Overview on the QCD phase structure

from functional approaches

Jan M. Pawlowski

Universität Heidelberg & ExtreMe Matter Institute

Phase transitions in particle physics, Firence 28th 2022

for the fQCD collaboration

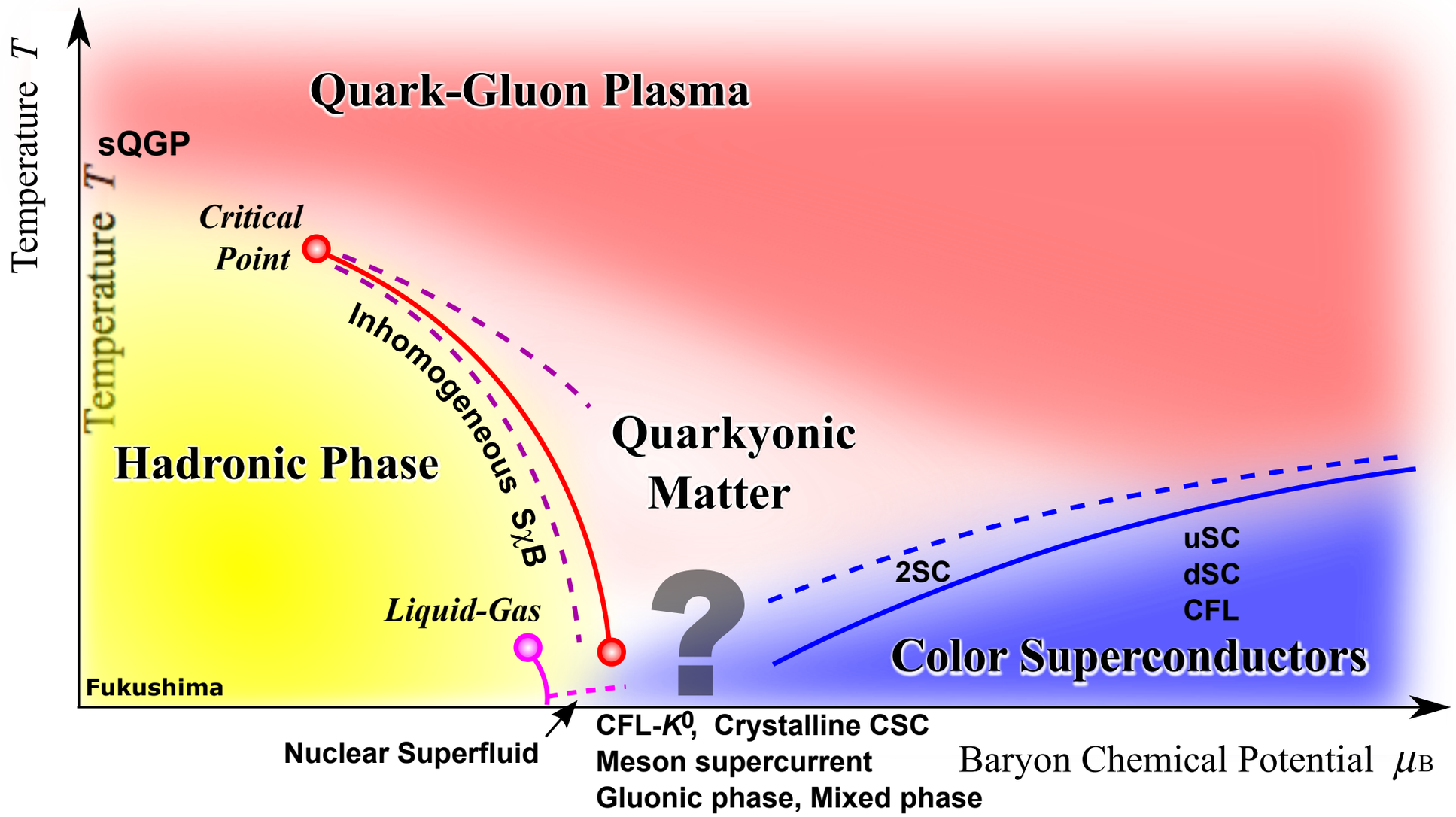
GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

STRUCTURES CLUSTER OF EXCELLENCE

isoQuant SFB1225

EMMI



fQCD collaboration

Braun, Chen, Fu, Gao, Geissel, Horak, Huang, Ihssen, JMP, Rennecke, Sattler, Schallmo, Tan, Töpfel, Wen, Wessely, Wink, Yin

Dalian, Beijing, Darmstadt, Heidelberg, Gießen

Outline

- QCD phase structure: Where do we stand?

- QCD phase structure: observables, estimates & systematics

- Chiral dynamics & phenomenological applications

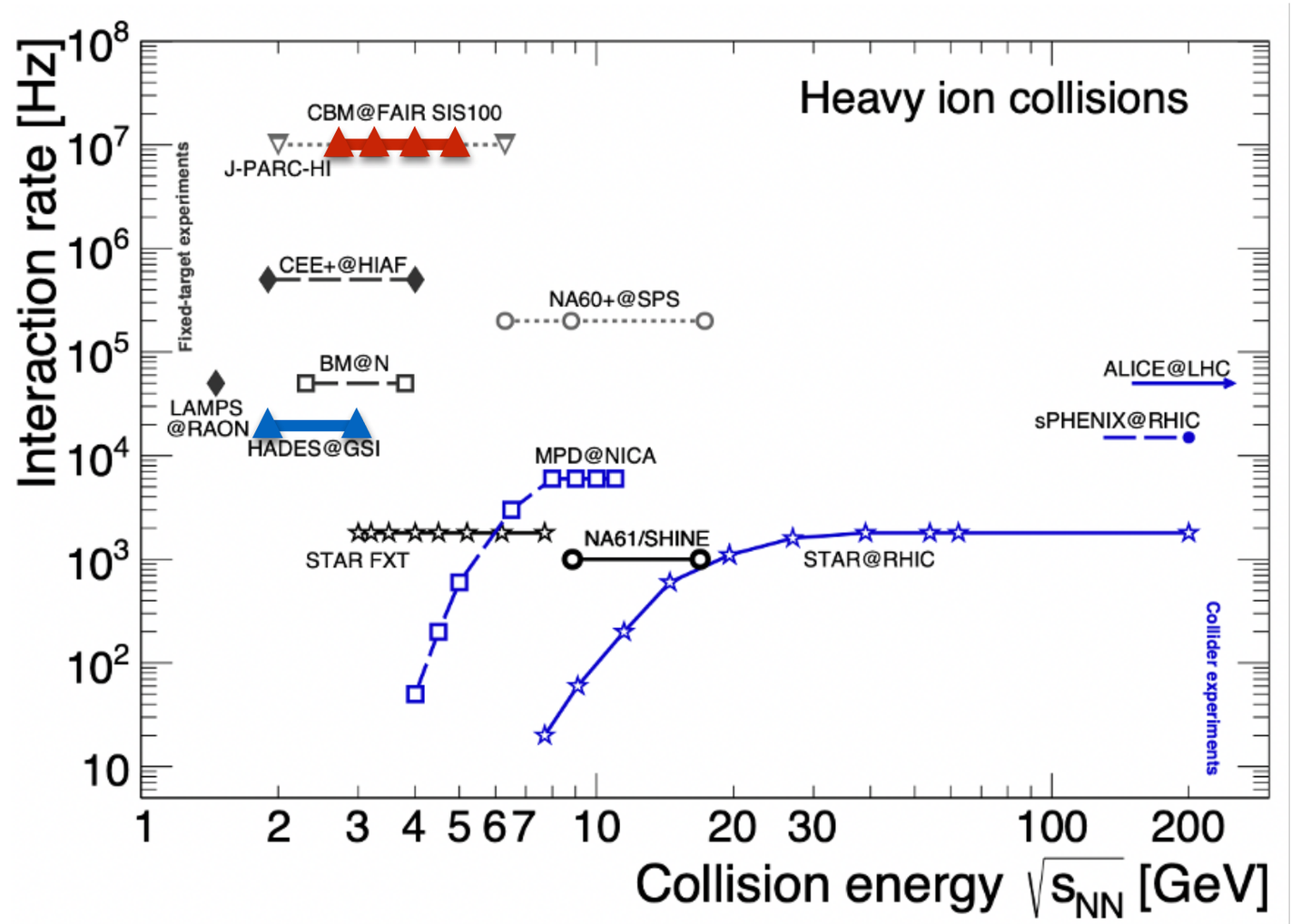
- Many flavour QCD & the conformal window

- Summary & outlook

Experimental landscape

'The (experimental) future is bright'

Tetyana Galatyuk, Erice 2021



Galatyuk, A982 (2019) update 2021; CBM, EPJA 53 3 (2017) 60

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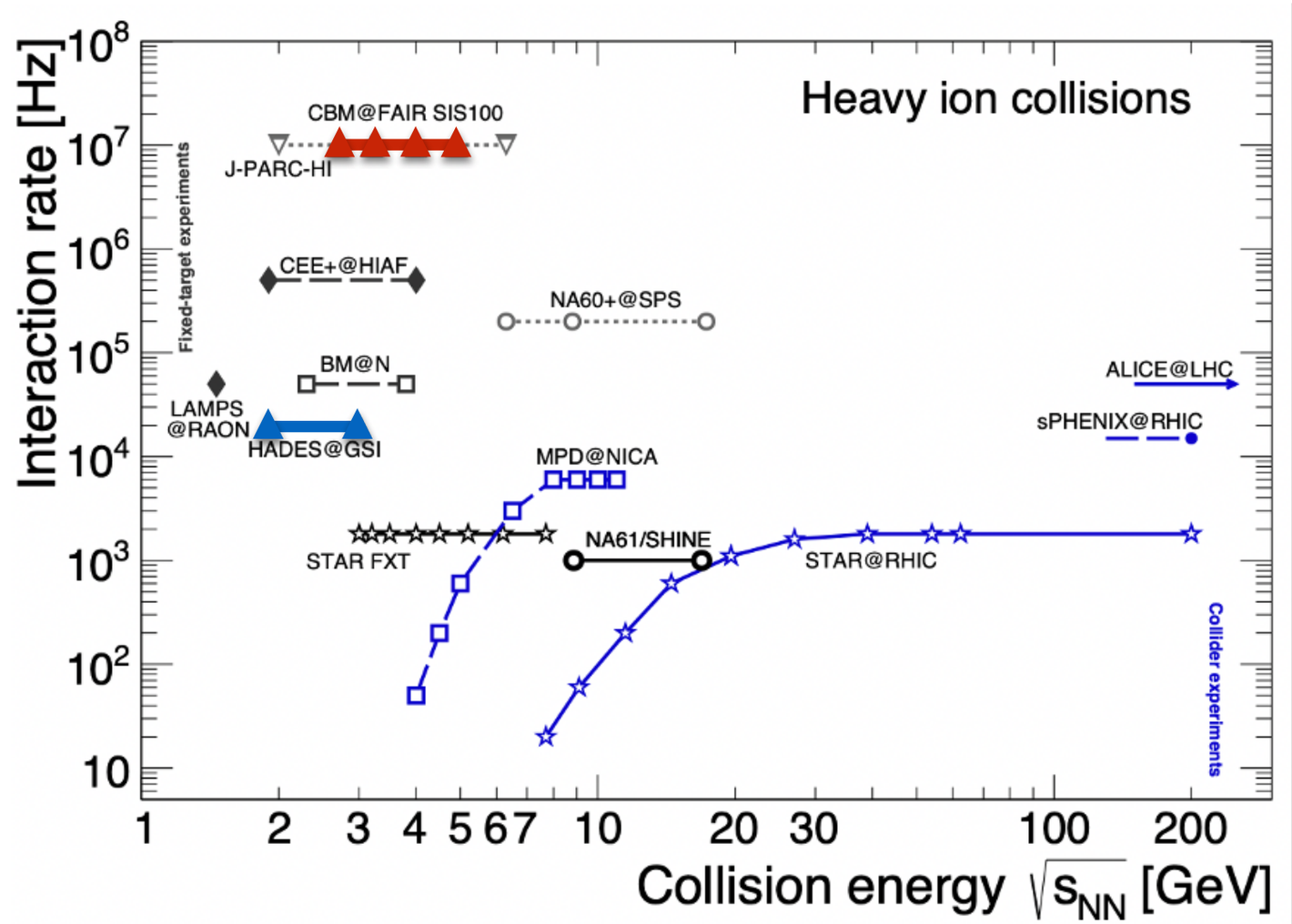
and ~2 hours ago



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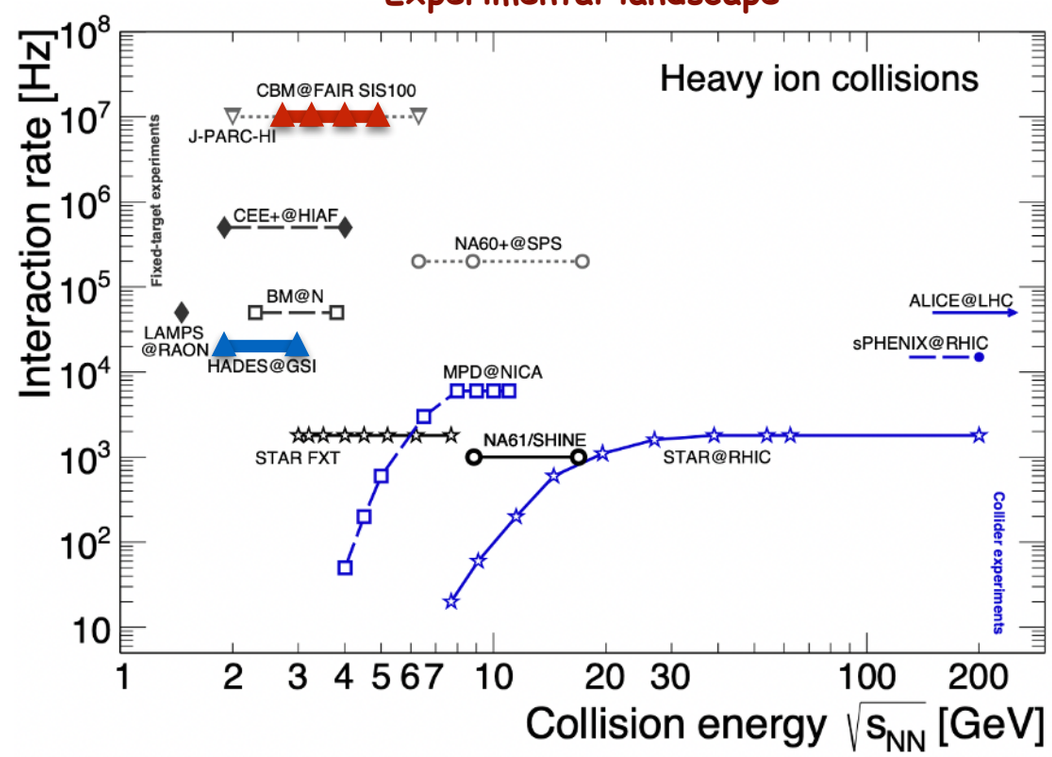
How bright does it get?

Experimental landscape



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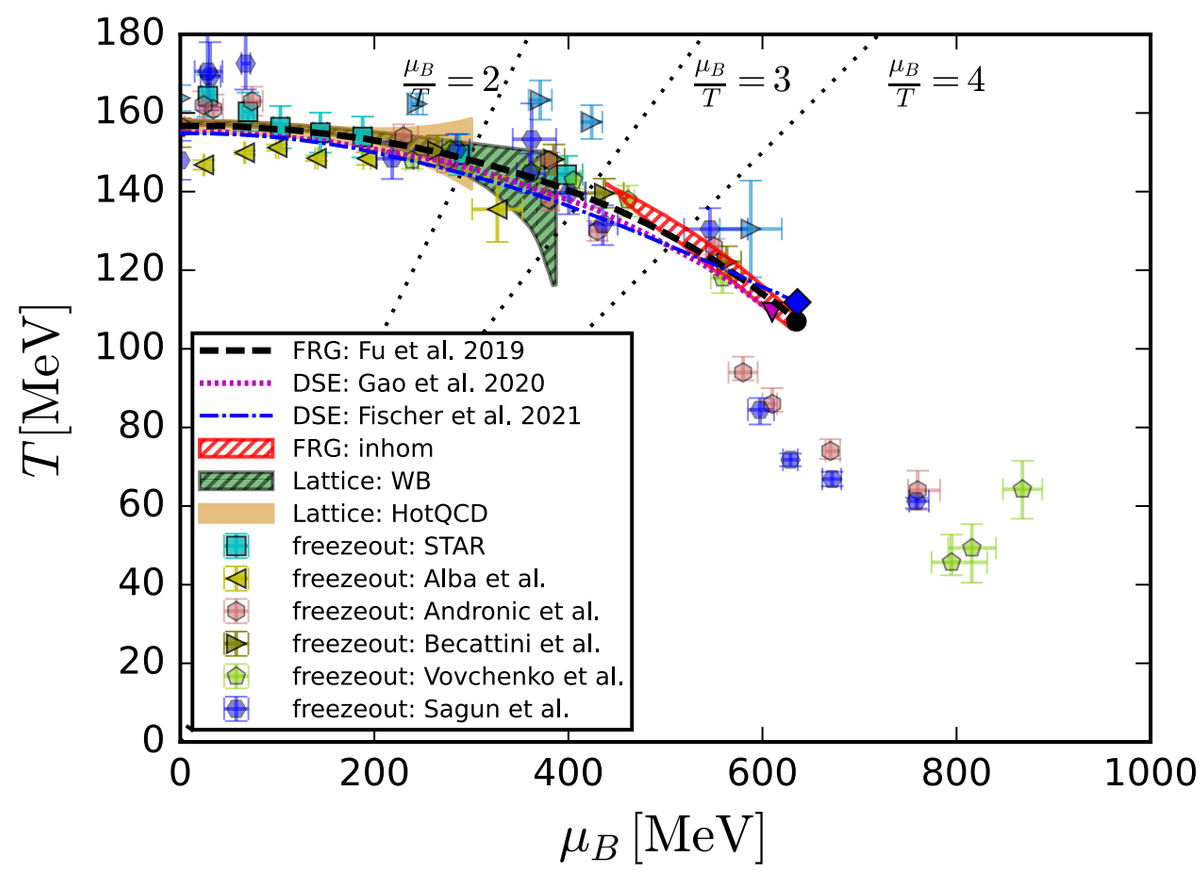
Chiral phase structure (theory) & freeze out data (Exp. data+Pheno)



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

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 5, 054022

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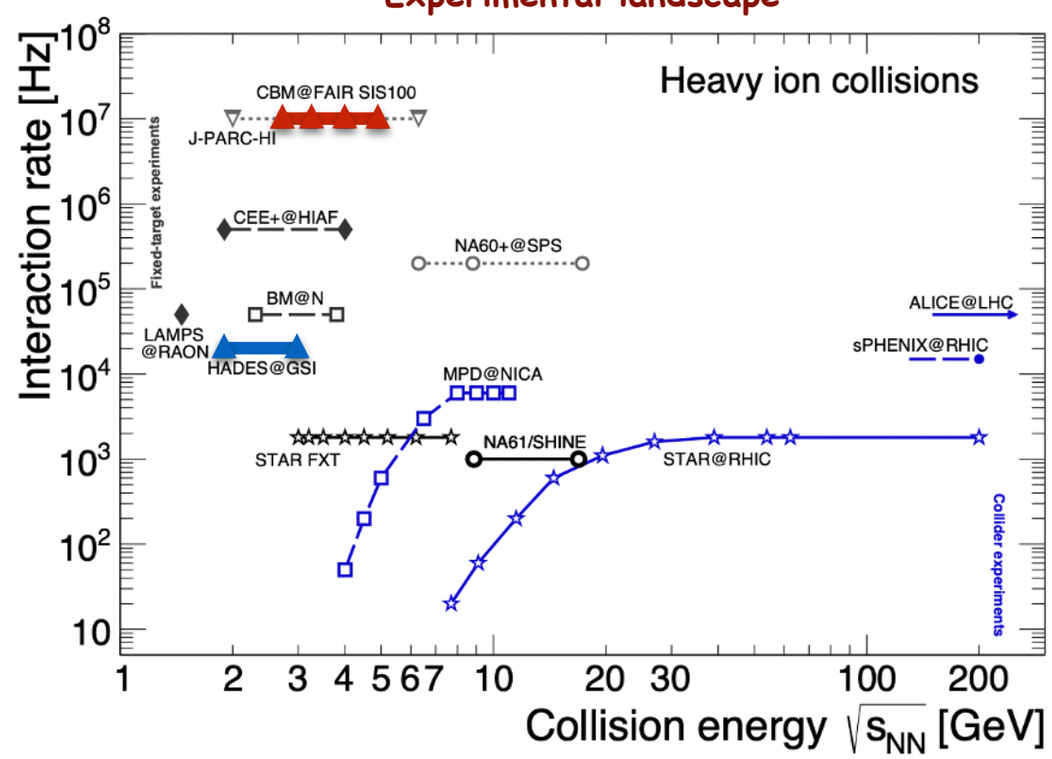

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Freezeout curve

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

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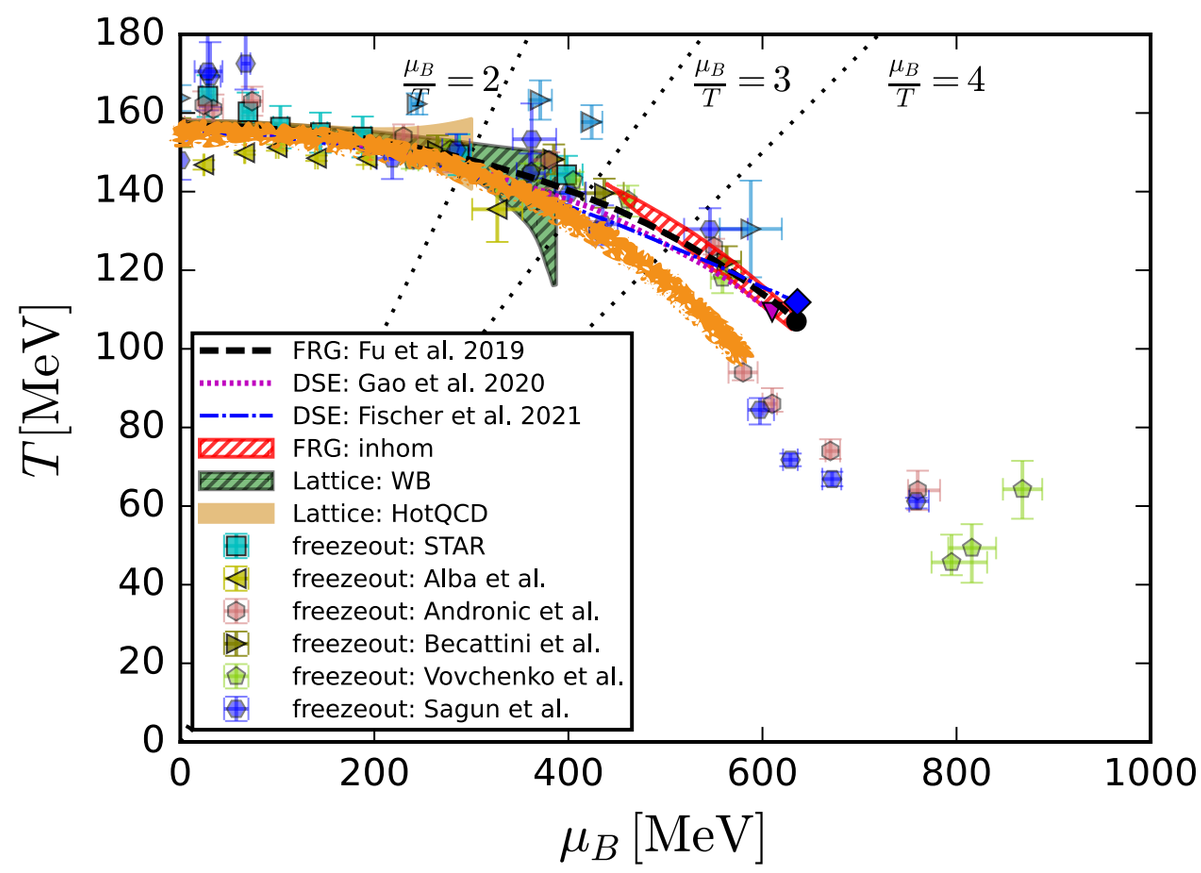

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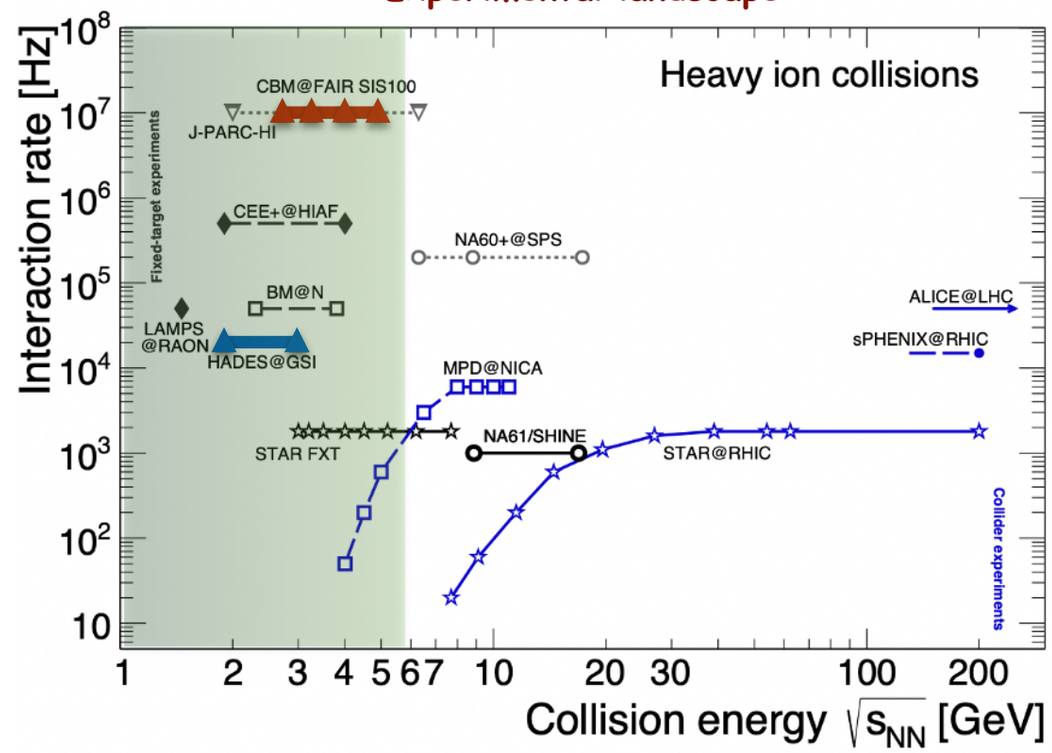

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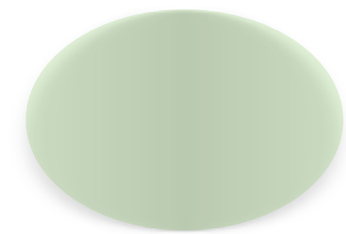
CEP or other NEW physics/phases



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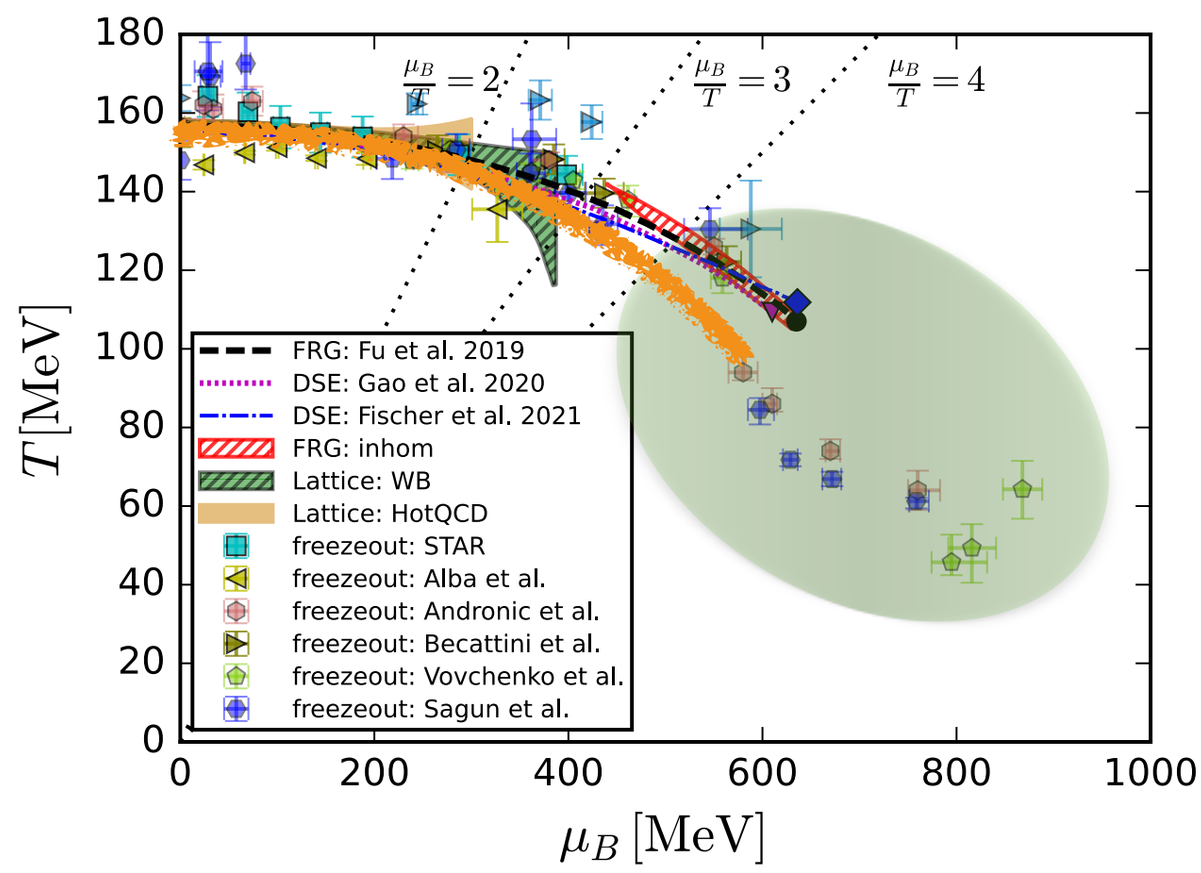

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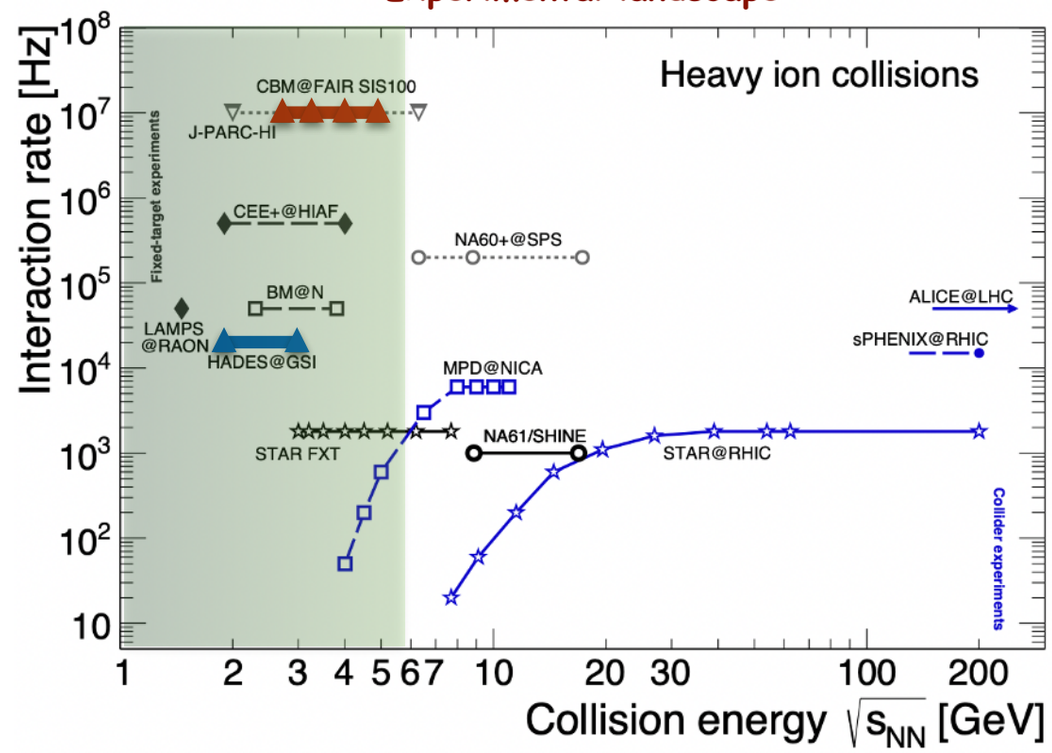

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CBM/STAR

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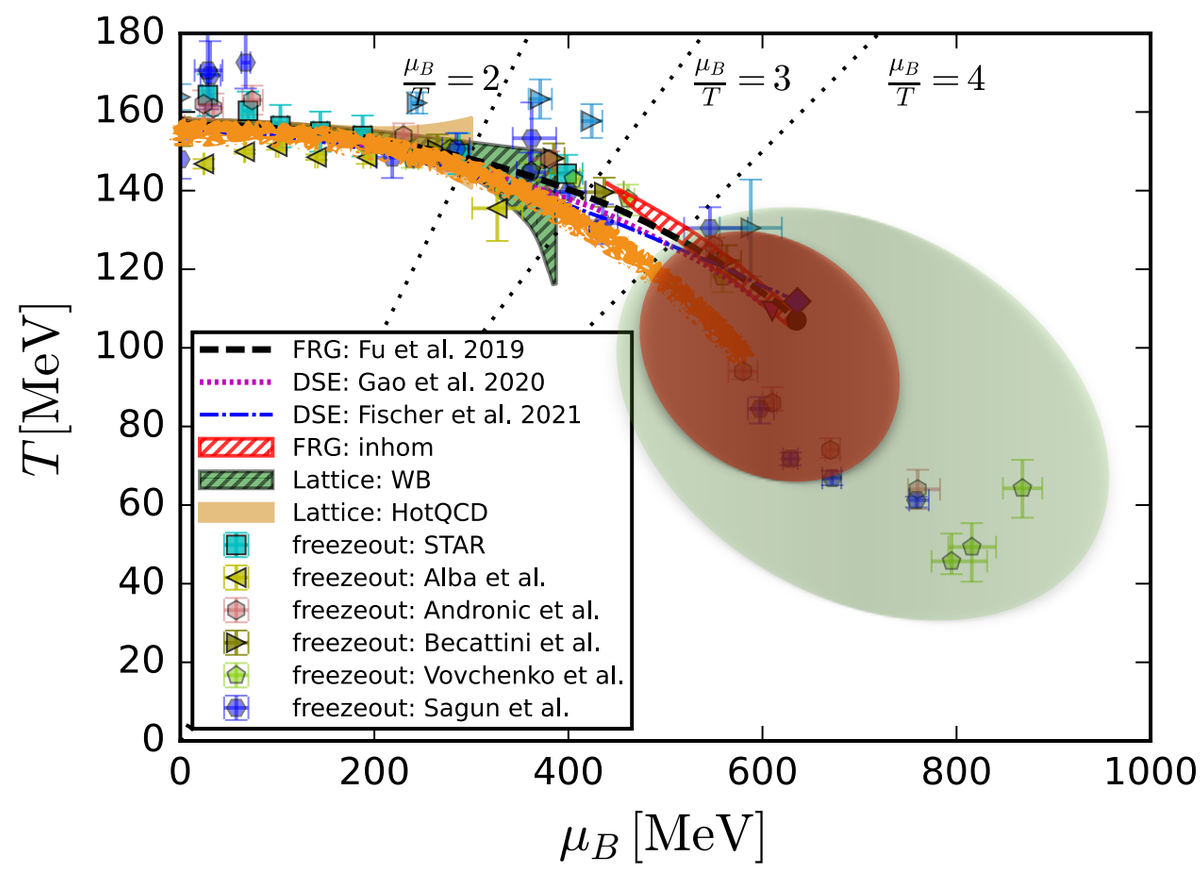

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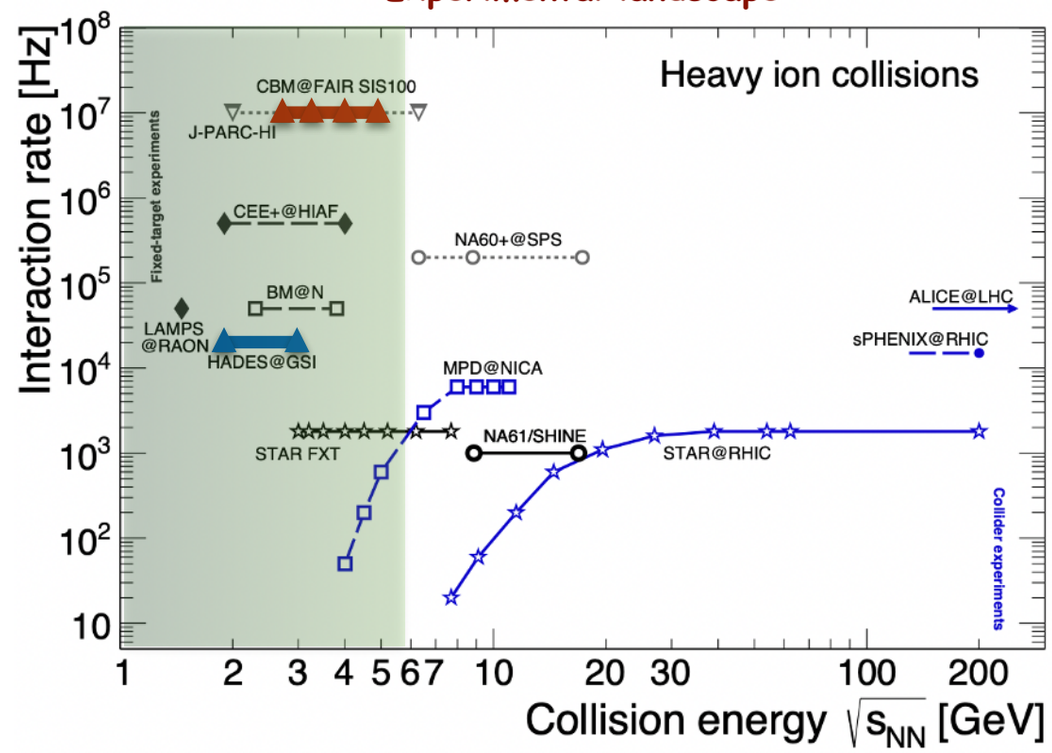

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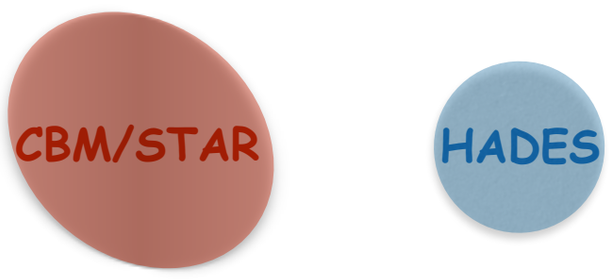

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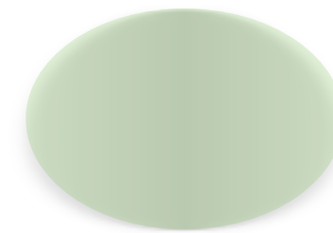

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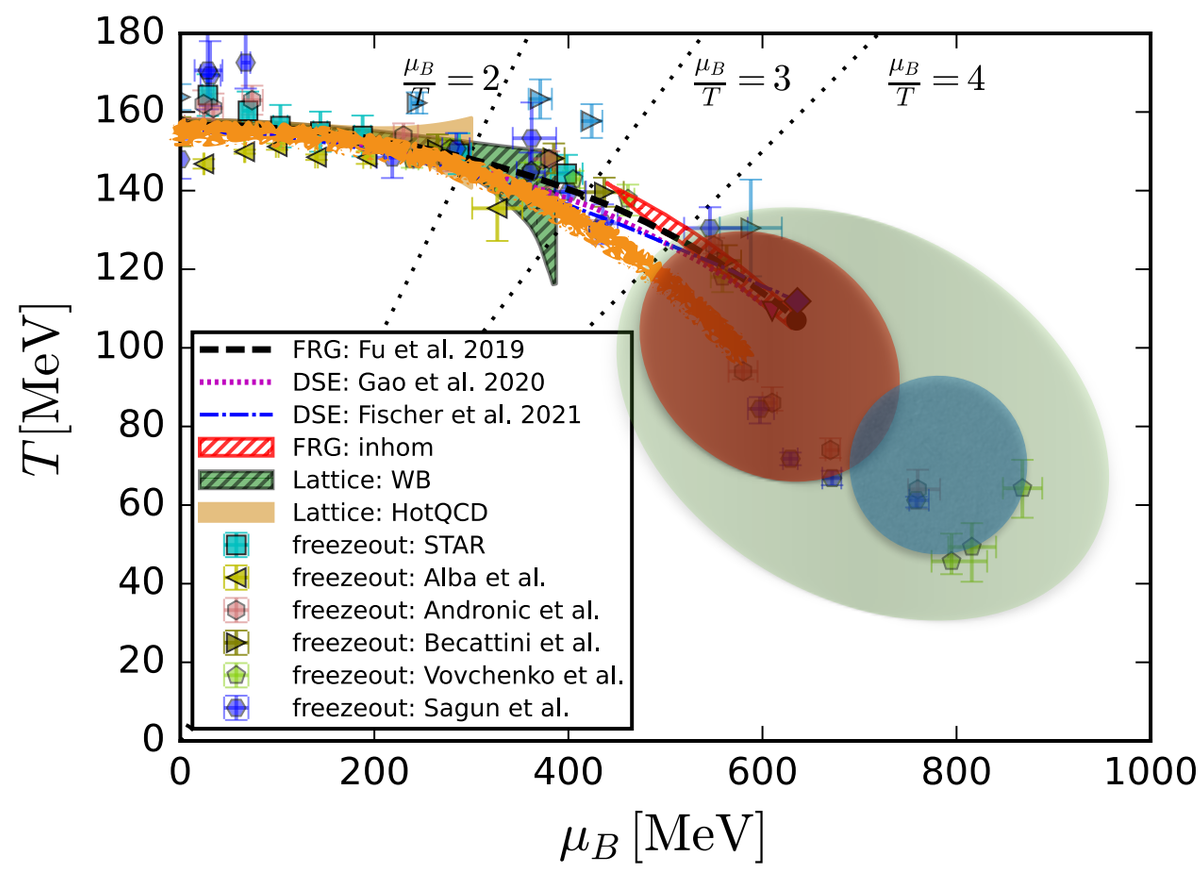

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Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 5, 054022

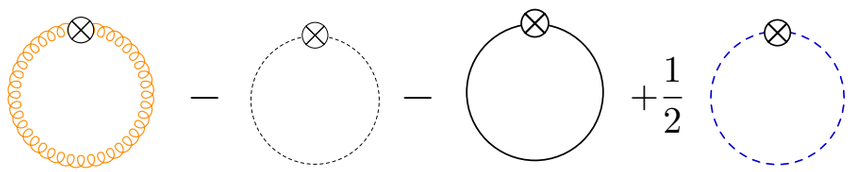
QCD with Functional Approaches

ab initio & closed form

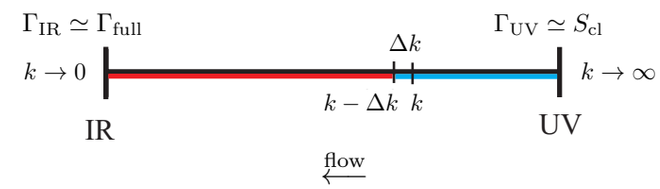
Diagrammatic Functional relations for the free energy $\Gamma[\phi]$

functional RG:

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}$$



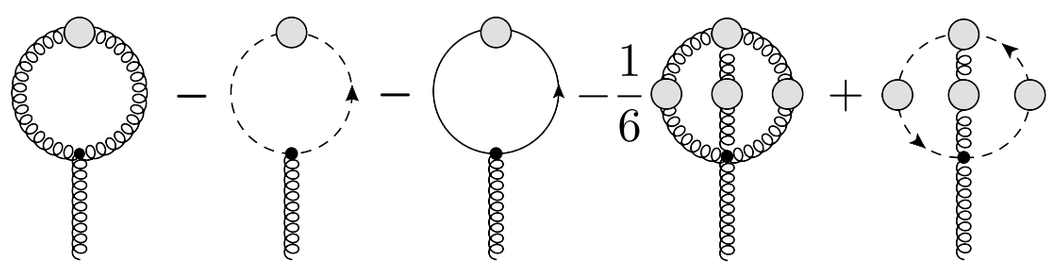
free energy/ grand potential



RG-scale k: $t = \ln k$

functional DSE :

$$\frac{\delta(\Gamma - S)}{\delta A_0} = \frac{1}{2}$$

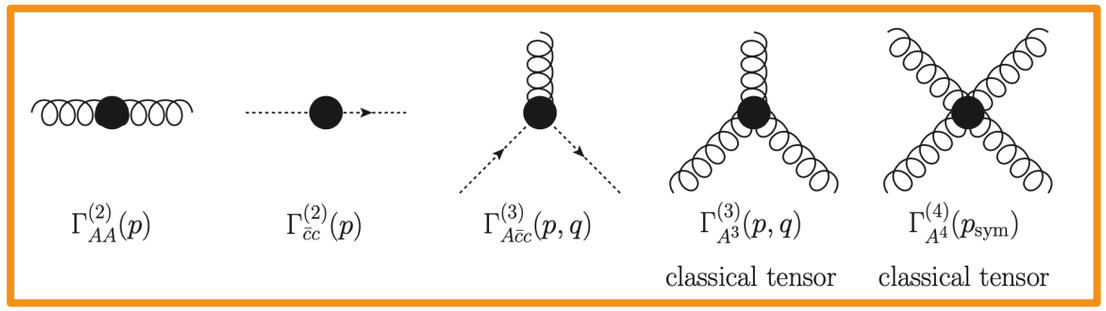


A_0 **: background field**

FRG: JMP, NPA 931 (2014) 113
Dupuis et al, Phys.Rept. 910 (2021) 1

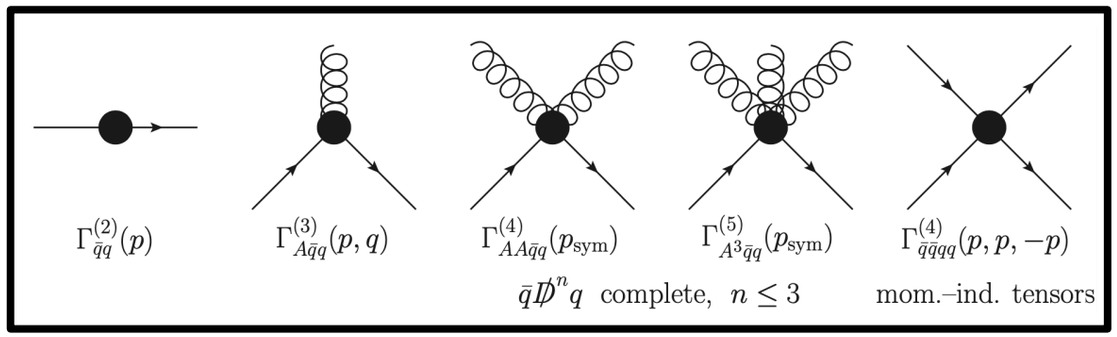
DSE: Fischer, PPNP 105 (2019) 1

vacuum fQCD: current set of correlation functions

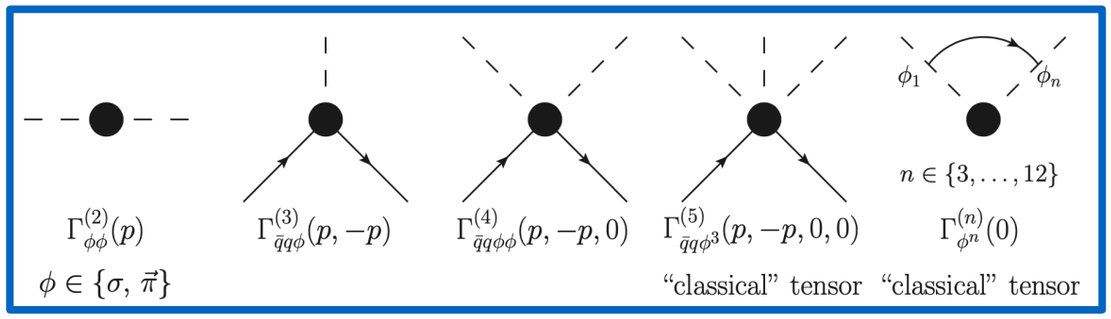


glue sector

FRG

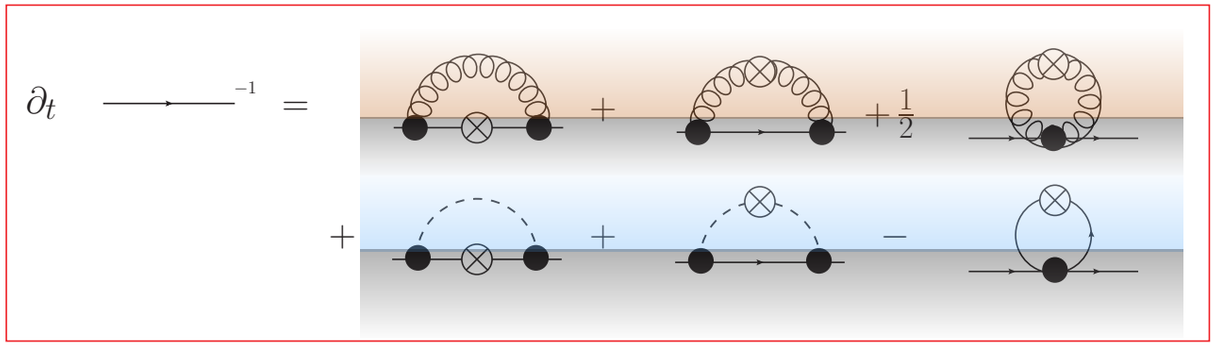


quark-glue sector



quark-meson sector

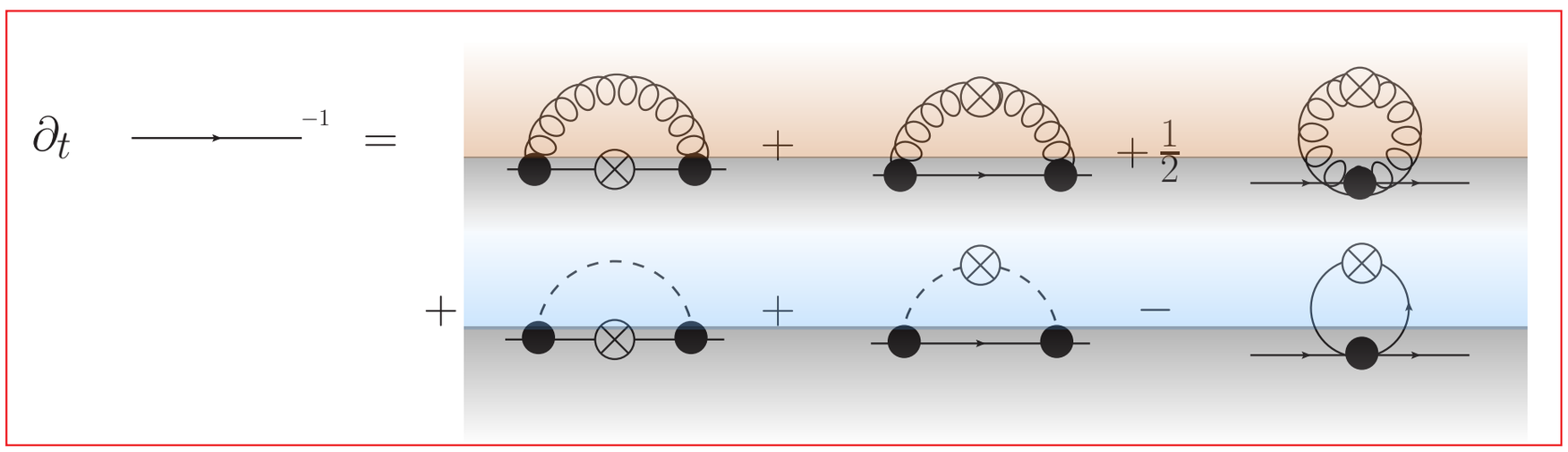
Aiming at apparent convergence



Analyticity considerations at finite density

- **Self-consistent truncations to functional relations define analytic functions in μ_{B}, eg:**

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



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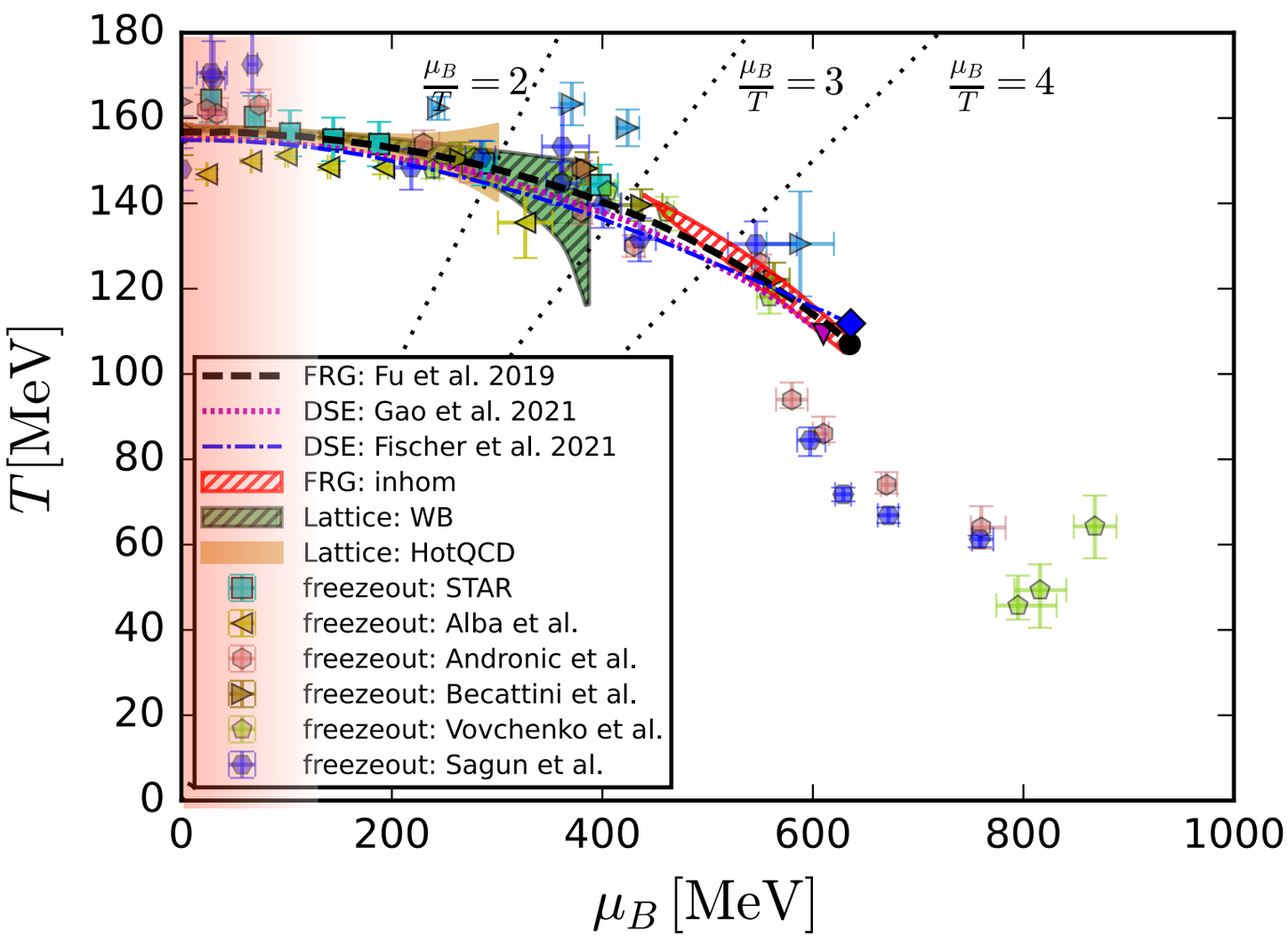
- **Consequences for functional QCD predictions at finite density**



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

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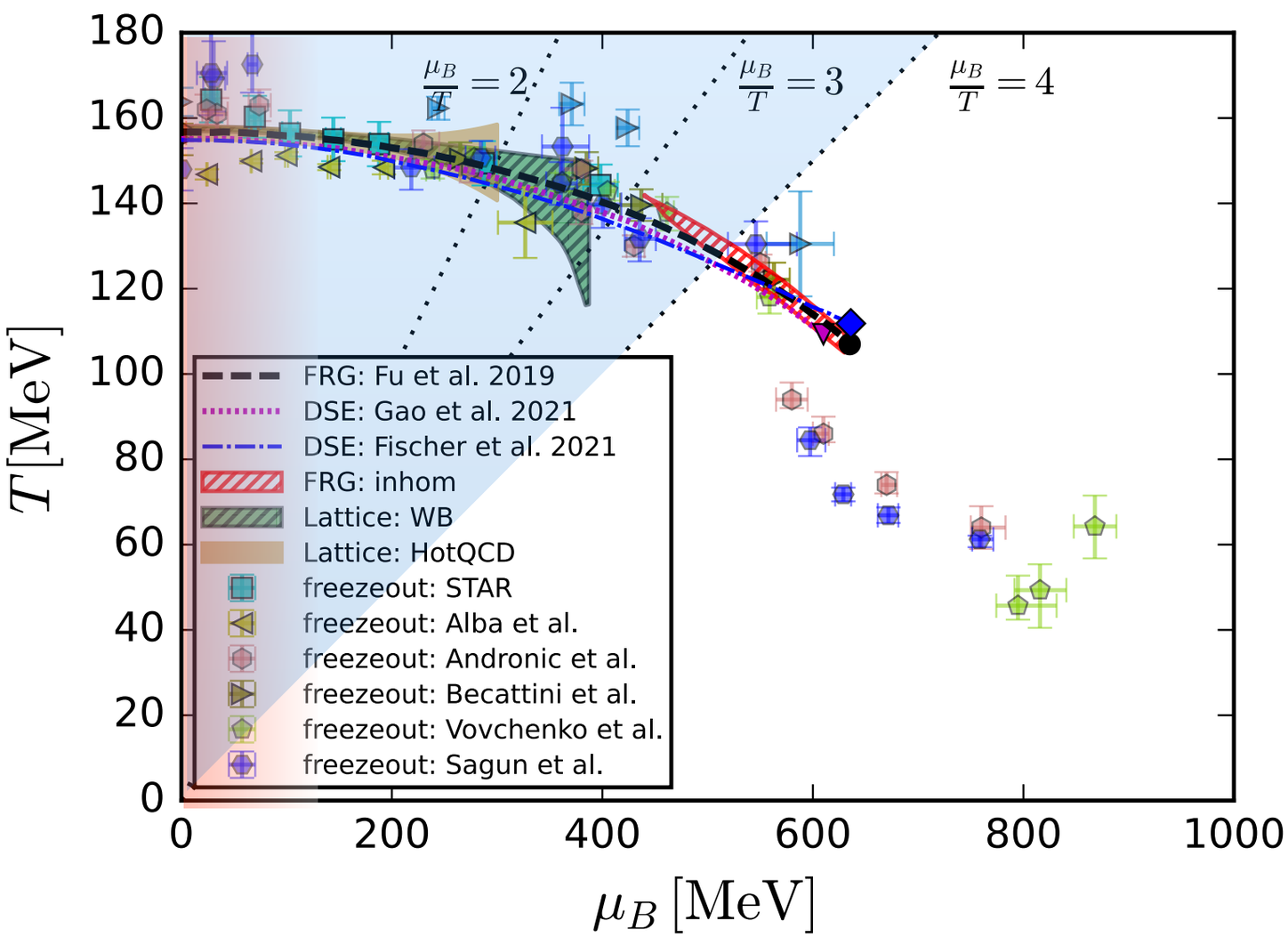

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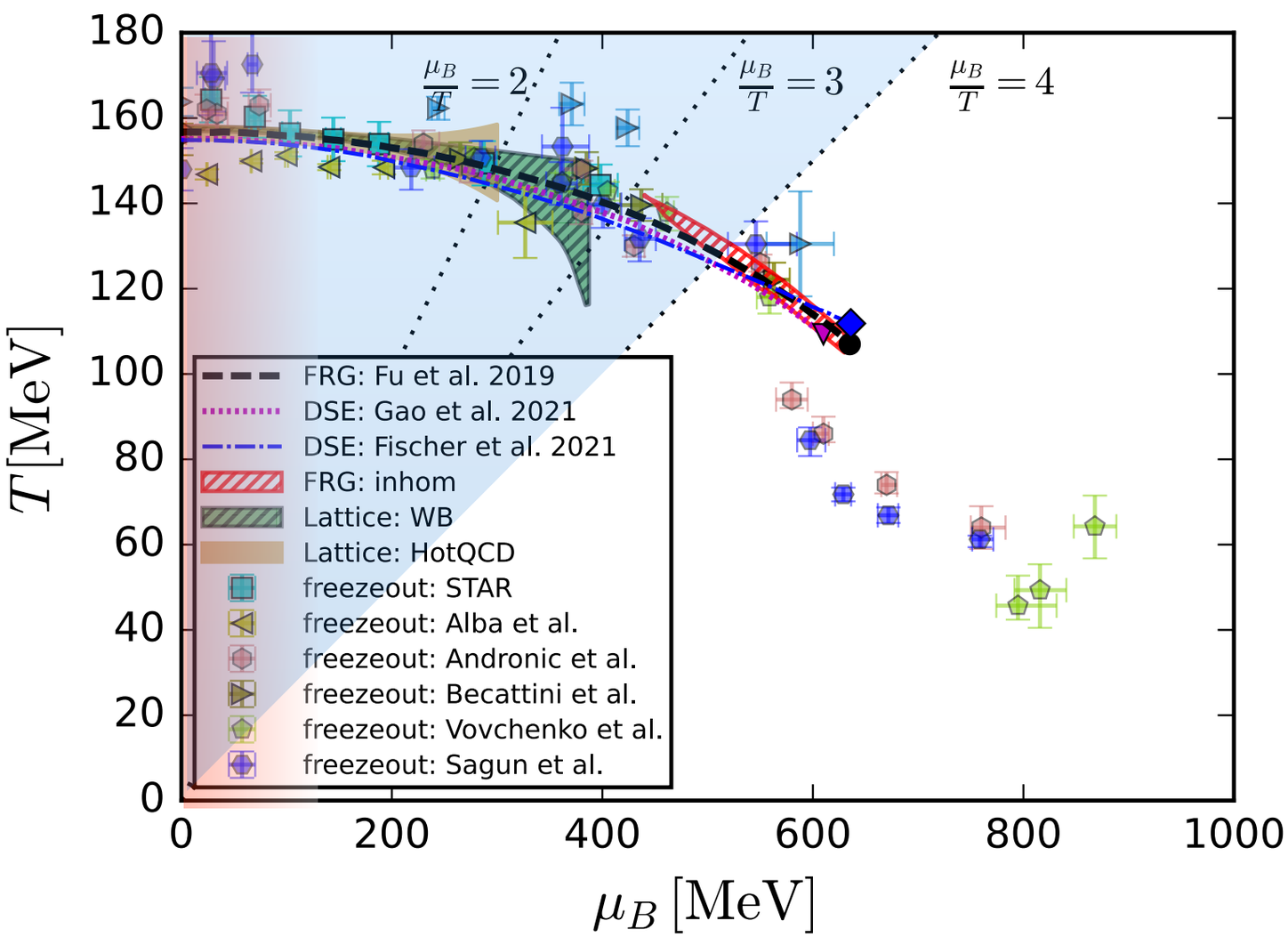

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Unique: QCD-based analytic continuations that satisfy the lattice benchmarks at small chemical potential.

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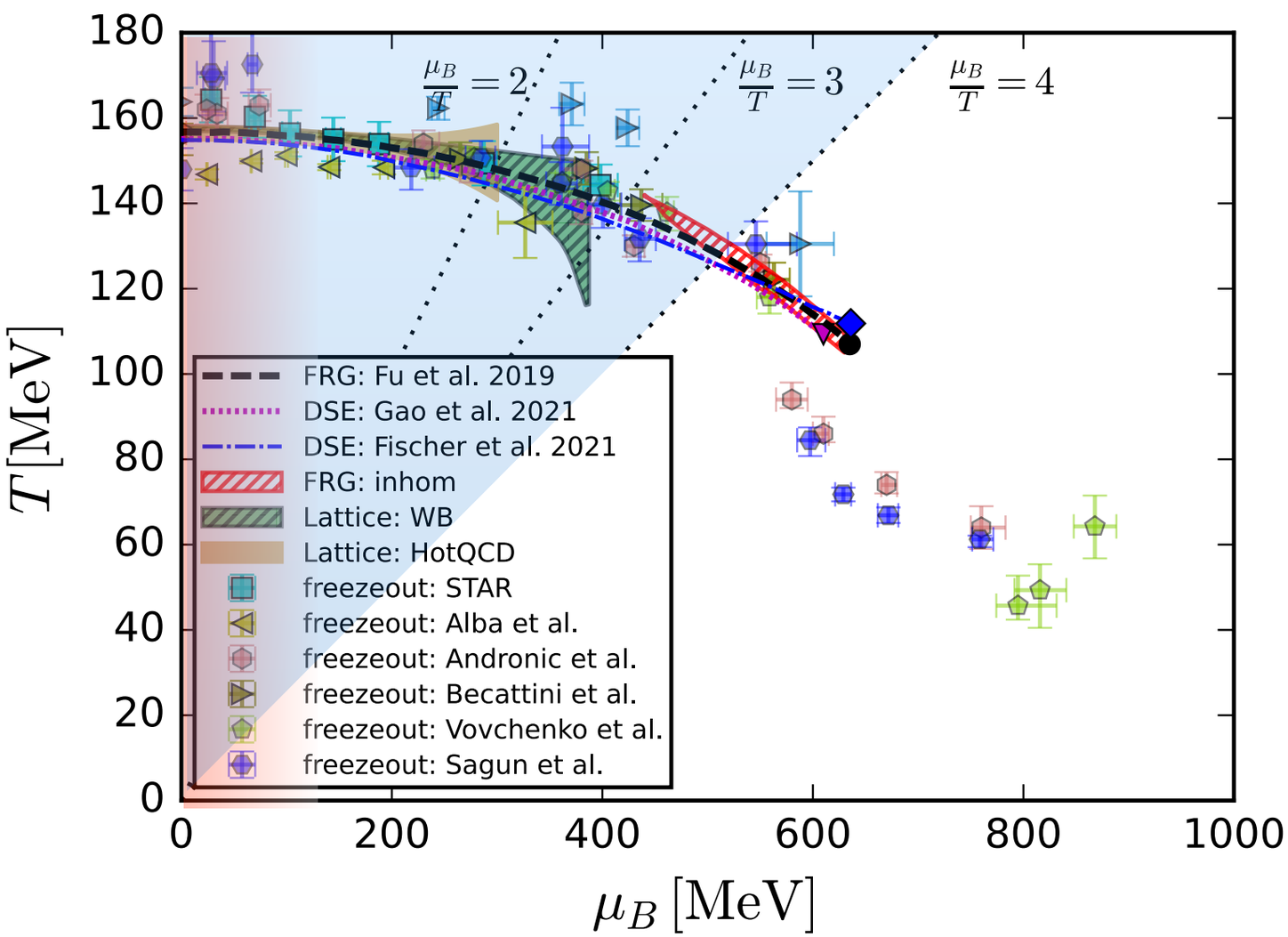

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Unique: QCD-based analytic continuations that satisfy the lattice benchmarks at small chemical potential.

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

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- QCD phase structure: Where do we stand?

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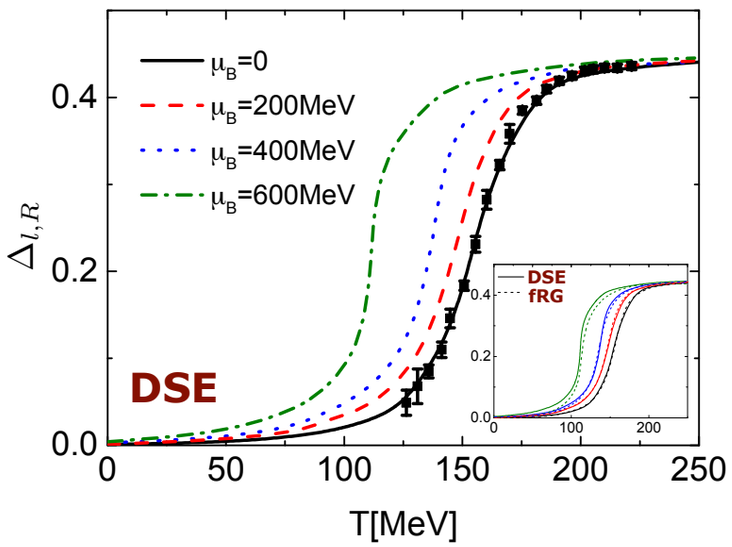
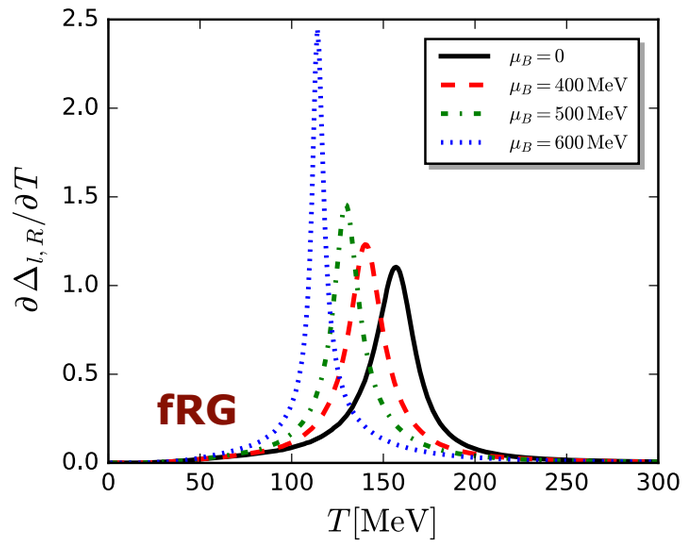
Chiral condensates

renormalised condensate





$$\Delta_{l,R}(T,\mu_B) \simeq \Delta_l(T,\mu_B) - \Delta_l(0,0)$$

$$\Delta_q(T,\mu_B) = \frac{T}{\mathcal{V}}\, m_q^0 \int_x \langle \bar{q}(x) q(x) \rangle$$

lattice: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, C. Ratti, and K. K. Szabo, JHEP 09, 073 (2010)

DSE: quark condensates

See also

Fischer, Luecker, PLB 718 (2013) 1036
Fischer, Luecker,Welzbacher, PRD 90 (2014) 034022
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011

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

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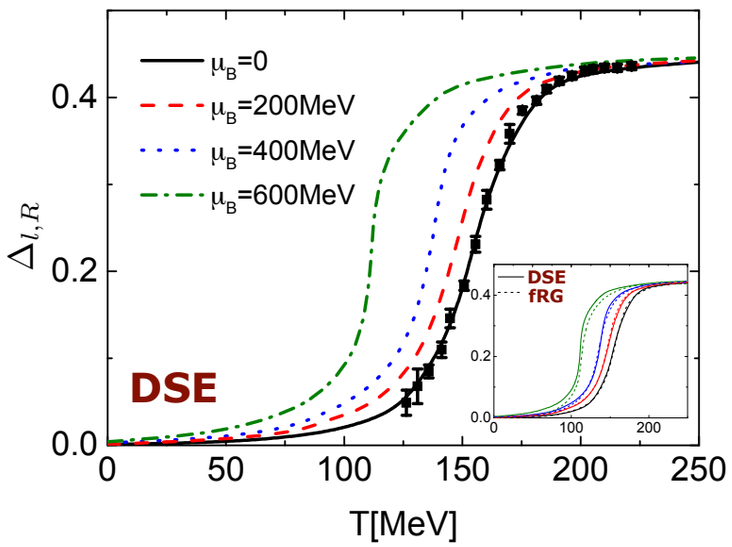

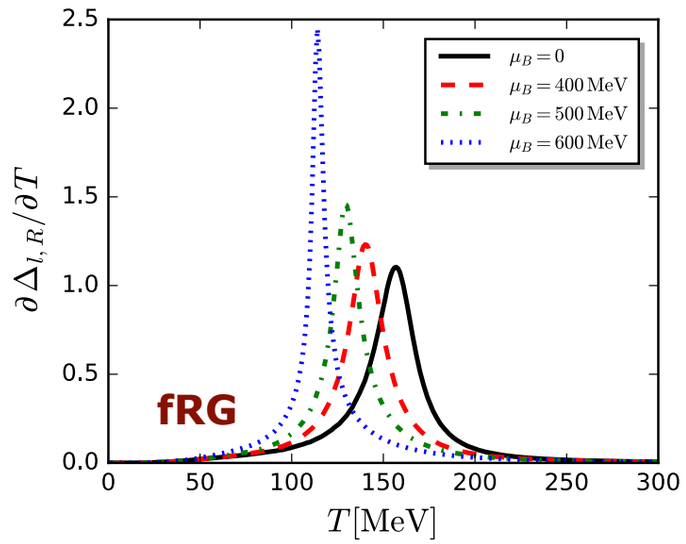

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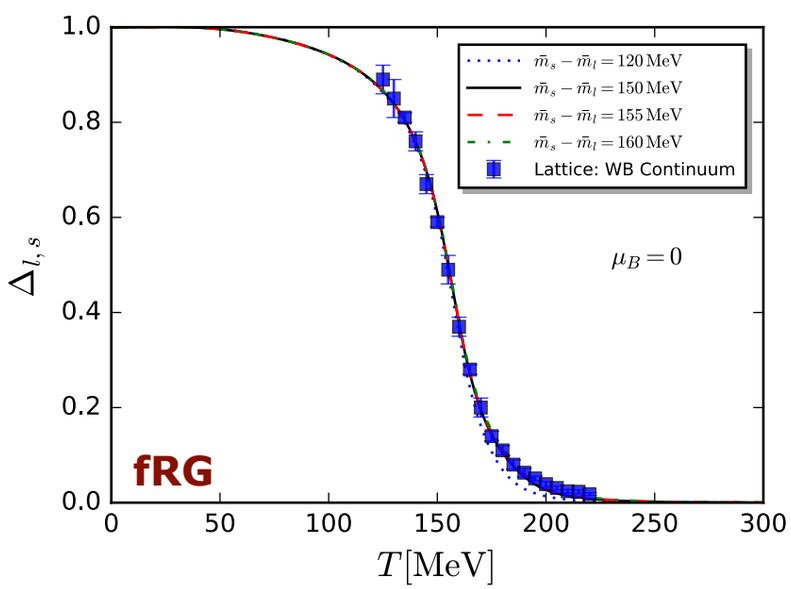
reduced condensate

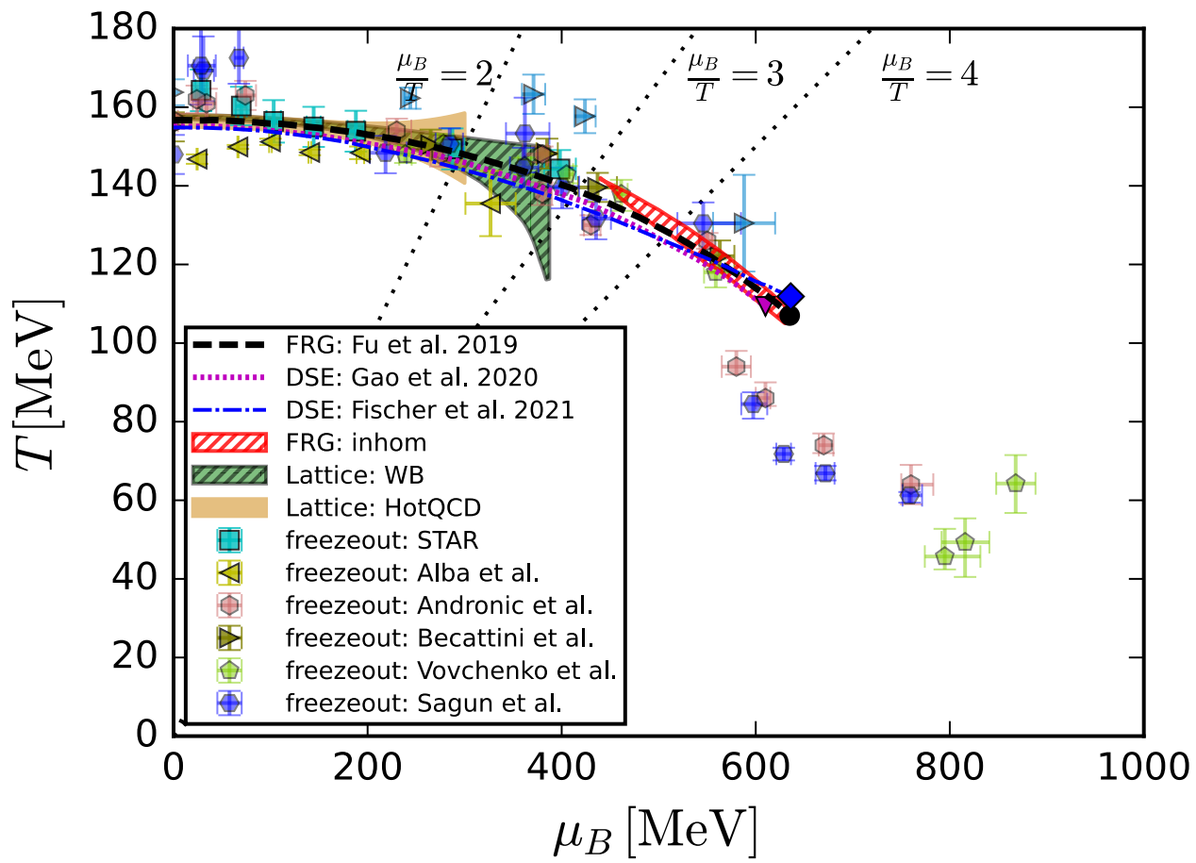


$$\Delta_{l,s}(T,\mu_B) = \frac{\Delta_l(T,\mu_B) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(T,\mu_B)}{\Delta_l(0,0) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(0,0)}$$

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

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

Curvature of the chiral transition line



fQCD

$$\kappa_{\rm FRG} = 0.0142(2)$$

$$\kappa_{\rm DSE} = 0.0147(5)$$

lattice

$$\kappa_{\rm WB} = 0.0149(21)$$

WB, PLB 751 (2015) 559

$$\kappa_{\rm hotQCD} = 0.015(4)$$

hotQCD, PLB 795 (2019) 15

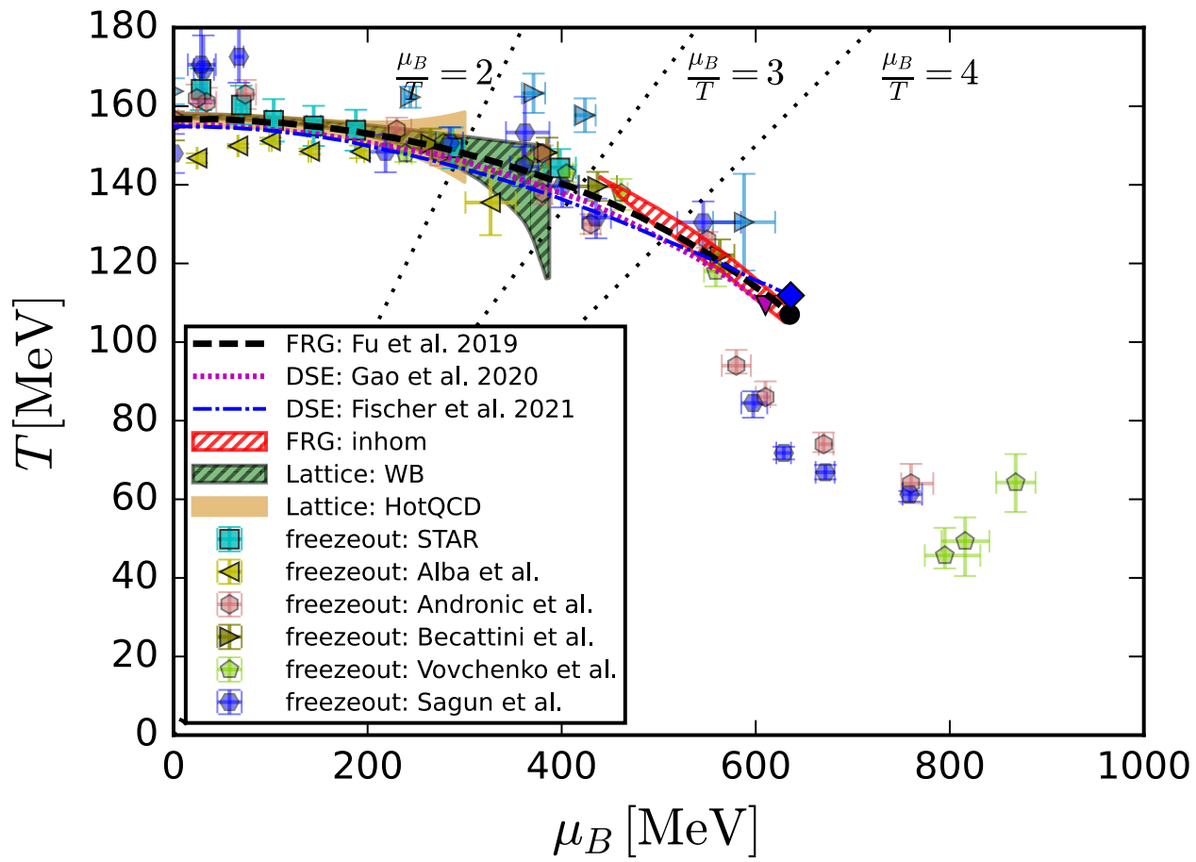
DSE: see also

Gunkel, Fischer, PRD 104 (2021) 054022

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

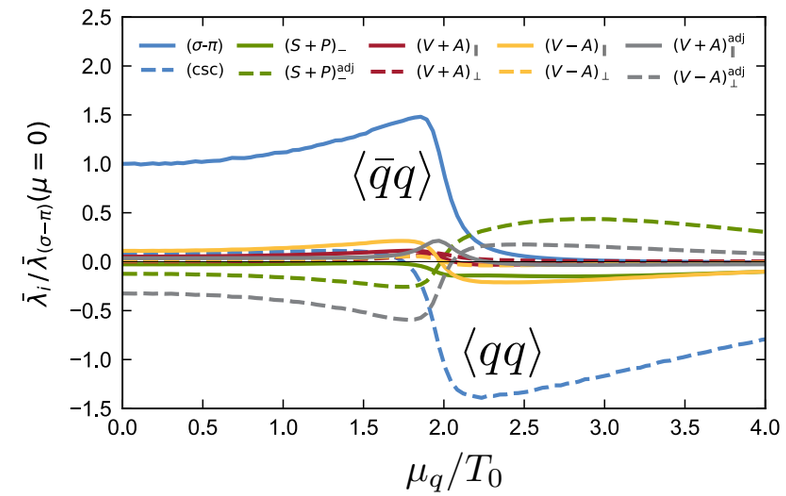
DSE: **Gao, JMP, PLB 820 (2021) 136584**

Systematic error control (CEP)

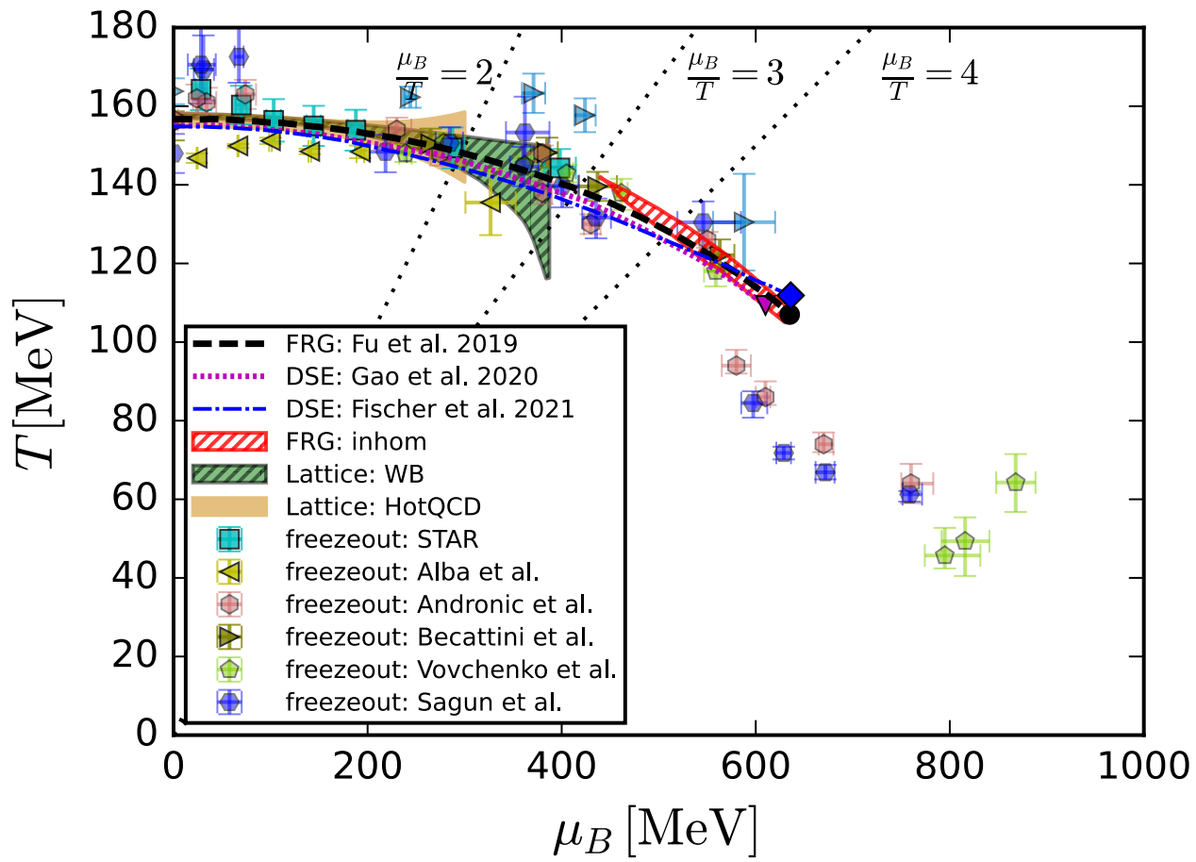


Dominant channels I (fRG)

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

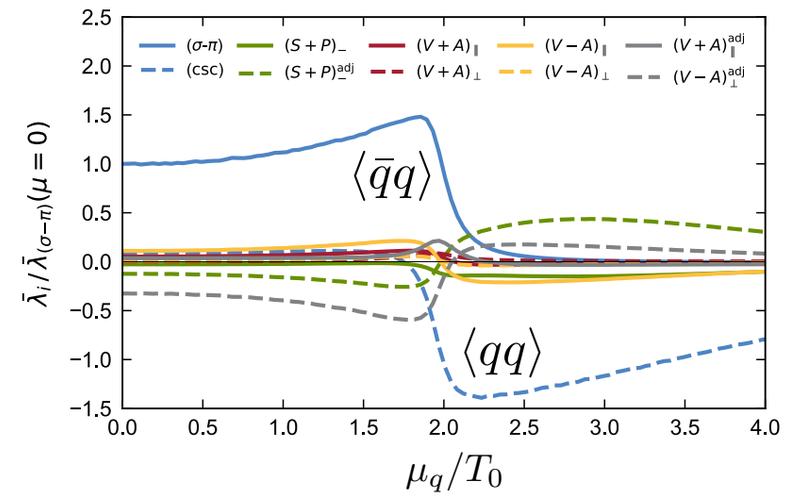


Systematic error control (CEP)



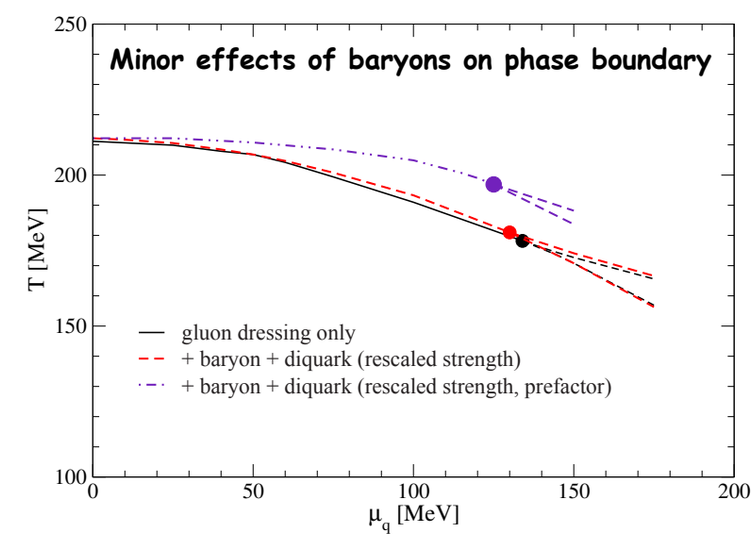
Dominant channels I (fRG)

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



Dominant channels II (DSE)

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



Minor effects of mesons

Gunkel, Fischer, PRD 104 (2021) 054022

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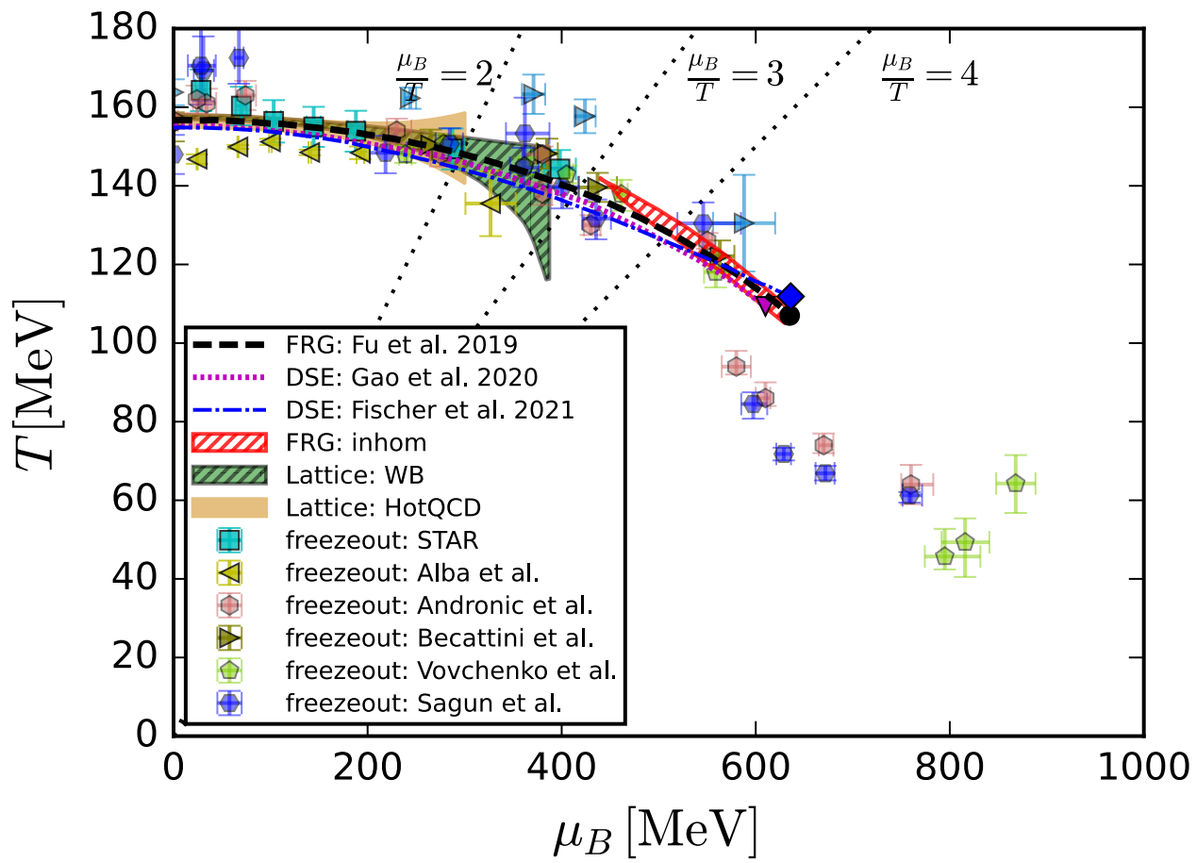

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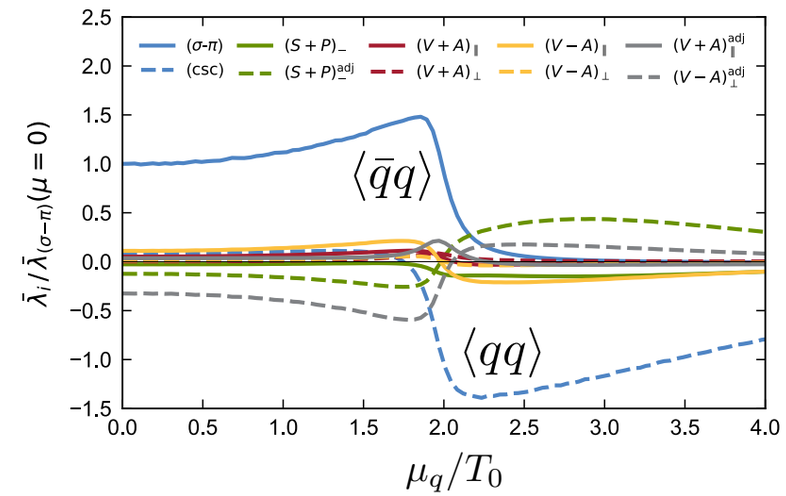

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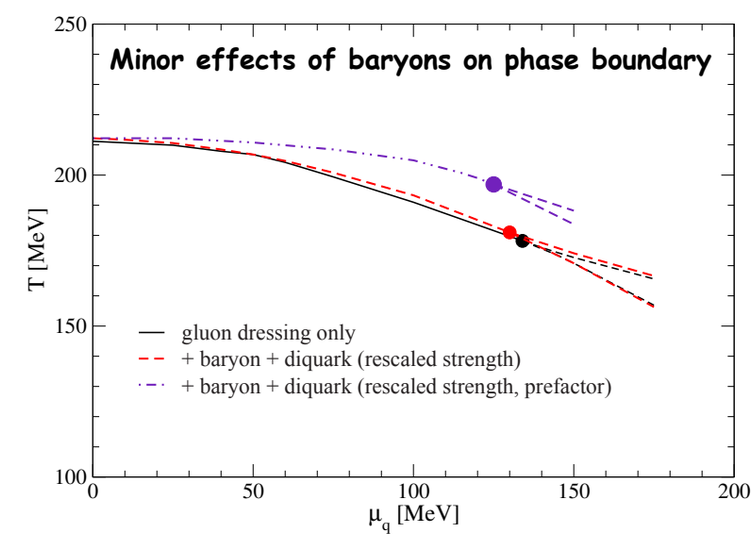

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Gunkel, Fischer, PRD 104 (2021) 054022

I+II → Fierz-complete computation

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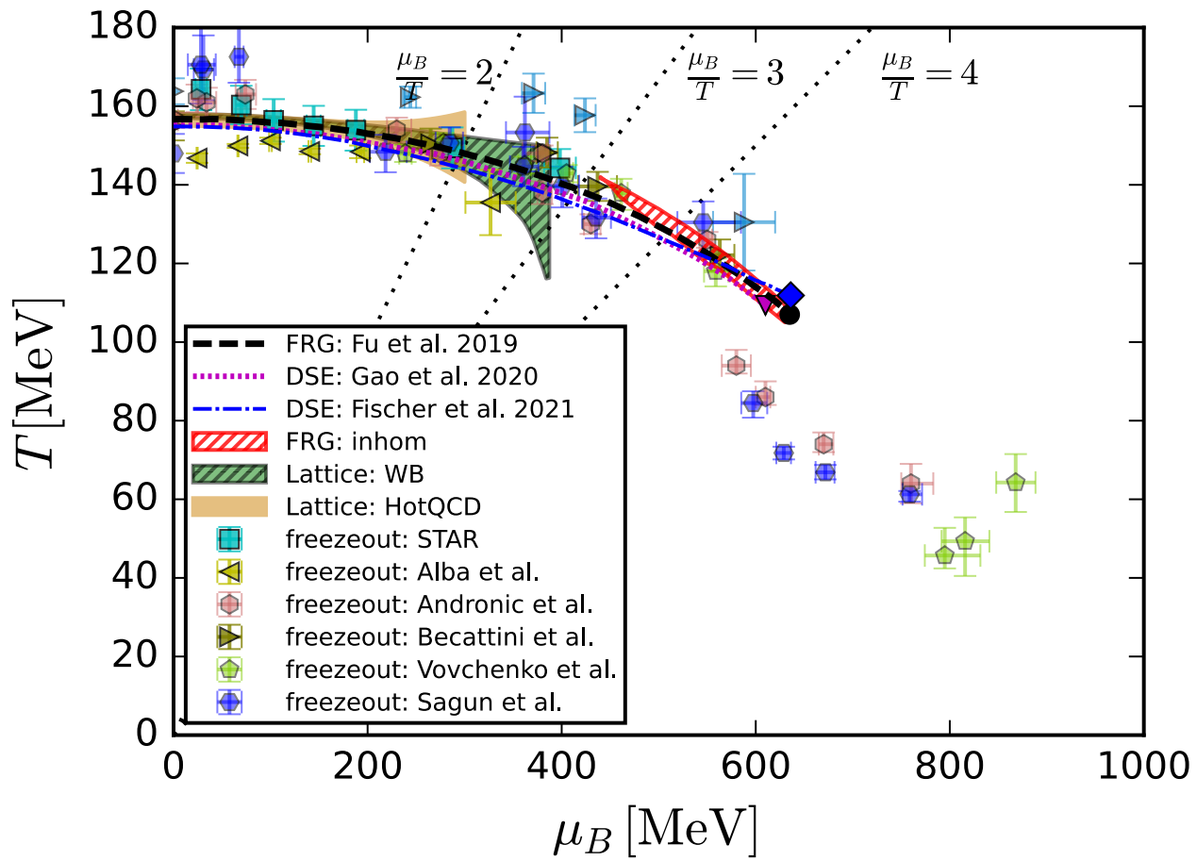

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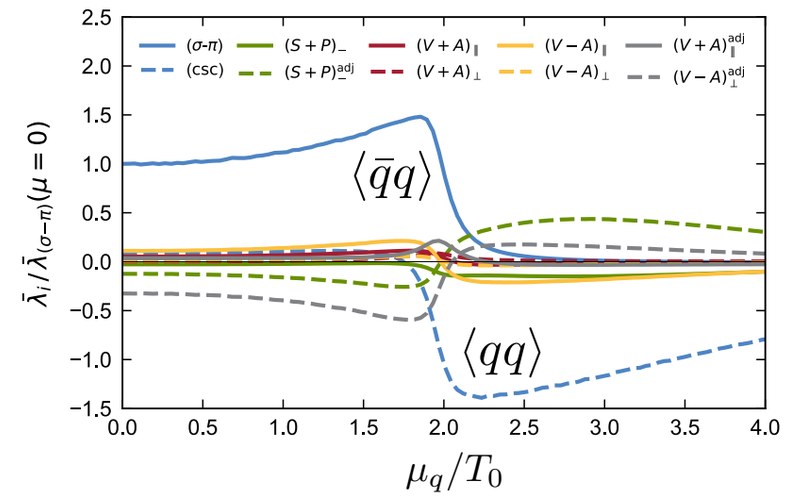

Moat and 'inhomogeneous' phases

: Pion dispersion has minimum at non-vanishing spatial momentum & sizeable chiral condensate

Fu, JMP, Rennecke, PRD 101, (2020) 054032
Moat: Pisarski, Rennecke, PRL 127 (2021) 152302

→ Non-trivial background

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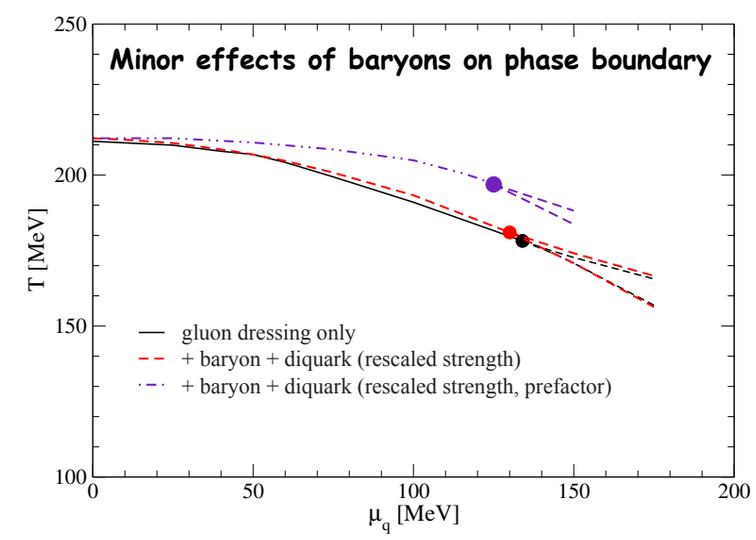
Eichmann, Fischer, Welzbacher, PRD 93 (2016) 034013



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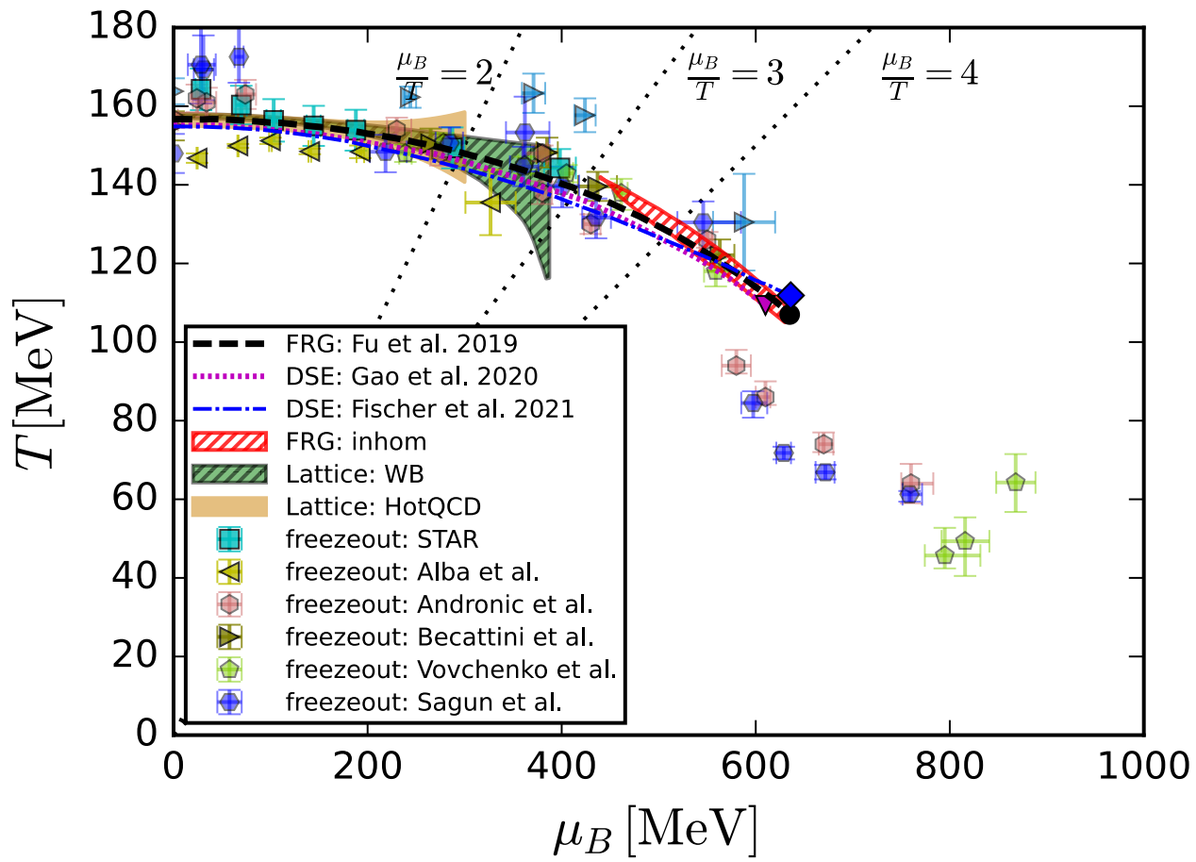

$\mu_B/T \lesssim 4$

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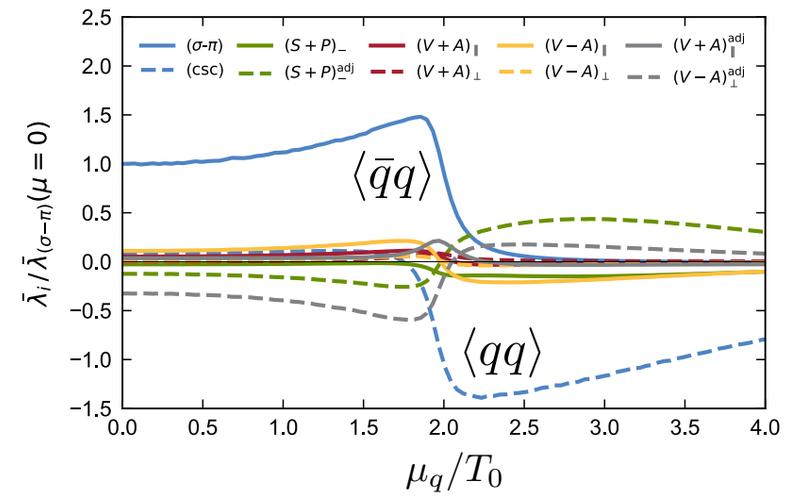

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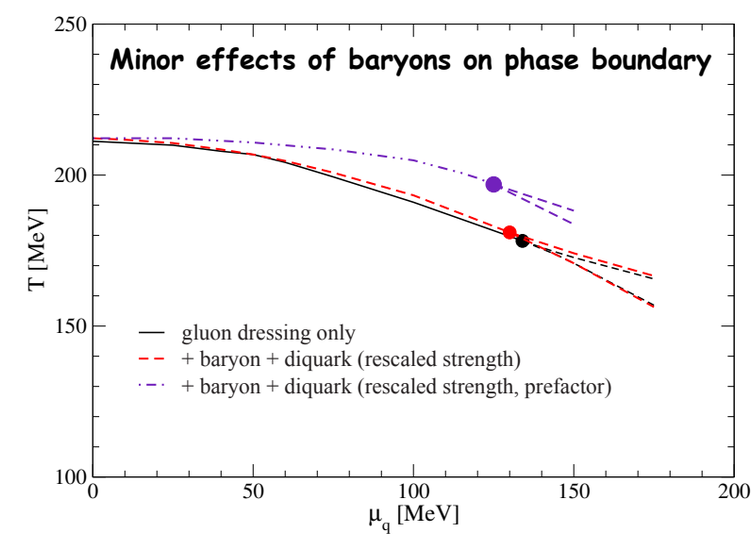

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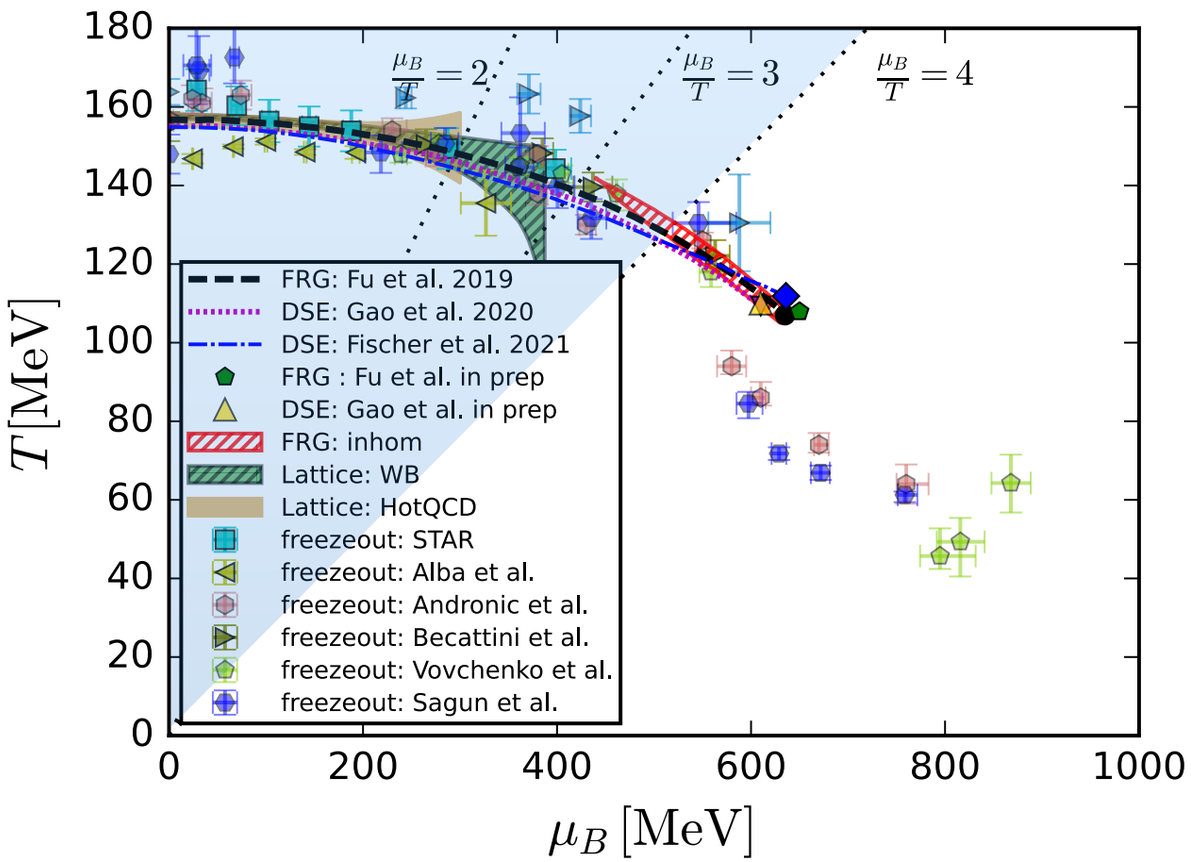
Systematic error control (CEP)

Improving the approximation & apparent convergence



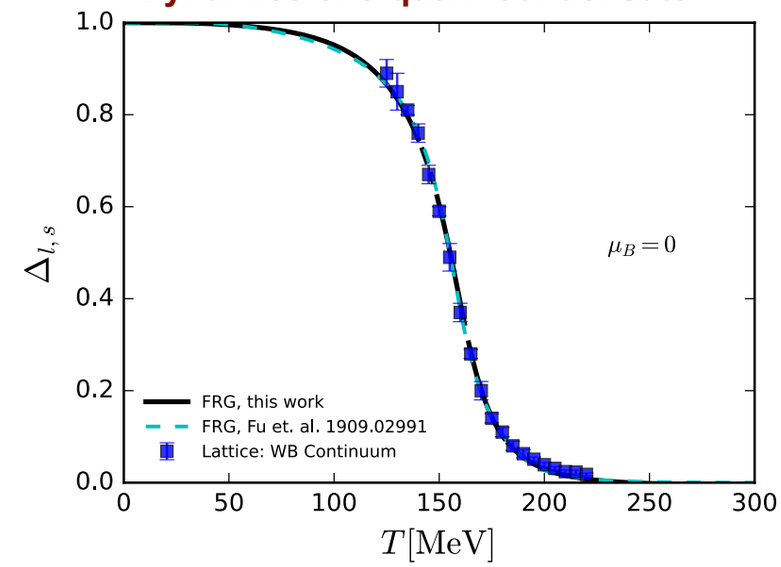
preliminary

Regime of reliability of current best truncation

fQCD matter sector approximation
-unique properties-

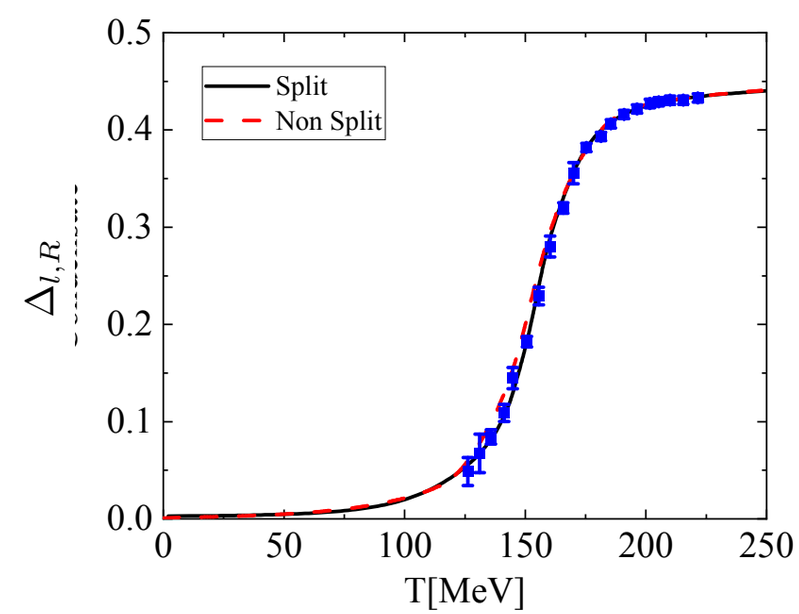
quark-gluon tensor structures (DSE full, fRG partial)
&
multi-scatterings of scalar-pseudoscalar channel/mesons (fRG)

Dynamics of s-quark condensate



Fu, JMP, Rennecke, Wen, Yin, in prep.

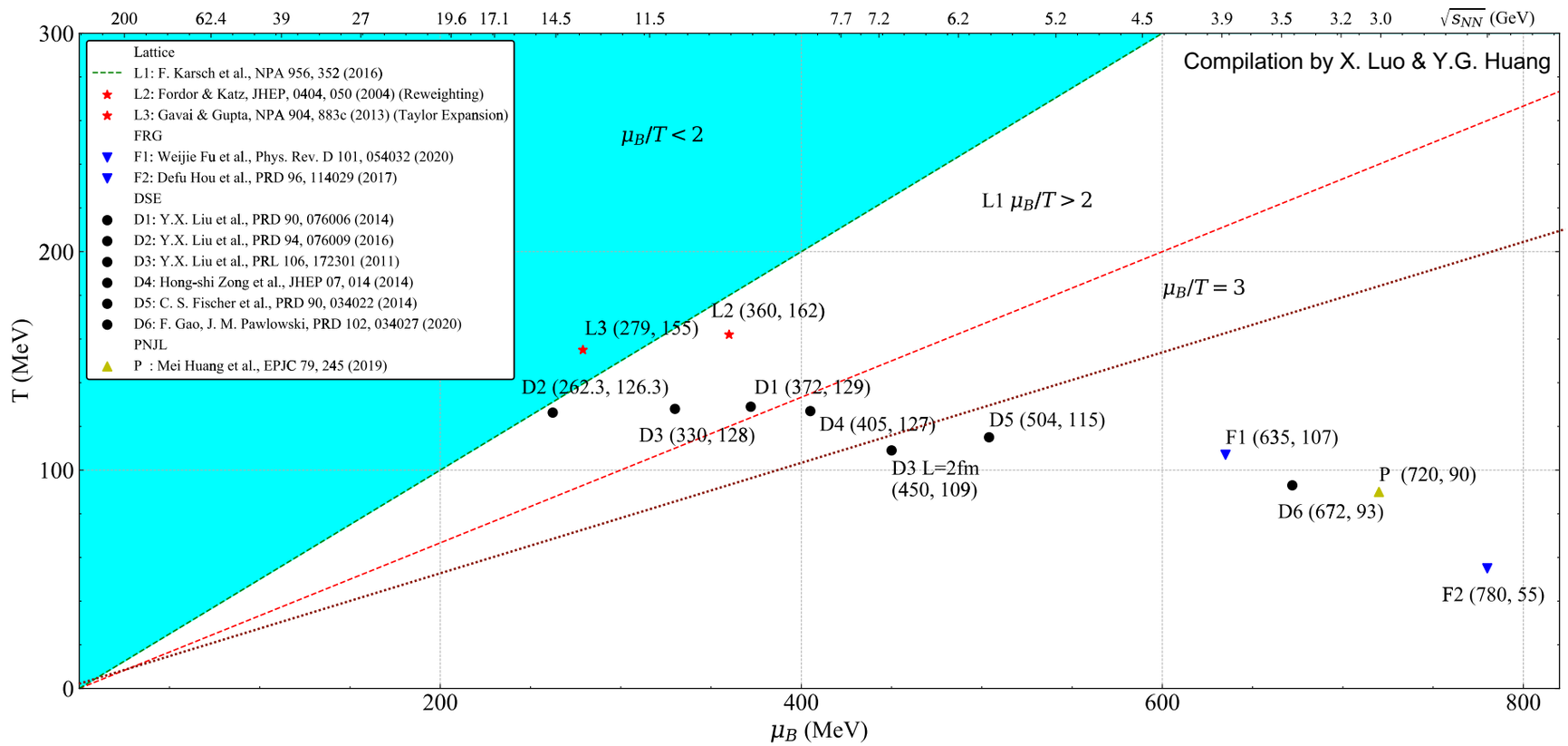
Chromo-magnetic & electric vertex splittings



Gao, JMP, Schneider, in prep.

Location of CP : Theoretical Prediction

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



Large uncertainties for the estimation of CP location.

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!

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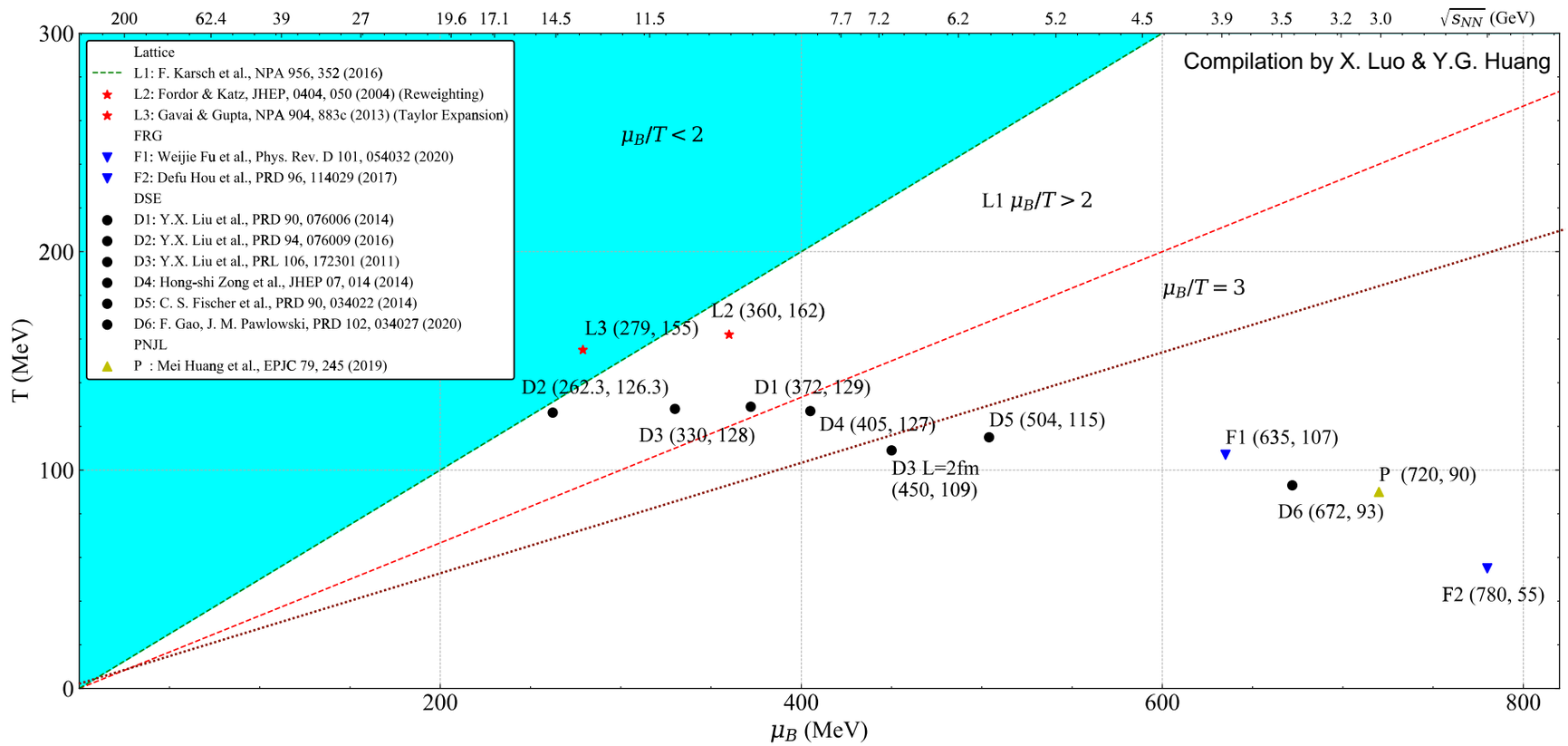

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Remove CEP-predictions

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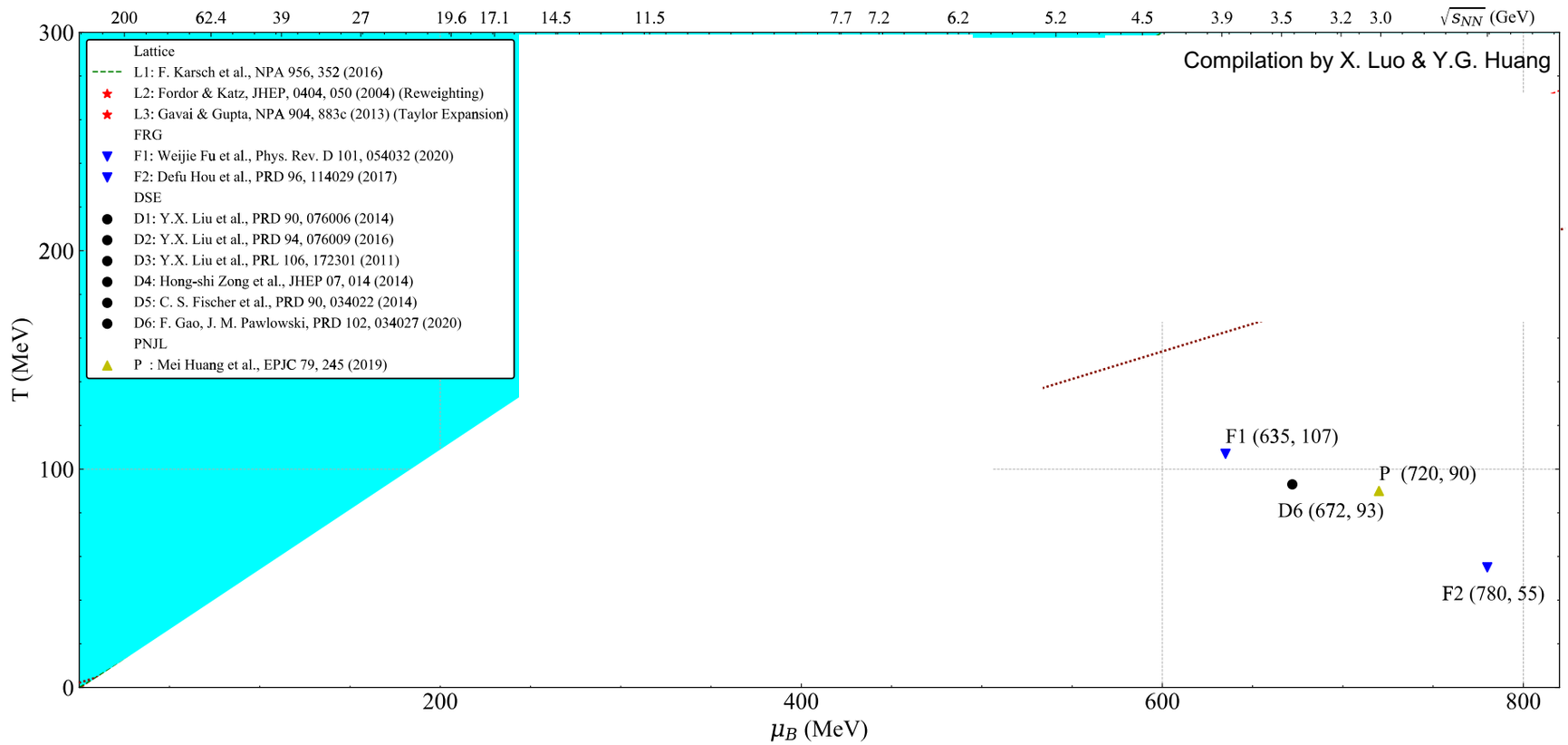

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Remove CEP-predictions

(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

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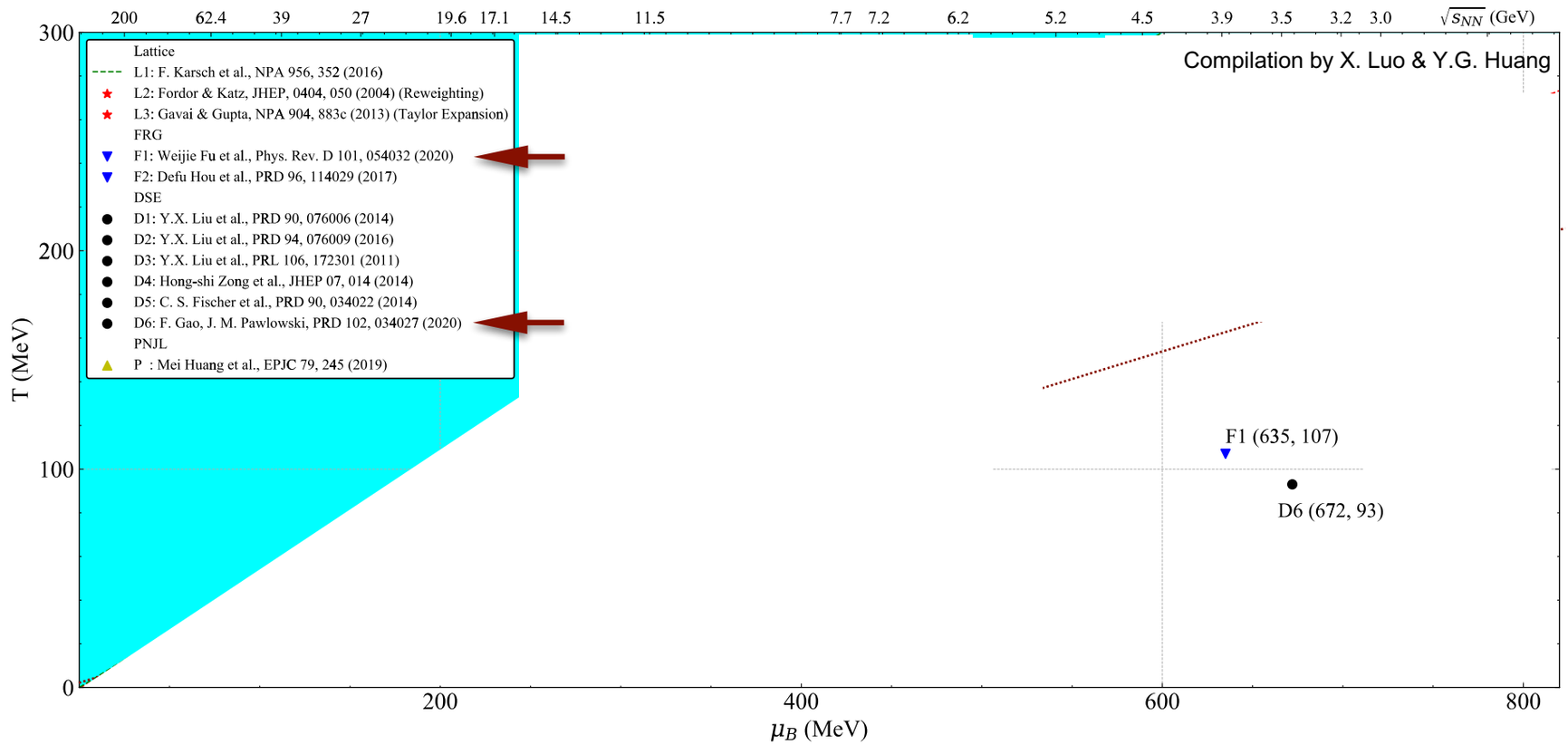

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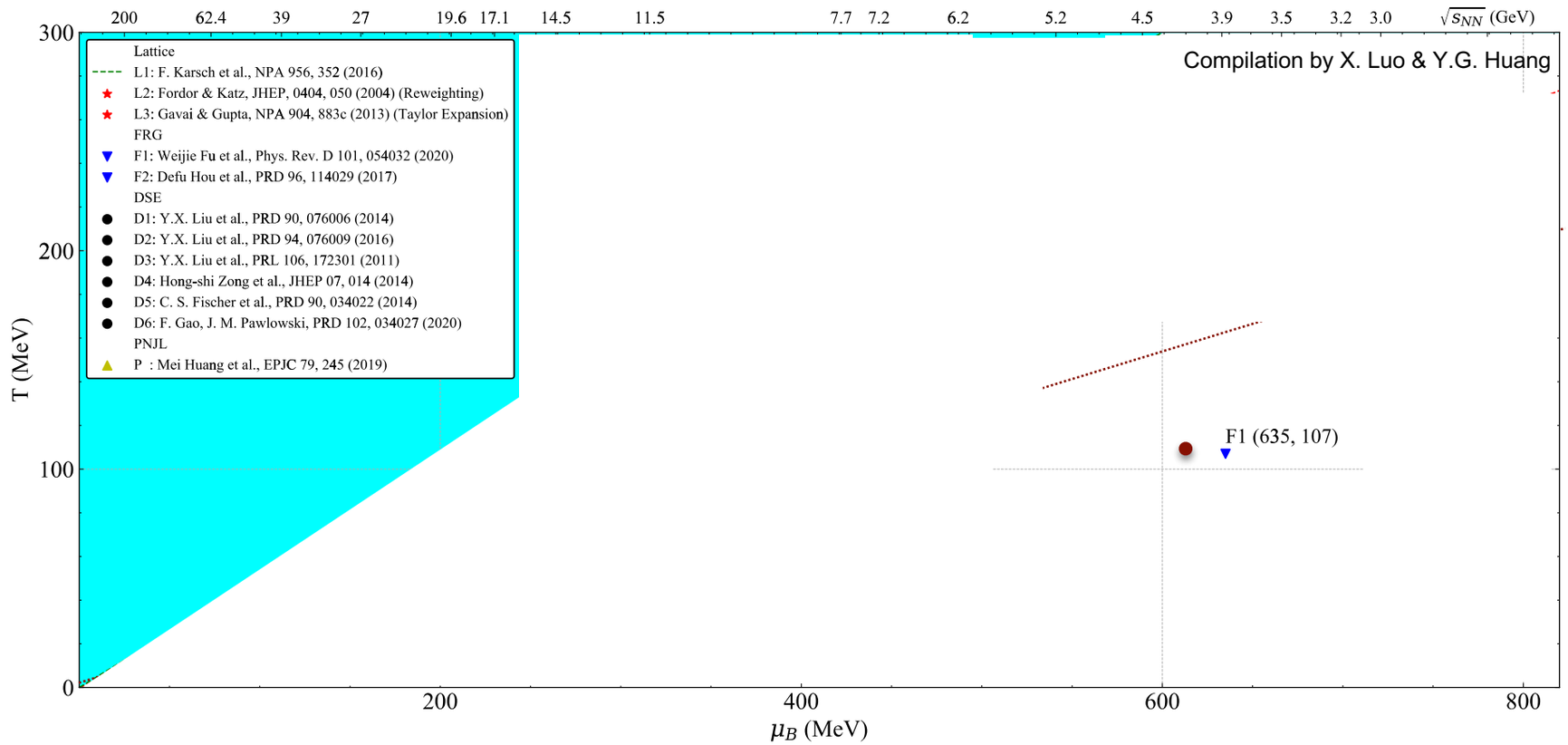

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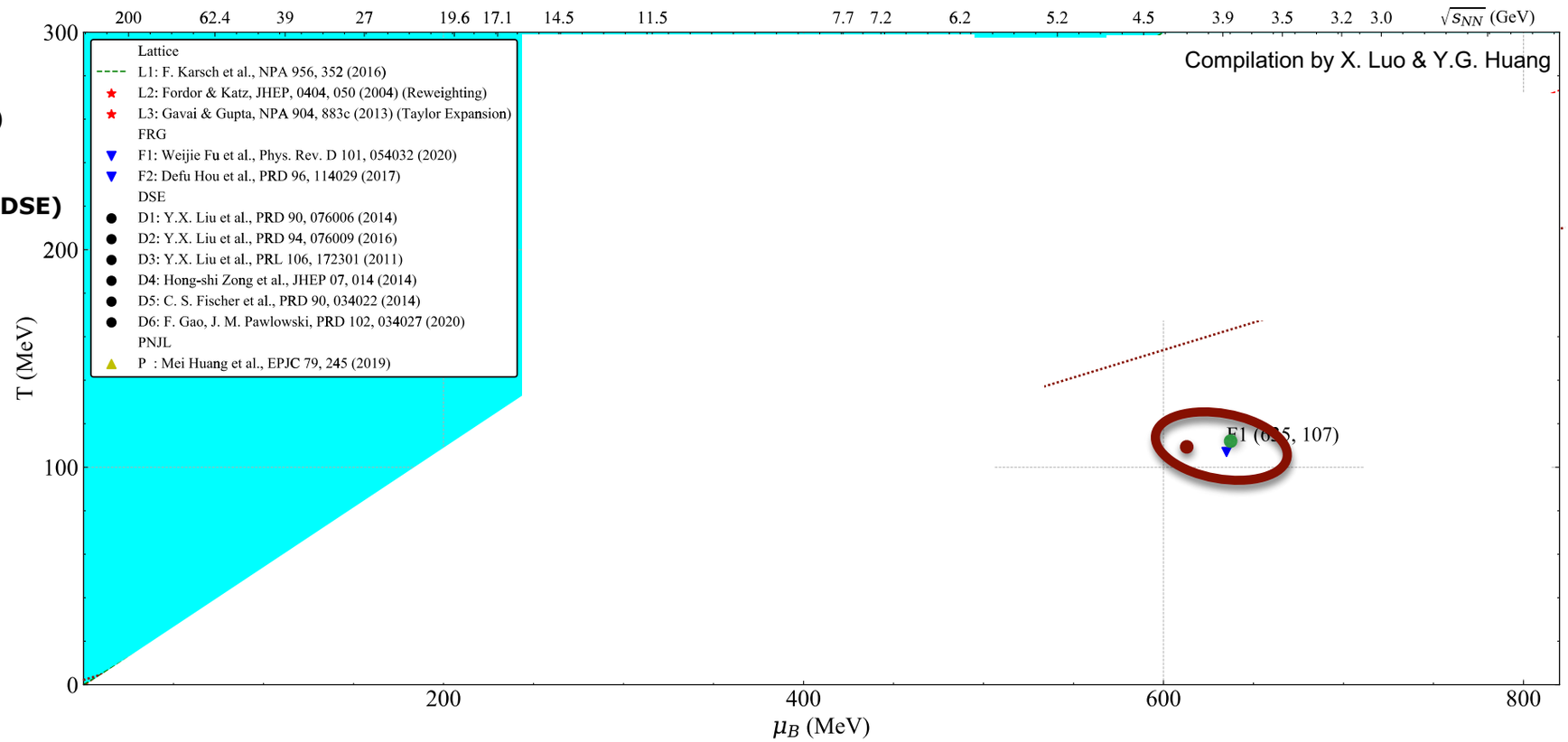

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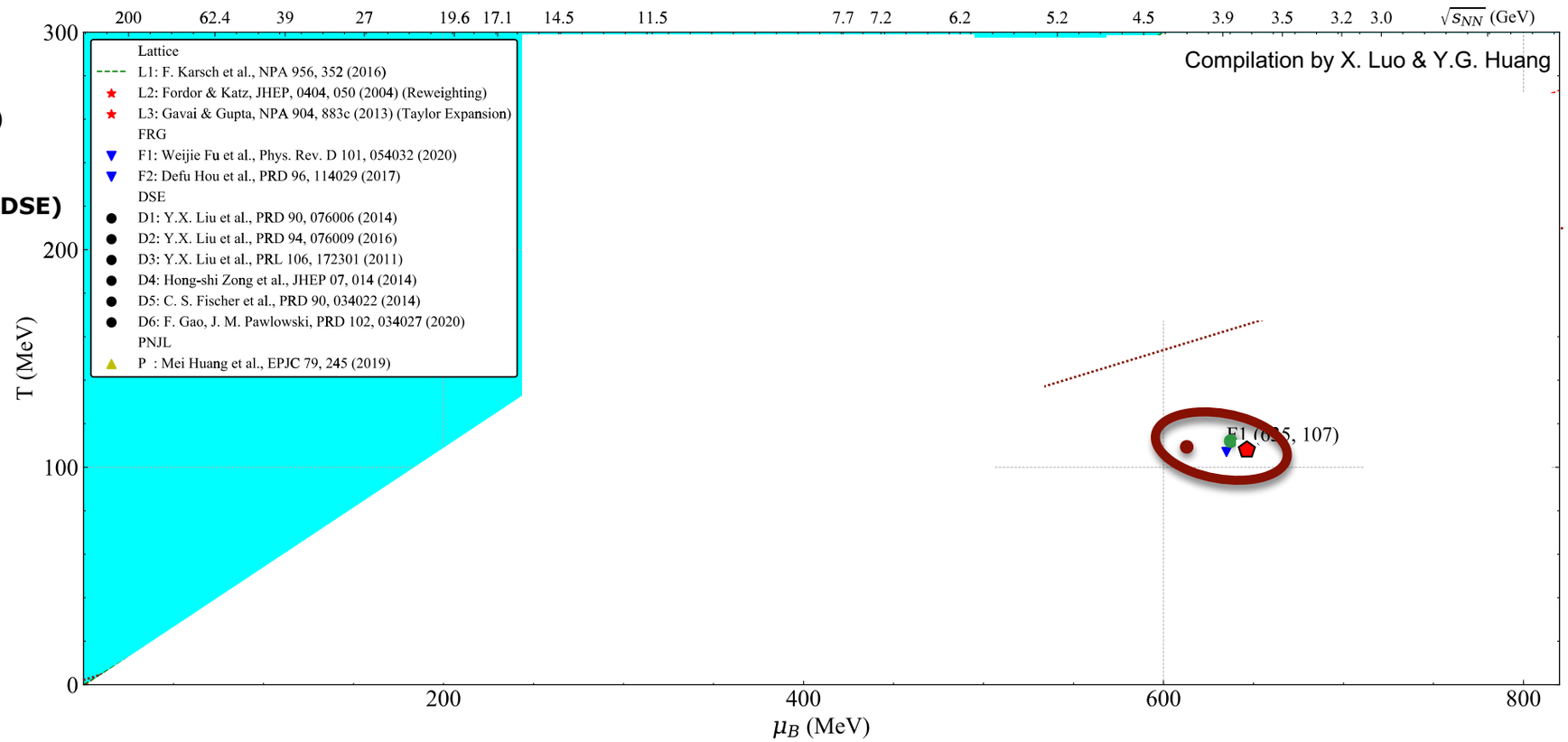

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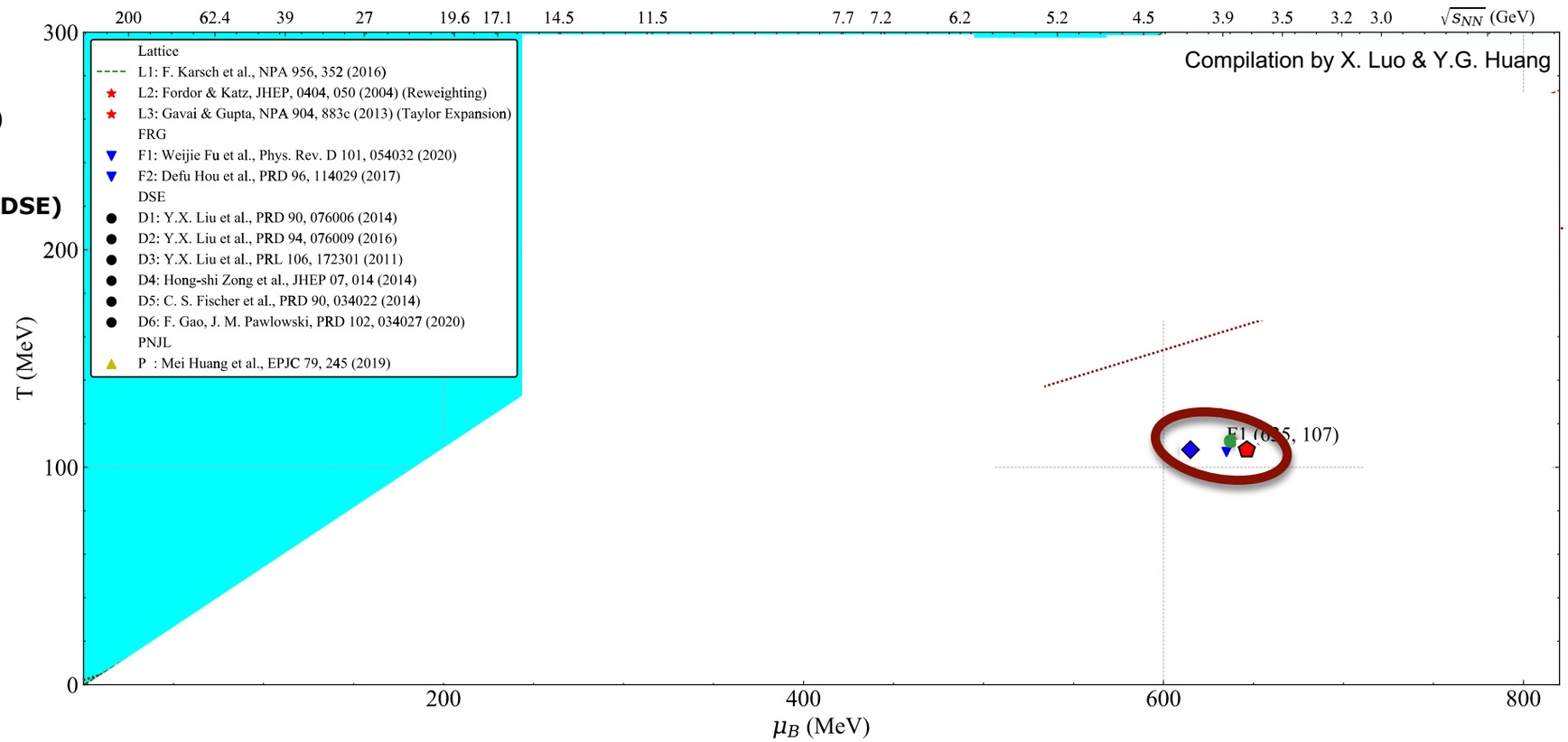

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Outline

- QCD phase structure: Where do we stand?

- QCD phase structure: observables, estimates & systematics

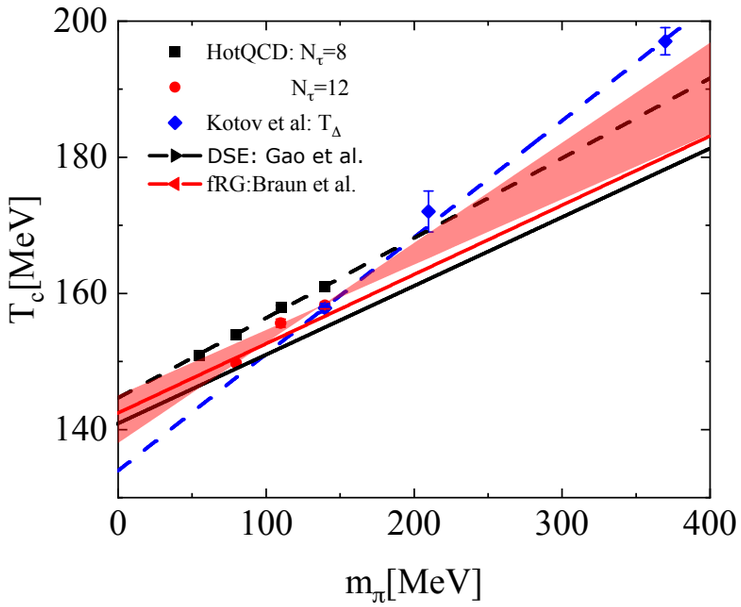
- Chiral dynamics & phenomenological applications

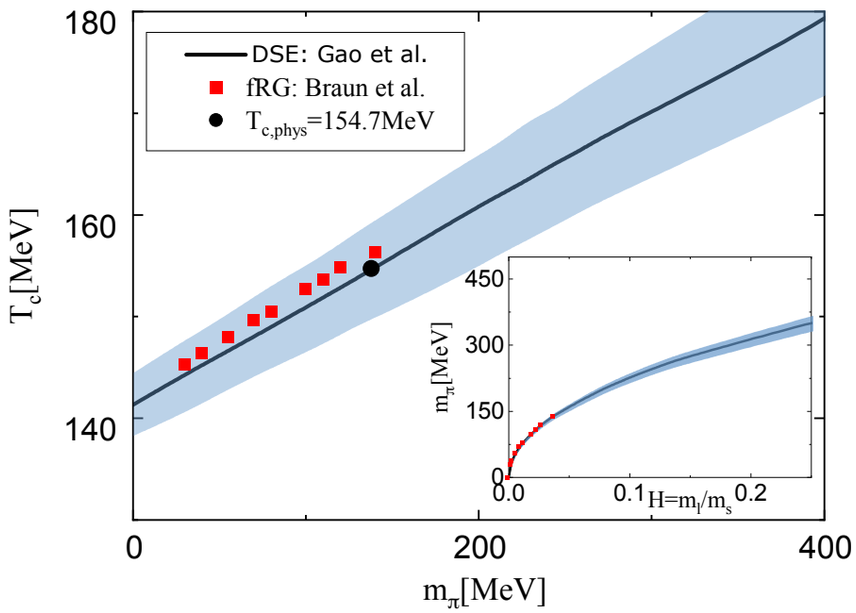
- Many flavour QCD & the conformal window

- Summary & outlook

To be (critical) or not (to be)

Chiral transition temperature





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

Gao, JMP, arXiv:2112.01395

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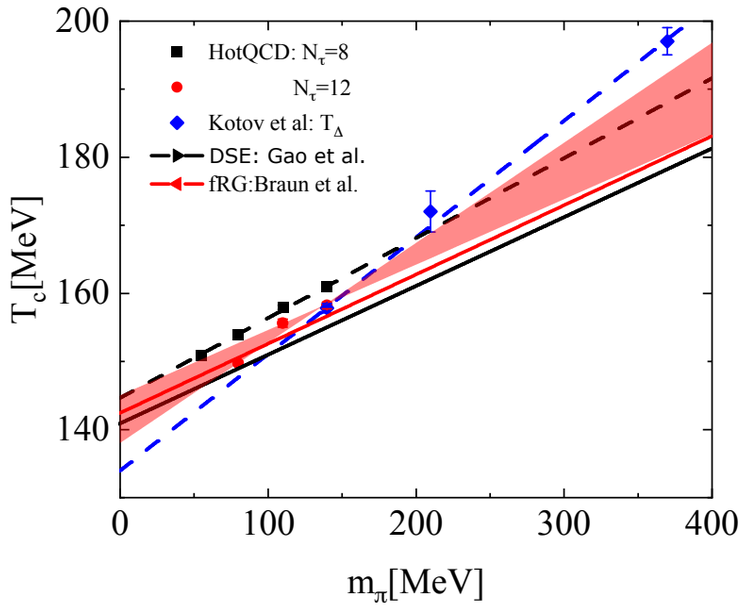
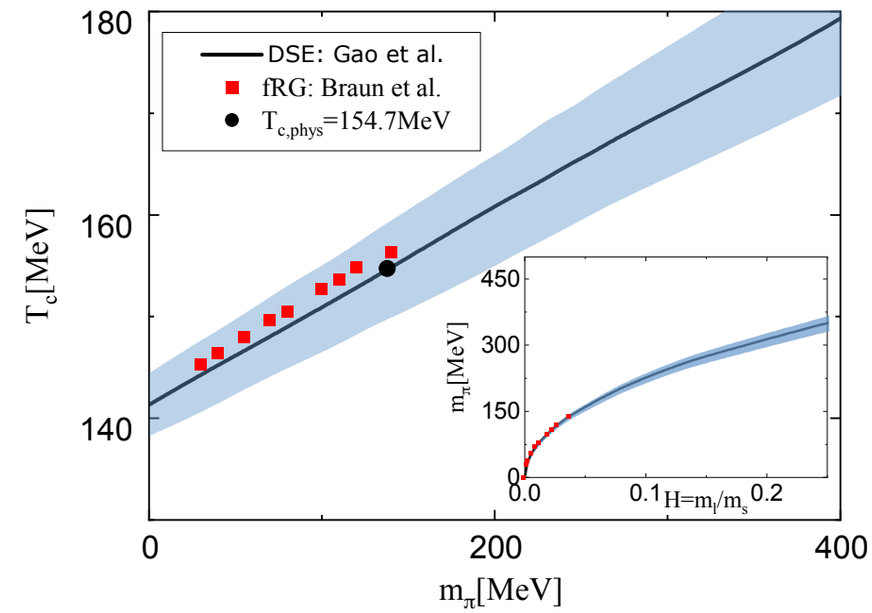


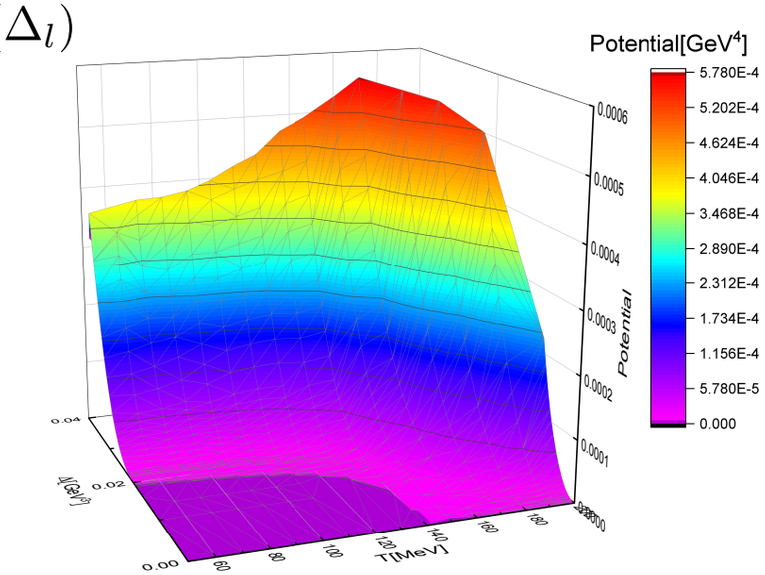


Order parameter potential & scaling

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

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

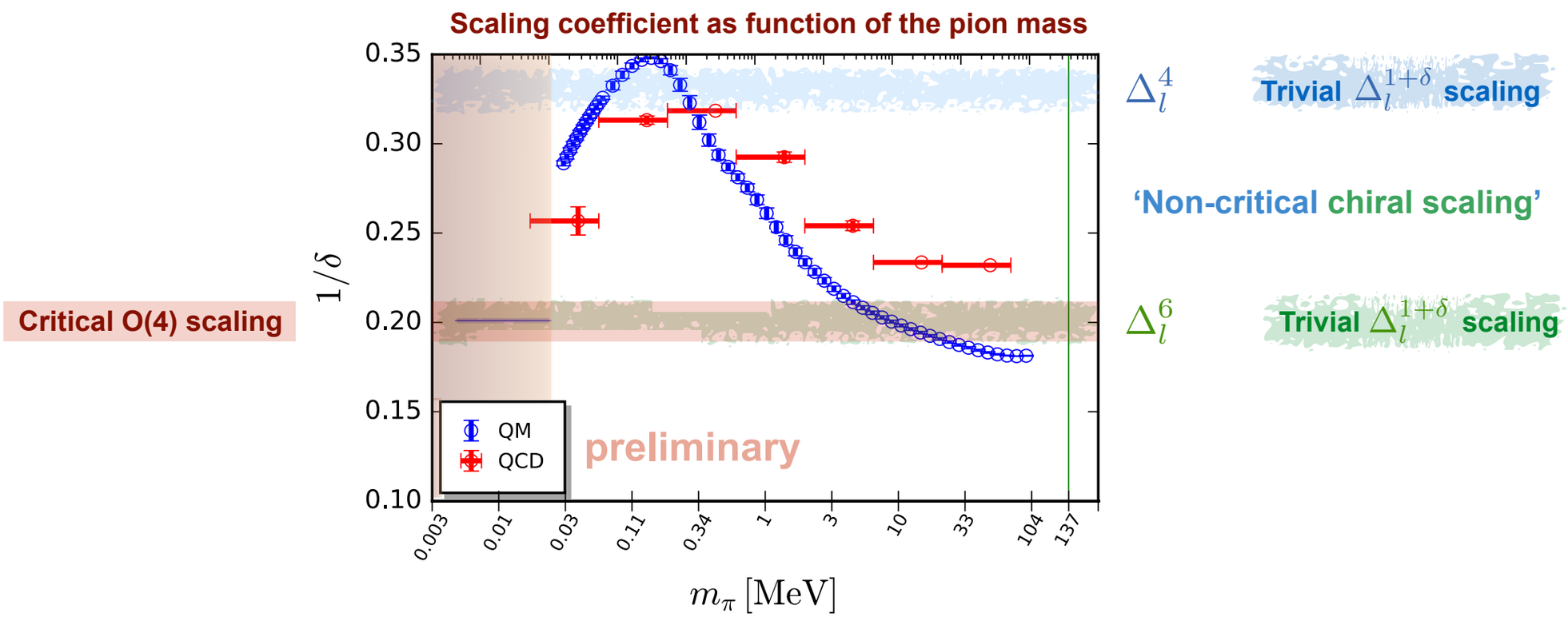
$V_\chi(\Delta_l)$



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

Gao, JMP, arXiv:2112.01395

Chiral dynamics & quasi-massless modes



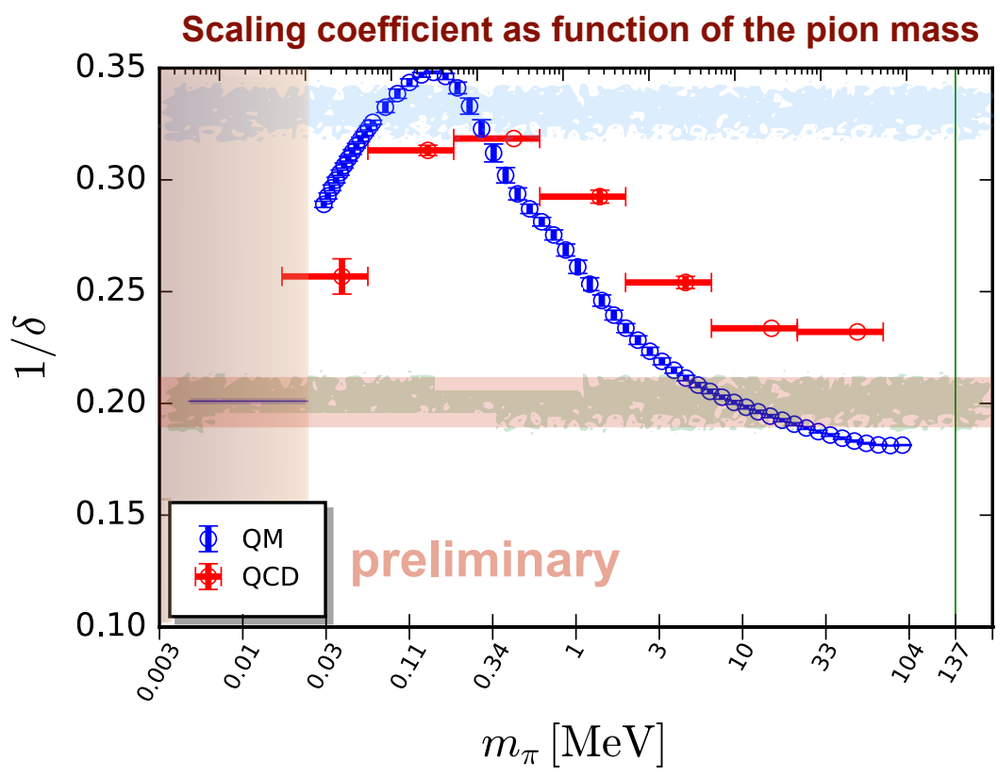
Gao, JMP, arXiv:2112.01395

QM: Chen, Wen, WF, PRD 104 (2021) 054009

QCD: fQCD collaboration, in preparation

Chiral dynamics & quasi-massless modes

Critical O(4) scaling

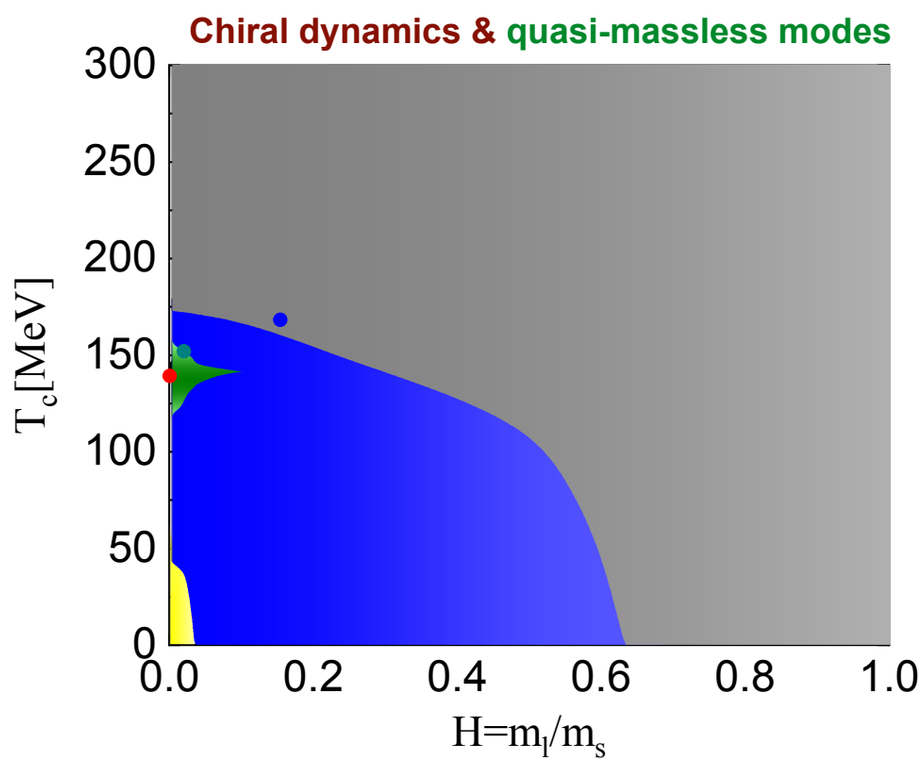


Δ_l^4 Trivial $\Delta_l^{1+\delta}$ scaling

'Non-critical chiral scaling'

Δ_l^6 Trivial $\Delta_l^{1+\delta}$ scaling

Critical scaling



'Non-critical chiral scaling'

Far away from the critical regime for $m_\pi \gtrsim 1-10\,\mathrm{MeV}$

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

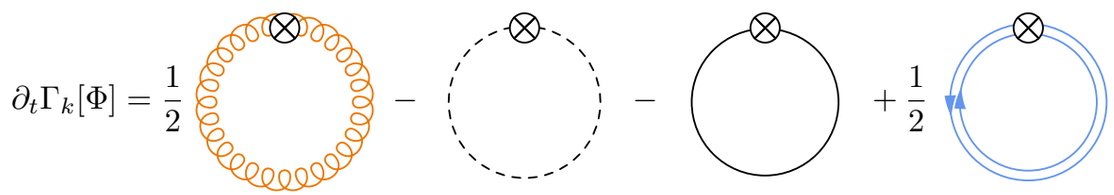
$V_\chi(\Delta_l) \propto$ Δ_l^6 Δ_l^4 Δ_l^2

Gao, JMP, arXiv:2112.01395

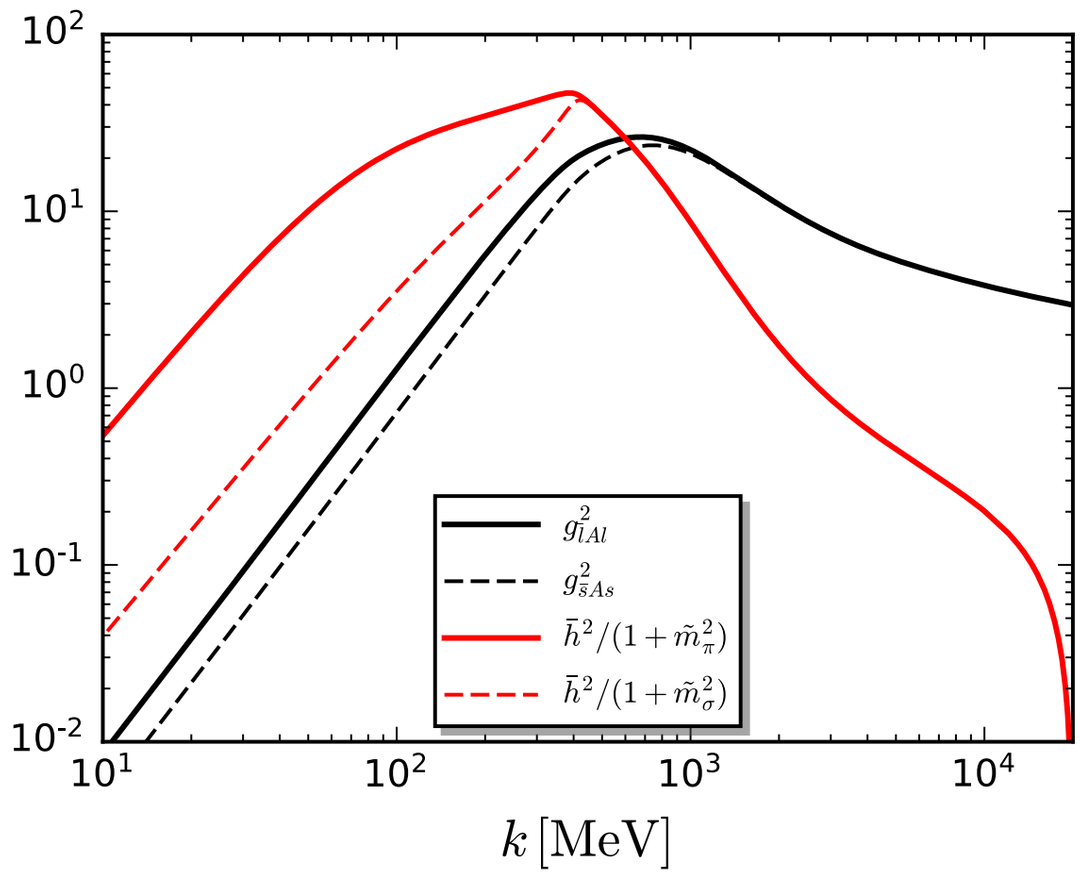
QM: Chen, Wen, WF, PRD 104 (2021) 054009

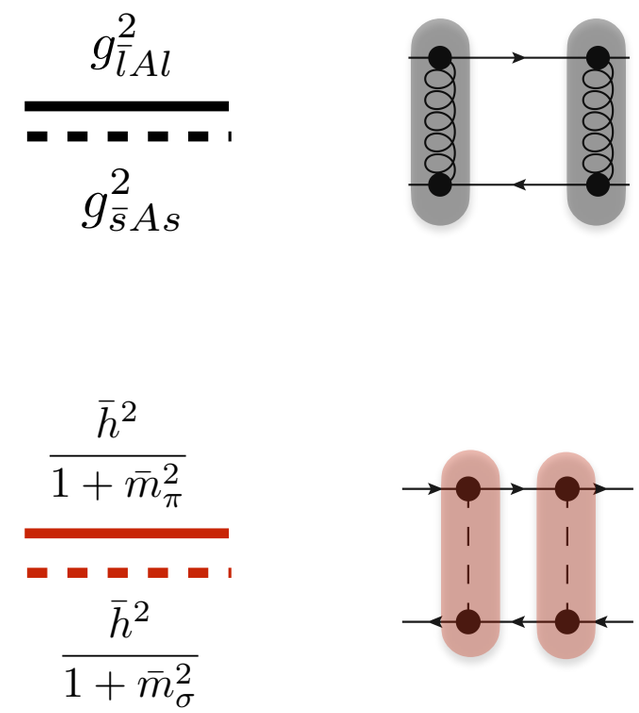
QCD: fQCD collaboration, in preparation

On the unreasonable effectiveness of low energy effective theories



Sequential decoupling of gluon, quark, sigma, pion fluctuations





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

Based on:

Braun, Fister, Haas, JMP, Rennecke, PRD 94 (2016) 034016

Rennecke, PRD 92 (2015) 076012

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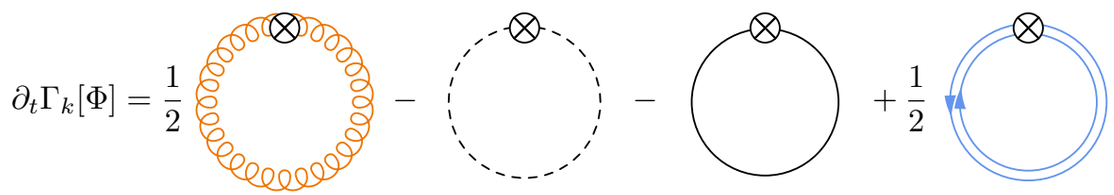

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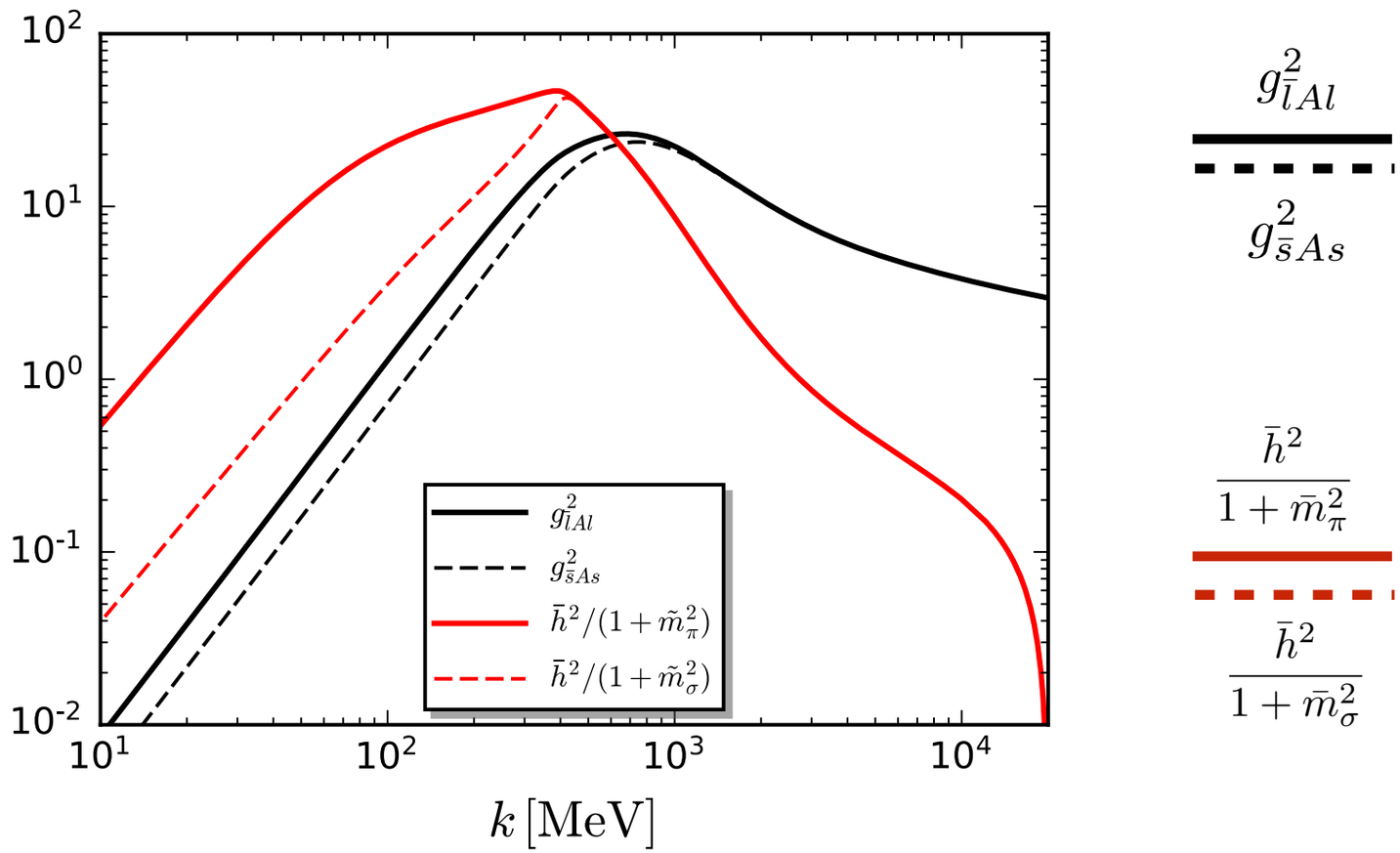

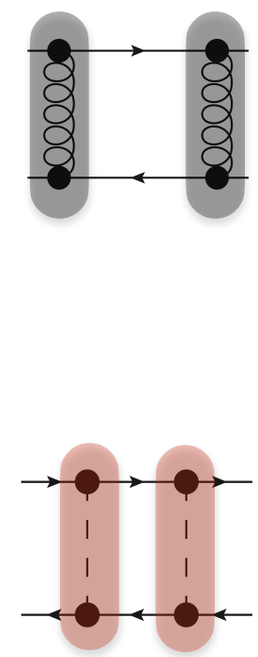

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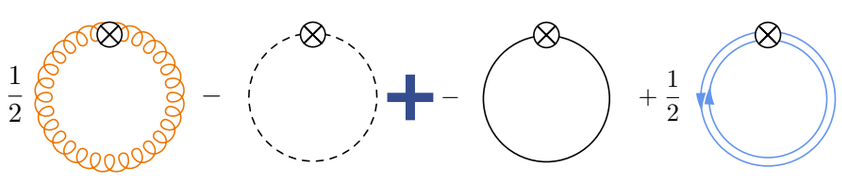
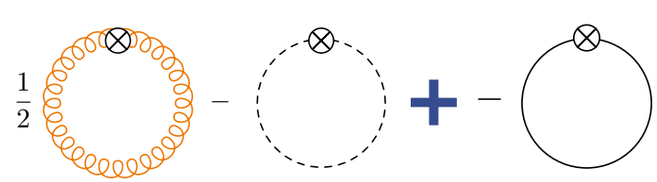
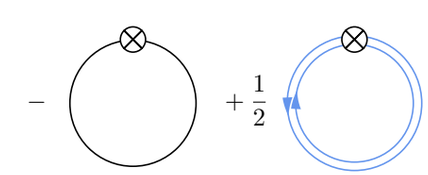
PQM-model



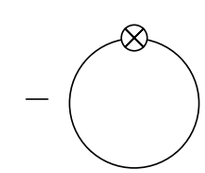
PNJL-model



QM-model



NJL-model

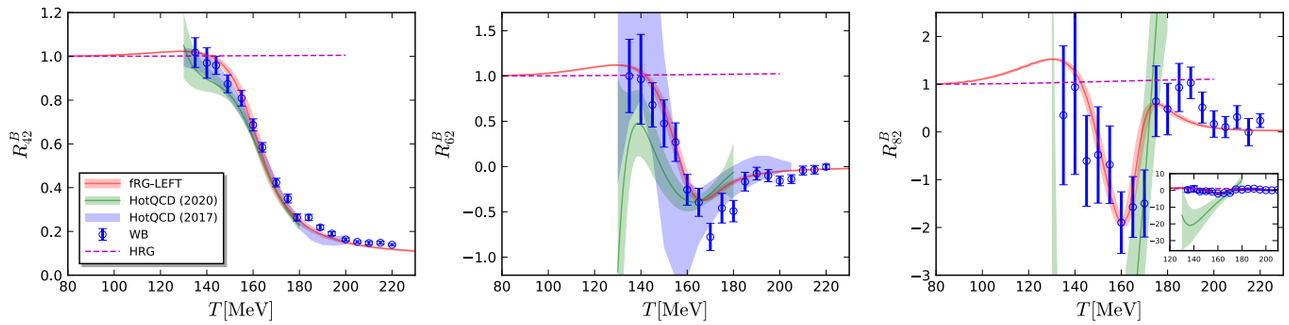


QCD-assisted low energy effective theories

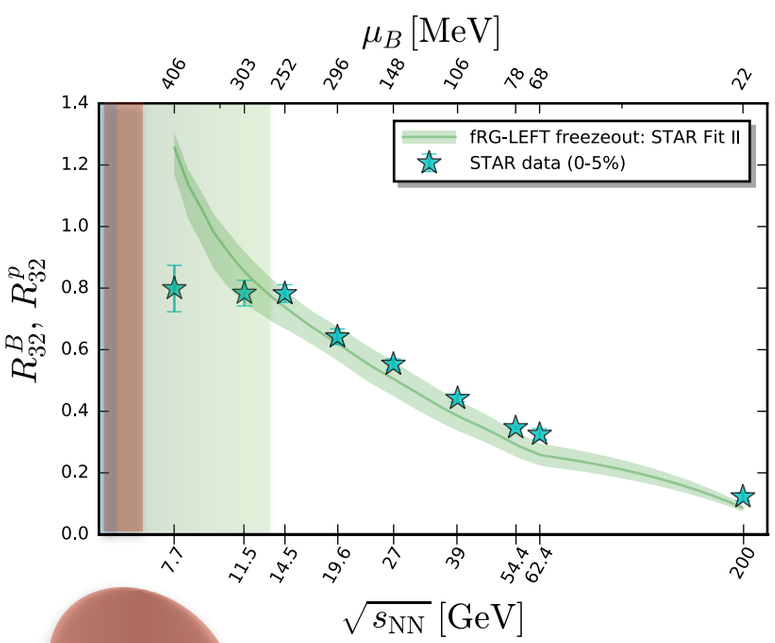
Fluctuations of conserved charges

Benchmark at vanishing density

QCD-assisted LEFT



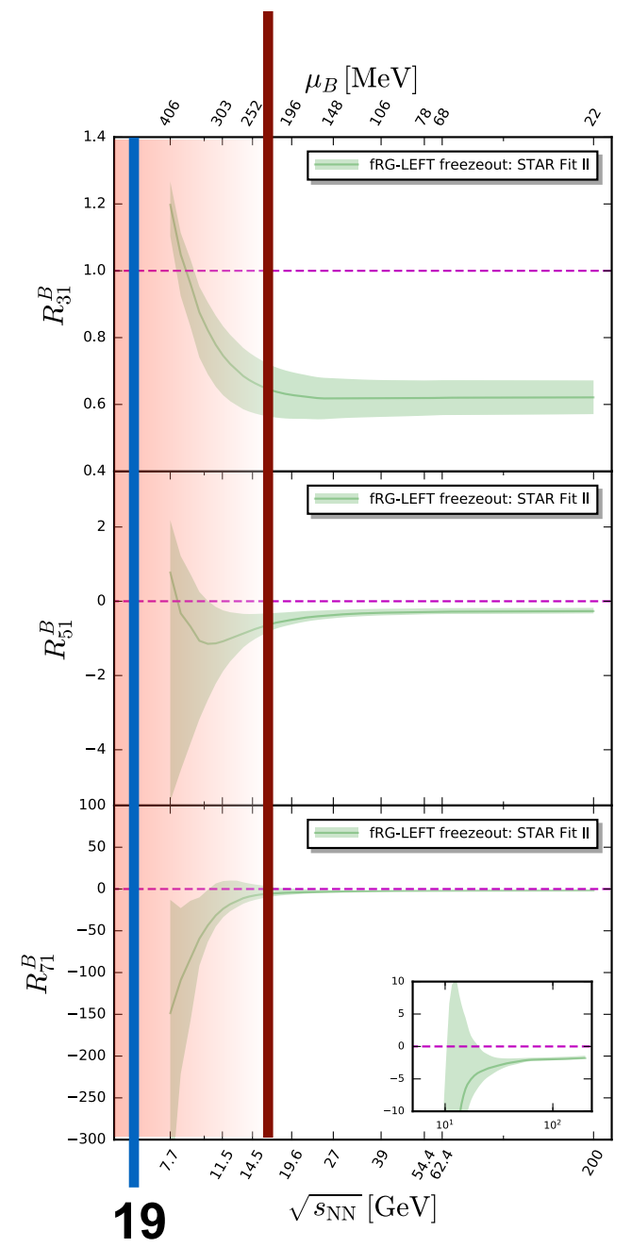
Baryon number conservation?

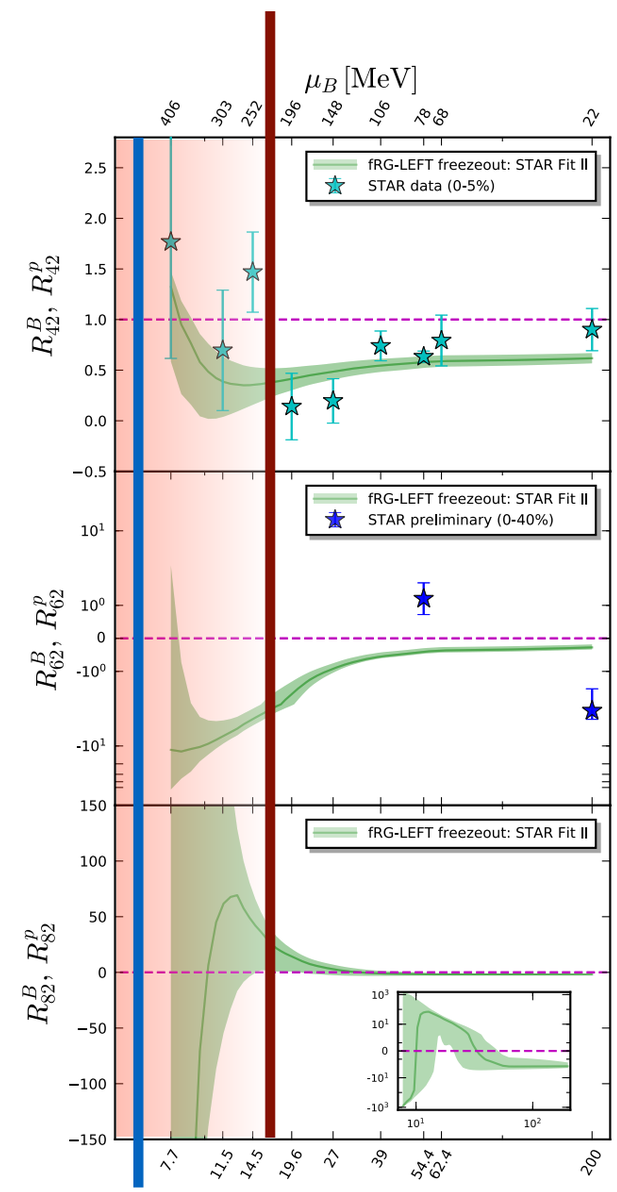


CBM

HADES

QCD-assisted LEFT





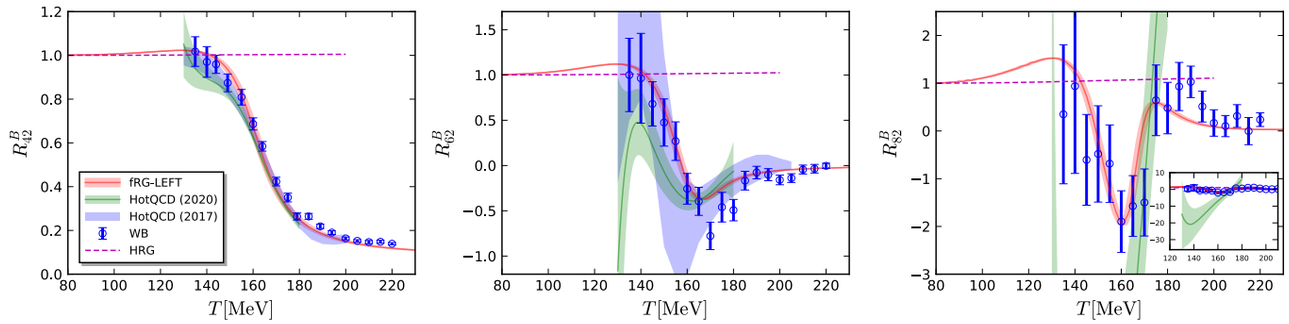
Fun QCD, in progress

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

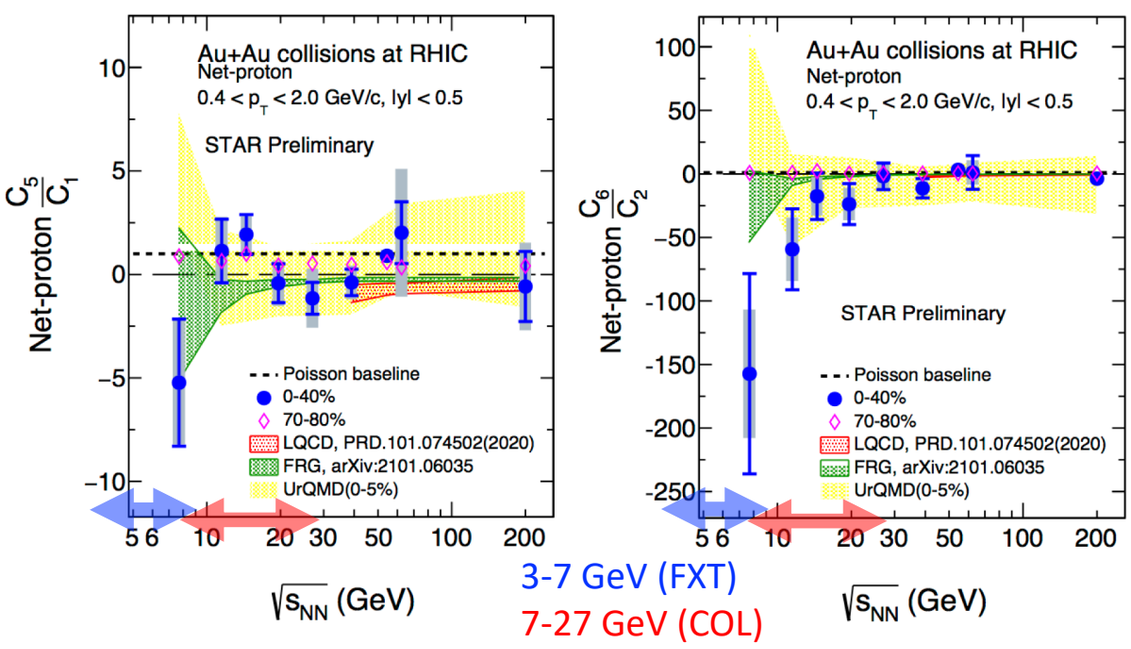
Fluctuations of conserved charges

QCD-assisted LEFT

Benchmark at vanishing density



STAR measurements

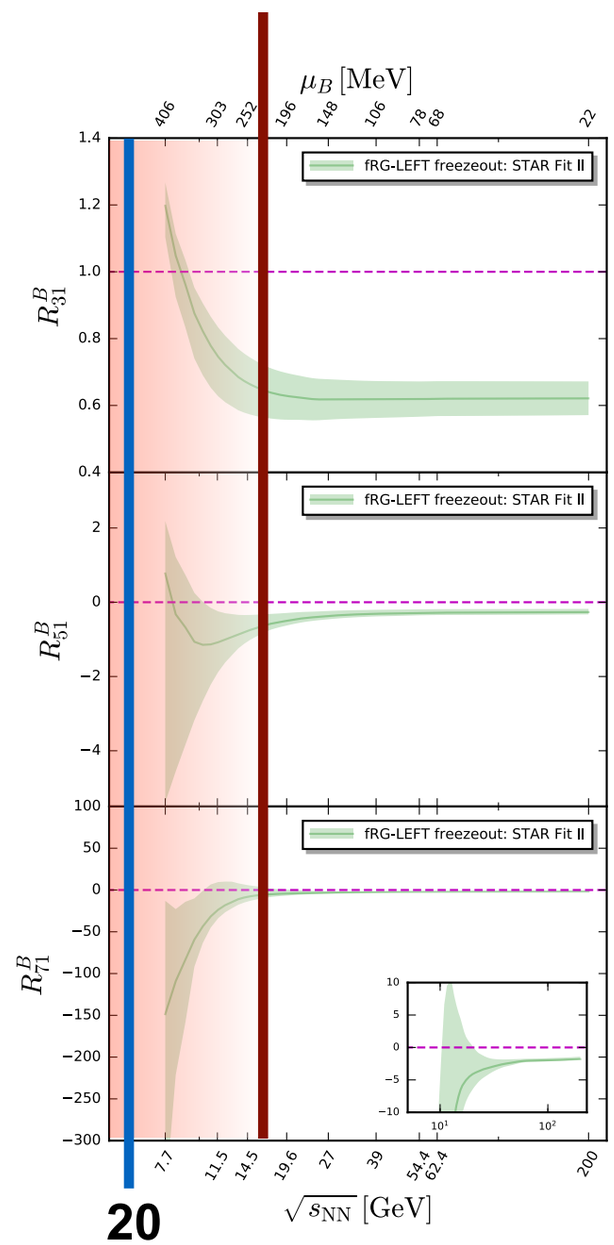


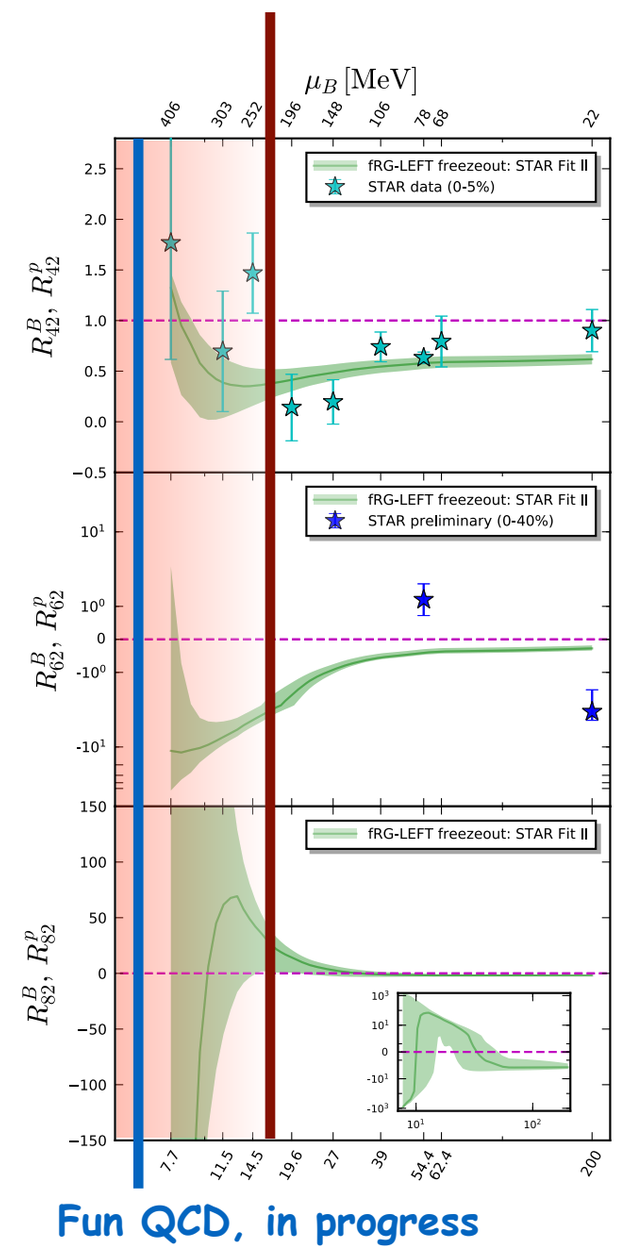
3-7 GeV (FXT)
7-27 GeV (COL)

S Results from RHIC-STAR, CPOD2021, 15-19/Mar, Online

S. Esumi, CPOD

QCD-assisted LEFT





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

Fluctuations of conserved charges

QCD-assisted LEFT

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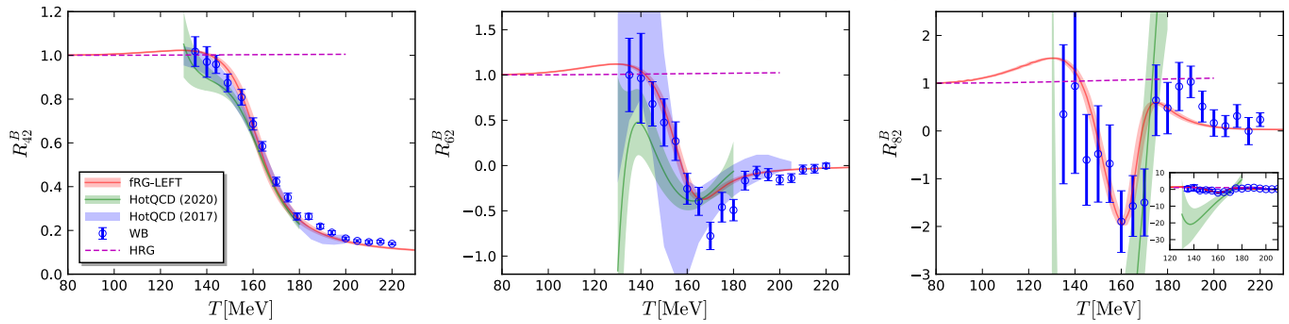
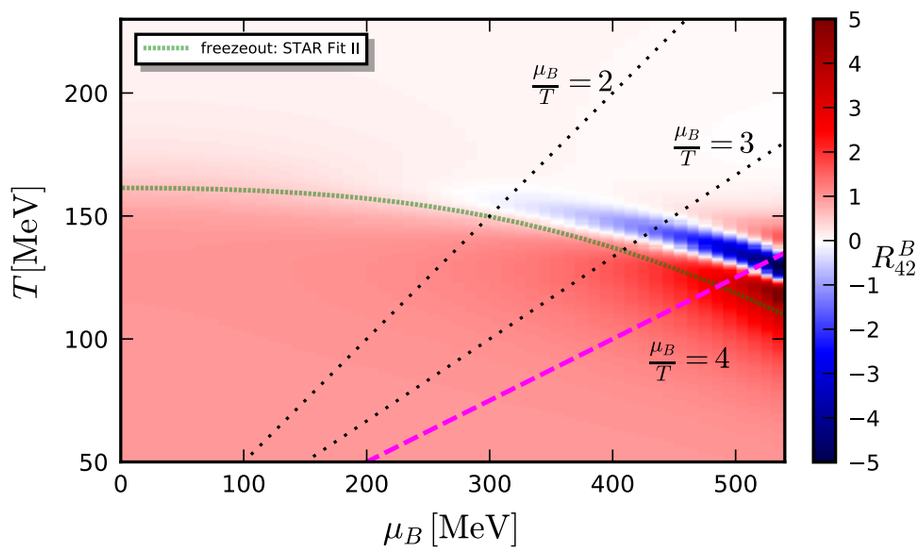


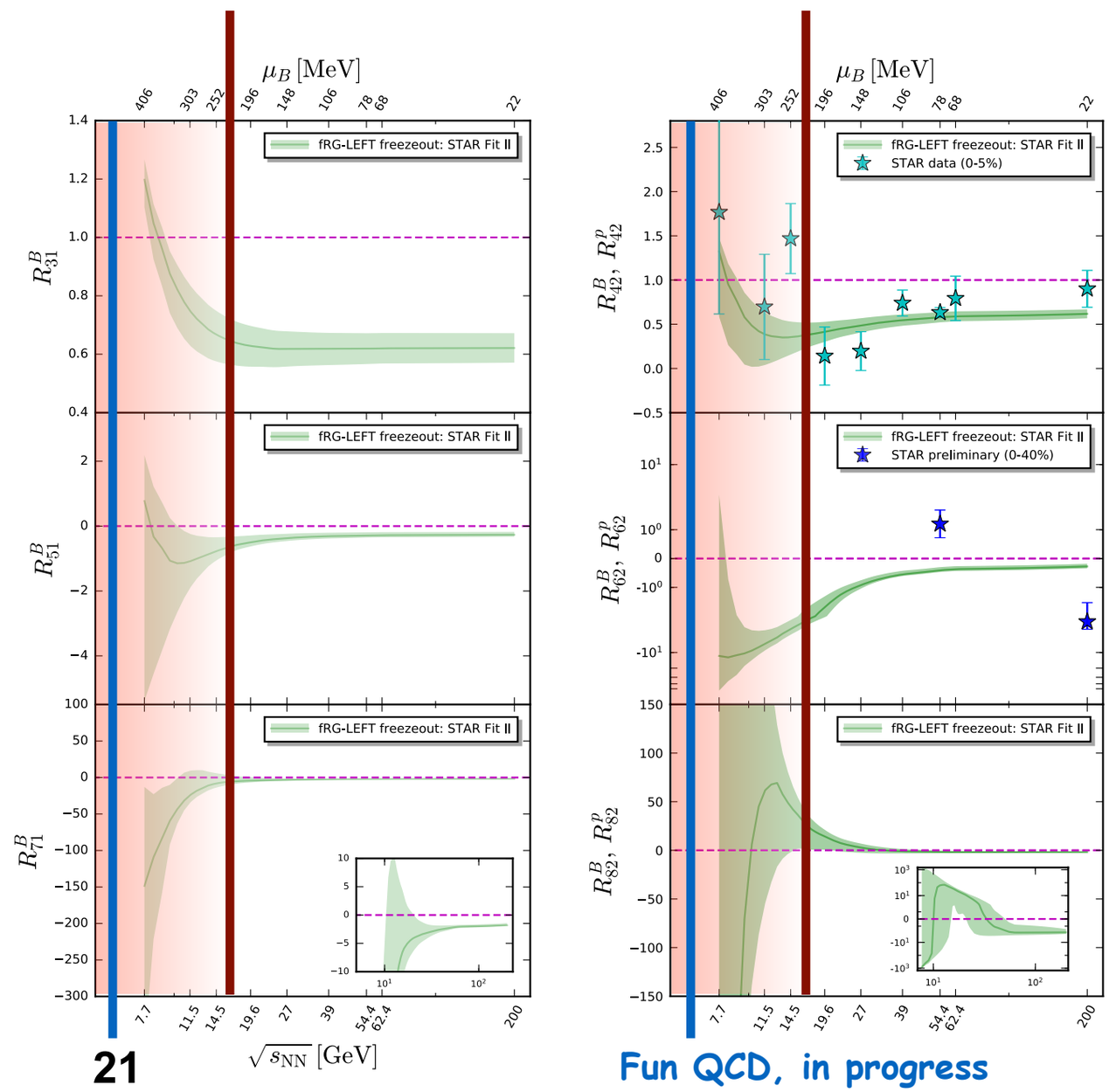
Freezeout curve



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

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

QCD-assisted LEFT

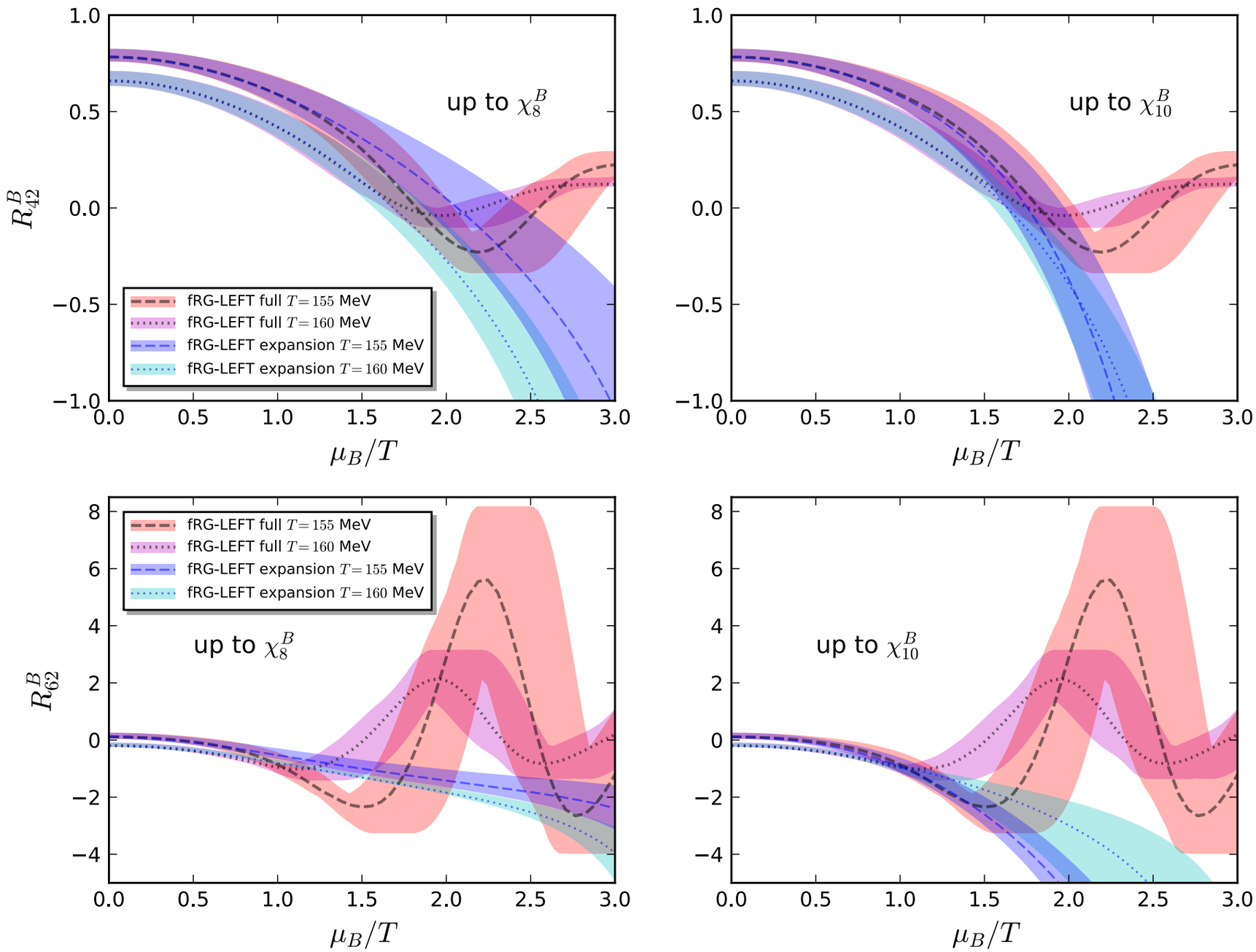


Fun QCD, in progress

Fluctuations of conserved charges

Fluctuation of conserved charges

QCD-assisted LEFT: Taylor expansion vs full results



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

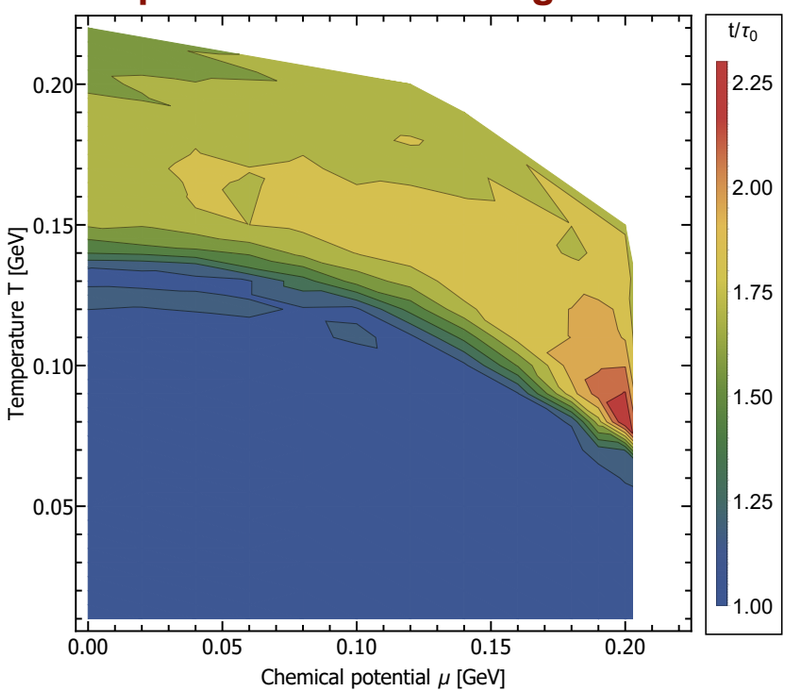
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

The need for dynamics

Showcases in linear sigma models

Transport with fRG spectral functions & potential

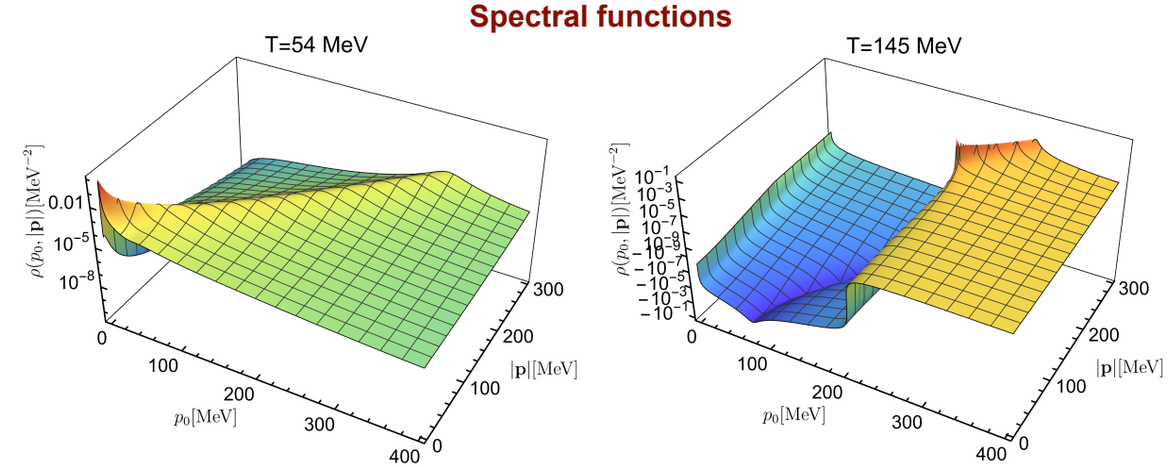
Equilibration time of sigma-kurtosis



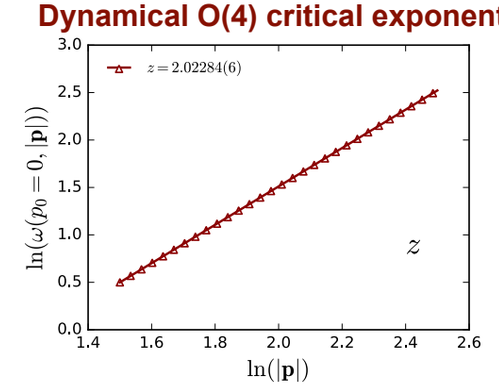
Blum, Jiang, Nahrgang, JMP, Rennecke, Wink, NPA 982 (2019) 871

Dynamical universality

Spectral functions



Dynamical O(4) critical exponent



$$\omega \propto (\vec{p}^{\,2})^{\frac{z}{2}}$$

Tan, Chen, Fu, SciPost Phys. 12 (2022) 026

Outline

- QCD phase structure: Where do we stand?

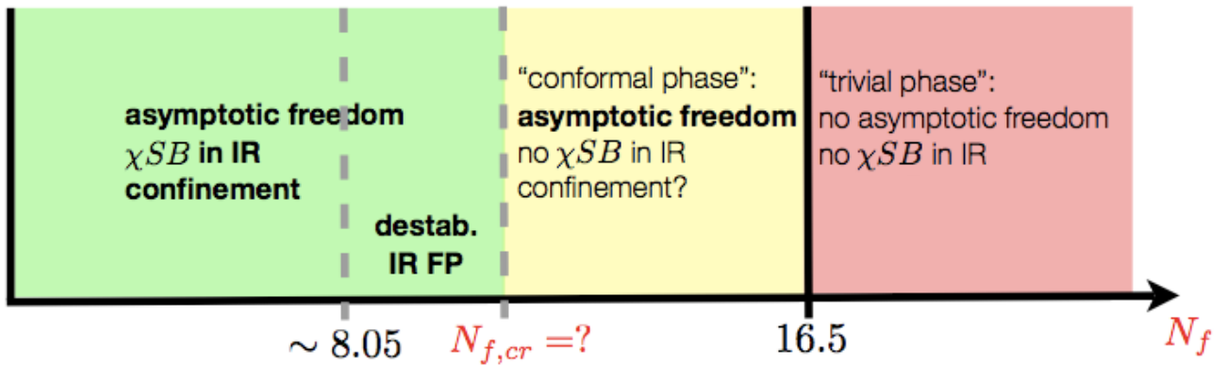
- QCD phase structure: observables, estimates & systematics

- Chiral dynamics & phenomenological applications

- Many flavour QCD & the conformal window

- Summary & outlook

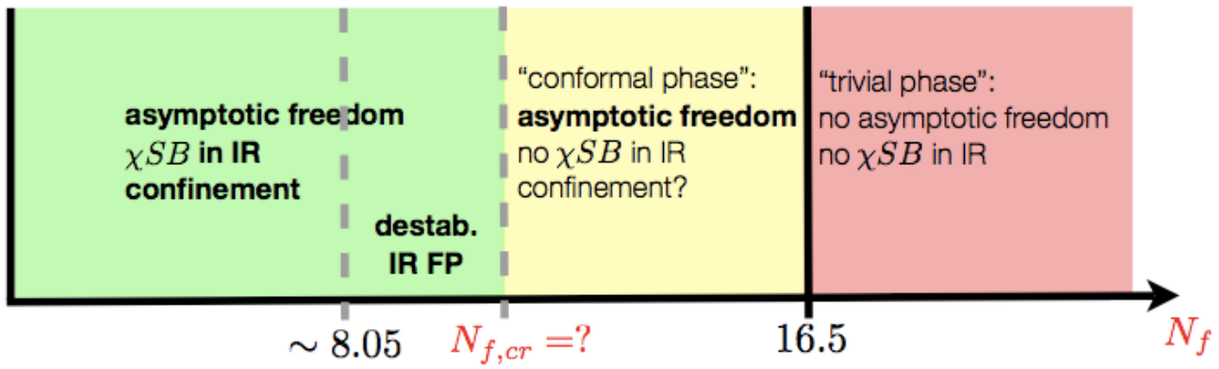
The phase structure of many-flavour QCD



Non-perturbative infrared chiral dynamics & confinement → Semi-perturbative IR beta functions → Perturbative IR beta functions

fRG schemes converges 'easily'

The phase structure of many-flavour QCD



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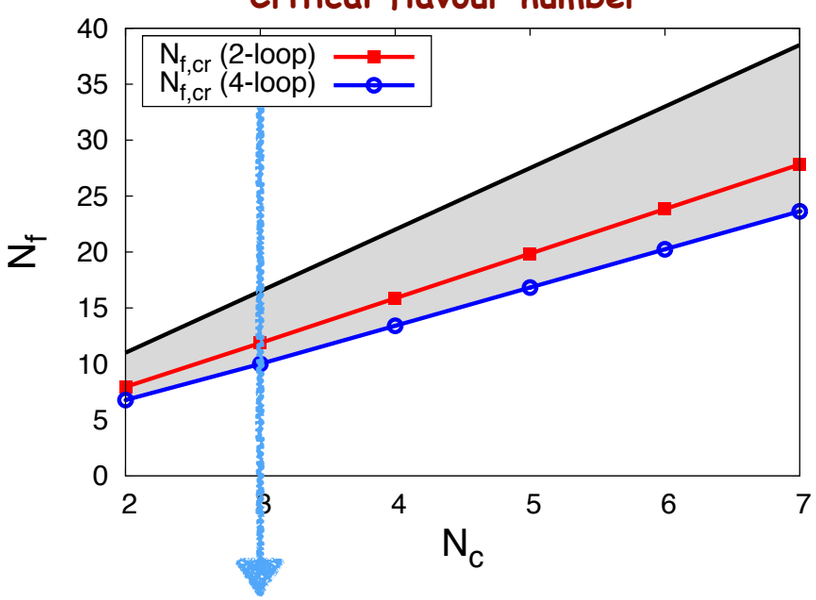
Critical flavour number

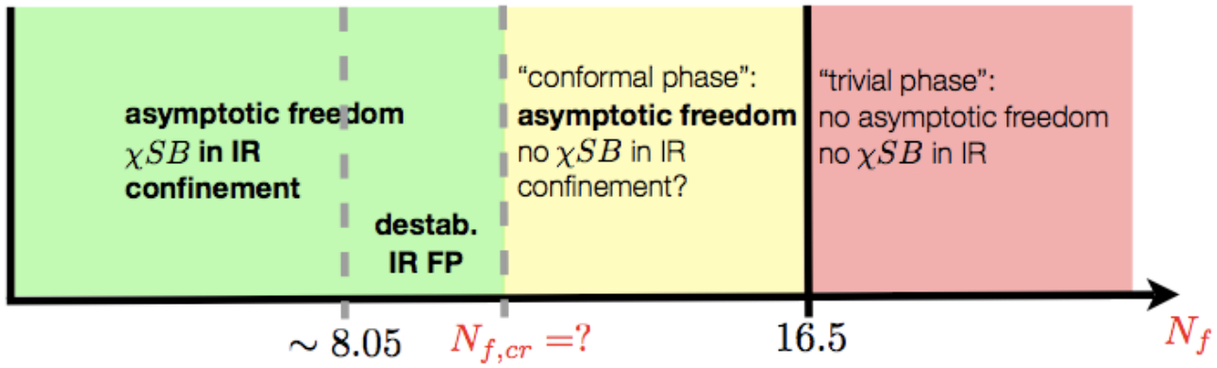


fRG: Braun, J.Phys.G 39 (2012) 033001

See also

Dietrich, Sannino '05
Gies & Jaeckel '05

The phase structure of many-flavour QCD



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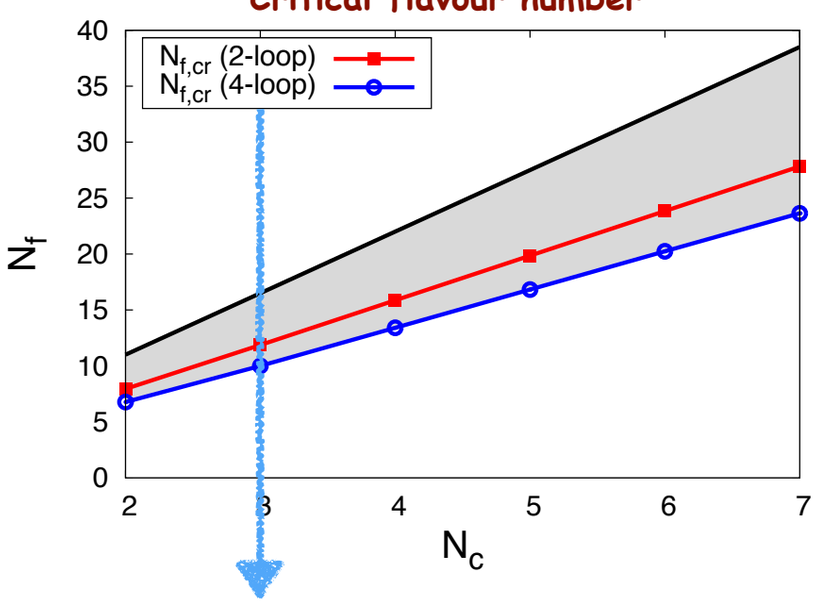
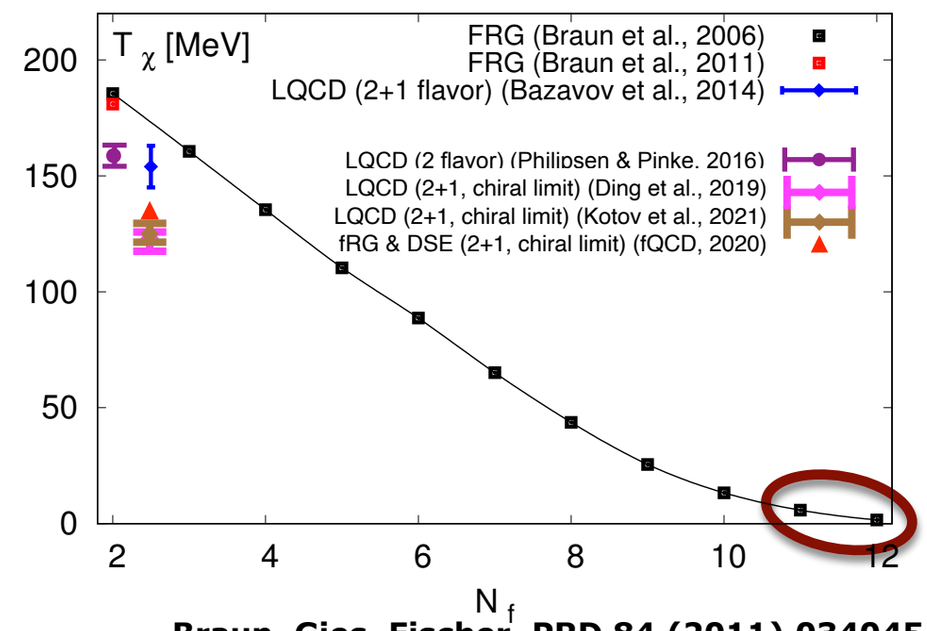


fRG: Braun, J.Phys.G 39 (2012) 033001

Transition temperature



Braun, Gies, Fischer, PRD 84 (2011) 034045

Scaling: Miransky & beyond

Jarvinen, Sannino, JHEP 02 (2011) 081

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Gies & Jaeckel '05

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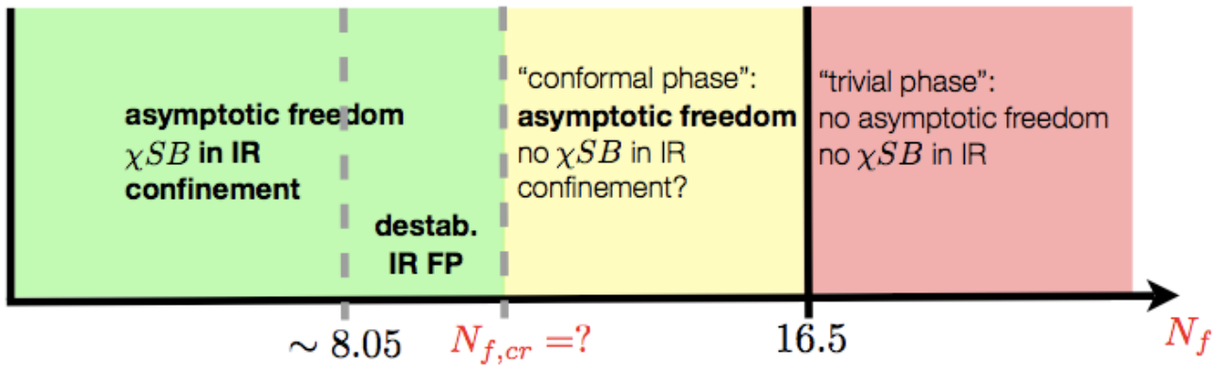


Non-perturbative infrared chiral dynamics & confinement → Semi-perturbative IR beta functions → Perturbative IR beta functions

fRG schemes converges 'easily'

Critical flavour number

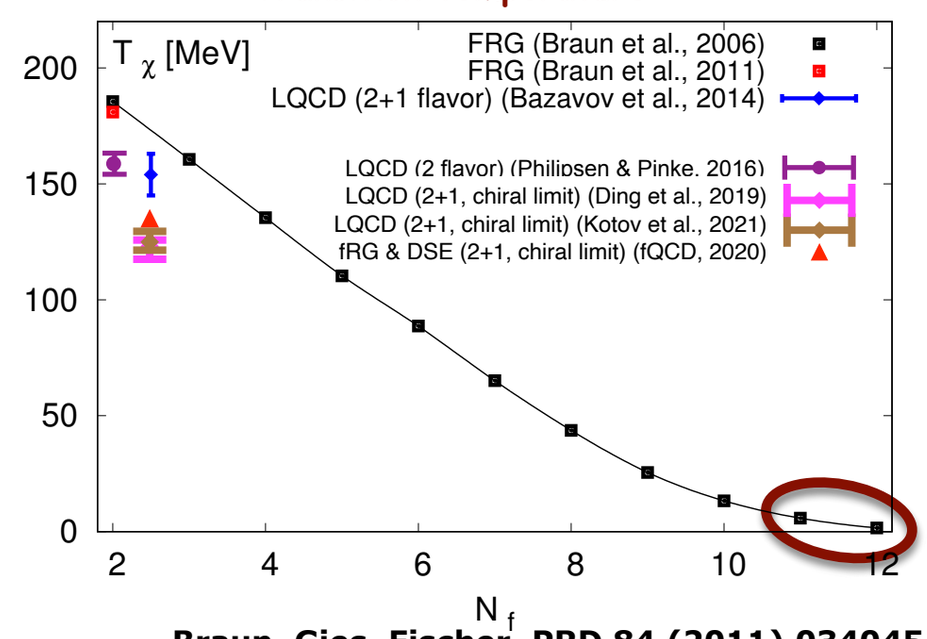
fRG $10 \lesssim N_{\mathrm{f,cr}} \lesssim 12$

Gies, Jäckel '05, Braun, Gies '05, 06

lattice $9 \lesssim N_{\mathrm{f,cr}} \lesssim 13$

e.g. **Appelquist, Fleming, Neil '08, '09**
Deuzeman, Lombardo, Pallante '08
Fodor et al. '08, '09
Fodor, Holland, Kuti, Nogradi, Schroeder '09
Jin, Mawhinney '09

Transition temperature



Braun, Gies, Fischer, PRD 84 (2011) 034045

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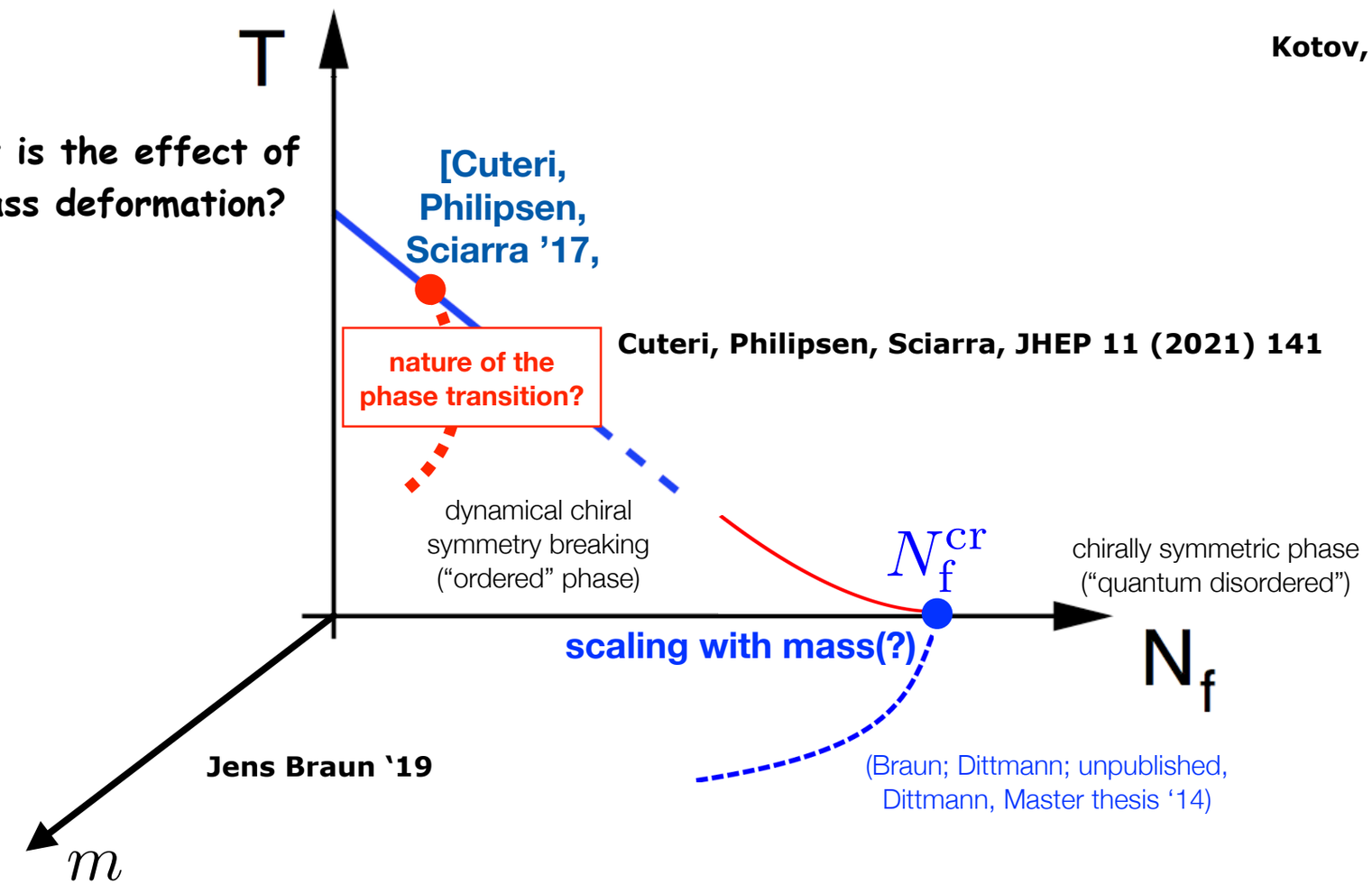
The phase structure of many-flavour QCD

Comprehensive depiction

Philipsen, *Symmetry* 13 (2021) 11
Kotov, Lombardo, Trunin, *Symmetry* 13 (2021) 10, 1833

What is the effect of a mass deformation?



Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141

Jens Braun '19

The phase structure of many-flavour QCD

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Philipsen, *Symmetry* 13 (2021) 11
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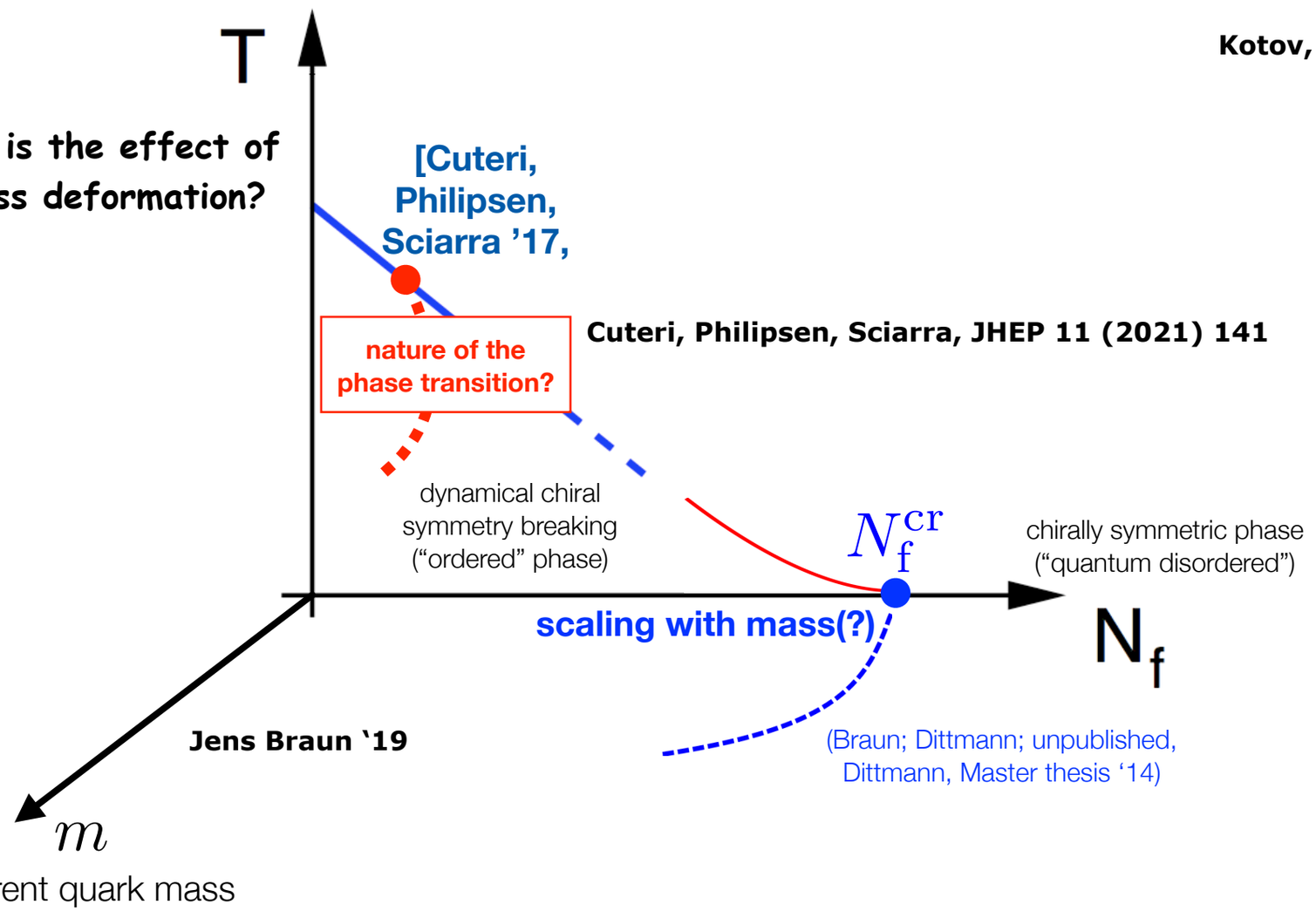

Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141

Jens Braun '19

Lattice shopping list & joint study?

Outline

- QCD phase structure: Where do we stand?
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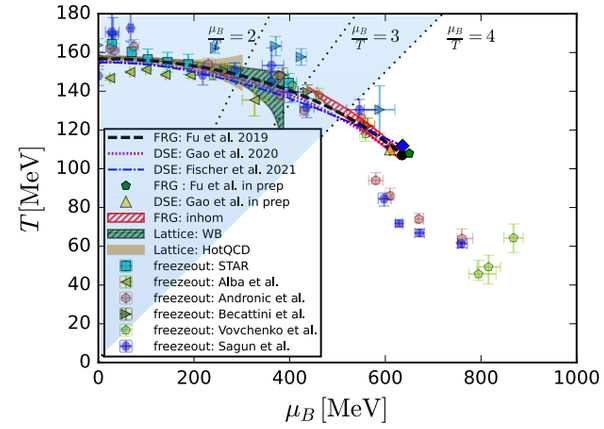
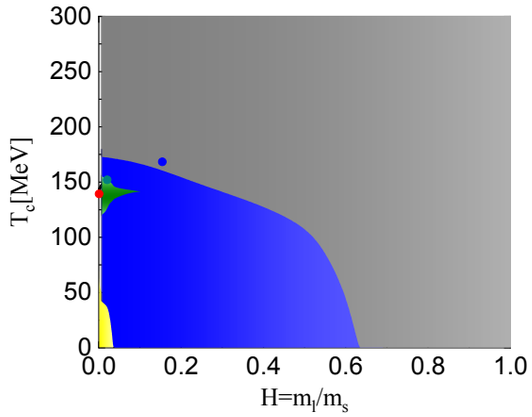
- Chiral dynamics & phenomenological applications
- Many flavour QCD & the conformal window
- Summary & outlook

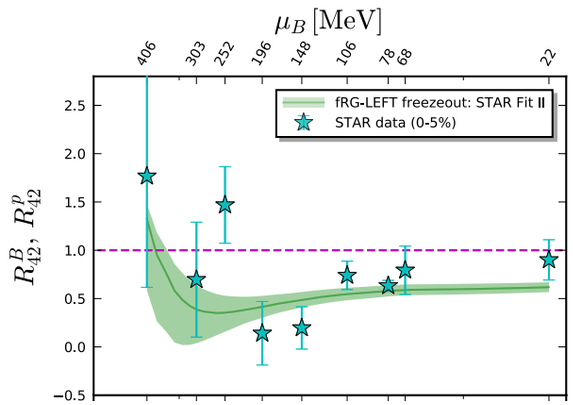
Summary & Outlook

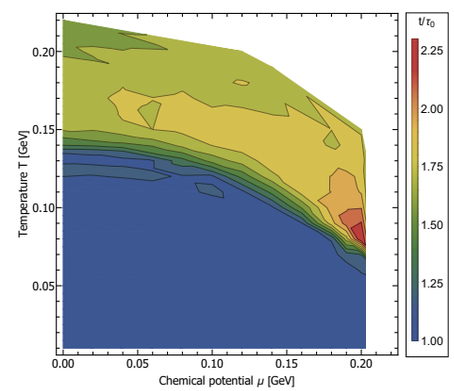
- QCD phase structure and CEP estimate



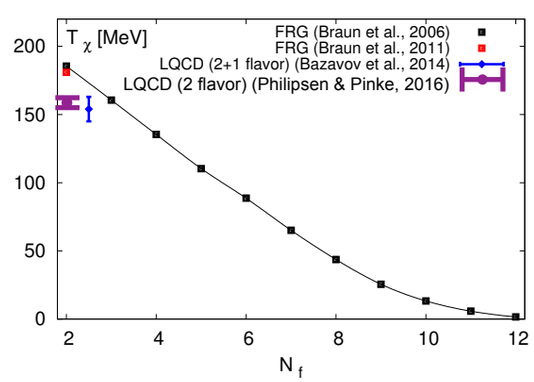
- Chiral dynamics & phenomenological applications





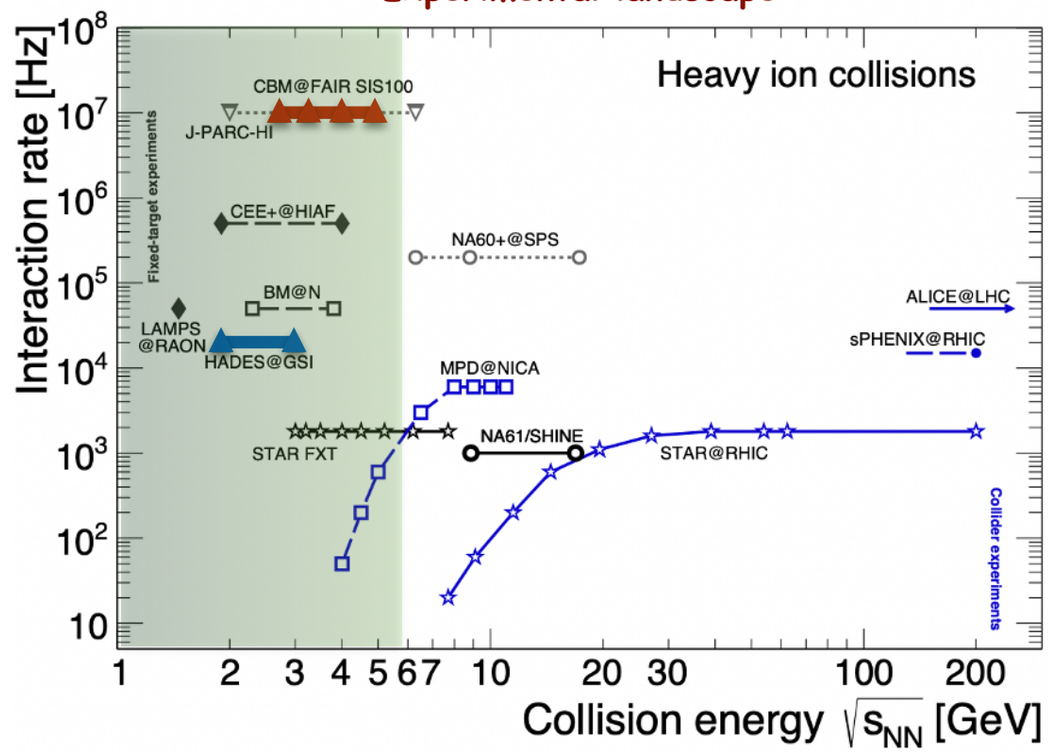


- Many flavour QCD



The future is bright

Experimental landscape



Galatyuk, A982 (2019) update 2021
CBM, EPJA 53 3 (2017) 60

Freezeout curve

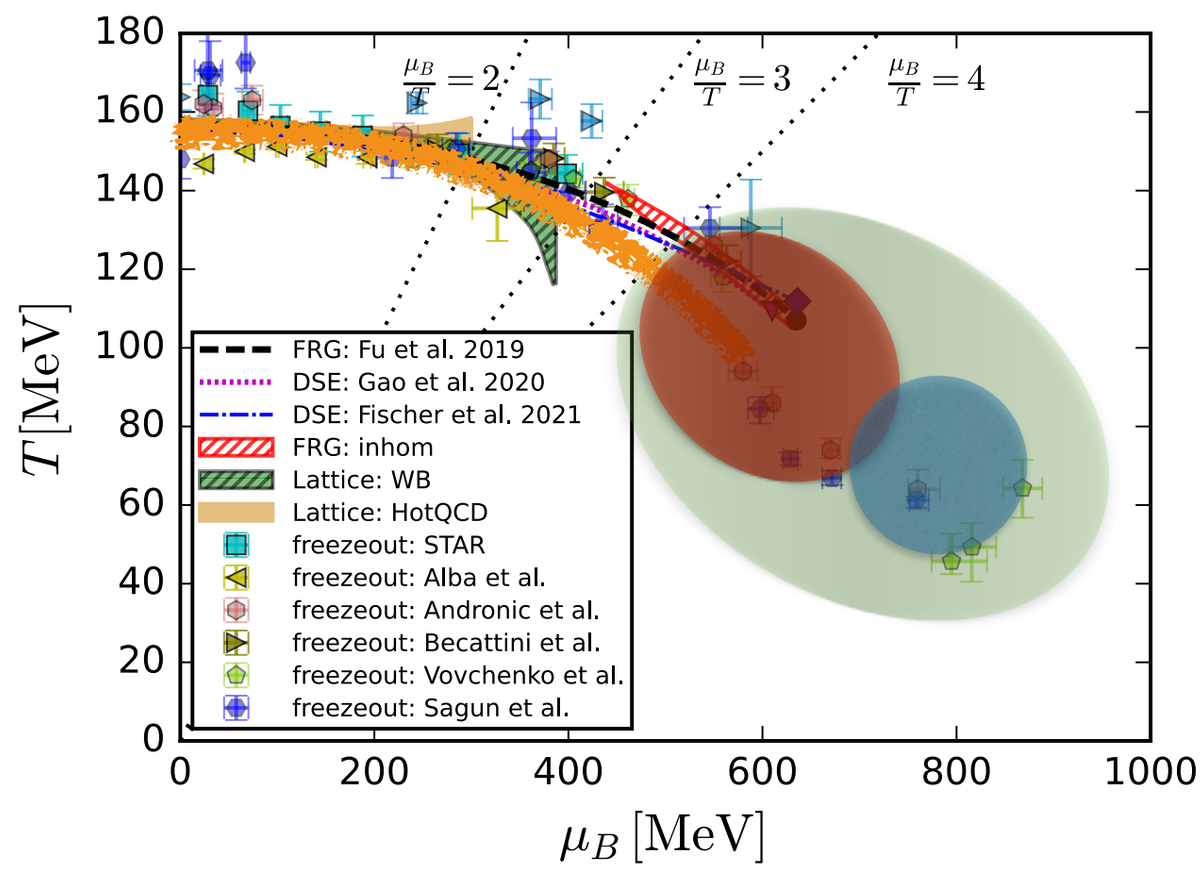
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

CBM/STAR

HADES

CEP or other NEW physics/phases

Chiral phase structure (theory) & freeze out data (Exp. data+Pheno)



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

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 5, 054022