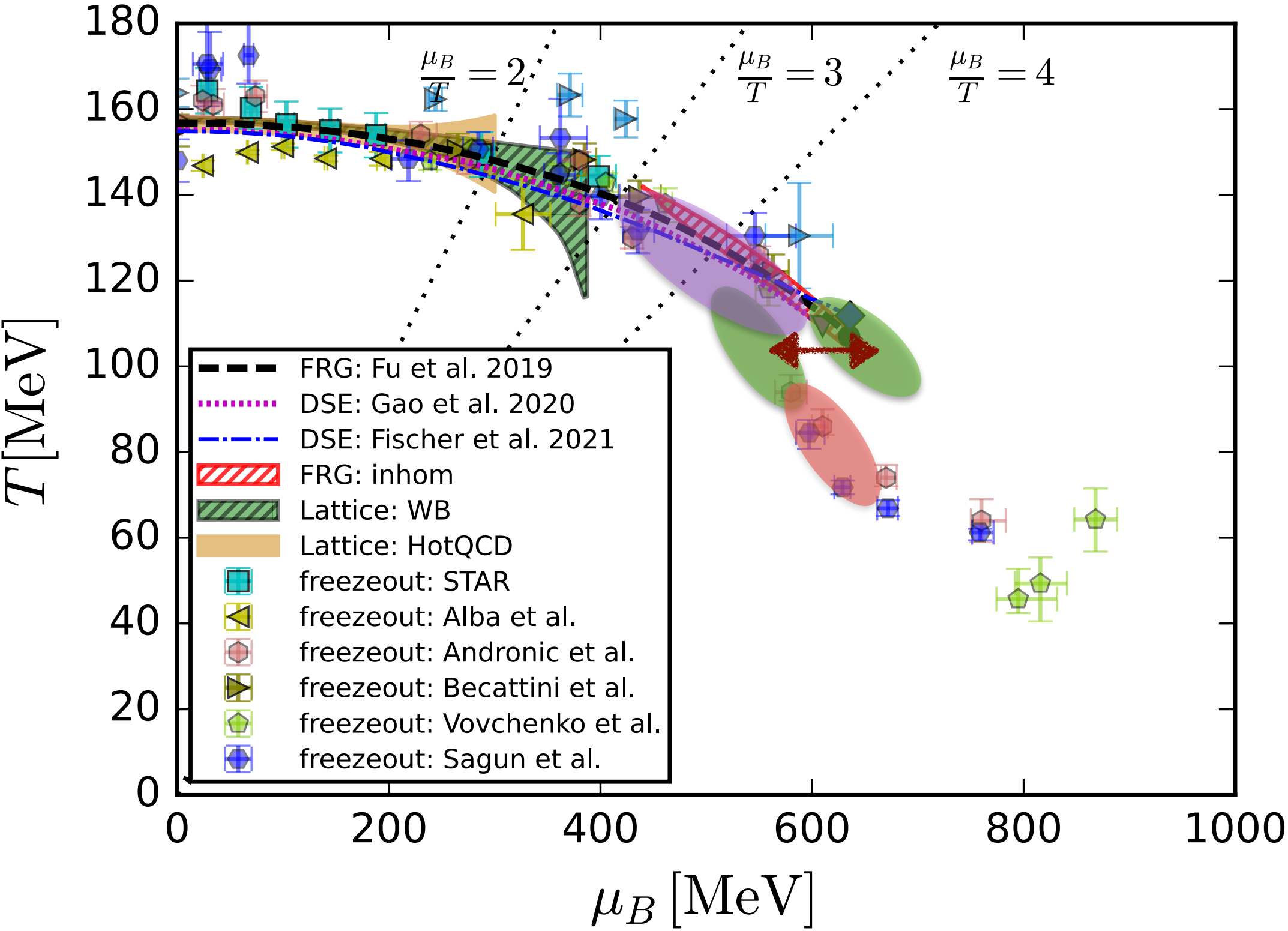
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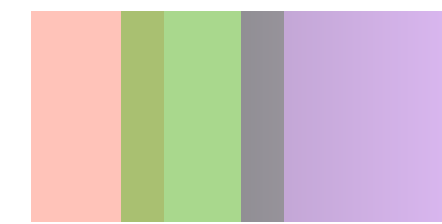
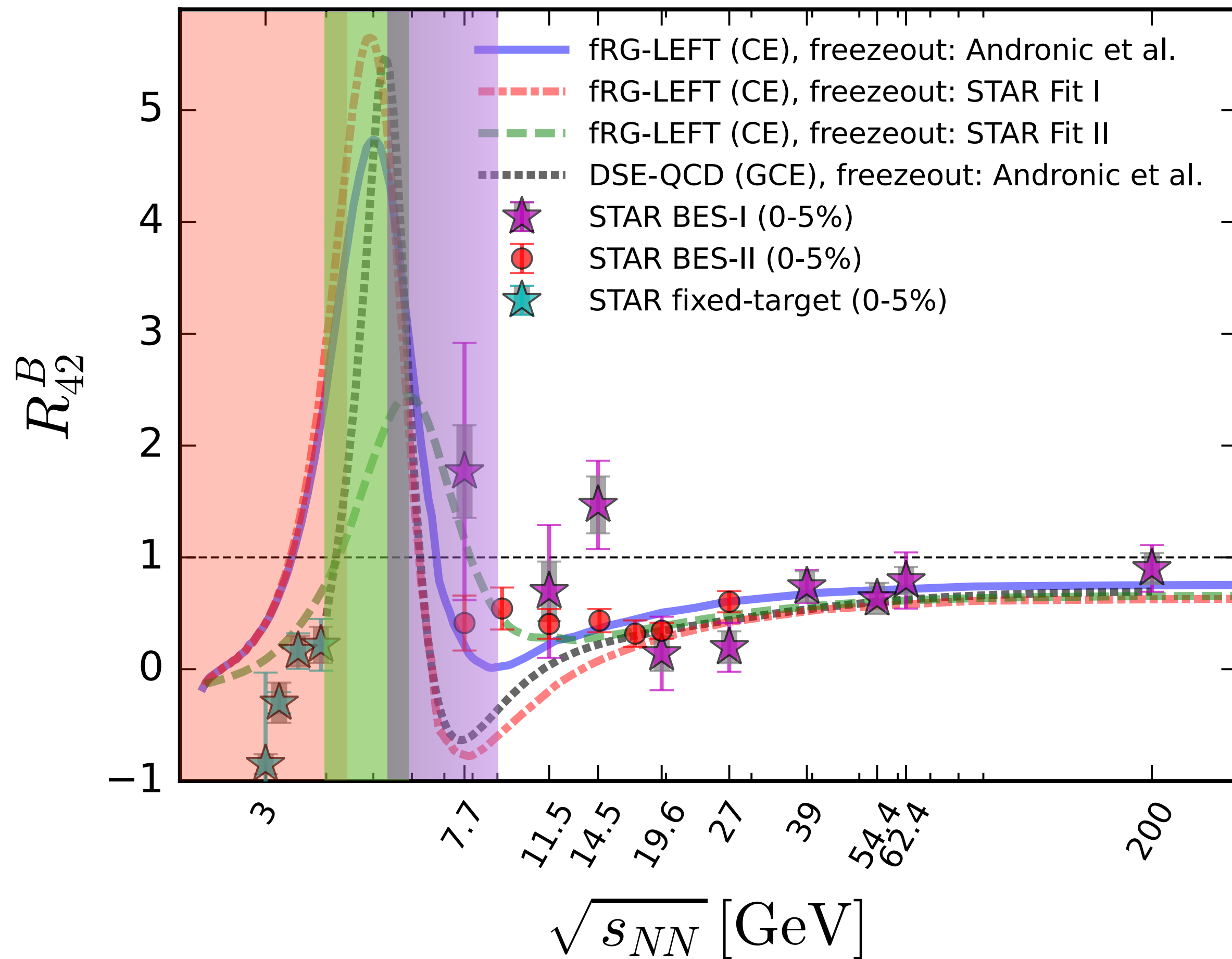
Lattice QCD

High density phase structure from functional QCD



Ripples of the critical point

net-baryon fluctuations in QCD vs net-proton fluctuations at STAR



Dominated by non-critical soft modes

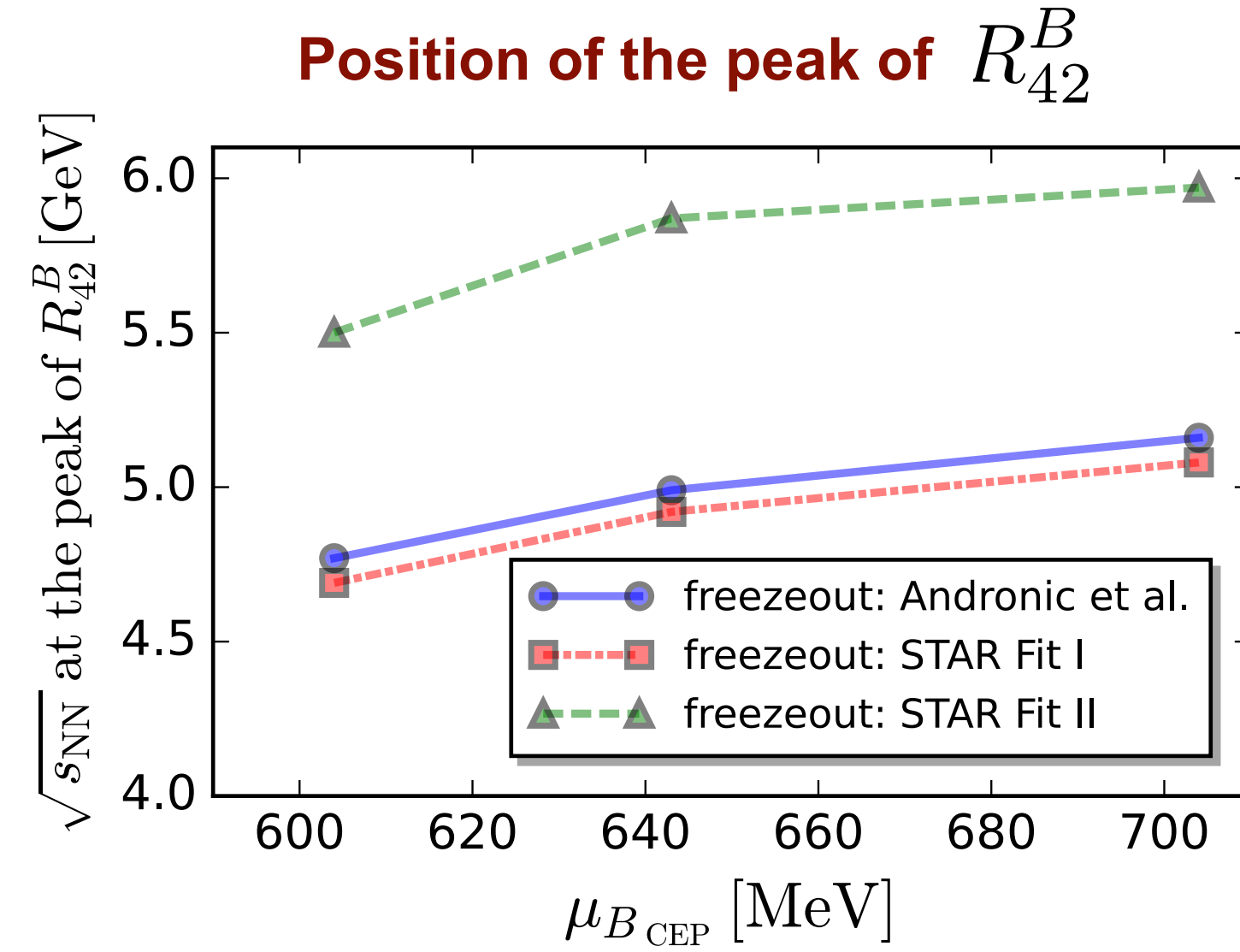
Results:
1st principles functional QCD computations
& low energy effective theories/extrapolations

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

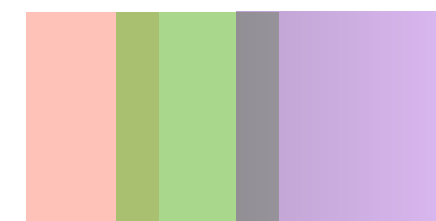
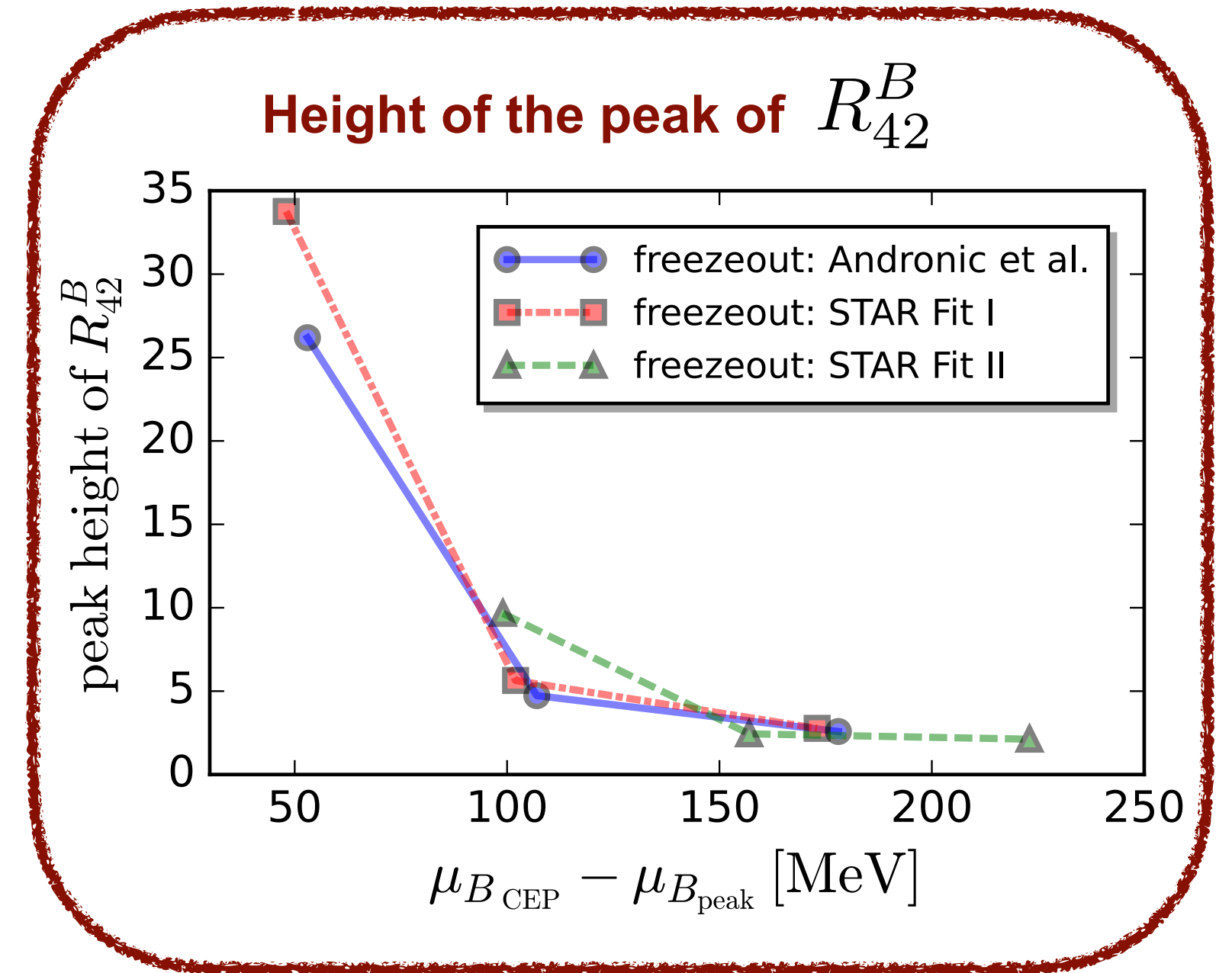
Fu, Luo, JMP, Rennecke, Yin, PRD 111, L031502

Lu, Gao, Liu, JMP, arXiv:2504.05099

Ripples of the critical point



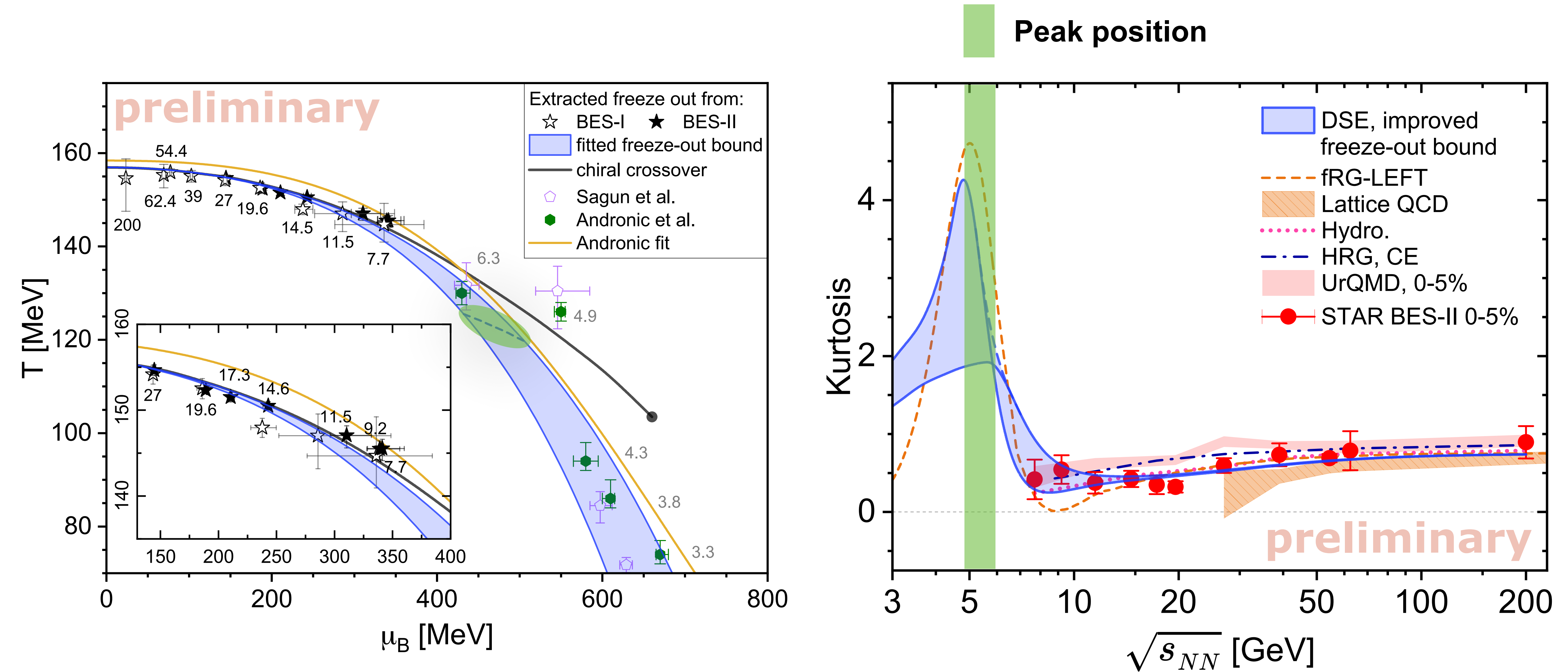
Reconstructing the CEP



Dominated by non-critical soft modes

Demand: Precise freeze-out line at high density

Functional Freeze-out

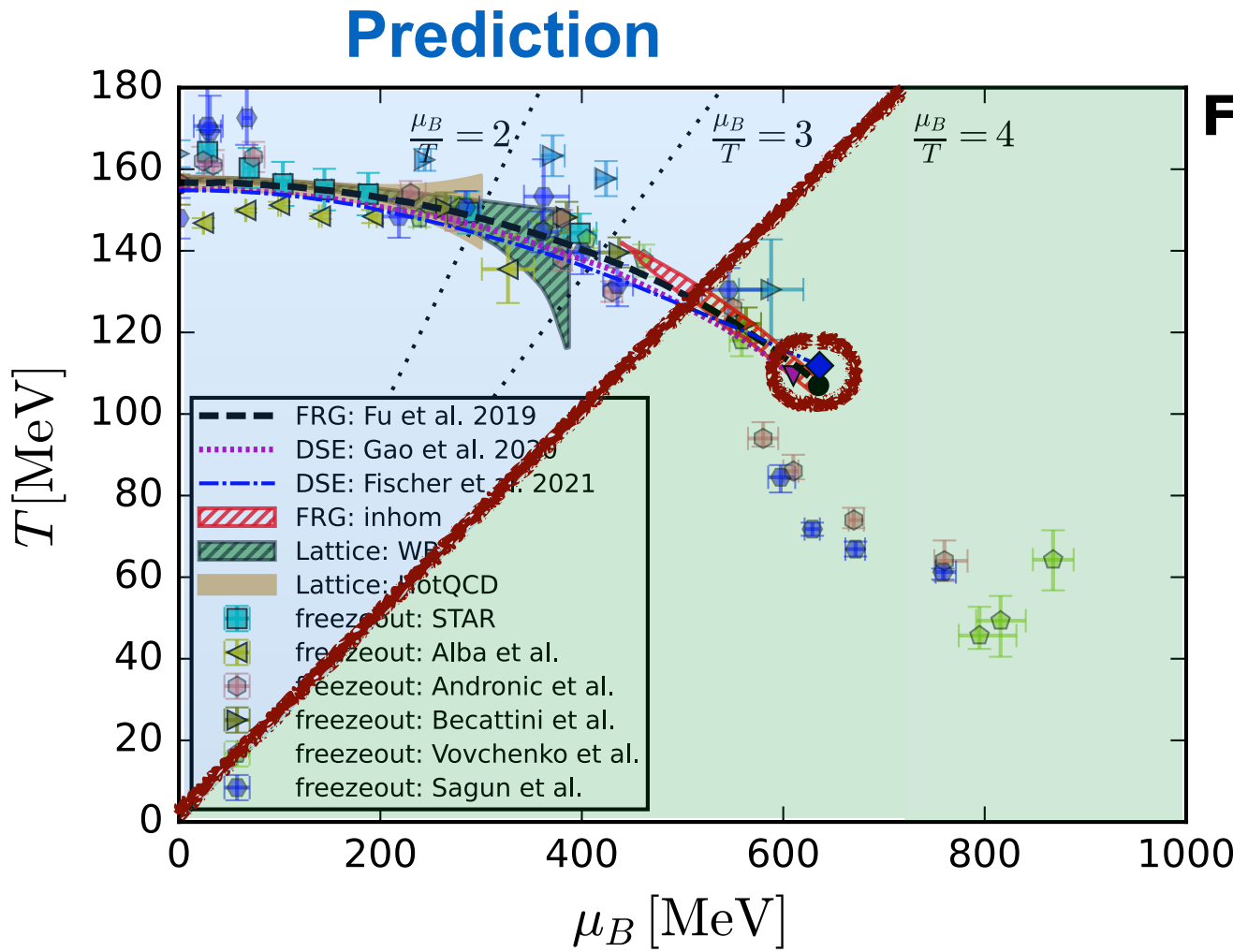


Demand: build in dynamics

The QCD Moat

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

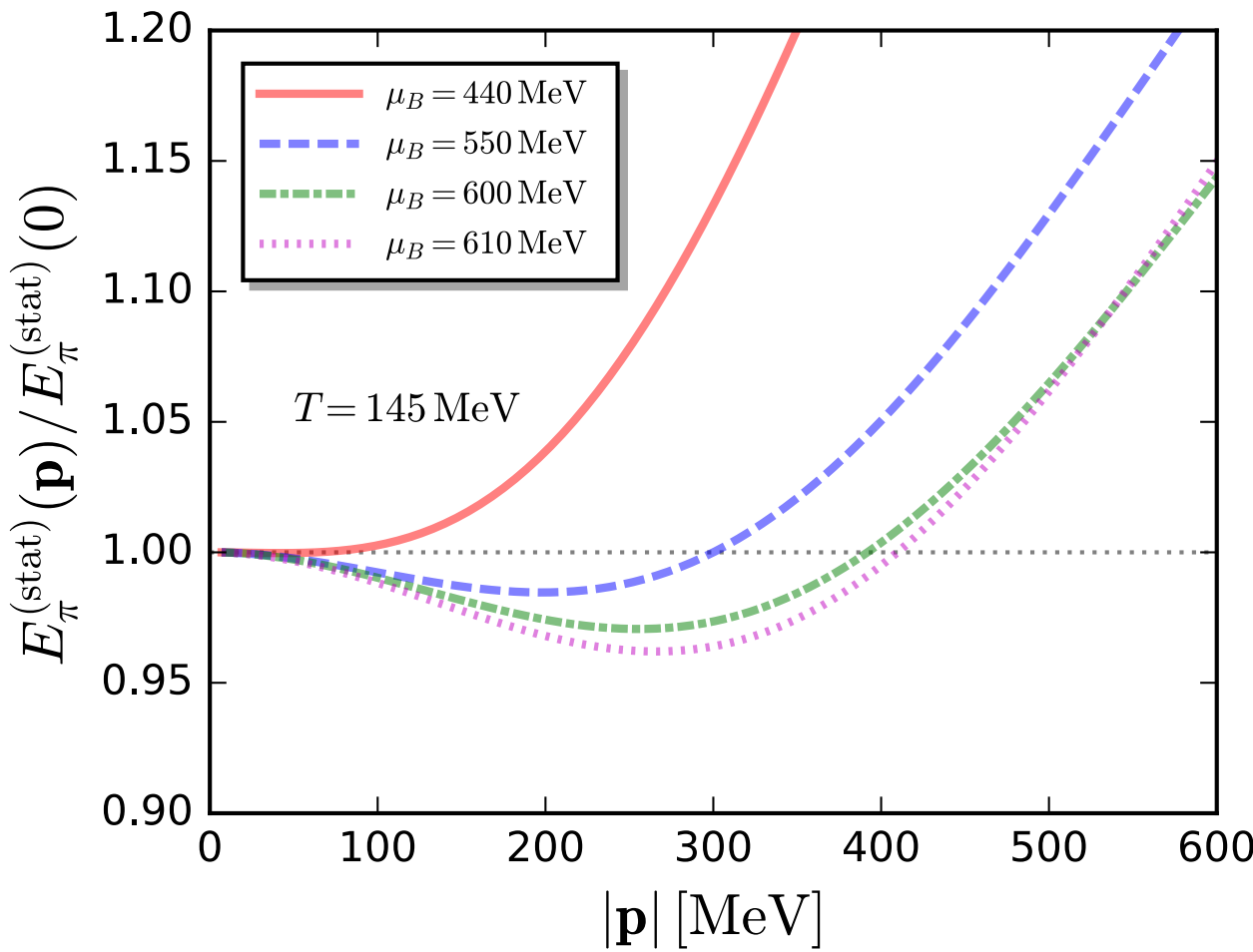


Fu, JMP, Rennecke, PRD 101 (2020) 054032

Regime of quantitative reliability
of
current best truncation

Estimate

Moat regime is not yet captured quantitatively



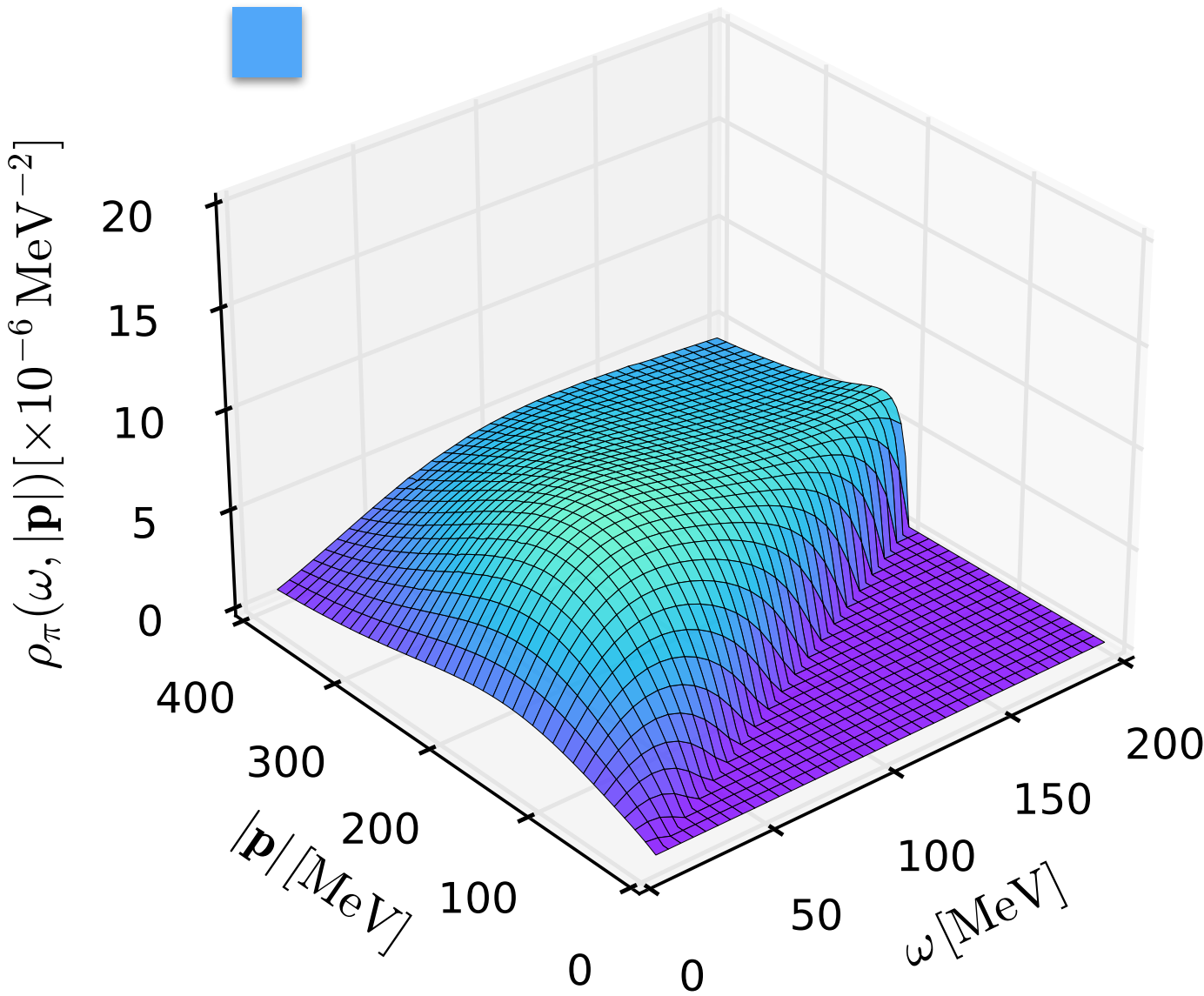
Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

The QCD Moat

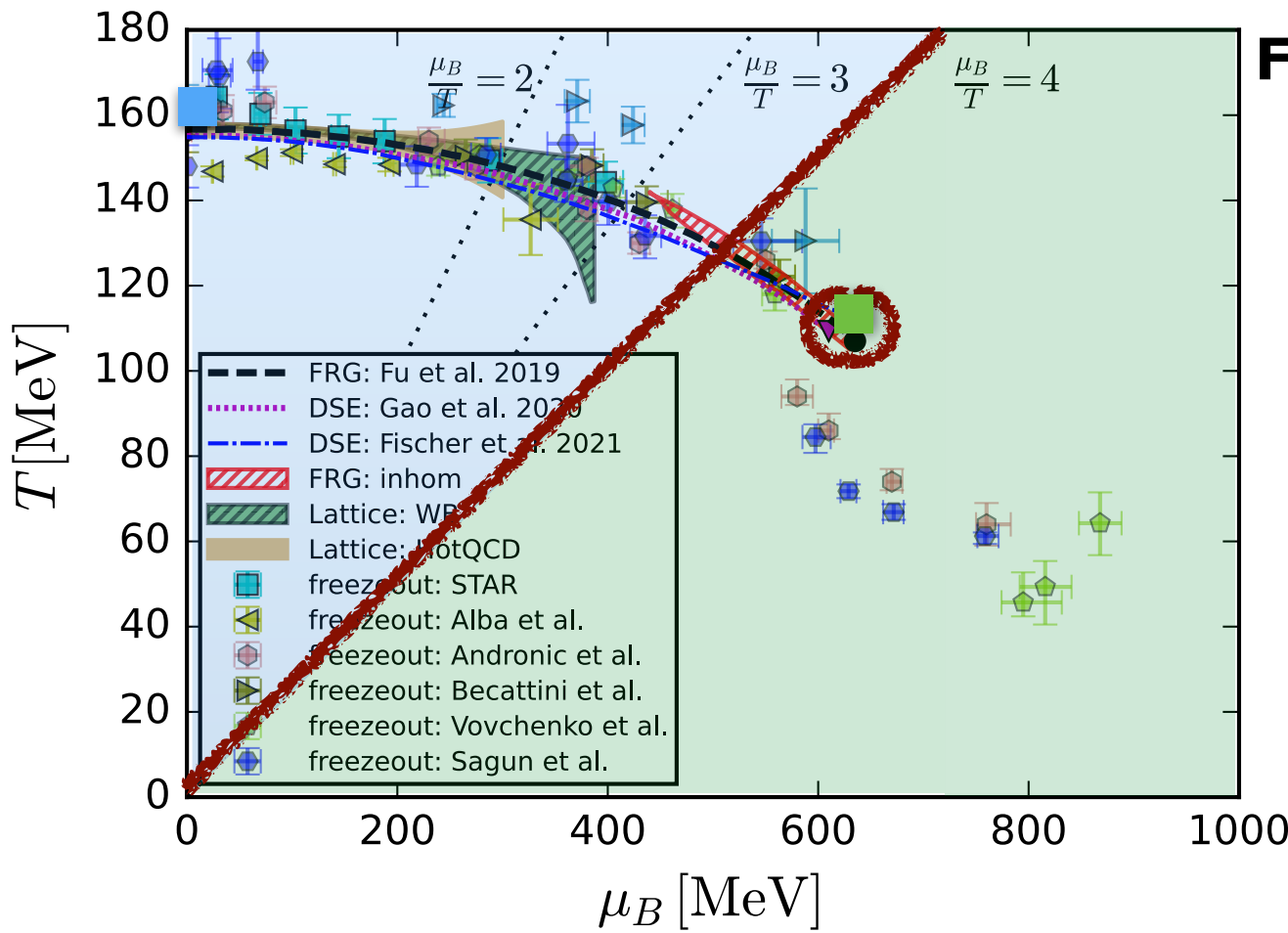
Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

T=160 MeV & $\mu_B=0$ MeV



Prediction



Fu, JMP, Rennecke, PRD 101 (2020) 054032

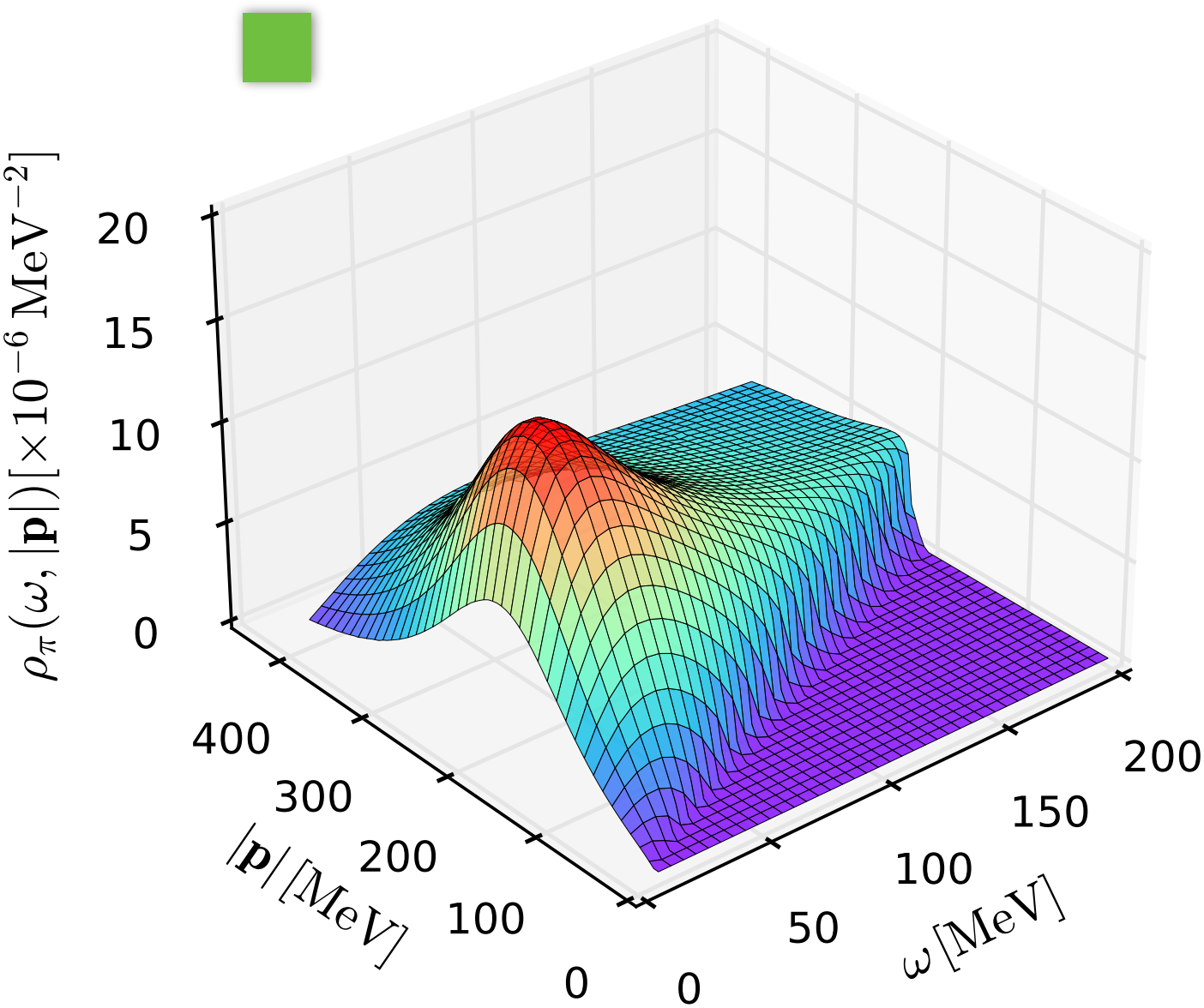
Regime of quantitative reliability
of
current best truncation

T=114 MeV & $\mu_B=630$ MeV

Estimate

Moat regime is not yet captured quantitatively

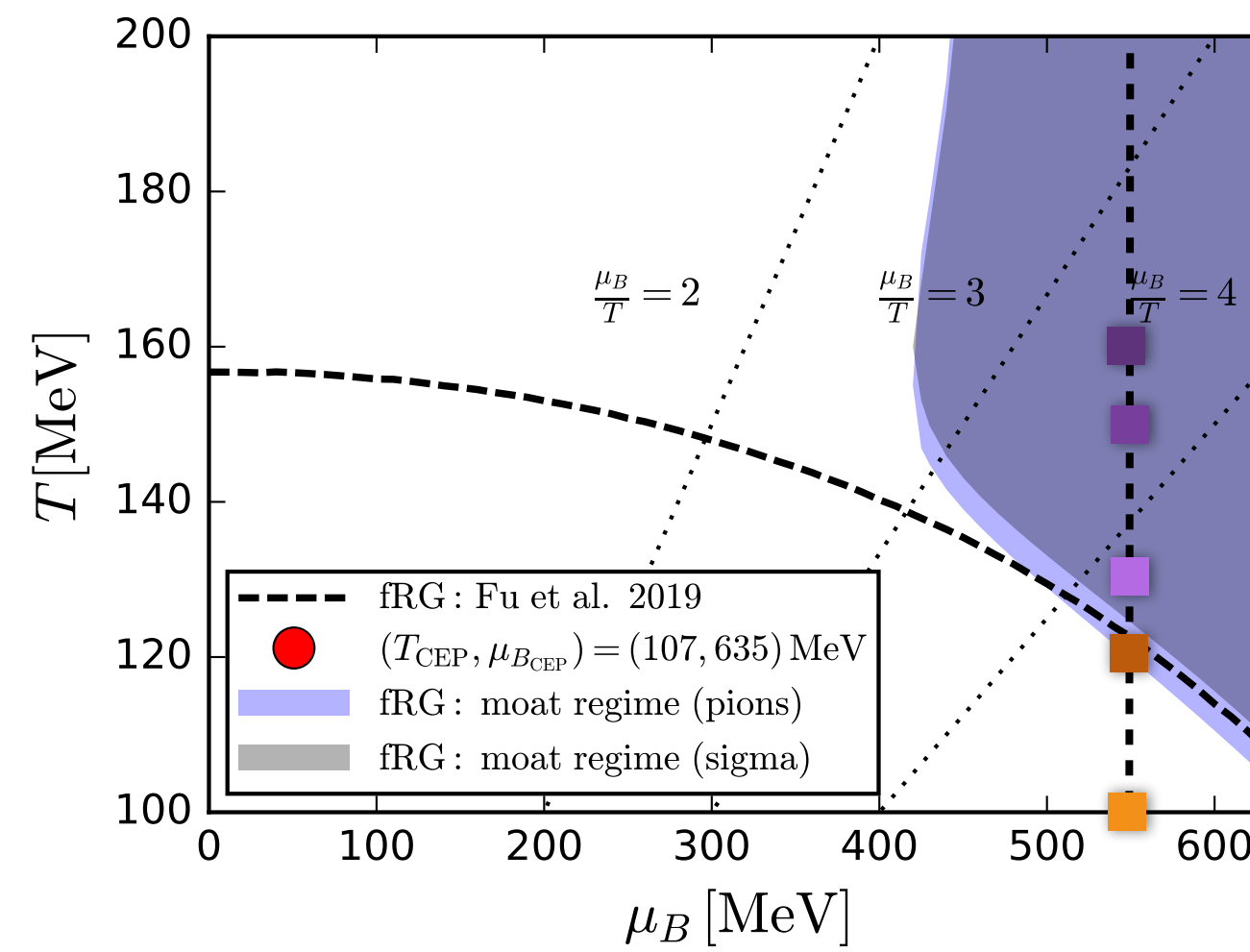
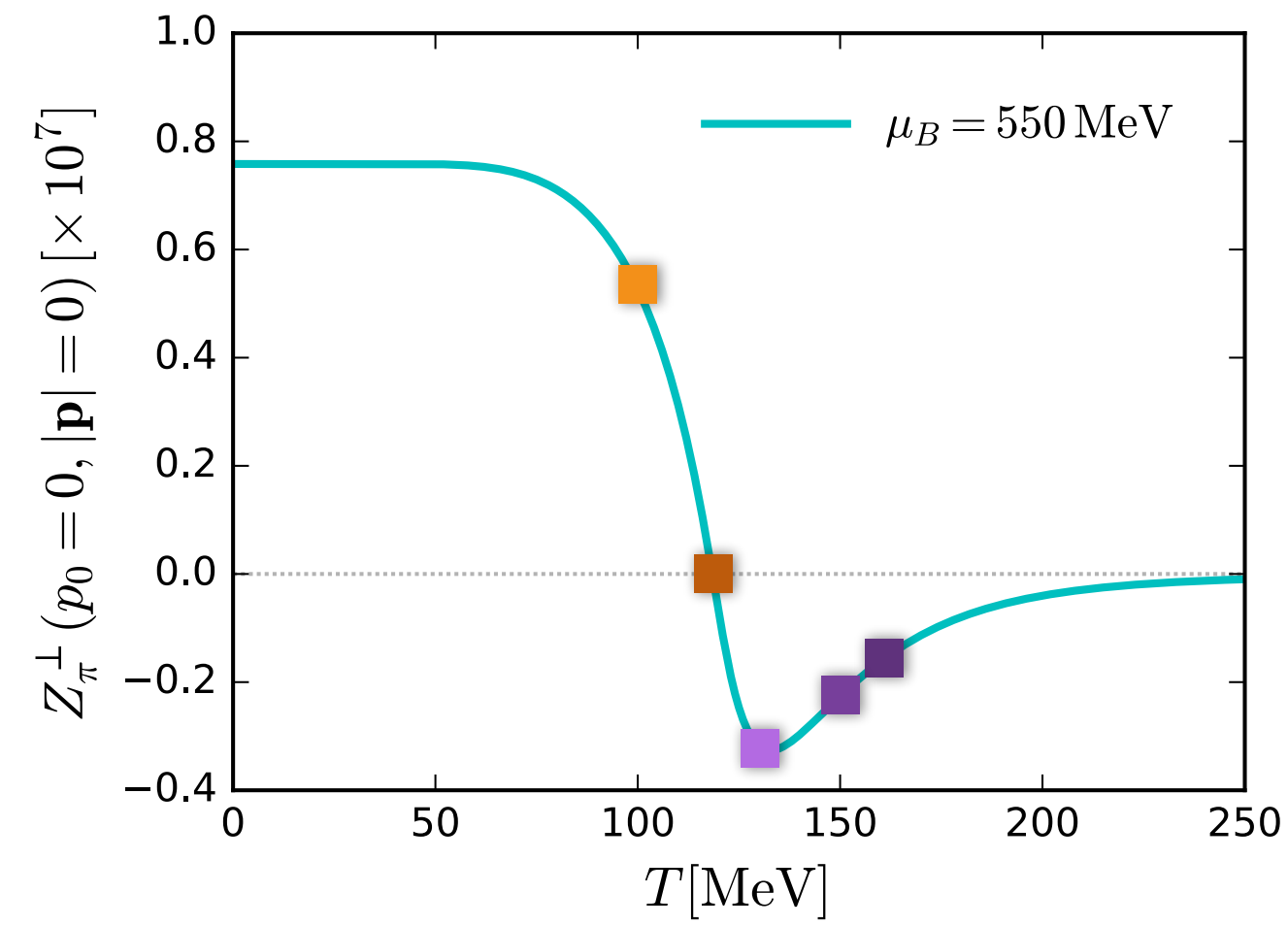
Pion spectral functions



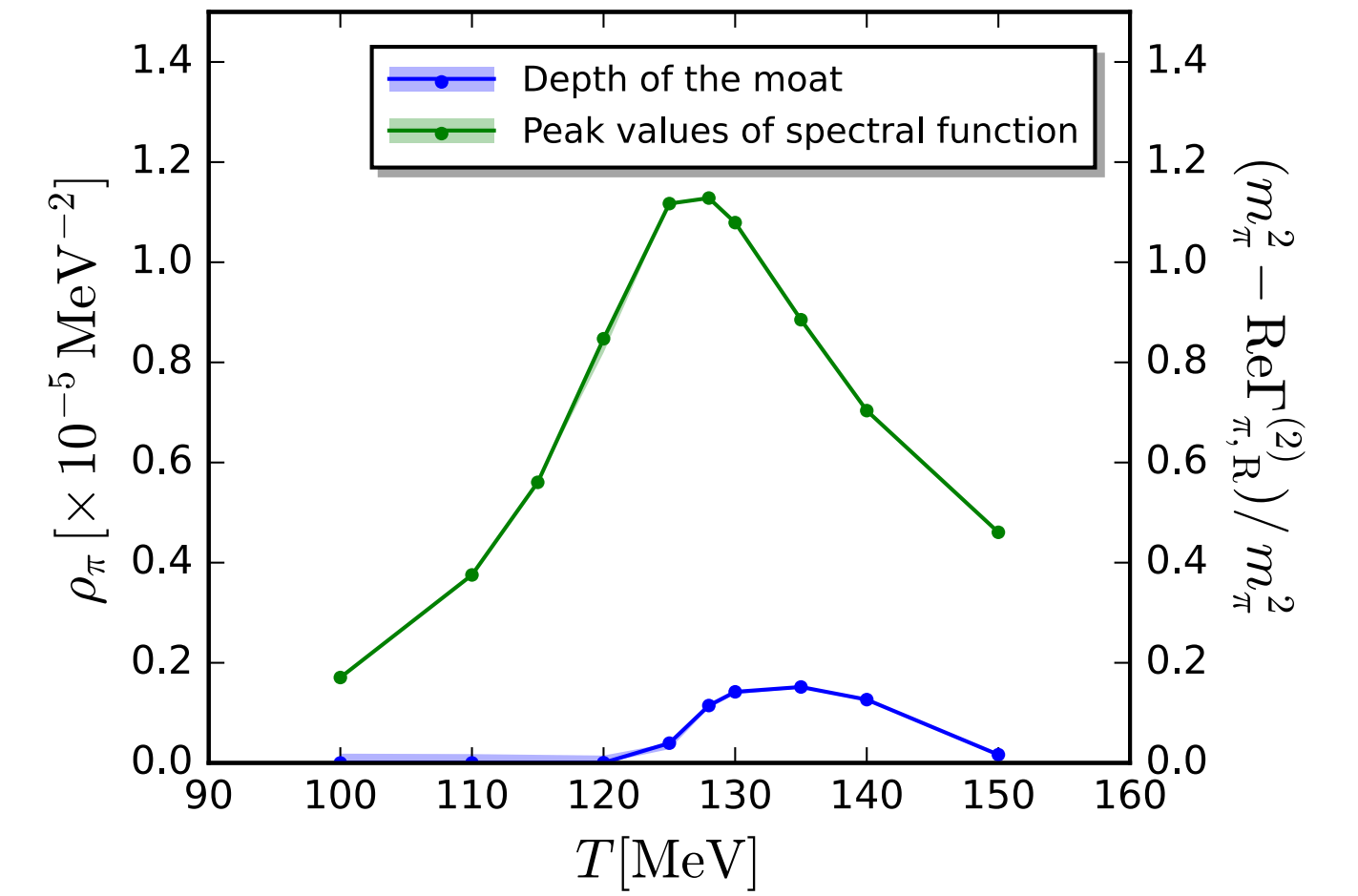
Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

The QCD Moat

Spatial wave function of the pion at $p=0$



Depth of the moat & spectral peak of the pion



Dissecting the moat & the moaton

$\mu_B = 650 \text{ MeV}$

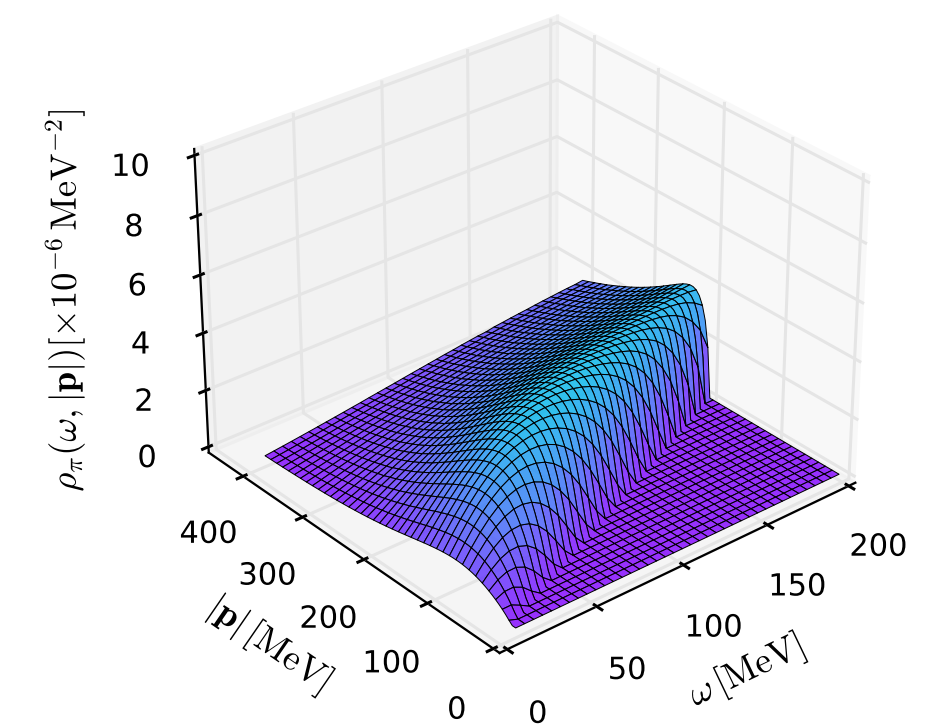
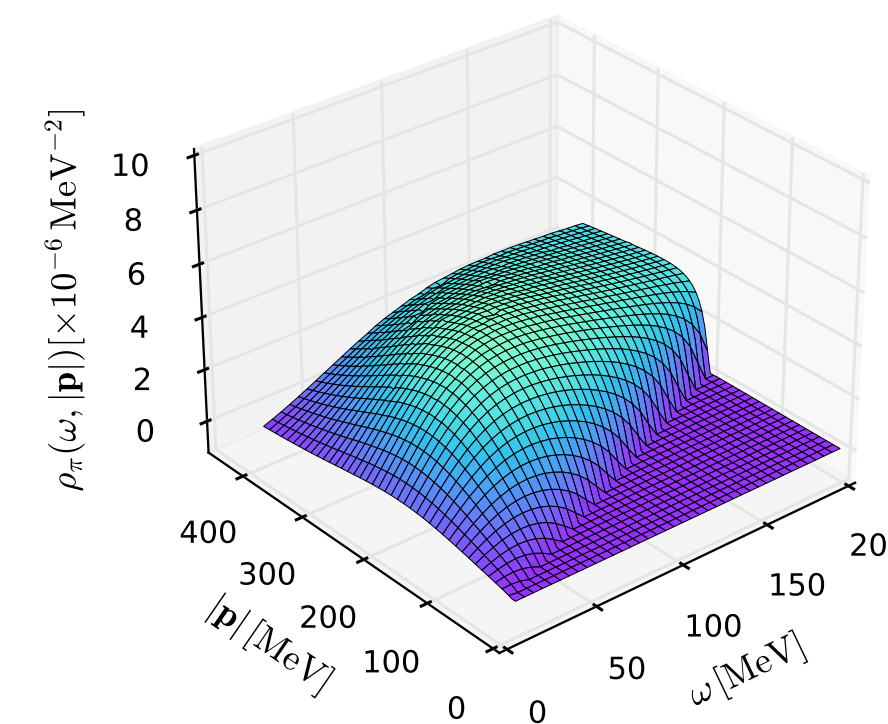
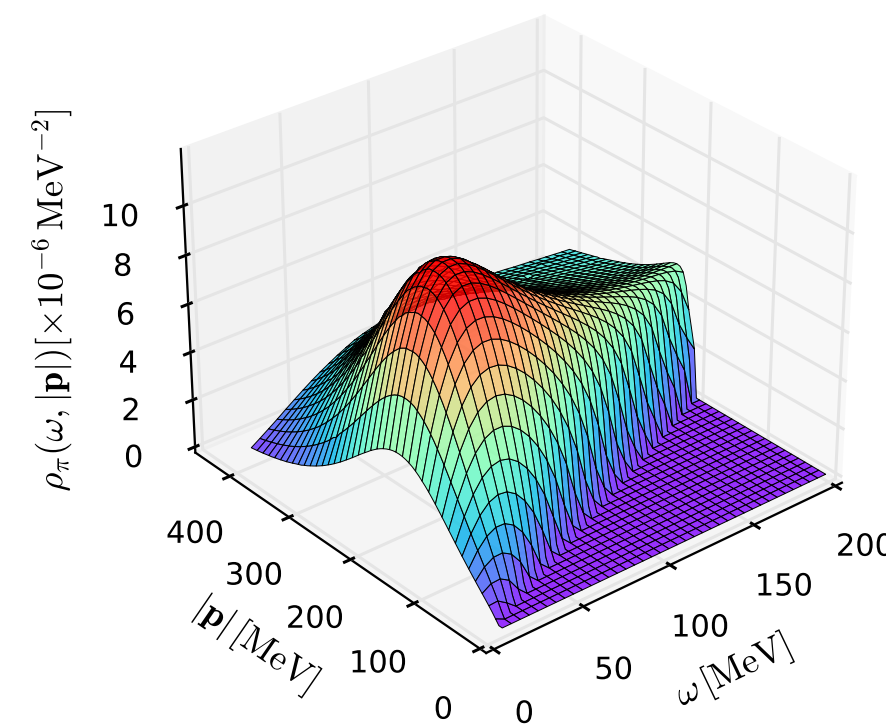
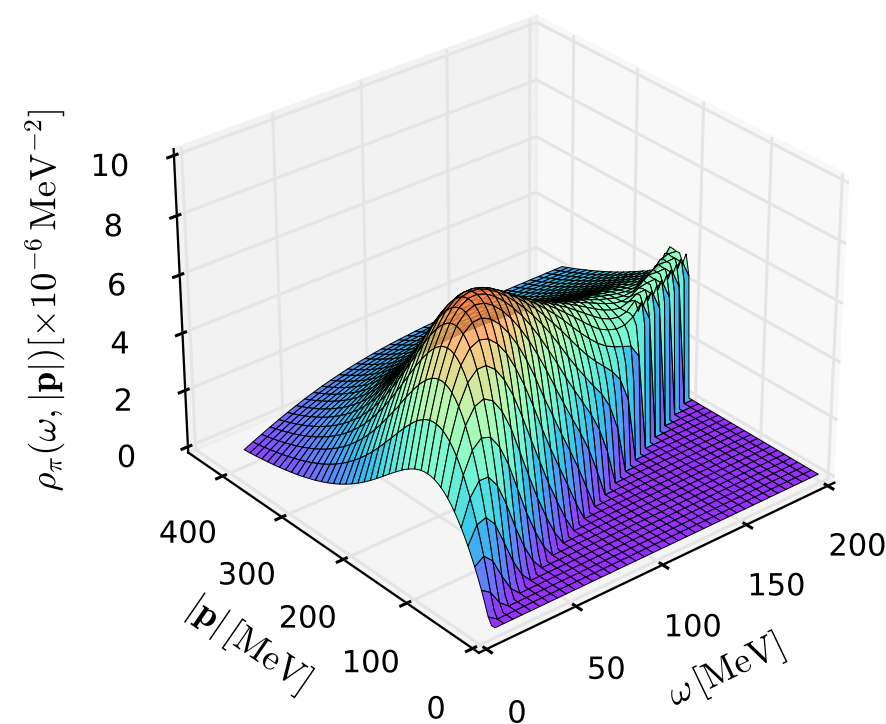
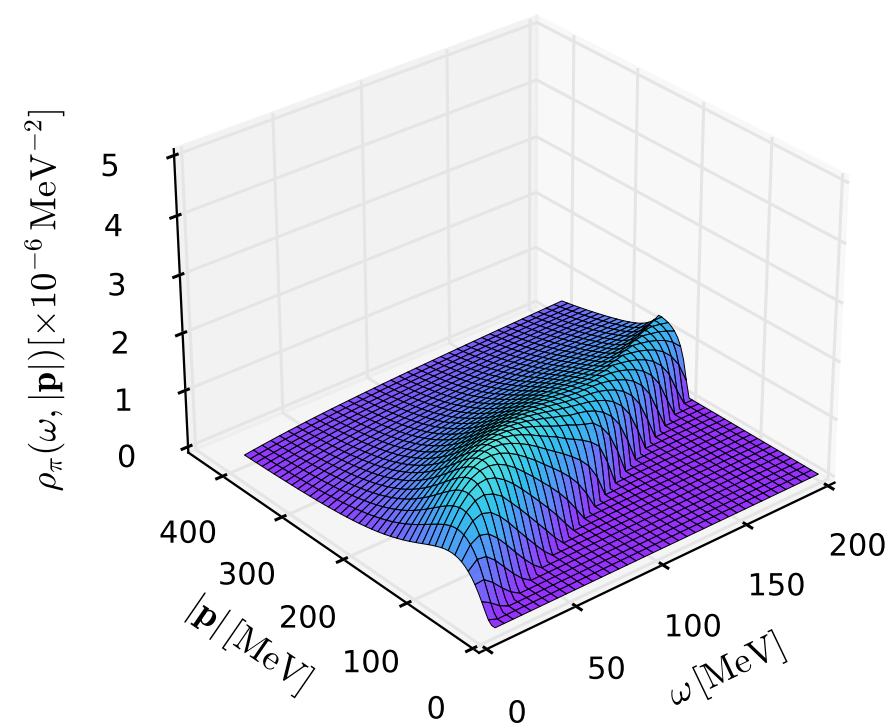
■ T=100 MeV

■ T=120 MeV

■ T=130 MeV

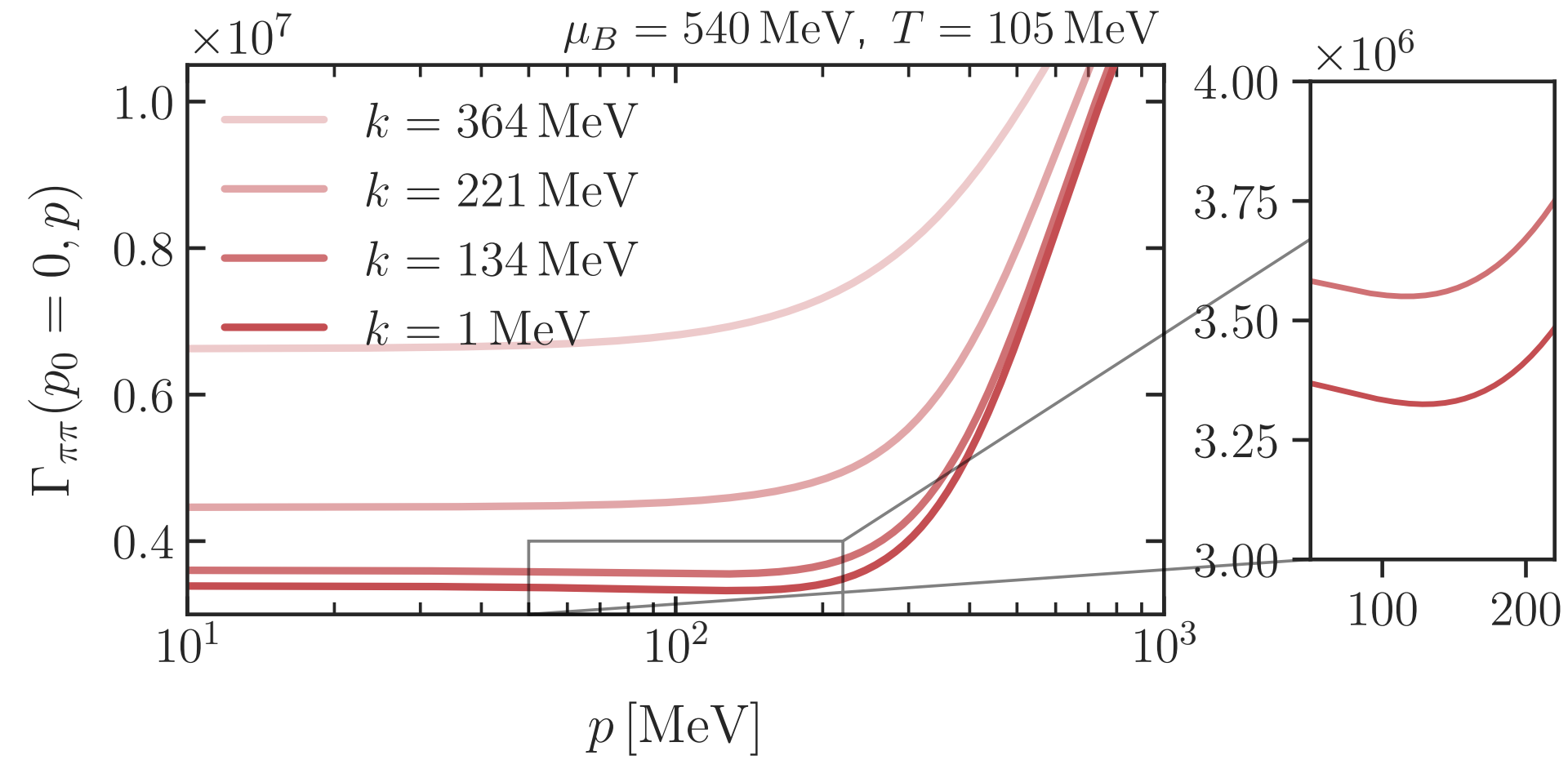
■ T=150 MeV

■ T=160 MeV

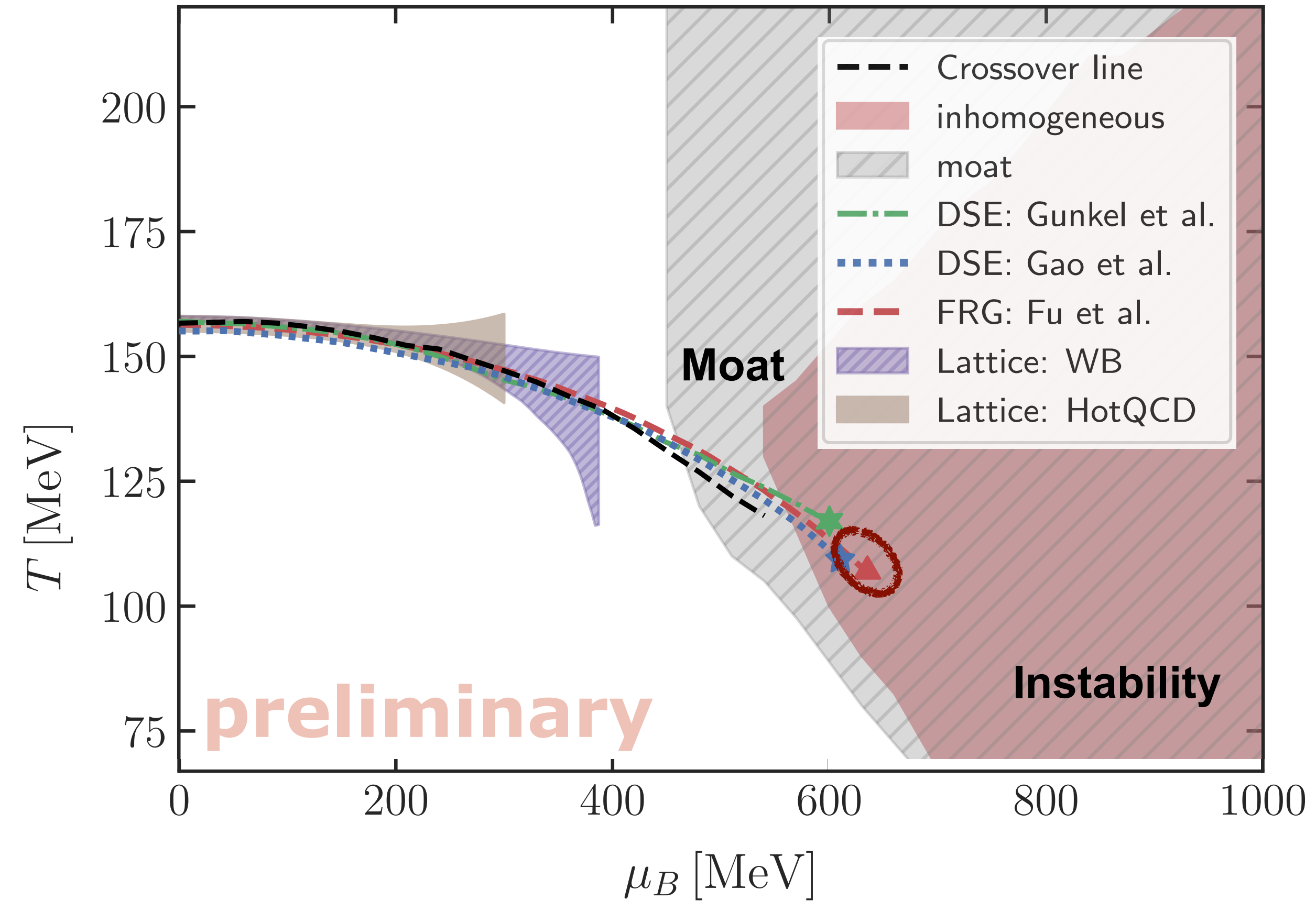
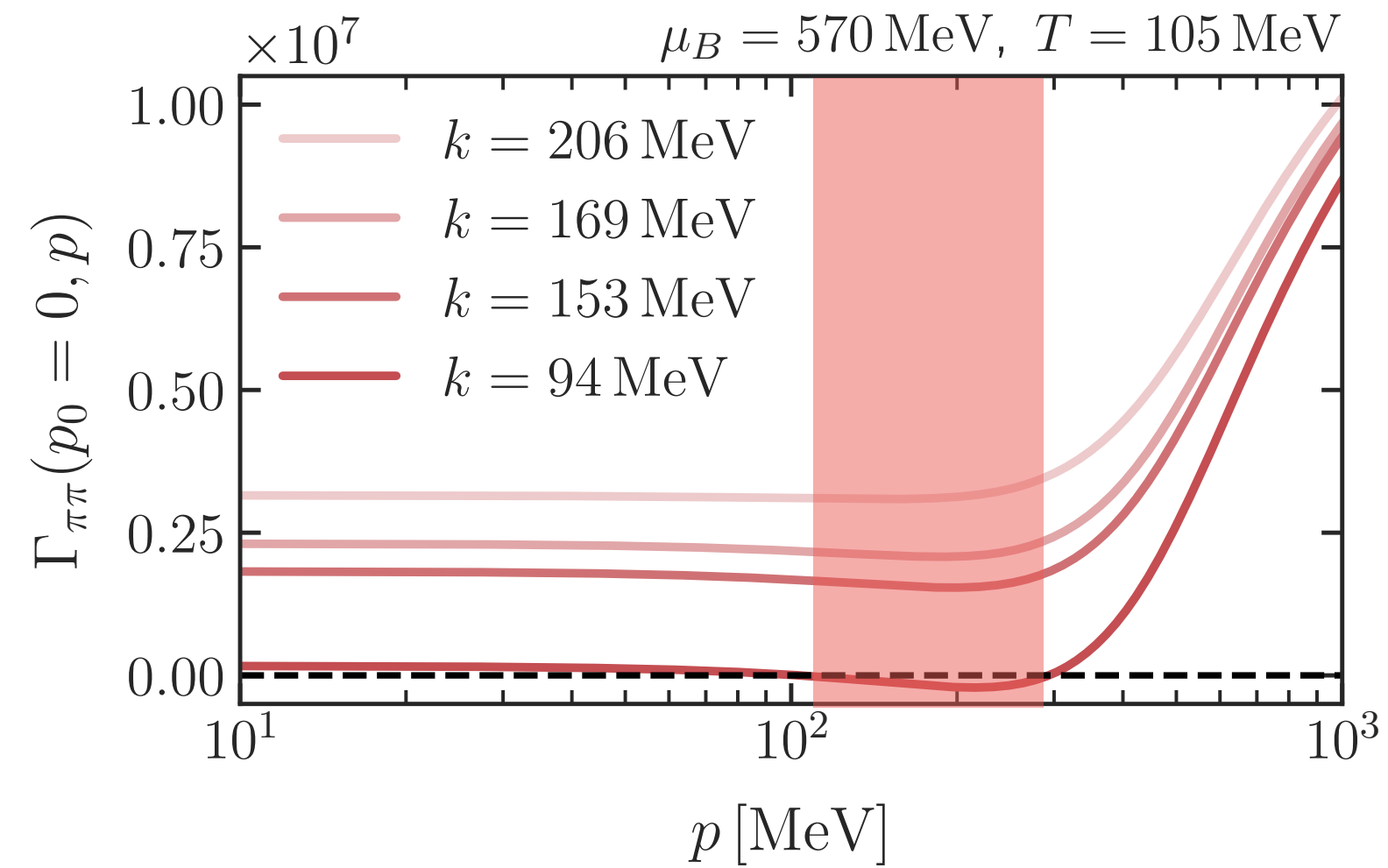


The QCD Moat

Moat



Instability

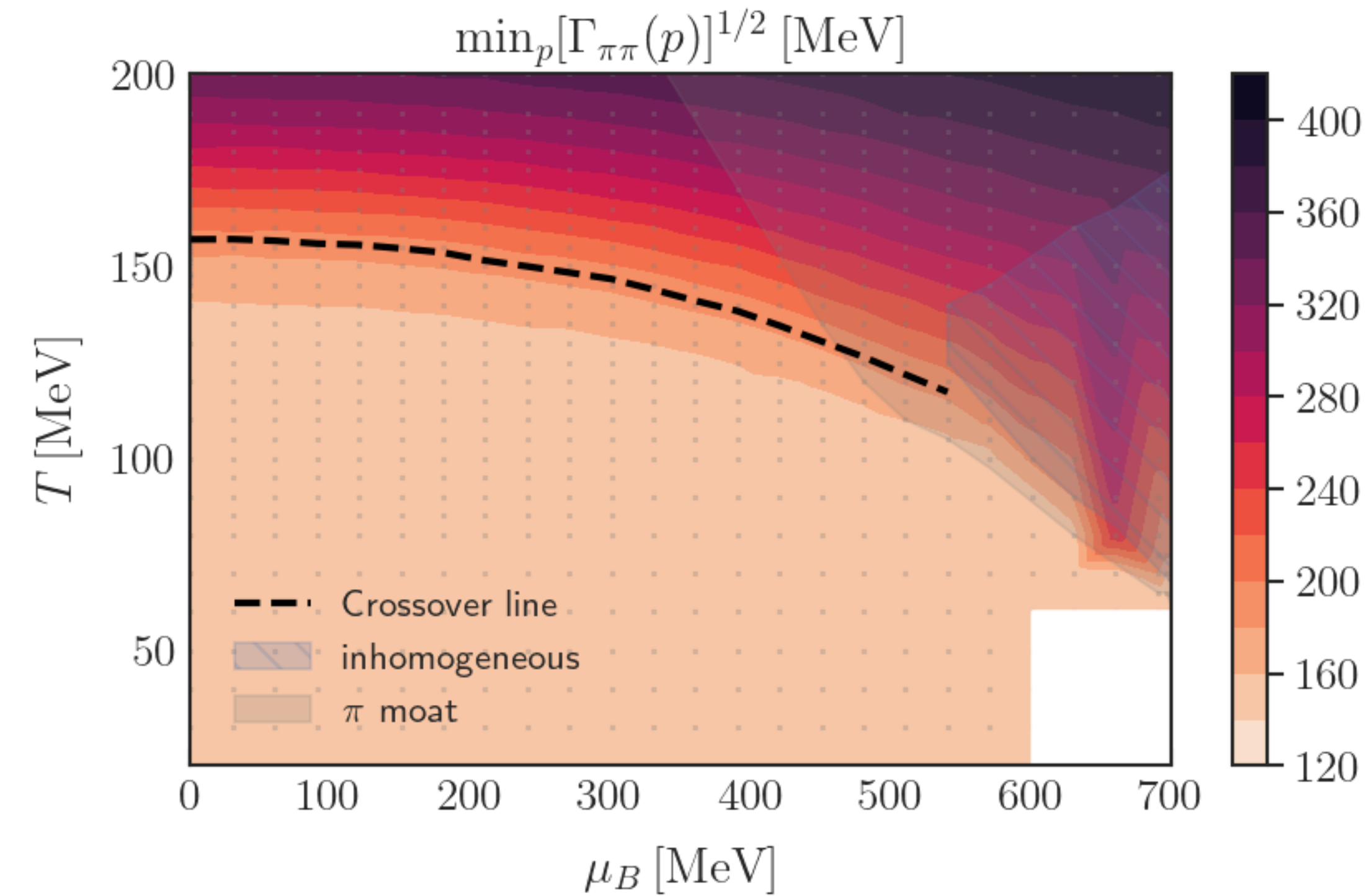


No full computation deep inside the instability regime

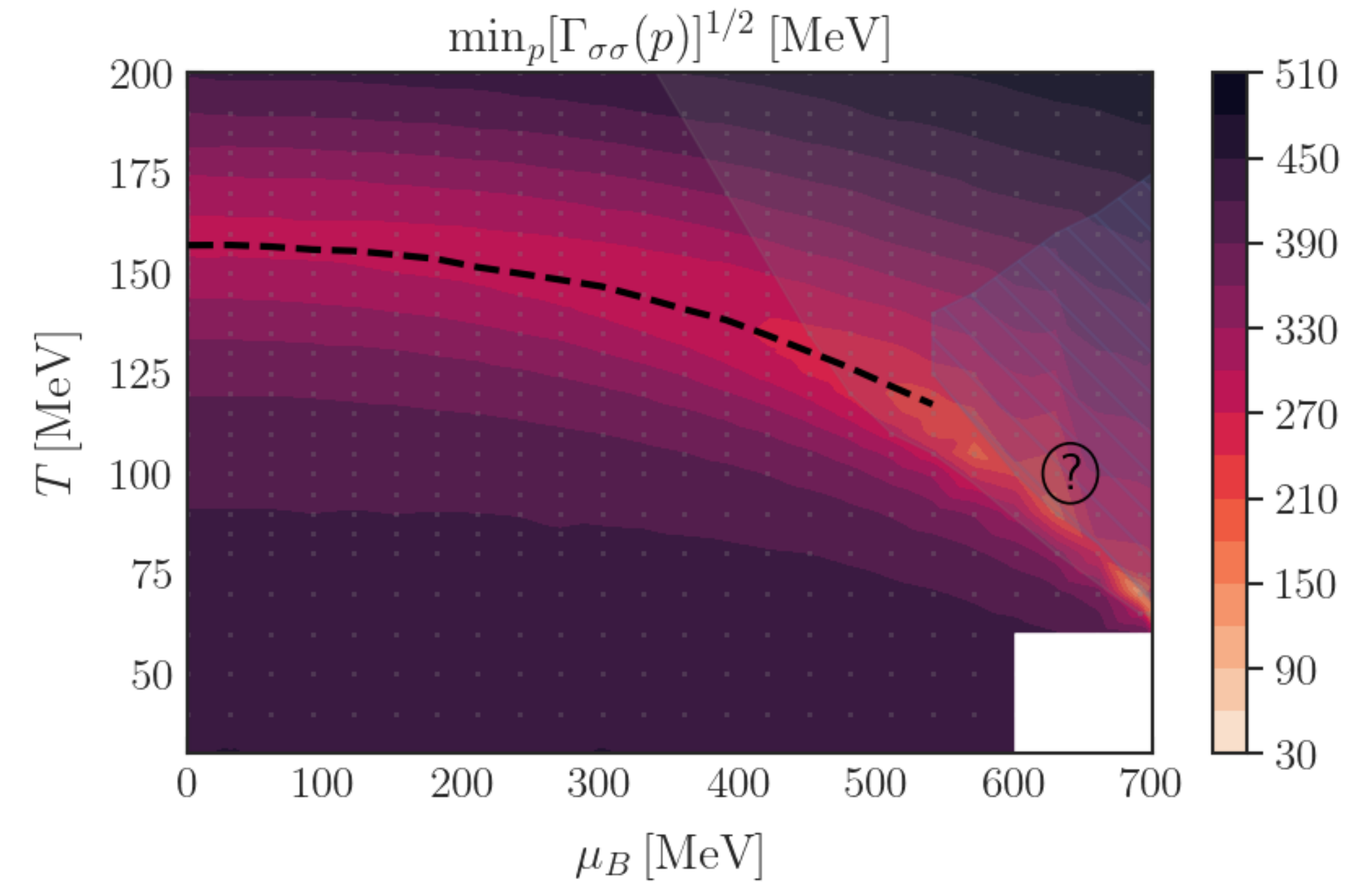
Estimated location of CEP

The QCD Moat

Pion ‘minimum’ mass



Scalar mode ‘minimum’ mass



preliminary

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No, it is not!

Most likely: too small to be measured