Locating the critical end point of QCD

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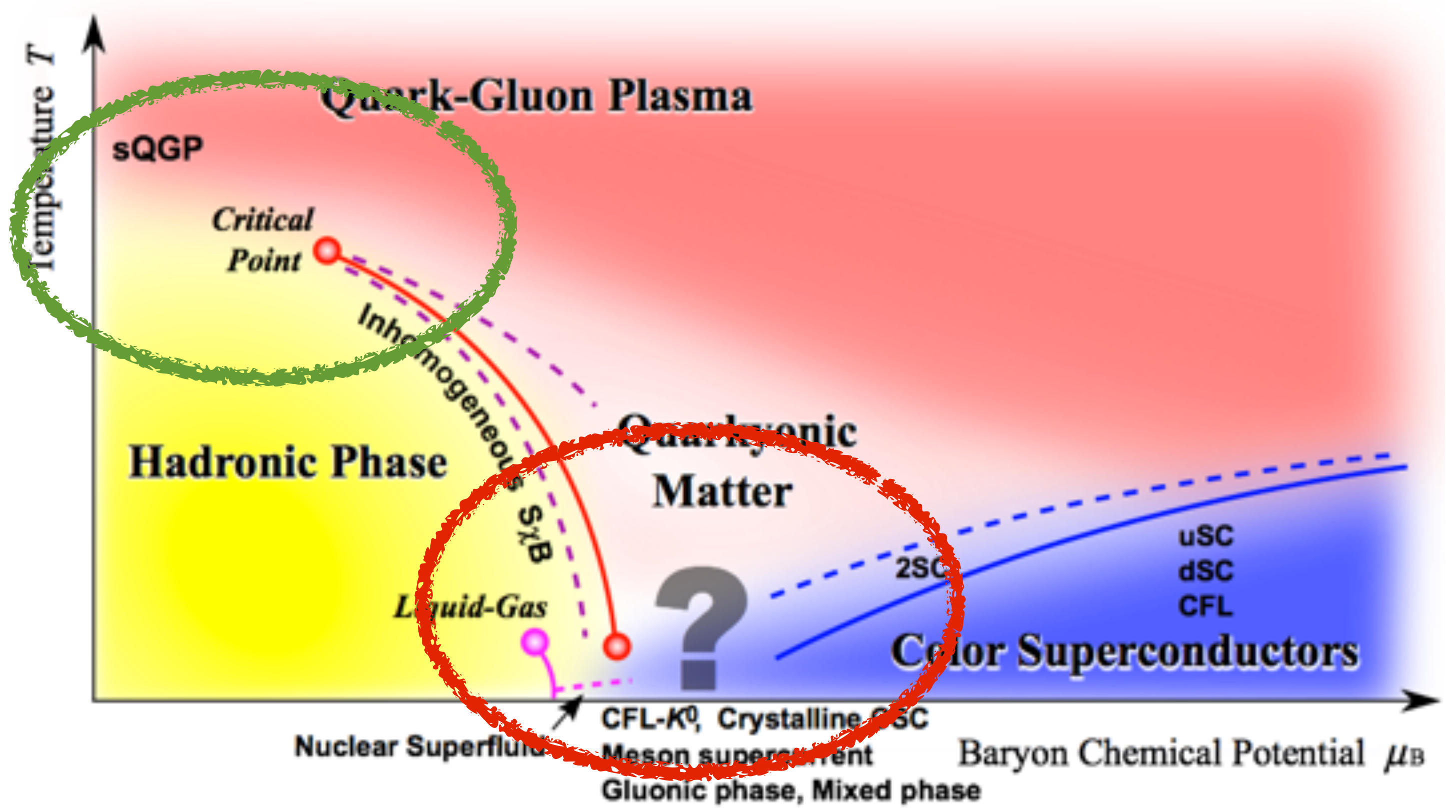
with Jan Luecker and Christian Wezbacher, arXiv:1405.4762

and Leonard Fister, Axel Maas, Jan Pawlowski

QCD phase transitions I

Fukushima, Hatsuda, Rept. Prog. Phys. 74 (2011) 014001



DSEs at low T, large μ:

Müller, Buballa, Wambach, EPJA 49 (2013), PLB 727 (2013) 240

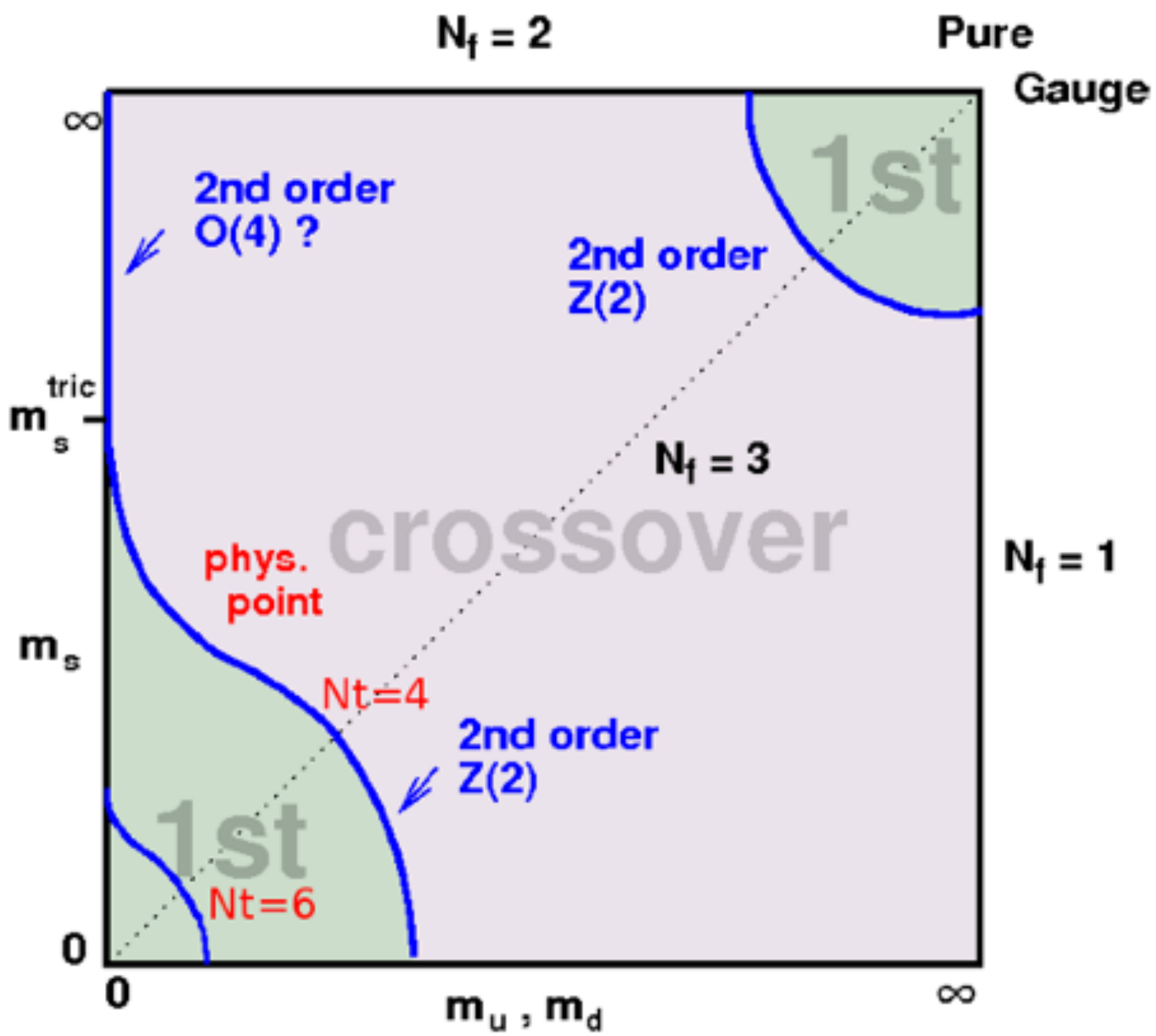
- Chiral limit ($M_{weak} \to 0$): order parameter chiral condensate

$$\langle \bar{\Psi}\Psi \rangle \sim Tr \int S$$

- Static quarks ($M_{weak} \to \infty$): order parameter Polyakov-loop

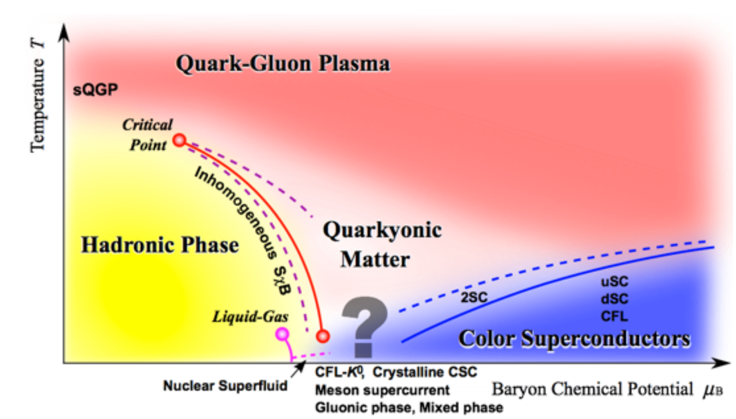
$$\langle |L| \rangle \sim e^{-F_q/T}$$

QCD phase transitions II

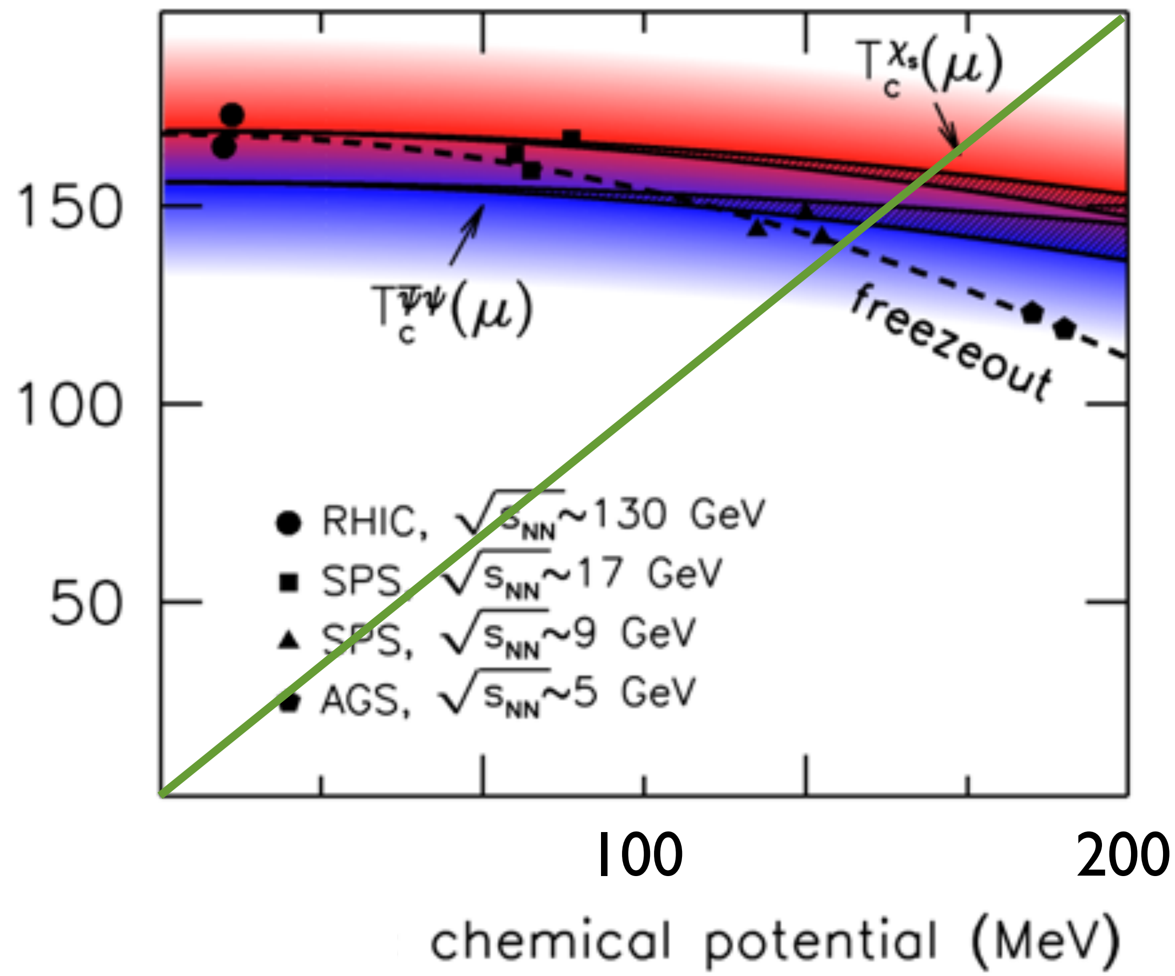


Plot: O. Philipsen

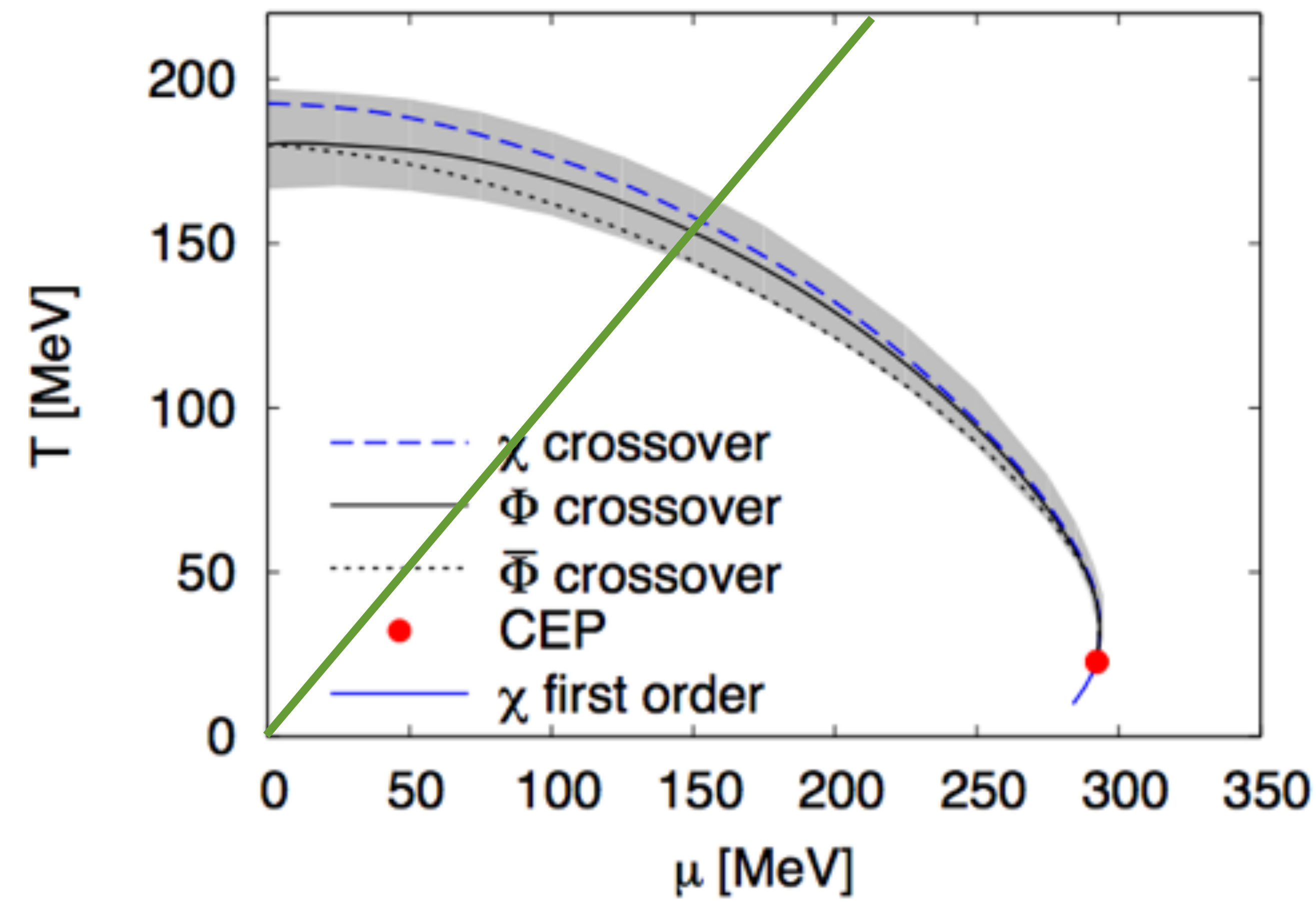
Is this happening ??



Phase diagram: Lattice - PQM



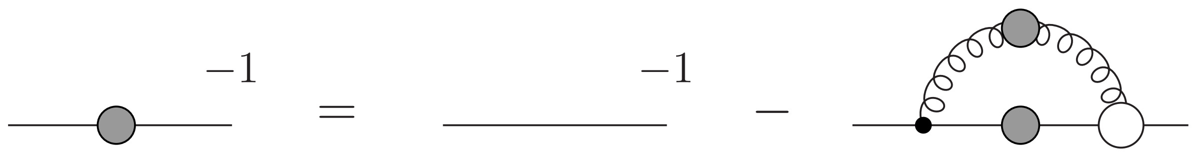
Endrodi, Fodor, Katz, Szabo, JHEP 1104 (2011) 001



Herbst, Pawlowski, Schaefer, PLB 696 (2011) 58

- Lattice extrapolation reliable for $\mu/T \leq 1$
- No CEP for small chemical potential
- PQM plus RG-methods (functional methods)

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:

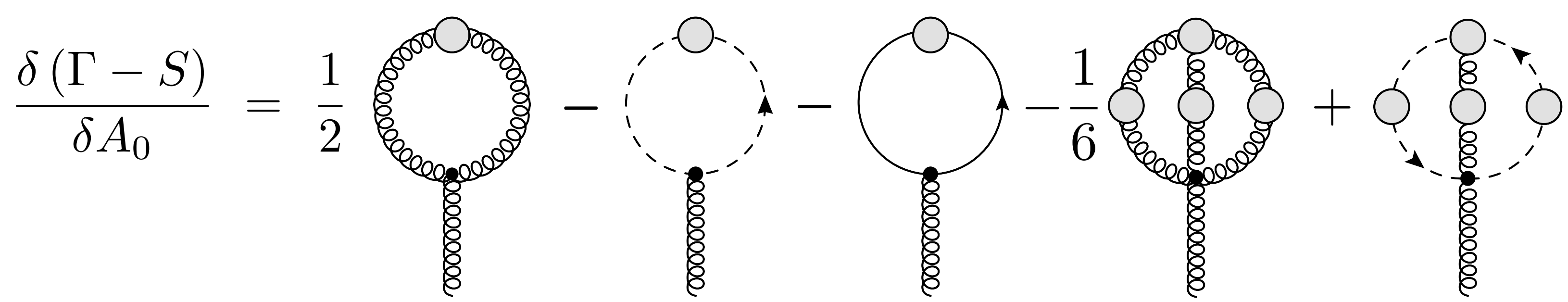
- dressed Polyakov loop

$$\Sigma = -\int_0^{2\pi} \frac{d\varphi}{2\pi} e^{-i\varphi} \langle \bar{\Psi}\Psi \rangle_{\varphi}$$

Synatschke, Wipf, Wozar, PRD 75, 114003 (2007)
Bilgici, Bruckmann, Gattringer, Hagen, PRD 77 094007 (2008)
CF, PRL 103 052003 (2009)

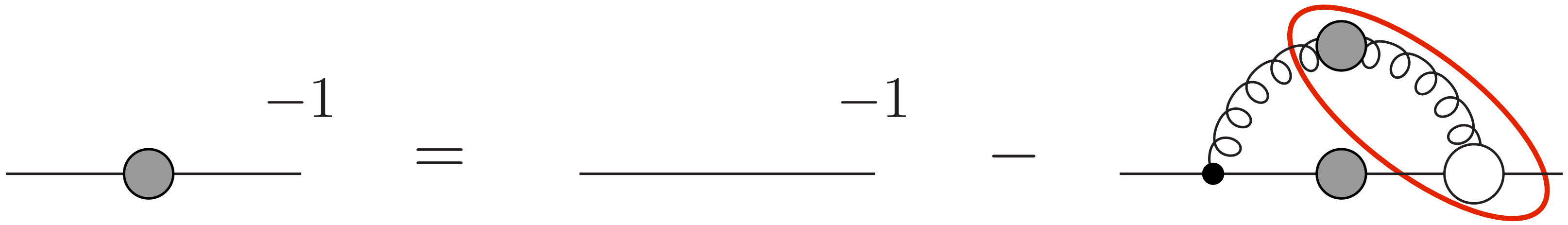
- Polyakov loop potential

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



Braun, Gies, Pawlowski, PLB 684, 262 (2010)
Braun, Haas, Marhauser, Pawlowski, PRL 106 (2011)
Fister, Pawlowski, PRD 88 045010 (2013)
CF, Fister, Luecker, Pawlowski, arXiv:1306.6022

The DSE for the quark propagator



$$[S(p)]^{-1} = [-i\not{p} + M(p^2)]/Z_f(p^2)$$

Input:

- dressed Gluon propagator
- dressed Quark-Gluon-Vertex

Two strategies: I. use model for gluon and vertex

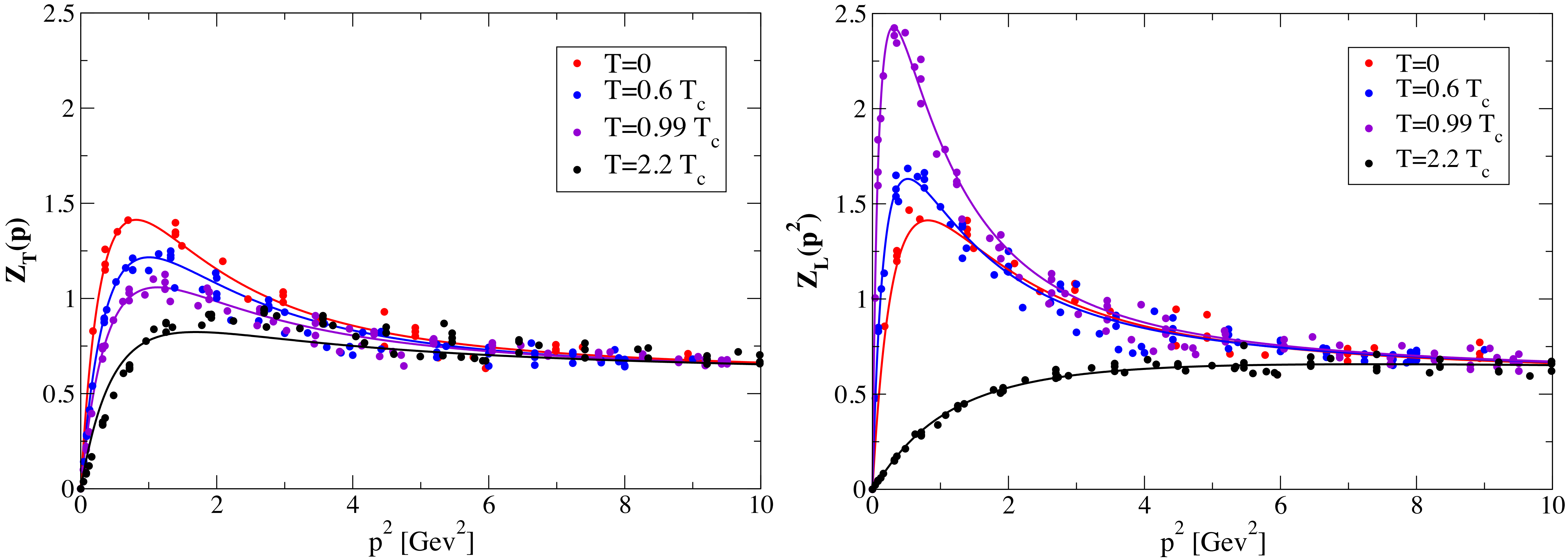
Qin, Chang, Chen, Liu and Roberts, PRL 106 (2011) 172301
Gutierrez, Ahmad, Ayala, Bashir and Raya, JPG 41 (2014) 075002

→ ok for first insights
→ not good enough for systematic study

II. determine gluon and vertex explicitly

Glue at finite temperature (T≠0)

T-dependent gluon propagator from quenched lattice simulations:

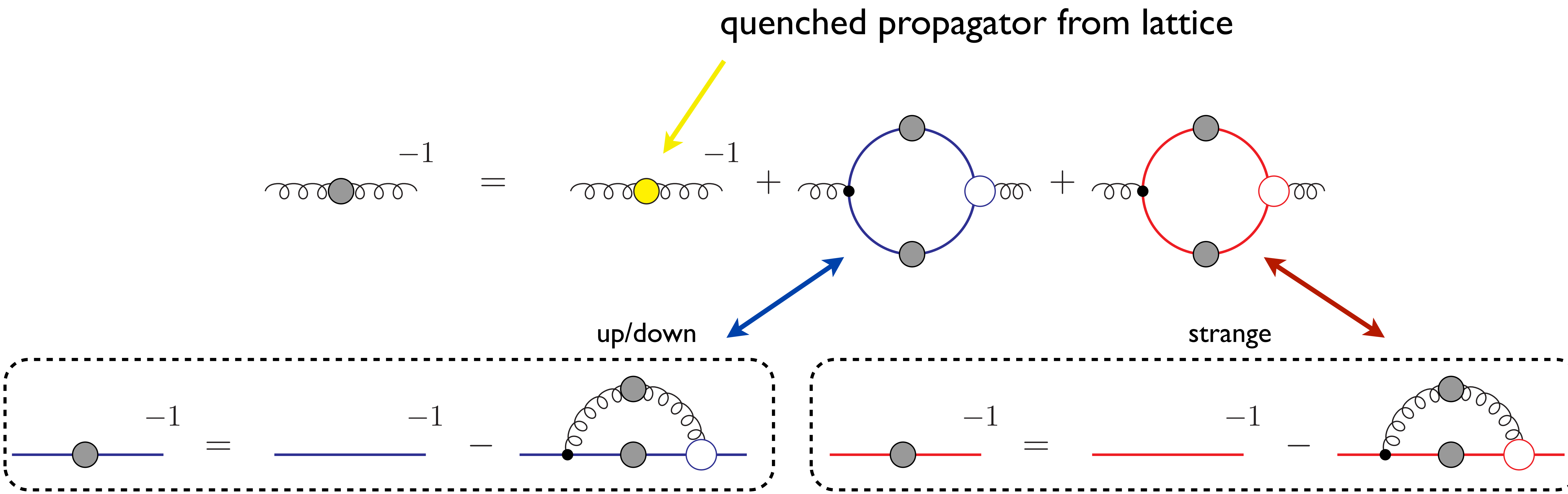


- Crucial difference between magnetic and electric gluon
- Maximum of electric gluon near Tc

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

FRG: Fister, Pawlowski, arXiv:1112.5440

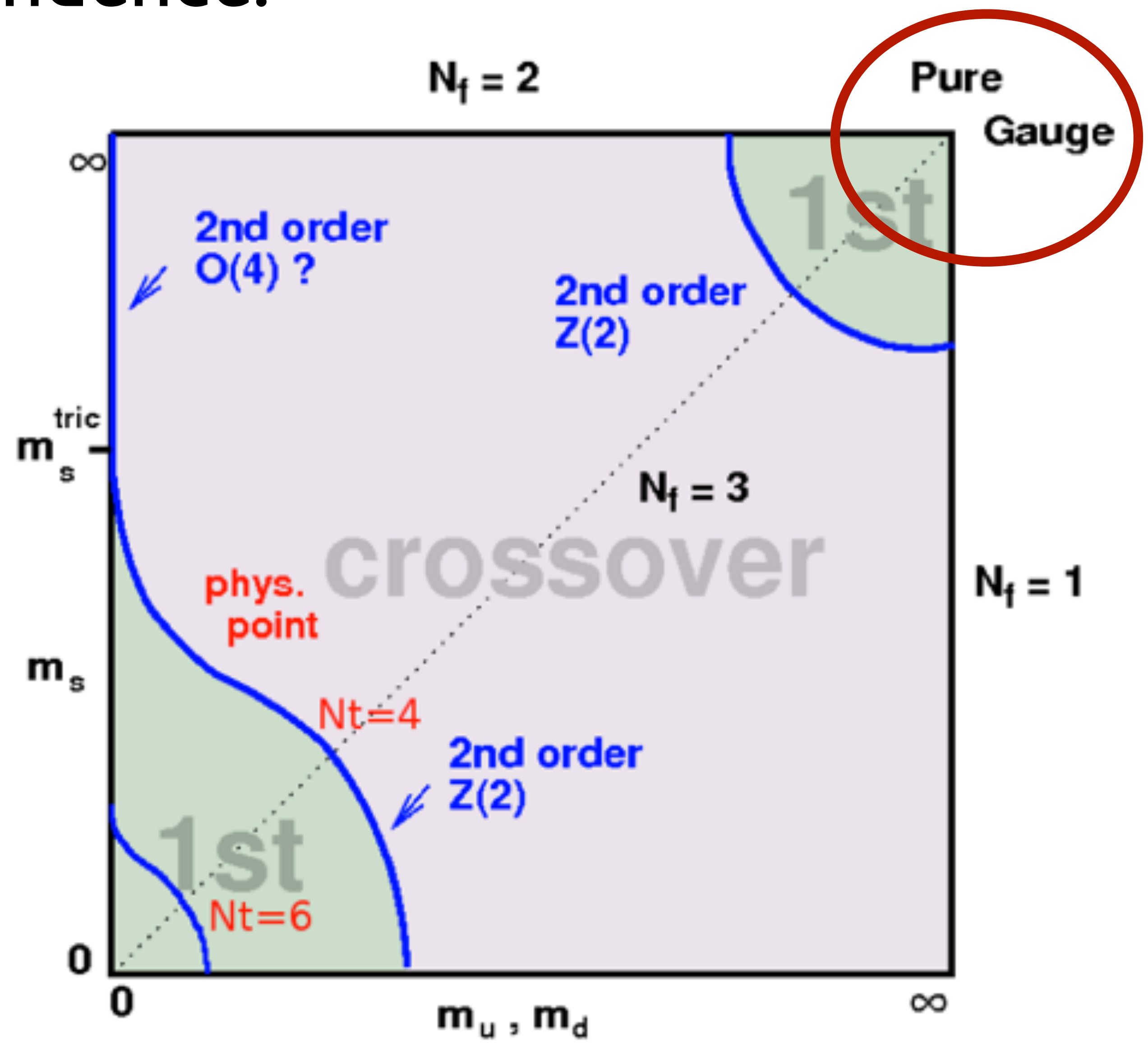
N_f=2+1-QCD with DSEs



- quenched: without quark-loop
- Nf=2: isospin symmetry
- Nf=2+1: solve coupled system of 2+3+3 equations

QCD phase transition: heavy quark limit/quenched

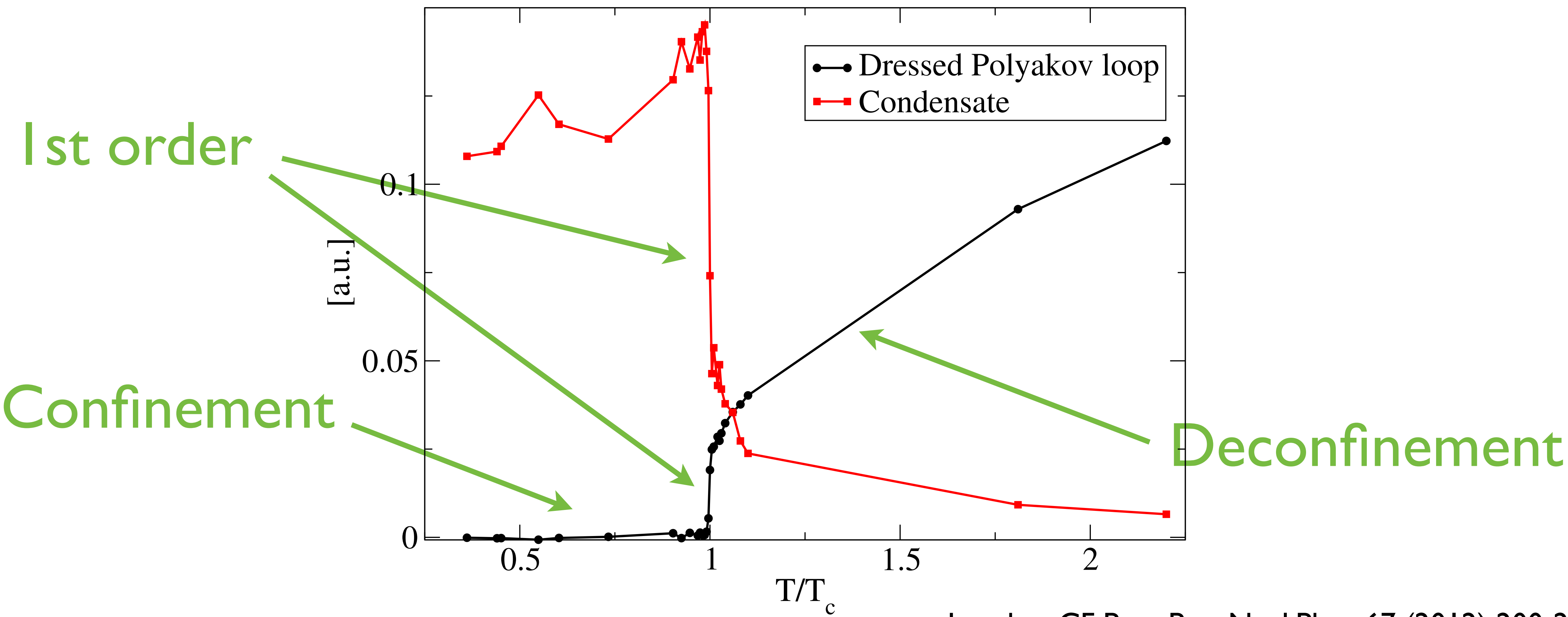
Quark mass dependence:



- Expect: Transitions controlled by deconfinement
- SU(2) second order, SU(3) first order

Transition temperatures, quenched

quenched DSE: SU(3)

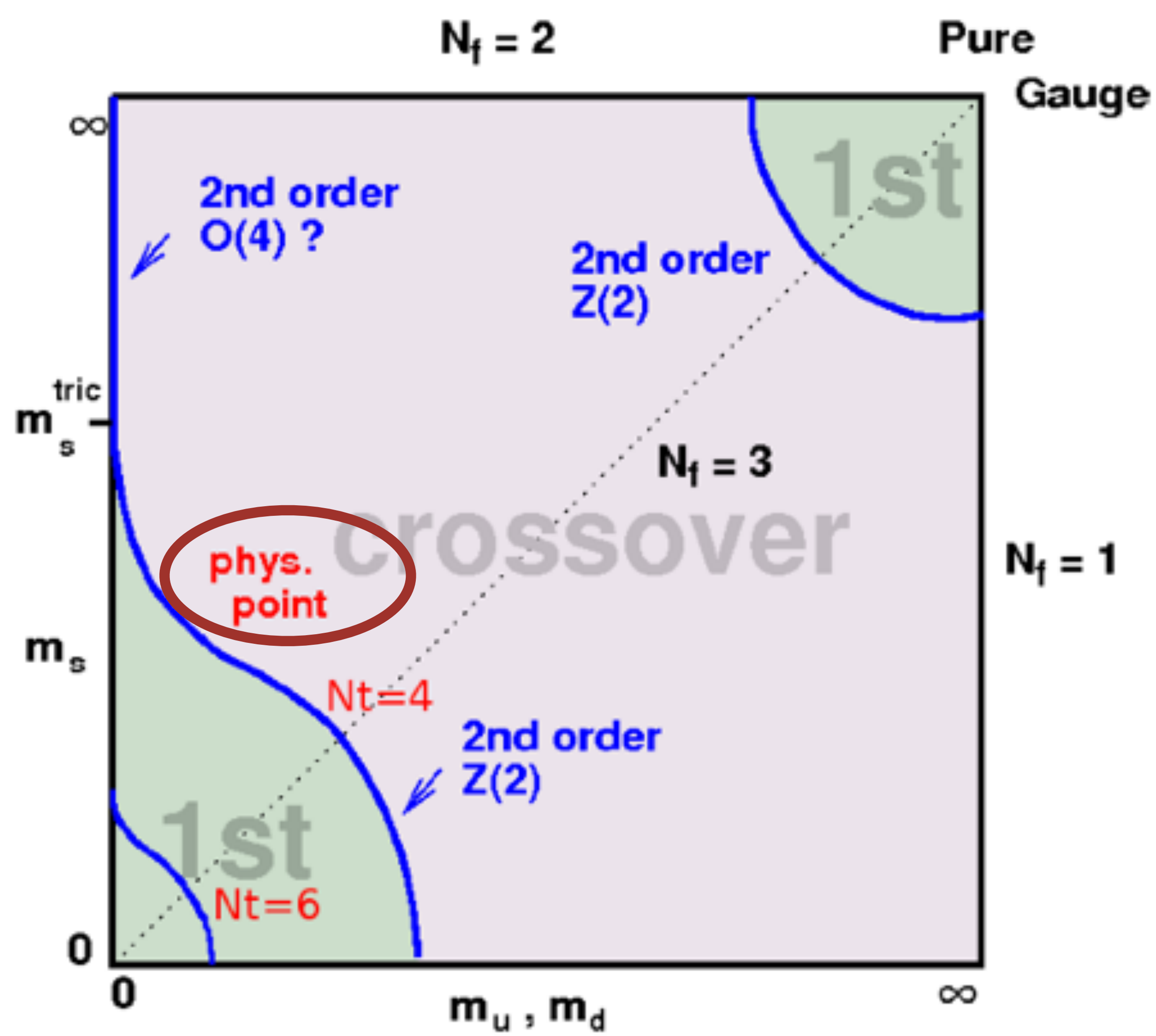


Luecker, CF, Prog.Part.Nucl.Phys. 67 (2012) 200-205
CF, Maas, Mueller EPJC 68 (2010)

- SU(2): $T_c \approx 305$ MeV
- SU(3): $T_c \approx 270$ MeV
- $T \leq T_c$: increasing condensate due to electric part of gluon

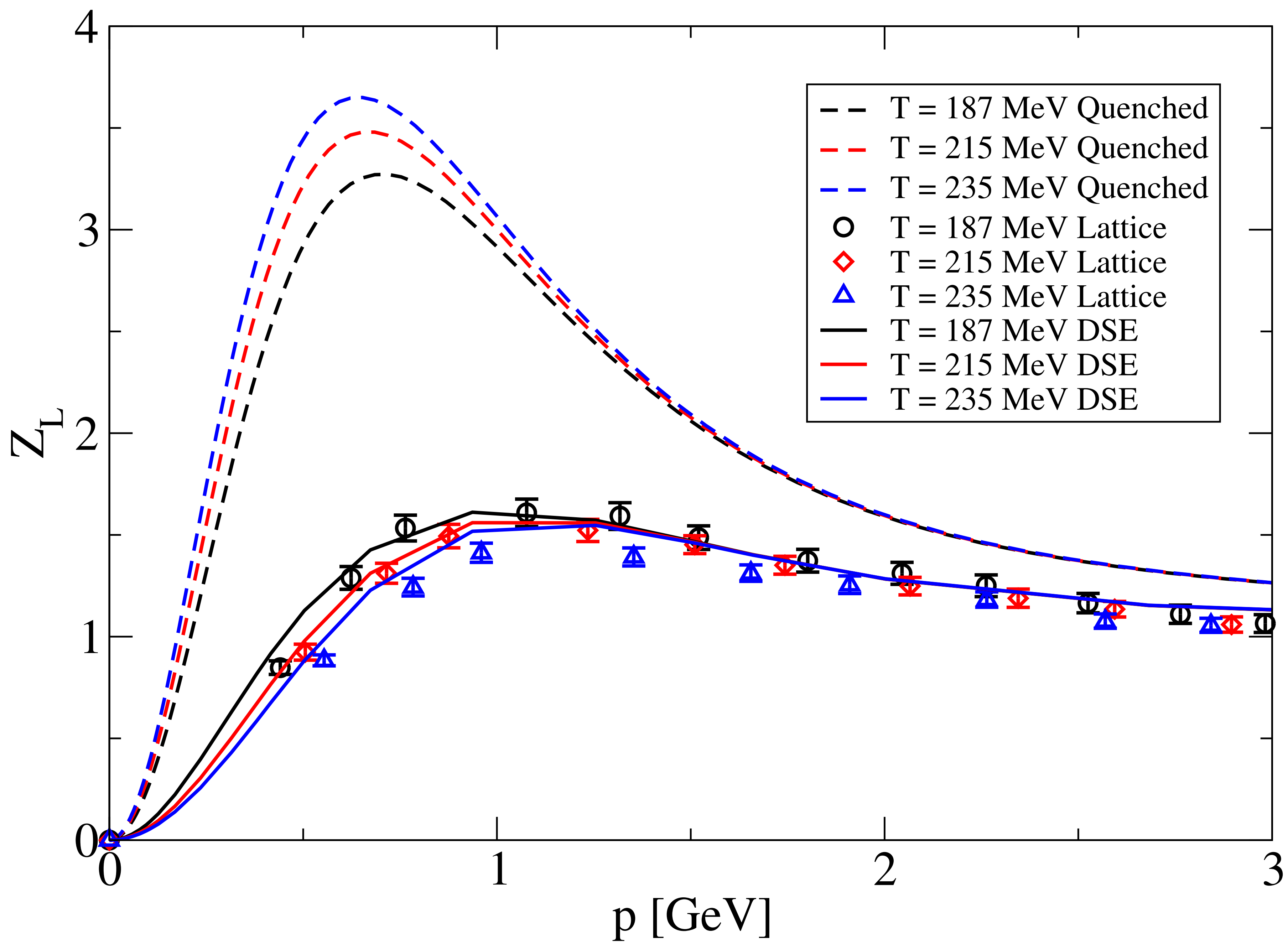
cf. Buividovich, Luschevskaya, Polikarpov, PRD 78 (2008) 074505
cf. Braun, Gies, Pawlowski, PLB 684 (2010) 262.

QCD phase transitions: N_f=2+1



- Physical up/down and strange quark masses
- Transition controlled by chiral dynamics
- at μ=0: compare to available lattice results

Unquenched Gluon DSE vs Lattice

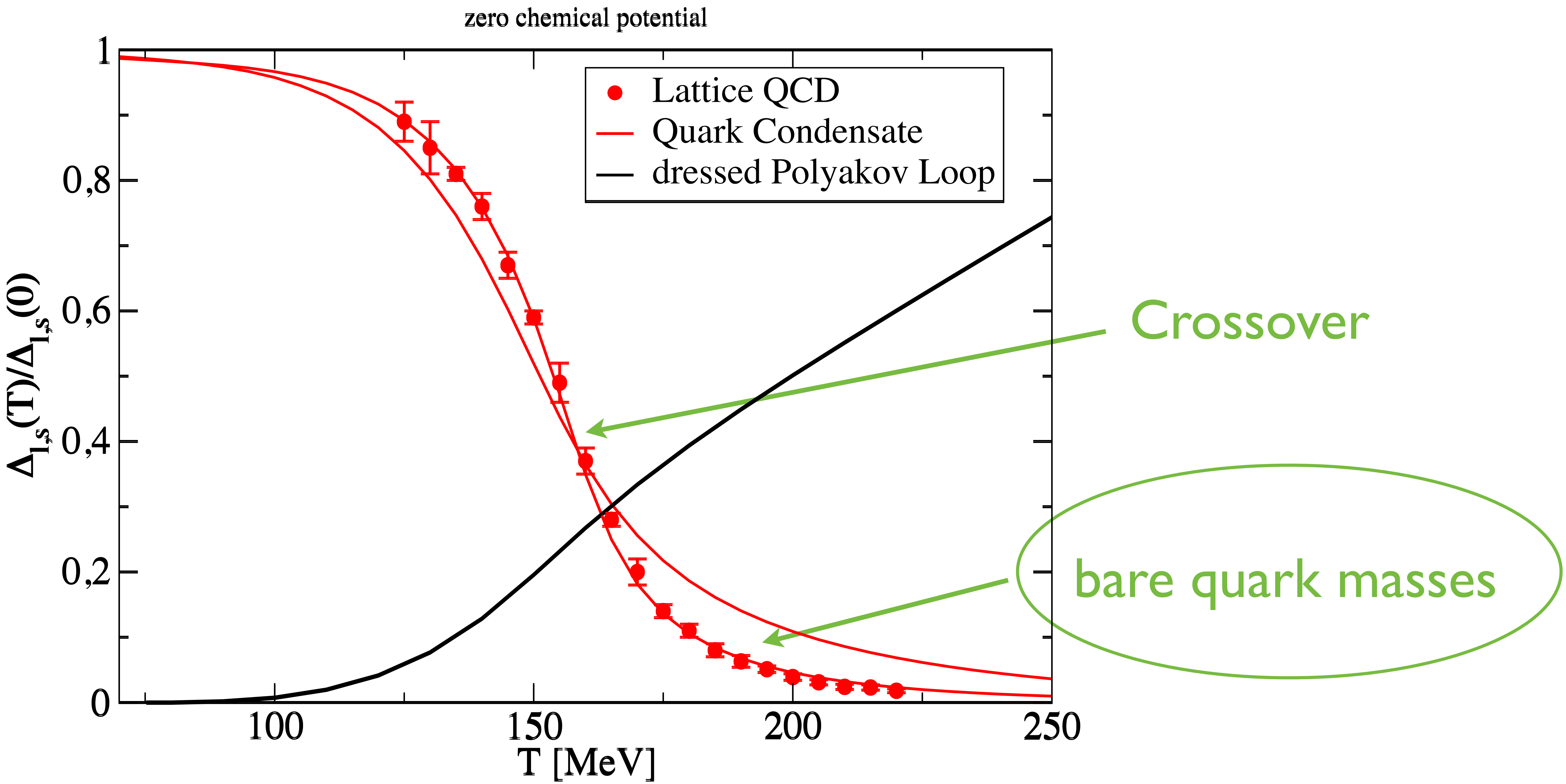


- quantitative agreement: DSE prediction verified by lattice

DSE: CF, Luecker, PLB 718 (2013) 1036 [arXiv:1206.5191]

Lattice: Aouane, Burger, Ilgenfritz, Muller-Preussker and Sternbeck, arXiv:1212.1102

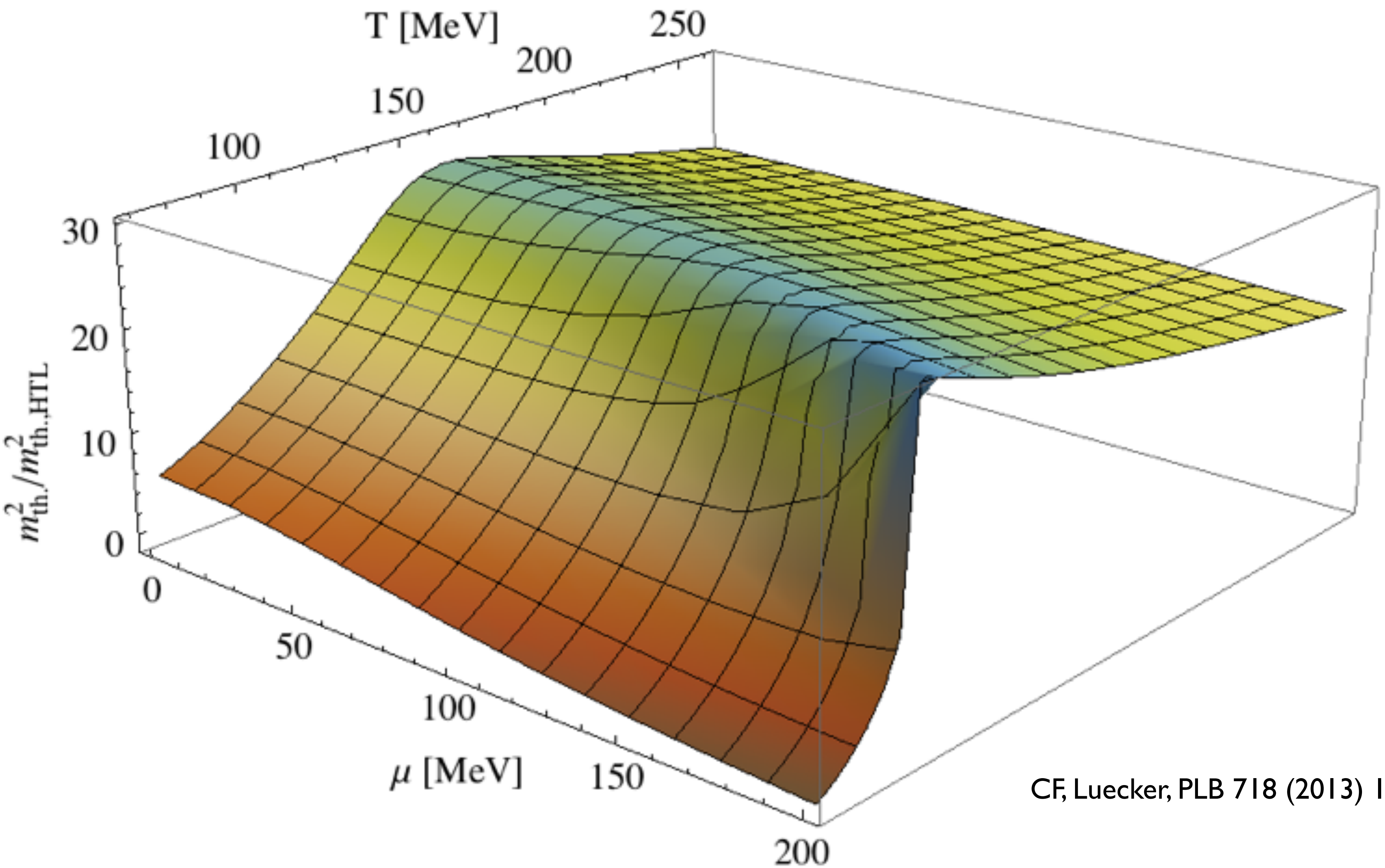
N_f=2+1, zero chemical potential



Lattice: Borsanyi *et al.* [Wuppertal-Budapest Collaboration], JHEP 1009(2010) 073
DSE: CF, Luecker, PLB 718 (2013) 1036, CF, Luecker, Welzbacher, arXiv:1405.4762

- quantitative agreement

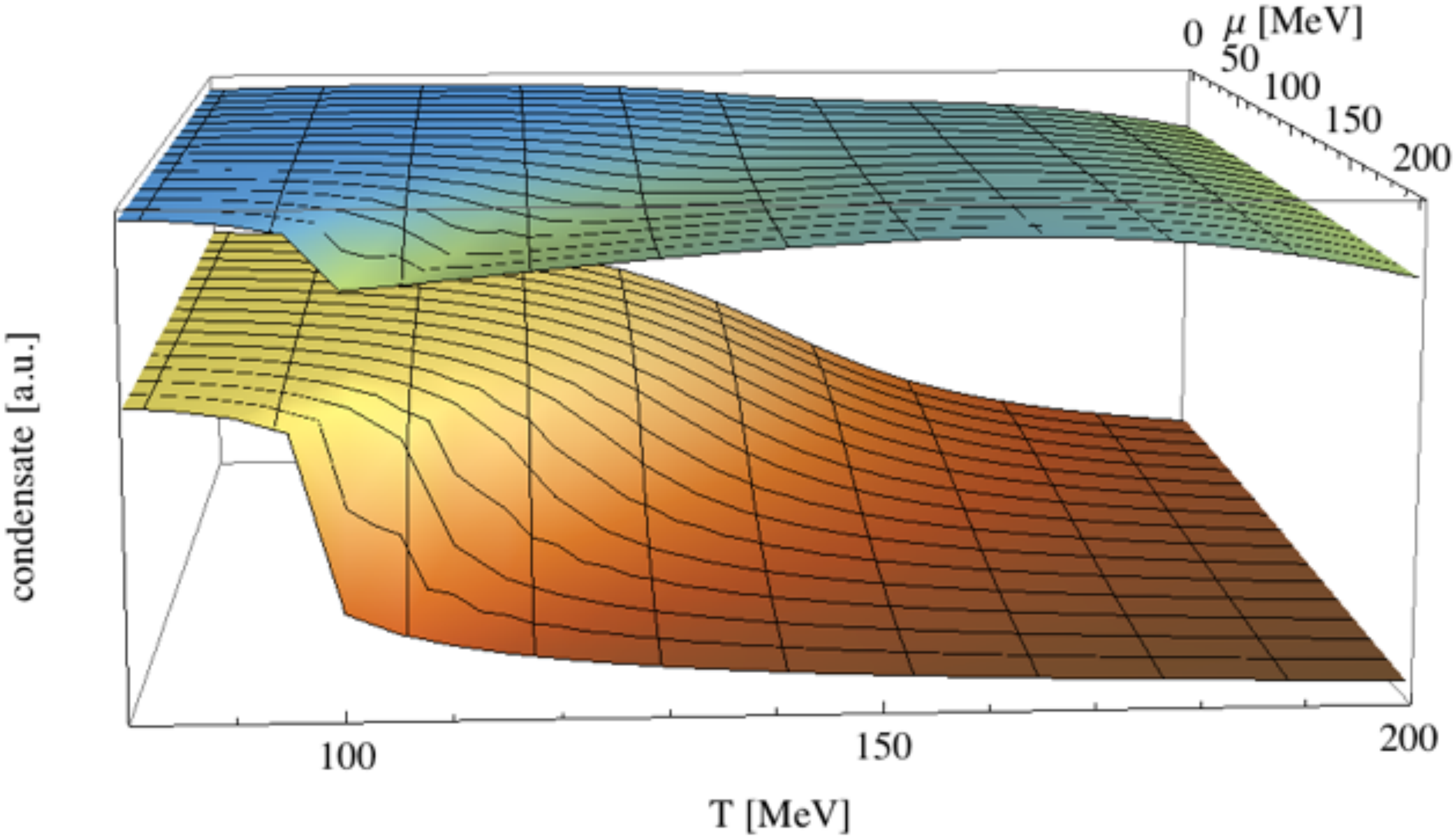
Nf=2+1: thermal electric gluon mass



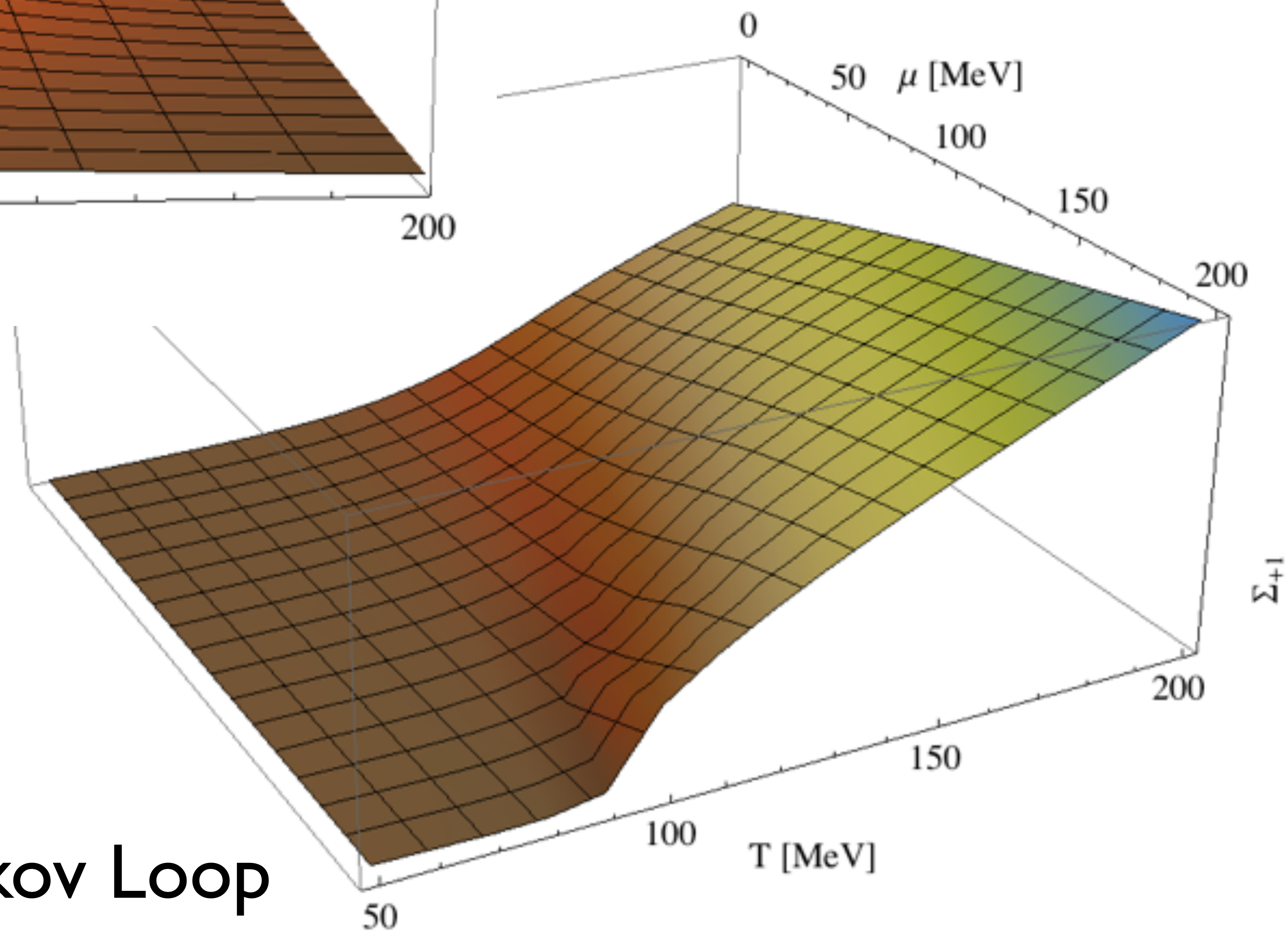
CF, Luecker, PLB 718 (2013) 1036

- large temperatures: behaviour as expected from HTL
- first order transition at large chemical potential

Nf=2+1: Condensate and dressed Polyakov Loop

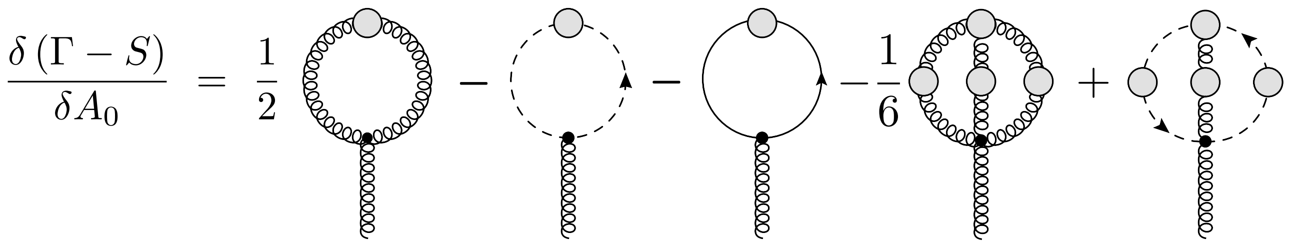


Quark condensate



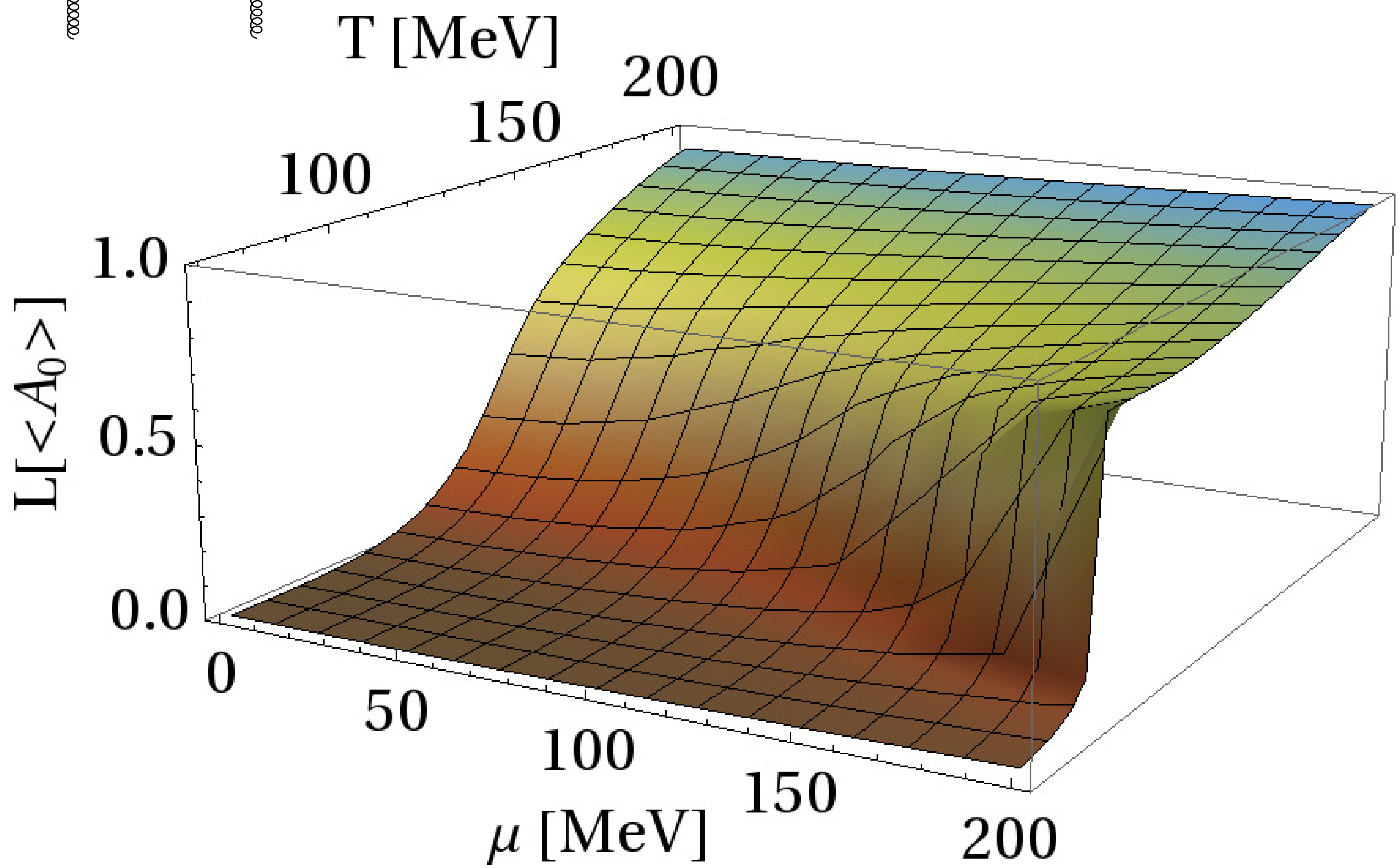
Dressed Polyakov Loop

N_f=2+1: Polyakov loop potential at finite μ



Polyakov-Loop

$$L = \frac{1}{N_c} tr\ e^{ig\int A_0}$$

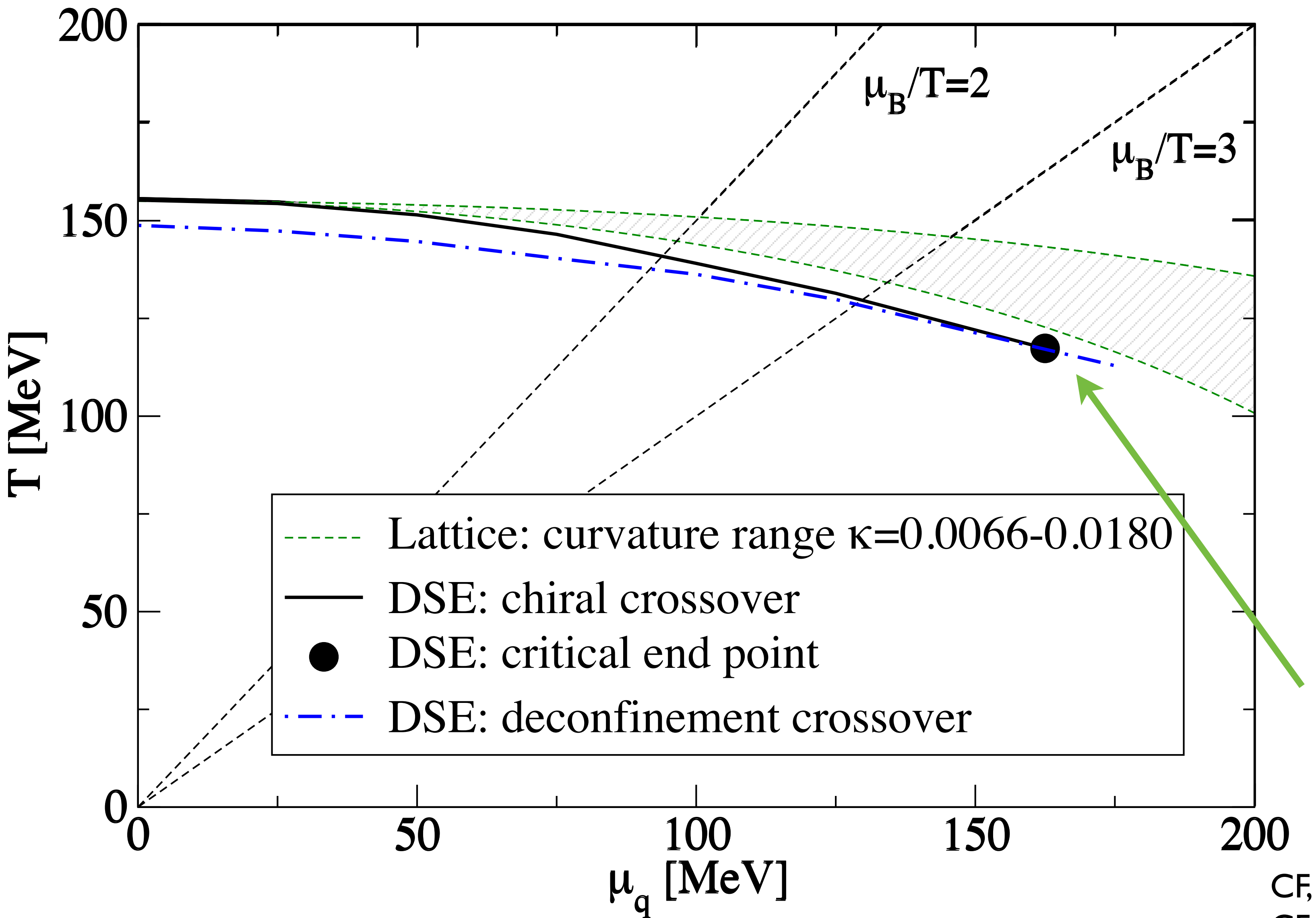


CF, Fister, Luecker, Pawlowski, PLB in press, arXiv:1306.6022

- evaluated from Polyakov-Loop potential
- important input for P-models: PQM, PNJL !

Herbst, Mitter, Pawlowski, Schaefer, Stiele, arXiv:1308.3621

N_f=2+1: Polyakov loop and phase diagram



Extrapolated curvature from lattice

Kaczmarek at al. PRD 83 (2011) 014504,
Endrodi, Fodor, Katz, Szabo, JHEP 1104 (2011) 001
Cea, Cosmai, Papa, PRD 89 (2014) 074512

CEP at large μ

CF, Luecker, PLB 718 (2013) 1036,
CF, Fister, Luecker, Pawlowski, PLB in press, arXiv:1306.6022
CF, Luecker, Welzbacher, arXiv:1405.4762

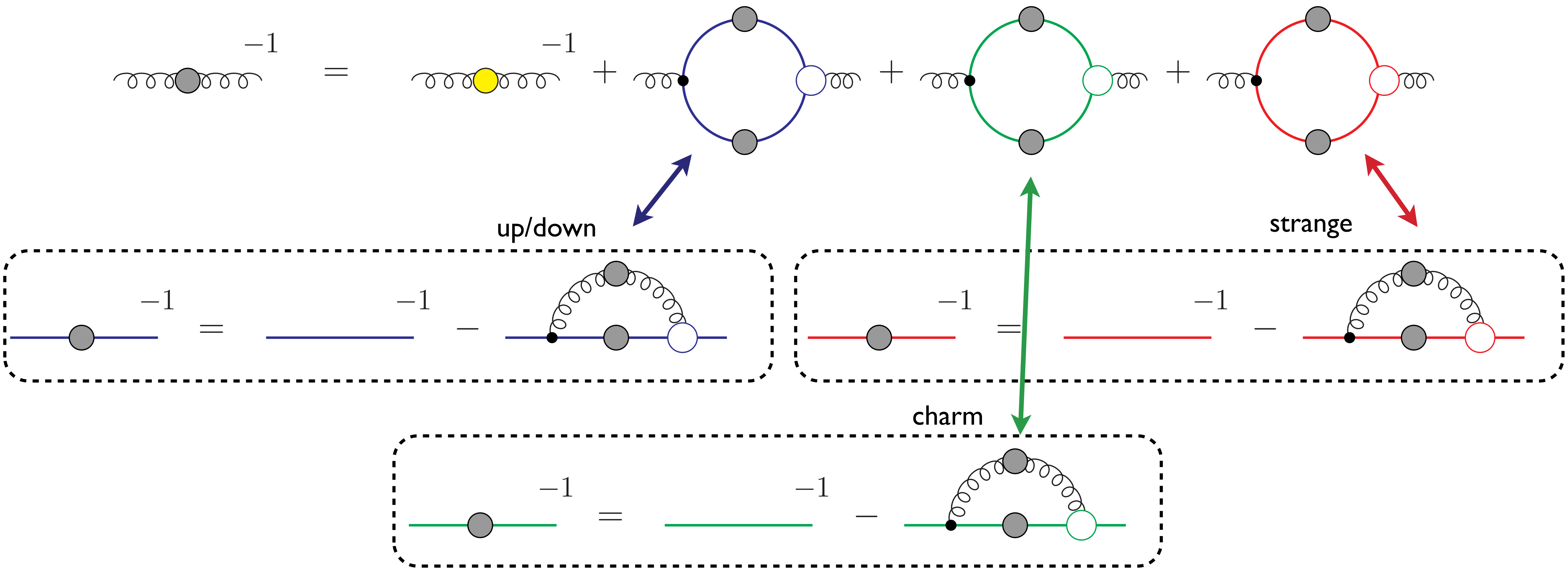
- no CEP at $\mu_B/T < 2$ in agreement with lattice and FRG

de Forcrand, Philipsen, JHEP 0811 (2008) 012; Nucl Phys. B642 (2002) 290-306
Endrodi, Fodor, Katz, Szabo, JHEP 1104 (2011) 001
Herbst, Pawlowski, Schaefer, PRD 88 (2013) 014007

Caveat: baryon effects missing...

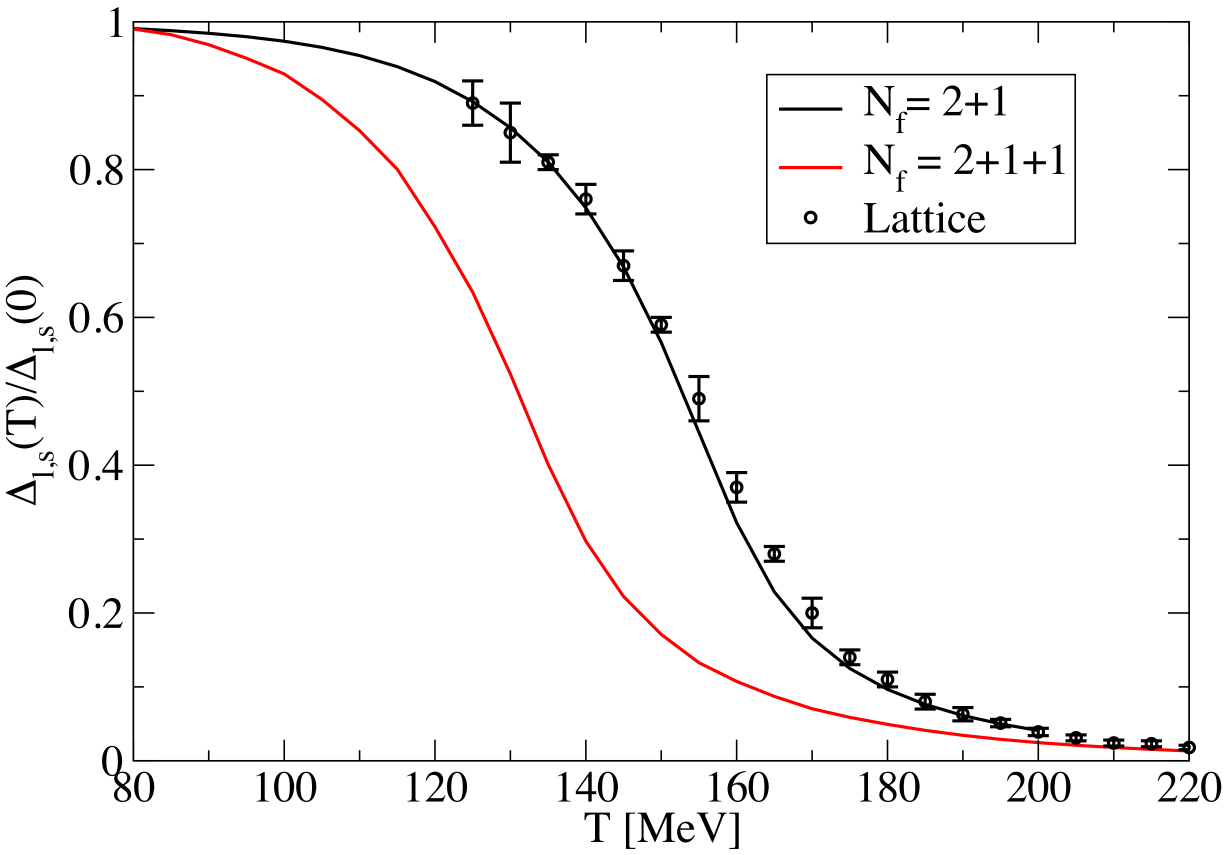
Nc=2: Brauner, Fukushima and Hidaka, PRD 80 (2009) 74035
Strodthoff, Schaefer and Smekal, PRD 85 (2012) 074007

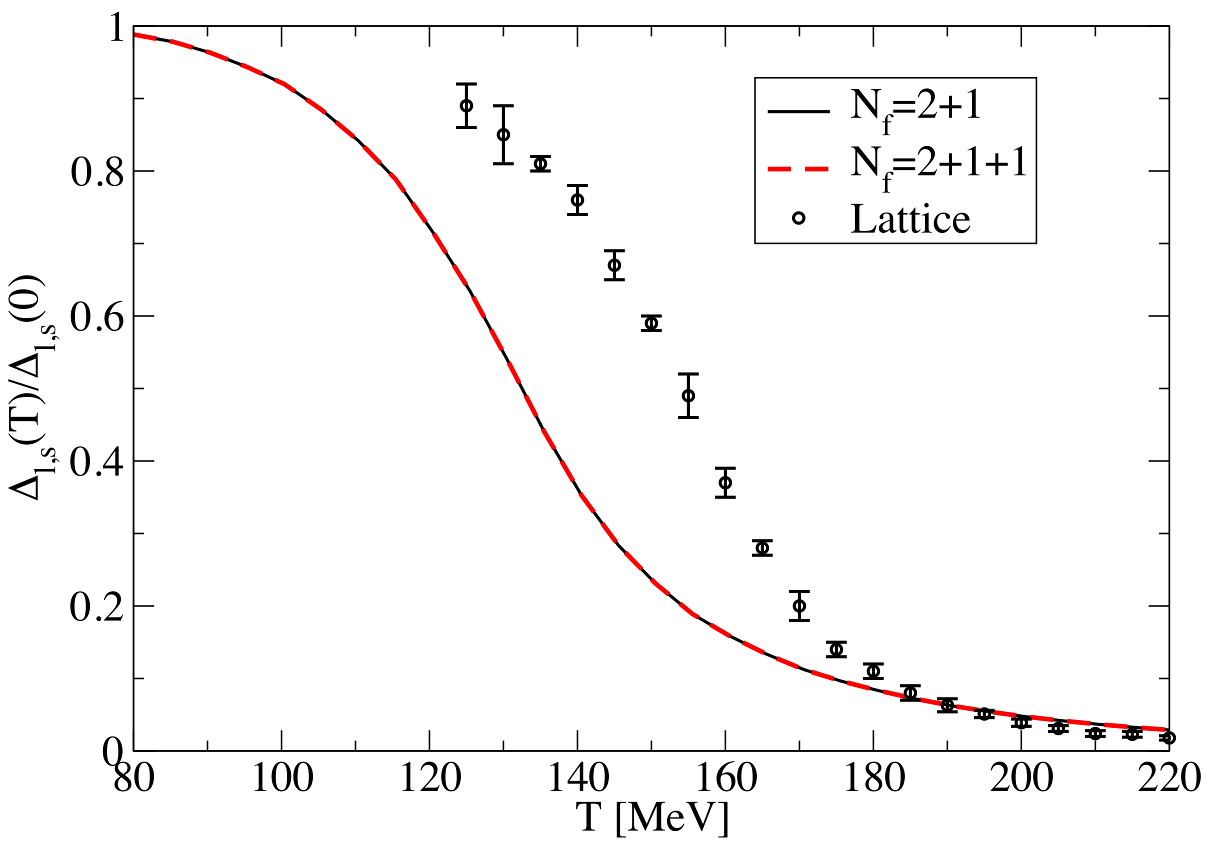
Nf=2+1+1-QCD with DSEs



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

Nf=2+1+1-QCD with DSEs

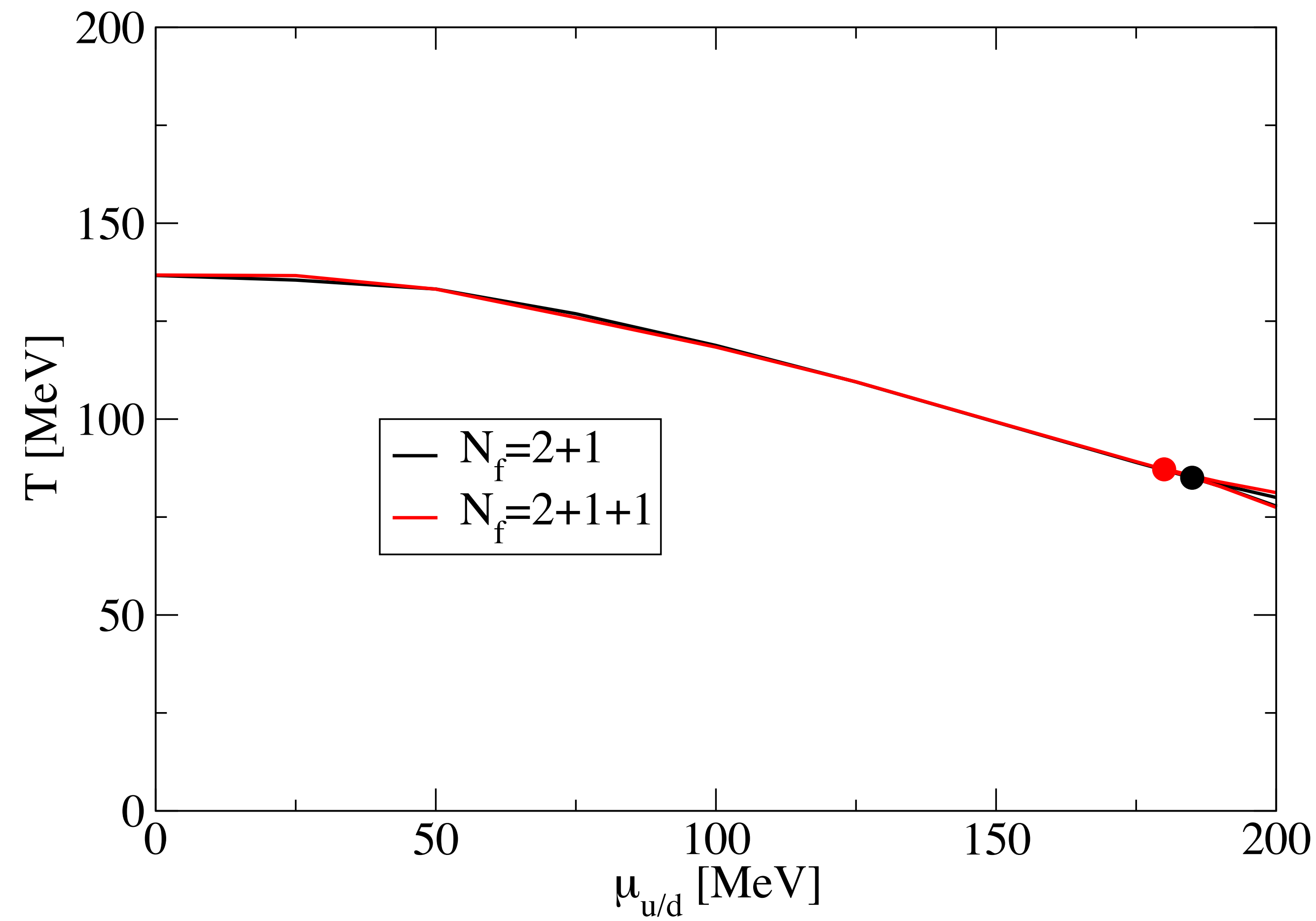




CF, Luecker, Welzbacher, arXiv:1405.4762

- Left: Interaction fixed: T_{PC} decreases by O(20 MeV)
- Right: Physics fixed (m_π, f_π): T_{PC} similar

Nf=2+1+1-QCD with DSEs



CF, Luecker, Welzbacher, arXiv:1405.4762

- Physics fixed (m_π, f_π): T_C similar
- Charm quark has no influence on QCD phase diagram

Summary

- Temperature dependent gluon propagator
  - characteristic behaviour of electric gluon
  - ‘melting’ of magnetic gluon with temperature
- Deconf. T_{pc} from dressed Polyakov-loop/Polyakov-loop potential
- QCD with finite chemical potential (beyond mean field)
  - backreaction of quarks onto gluons important
  - N_f=2+1 and N_f=2+1+1: CEP at $\mu_c/T_c > 1$

Work in progress: include baryons...
include magnetic field...

Mueller, Bonnet, CF, PRD in press, arXiv:1401.1647