Locating the critical end point of QCD

Christian S. Fischer

Justus Liebig Universität Gießen

HIC for FAIR
Helmholtz International Center

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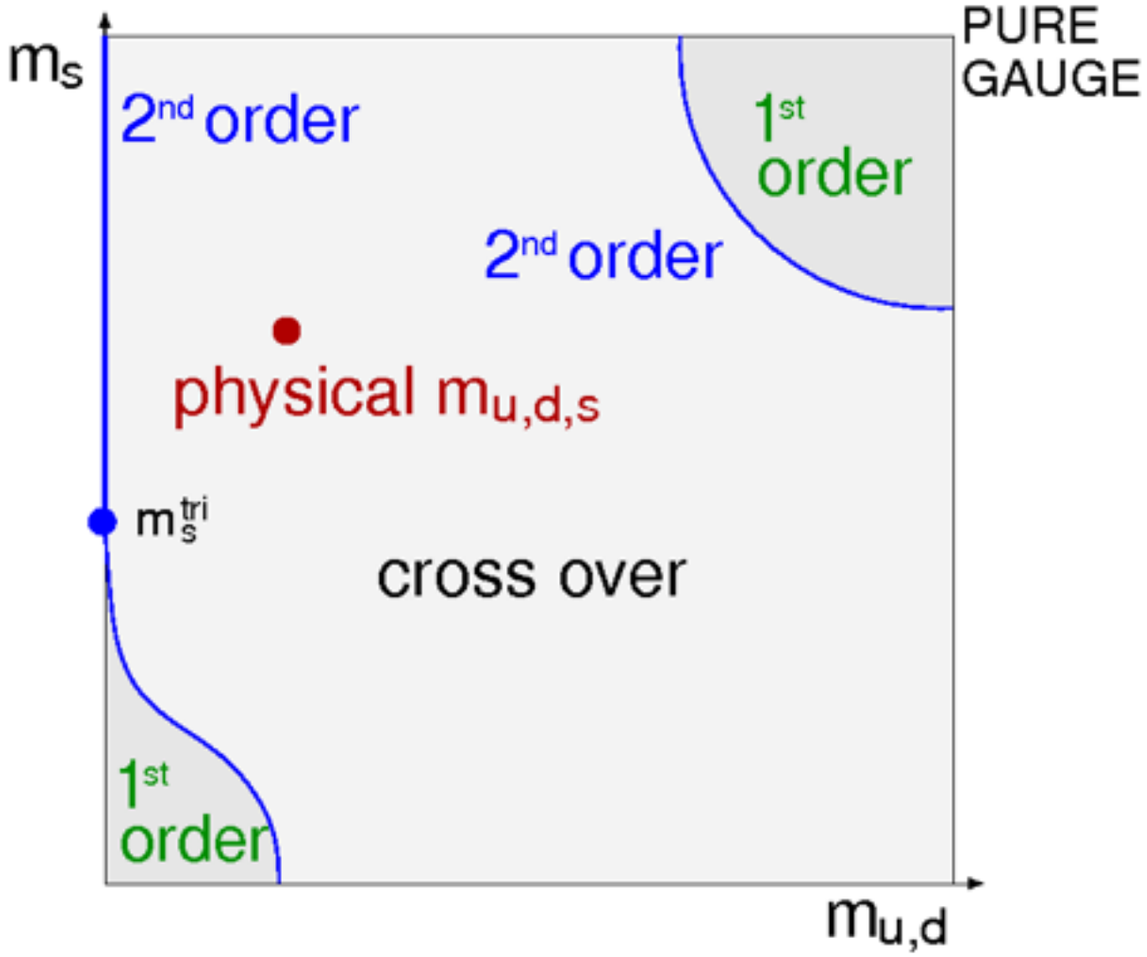
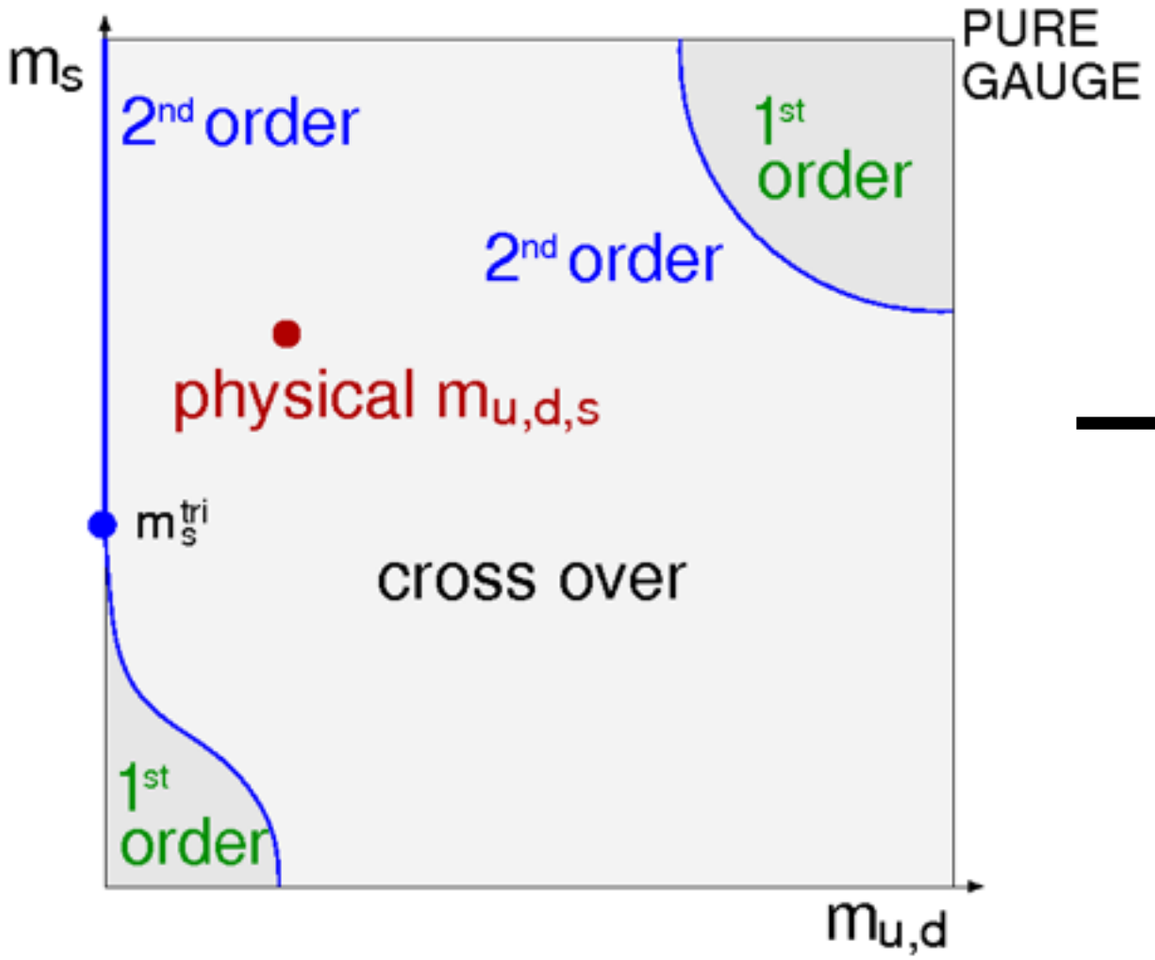
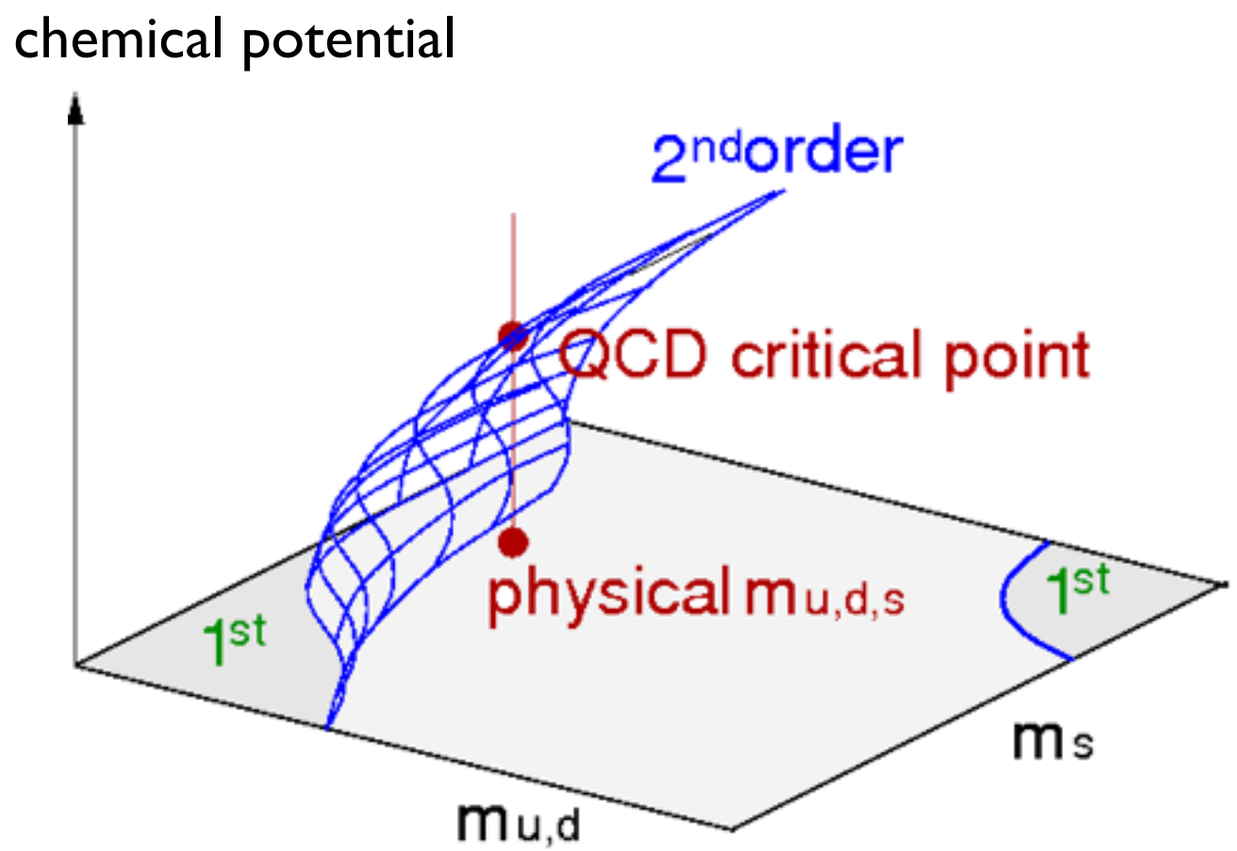
Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP in press [1606.09602]

QCD phase transitions

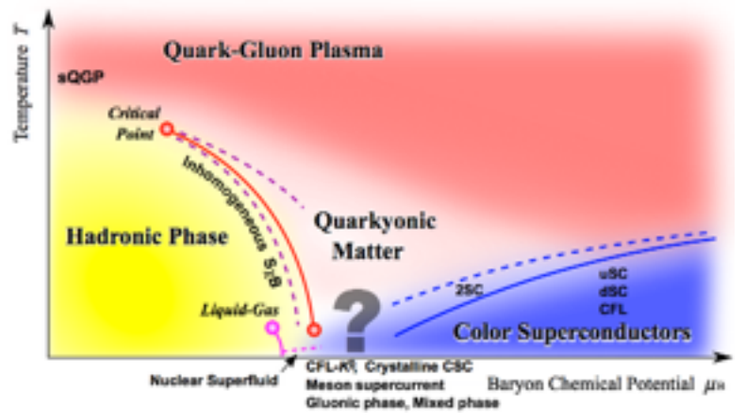


QCD phase transitions

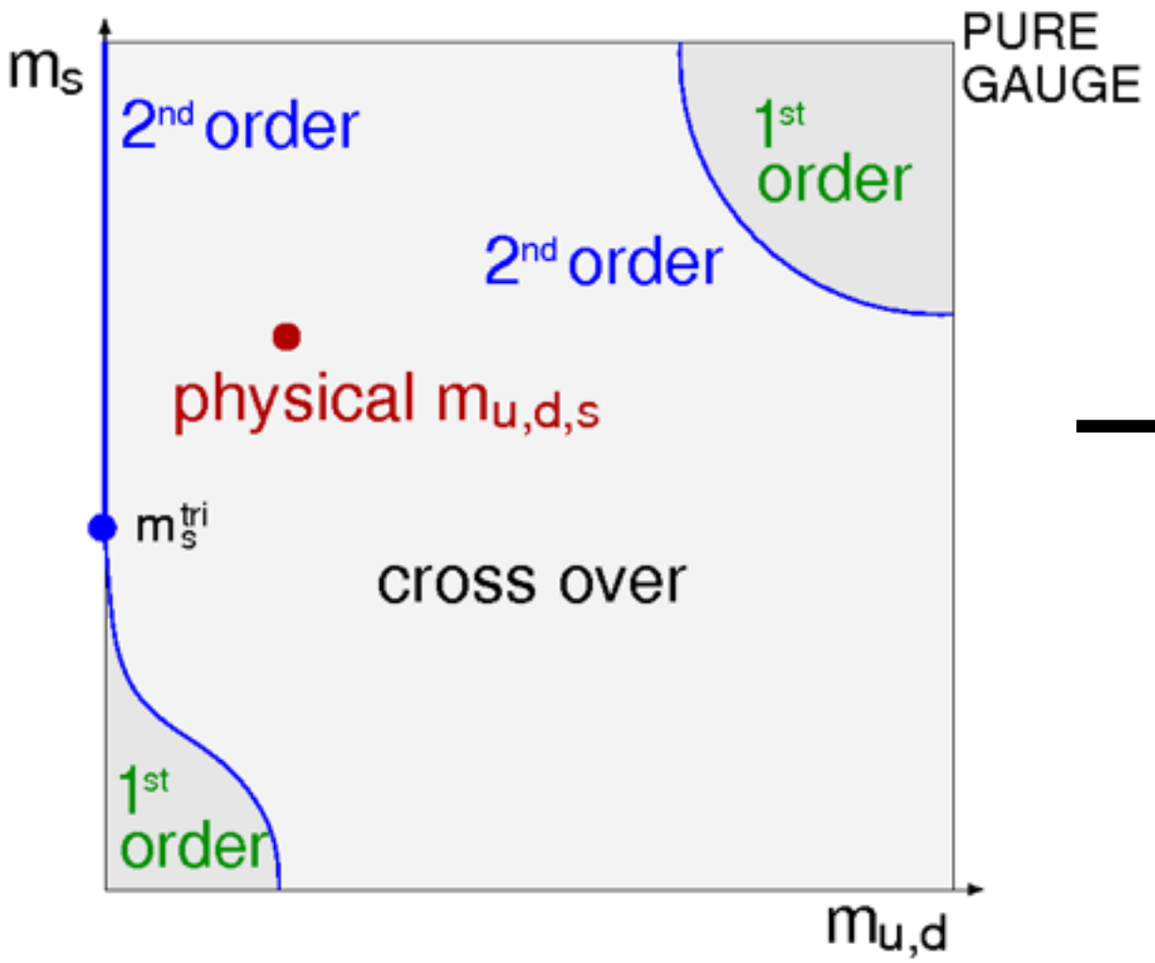


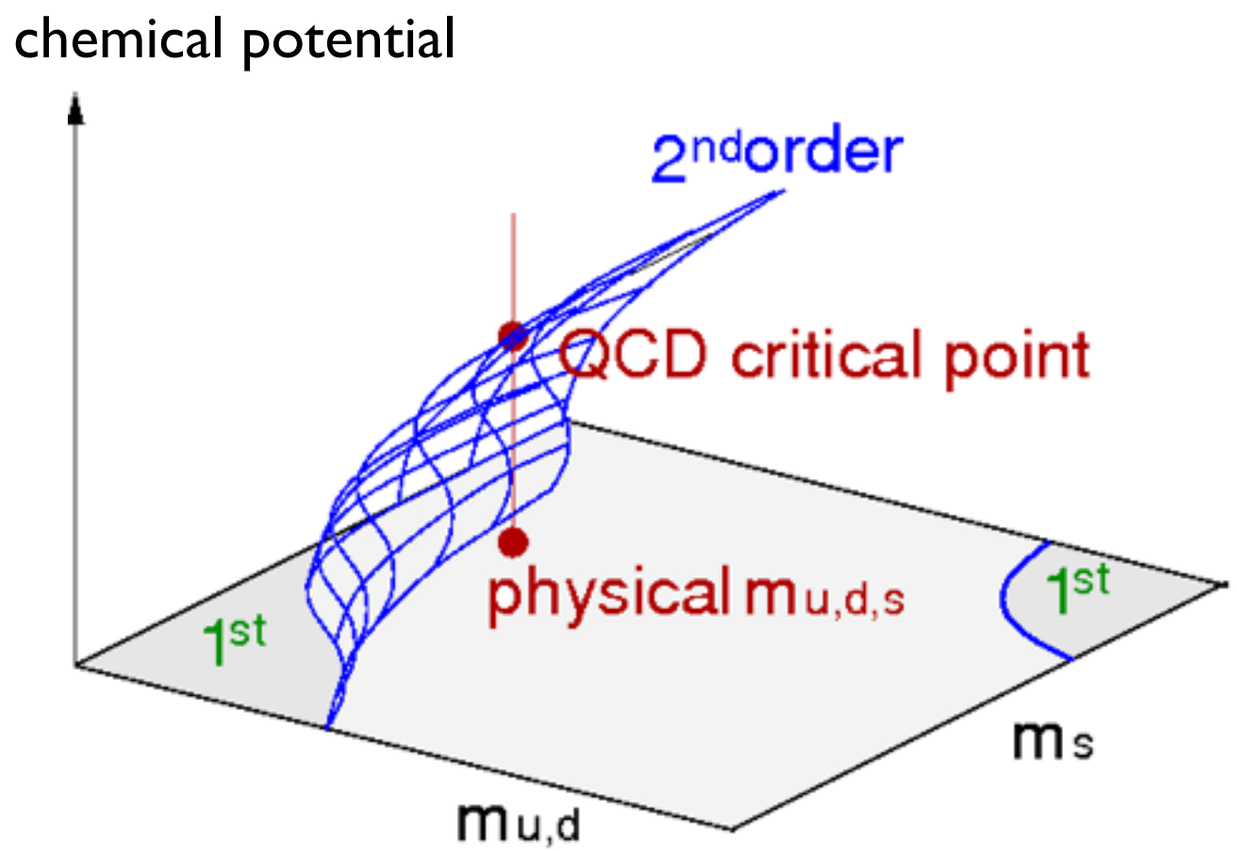


Is this happening ??



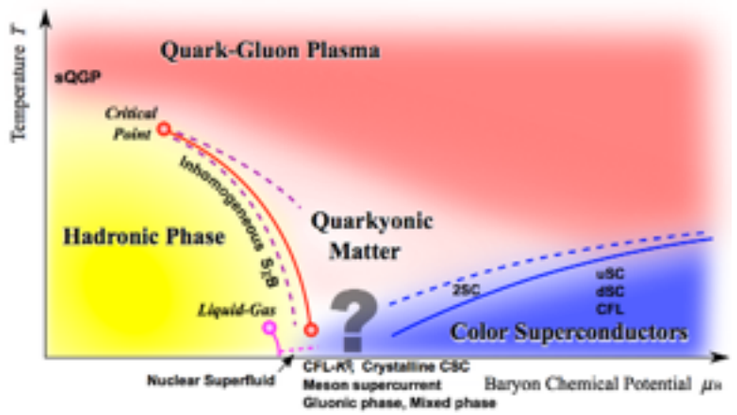
QCD phase transitions



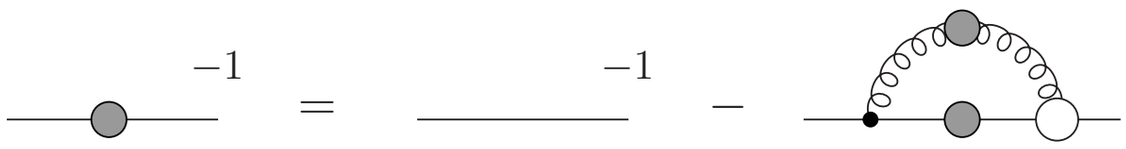


- Lattice-QCD
  - present: extrapolation
  - future: exact methods ?
- DSE/FRG
  - not exact, but allow for '10%-physics'

Is this happening ??



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:

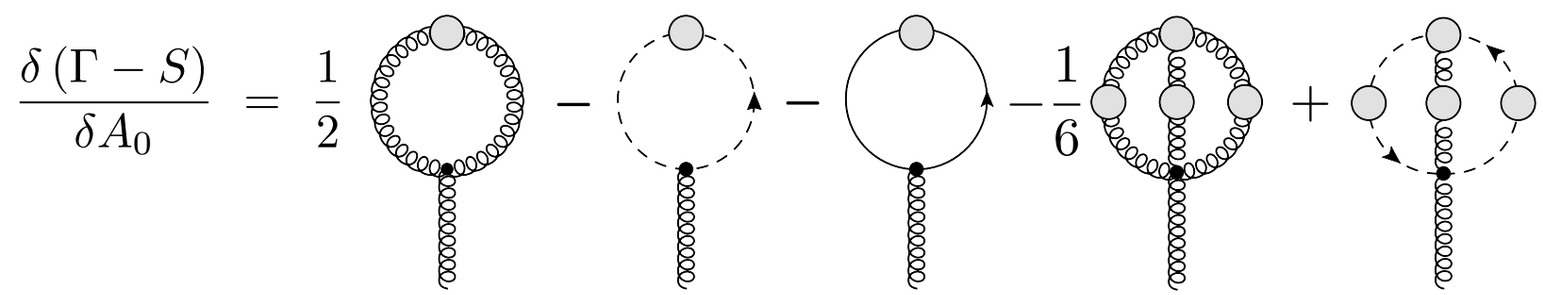
- dressed Polyakov loop

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

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

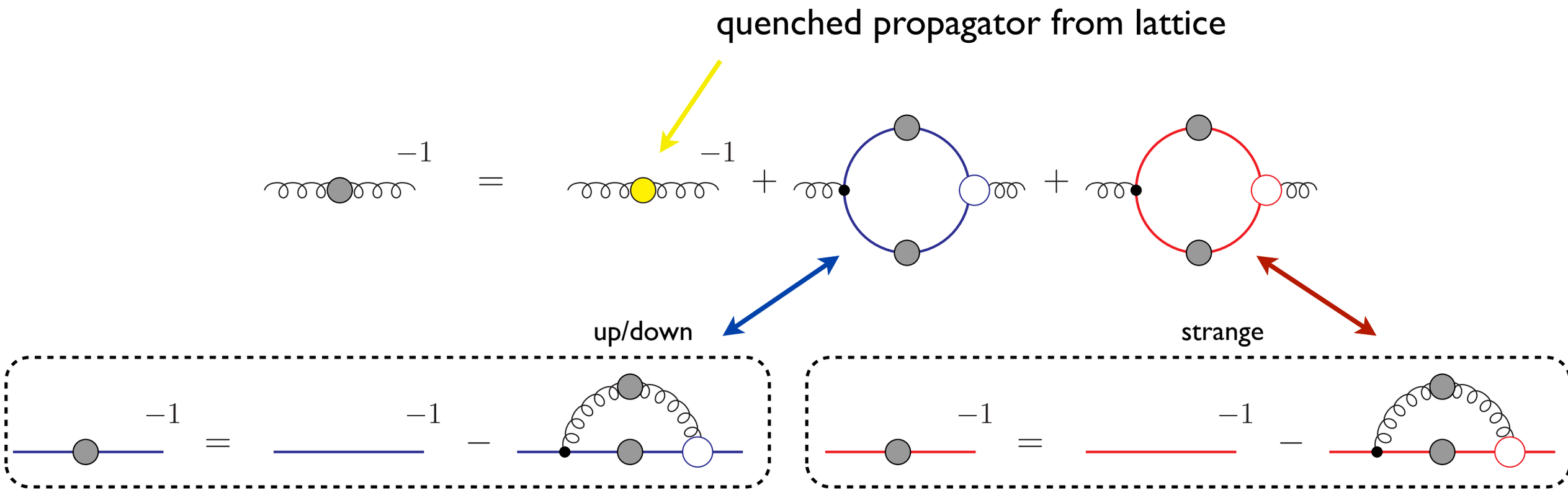
- Polyakov loop potential

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



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

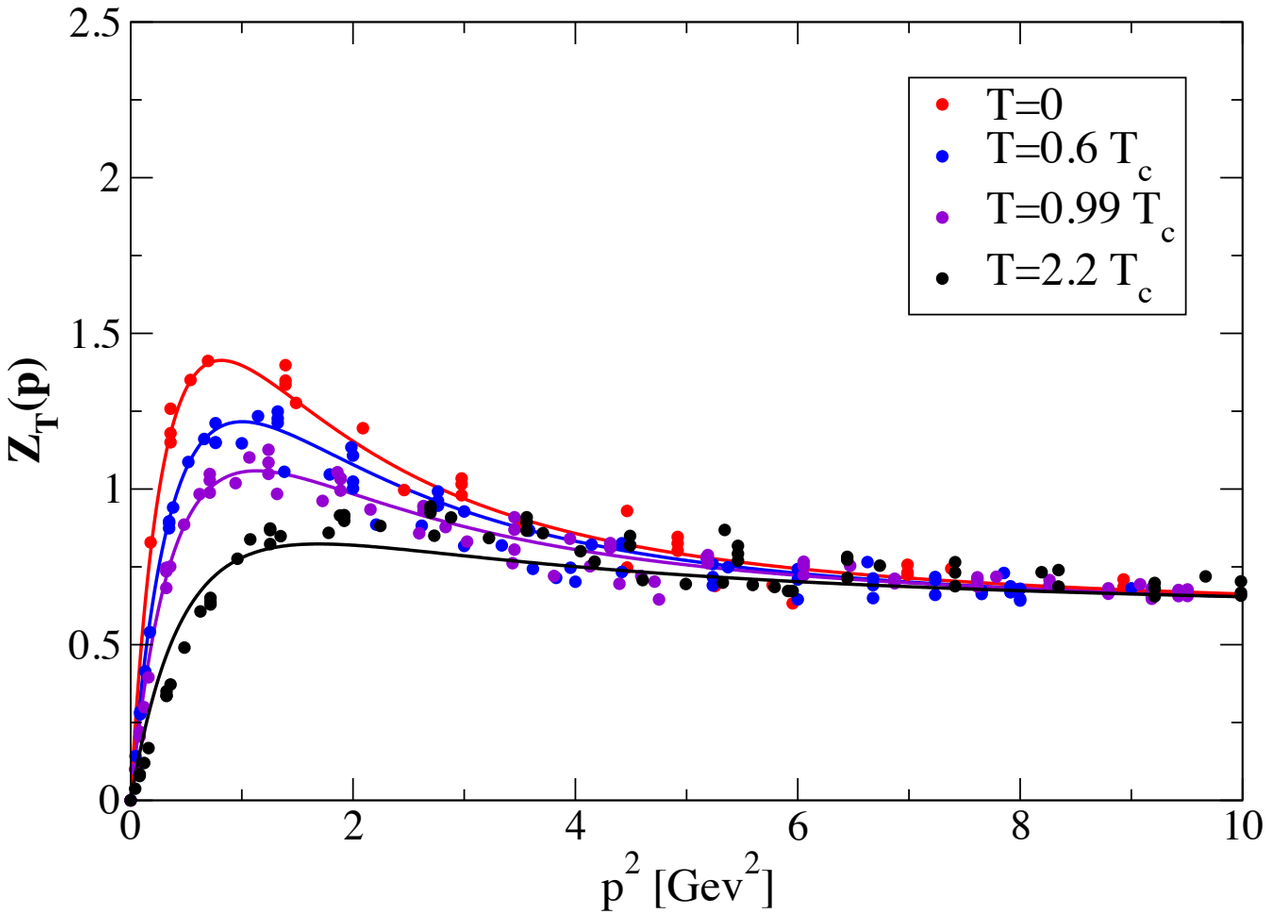
N_f=2+1-QCD with DSEs

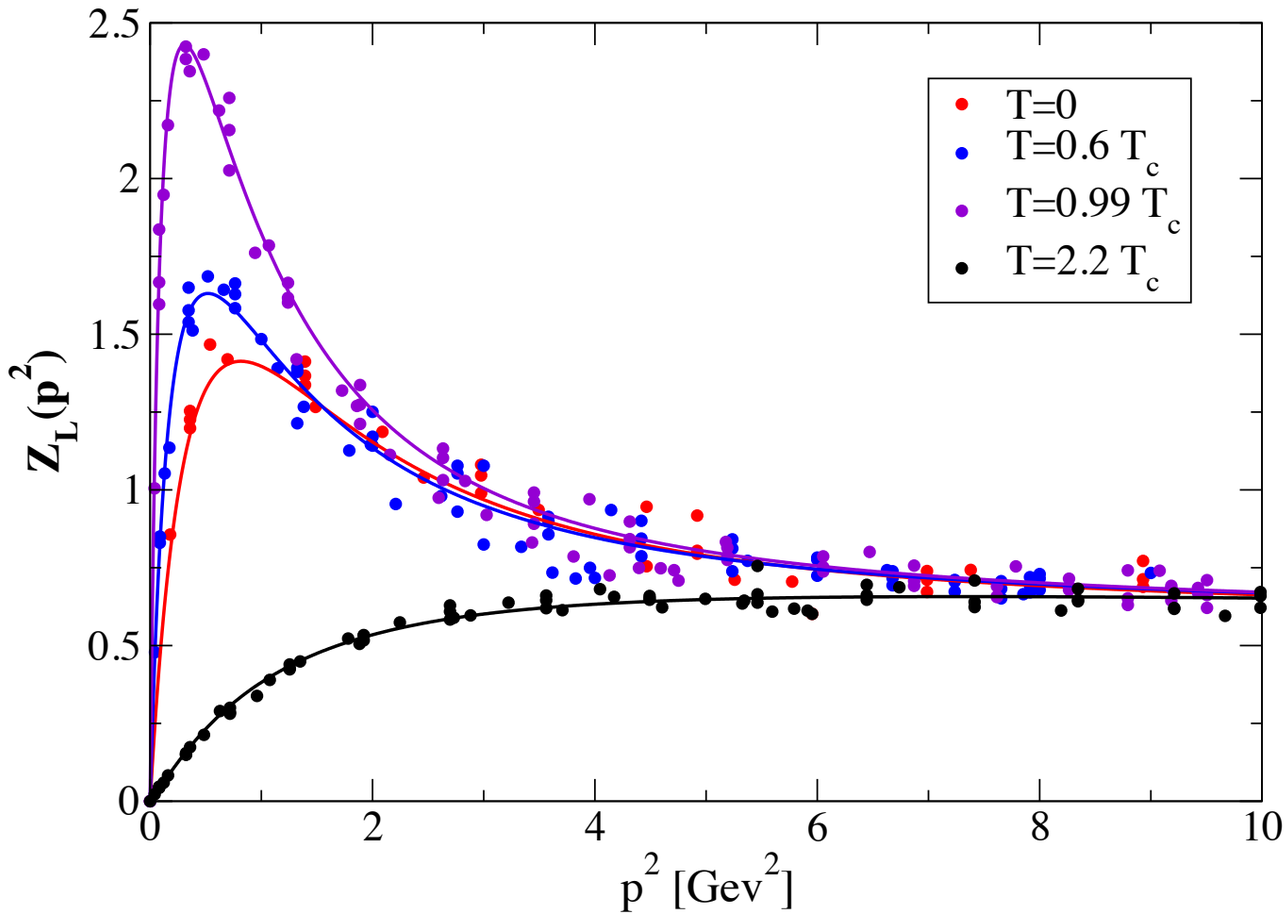


- quenched: without quark-loop
- Nf=2: isospin symmetry
- Nf=2+1: solve coupled system of 2+3+3 equations
- Vertex: ansatz built along STI and known UV/IR behaviour

Glue at finite temperature (T≠0)

T-dependent gluon propagator from quenched lattice simulations:



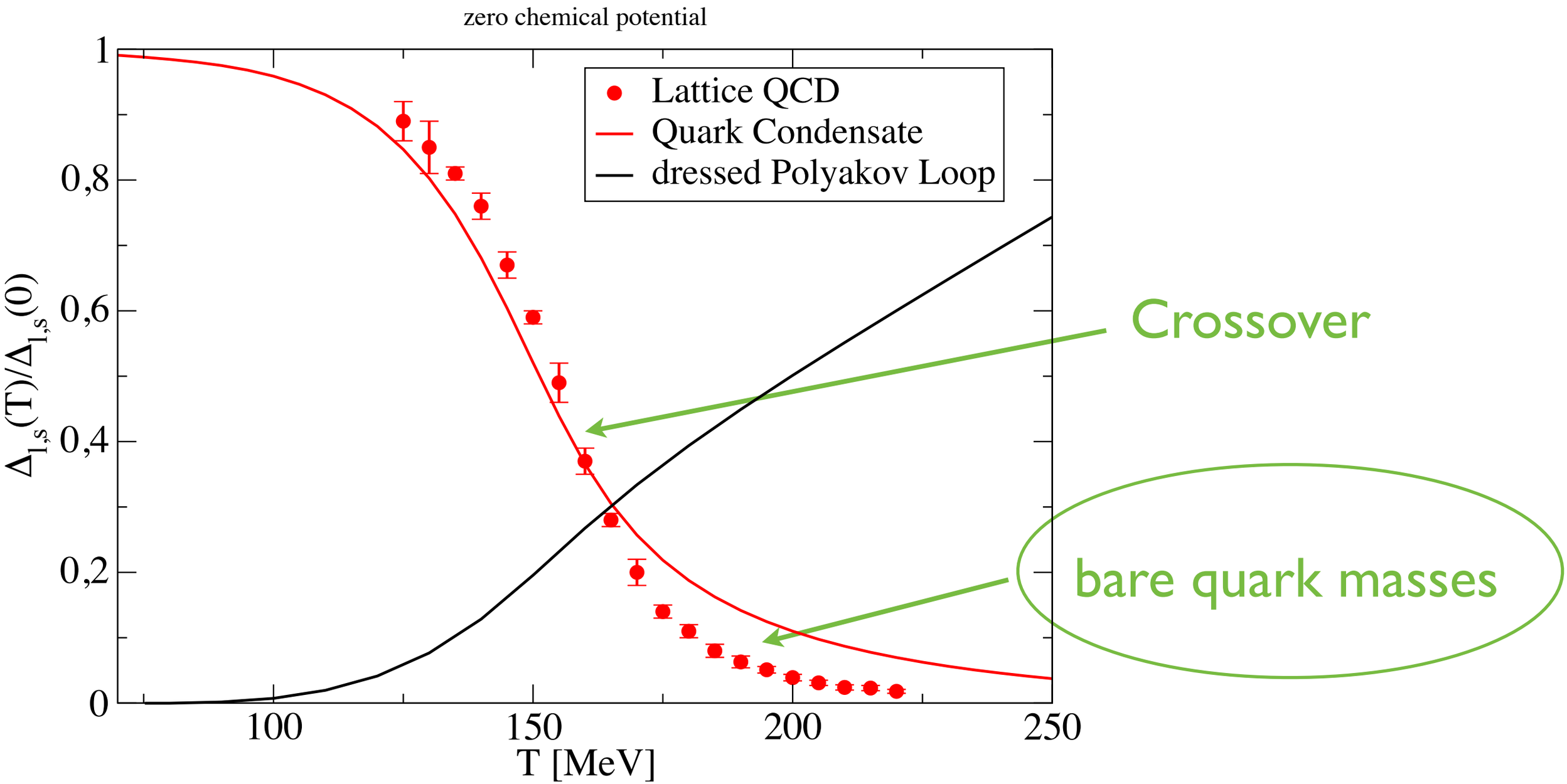


- Crucial difference between magnetic and electric gluon
- Maximum of electric gluon near Tc

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

N_f=2+1, zero chemical potential, physical point



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

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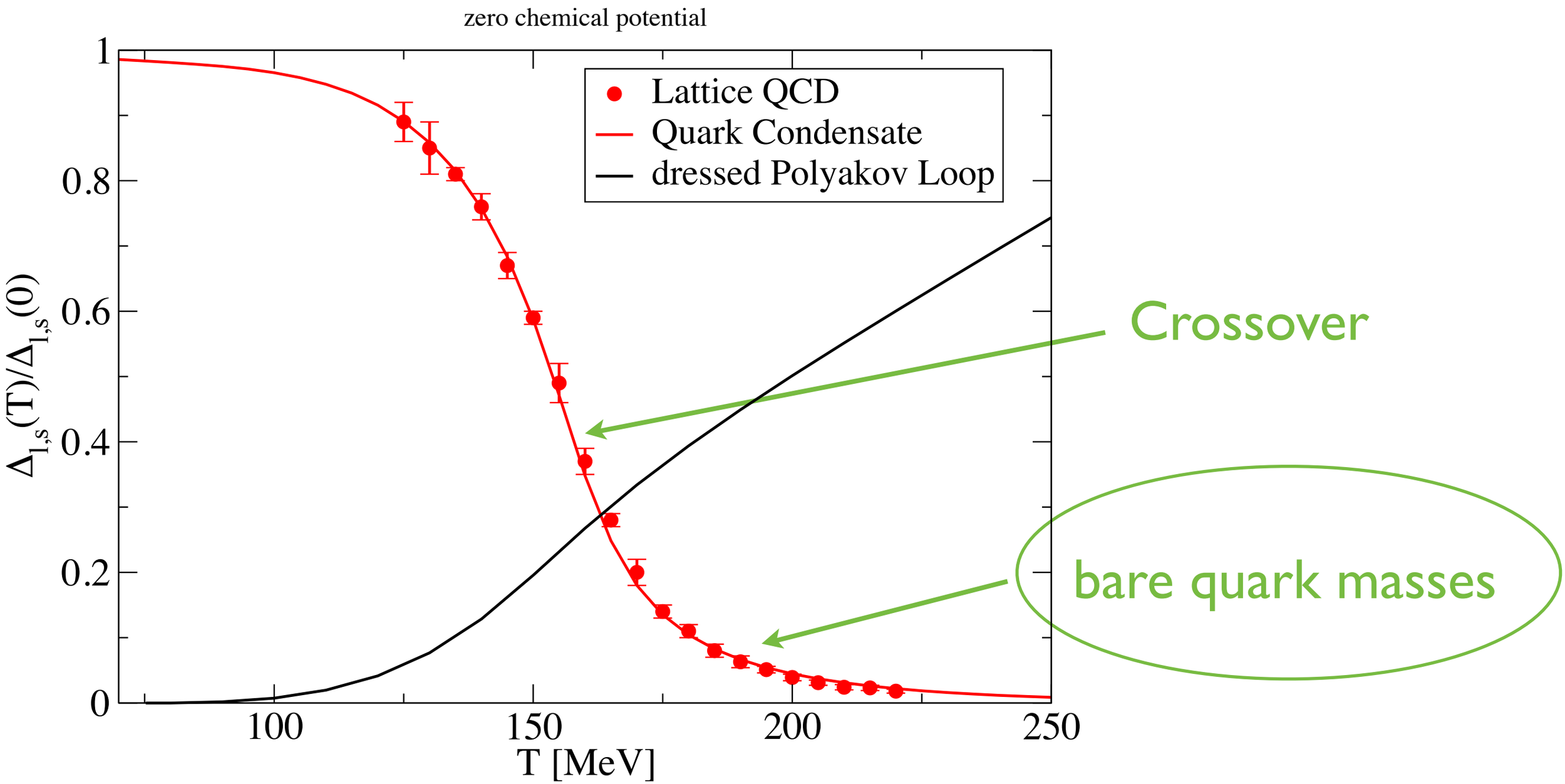

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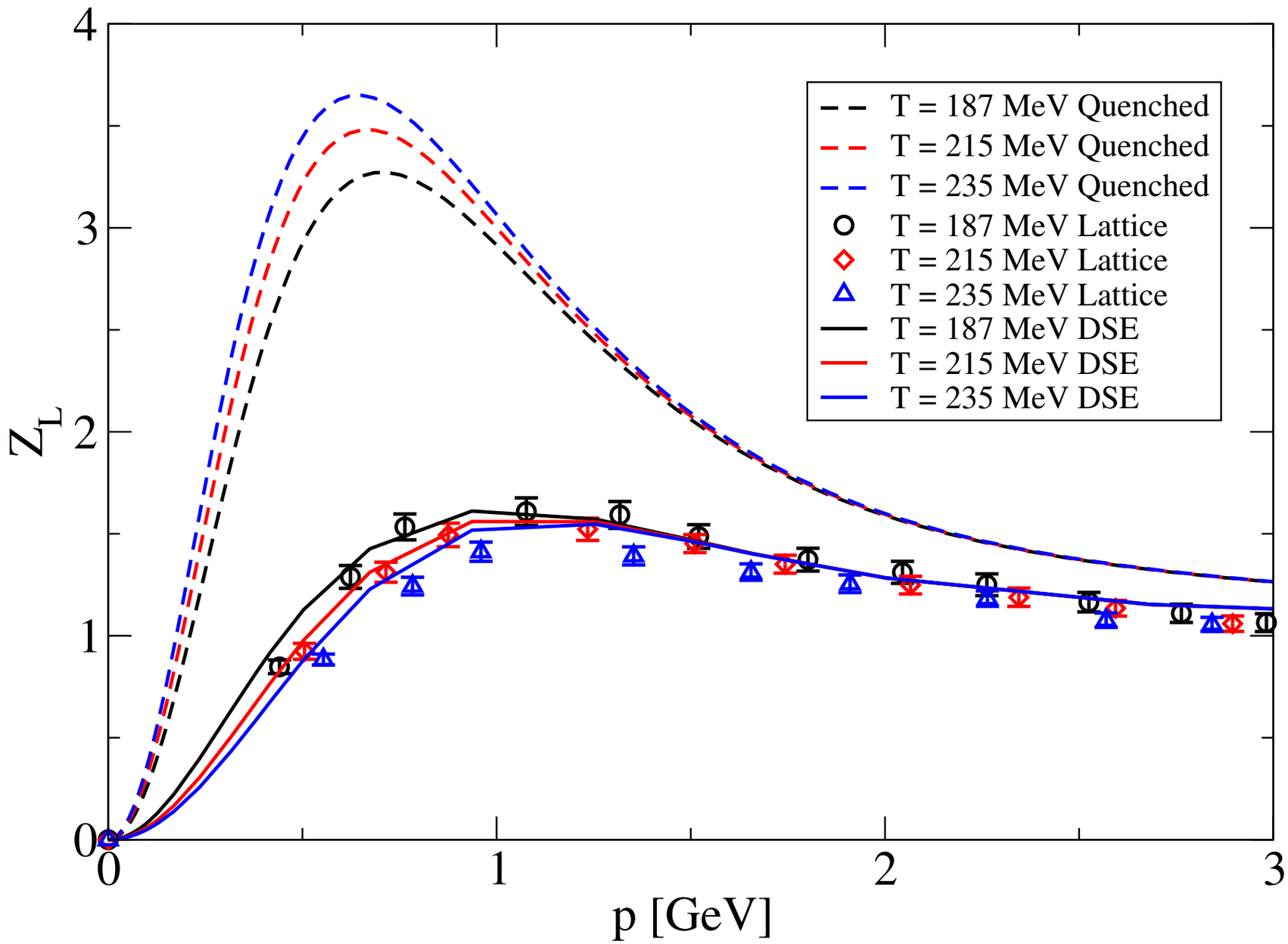
- quantitative agreement

Unquenched Gluon DSE vs Lattice

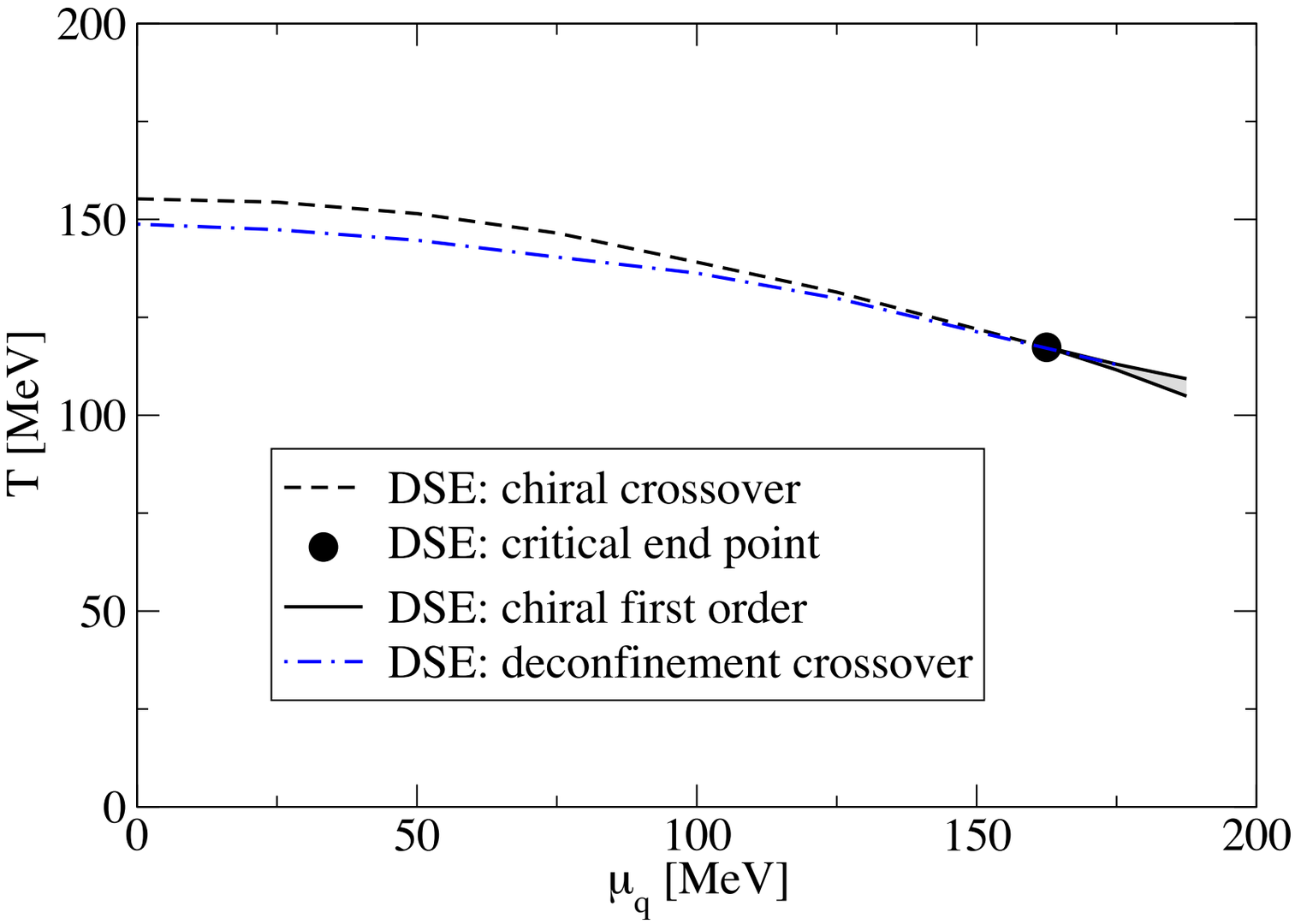


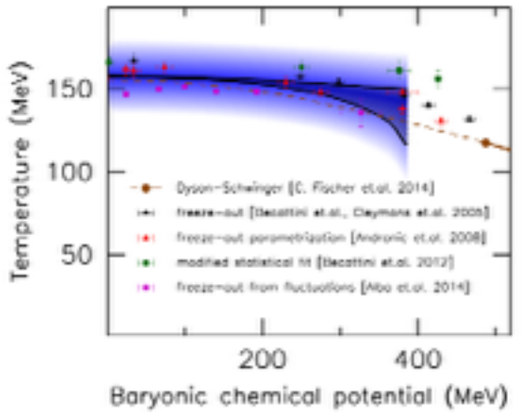
- quantitative agreement: DSE prediction verified by lattice

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

Lattice: Aouane, Burger, Ilgenfritz, Muller-Preussker and Sternbeck, PRD D87 (2013), [arXiv:1212.1102]

N_f=2+1: Polyakov loop and phase diagram





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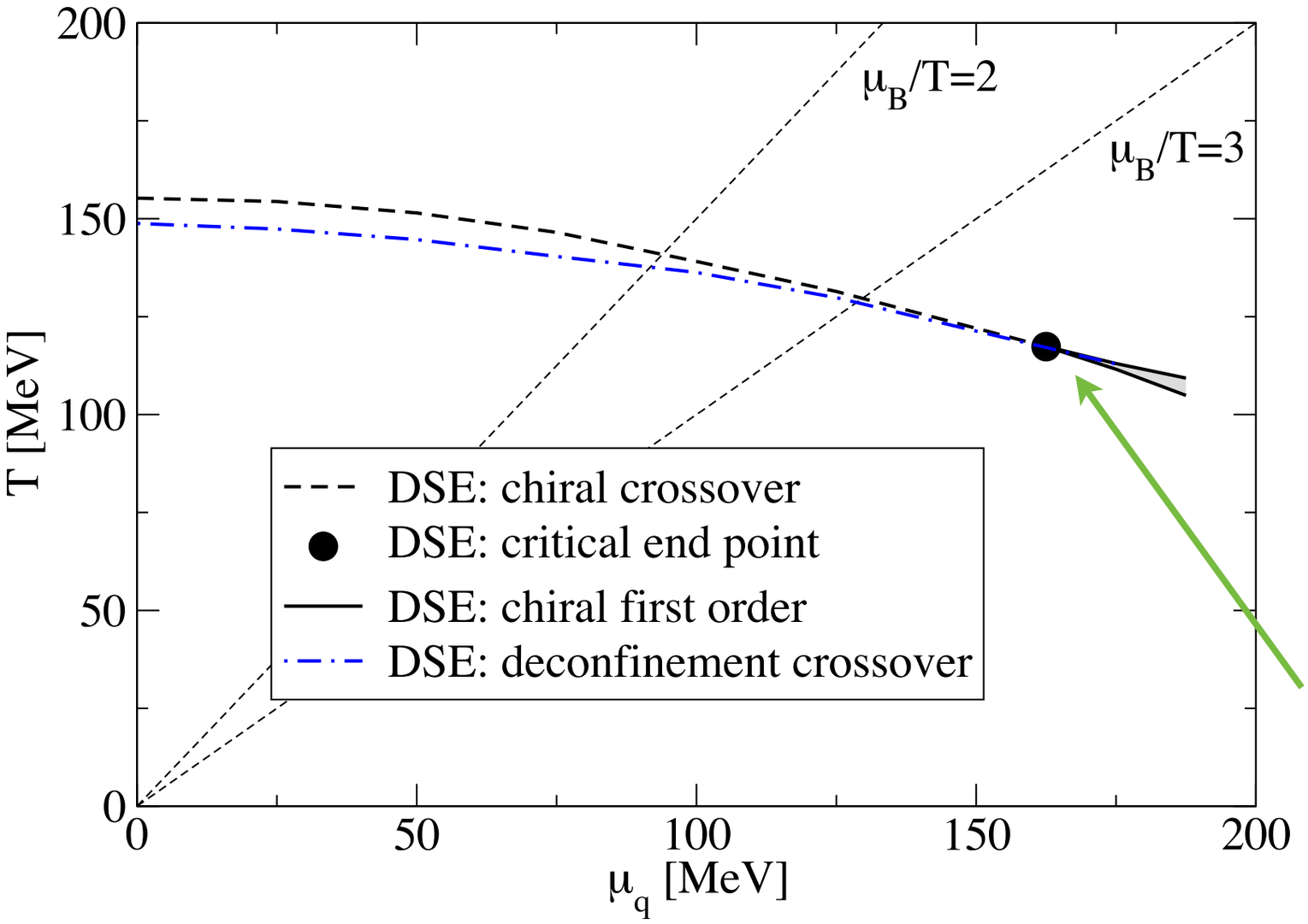

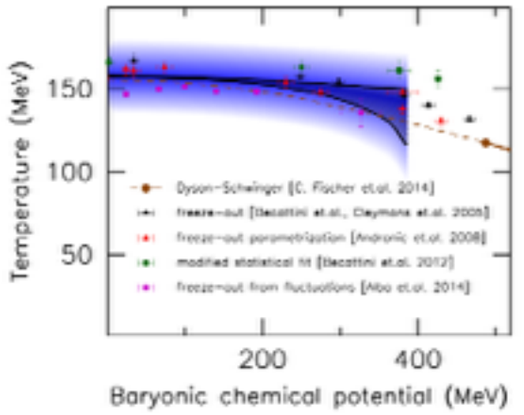

CEP at large μ

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

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

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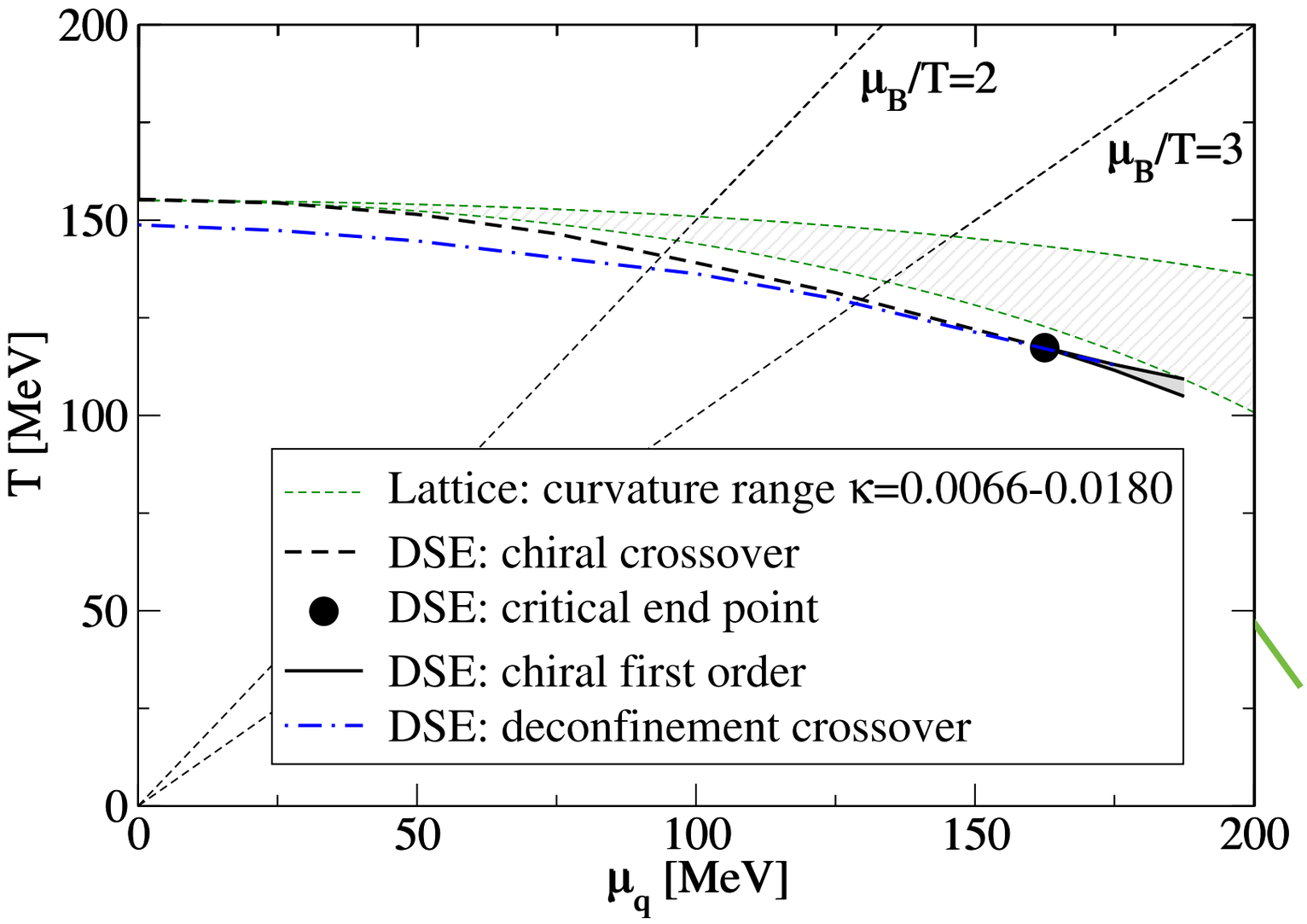

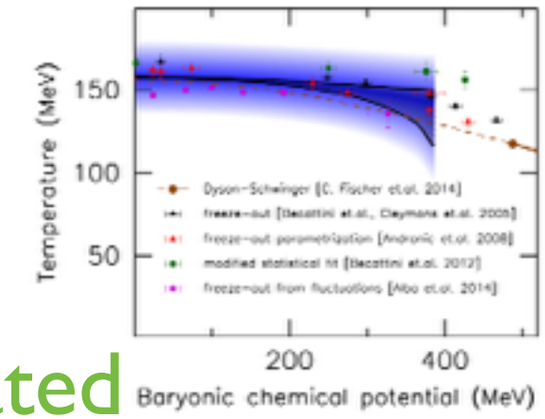

Extrapolated curvature from lattice

Kaczmarek at al. PRD 83 (2011) 014504,
Endrodi, Fodor, Katz, Szabo, JHEP 1104 (2011) 001
Cea, Cosmai, Papa, PRD 89 (2014), PRD 93 (2016)
Bonati et al., PRD 92 (2015) 054503
Bellwied et al. PLB 751 (2015) 559

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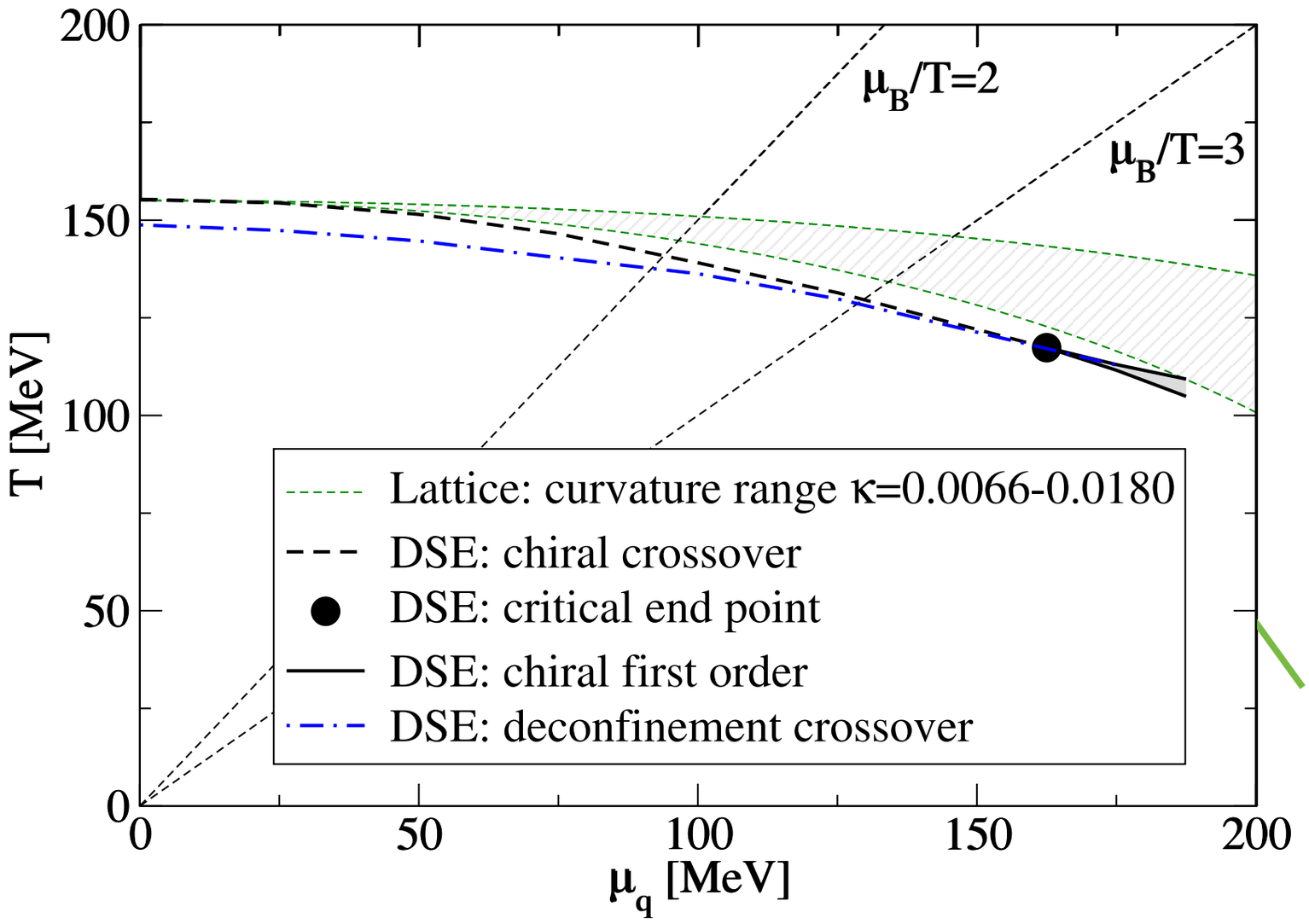

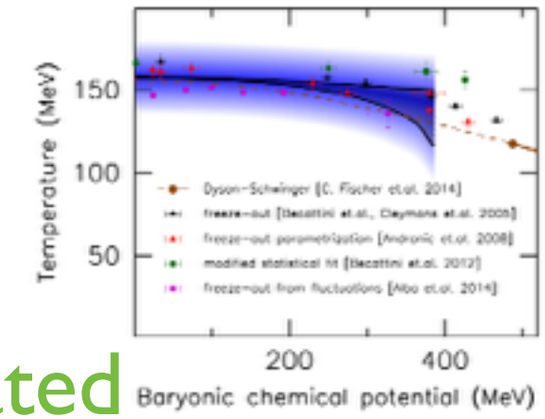

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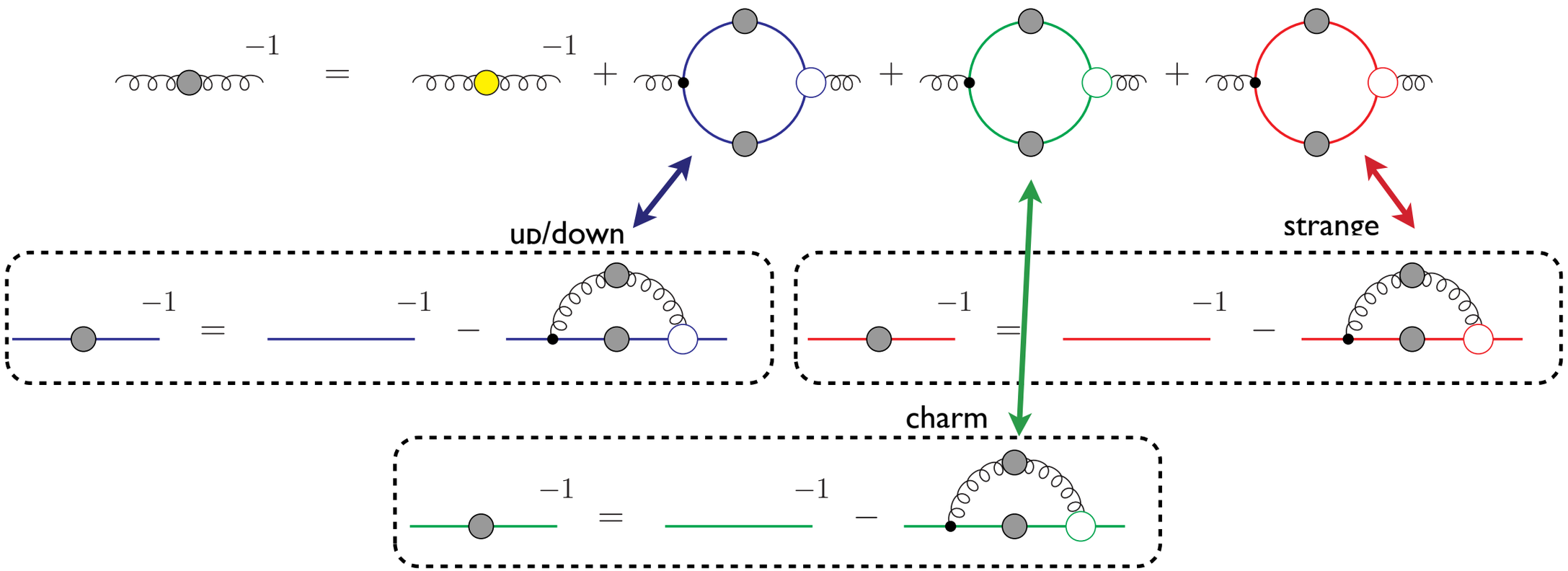
- combined evidence of FRG and DSE: no CEP at $\mu_B/T<2$

Caveat: baryon effects missing...

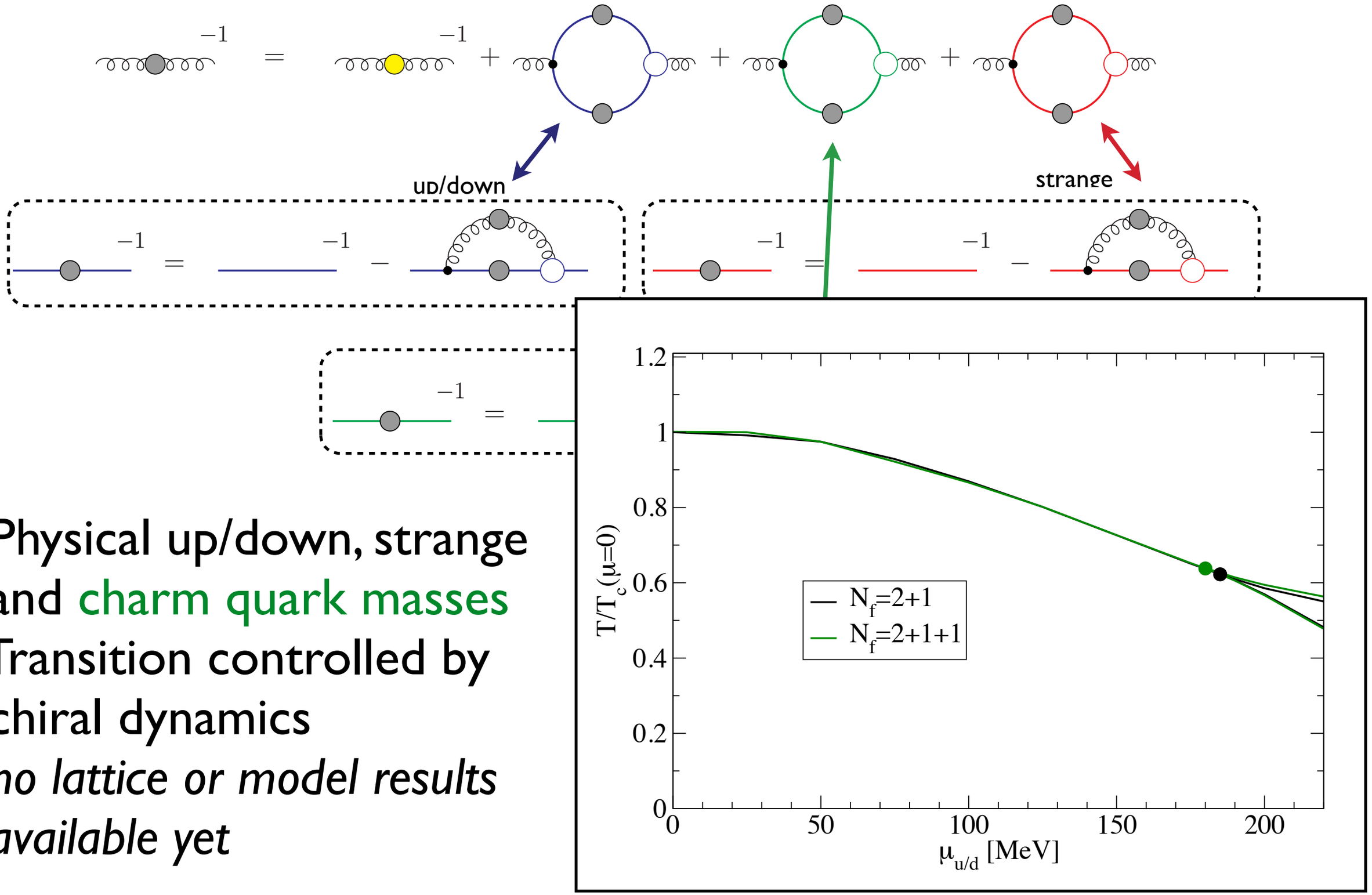
Nc=2: Brauner, Fukushima and Hidaka, PRD 80 (2009) 74035
Strodthoff, Schaefer and Smekal, PRD 85 (2012) 074007

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



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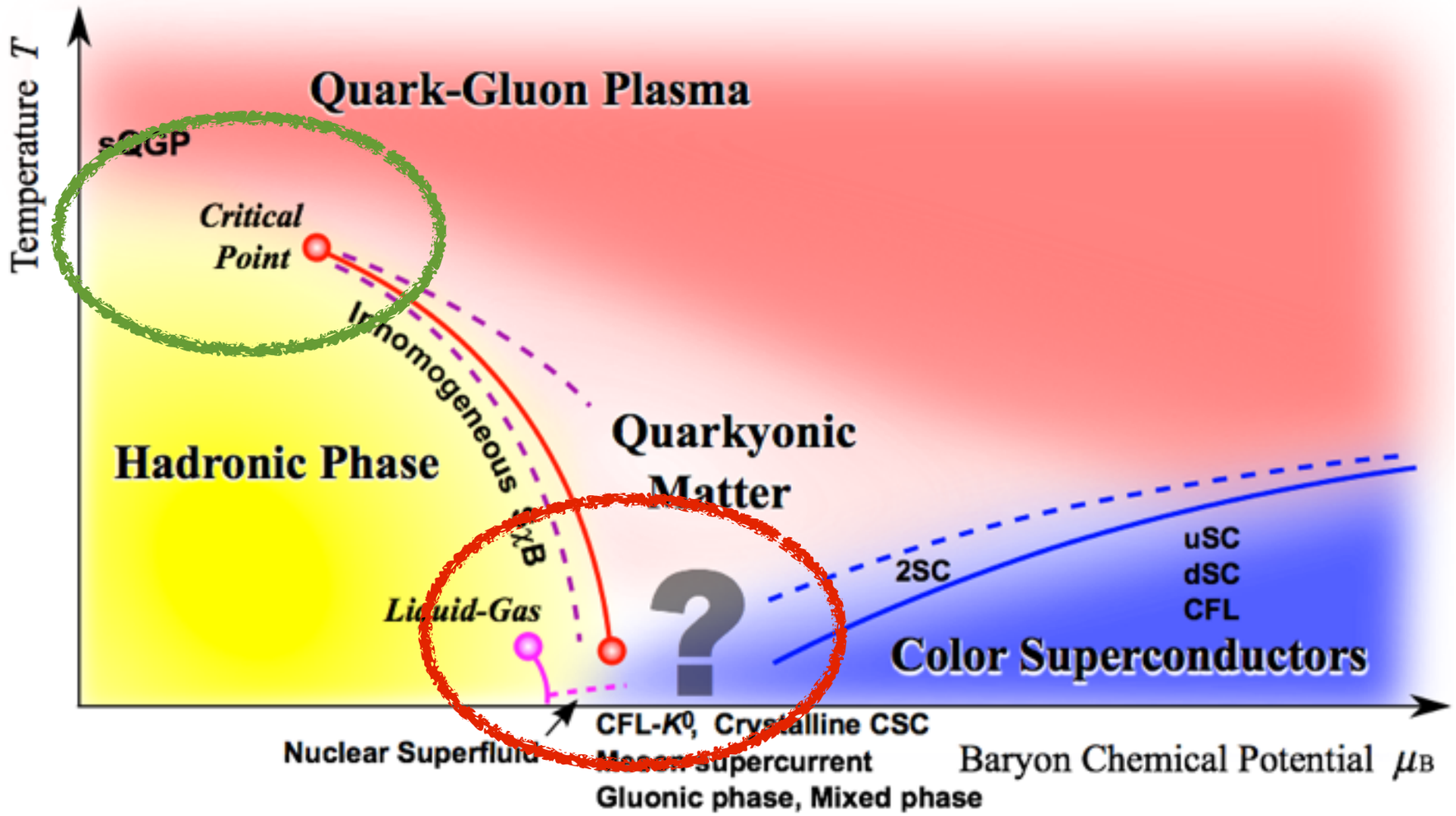
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

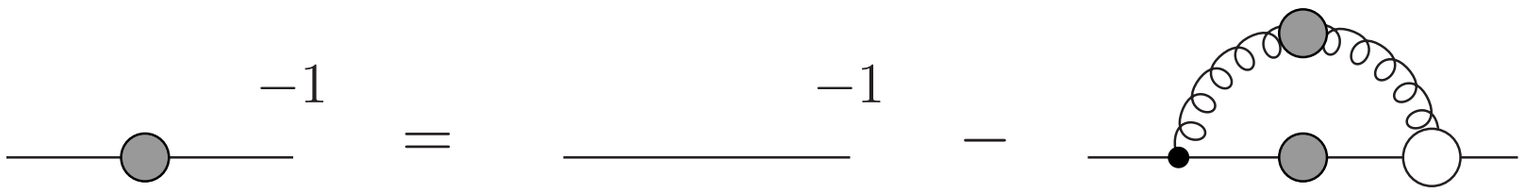
QCD phase transitions I

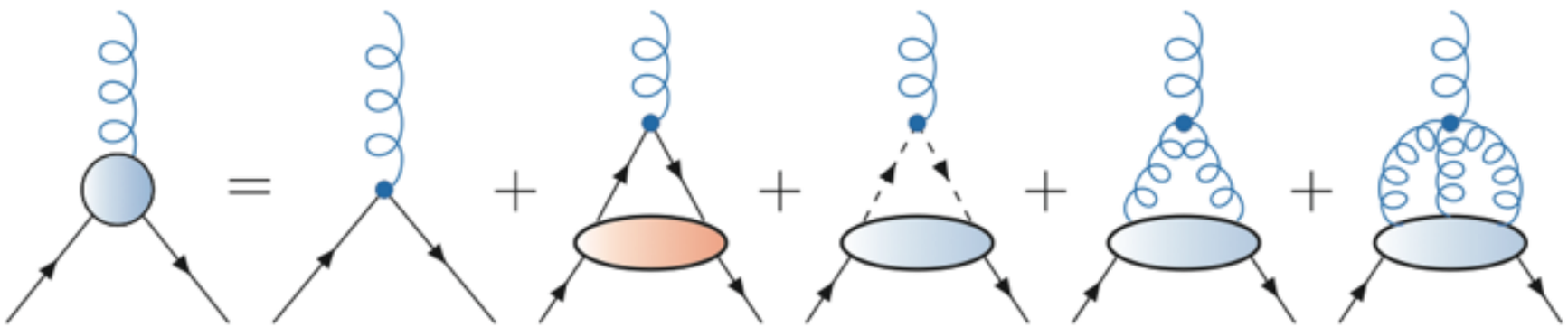
Fukushima, Hatsuda, Rept. Prog. Phys. 74 (2011) 014001

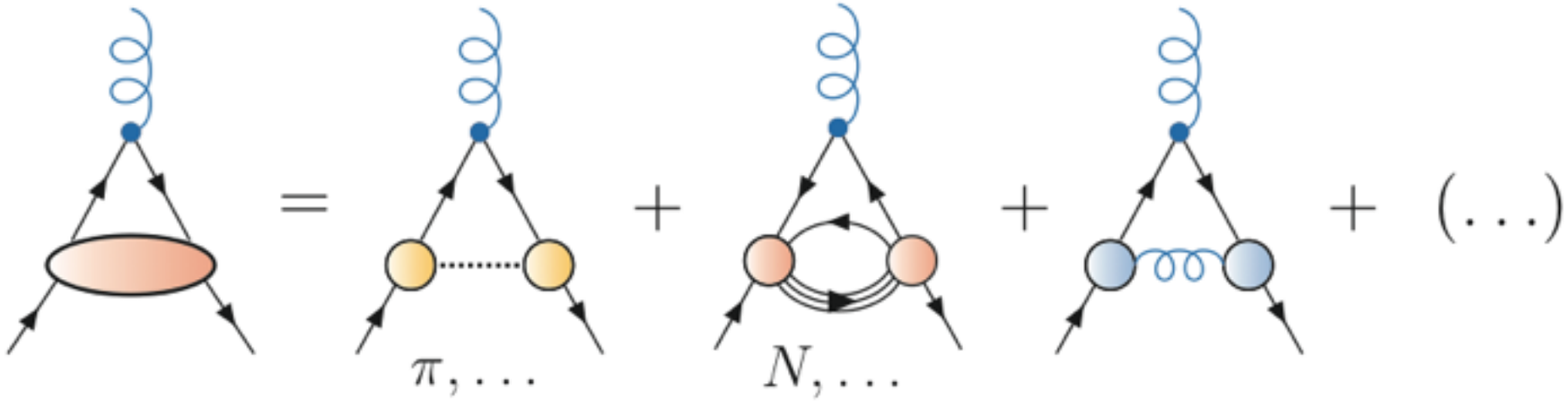


- Low temperatures, large chemical potential: baryons are important degrees of freedom
- How do baryons affect the quark condensate ??

Baryon effects onto quark I

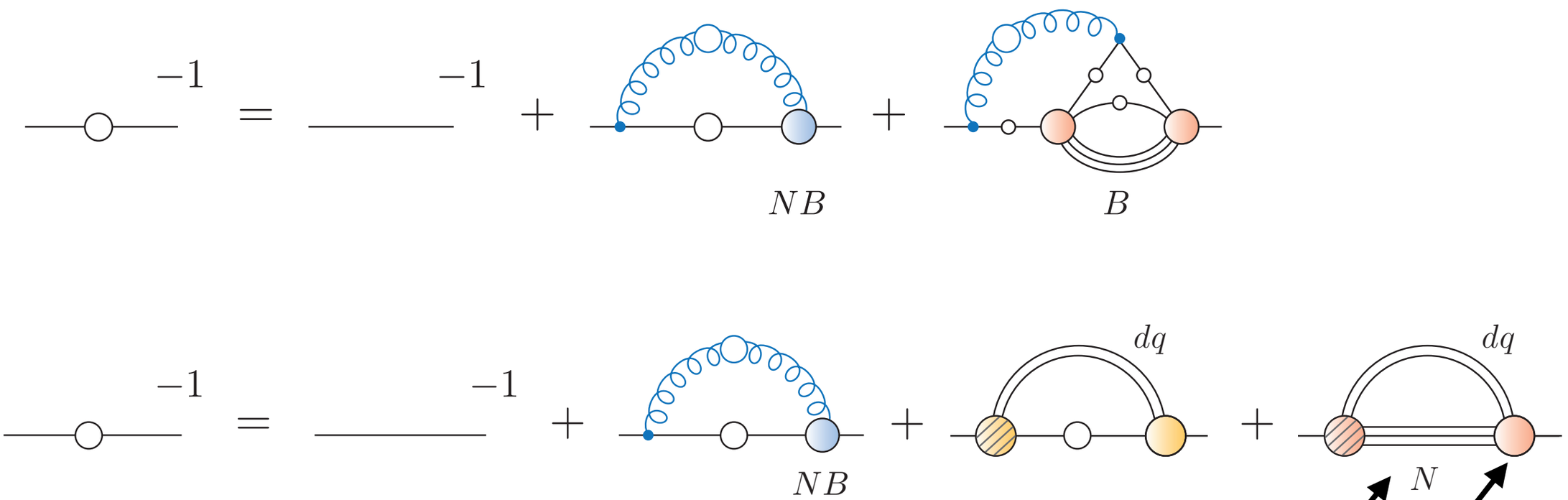






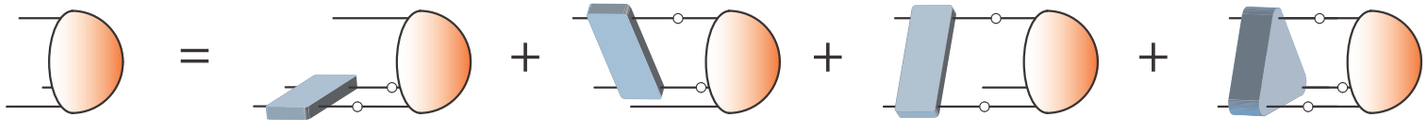
- ‘Off-shell baryons’ do affect quark condensate…

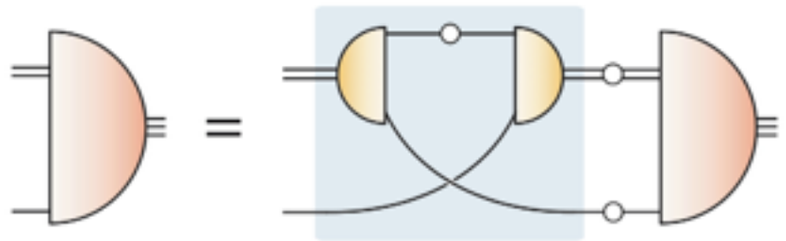
Baryon effects onto quark II



- Dependence on T and μ via -propagators
  -wave functions
- Exploratory calculation: use wave functions from T=μ=0

Baryons at zero temperature





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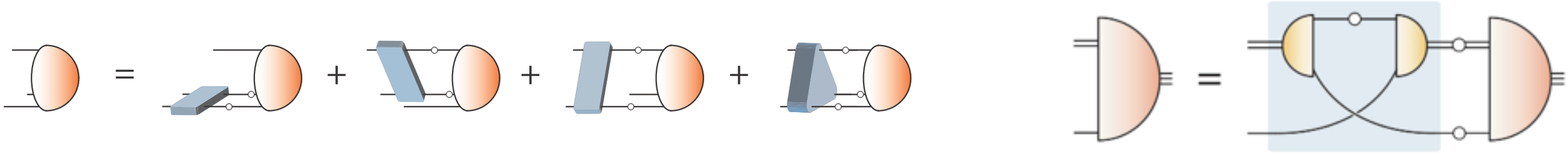
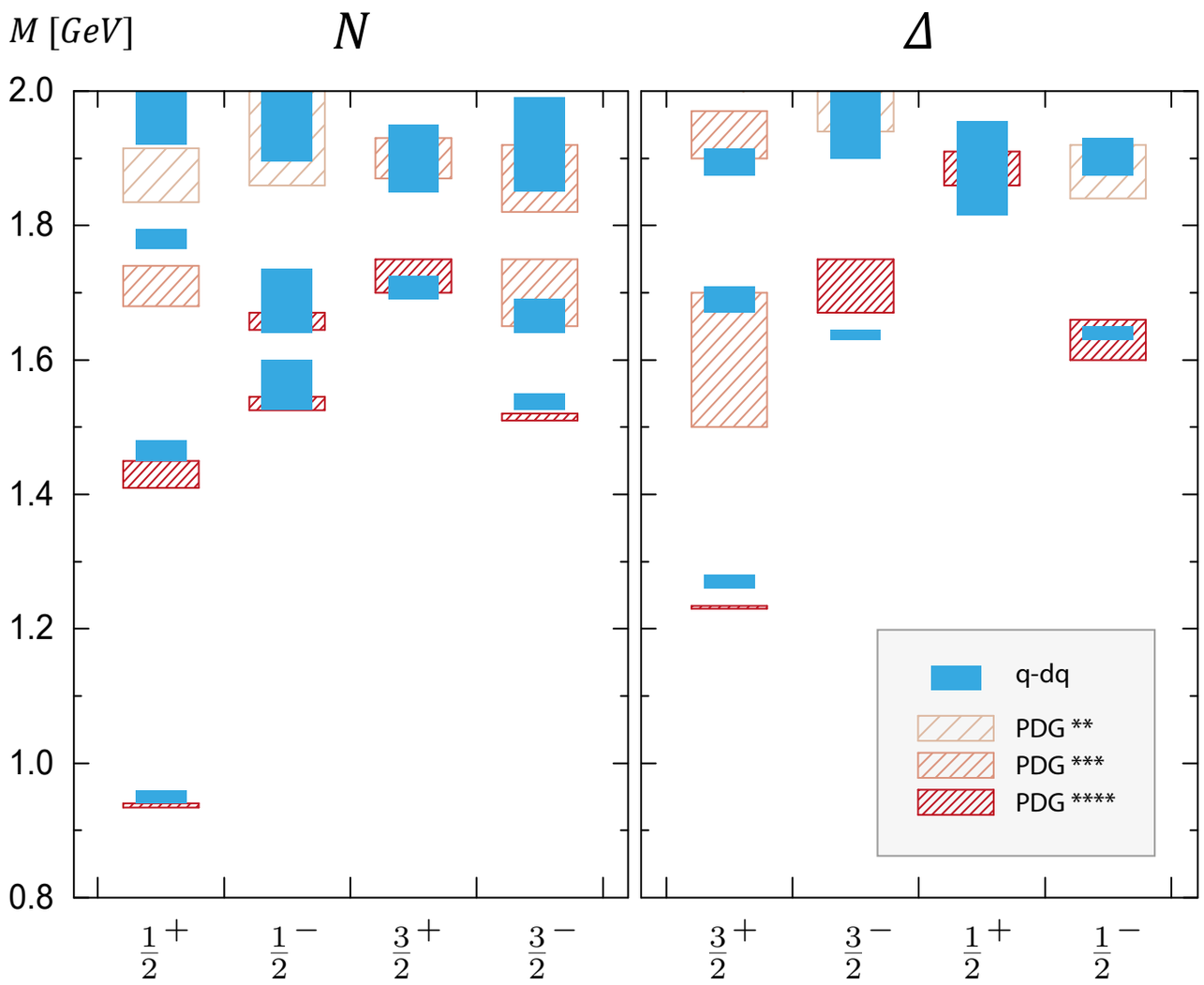
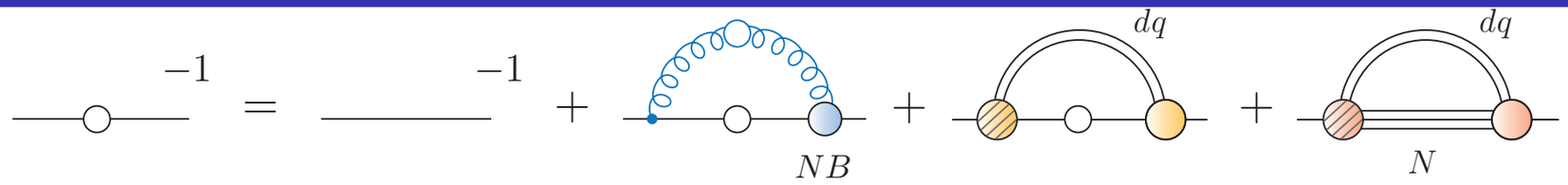


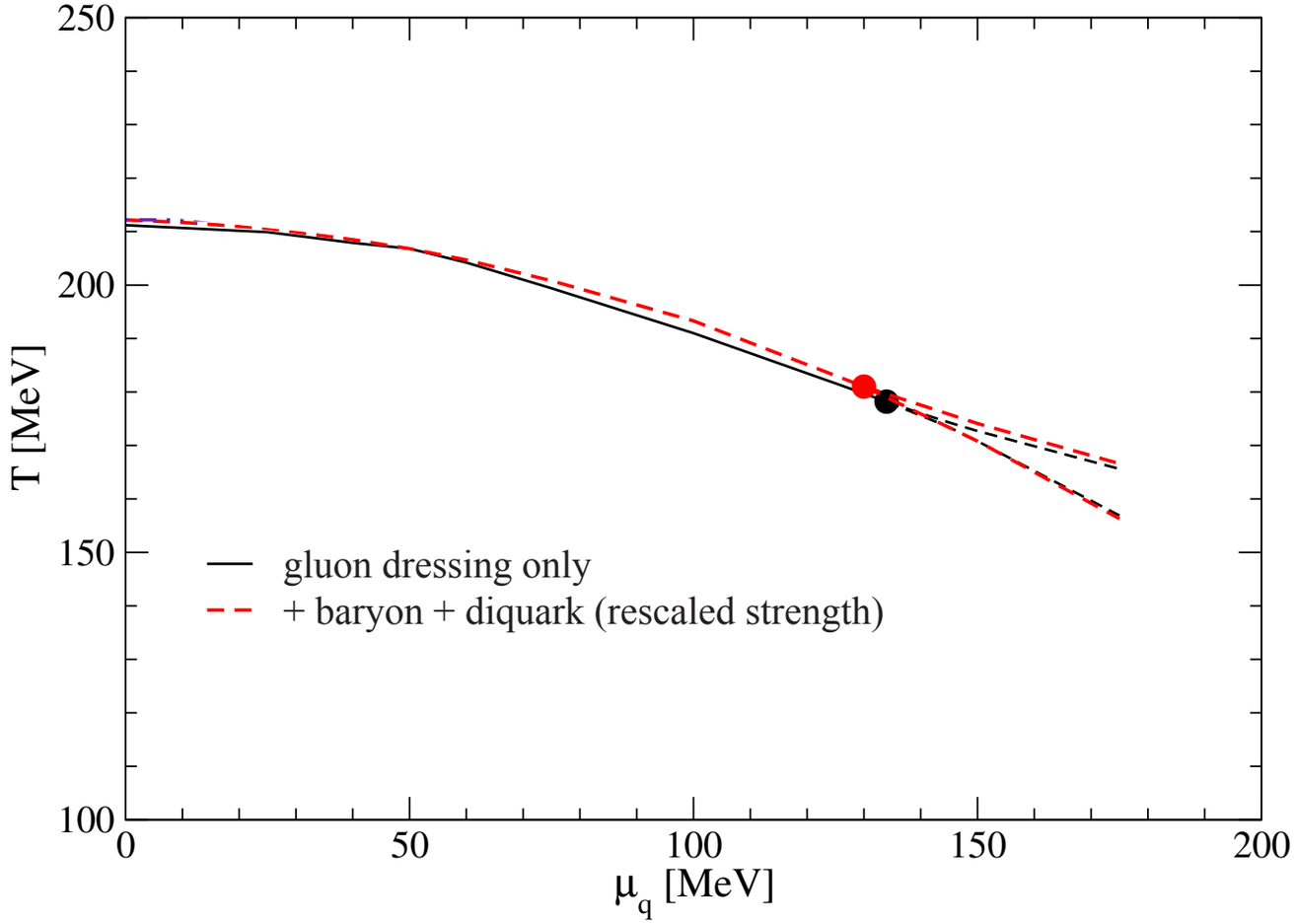


Eichmann, CF, Sanchis-Alepuz, 1607.05748
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP in press [1606.09602]

- Three-body and diquark-quark approach agree
- Spectrum in one-to-one agreement with experiment

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

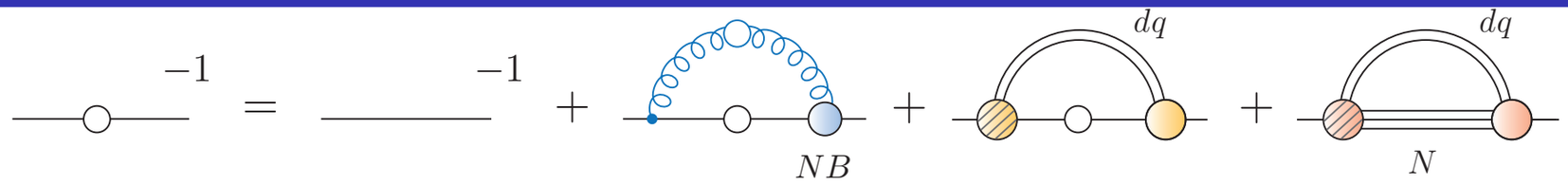


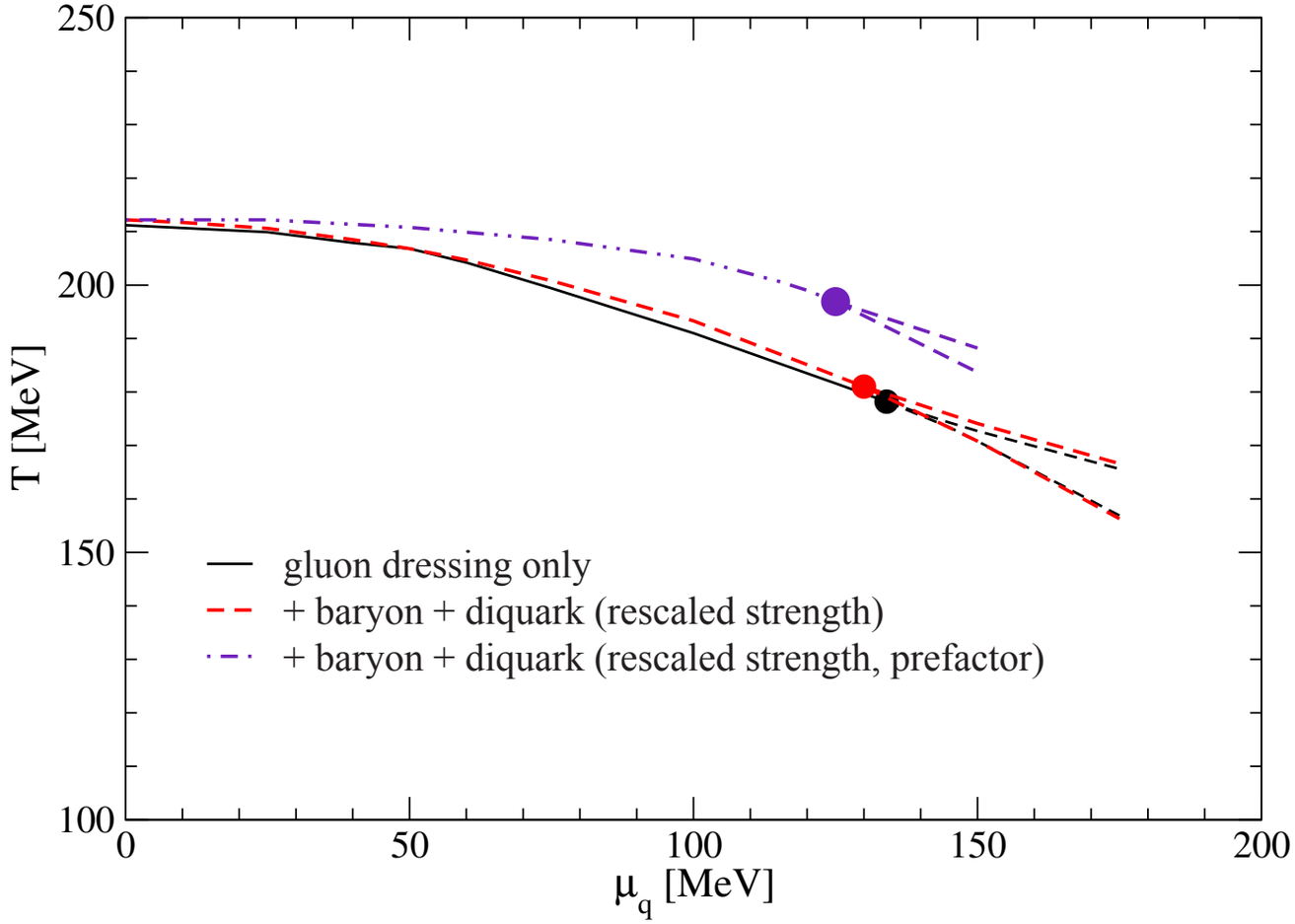


- Zero chemical potential: no effects after rescaling
- CEP: almost no effects

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

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





- Zero chemical potential: no effects after rescaling
- CEP: almost no effects
- But: strong μ-dependence of baryon wave function may change situation…

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

Summary

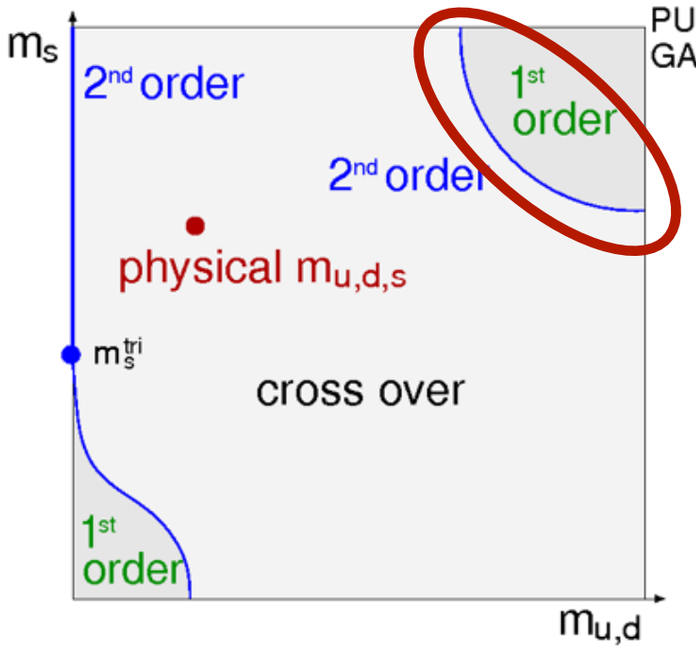
QCD with finite chemical potential:

- 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…

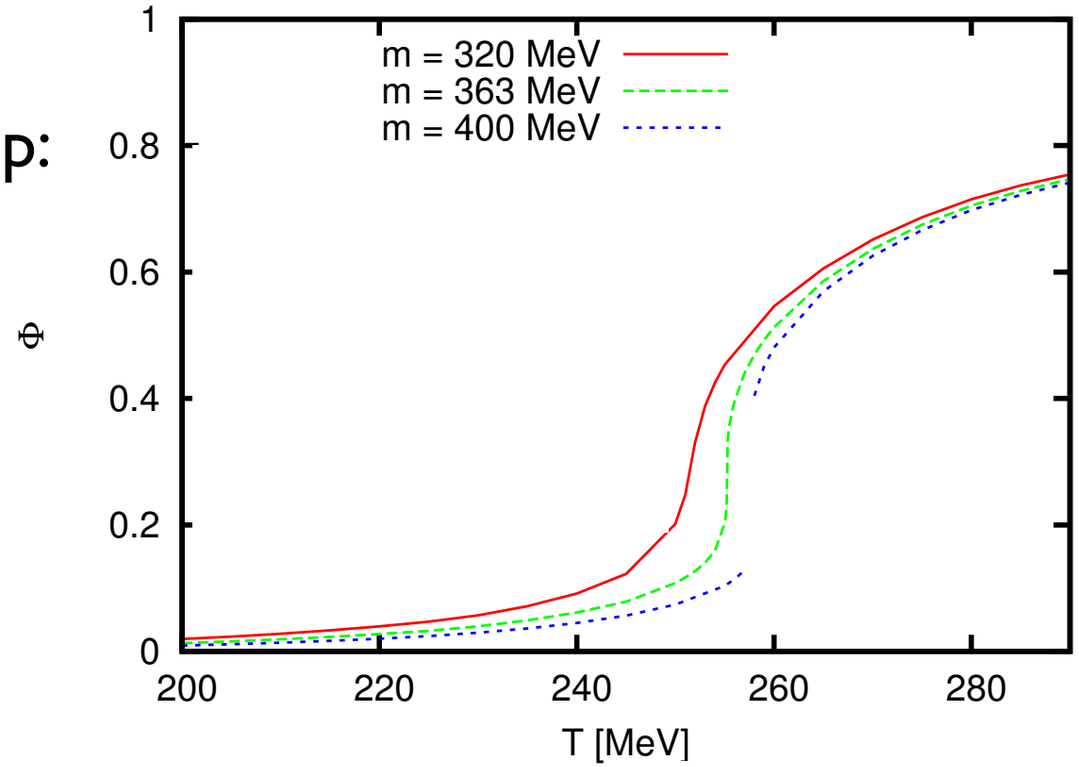
Work in progress: - mesons and baryons at finite T and μ
- volume effects of CEP from DSEs

Backup

Critical line/surface for heavy quarks

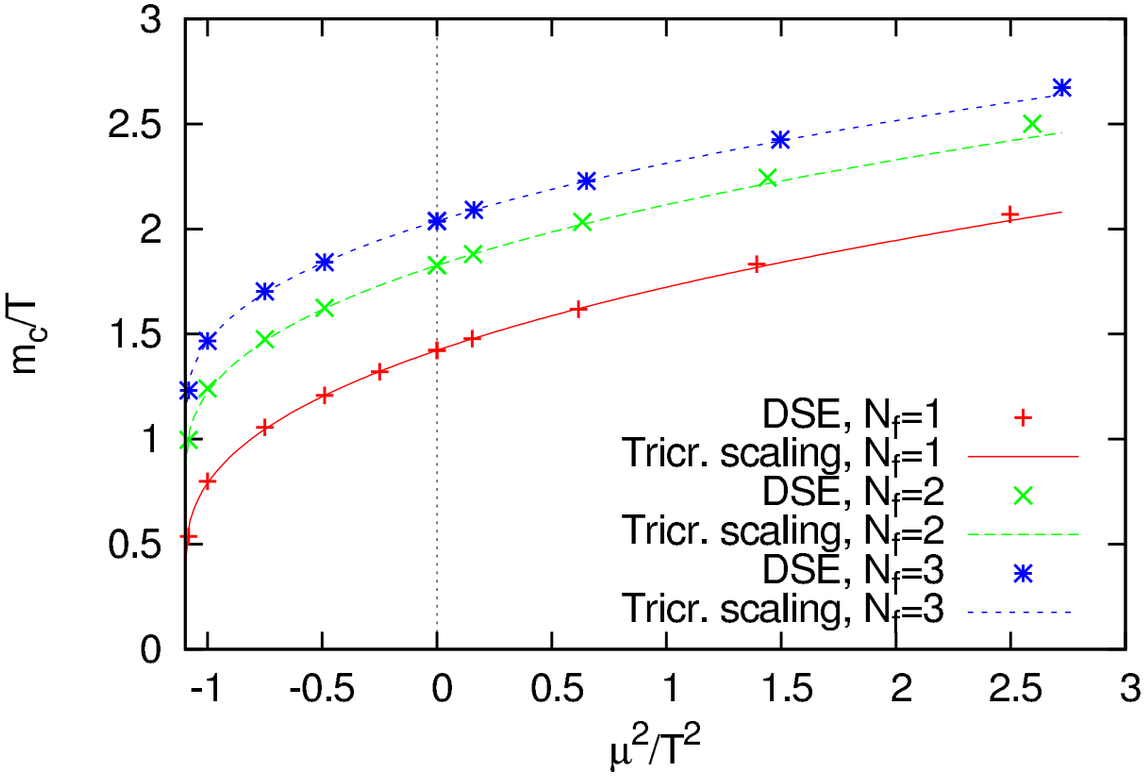


Polyakov Loop:



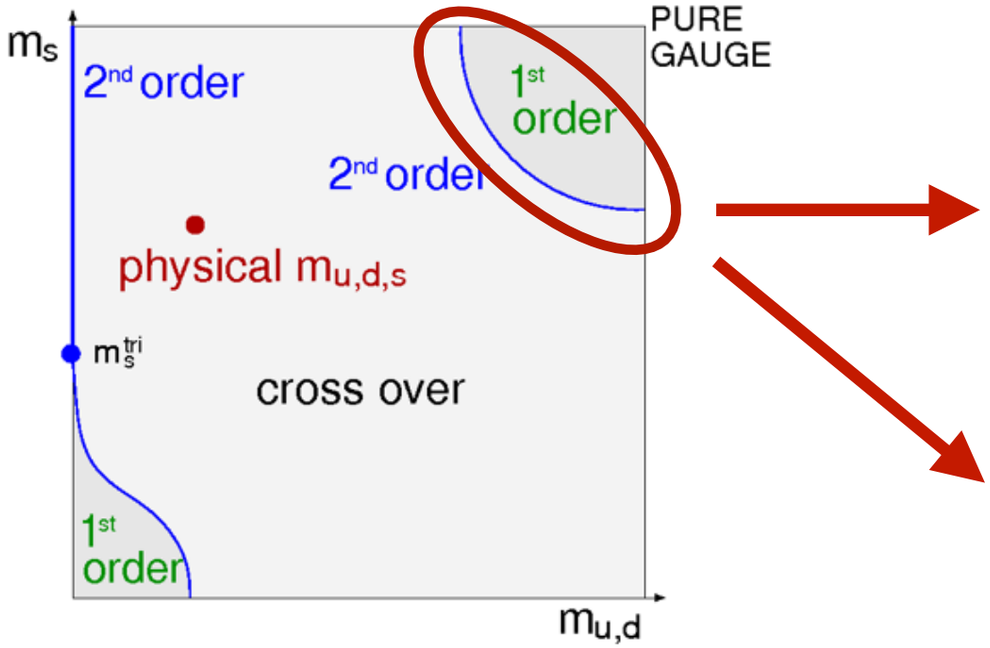
- Deconfinement transition in agreement with lattice QCD
- Correct tricritical scaling

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



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

Critical line/surface for heavy quarks



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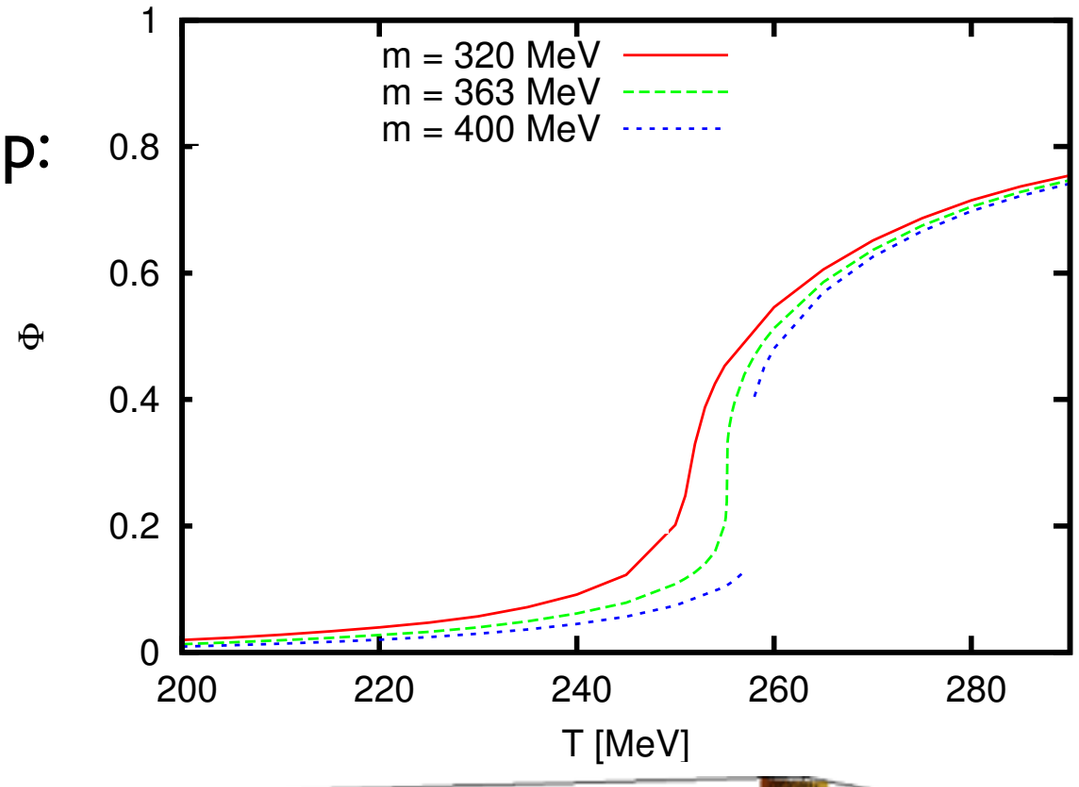

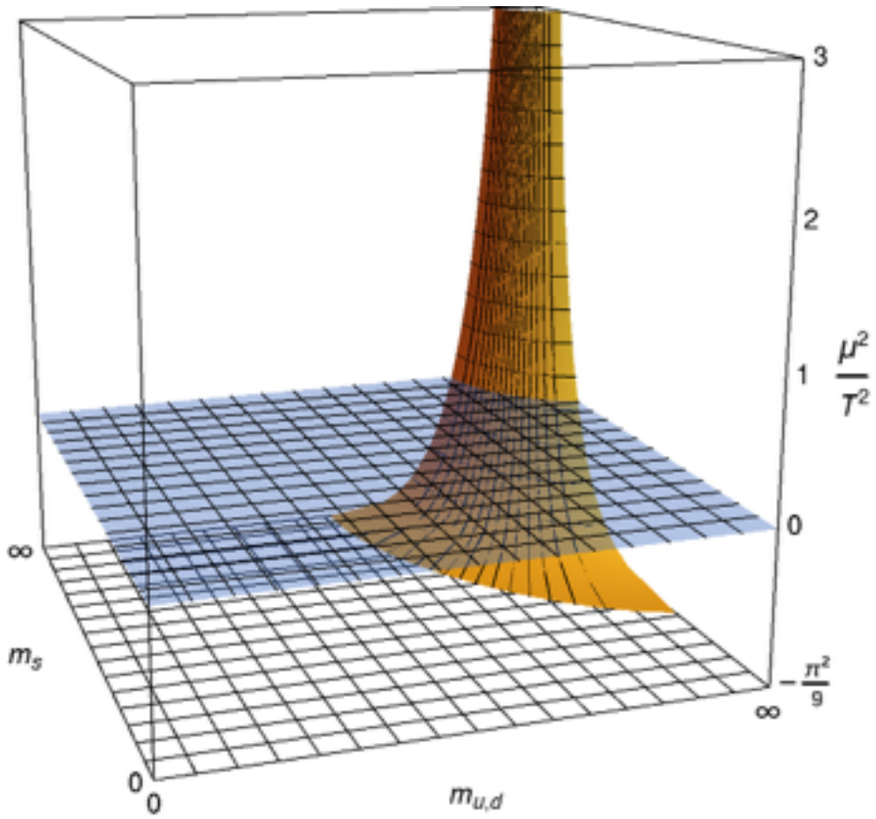

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Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

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

Approximation for Quark-Gluon interaction

- T,μ,m-dependent vertex:

Abelian WTI

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

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

Text

perturbation theory

Infrared ansatz:

- d2 fixed to match gluon input
- d1 fixed via quark condensate (see later)
- correct UV (quant.) and IR-behavior (qual.)

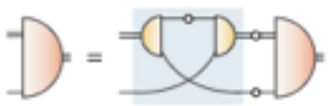
CF, Pawlowski, PRD 80 (2009) 025023
Mitter, Pawlowski and Strodthoff, PRD 91 (2015) 054035
Williams, Fischer, Heupel, PRD 93 (2016) 034026

DSE/Faddeev landscape (T=μ=0)

	Quark-diquark			Three-quark		
	Contact interaction	QCD-based model	DSE (RL)	RL	bRL	bRL + 3q
N, Δ masses	√	√	√	√	√	...
N, Δ em. FFs	√	√	√	√		
$N \to \Delta\gamma$	√	√	√	...		
Roper	√	√		...		
$N \to N^*\gamma$	√	√		...		
$N^*(1535), \ldots$	...	...		...	...	
$N \to N^*\gamma$	...	...				
	Roberts et al	Oettel, Alkofer Roberts, Bloch Segovia et al.	Eichmann, Alkofer Nicmorus, Krassnigg	Eichmann, Alkofer Sanchis-Alepuz, CF	Sanchis-Alepuz, CF Williams	

Eichmann, N*-Workshop, Trento 2015

DSE/Faddeev landscape (T=μ=0)

	Contact interaction	QCD-based model	DSE (RL)	RL	bRL	bRL + 3q
		Quark-diquark 		Three-quark 		
N, Δ					√	...
N, Δ						
$N \to$						
Roper						
$N \to$						
$N^*(1535), \ldots$	...	...		...	...	
$N \to N^*\gamma$	...	...				
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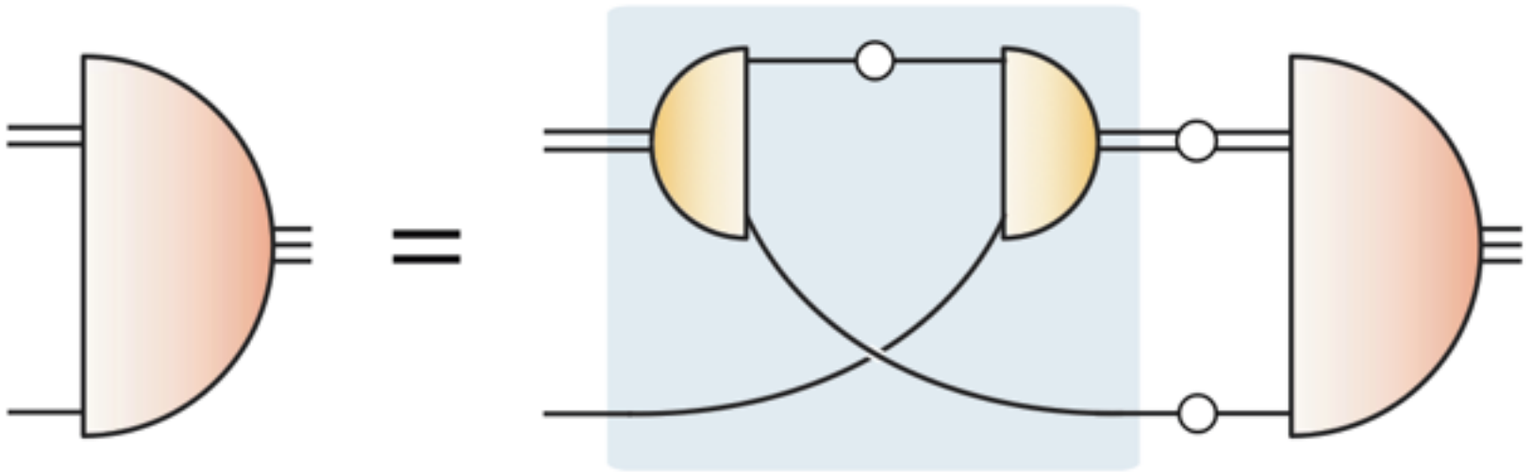

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Roper	√	√		...		
$N \to N^*\gamma$	√	√		...		
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