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JUSTUS-LIEBIG-
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GIESSEN

HFHF
Helmholtz Forschungsakademie Hessen für FAIR

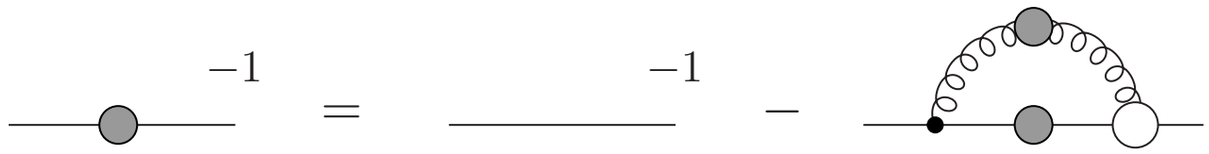
Trento, 2023

Mesons effects on the QCD phase diagram at physical and unphysical quark masses

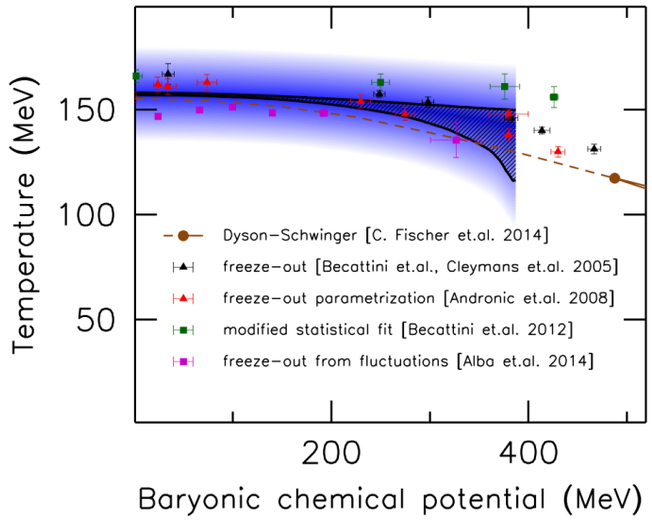
Gunkel, CF, Isserstedt, EPJA 55 (2019) no 9, 169
Gunkel, CF, EPJA 57 (2021) no 4, 147
Gunkel, CF, PRD 104 (2021) 5, 054022
Bernhardt, CF, arXiv: 2305.01434
Bernhardt, CF, in preparation

Overview

1.Introduction

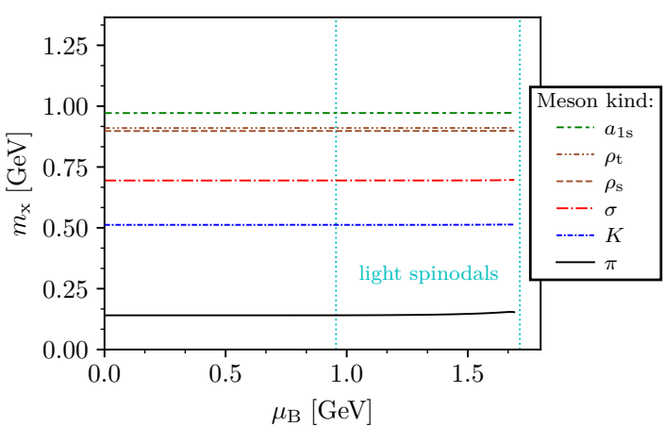


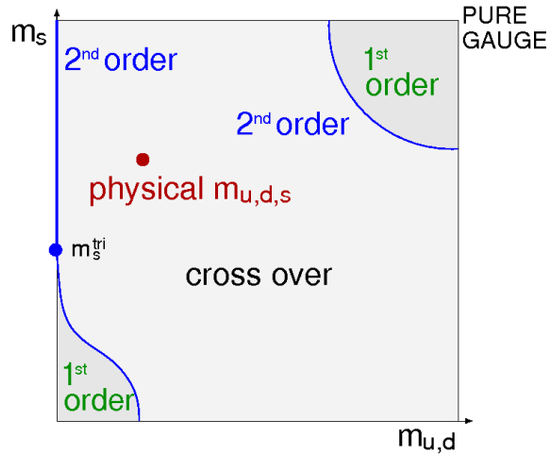
2.Mesons in vacuum



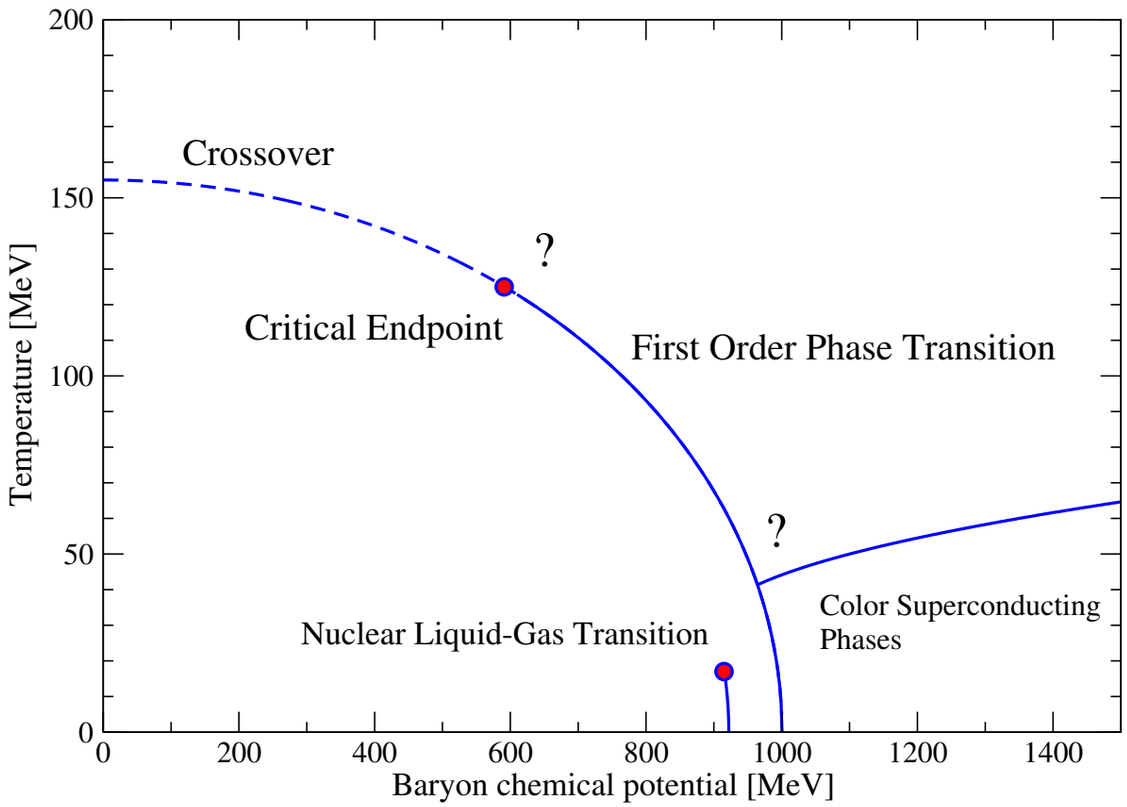
3.QCD phase diagram and the CEP

4.Mesons at finite μ, at the CEP and in the chiral limit





QCD phase transitions: fun fact



CF, PPNP 105 (2019) [1810.12938]

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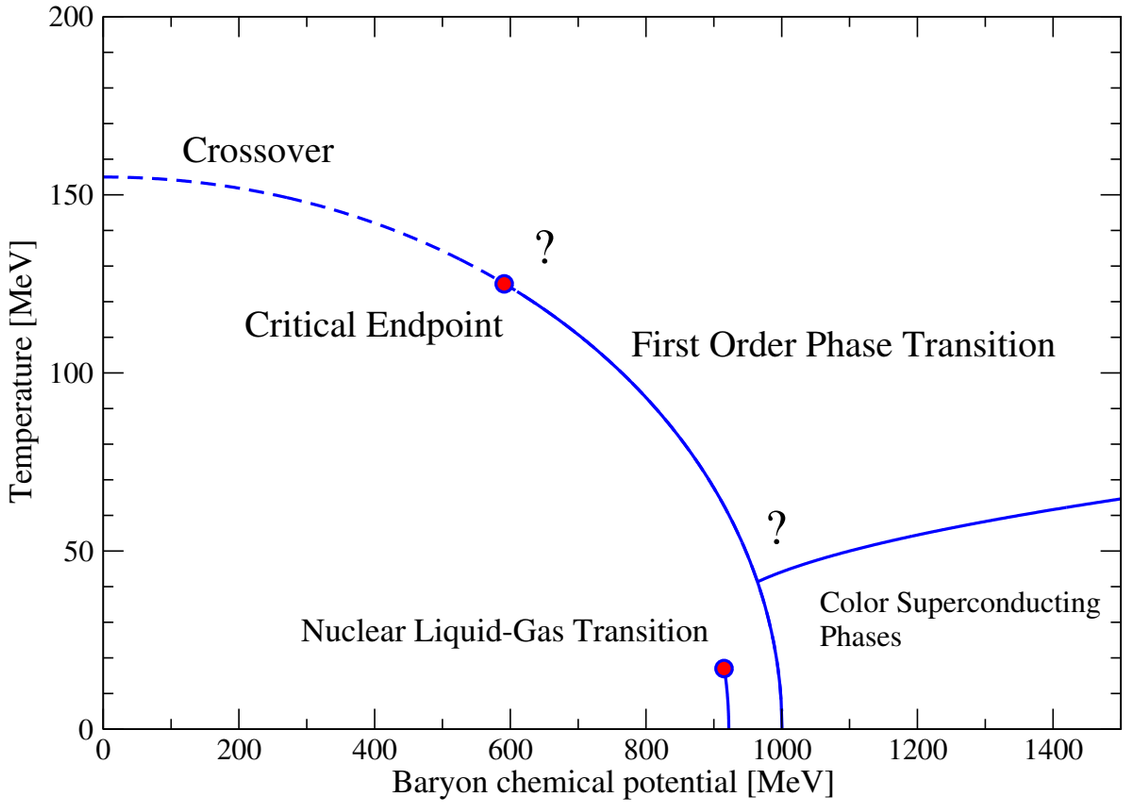

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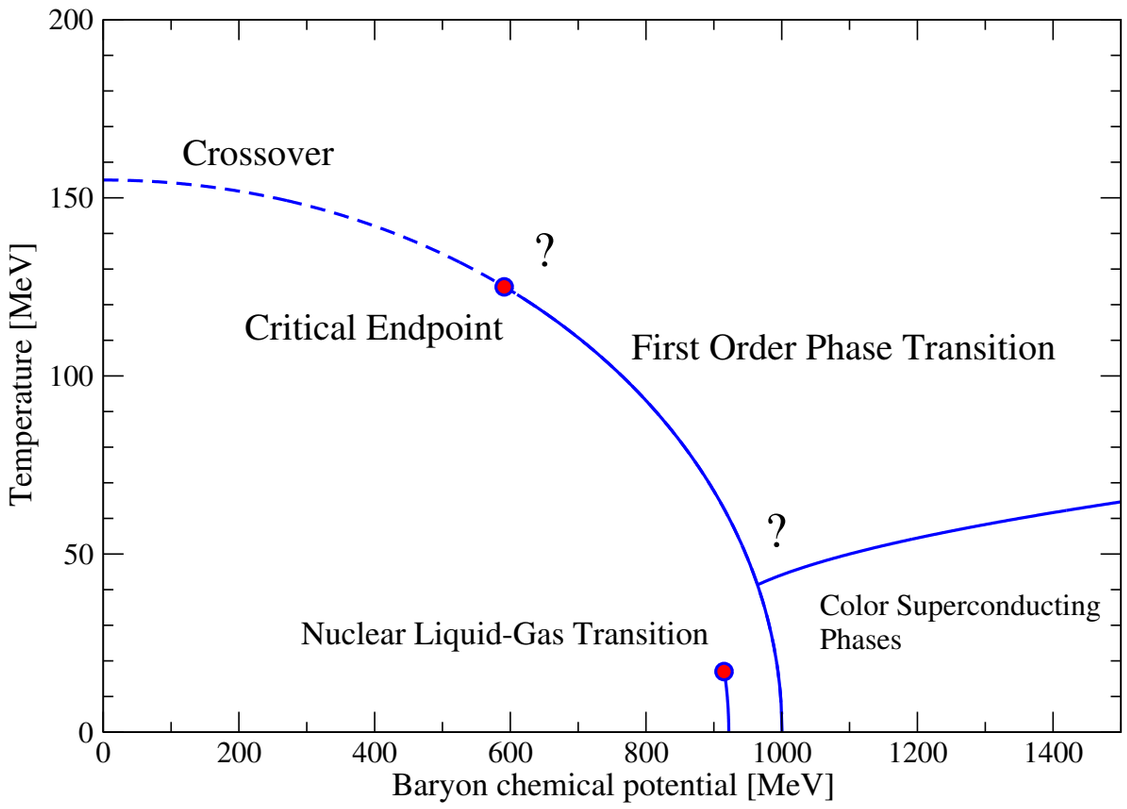

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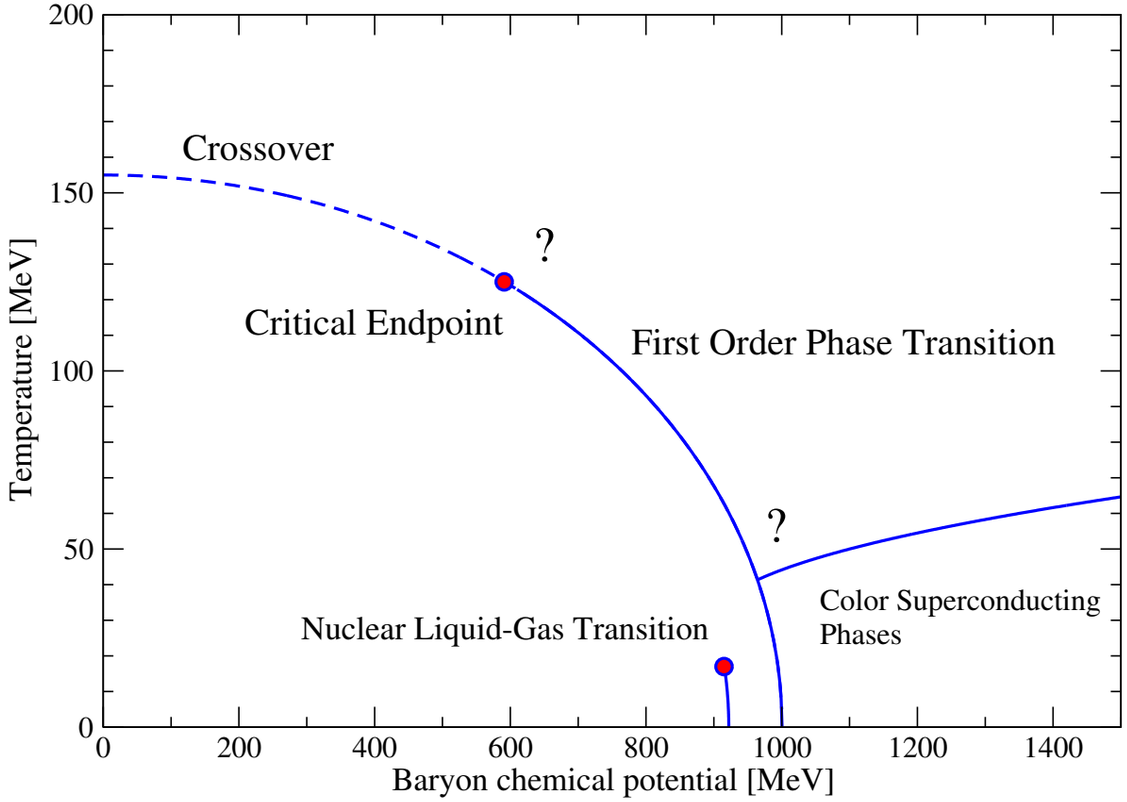

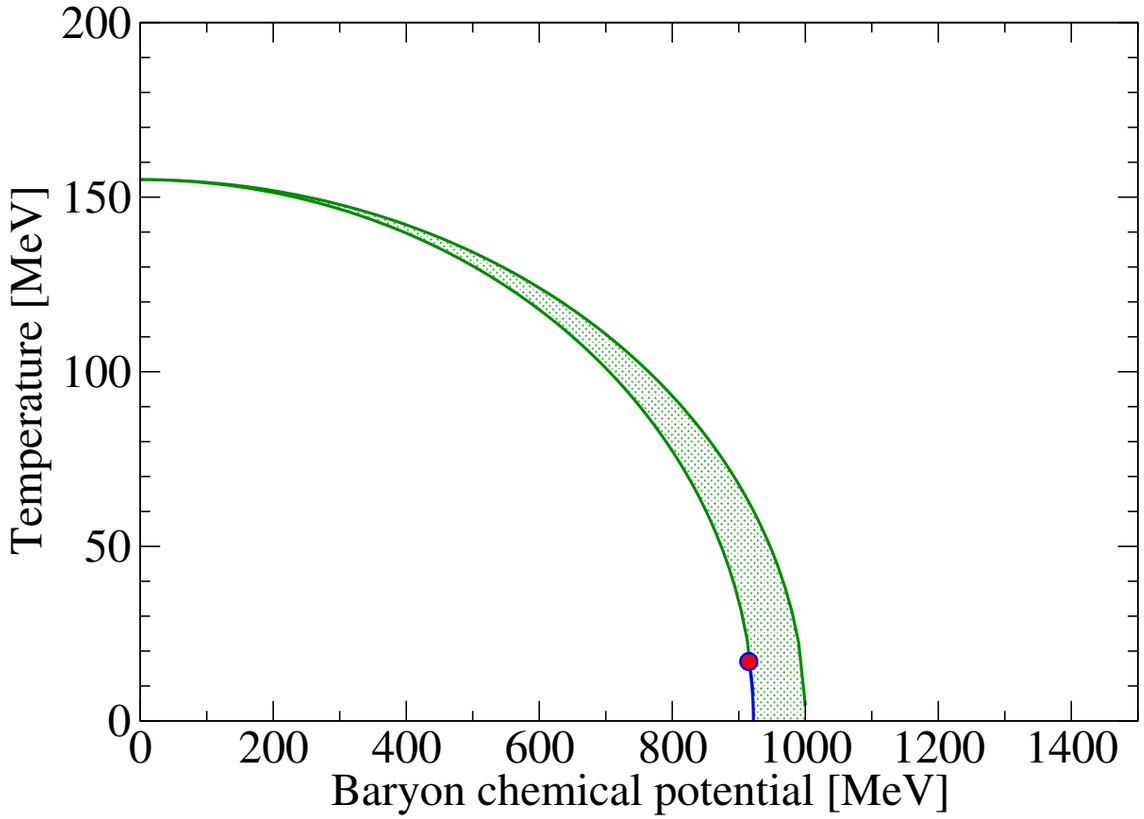

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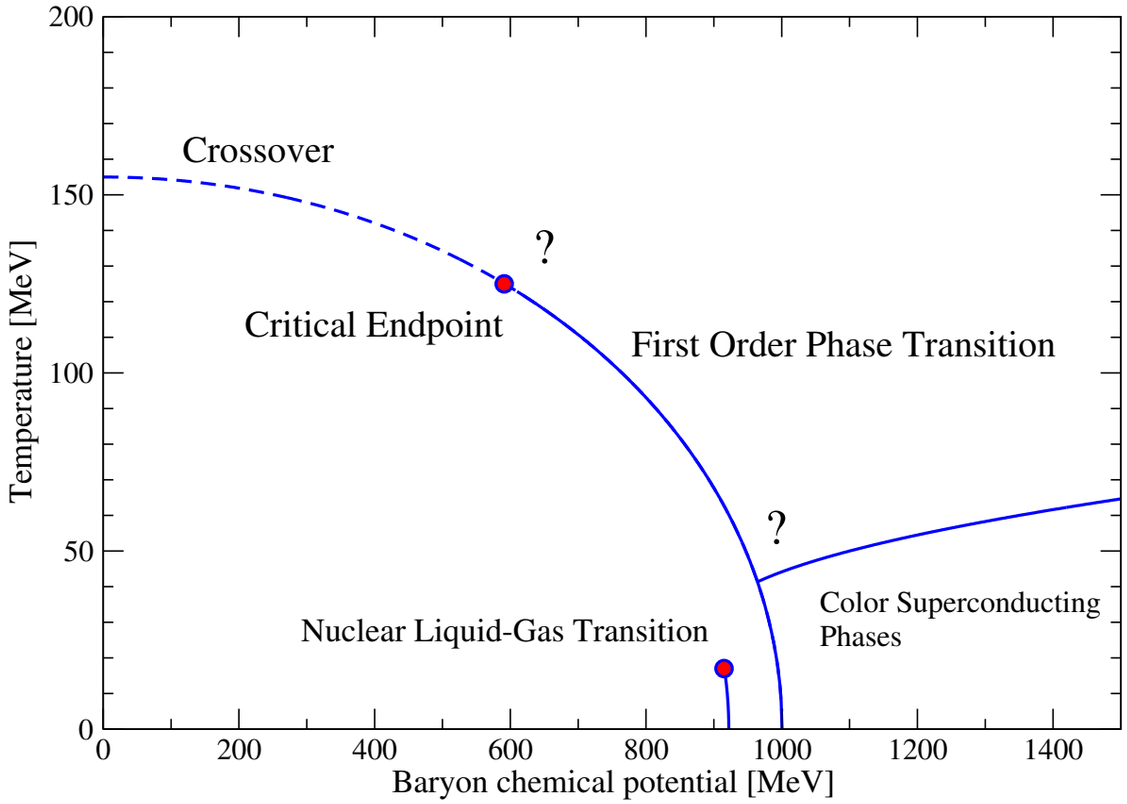

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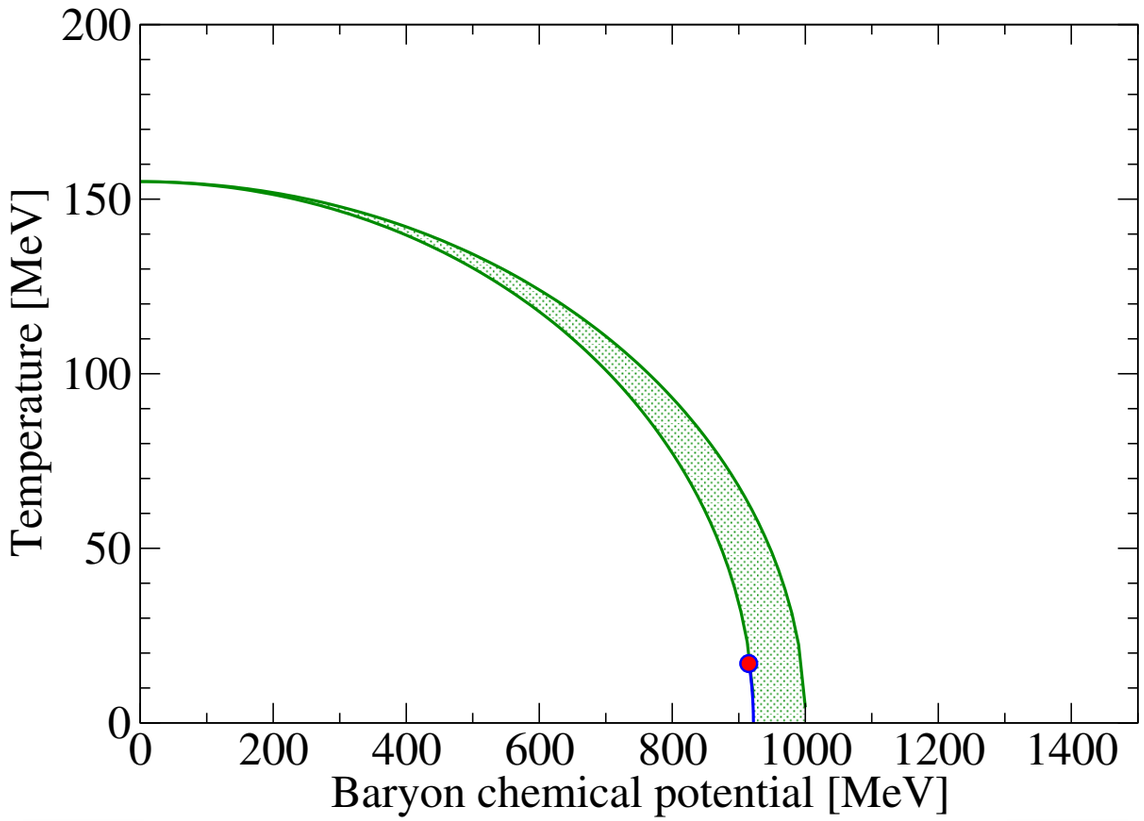
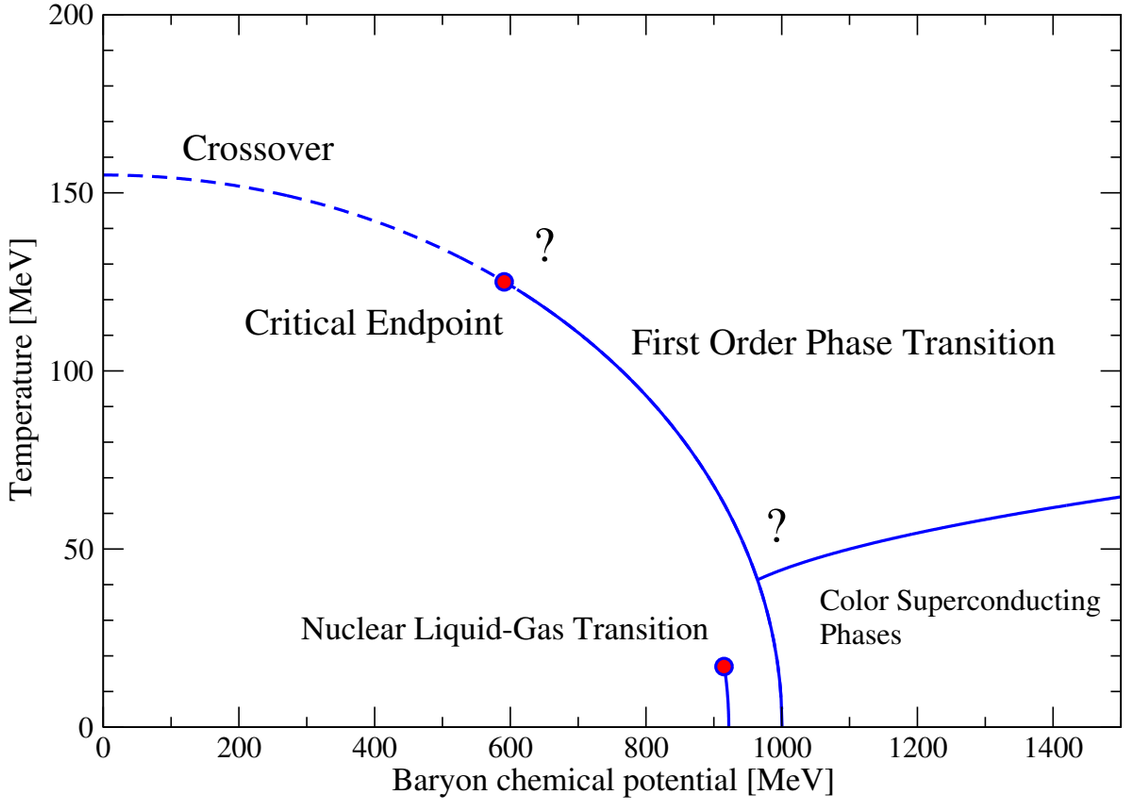


Lattice QCD:

$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa\left(\frac{\mu_B}{T_c}\right)^2 - \lambda\left(\frac{\mu_B}{T_c}\right)^4 \cdots,$$

QCD phase transitions: fun fact



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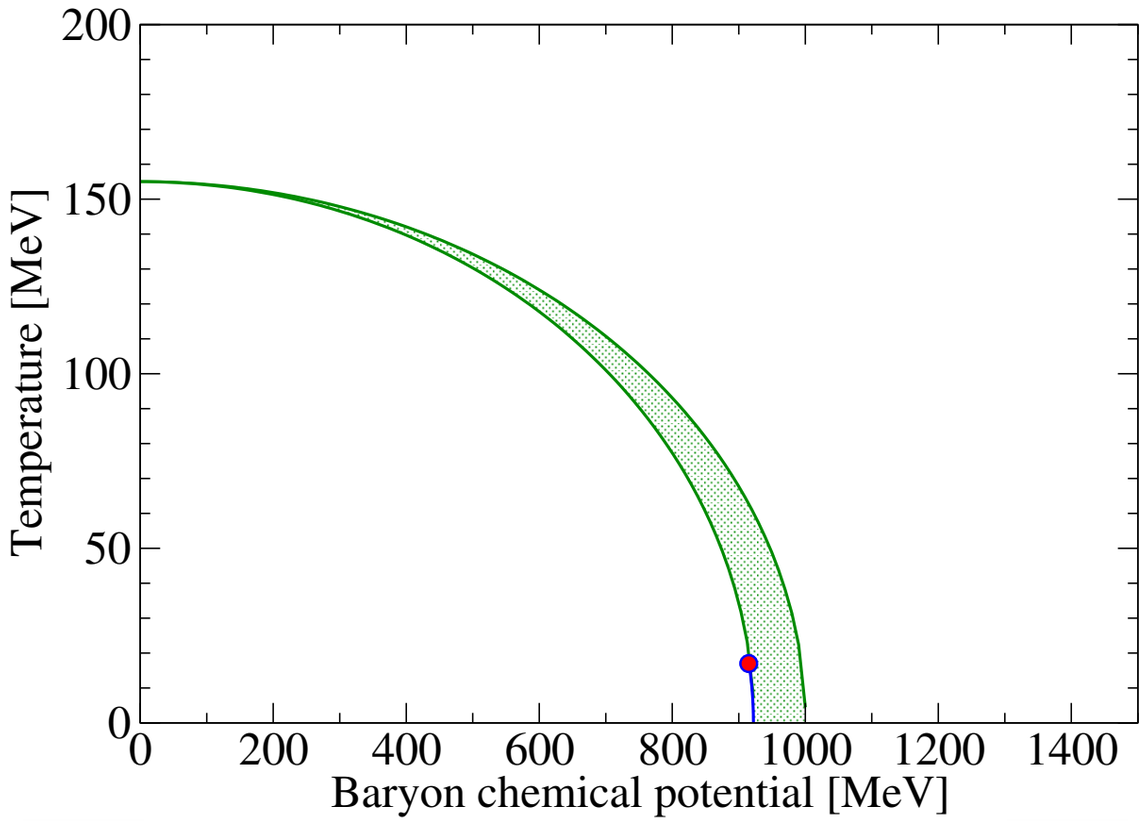

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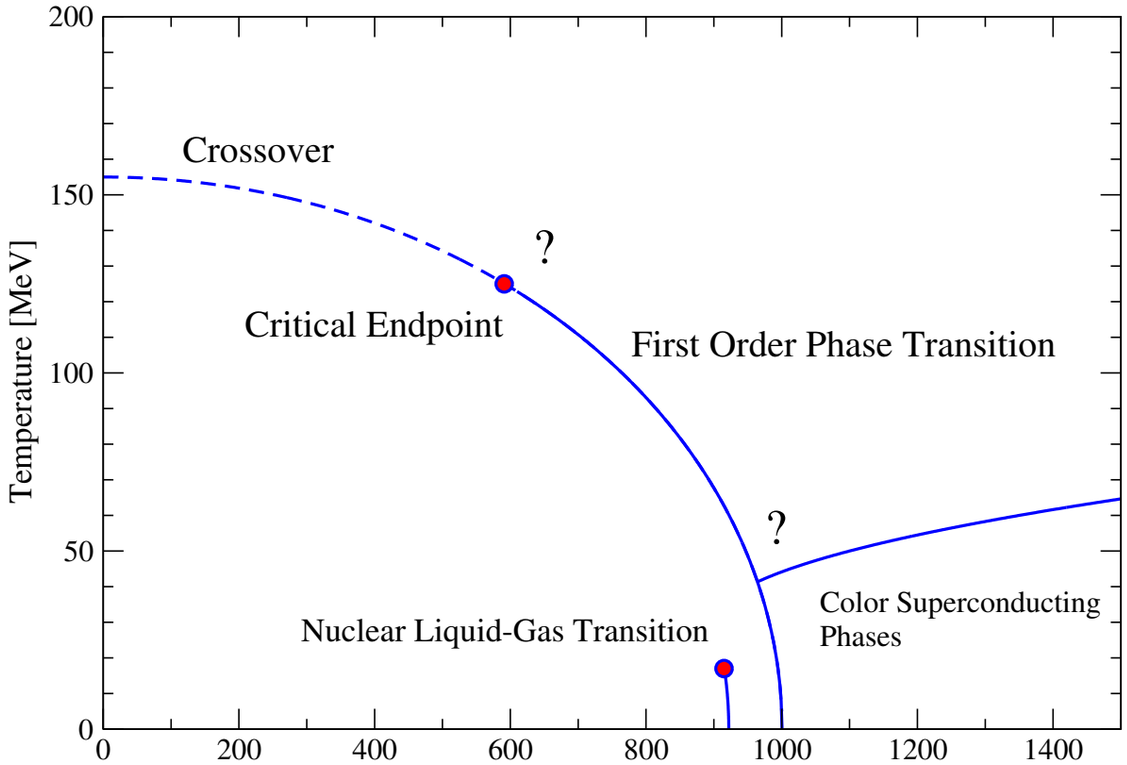

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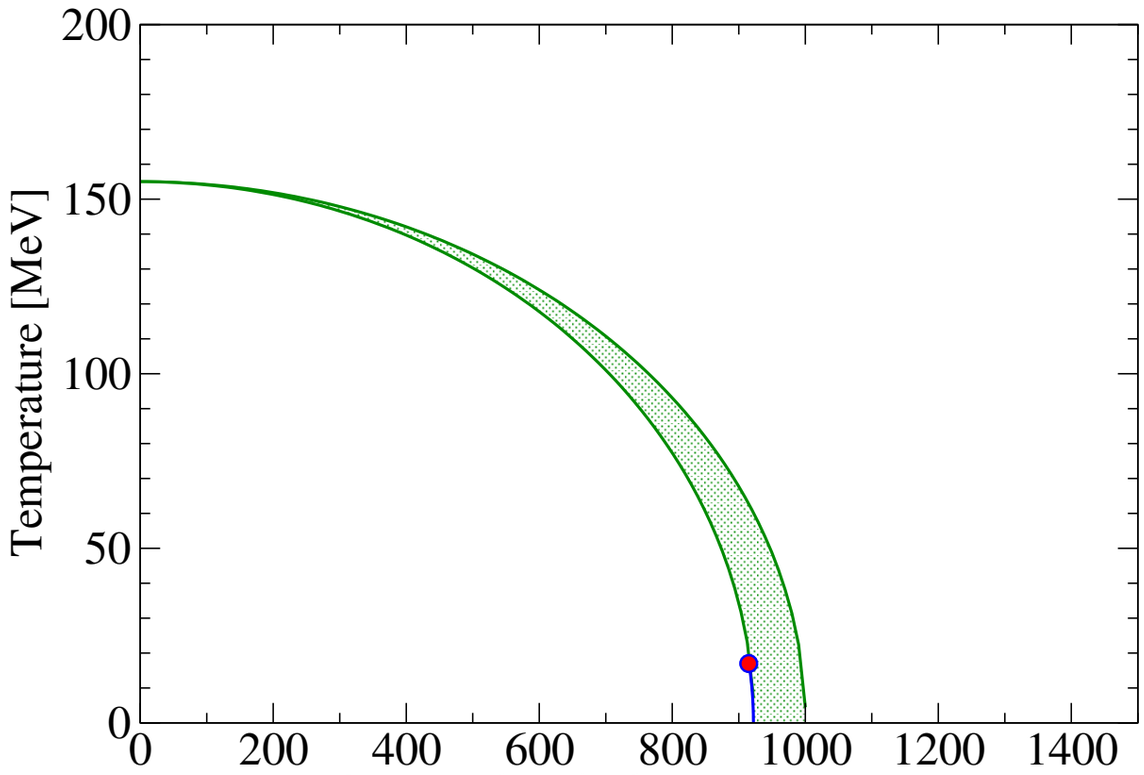

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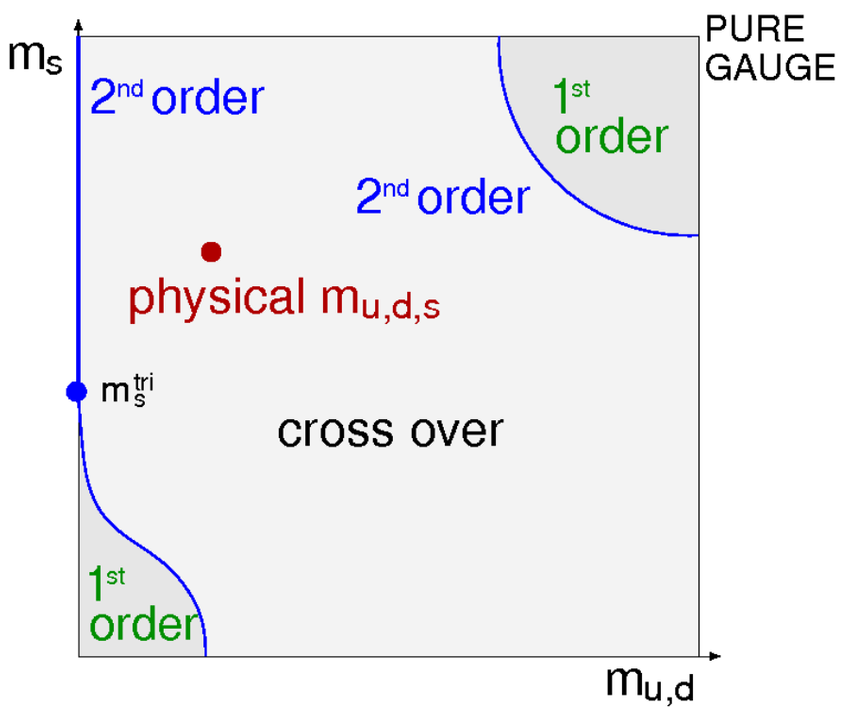
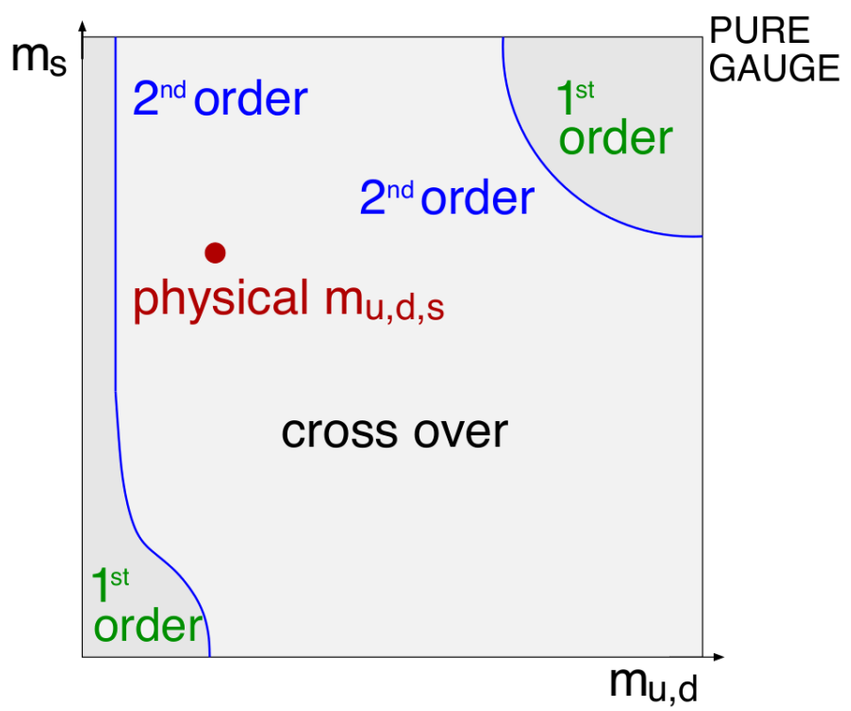
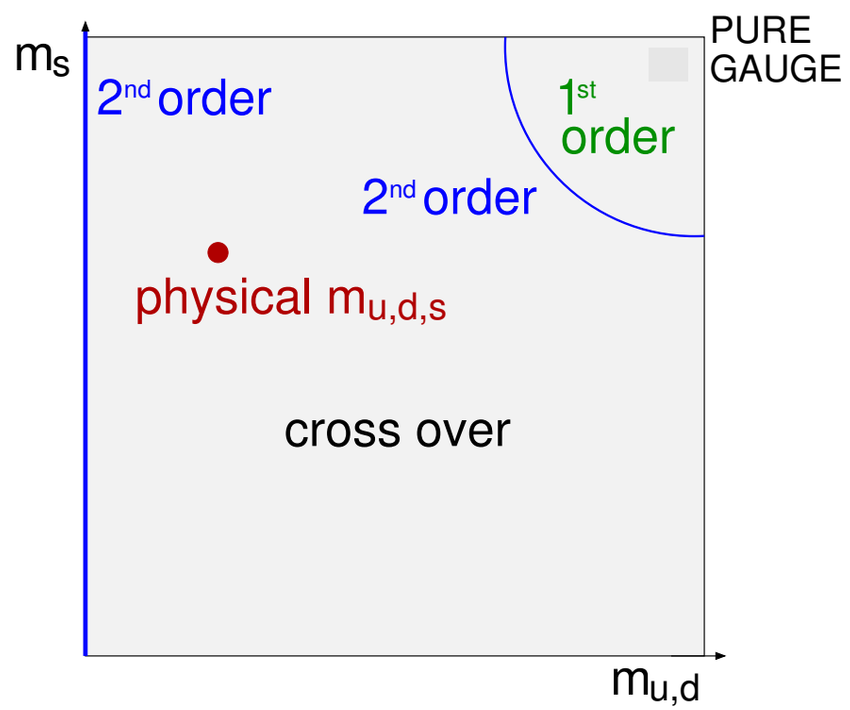
$$\kappa = \begin{cases} 0.0145(25) & \text{Bonati et al., PRD 98 (2018)} \\ 0.0120(40) & \text{Bazavov et al., PLB 795 (2018)} \\ 0.0153(18) & \text{Borsanyi et al., PRL 125 (2020)} \end{cases}$$

$$\lambda = \begin{cases} 0.000(4) & \text{Bazavov et al., PLB 795 (2018)} \\ 0.00032(67) & \text{Borsanyi et al., PRL 125 (2020)} \end{cases}$$

QCD phase transitions







$U_A(1)$ broken at T_c

$U_A(1)$ restored at T_c

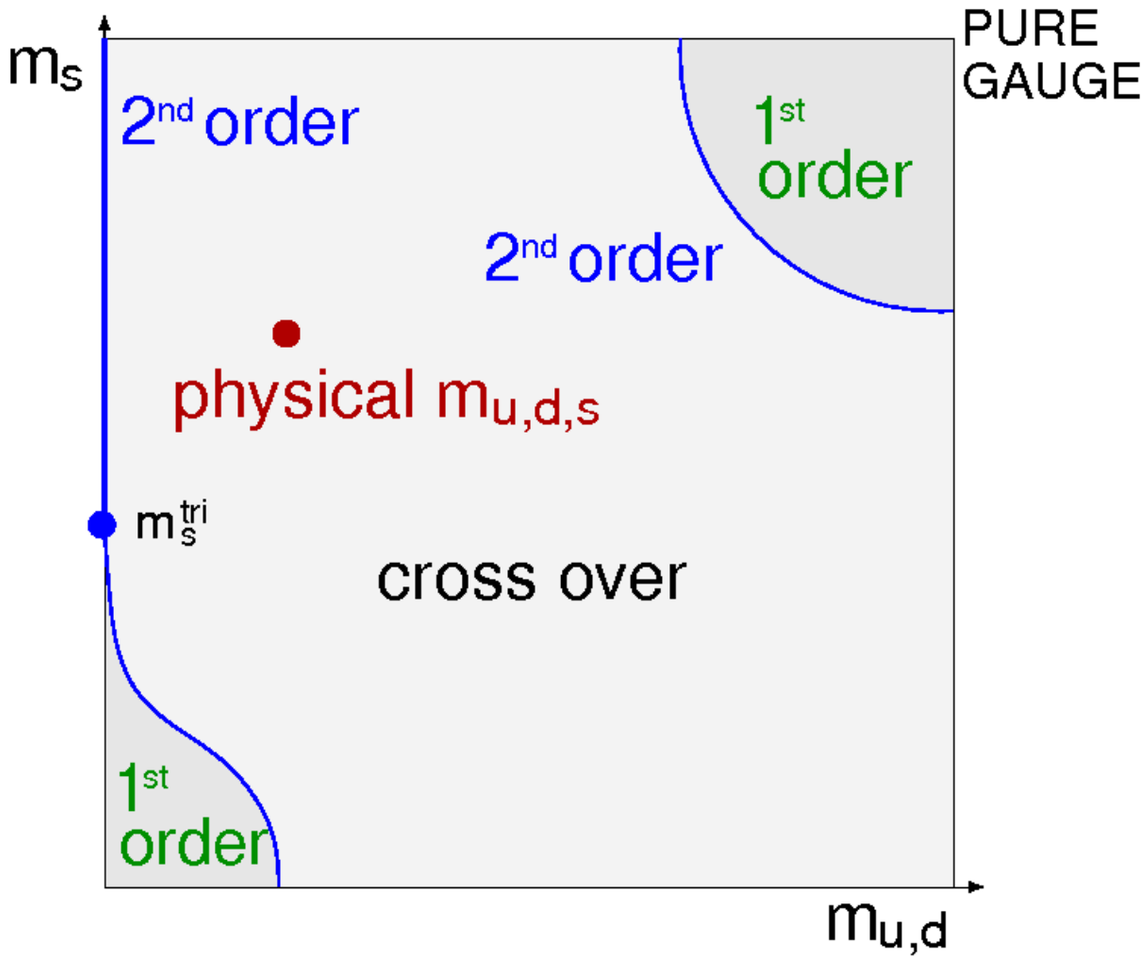
Is there chiral 1st order at all?

Pisarski and Wilczek, PRD 29 (1984), 338-341
Resch, Rennecke and Schaefer, PRD 99 (2019)

and many more…

Cuteri, Philipsen and Sciarra, JHEP 11 (2021), 141
Dini, et al, PRD 105 (2022) no.3, 034510
Fejos, PRD 105 (2022) no.7, L071506

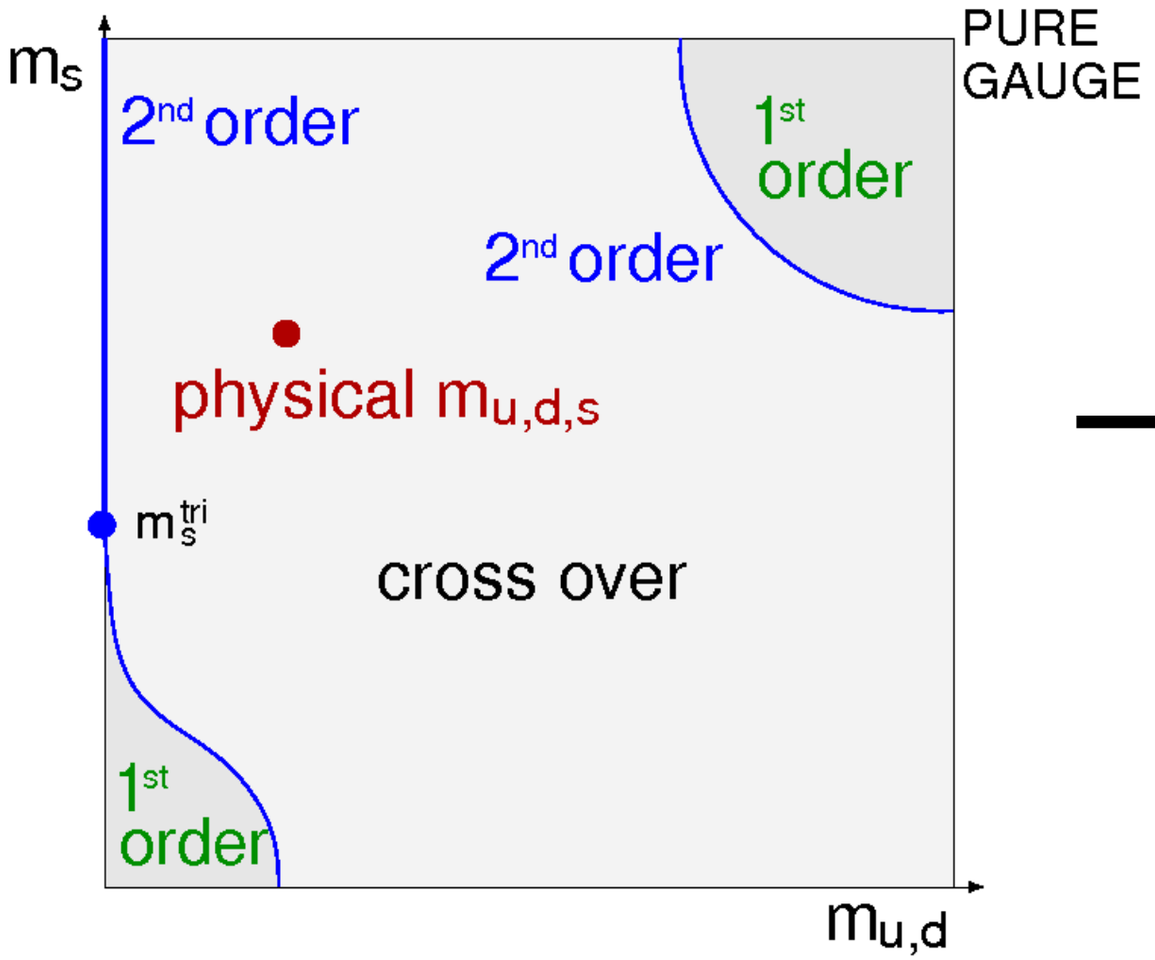
QCD phase transitions

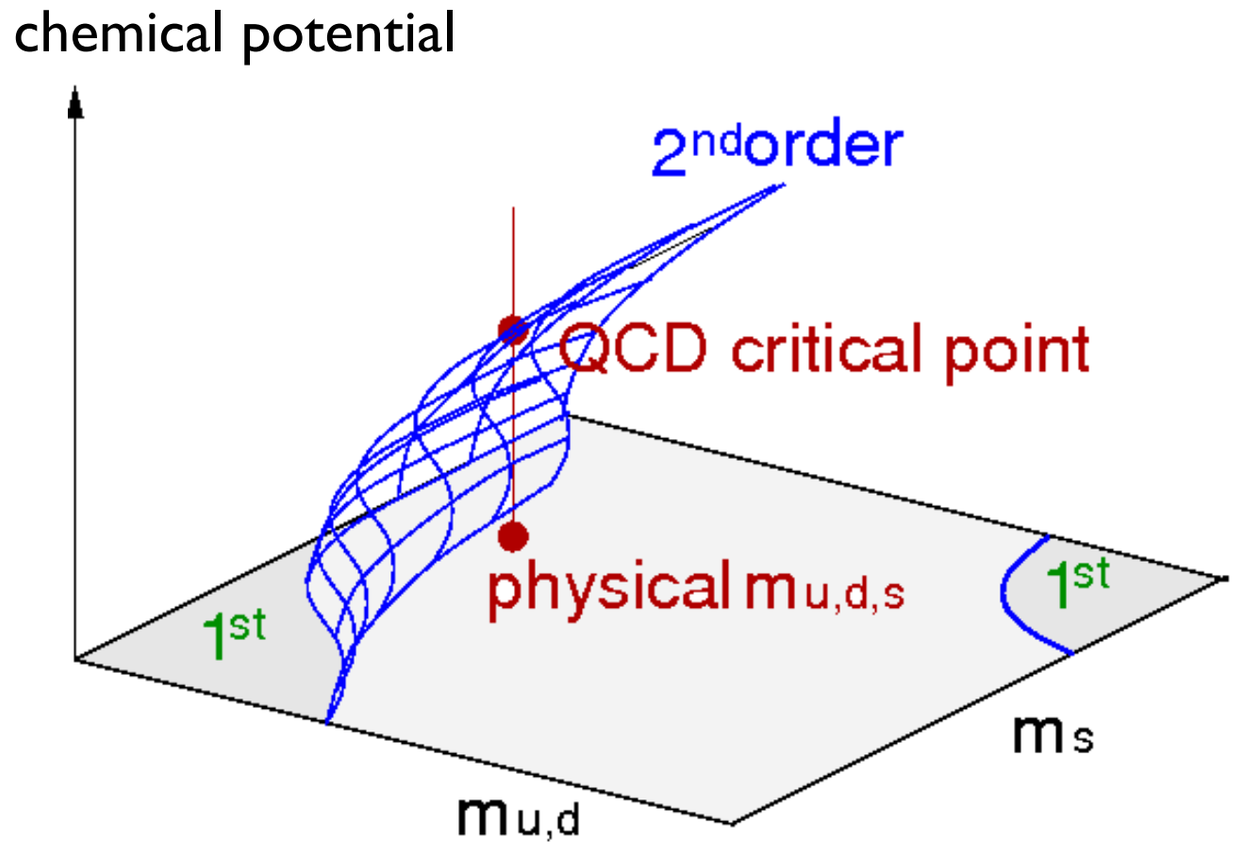


Is this happening ??
Maybe yes, maybe not..

de Forcrand, Philipsen, JHEP 0811 (2008) 012;
NPB 642 (2002) 290

QCD phase transitions





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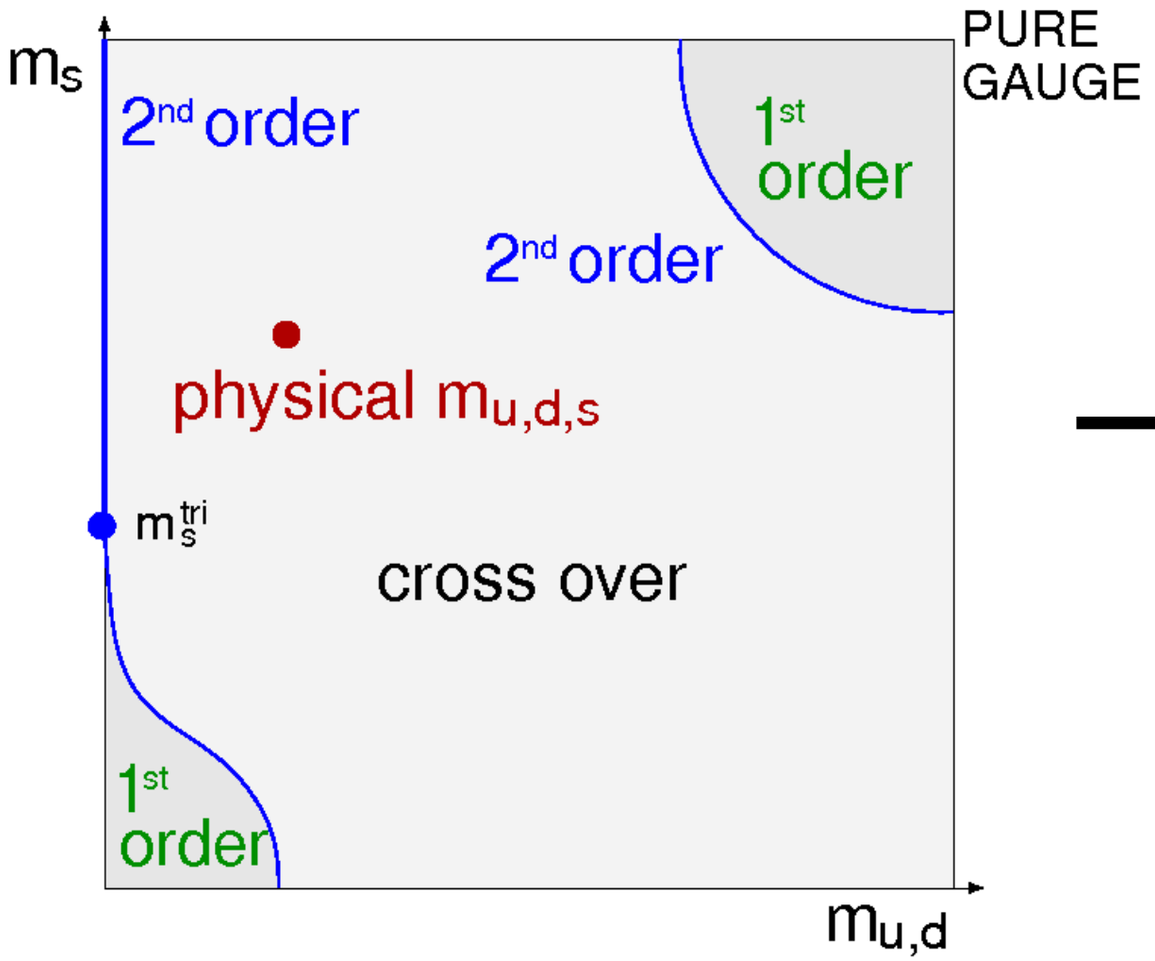

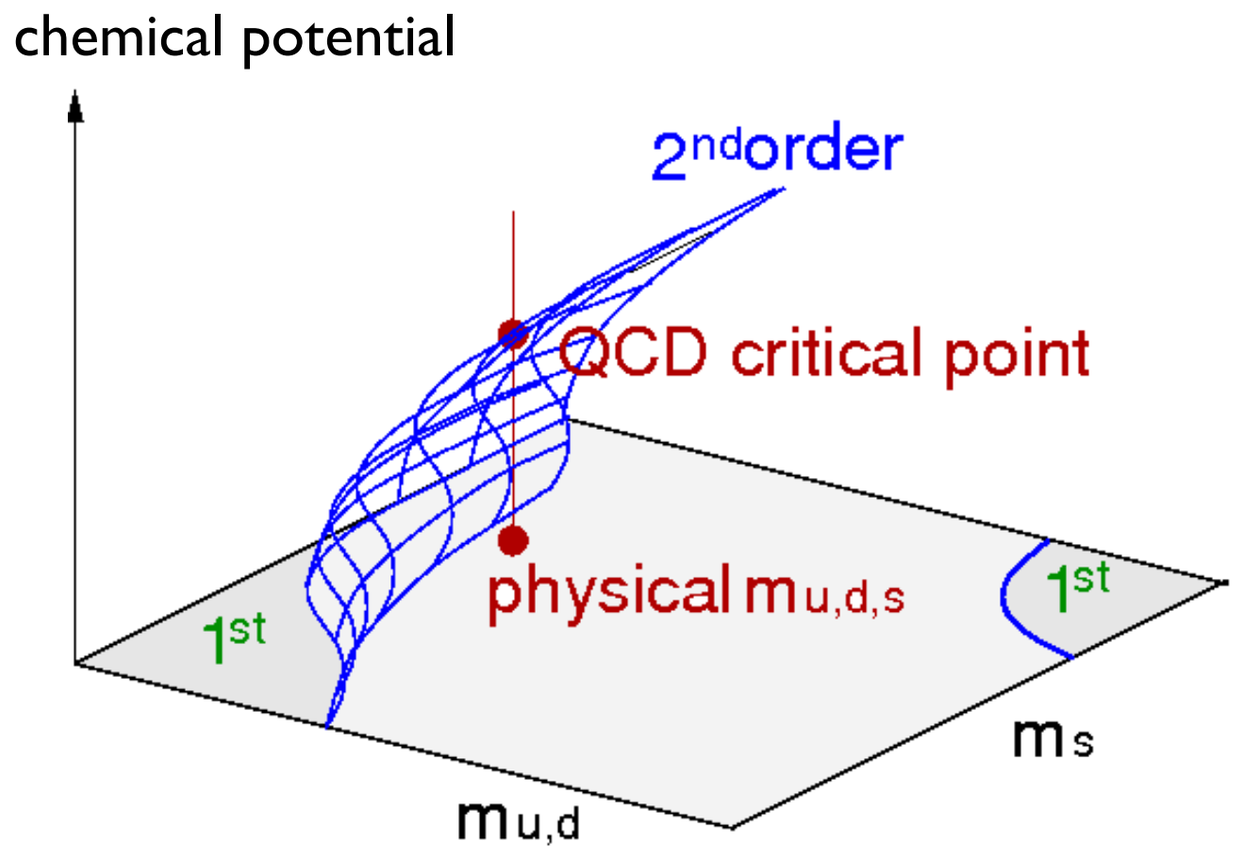

- Lattice-QCD
  - present: extrapolation
  - future: exact methods?
- DSE/FRG
  - can do! but typical errors 5-30%

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de Forcrand, Philipsen, JHEP 0811 (2008) 012;
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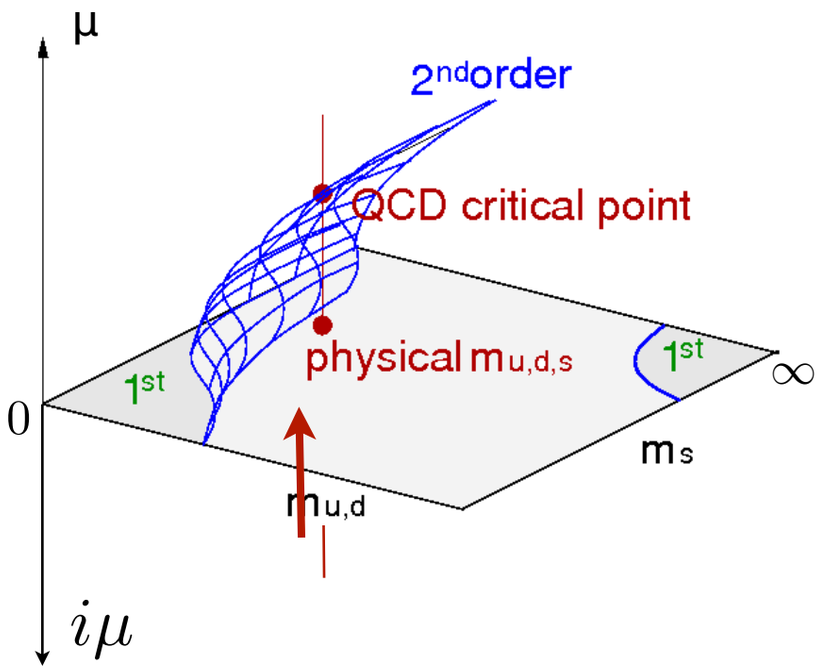
Chiral transition line from analytic continuation

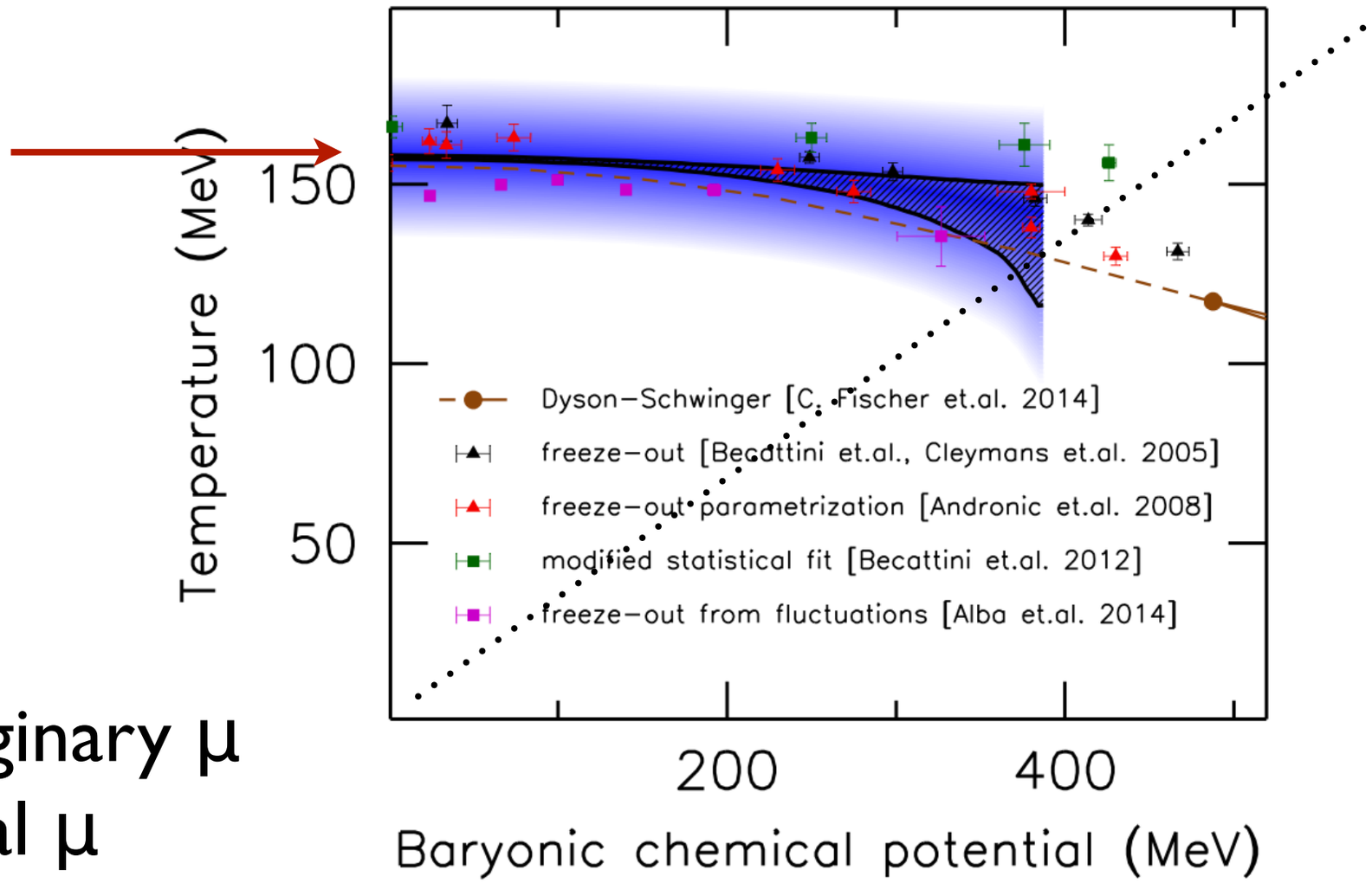


Lattice method:

- Det. crossover at imaginary μ and extrapolate to real μ
- Control systematics

Main result:

- See no transition for $\mu_B/T < 2\text{-}3$

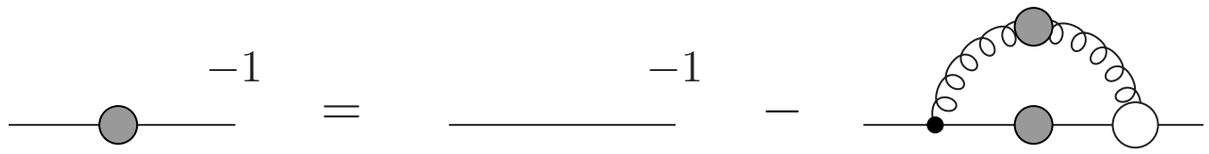


Bellwied, Borsanyi, Fodor, Günther,
Katz, Ratti and Szabo, PLB 751 (2015) 559

HOT-QCD: similar results

Overview

1.Introduction



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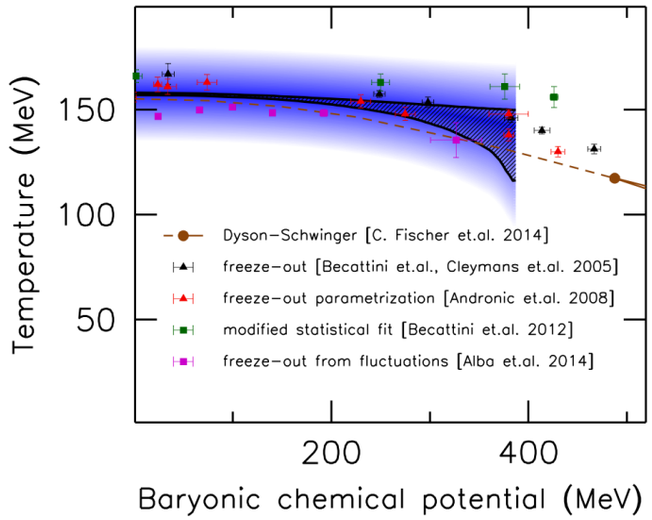

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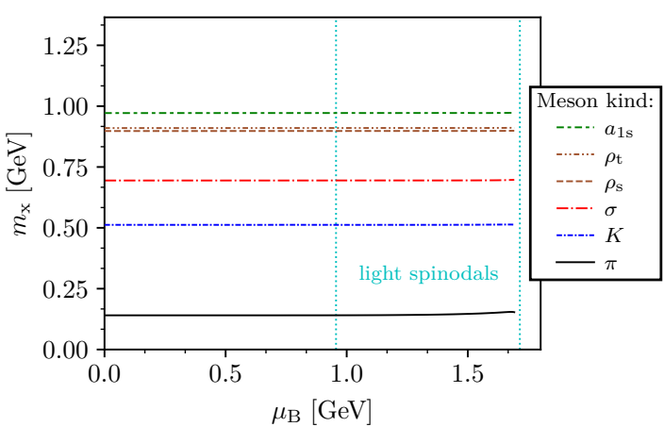
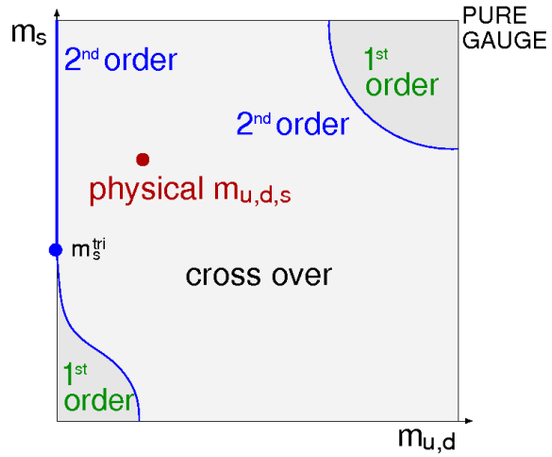
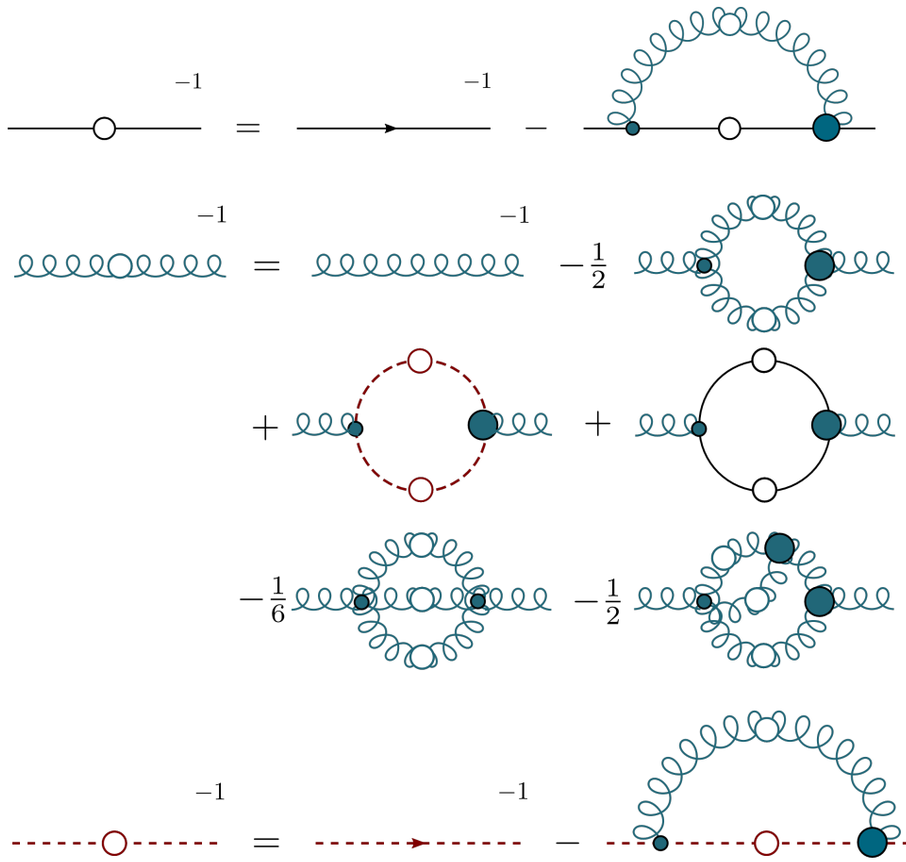




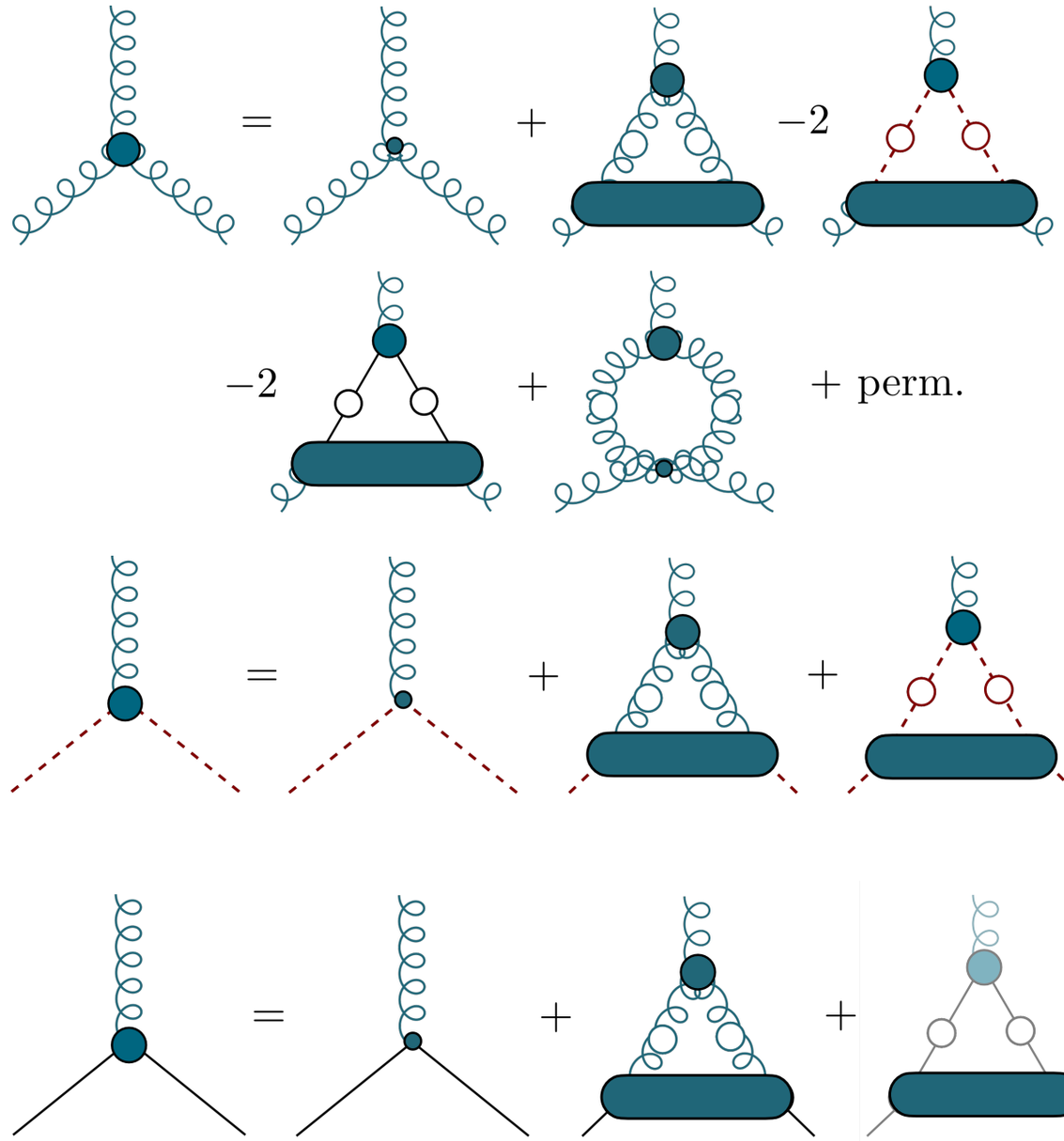
3PI-truncation (T=0, μ=0)

propagators



for different BRL approaches see work of
Aguilar, Alkofer, Binosi, Blum, Chang, Cyrol, Eichmann, Fister,
Gao, Huber, Maas, Mitter, Papavassiliou, Pawlowski, Roberts, Smekal,
Strodthoff, Vujinovic, Watson, Williams…

vertices



CF, Alkofer, PRD67 (2003) 094020
Williams, CF, Heupel, PRD93 (2016) 034026
Huber, PRD 101 (2020) 114009

Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

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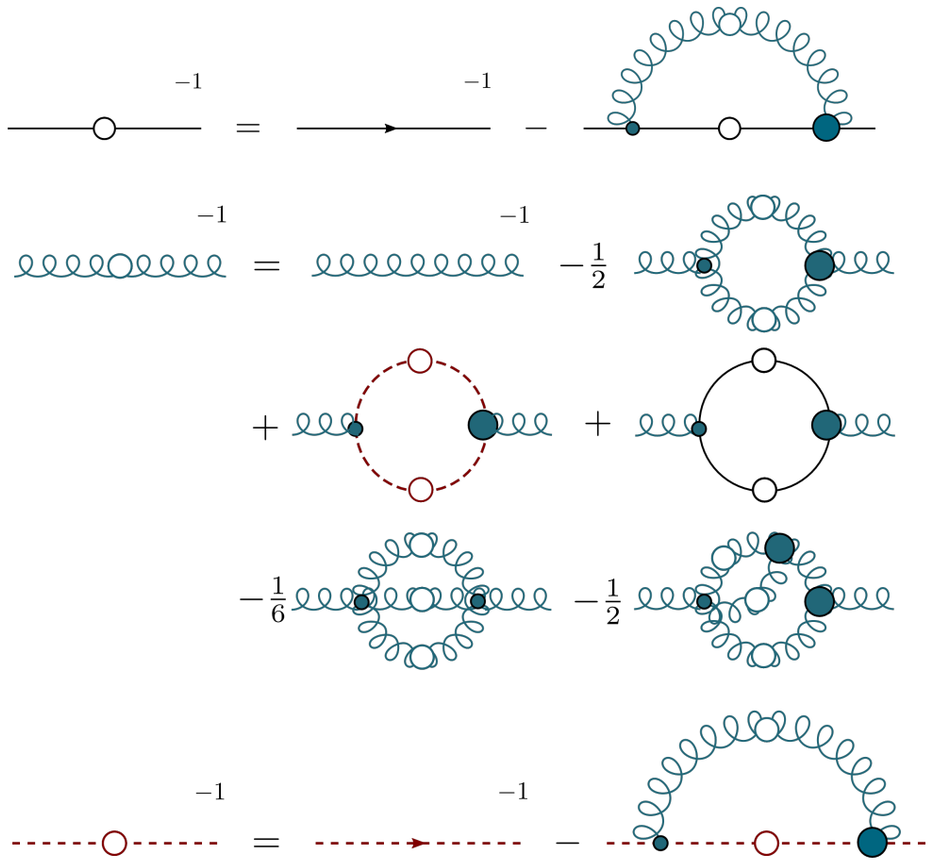

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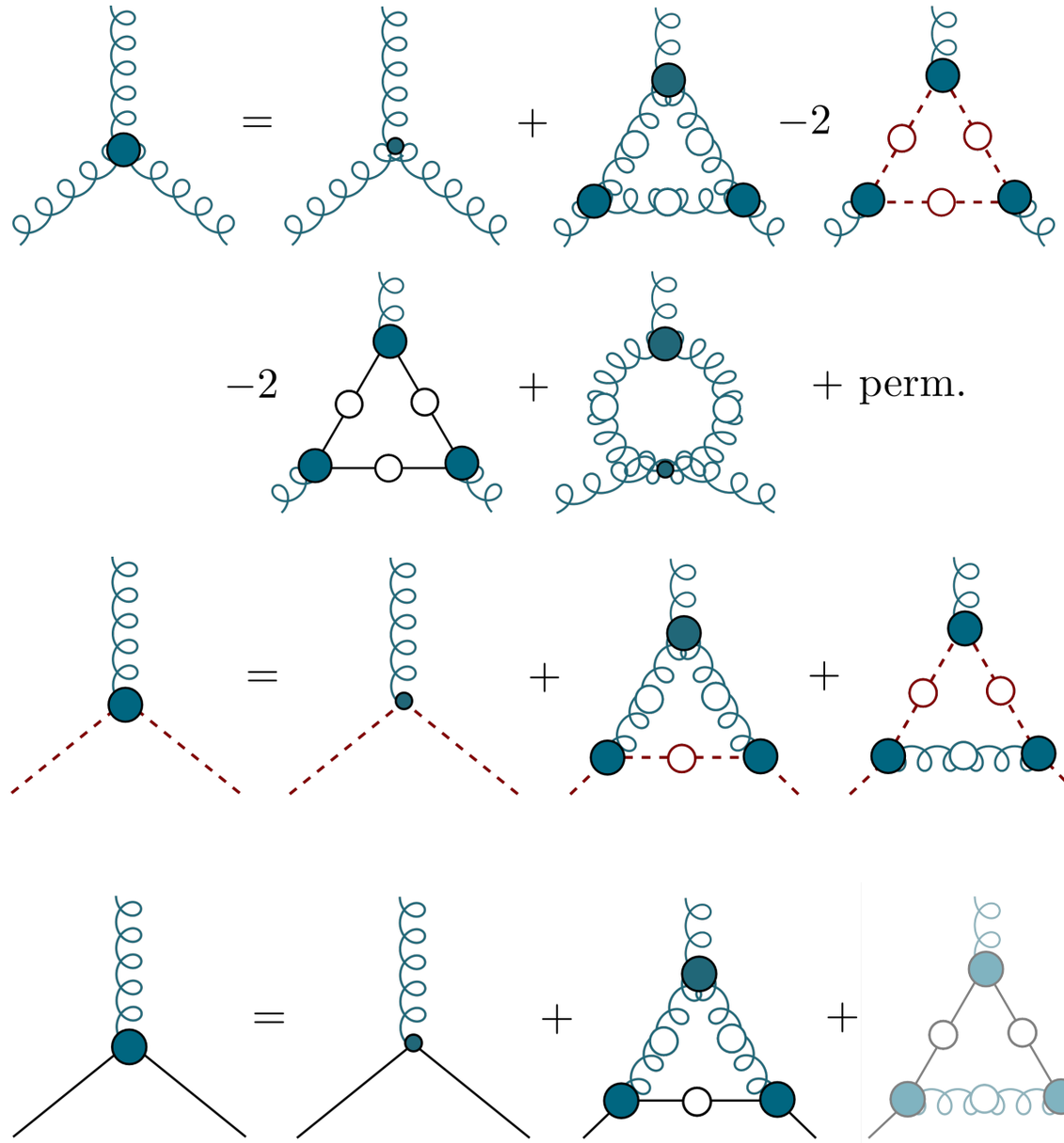

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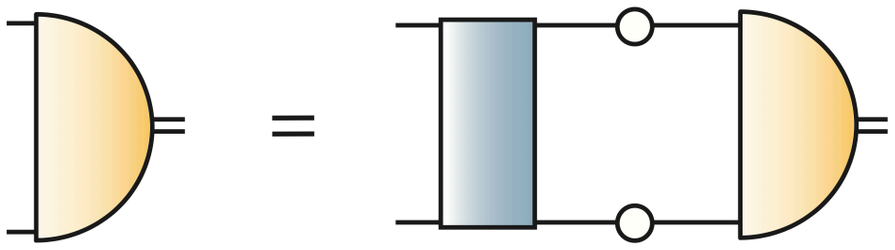
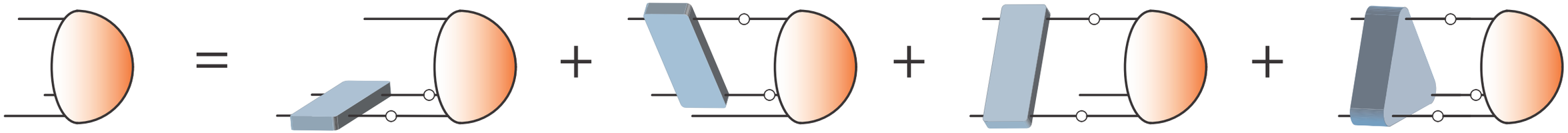
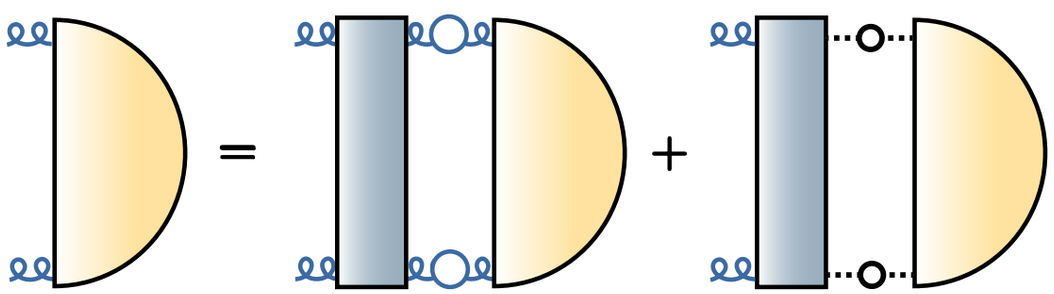
Bound states and Bethe-Salpeter equations

BSEs:







Eigenvalue equations: masses and wave functions

Bound states and Bethe-Salpeter equations

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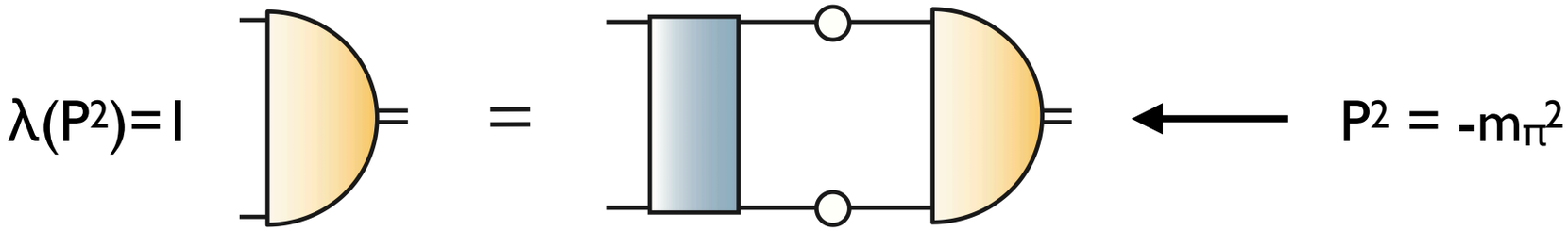
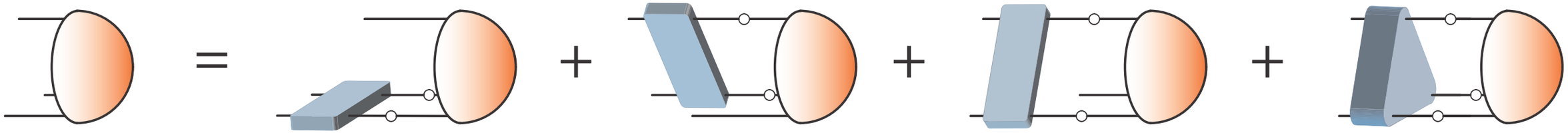
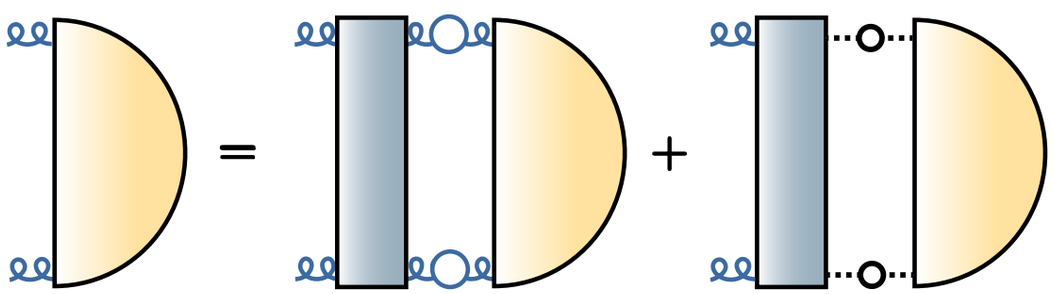


Bethe-Salpeter Amplitude

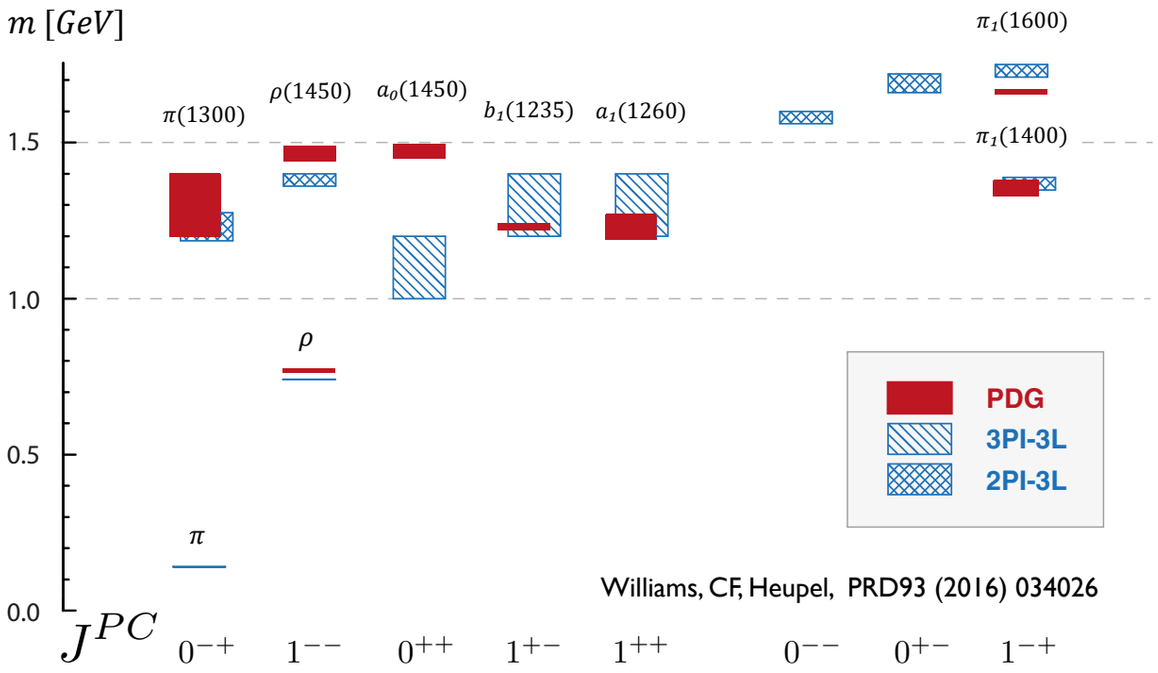




Eigenvalue equations: masses and wave functions

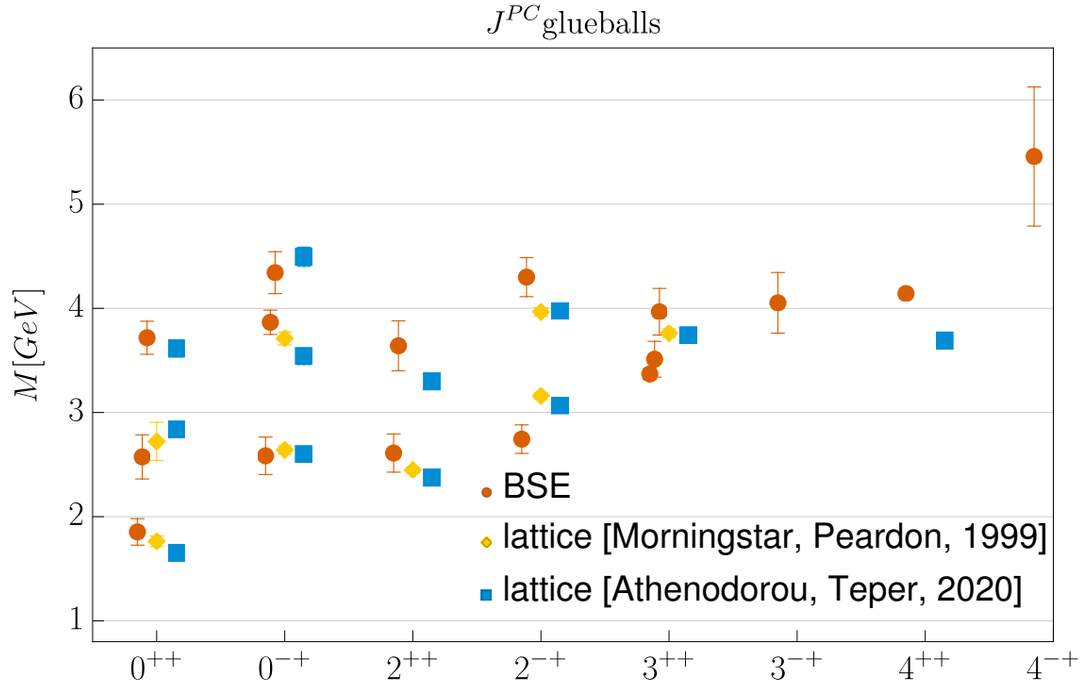
Hadron spectra: mesons, baryons, glueballs

Mesons:



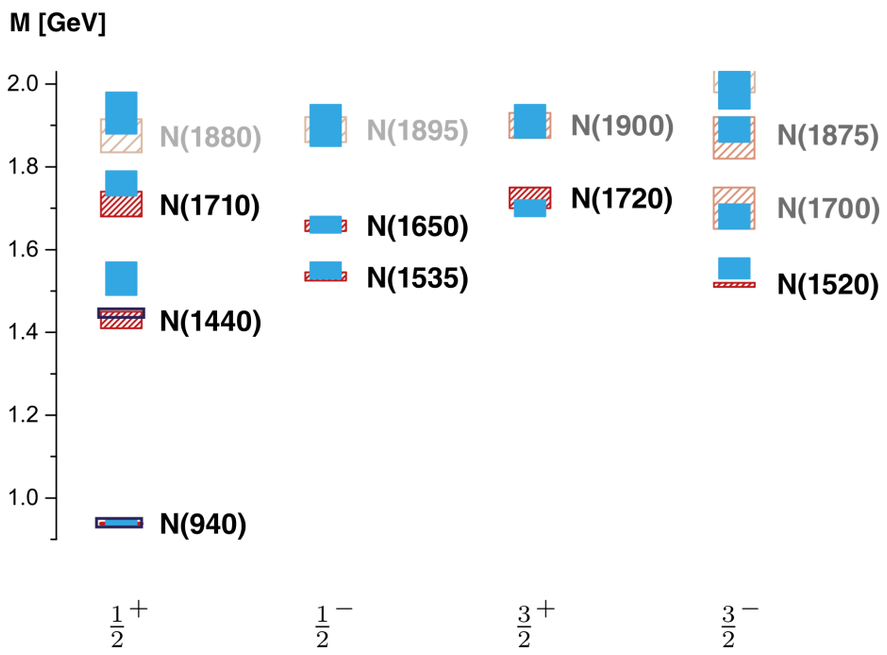
Williams, CF, Heupel, PRD93 (2016) 034026

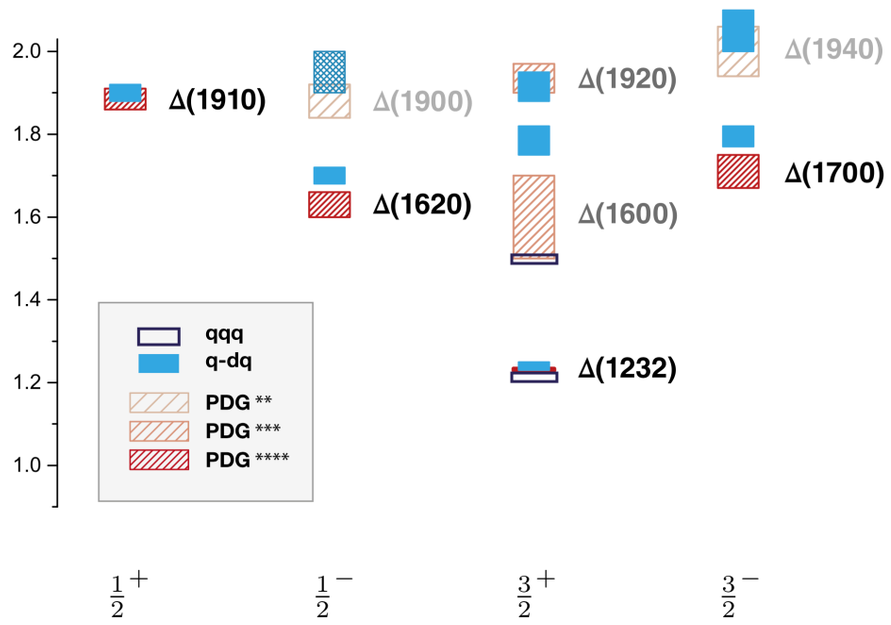
Glueballs:



CF, Huber, Sanchis-Alepuz, EPJC 80 (2020)
Huber, CF, Sanchis-Alepuz, EPJC 81 (2021)

Baryons:





Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2

Overview

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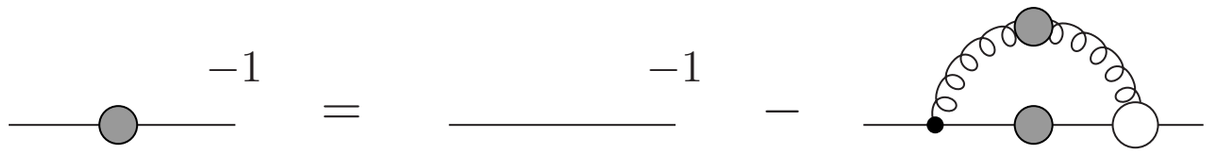

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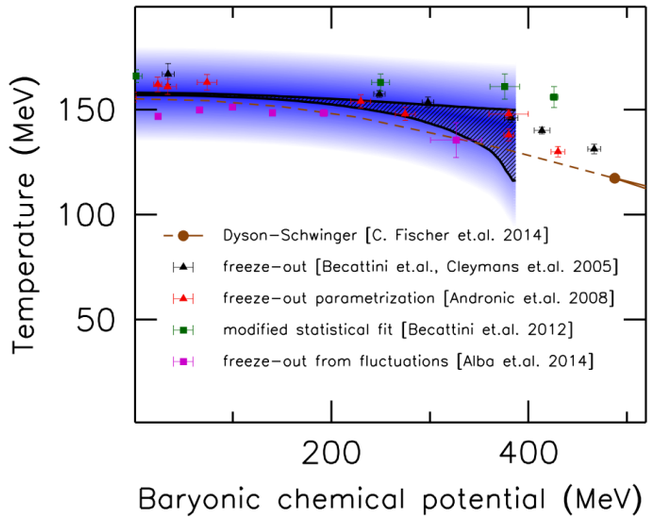

3.QCD phase diagram and the CEP

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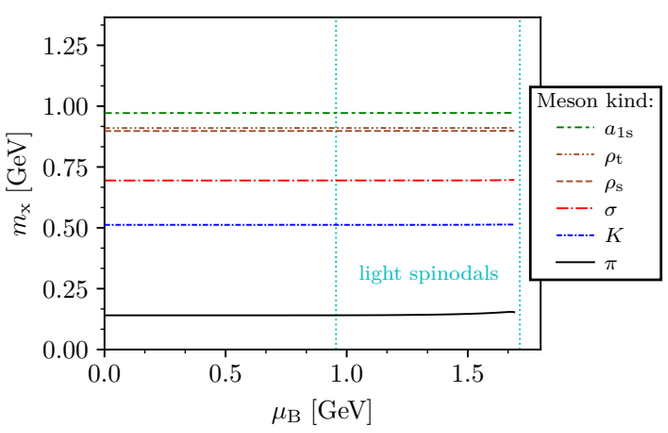
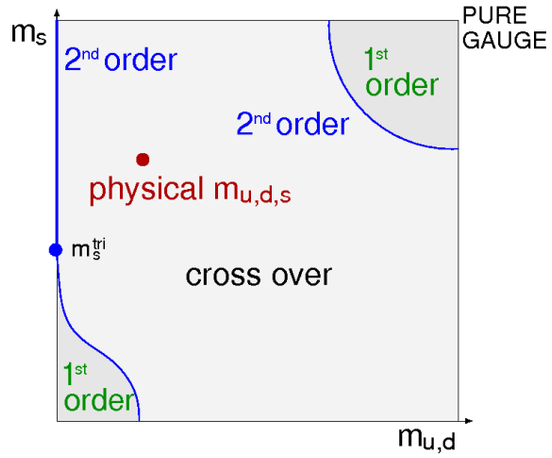
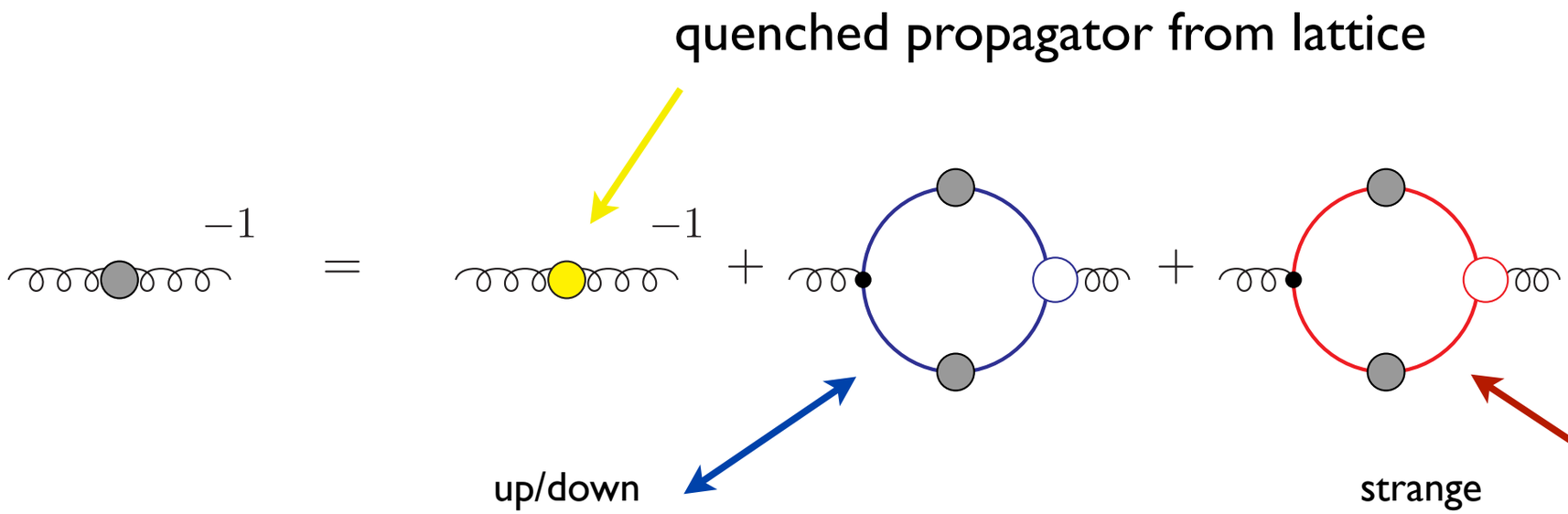
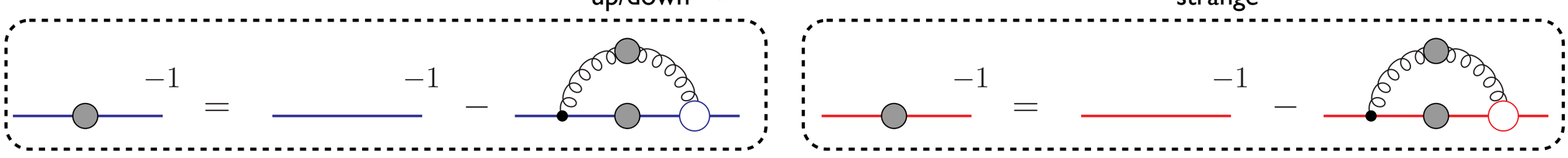




N_f=2+1-QCD with DSEs





$$S^{-1}(\omega_p,\vec{p}) = i\vec{\not{p}}\,A(\omega_p,\vec{p}) + i\gamma_4\omega_p C(\omega_p,\vec{p}) + B(\omega_p,\vec{p})$$

- quenched: without quark-loop
- N_f=2: isospin symmetry $m_{u/d}$ fixed by m_π
- N_f=2+1: coupled system of 2+3+3 equations
- Vertex: ansatz built along STI and known UV/IR behavior

→ T,μ,m-dependent

QCD order parameters from propagators

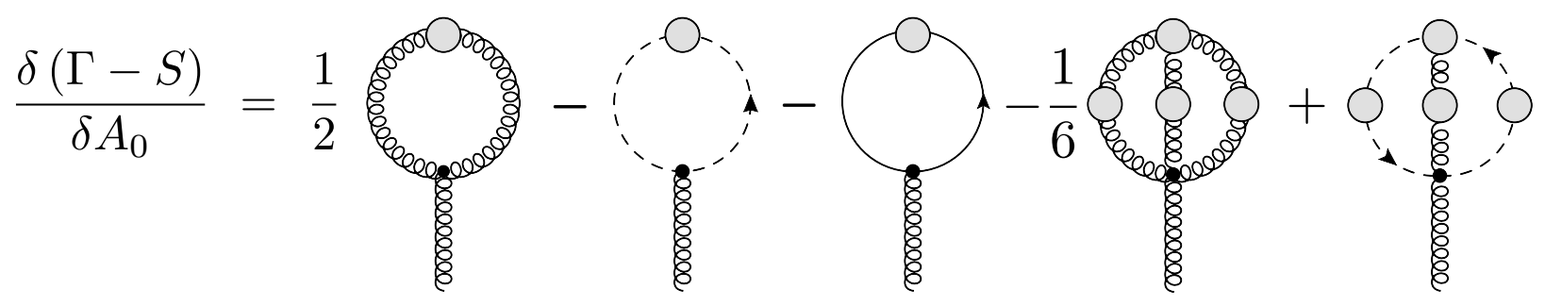
Chiral order parameter:

$$\langle \bar{\Psi}\Psi \rangle = Z_2 N_c Tr_D \frac{1}{T} \sum_\omega \int \frac{d^3p}{(2\pi)^3} S(\vec{p},\omega)$$

Deconfinement:

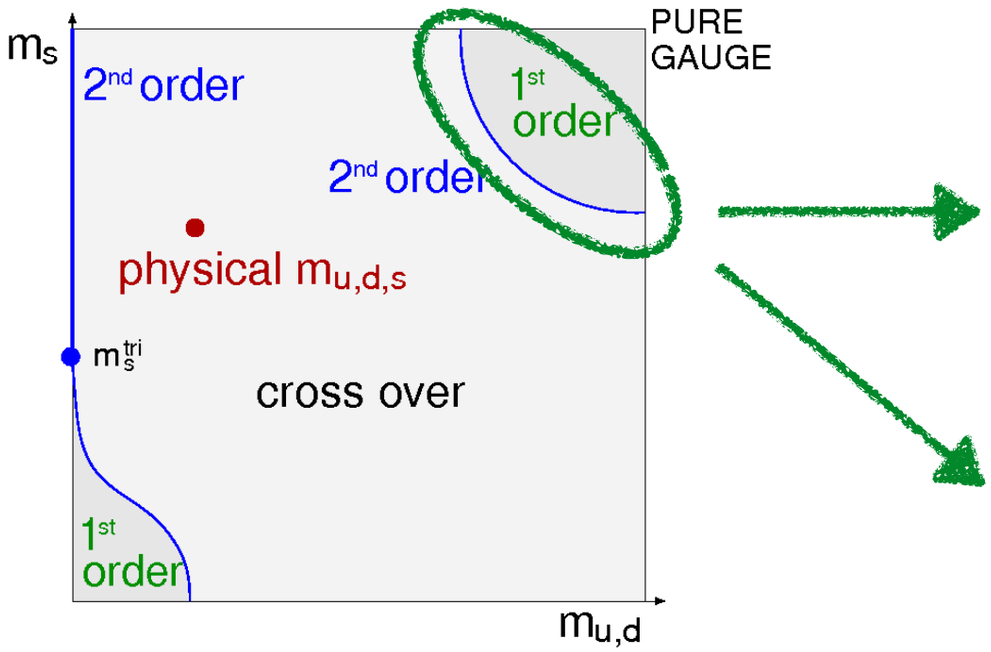
- Polyakov loop potential

$$L = \frac{1}{N_c} Tr\, e^{ig\beta A_0}$$

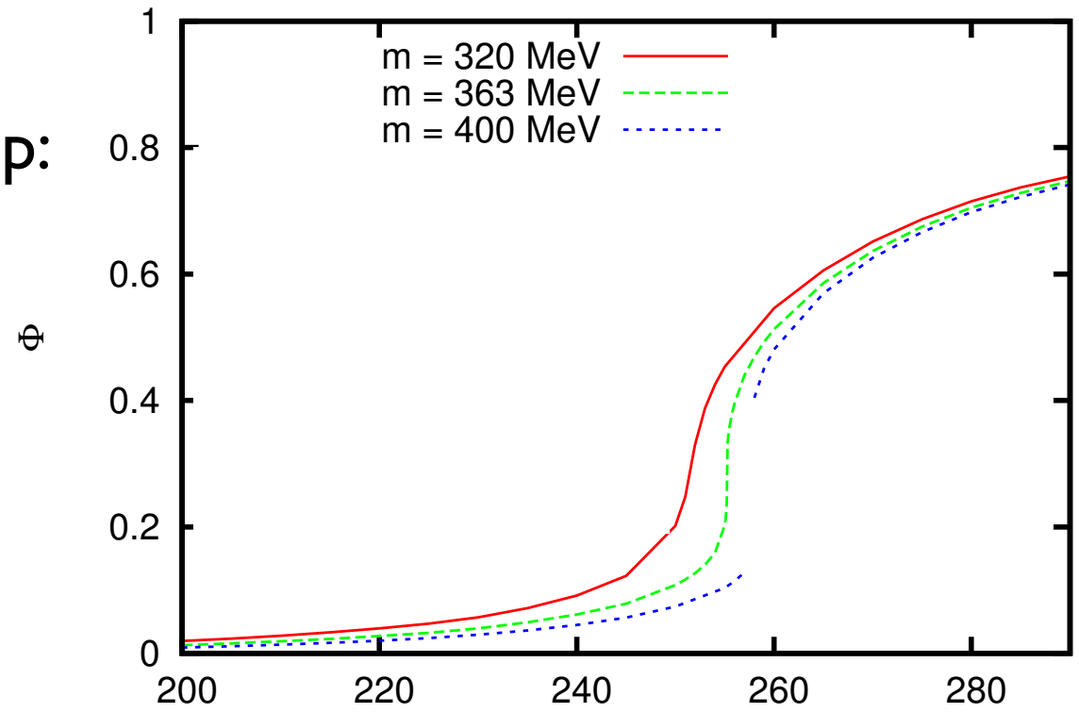


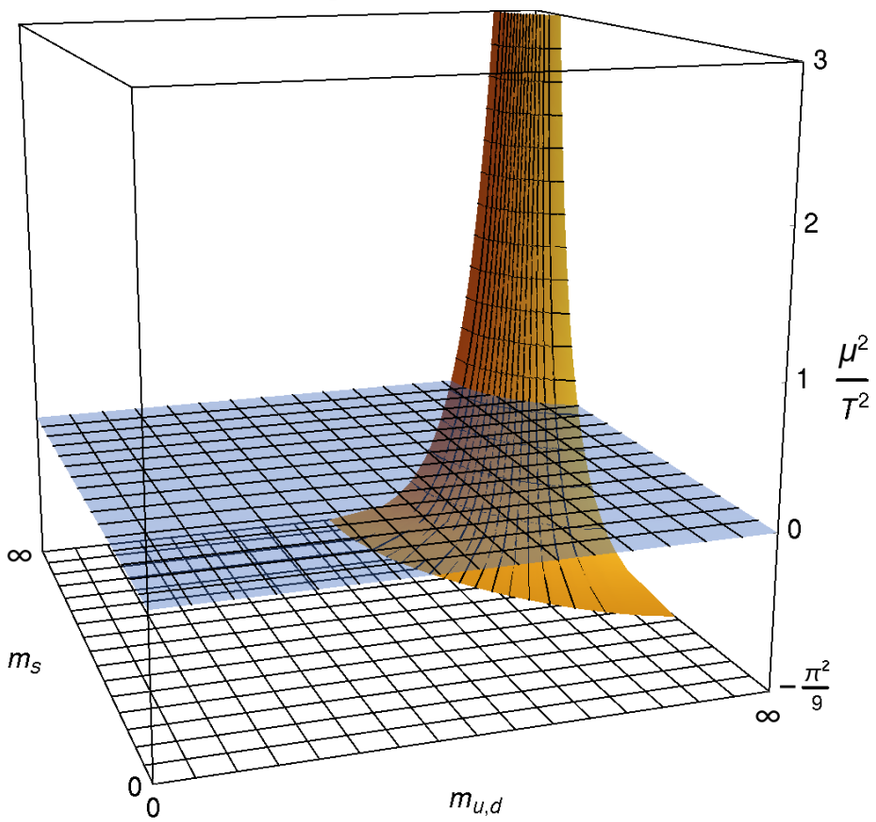
Braun, Gies, Pawlowski, PLB 684, 262 (2010)
Braun, Haas, Marhauser, Pawlowski, PRL 106 (2011)
Fister, Pawlowski, PRD 88 045010 (2013)
CF, Fister, Luecker, Pawlowski, PLB 732 (2013)

Critical line/surface for heavy quarks



Polyakov Loop:



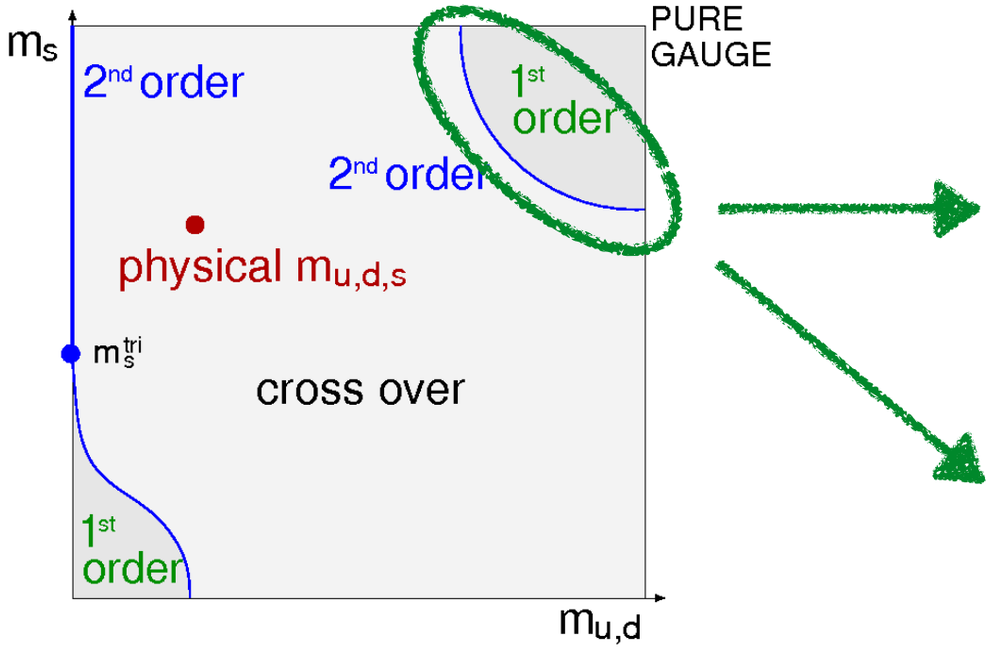


- Deconfinement transition in agreement with lattice QCD
- Correct tricritical scaling
- Roberge-Weiss-transition seen

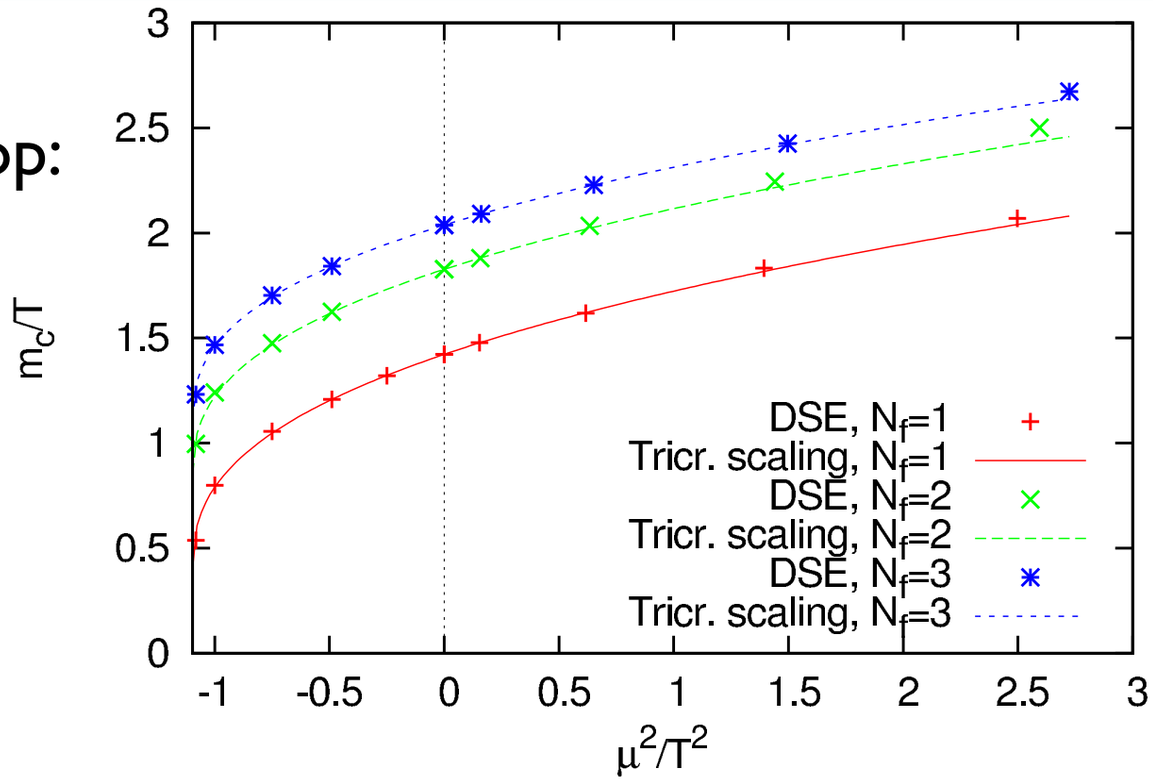
Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

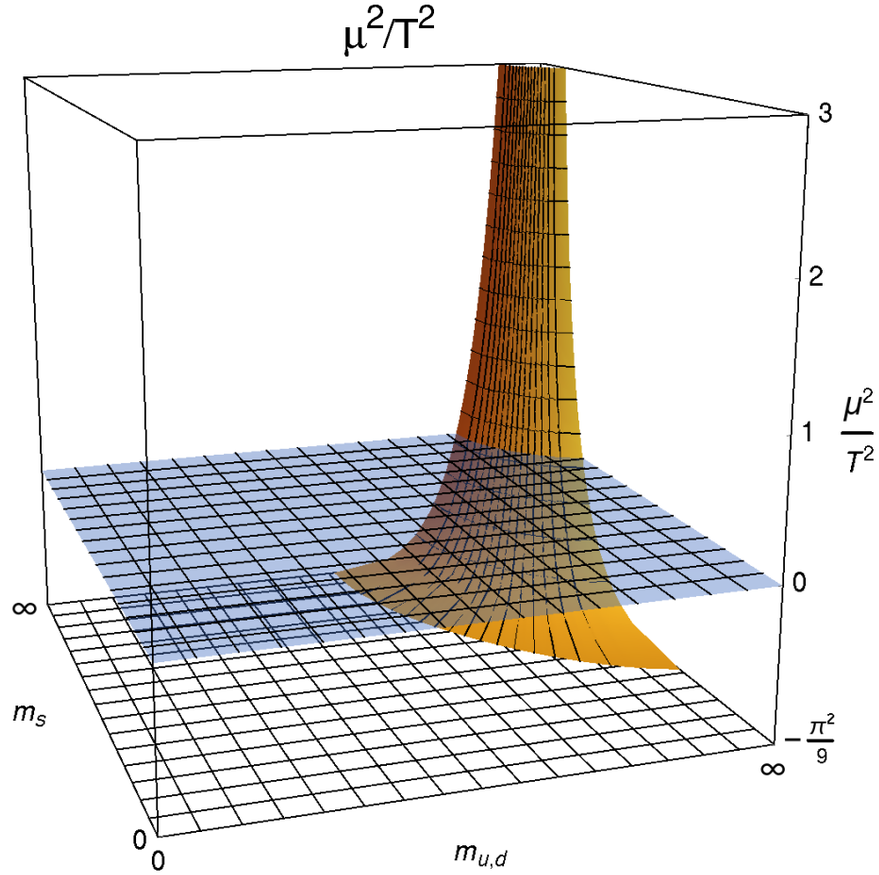
CF, Luecker, Pawlowski, PRD 91 (2015) 1

Critical line/surface for heavy quarks



Polyakov Loop:





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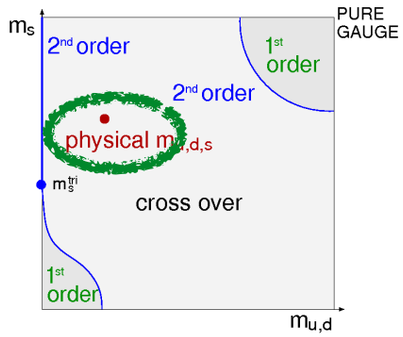
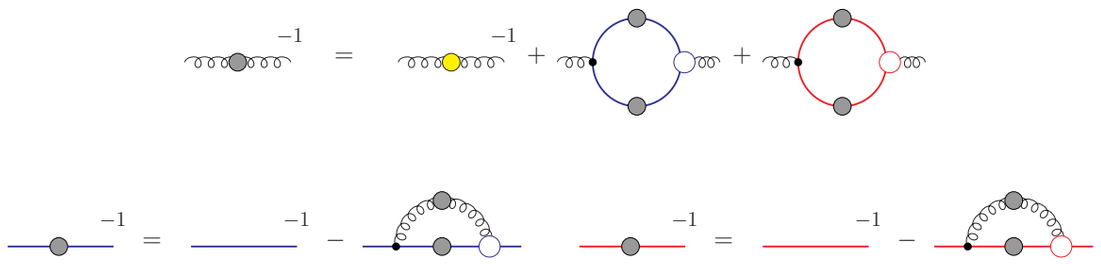
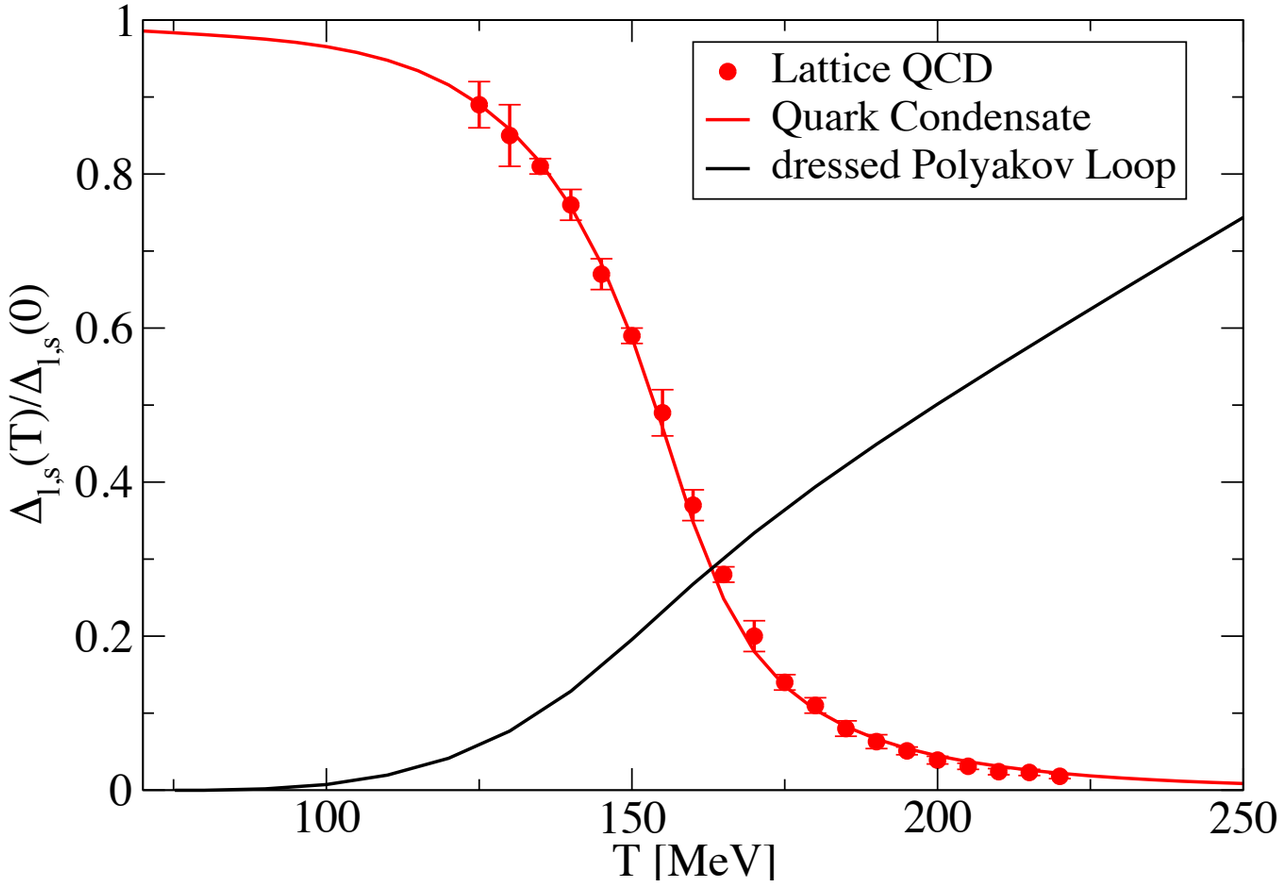
N_f=2+1, μ=0, physical point







Lattice: Borsanyi *et al.* [Wuppertal-Budapest], JHEP 1009(2010) 073
DSE: CF, Luecker, PLB 718 (2013) 1036,
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

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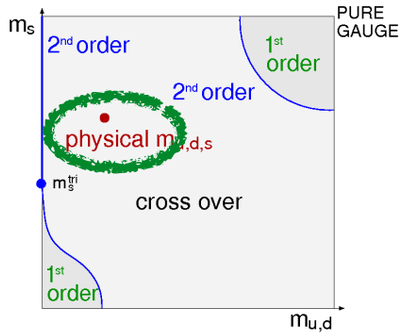

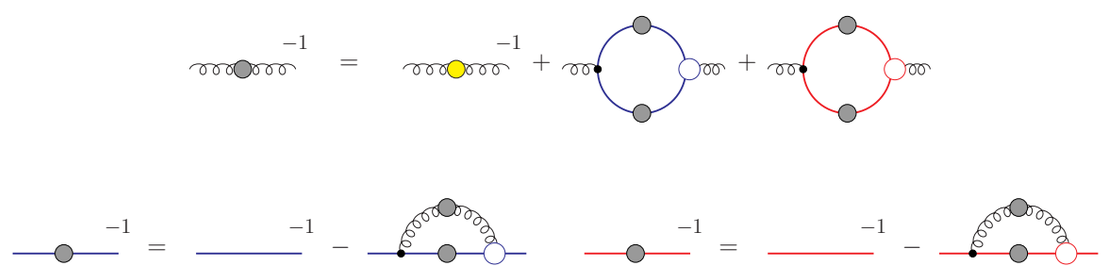

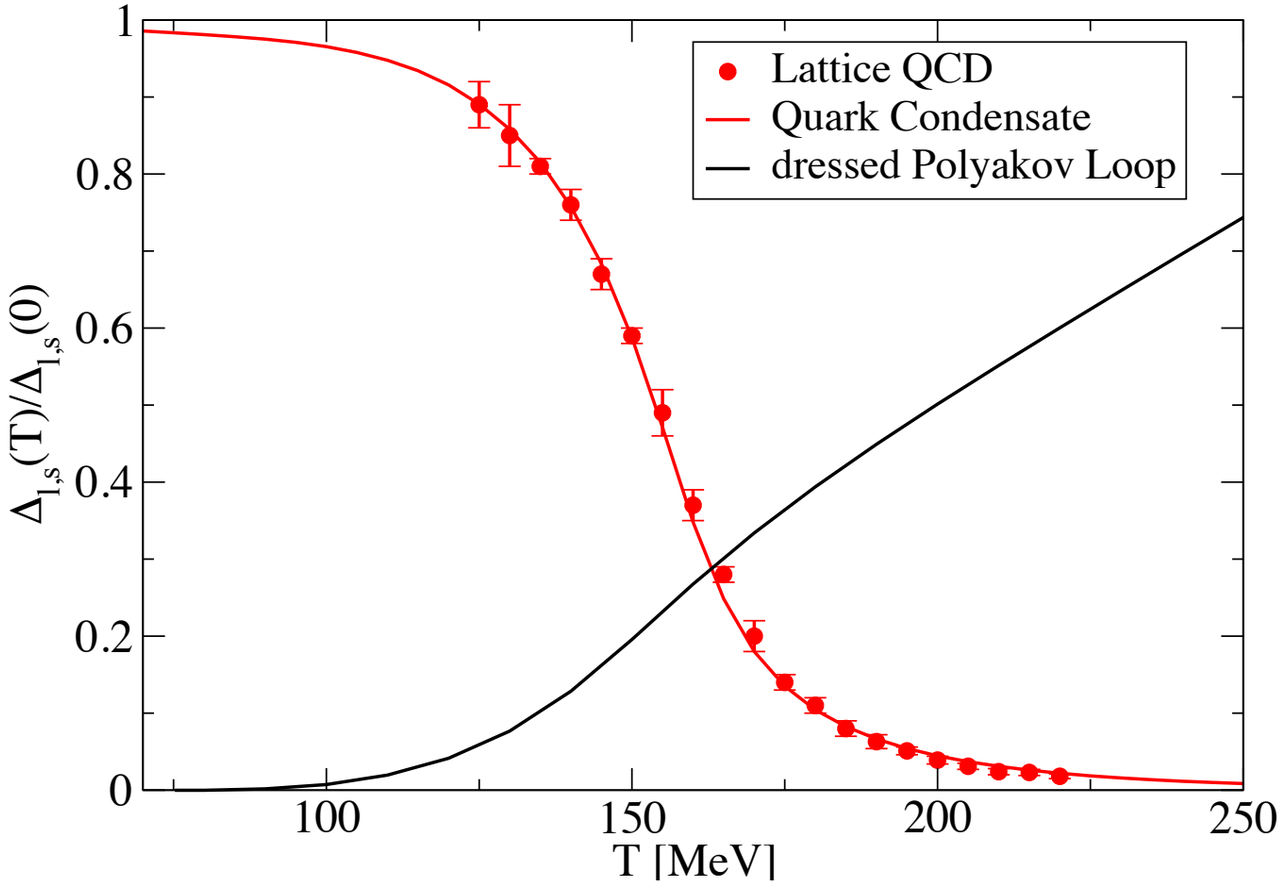

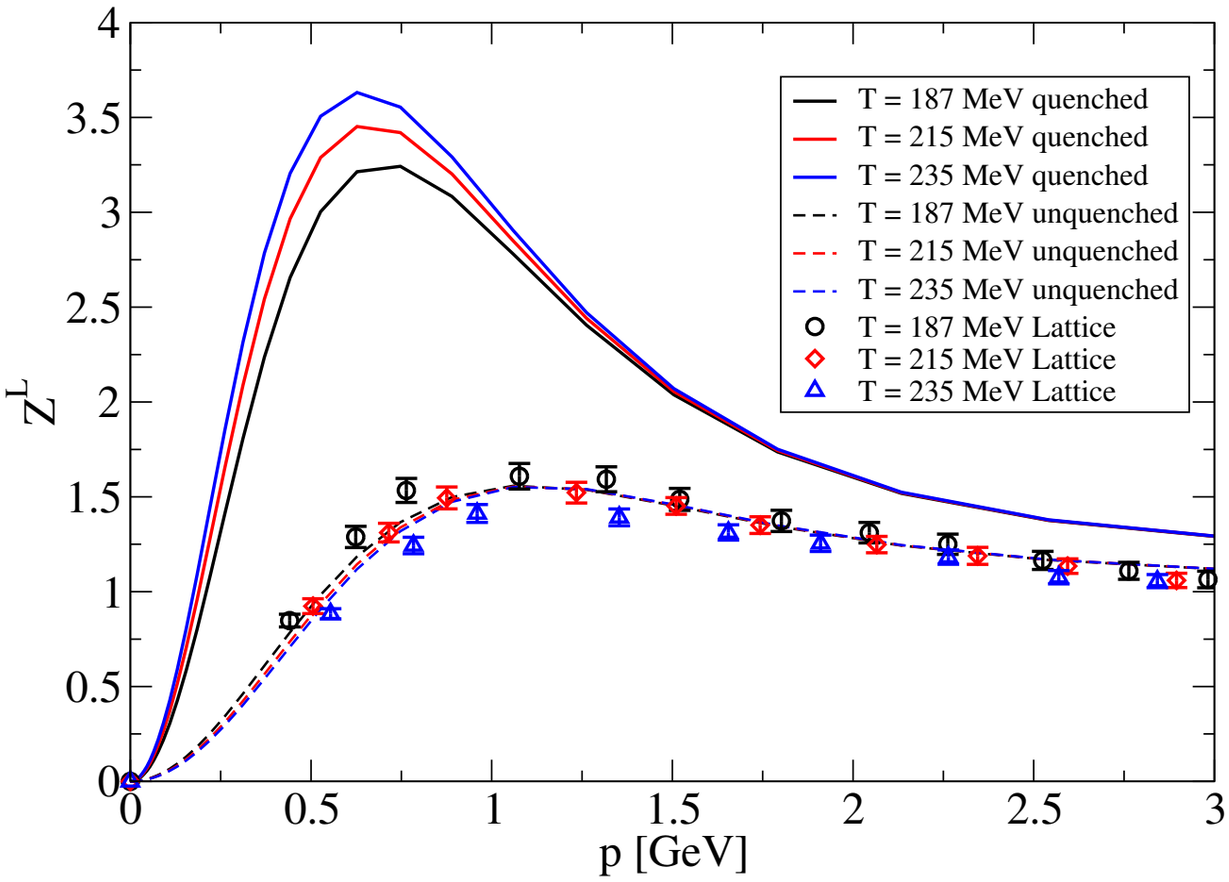

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- quantitative agreement: DSE prediction verified by lattice

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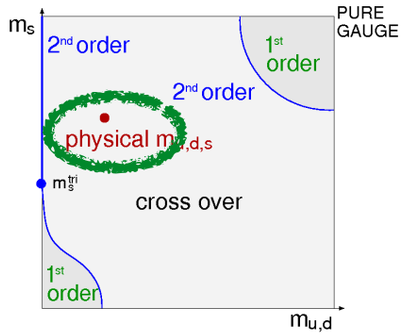

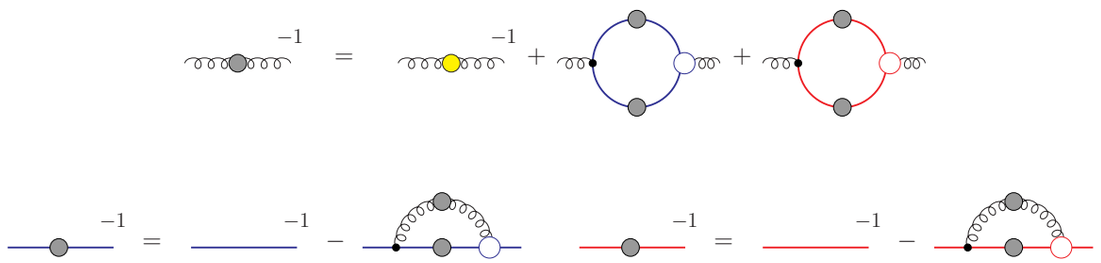

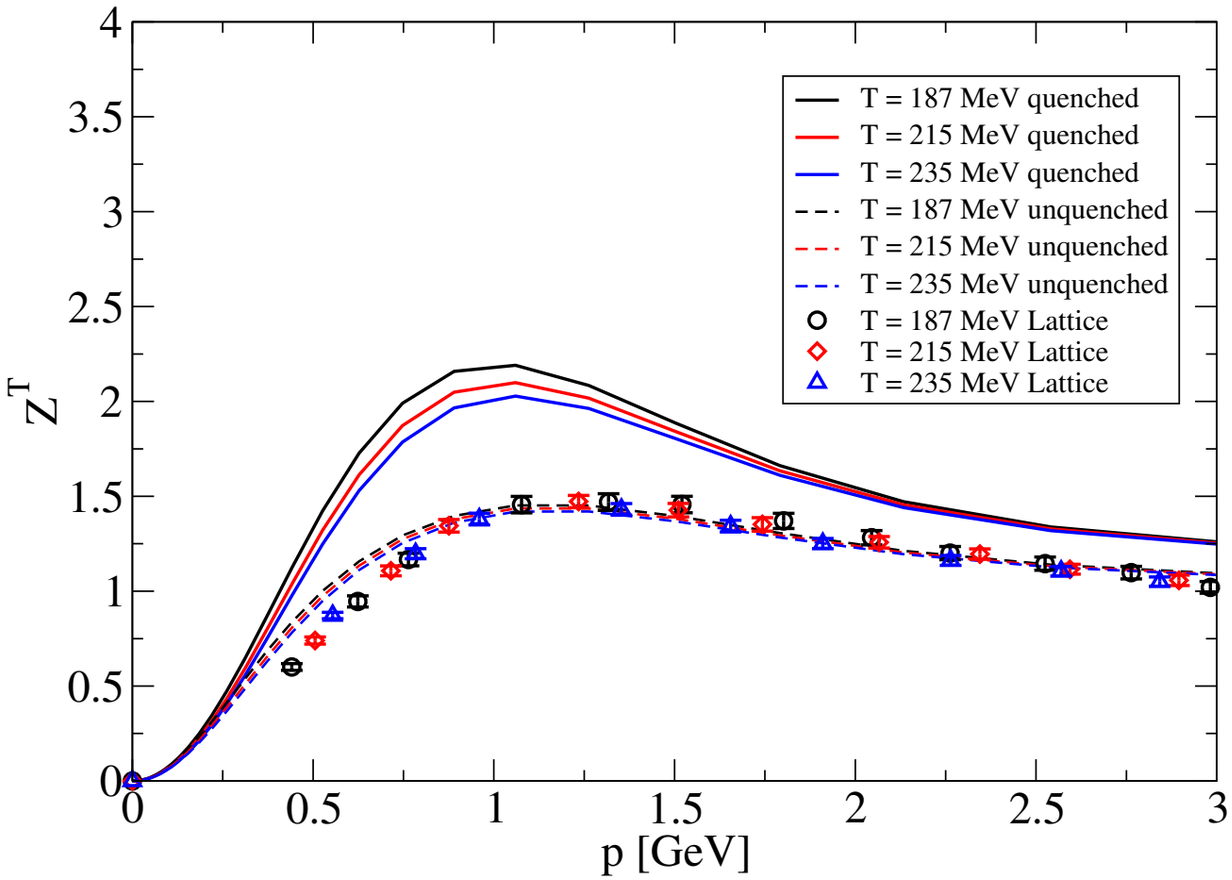

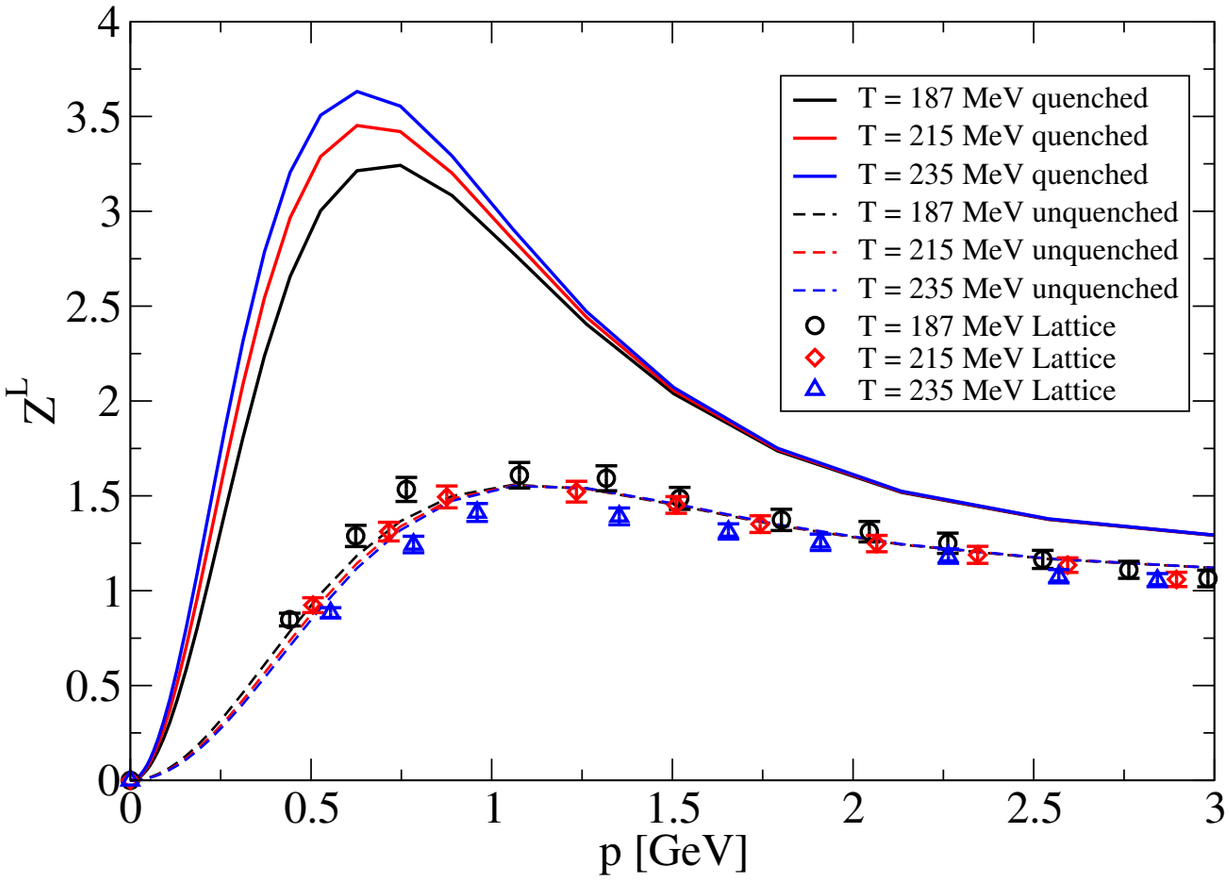

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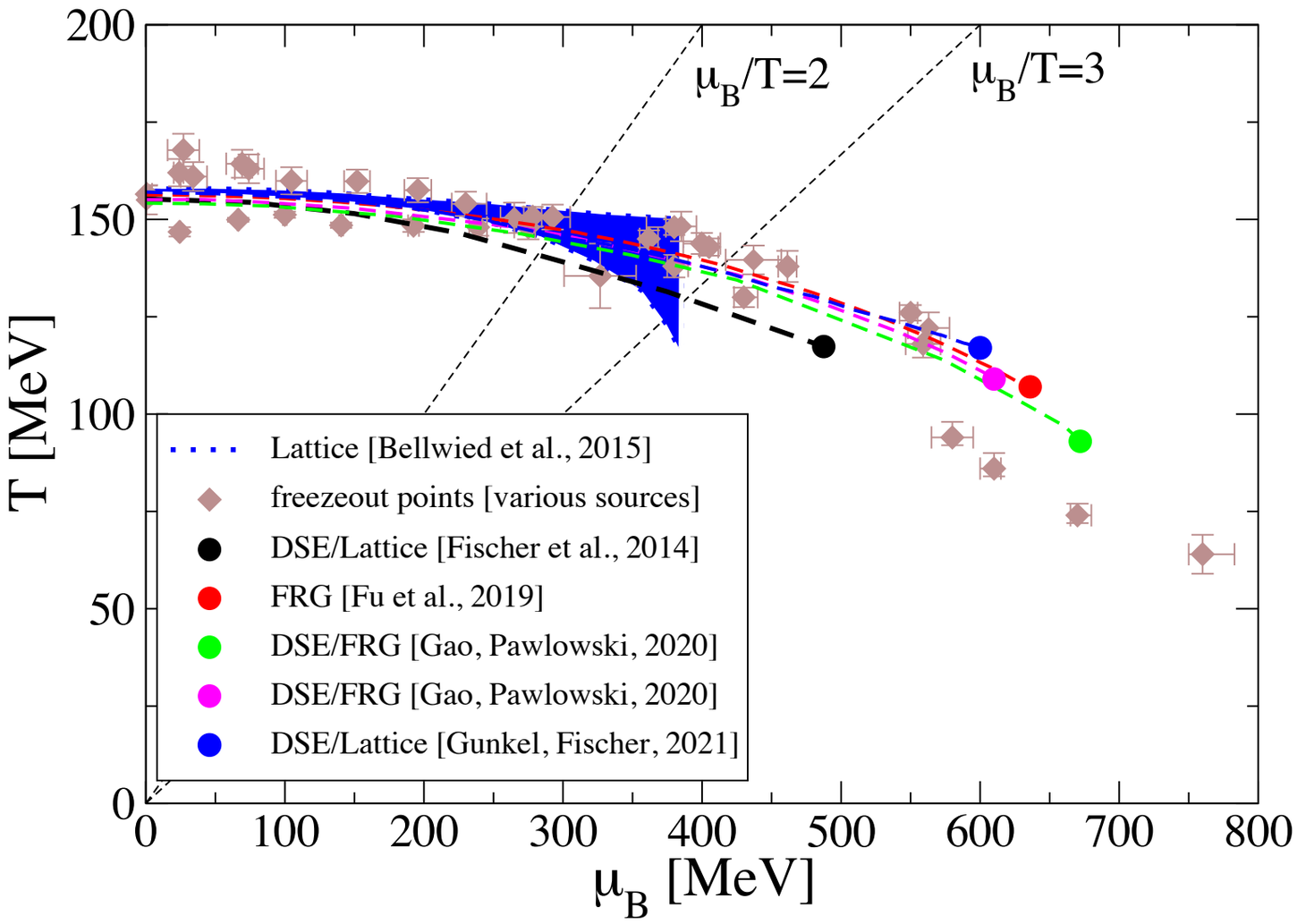
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

- quantitative agreement: DSE prediction verified by lattice

Location of CEP in freeze-out landscape



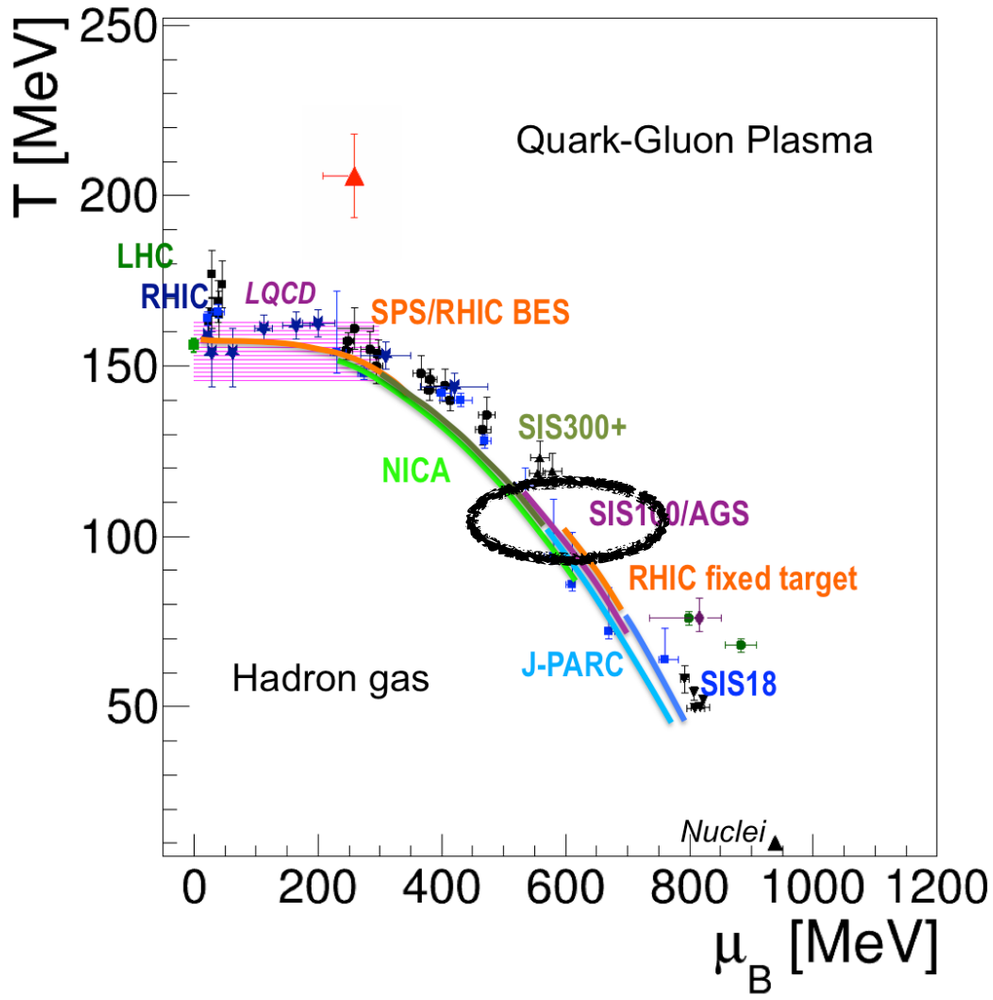
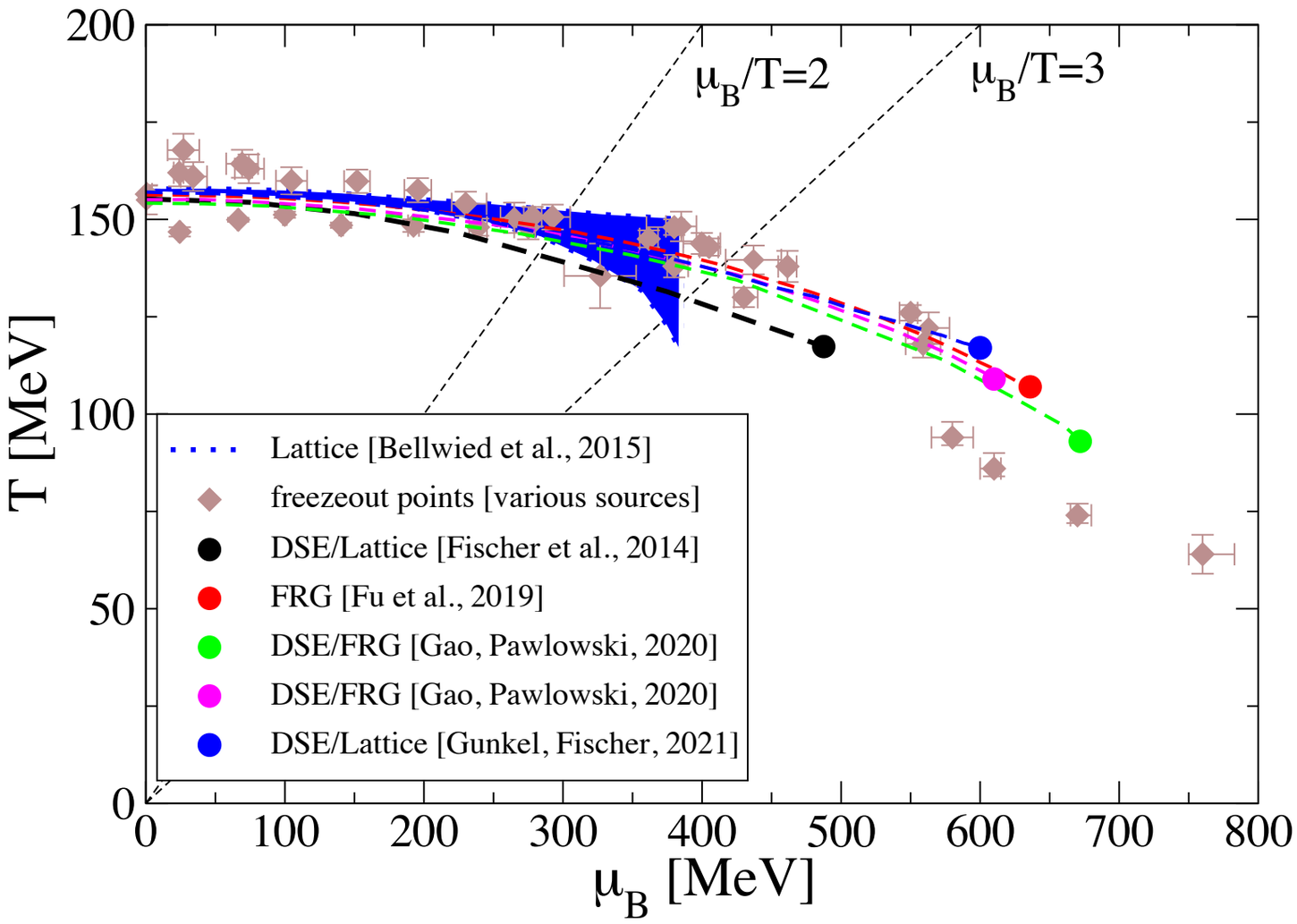


Figure adapted from talk of T. Galatyuk, Erice 2016

- what about truncation error ? how stable is this result ??
  - N_f=2+1+1
  - baryon and meson effects ?
  - crosscheck with FRG

Location of CEP in freeze-out landscape



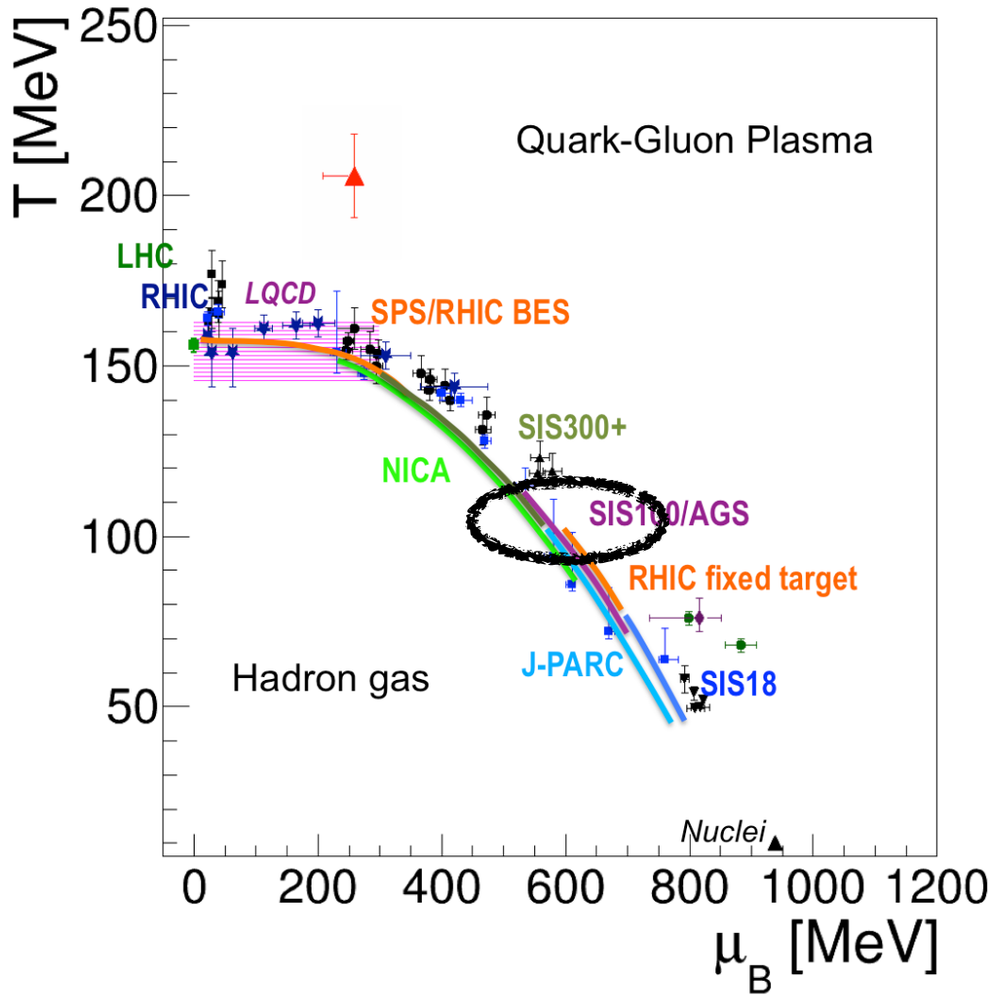
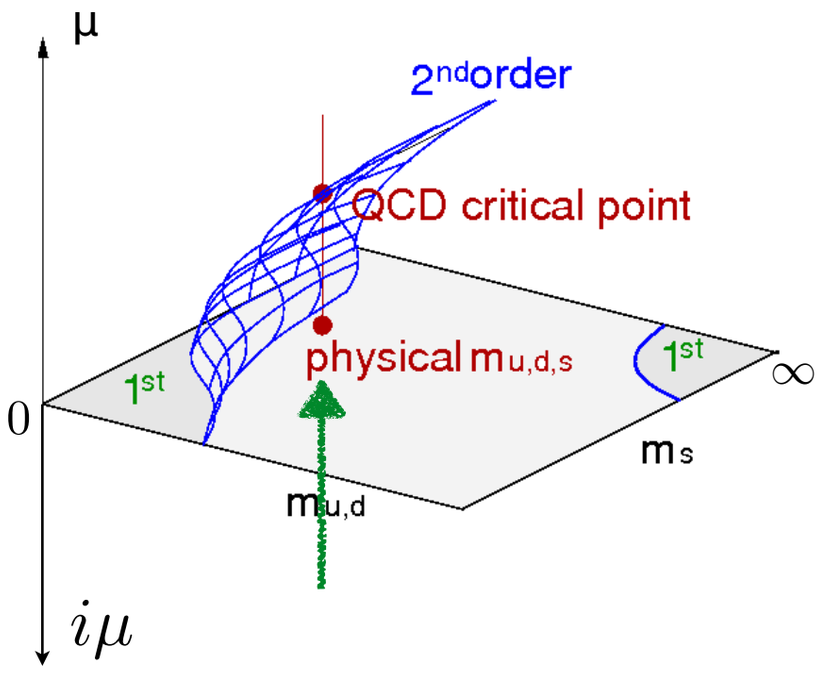


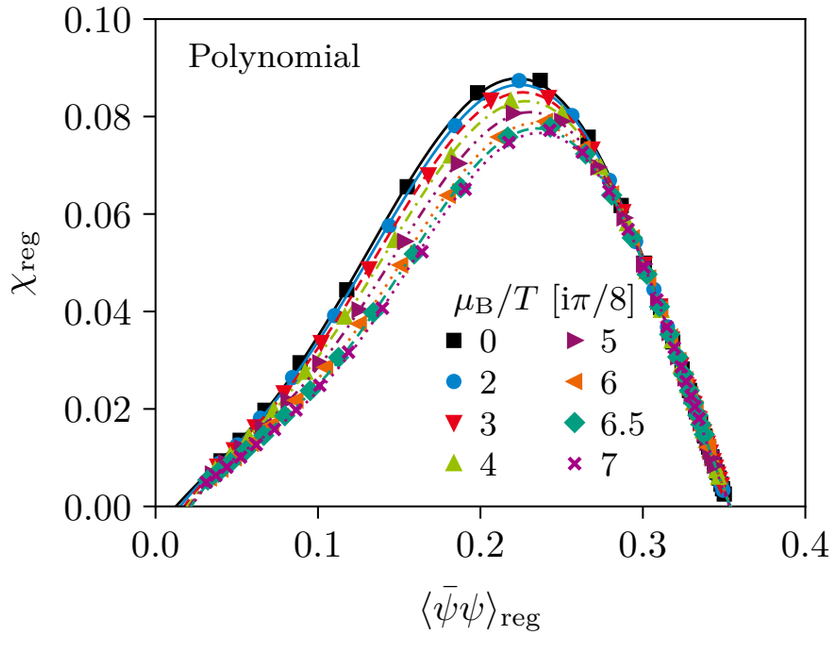
Figure adapted from talk of T. Galatyuk, Erice 2016

- what about truncation error ? how stable is this result ??
  - N_f=2+1+1
  - baryon and meson effects ?
  - crosscheck with FRG
- inhomogeneous phases ?

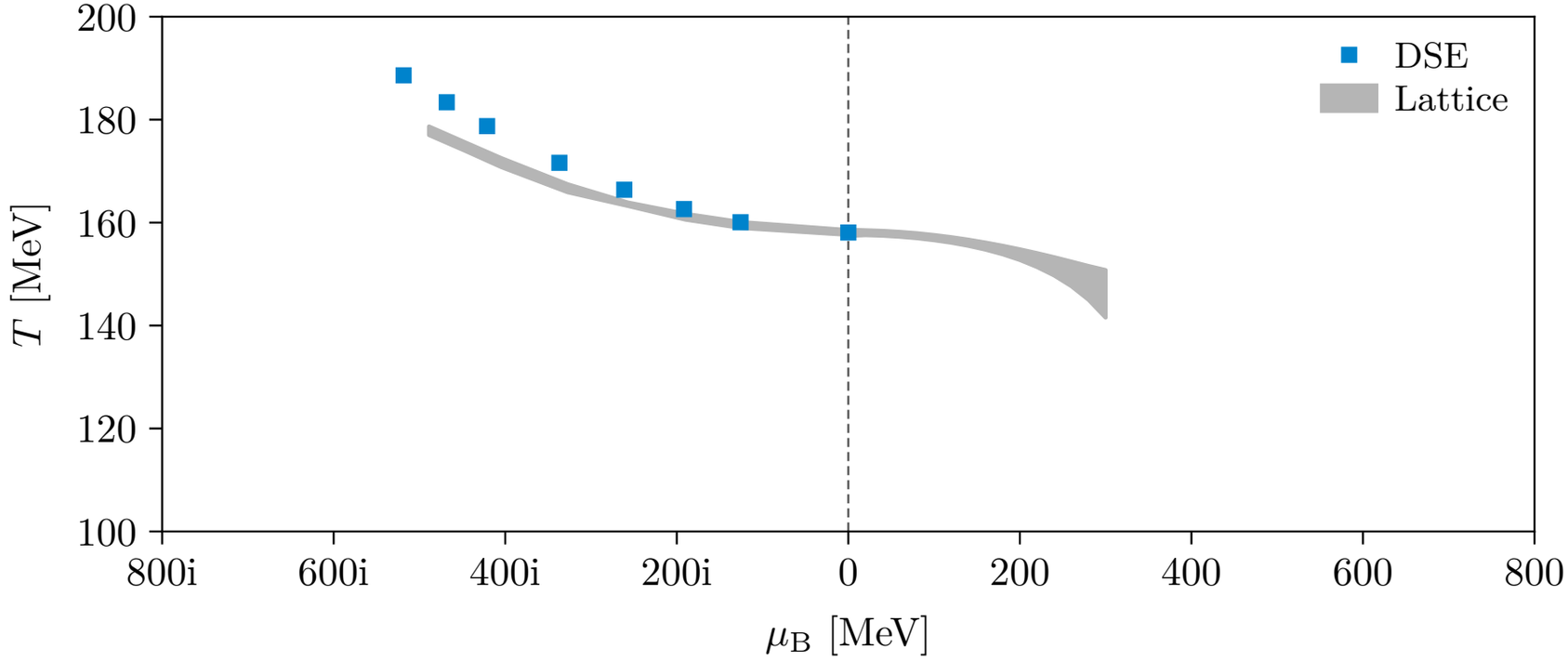
Buballa and Carignano, PPNP 81 (2015) 39

Extrapolation from imaginary chemical potential





$$\chi(T) = \frac{\partial\langle\bar{\psi}\psi\rangle(T)}{\partial m_{\rm u}}$$

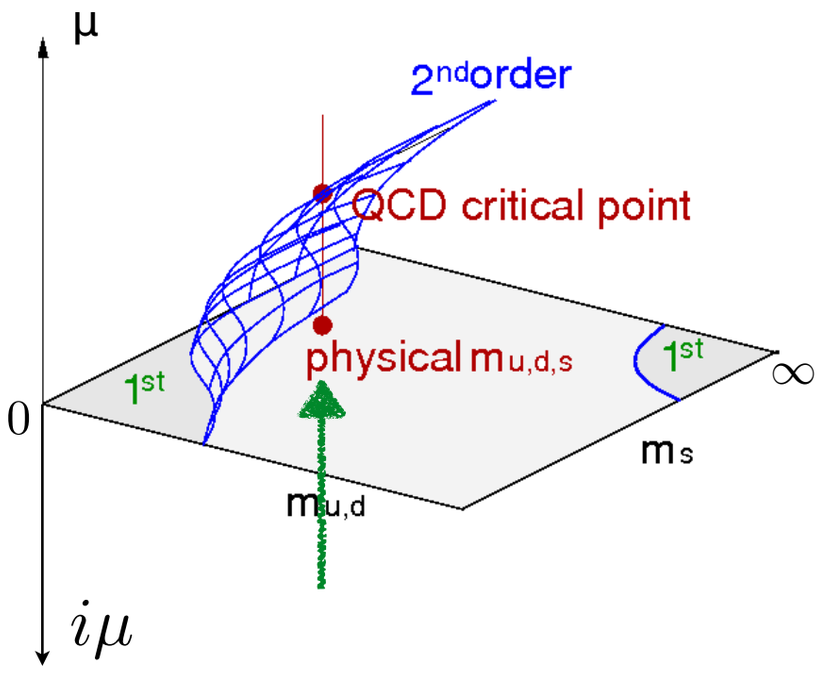


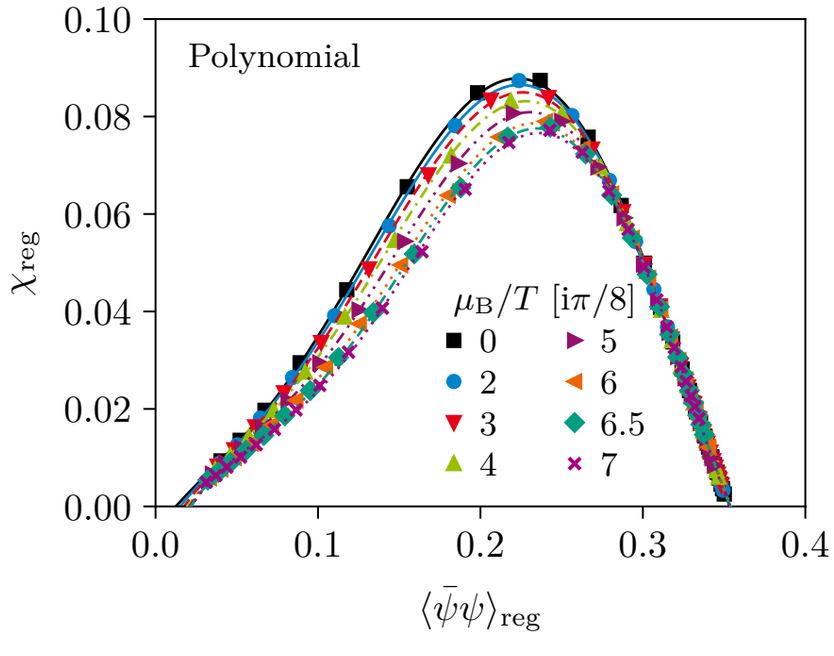
Lattice: Borsanyi et al. PRL 125 052001 (2020)
DSE: Bernhardt, CF, arXiv: 2305.01434

$$\frac{T_{\rm c}(\mu_{\rm B})}{T_{\rm c}} = 1 - \kappa_2\left(\frac{\mu_{\rm B}}{T_{\rm c}}\right)^2 - \kappa_4\left(\frac{\mu_{\rm B}}{T_{\rm c}}\right)^4$$

$$\kappa_2^{\rm poly} = 0.0196\,, \quad \kappa_4^{\rm poly} = 0.00015\,,$$

Extrapolation from imaginary chemical potential





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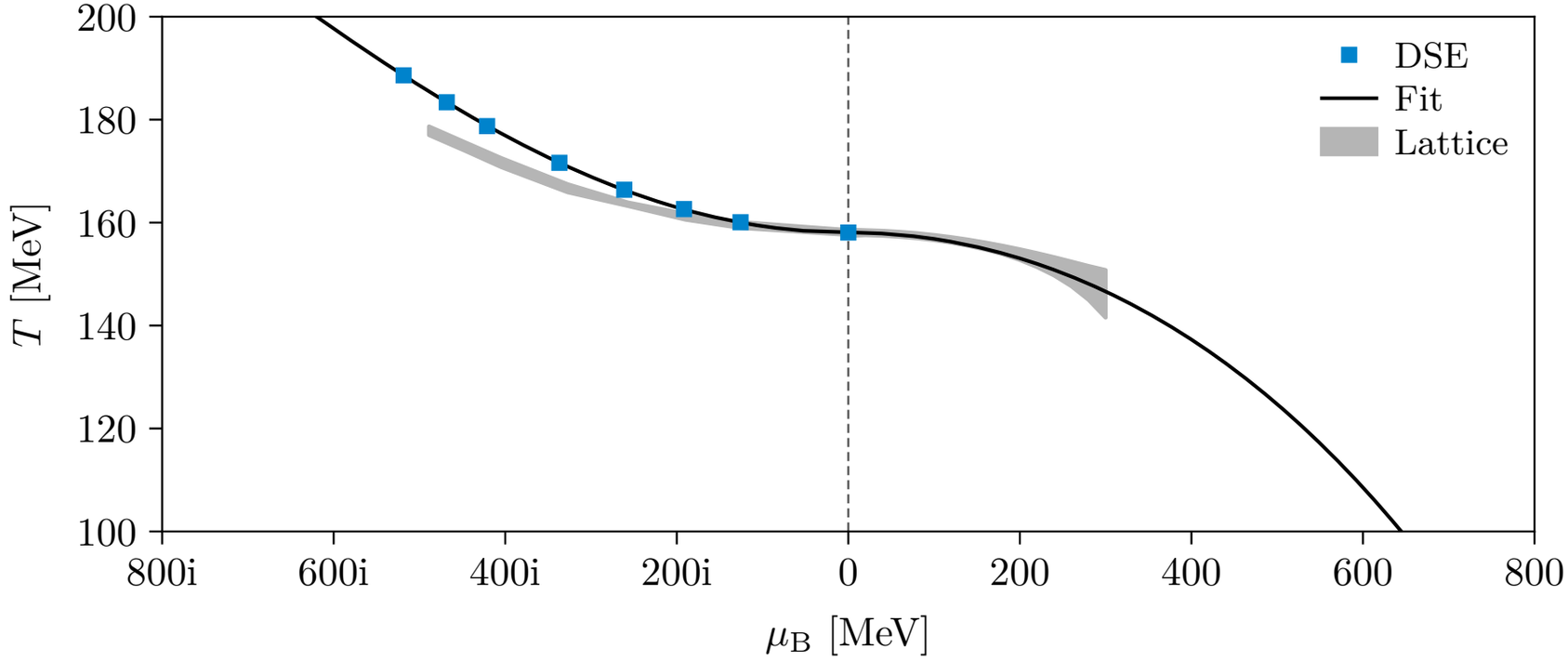

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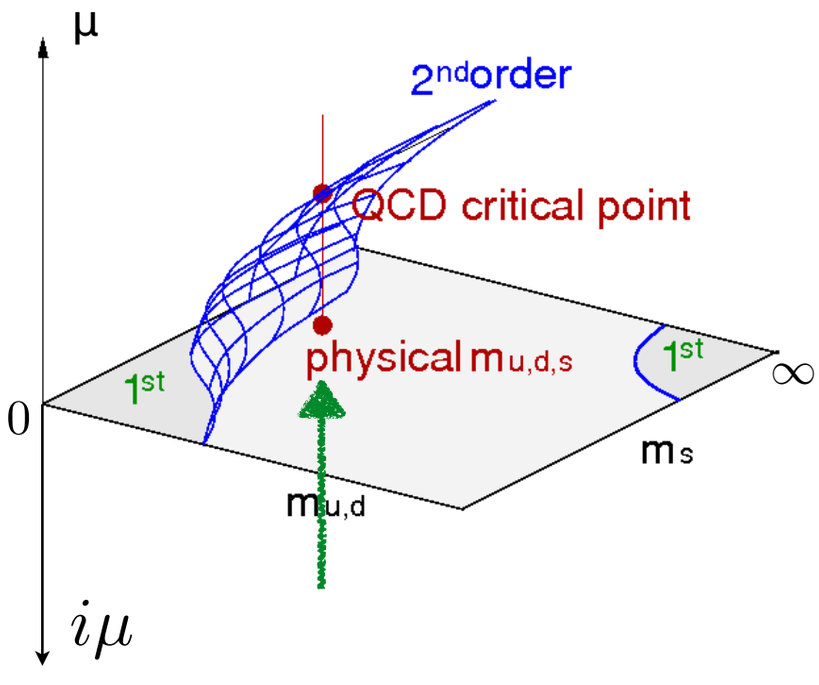

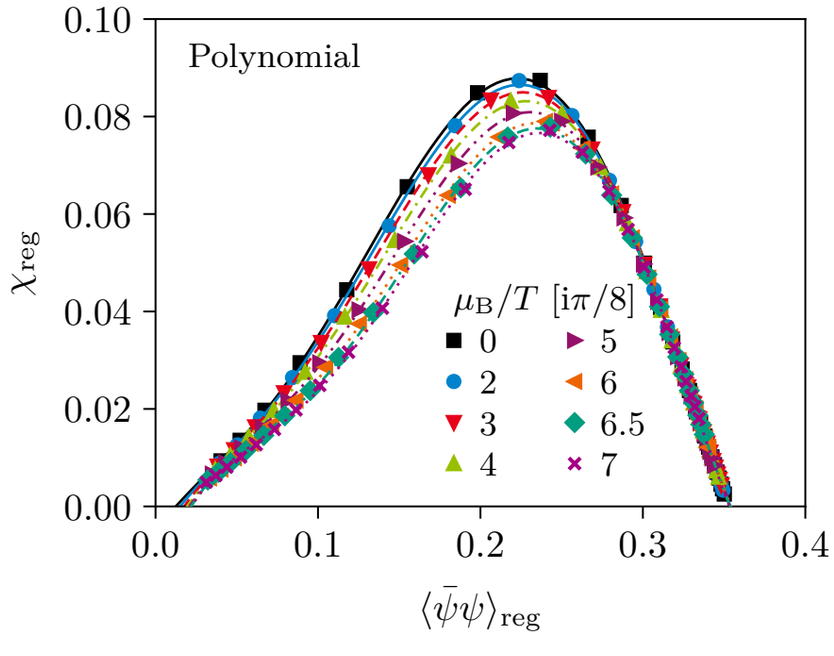

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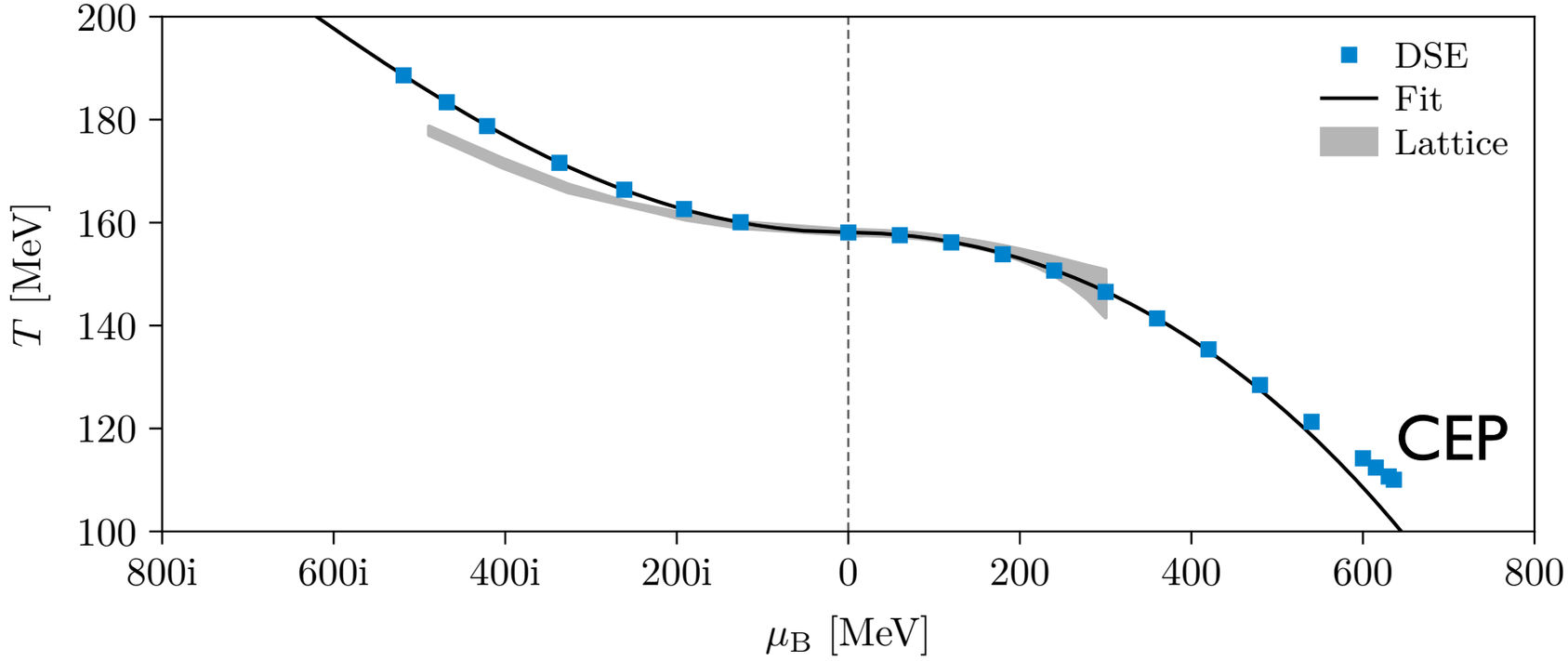

Lattice: Borsanyi et al. PRL 125 052001 (2020)
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- Extrapolation works very well!

$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa_2\left(\frac{\mu_B}{T_c}\right)^2 - \kappa_4\left(\frac{\mu_B}{T_c}\right)^4$$

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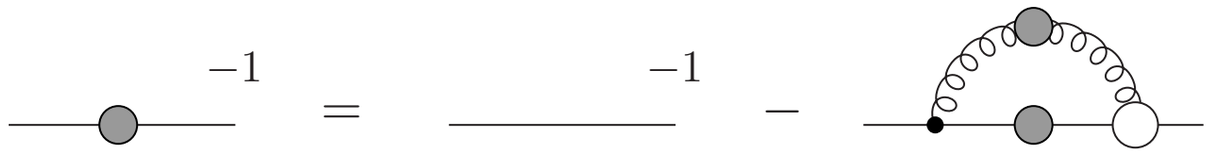
Overview

1.Introduction



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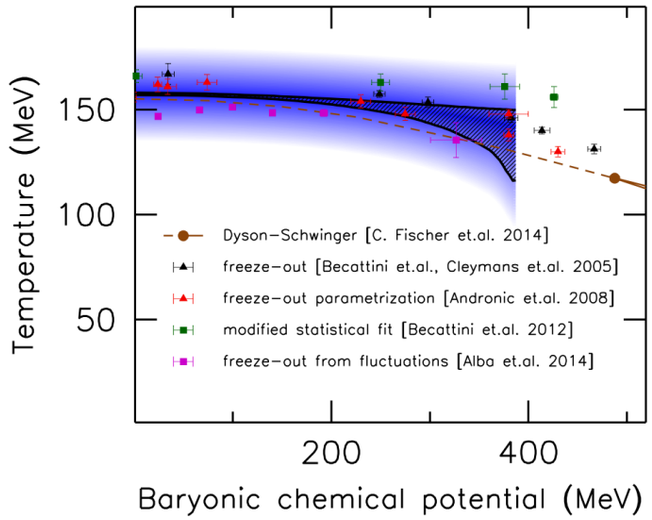

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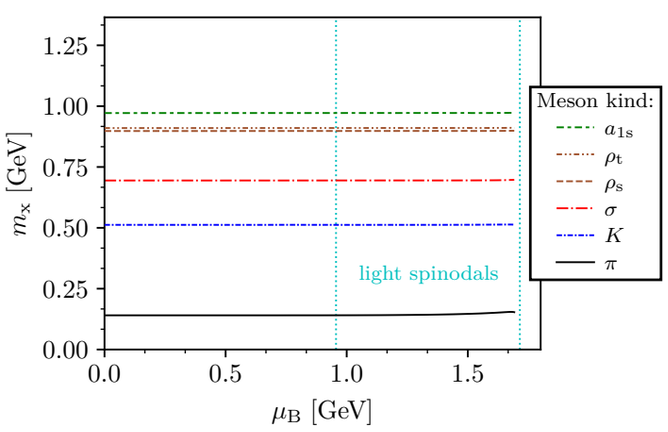
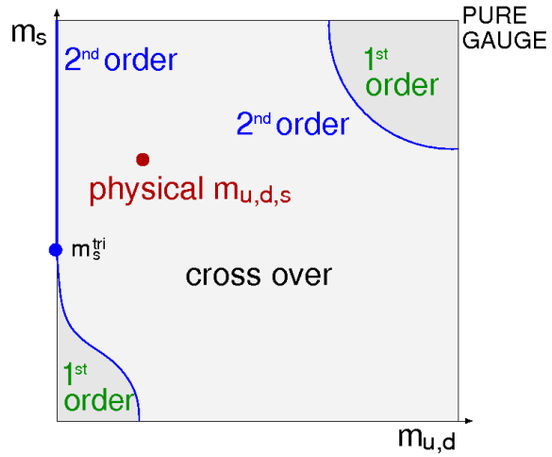
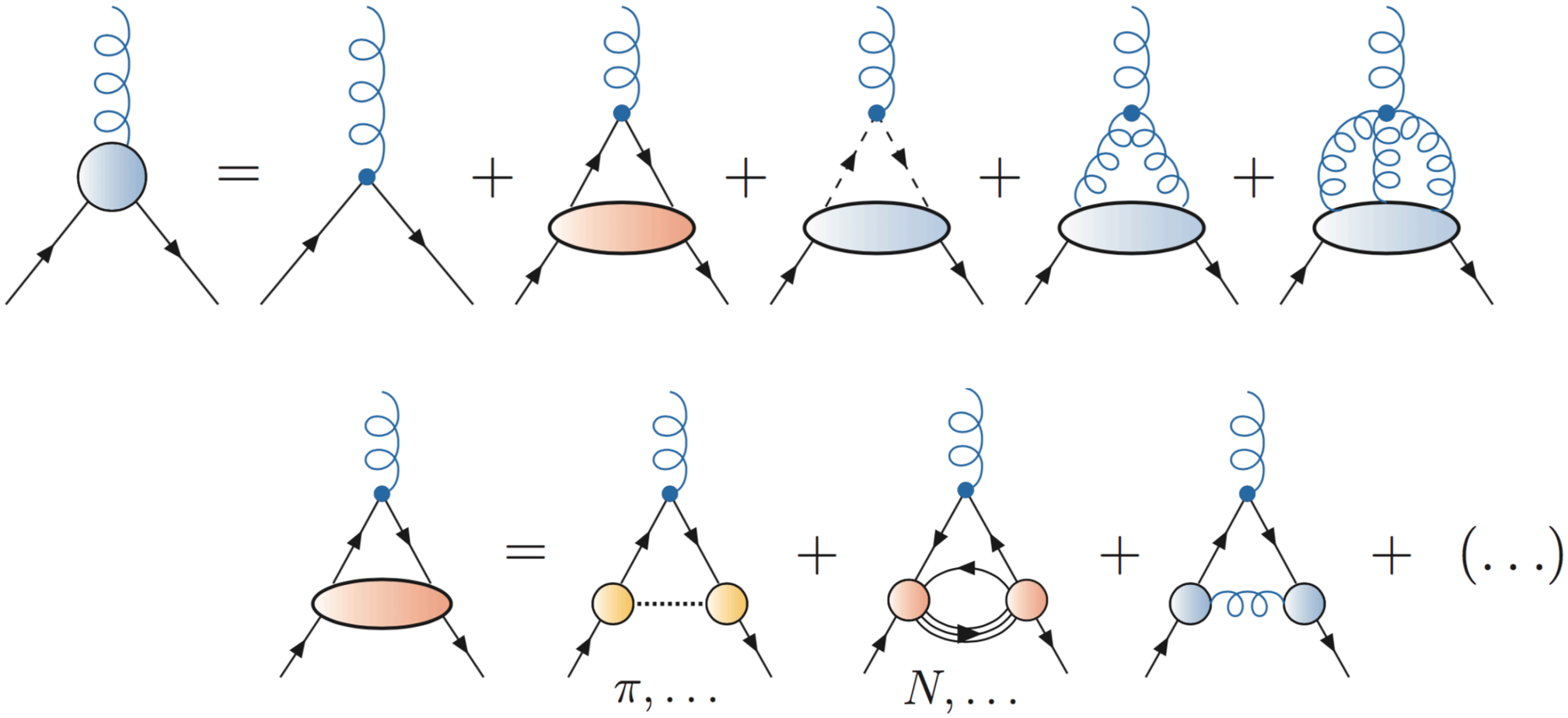


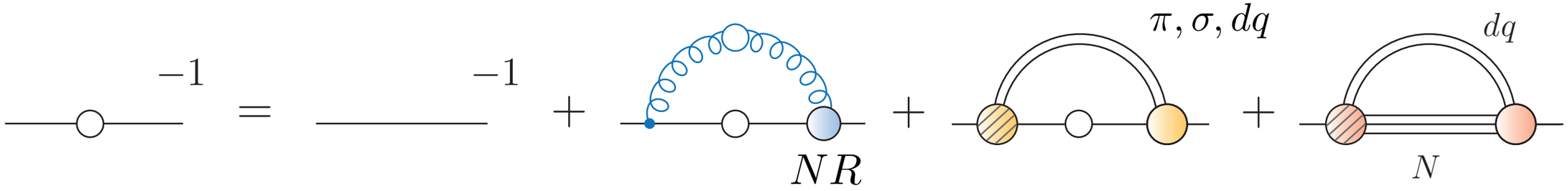


Hadron effects in quark-gluon interaction

quark-gluon vertex:



quark:



Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]

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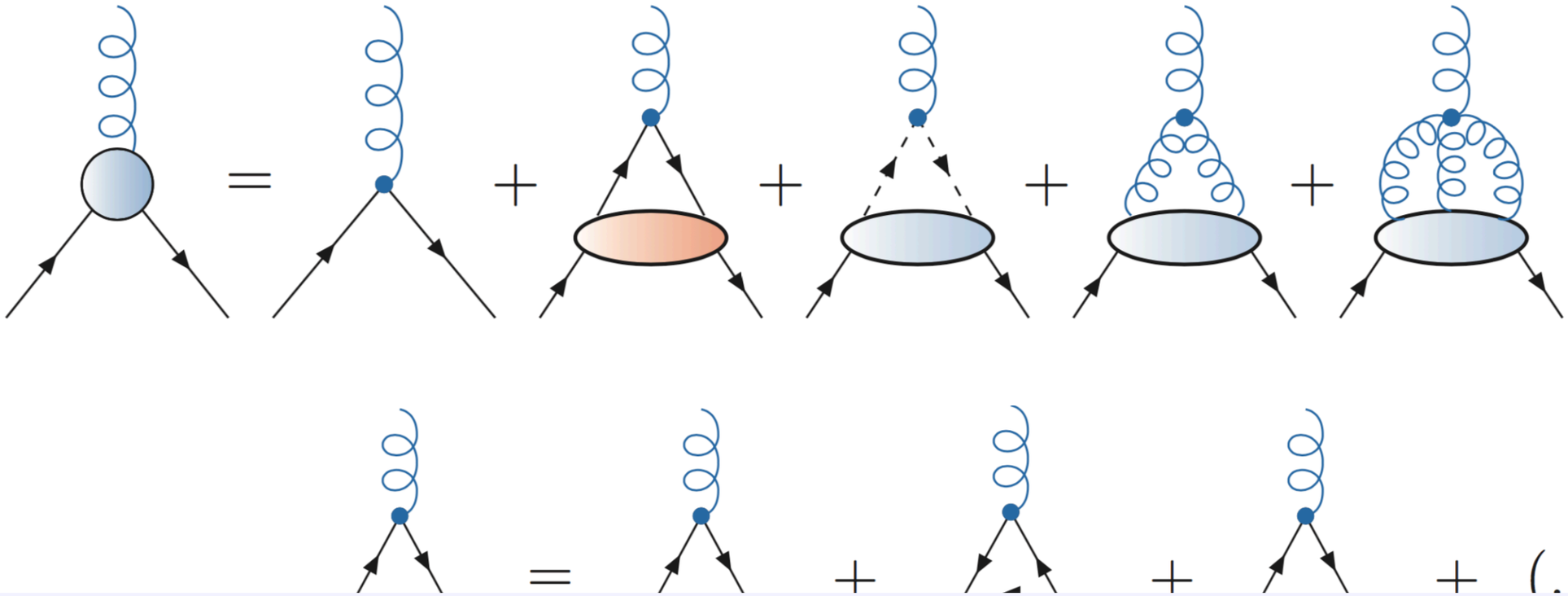
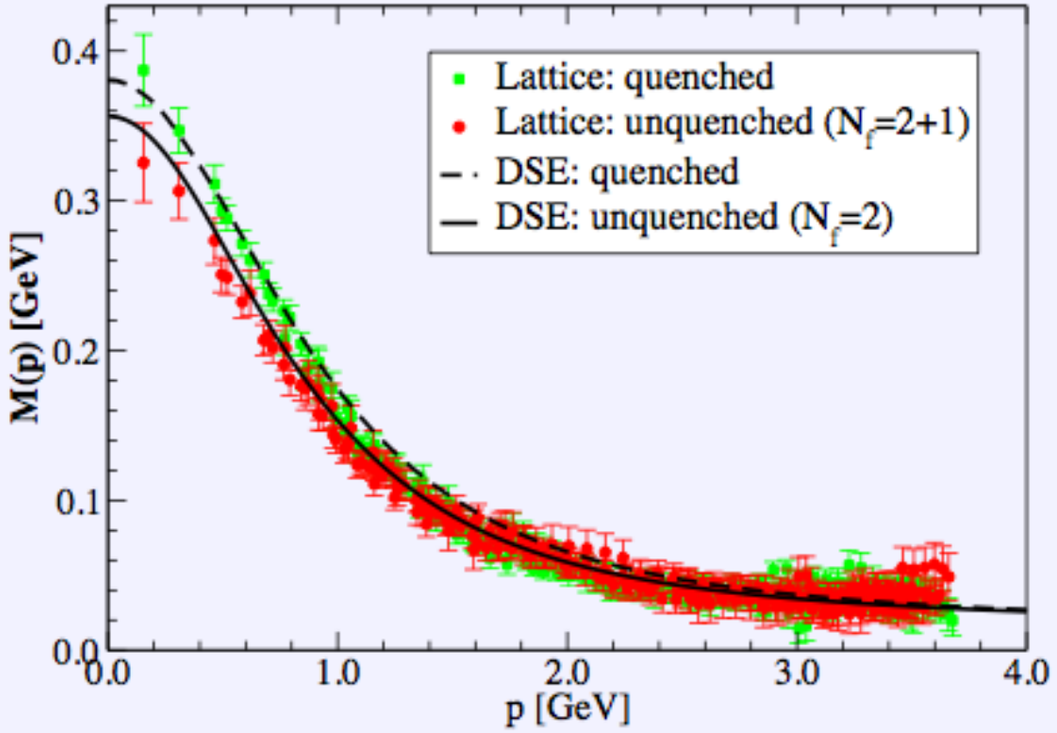
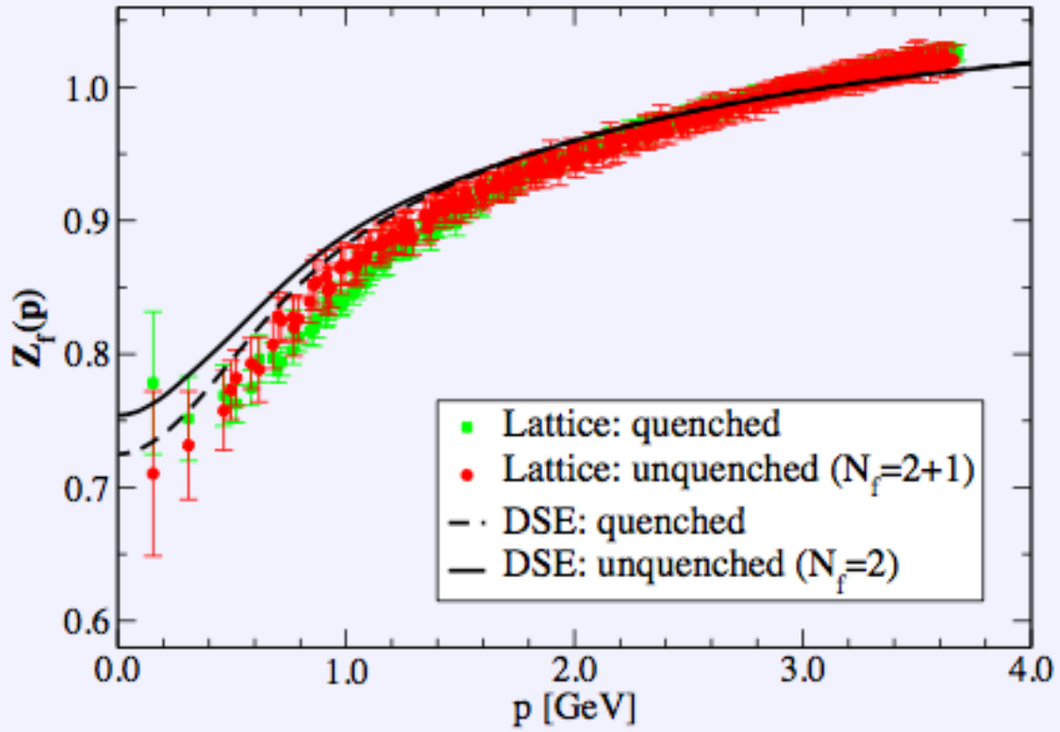


quark:

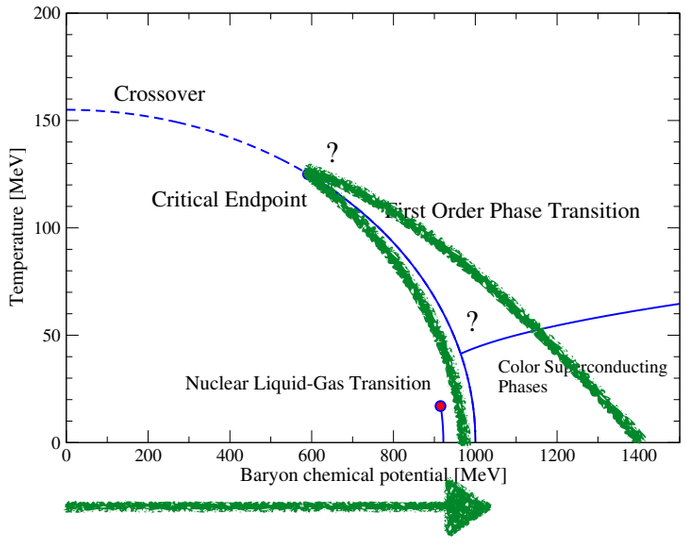


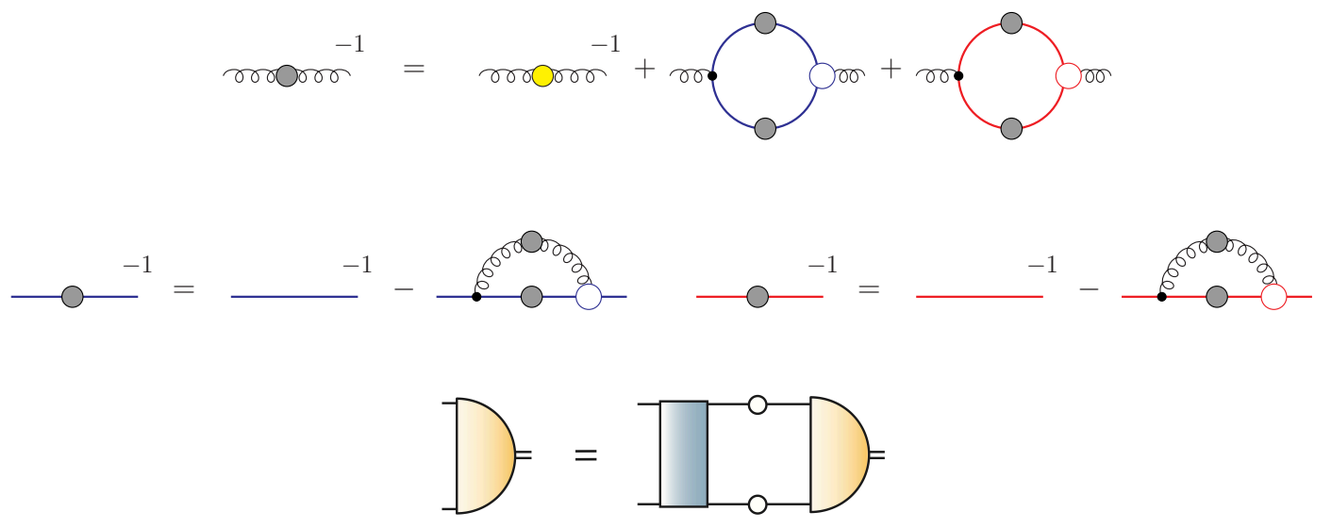


CF, D. Nickel and R. Williams, EPJC **60**, 1434 (2008)

Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]

Meson properties at finite chemical potential

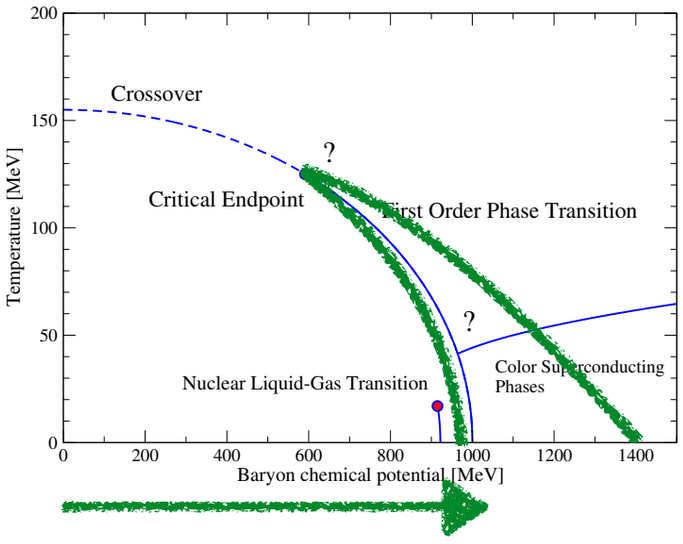


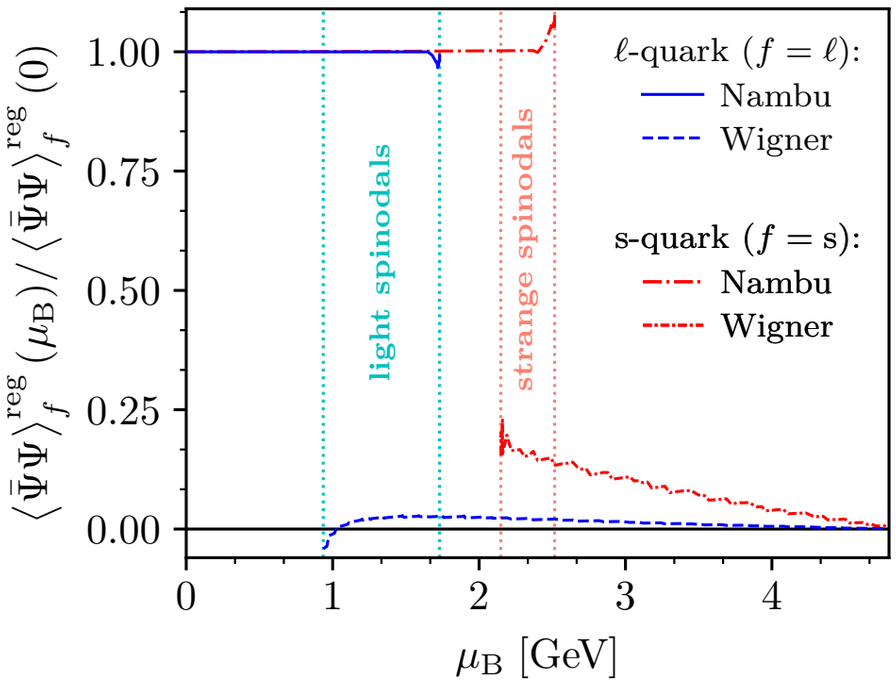


- Quarks/meson wave functions do change !

Gunkel, CF, Isserstedt, EPJ A 55 (2019) no.9, 169
Gunkel, CF, EPJ A 57 (2021) no. 4, 147

Meson properties at finite chemical potential

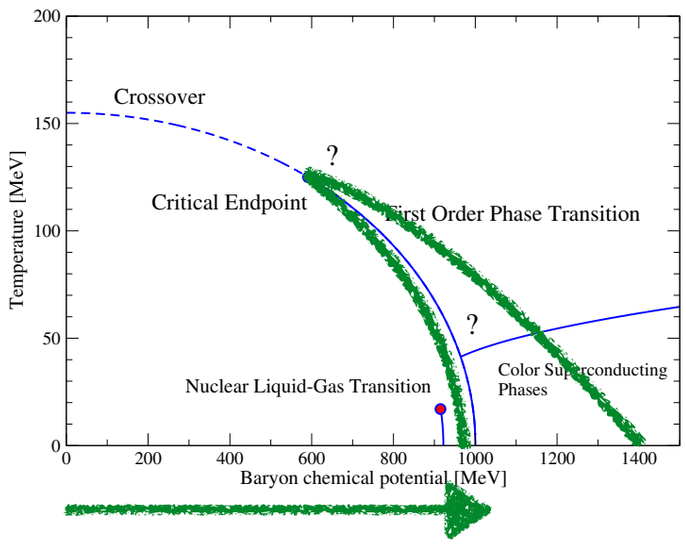


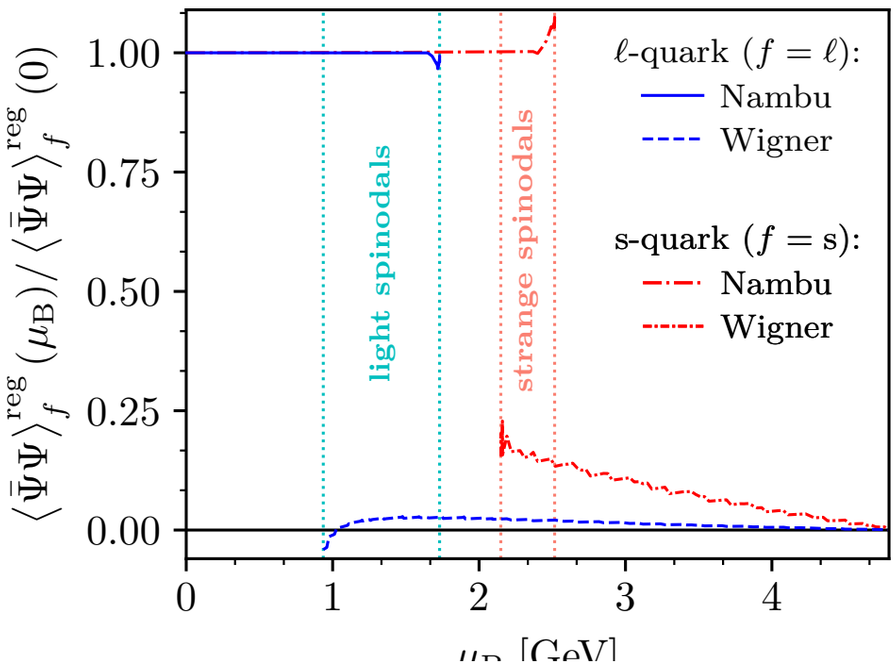


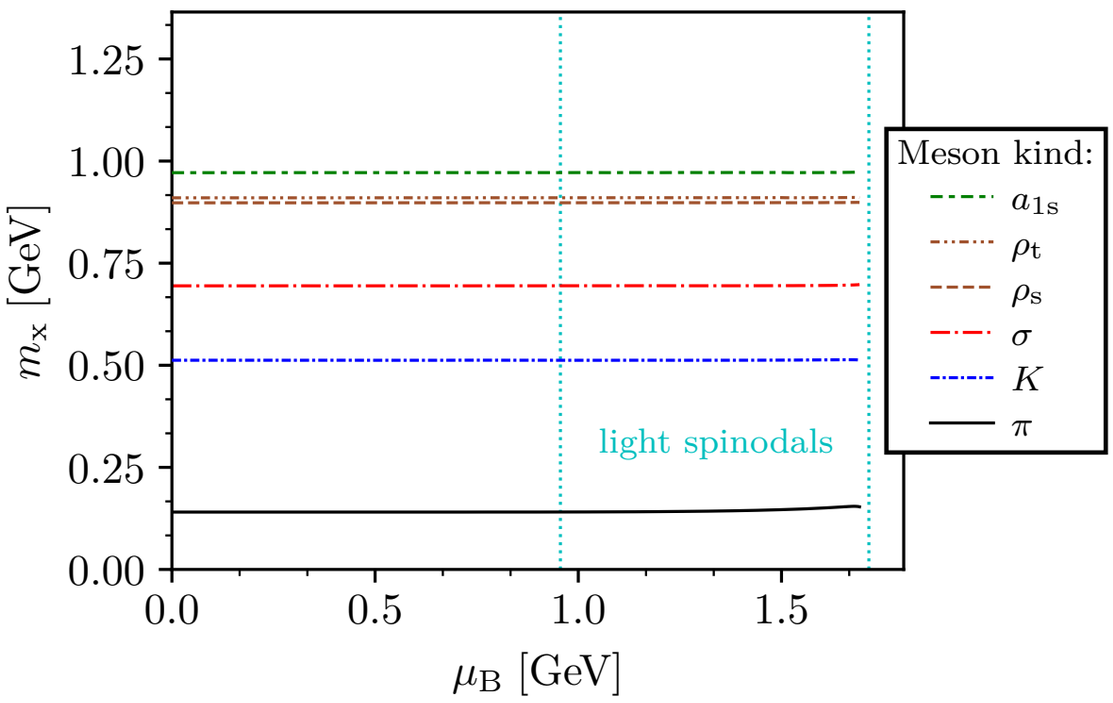
- Quarks/meson wave functions do change !

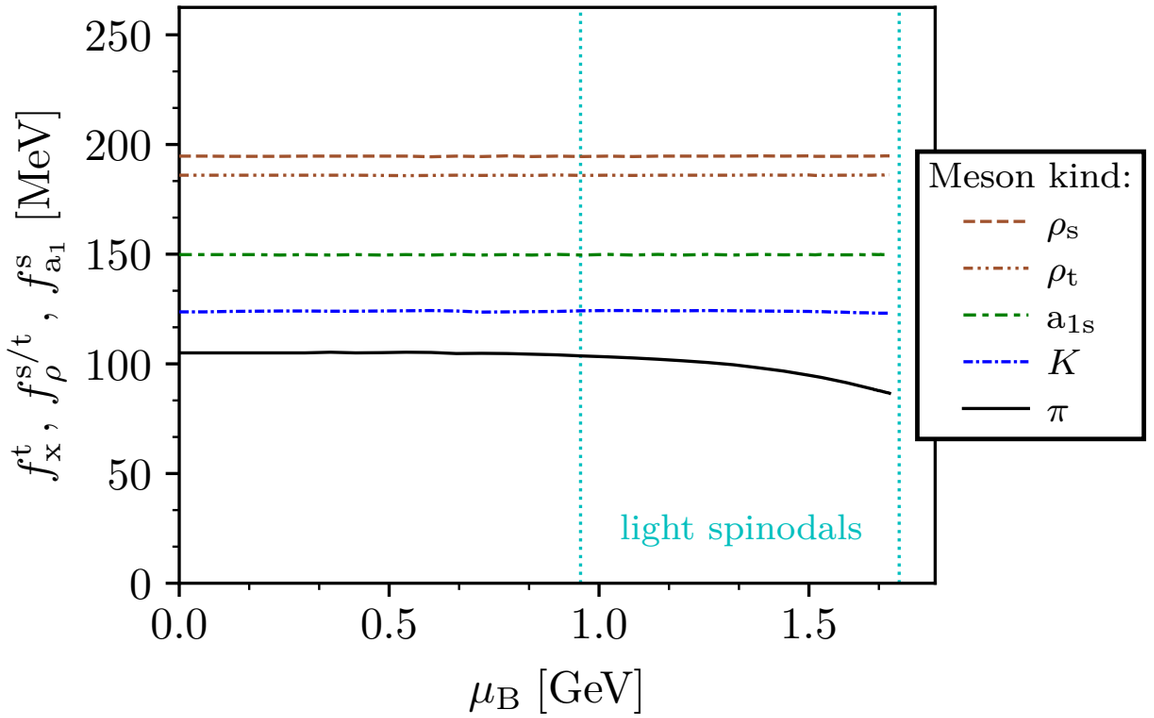
Gunkel, CF, Isserstedt, EPJ A 55 (2019) no.9, 169
Gunkel, CF, EPJ A 57 (2021) no. 4, 147

Meson properties at finite chemical potential







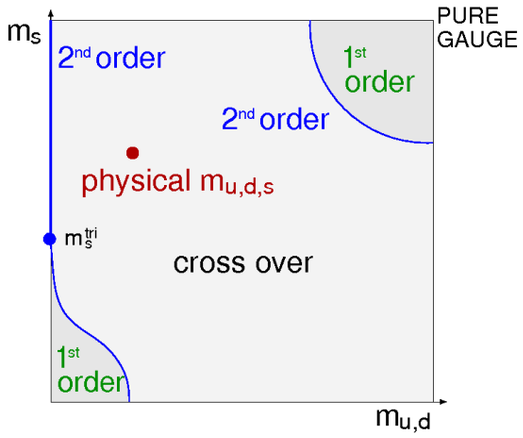


- Quarks/meson wave functions do change !
- But: Silver blaze satisfied

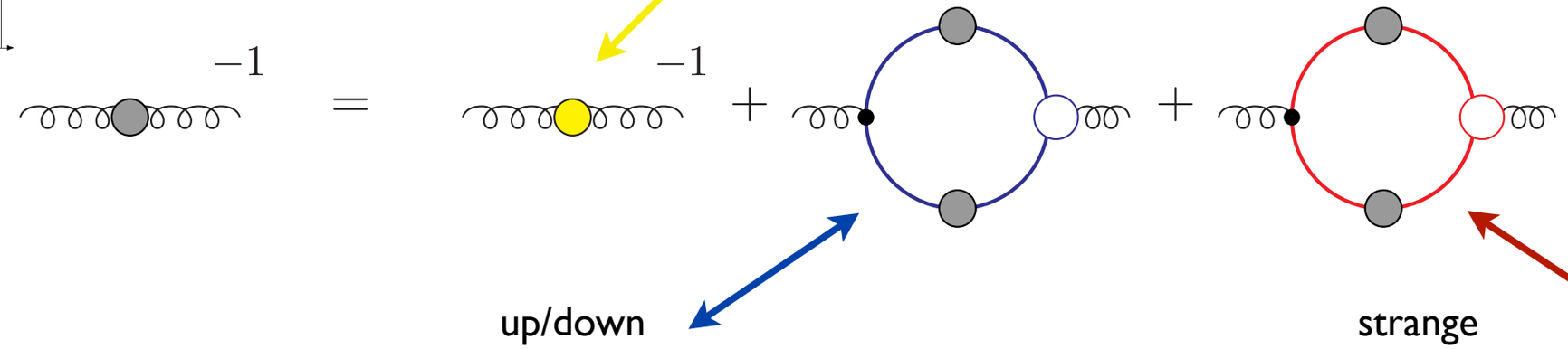
Gunkel, CF, Isserstedt, EPJ A 55 (2019) no.9, 169
Gunkel, CF, EPJ A 57 (2021) no. 4, 147

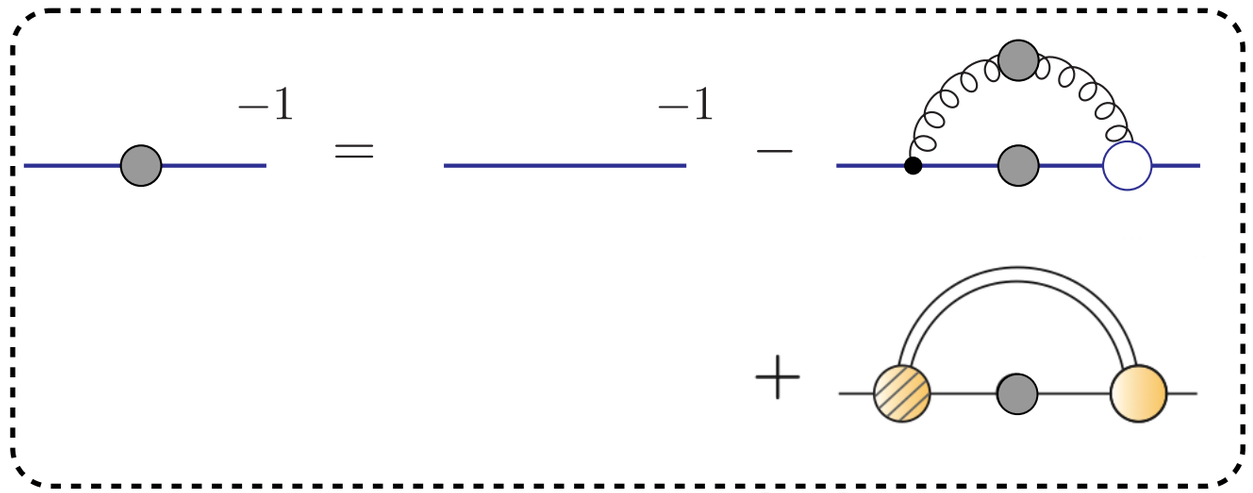
T. D. Cohen, PRL 91 , 222001 (2003)

N_f=2+1-QCD with DSEs and meson backcoupling

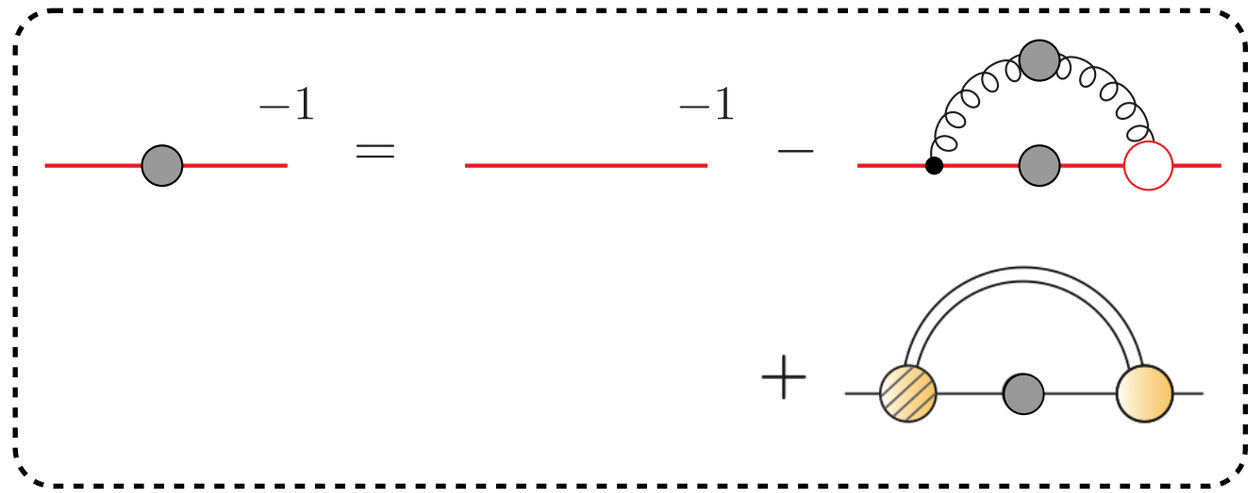


quenched propagator from lattice





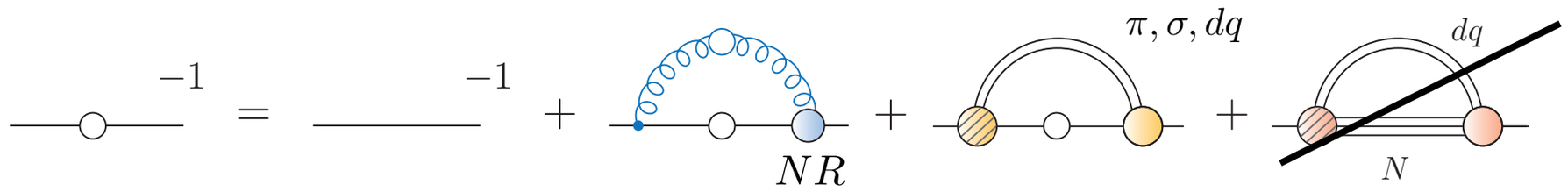
light mesons

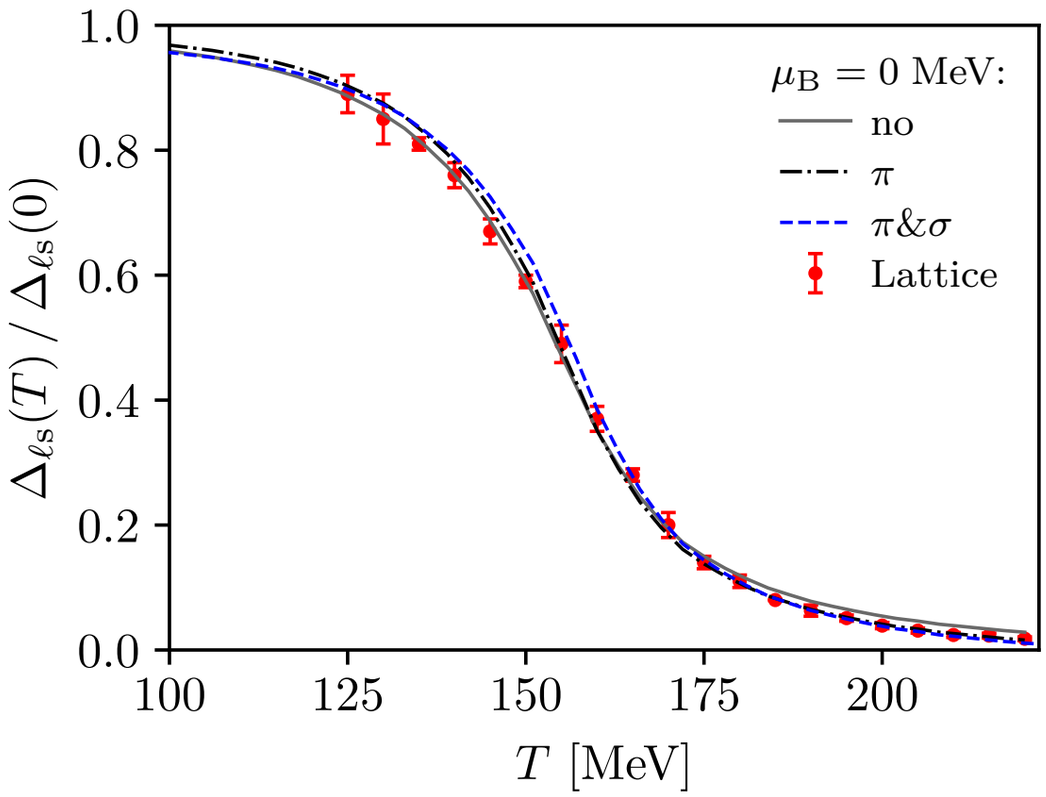


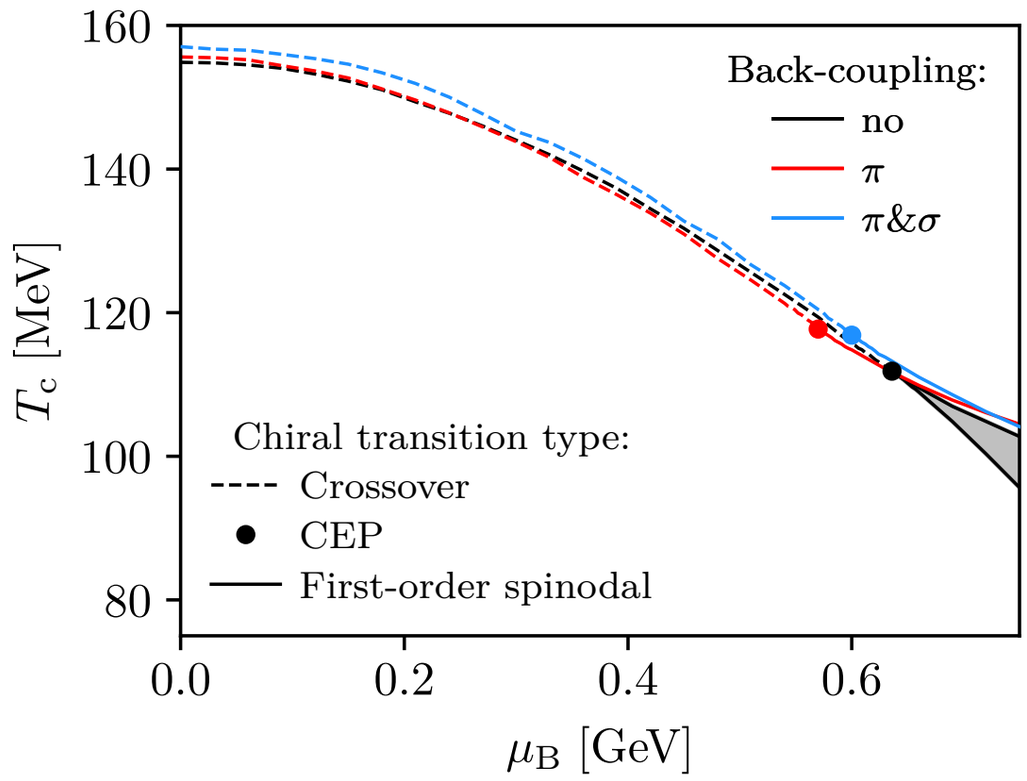
strange mesons

- use μ-dependent BSA for mesons: CEP
- use chiral form B/f_π of leading BSA for mesons: Columbia plot

Meson effects on the CEP - results (N_f=2+1)







Gunkel, CF, PRD 104 (2021) [2106.08356]

- Vanishing chemical potential: no effect

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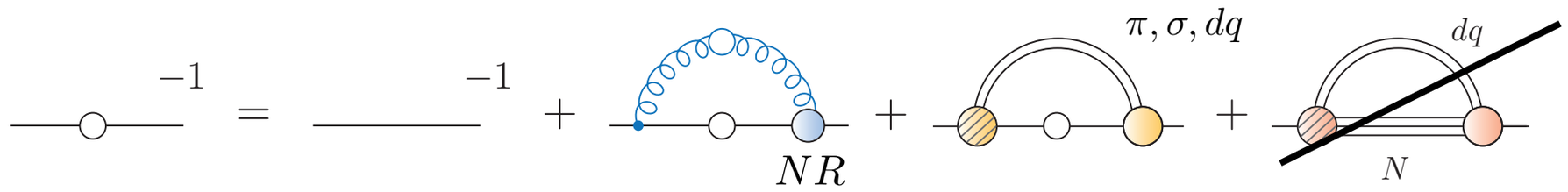

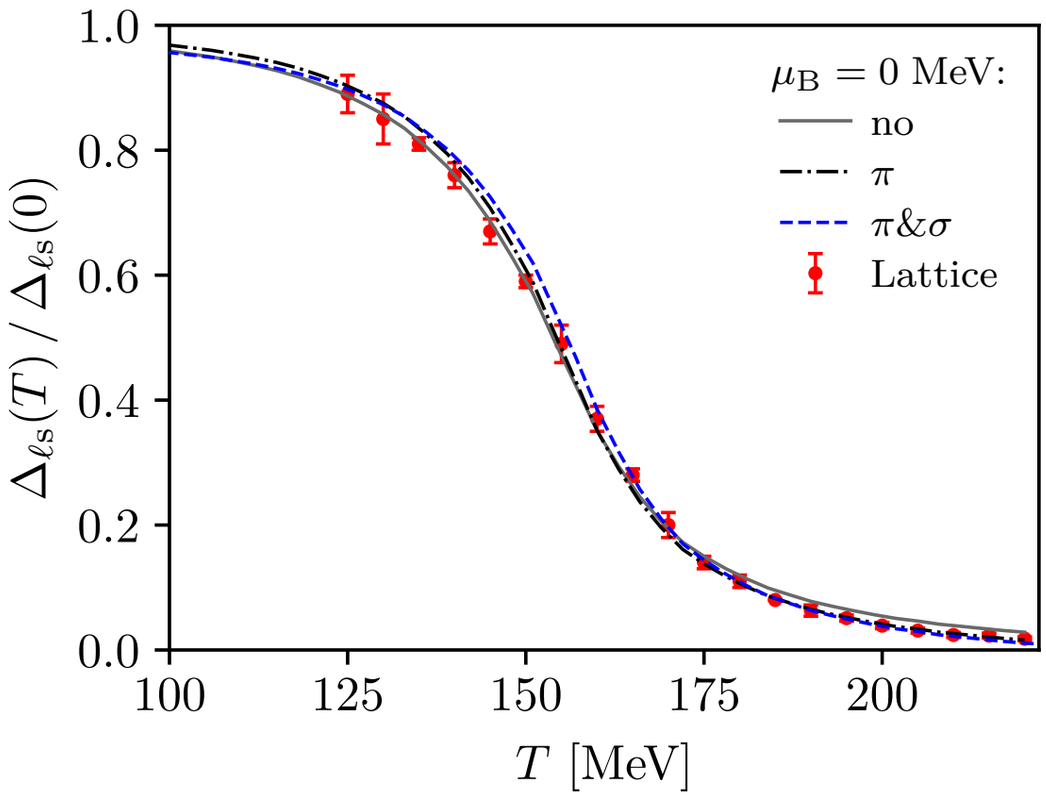

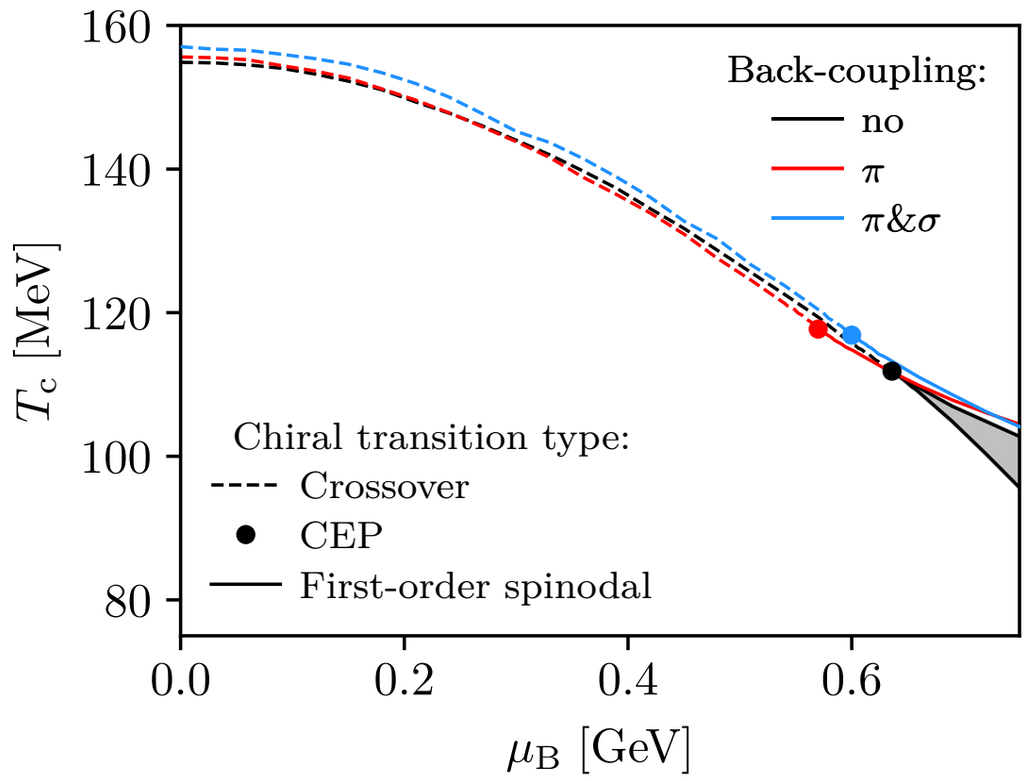

Gunkel, CF, PRD 104 (2021) [2106.08356]

- Vanishing chemical potential: no effect
- small effects on location of CEP
- μ-dependence of meson wave function taken into account

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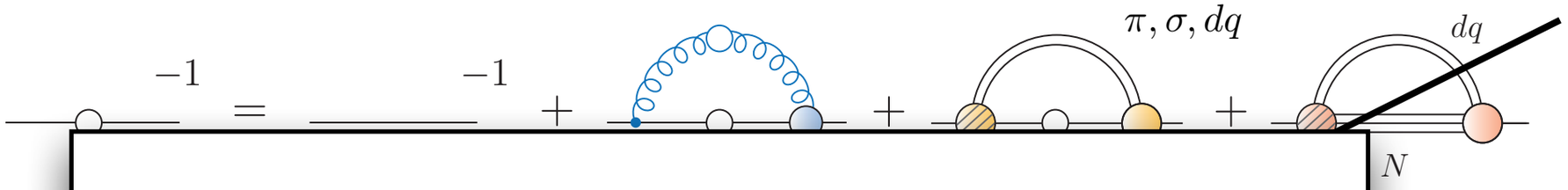

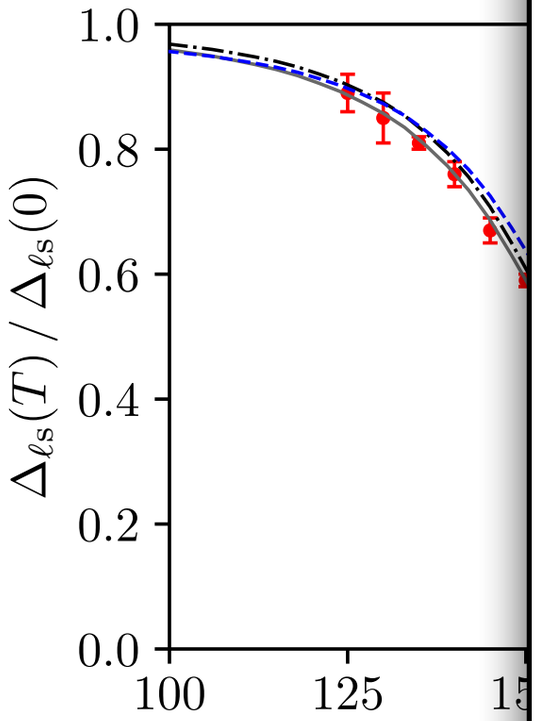

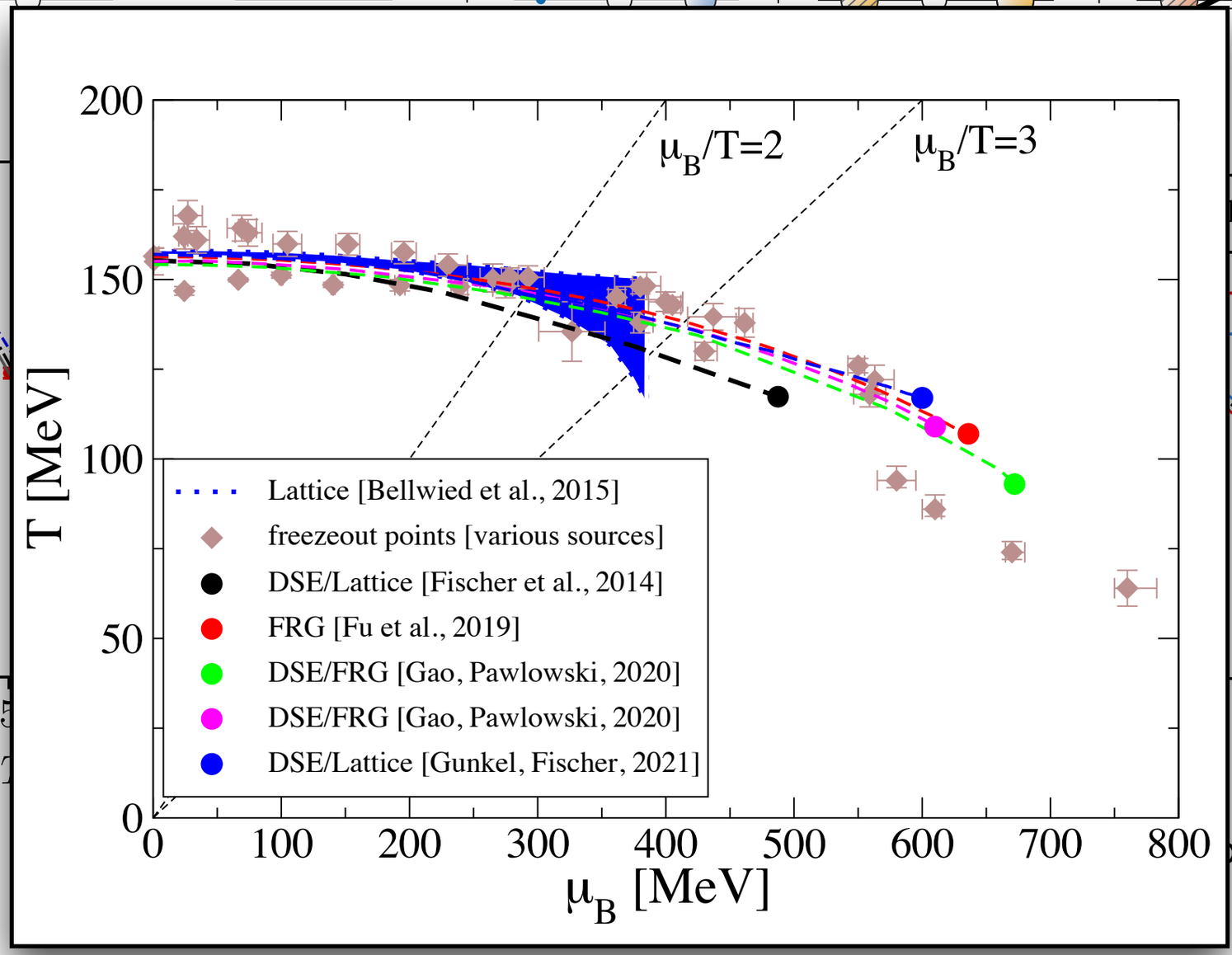

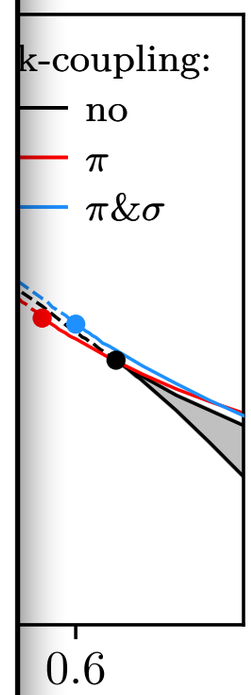

104 (2021) [2106.08356]

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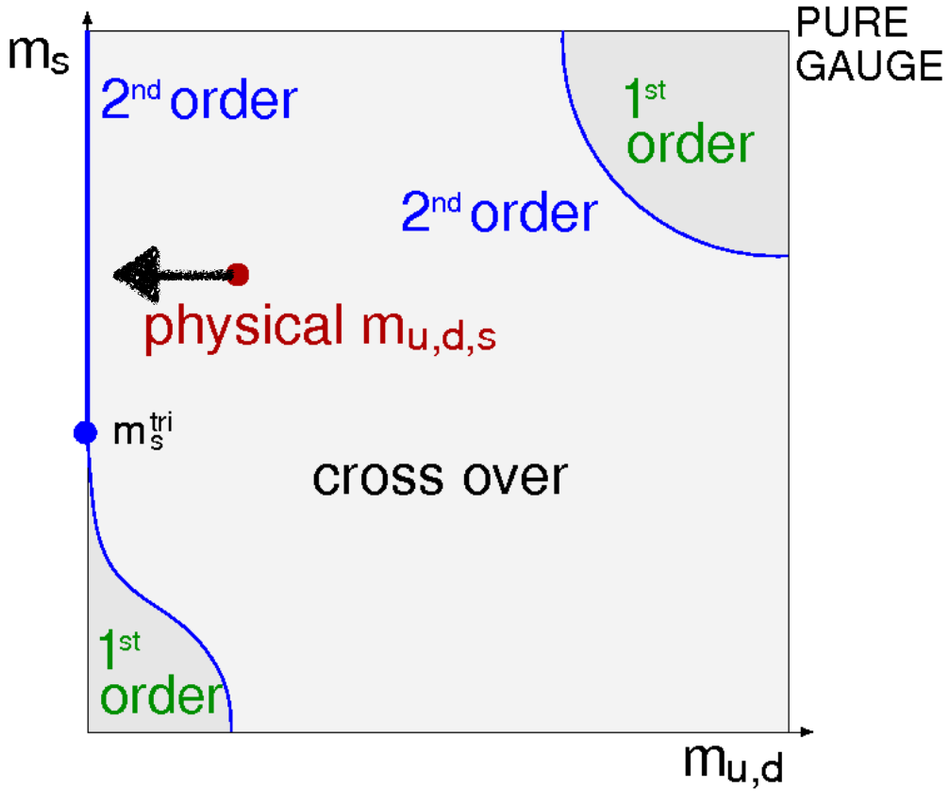
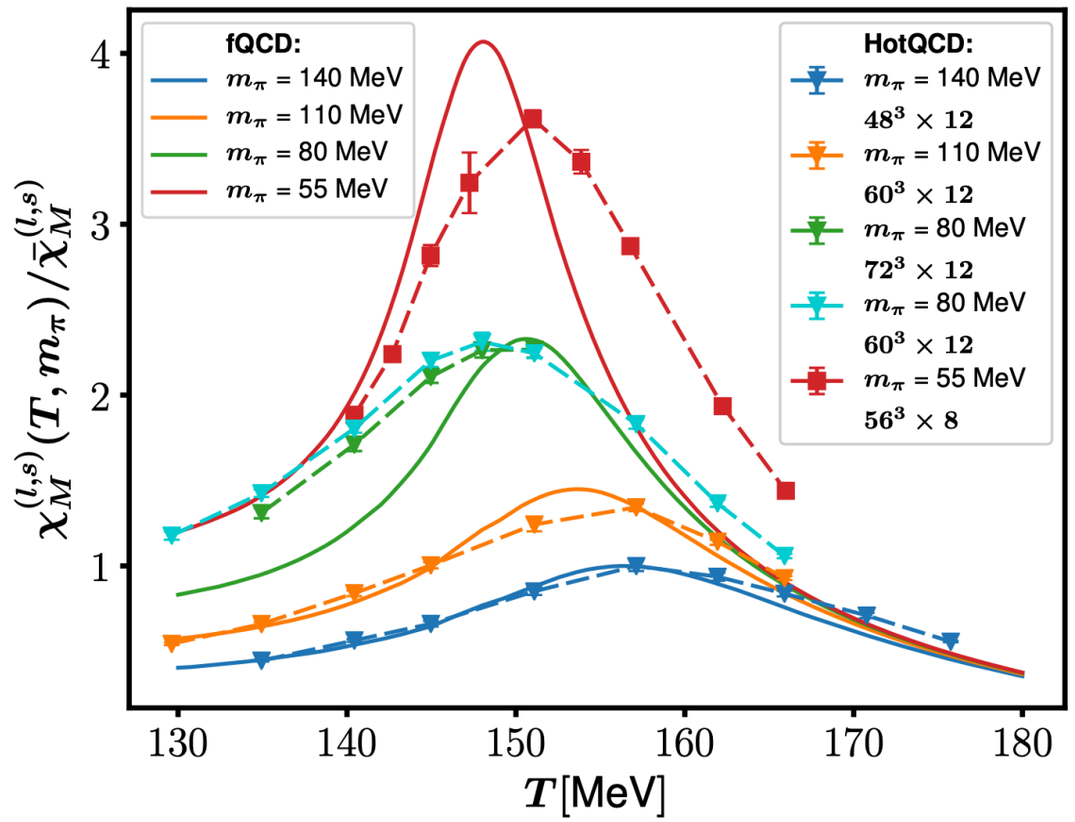
Towards the chiral limit…





HotQCD: Ding et al. PRL 123, 062002 (2019)
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DSE: Bernhardt and CF, in preparation

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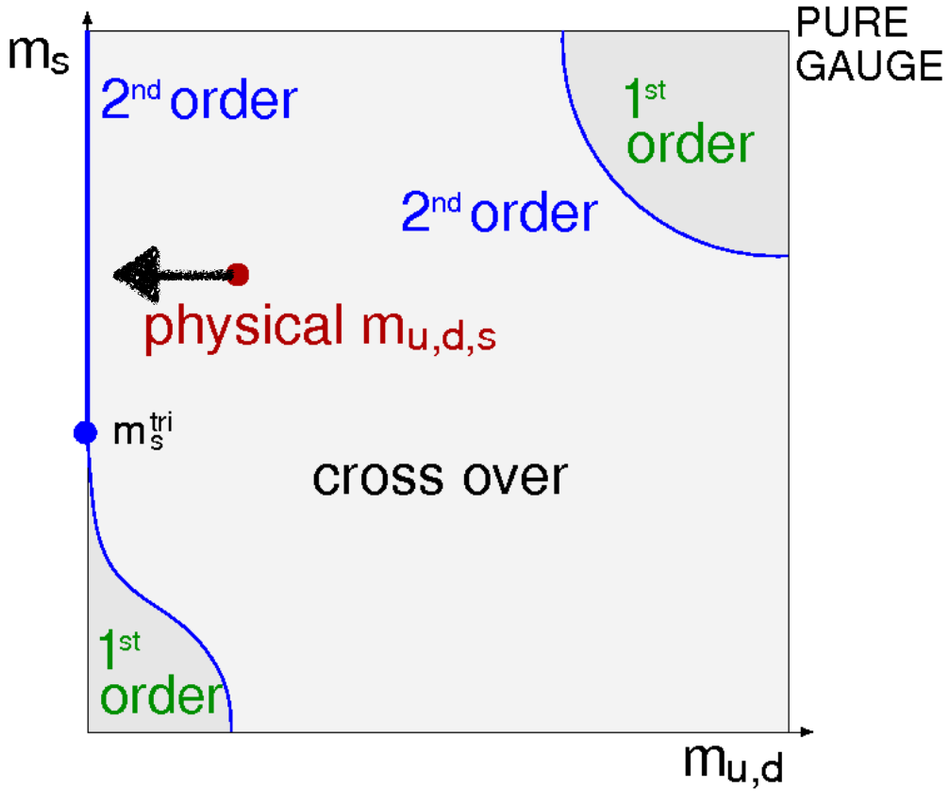

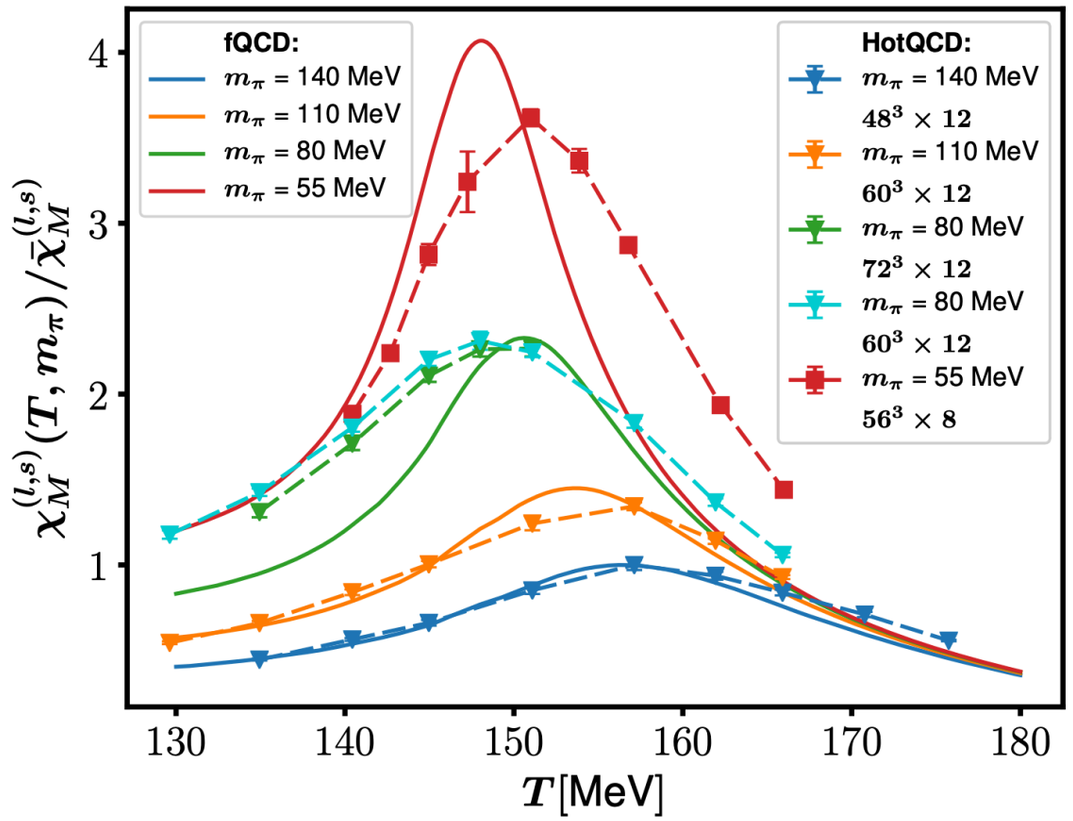

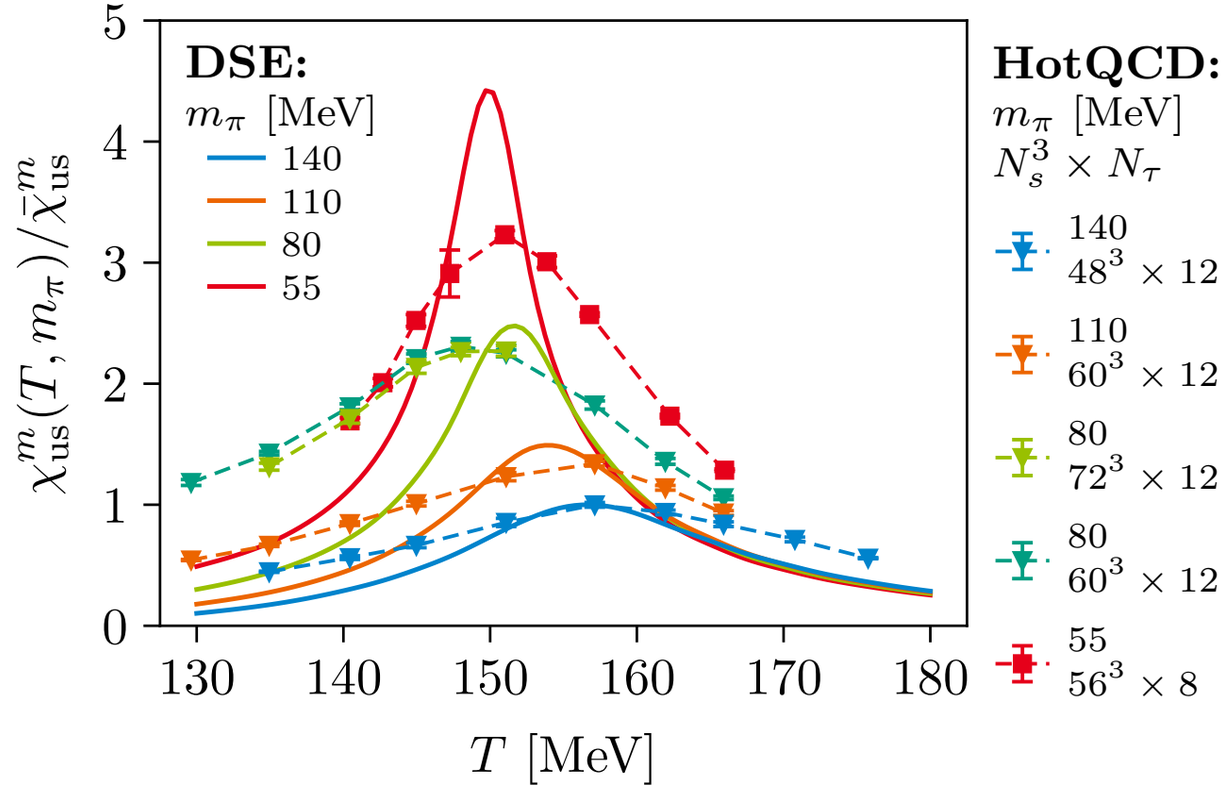

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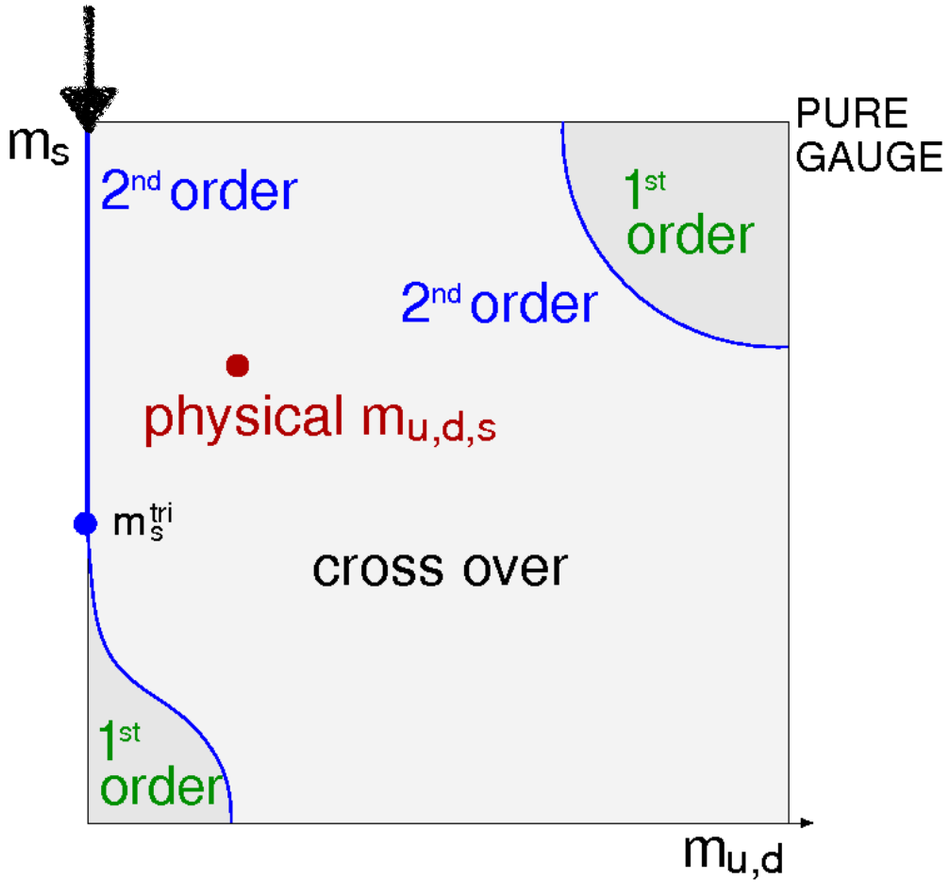

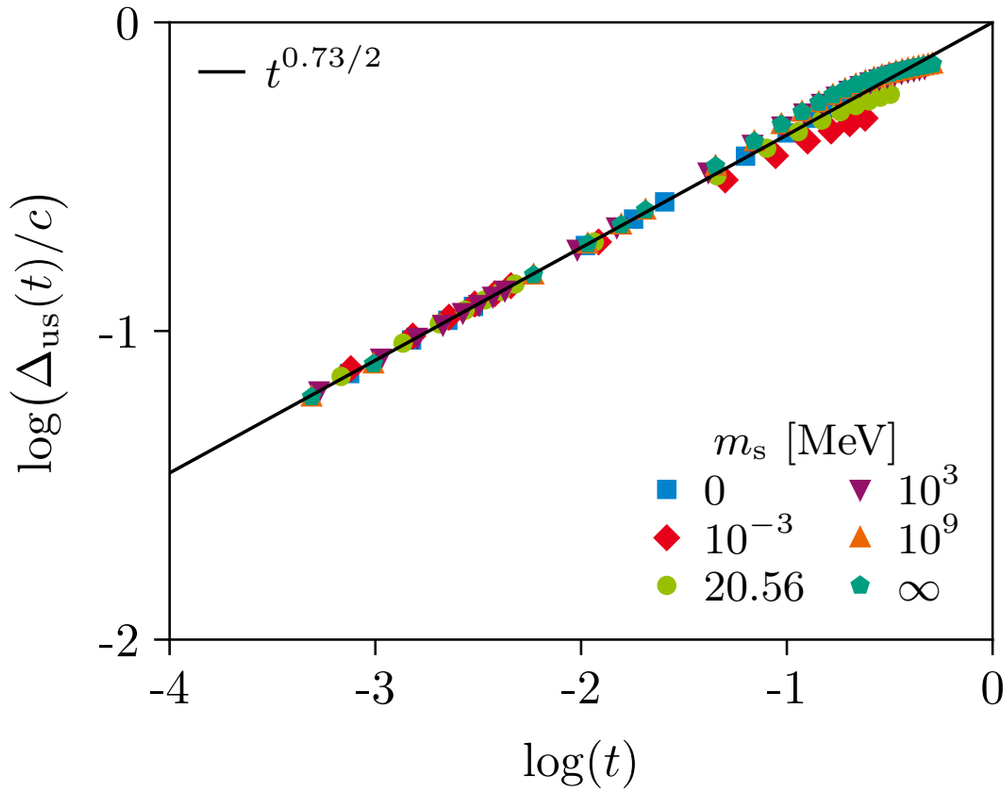

reproduce CF and Mueller, PRD 84 (2011) 054013

DSE: Bernhardt and CF, in preparation

Lattice: Dini, et al, PRD 105 (2022) no.3, 034510
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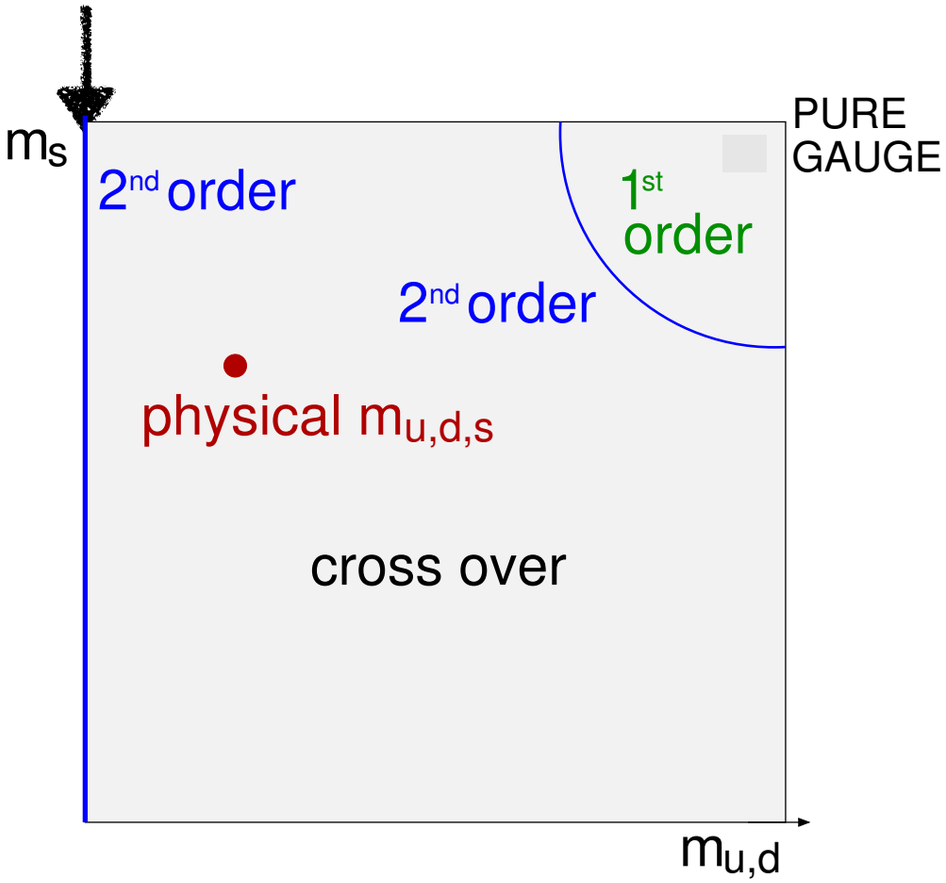

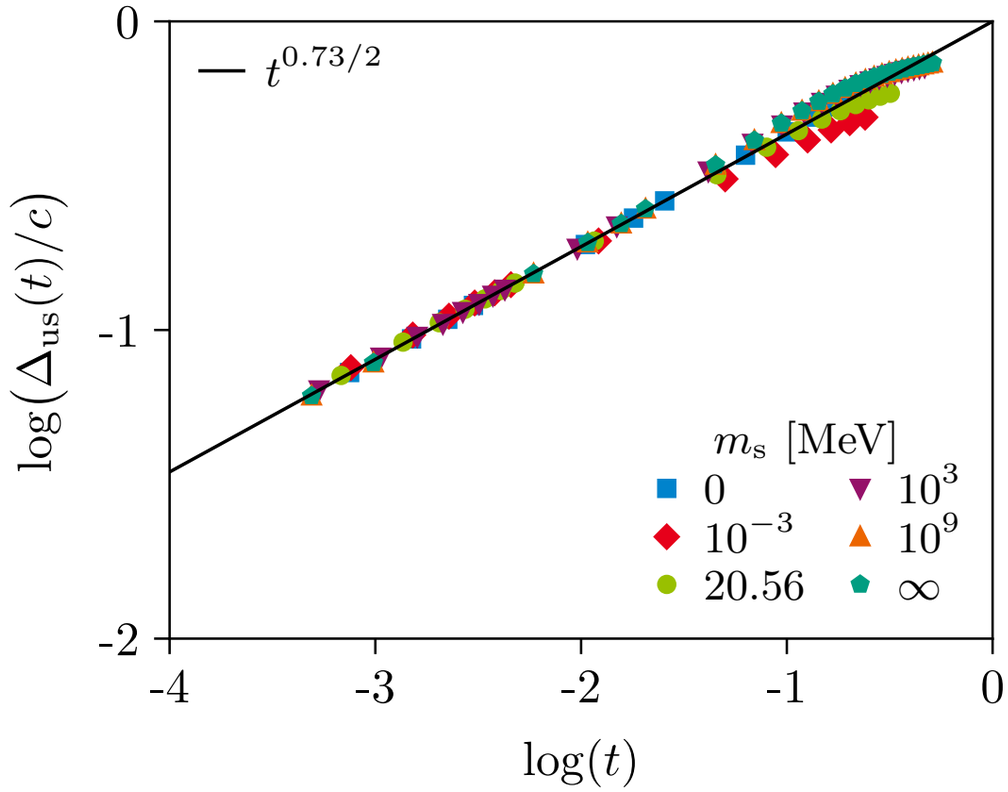

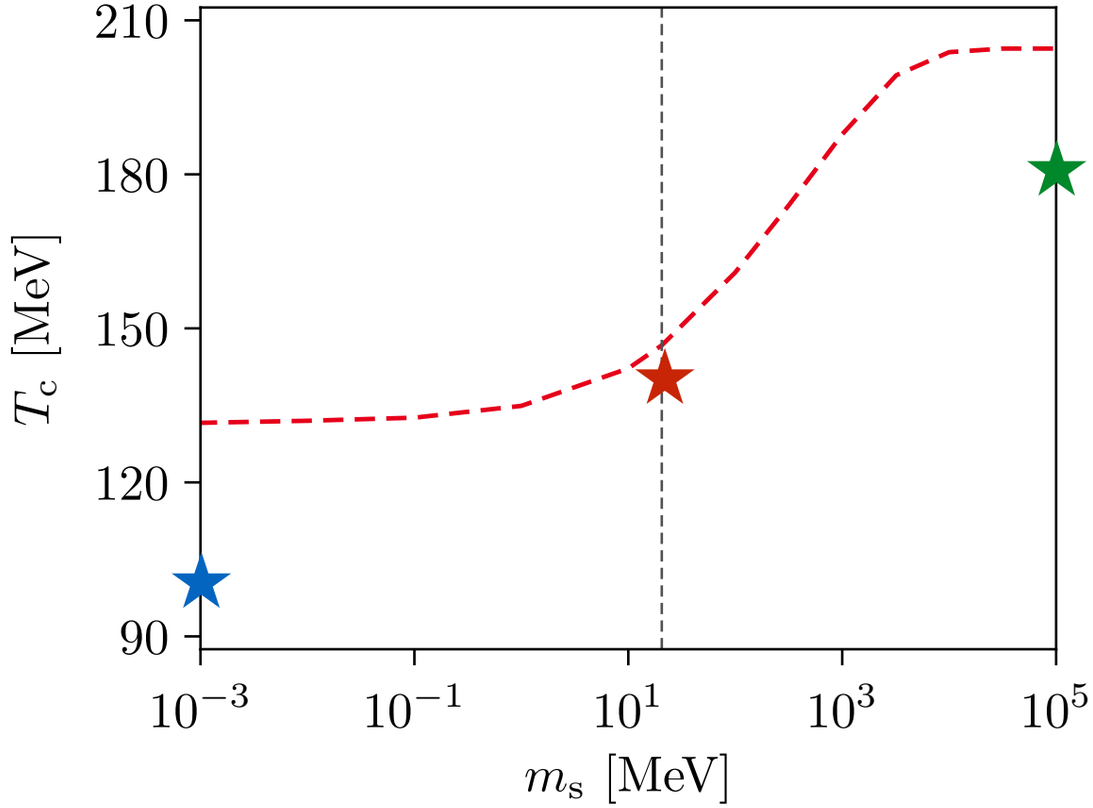

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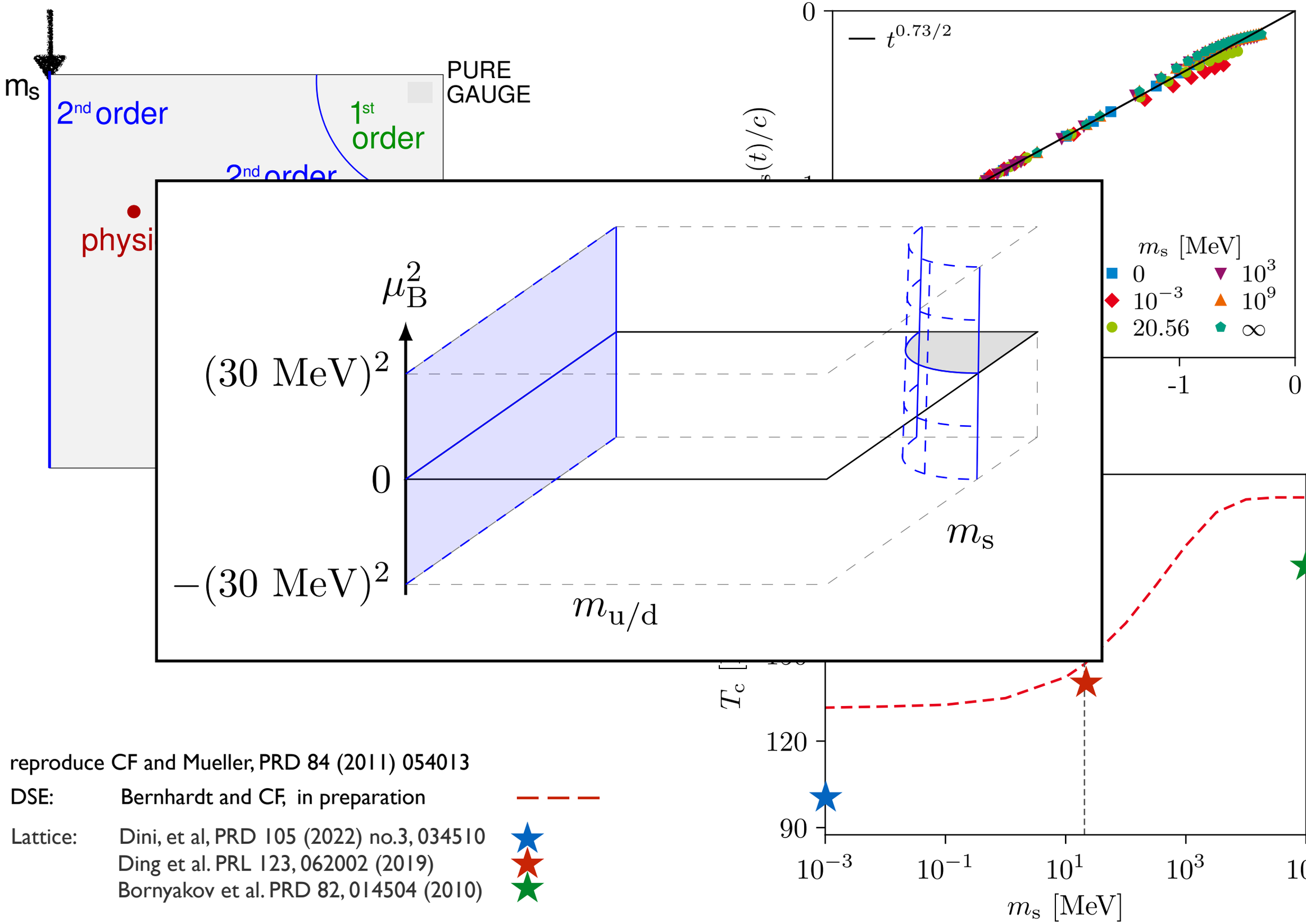

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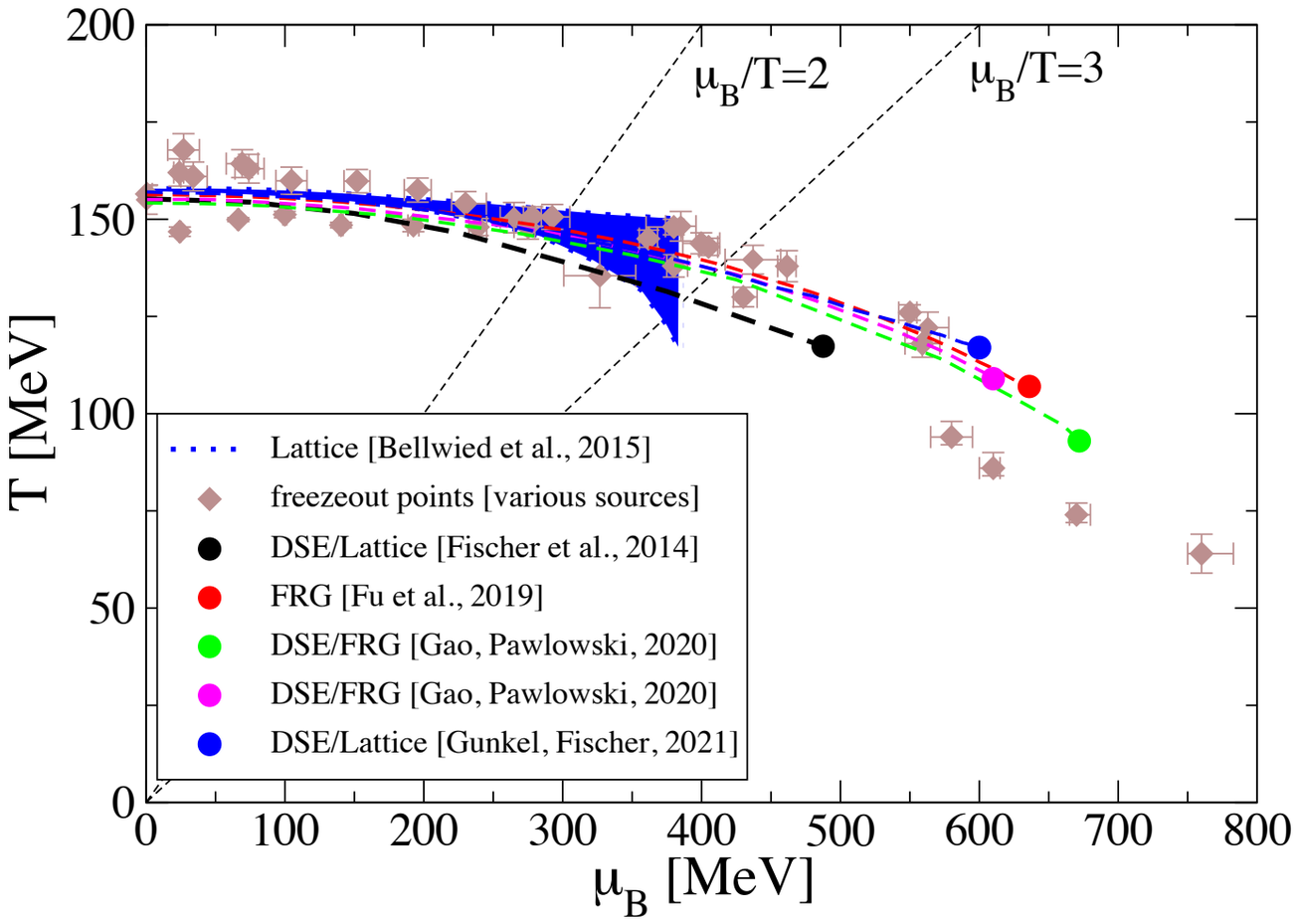
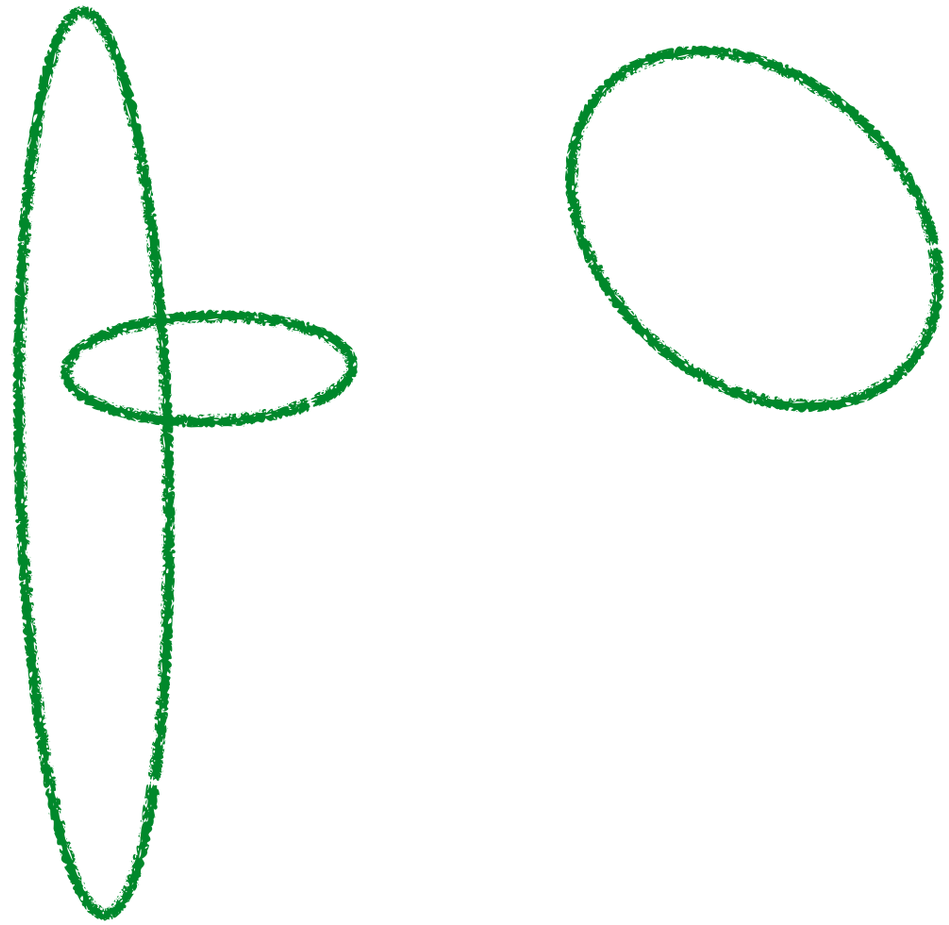
Summary: QCD with functional methods

Main goals:

- **one** framework for all areas of hadron physics:
  mesons, baryons, 'exotic states', form factors,
  hadronic contributions to precision observables (g-2)
- **same** framework for QCD phase diagram

Main results:





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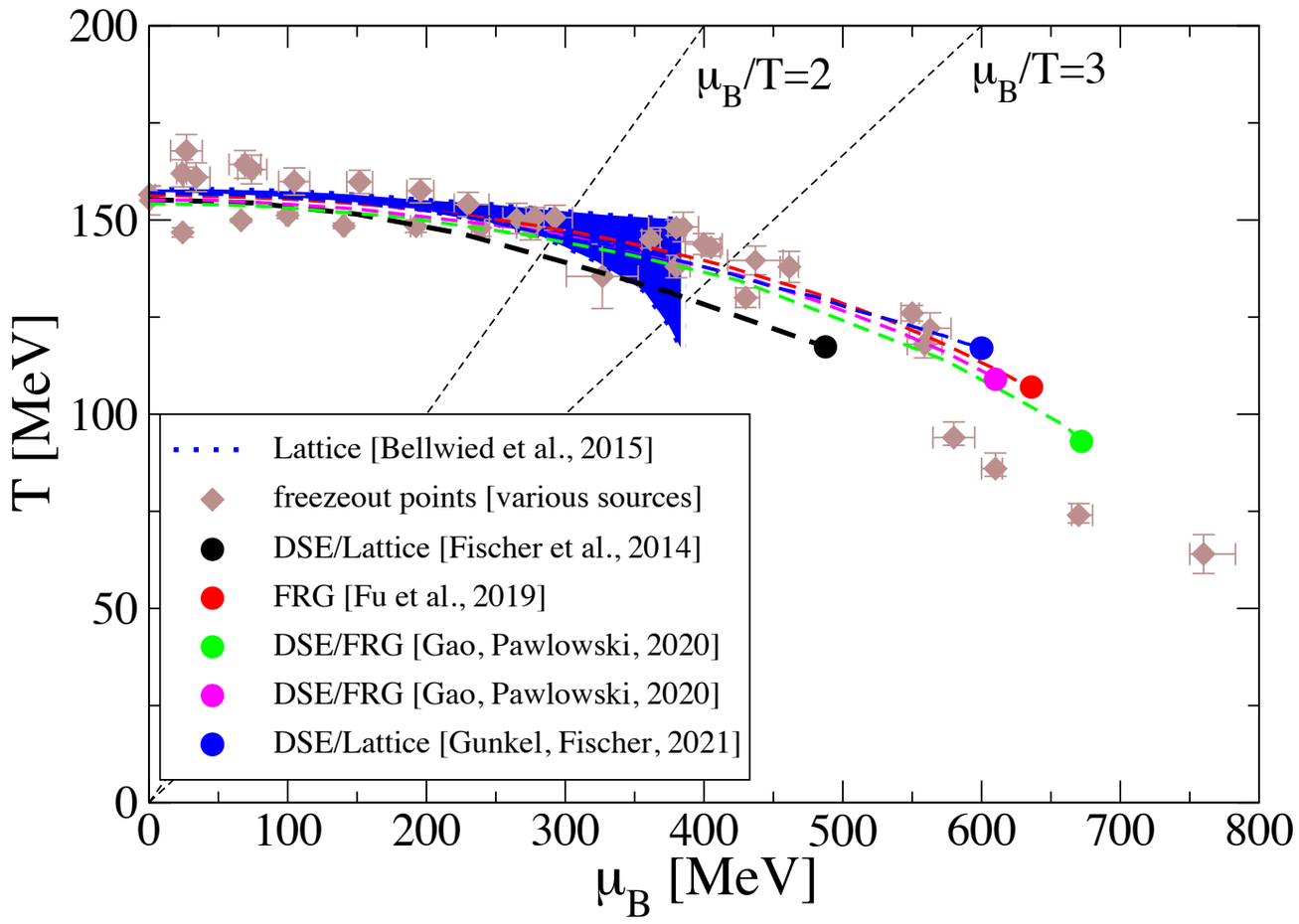
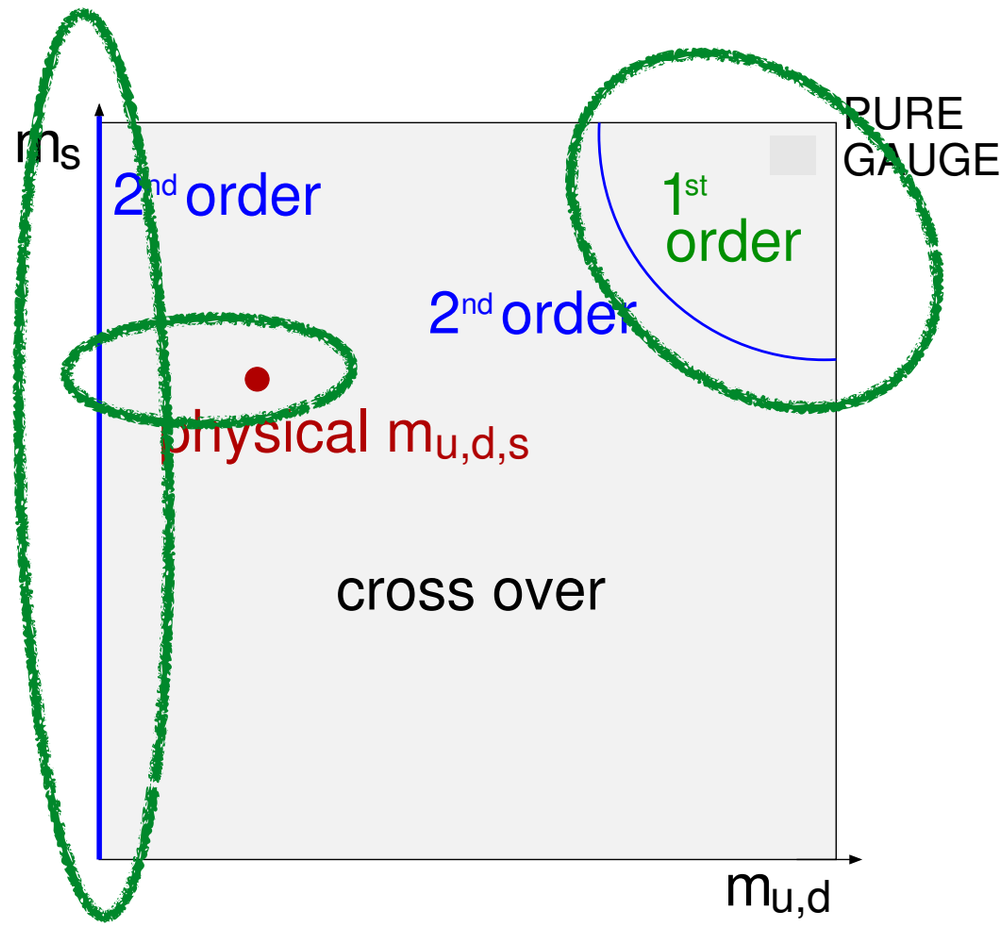
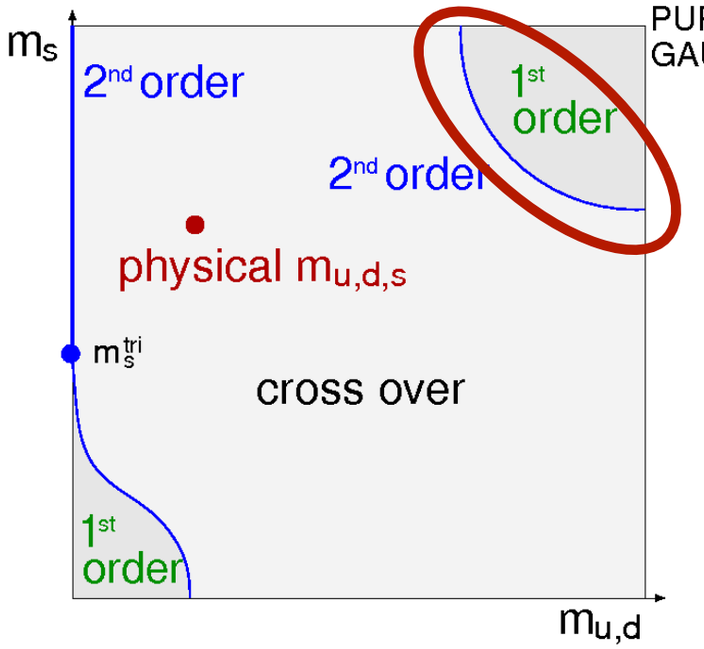
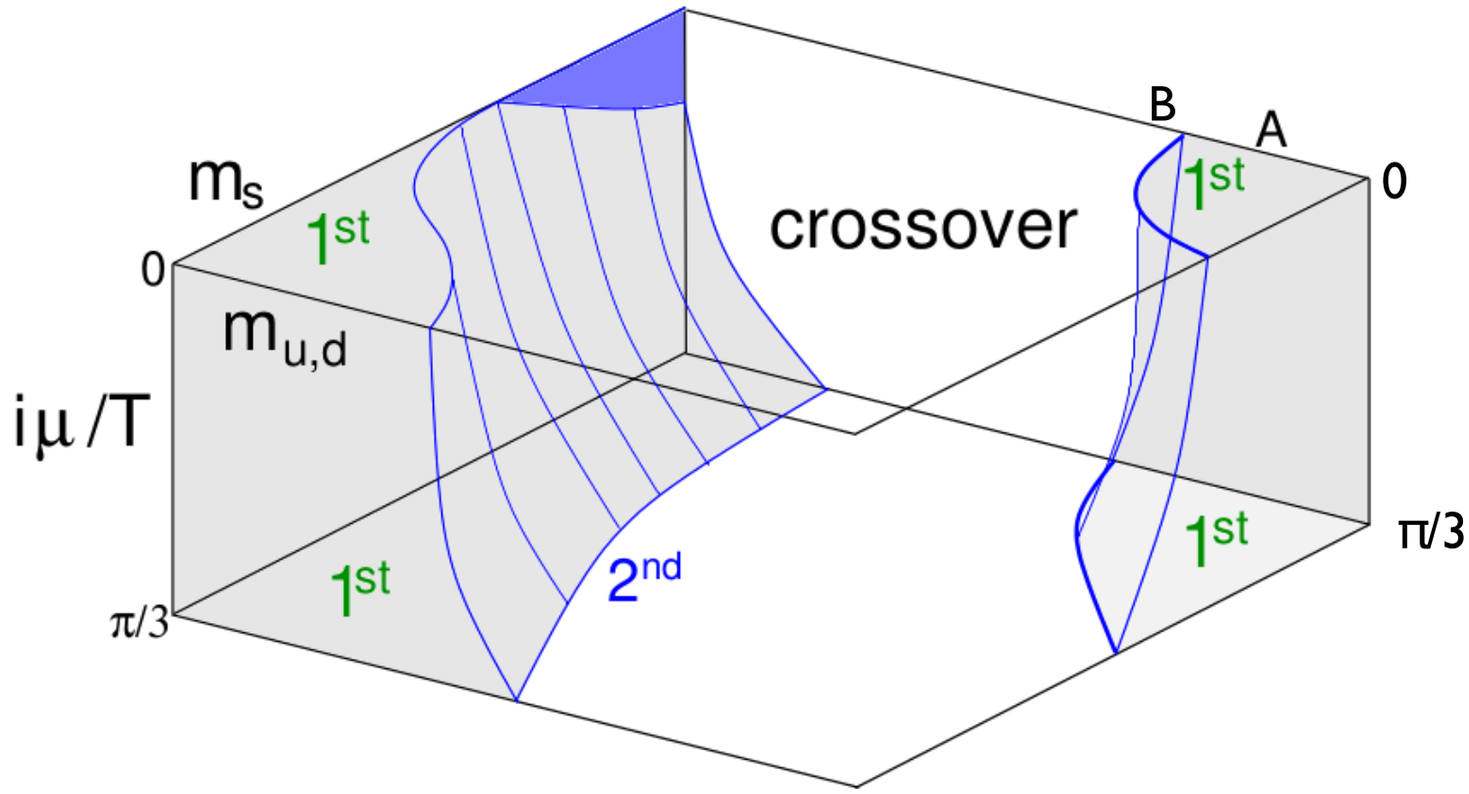


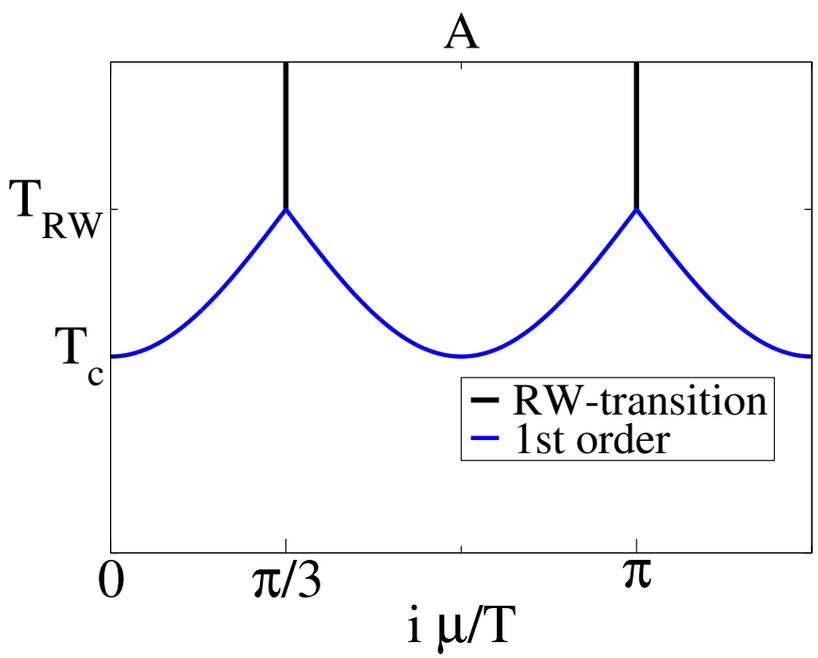


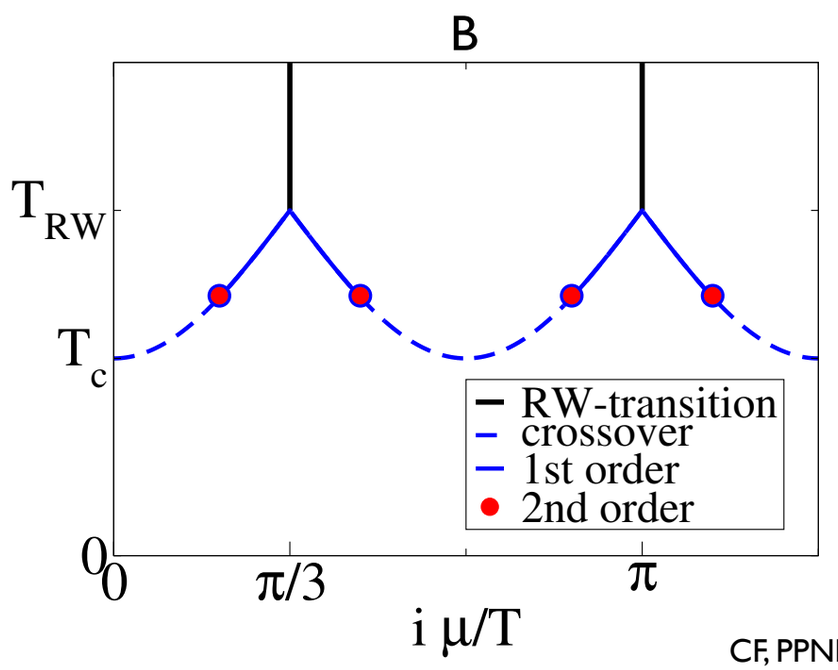
Backup

Critical line/surface for heavy quarks



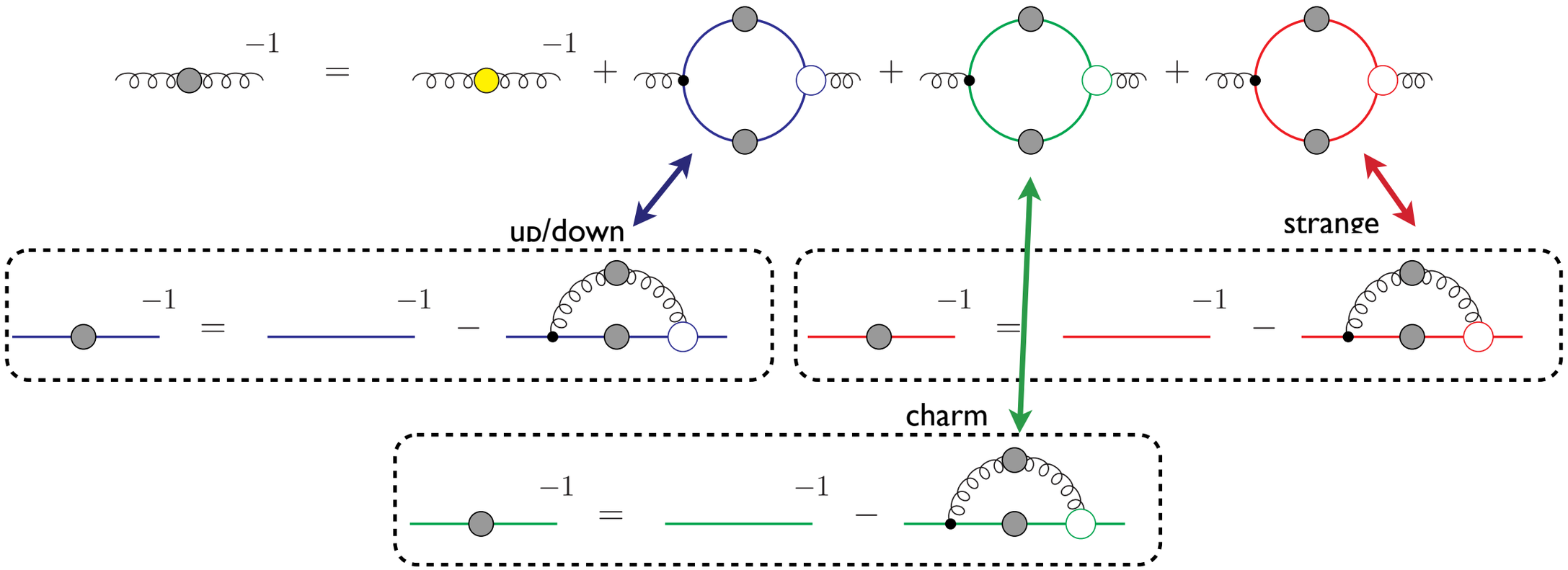






CF, PPNP 105 (2019) [1810.12938]

N_f=2+1+1: effects of charm



- Physical up/down, strange and charm quark masses
- Transition controlled by chiral dynamics
- *no lattice or model results available yet*

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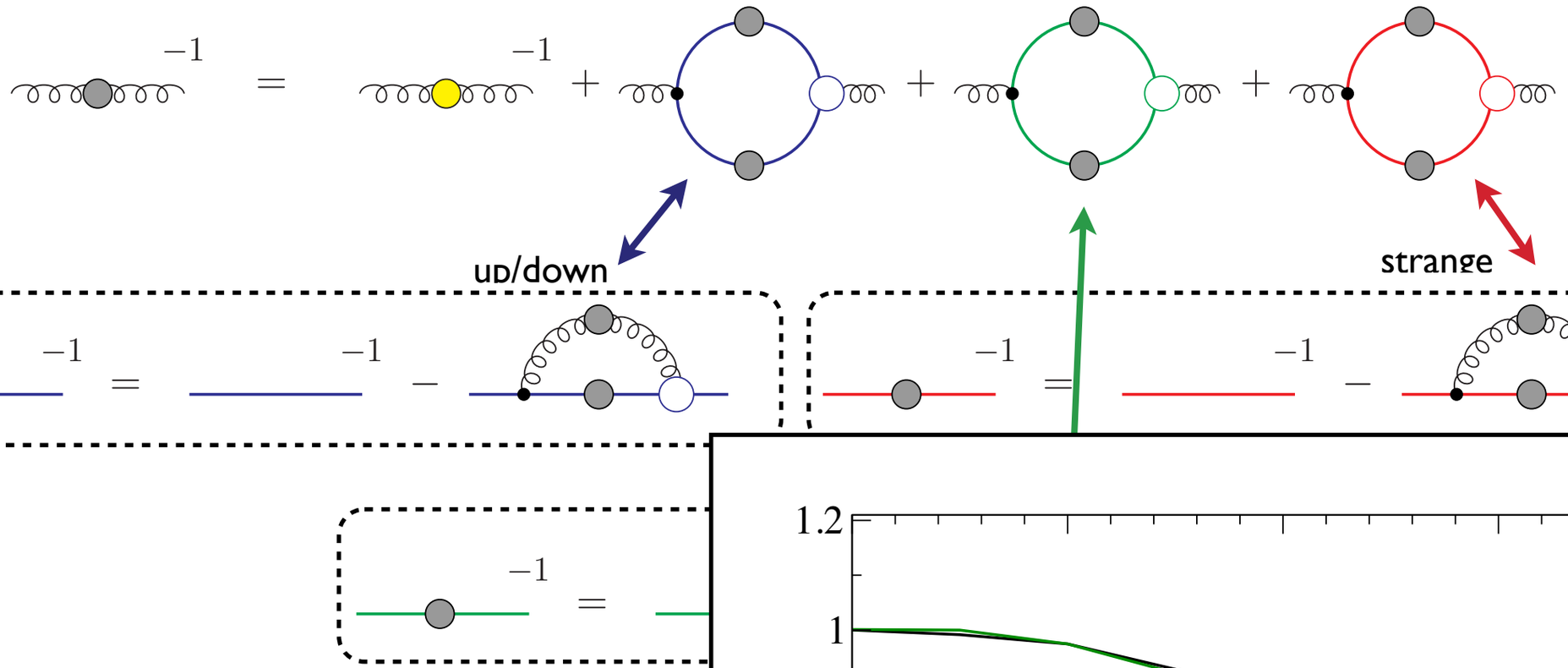

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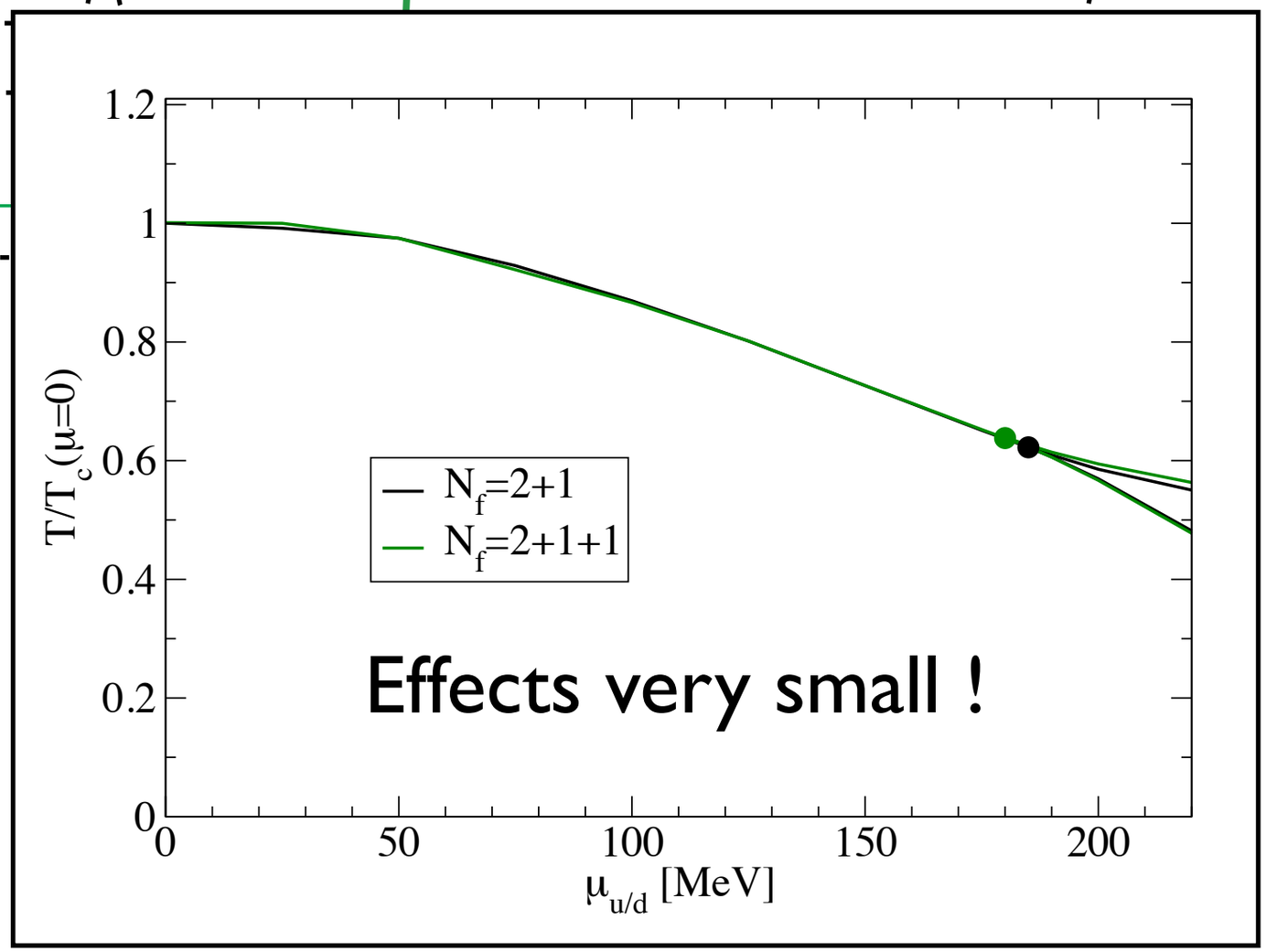


CF, Luecker, Welzbacher, PRD 90 (2014) 034022

Contact with experiment: fluctuations

X.~Luo and N.~Xu, Nucl. Sci. Tech. 28 (2017) no.8, 112 [arXiv:1701.02105 [nucl-ex]].

Quark chemical potentials related to those of conserved charges:

$$\mu_u = \mu_B/3 + 2\mu_Q/3$$
$$\mu_d = \mu_B/3 - \mu_Q/3$$
$$\mu_s = \mu_B/3 - \mu_Q/3 - \mu_S$$

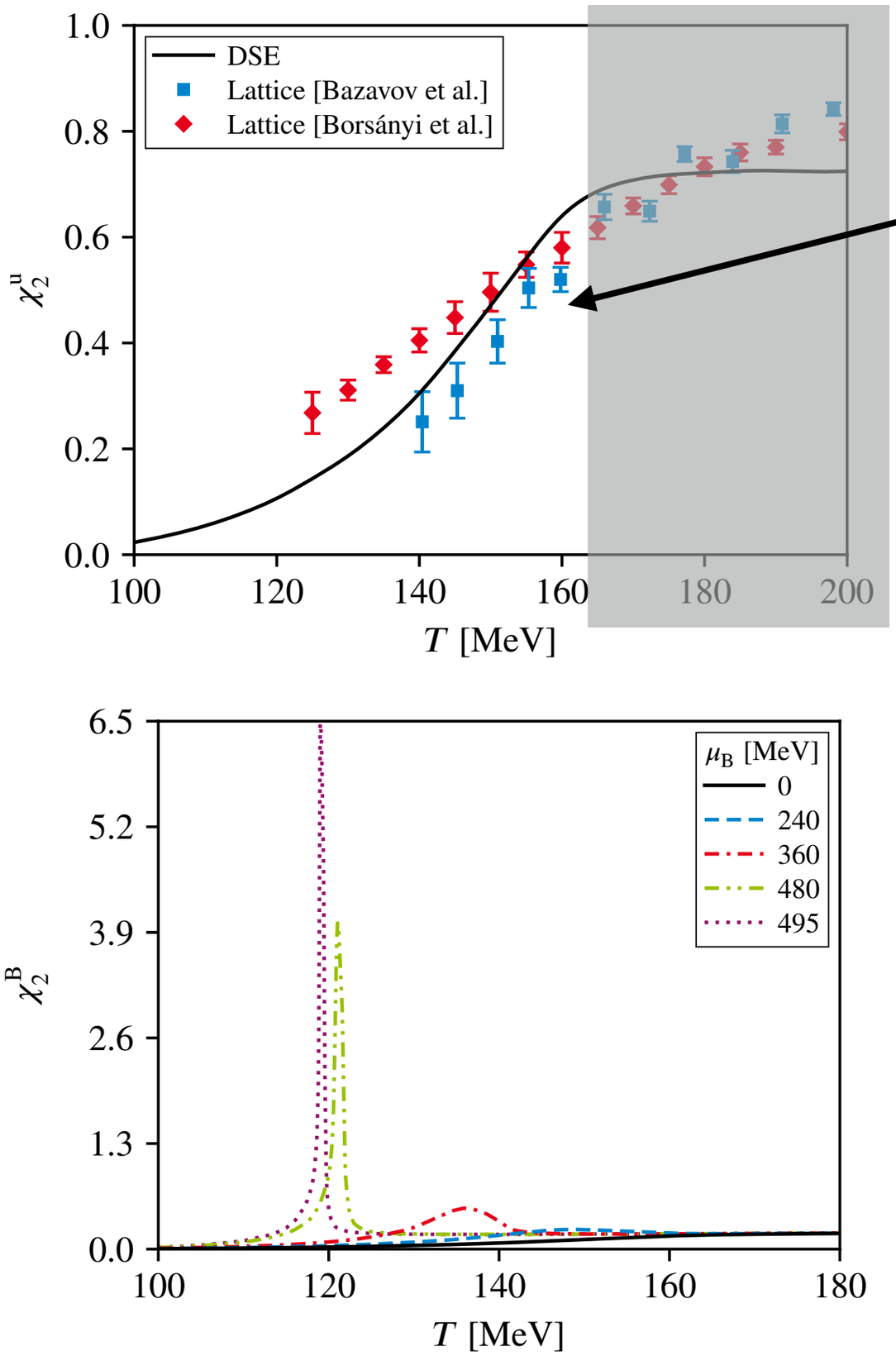
Serve to calculate susceptibilities:

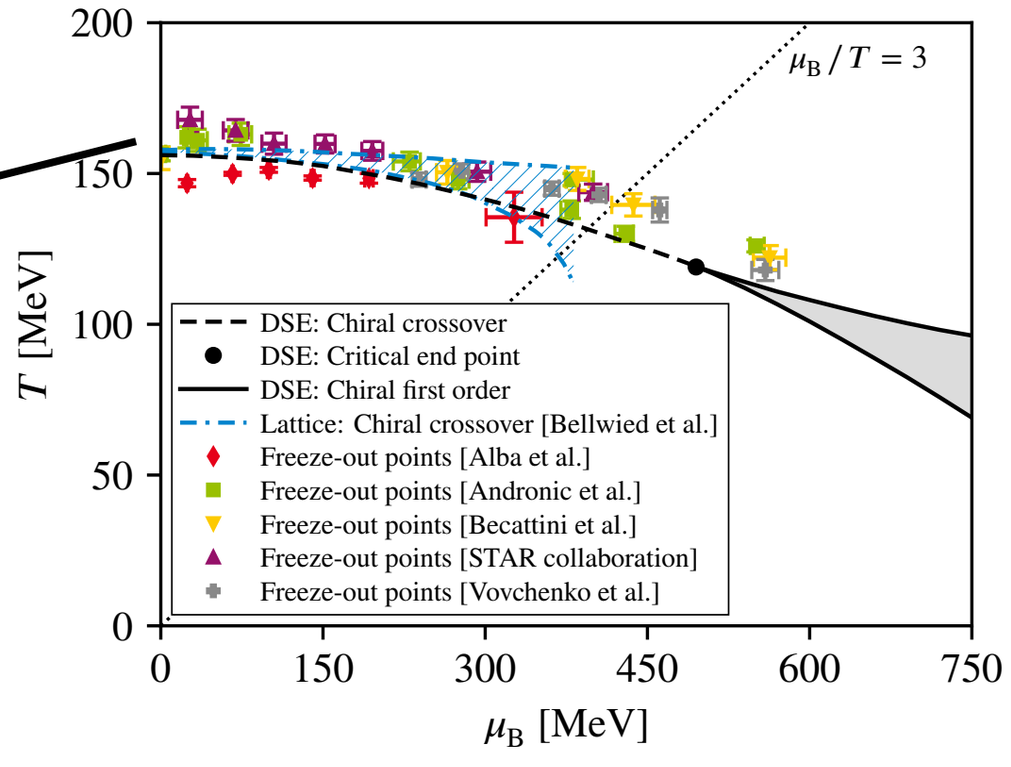
$$\chi^{BSQ}_{lmn} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}$$

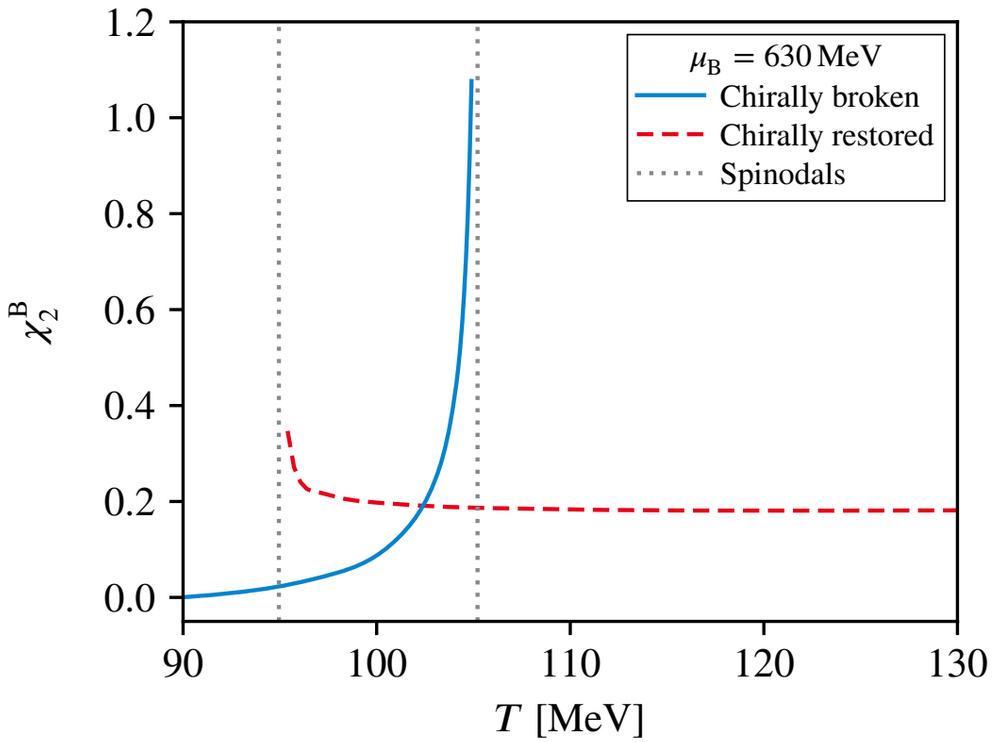
Related to cumulants, which can be extracted from experiment:

$$C^{BSQ}_{lmn} = VT^3 \chi^{BSQ}_{lmn}$$

Fluctuations at the CEP

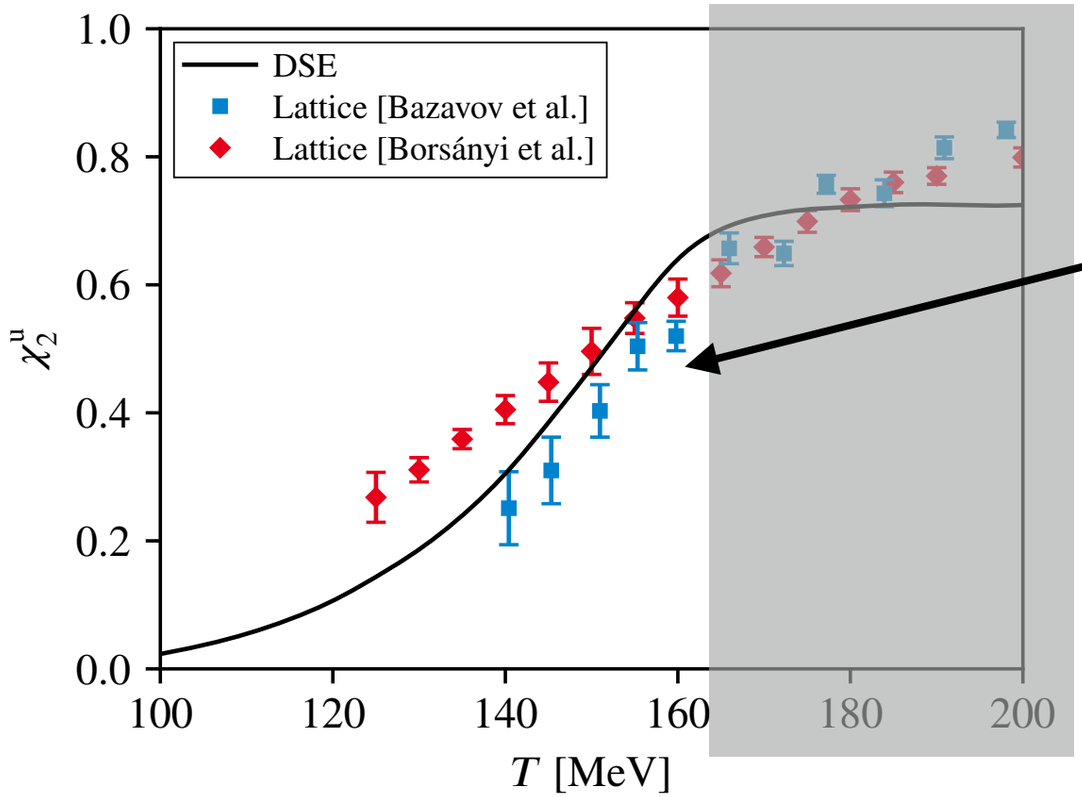


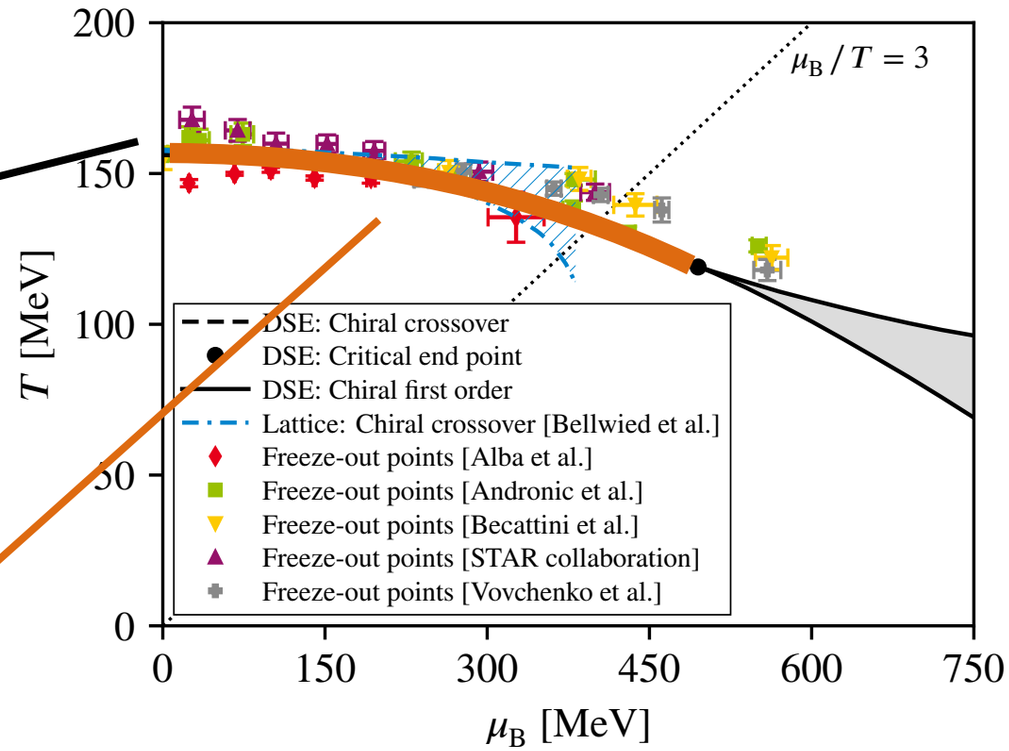


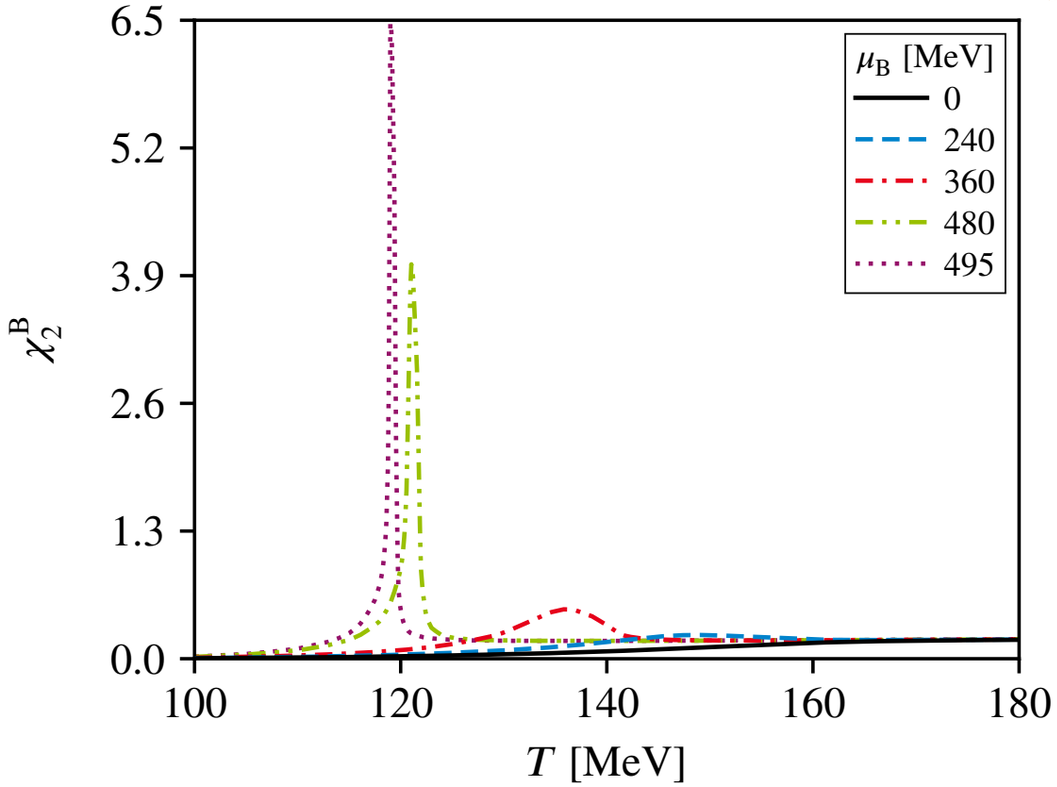


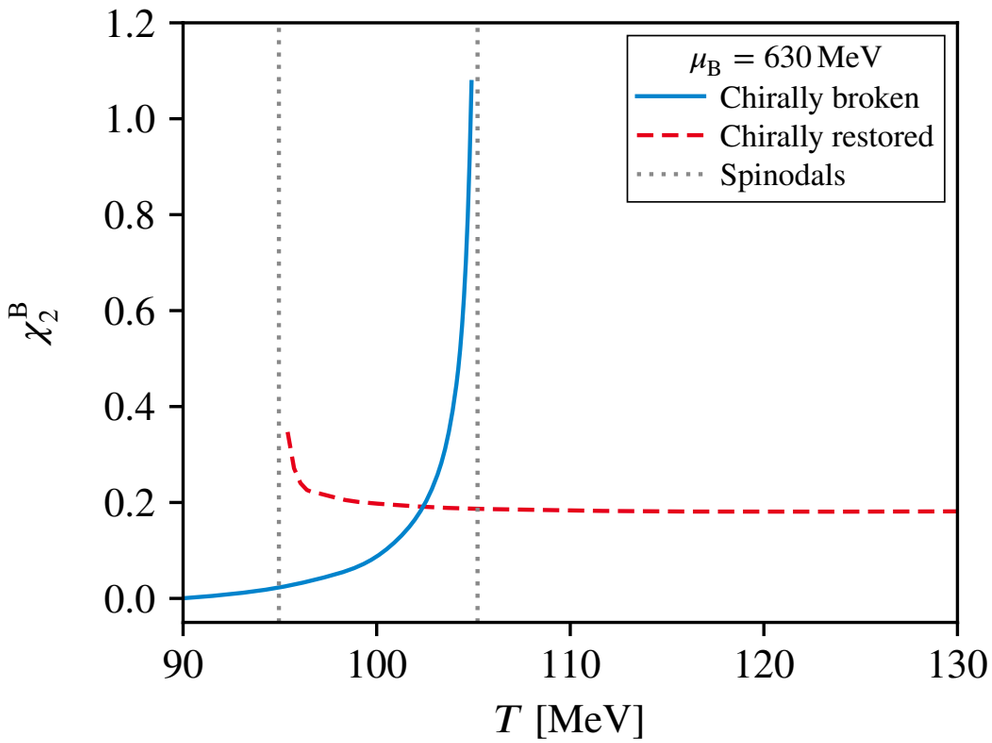
Isserstedt, Buballa, CF, Gunkel, PRD 100 (2019) no.7, 074011

Fluctuations at the CEP









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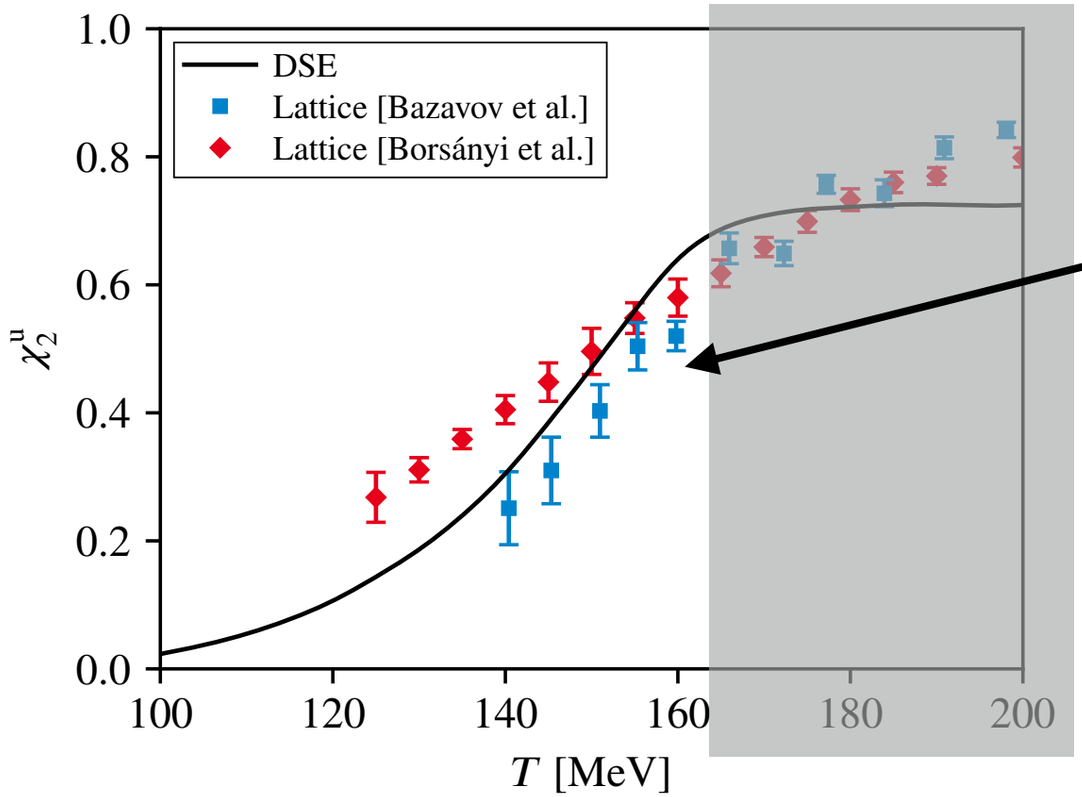
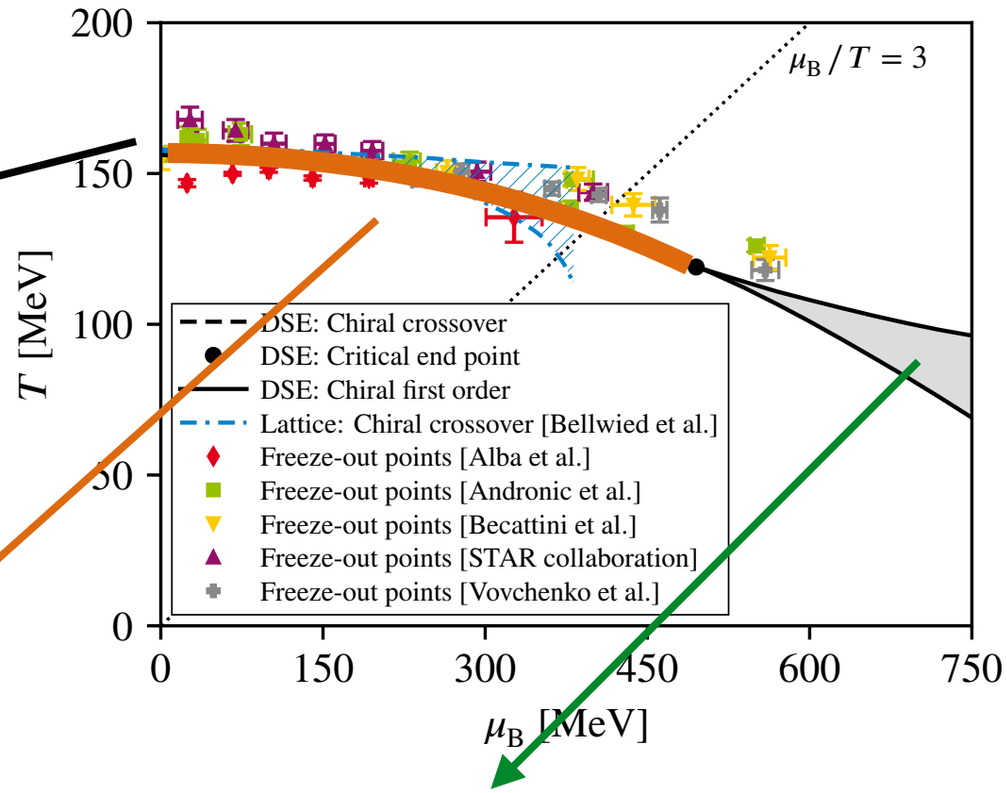
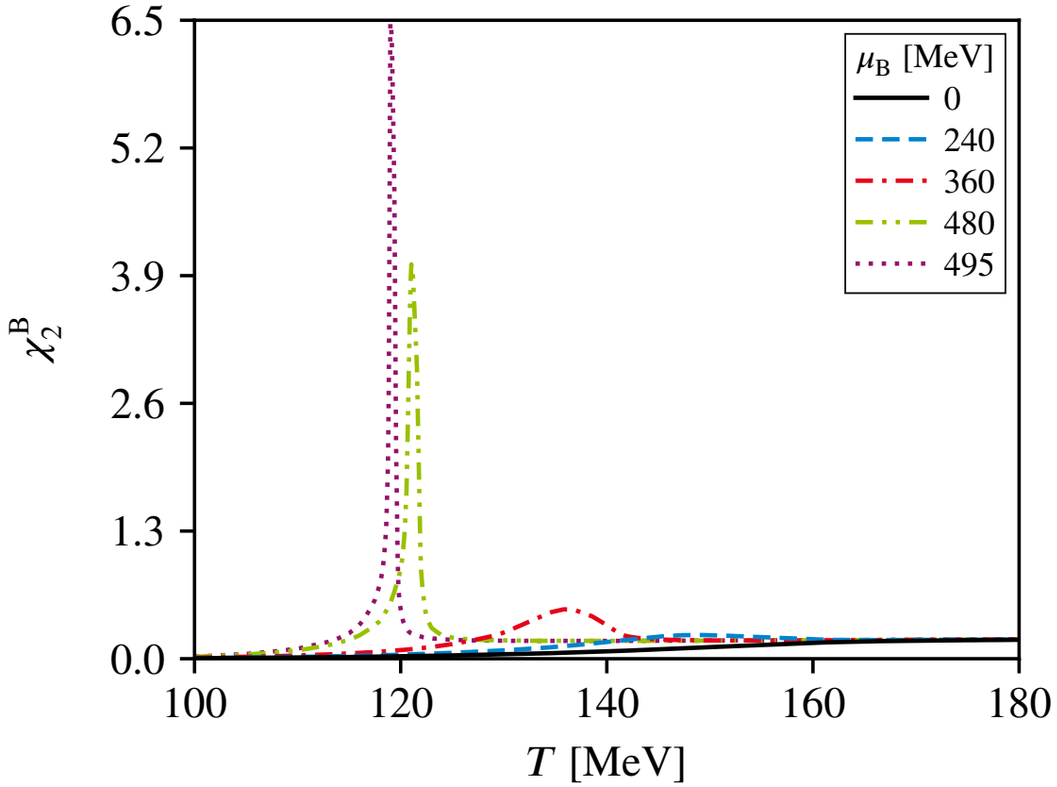
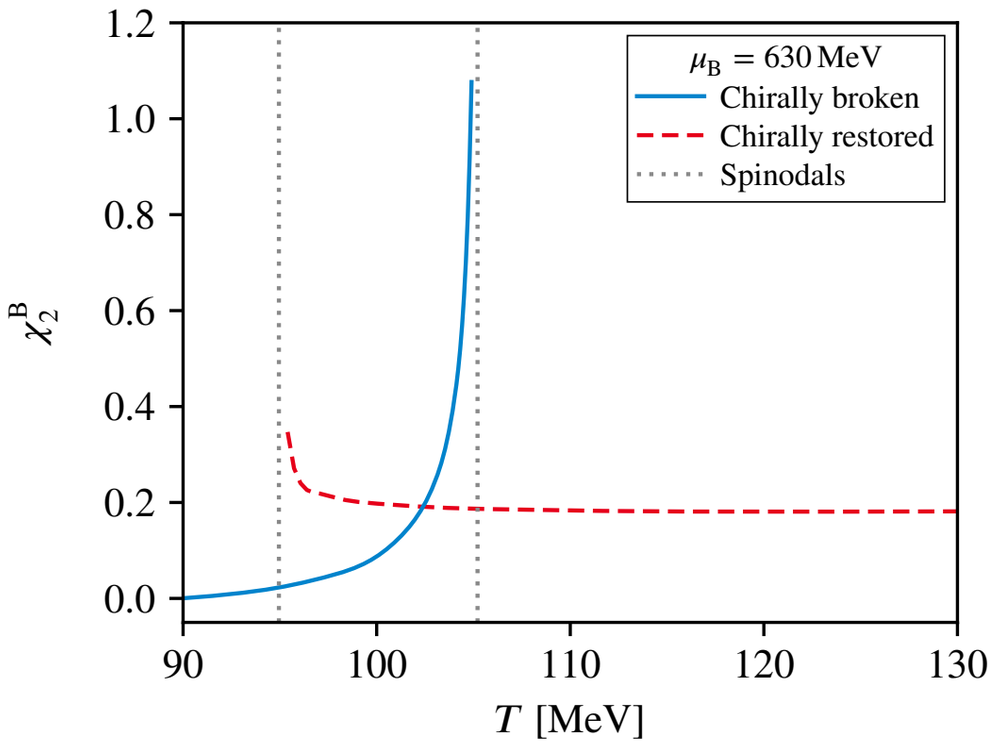


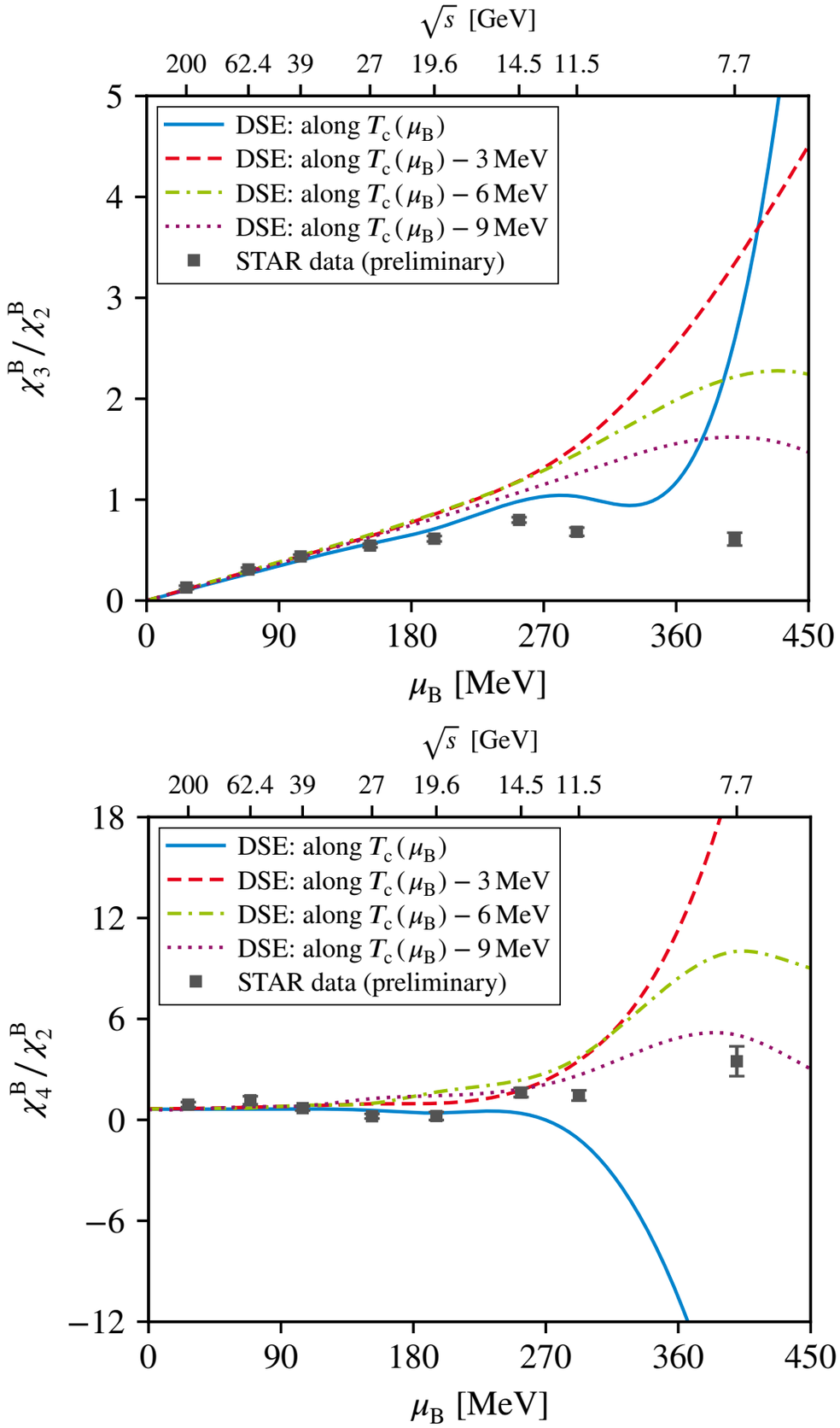


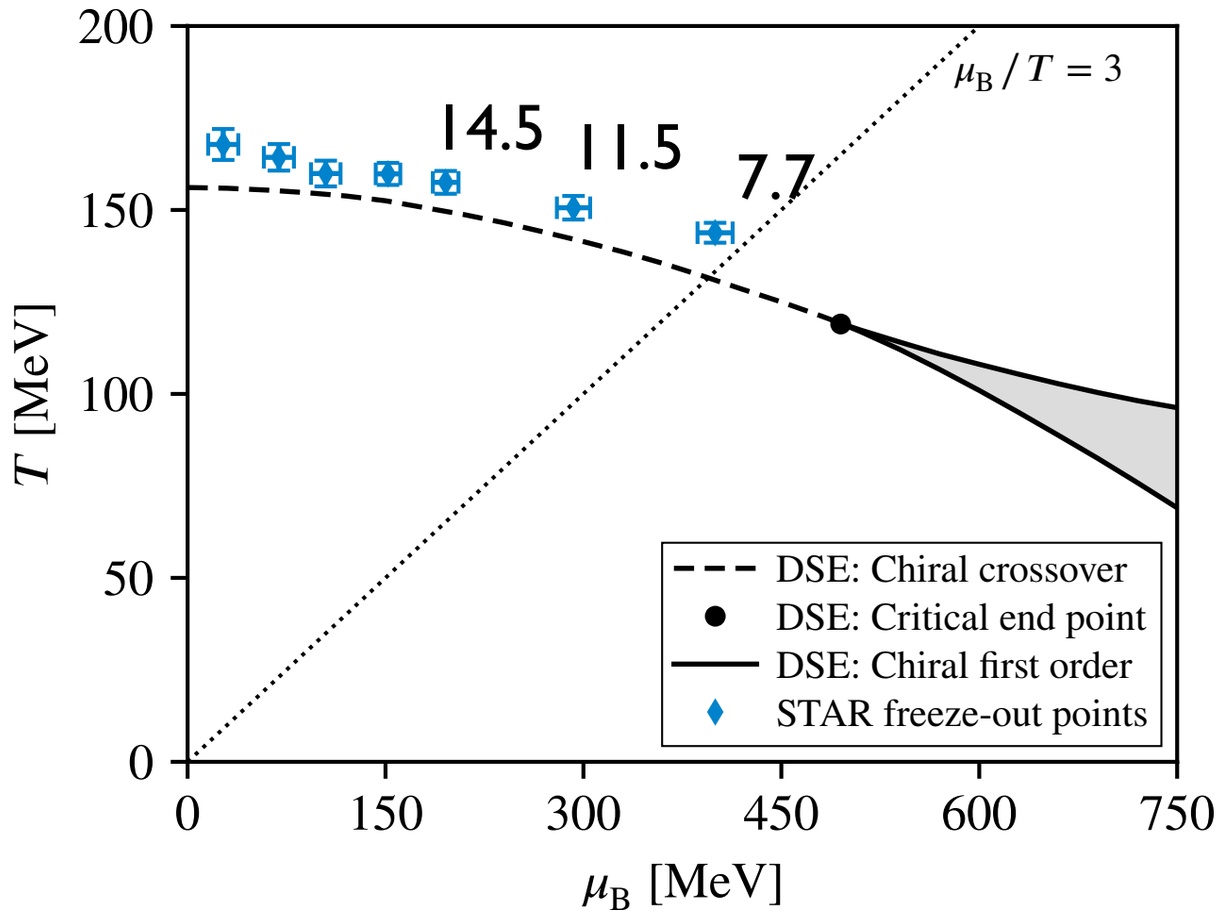




Isserstedt, Buballa, CF, Gunkel, PRD 100 (2019) no.7, 074011

Ratios: skewness and curtosis





$\sqrt{s} \geq 14.5$: good agreement

$\sqrt{s} = 11.5$: trend ok !

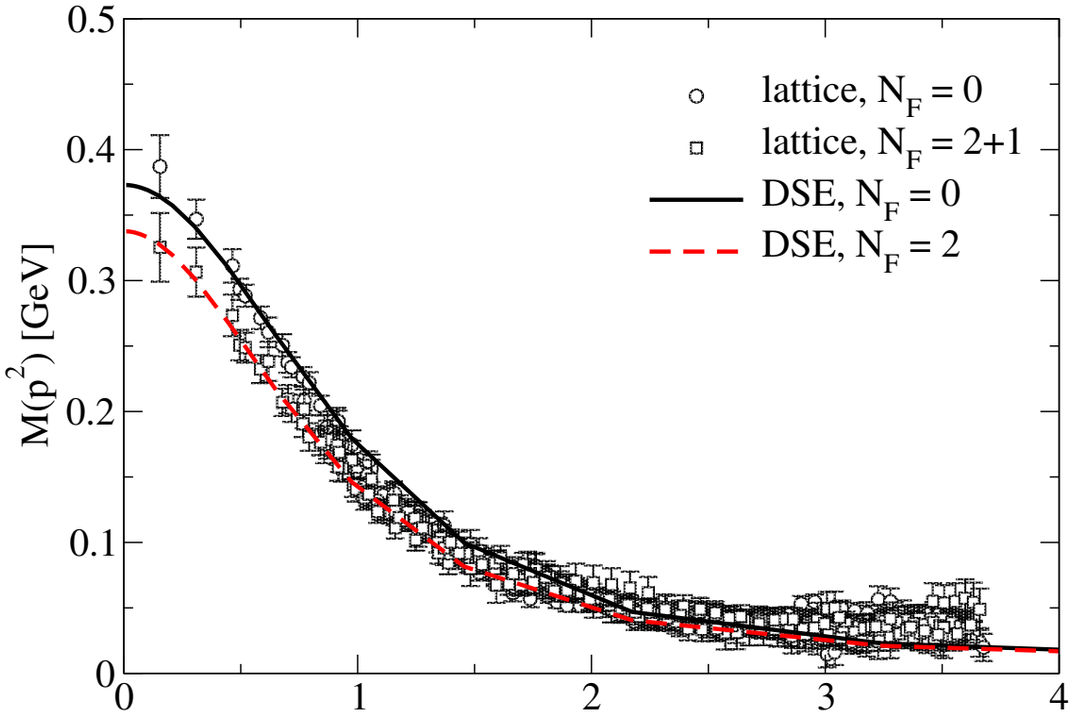
$\sqrt{s} \leq 7.7$: freezeout line $\neq$ transition line ?!

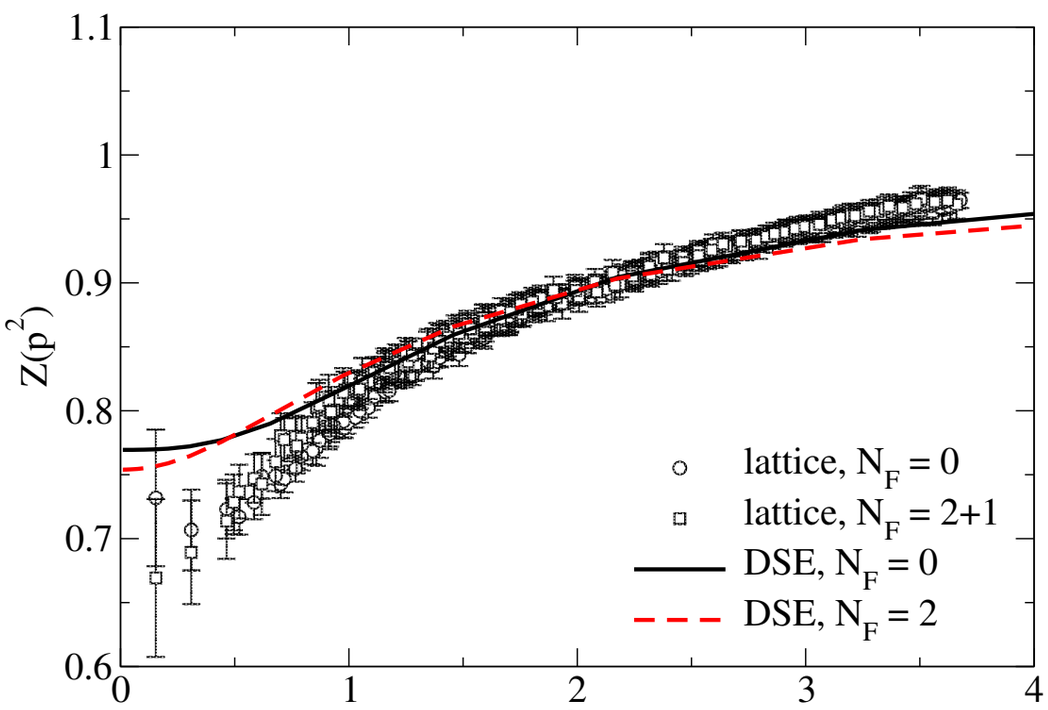
Isserstedt, Buballa, CF, Gunkel, PRD 100 (2019) no.7, 074011

Selected results for Green's functions

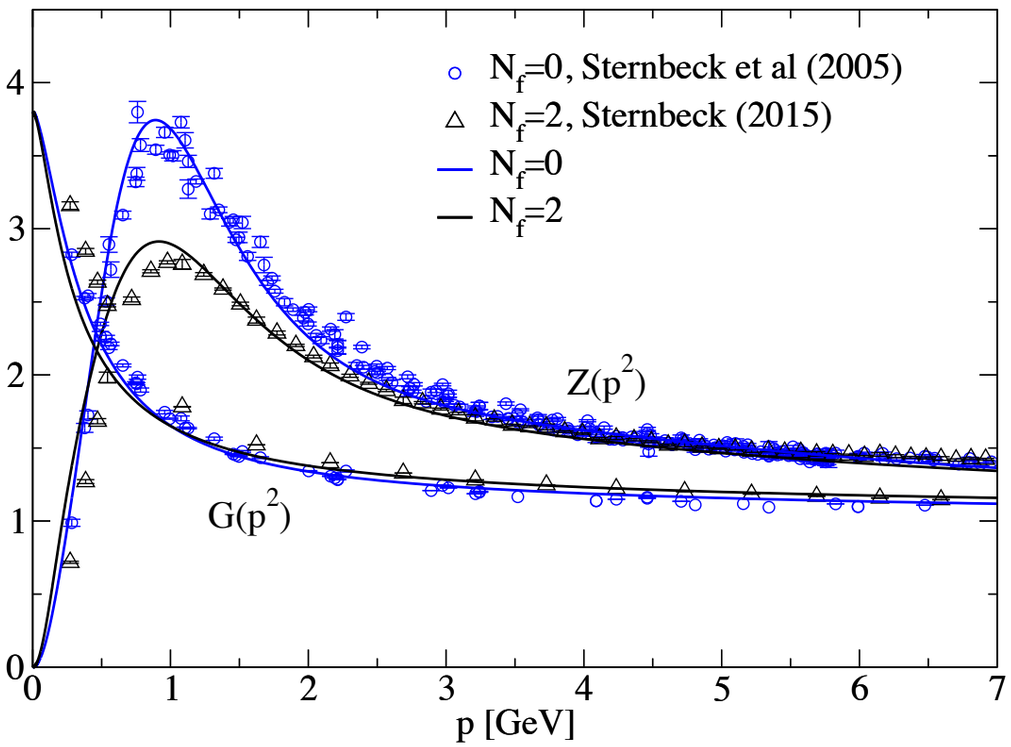
Quark

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

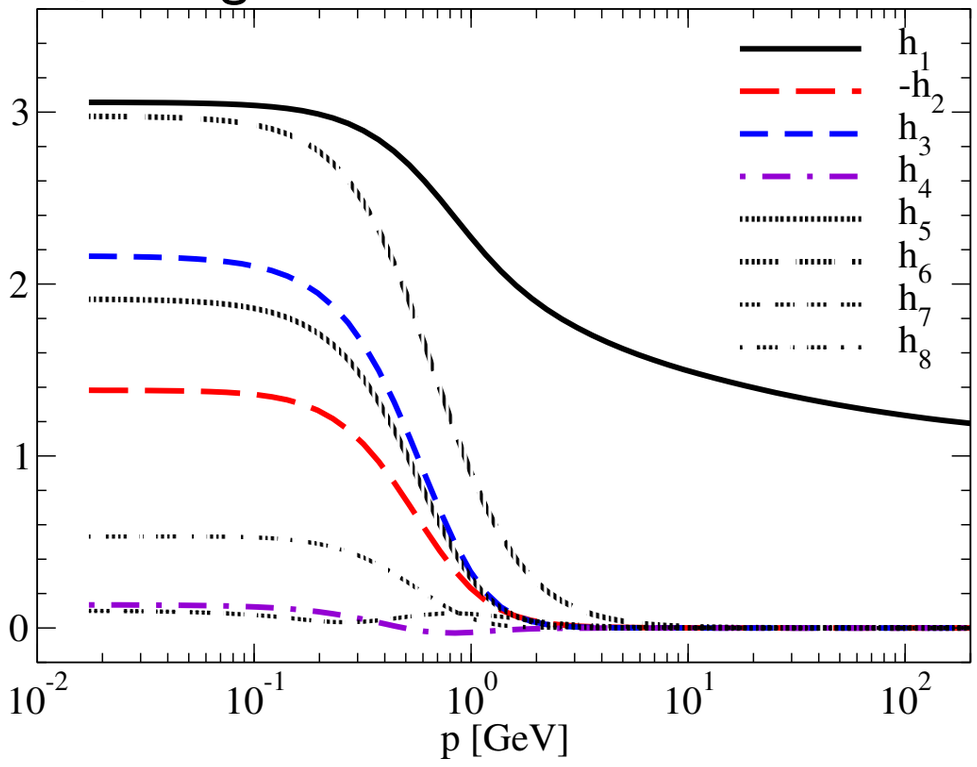




Gluon



Quark-gluon-vertex



Approximation for Quark-Gluon interaction

- Lattice input for vertex: not yet available…
- Diagrammatics: vertex-DSE (see later…)

explicit solutions at T=0: Mitter, Pawlowski and Strodthoff, PRD 91 (2015) 054035
Williams, CF, Heupel, PRD PRD 93 (2016) 034026

- Slavnov-Taylor identity: T,μ,m-dependent vertex

$$\Gamma_\nu(q,k,p) = \widetilde{Z}_3 \left(\delta_{4\nu}\gamma_4 \frac{C(k)+C(p)}{2} + \delta_{j\nu}\gamma_j \frac{A(k)+A(p)}{2} \right) \times$$

$$\times \left(\frac{d_1}{d_2+q^2} + \frac{q^2}{\Lambda^2+q^2} \left(\frac{\beta_0 \alpha(\mu) \ln[q^2/\Lambda^2+1]}{4\pi} \right)^{2\delta} \right)$$

STI

PT

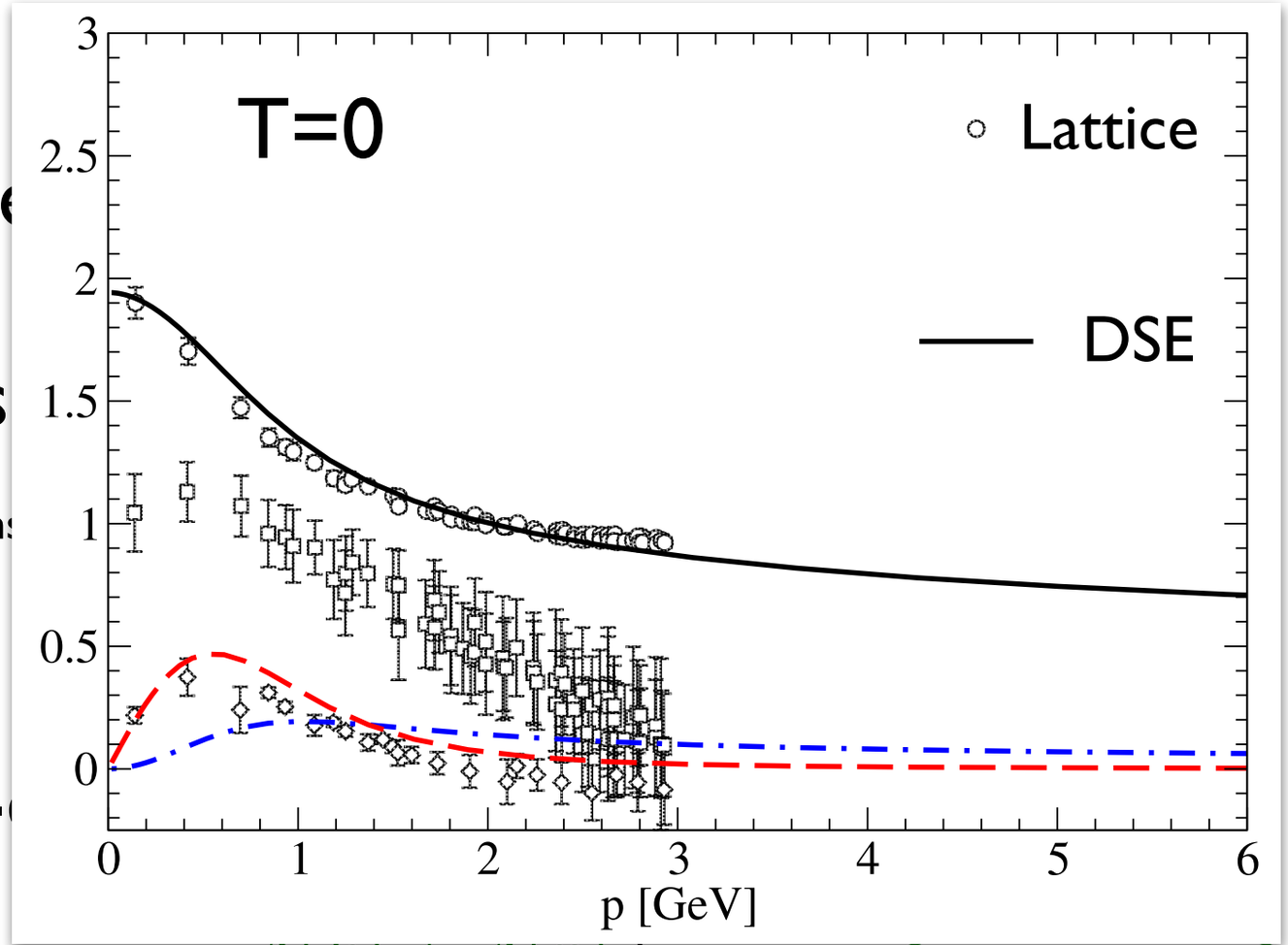
- d_1 fixed via T_c
- d_2 fixed to match scale of lattice gluon input

Approximation for Quark-Gluon interaction

- Lattice input for vertex: not ye
- Diagrammatics: vertex-DSE (s

explicit solutions

- Slavnov-Taylor identity: T,μ,m-



$$\Gamma_\nu(q,k,p) = \widetilde{Z}_3 \left(\delta_{4\nu}\gamma_4 \frac{C(k)+C(p)}{2} + \delta_{j\nu}\gamma_j \frac{A(k)+A(p)}{2} \right) \times$$

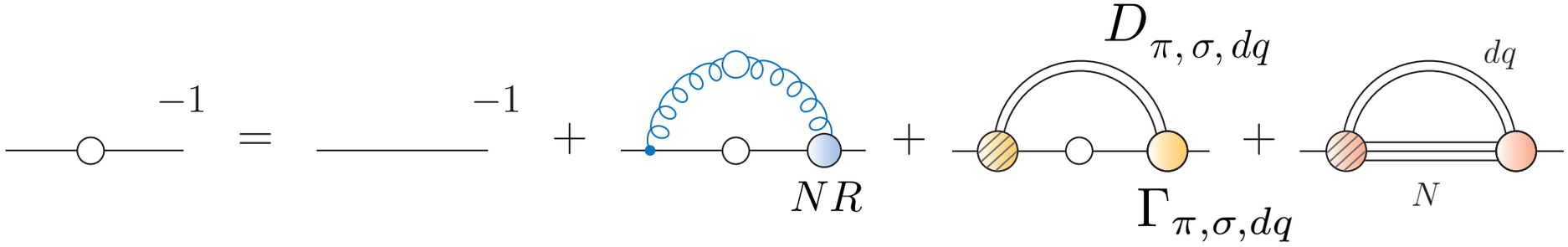
STI

$$\times \left(\frac{d_1}{d_2+q^2} + \frac{q^2}{\Lambda^2+q^2} \left(\frac{\beta_0 \alpha(\mu) \ln[q^2/\Lambda^2+1]}{4\pi} \right)^{2\delta} \right)$$

PT

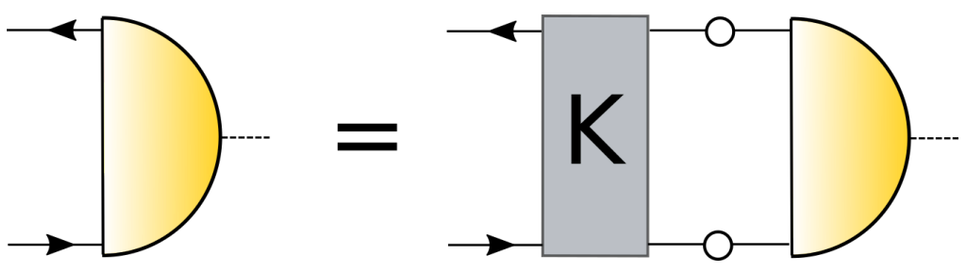
- d_1 fixed via T_c
- d_2 fixed to match scale of lattice gluon input

Meson effects at finite T and μ



$$D_\pi(p) = \frac{1}{p_4^2 + u^2(\vec{p}^{\,2} + m_\pi(T,\mu)^2)} \qquad u = \frac{f_s}{f_t}$$

Son, Stephanov, PRD 66 (2002) 7



$$\Gamma_\pi(P,q) = \gamma_5\, E(P,q,T,\mu) + \dots$$

chiral limit: $\Gamma_\pi = \gamma_5 \dfrac{B}{f_t}$