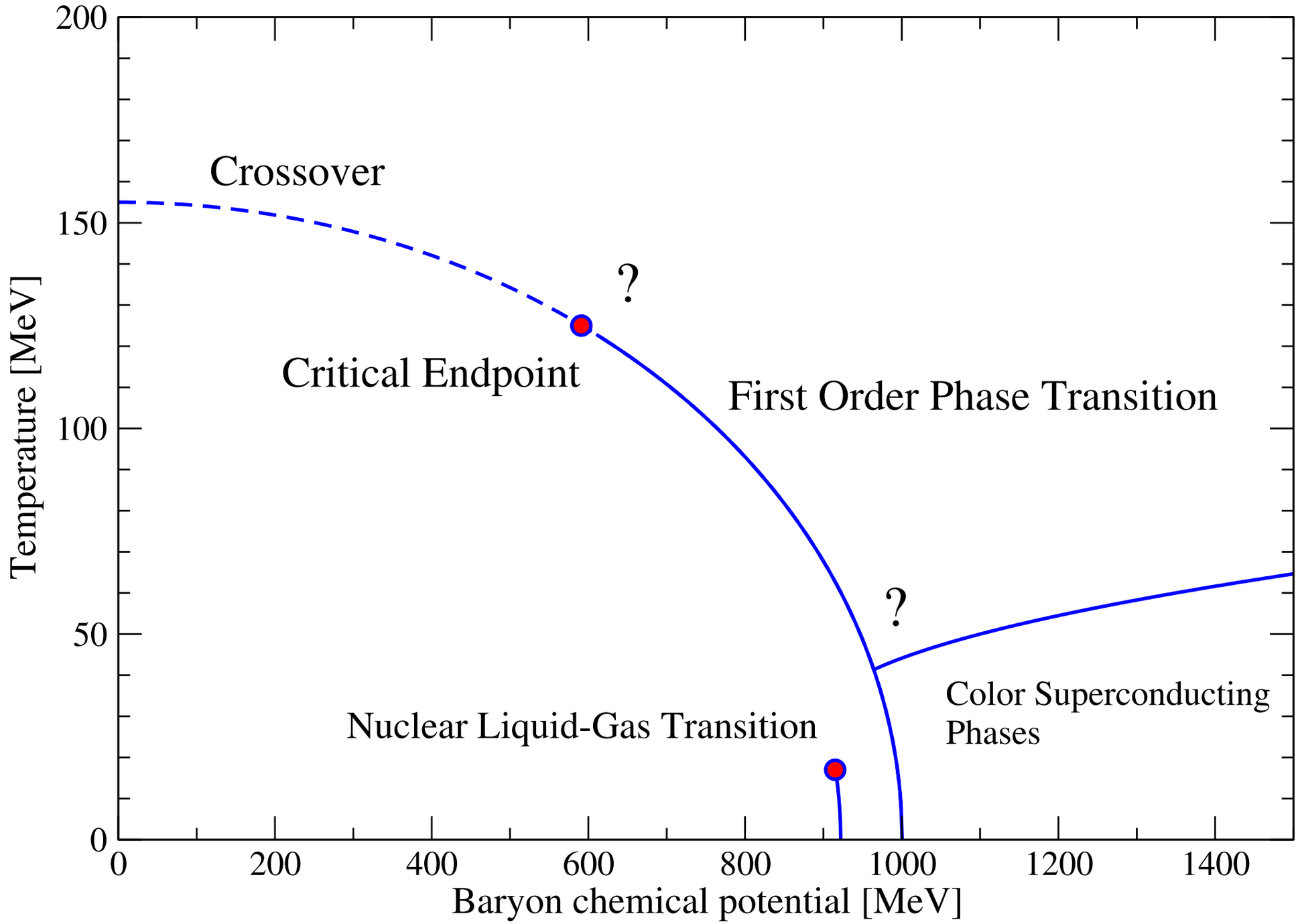
JLU
NEUE WEGE. SEIT 1607.

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

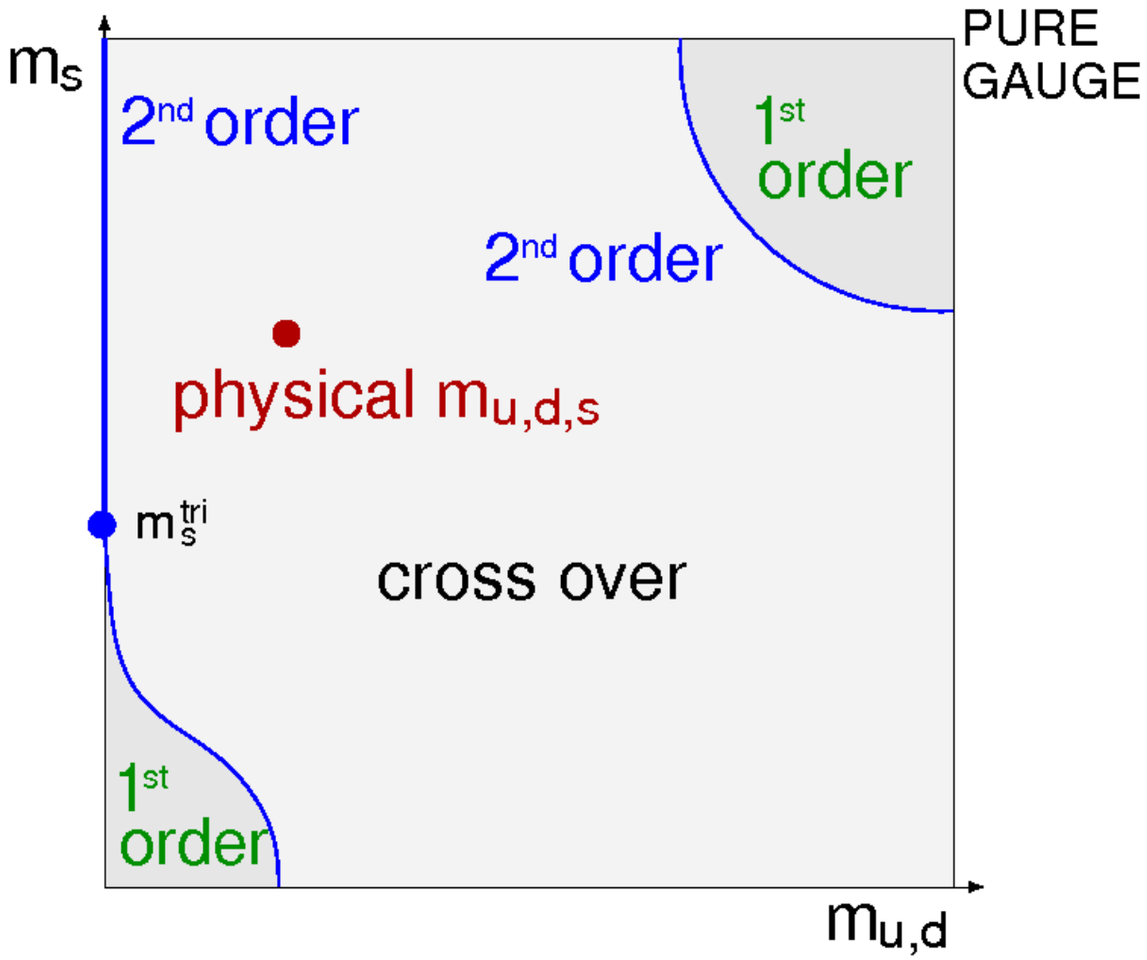
Review: CF, PPNP in press,
arXiv:1810.12938

QCD's phase diagram from DSEs

QCD phase transitions



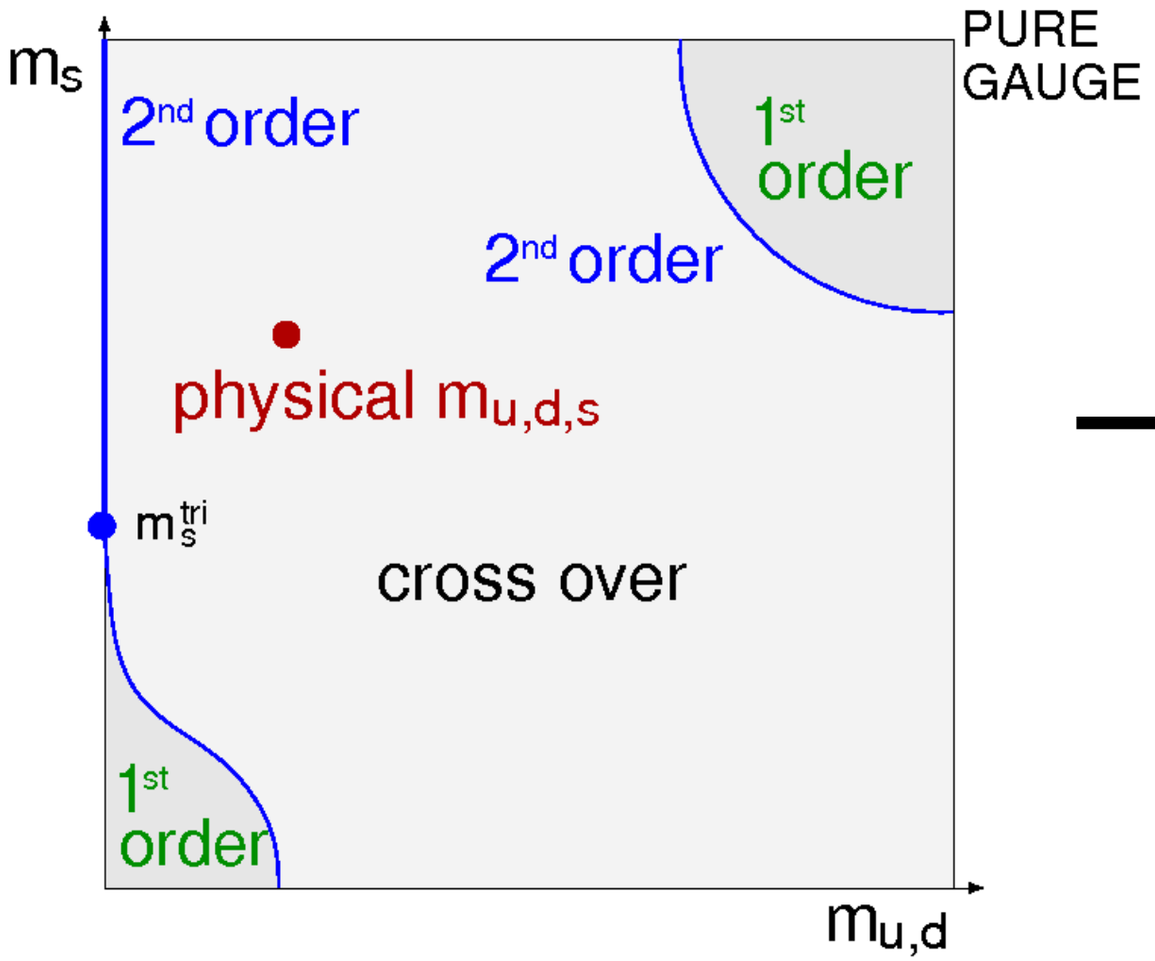
QCD phase transitions

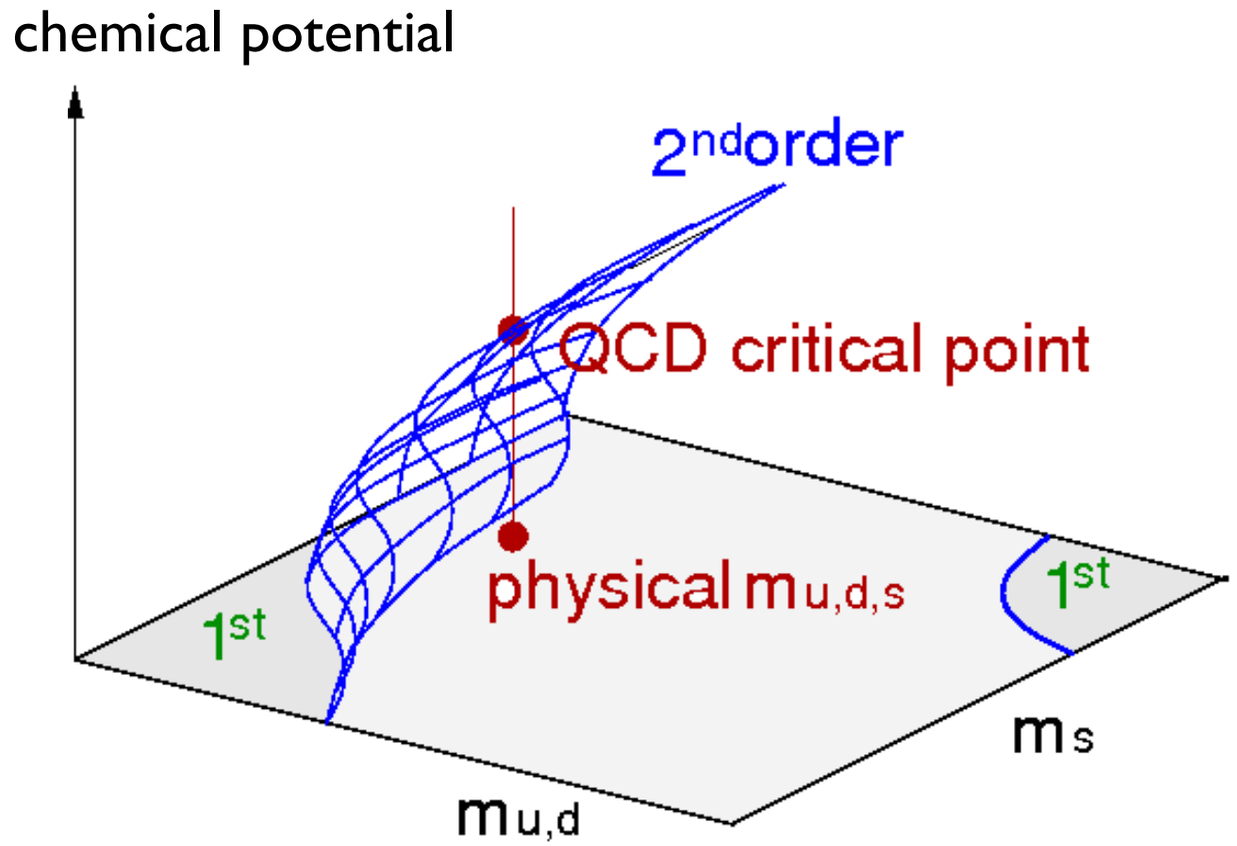


Is this happening ??
Maybe yes, maybe not..

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

QCD phase transitions





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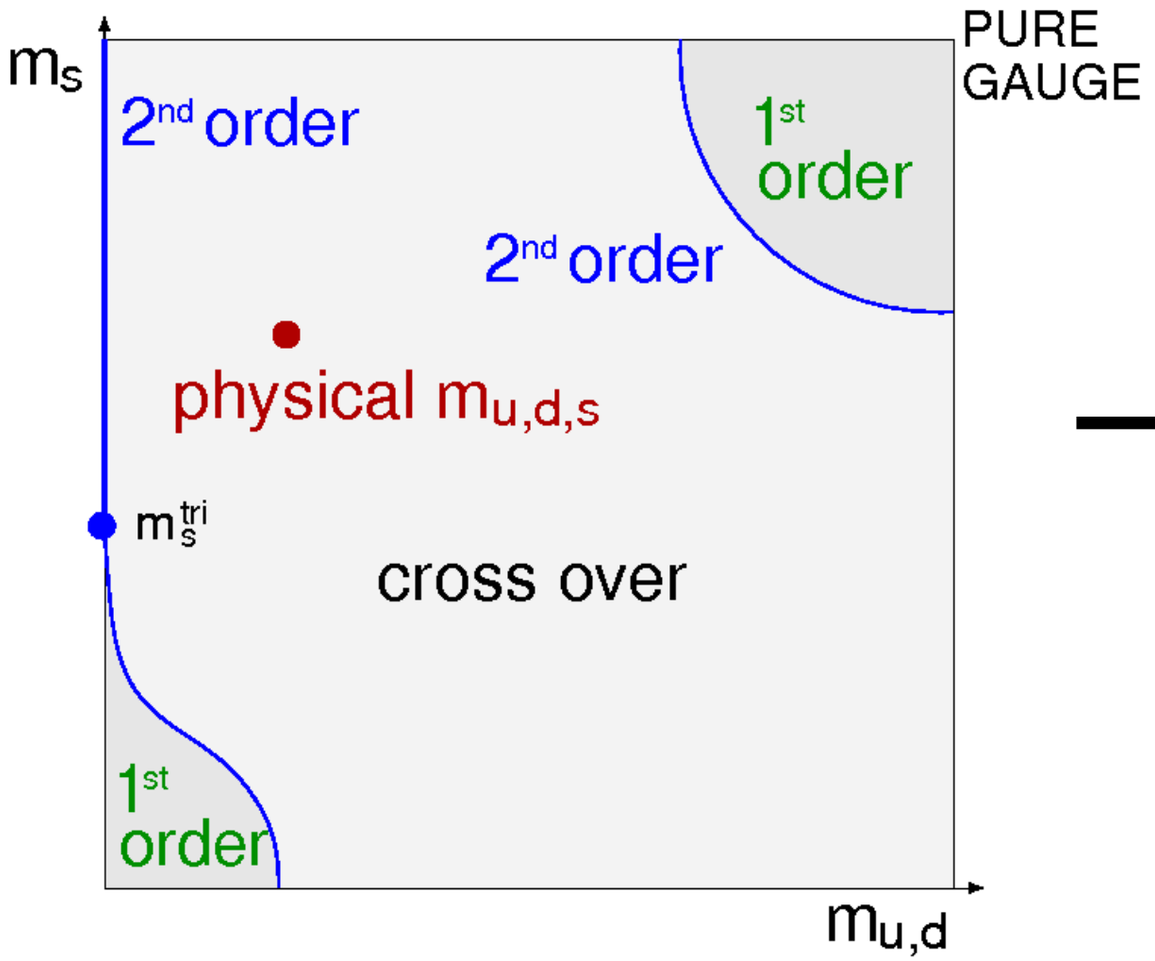
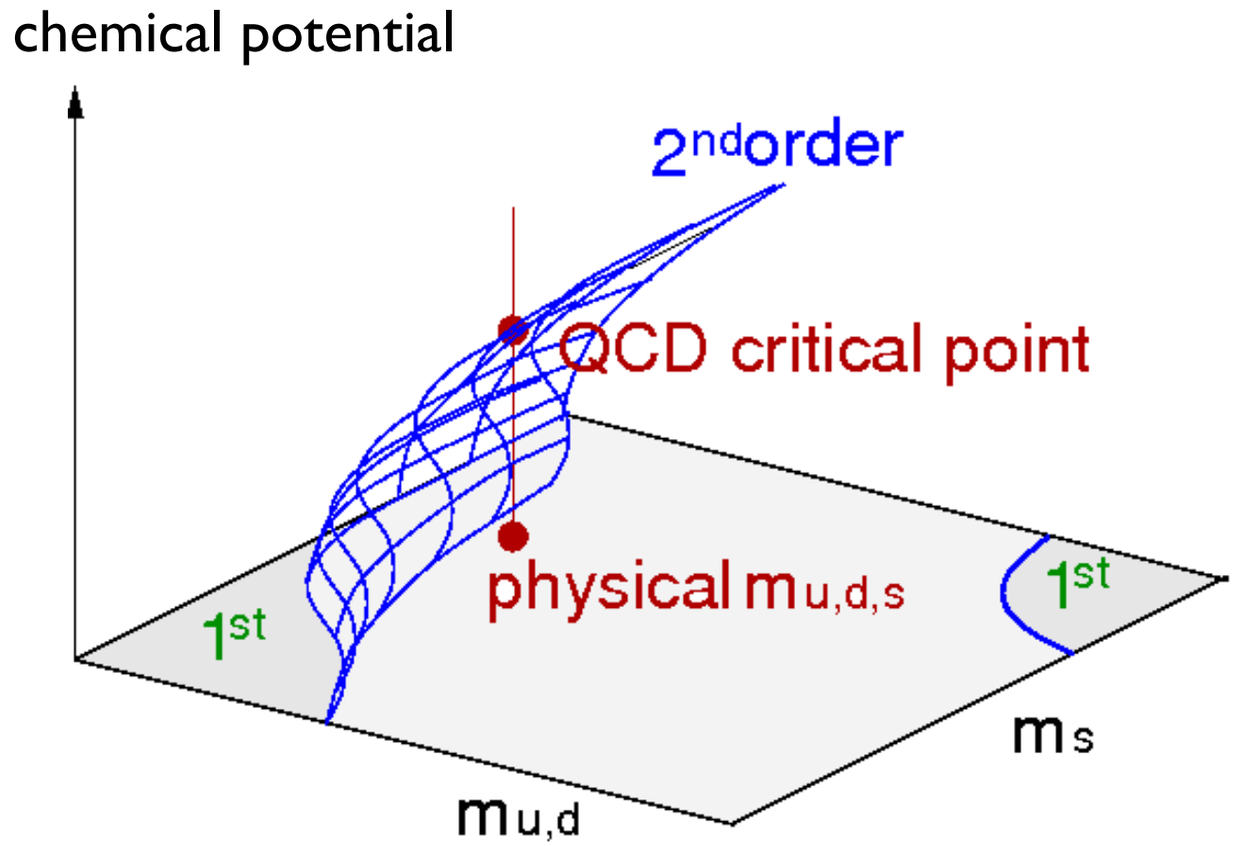
QCD phase transitions





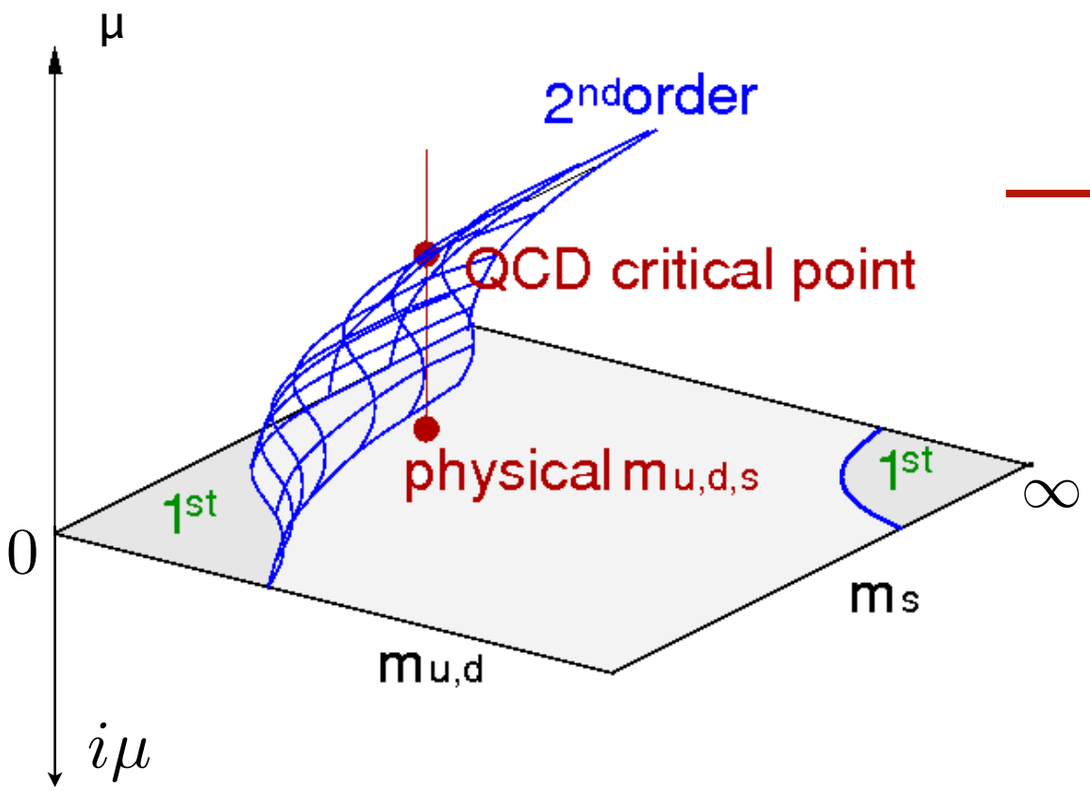
- Lattice-QCD
  - present: extrapolation
  - future: exact methods ?

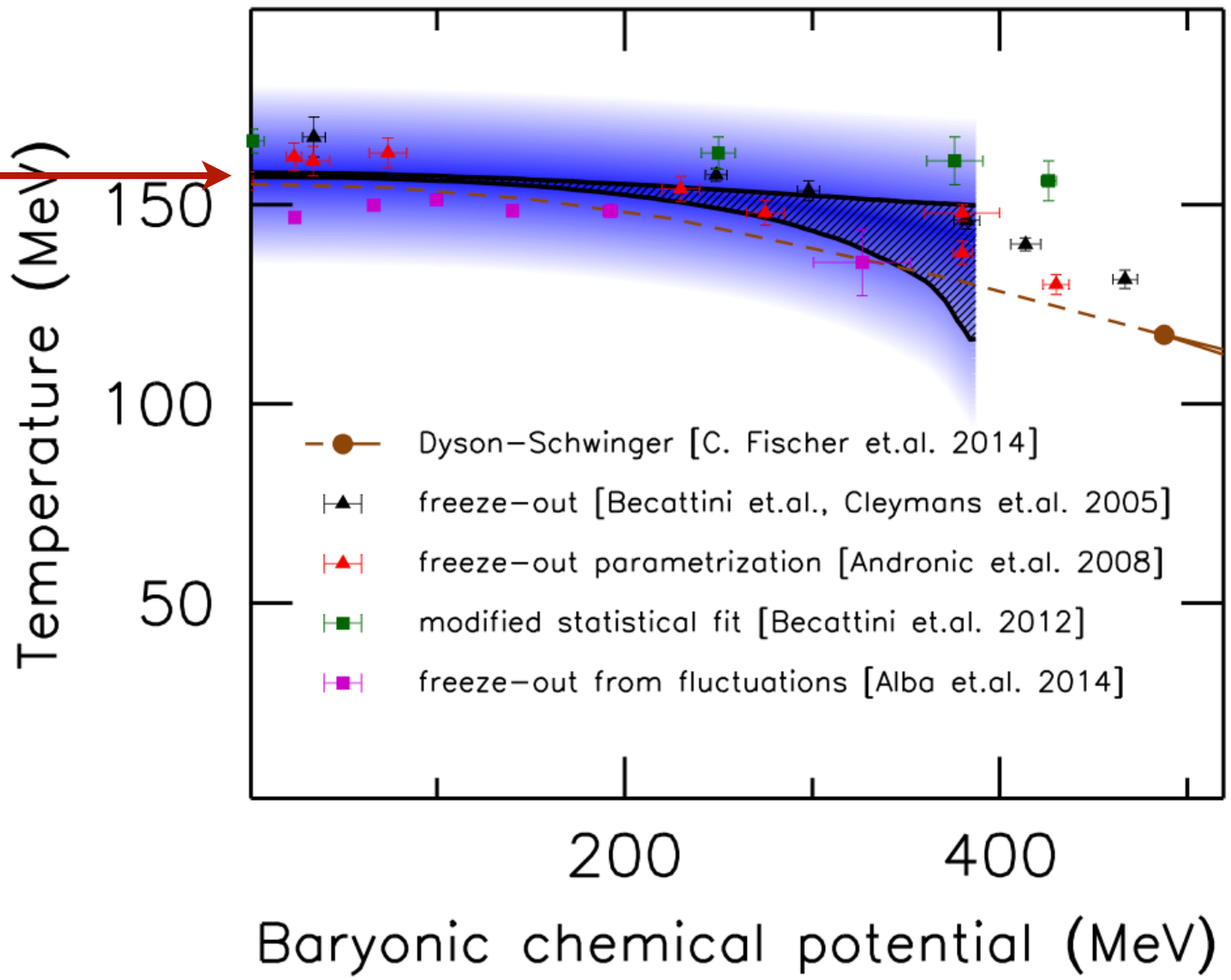
Is this happening ??
Maybe yes, maybe not..

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

- DSE/FRG
  - alternative tool on precision level 5-10%

Chiral transition line from analytic continuation





Lattice method:

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

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

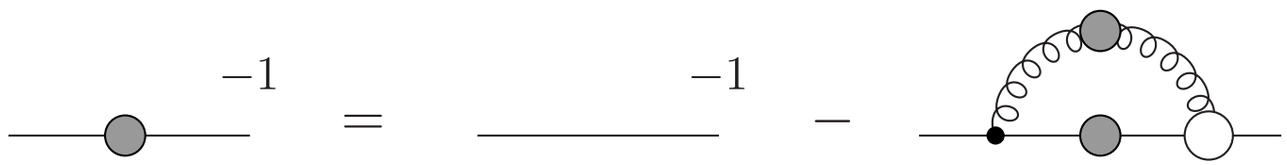
HOT-QCD: similar results

Main result: no CEP for $\mu_B/T < 2\text{-}3$

QCD order parameters from propagators

Chiral order parameter:

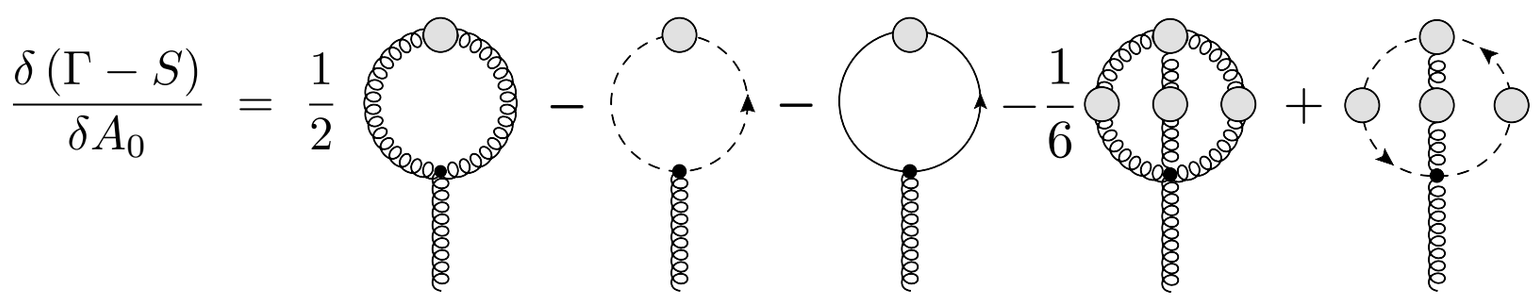
$$\langle \bar{\Psi}\Psi \rangle = Z_2 N_c Tr_D \frac{1}{T} \sum_\omega \int \frac{d^3p}{(2\pi)^3} S(\vec{p},\omega)$$



Deconfinement:

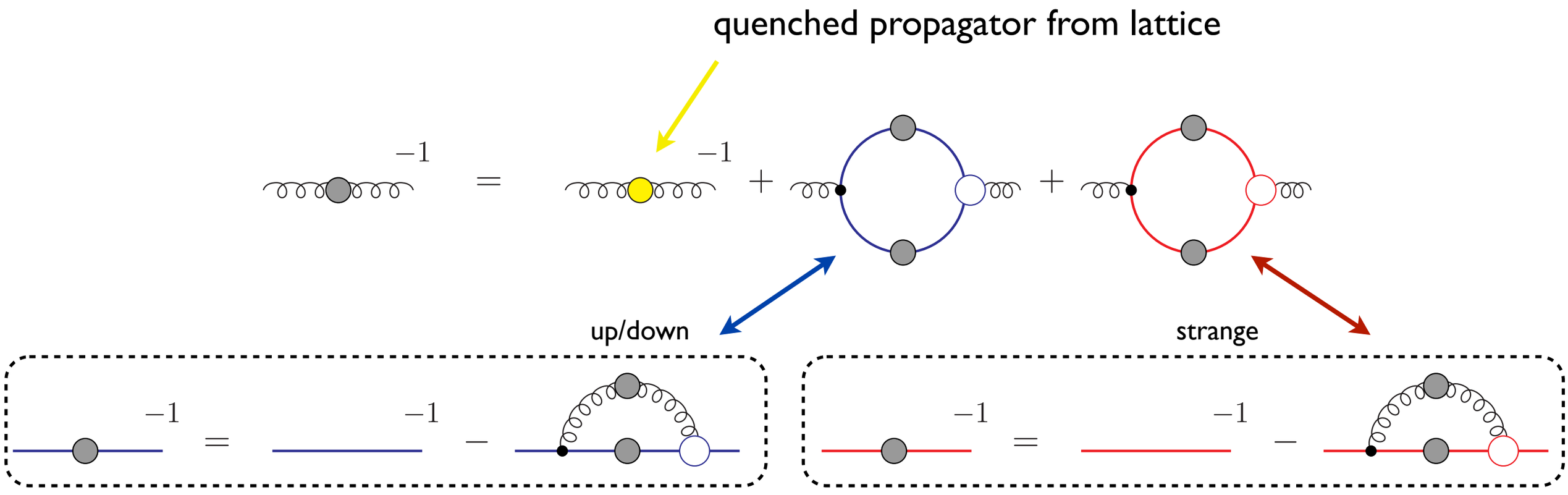
- Polyakov loop potential

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



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)

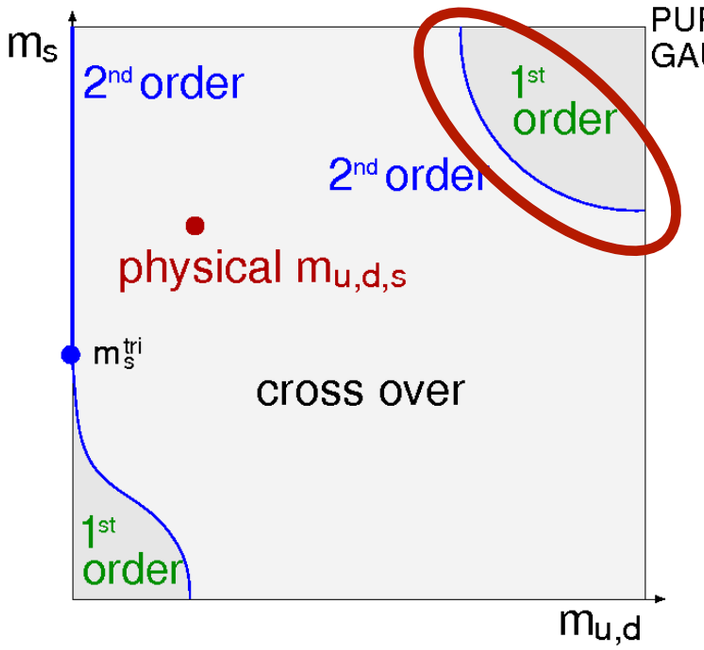
N_f=2+1-QCD with DSEs



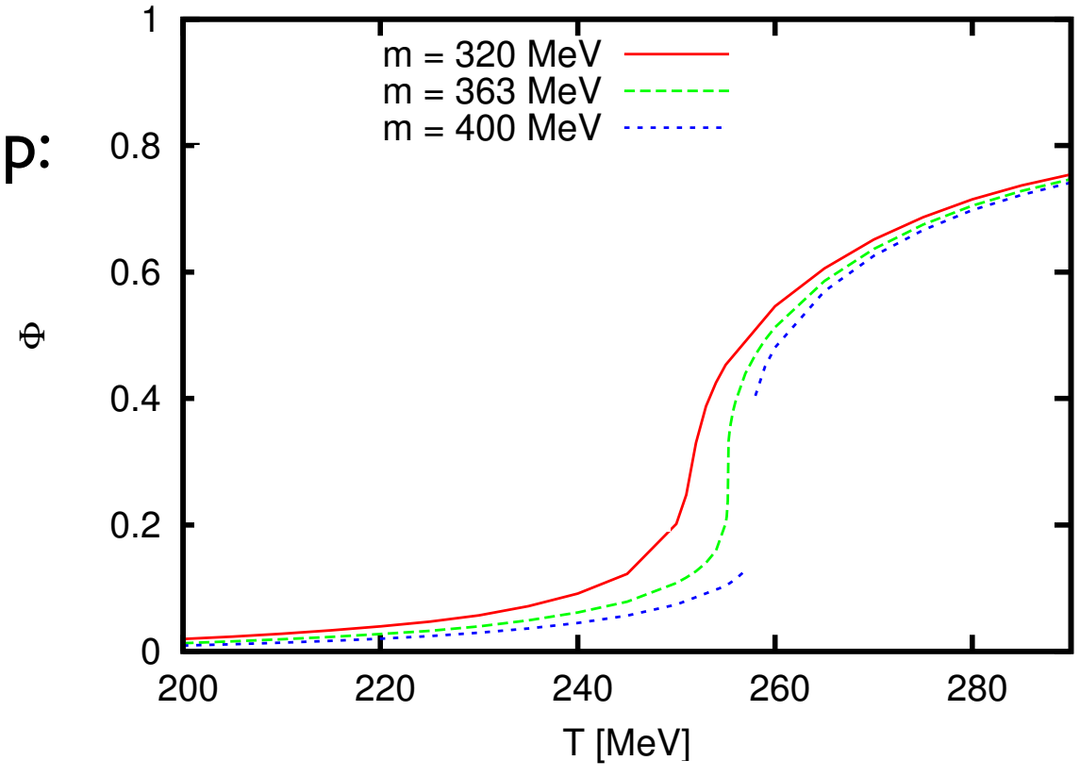
- allows for systematic variation of $m_{u/d}$ and m_s
- quark-gluon vertex:
  ansatz built along STI and known UV/IR behavior

  → T,μ,m-dependent

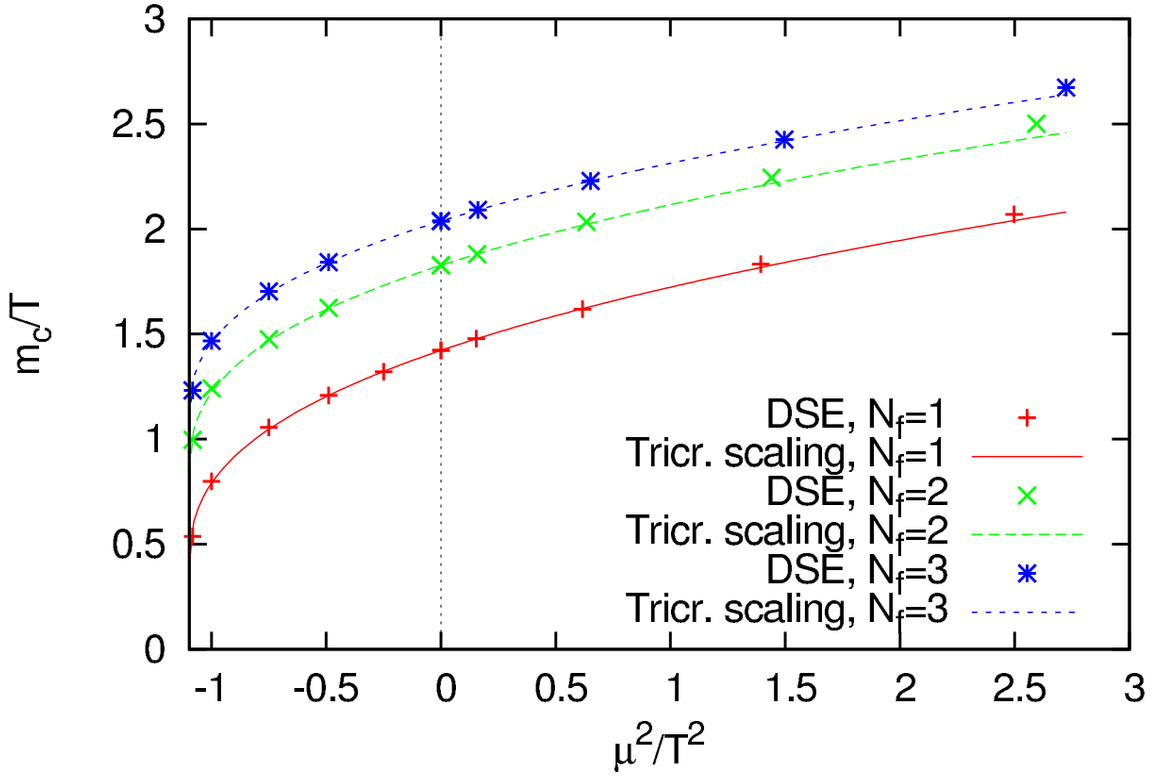
Critical line/surface for heavy quarks



Polyakov Loop:



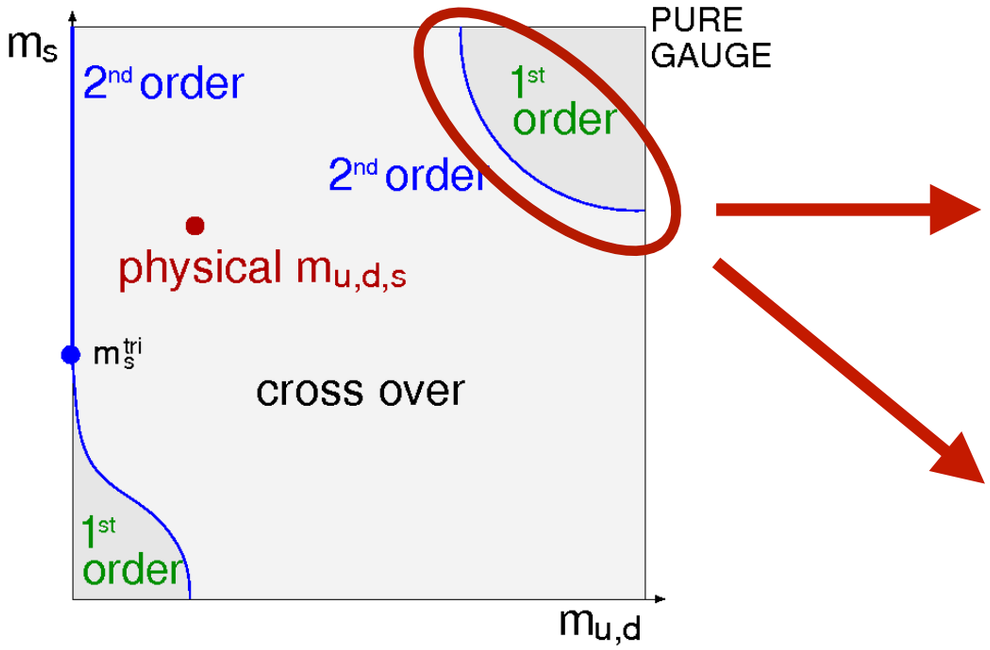
- Deconfinement transition in agreement with lattice QCD
- Correct tricritical scaling
- Roberge-Weiss-transition seen



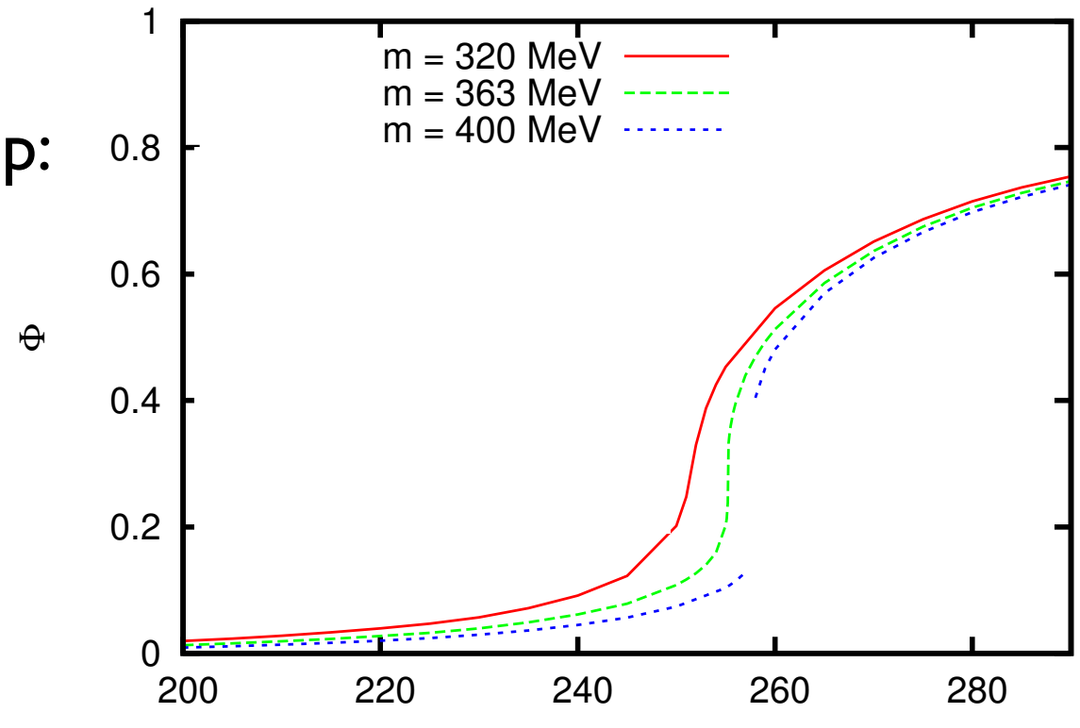
Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

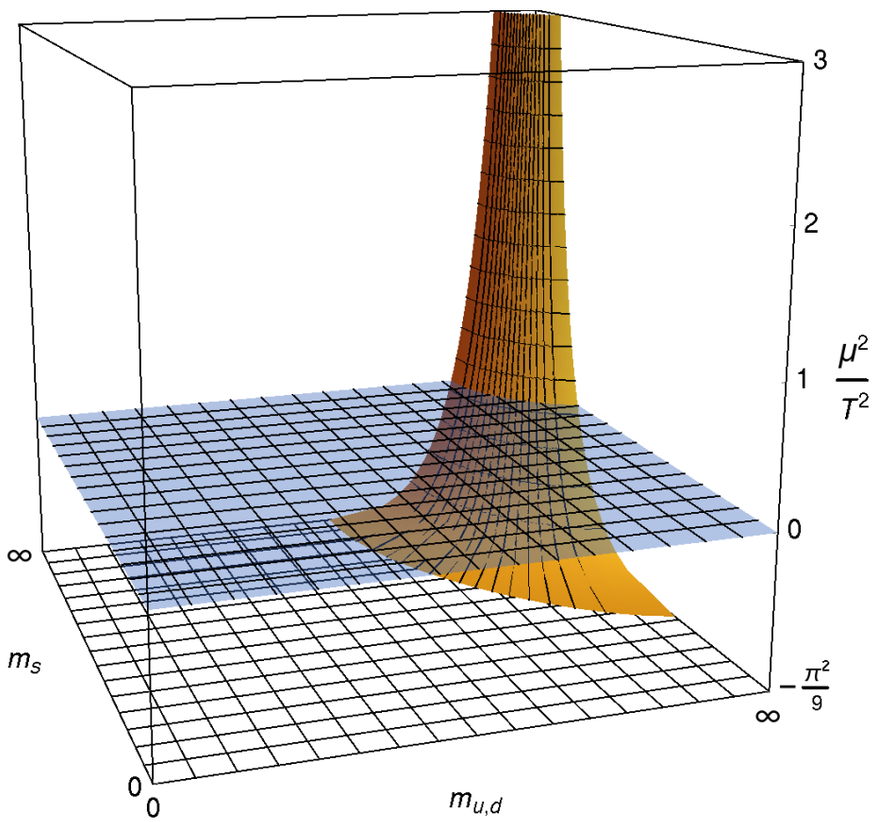
CF, Luecker, Pawlowski, PRD 91 (2015) 1

Critical line/surface for heavy quarks



Polyakov Loop:





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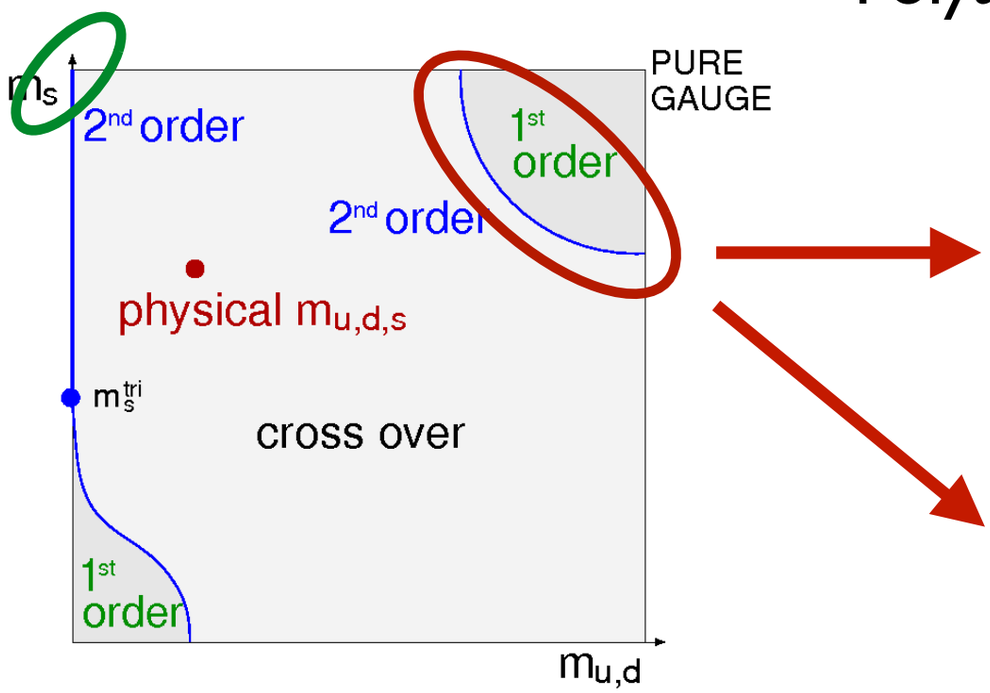
Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

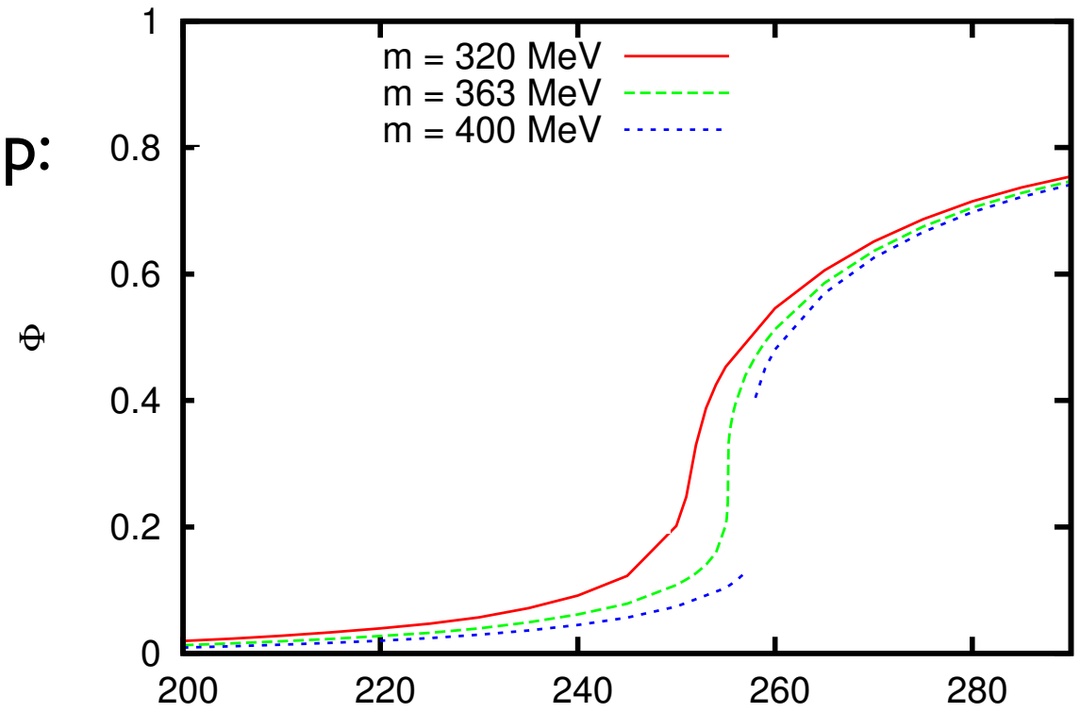
CF, Luecker, Pawlowski, PRD 91 (2015) 1

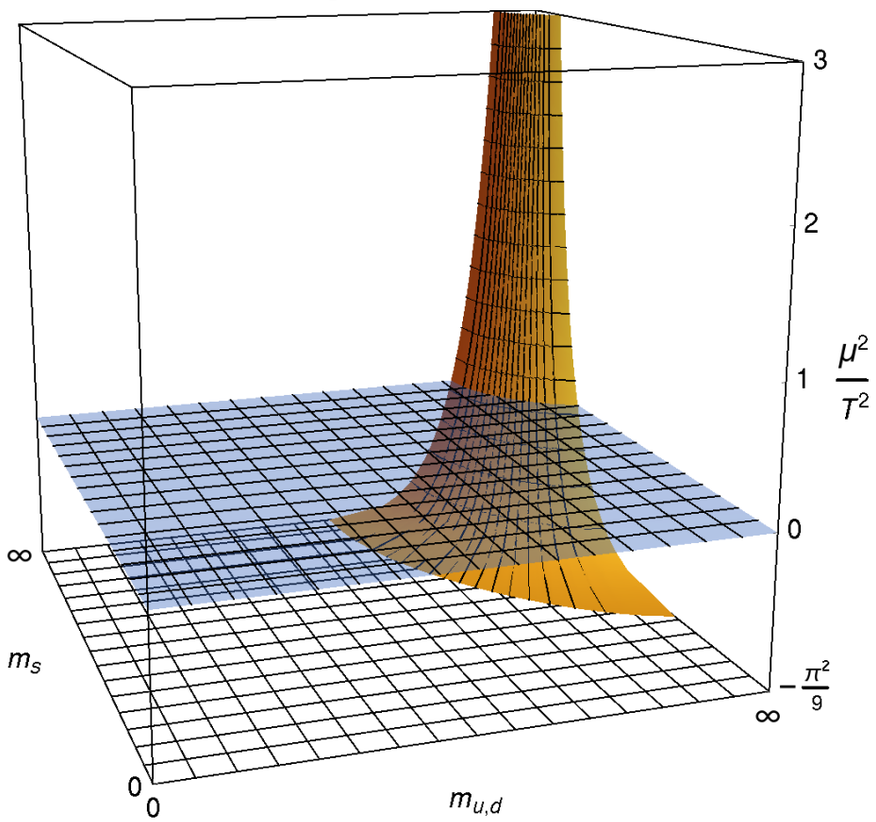
Critical line/surface for heavy quarks

Nf=2: CF and Mueller, PRD 84 (2011) 054013



Polyakov Loop:



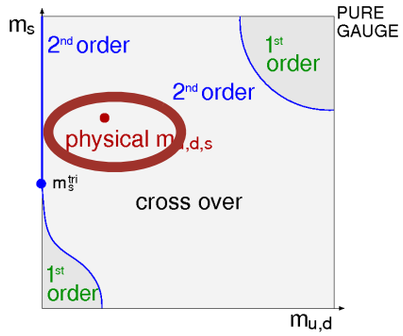


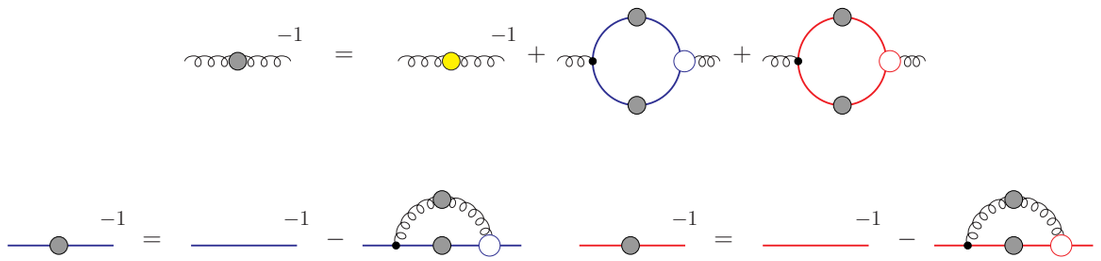
- Deconfinement transition in agreement with lattice QCD
- Correct tricritical scaling
- Roberge-Weiss-transition seen

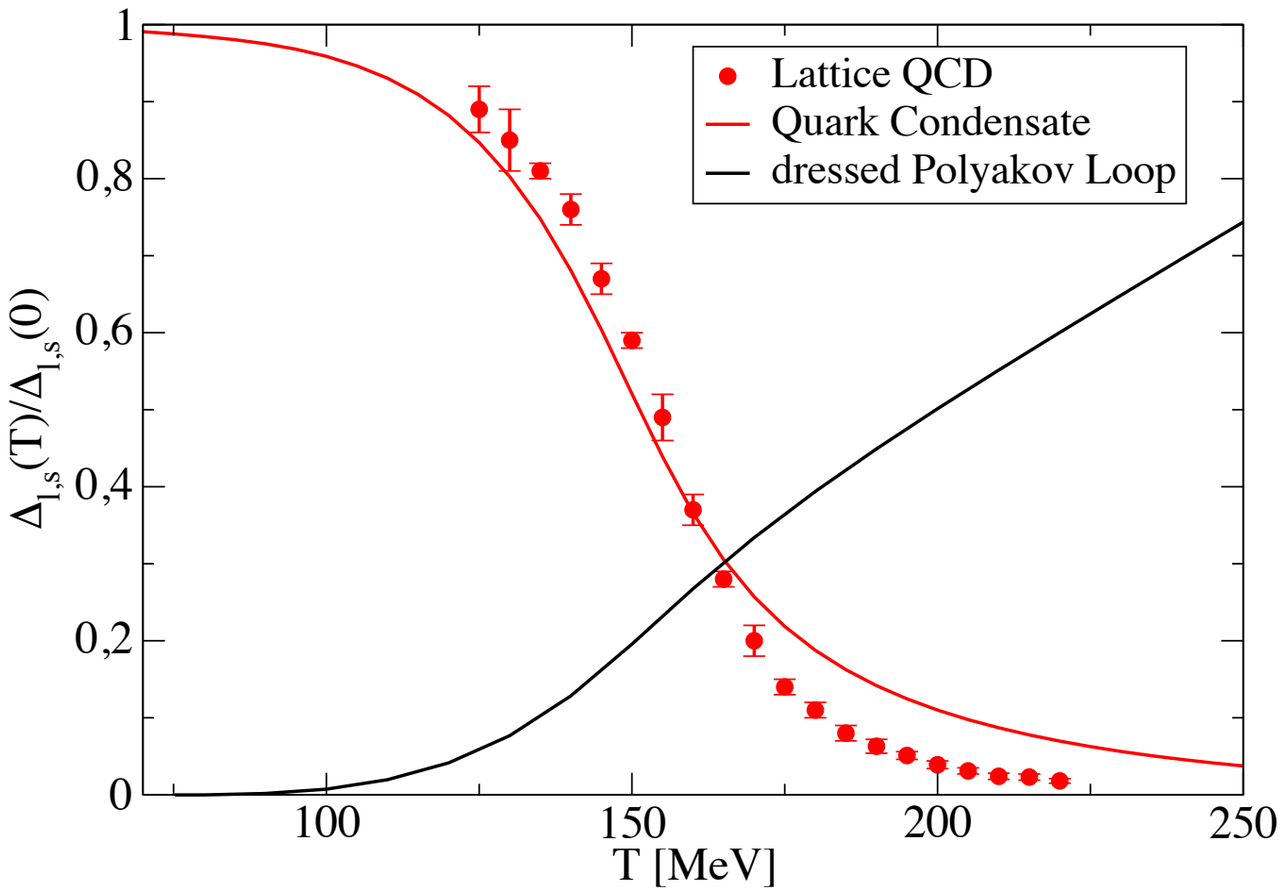
Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

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

N_f=2+1, μ=0, physical point

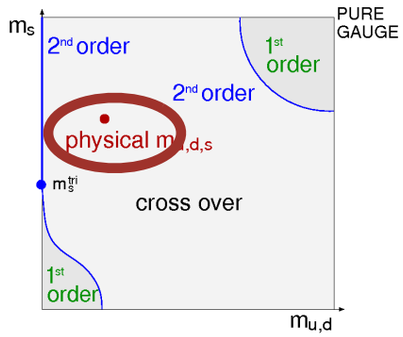


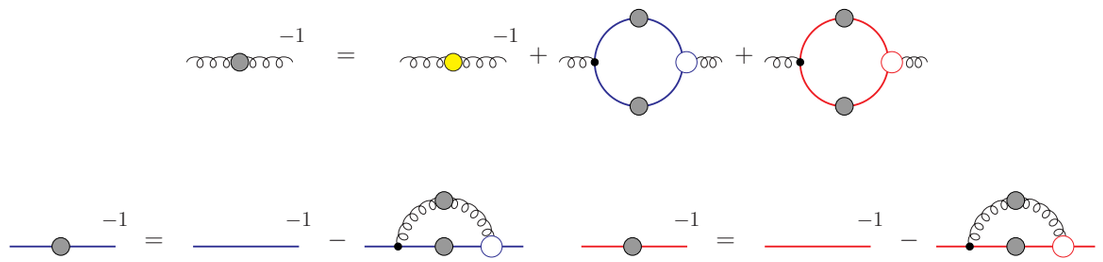


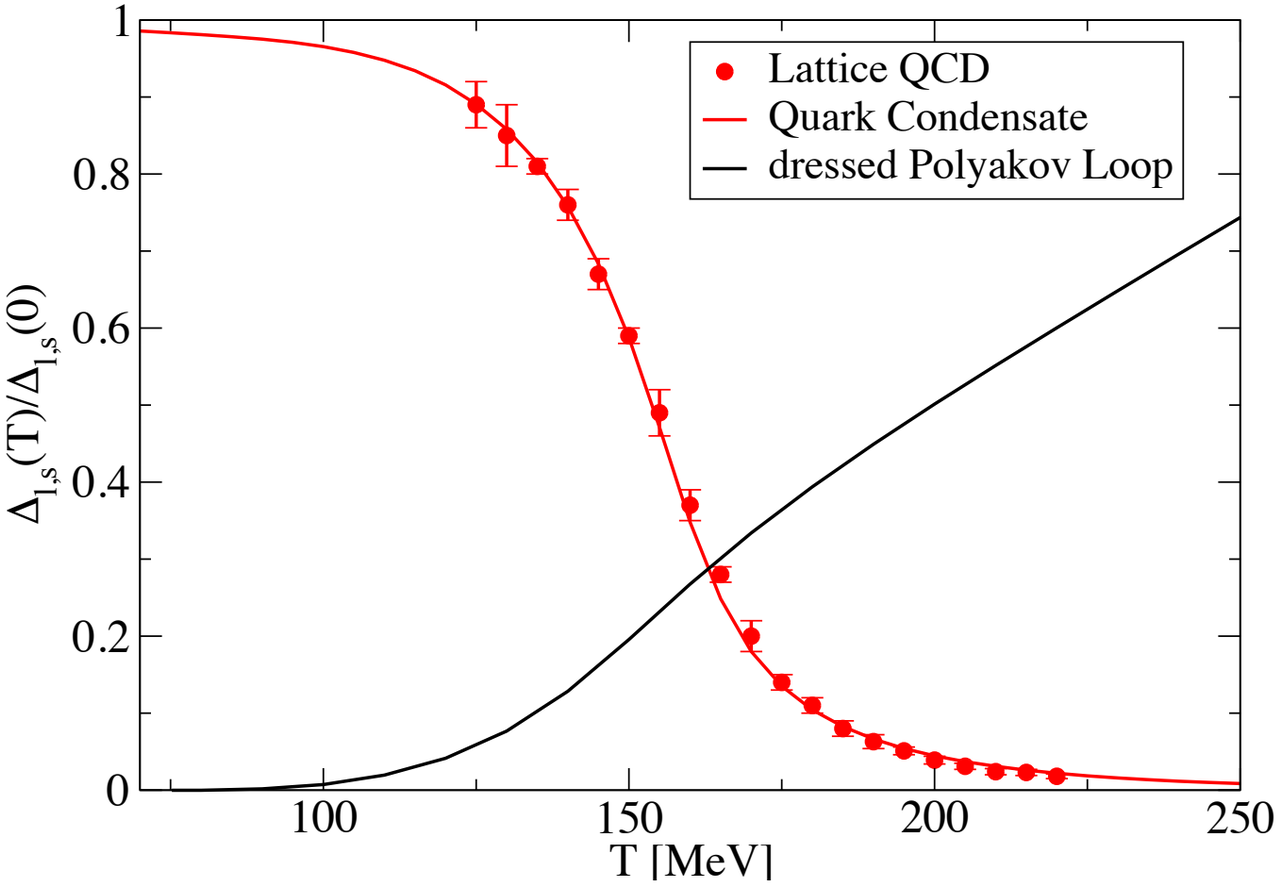


Lattice: Borsanyi *et al.* [Wuppertal-Budapest], JHEP 1009(2010) 073
DSE: CF, Luecker, PLB 718 (2013) 1036,
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

N_f=2+1, μ=0, physical point







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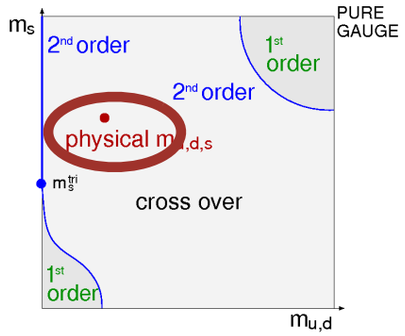

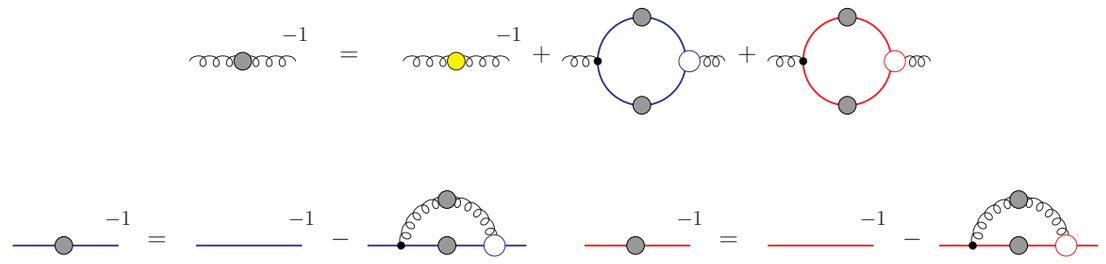

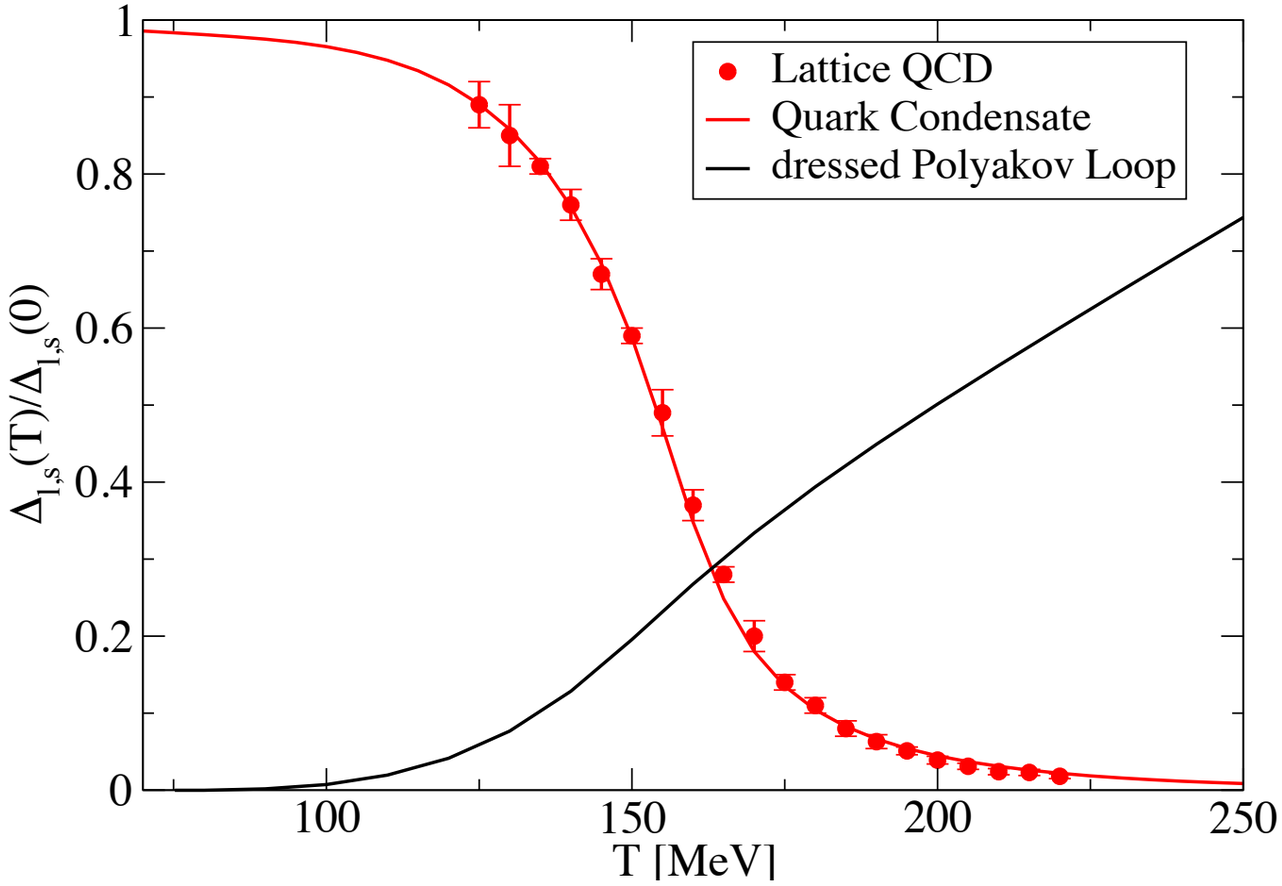

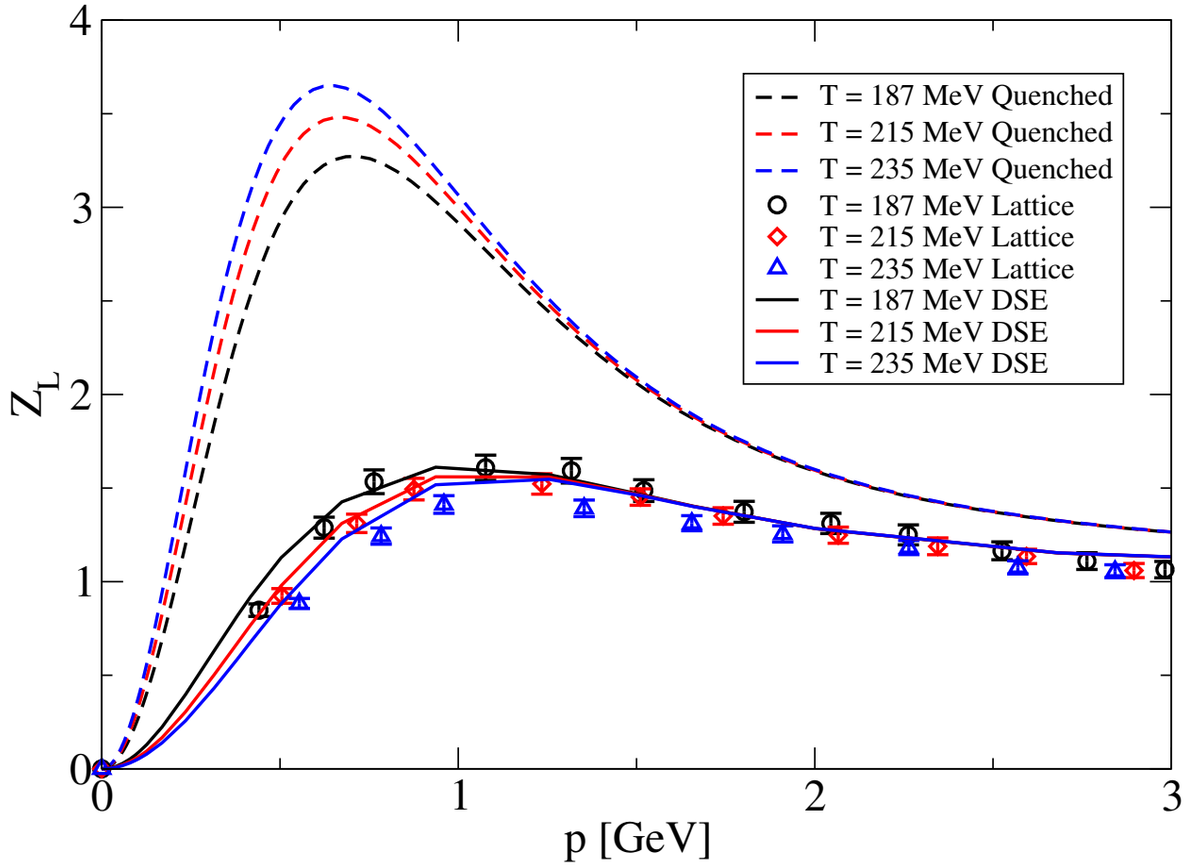

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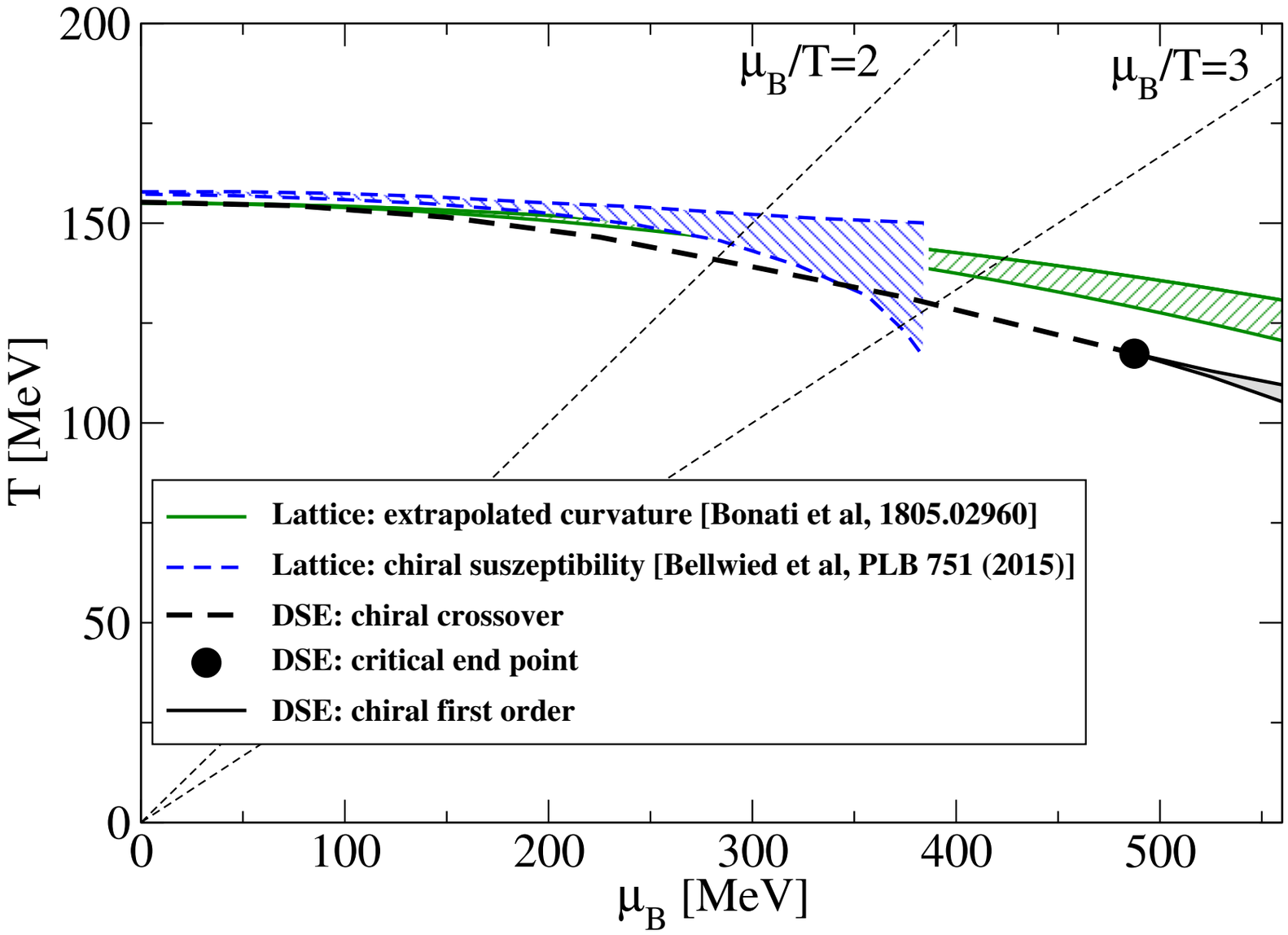
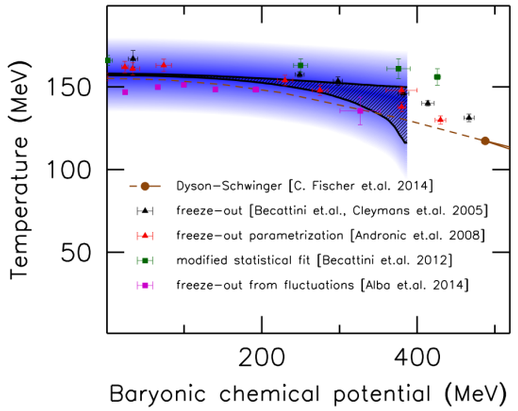
DSE: CF, Luecker, PLB 718 (2013) 1036,
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

Lattice: Aouane, et al.PRD D87 (2013), [arXiv:1212.1102]
DSE: CF, Luecker, PLB 718 (2013) 1036, [arXiv:1206.5191]

- quantitative agreement: DSE prediction verified by lattice

N_f=2+1: phase diagram





Extrapolated curvature from lattice

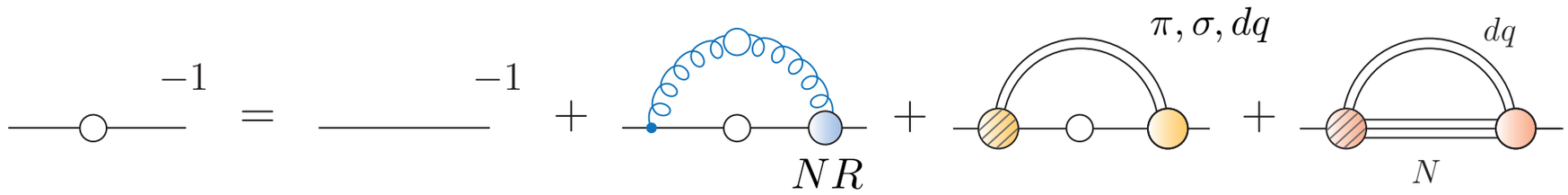
Bonati et al., PRD 92 (2015) 054503
Bellwied et al. PLB 751 (2015) 559
Cea, Cosmai, Papa, PRD 89 (2014), PRD 93 (2016)
Bonati et al., arXiv:1805.02960

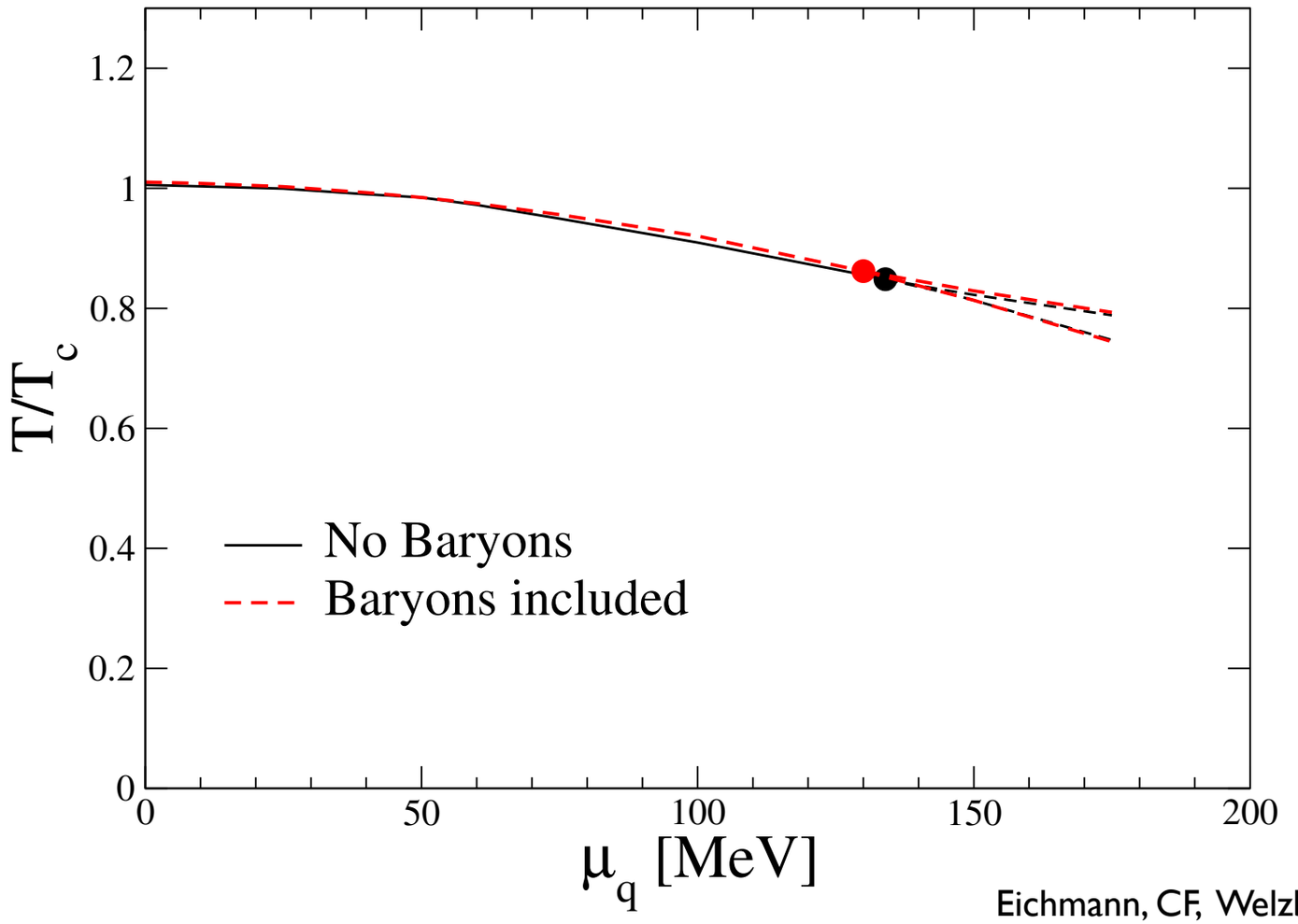
CEP at large μ

CF, Luecker, PLB 718 (2013) 1036,
CF, Fister, Luecker, Pawlowski, PLB 732 (2014) 273
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

- combined evidence of DSE, FRG and lattice: no CEP at $\mu_B/T<2$

Hadron effects on the CEP - results (N_f=2)

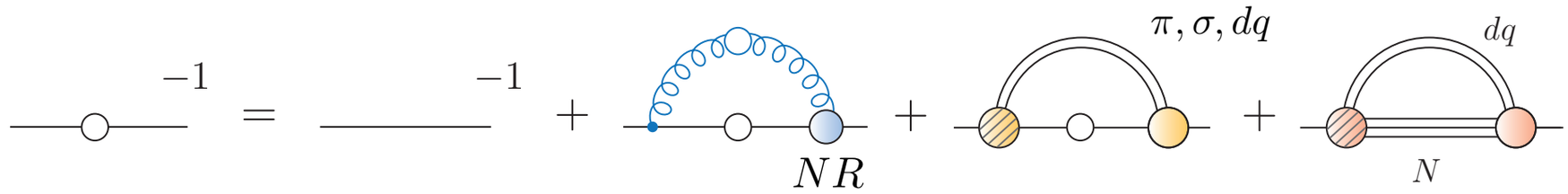




Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]

- Zero chemical potential: no effect
- almost no effect on location of CEP (mesons: similar)

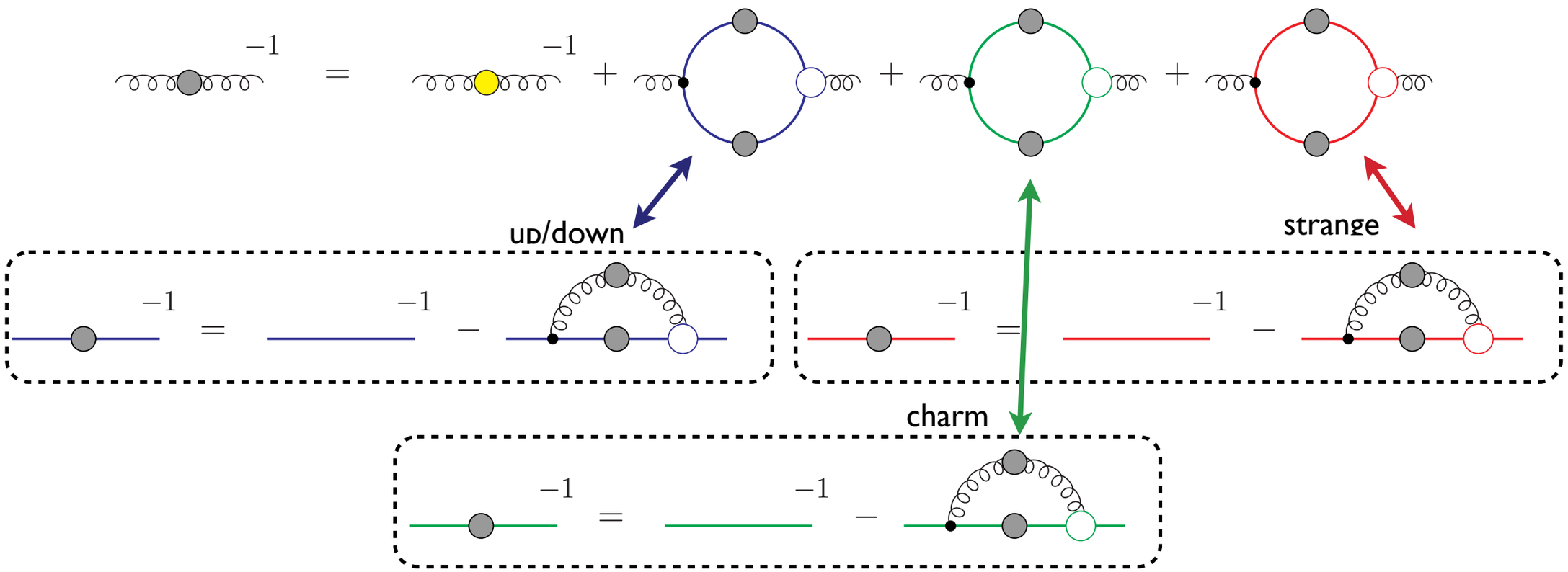
Hadron effects on the CEP - results (N_f=2)



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

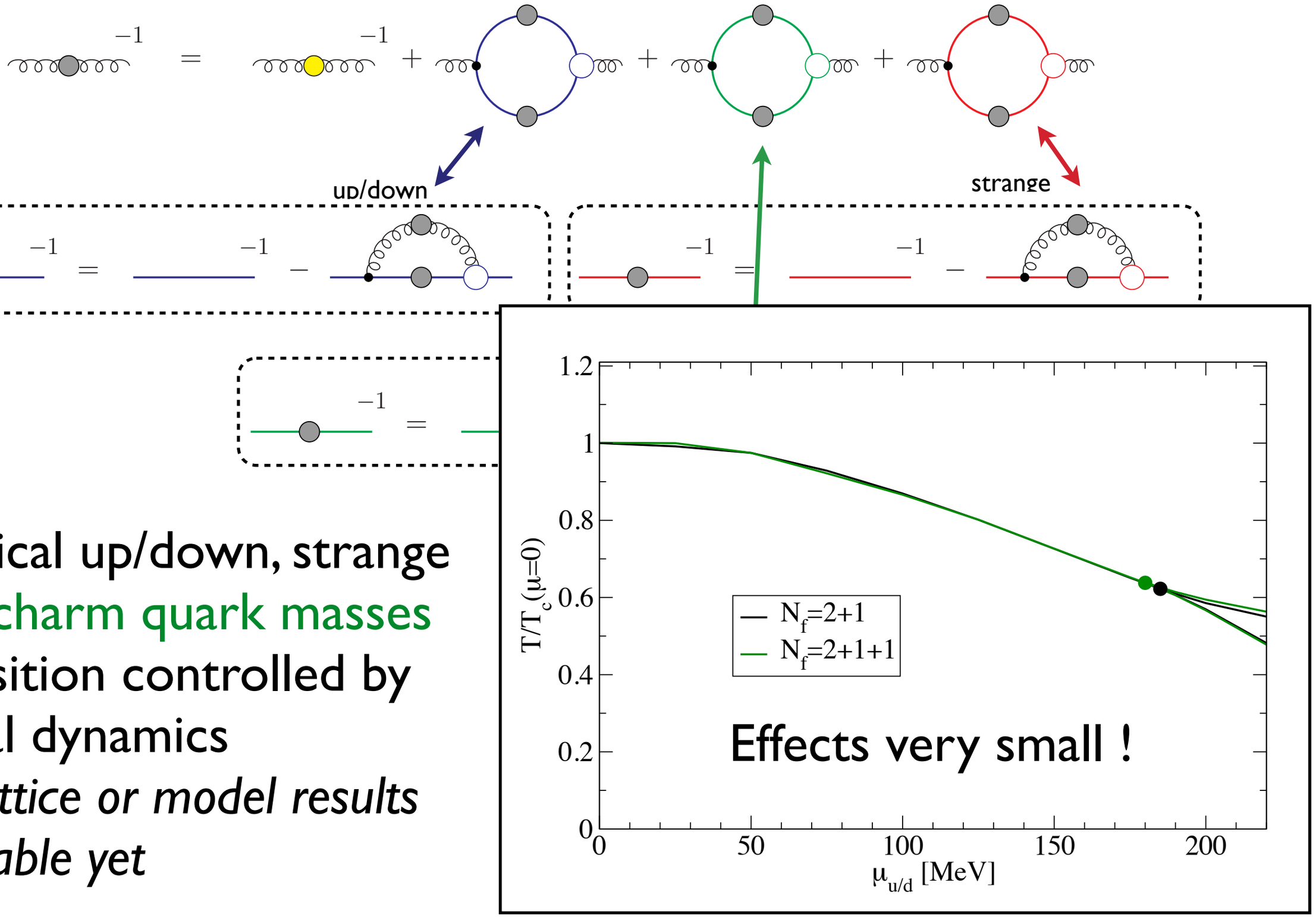
- Zero chemical potential: no effect
- almost no effect on location of CEP (mesons: similar)
- But: strong μ-dependence of baryon wave function may change situation…

Nf=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*

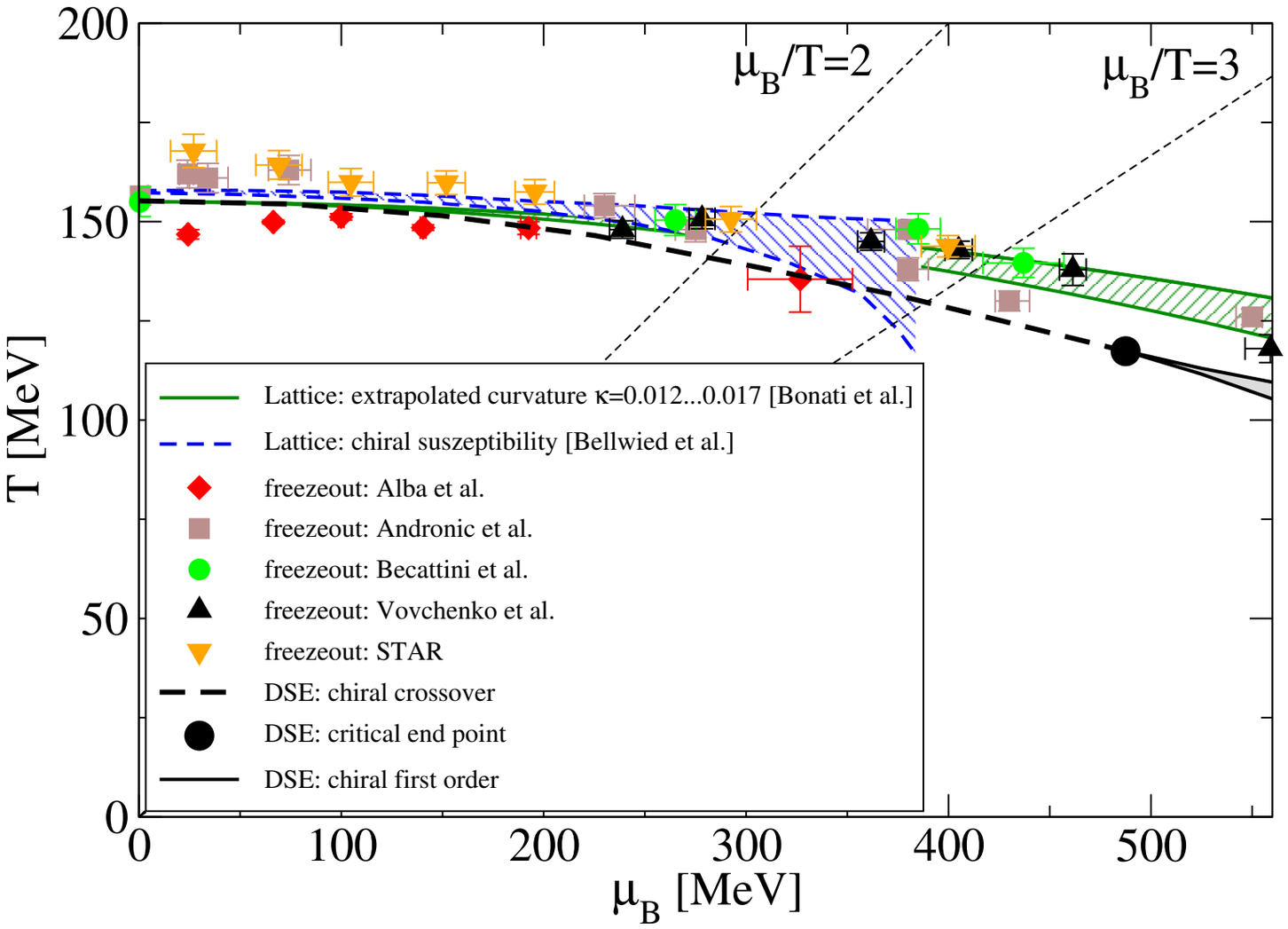
Nf=2+1+1: effects of charm



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

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

Location of CEP in freece-out landscape



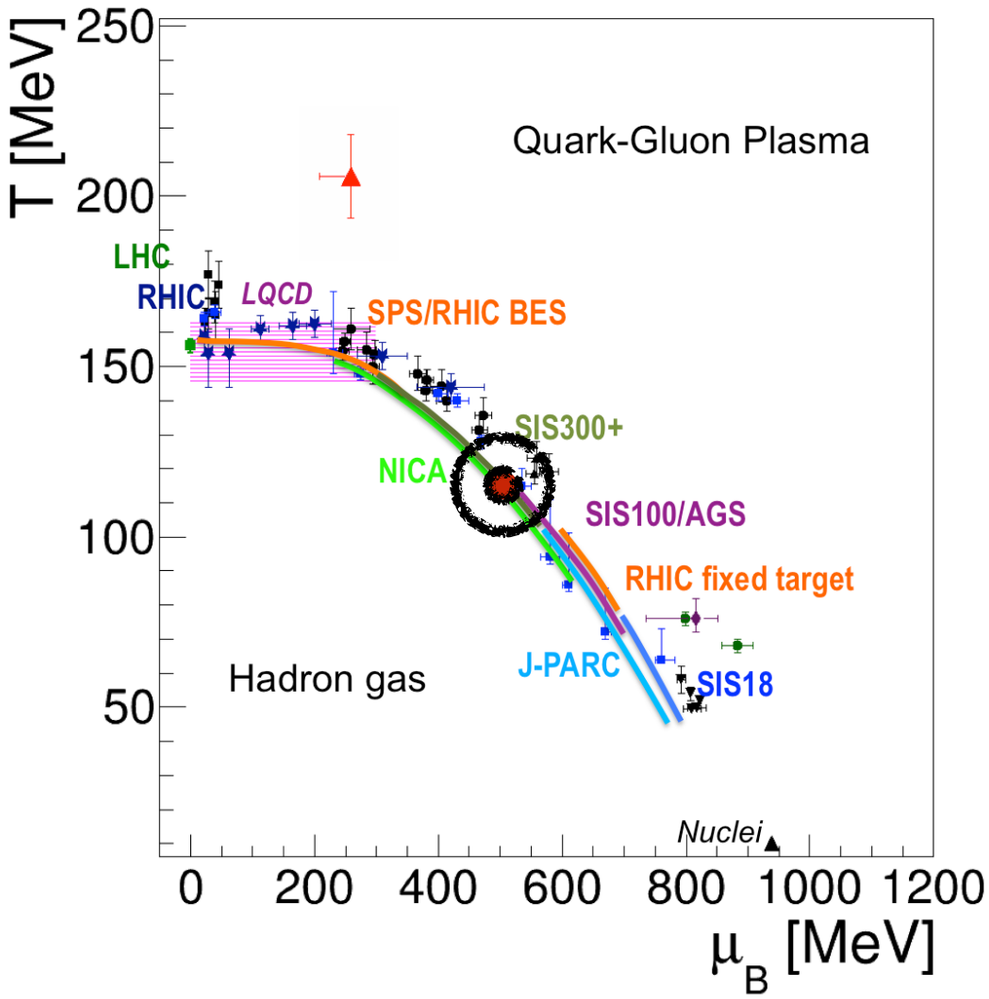


Figure adapted from talk of T. Galatyuk, Erice 2016

Caveats:

- inhomogeneous phases
- effects of baryons ?
- …

Müller, Buballa and Wambach, PLB 727 (2013) 240

Nc=2: Brauner, Fukushima and Hidaka, PRD 80 (2009) 74035
Strodthoff, Schaefer and Smekal, PRD 85 (2012) 074007

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:

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

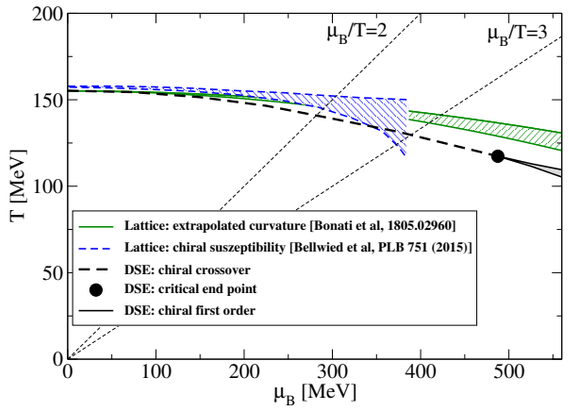
Serve to calculate susceptibilities:

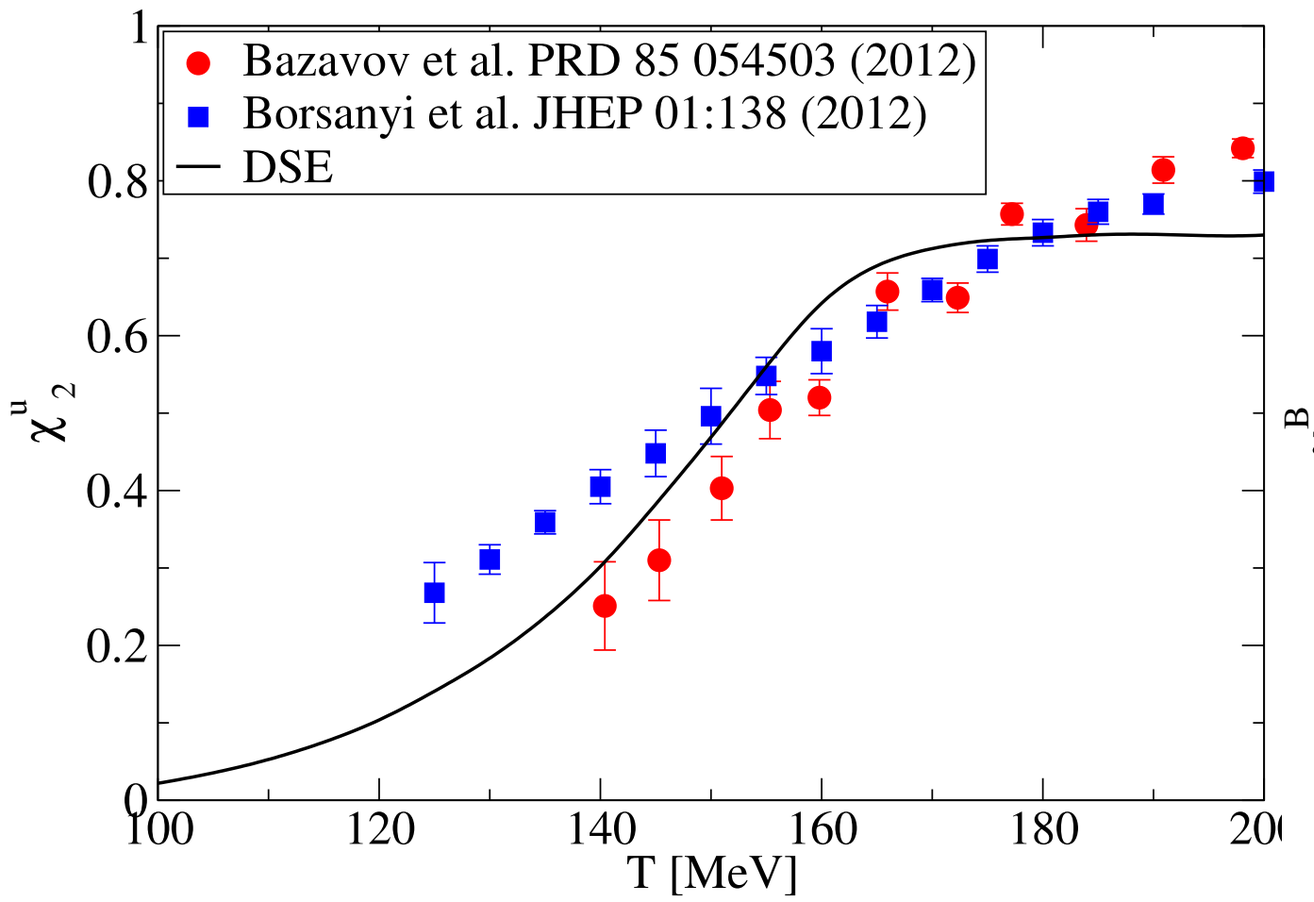
$$\chi^{BSQ}_{lmn} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}$$

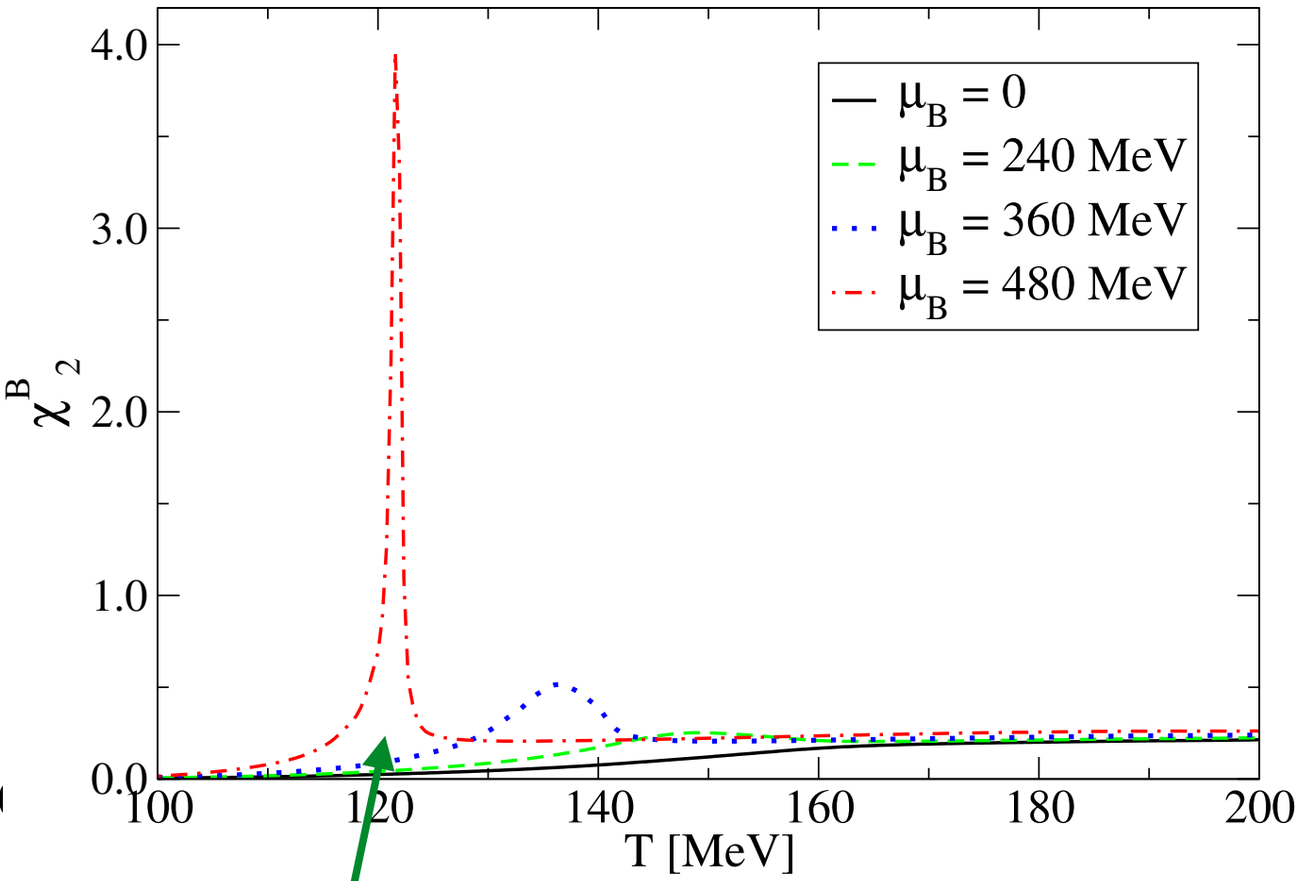
Related to cumulants, which can be extracted from experiment:

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

Results for fluctuations







location of CEP

- first result: works !

Isserstedt et al. in preparation

Summary

QCD with finite chemical potential:

- back-reaction of quarks onto gluons important
- N_f=2+1 and N_f=2+1+1: CEP at $\mu_c/T_c > 3$
- charm quark does not influence CEP
- Baryon effects may or may not be significant for CEP…

Work in progress: - mesons and baryons at finite T and μ

w. Pascal Gunkel

- thermodynamics and fluctuations

w. Philipp Isserstedt

- quark spectral functions

CF, Pawlowski, Rothkopf and Welzbacher, arXiv:1705.03207 [hep-ph]

St Goar: Bound states in QCD and beyond III

Topics:

- Bound states in quantum field theory
- Baryons, mesons, glueballs, and exotics in QCD
- Excited state spectroscopy
- Resonances and decays
- Bound states beyond the standard model
- Experimental detection of bound states
- Structure of bound states

9th - 12th of April 2019

Register preferably until next week !

Invited speakers:

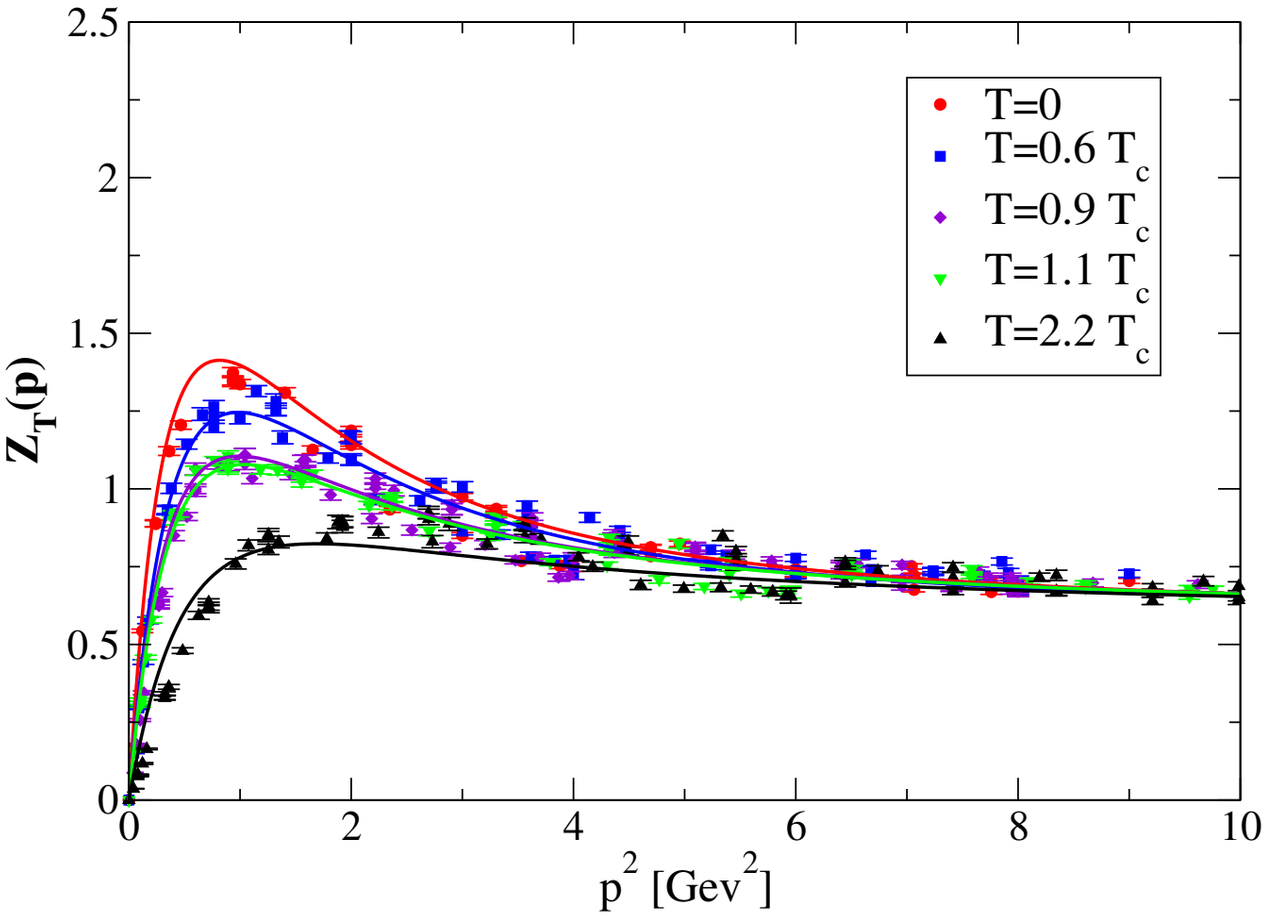
- Raul Briceno (JLAB, USA)
- Ian Cloet (ANL, USA)
- Stefania de Curtis (Florence, Italy)
- Zohreh Davoudi (Maryland, USA)
- Evgeny Epelbaum (Bochum, Germany)
- Anthony Francis (CERN, Switzerland)
- Anna Hasenfratz (Colorado, USA)
- Ryan Mitchel (Indiana, USA)
- Jose Ramon Pelaez (Madrid, Spain)
- Alessandro Pilloni (JLAB, USA)
- Nobuo Sato (JLAB, USA)
- Daria Sokhan (Glasgow, UK)
- Justin Stevens (Williamsburg, USA)
- Ulrike Thoma (Bonn, Germany)

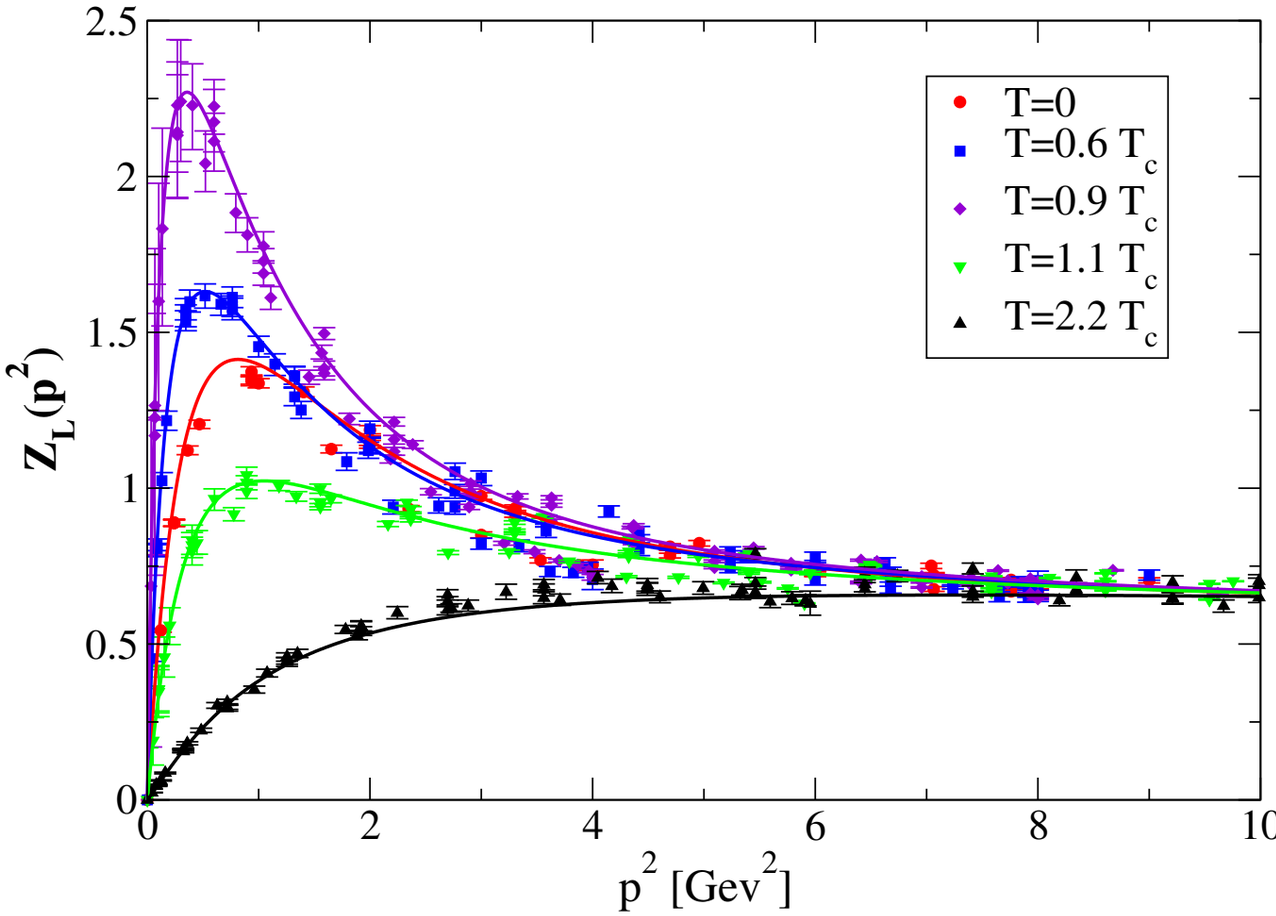
http://physik.uni-graz.at/stgoar2019/index.php

Backup

Glue at finite temperature (T≠0)

T-dependent gluon propagator from quenched lattice simulations:





- Crucial difference between magnetic and electric gluon
- Maximum of electric gluon near Tc

Cucchieri, Maas, Mendes, PRD 75 (2007)
CF, Maas, Mueller, EPJC 68 (2010)
Cucchieri, Mendes, PoS FACESQCD 007 (2010)
Aouane, Bornyakov, Ilgenfritz, Mitrjushkin, Muller-Preussker and Sternbeck, PRD 85 (2012) 034501
Silva, Oliveira, Bicudo, Cardoso, PRD 89 (2014) 074503

FRG: Fister, Pawlowski, arXiv:1112.5440

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

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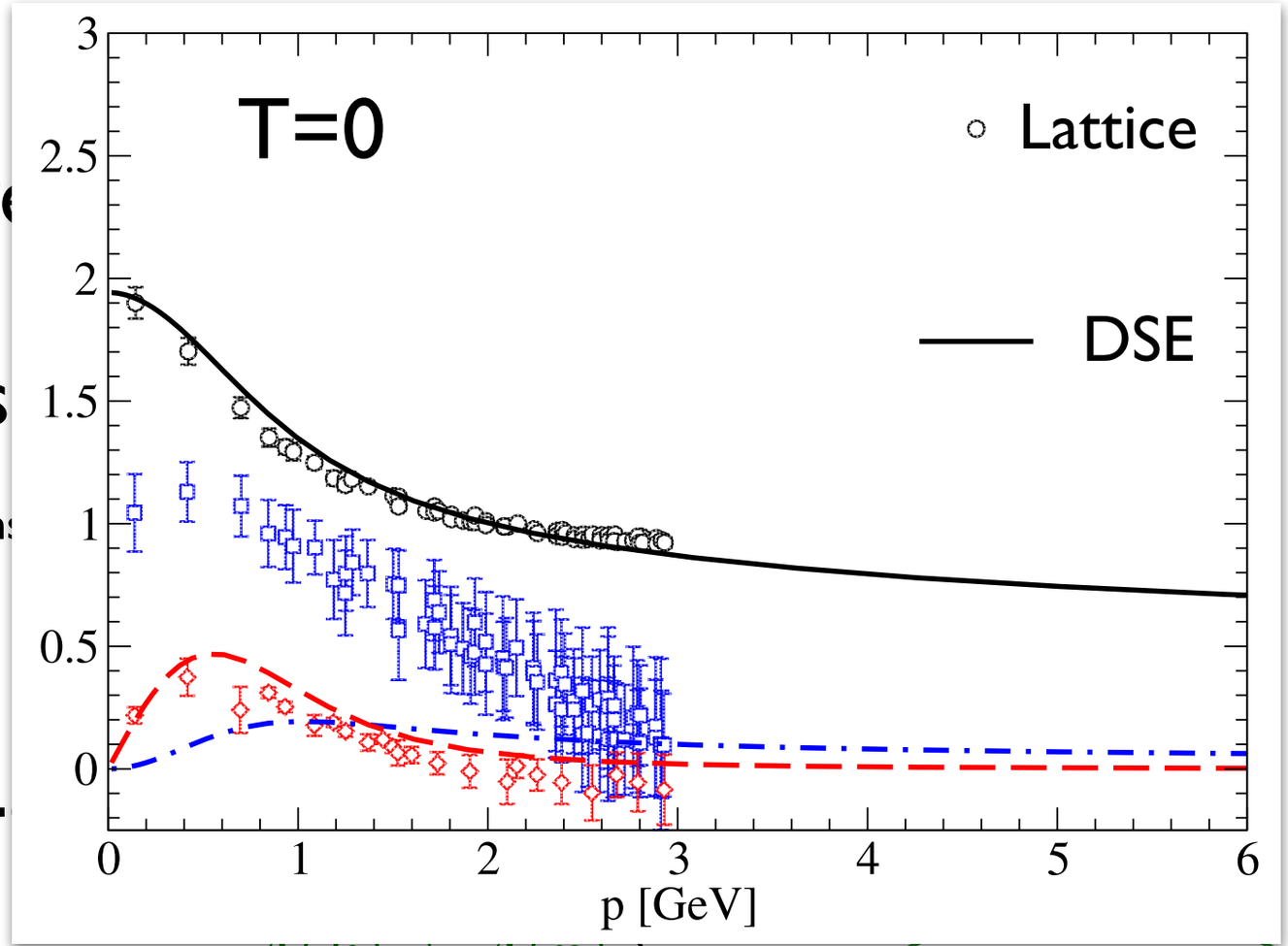

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STI

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PT

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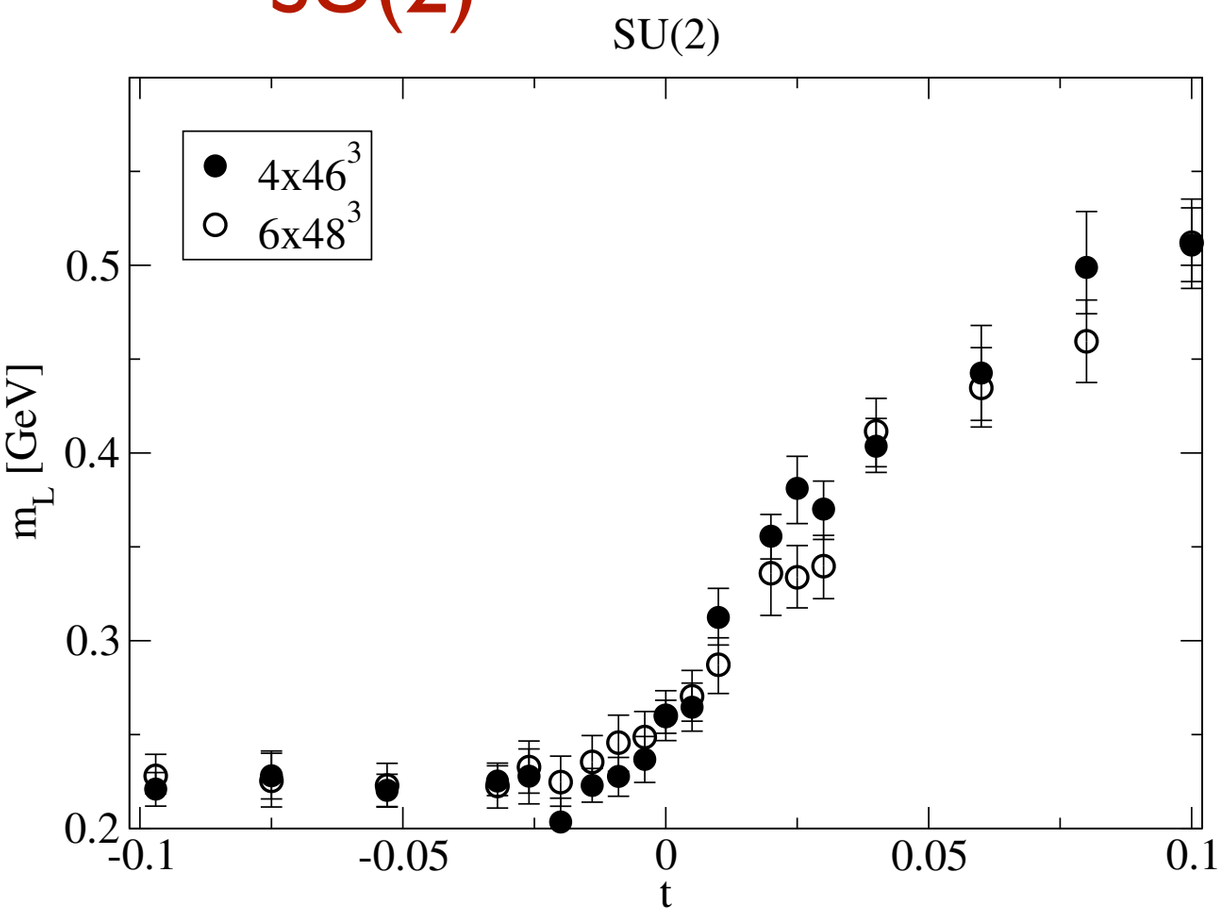
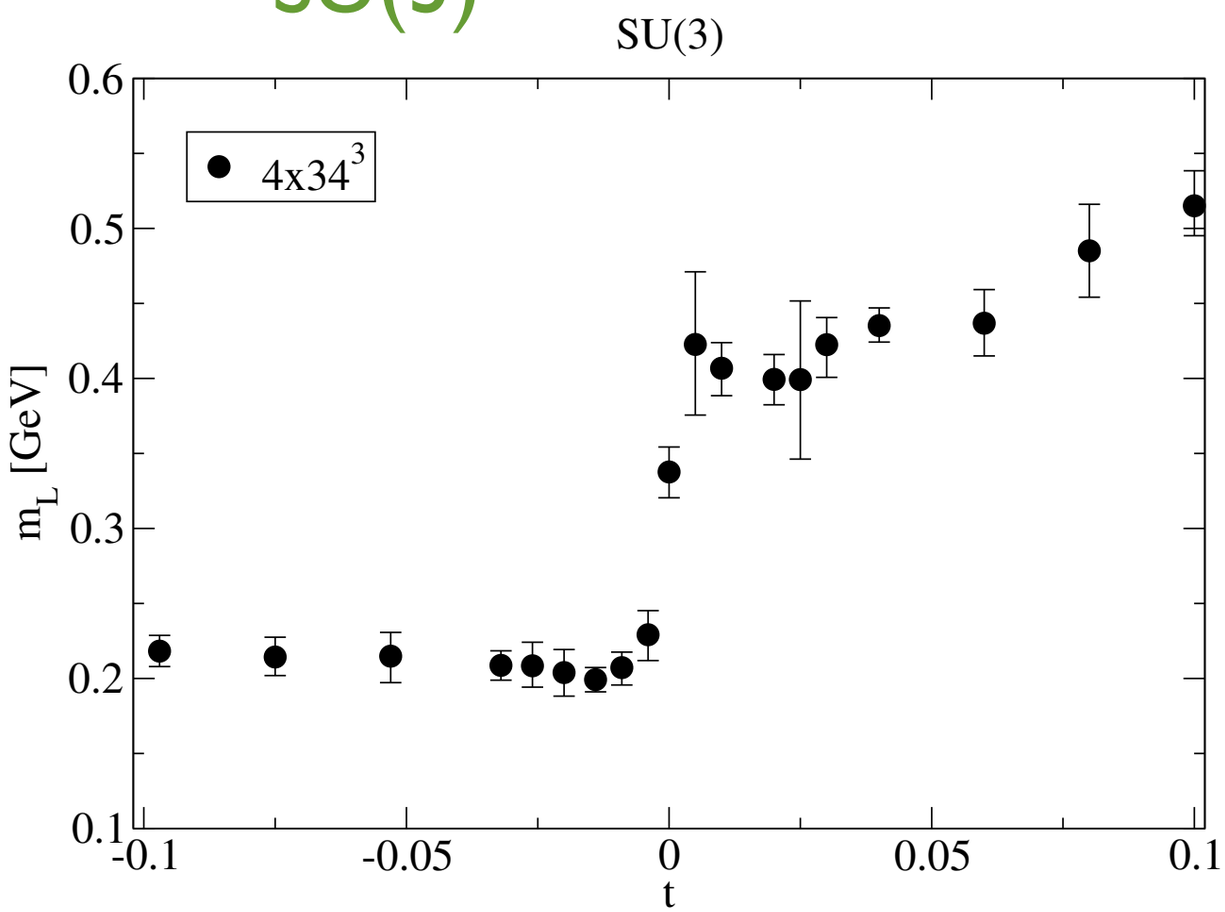
Gluon electric screening mass: SU(2) vs. SU(3)

SU(2)



SU(3)

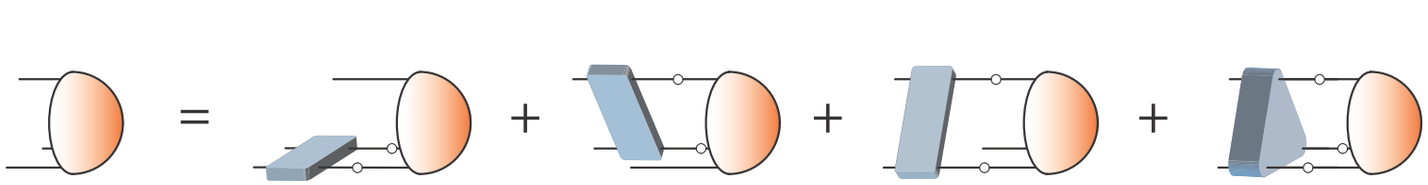


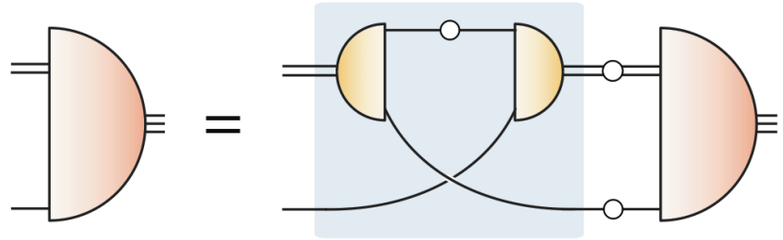
Maas, Pawlowski, Smekal, Spielmann, PRD 85 (2012) 034037
CF, Maas, Mueller, EPJC 68 (2010)

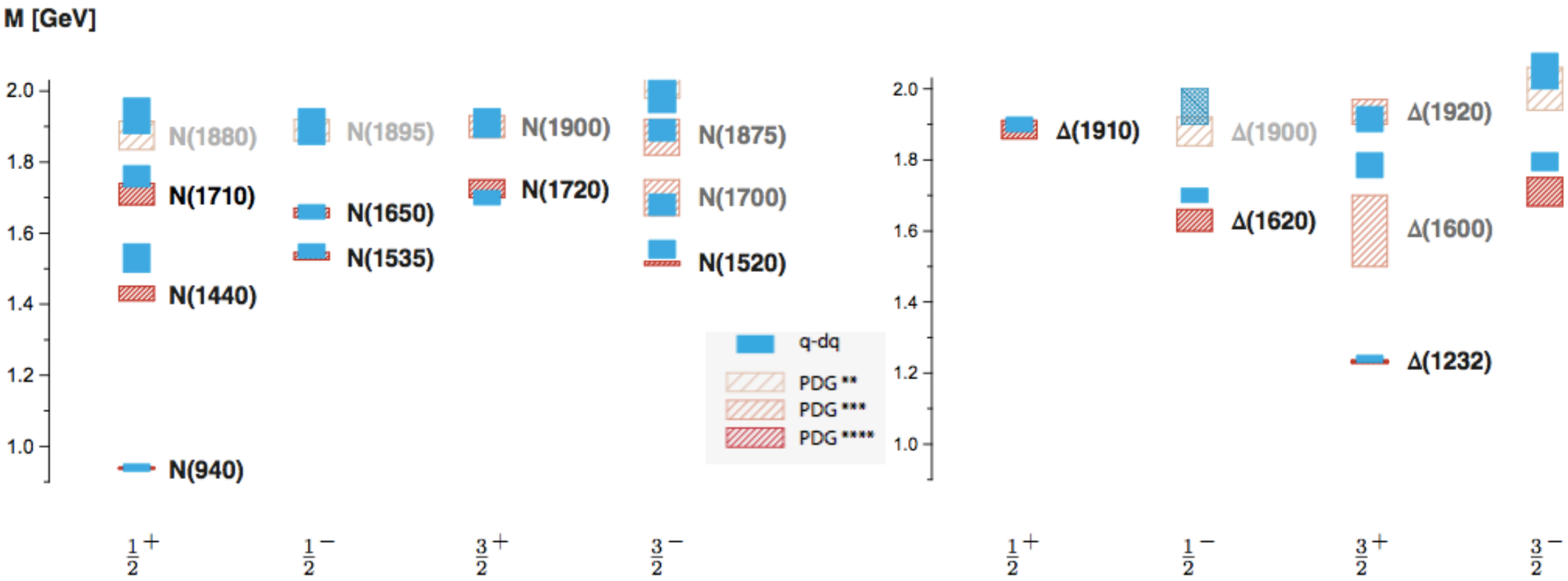
$t = (T-T_c)/T_c$

- phase transition of second and first order visible in electric screening mass

Vacuum: Light baryon spectrum

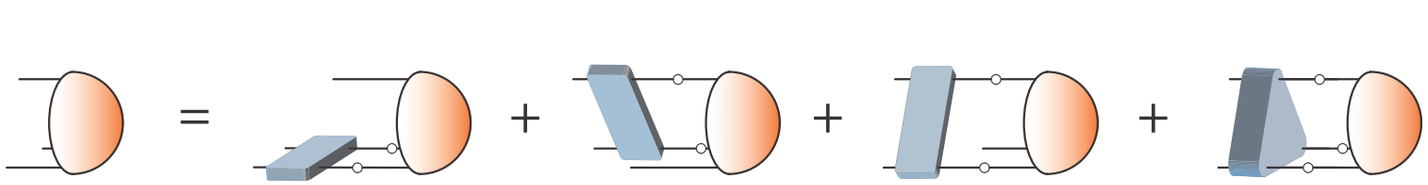


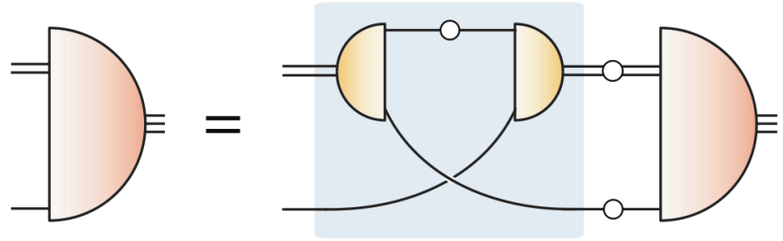


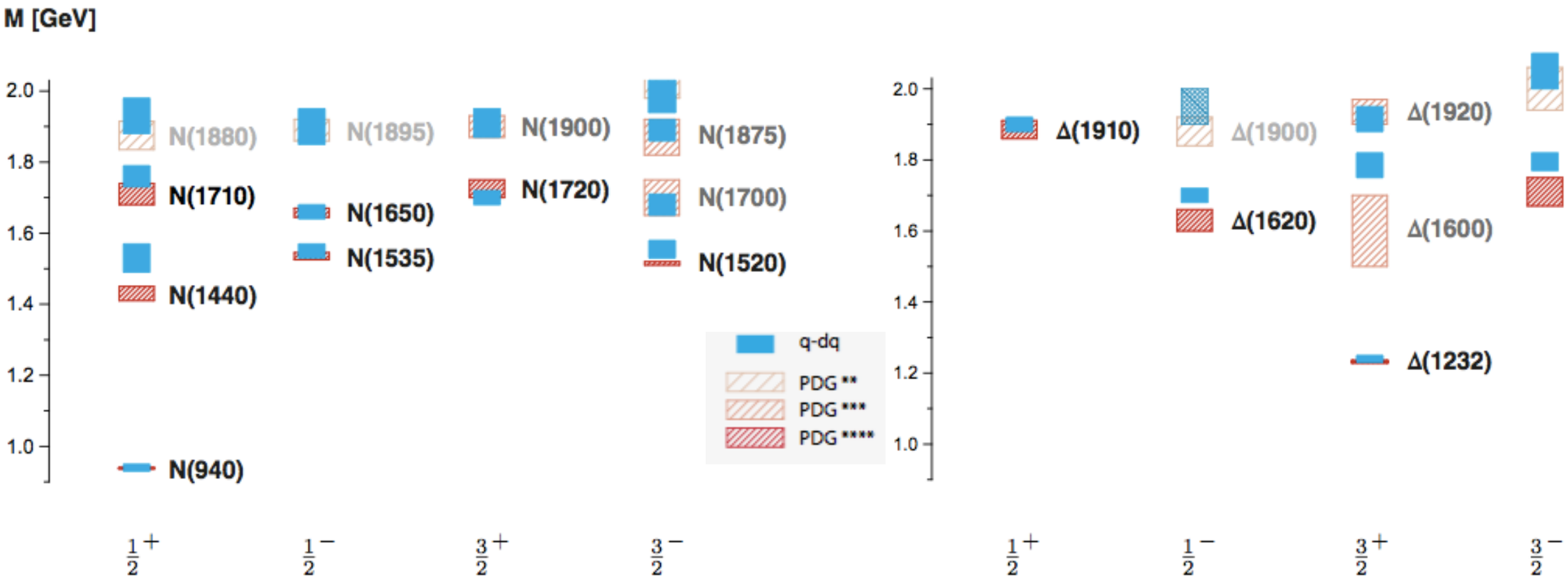


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, in preparation

Vacuum: Light baryon spectrum







Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, in preparation

- Spectrum in one-to-one agreement with experiment
- Correct level ordering (wo. coupled channel effects) !