Locating QCD's critical end point

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HIC for FAIR
Helmholtz International Center

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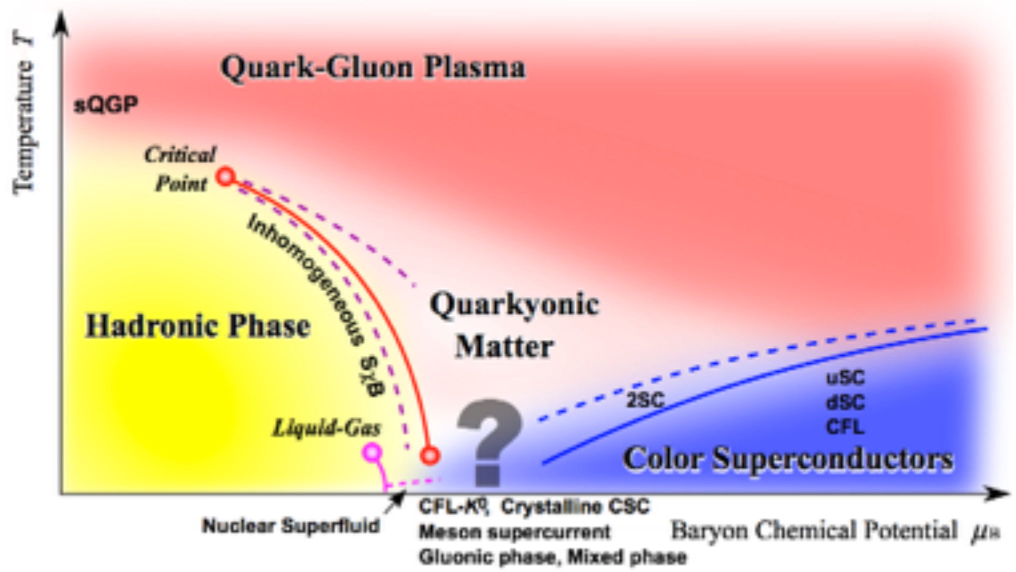
HELMHOLTZ GEMEINSCHAFT

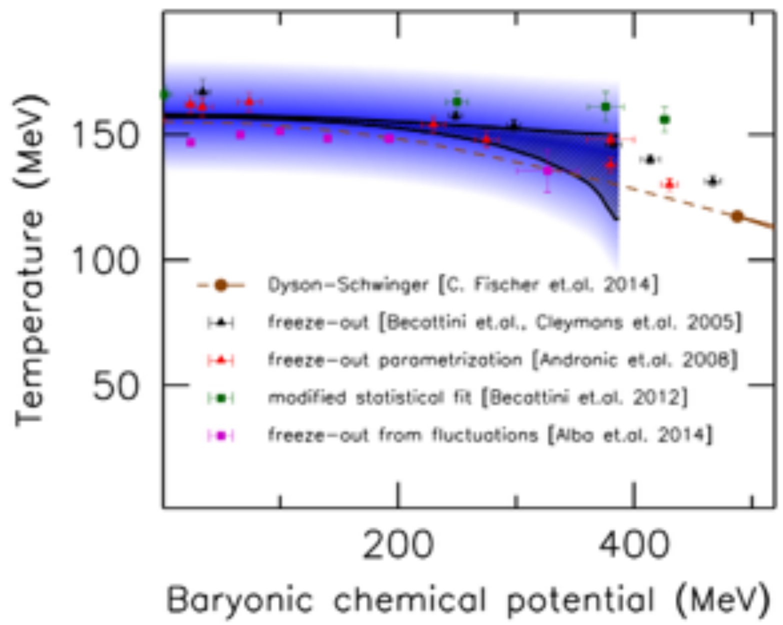
Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP in press [1606.09602]

Overview

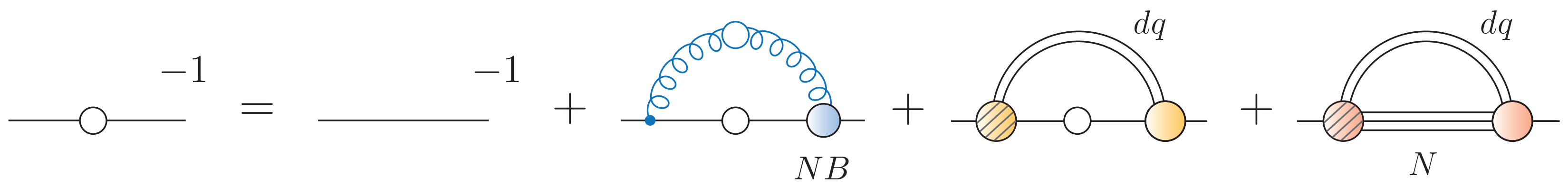
1. Introduction



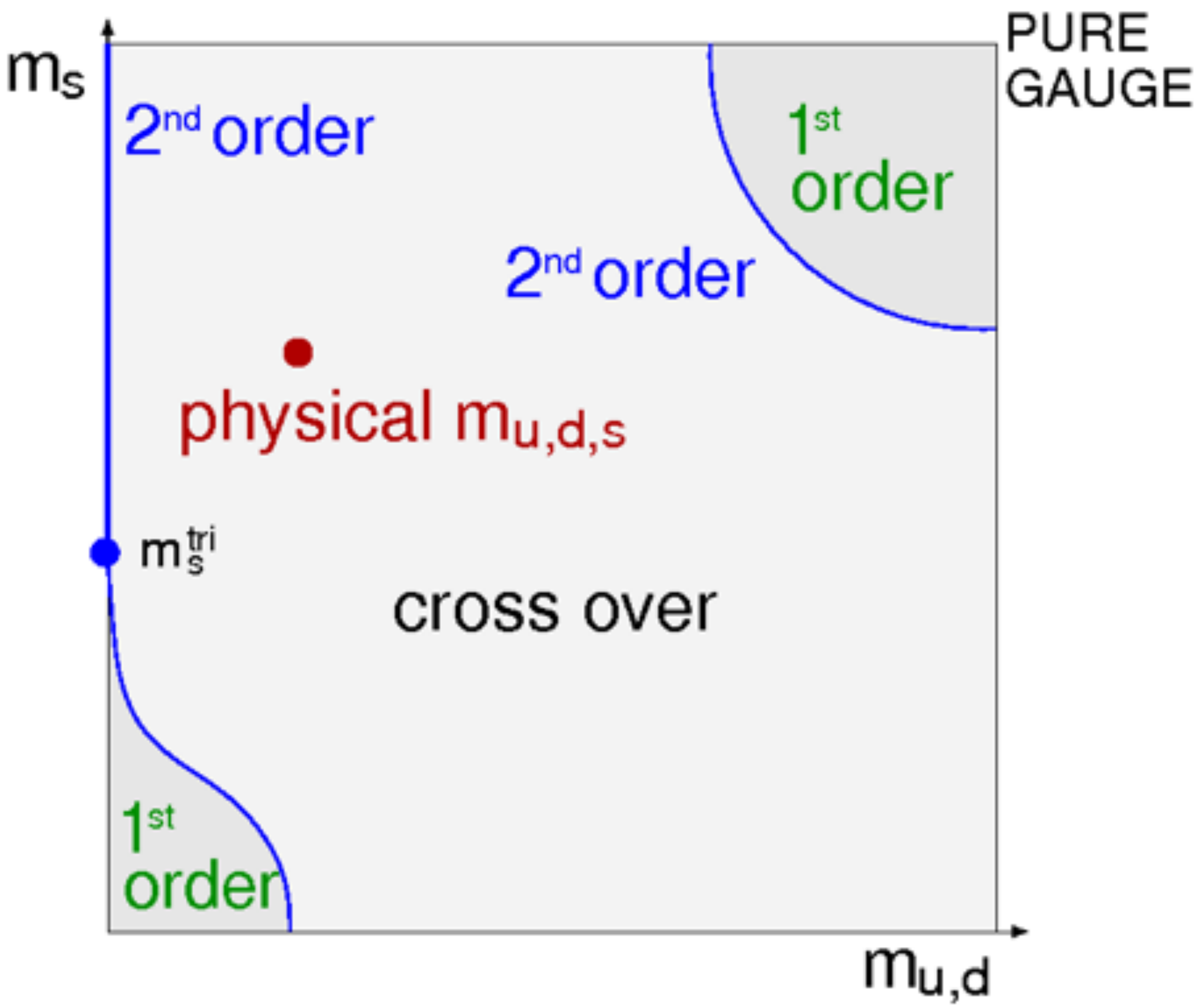
2. Gluons, quarks and the CEP



3. Baryon effects on the CEP



QCD phase transitions



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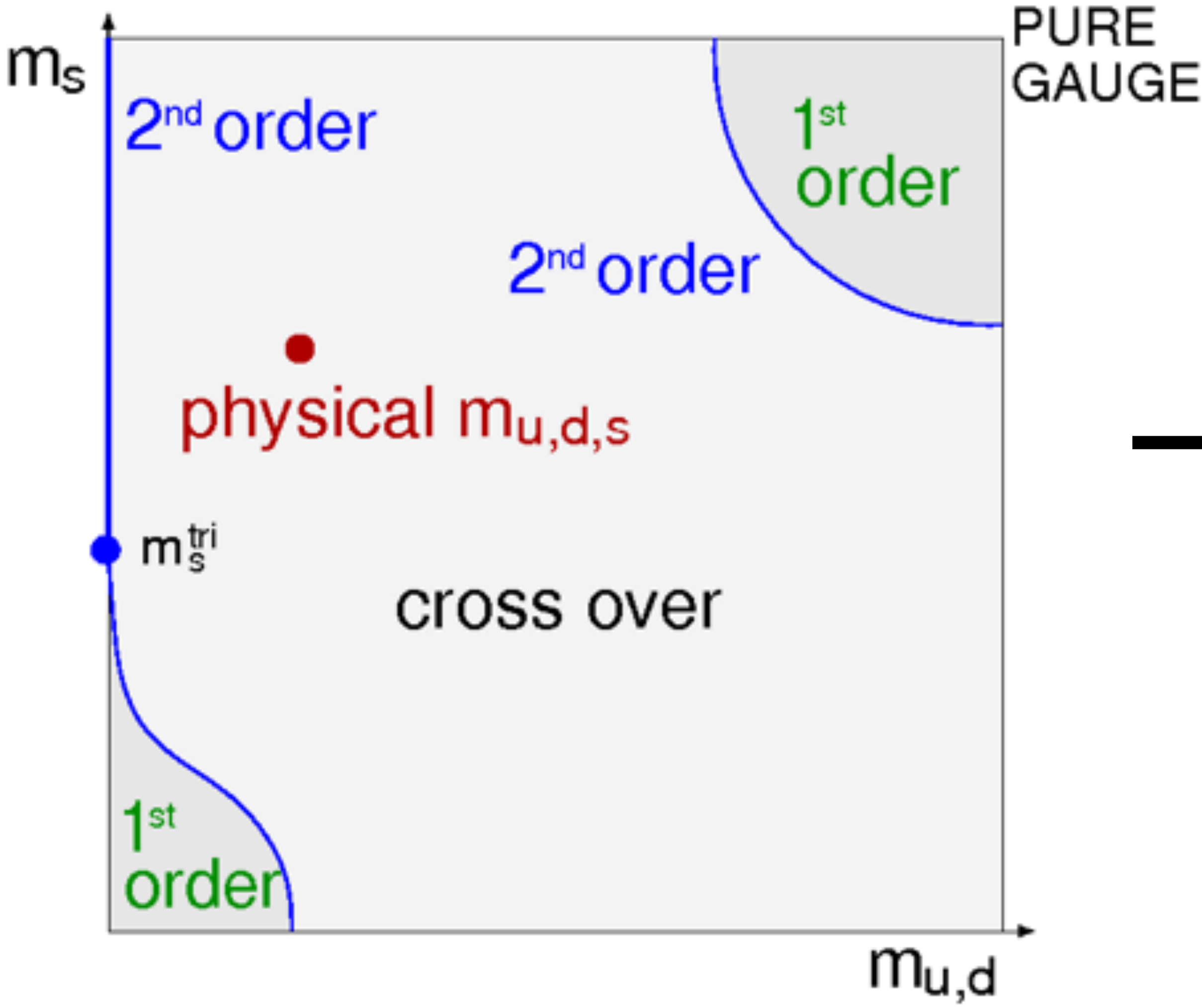
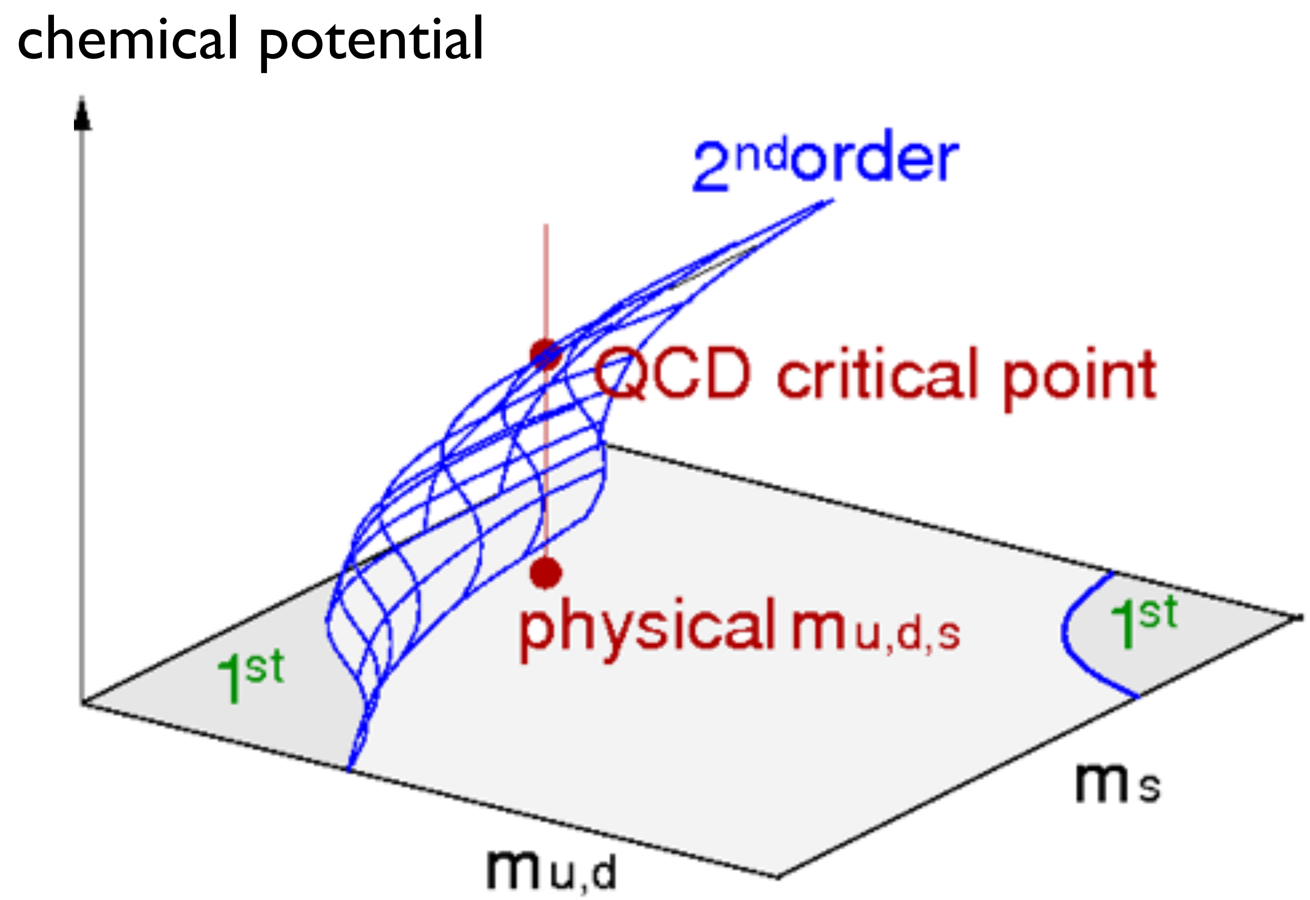
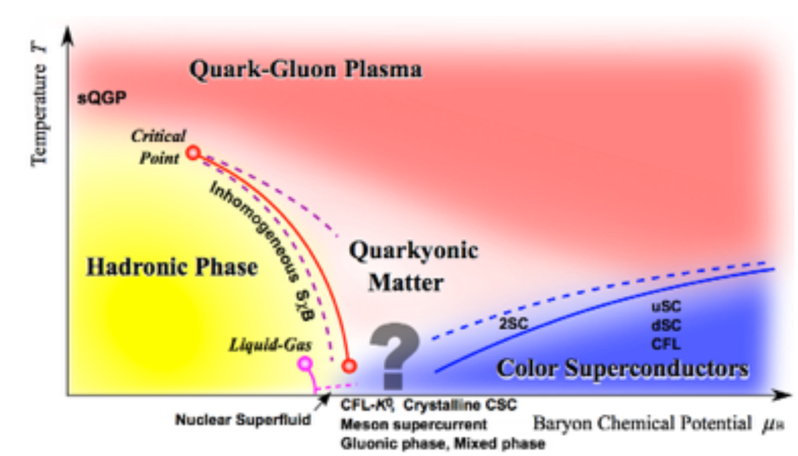
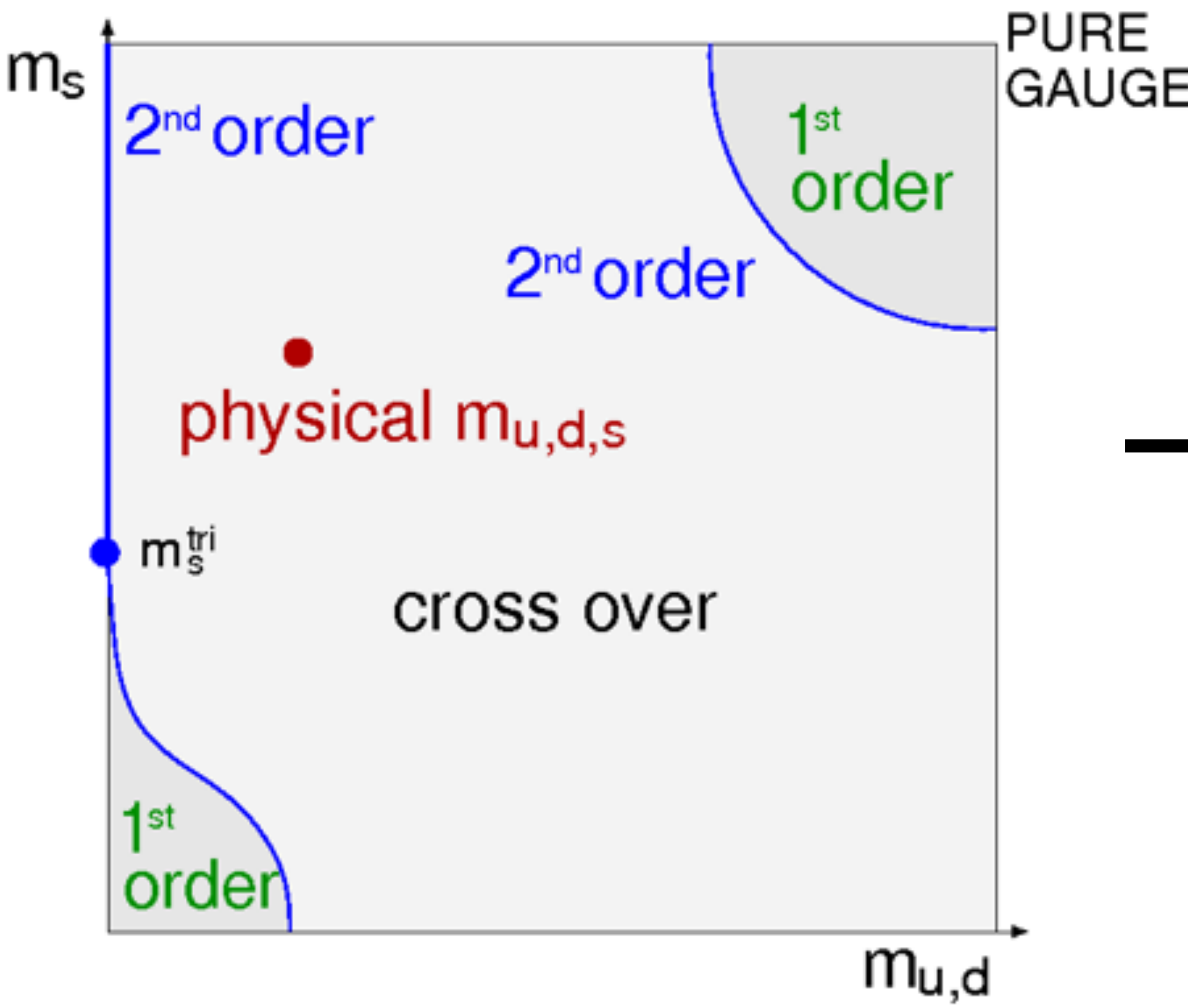


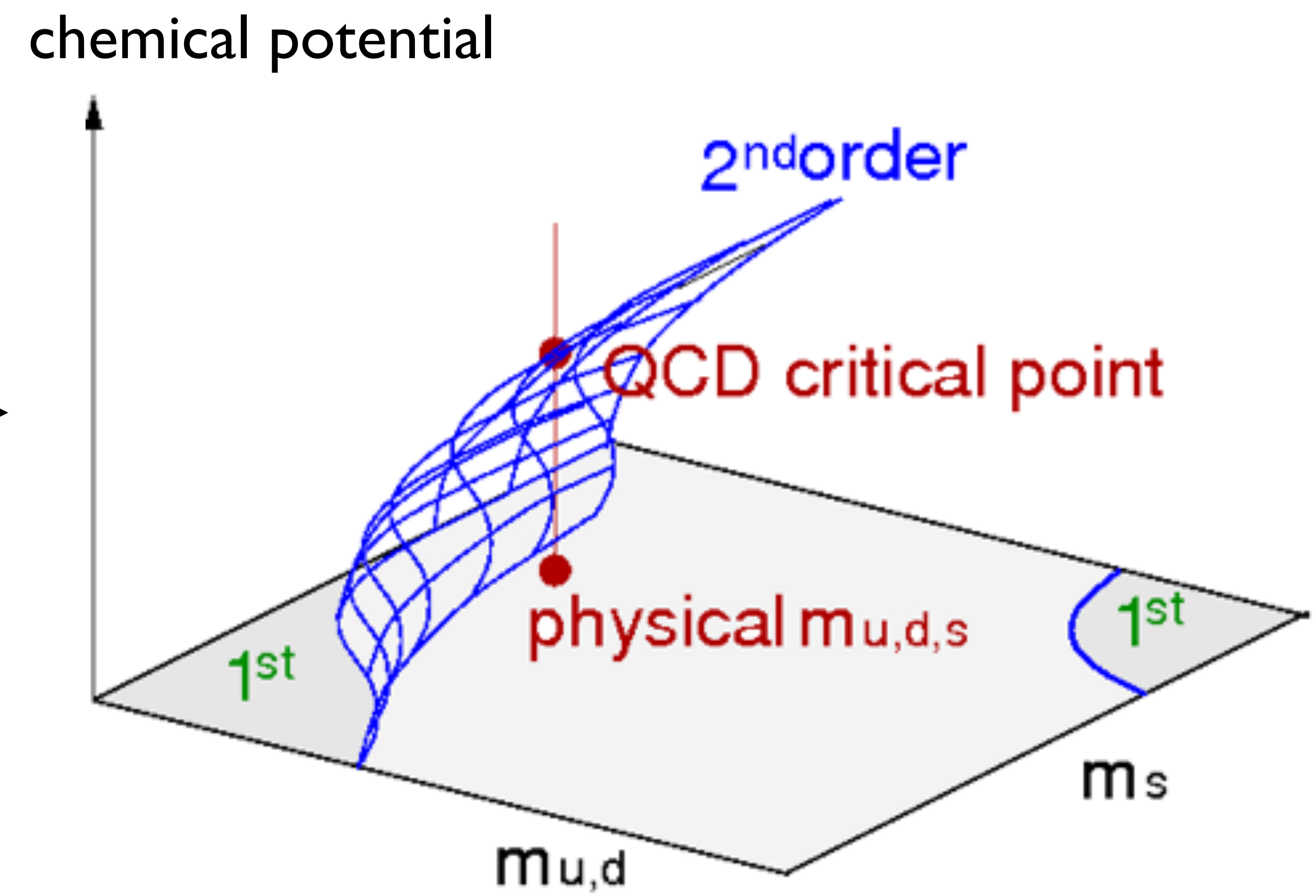


Is this happening ??



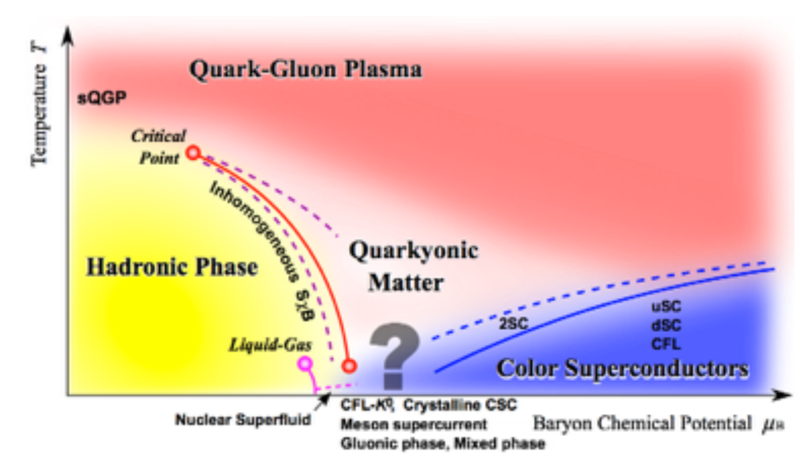
QCD phase transitions





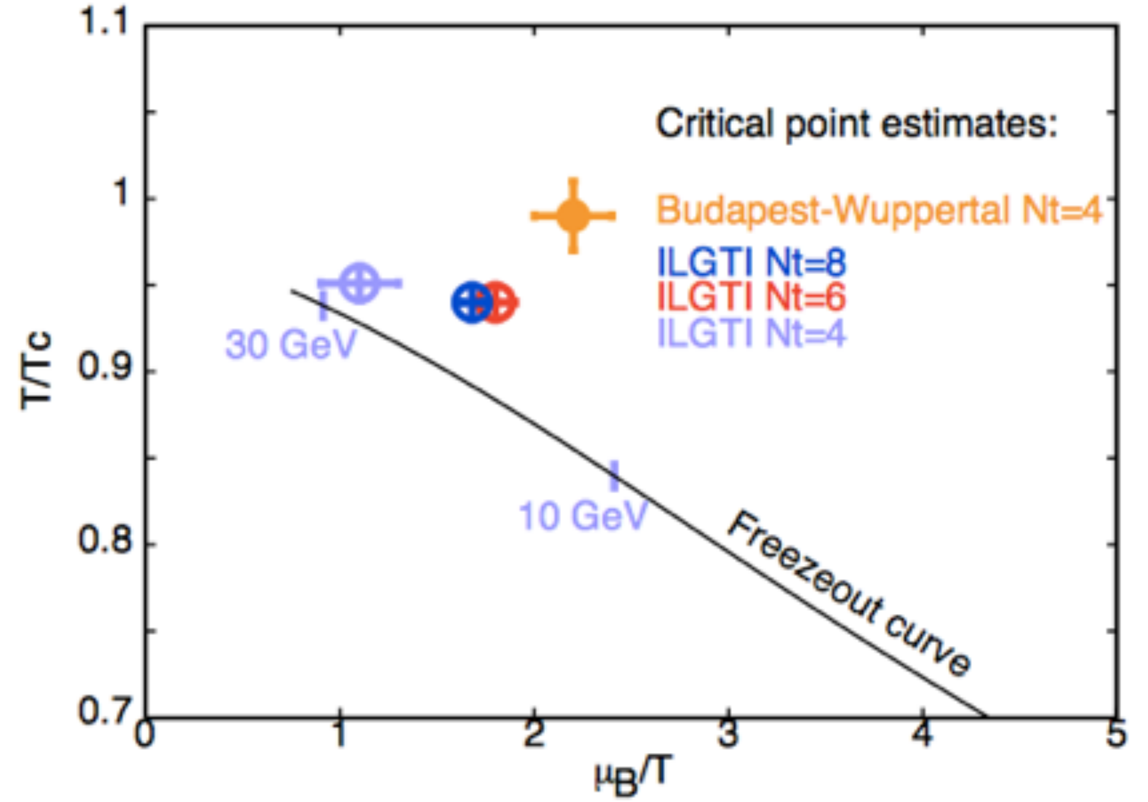
- Lattice-QCD
  - present: extrapolation
  - future: exact methods ?
- DSE/FRG
  - not exact, but allow for ’10%-physics’

Is this happening ??



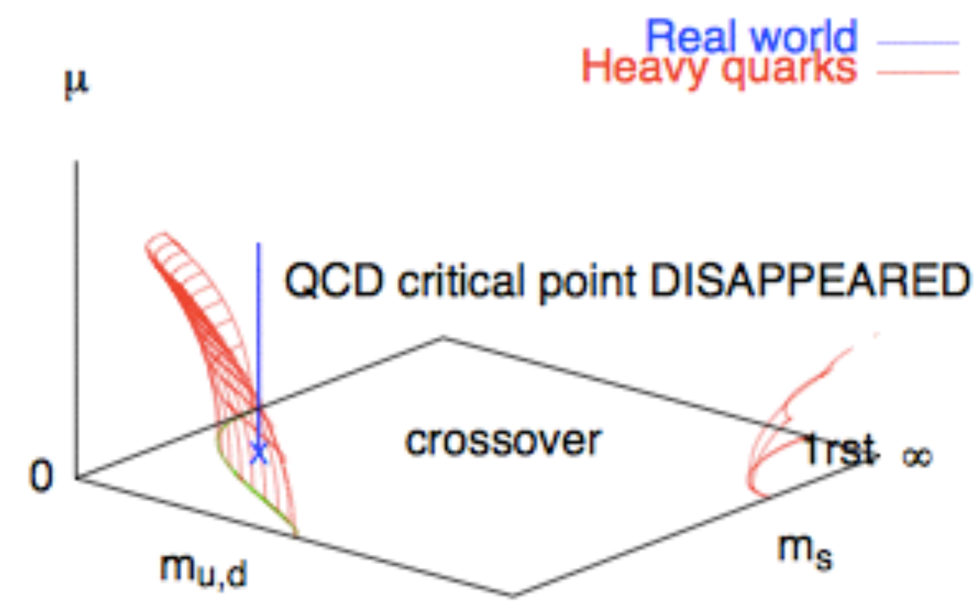
Search for the CEP

- Taylor expansion (N_f=2):
  Datta, Gavai and Gupta, NPA 904-905 (2013) 883c
  Gavai, Gupta, PRD 71 (2005) 114014

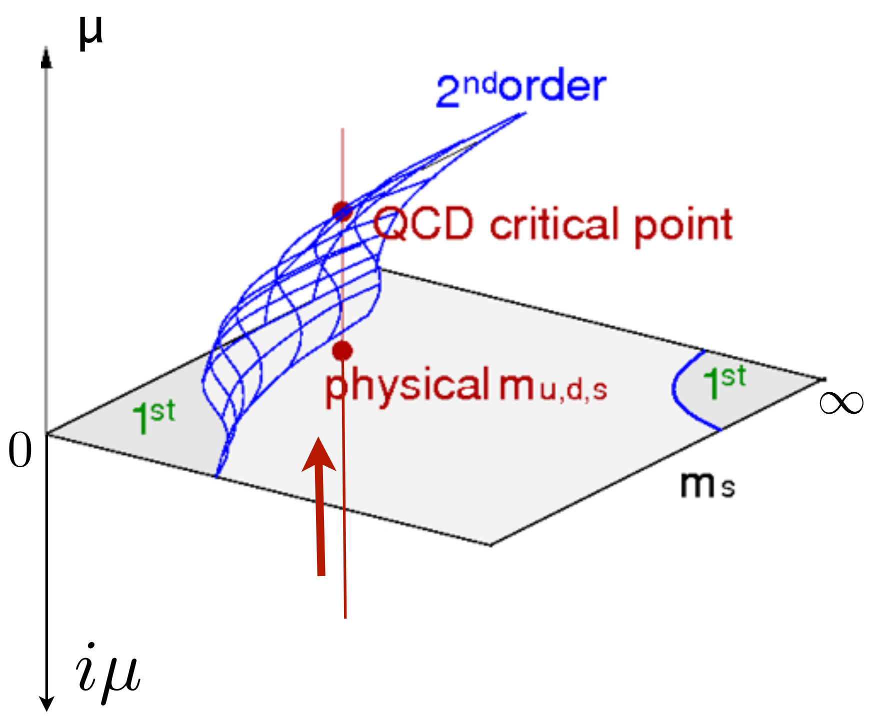


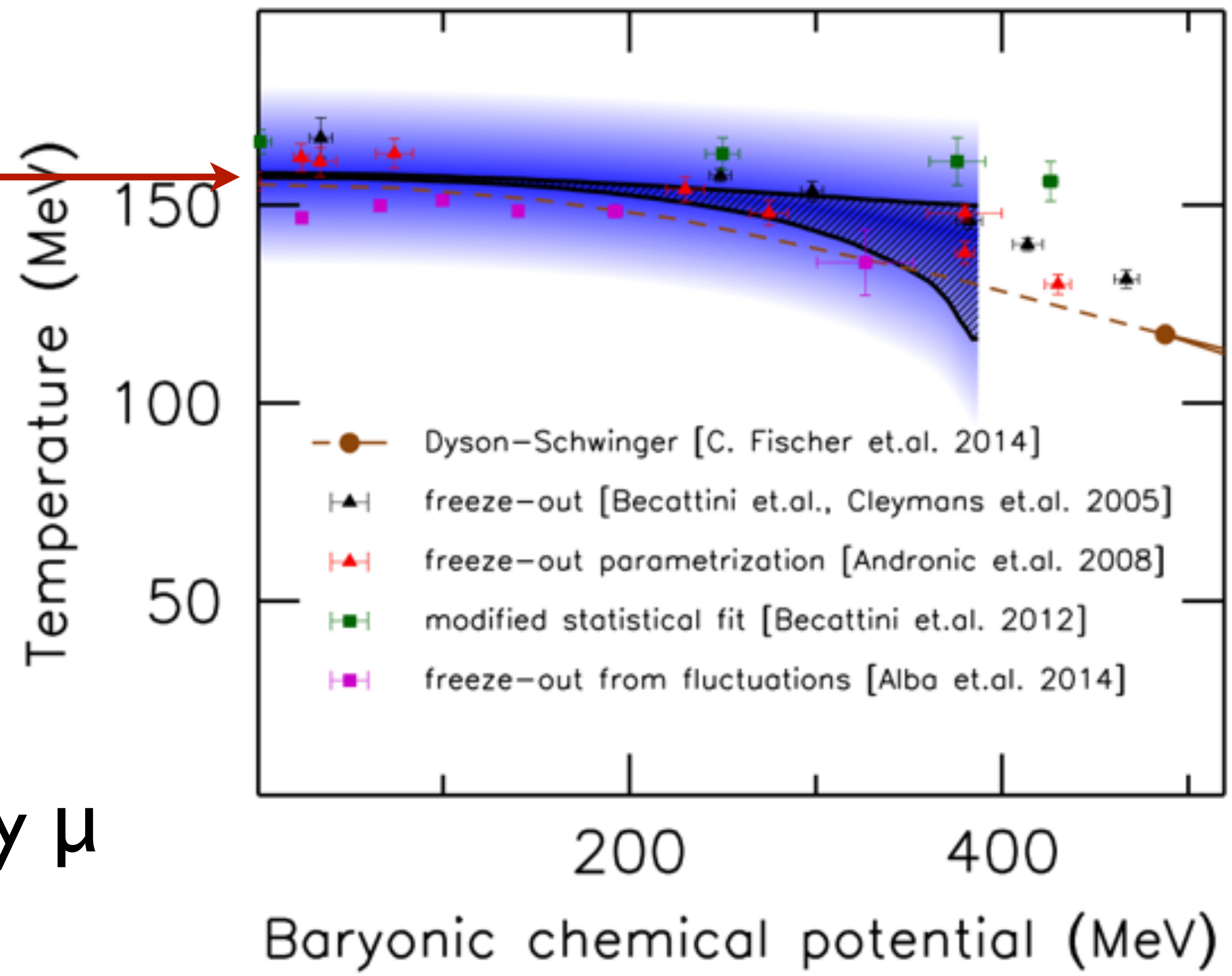
- Reweighting (N_f=2+1):
  Fodor, Katz, JHEP 0404 (2004) 050

- Analytic continuation (N_f=3):
  de Forcrand, Philipsen, JHEP 0811 (2008) 012;
  NPB 642 (2002) 290



Chiral transition line from analytic continuation





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

Lattice method:

- Calc. boundary at imaginary μ and extrapolate to real μ
- Control systematics

Results:

- Larger curvature than previous results (but: different definitions and error budget)

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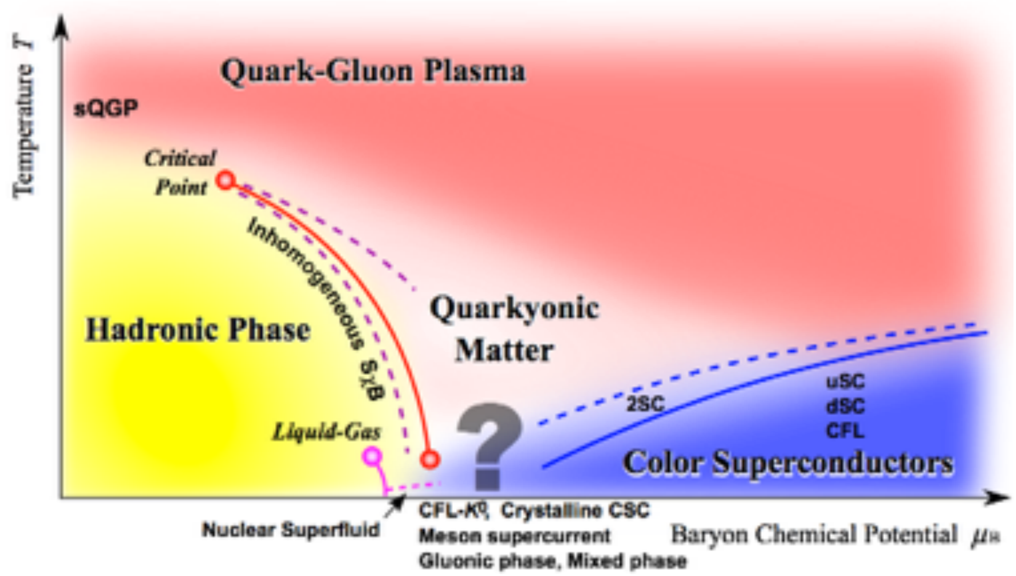

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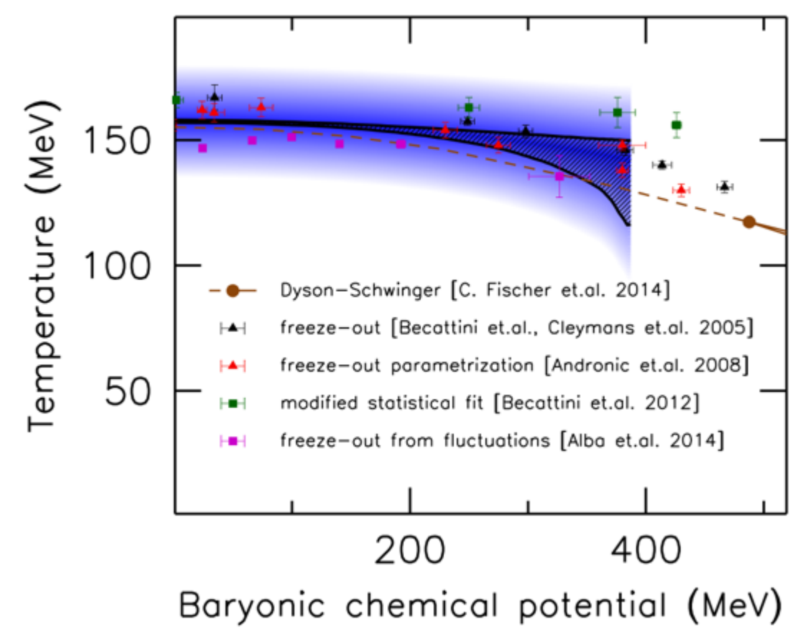

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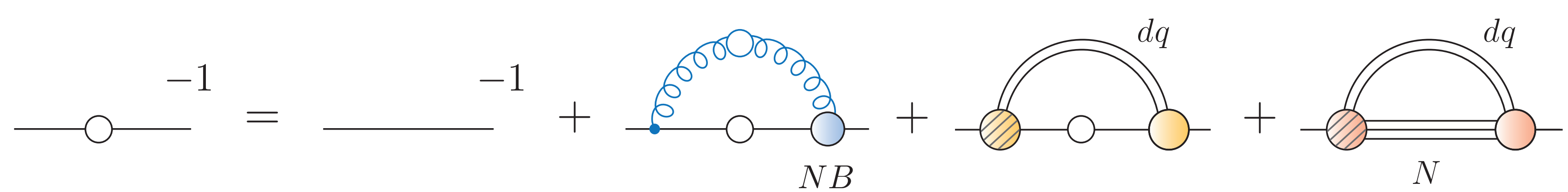
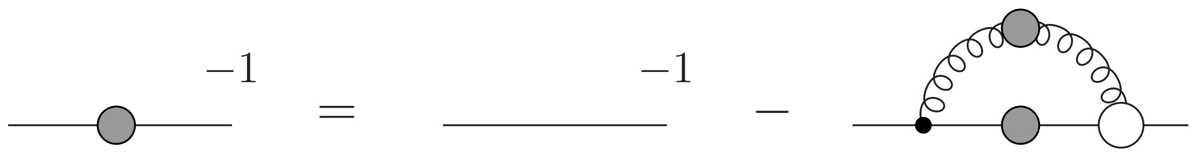




Chiral order parameter:

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

Deconfinement:

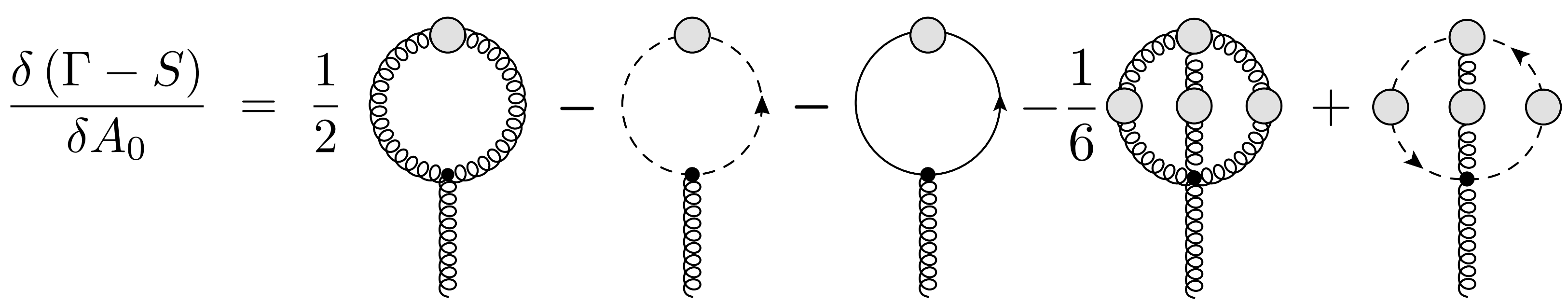
- dressed Polyakov loop

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

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

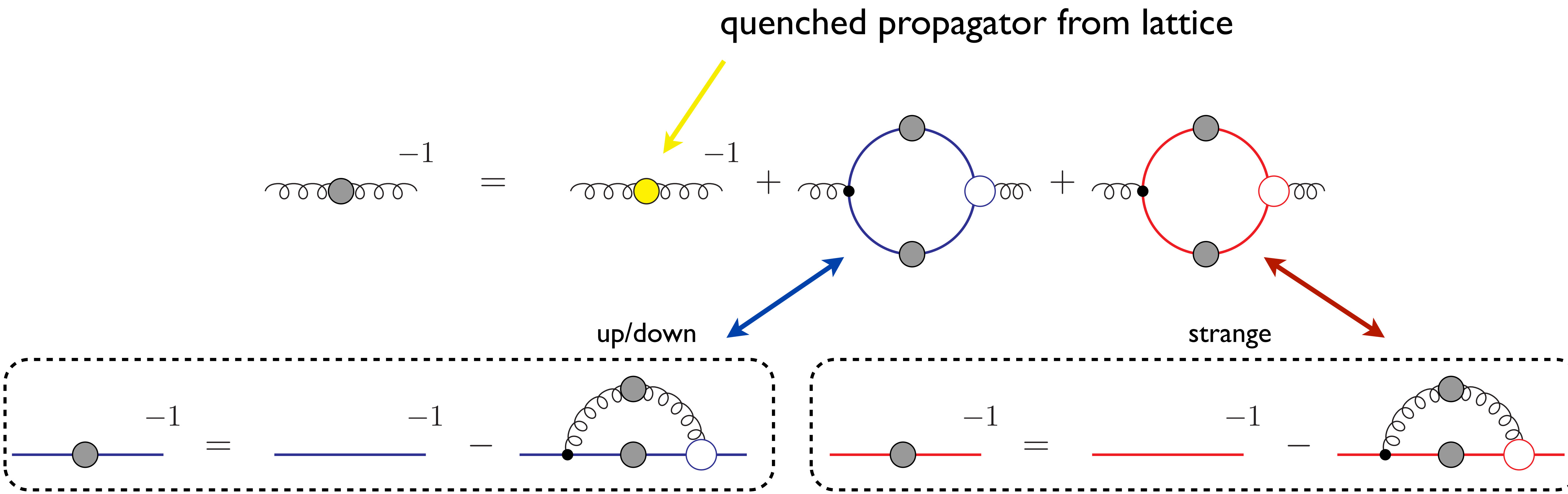
- Polyakov loop potential

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



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)

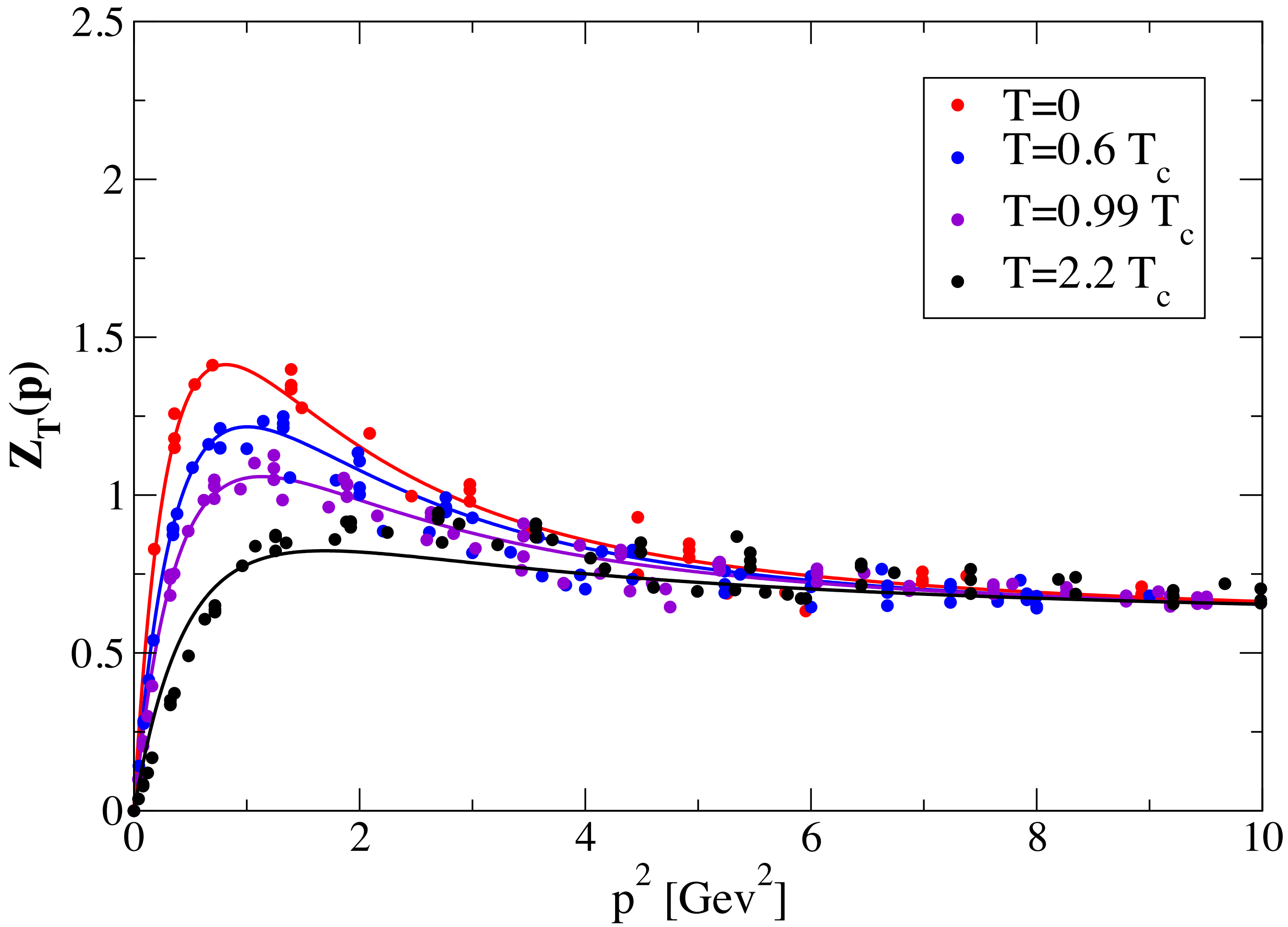
Nf=2+1-QCD with DSEs

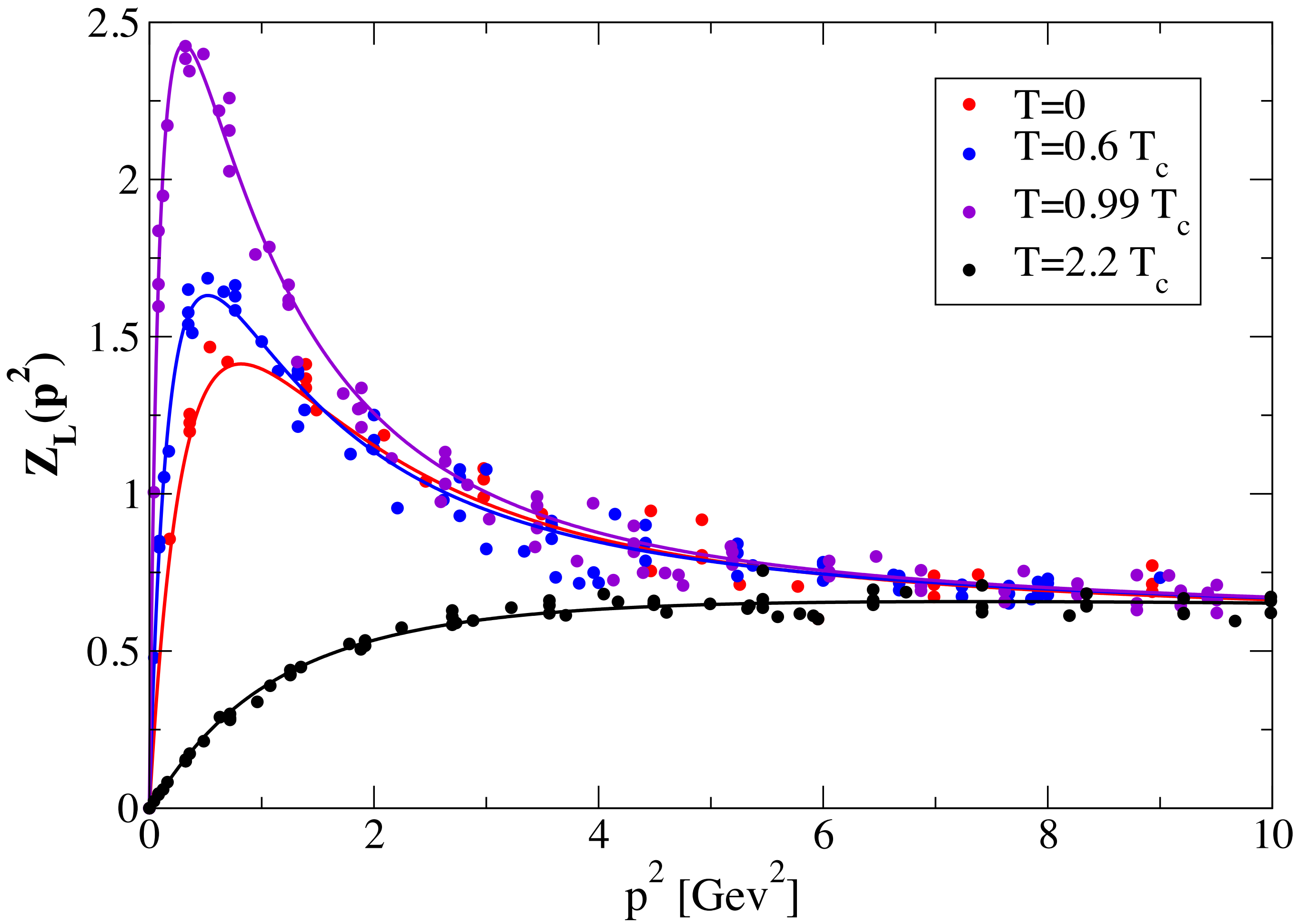


- quenched: without quark-loop
- Nf=2: isospin symmetry
- Nf=2+1: solve coupled system of 2+3+3 equations
- Vertex: ansatz built along STI and known UV/IR behaviour

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

Approximation for Quark-Gluon interaction

- T,μ,m-dependent vertex:

Abelian WTI

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

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

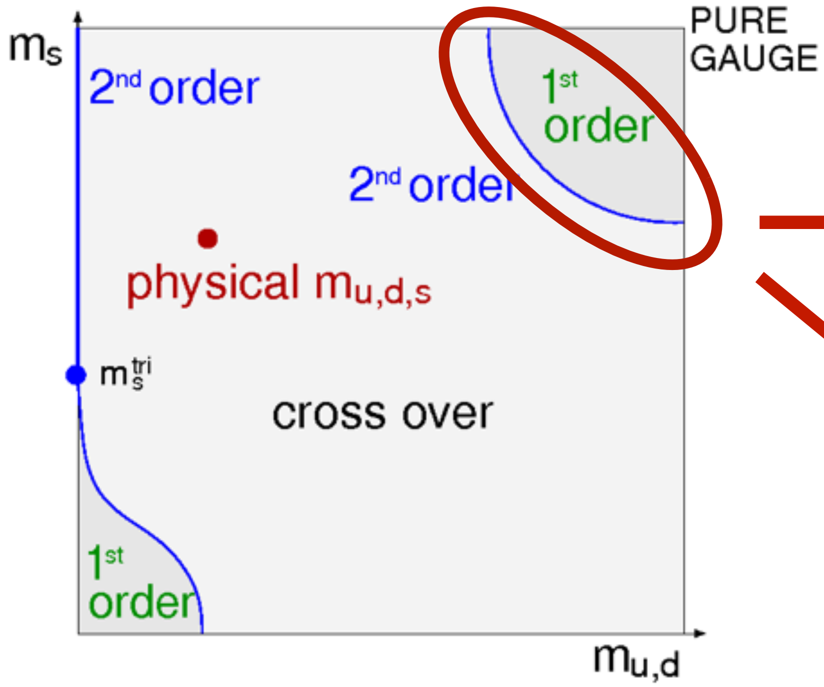
perturbation theory

Infrared ansatz:

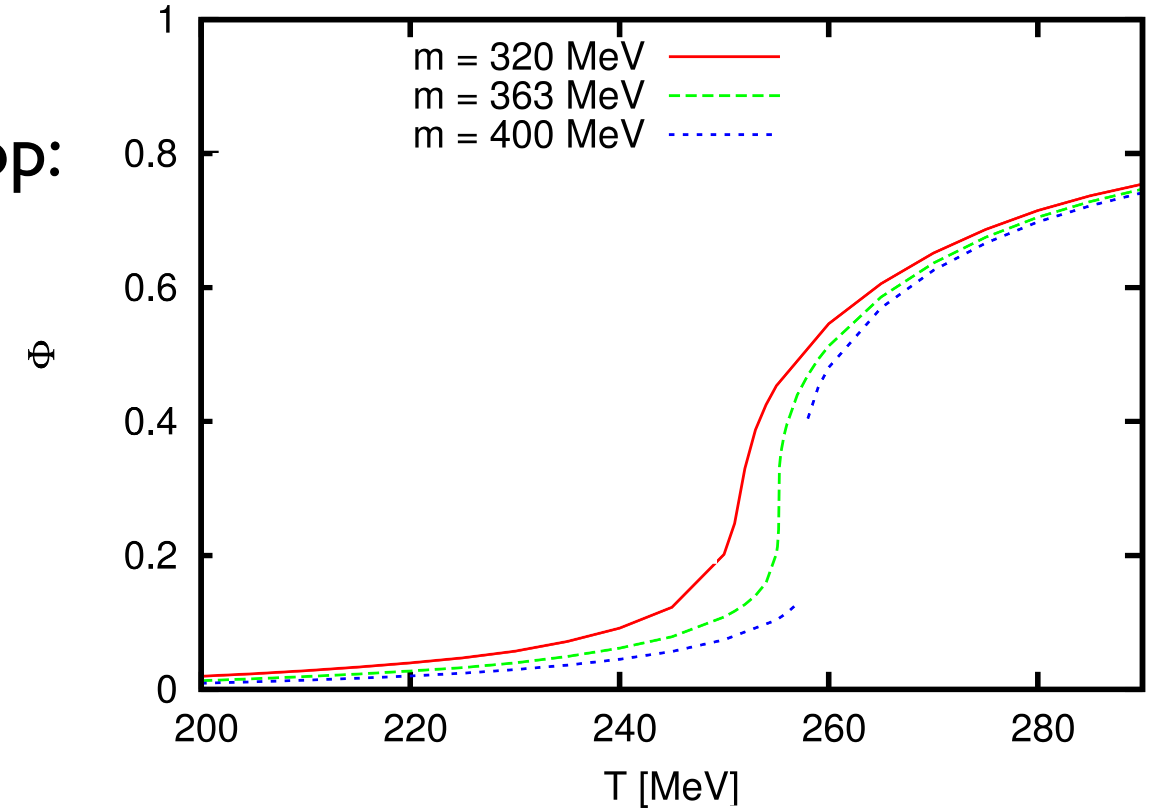
- d2 fixed to match gluon input
- d1 fixed via quark condensate (see later)
- correct UV (quant.) and IR-behavior (qual.)

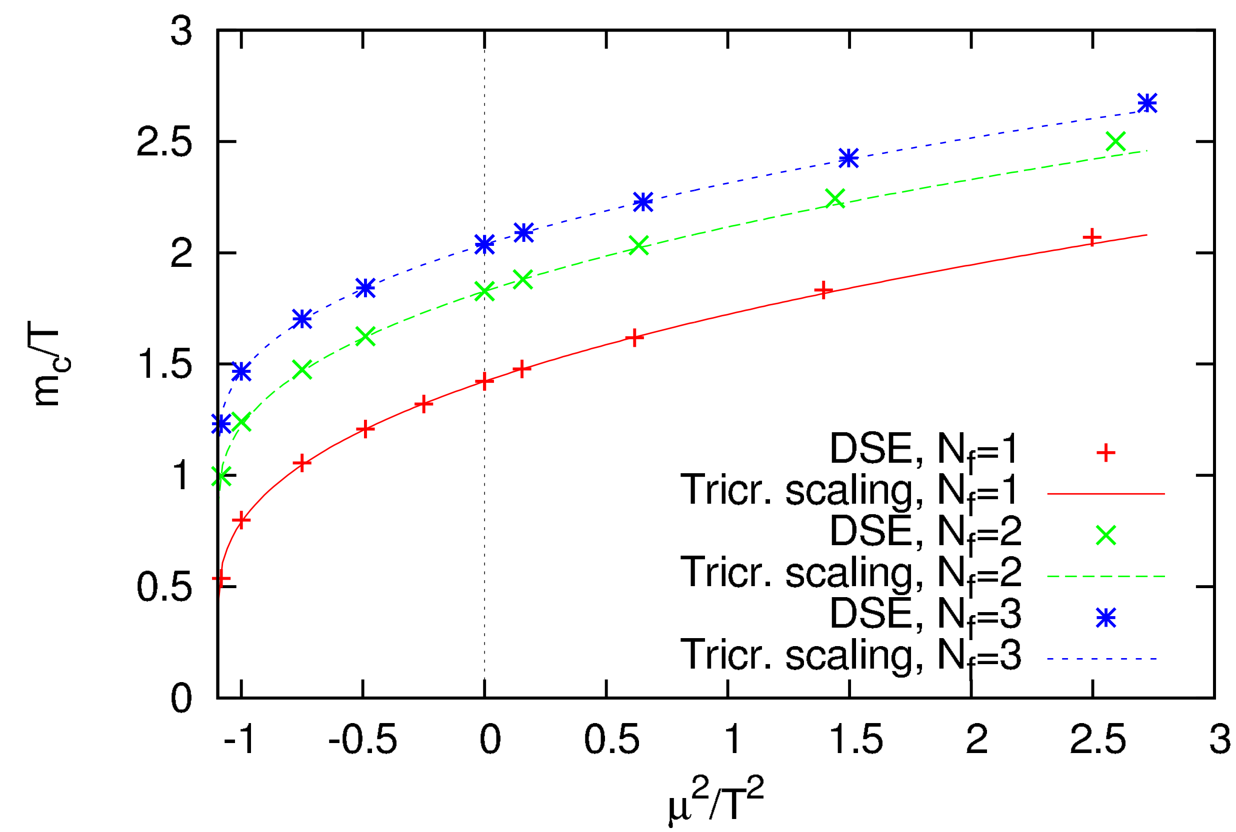
explicit solutions at T=0: Mitter, Pawlowski and Strodthoff, PRD 91 (2015) 054035
Williams, CF, Heupel, PRD PRD 93 (2016) 034026

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

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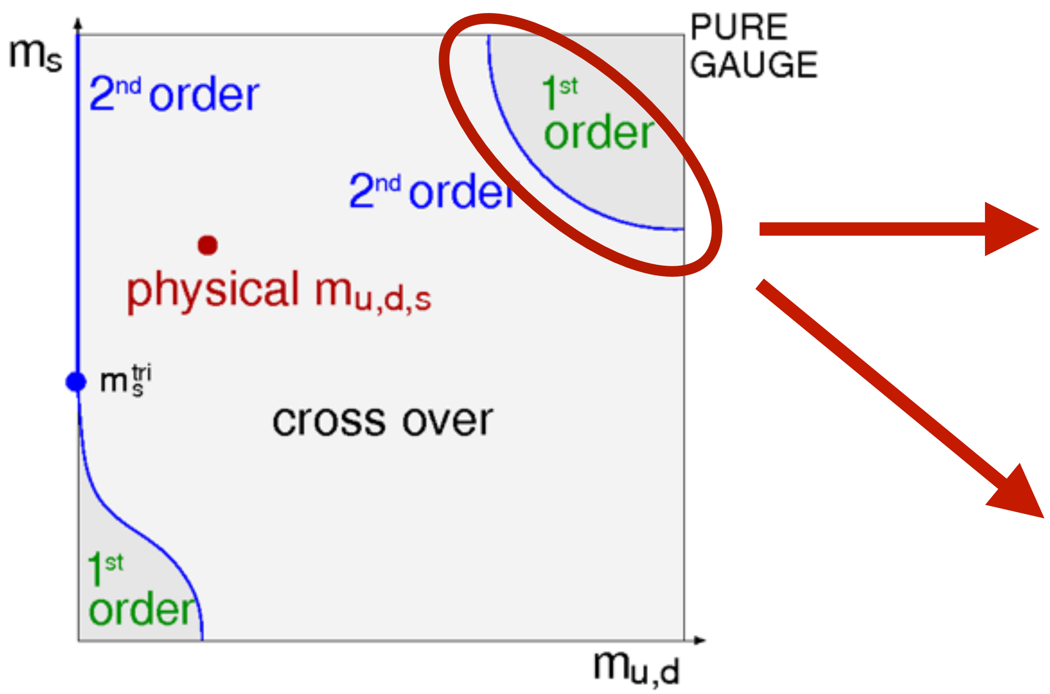

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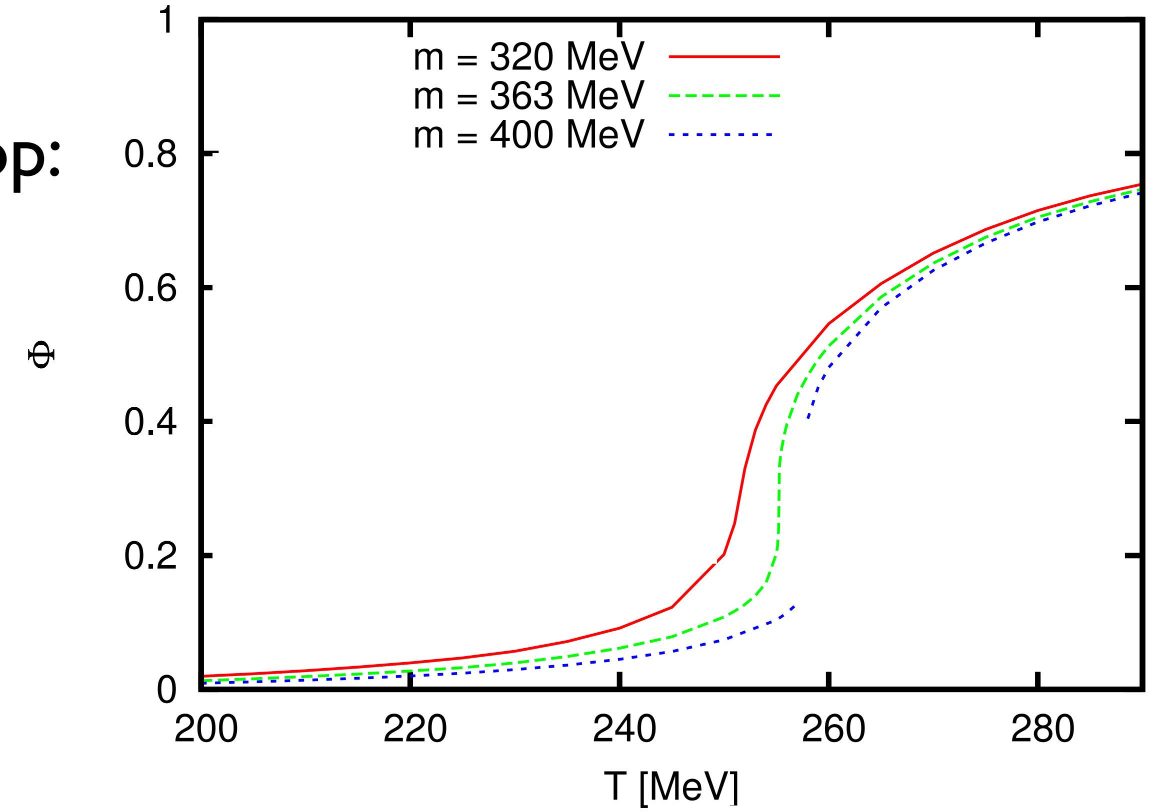

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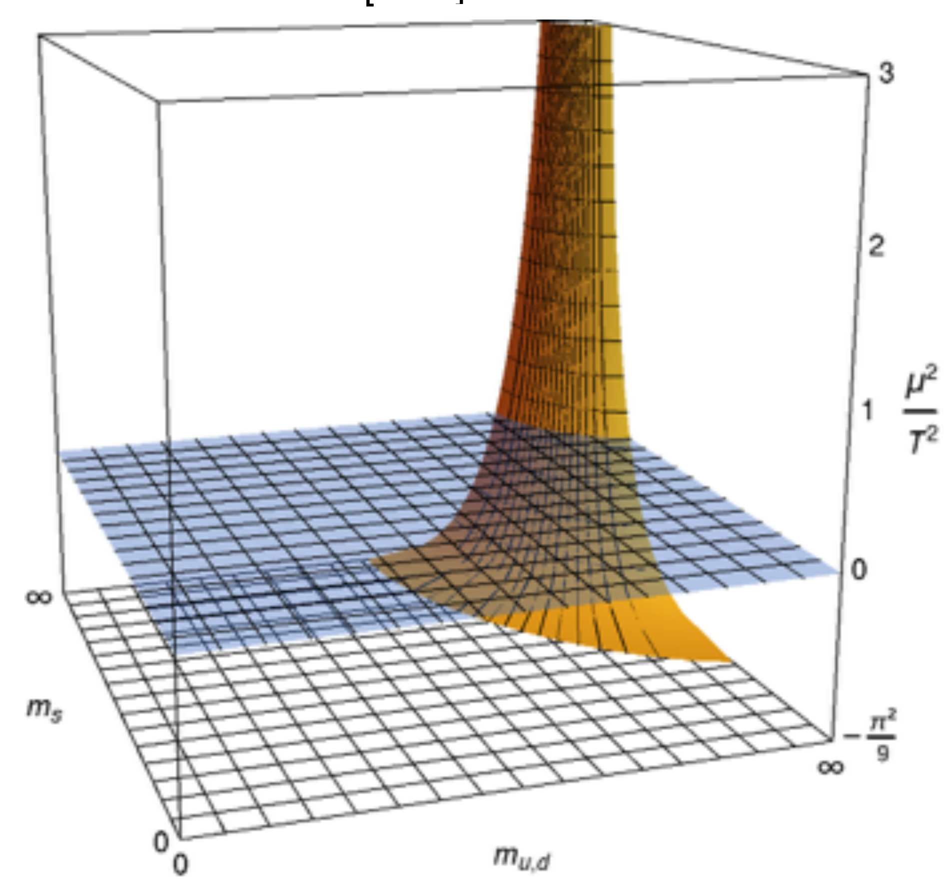
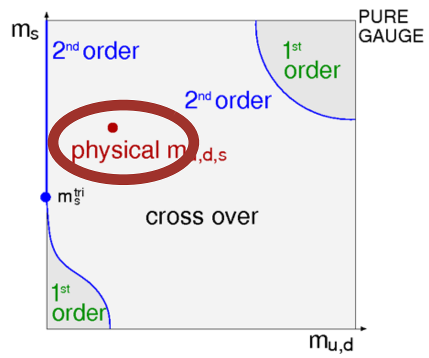
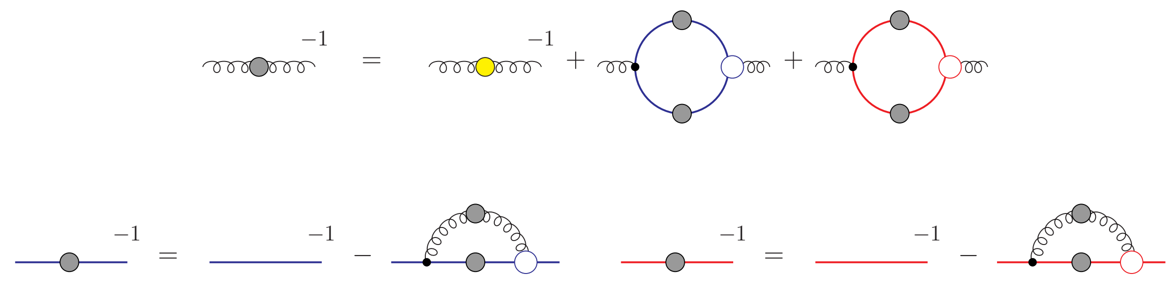
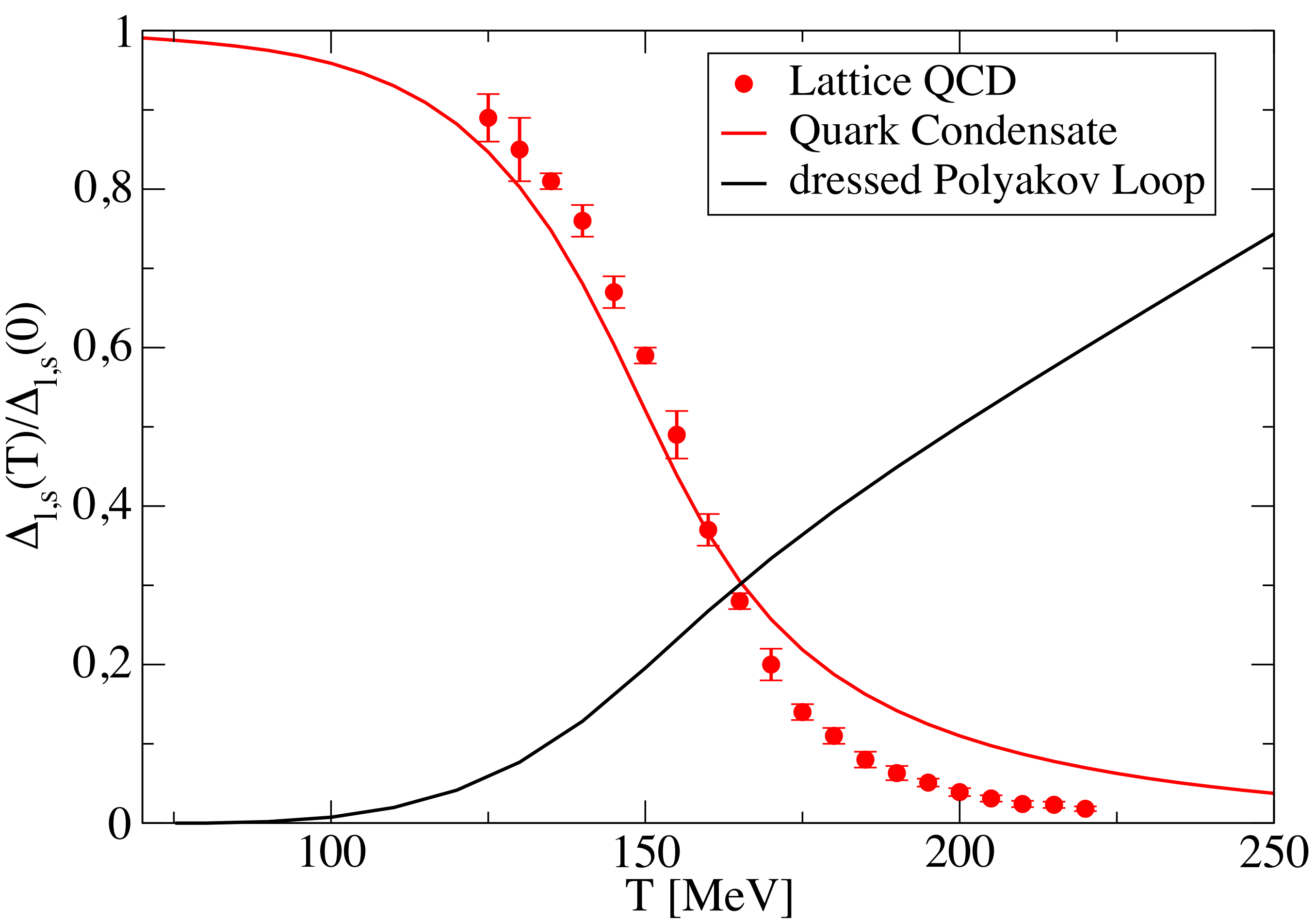


CF, Luecker, Pawlowski, PRD 91 (2015) 1

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

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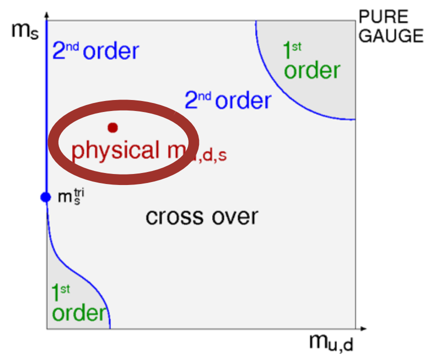

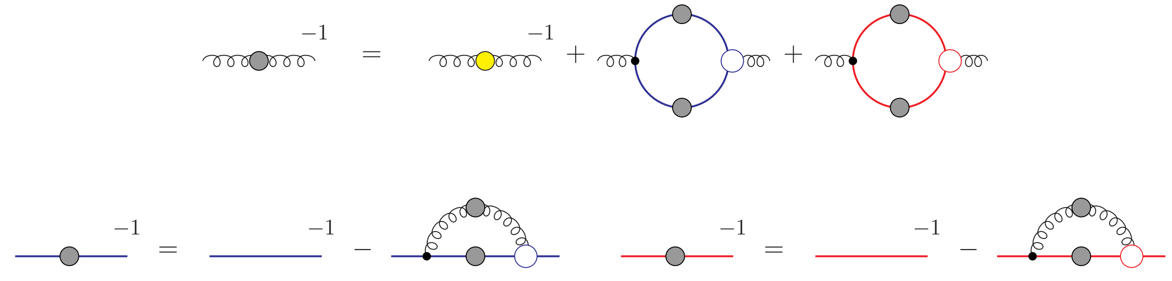

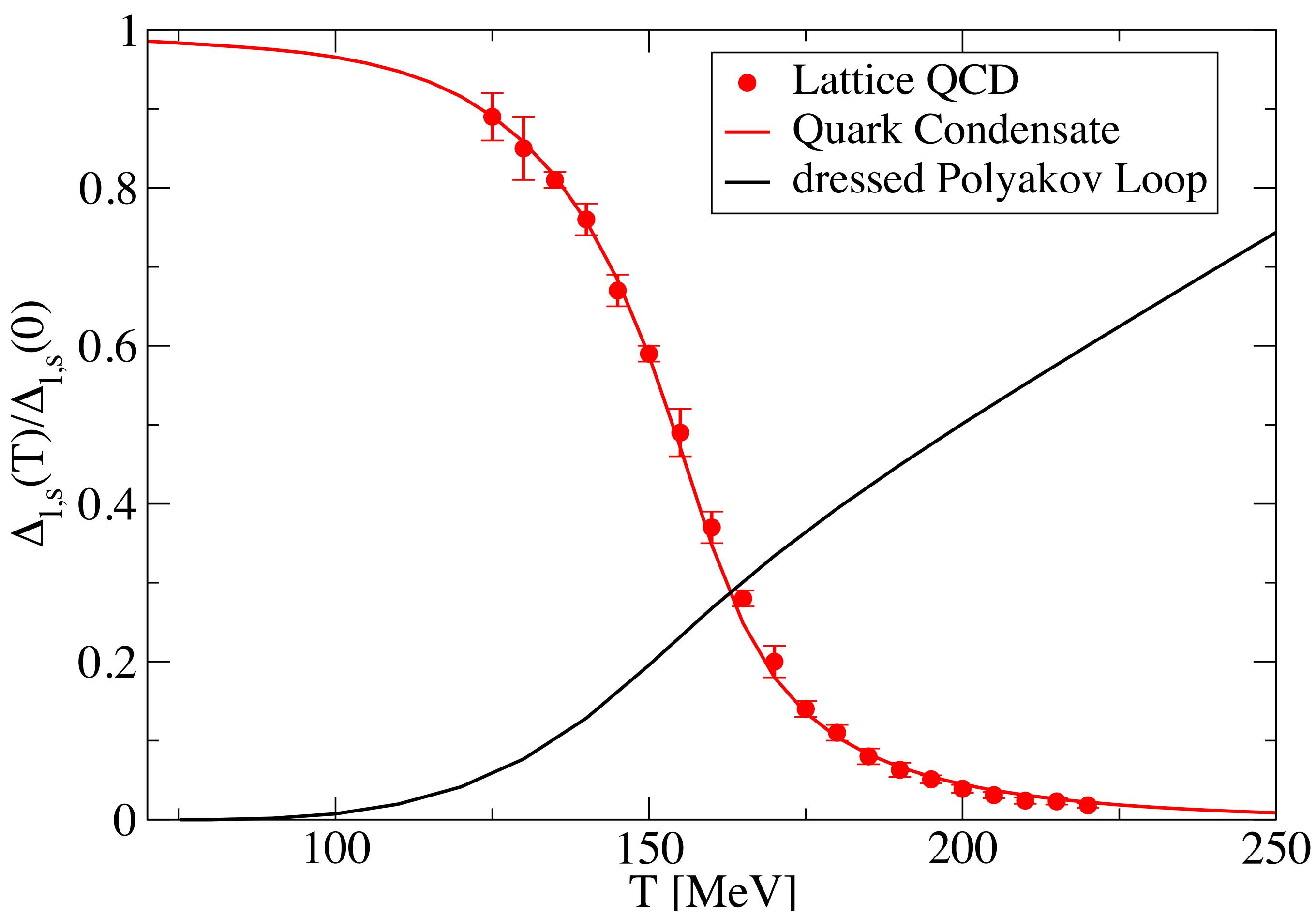

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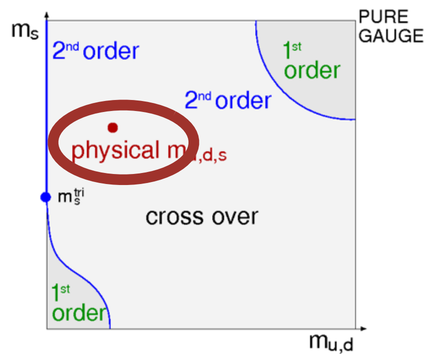

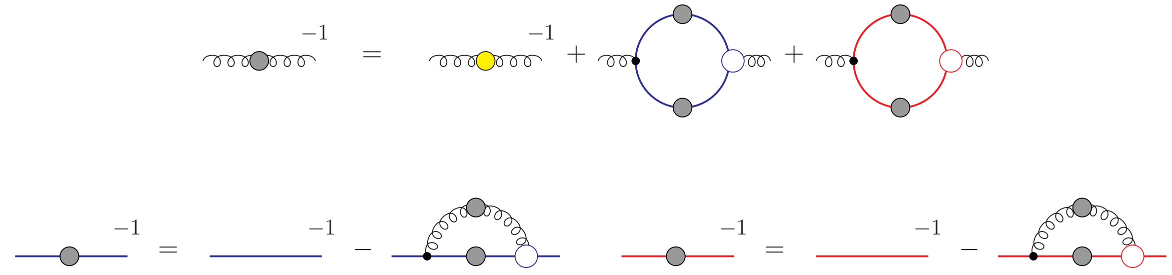

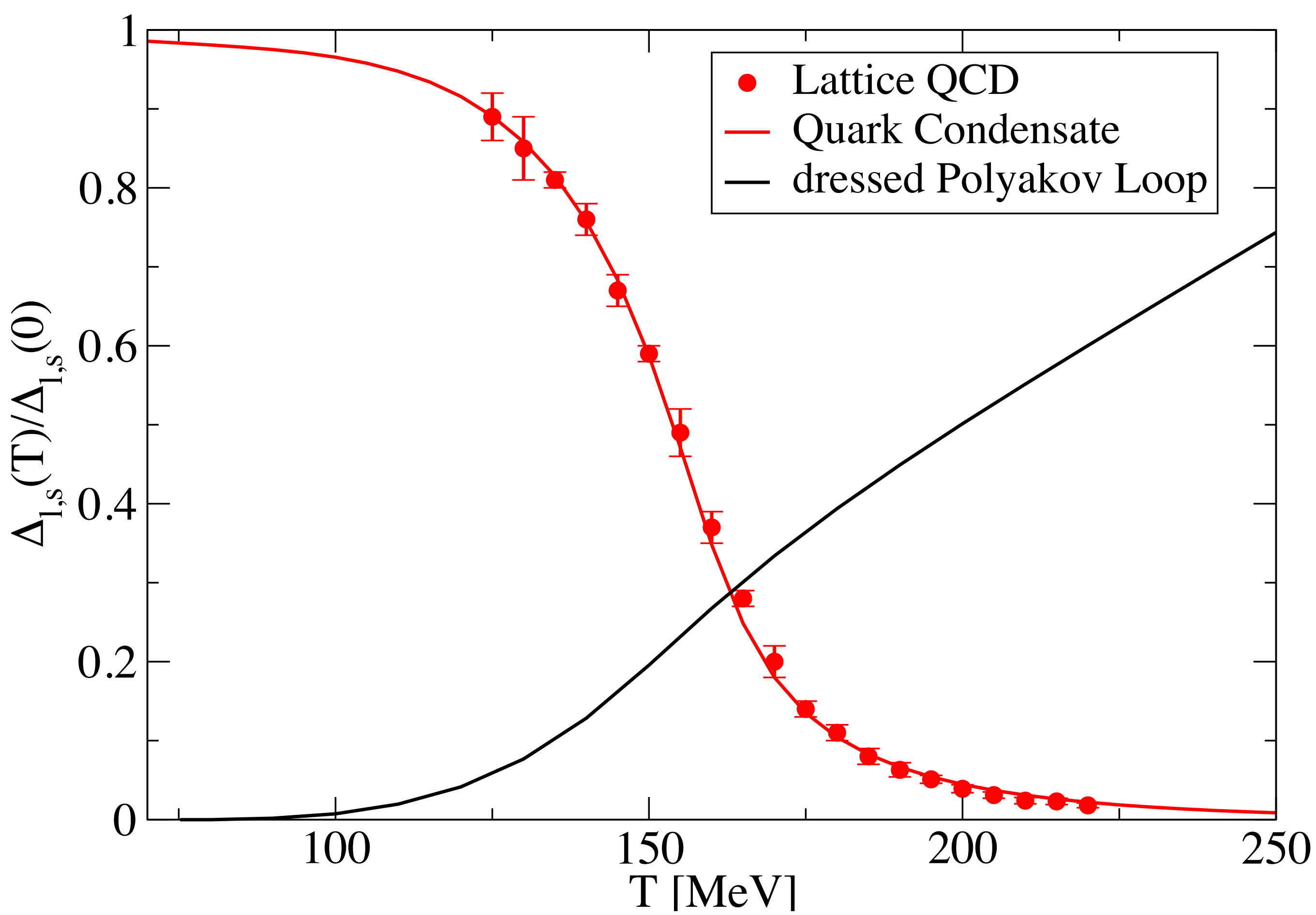

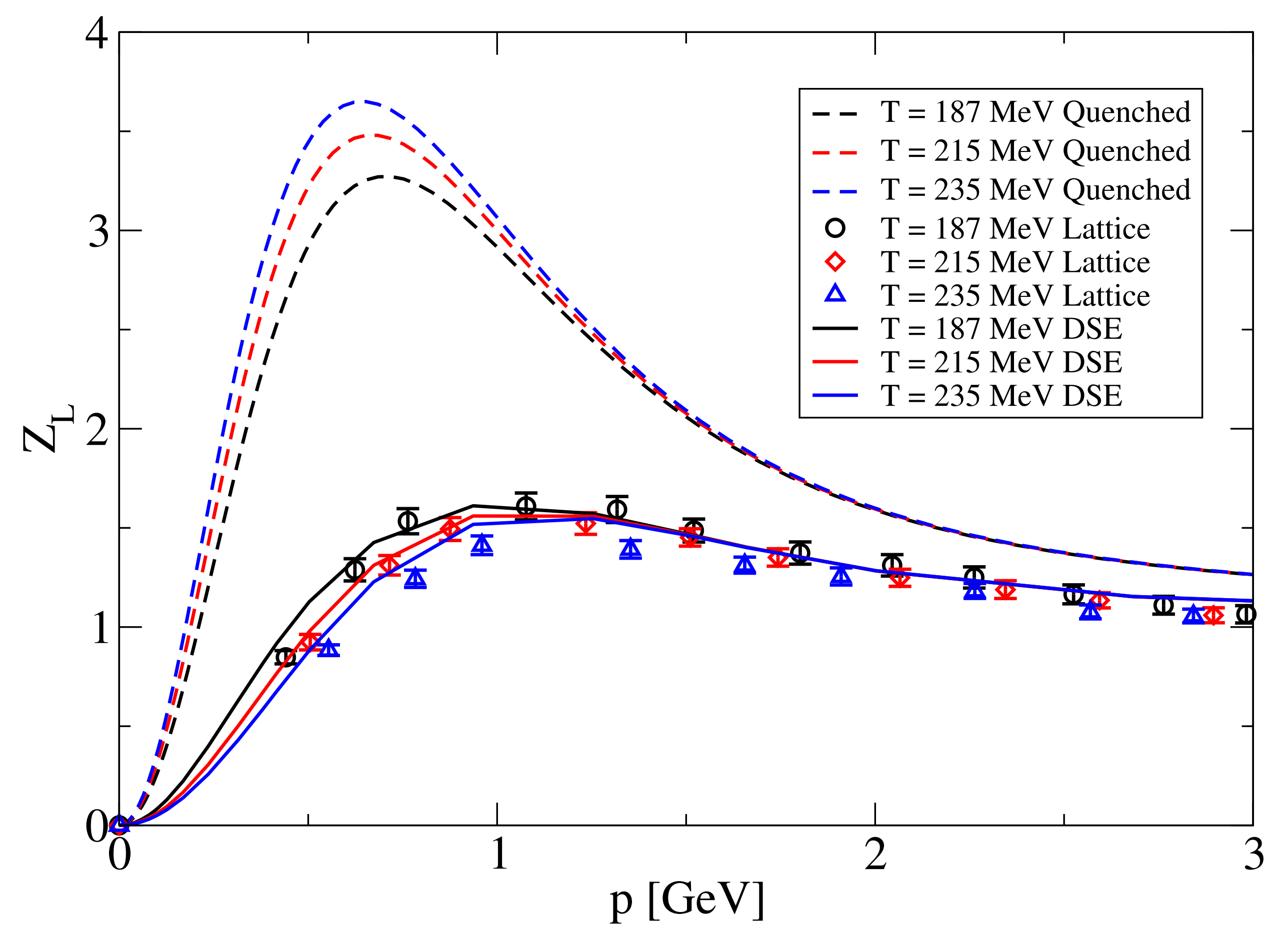

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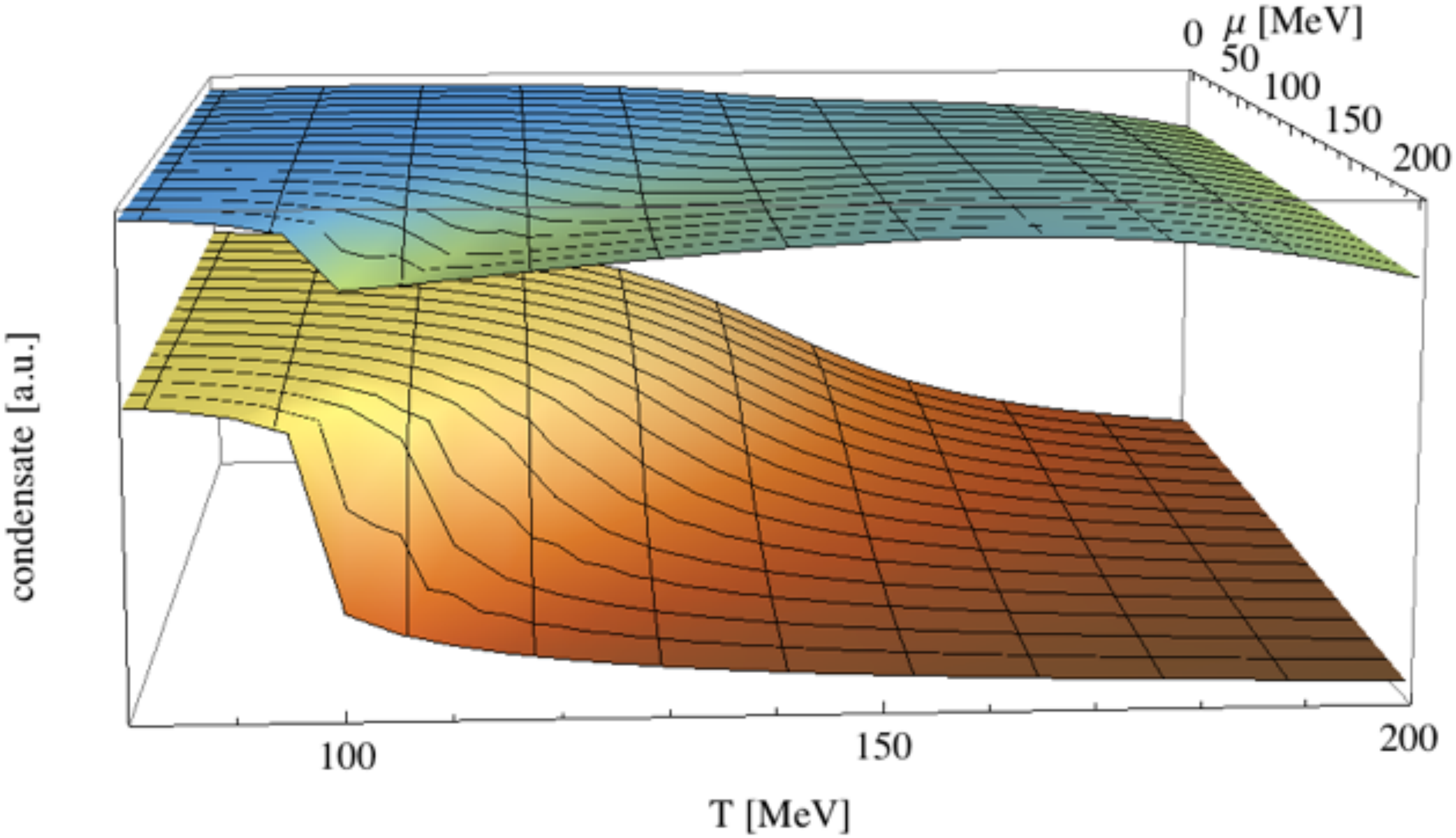
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

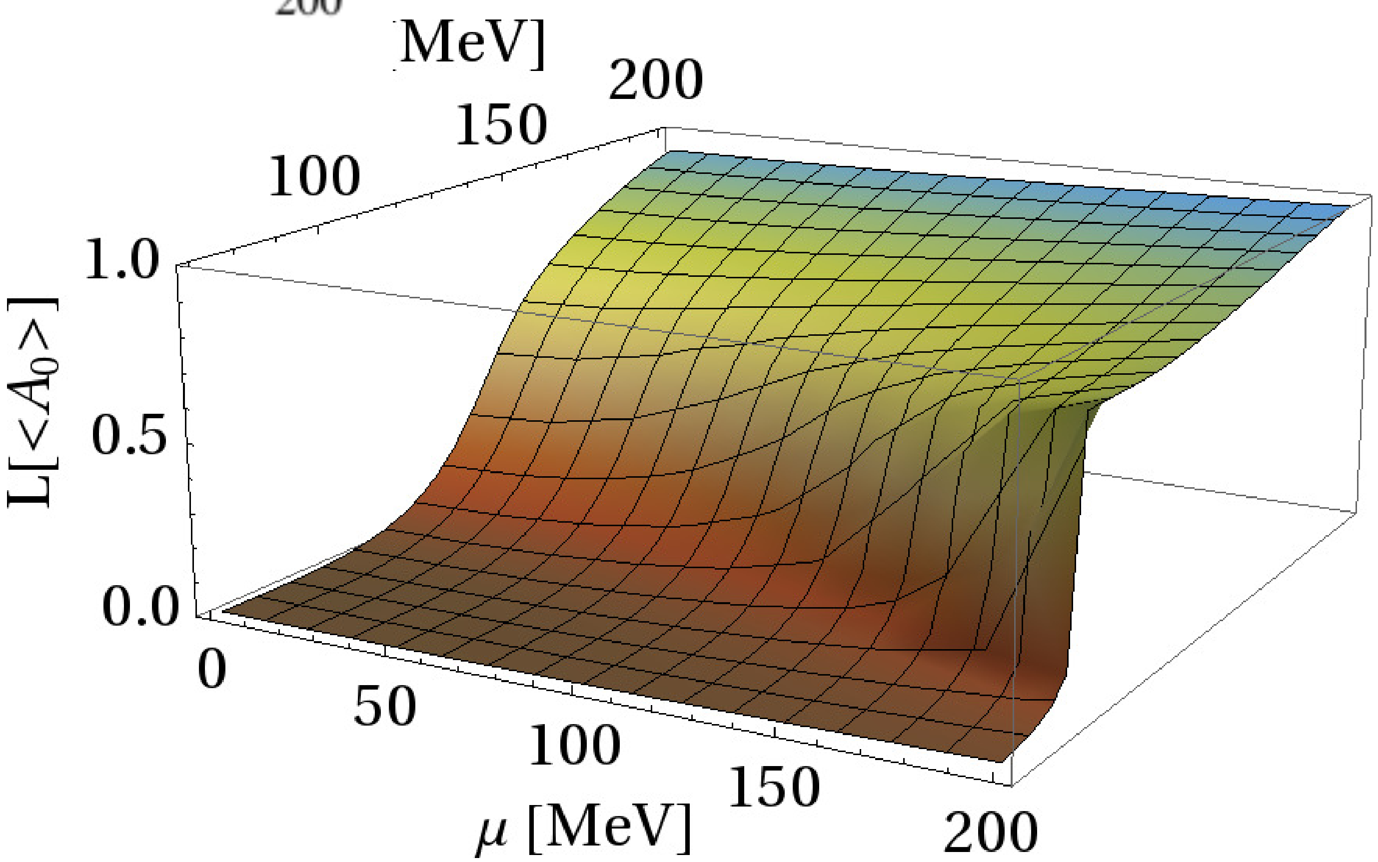
Lattice: Aouane, et al.PRD D87 (2013), [arXiv:1212.1102]
DSE: CF, Luecker, PLB 718 (2013) 1036, [arXiv:1206.5191]

- quantitative agreement: DSE prediction verified by lattice

Nf=2+1: Condensate and dressed Polyakov Loop



Quark condensate

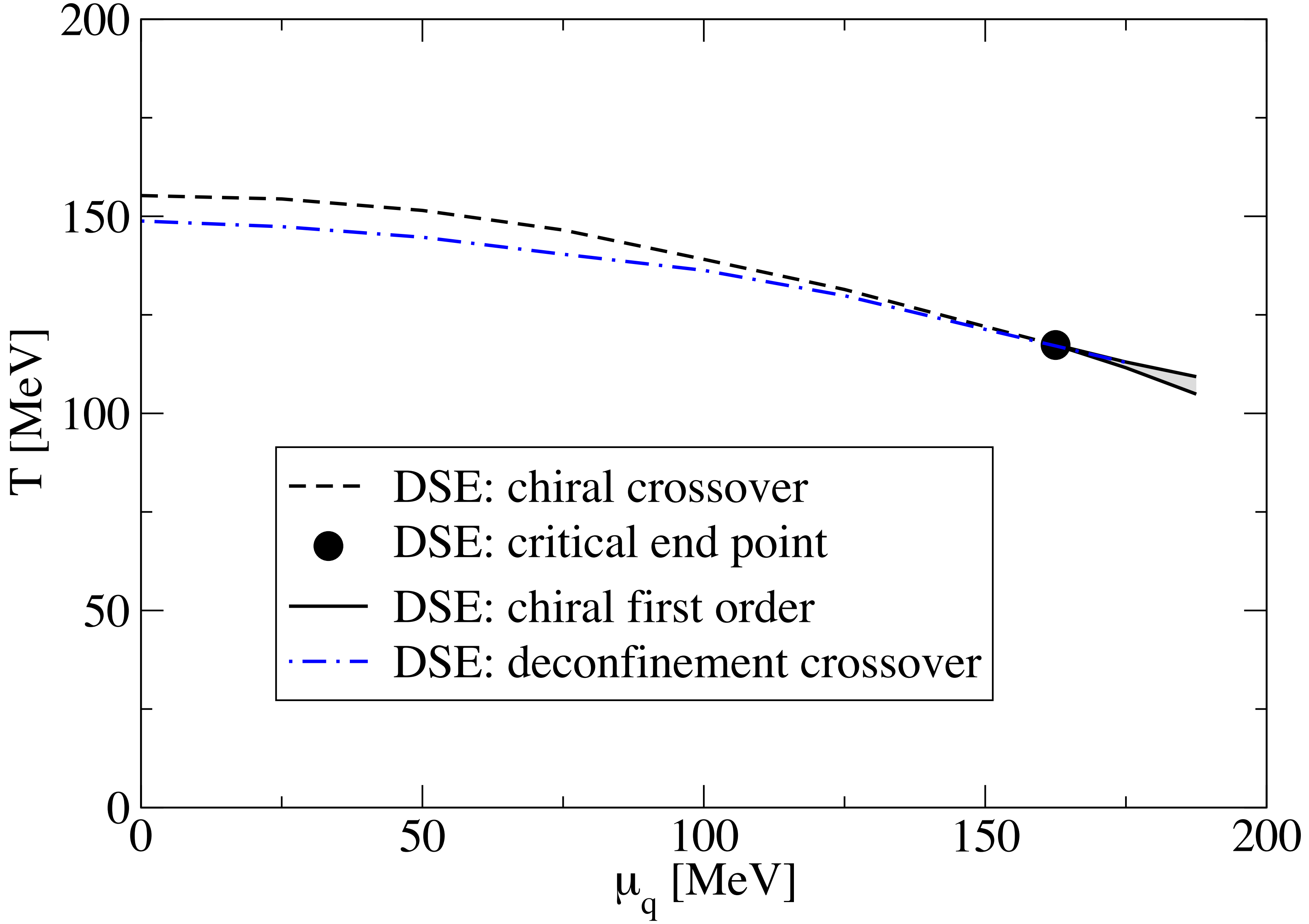


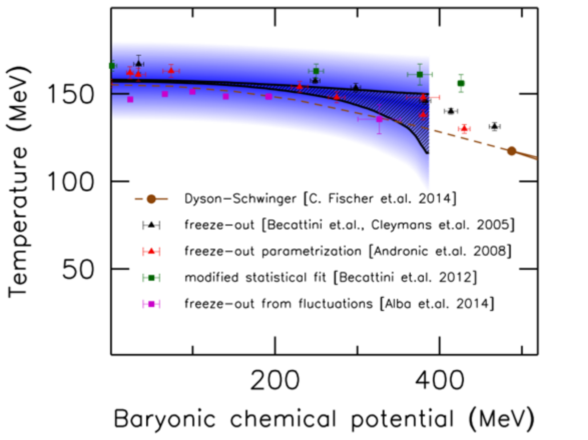
Polyakov-Loop

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

CF, Fister, Luecker, Pawlowski, PLB 732 (2014) 273

N_f=2+1: phase diagram





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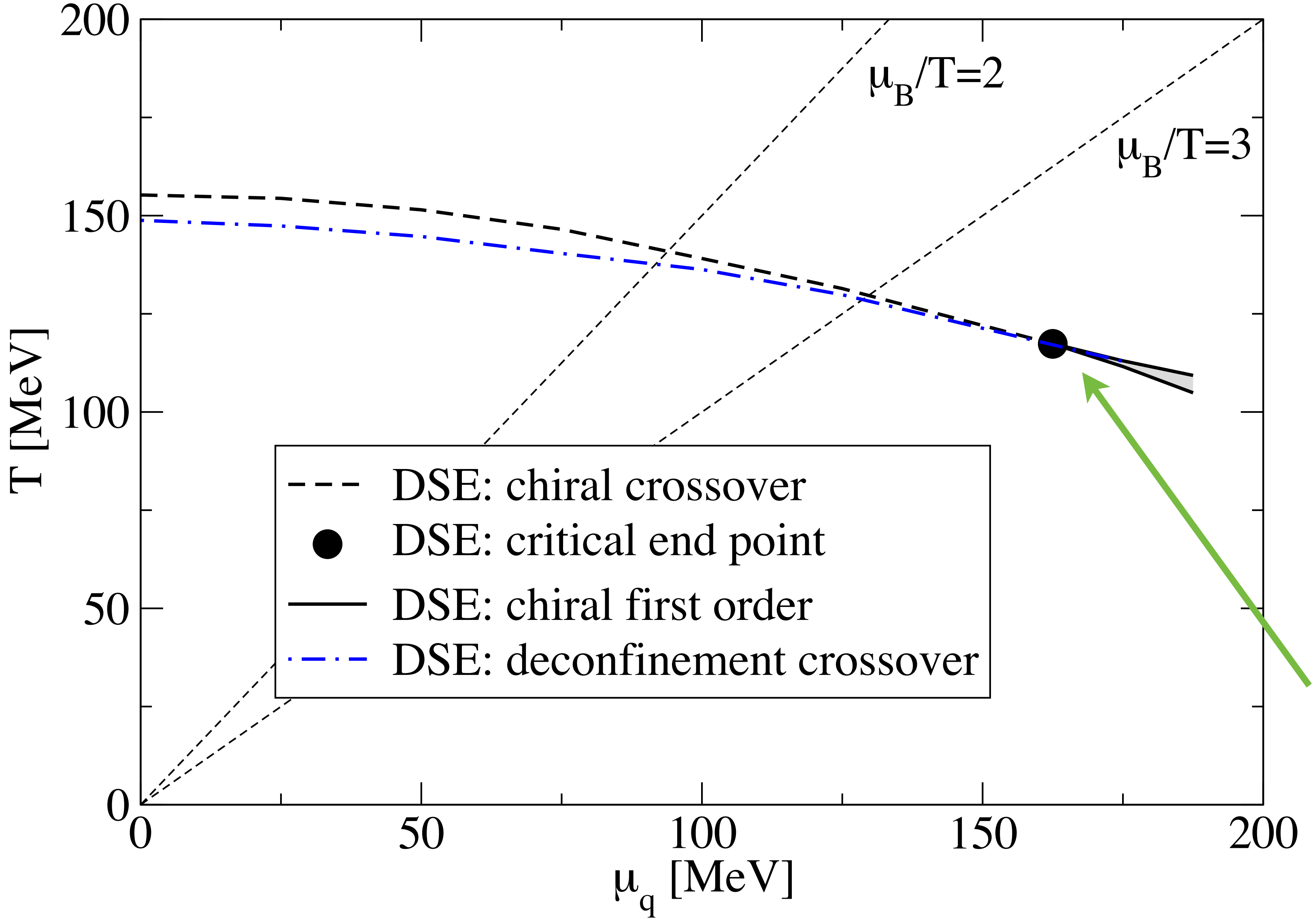

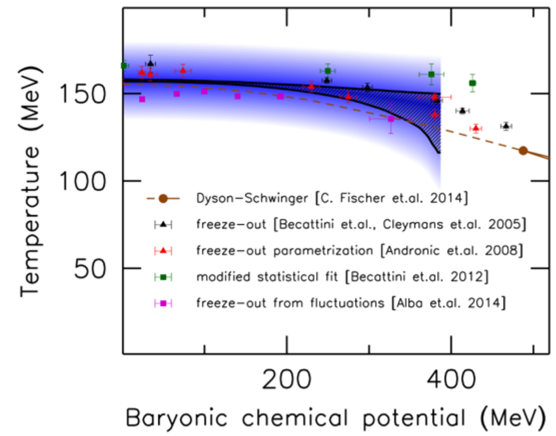

CEP at large μ

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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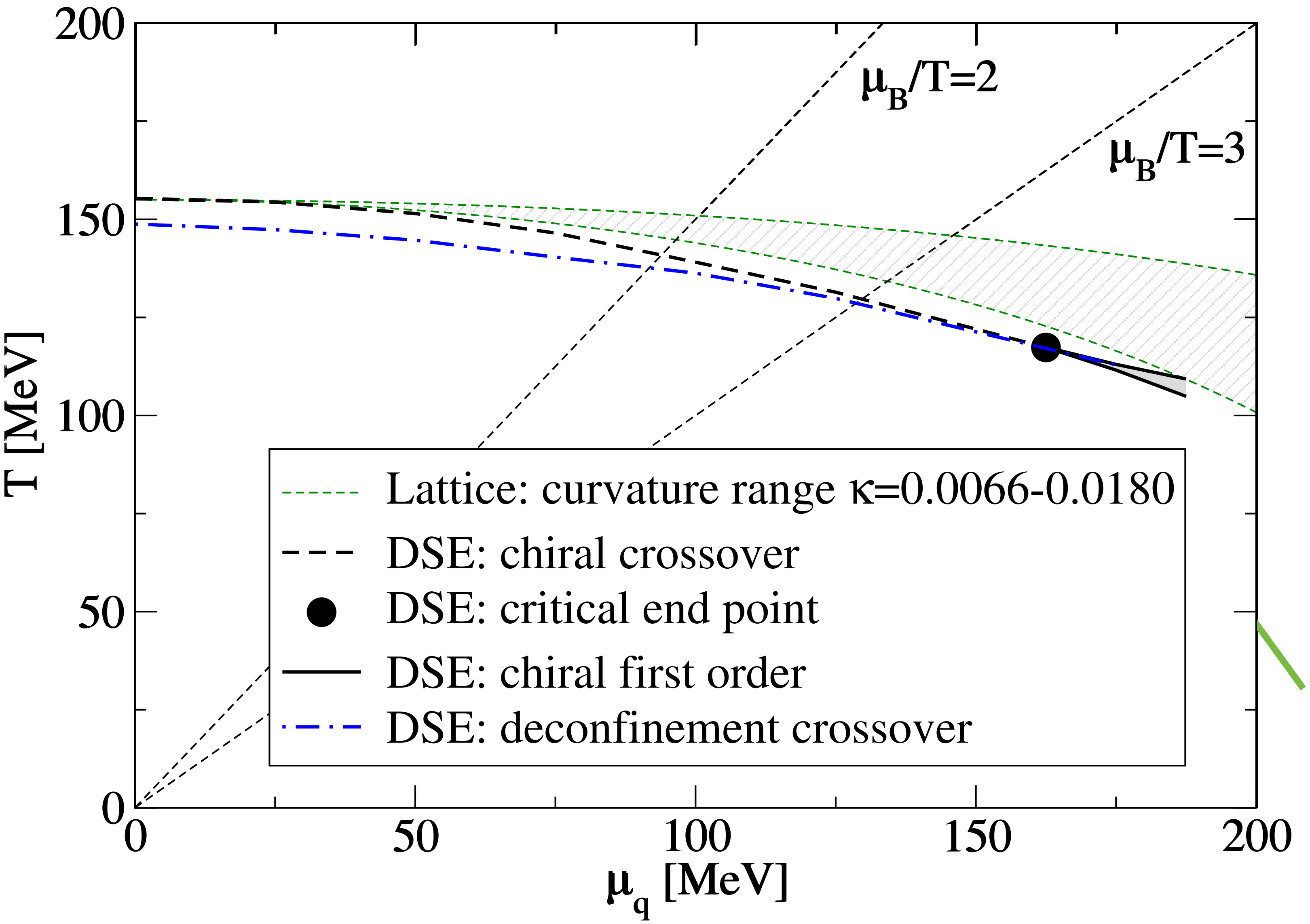

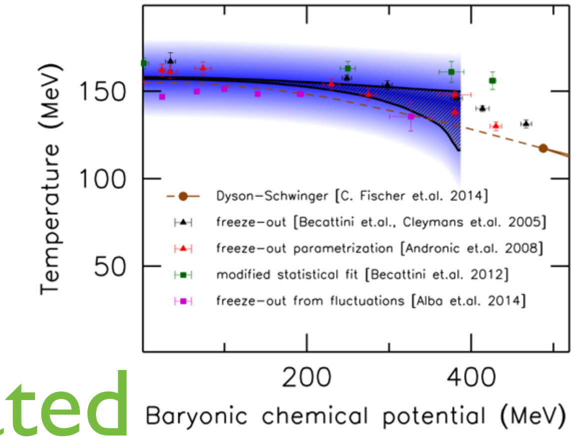

Extrapolated curvature from lattice

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

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

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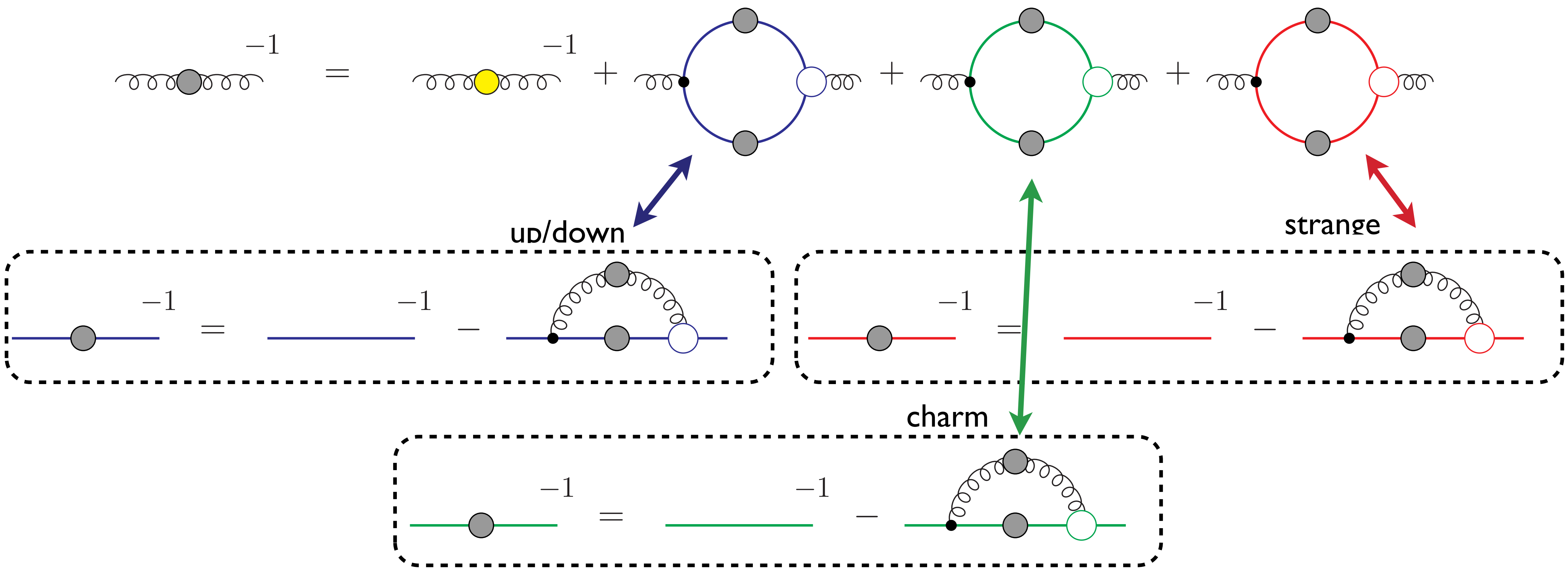
Nf=2+1+1: effects of charm



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

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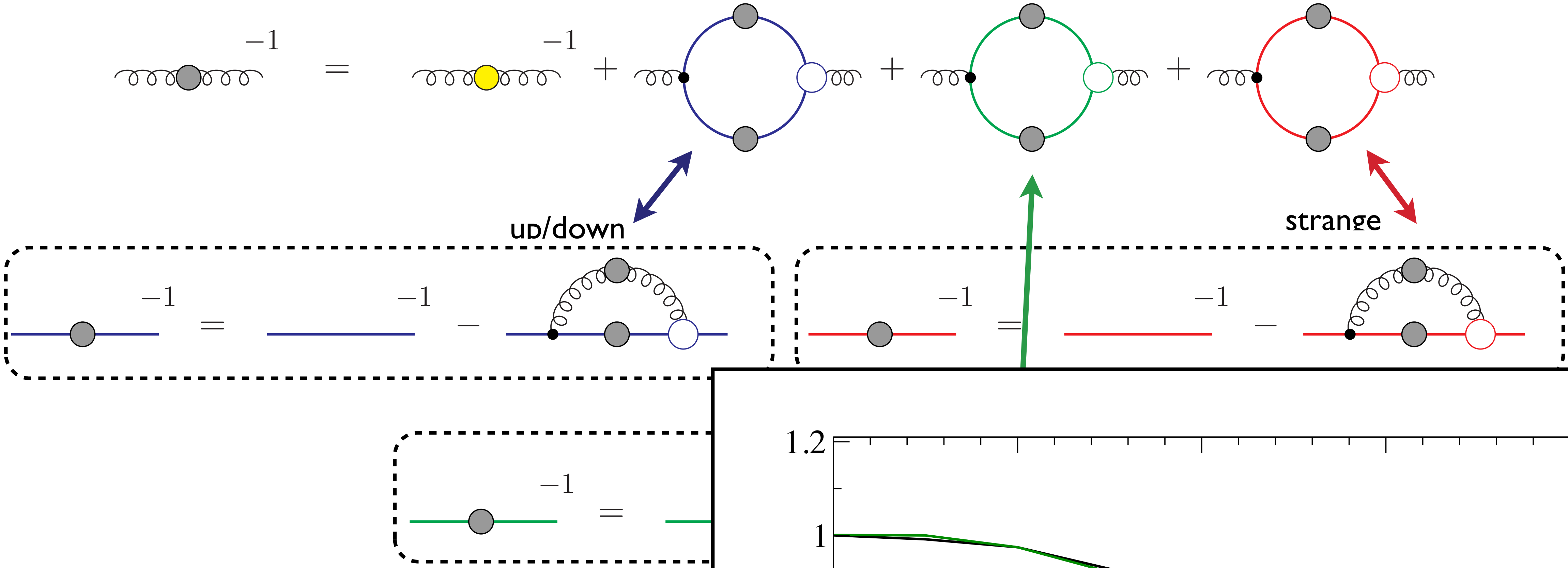

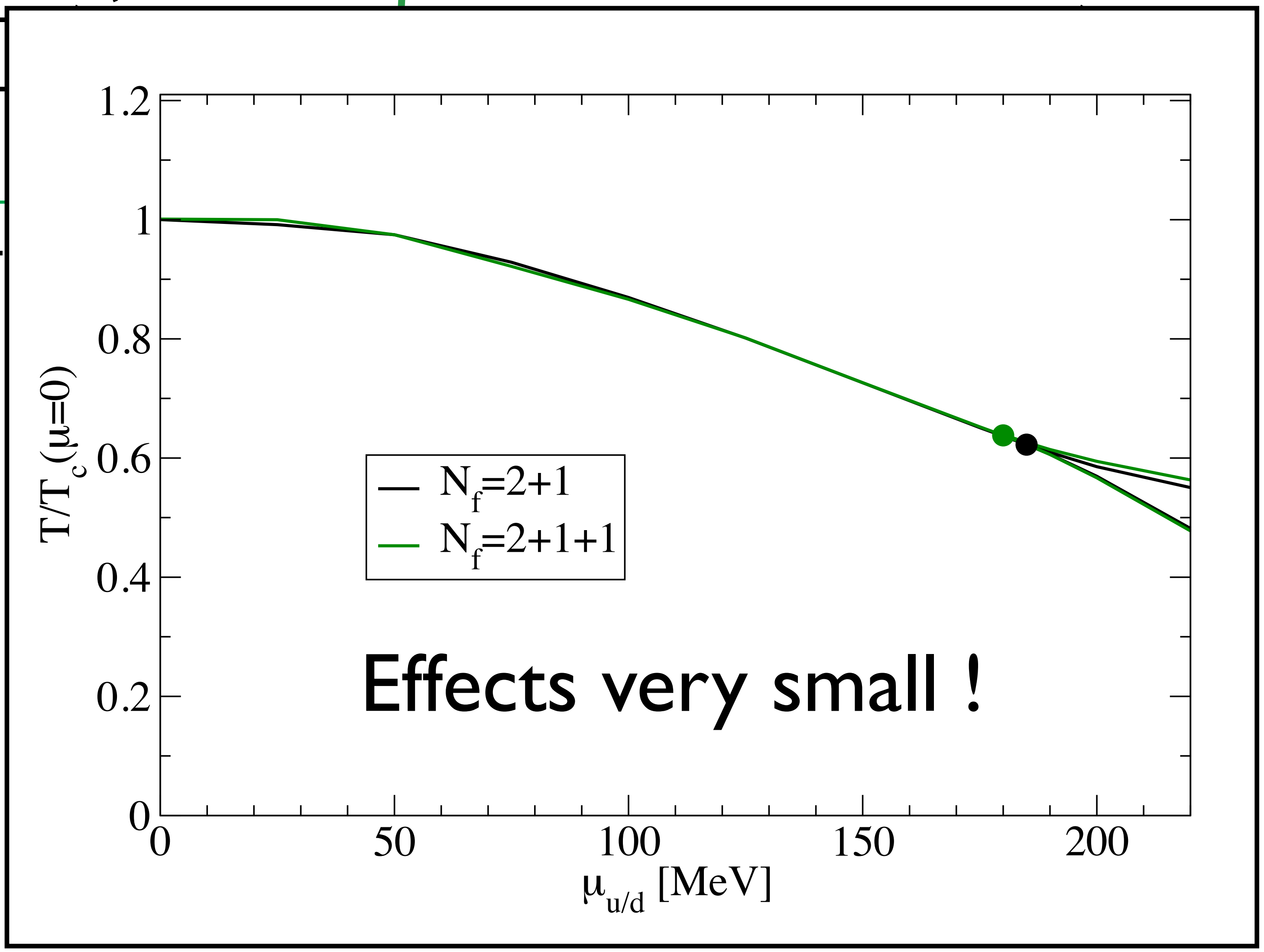

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CF, Luecker, Welzbacher, PRD 90 (2014) 034022

Location of CEP in freece-out landscape

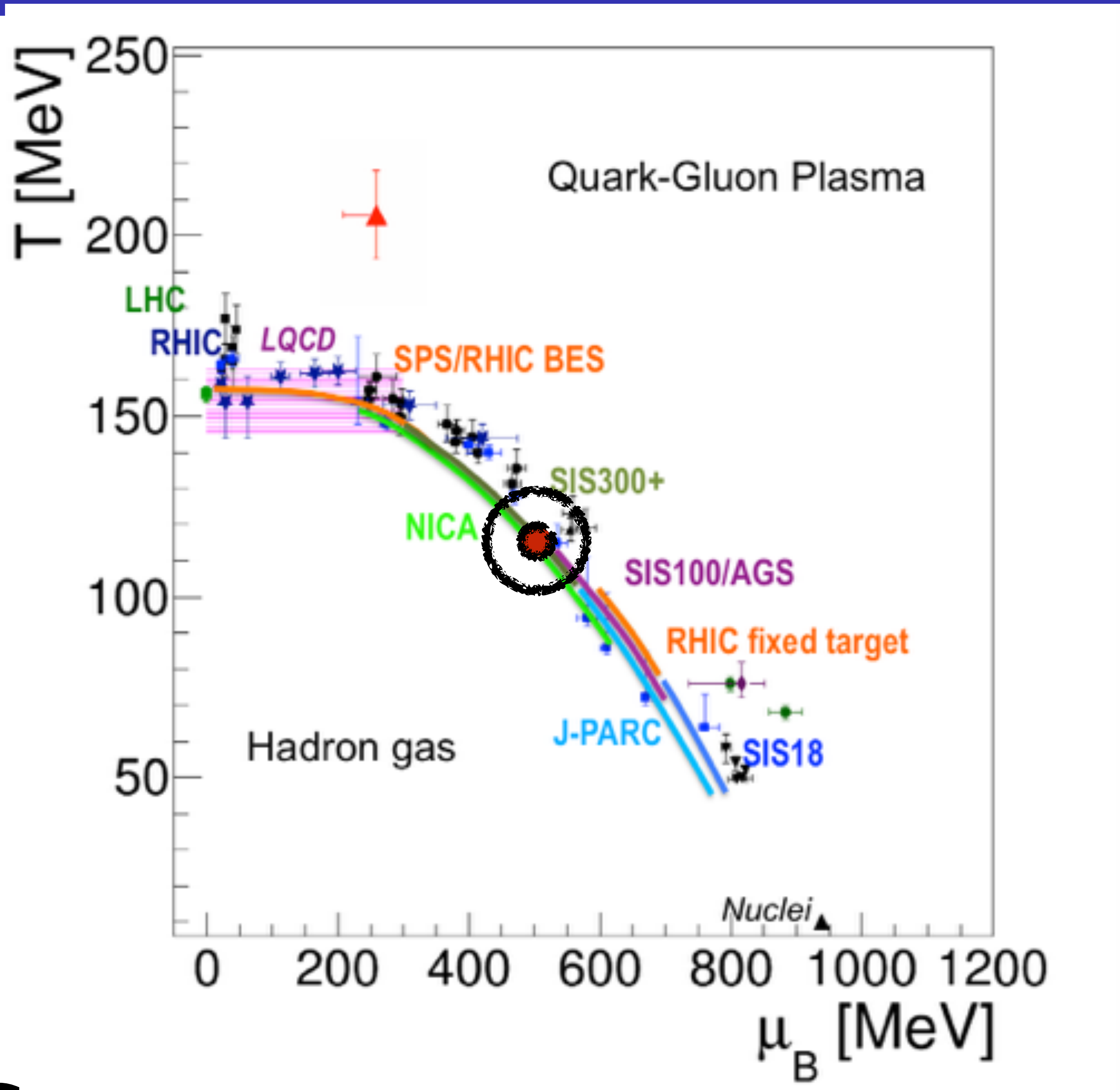

Figure taken from talk of T. Galatyuk, Erice 2016

Caveats:

- inhomogeneous phases
- effects of baryons ?
- finite size
- …

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

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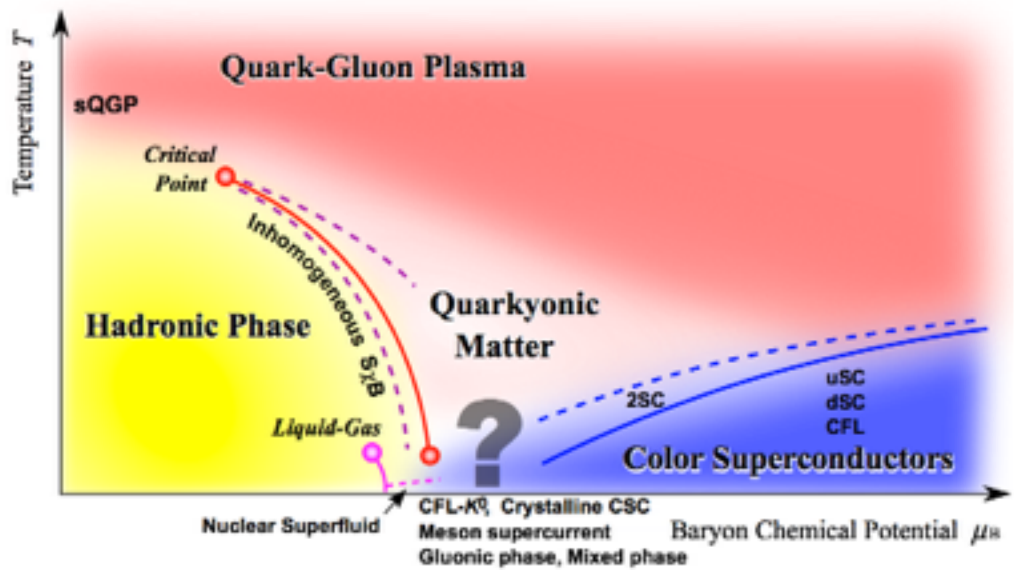

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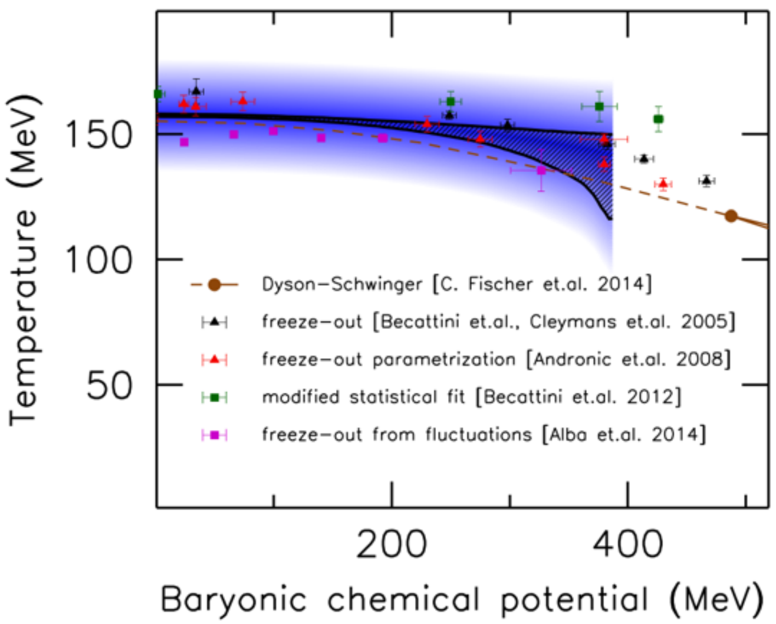

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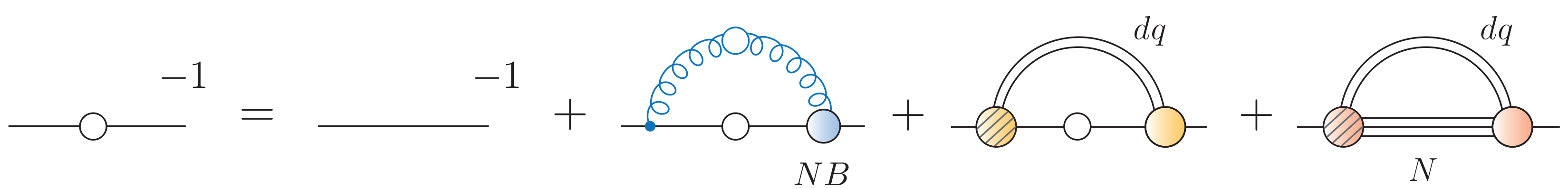
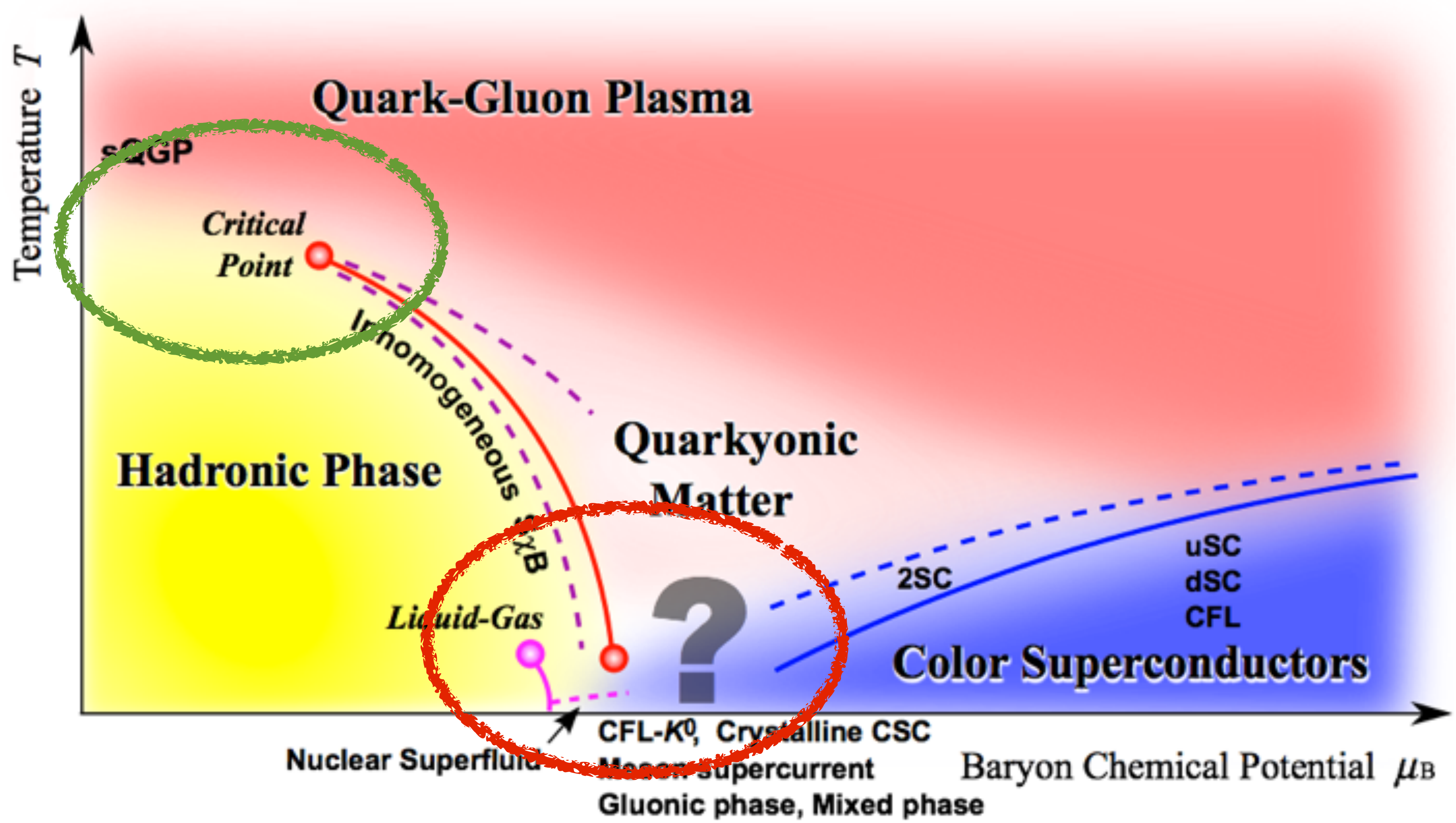
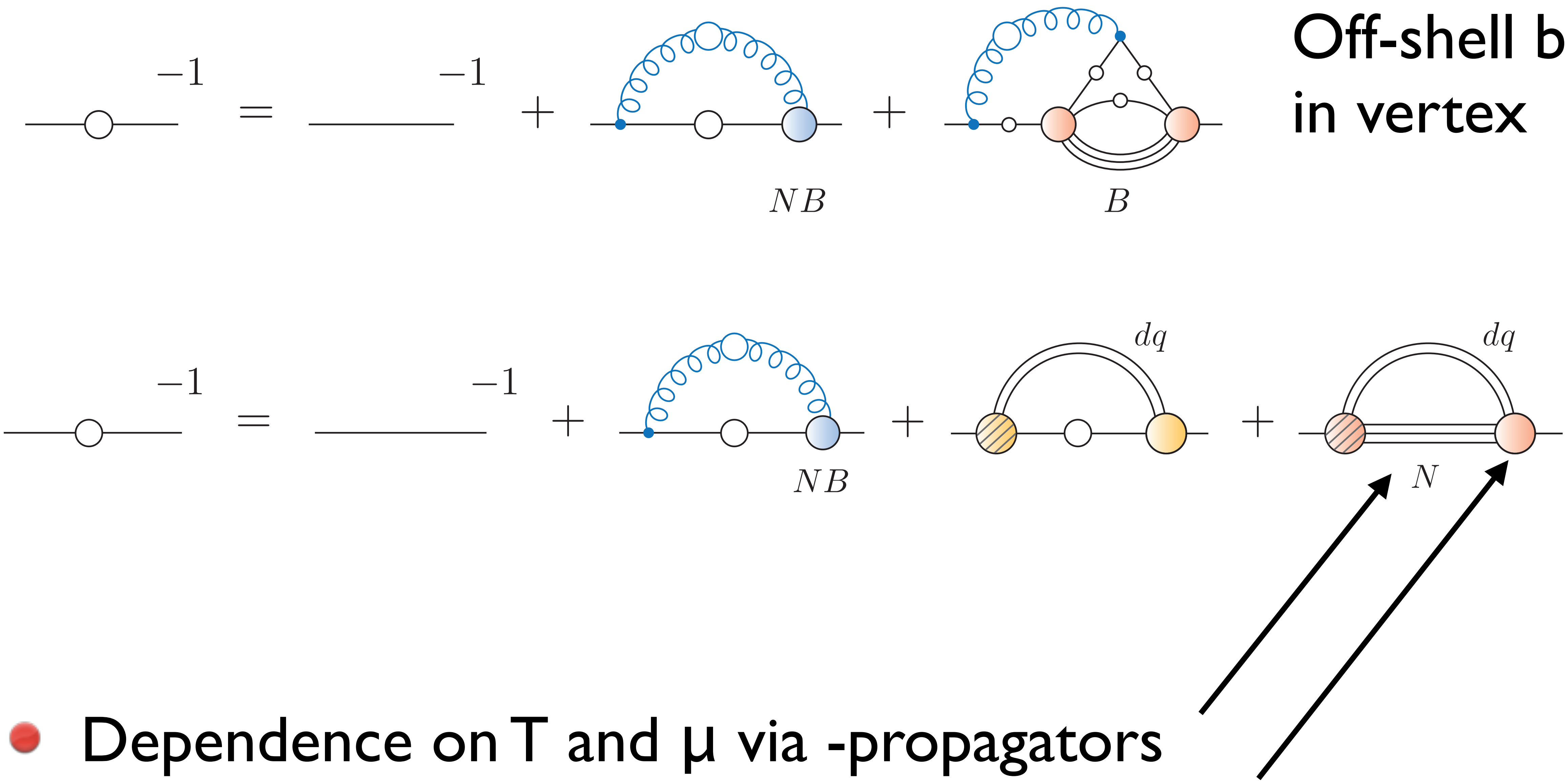


Fukushima, Hatsuda, Rept. Prog. Phys. 74 (2011) 014001



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

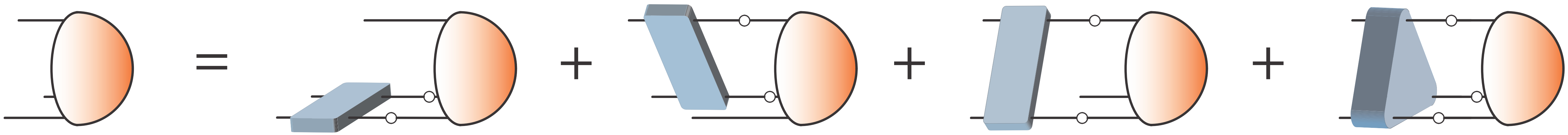
Baryon effects onto quark



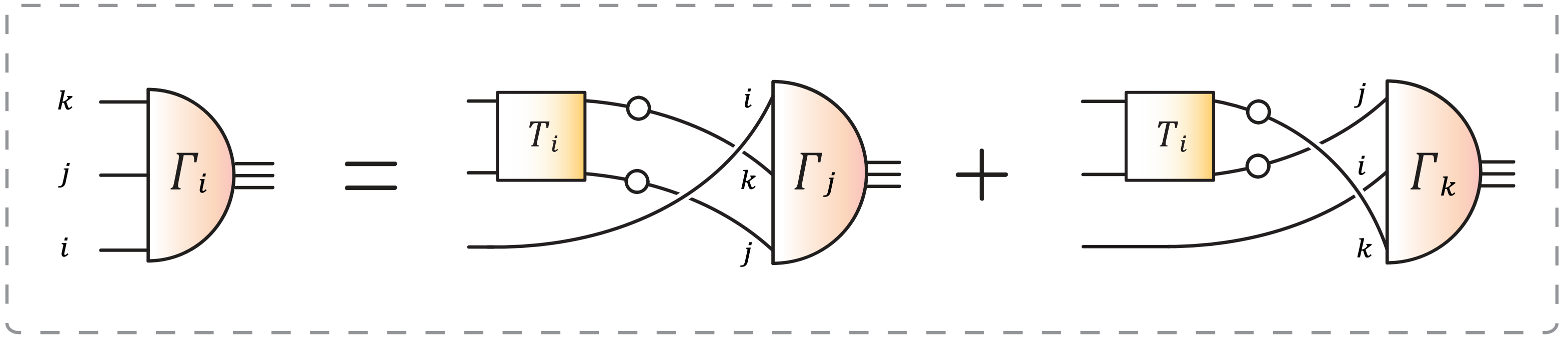
Off-shell baryon in vertex

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

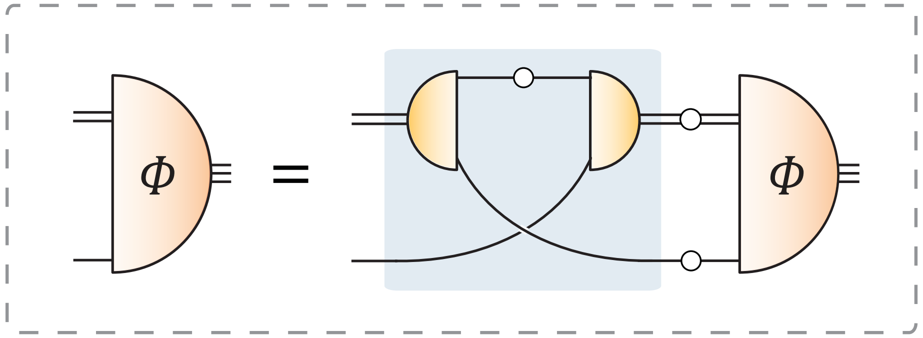
BSE for baryons (derived from equation of motion for G)



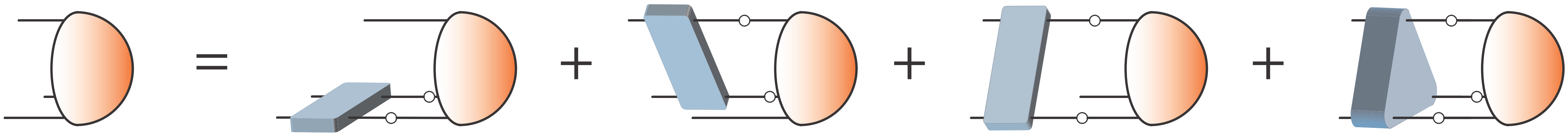
Faddeev equation (no three-body forces)



Diquark-quark



BSE for baryons (derived from equation of motion for G)



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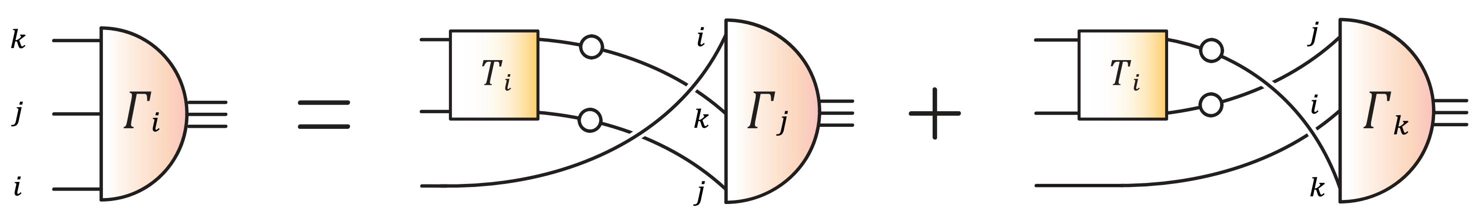
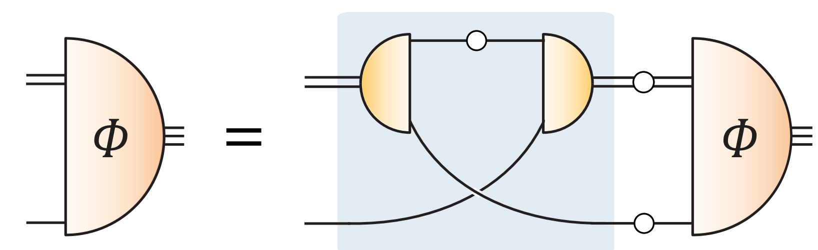
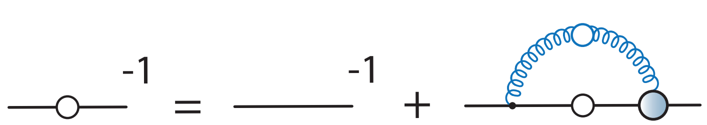
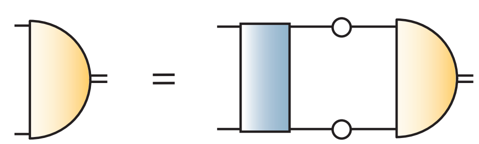
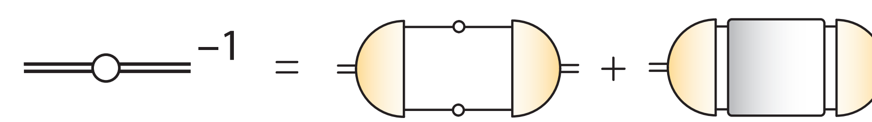


Diquark-quark

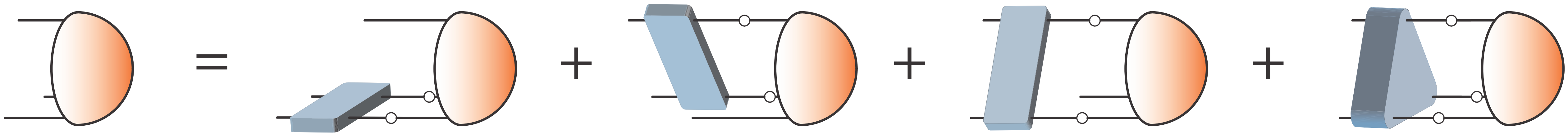




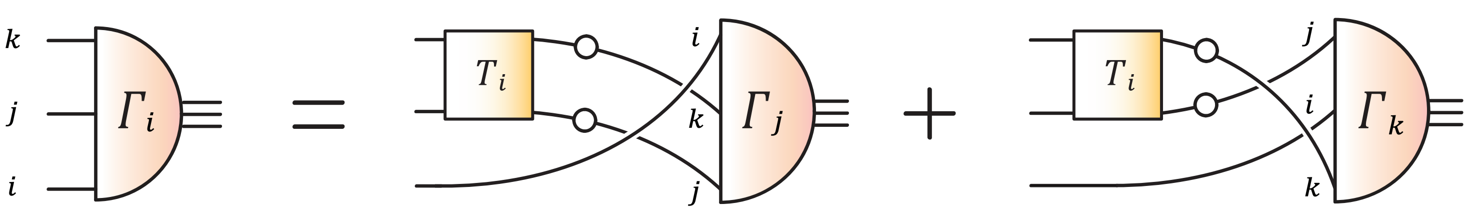




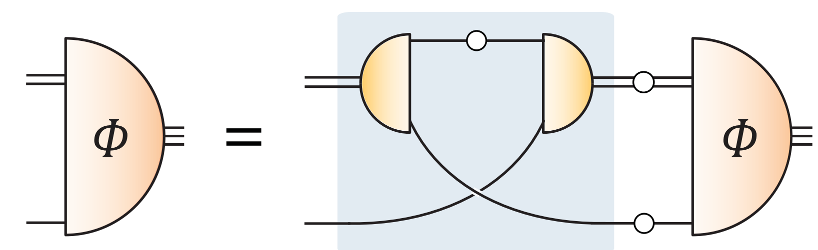
BSE for baryons (derived from equation of motion for G)

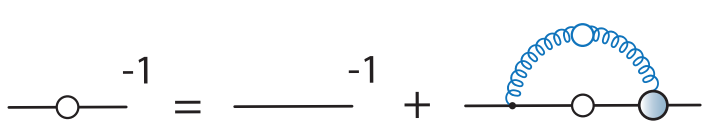


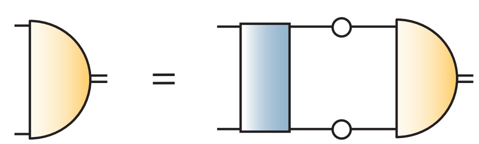
Faddeev equation (no three-body forces)

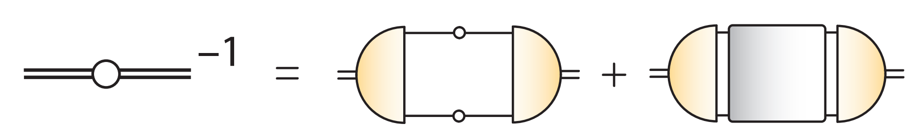


Diquark-quark

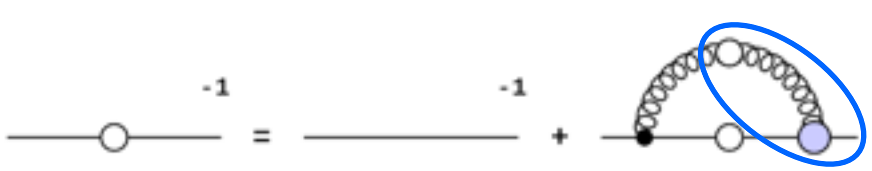






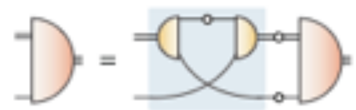


- Input: Non-perturbative quark, quark-gluon interaction (RL)



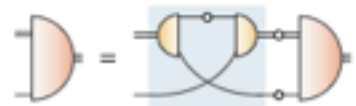
$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

Vacuum: DSE/Faddeev landscape

	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

Vacuum: DSE/Faddeev landscape

	Quark-diquark 			Three-quark 		
	Contact interaction	QCD-based model	DSE (RL)	RL	bRL	bRL + 3q
N, Δ masses	√	√	√	√	√	$\dots$
N, Δ em. FFs	√	√	√	√		
$N \to \Delta\gamma$	√	√	√	$\dots$		
Roper	√	√		$\dots$		
$N \to N^*\gamma$	√	√		$\dots$		
$N^*(1535), \dots$	$\dots$	$\dots$		$\dots$	$\dots$	
$N \to N^*\gamma$	$\dots$	$\dots$				
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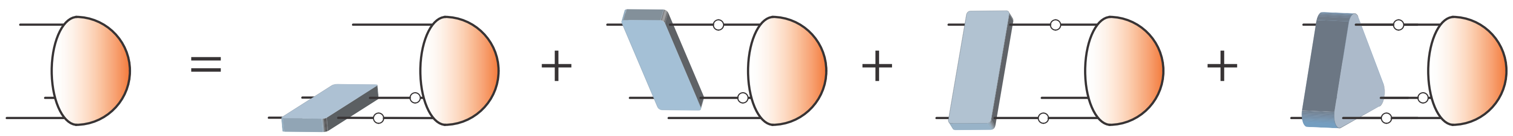
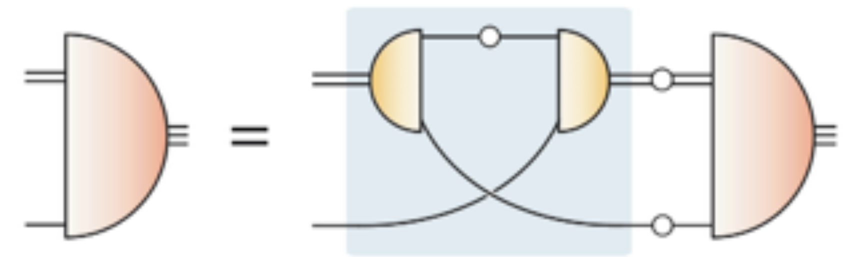
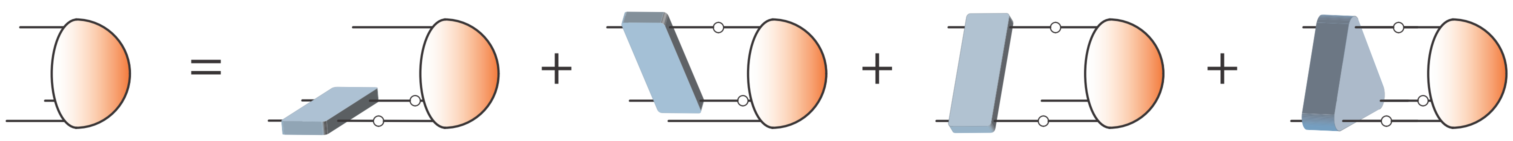
Eichmann, N*-Workshop, Trento 2015

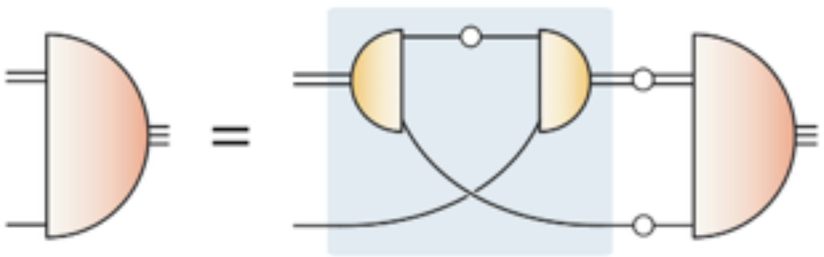
Vacuum: Light baryon spectrum

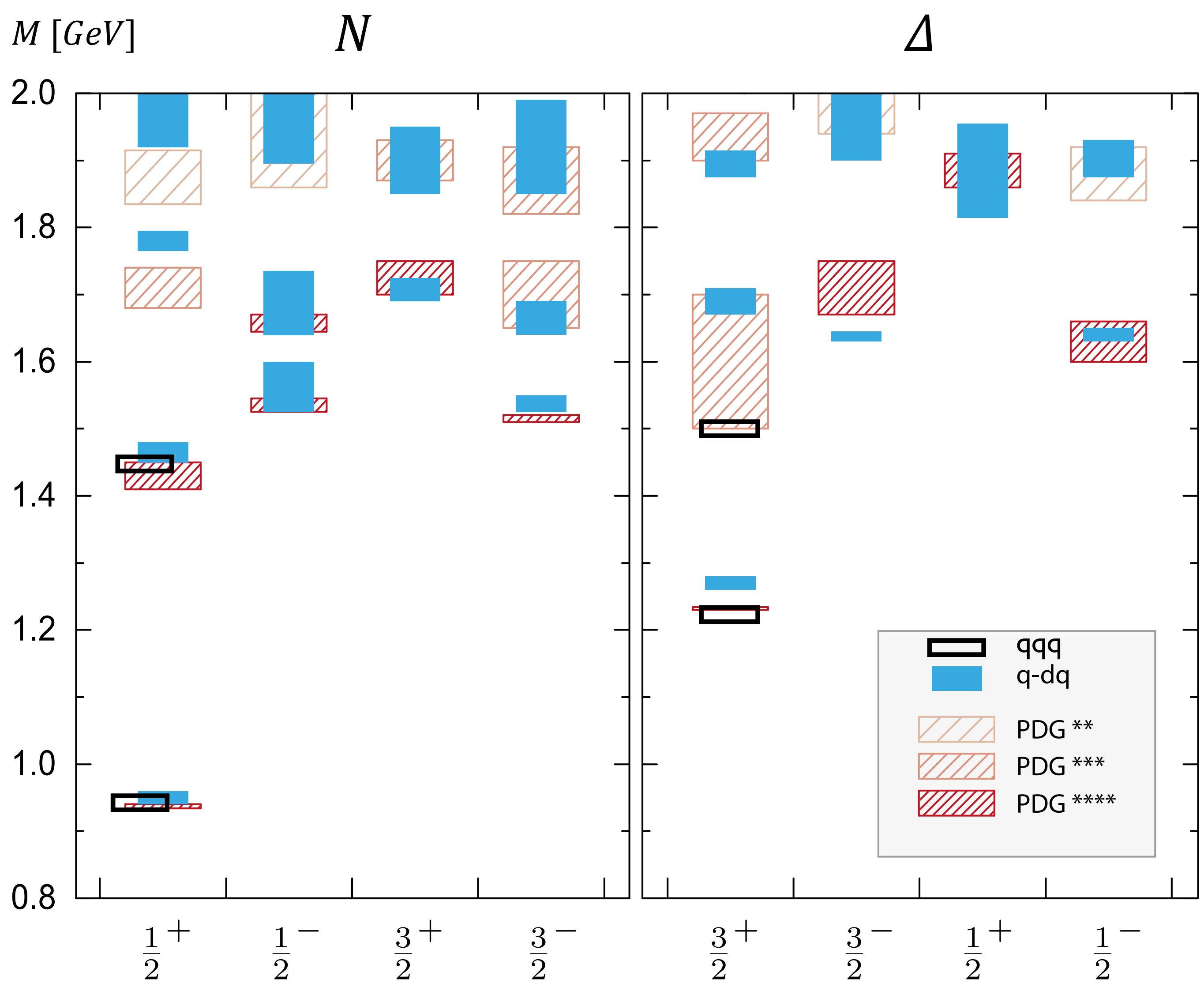




Vacuum: Light baryon spectrum



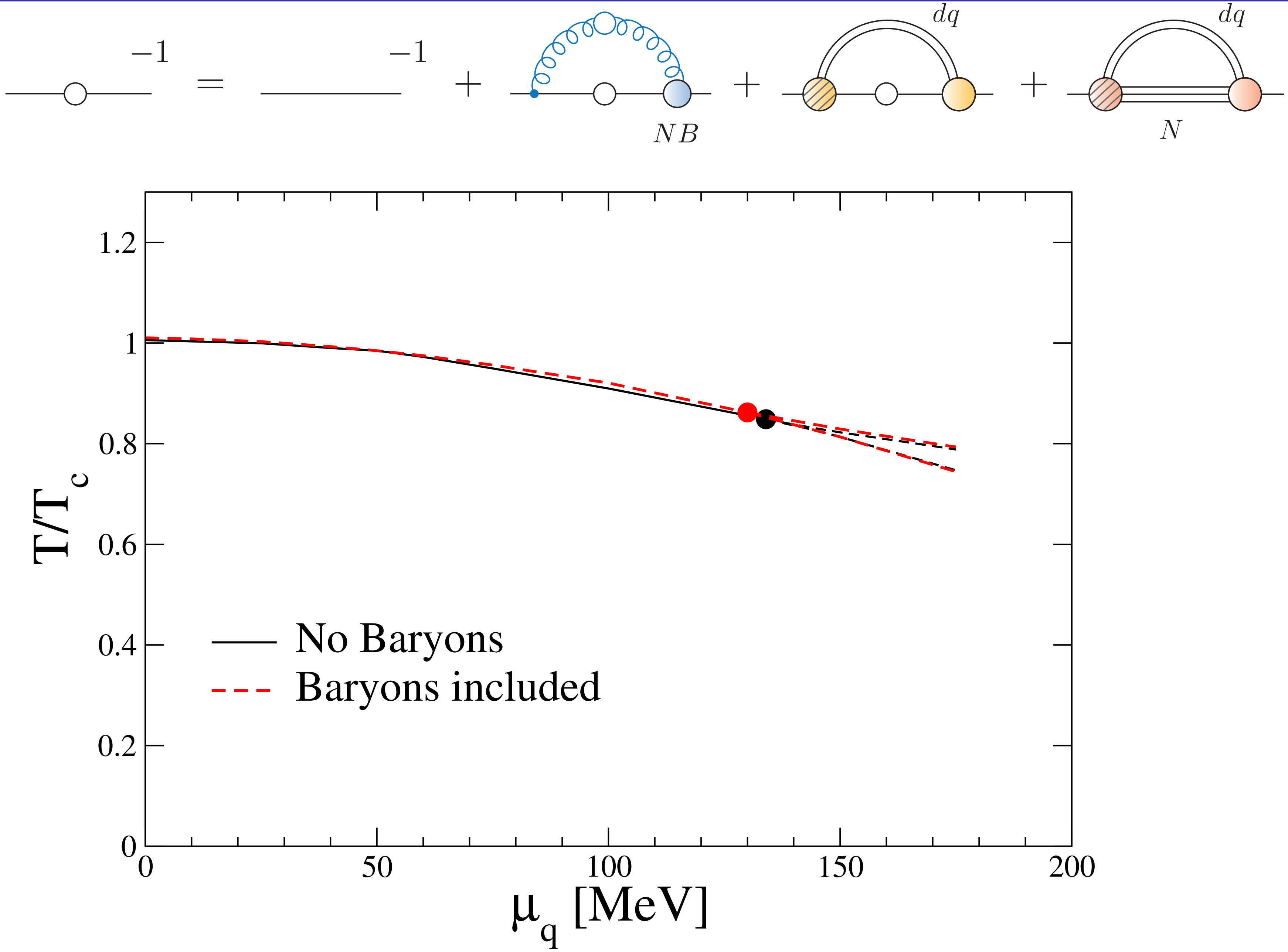




Eichmann, CF, Sanchis-Alepuz, 1607.05748
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP in press [1606.09602]

- Three-body and diquark-quark approach agree qualitatively
- Spectrum in one-to-one agreement with experiment
- Correct level ordering (wo. coupled channel effects) !

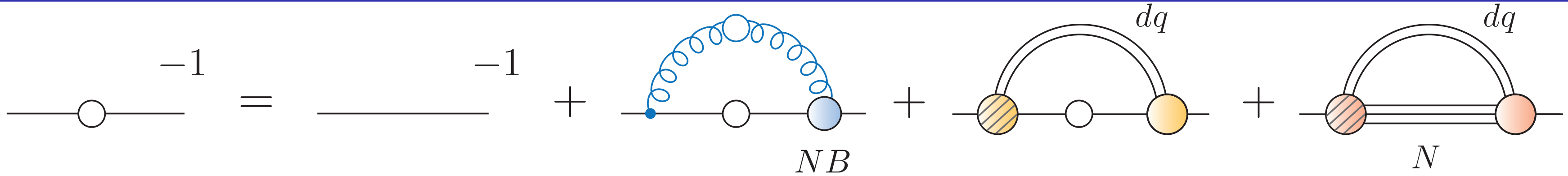
Baryon effects on the CEP - results (N_f=2)

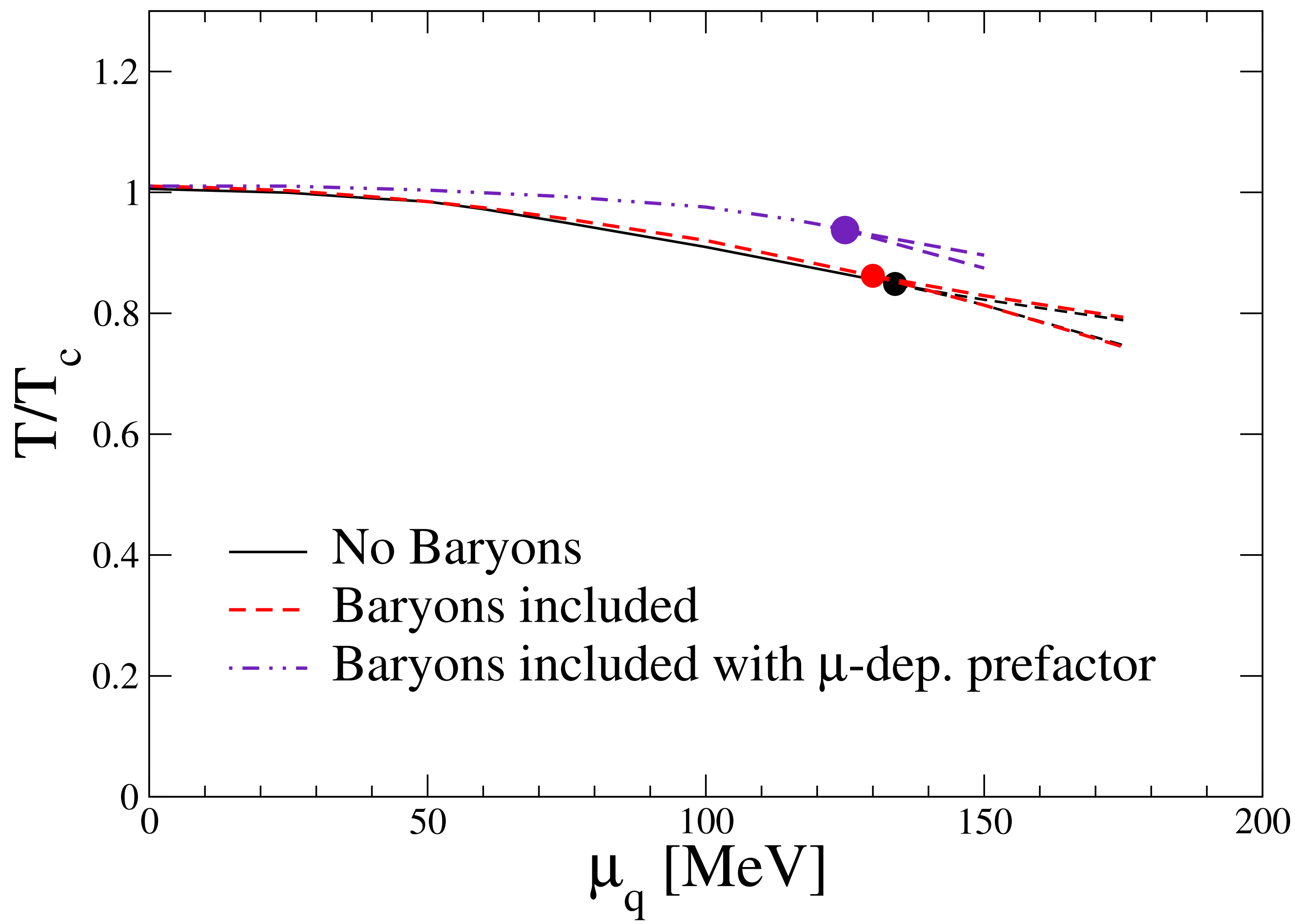


- Zero chemical potential: no effects after rescaling
- CEP: almost no effects

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

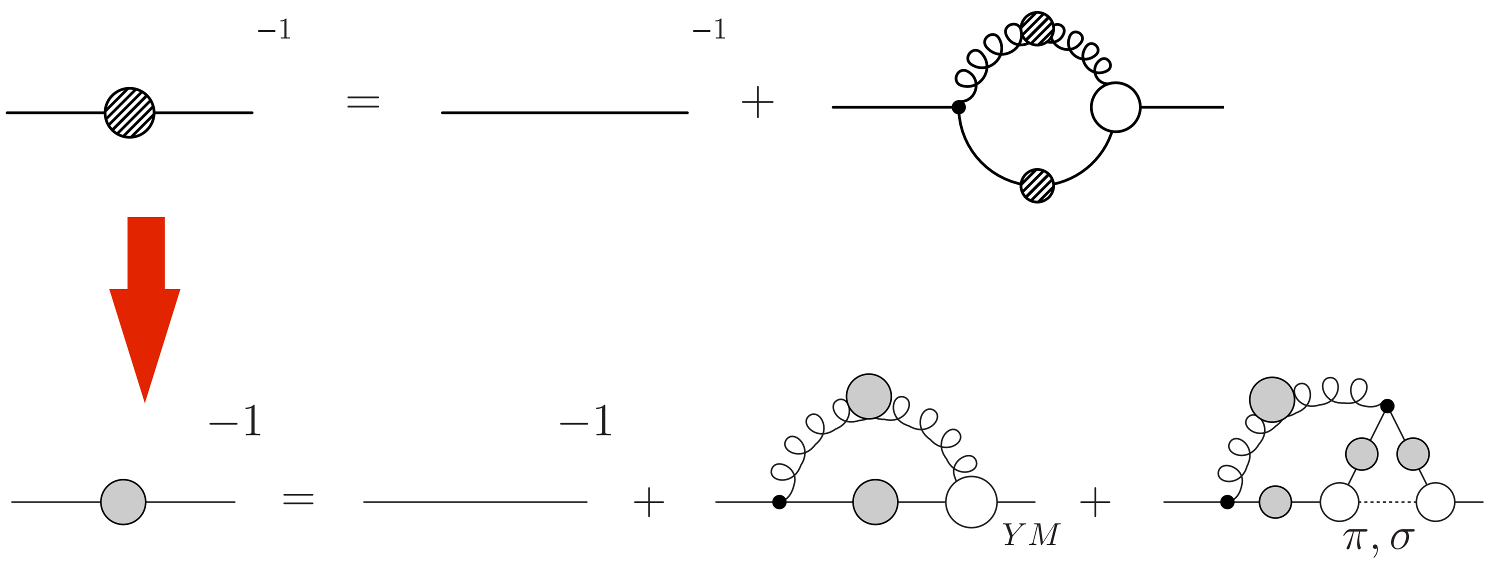
QCD with finite chemical potential:

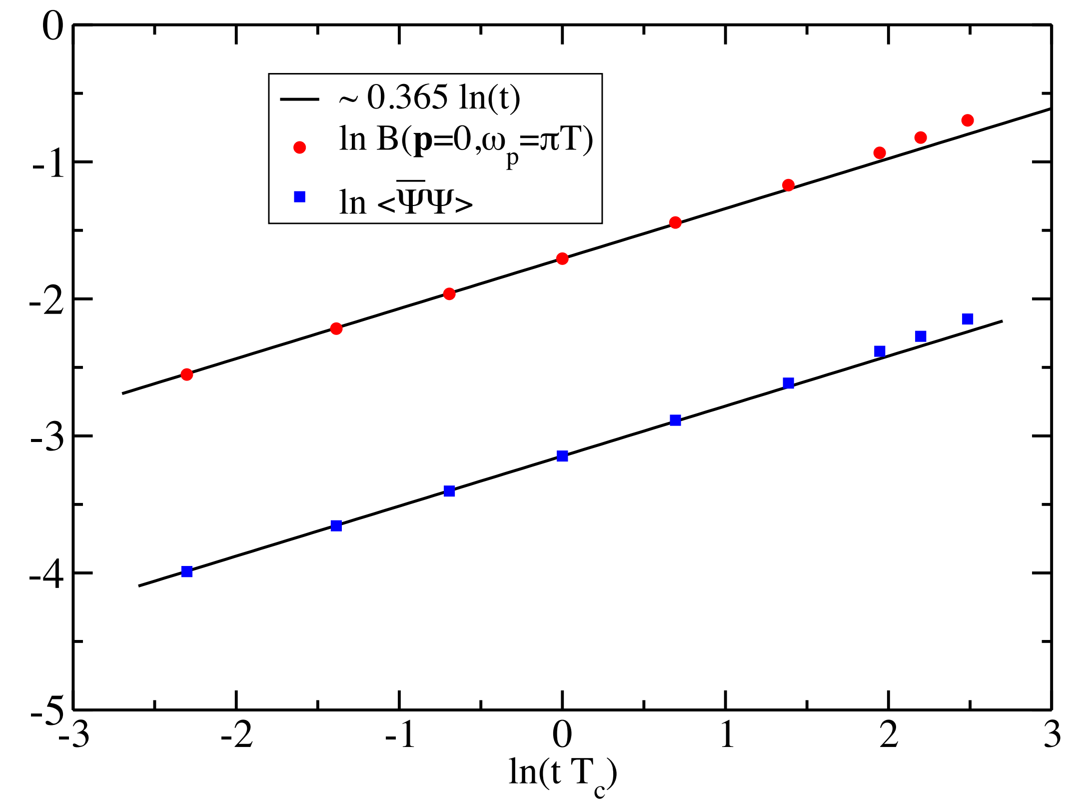
- back-reaction of quarks onto gluons important
- N_f=2+1 and N_f=2+1+1: CEP at $\mu_c/T_c > 3$
- charm quark does not influence CEP
- Baryon effects may or may not be significant for CEP…

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

Backup

Critical scaling from DSEs





- Need to take meson part of vertex explicitly into account
- T=0: meson cloud corrections of order of 10-20 %
  CF, Williams, PRD 78 (2008) 074006
- T=T_c: meson corrections are dominant !
- Critical scaling: $\langle\bar{\Psi}\Psi\rangle(t) \sim B(t) \sim t^{\nu/2}$

$$f^2_{\pi,s} \sim t^\nu \qquad (t = (T_c - T)/T_c)$$

CF and Mueller, PRD 84 (2011) 054013