

On the phase structure of QCD

Jan M. Pawłowski

Universität Heidelberg & ExtreMe Matter Institute

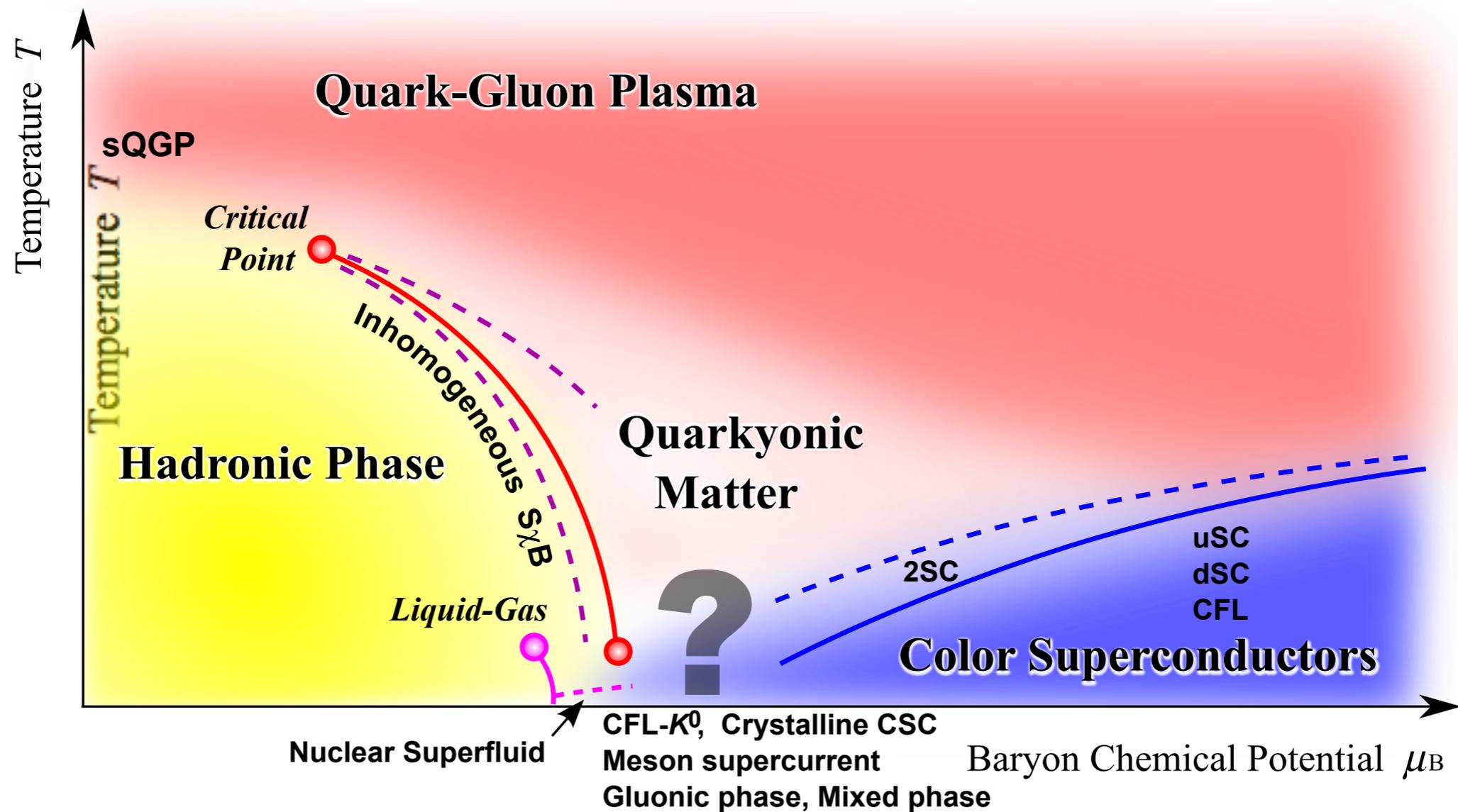
Protvino, November 11th 2020

for the fQCD collaboration



STRUCTURES
CLUSTER OF
EXCELLENCE





fQCD collaboration

Braun, Chen, Fu, Huang, Ihssen, Horak, JMP, Rennecke,
Rosenblüh, Schallmo, Schneider, Tan, Töpfel, Wen, Wink, Yin

Brookhaven, Dalian, Darmstadt, Heidelberg

Functional Methods for QCD

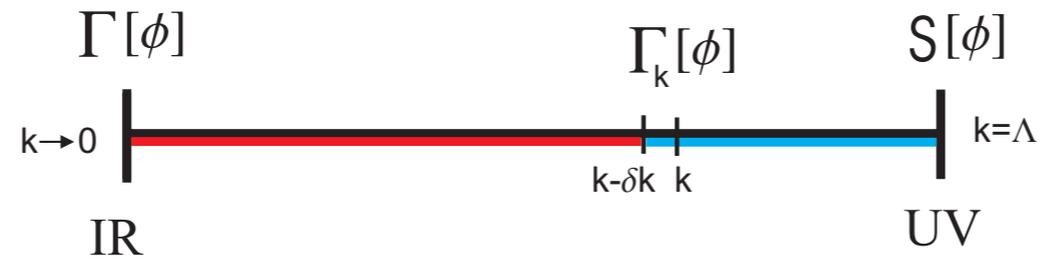
FRG:

JMP, NPA 931 (2014) 113
Dupuis et al, arXiv:2006.04853

DSE:

Fischer, PPNP 105 (2019) 1

free energy at momentum scale k



ab initio

Functional Methods for QCD

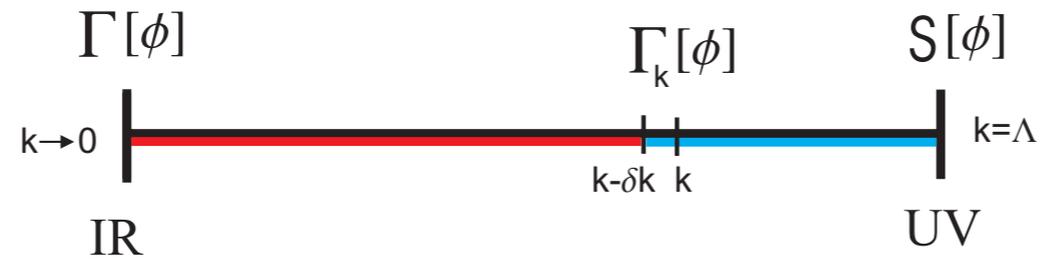
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free energy at momentum scale k



ab initio

functional RG:

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \left(\text{glue quantum fluctuations} - \text{quark quantum fluctuations} + \text{hadronic quantum fluctuations} \right)$$

free energy/
grand potential

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

closed form

Functional Methods for QCD

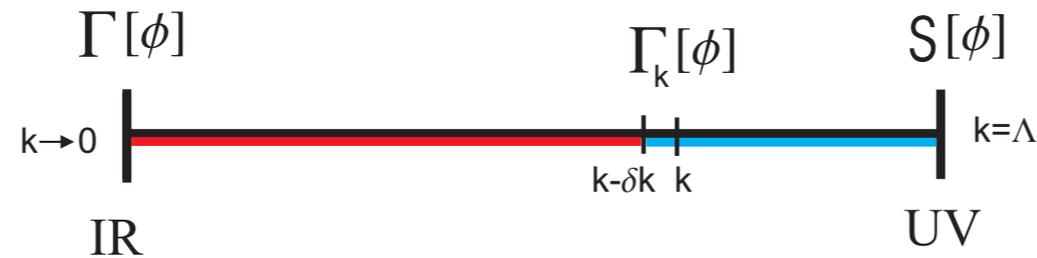
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closed form

functional DSE :

$$\frac{\delta(\Gamma - S)}{\delta A_0} = \frac{1}{2} \left(\text{glue loop with ghost} - \text{ghost loop} - \text{quark loop} - \frac{1}{6} \text{glue loop with ghost and quark} + \text{ghost loop with quark} \right)$$

A_0 : background field

Functional Methods for QCD

FRG:

JMP, NPA 931 (2014) 113
Dupuis et al, arXiv:2006.04853

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glue quantum fluctuations

quark quantum fluctuations

hadronic quantum fluctuations

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Aiming at apparent convergence

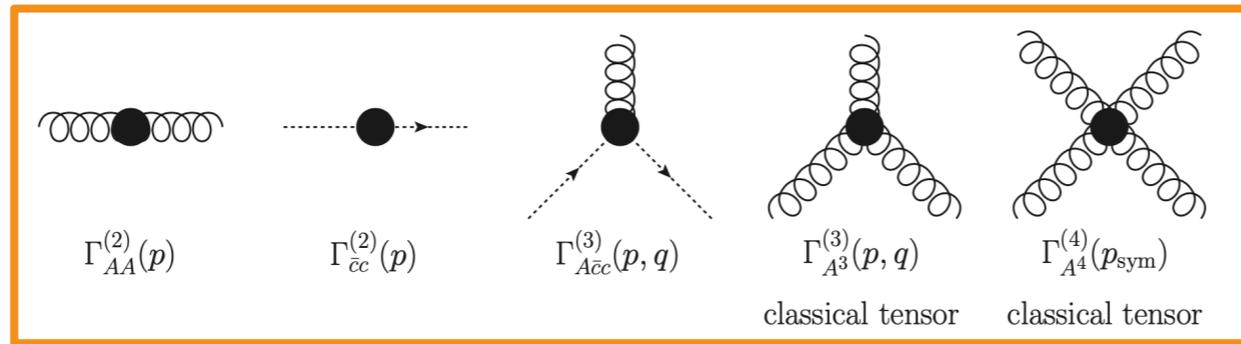
closed form

functional DSE :

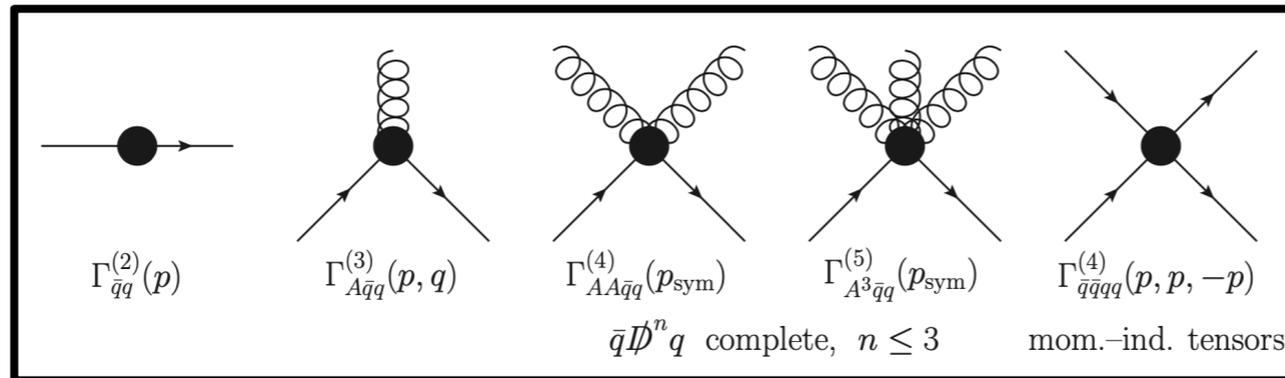
$$\frac{\delta(\Gamma - S)}{\delta A_0} = \frac{1}{2} \left(\text{glue loop with vertex} - \text{quark loop with vertex} - \text{quark loop with vertex} - \frac{1}{6} \text{glue loop with vertex} + \text{quark loop with vertex} \right)$$

A_0 : background field

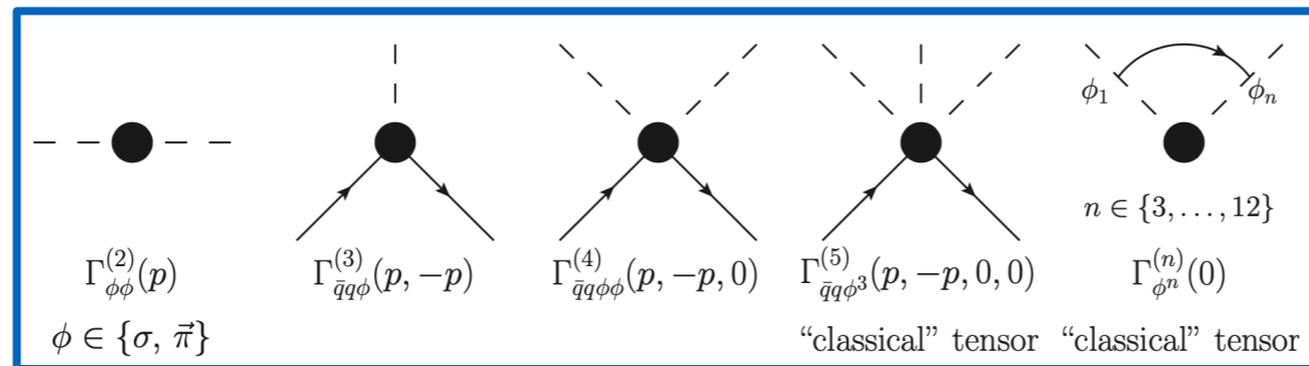
vacuum QCD: current set of correlation functions



glue sector



quark-gluon sector



quark-meson sector

Aiming at apparent convergence

Extension, work in progress:

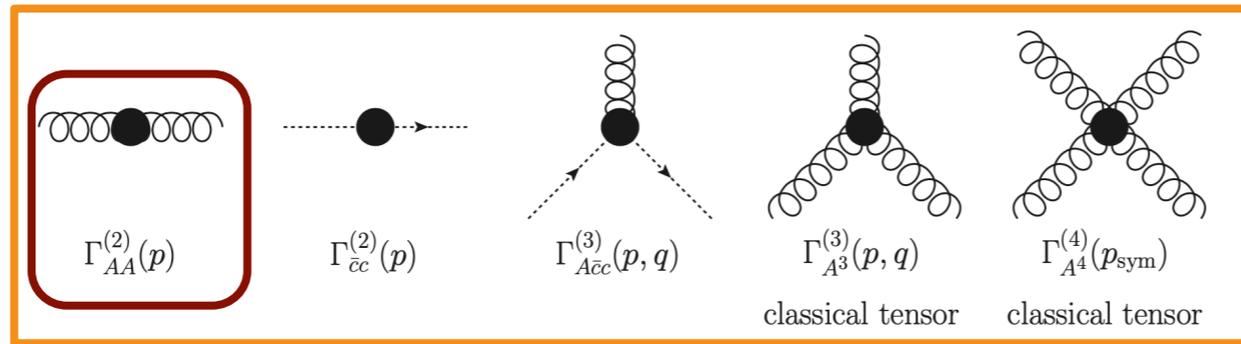
Fu, Huang, Ihssen, JMP, Schneider, Tan, Wink

Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006,
PRD 97 (2018) 054015

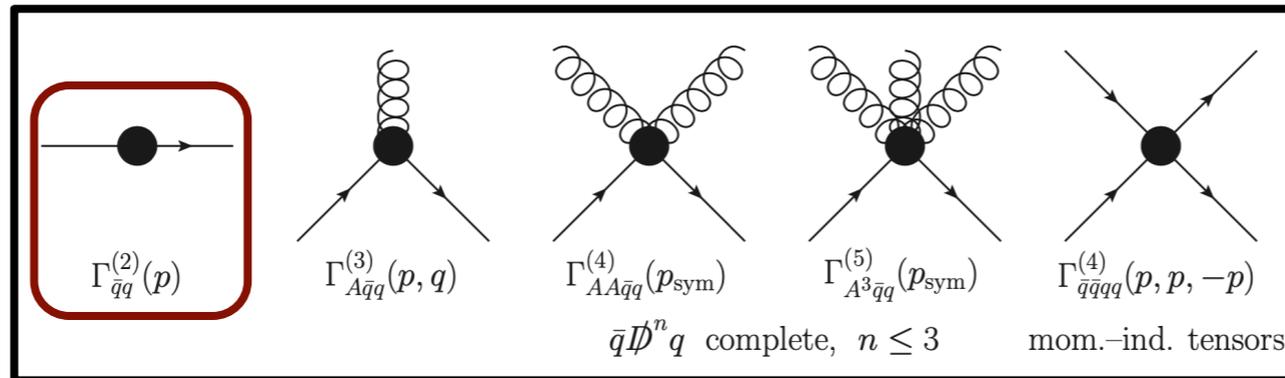
Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

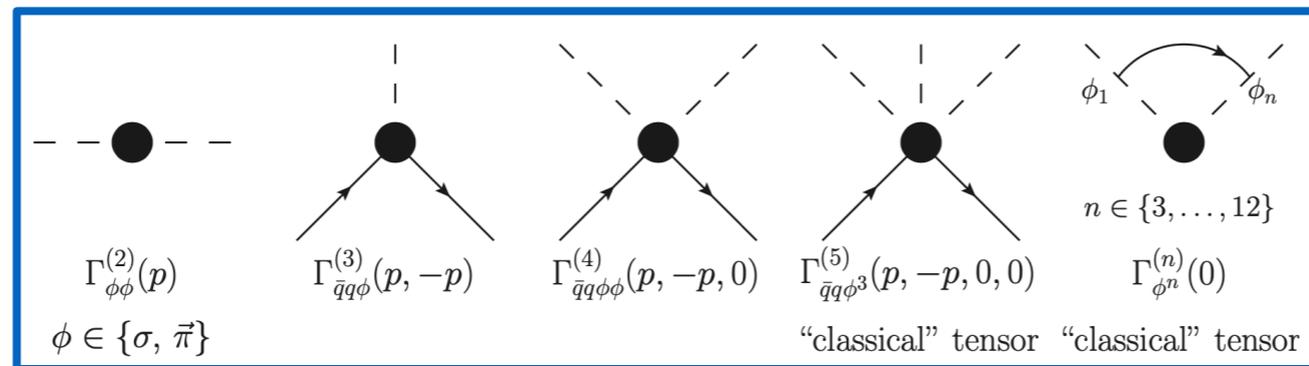
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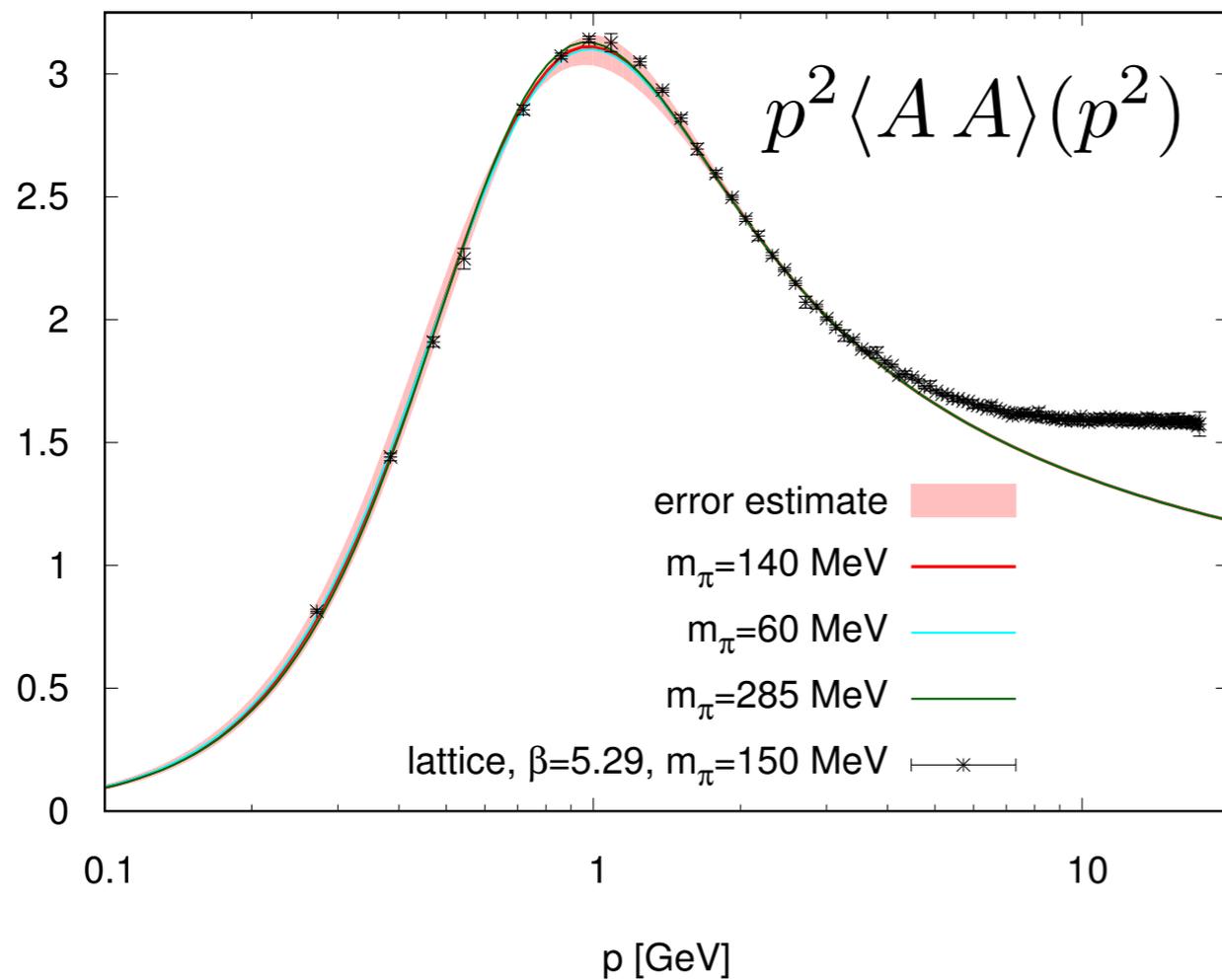
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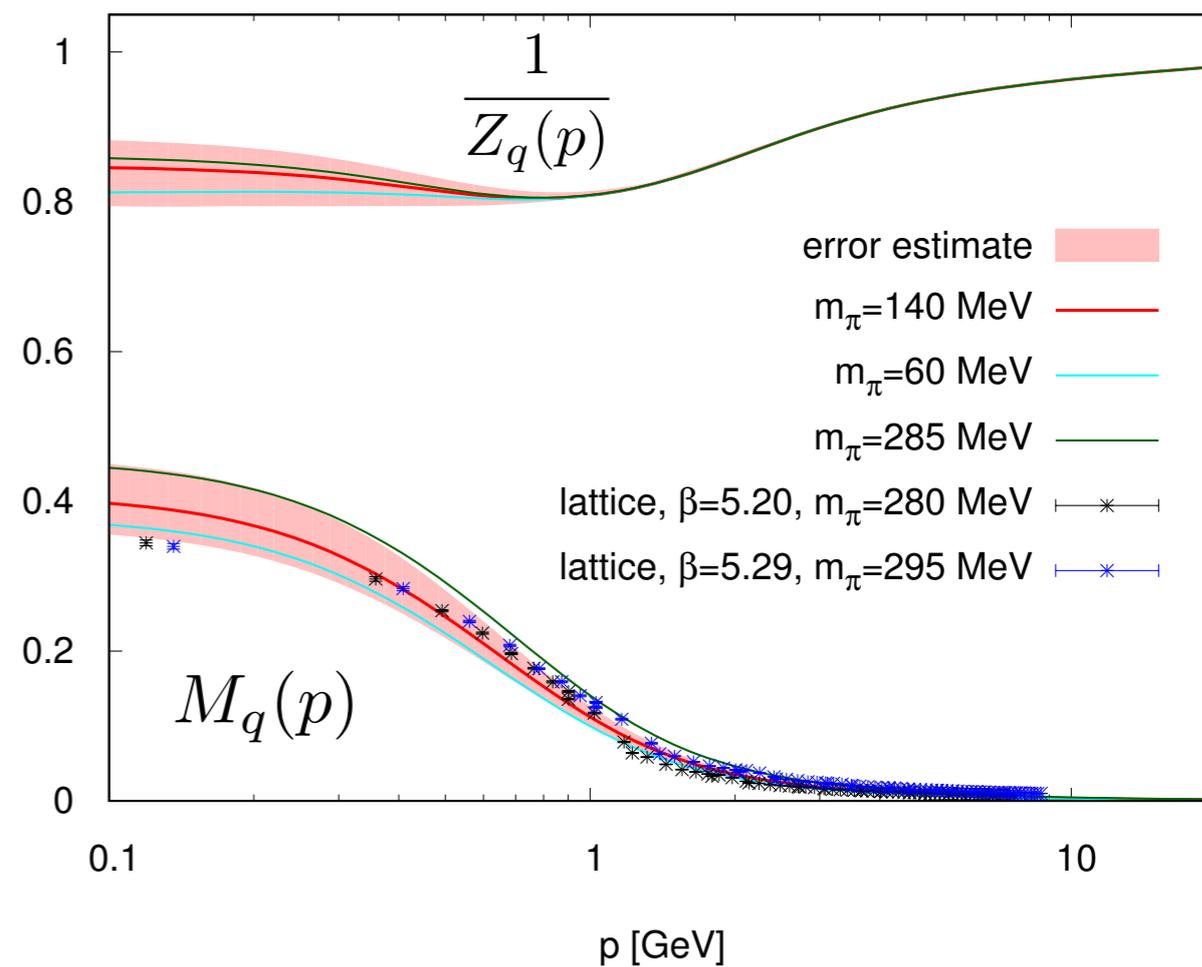
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vacuum QCD: Euclidean propagators

Two-flavour QCD



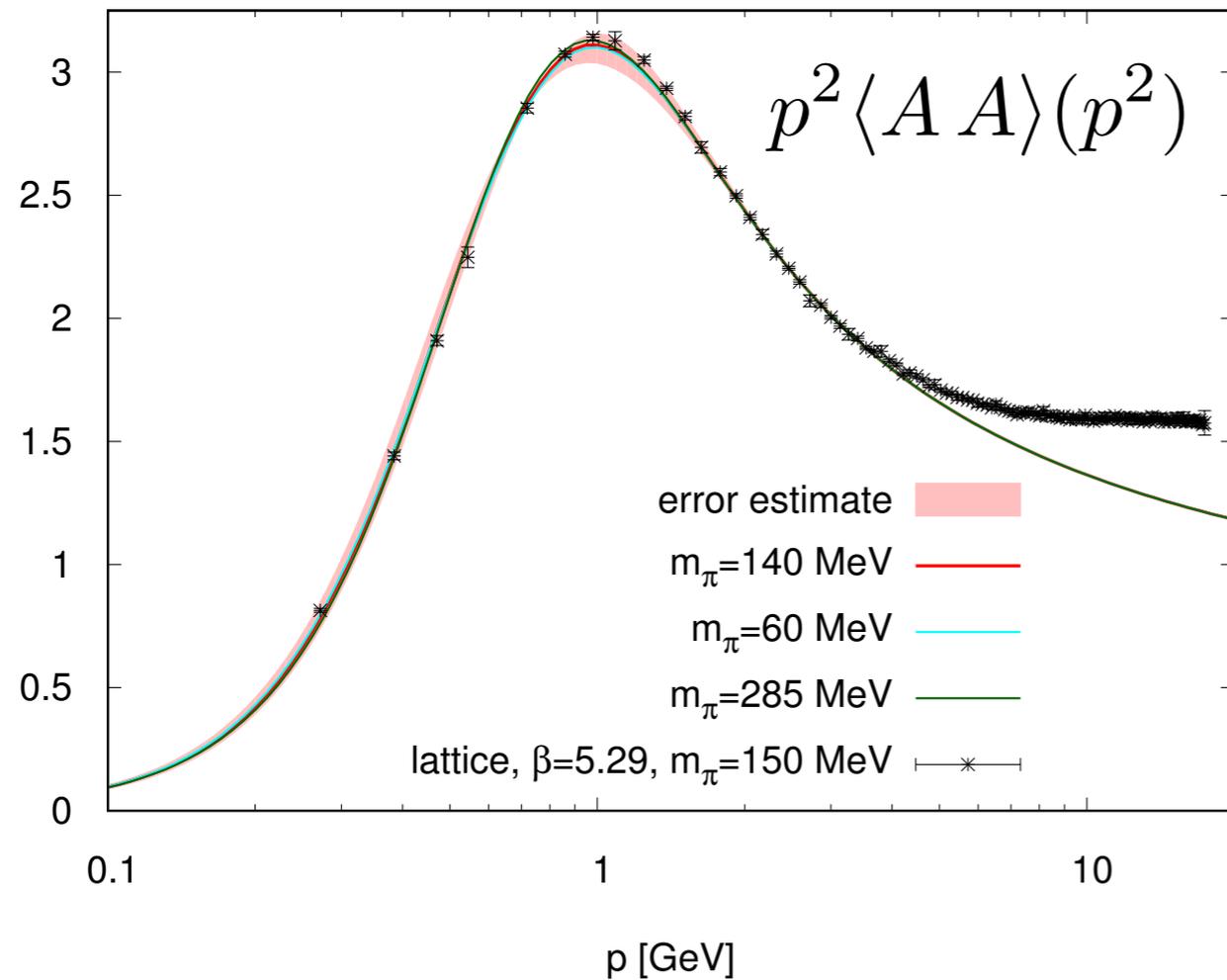
$$\frac{1}{Z_q(p)} \frac{1}{i \not{p} + M_q(p)}$$



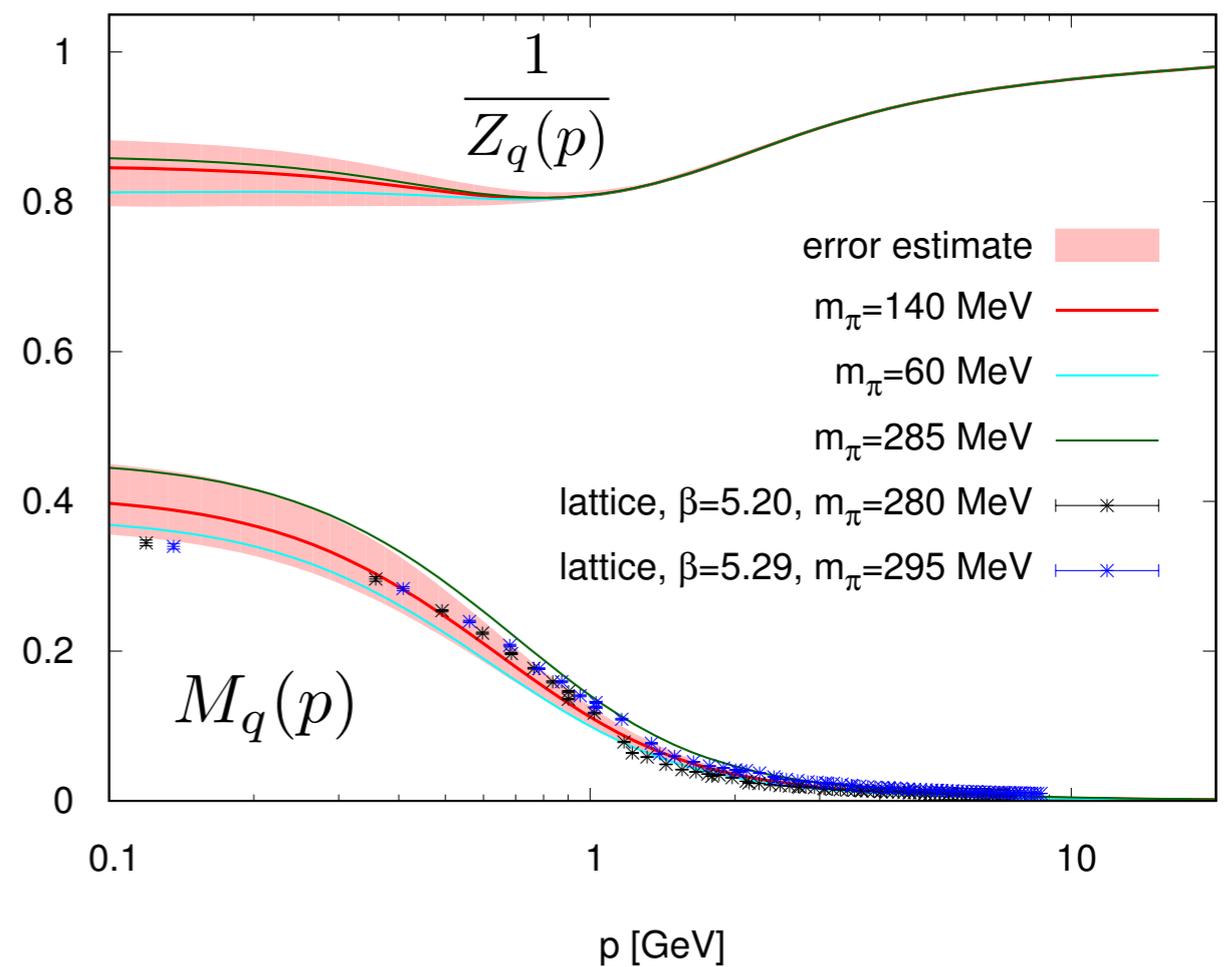
lattice, e.g.: Oliviera et al, Acta Phys.Polon.Supp. 9 (2016) 363
 Sternbeck et al, PoS LATTICE2016 (2017)
 A. Athenodorou et al, PLB 761 (2016) 444

vacuum QCD: Euclidean propagators

Two-flavour QCD



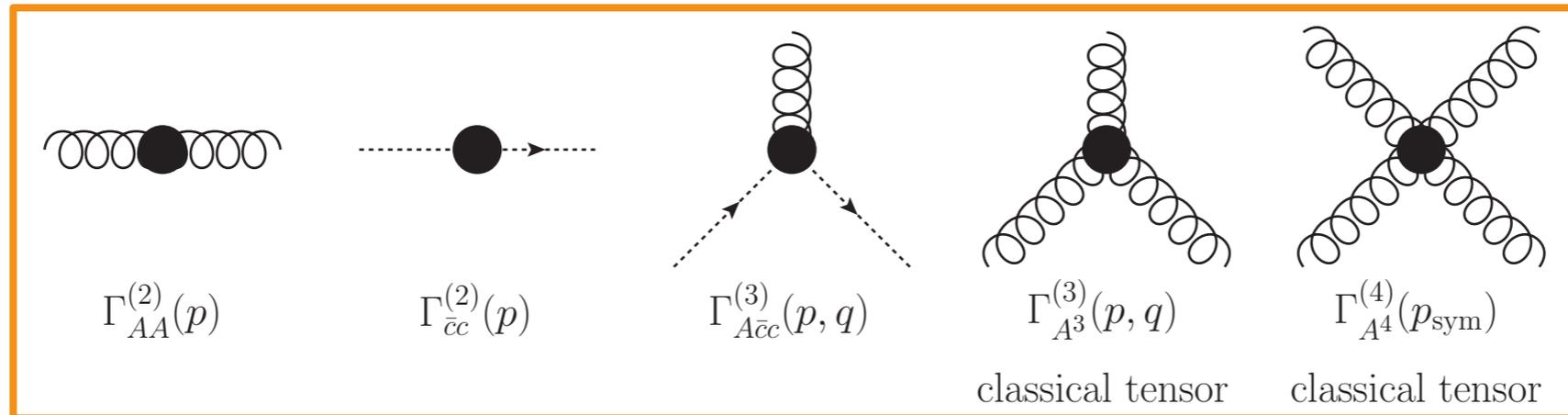
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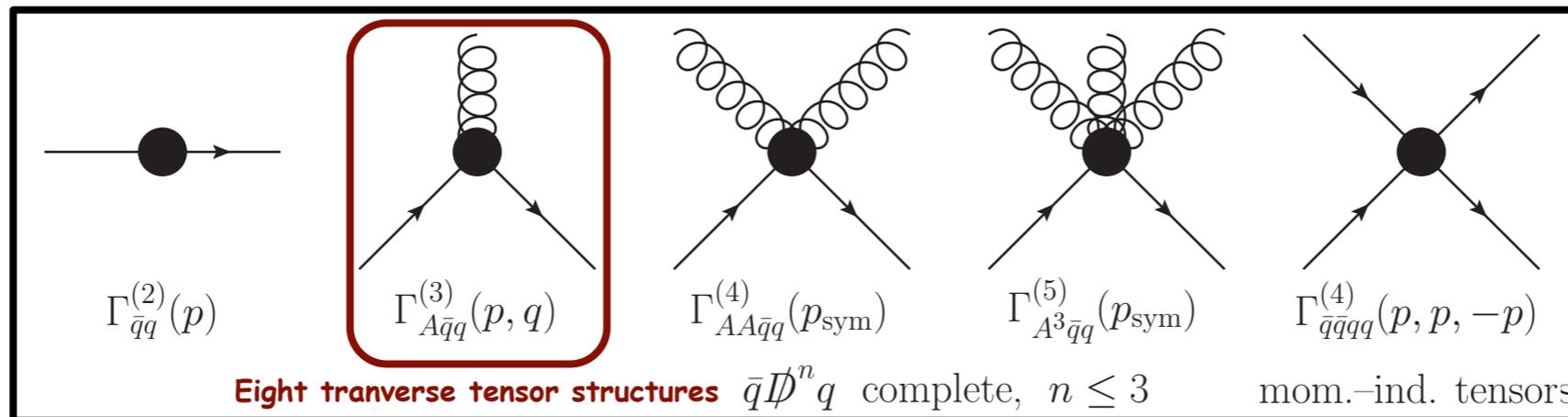
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simple correlations

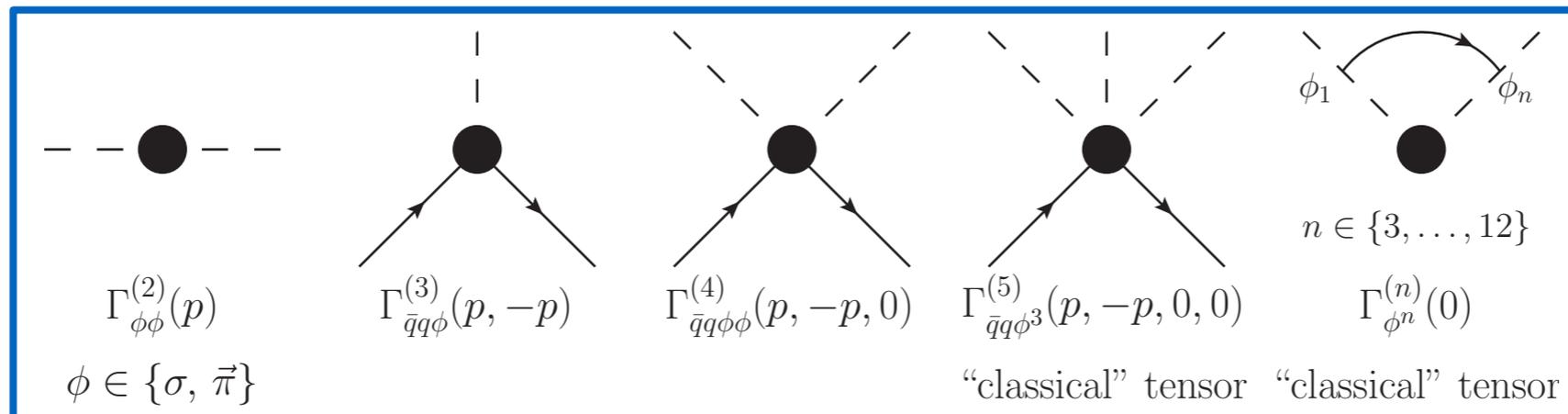
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Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

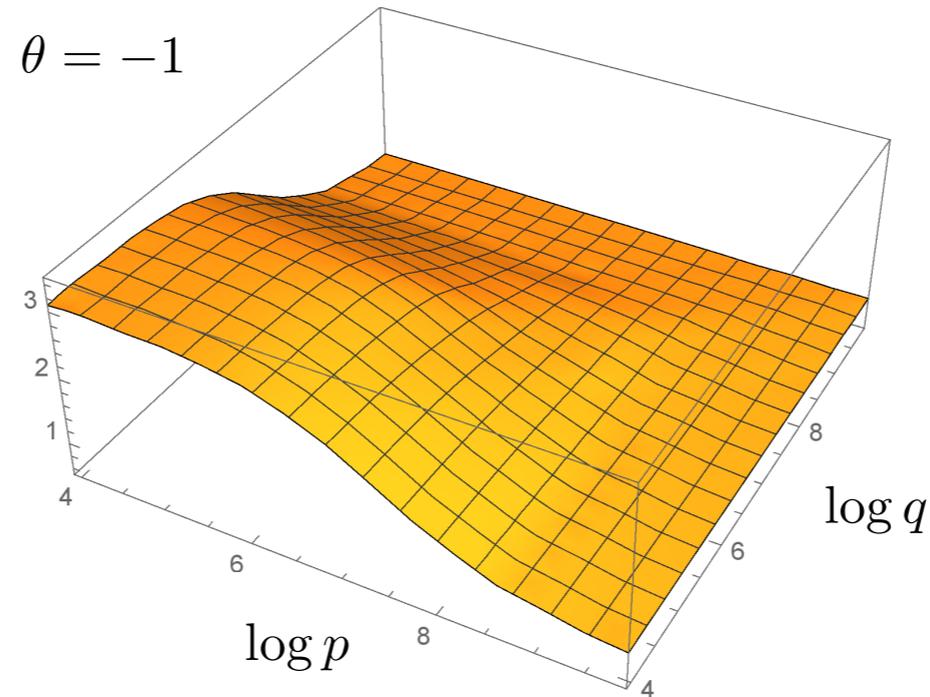
Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

vacuum QCD: Quark-gluon vertex

Two-flavour QCD

$$\theta = \frac{p \cdot q}{\sqrt{p^2 q^2}}$$

p, q in MeV



$$\lambda_1(p, q)$$

All (eight) tensor structures!

up-to-date 1st principles works:

FunMethods: Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

Williams, EPJ A51 (2015) 57

Sanchis-Alepuz, Williams, PLB 749 (2015) 592

Williams, Fischer, Heupel, PRD 93 (2016) 034026

Contant, Huber, Fischer, Welzbacher, Williams, APP.Supp. 11 (2018) 483

Aguilar, Binosi, Ibanez, Papavassiliou, PRD 89 (2014) 065027

Binosi, Chang, Papavassiliou, Qin, Roberts, PRD 95 (2017) 031501

Aguilar, Cardona, Ferreira, Papavassiliou, PRD 96 (2017) 014029

PRD 98 (2018) 014002

Pelaez, Tissier, Wschebor, PRD 92 (2015) 045012

Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016) 1

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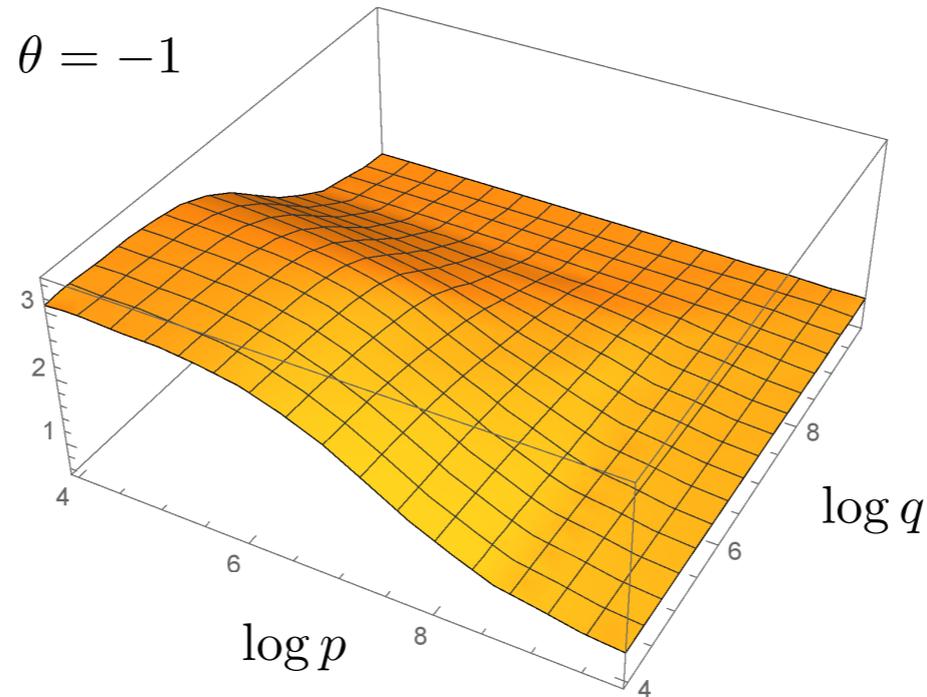
Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

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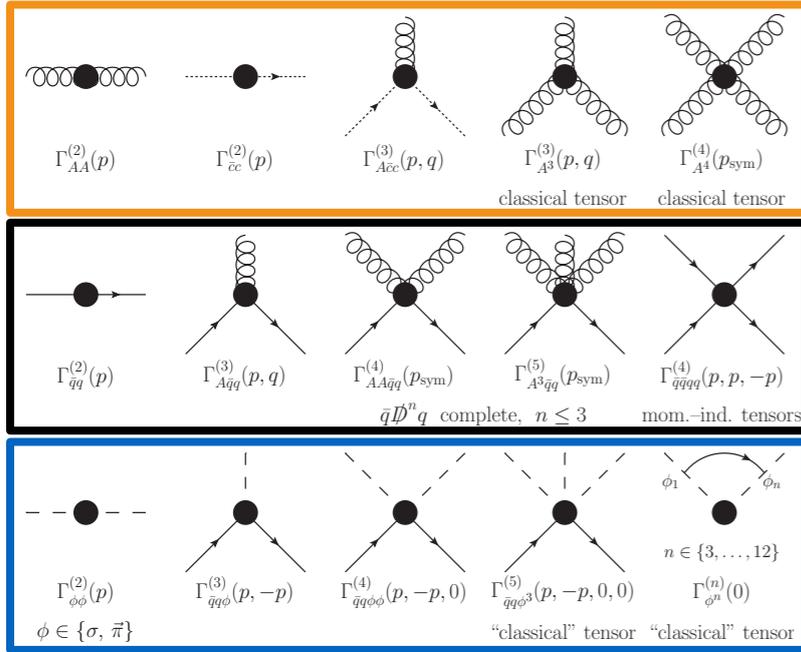
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Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

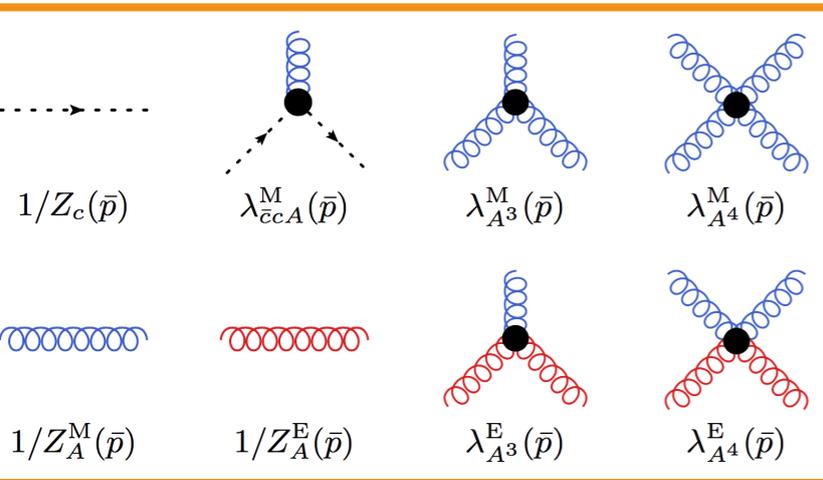
QCD at finite density

Input

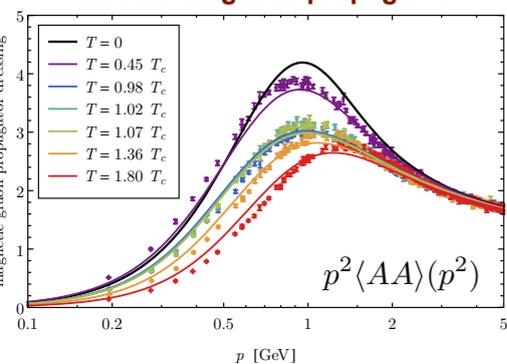
two flavour vacuum QCD



finite T Yang-Mills



chromo-magnetic propagator



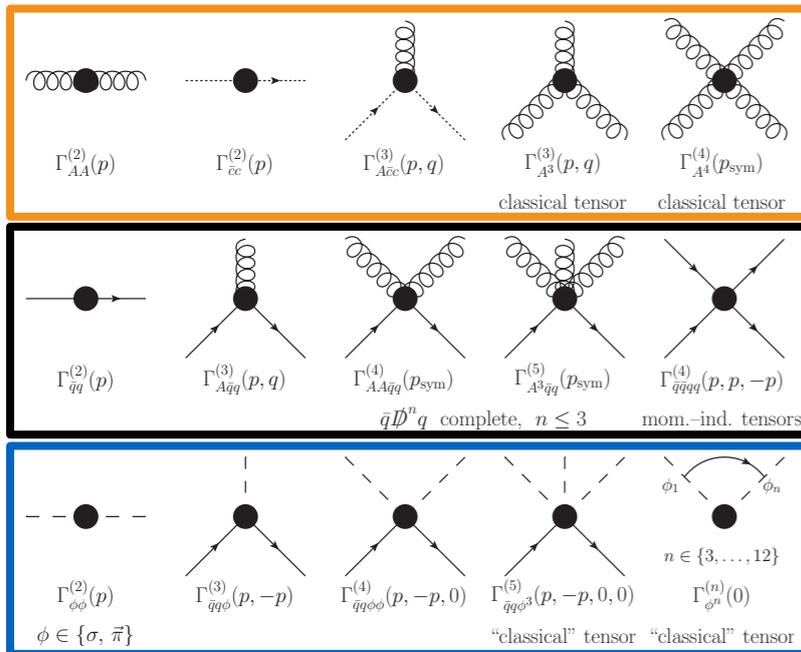
Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 97 (2018) 054015

$$\Gamma^{(n)} = \left[\Gamma^{(n)} \right]_{\text{Input}} + \Delta\Gamma^{(n)}$$

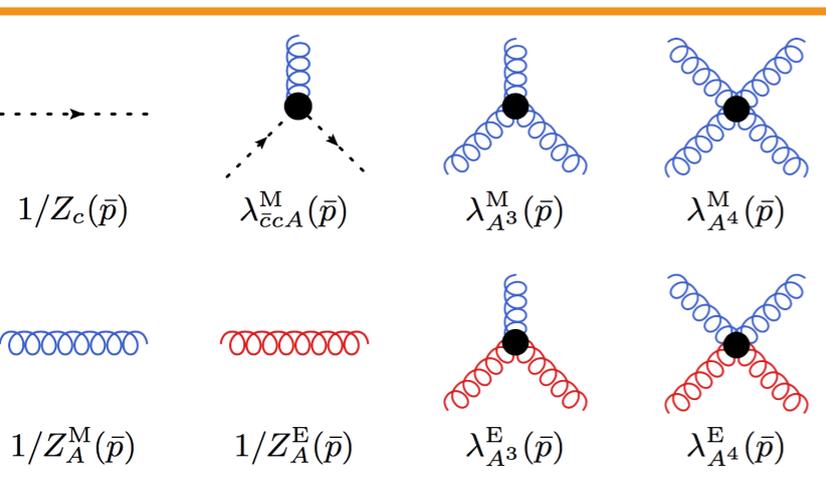
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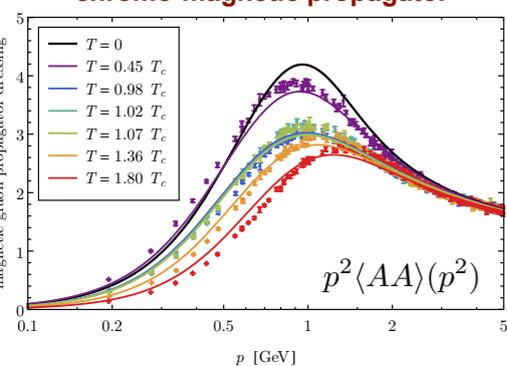
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chromo-magnetic propagator



Cyrol, Fister, Mitter,
JMP, Strodthoff,
PRD 97 (2018) 054015

Output

$$\partial_t \Delta \Gamma^{(n)} = \left[\partial_t \Gamma^{(n)} \right]_{\text{Input}} + \Delta \text{Flow}^{(n)} \left[\left\{ \left[\Gamma^{(m)} \right]_{\text{Input}} \right\}, \left\{ \Delta \Gamma^{(m)} \right\} \right]$$

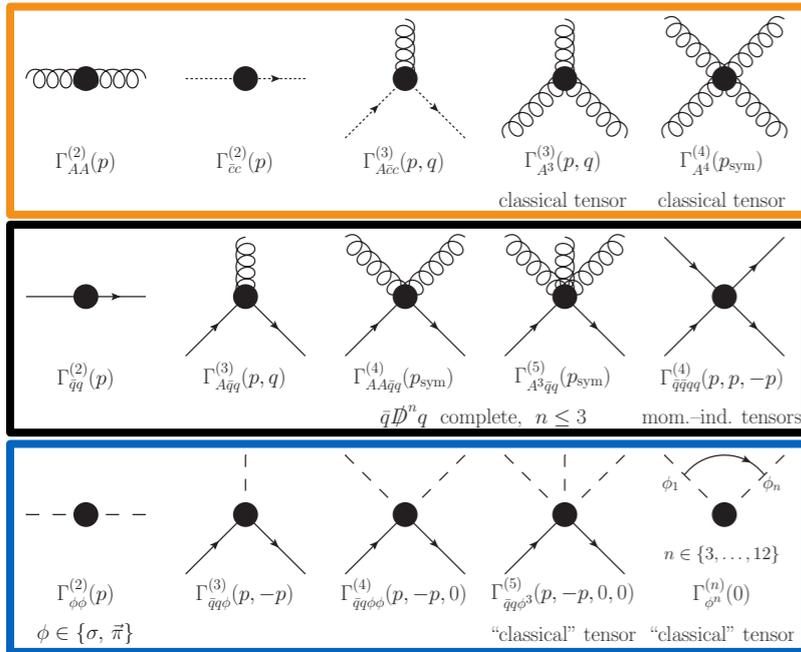
vacuum: Braun, Fister, Pawłowski, Rennecke, PRD 94, 034016 (2016)

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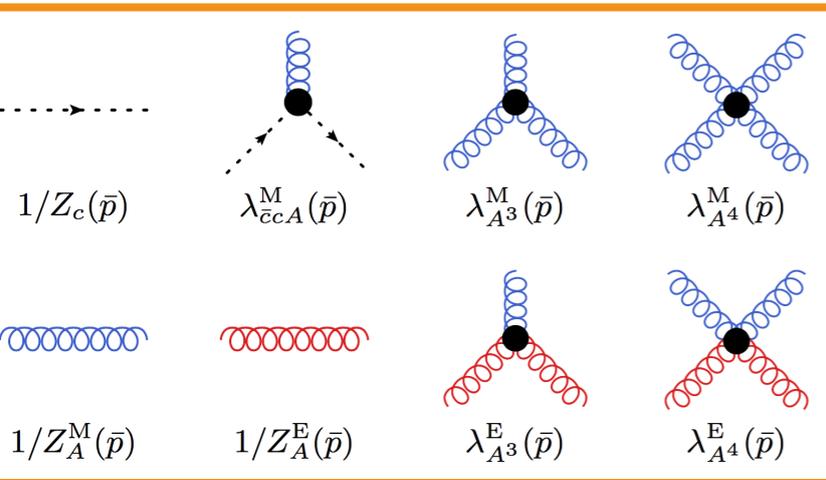
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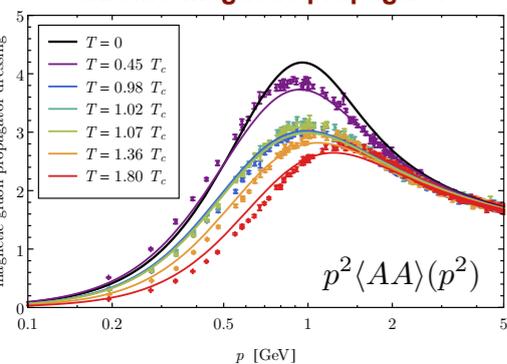
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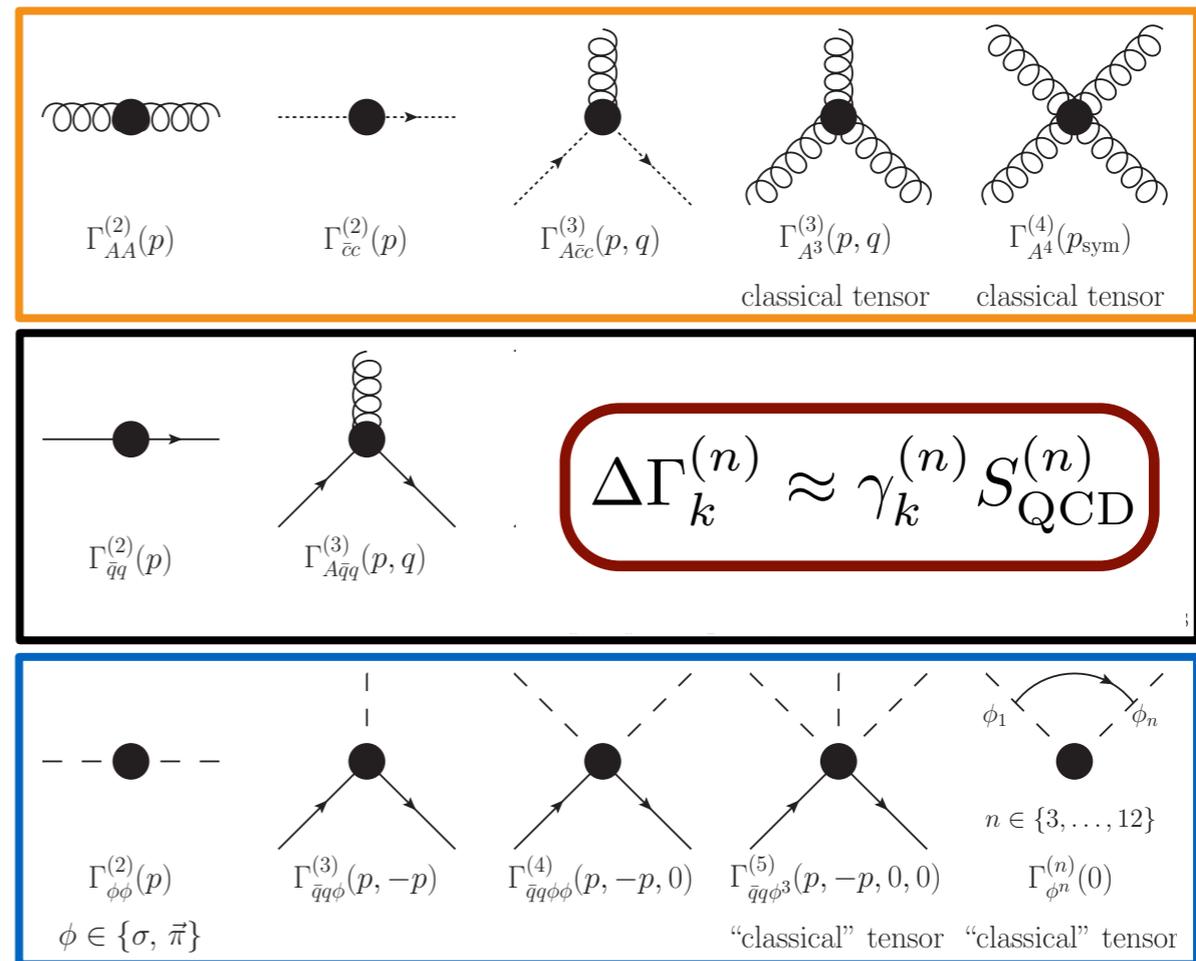
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2+1 flavour QCD at finite T & mu

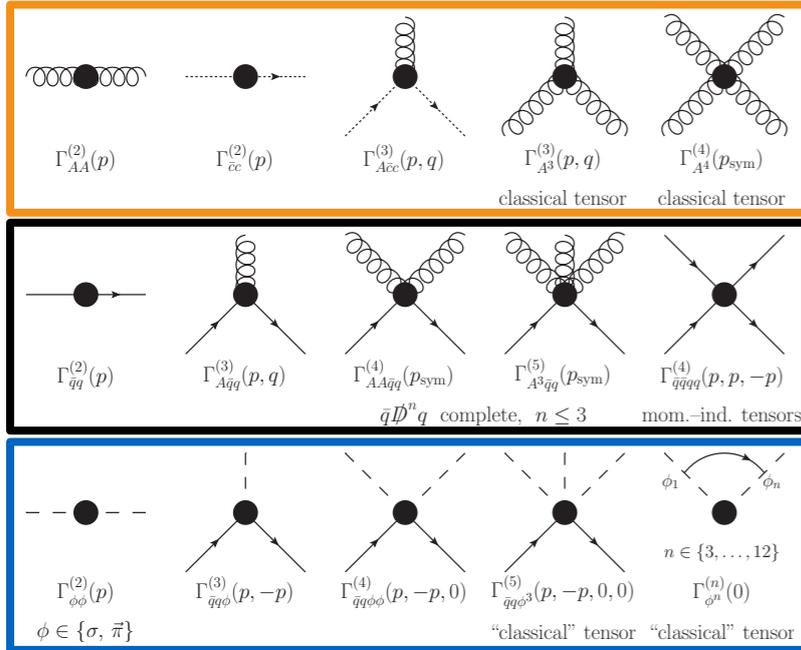


Fu, JMP, Rennecke, PRD 101, (2020) 054032

QCD at finite density

Input

two flavour vacuum QCD



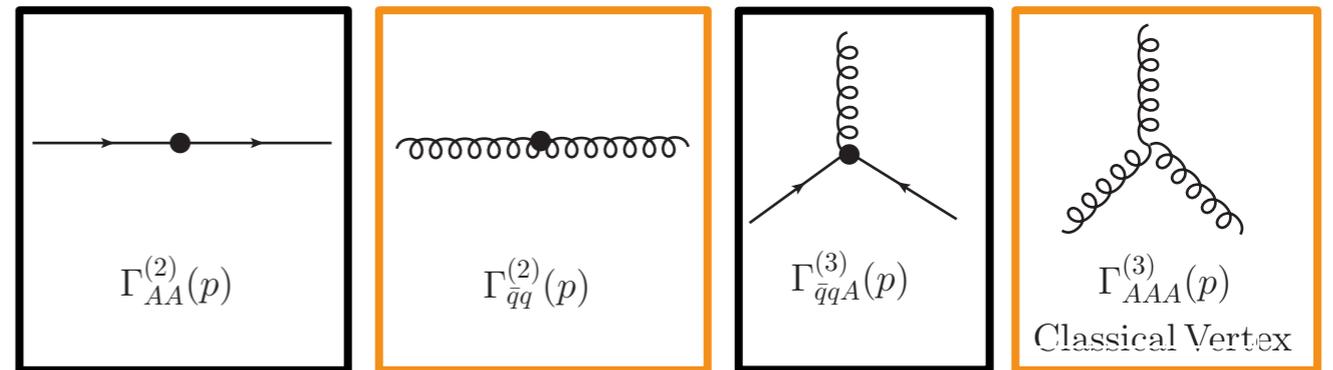
Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

Output

$$\Delta\Gamma^{(n)} = \left[\Gamma^{(n)} \right]_{\text{Input}} + \Delta\text{DSE}^{(n)} \left[\left\{ \left[\Gamma^{(m)} \right]_{\text{Input}} \right\}, \left\{ \Delta\Gamma^{(m)} \right\} \right]$$

fRG-assisted DSE

2+1 flavour QCD at finite T & mu

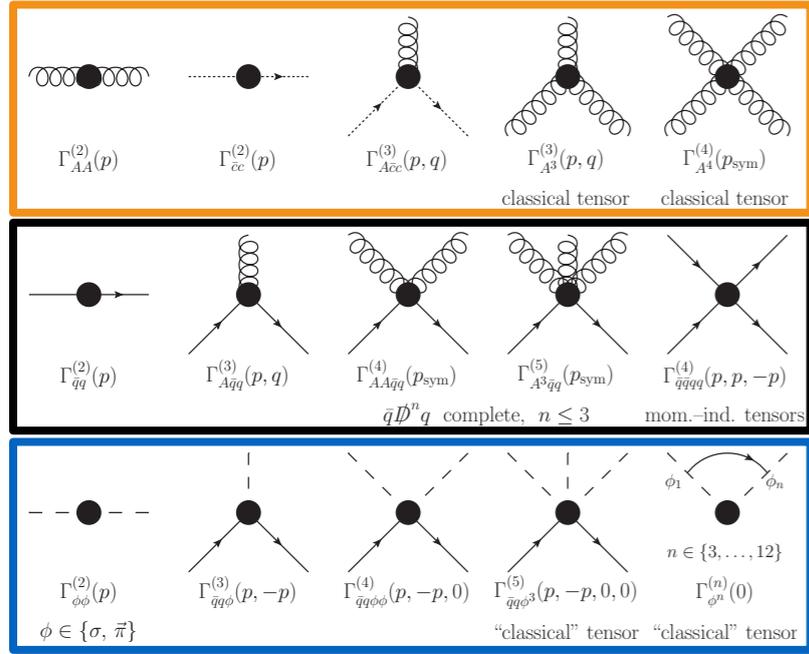


Eight tensor structures

QCD at finite density

Input

two flavour vacuum QCD



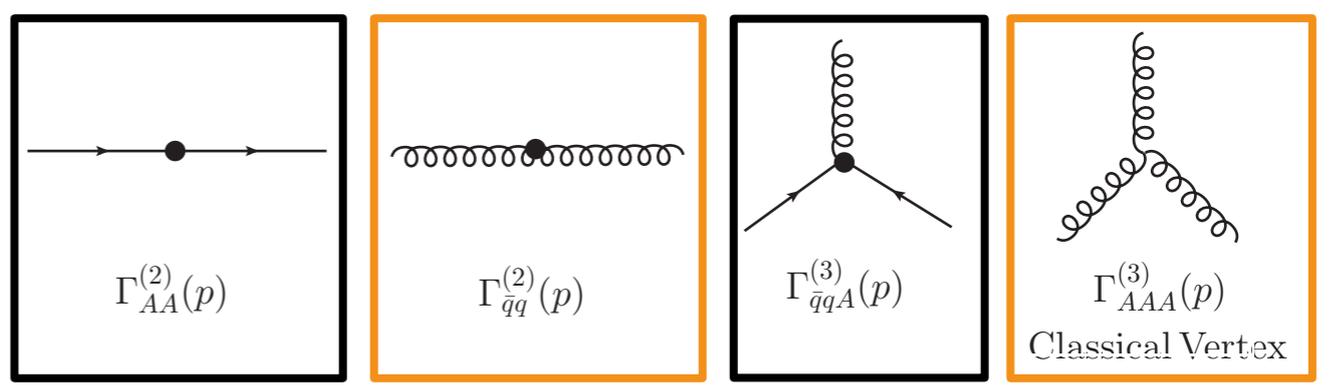
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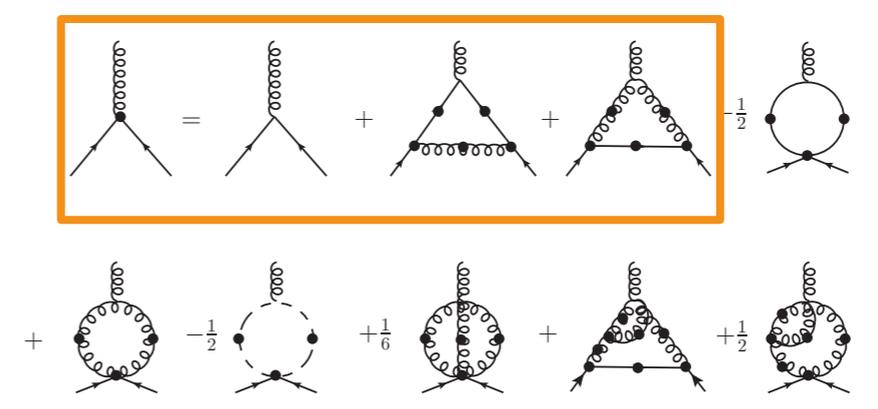
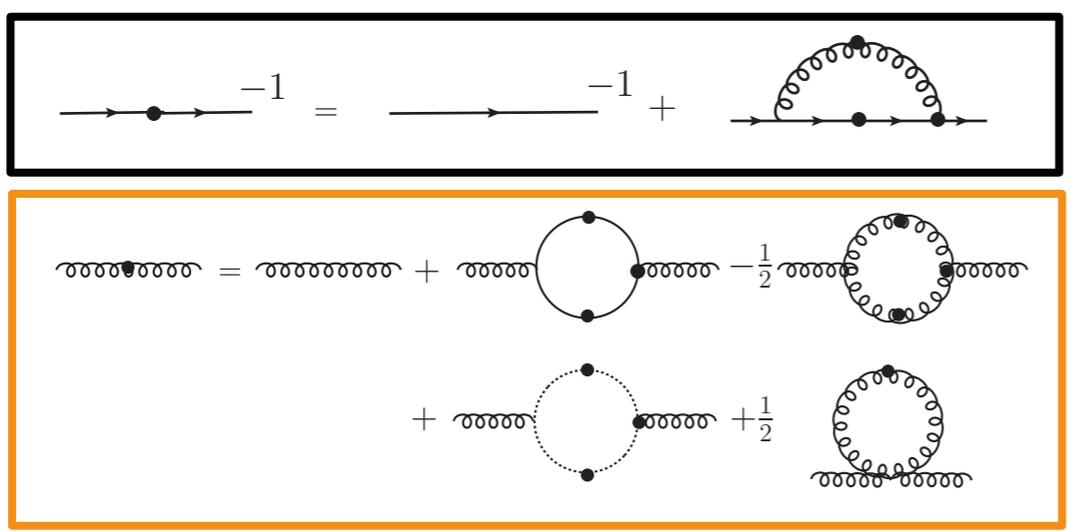
fRG-assisted DSE

2+1 flavour QCD at finite T & mu



Eight tensor structures

System of DSEs

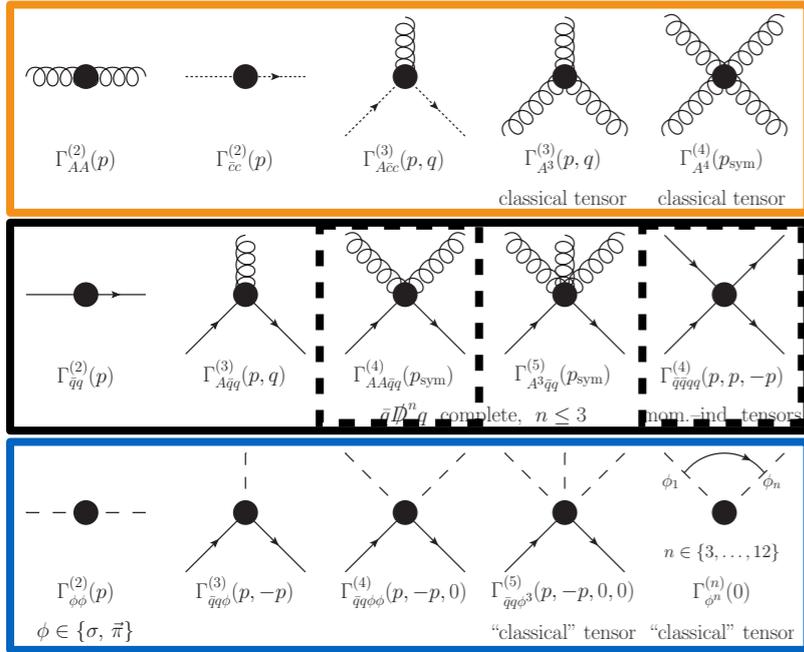


Gao, JMP, PRD 102, (2020) 034027
arXiv:2010.137005

QCD at finite density

Input

two flavour vacuum QCD



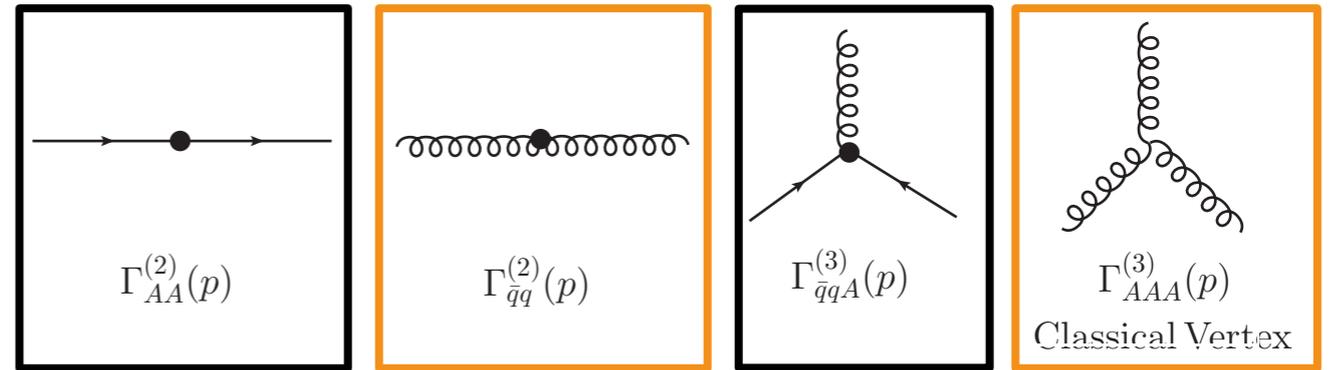
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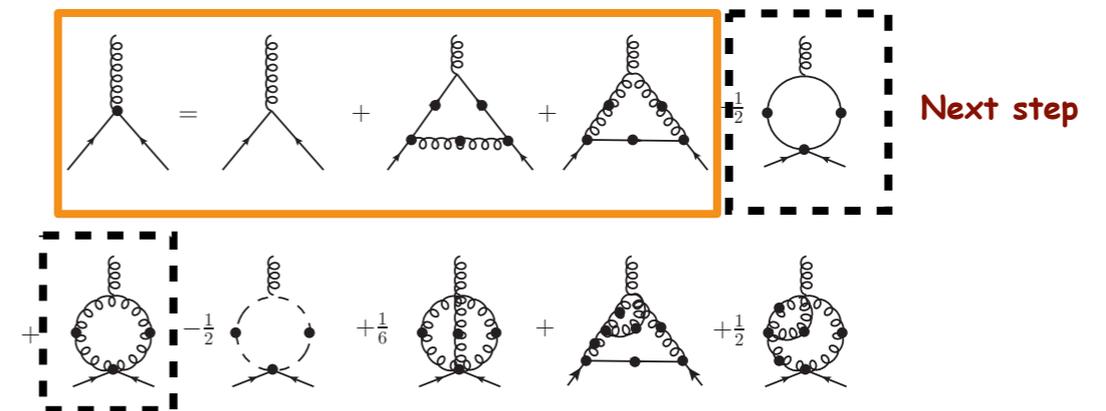
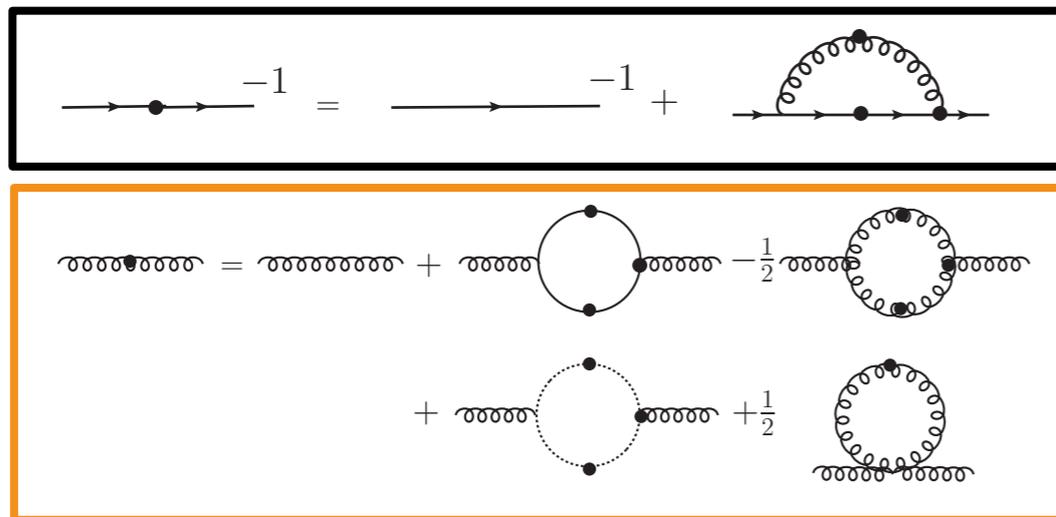
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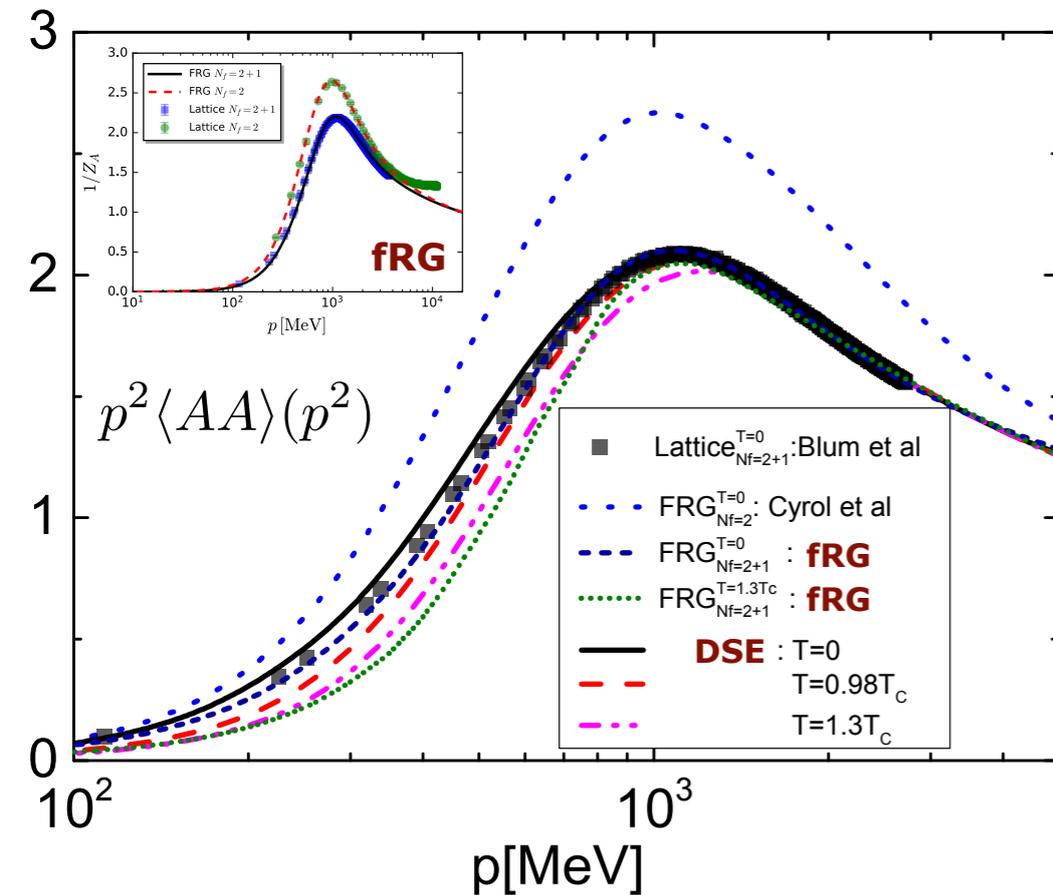


Gao, JMP, PRD 102, (2020) 034027
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QCD at finite density

Nf=2+1 Gluon and quark benchmark results in the vacuum and at finite T

vacuum



$$\vec{p}^2 \langle AA \rangle (\vec{p}^2)$$

DSE: vacuum & finite T

See also talk of C. Fischer

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

DSE: Gao, JMP, PRD 102, (2020) 034027
arXiv:2010.137005

Fischer, Luecker, PLB 718 (2013) 1036

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

Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011

lattice: Nf=2: Sternbeck, Maltman, Müller-Preussker,
von Smekal, PoS LATTICE2012, 243 (2012)

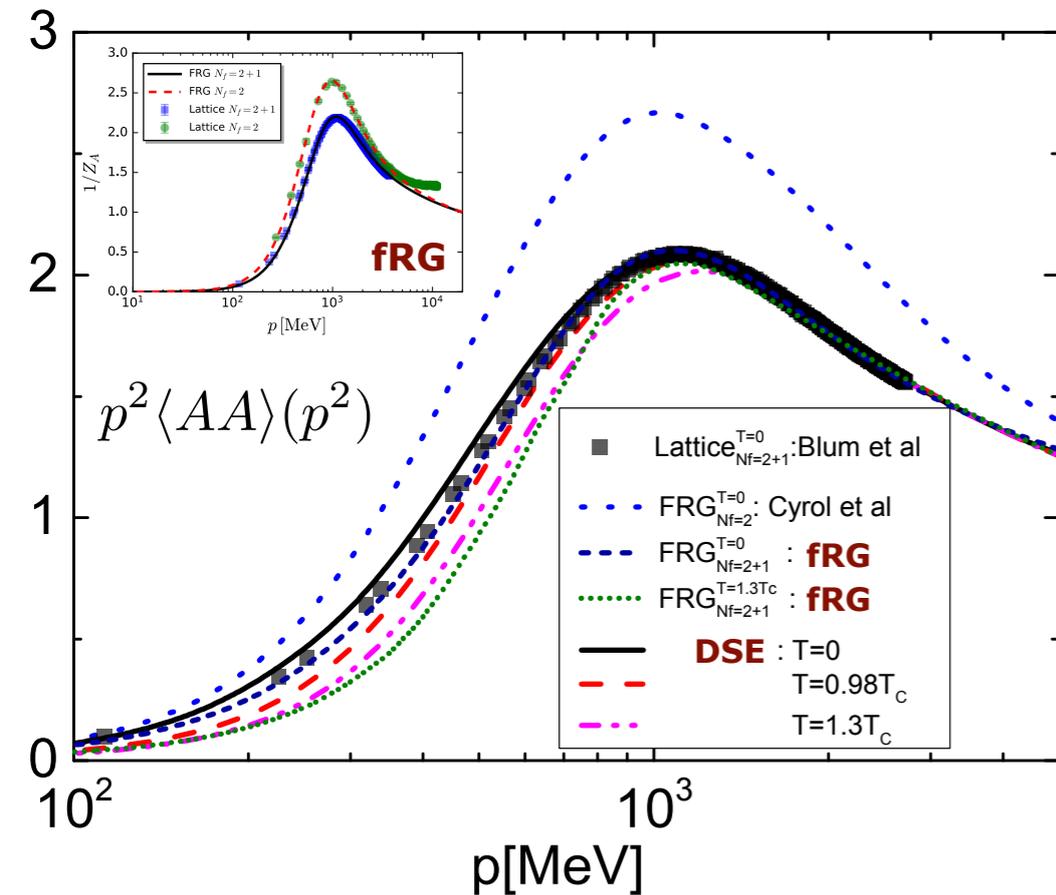
Nf=2+1: Aguilar, De Soto, Ferreira, Papavassiliou, Rodriguez-Quintero,
Zafeiropoulos, EPJC 80 (2020) 2, 154,
Boucaud, De Soto, Raya, Rodriguez-Quintero,
Zafeiropoulos, PRD 98, 114515 (2018)

Finite T: Ilgenfritz, JMP, Rothkopf, Trunin, EPJ C78, 127 (201)
(Nf=2+1+1)

QCD at finite density

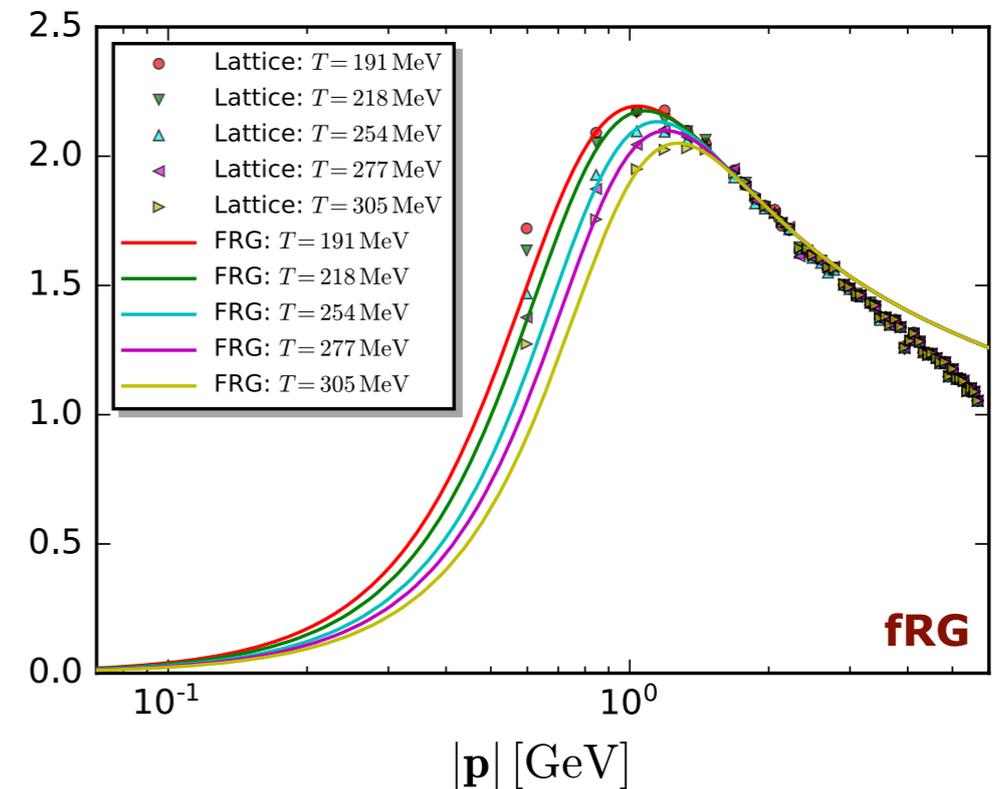
Nf=2+1 Gluon and quark benchmark results in the vacuum and at finite T

vacuum



$$\vec{p}^2 \langle AA \rangle (\vec{p}^2)$$

finite T



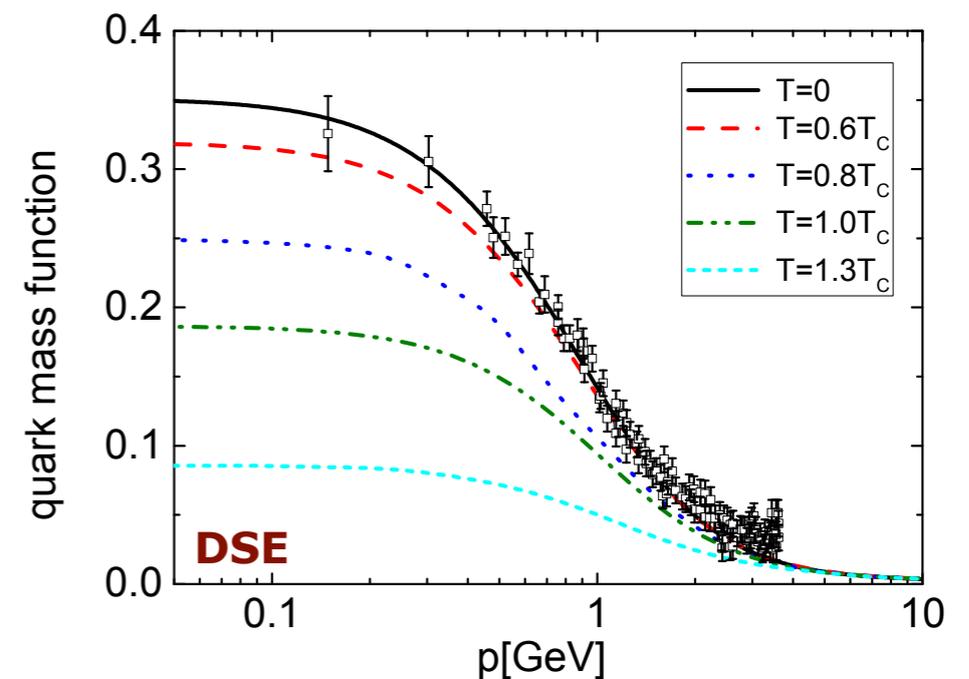
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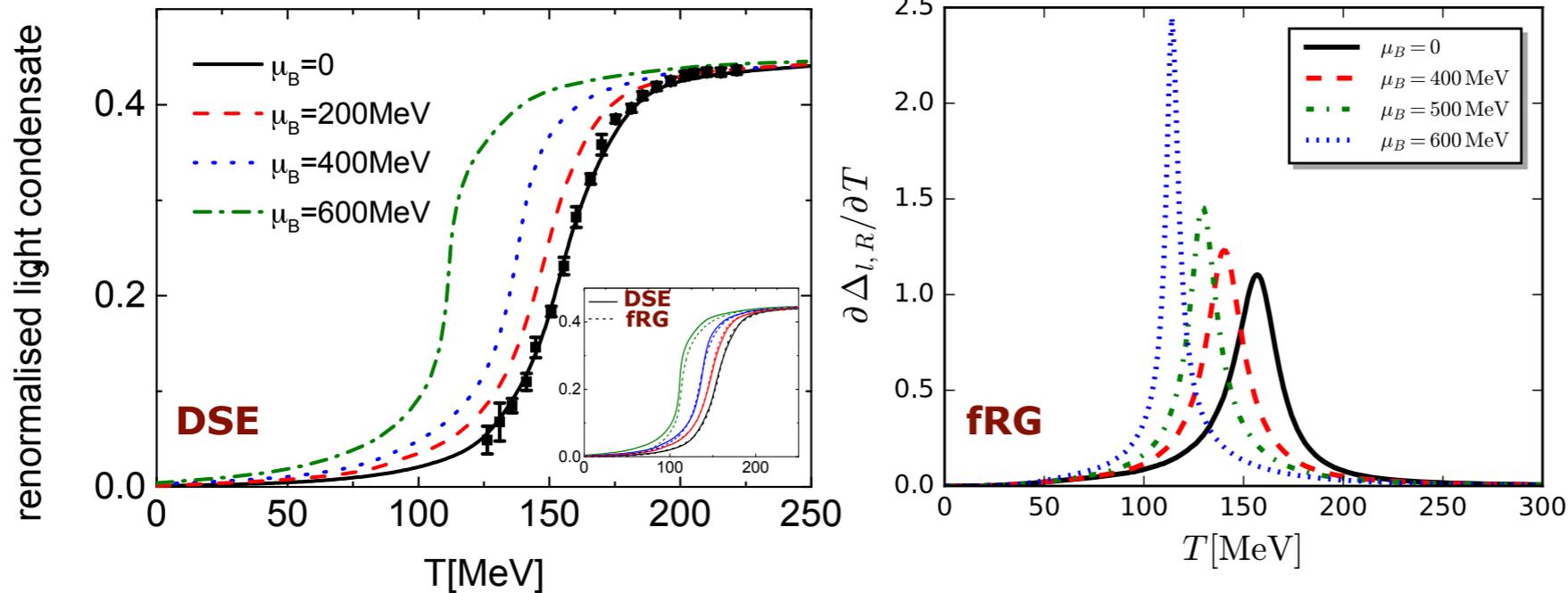
Finite T: Ilgenfritz, JMP, Rothkopf, Trunin, EPJ C78, 127 (201)
(Nf=2+1+1)



QCD at finite density

Chiral order parameter benchmark results at finite T

renormalised condensate



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 talk of C. Fischer

Fischer, Luecker, PLB 718 (2013) 1036

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

Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011

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

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

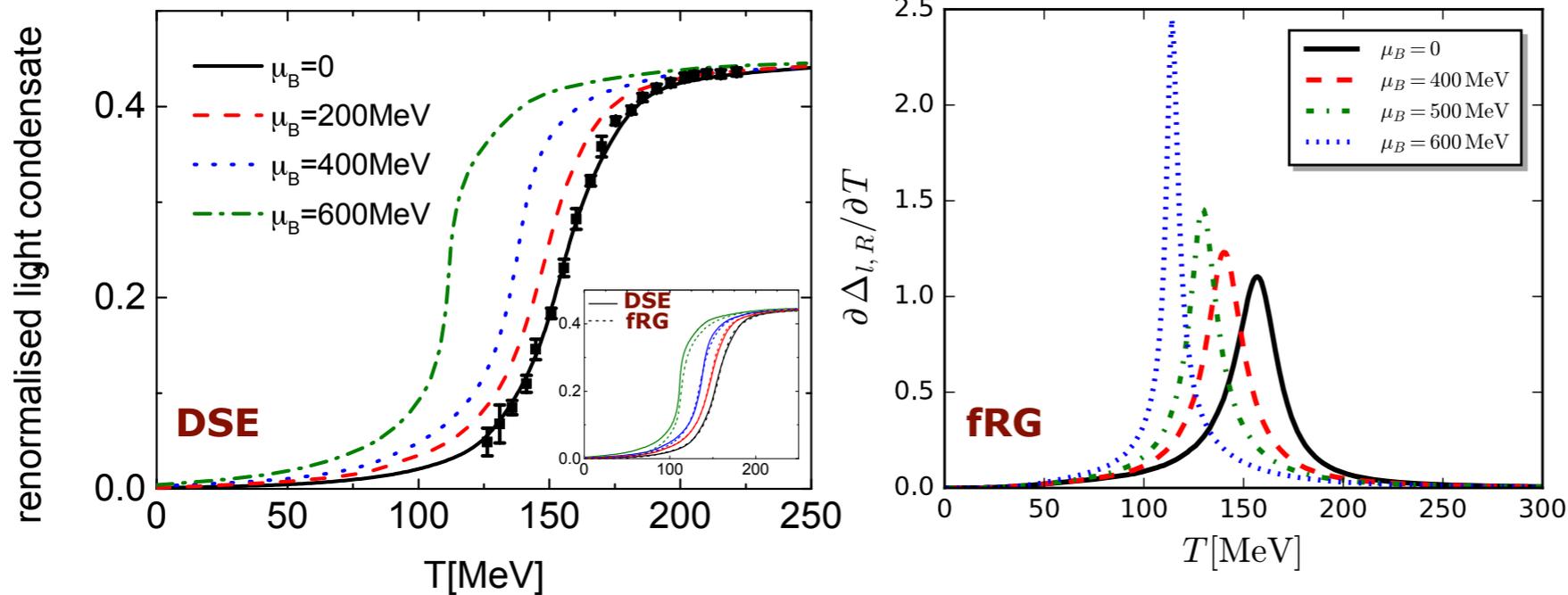
fRG: Fu, JMP, Rennecke, PRD 101, (2020) 054032

DSE: Gao, JMP, arXiv:2010.137005

QCD at finite density

Chiral order parameter benchmark results at finite T

renormalised condensate

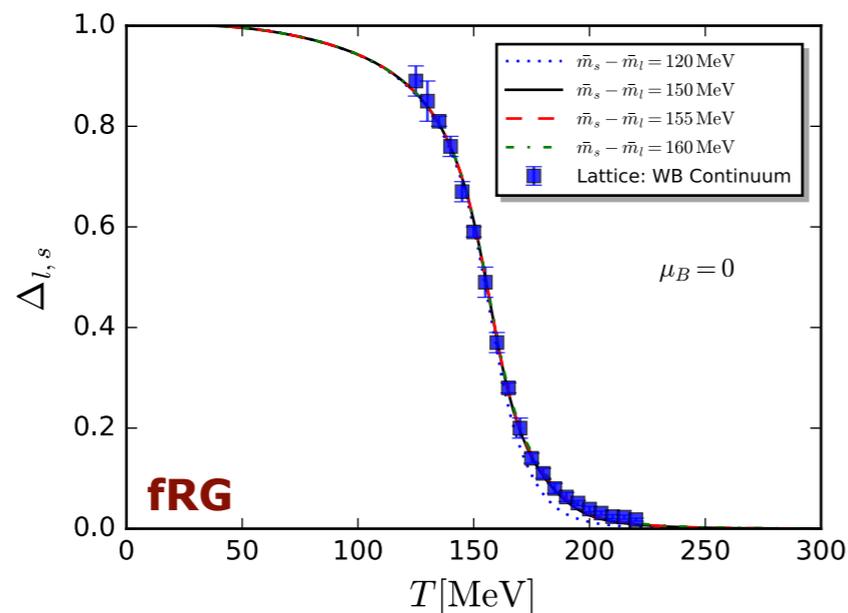


lattice: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, C. Ratti, and K. K. Szabo, JHEP 09, 073 (2010)

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reduced condensate

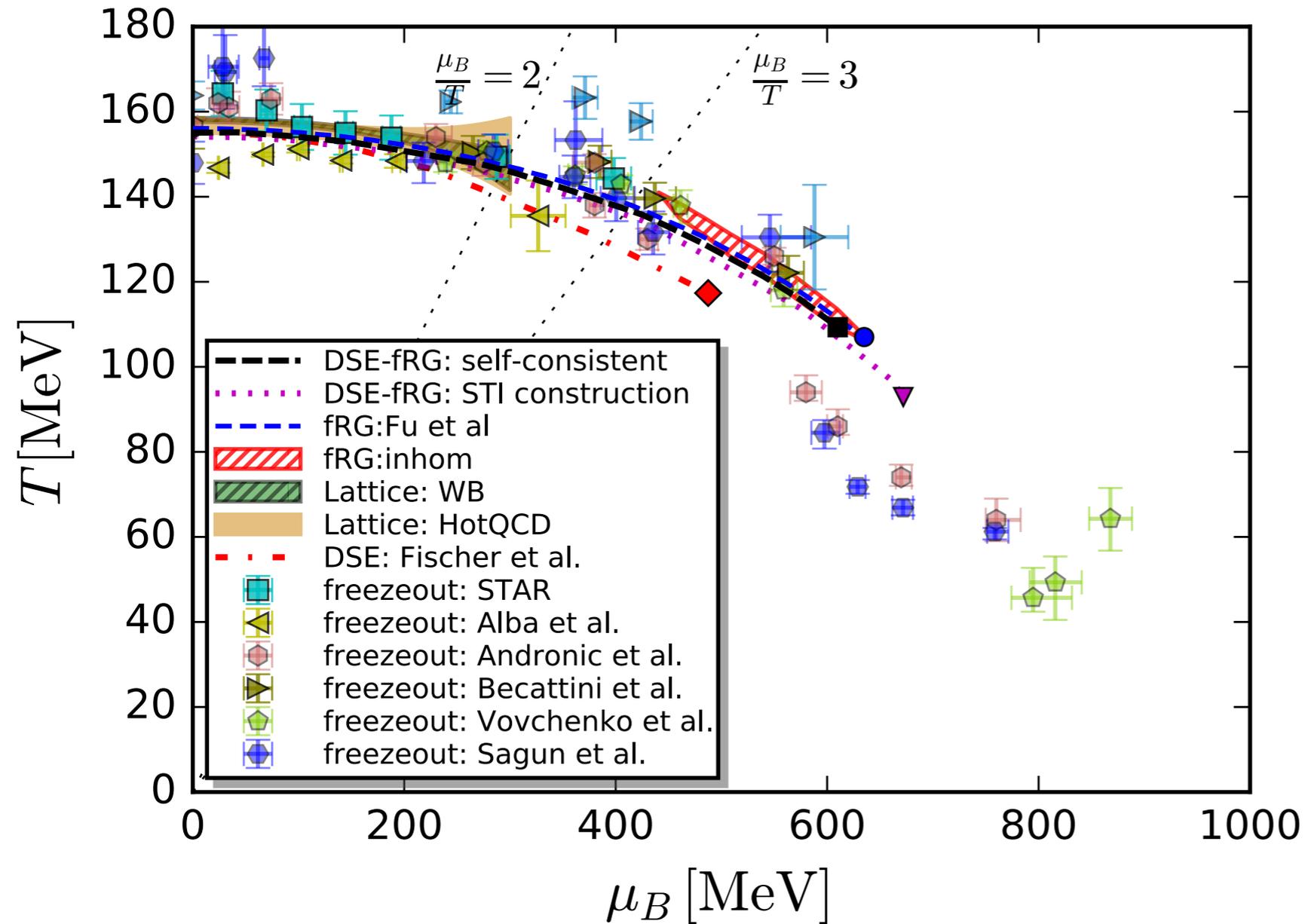


$$\Delta_{l,s}(T, \mu_B) = \frac{\Delta_l(T, \mu_B) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(T, \mu_B)}{\Delta_l(0, 0) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(0, 0)}$$

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

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QCD phase structure



See also talk of C. Fischer

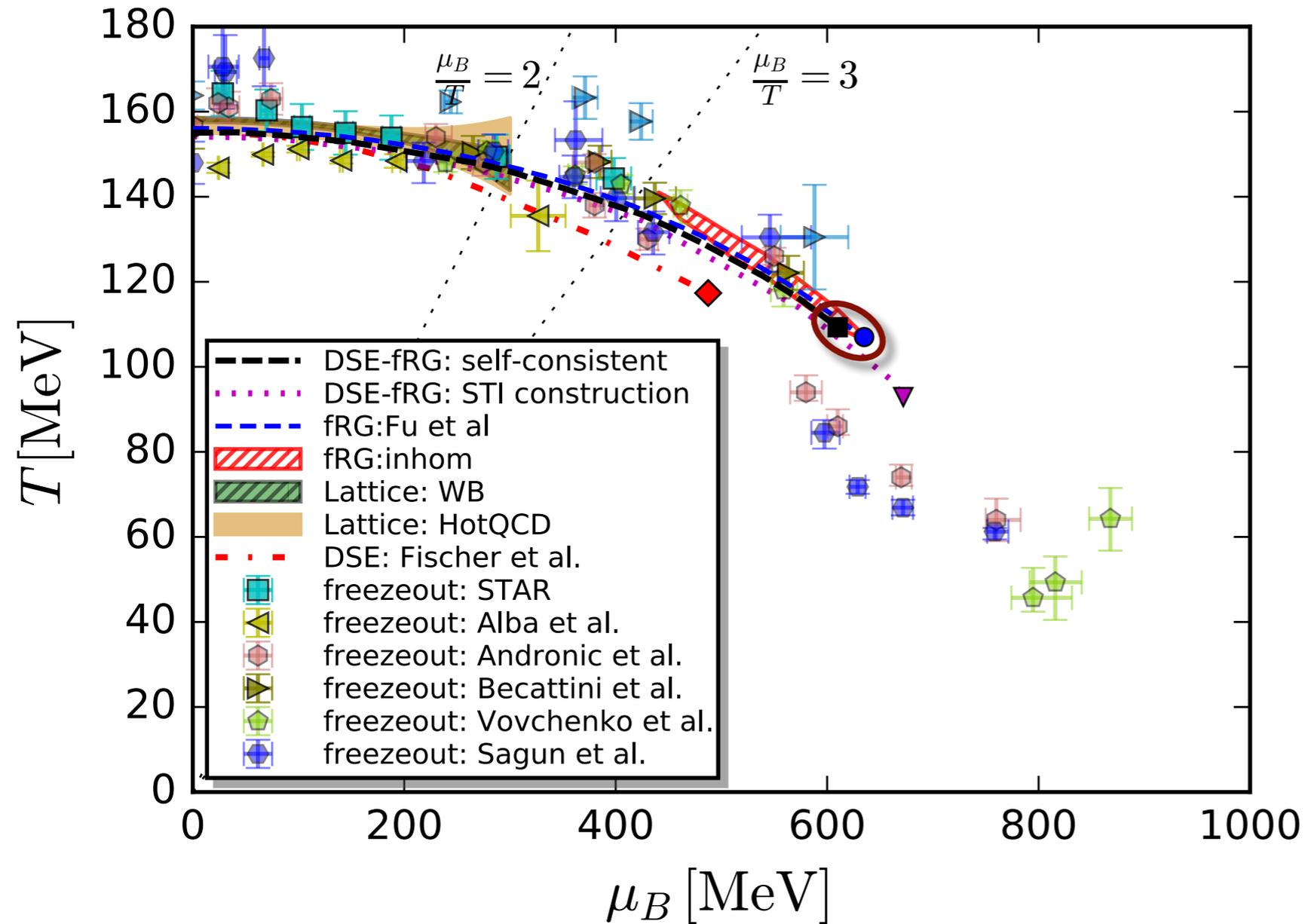
Fischer, Luecker, Welzbacher, PRD 90 (2014) 034022

Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011

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

DSE: Gao, JMP, arXiv:2010.137005

QCD phase structure



CEP fRG-DSE

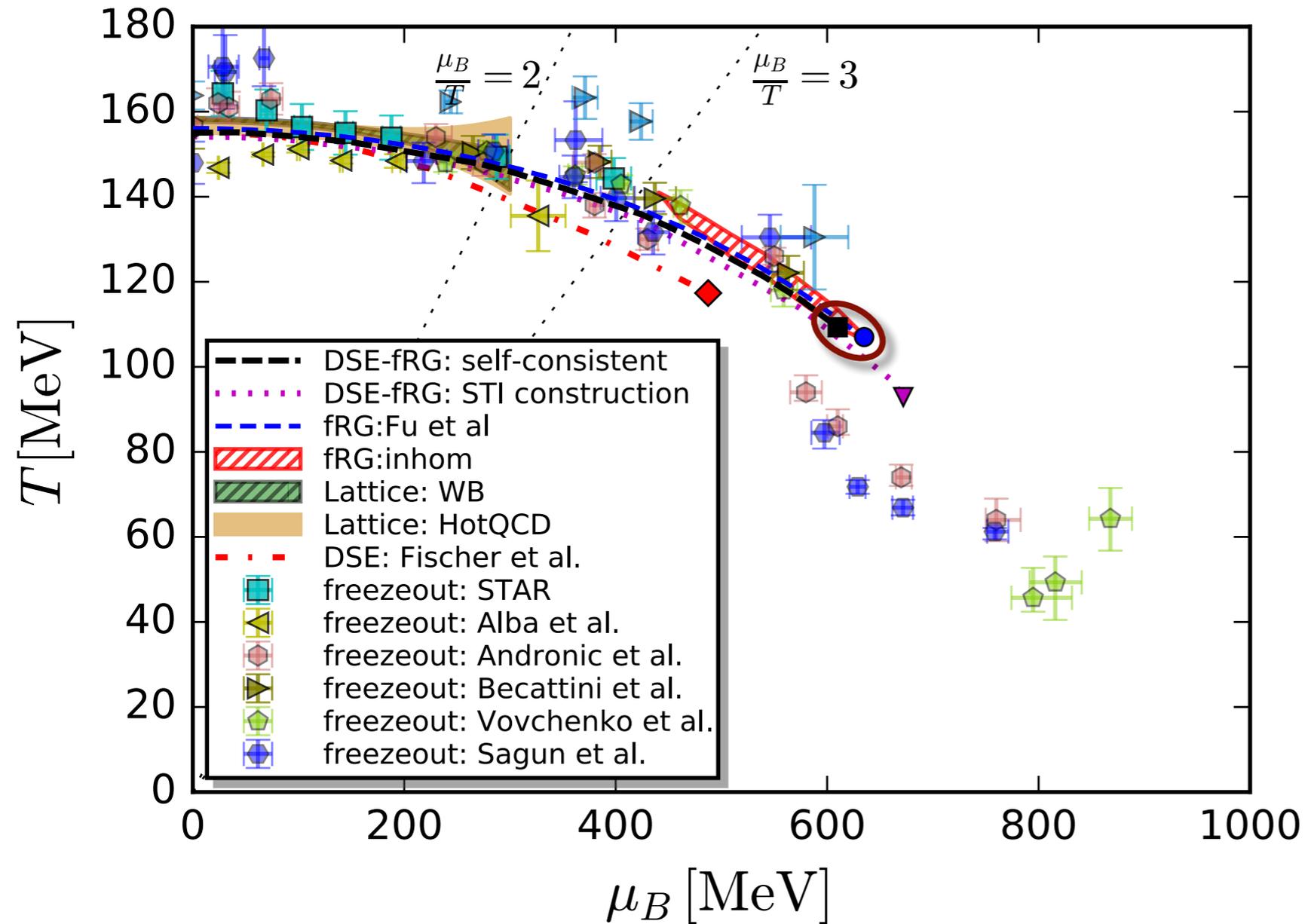
$$(T, \mu_B)_{\text{CEP}} = (107, 635) \text{ MeV}$$

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

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QCD phase structure



curvature fRG-DSE

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

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

curvature lattice

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

WB, PLB 751 (2015) 559

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

hotQCD, PLB 795 (2019) 15

CEP fRG-DSE

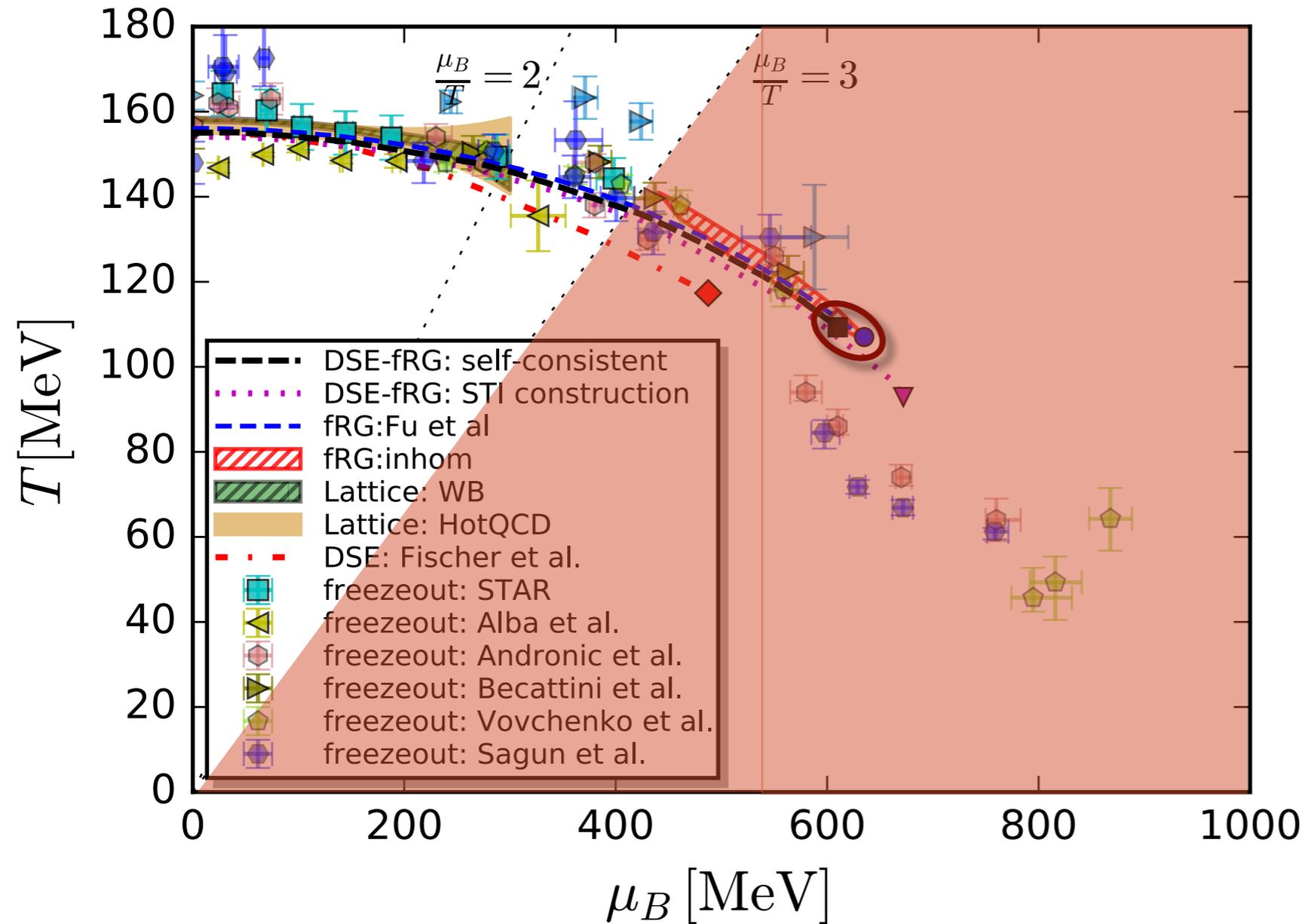
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WB, PLB 751 (2015) 559

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hotQCD, PLB 795 (2019) 15

area beyond quantitative reliability bound

CEP fRG-DSE

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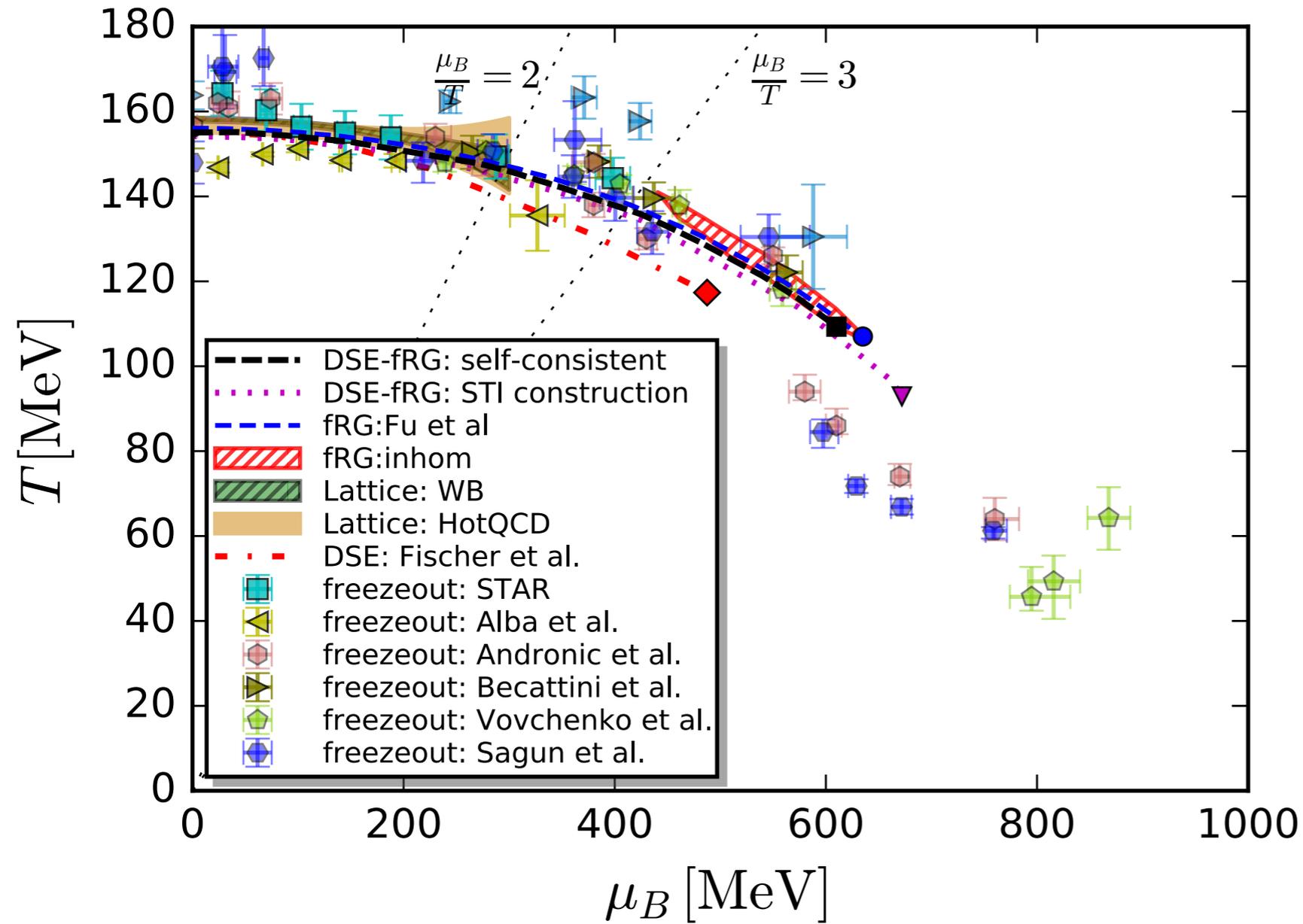
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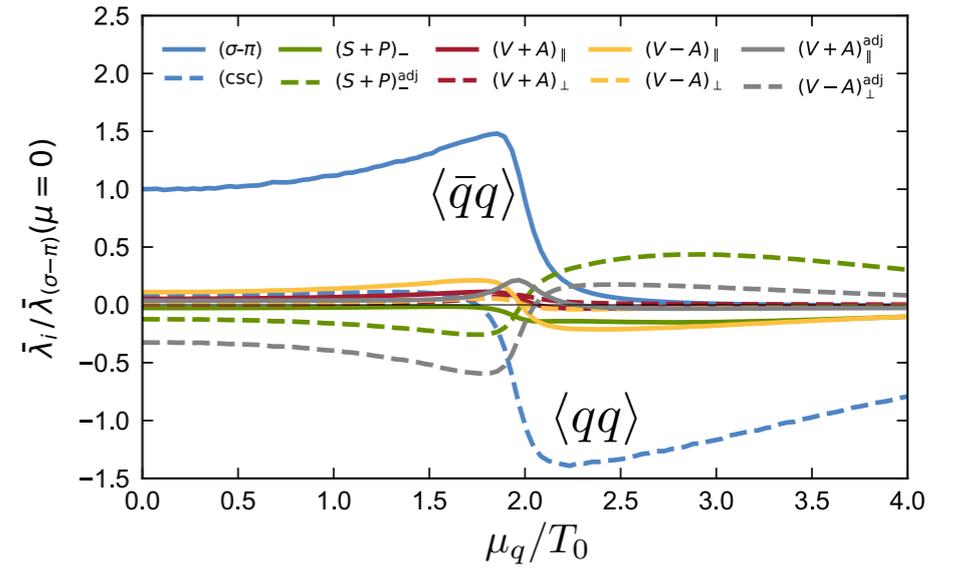
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QCD phase structure

Estimate for CEP



Dominant channels I (fRG)



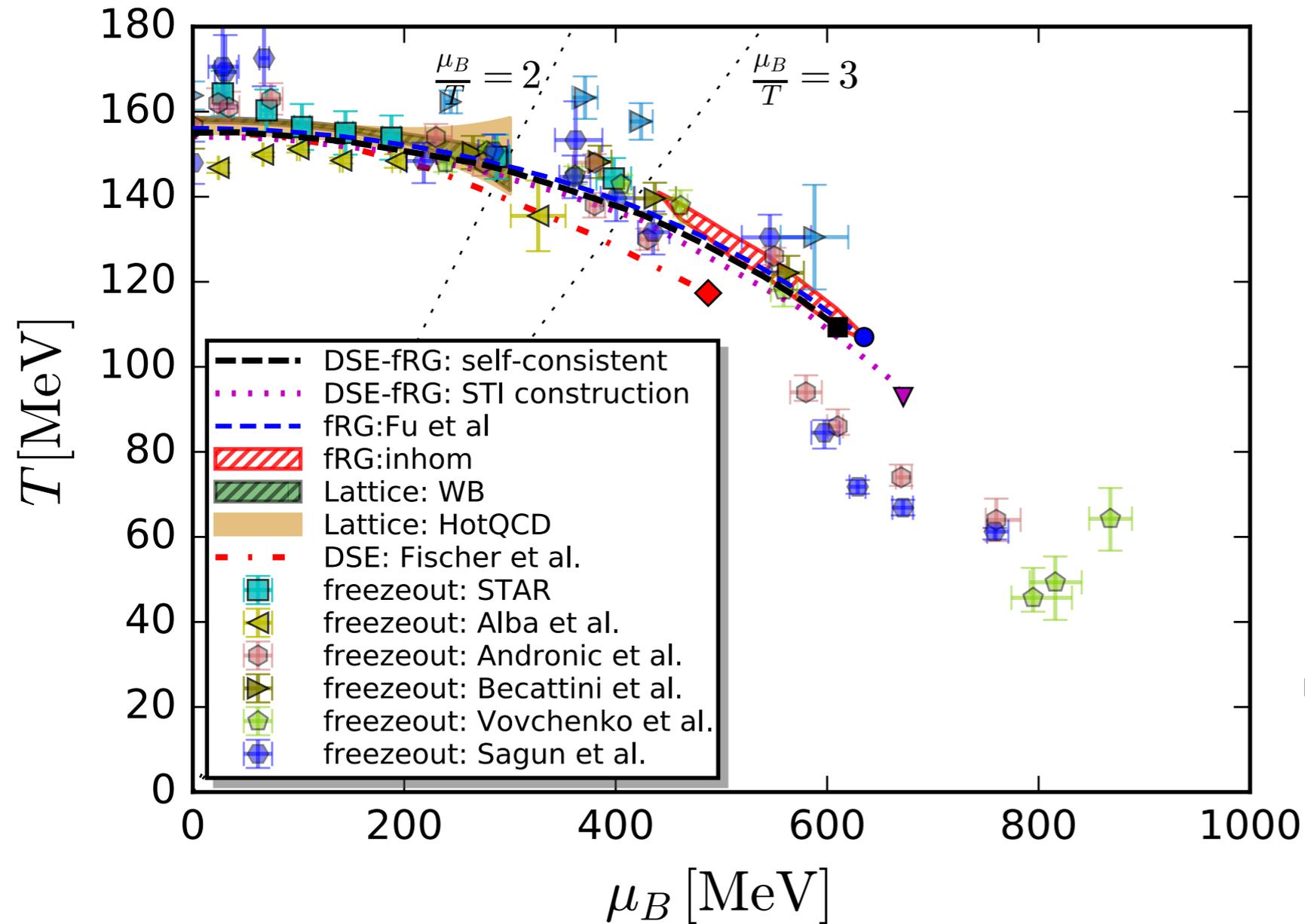
Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

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

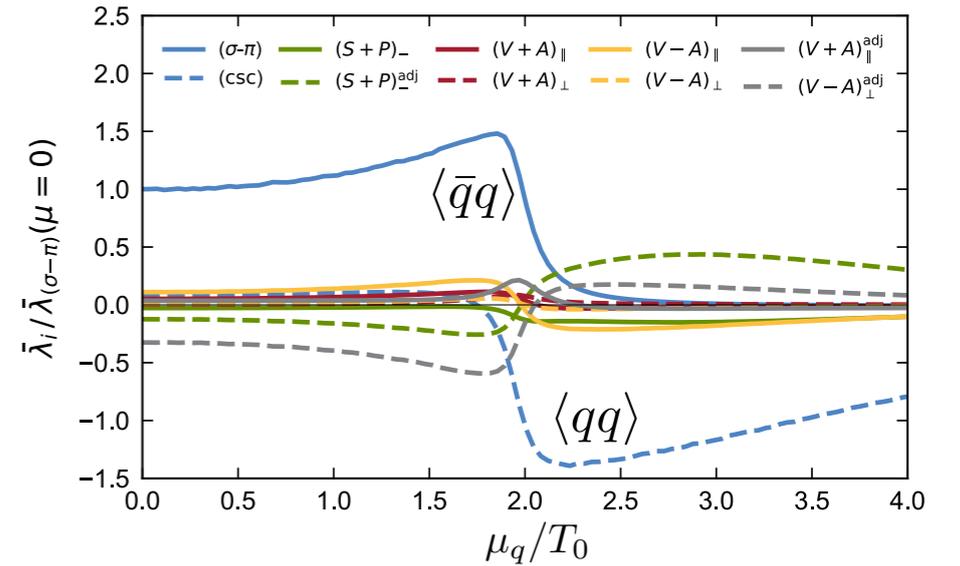
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QCD phase structure

Estimate for CEP



Dominant channels I (fRG)



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

Dominant channels II (DSE)

Minor effects of baryons on phase boundary

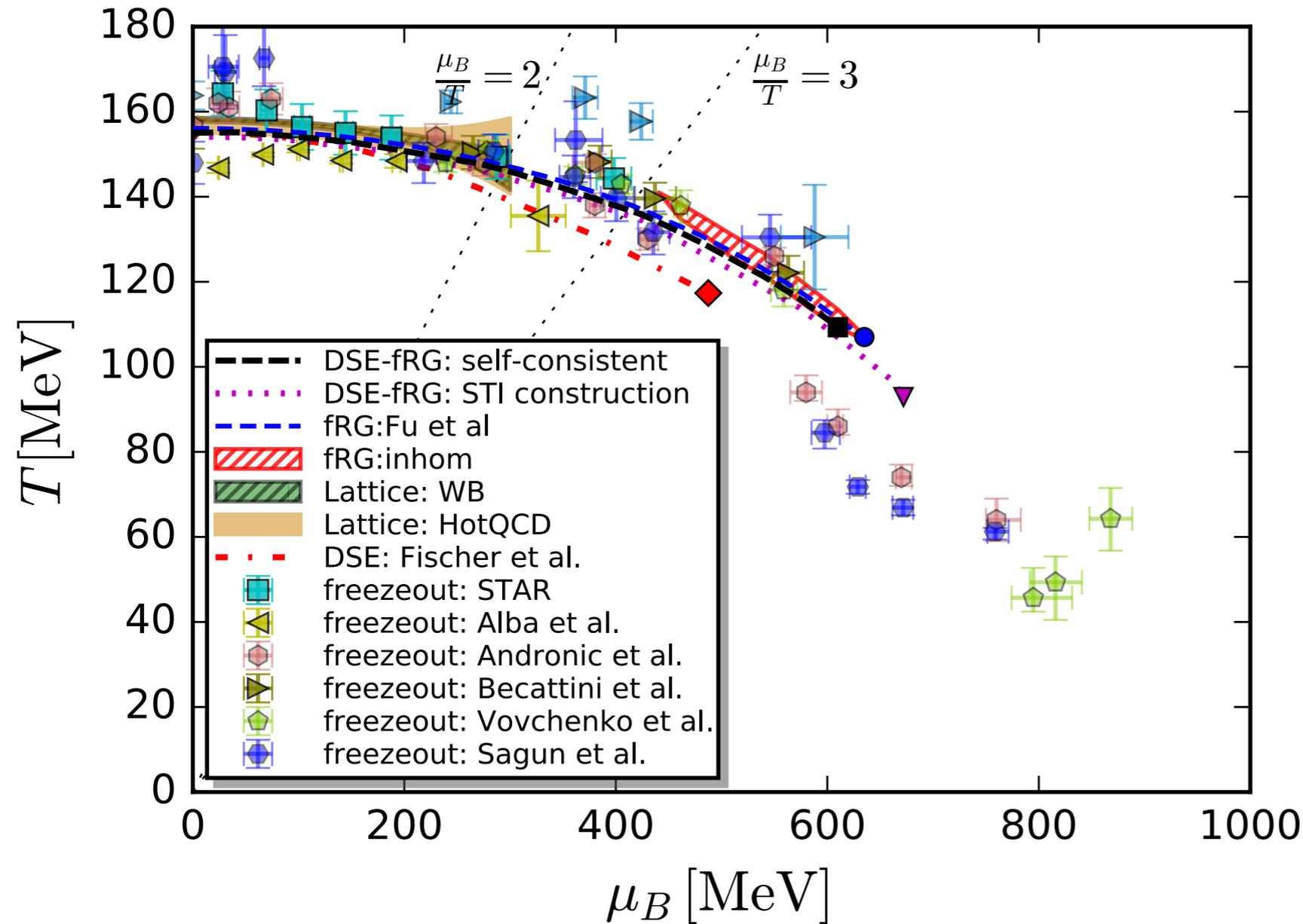
Eichmann, Fischer, Welzbacher, PRD 93 (2016) 034013

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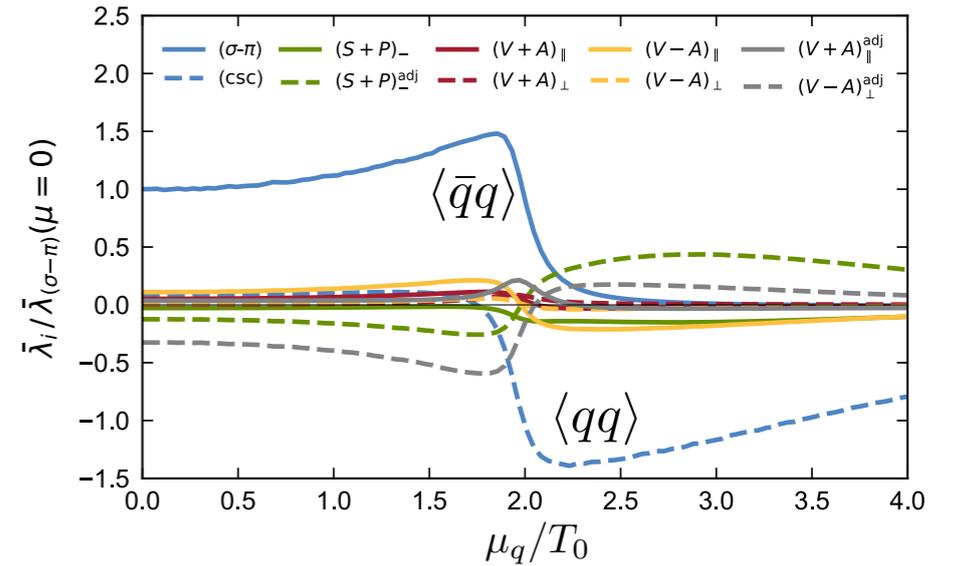
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QCD phase structure

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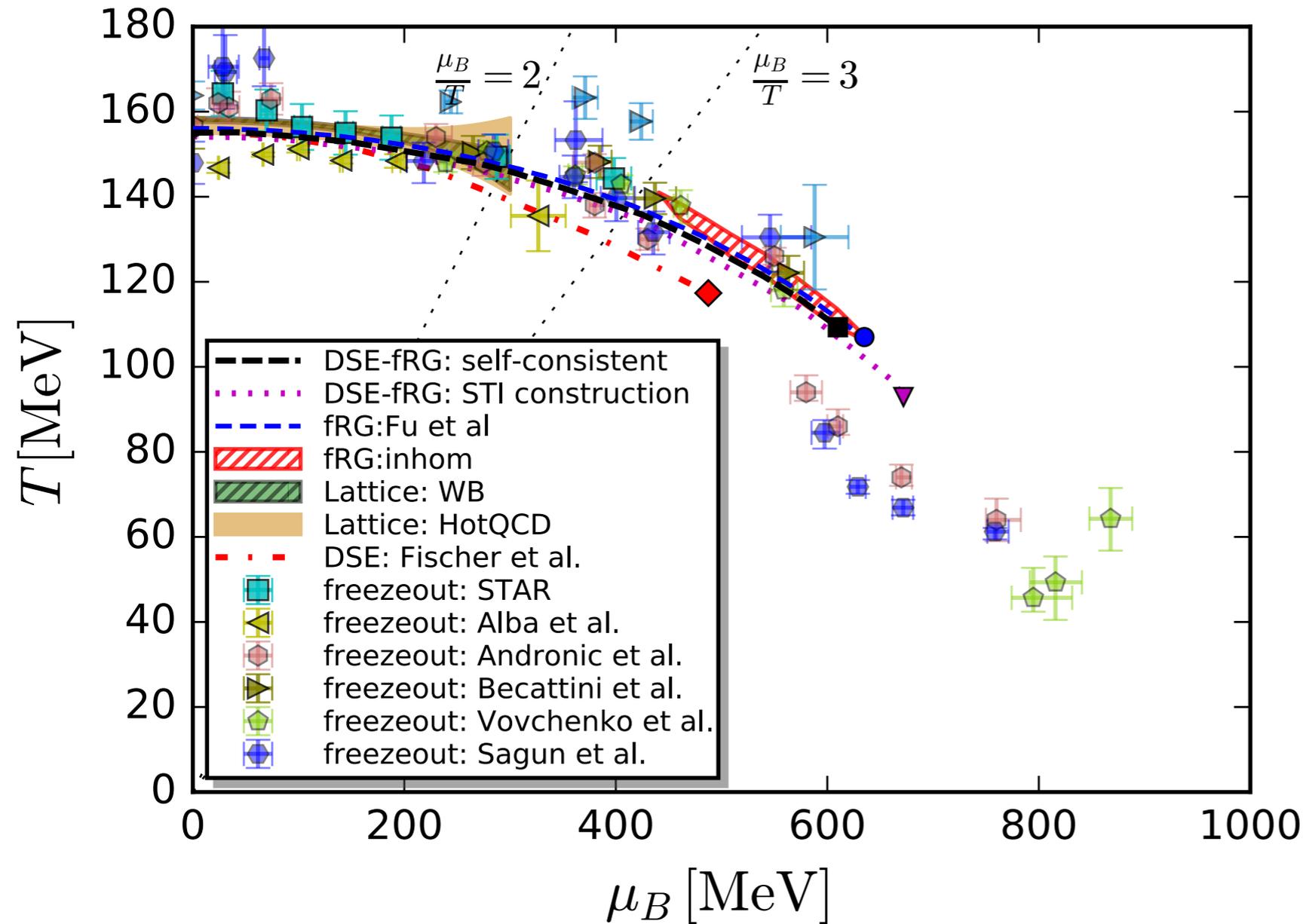
I+II → Fierz-complete computation

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

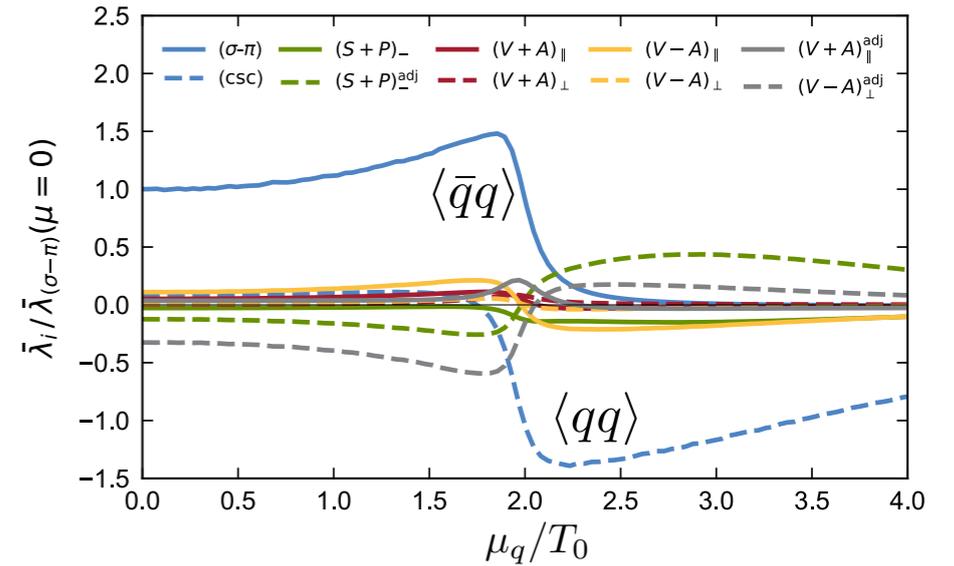
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QCD phase structure

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'Inhomogeneous' phase

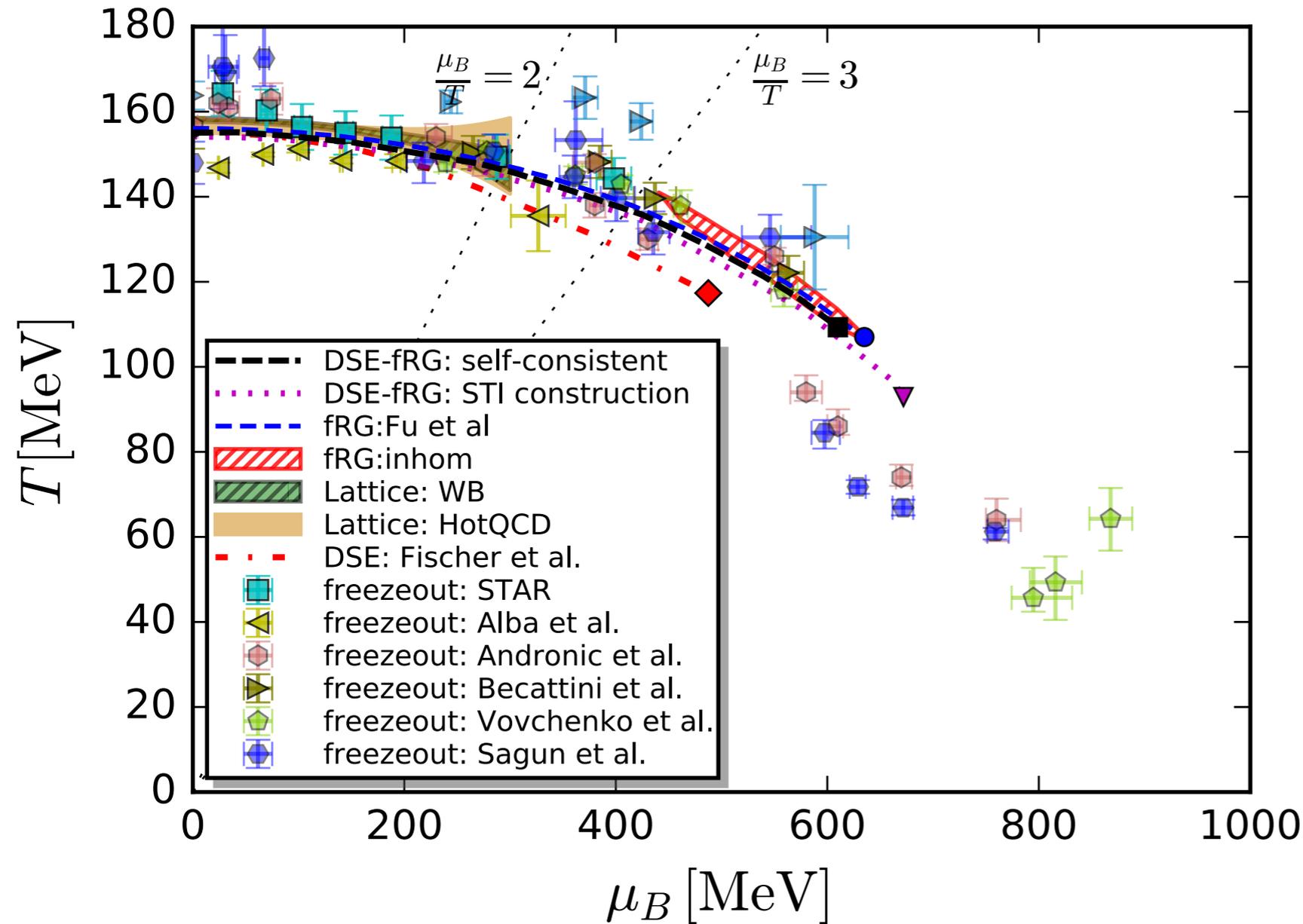
▨ : Pion dispersion has minimum at non-vanishing spatial momentum

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

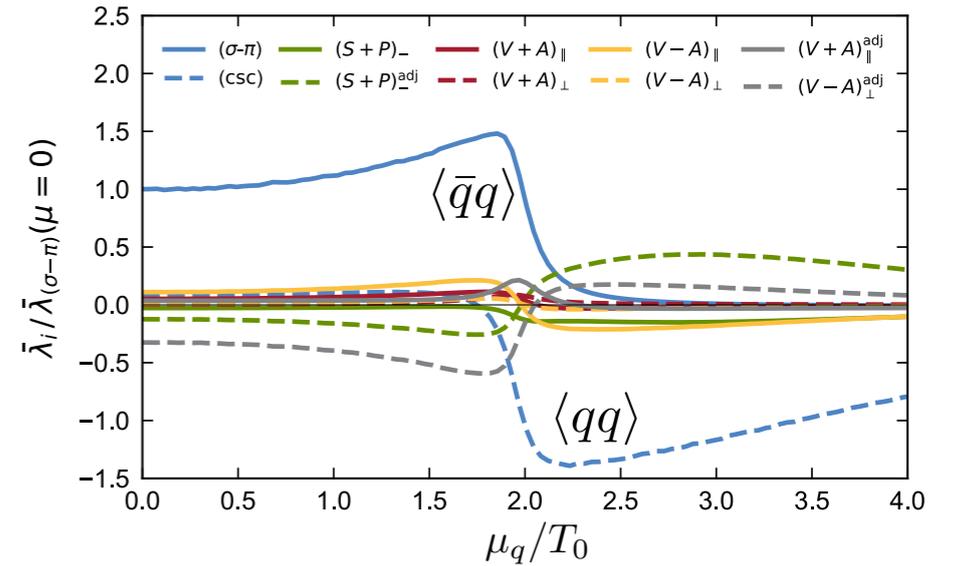
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QCD phase structure

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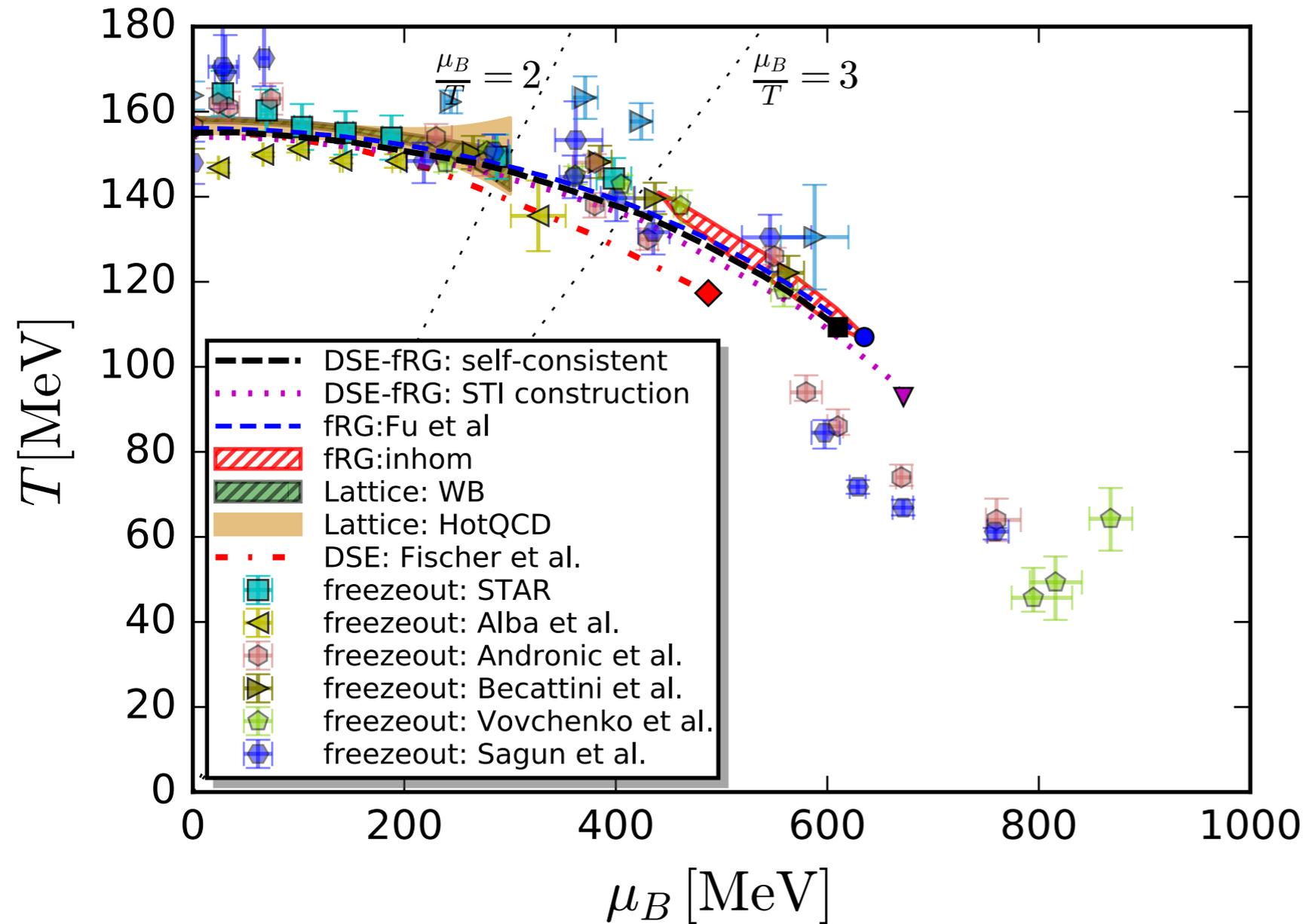
→ Non-trivial background

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

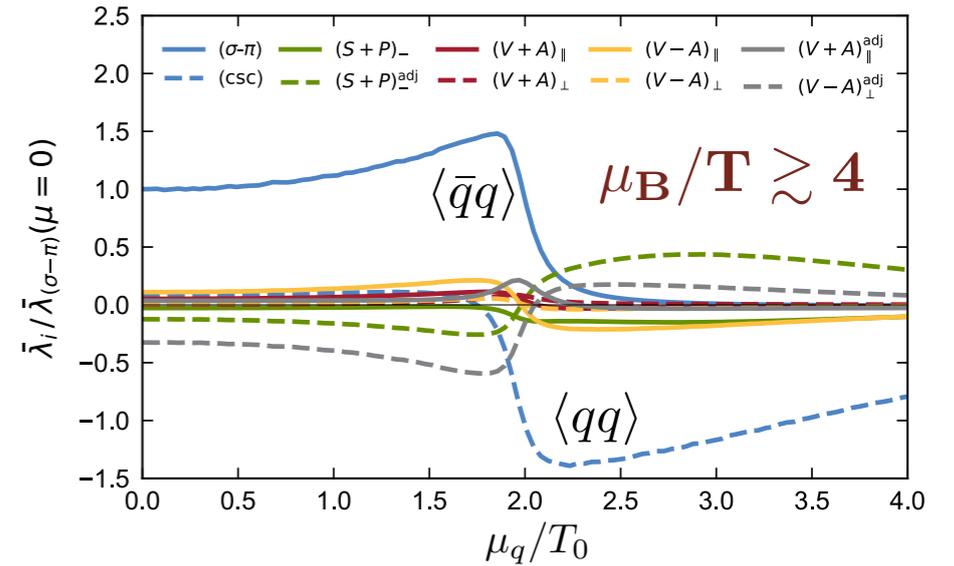
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QCD phase structure

Estimate for CEP



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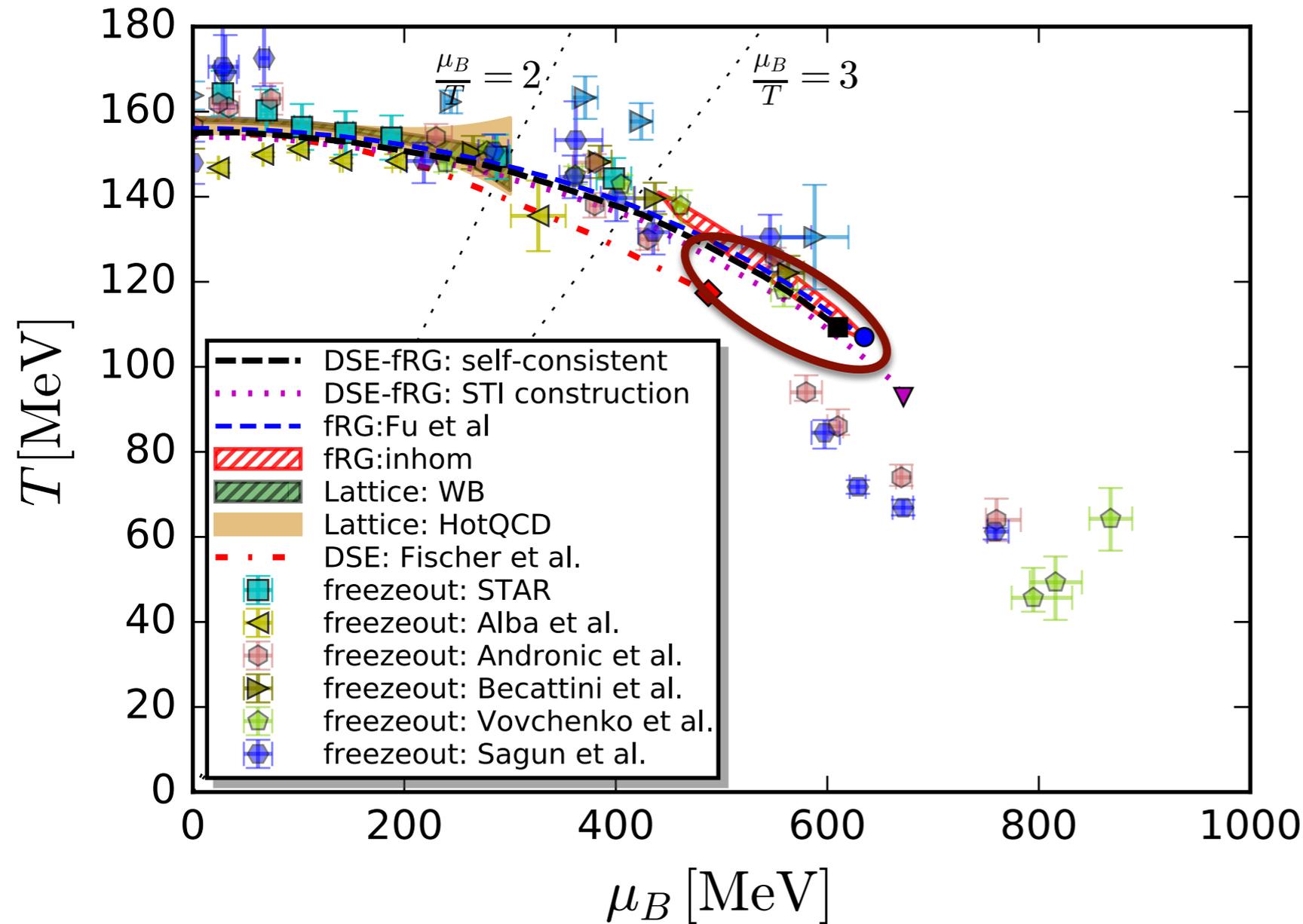
$\mu_B/T \gtrsim 4$

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

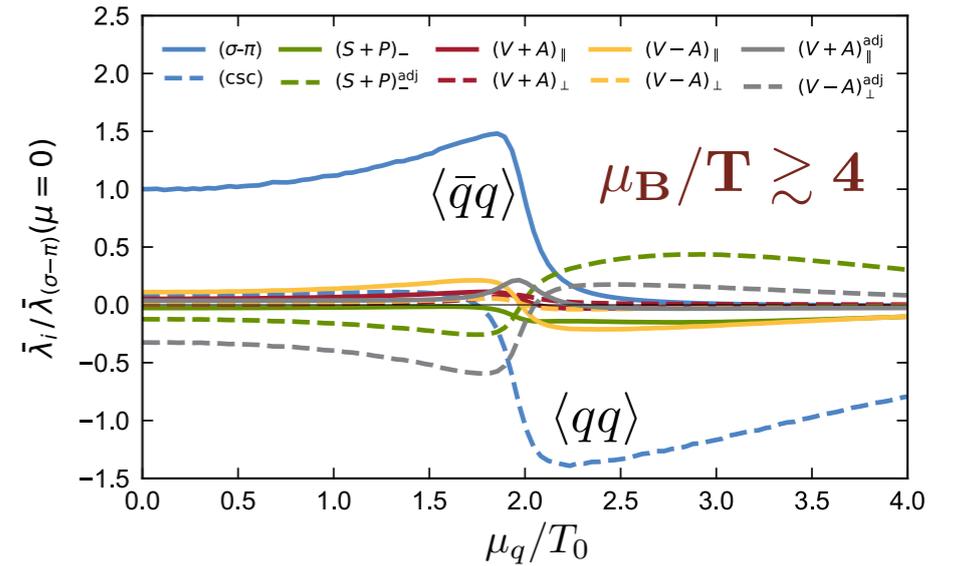
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CEP-estimate fRG-DSE

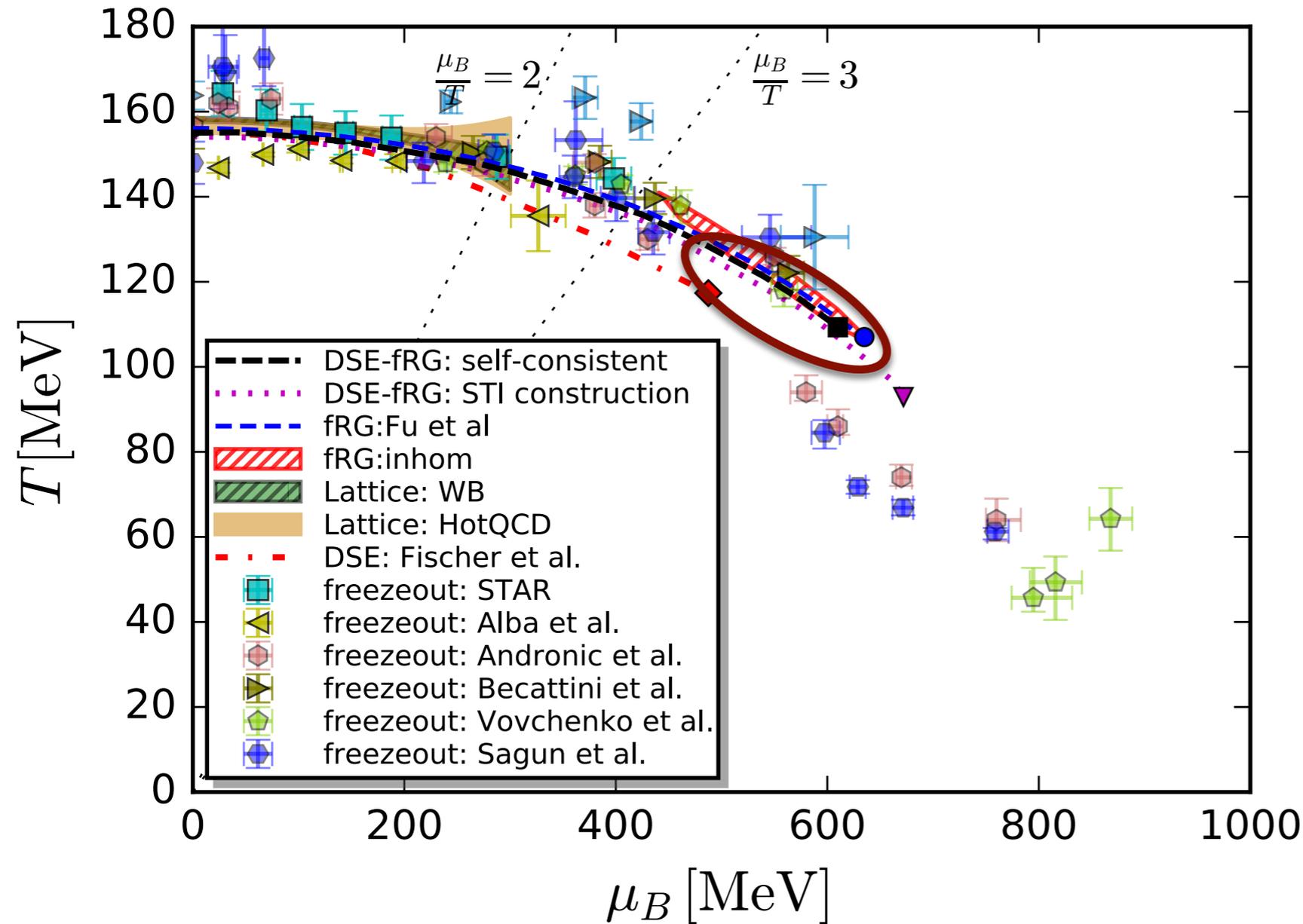
$$(135, 450) \text{ MeV} \lesssim (T_{\text{CEP}}, \mu_{B_{\text{CEP}}}) \lesssim (100, 650) \text{ MeV}$$

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

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QCD phase structure

Estimate for CEP

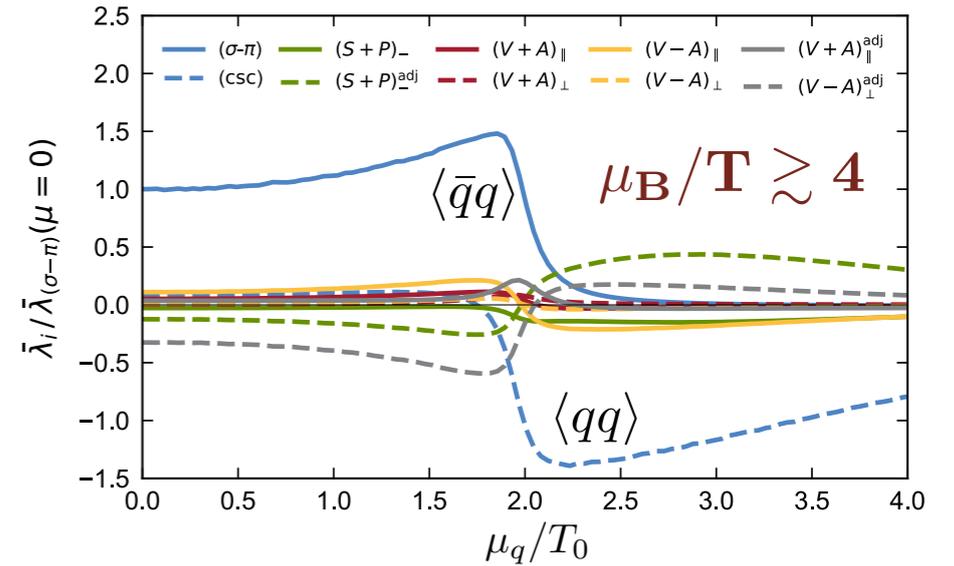


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Stay tuned!

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

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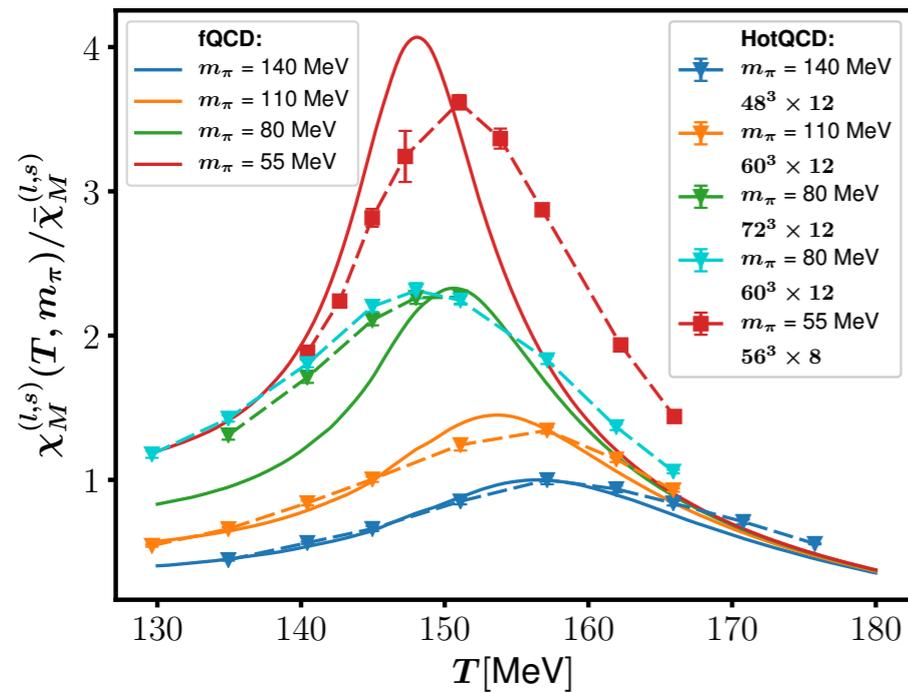
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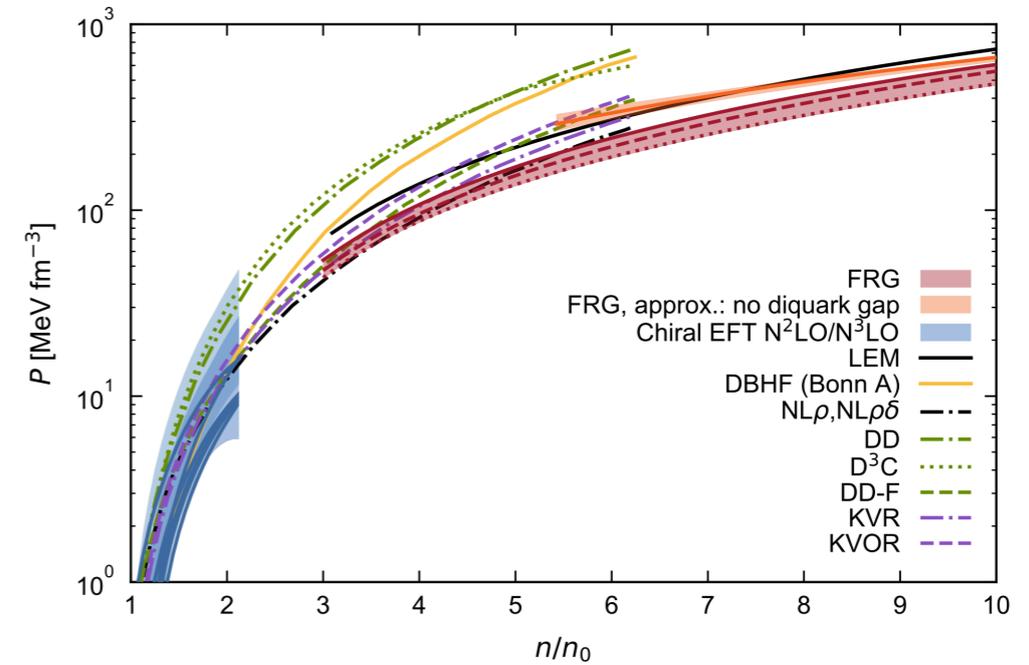
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Some applications (fQCD)

Magnetic EoS

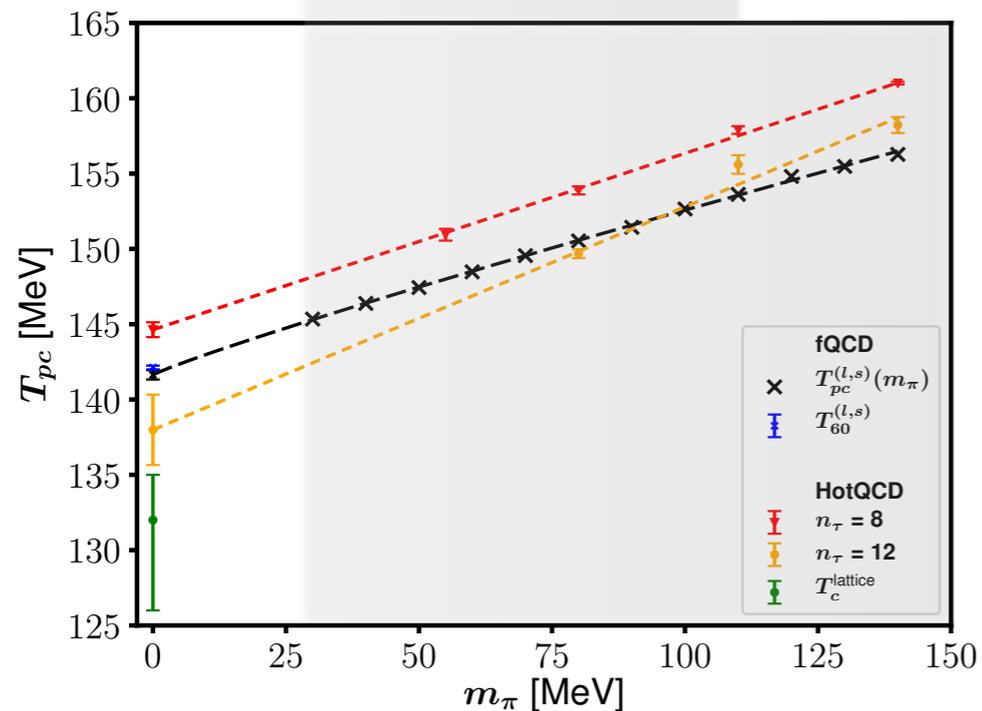


EoS of symmetric nuclear matter



Leonhardt, Pospiech, Schallmo, Braun, Drischler, Hebeler, Schwenk, PRL 125 (2020) 142502

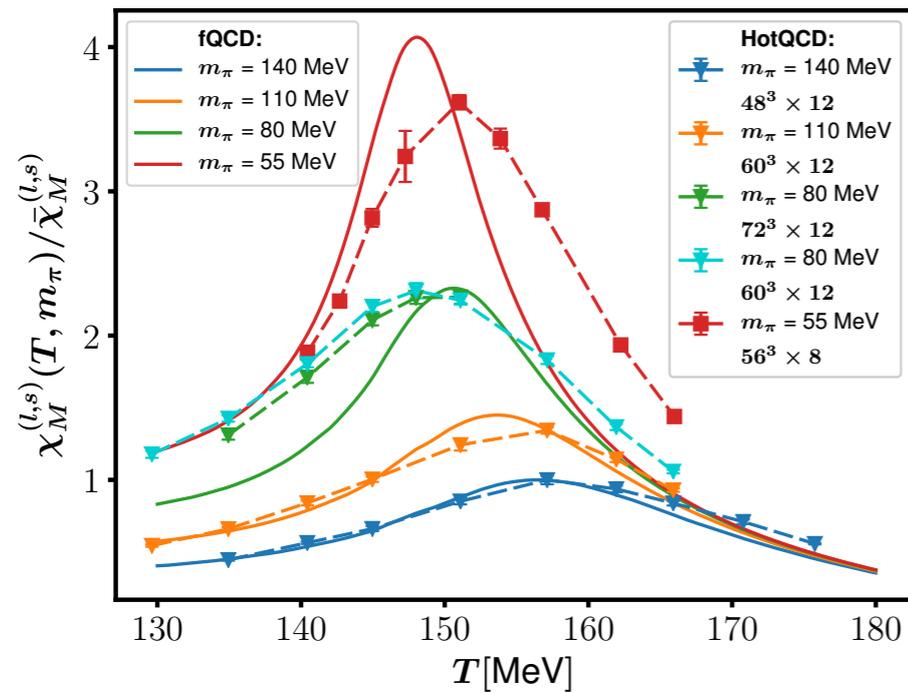
No critical scaling



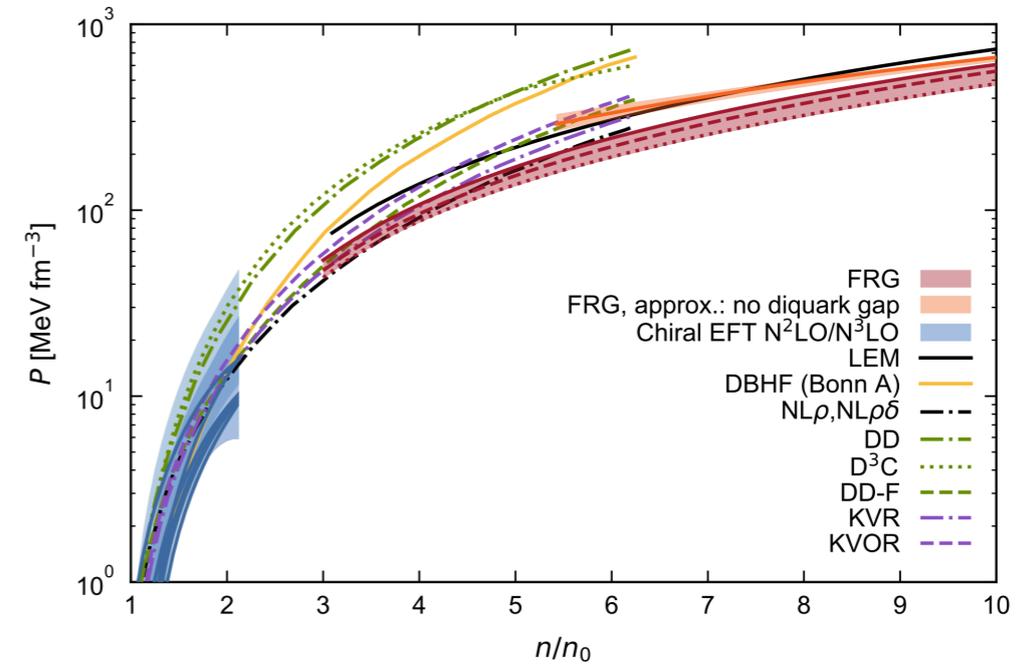
Braun, Fu, JMP, Rennecke, Rosenblüh, Yin, PRD 102 (2020) 056010

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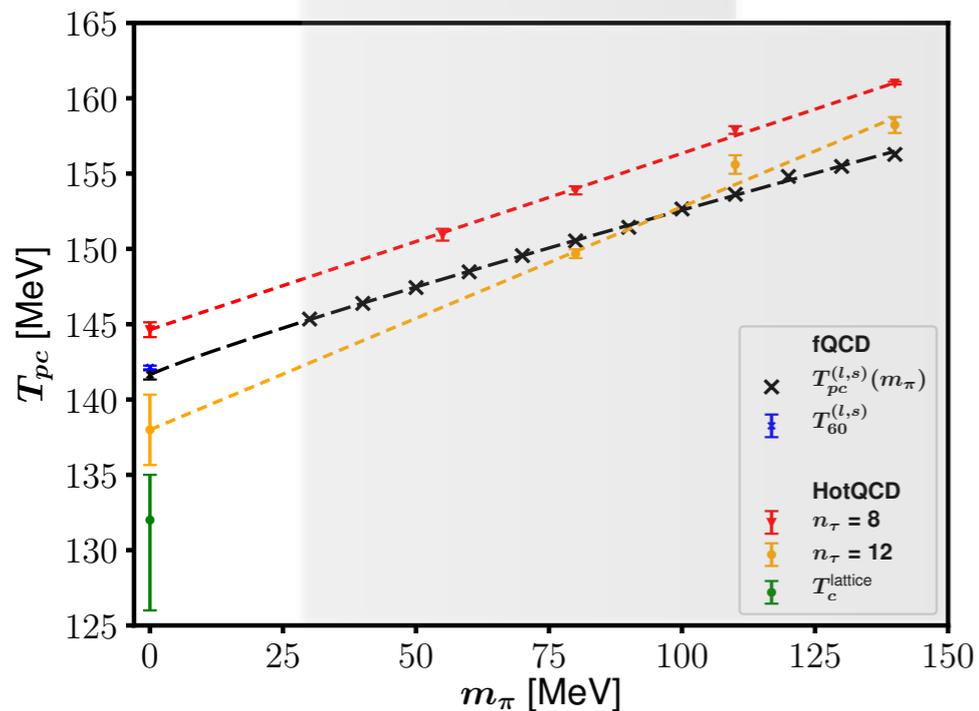


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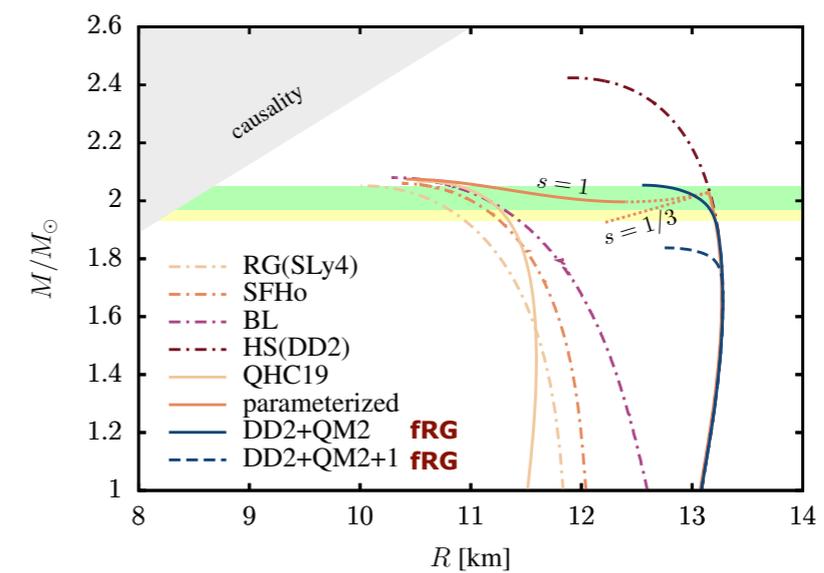
Leonhardt, Pospiech, Schallmo, Braun, Drischler, Hebeler, Schwenk, PRL 125 (2020) 142502

No critical scaling



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

Recent fRG work on EoS in cold and dense matter



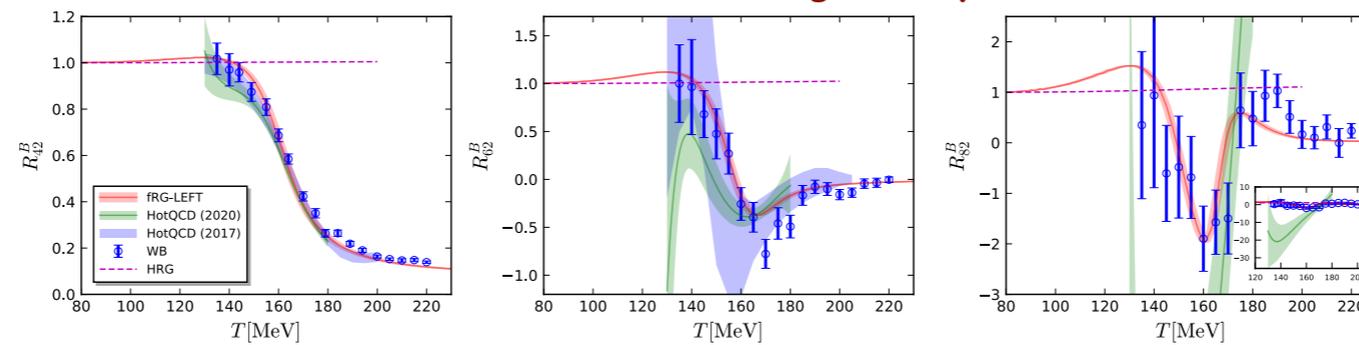
Otto, Oertel, Schaefer, PRD 101 (2020) 10, 103021; 2007.07394

Some applications (fQCD)

Fluctuation of conserved charges

Benchmark at vanishing density

QCD-assisted LEFT



Builds on

Fu, JMP, PRD 93 (2016) 091501

Fu, JMP, Schaefer, Rennecke, PRD 94 (2016) 116020

Strangeness

Fu, JMP, Rennecke, SciPost Phys. Core 2, 002 (2020)

PRD 100 (2019) 11, 111501

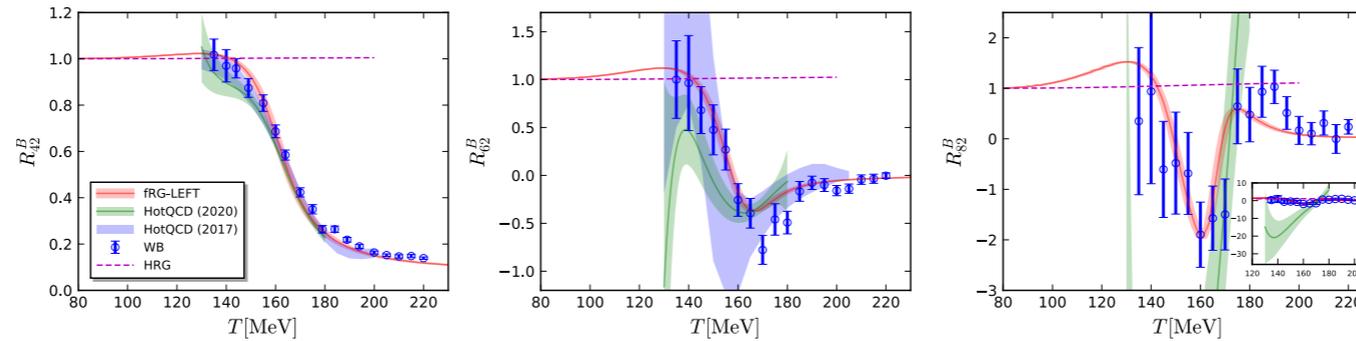
Wen, Huang, Fu, PRD 99 (2019) 094019

Fu, Luo, JMP, Rennecke, Wen, Yin, in preparation

Some applications (fQCD)

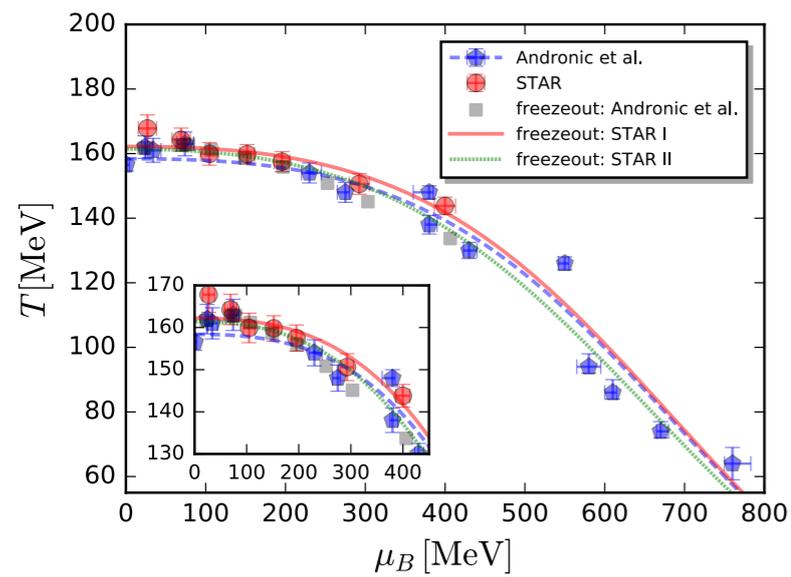
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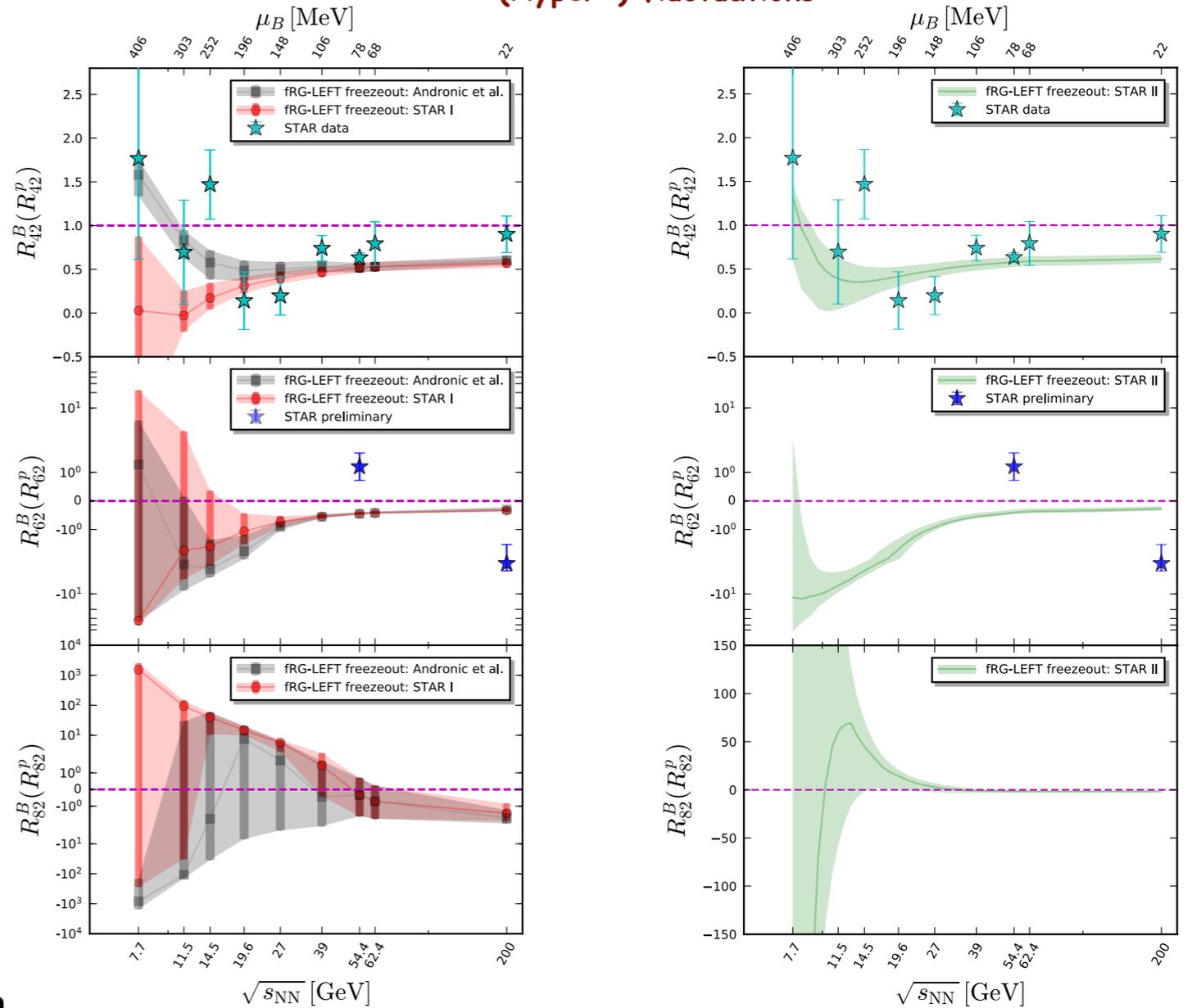


QCD-assisted LEFT

Freezeout curve



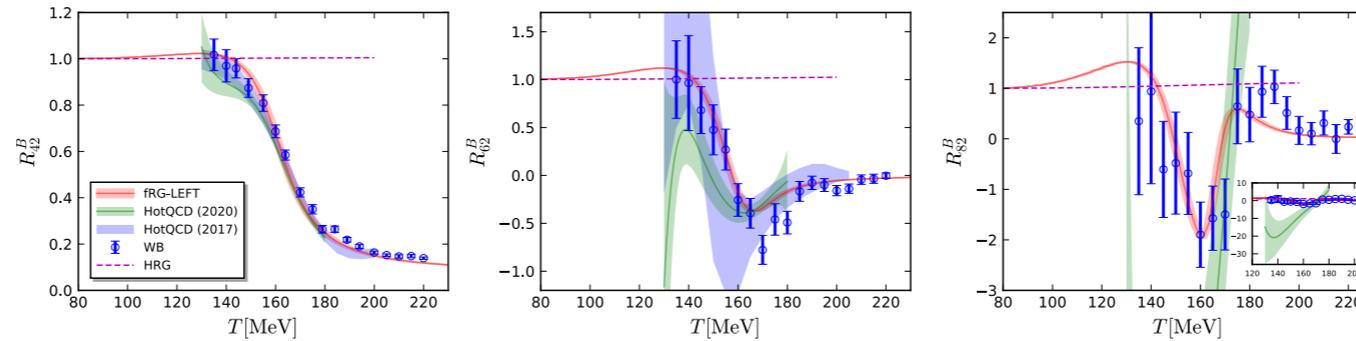
(Hyper-) fluctuations



Some applications (fQCD)

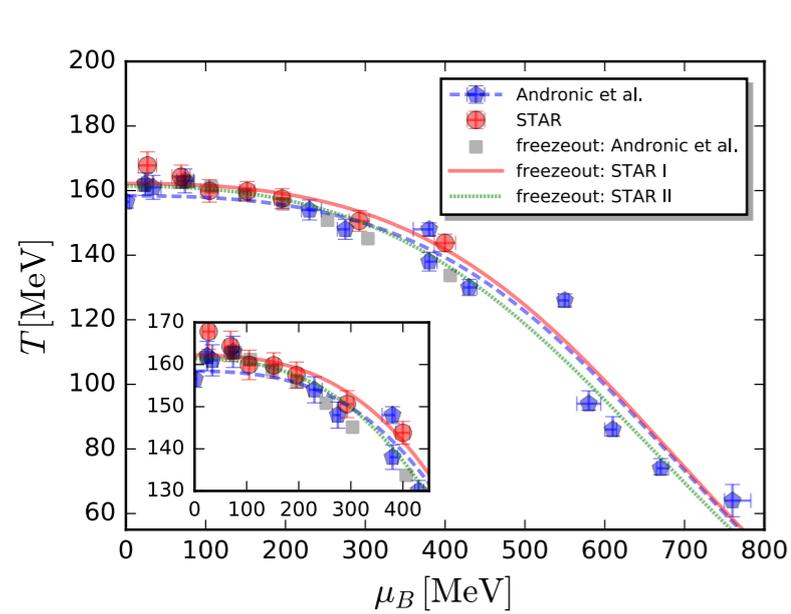
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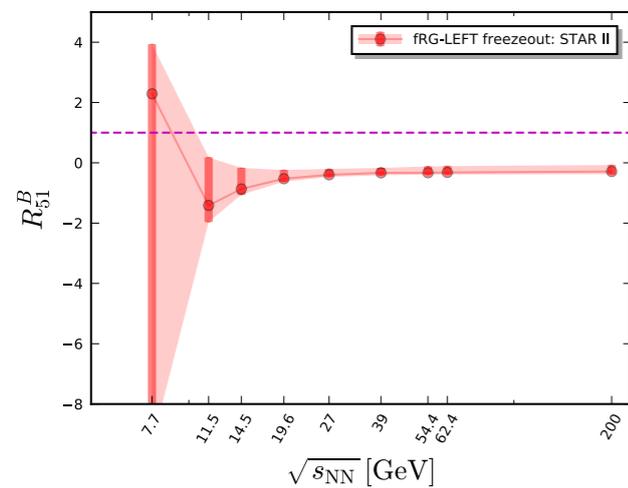
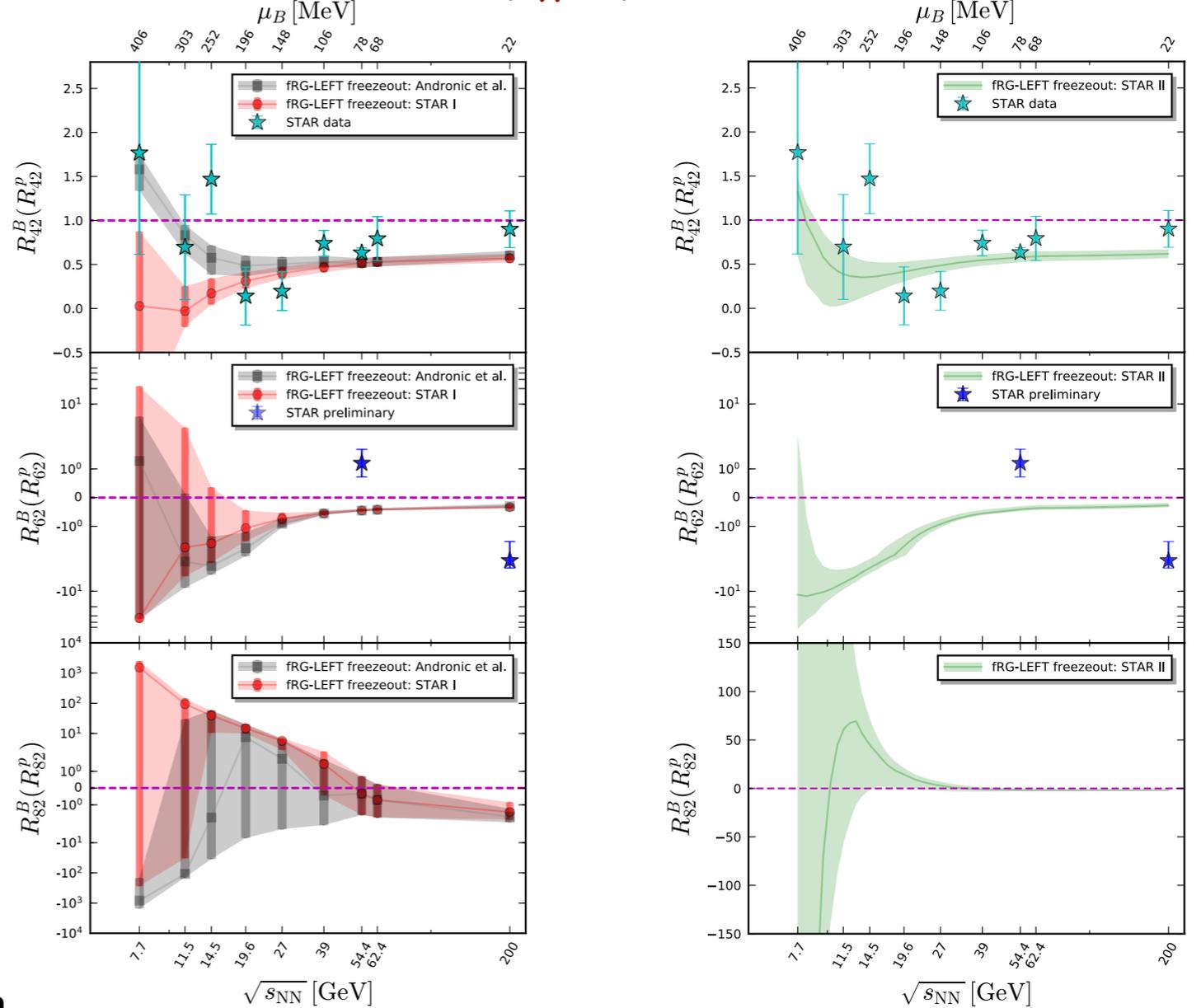


QCD-assisted LEFT

Freezeout curve



(Hyper-) fluctuations



Summary & Outlook

- **Towards apparent convergence in functional approaches to QCD**
- **Results & predictive power for the phase structure of QCD**
 - **Observables: quark condensates, fluctuations of conserved charges**
- **Towards quantitative precision at high densities**
 - **Systematic improvements under way for $\mu_B/T \gtrsim 3$**

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- **Transport, hydro, and critical region**

- **Real-time correlation functions**
- **Transport at finite μ & T**
- **Transport coefficients**

