The QCD phase structure at finite density: Facts & Fiction

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Universität Heidelberg & ExtreMe Matter Institute

ECT* Trento, September 11th 2025

fqcd-collaboration.github.io

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Dalian, Beijing, Darmstadt, Heidelberg, Gießen

Braun, Chen, Fu, Gao, Geissel, Huang, Ihssen, Lu, Pawlowski, Rennecke,
Sattler, Schallmo, Tan, Töpfel, Wen, Wessely, Yin, Wang, Zheng, Zorbach

Selected talks

Workshop Confinement and symmetry from vacuum to QCD phase diagram:
The QCD phase structure from first principles

Satellite meeting Quark Matter 2025: Physics at high net-baryon densities:
New Insights on the Phase Structure with Functional QCD

PhD school xQCD 2024:
Functional QCD and the QCD phase structure

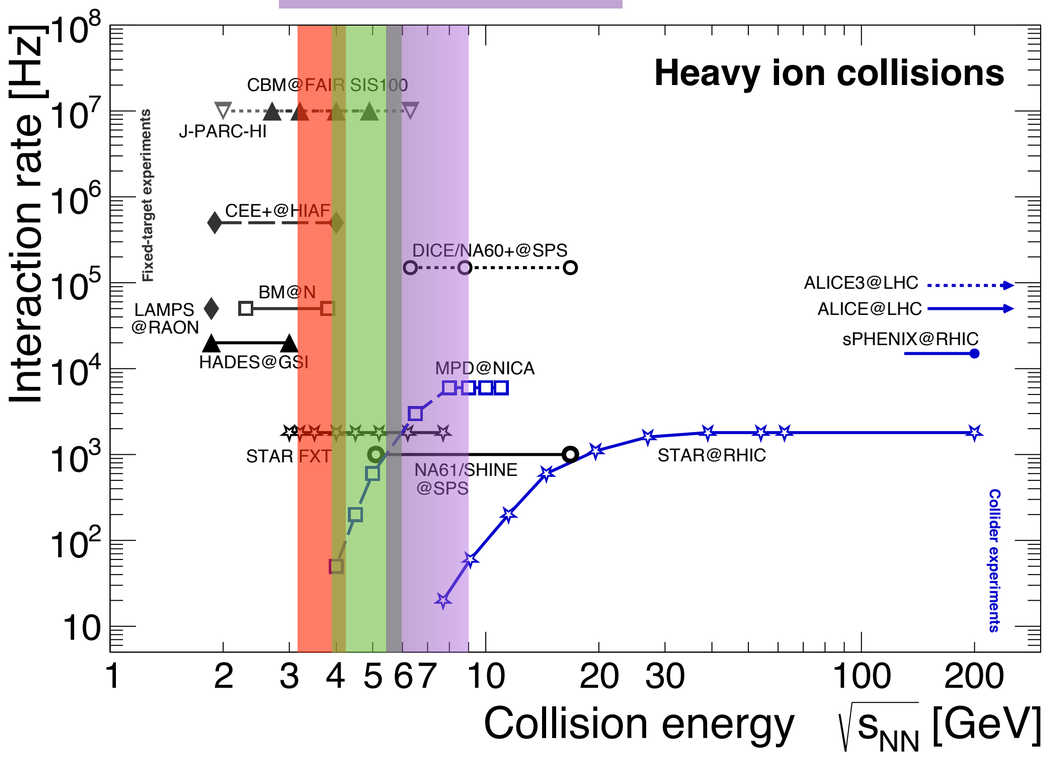
Experimental & Theoretical Landscape

Experimental landscape

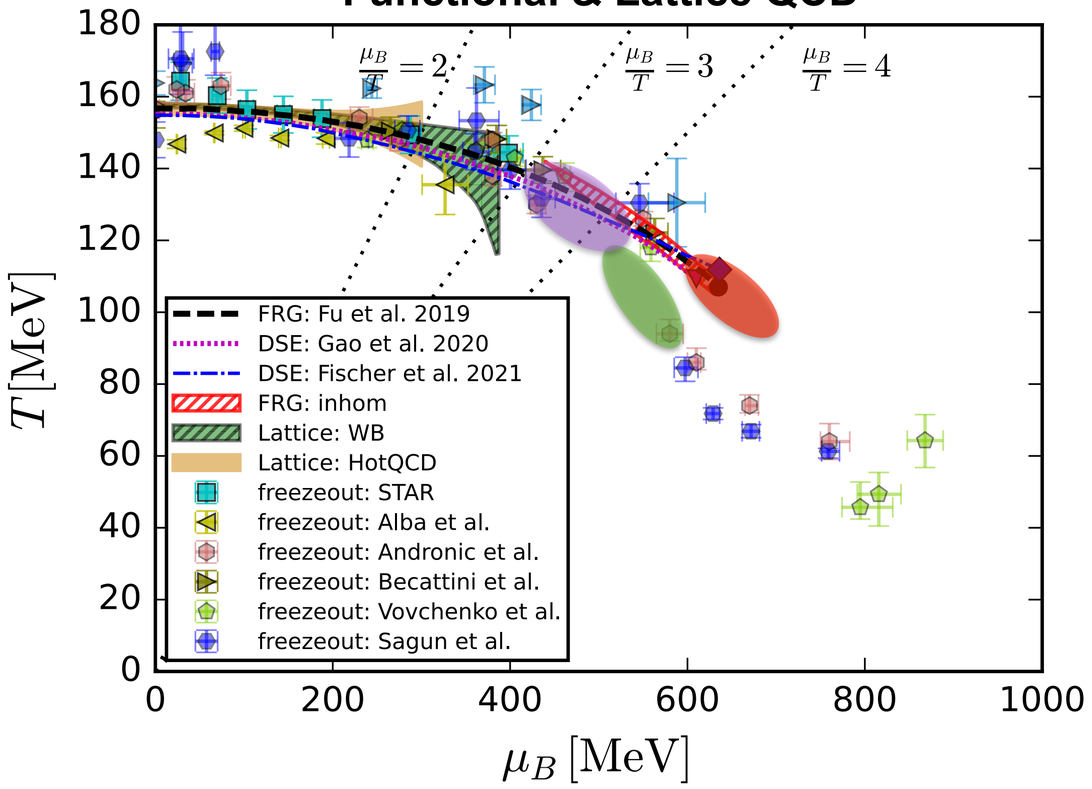
Theoretical landscape

Onset of new physics (CEP)

Transition regime



Functional & Lattice QCD



Peak of kurtosis at the freeze-out line

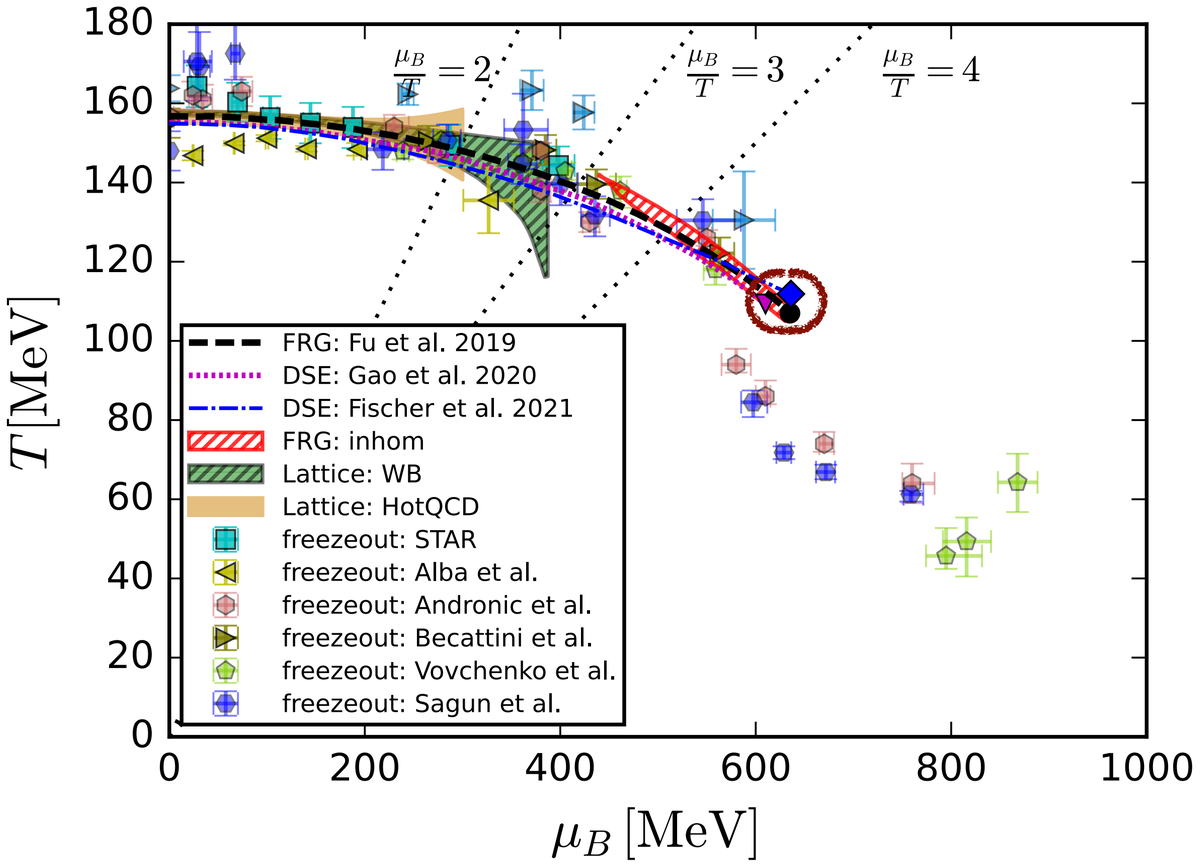
Galatyuk, A982 (2019) update 2025; CBM, EPJA 53 3 (2017) 60

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

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

Comprehensive QCD phase structure



Functional QCD: CEP estimate

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

DSE: Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

$$(\mu_B\,,\,T)_{\mathrm{CEP}} \sim (600-650\,,\,105-115)\ \mathrm{MeV}$$

Lattice:

HotQCD:
Bazavov, Ding, Hegde, Kaczmarek, Karsch, Karthik, Laermann, Lahiri, Larsen, Li, Mukherjee, Ohno, Petreczky, Sandmeyer, Schmidt, Sharma, Steinbrecher,
PLB 795 (2019)

WB:
Borsányi, Fodor, Guenther, Kara, Katz, Parotto, Pasztor, Ratti, Szabo,
PRL 125 (2020) 052001

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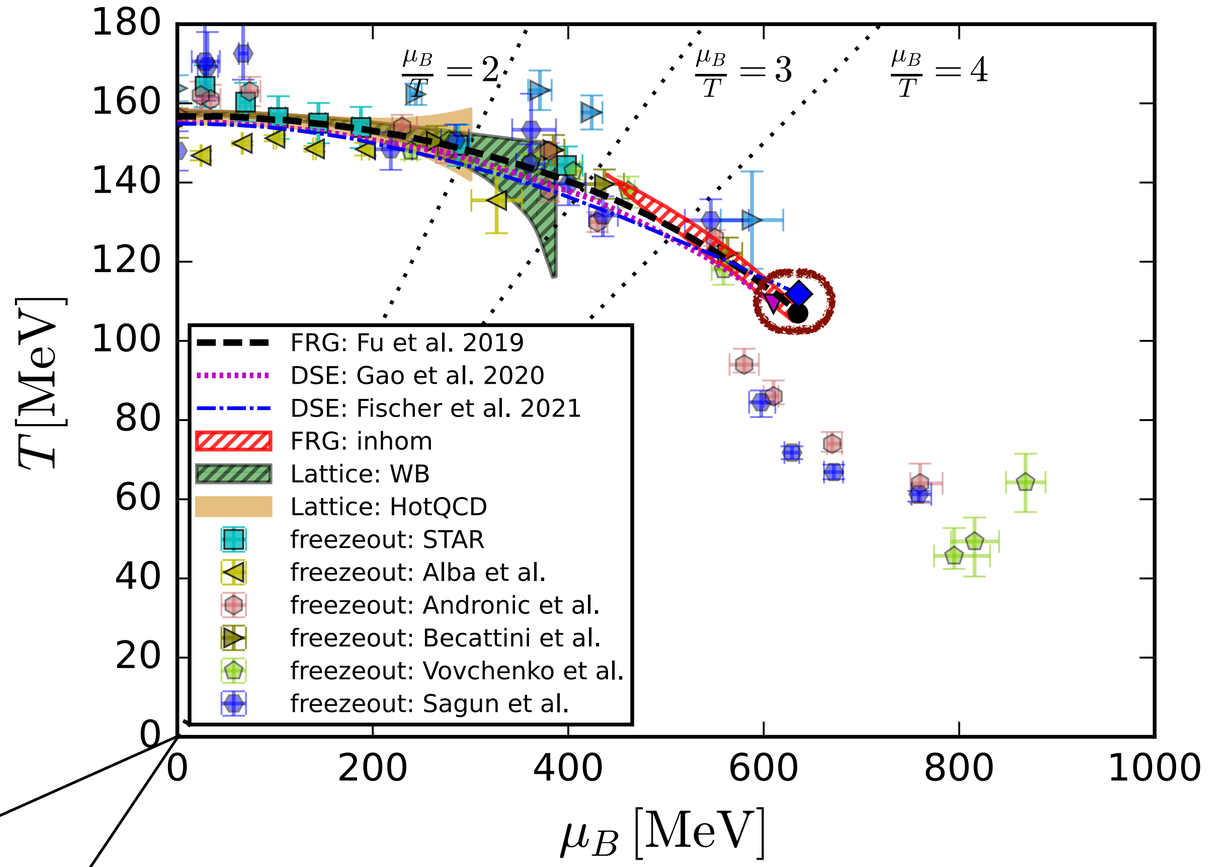

$\mu_{B,\mathrm{Im}}$

m_q

μ_{Iso} B

Collect all possible information/structure for physics understanding & extrapolations

Functional QCD: CEP estimate

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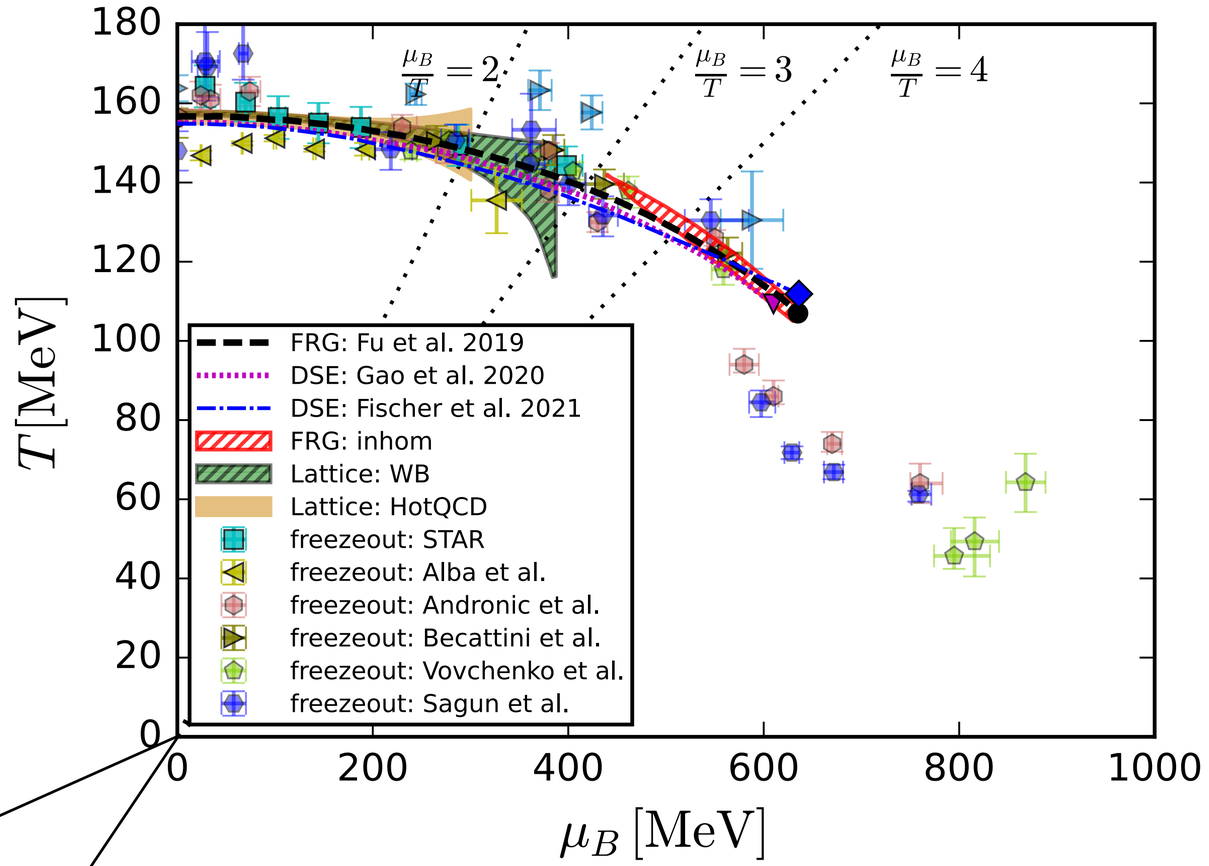

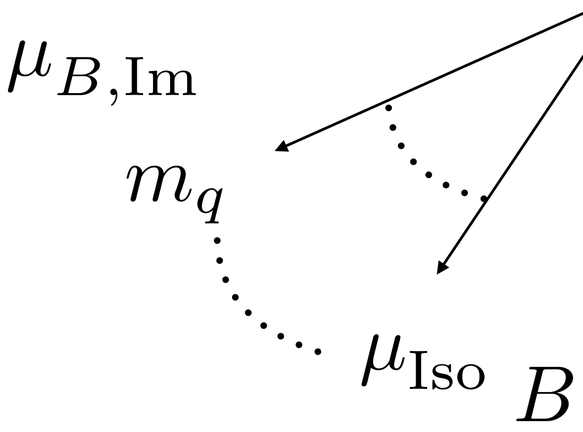

- **What bases work**
- **Extrapolation limits**

⋮

Direct computations and the minimal point of view

Those are my interpretations,
and if you don't like them….
well, I have others

- **Self-consistent truncations to functional relations define analytic functions in μ_B , eg:**

$$\partial_t \Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B) = \mathrm{Loop}\left[\Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B),\ \Big\langle q(x)A_\mu(y)\bar{q}(z)\Big\rangle(\mu_B), \cdots;\ \mu_B\right]$$

Yang-Lee: see talk of Fei Gao

Extrapolations: See talk of Shi Yin

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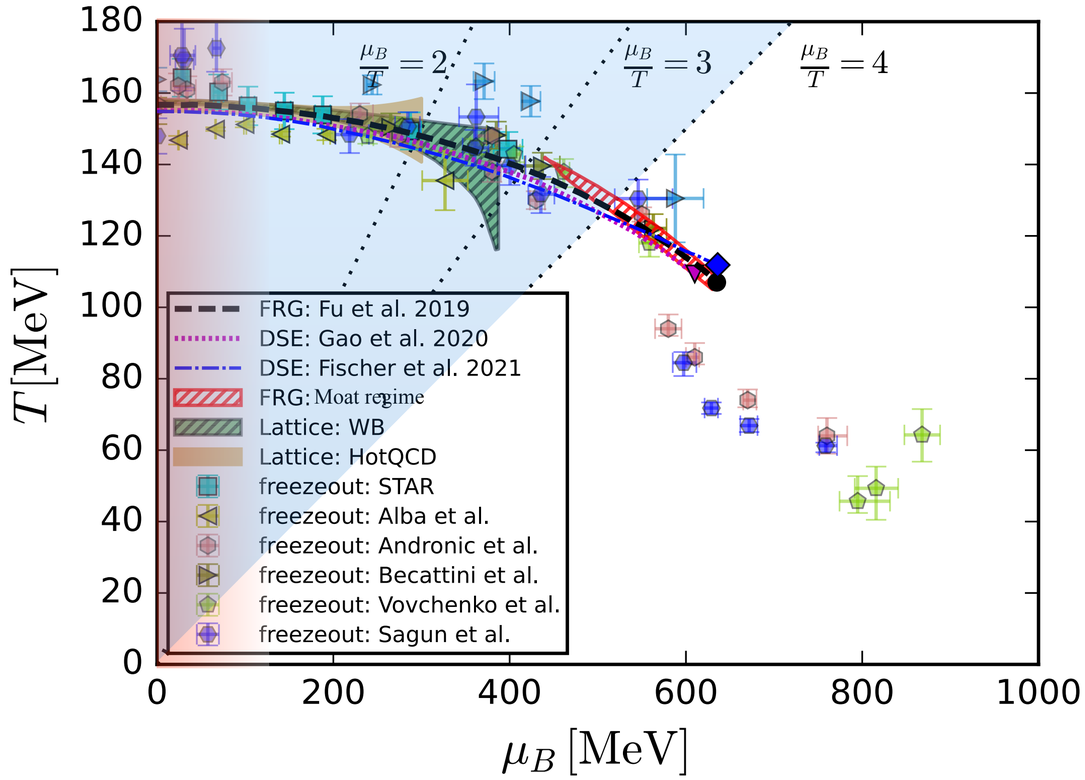
Yang-Lee: see talk of Fei Gao

- **Consequences for functional QCD predictions at finite density**

Extrapolations: See talk of Shi Yin



By now the best truncations to functional QCD pass lattice benchmark tests at vanishing and small chemical potential

Regime of quantitative reliability of current best truncation

Unique: QCD-based analytic continuations that satisfy the lattice benchmarks at small chemical potential.

Great opportunity for a combined analysis of high density QCD (Exp. data + lattice QCD + functional QCD + LEFTs)

QCD phase structure at finite density: Facts & Fiction

Facts

$\mu_B = 0$

- **Chiral crossover at about**

$$T_\chi \approx 155\,\mathrm{MeV}$$

- **Strongly correlated phase for temperatures**

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

$\mu_B \neq 0$

- **No chiral critical end point for**

$$\mu_B \lesssim 600\,\mathrm{MeV}$$

- **No chiral crossover for**

$$\mu_B \gtrsim 700\,\mathrm{MeV}$$

Fiction

$\mu_B = 0$

- **Physical QCD is in the chiral scaling regime**

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

Soft modes are commonplace

- **Confinement crossover is at XXX**

$$T_\chi \lesssim T_{\mathrm{conf}} \lesssim 2\,T_\chi$$

$\mu_B \neq 0$

- **There is a CEP**

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

- **Scaling regime (Ising) of the CEP is humongous**

No, it is not! **Most likely: too small to be measured**

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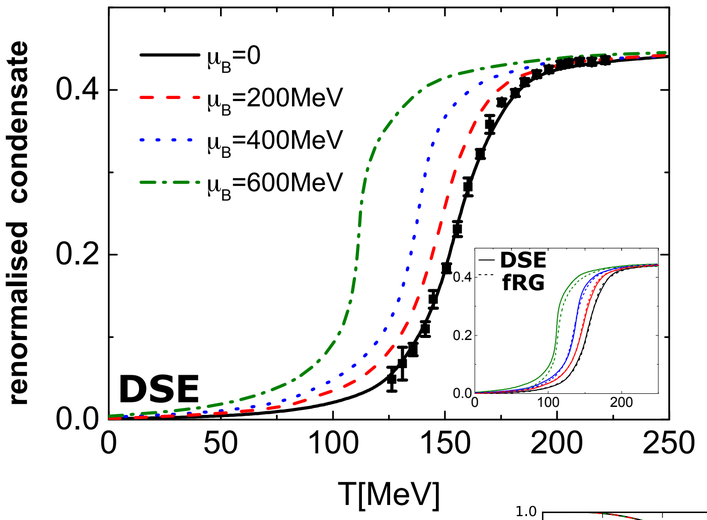
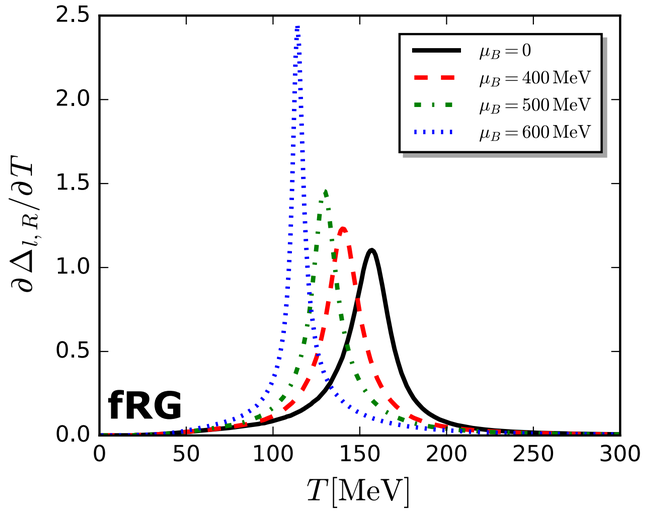
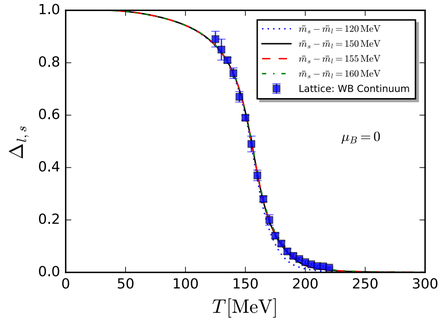
Functional QCD

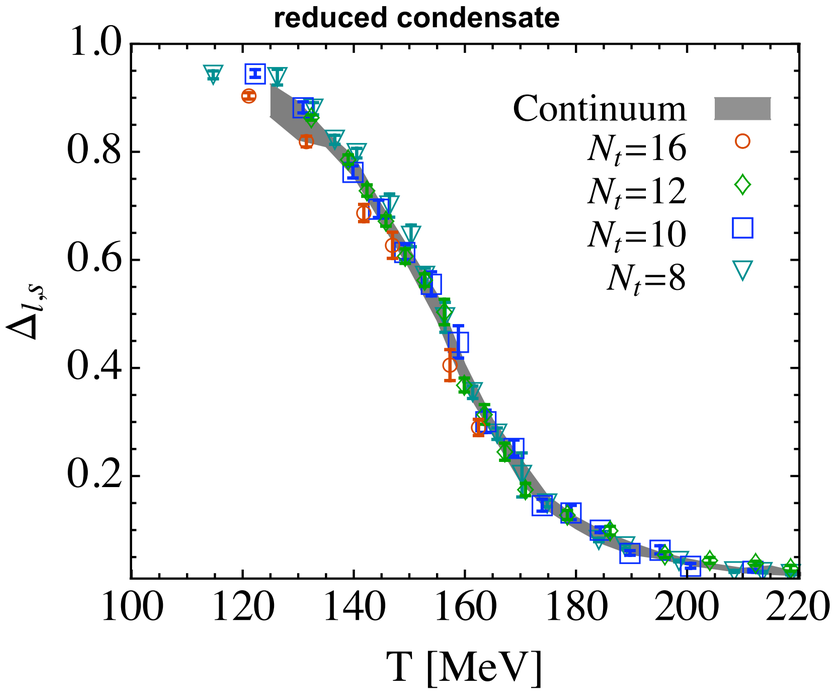






reduced condensate

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

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

⋮

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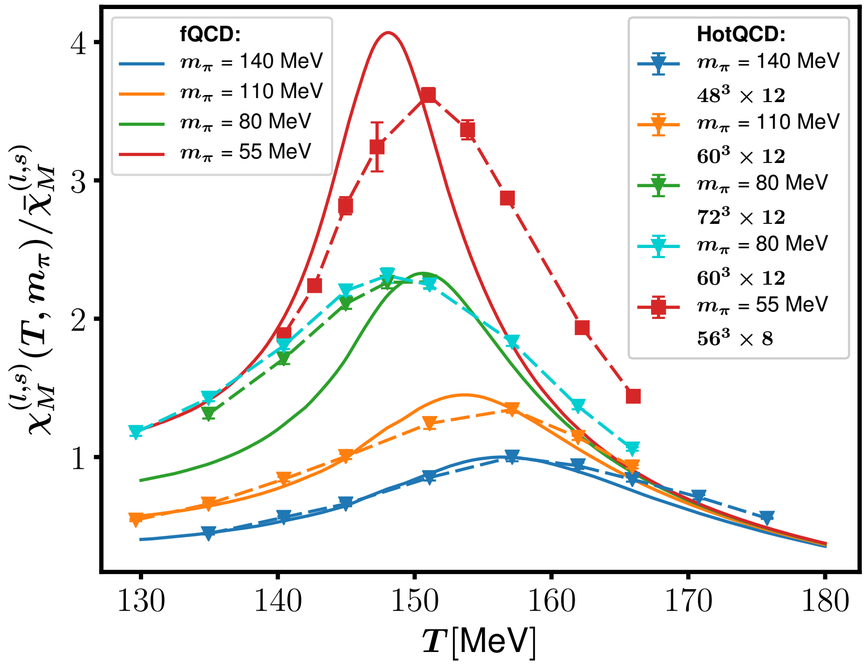
QCD phase structure at finite density: Facts & Fiction

Scaling regime of QCD for $m_\pi \lesssim 10\,\mathrm{MeV}$

Functional QCD

Lattice QCD

Magnetic susceptibility



Gao, JMP, PRD 105 (2022) 094020

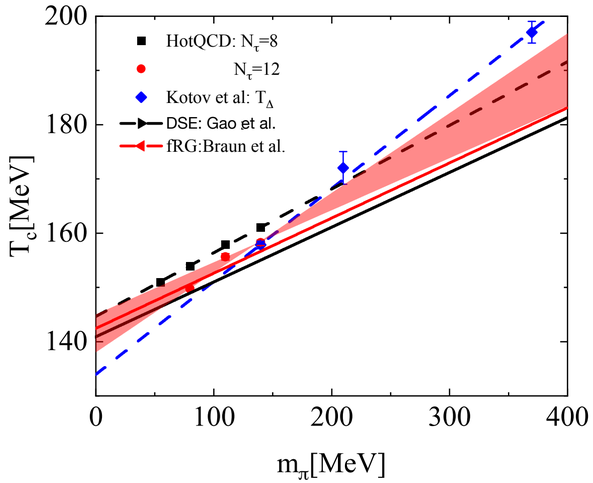
Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

Columbia plot: Bernhardt, Fischer, 2507.21680

Ding, Hegde, Kaczmarek, Karsch, Lahiri, Li, Mukherjee, Ohno, Petreczky Schmidt, Steinbrecher, PRL 123 (2019) 062002

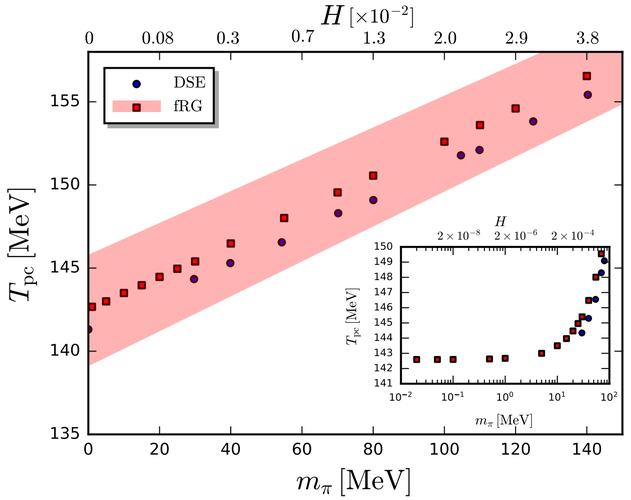
⋮

To be (critical) or not (to be)



Chiral transition temperature

$$H = \frac{m_l}{m_s}$$



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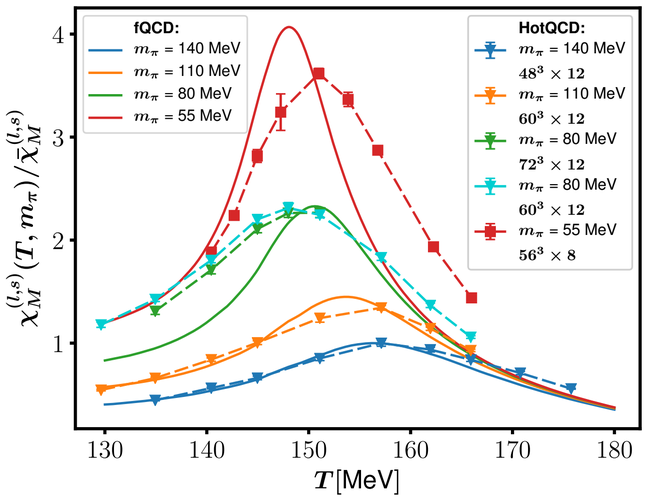

Braun, Fu, JMP, Rennecke, Rosenblüh, Yin, PRD 102 (2020) 056010

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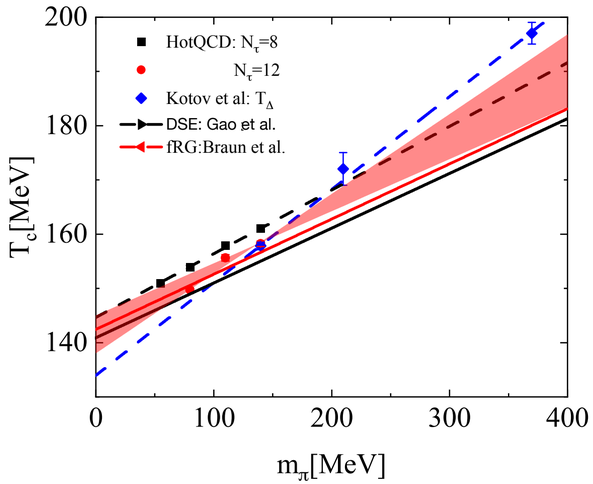

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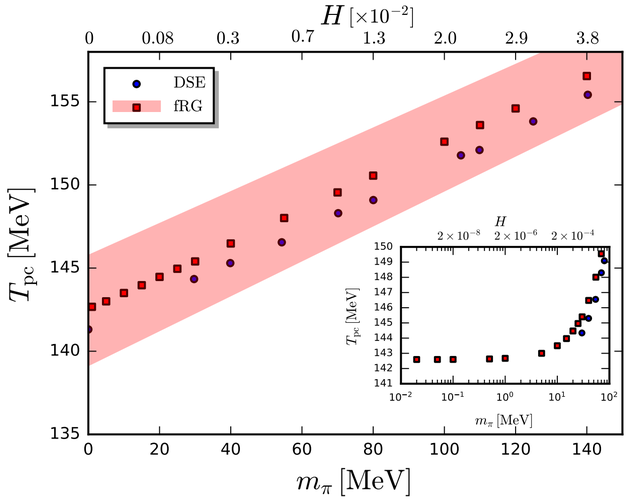
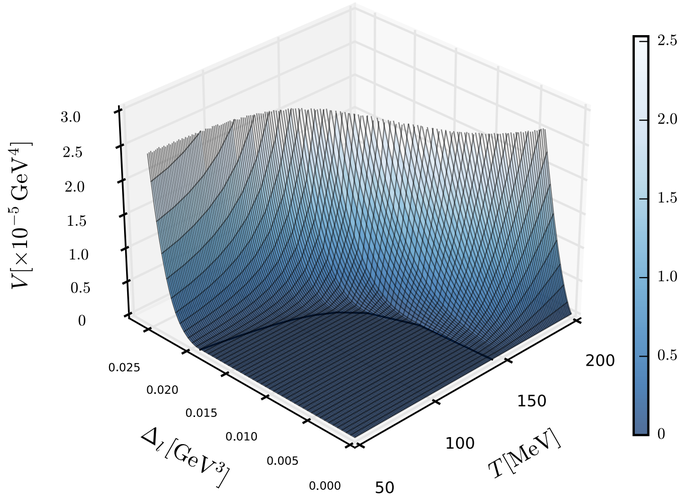


Order parameter potential & scaling

$$V_\chi \approx \Delta_l^n \quad \Longleftrightarrow \quad \Delta_l(H) \propto H^{\frac{1}{n-1}}$$



$$V_\chi^{(\rm fRG)} \approx V_\chi^{(\rm DSE)}$$

(Critical) exponent: $\frac{1}{\delta} = \frac{1}{n-1}$

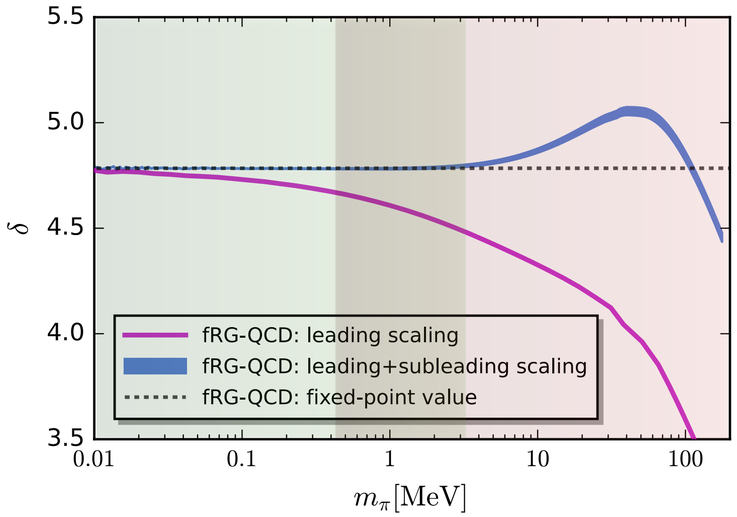
Braun, Fu, JMP, Rennecke, Rosenblüh, Yin, PRD 102 (2020) 056010

Gao, JMP, PRD 105 (2022) 094020

Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

Chiral dynamics & quasi-massless modes

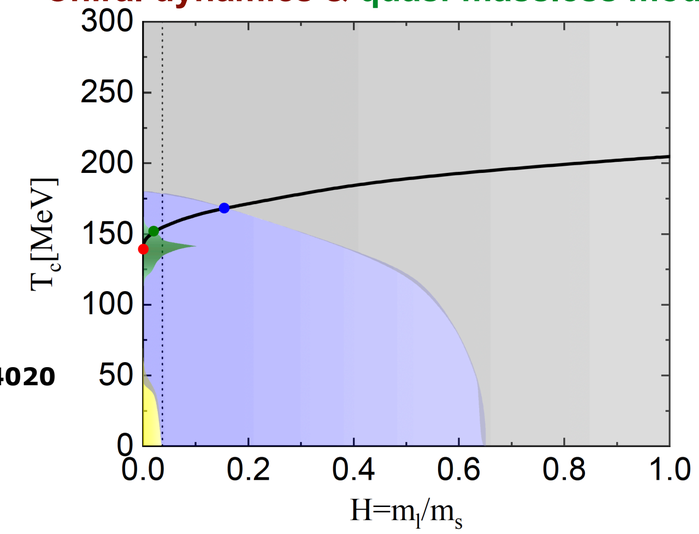
Scaling coefficient as function of the pion mass



Critical O(4) scaling

Trivial $\Delta_l^{1+\delta}$ scaling

Chiral dynamics & quasi-massless modes



Critical scaling

Gao, JMP, PRD 105 (2022) 094020

Far away from the critical regime for $m_\pi \gtrsim 1\,\mathrm{MeV}$

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

$$V_\chi(\Delta_l) \propto \quad \Delta_l^6 \quad \Delta_l^4 \quad \Delta_l^2$$

Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

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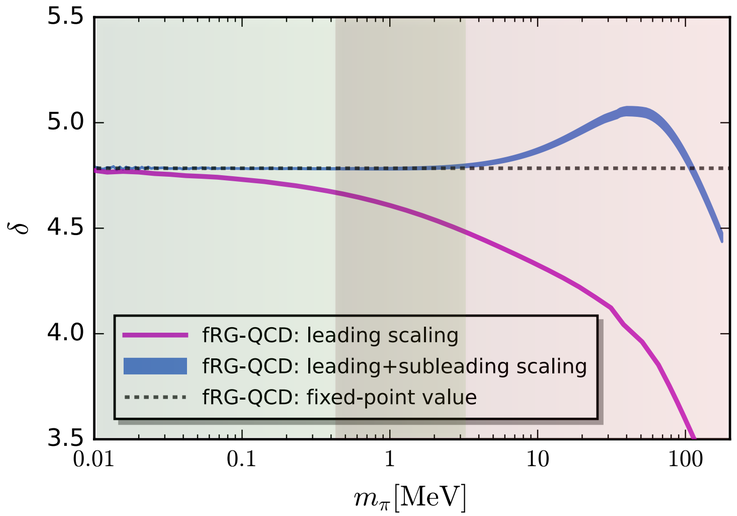

Trivial $\Delta_l^{1+\delta}$ scaling

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

Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

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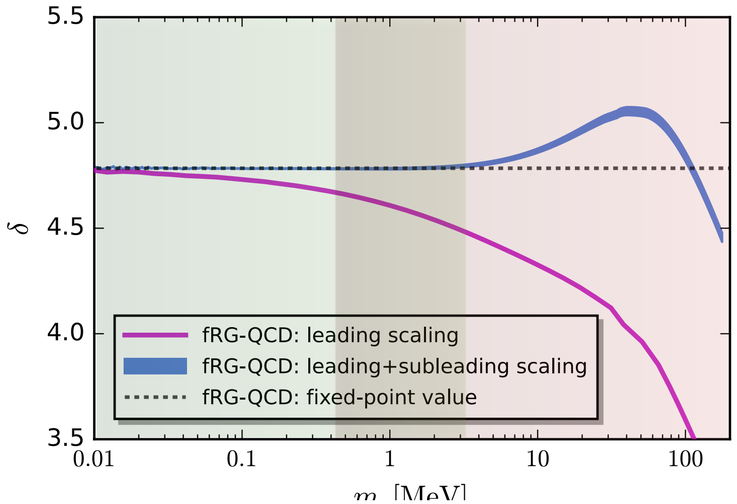

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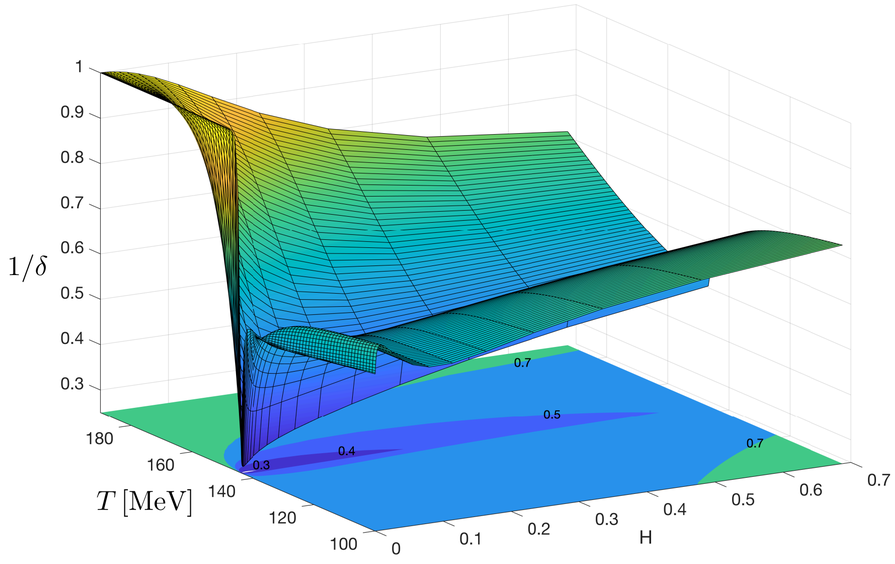

Small chiral scaling regime

↓

Small critical regime around pot. CEP

Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

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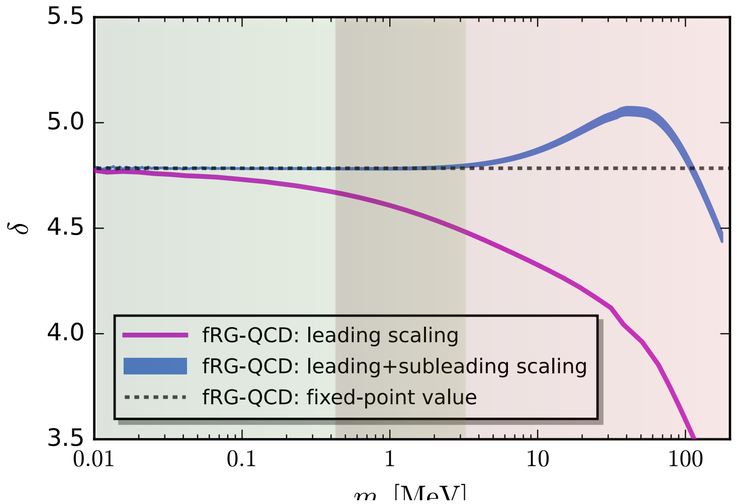

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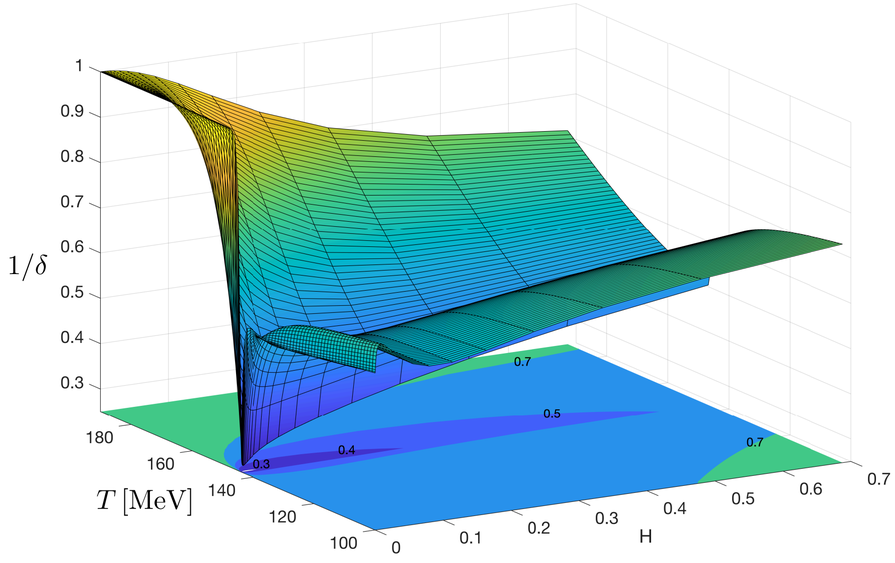

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!!Great News!!

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

Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

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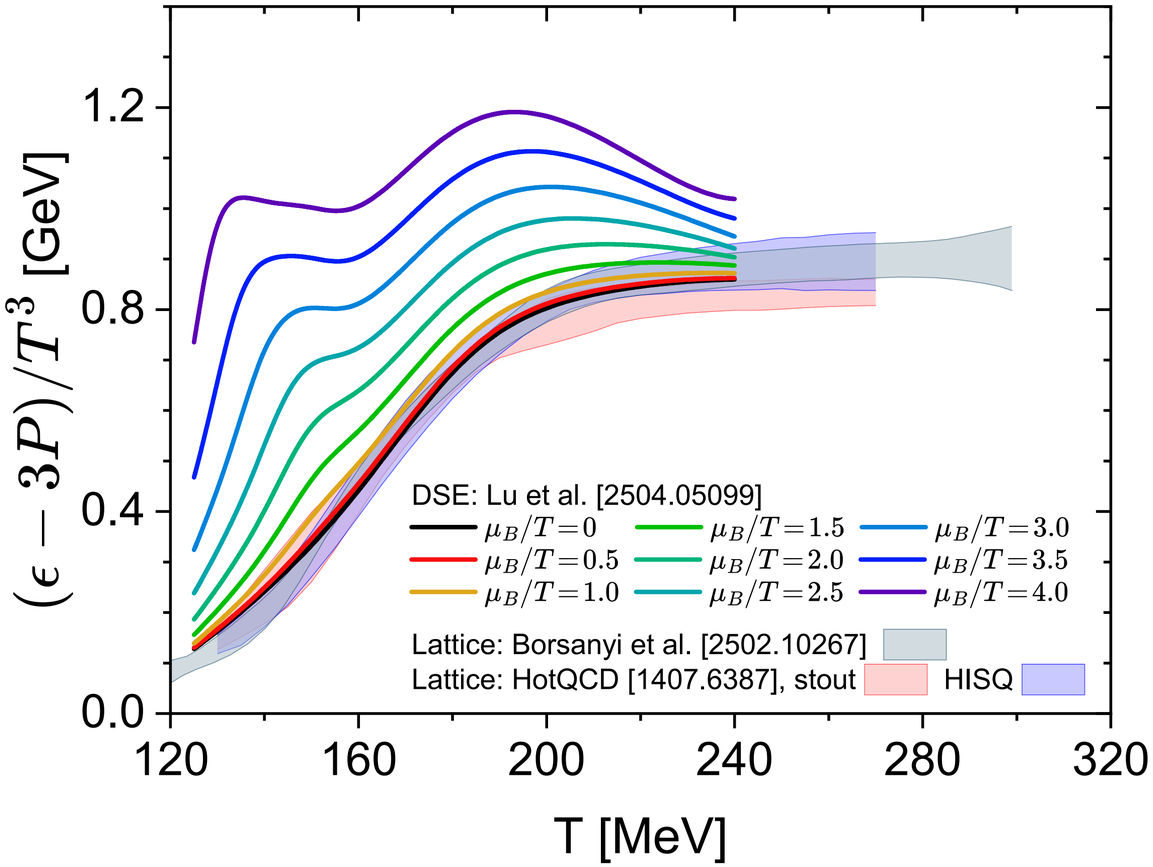
Strongly correlated phase for temperatures $T_\chi \lesssim T \lesssim 2\,T_\chi$

Functional QCD **Lattice QCD**



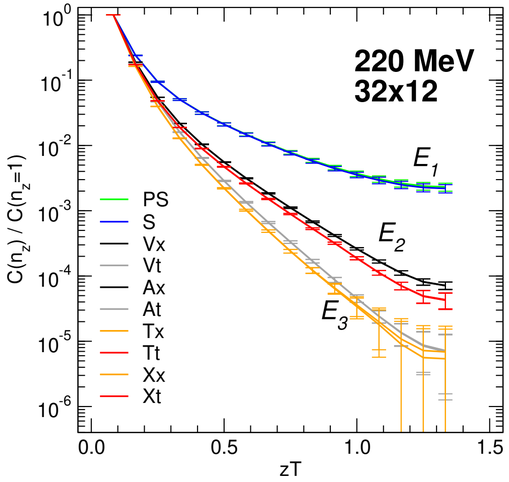
Lu, Gao, Liu, JMP, arXiv:2504.05099

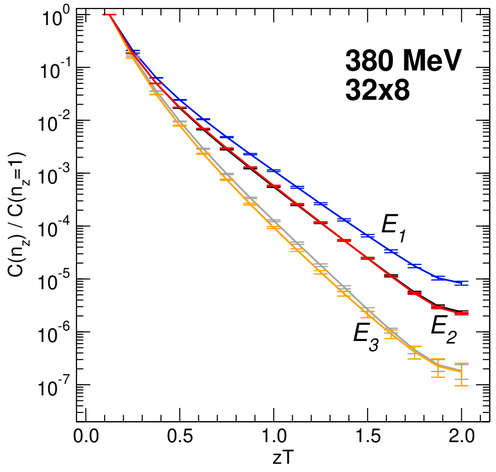
QCD phase structure at finite density: Facts & Fiction

Spin symmetry for $T_\chi \lesssim T \lesssim 2\,T_\chi$

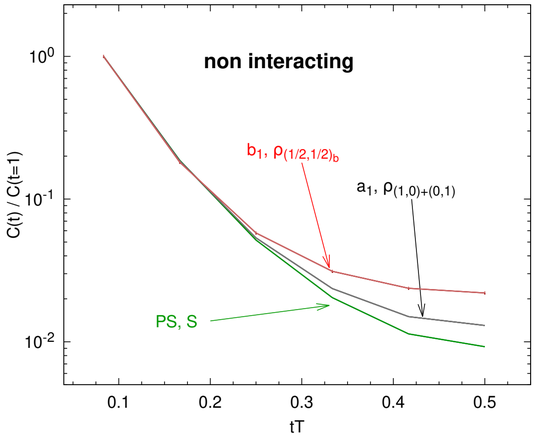
Functional QCD

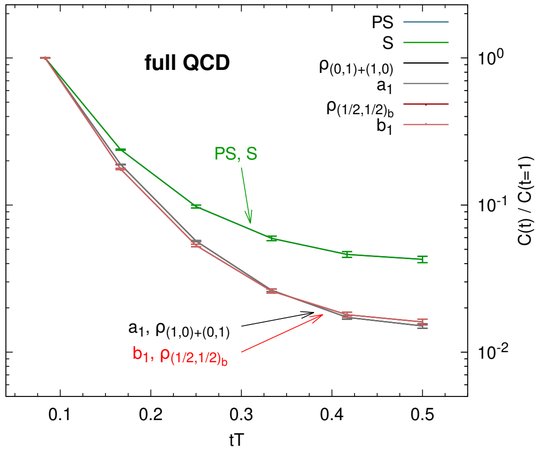
not yet





Lattice QCD





⋮

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

⋮

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

⋮

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QCD phase structure at finite density: Facts & Fiction

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

Functional QCD

Lattice QCD

Variants of the
traced Polyakov loop

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

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

⋮

Lu, Gao, Liu, JMP, arxiv:2504.05099

⋮

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

⋮

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

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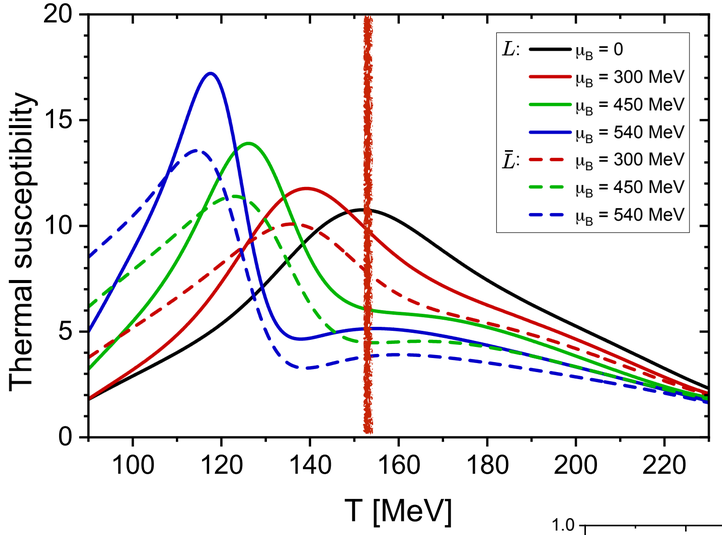

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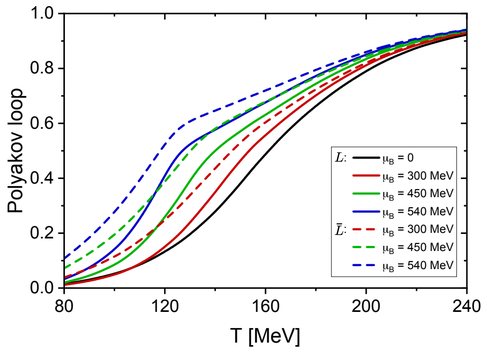
$$\propto P\big(\langle \mathrm{ev}(\varphi)\rangle\big)$$

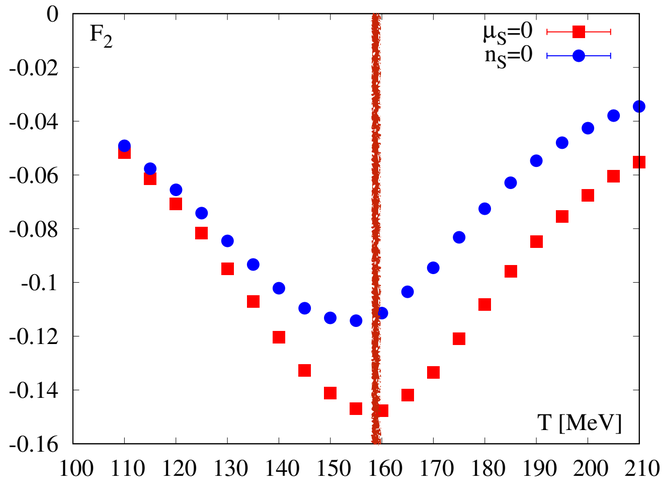


Braun, Gies, JMP, PLB 684 (2010) 262-267

⋮

Lu, Gao, Liu, JMP, arxiv:2504.05099

Lattice QCD



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

⋮

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

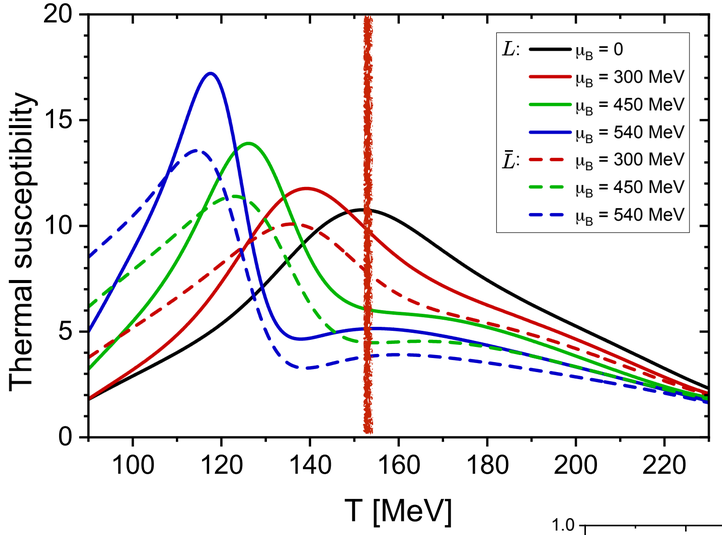
⋮

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

QCD phase structure at finite density: Facts & Fiction

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

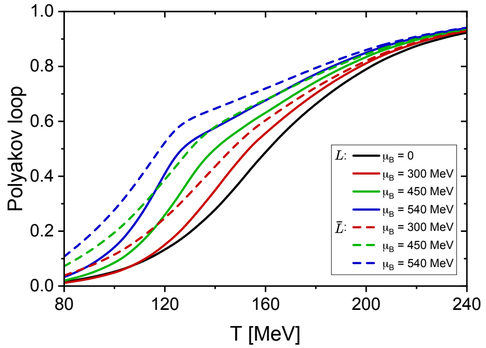
Functional QCD



Variants of the traced Polyakov loop

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

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



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

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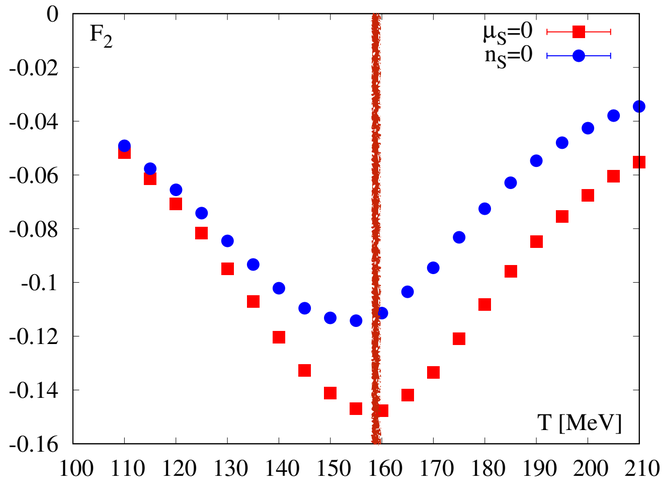
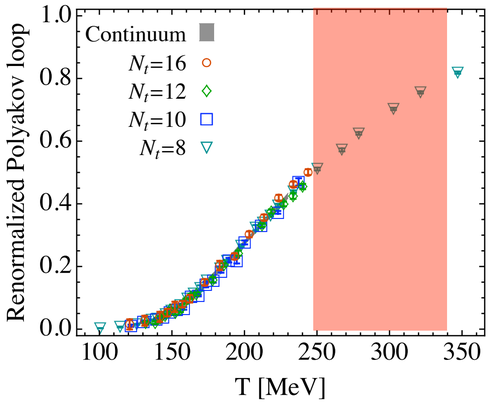
Lu, Gao, Liu, JMP, arxiv:2504.05099

Lattice QCD



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

$$\propto \langle P\rangle$$



⋮

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

⋮

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

QCD phase structure at finite density: Facts & Fiction

Facts

$\mu_B = 0$

- Chiral crossover at about

$$T_\chi \approx 155\,\mathrm{MeV}$$

- Strongly correlated phase for temperatures

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

$\mu_B \neq 0$

- No chiral critical end point for

$$\mu_B \lesssim 600\,\mathrm{MeV}$$

chiral: driven by scalar-pseudoscalar fluctuations

Fiction

$\mu_B = 0$

- Physical QCD is in the chiral scaling regime

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

Soft modes are commonplace

- Confinement crossover is at XXX

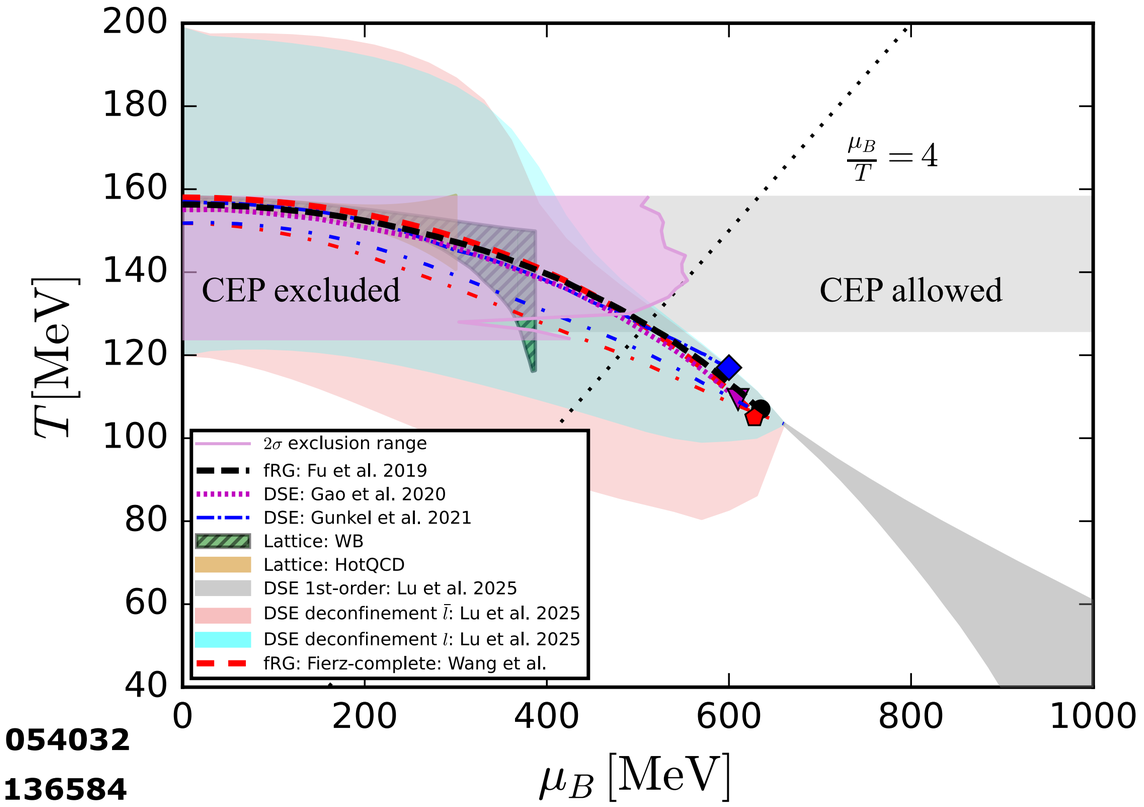
$$T_\chi \lesssim T_{\mathrm{conf}} \lesssim 2\,T_\chi$$

QCD phase structure at finite density: Facts & Fiction

No chiral critical end point for $\mu_B \lesssim 600\,\mathrm{MeV}$

Functional QCD

Functional QCD CEP+ lattice QCD exclusion plot



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

Lattice QCD

$\mu_B \lesssim 450\,\mathrm{MeV}$

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

QCD phase structure at finite density: Facts & Fiction

Facts

$\mu_B = 0$

- **Chiral crossover at about**

$$T_\chi \approx 155\,\mathrm{MeV}$$

- **Strongly correlated phase for temperatures**

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

$\mu_B \neq 0$

- **No chiral critical end point for**

$$\mu_B \lesssim 600\,\mathrm{MeV}$$

- **No chiral crossover for**

$$\mu_B \gtrsim 700\,\mathrm{MeV}$$

Fiction

$\mu_B = 0$

- **Physical QCD is in the chiral scaling regime**

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

Soft modes are commonplace

- **Confinement crossover is at XXX**

$$T_\chi \lesssim T_{\mathrm{conf}} \lesssim 2\,T_\chi$$

$\mu_B \neq 0$

- **There is a CEP**

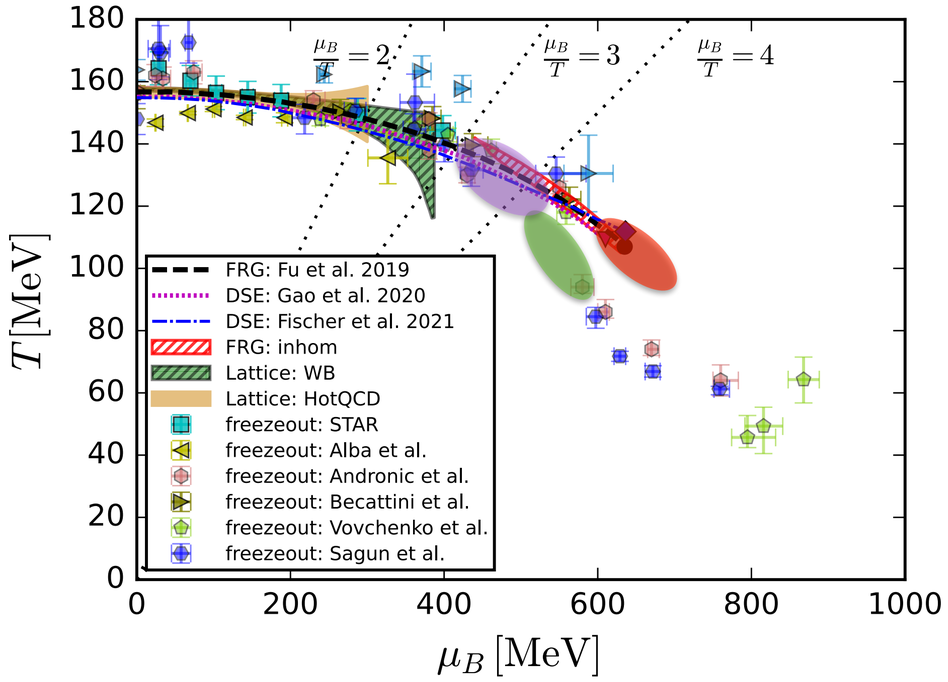
Onset of new phases $600\,\mathrm{MeV} \lesssim \mu_B^{\mathrm{onset}} \lesssim 700\,\mathrm{MeV}$

QCD phase structure at finite density: Facts & Fiction

Onset of new phases at $600\,\mathrm{MeV} \lesssim \mu_B^{\mathrm{onset}} \lesssim 700\,\mathrm{MeV}$

Functional QCD

High density phase structure from function



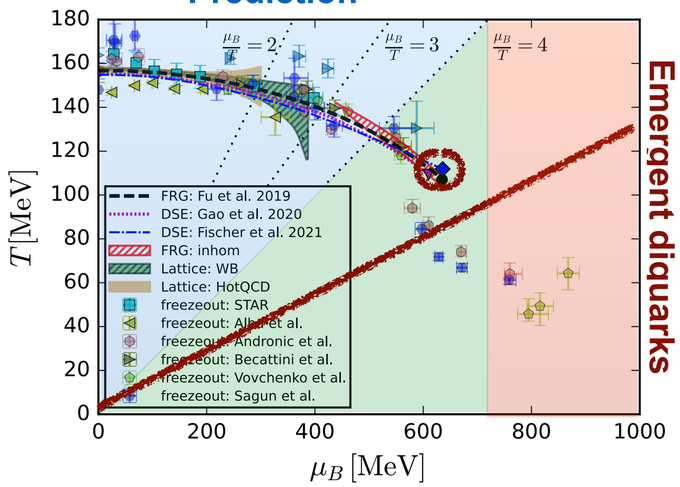
Lattice QCD

not yet

Predictions & estimates

Emergent diquarks

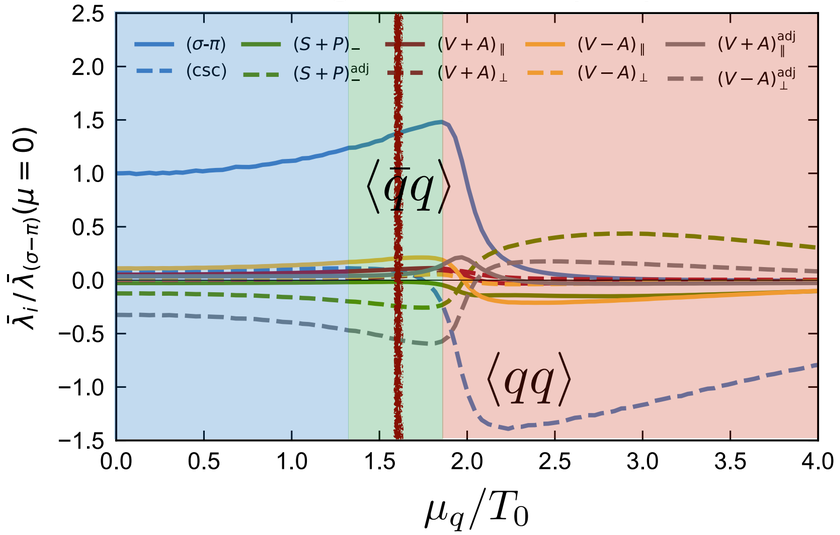
Prediction



Estimate

Regime of quantitative reliability of current best truncation

Emergent diquarks (fRG)

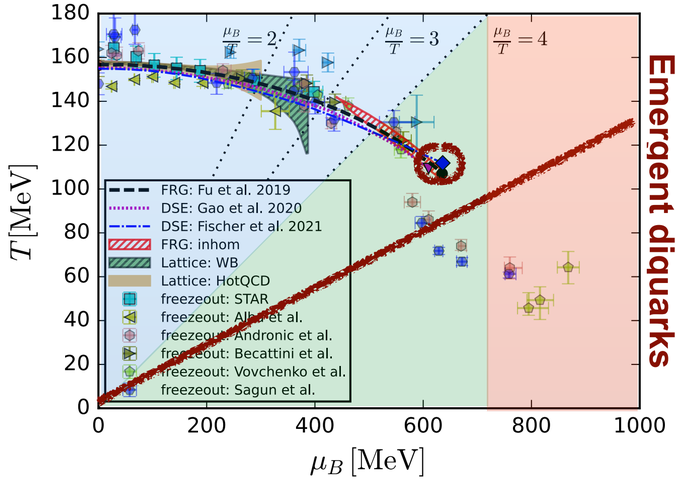


Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Predictions & estimates

Emergent diquarks

Prediction



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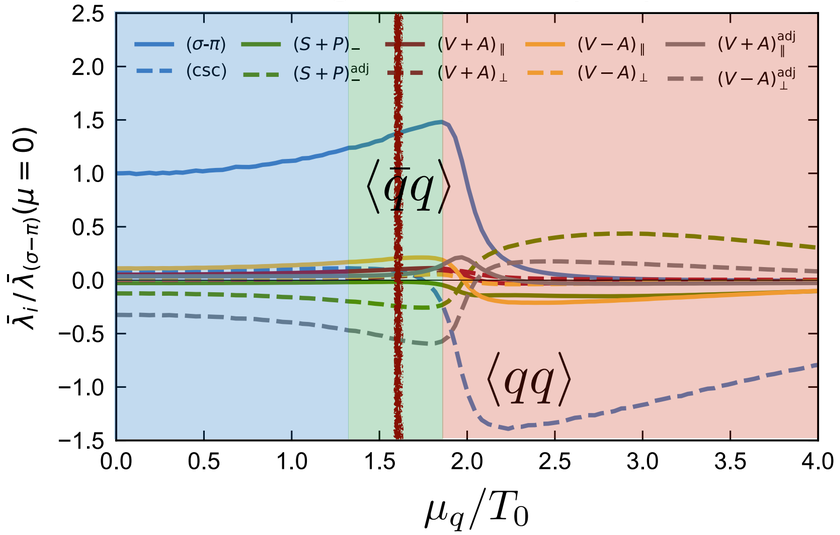


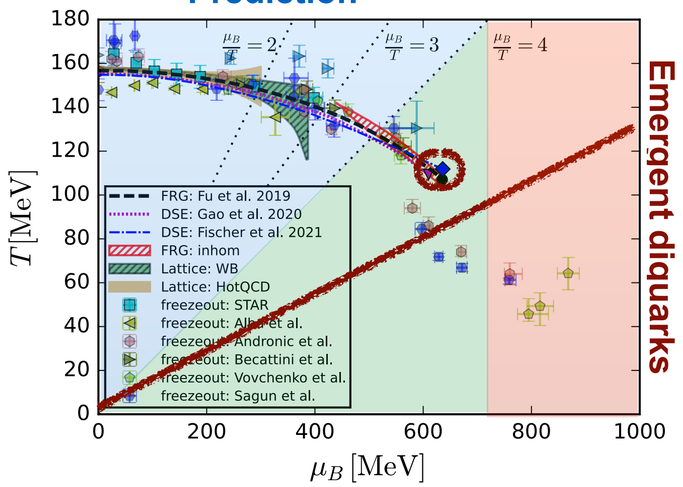
Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Emergent diquarks are not captured by extrapolations

Predictions & estimates

Emergent diquarks

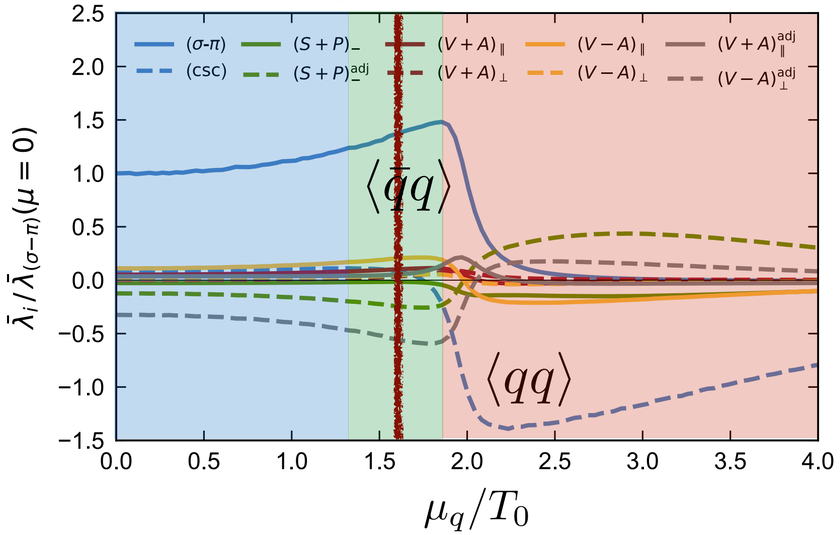
Prediction



Regime of quantitative reliability of current best truncation

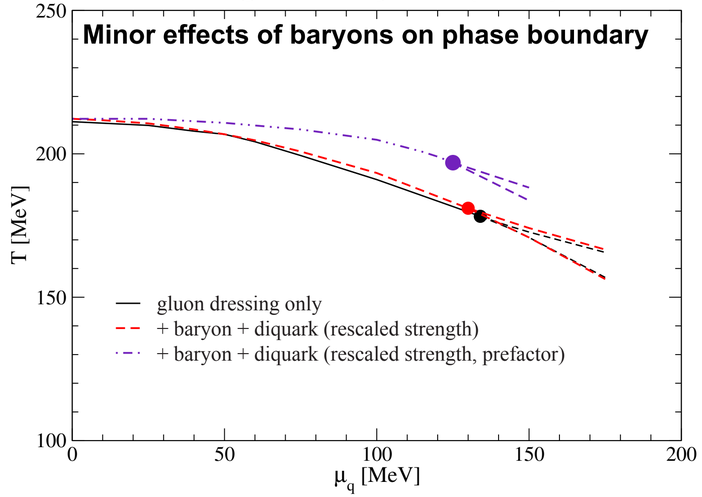
Estimate

Emergent diquarks (fRG)



Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Emergent baryons (DSE)



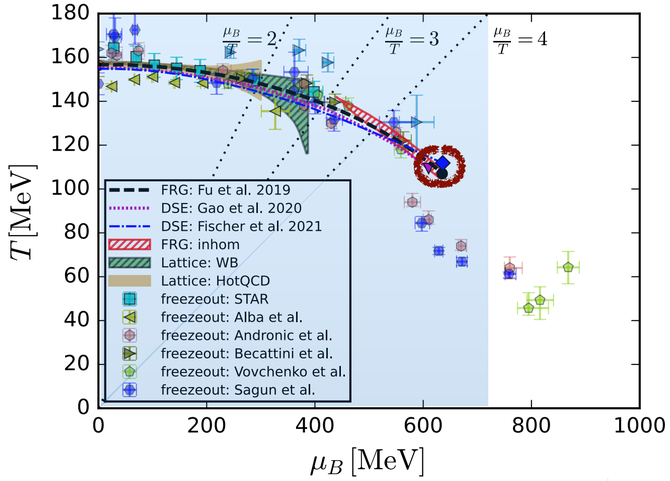
Eichmann, Fischer, Welzbacher, PRD 93 (2016) 034013

Predictions & estimates

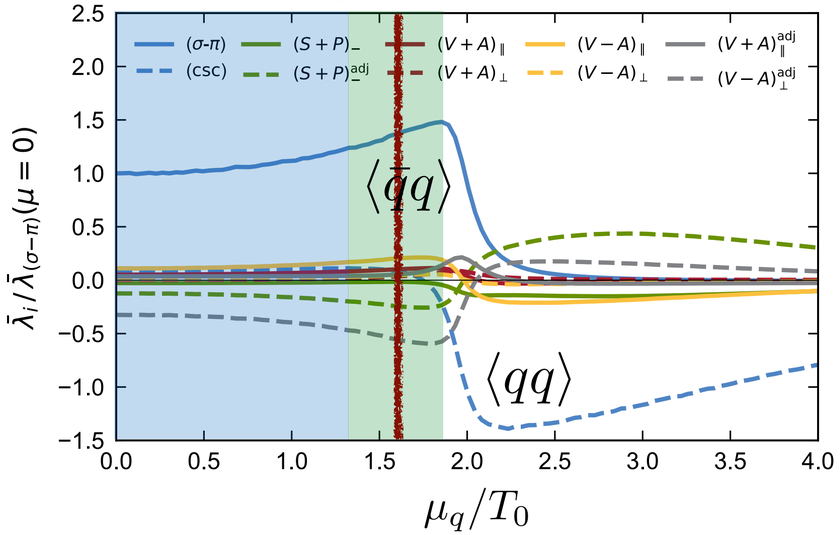
Dominance of scalar-pseudoscalar fluctuations

Pions & sigma mode

Prediction

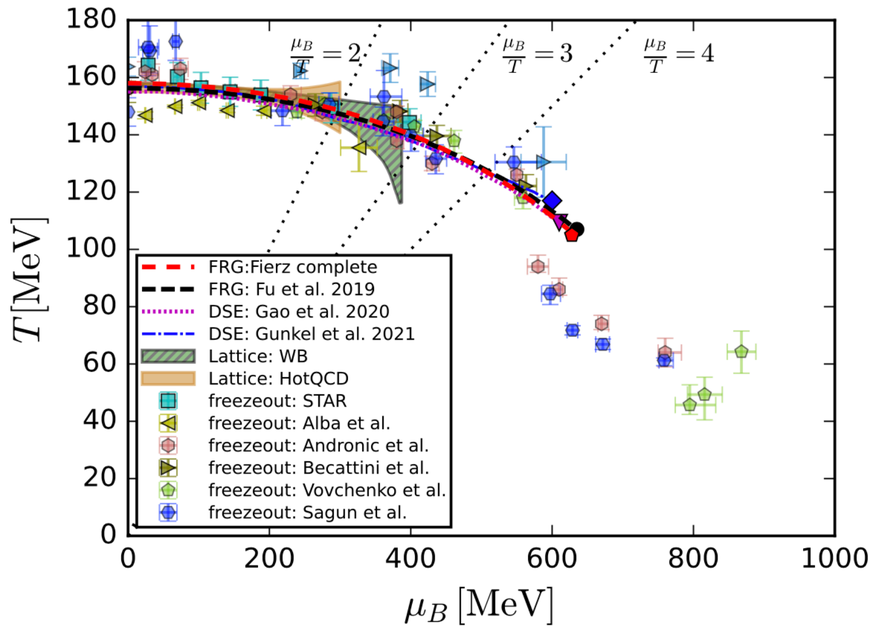


Emergent diquarks (fRG)



Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Fierz-complete phase structure



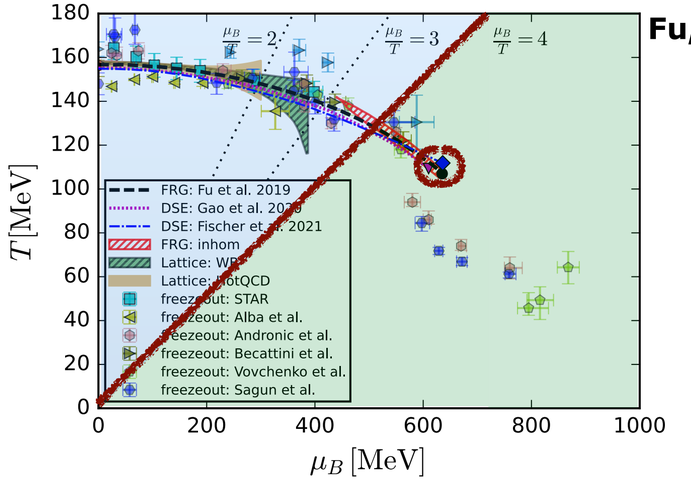
Wang et al, in preparation

Predictions & estimates

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

Prediction

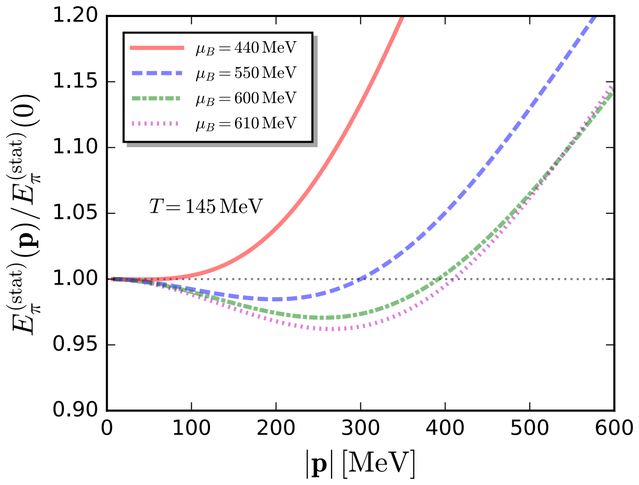


Fu, JMP, Rennecke, PRD 101 (2020) 054032

Regime of quantitative reliability of current best truncation

Estimate

Moat regime is not captured quantitatively



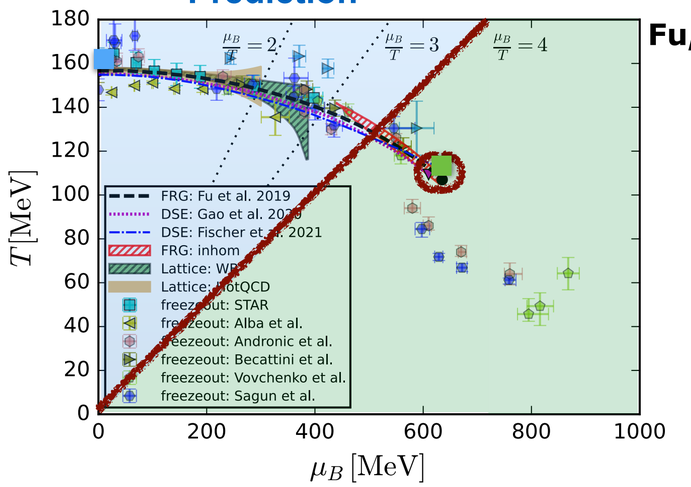
Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

Predictions & estimates

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

Prediction



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

Regime of quantitative reliability of current best truncation

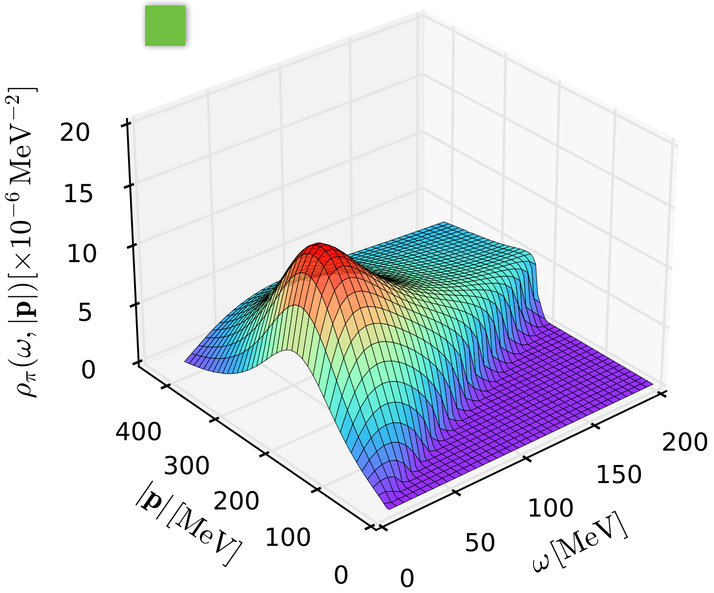
T=114 MeV & μ_B =630 MeV

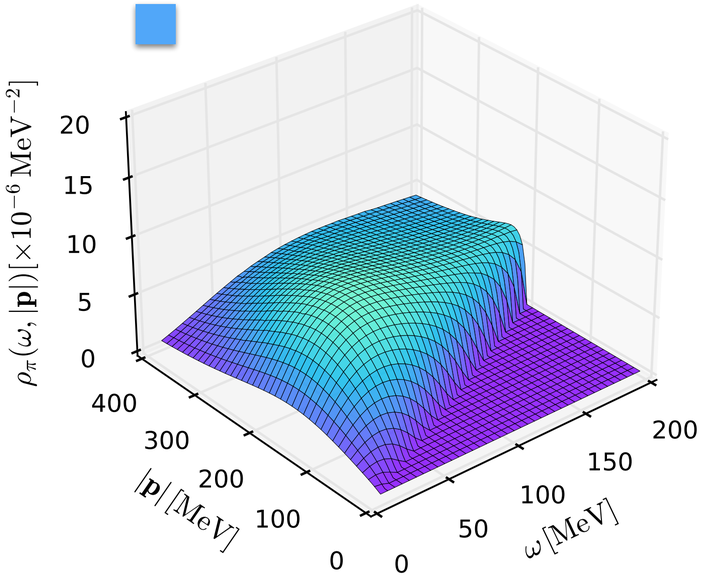
Estimate

T=160 MeV & μ_B =0 MeV

Moat regime is not captured quantitatively

Pion spectral functions

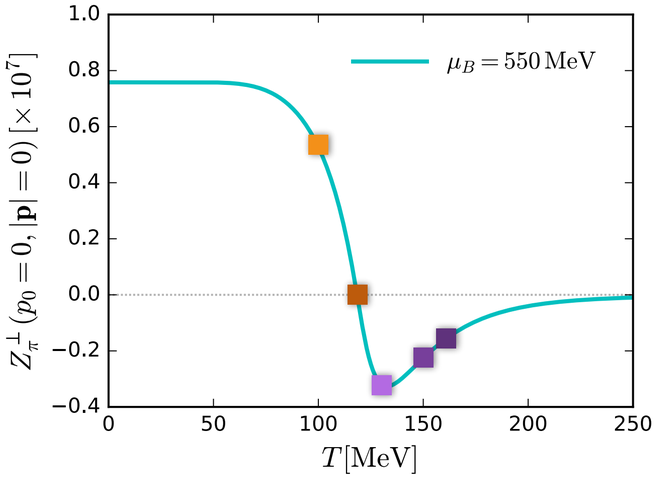


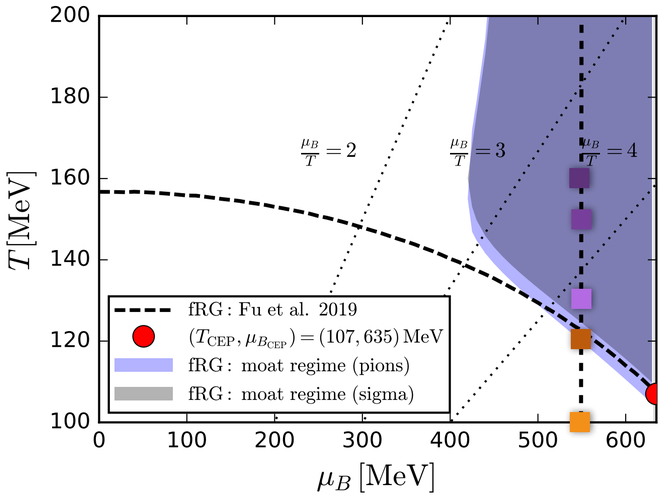


Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

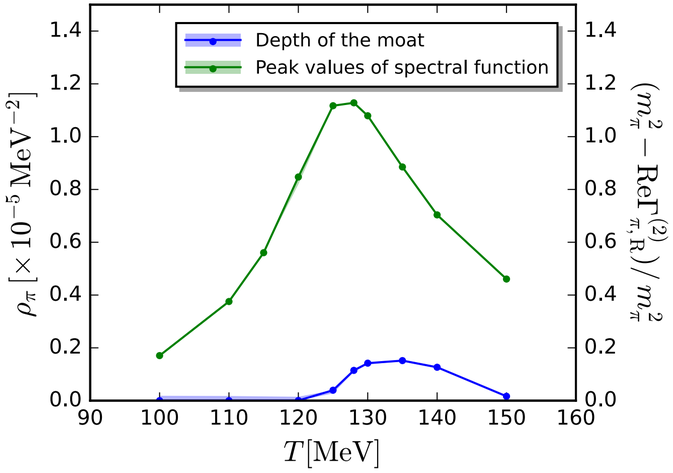
Predictions & estimates

Spatial wave function of the pion at p=0





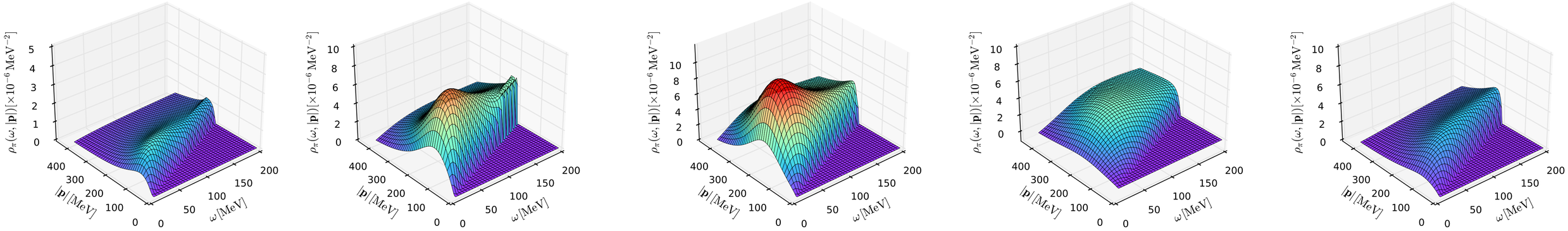
Depth of the moat & spectral peak of the pion



Dissecting the moat & the moaton

μ_B = 650 MeV

T=100 MeV T=120 MeV T=130 MeV T=150 MeV T=160 MeV

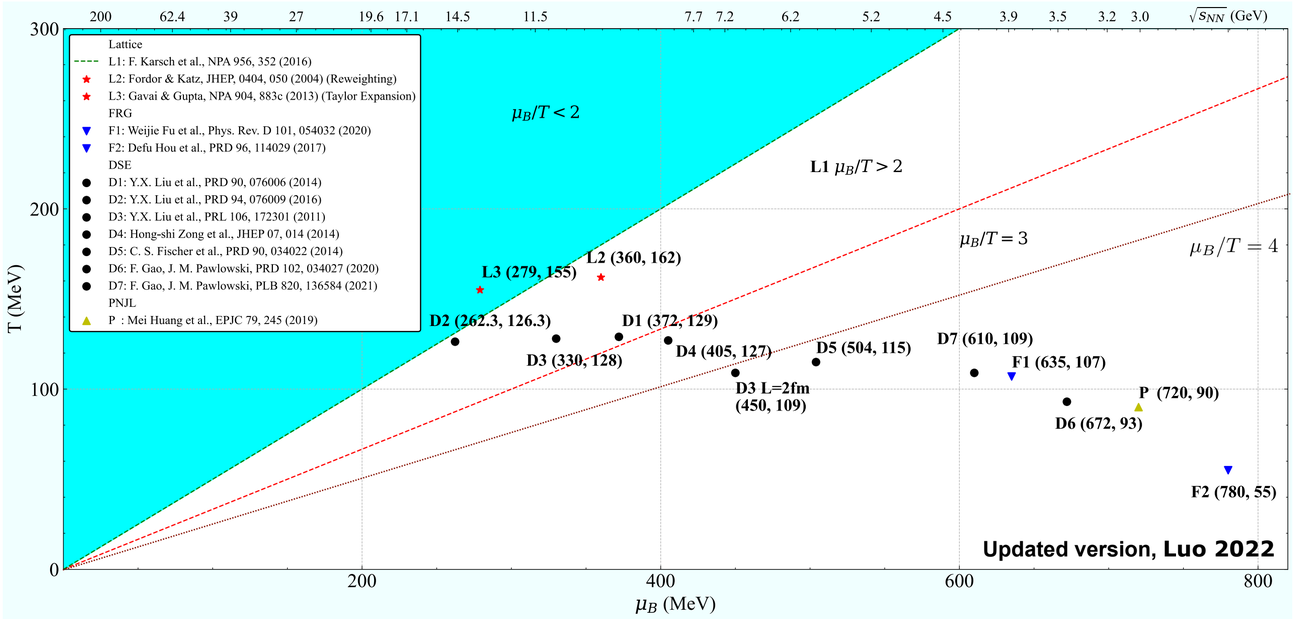


Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

Predictions, estimates & extrapolations and how to judge them

Location of CP : Theoretical Prediction

Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



Large uncertainties for the estimation of CP location.

RHIC-BES Seminar Oct. 6th 2020, Xiaofeng Luo

Disclaimer

Most functional computations (LEFT or QCD) have not been set-up for CEP-predictions!

Lack of predictive power for CEP-predictions is no quality measure!

CEP is standing for 'regime with new physics'

Predictions, estimates & extrapolations and how to judge them

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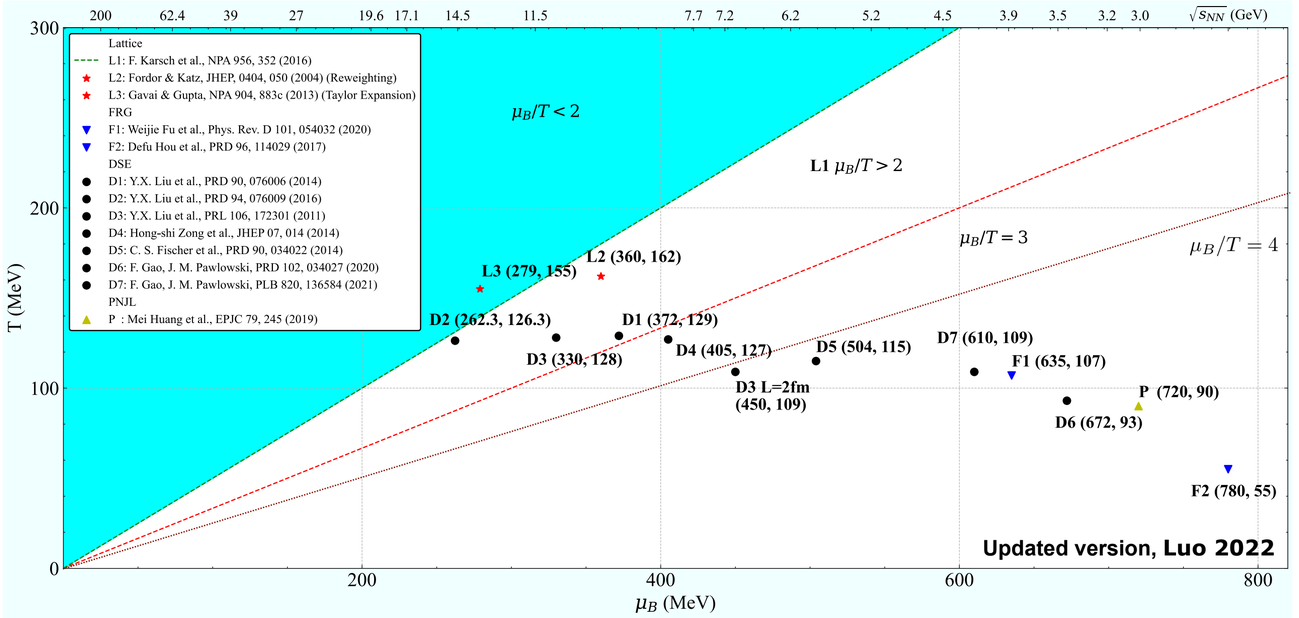

Common folklore since ~2004 ⟷ Large uncertainties for the estimation of CP location.

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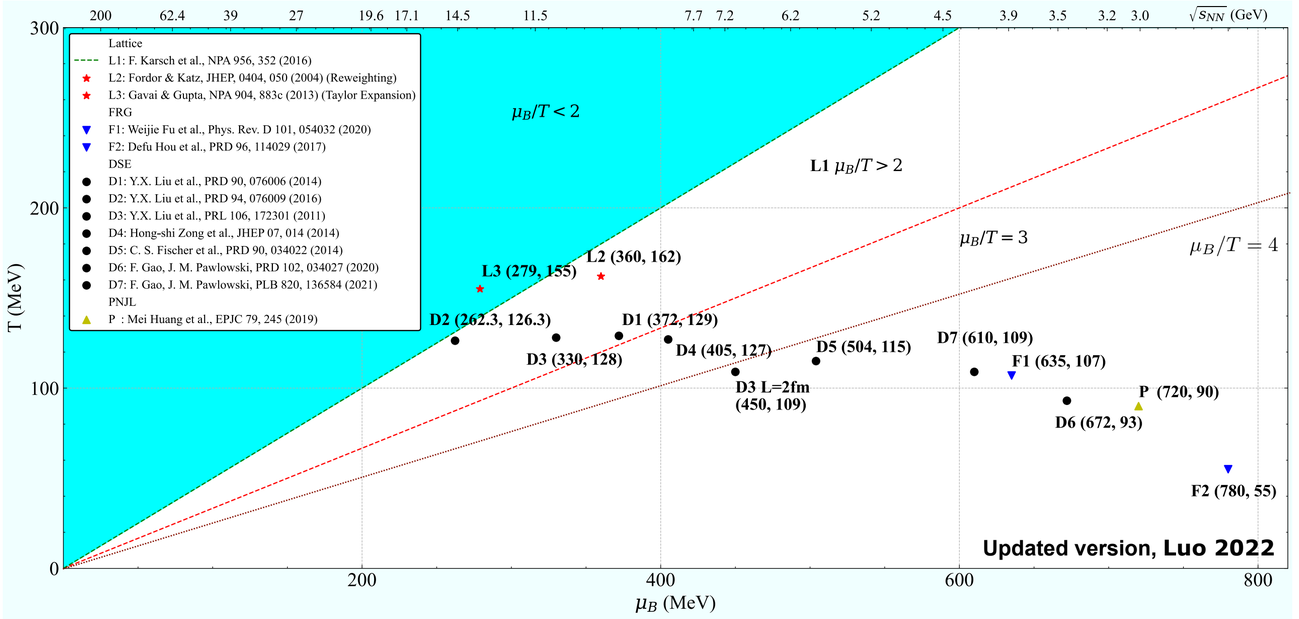

Large uncertainties for the estimation of CP location.

Remove CEP-predictions

(i) 'old' CEPs: lattice, Functional QCD approaches, LEFTS (updated computations available)

(ii) LEFTs & Functional Results (qualitative approximations) that miss lattice benchmarks at μ_B =0

(iii) LEFTs with CEPs at large density (missing quark-gluon back reaction)

Predictions, estimates & extrapolations and how to judge them

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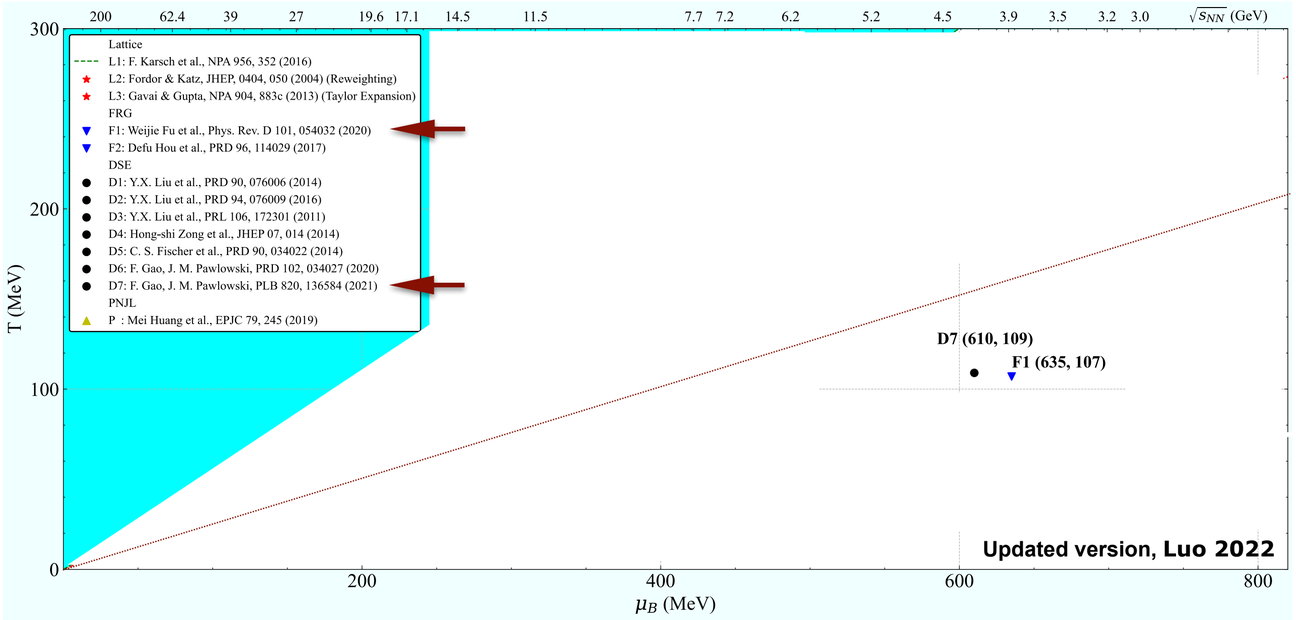
Functional QCD



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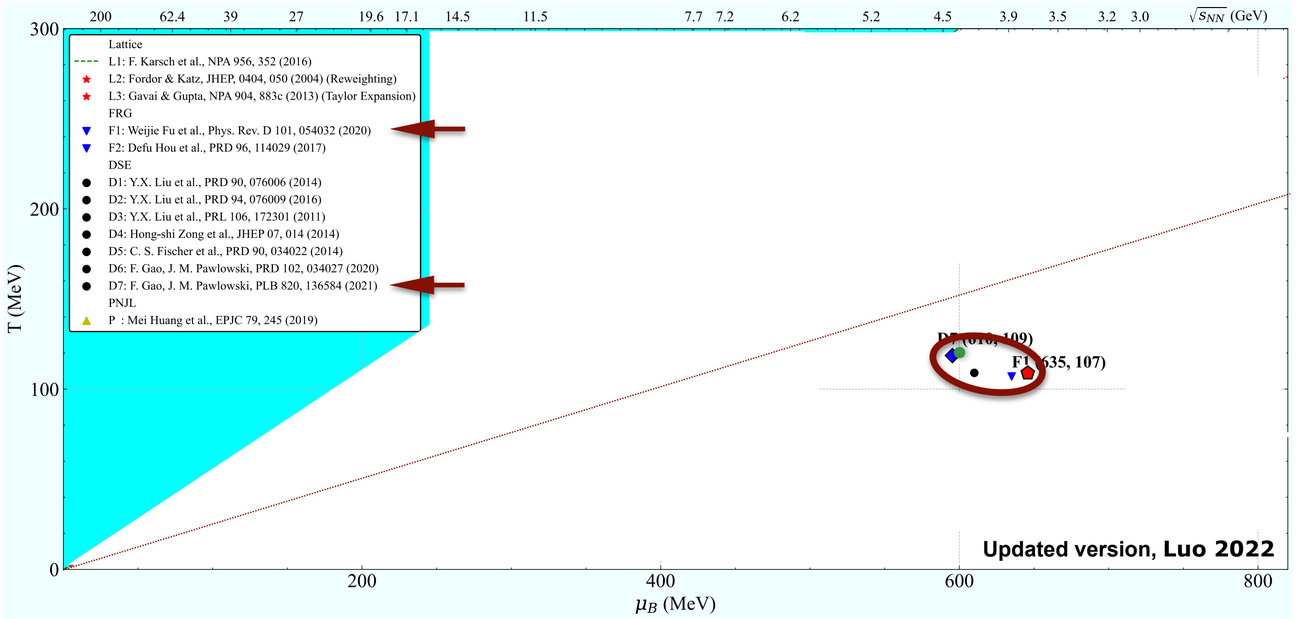
- **Fu, JMP, Rennecke, Wen, Yin, in prep (fRG)**
- **Gunkel, Fischer, PRD 104 (2021) 054022 (DSE)**



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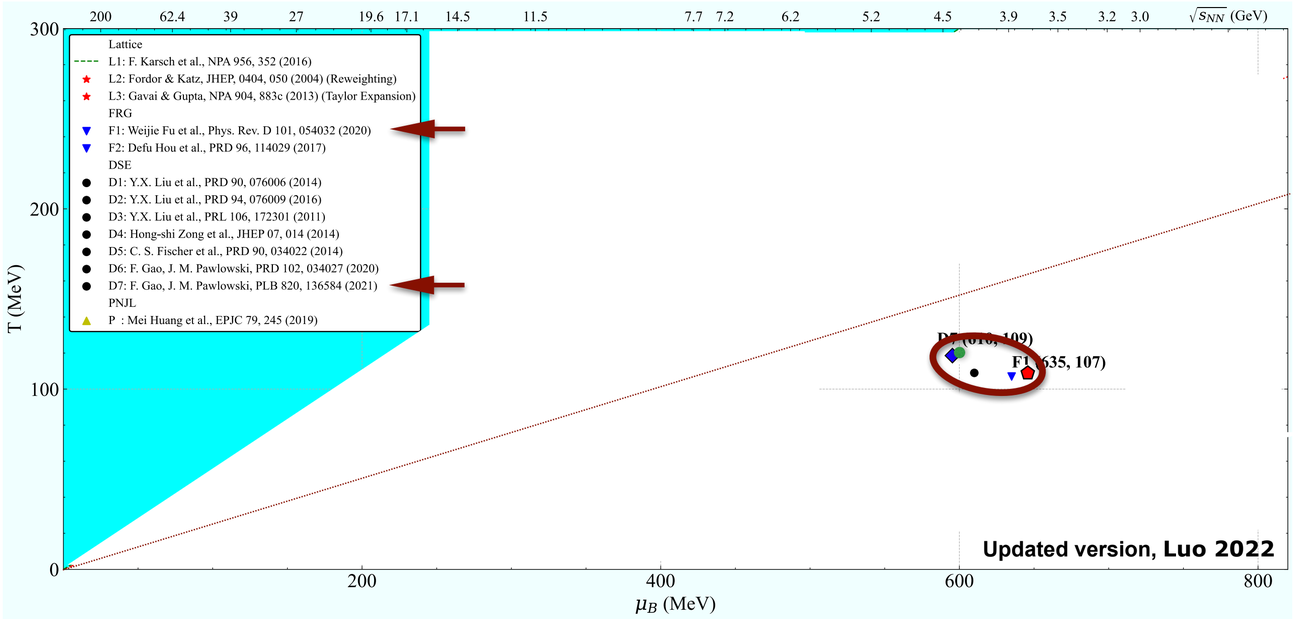

Still small uncertainties for the estimation of CP location **/Onset of new phases**

Remove CEP-predictions

RHIC-BES Seminar Oct. 6th 2020, Xiaofeng Luo

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Predictions, estimates & extrapolations and how to judge them

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- Gunkel, Fischer, PRD 104 (2021) 054022 (DSE)

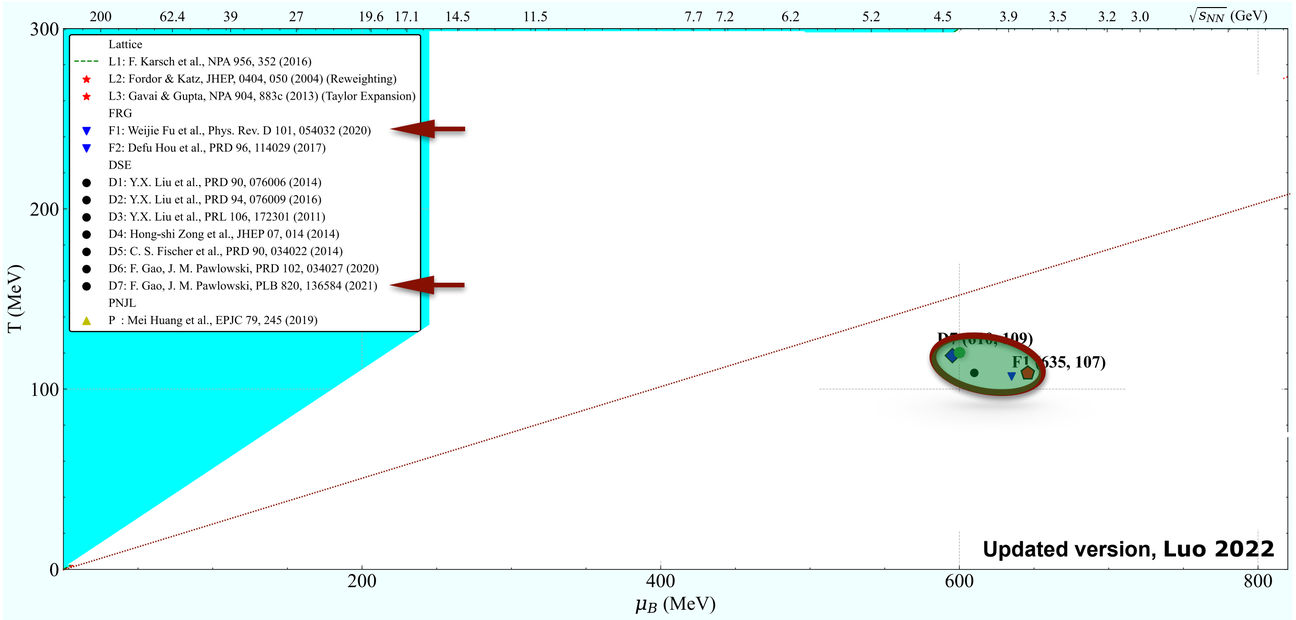
Extrapolations

Lattice extrapolations: Basar, PRC 110 (2024) 015203
Bielefeld-Parma, arXiv:2405.10196

⋮

Holographic models: Hippert, Grefa, Manning, Noronha, Noronha-Hostler, Portillo Vazquez, Ratti, Rougemont, Trujillo, arXiv: 2309.00579

⋮



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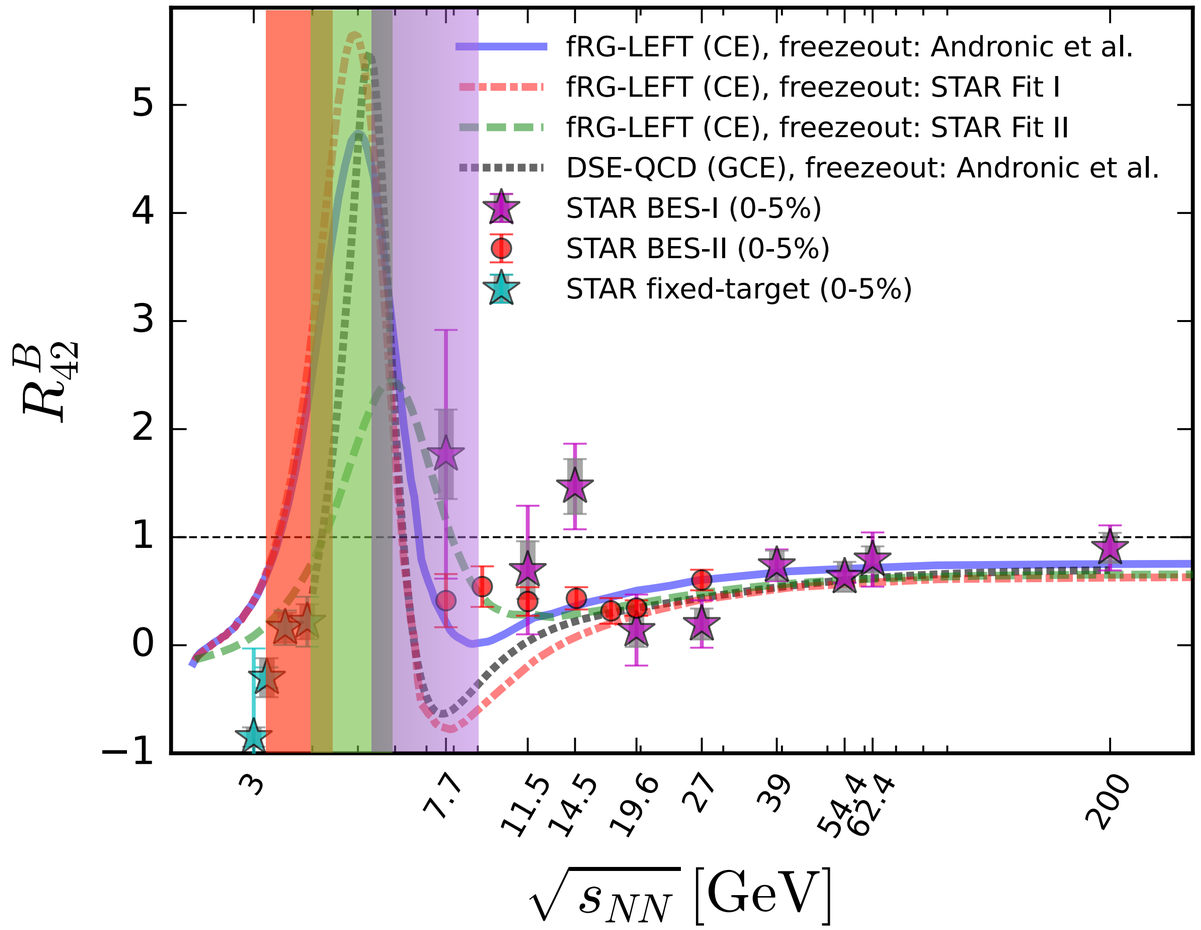
Ripples of the critical point

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
explicit & implicit assumptions

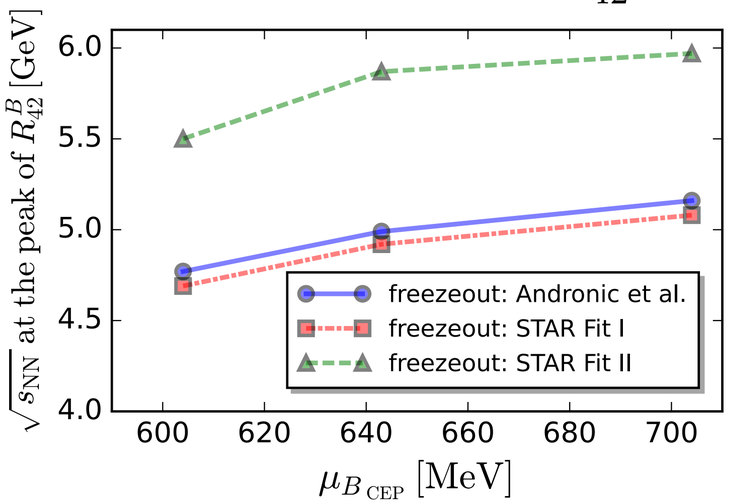
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

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

Lu, Gao, Liu, JMP, arXiv:2504.05099

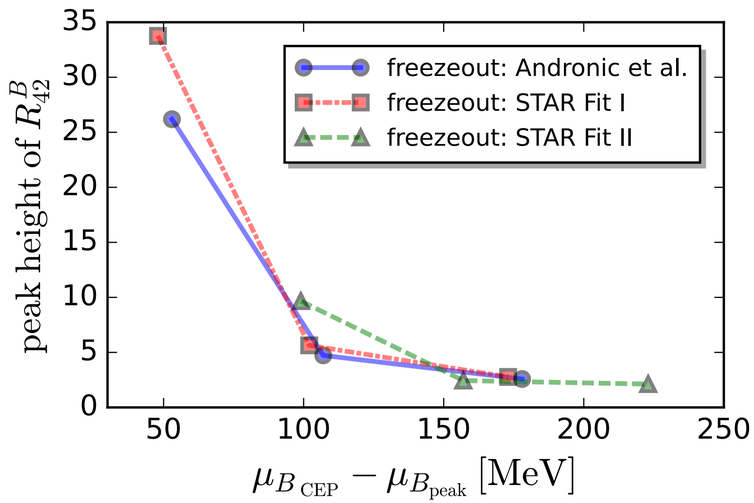
Ripples of the critical point

Position of the peak of R^B_{42}



Reconstructing the CEP

Height of the peak of R^B_{42}



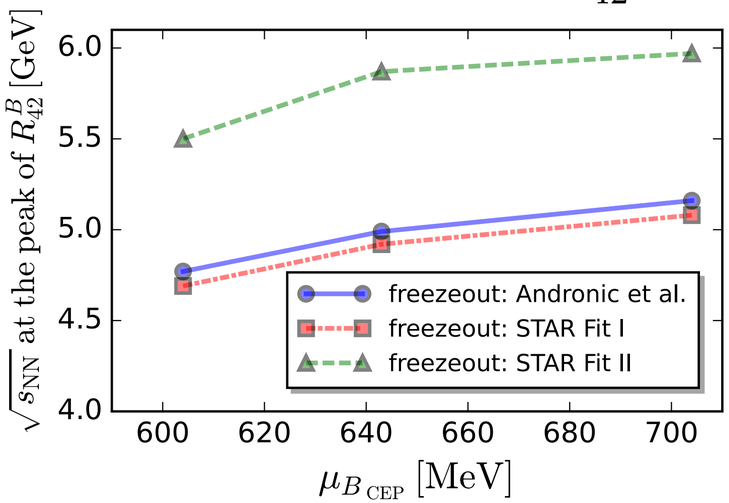
Dominated by non-critical soft modes

Demand: Precise freeze-out line at high density

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

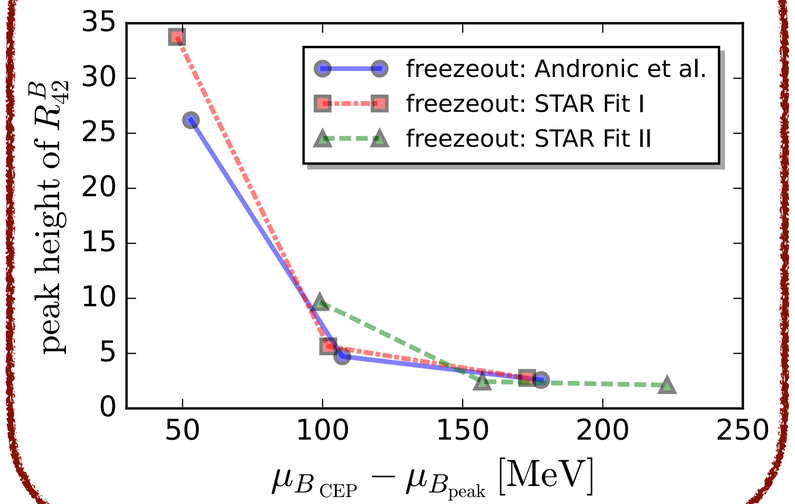
Ripples of the critical point

Position of the peak of R^B_{42}



Reconstructing the CEP

Height of the peak of R^B_{42}



Dominated by non-critical soft modes

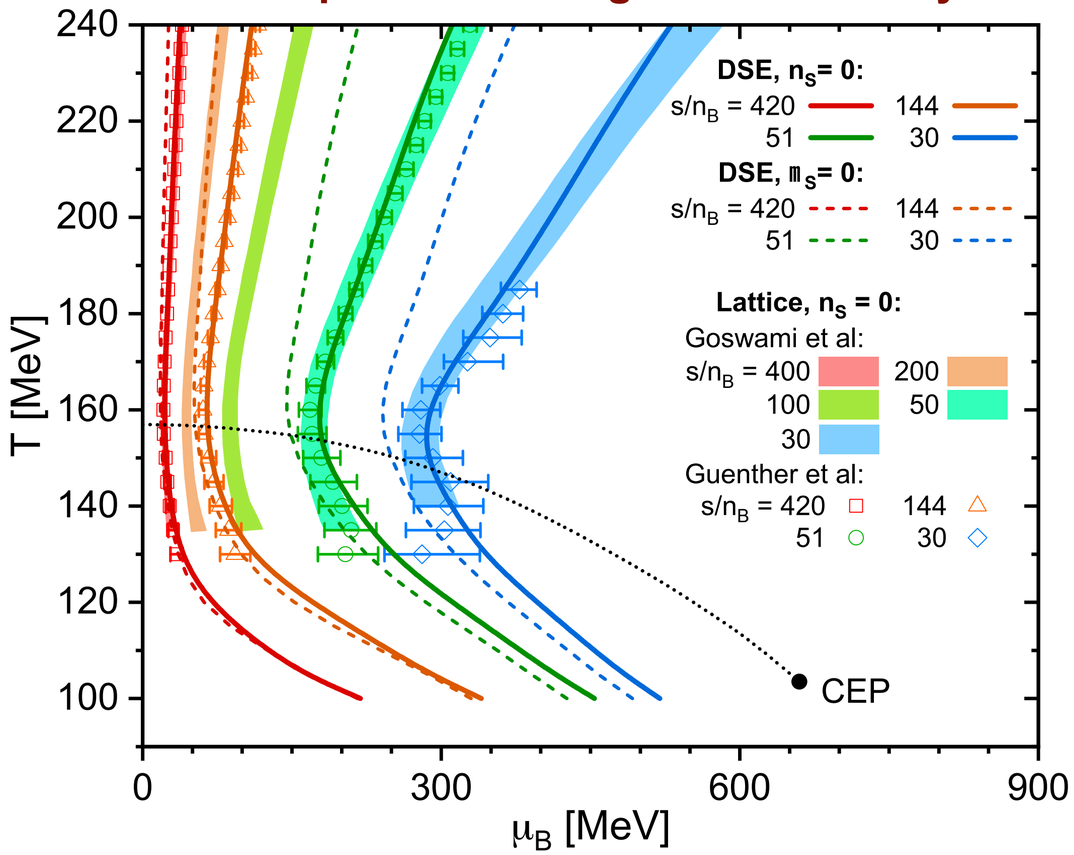
Unfolding the high density regime with new phases & physics

Great opportunity for a combined high precision analysis of high density QCD (Exp. data + lattice QCD + functional QCD)

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

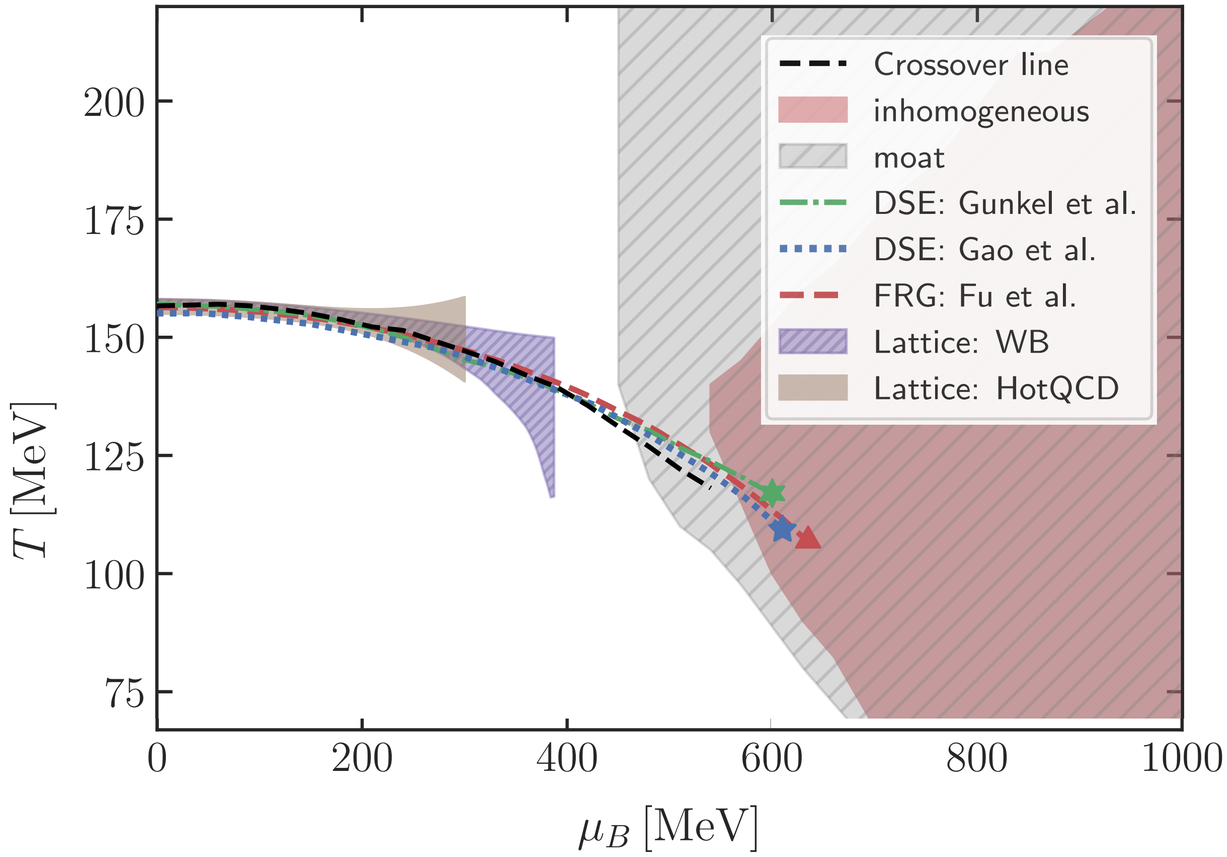
Ripples of the critical point: Sneak preview

isentropes with strangeness neutrality



Lu, Gao, Liu, JMP, arXiv:2504.05099 & in preparation

resolution of the moat regime in QCD



JMP, Rennecke, Sattler, in preparation

QCD phase structure at finite density: Facts & Fiction

Facts

$\mu_B = 0$

- **Chiral crossover at about**

$$T_\chi \approx 155\,\mathrm{MeV}$$

- **Strongly correlated phase for temperatures**

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

$\mu_B \neq 0$

- **No chiral critical end point for**

$$\mu_B \lesssim 600\,\mathrm{MeV}$$

- **No chiral crossover for**

$$\mu_B \gtrsim 700\,\mathrm{MeV}$$

Fiction

$\mu_B = 0$

- **Physical QCD is in the chiral scaling regime**

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

Soft modes are commonplace

- **Confinement crossover is at XXX**

$$T_\chi \lesssim T_{\mathrm{conf}} \lesssim 2\,T_\chi$$

$\mu_B \neq 0$

- **There is a CEP**

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

- **Scaling regime (Ising) of the CEP is humongous**

No, it is not! **Most likely: too small to be measured**

See talk of Shi Yin