QCD's phase diagram from DSEs

Christian S. Fischer

Justus Liebig Universität Gießen

JINR Dubna 2018

CF, Mueller, PRD 84 (2011) 054013
CF, Luecker, PLB 718 (2013) 1036,
CF, Luecker, Welzbacher, PRD 90 (2014) 034022
Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]

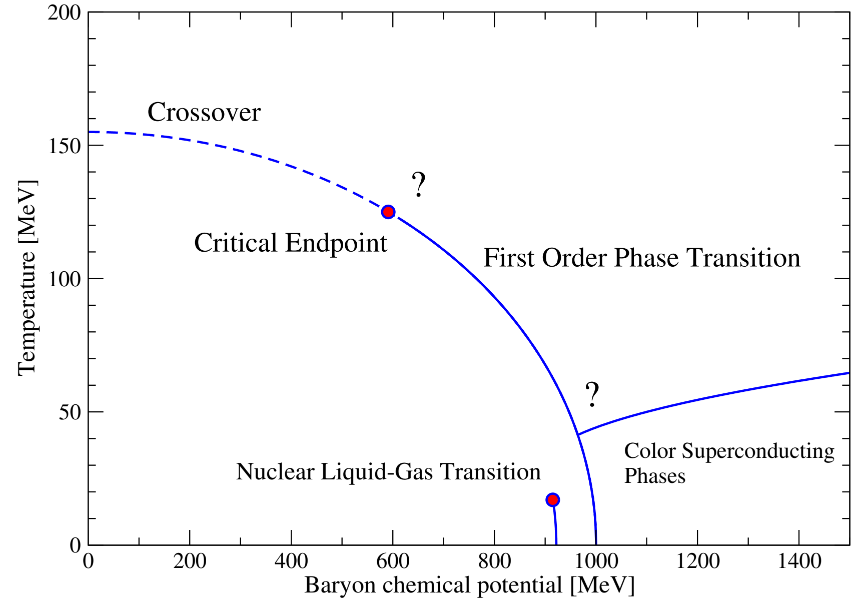
Review: CF, in preparation

Bundesministerium für Bildung und Forschung

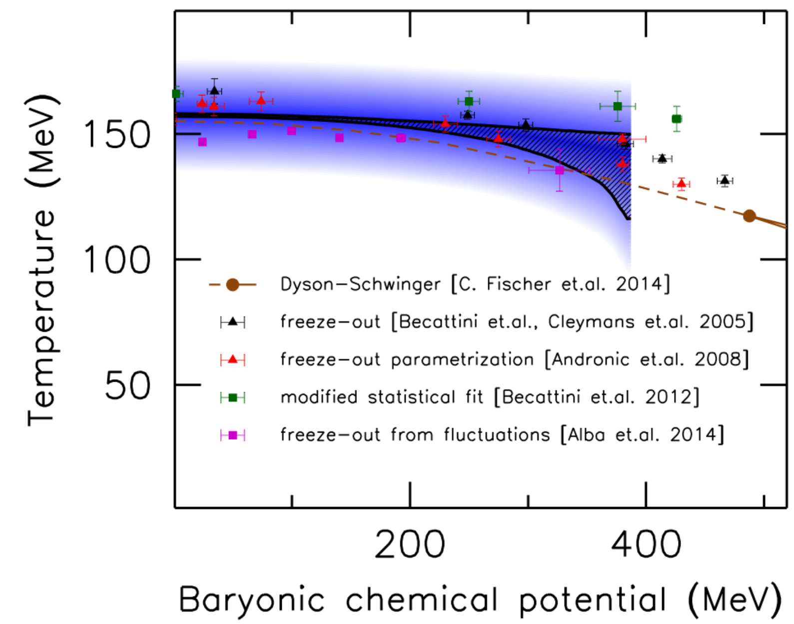
HIC for FAIR Helmholtz International Center

Overview

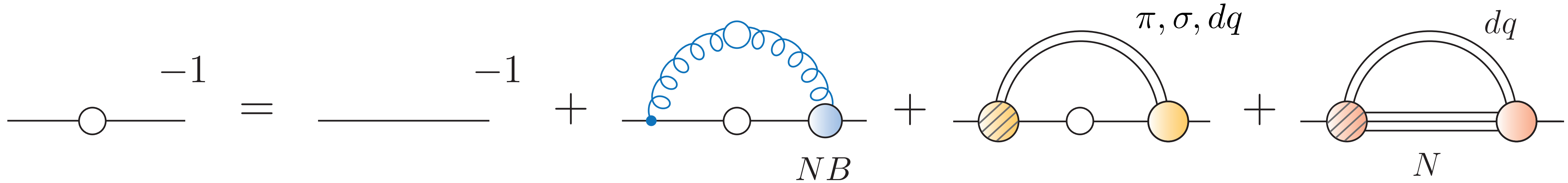
1. Introduction



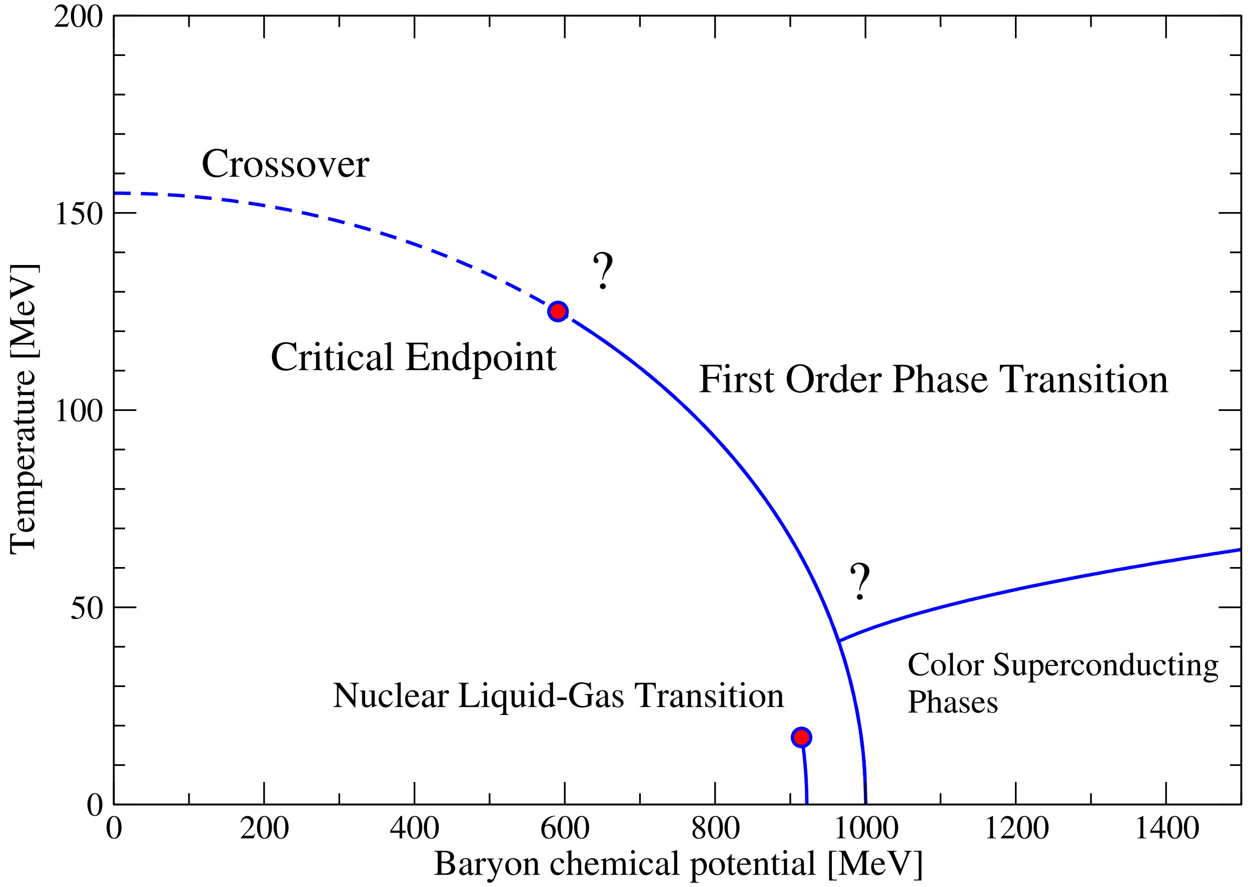
2. Gluons, quarks and the CEP



3. Hadron effects on the phase diagram



QCD phase transitions



$$Z\left(\frac{\mu_B}{T}\right) = Z\left(-\frac{\mu_B}{T}\right)$$

$$\left(\frac{T(\mu_B)}{T_c}\right)^2 = 1 + 2\kappa\left(\frac{\mu_B}{T_c}\right)^2$$

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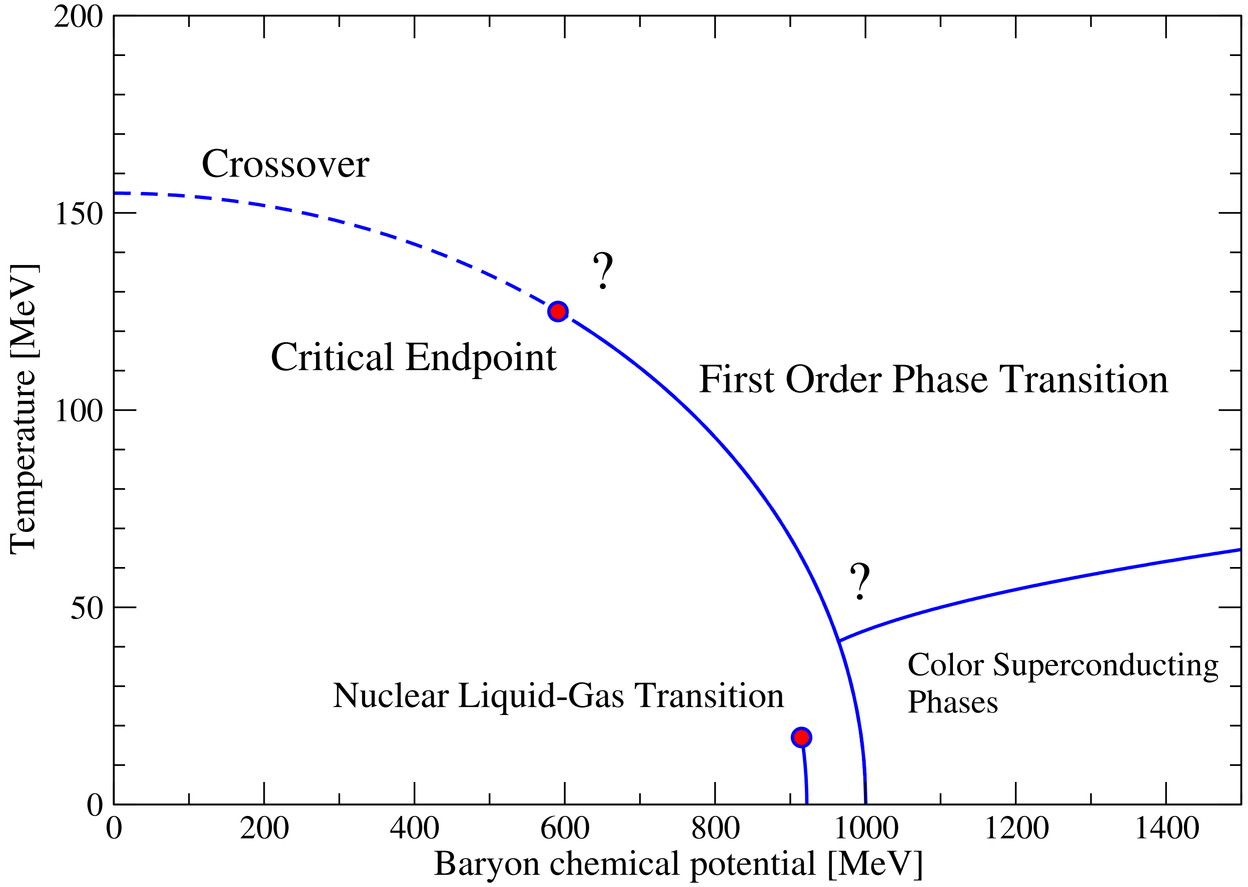

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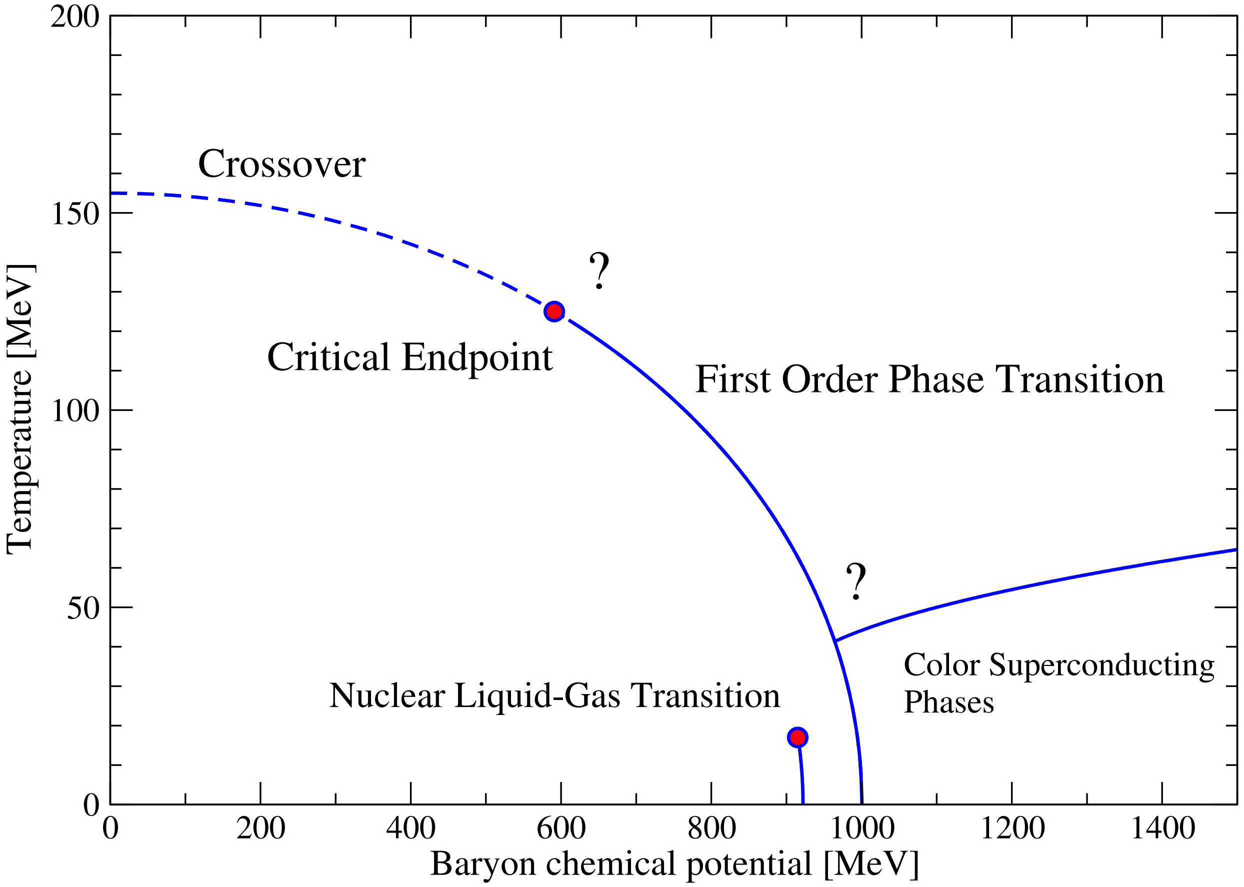

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Bonati et al., arXiv:1805.02960

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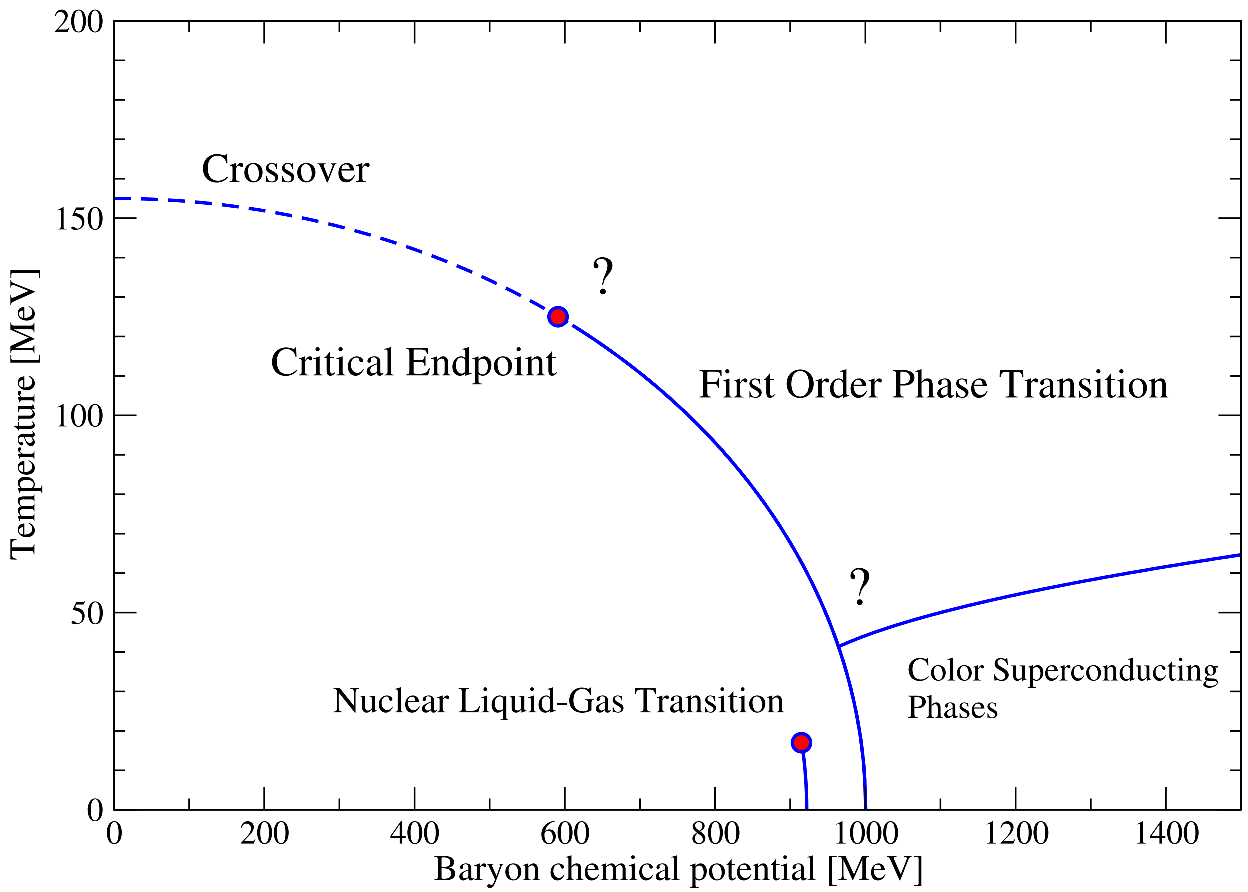

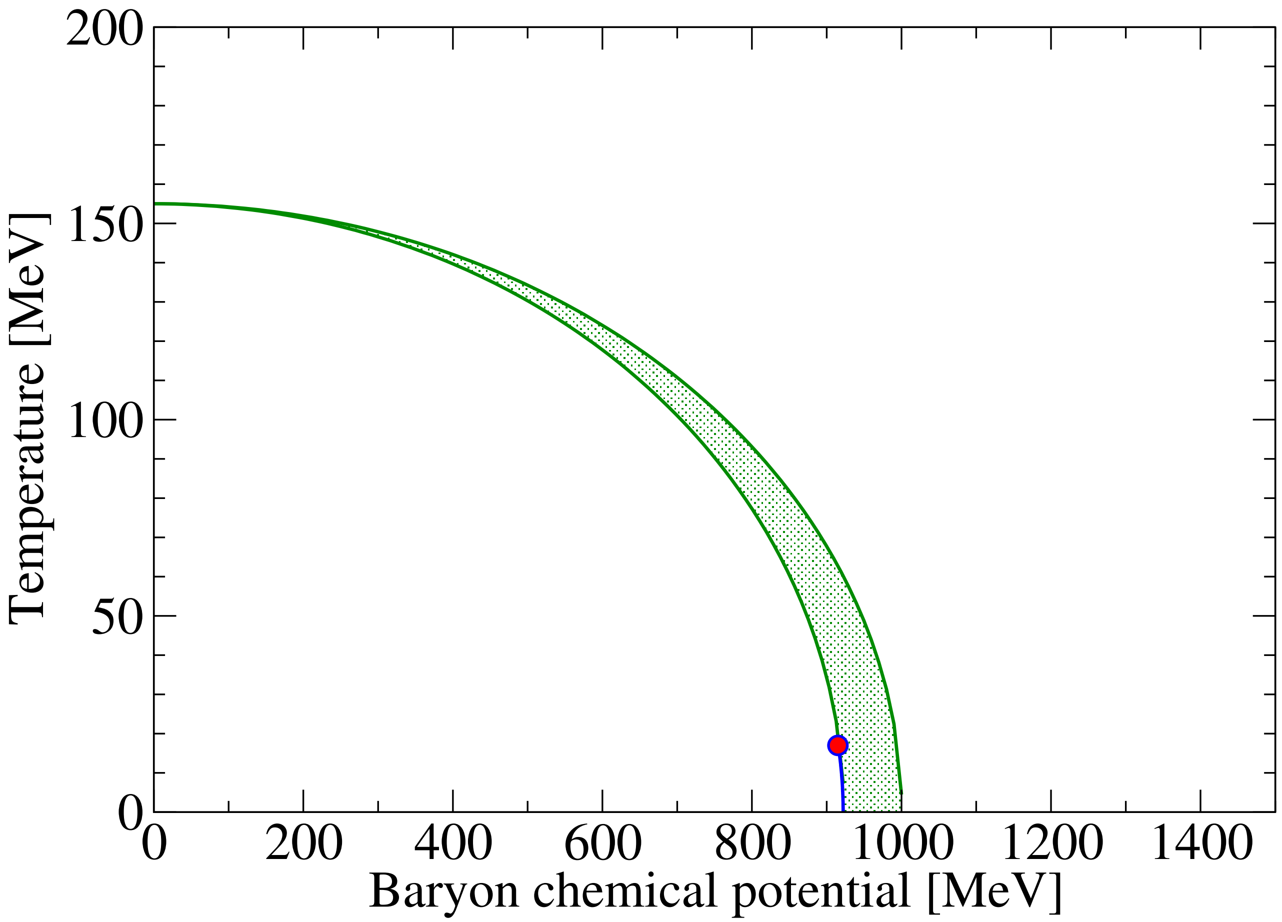

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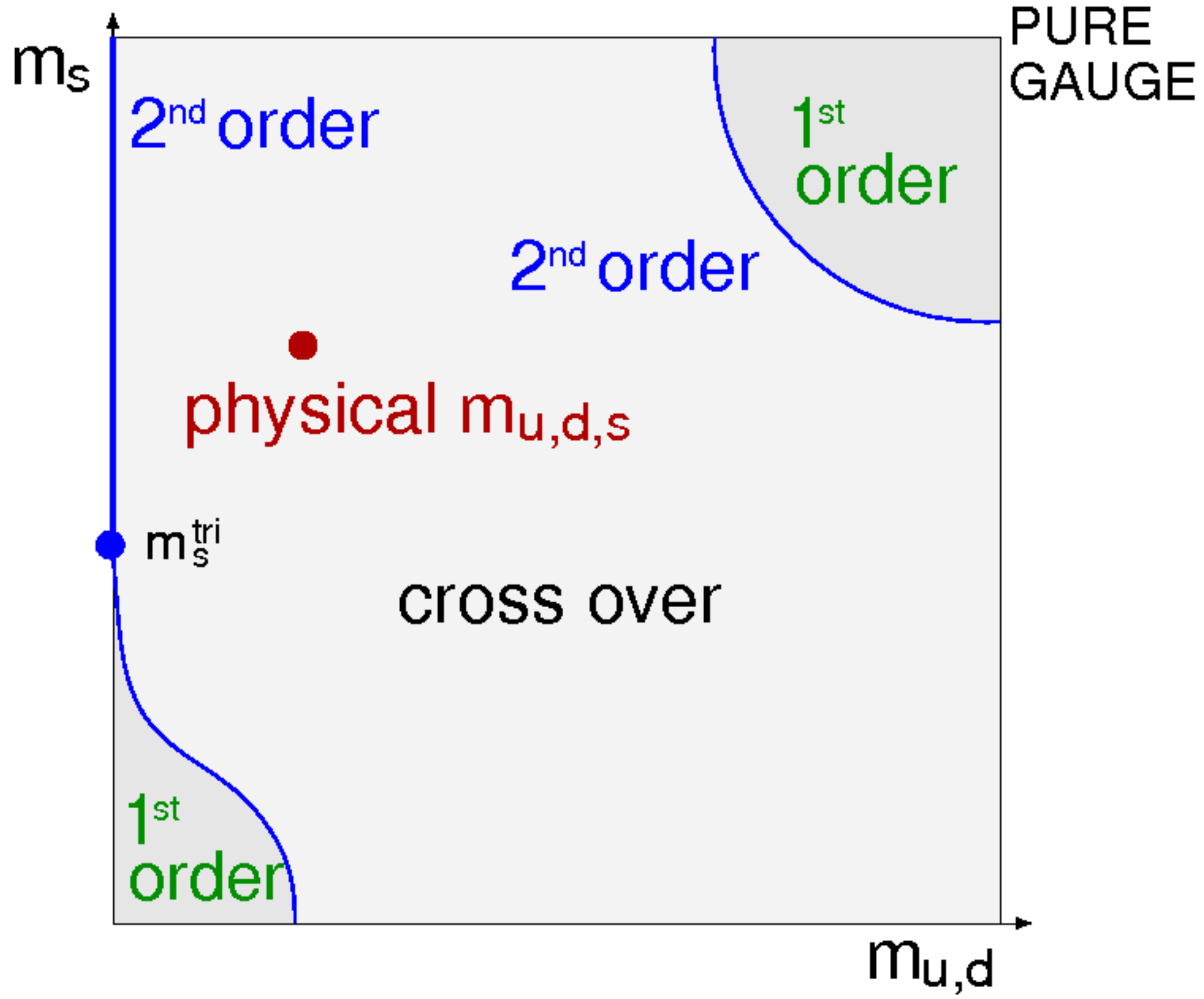
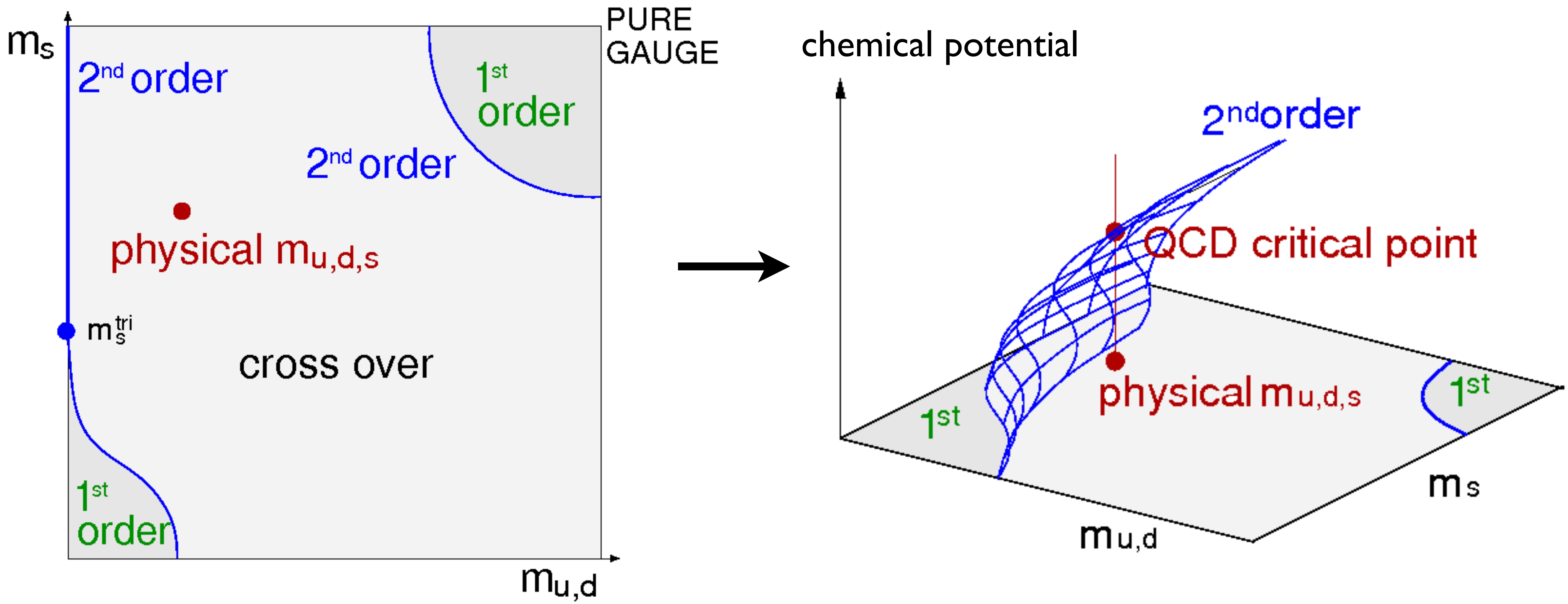


Is this happening ??
Maybe yes, maybe not..

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

QCD phase transitions



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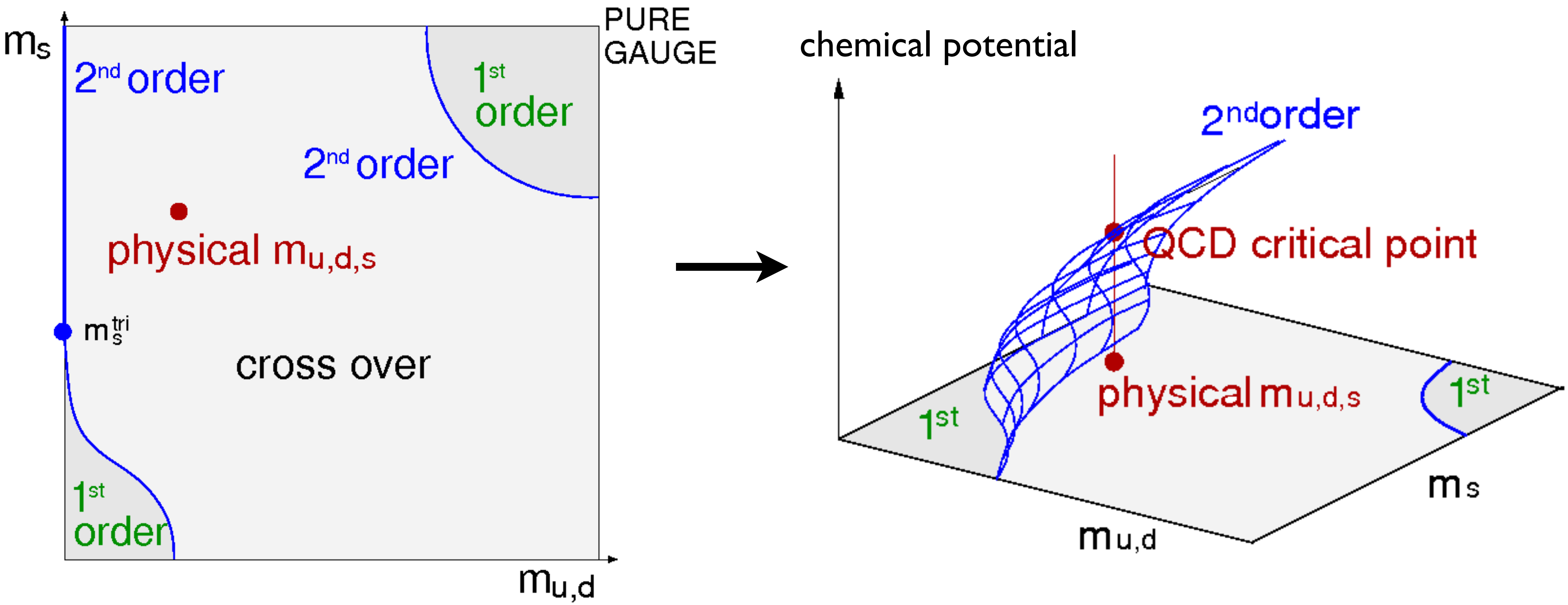

- Lattice-QCD
  - present: extrapolation
  - future: exact methods ?
- DSE/FRG
  - not exact, but allow for '10%-physics'

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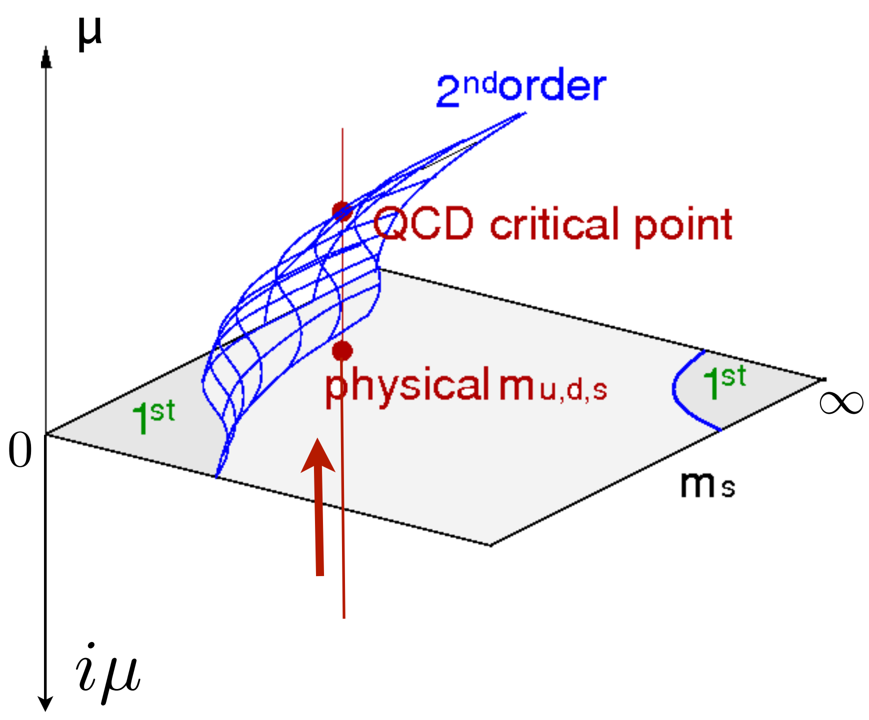
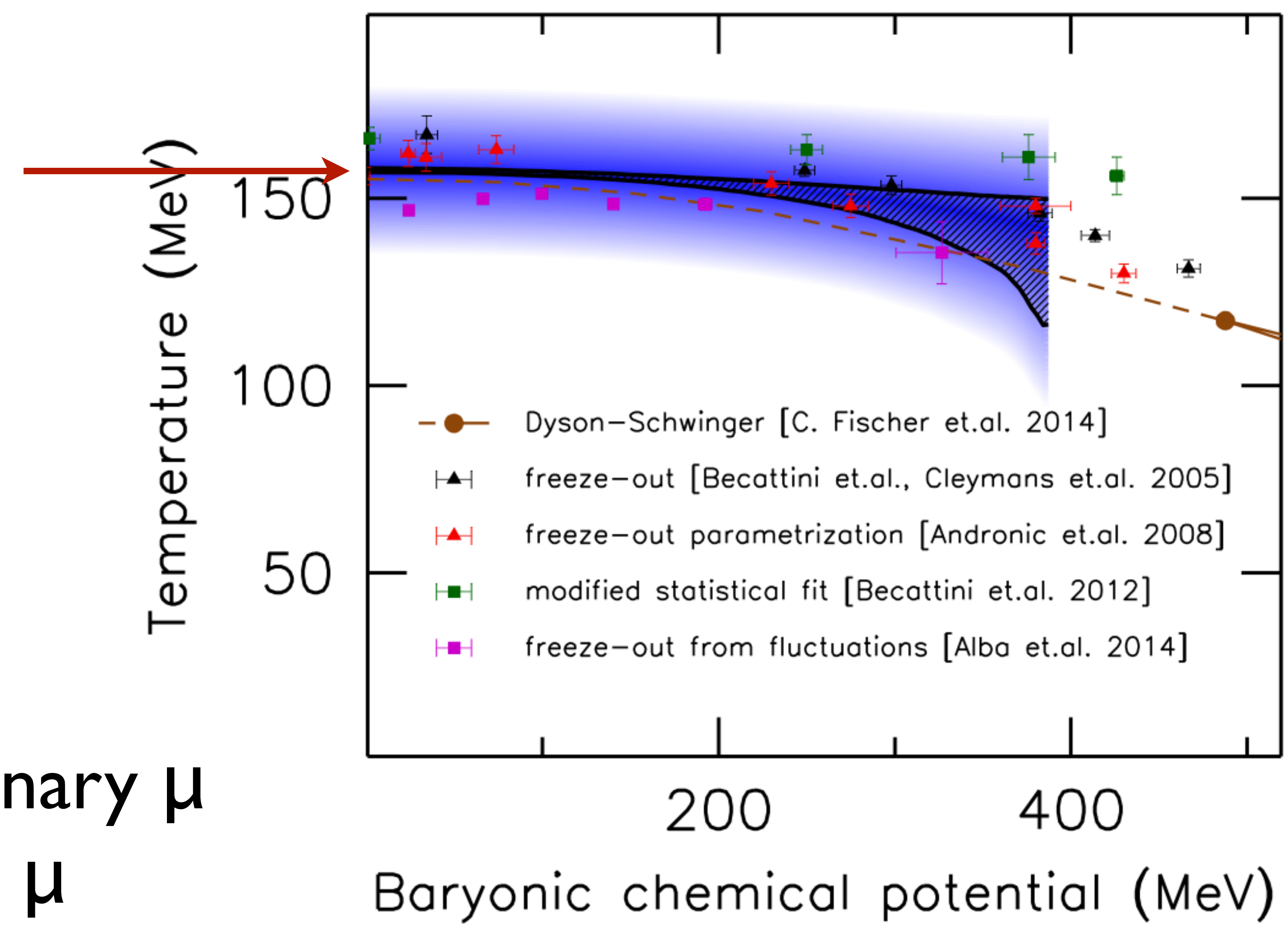
Chiral transition line from analytic continuation





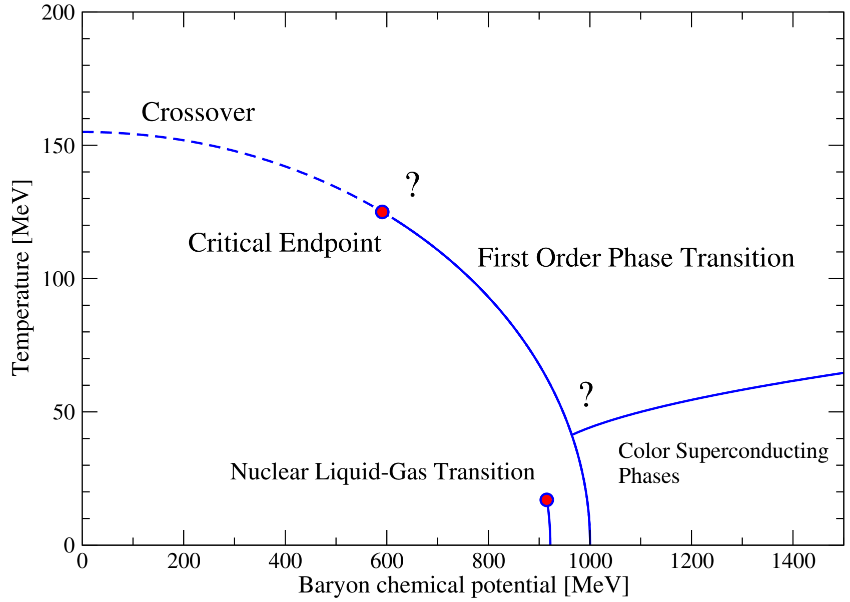
Bellwied, Borsanyi, Fodor, Günther,
Katz, Ratti and Szabo, PLB 751 (2015) 559

Lattice method:

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

Main result:

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



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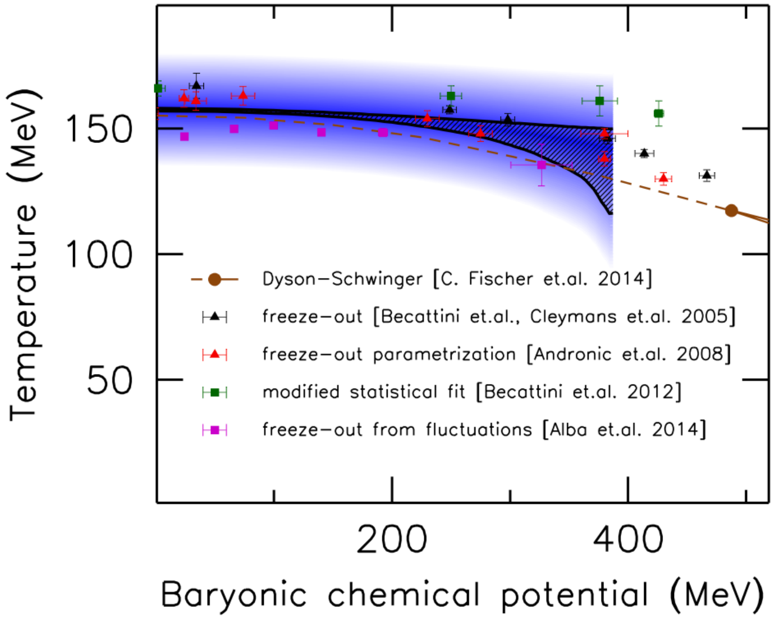

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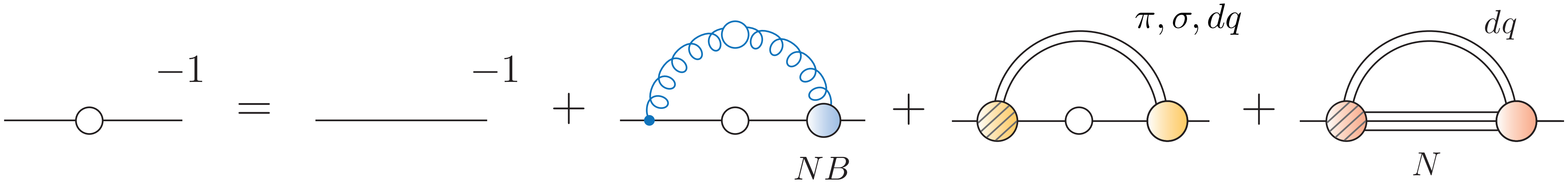
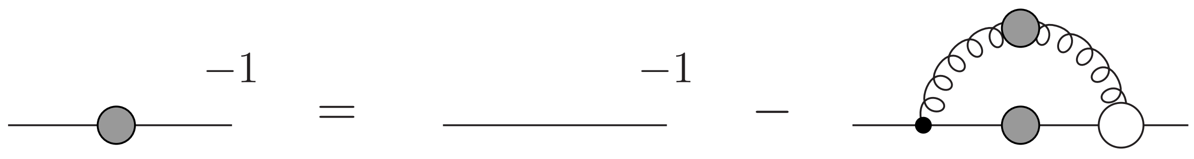


QCD order parameters from propagators



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

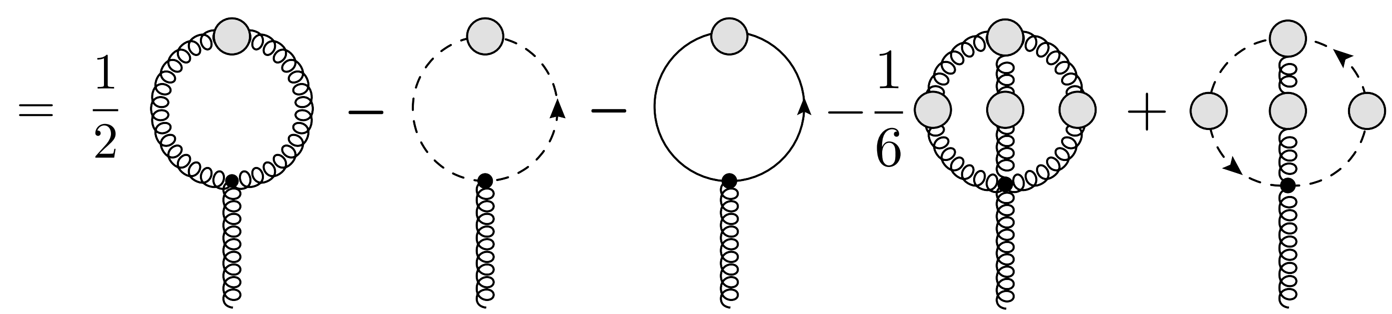
$$\Sigma = -\int_0^{2\pi} \frac{d\varphi}{2\pi} e^{-i\varphi} \langle\bar\Psi\Psi\rangle_\varphi$$

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

- Polyakov loop potential

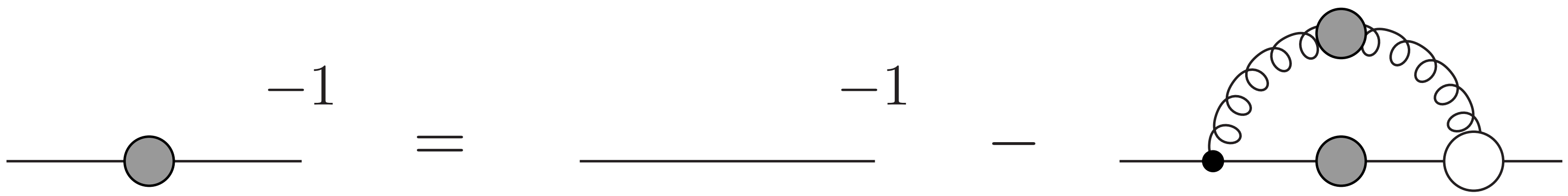
$$L = \frac{1}{N_c} Tr\, e^{ig\beta A_0}$$

$$\frac{\delta(\Gamma - S)}{\delta A_0} =$$



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)

The DSE for the quark propagator



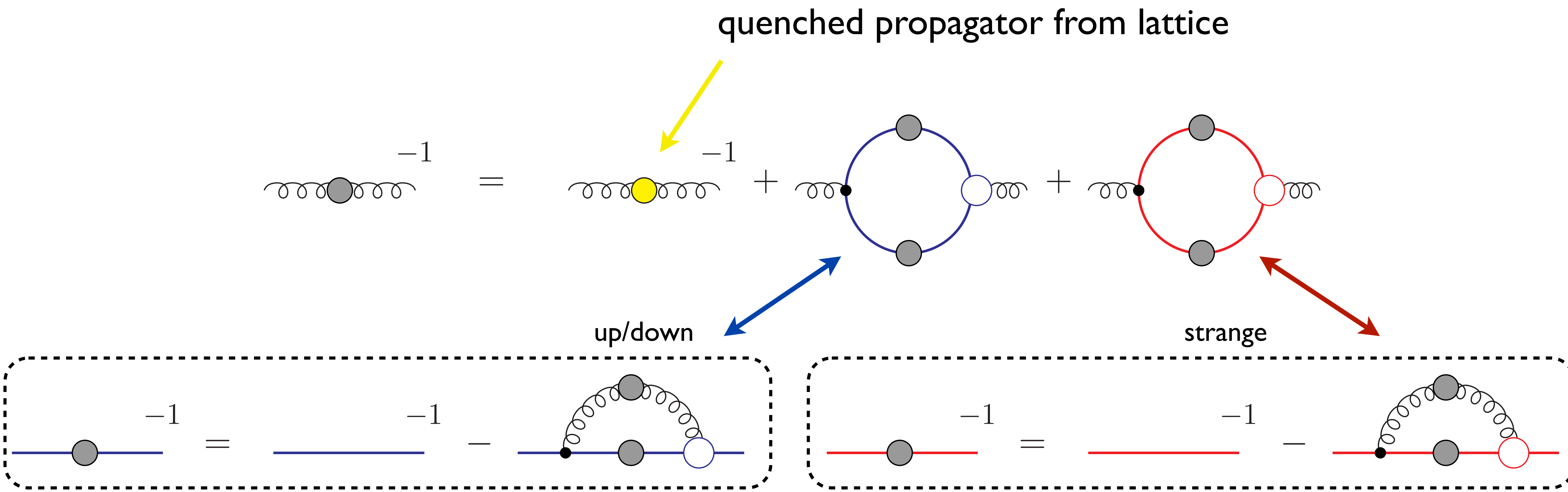
Two strategies: I. use model for gluon

Qin, Chang, Chen, Liu and Roberts, PRL 106 (2011) 172301
Y. Jiang, L.-J. Luo, and H.-S. Zong, JHEP 02 (2011) 066
Gutierrez, Ahmad, Ayala, Bashir and Raya, JPG 41 (2014) 075002
C. Shi, Y.-L. Du, S.-S. Xu, X.-J. Liu, and H.-S. Zong, PRD93 (2016) no. 3, 036006
F. Gao and Y.-x. Liu, PRD 94 (2016) no. 7, 076009
F. Gao and Y.-x. Liu, PRD 94 (2016) no. 9, 094030

→ valuable for exploratory studies
→ not good enough for quantitative and/or systematic studies

II. treat Yang-Mills sector explicitly

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 behavior → T,μ,m-dependent

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

⟶ talk of Pawlowski

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

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

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

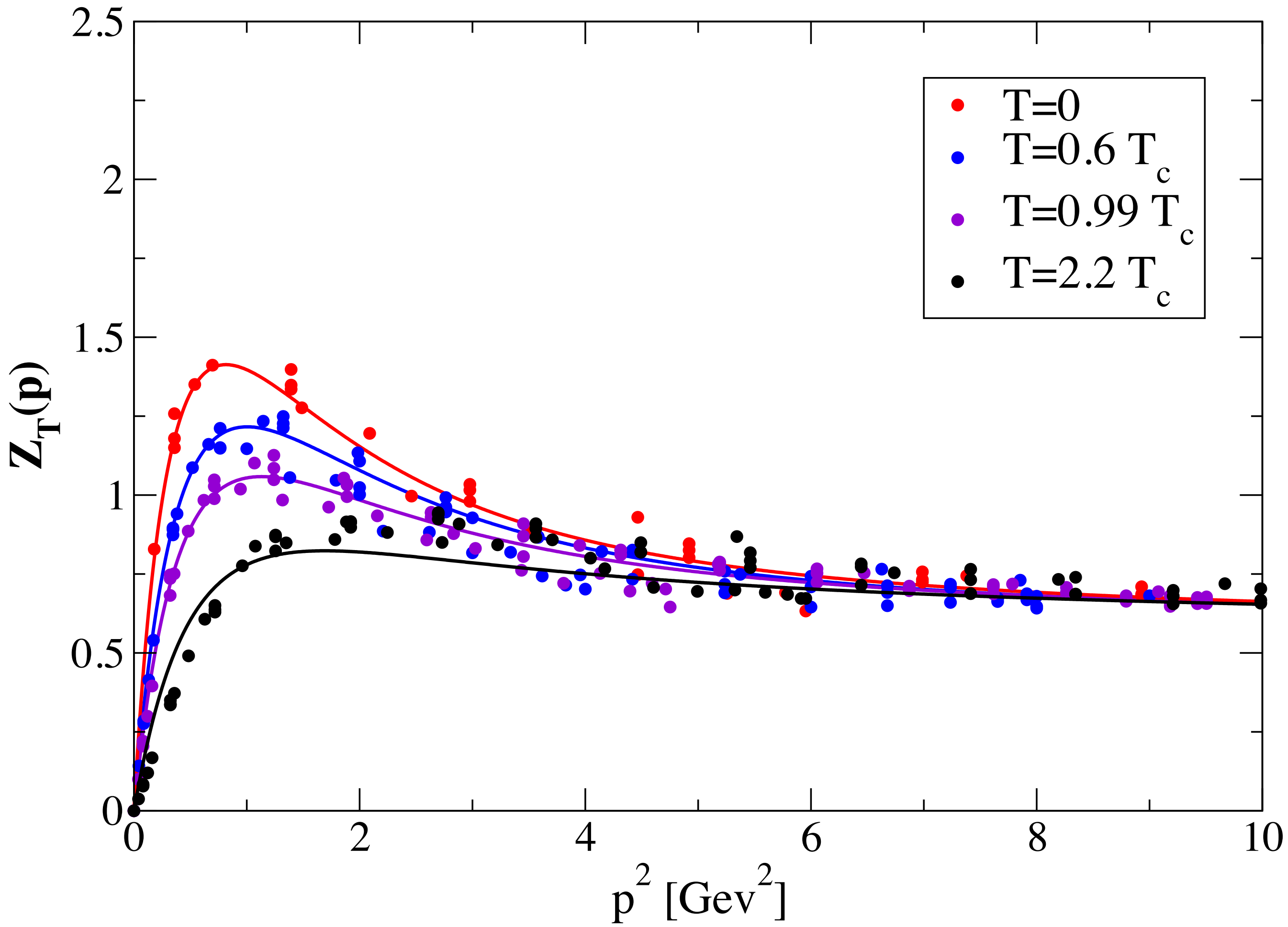
STI

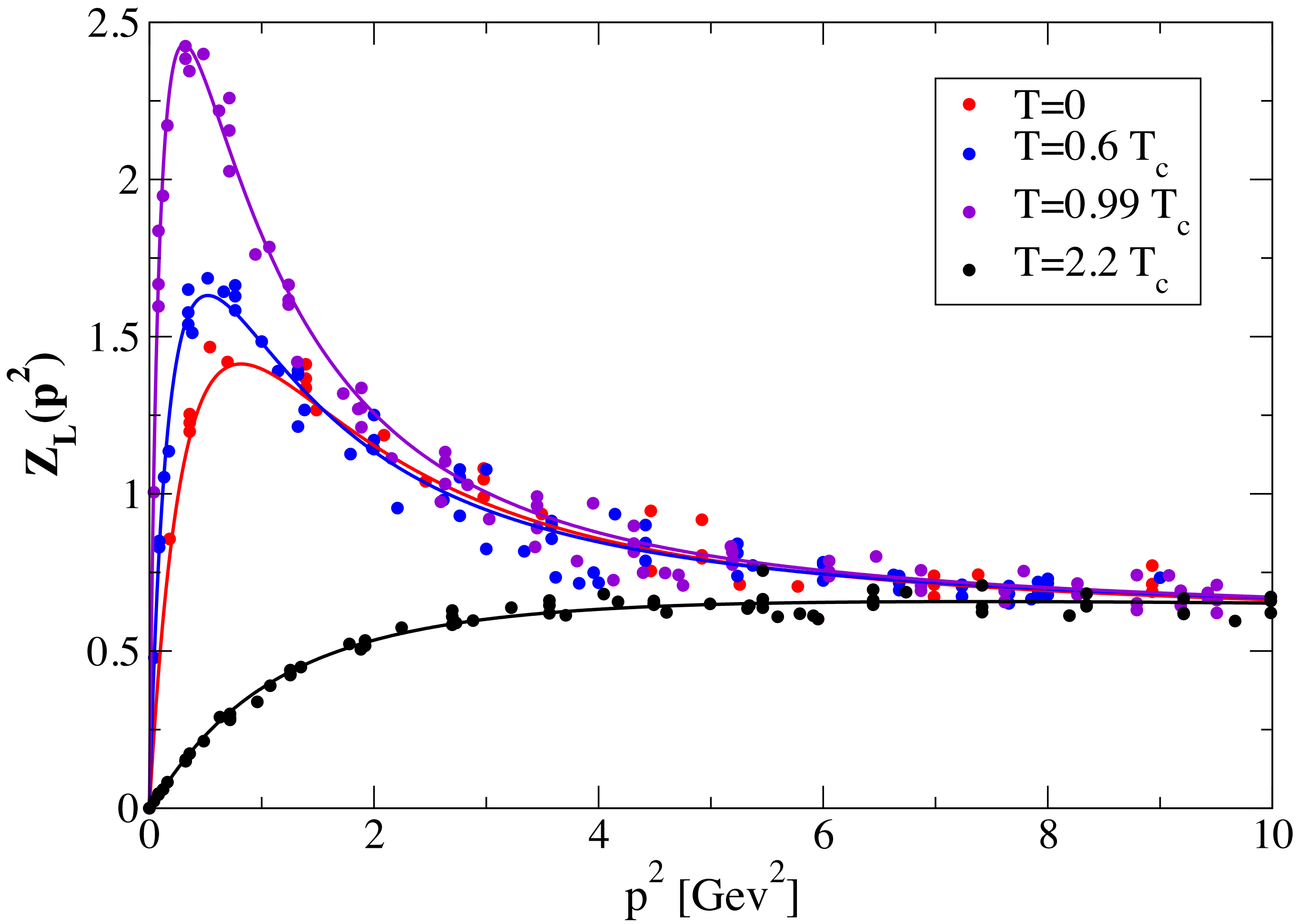
PT

- d1 fixed via T_c
- d2 fixed to match scale of lattice gluon input

Glue at finite temperature (T≠0)

T-dependent gluon propagator from quenched lattice simulations:



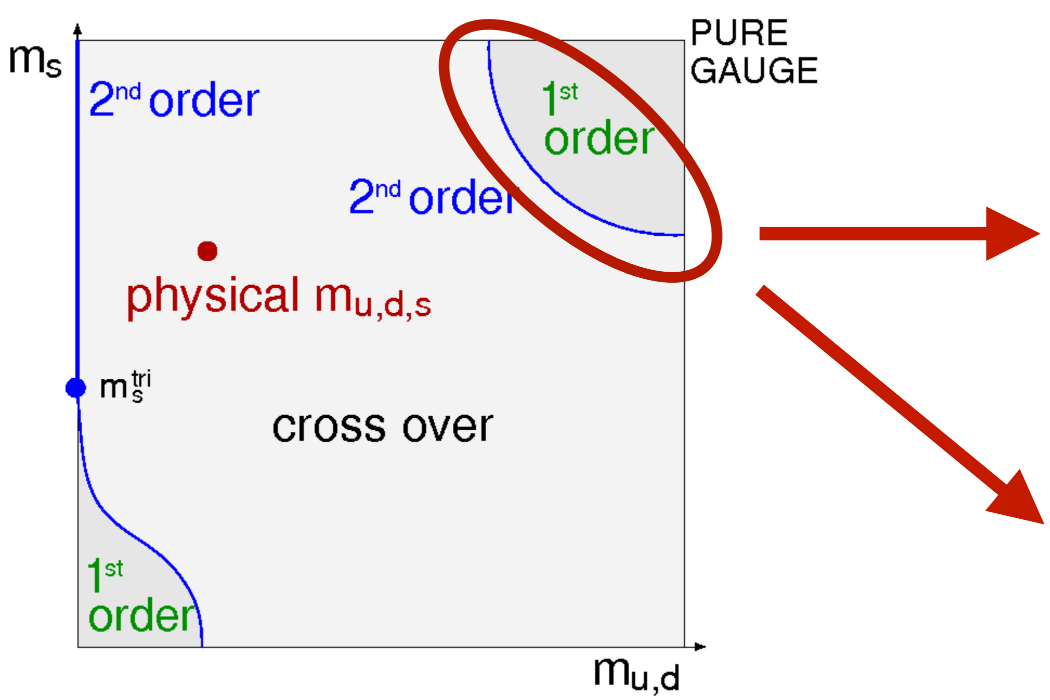


- Crucial difference between magnetic and electric gluon
- Maximum of electric gluon near Tc

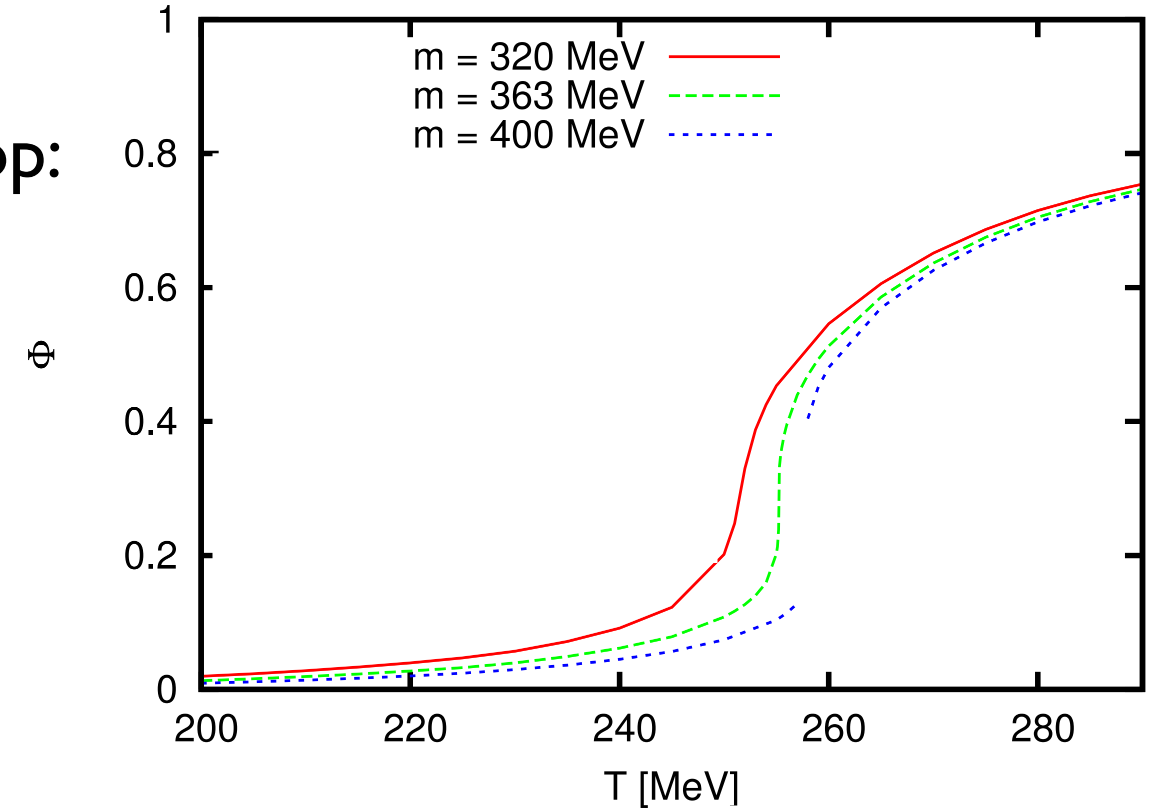
Cucchieri, Maas, Mendes, PRD 75 (2007)
CF, Maas, Mueller, EPJC 68 (2010)
Cucchieri, Mendes, PoS FACESQCD 007 (2010)
Aouane, Bornyakov, Ilgenfritz, Mitrjushkin, Muller-Preussker and Sternbeck, PRD 85 (2012) 034501
Silva, Oliveira, Bicudo, Cardoso, PRD 89 (2014) 074503

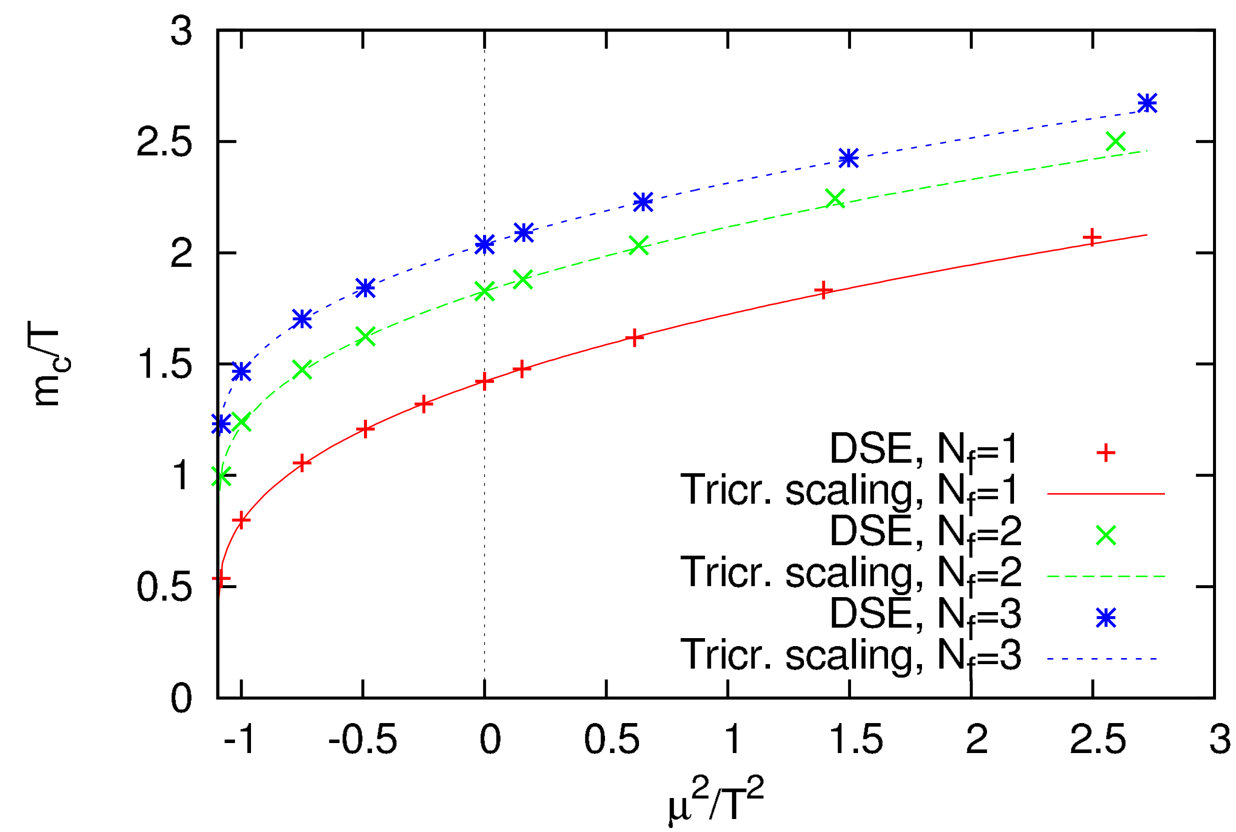
FRG: Fister, Pawlowski, arXiv:1112.5440

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

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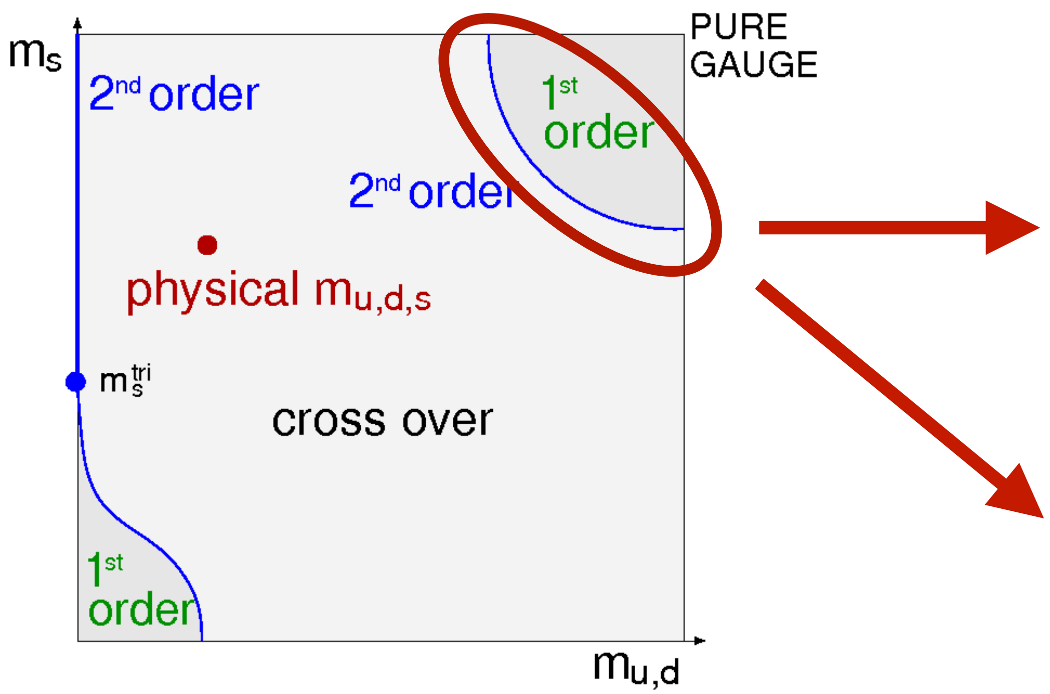

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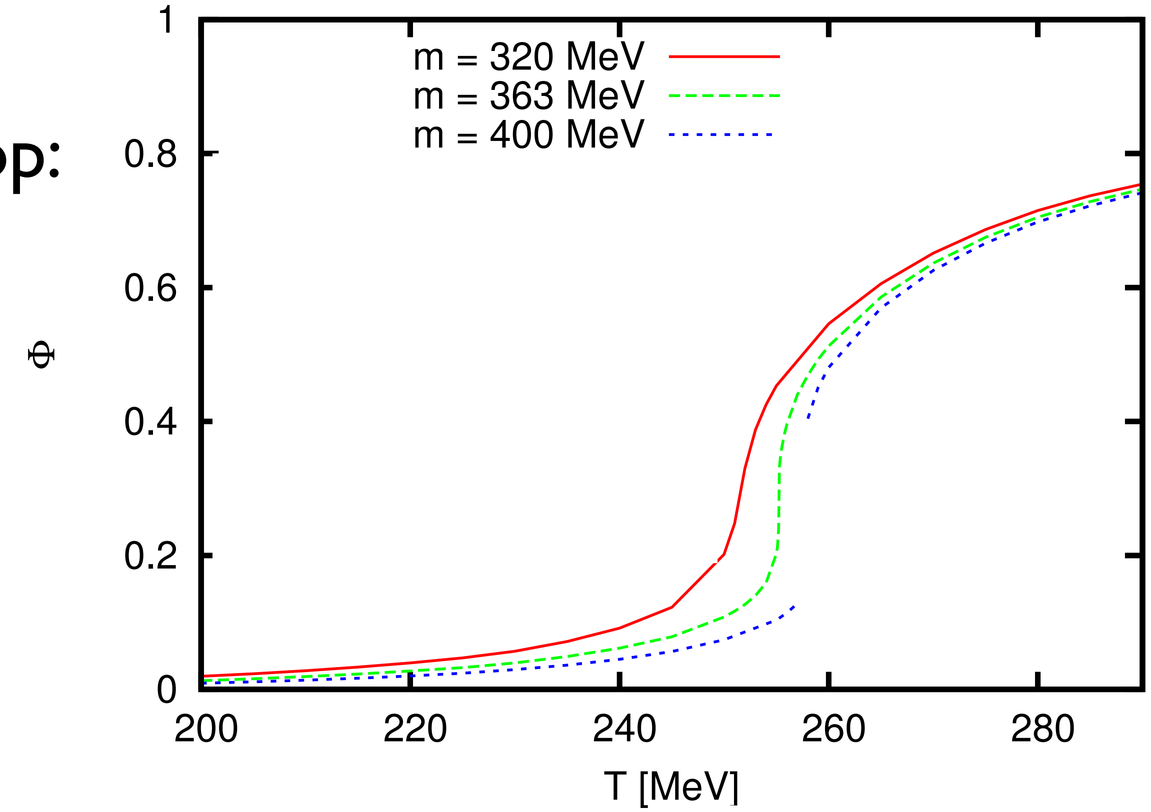

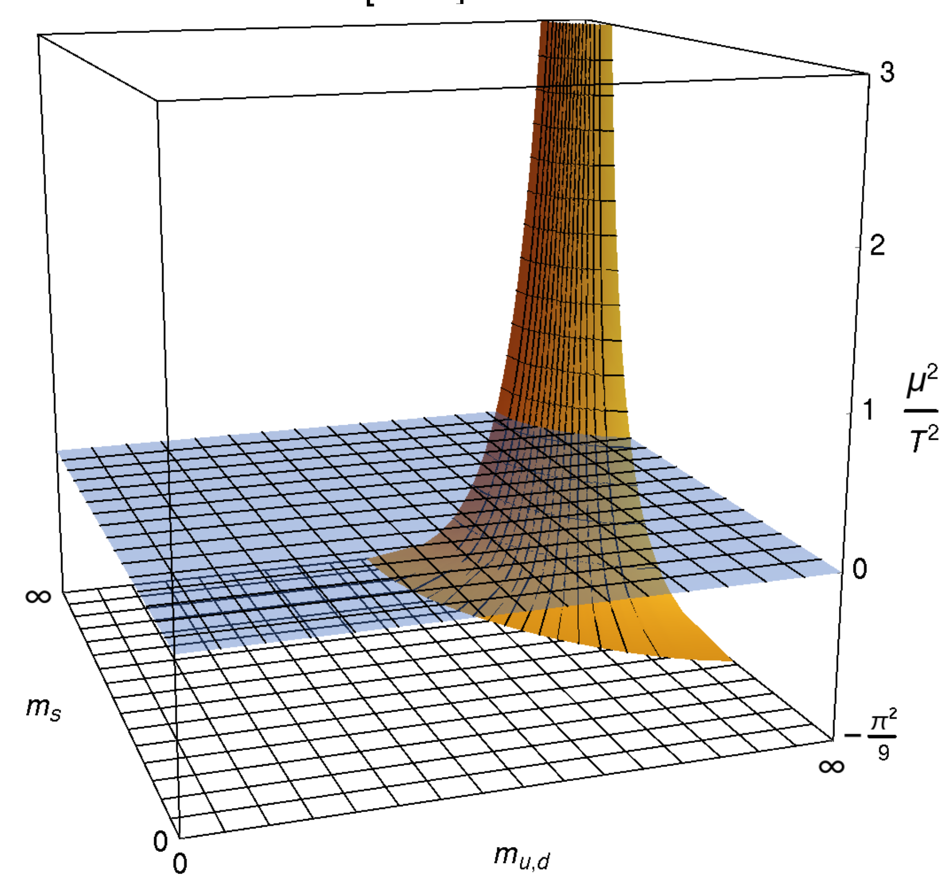

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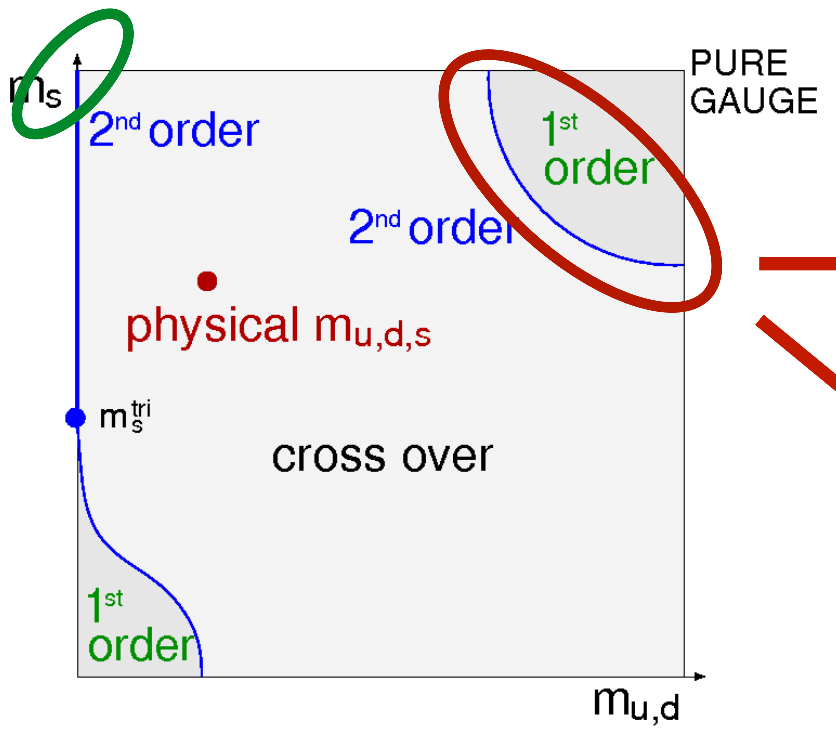
Nf=2: CF and Mueller, PRD 84 (2011) 054013



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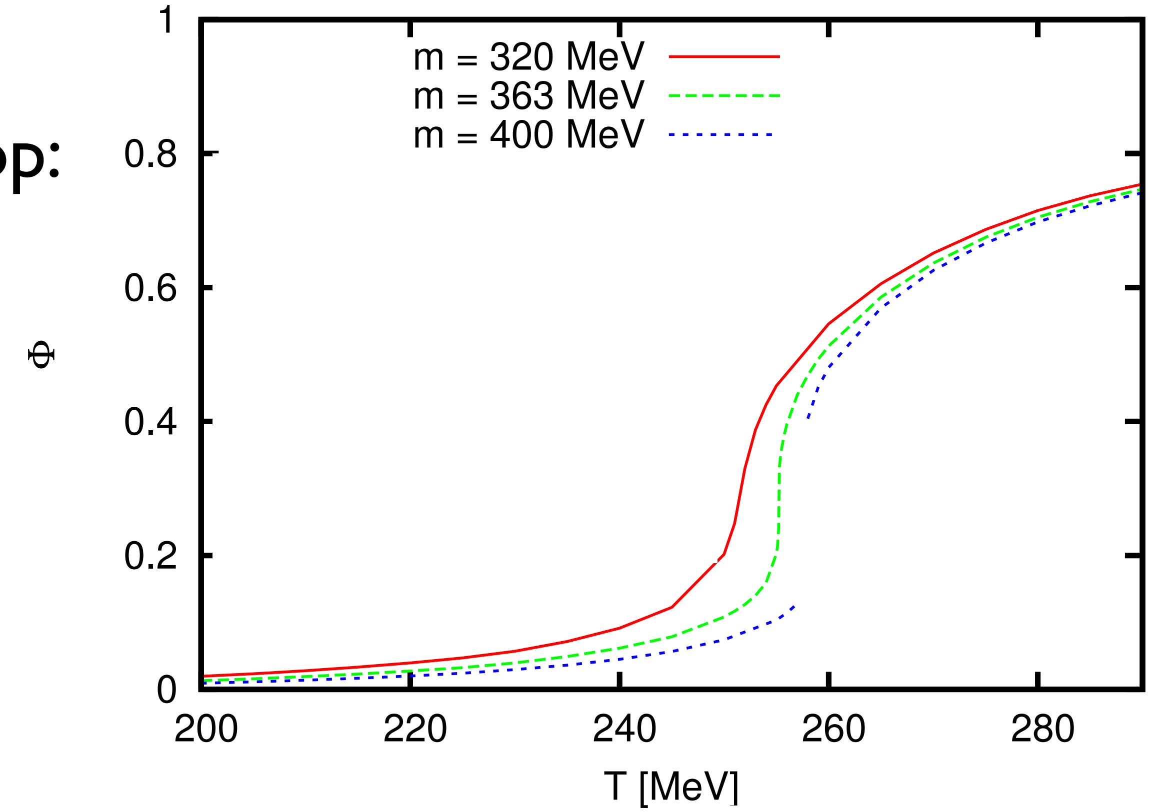

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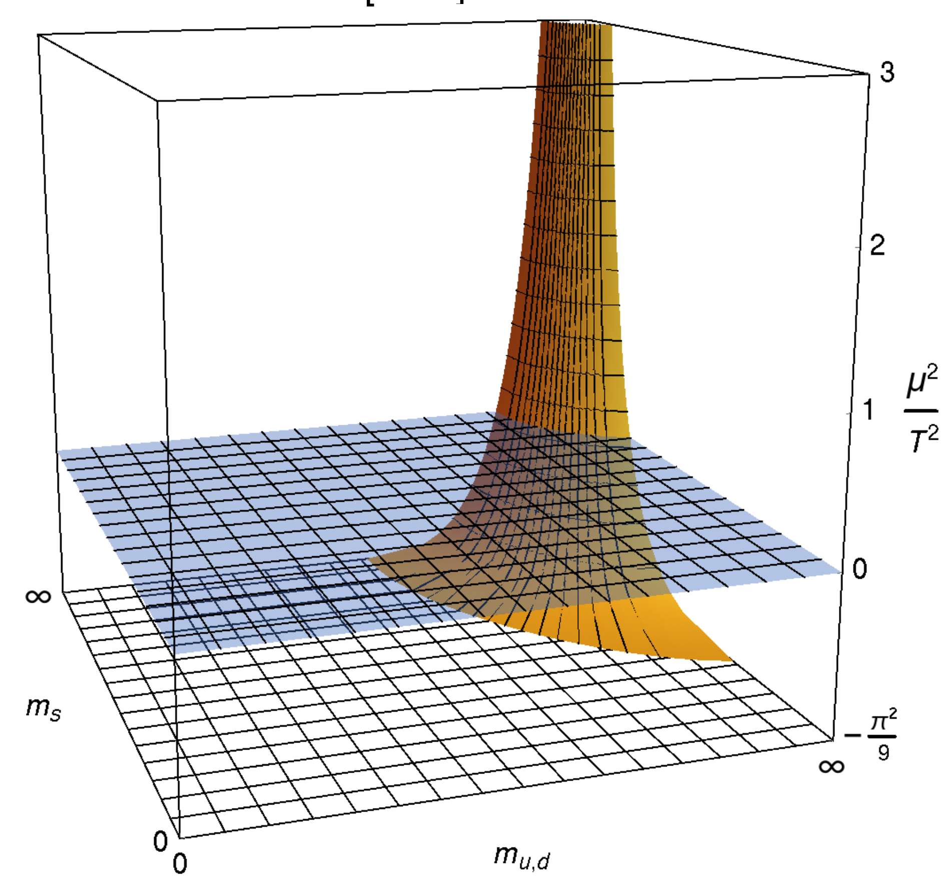

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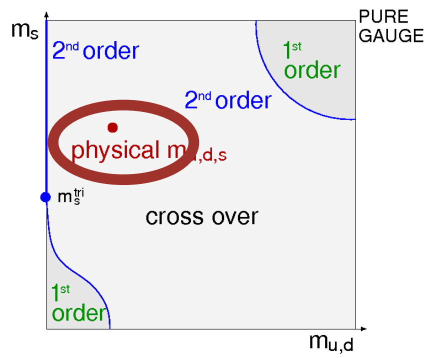
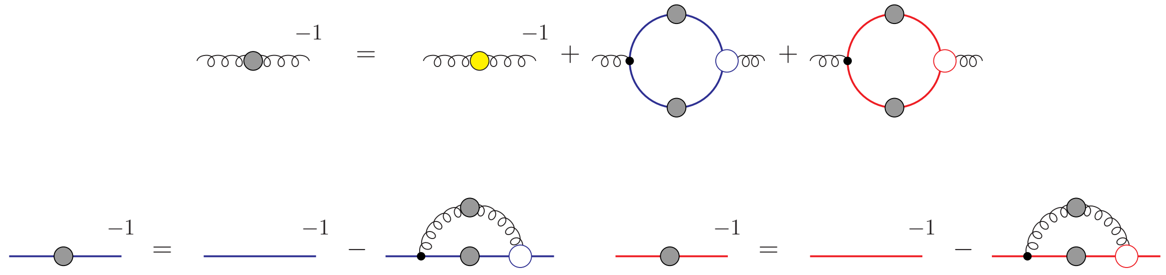
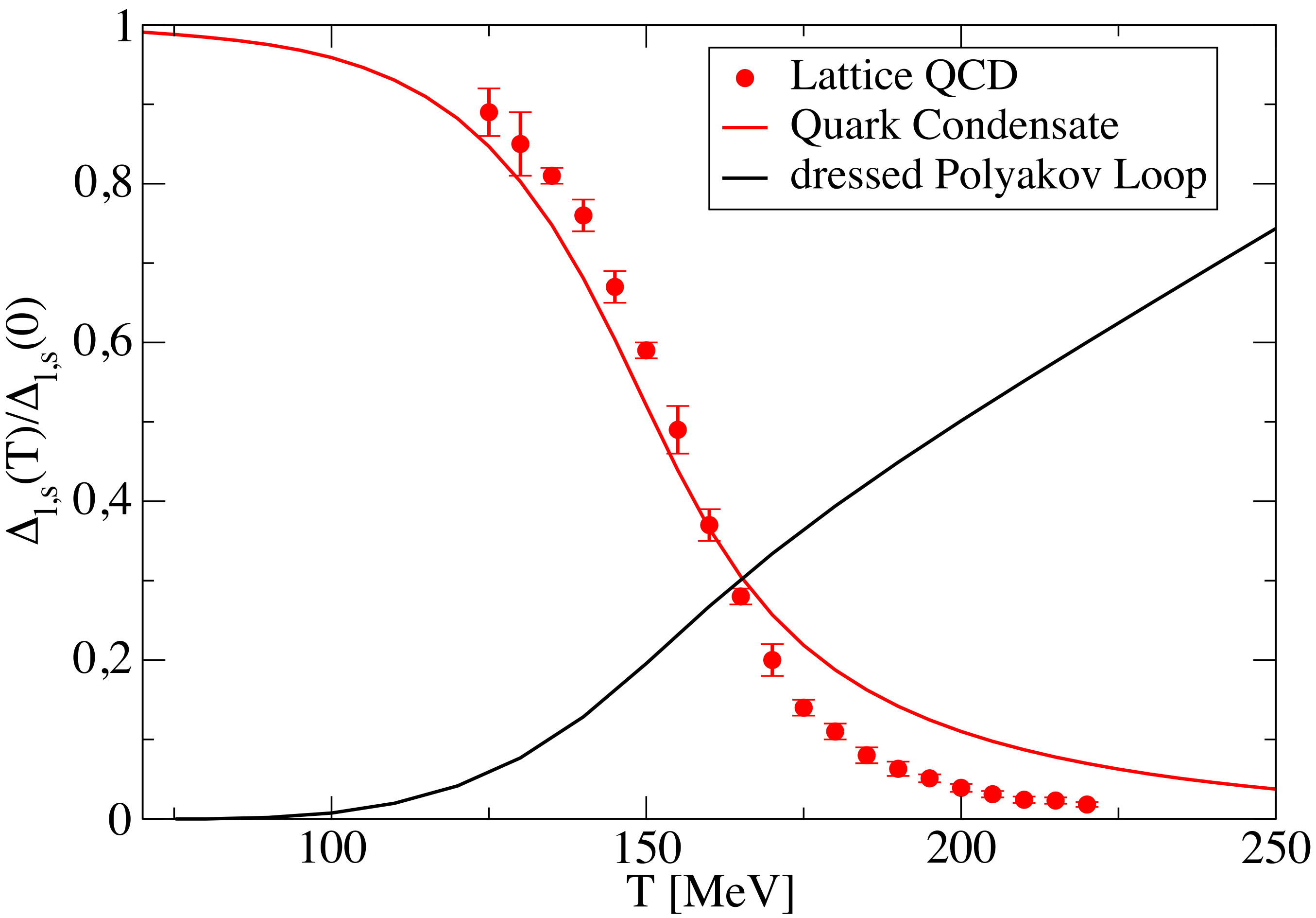
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

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

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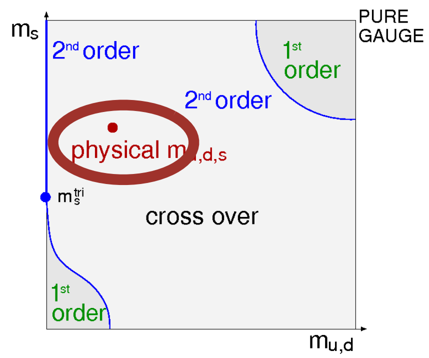

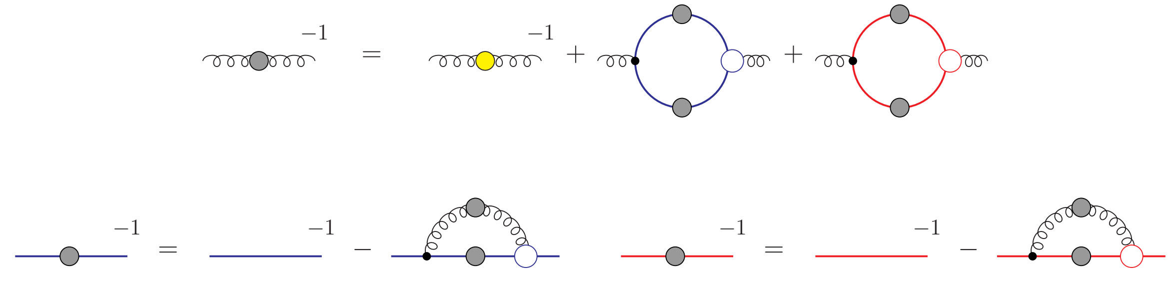

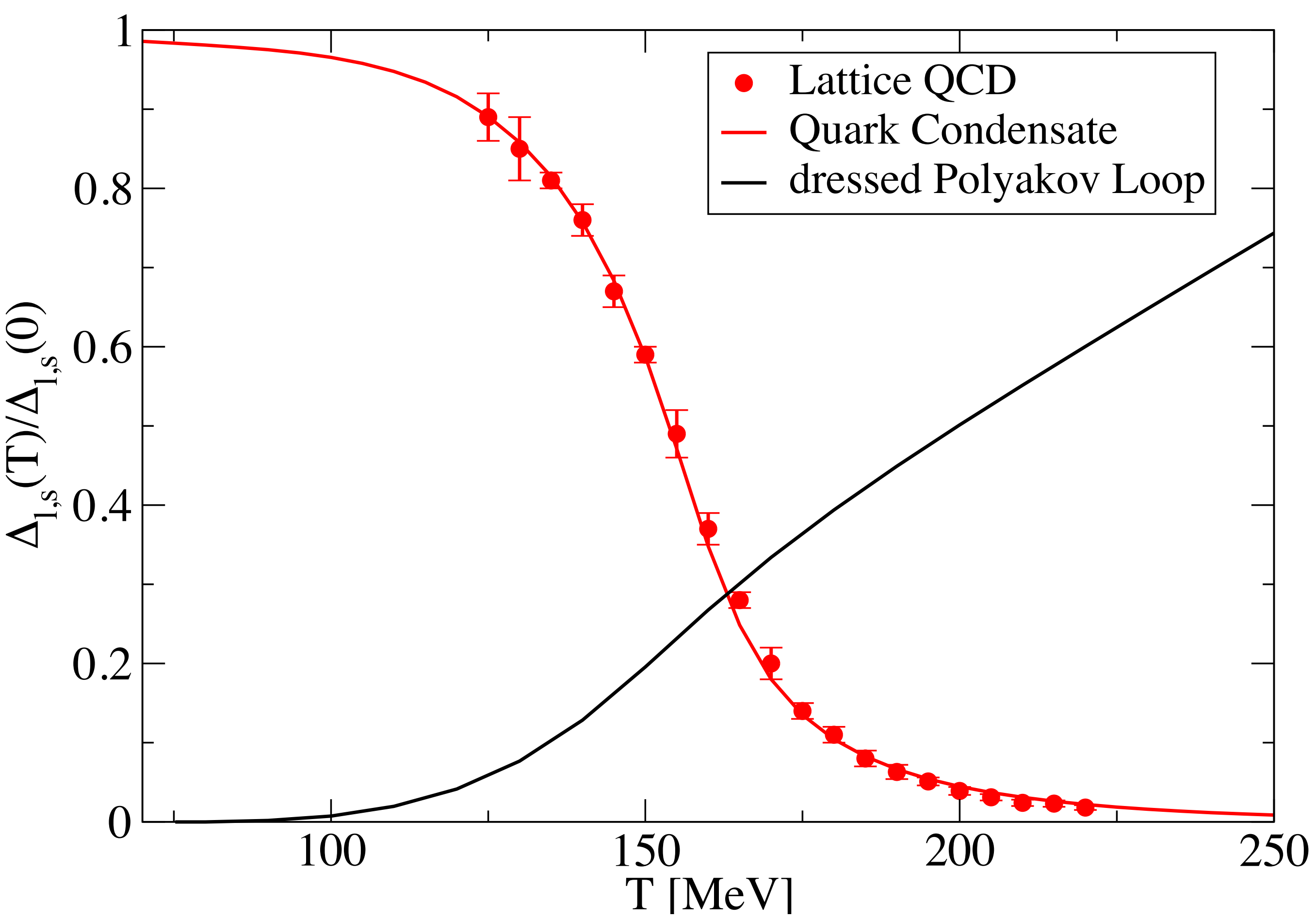

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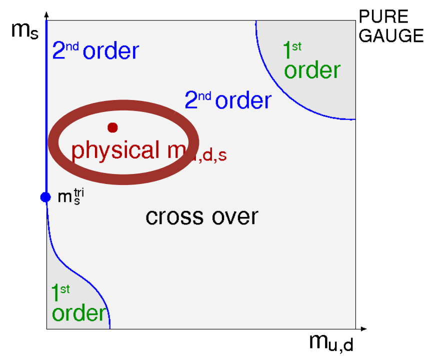

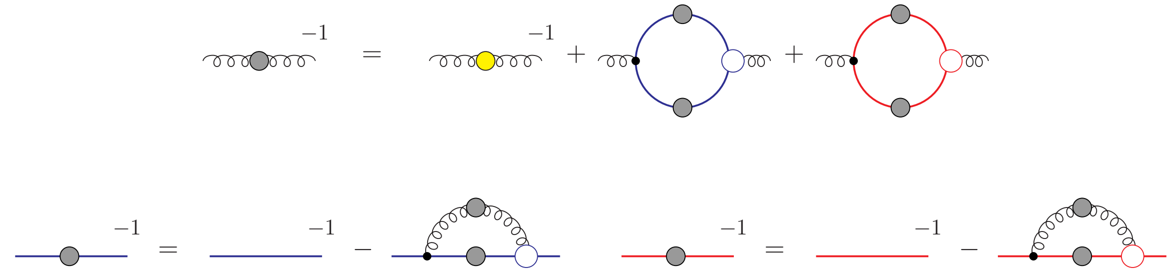

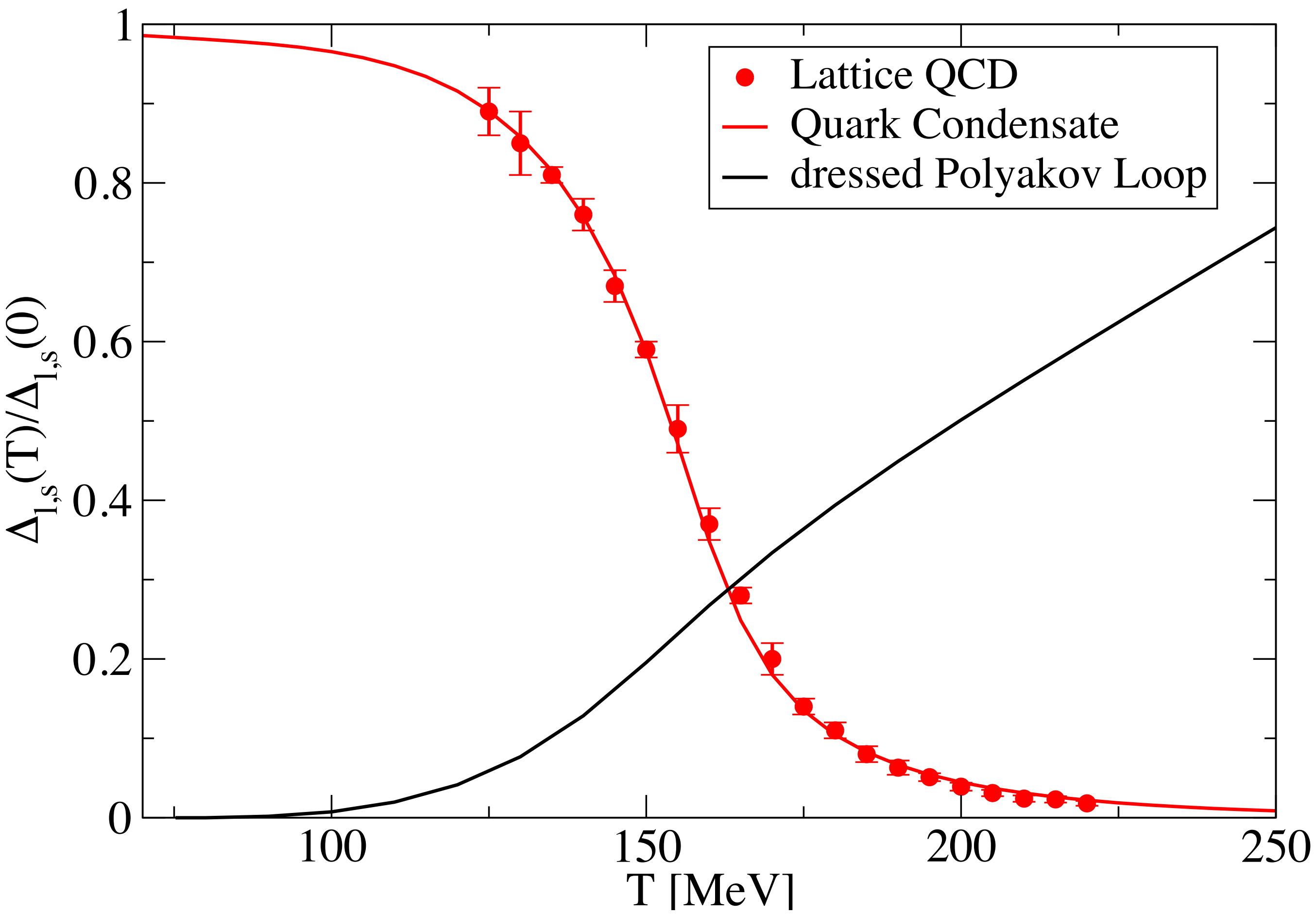

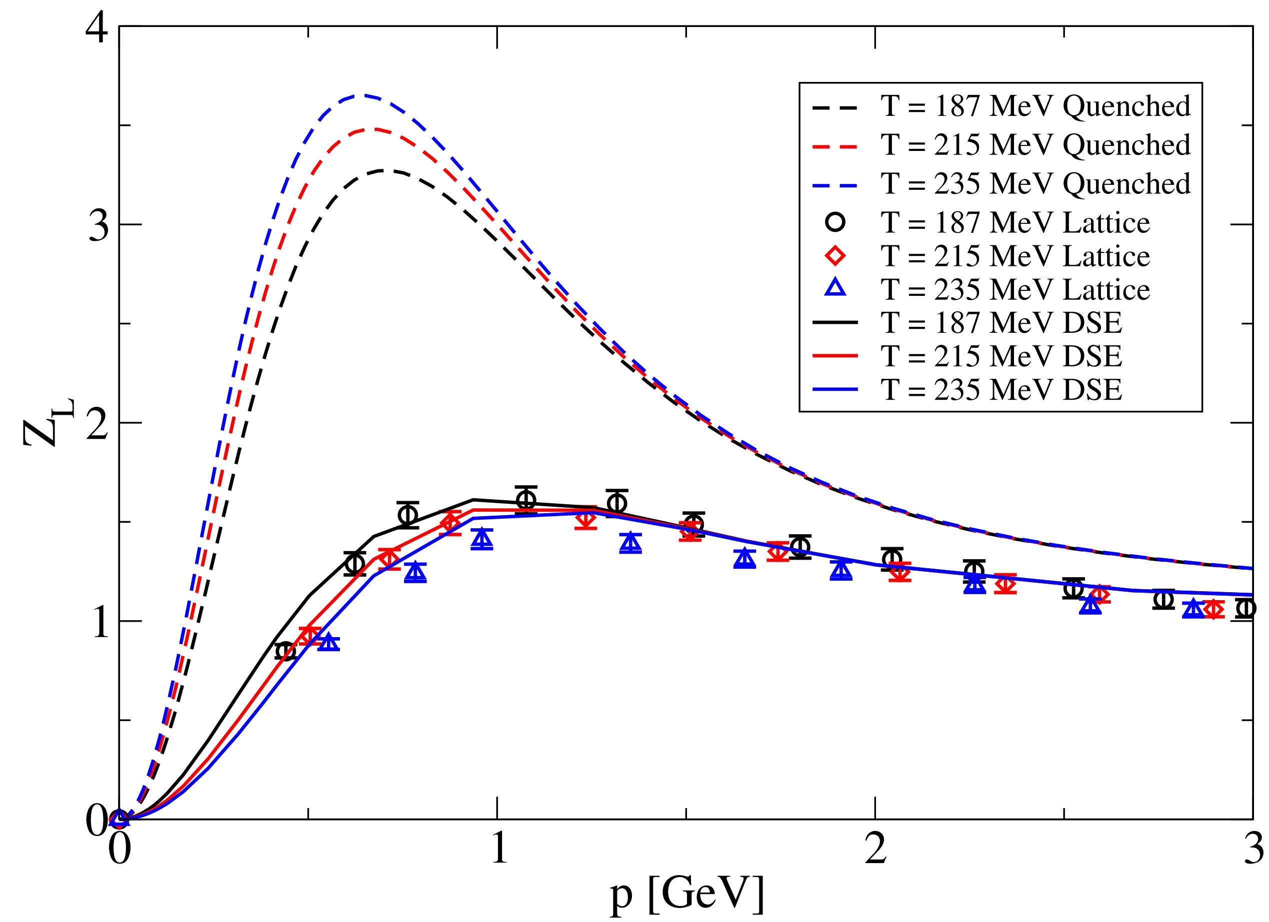

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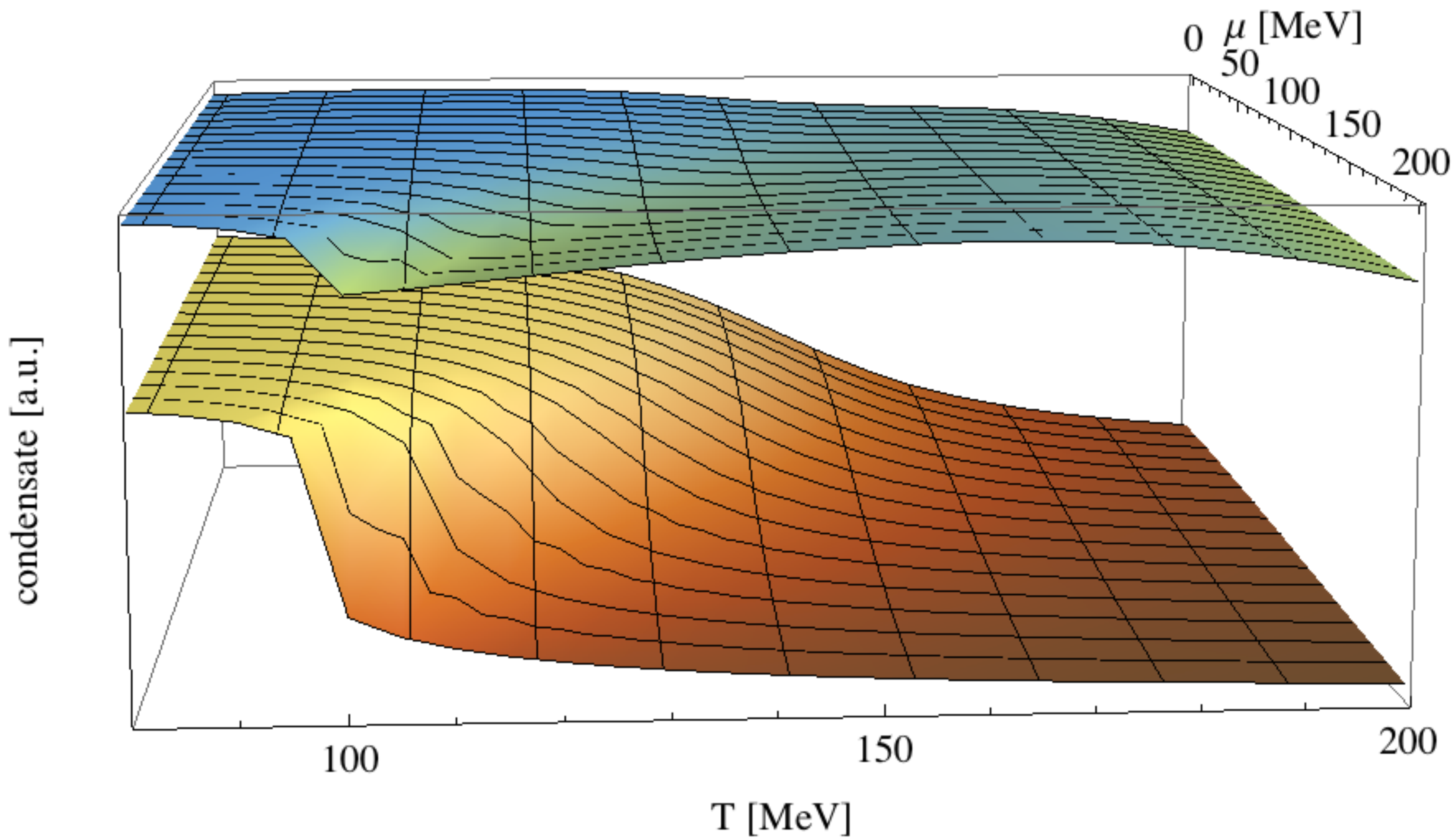
DSE: CF, Luecker, PLB 718 (2013) 1036,
CF, Luecker, Welzbacher, PRD 90 (2014) 034022

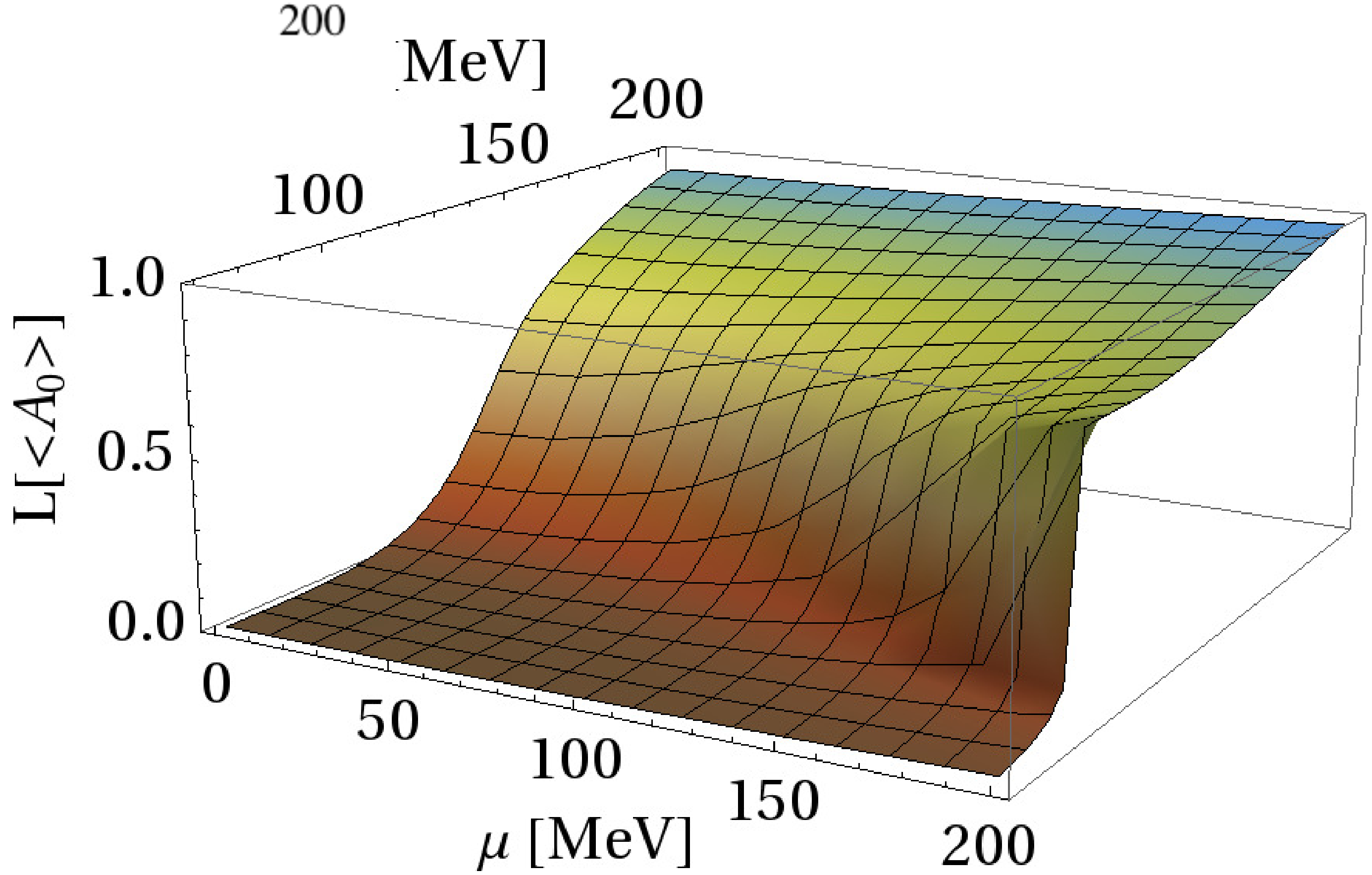
Lattice: Aouane, et al.PRD D87 (2013), [arXiv:1212.1102]
DSE: CF, Luecker, PLB 718 (2013) 1036, [arXiv:1206.5191]

- quantitative agreement: DSE prediction verified by lattice

Nf=2+1: Condensate and dressed Polyakov Loop



Quark condensate

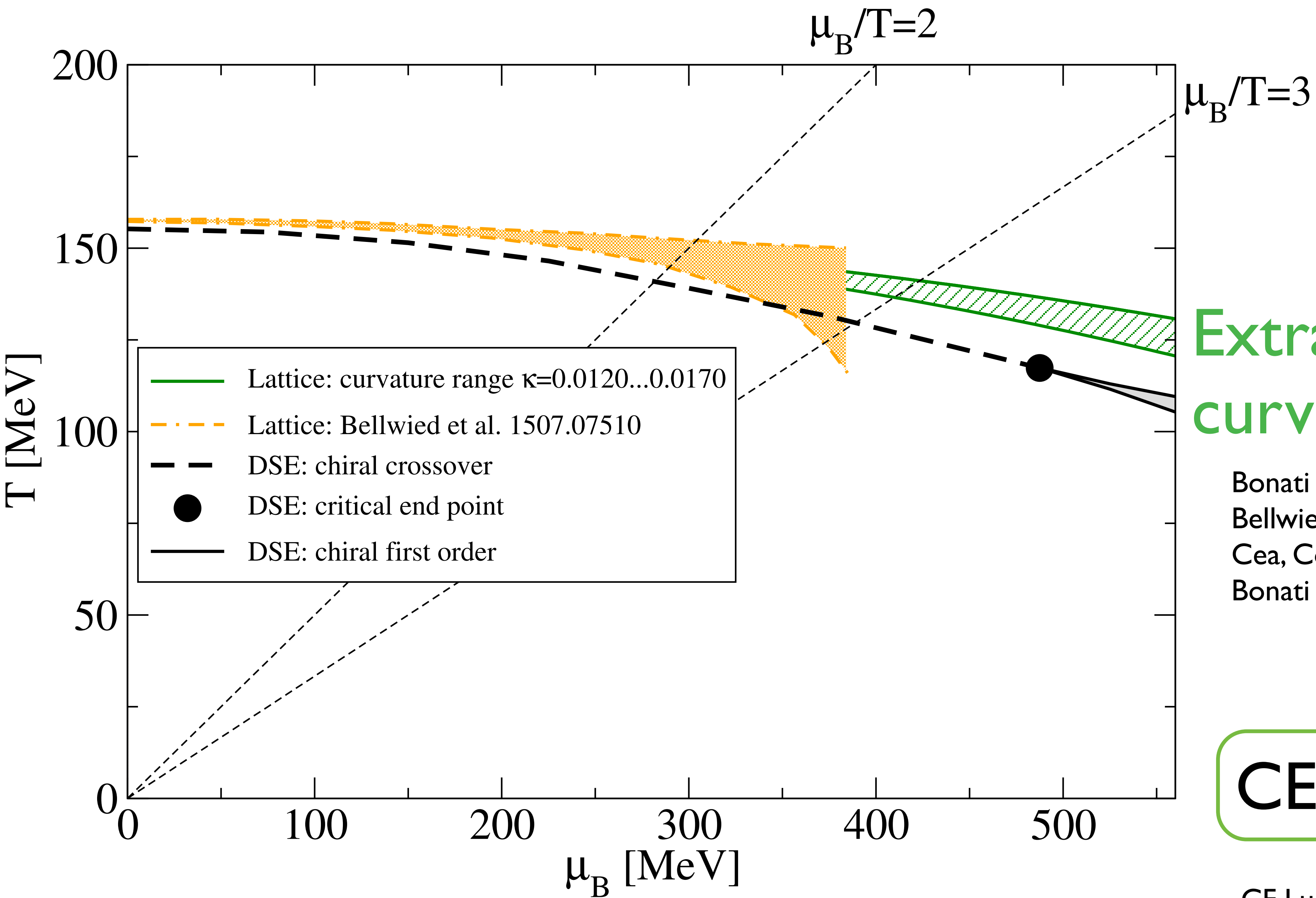


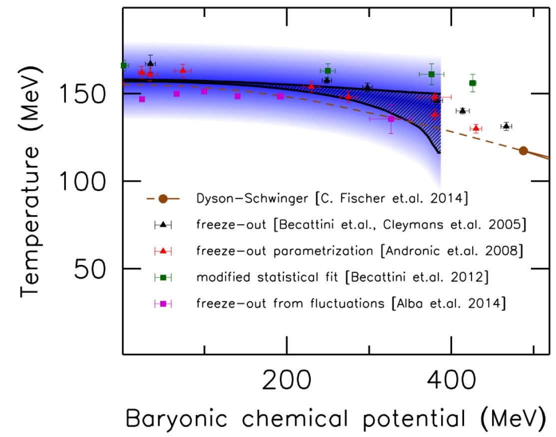
Polyakov-Loop

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

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

N_f=2+1: phase diagram





Extrapolated curvature from lattice

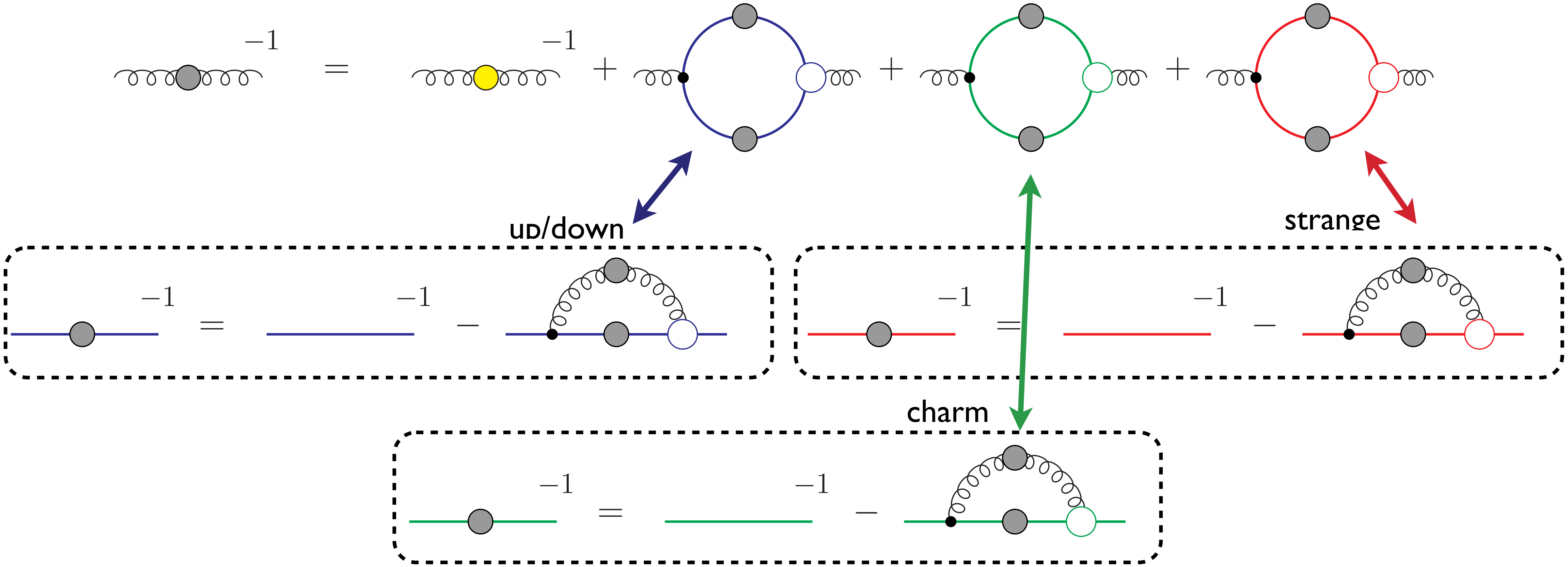
Bonati et al., PRD 92 (2015) 054503
Bellwied et al. PLB 751 (2015) 559
Cea, Cosmai, Papa, PRD 89 (2014), PRD 93 (2016)
Bonati et al., arXiv:1805.02960

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 FRG and DSE: no CEP at $\mu_B/T<2$

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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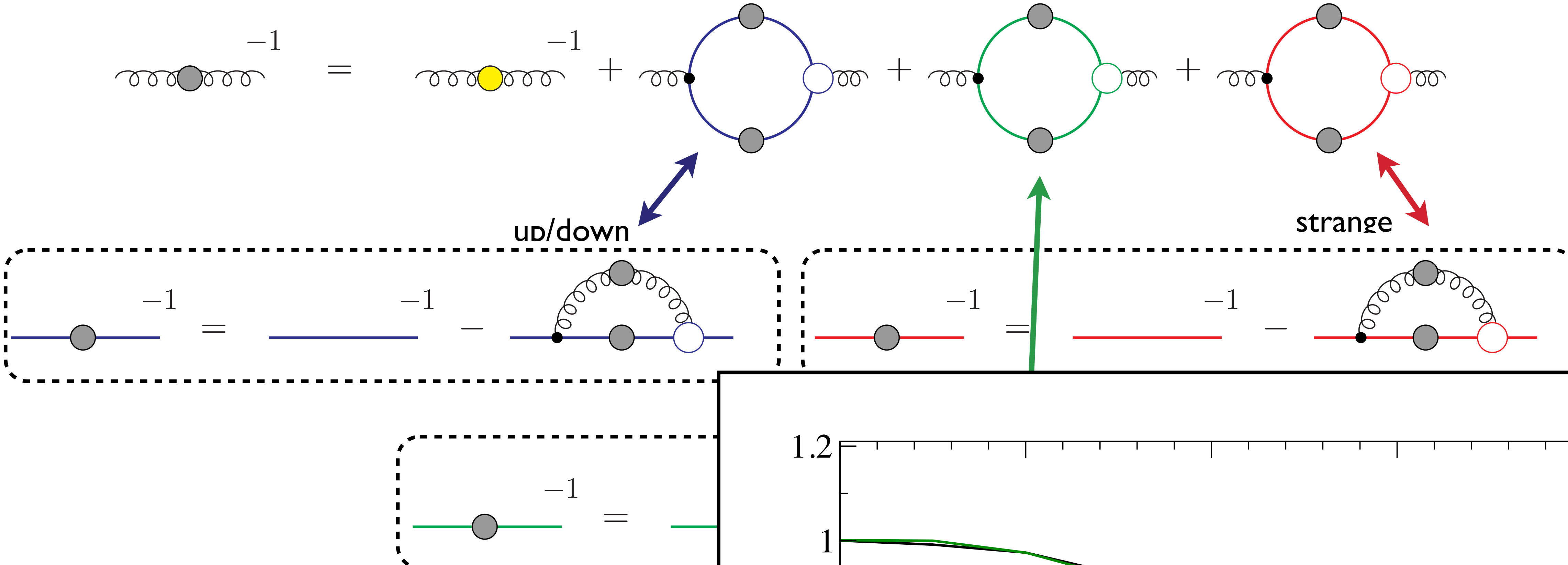

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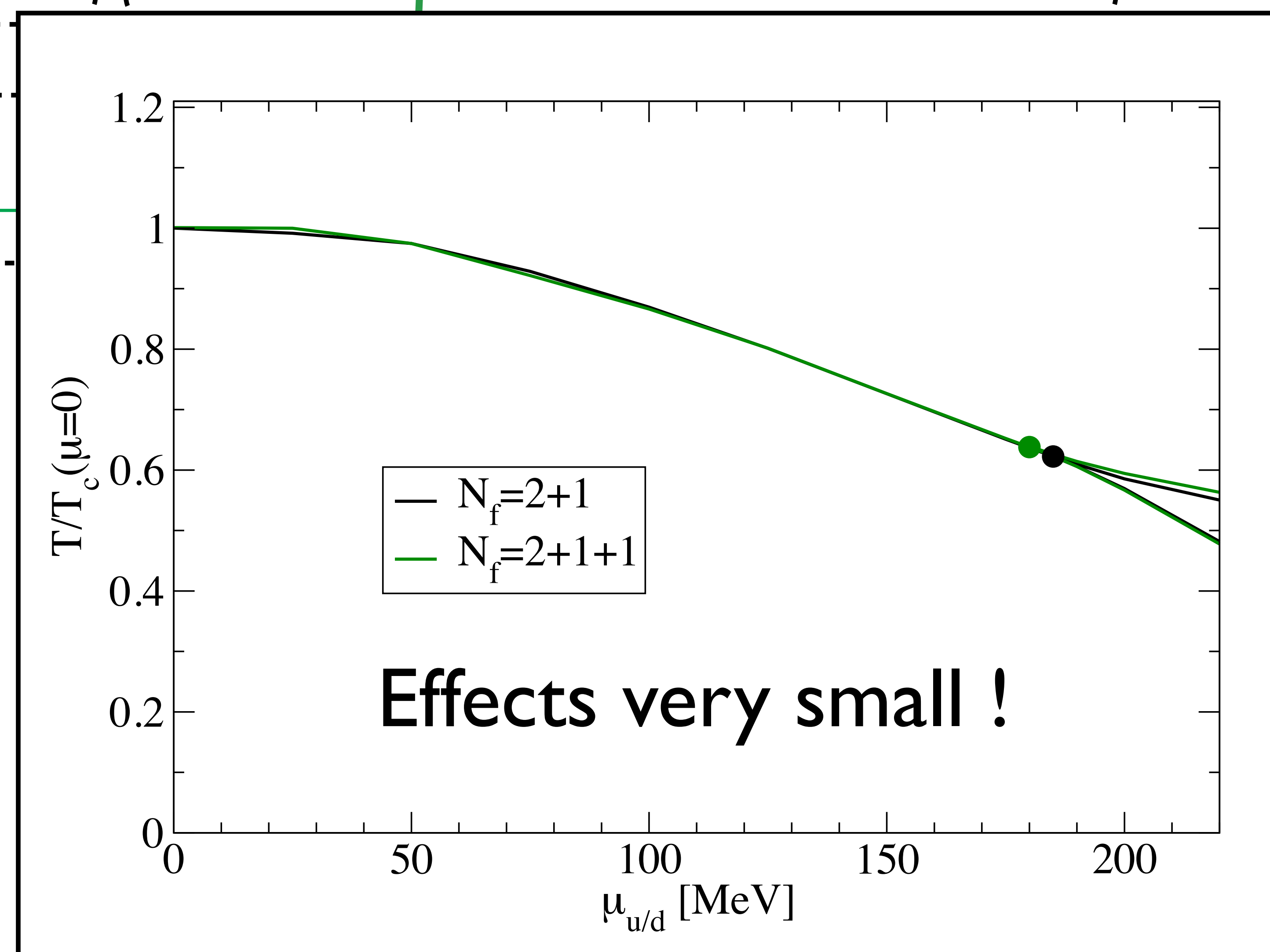
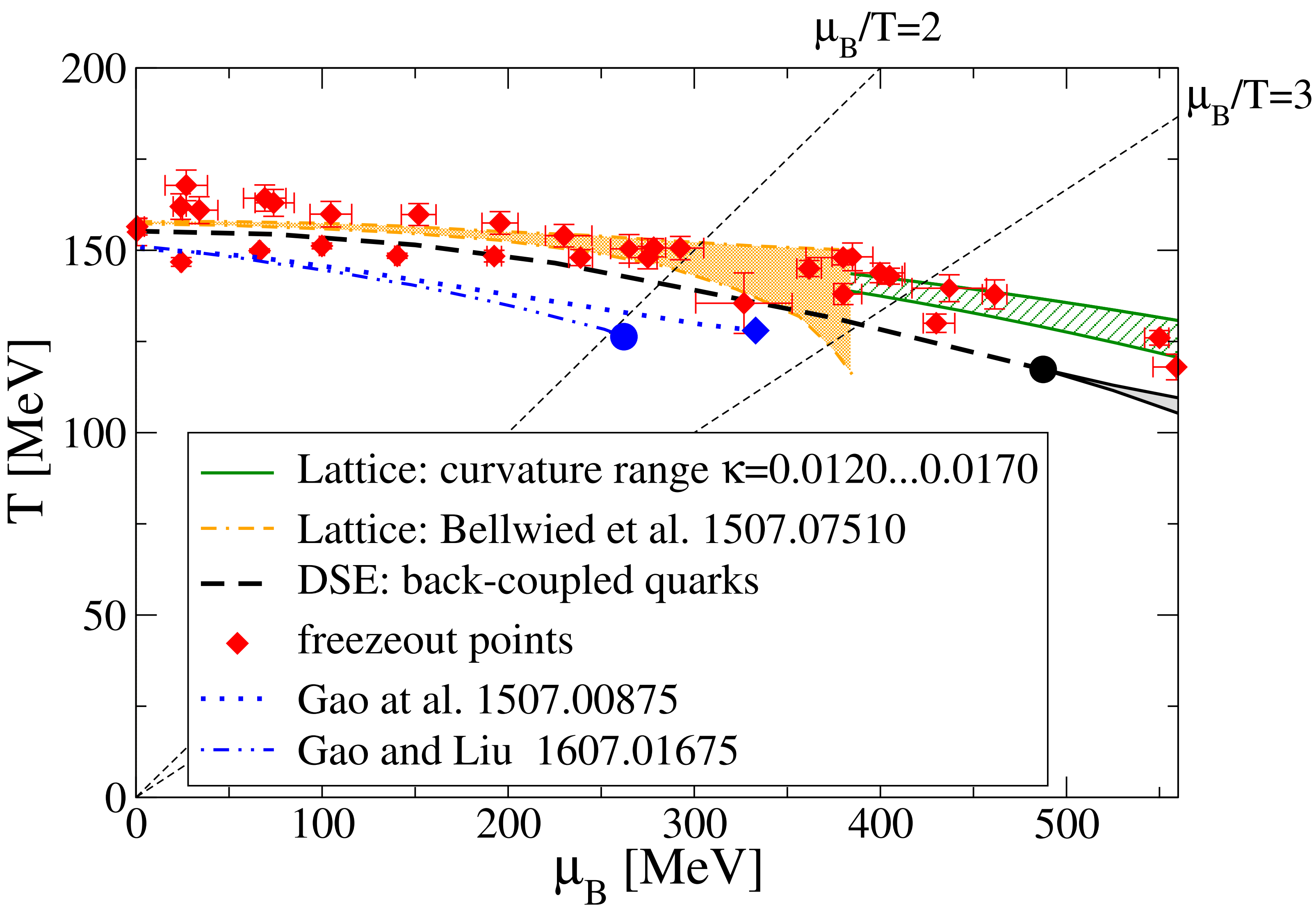


CF, Luecker, Welzbacher, PRD 90 (2014) 034022

Location of CEP in freece-out landscape



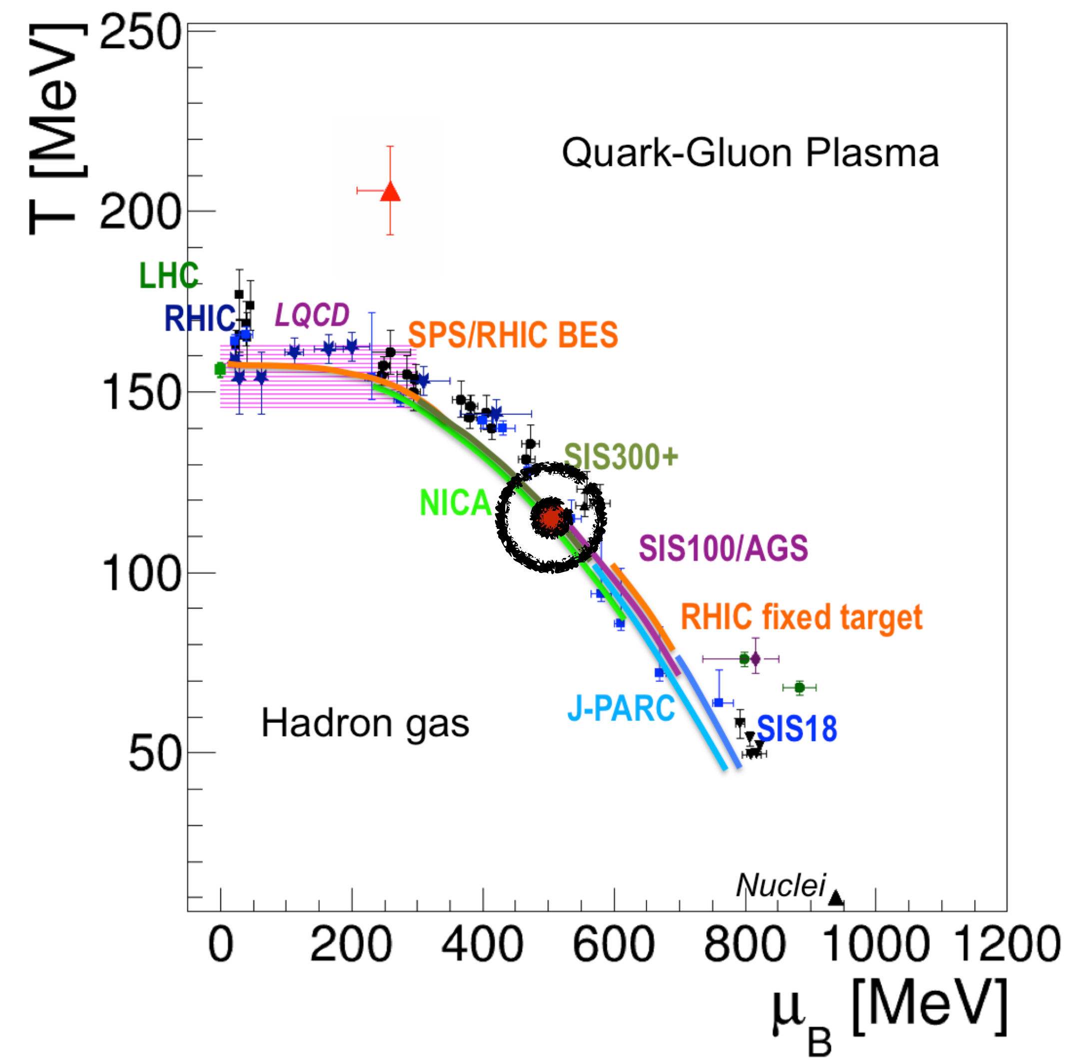
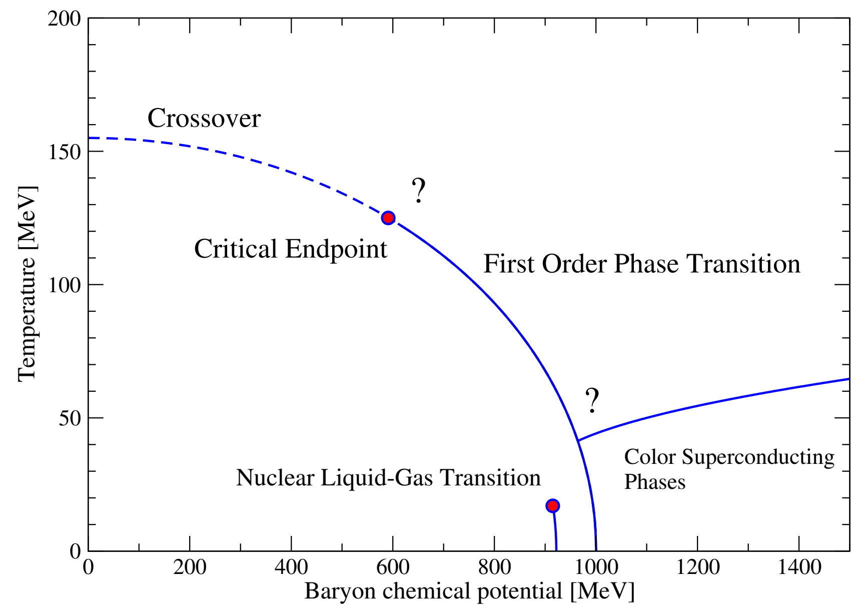


Figure adapted from talk of T. Galatyuk, Erice 2016

Caveats:

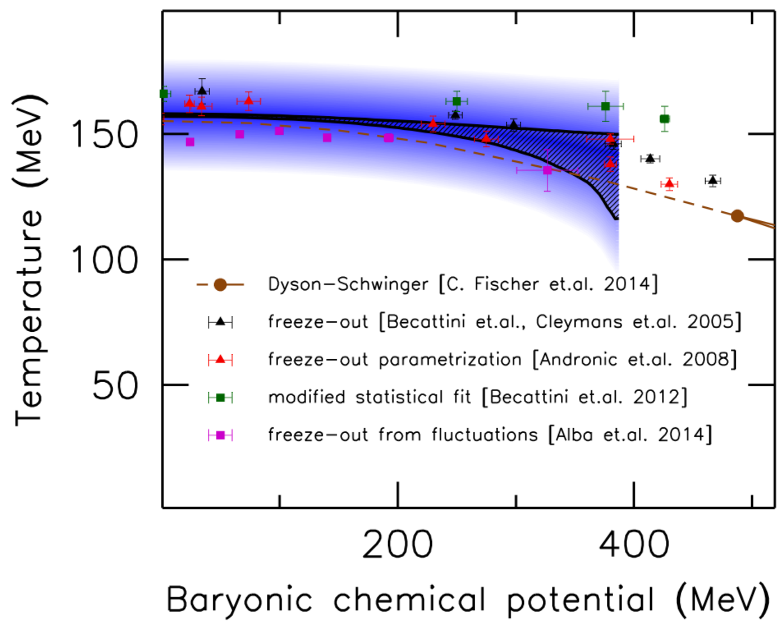
- inhomogeneous phases — Müller, Buballa and Wambach, PLB 727 (2013) 240
- effects of baryons ? — Nc=2: Brauner, Fukushima and Hidaka, PRD 80 (2009) 74035; Strodthoff, Schaefer and Smekal, PRD 85 (2012) 074007
- ...

Overview

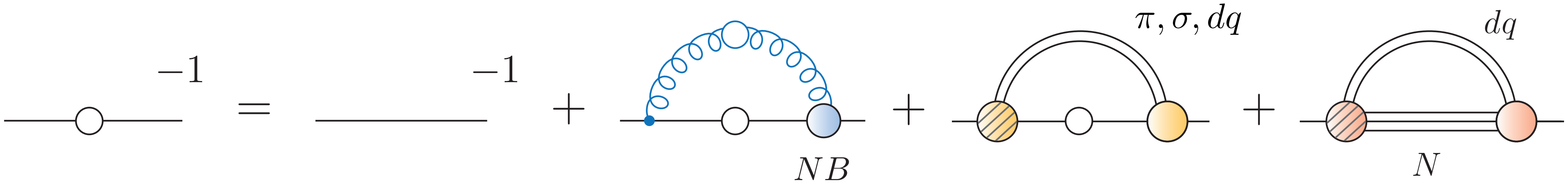


1. Introduction

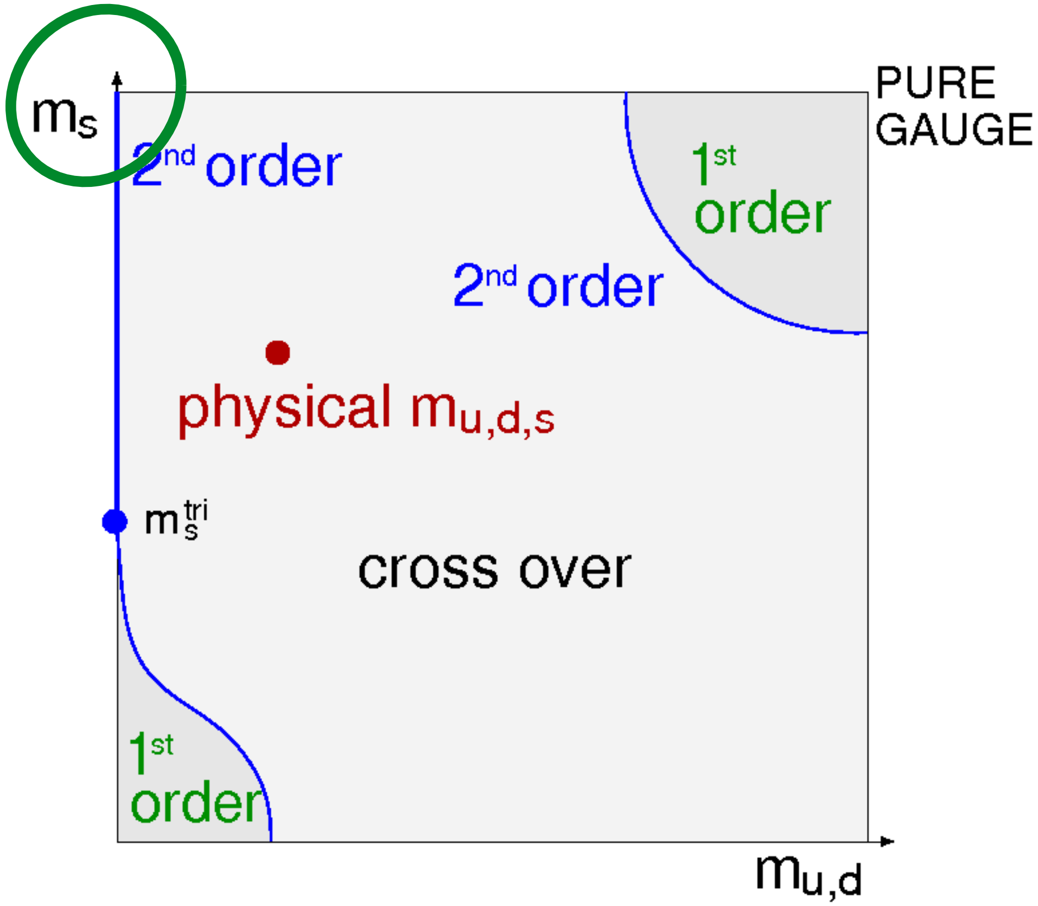
2. Gluons, quarks and the CEP

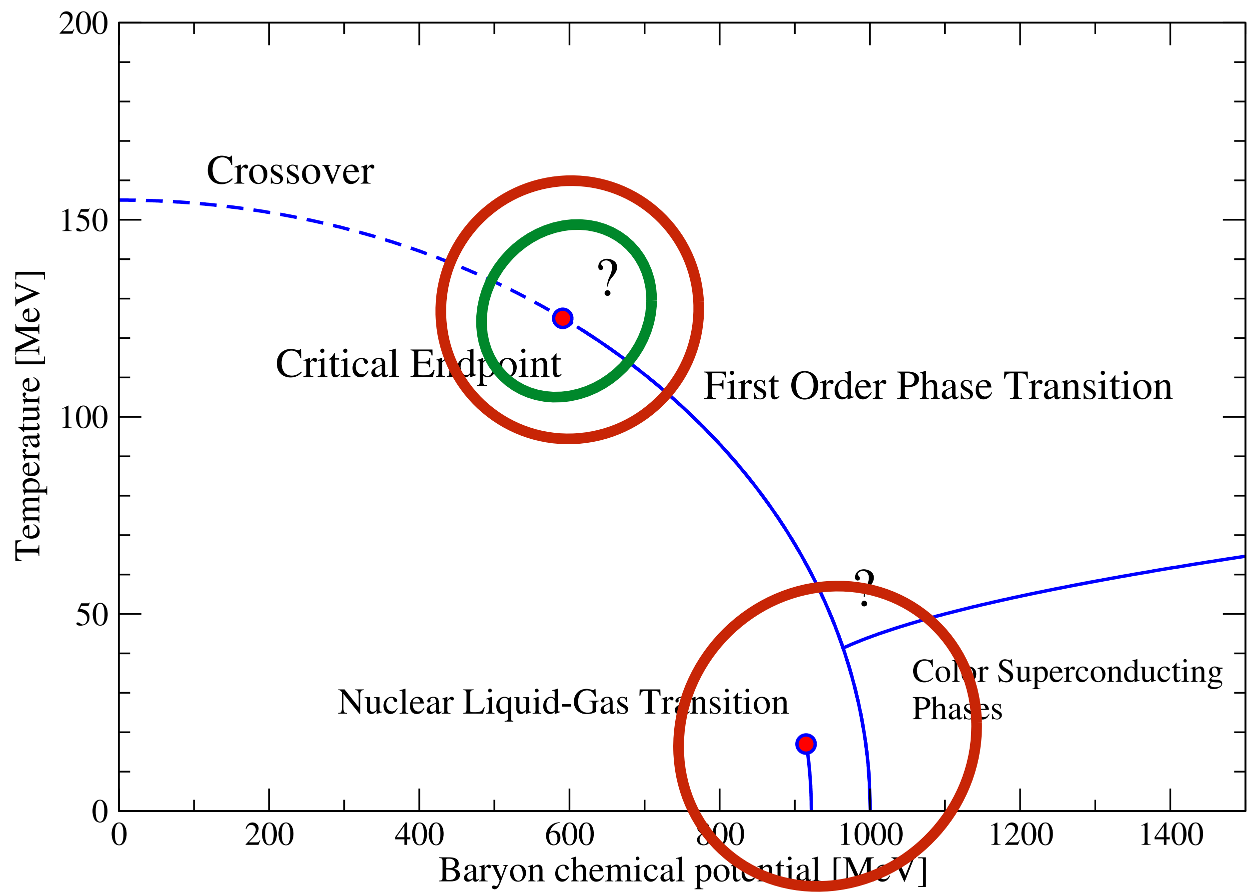


3. Hadron effects



Hadron effects in the QCD phase diagram





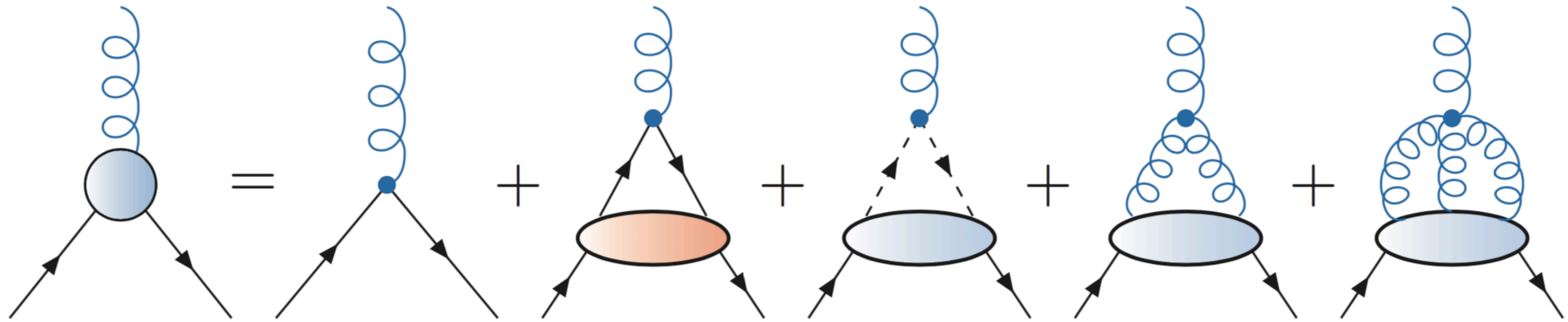
- Meson effects: critical chiral physics, …
- Baryon effects

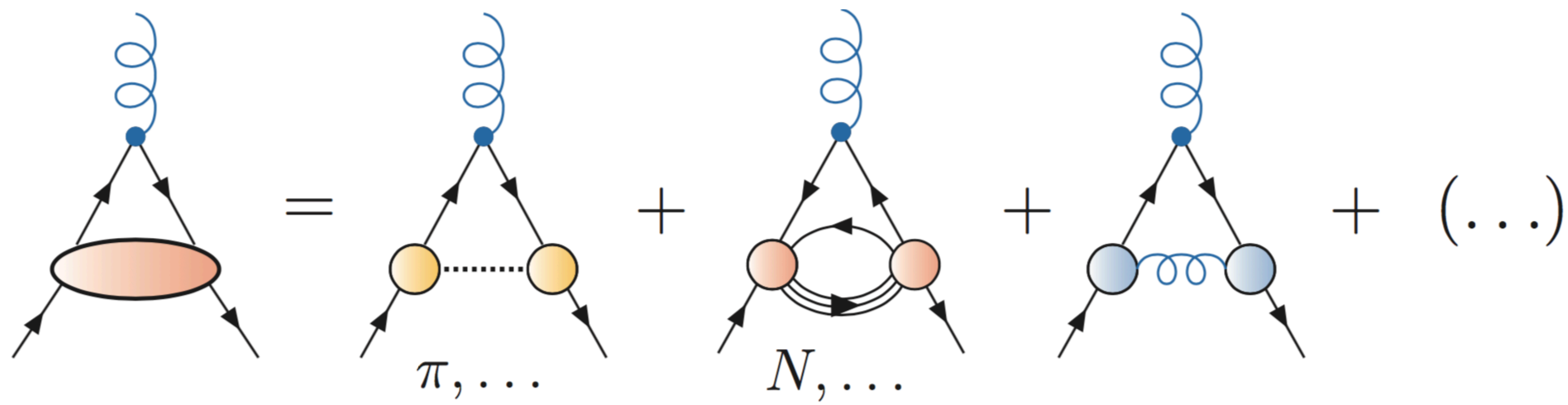
Chiral mirror model: Weyrich, Strodthoff and von Smekal, PRC 92 (2015) no.1, 015214

⟶ truncation of DSEs good enough to include these effects ?

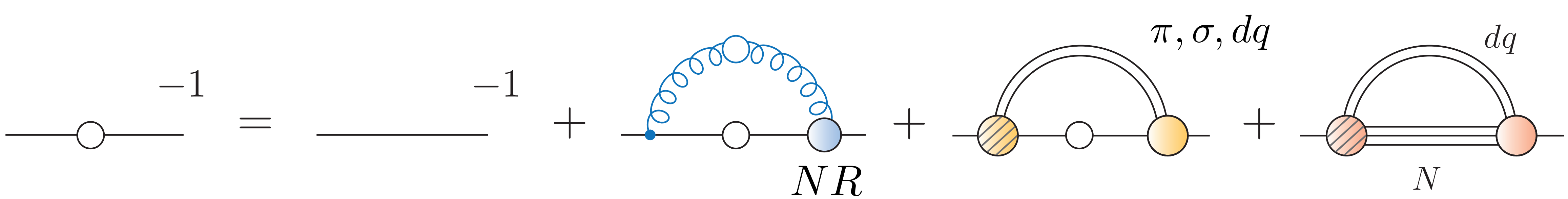
Hadron effects in quark-gluon interaction

quark-gluon vertex:





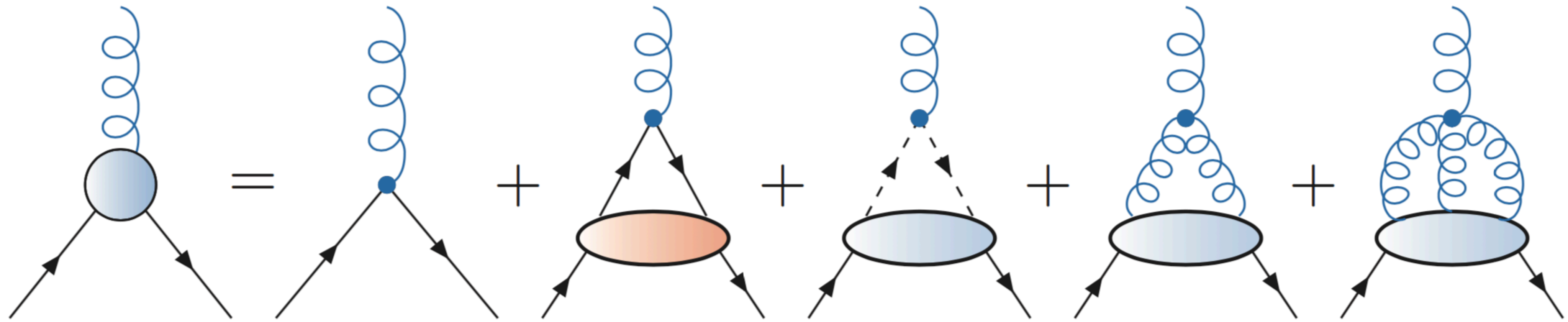
quark:

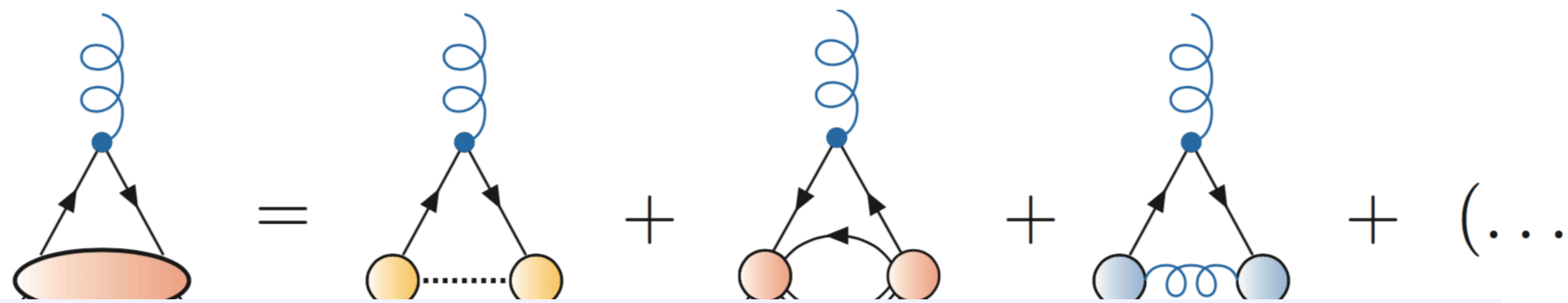


Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]

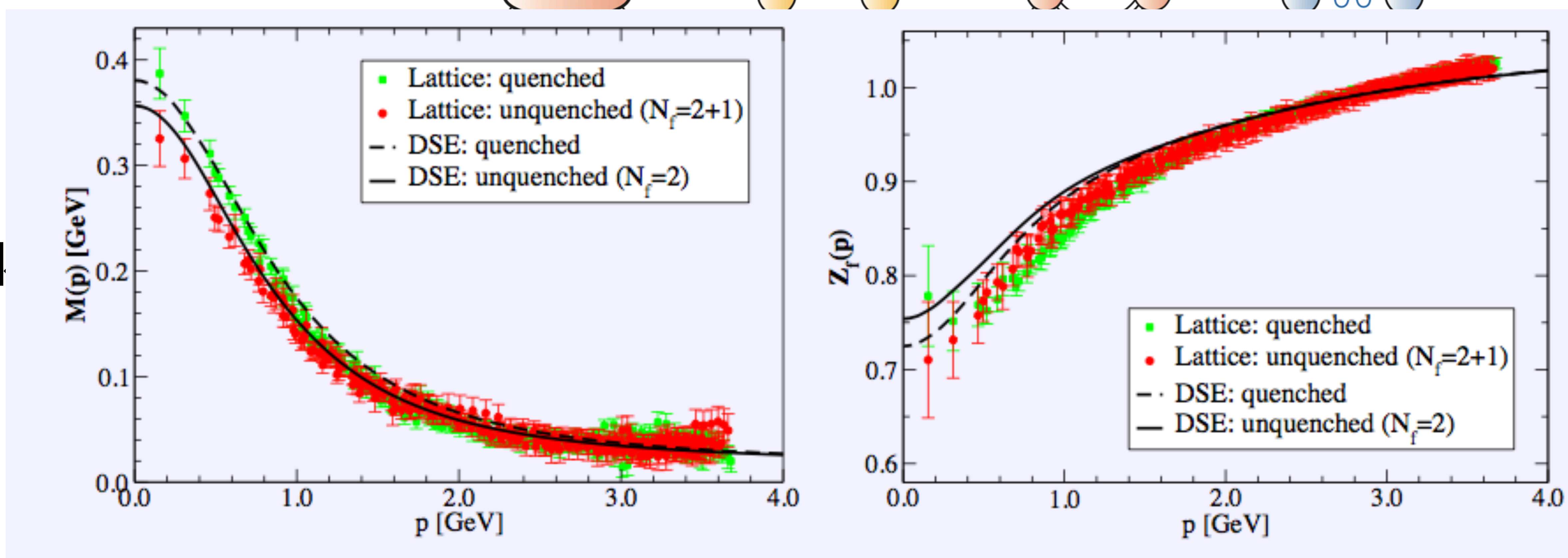
Hadron effects in quark-gluon interaction

quark-gluon vertex:





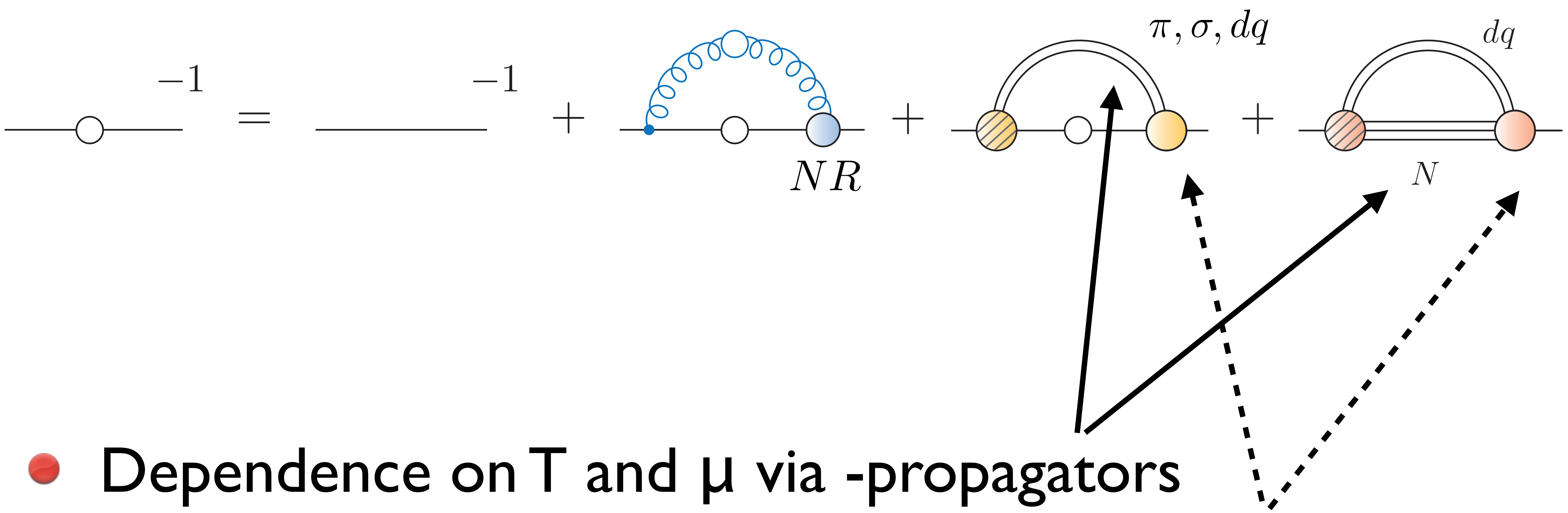
quar



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

2]

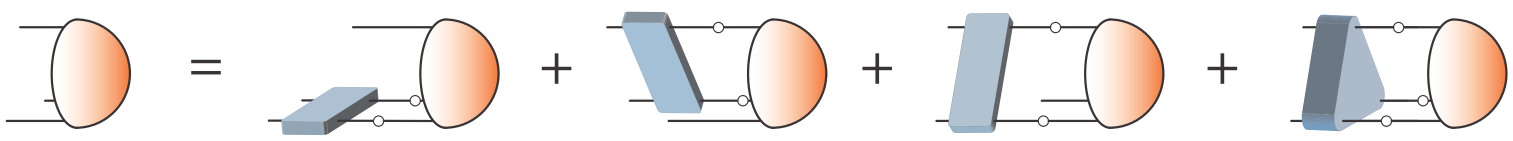
Hadron effects onto quark

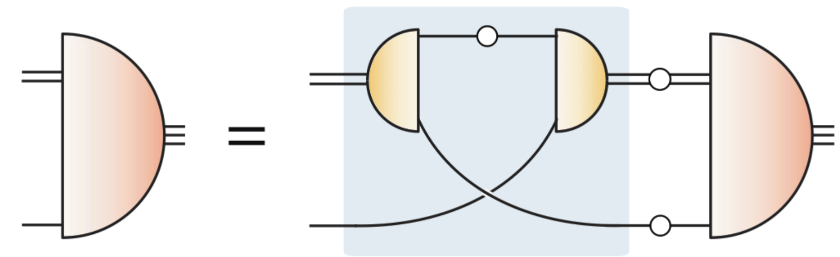


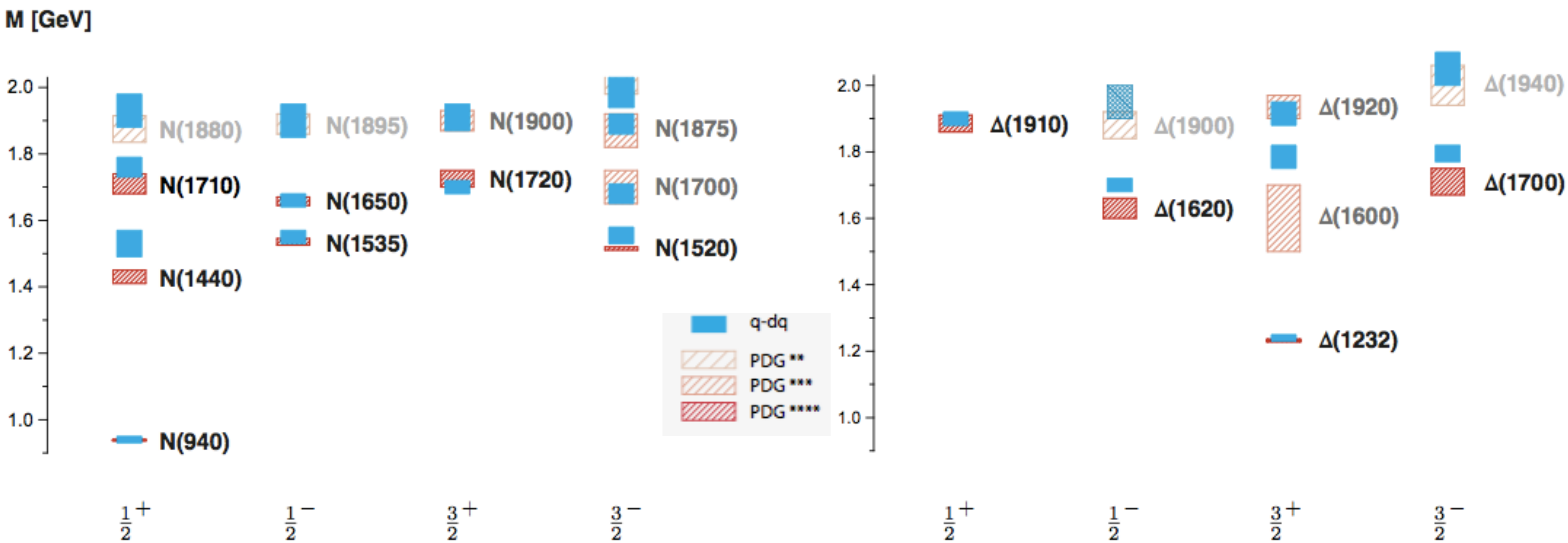
- Dependence on T and μ via -propagators
  -wave functions

- Exploratory calculation: use wave functions from T=μ=0

Vacuum: Light baryon spectrum

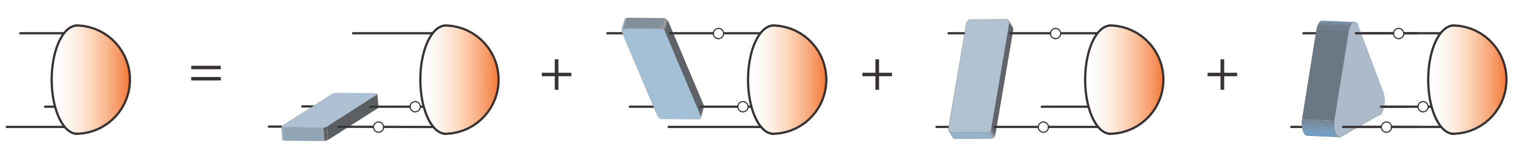


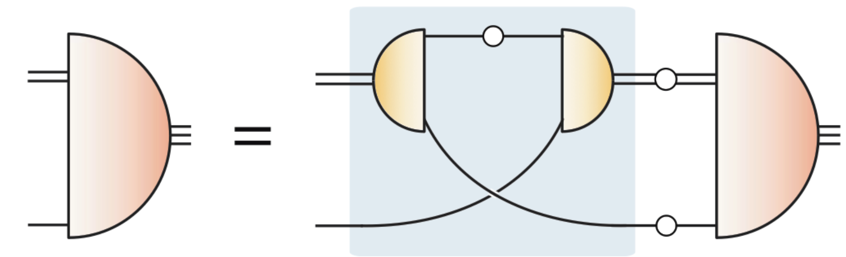


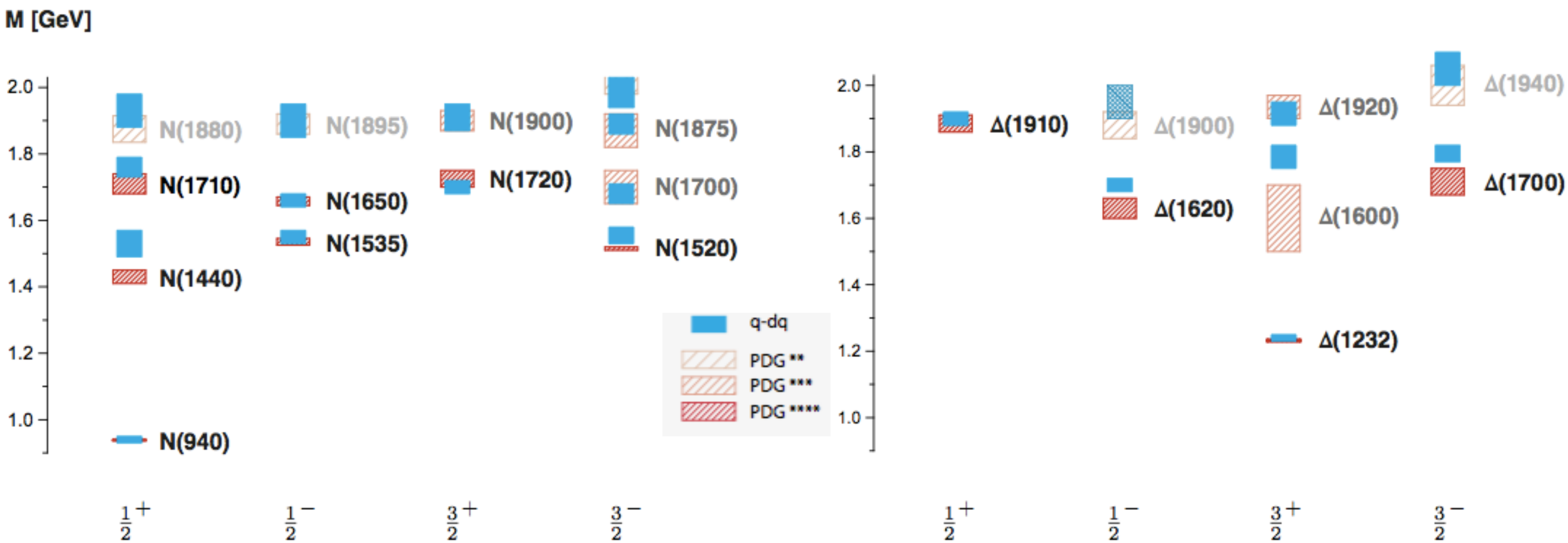


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, in preparation

Vacuum: Light baryon spectrum



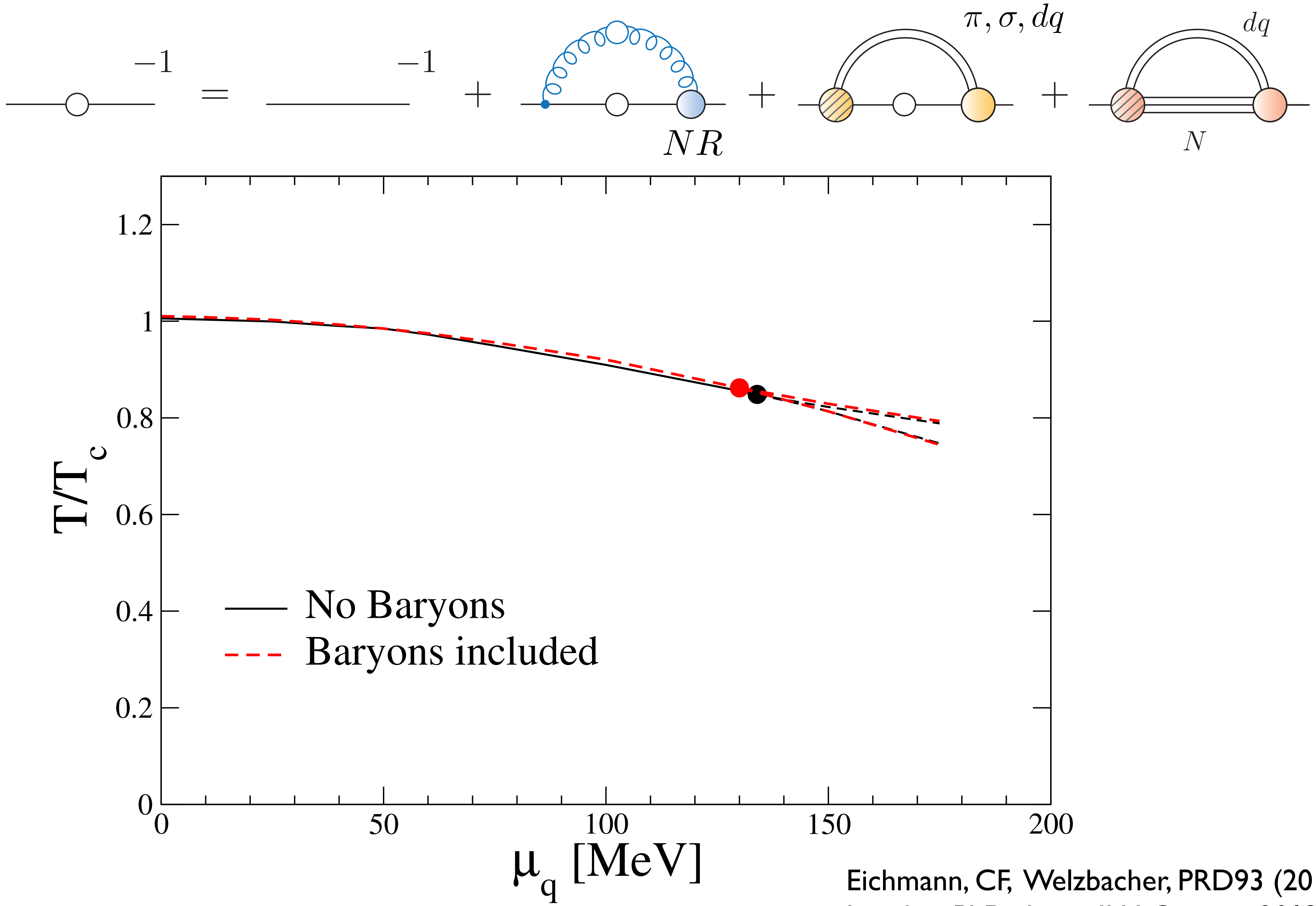




Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, in preparation

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

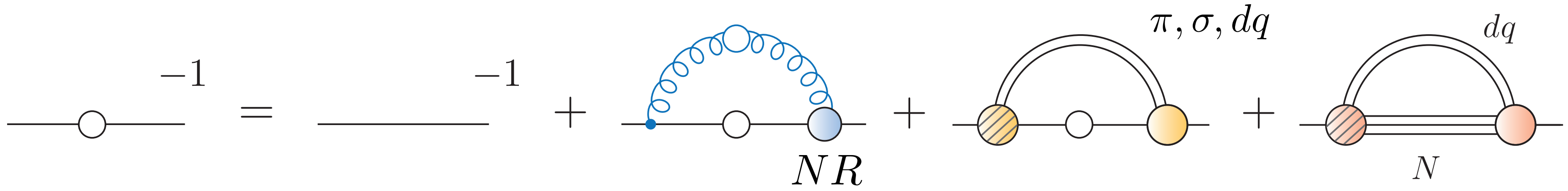
Hadron effects on the CEP - results (N_f=2)

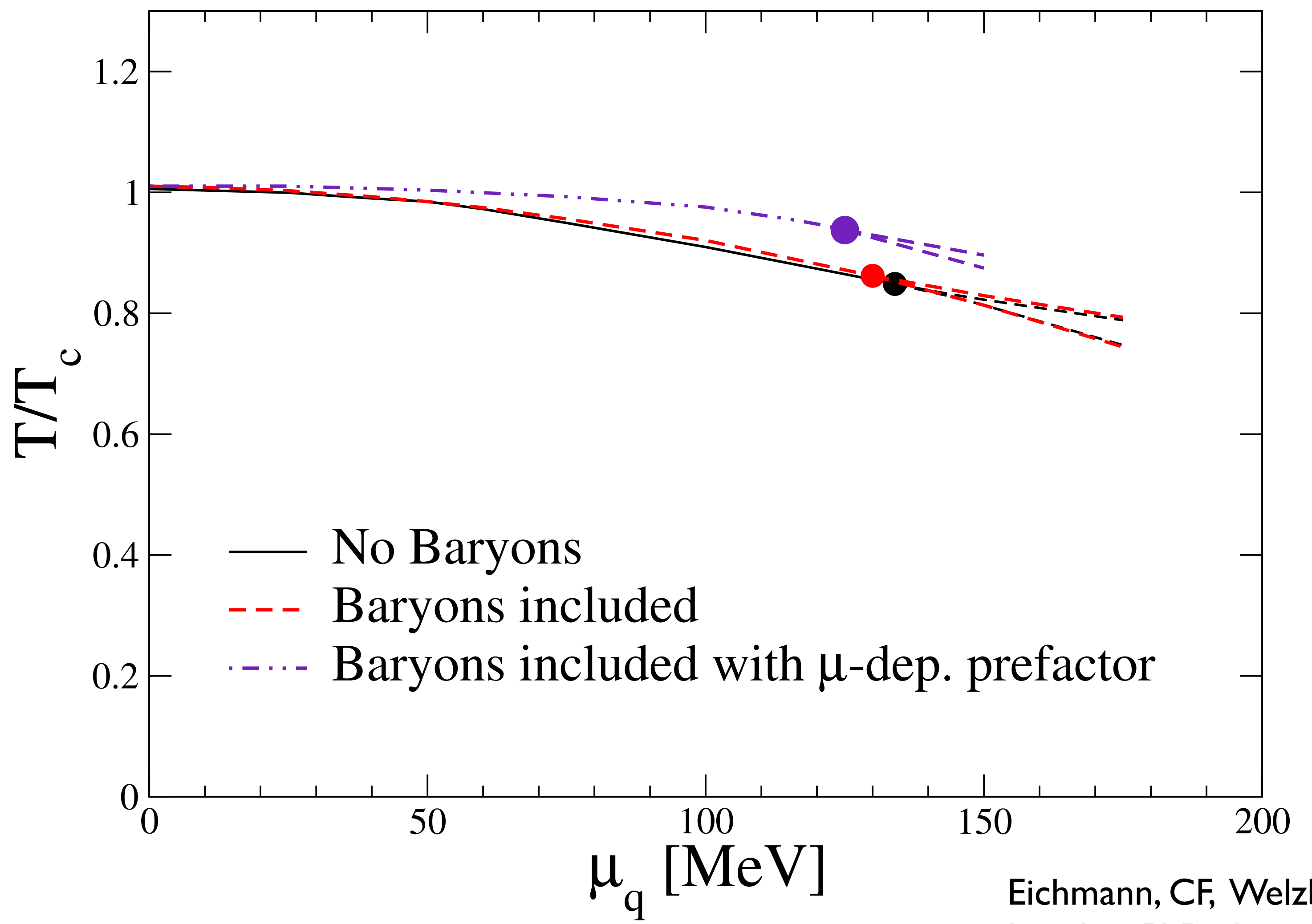


Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]
Luecker, PhD-thesis, JLU Giessen, 2013

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

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

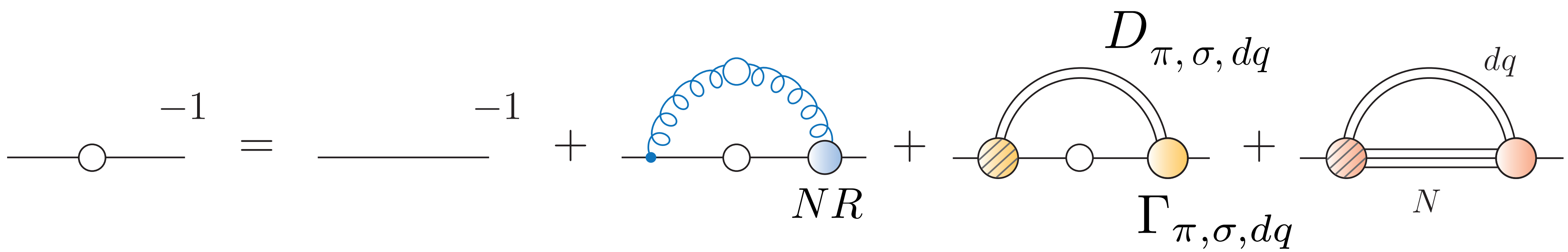




Eichmann, CF, Welzbacher, PRD93 (2016) [1509.02082]
Luecker, PhD-thesis, JLU Giessen, 2013

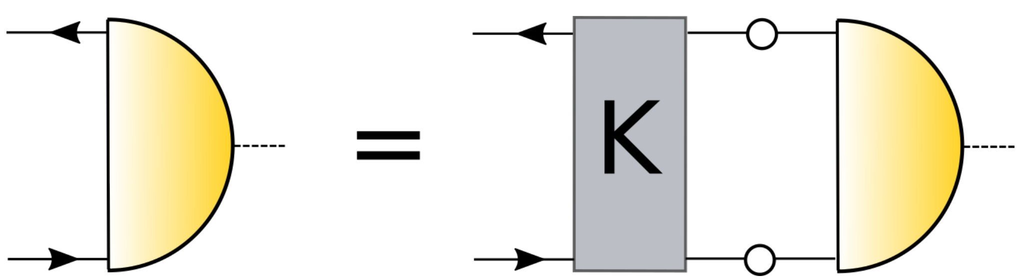
- Zero chemical potential: no effect
- almost no effect on location of CEP (mesons: similar)
- But: strong μ-dependence of baryon wave function may change situation…

Meson effects at finite T and μ



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

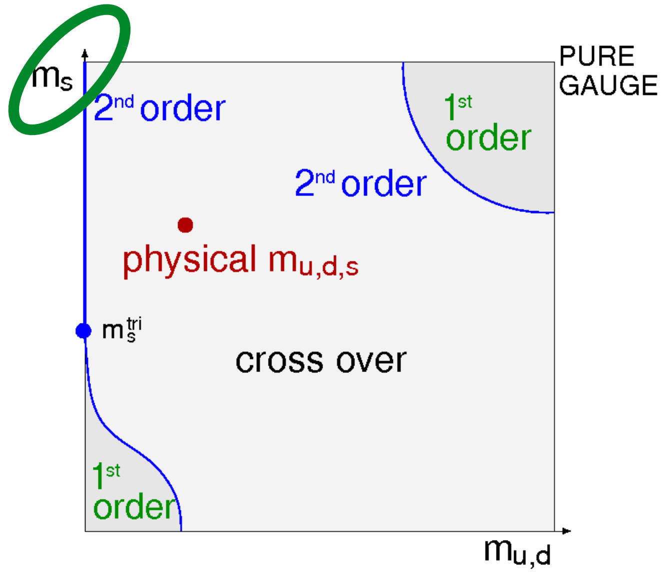
Son, Stephanov, PRD 66 (2002) 7

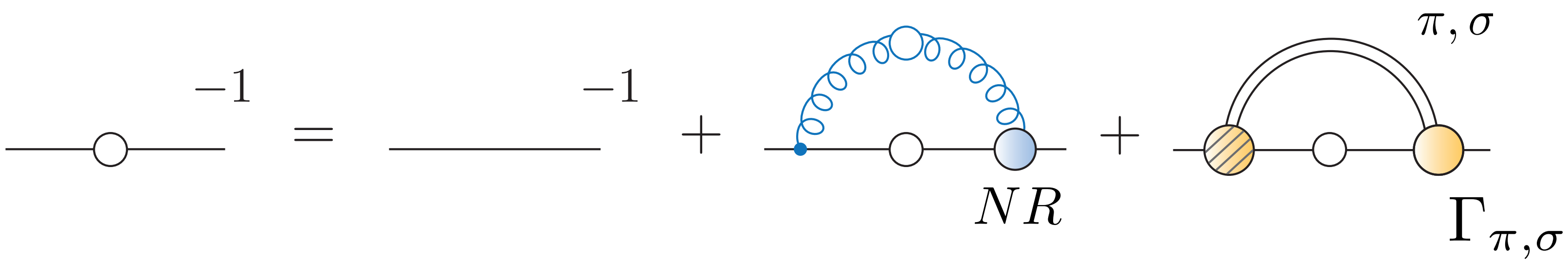


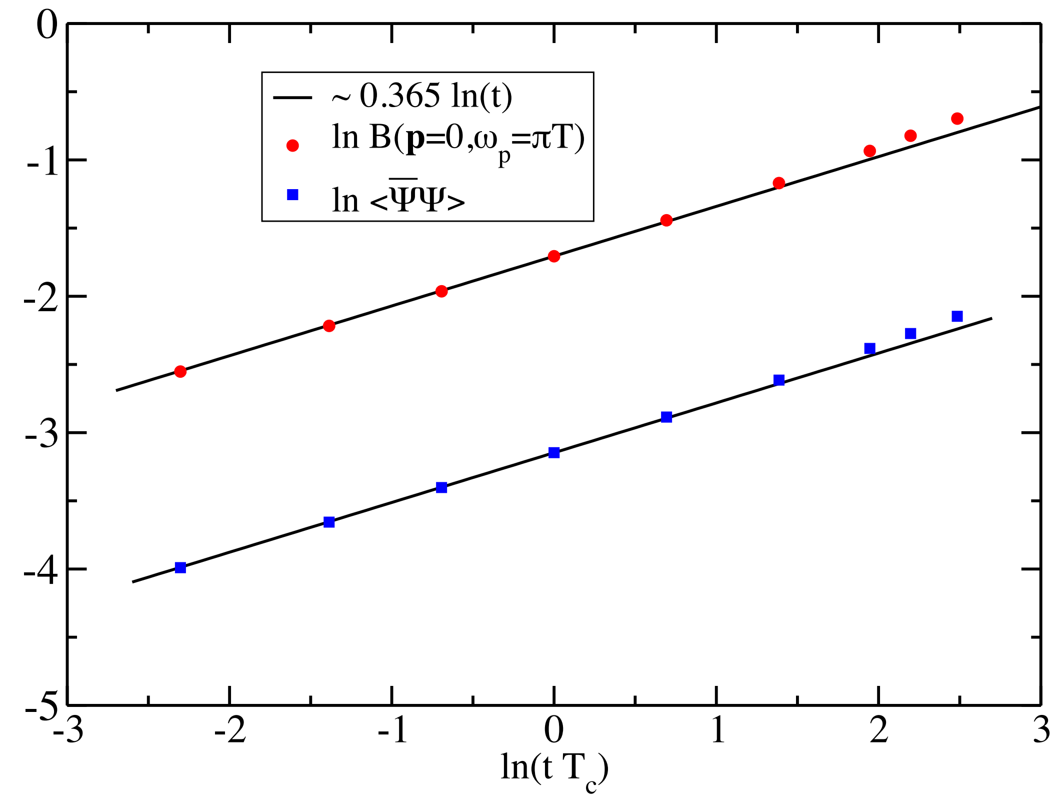
$$\Gamma_\pi(P,q) = \gamma_5\, E(P,q,T,\mu) + \ldots$$

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

Critical scaling from DSEs: N_f=2, chiral limit







- T=0: meson contributions of order of 10-20 %

CF, Nickel, Williams EPJC 60 1434 (2008); CF, Williams, PRD 78 (2008) 074006

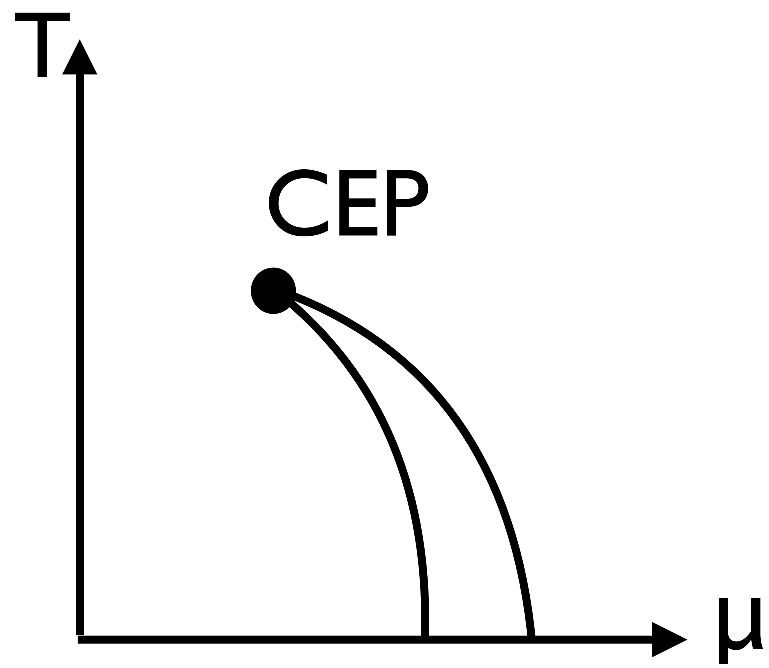
- T=T_c: meson contributions are dominant - universality !

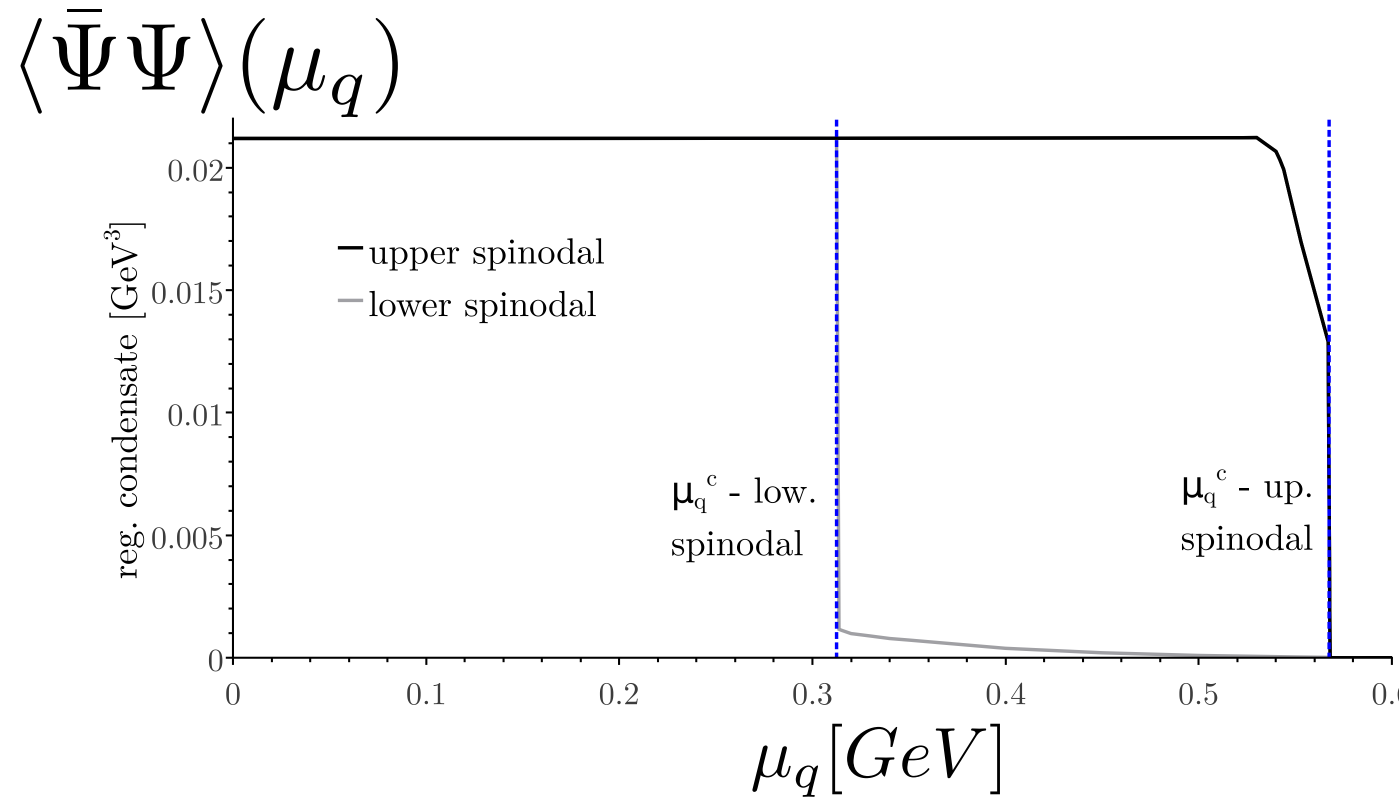
- Critical scaling: $$\langle\bar{\Psi}\Psi\rangle(t) \sim B(t) \sim t^{\nu/2}$$ $$f_{\pi,s}^2 \sim t^{\nu}$$

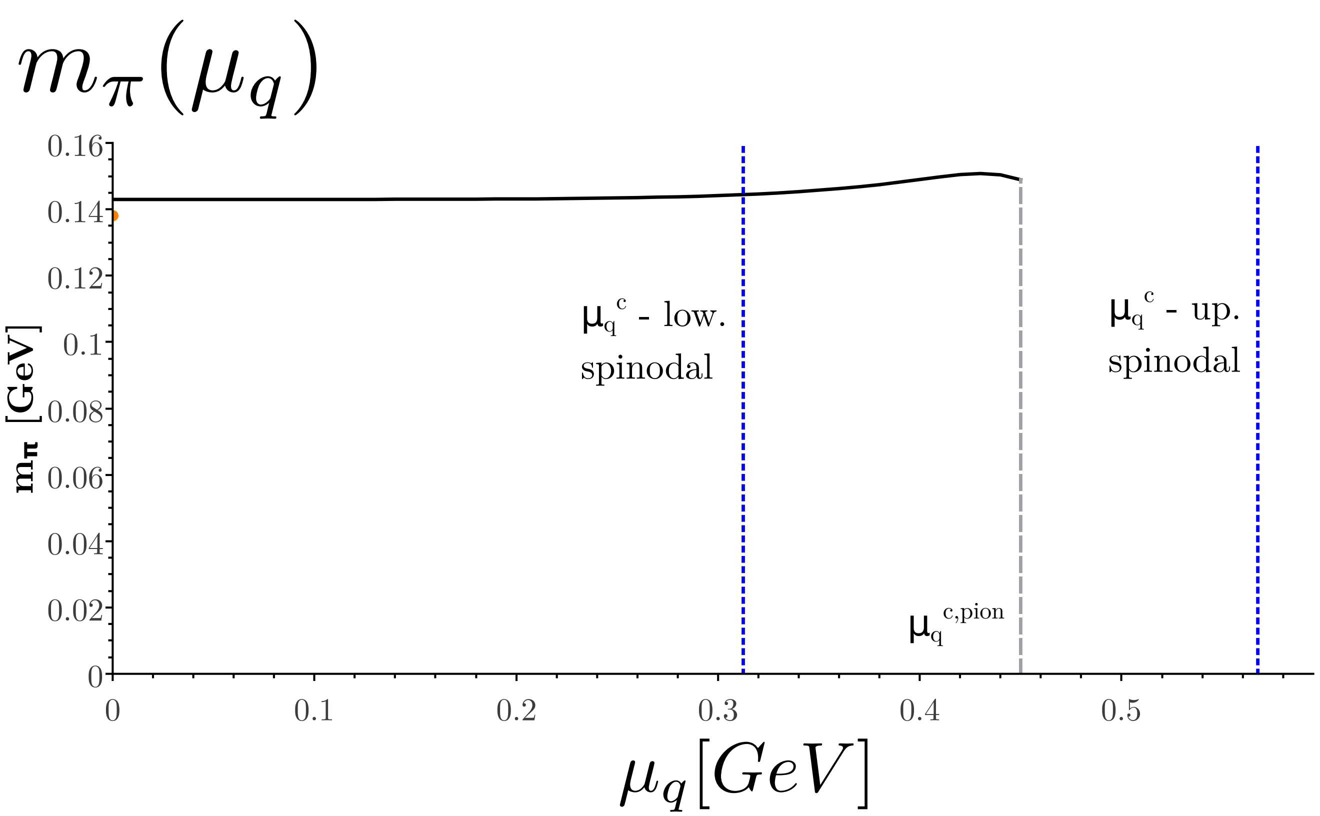
$$t := \frac{T_c - T}{T_c}$$

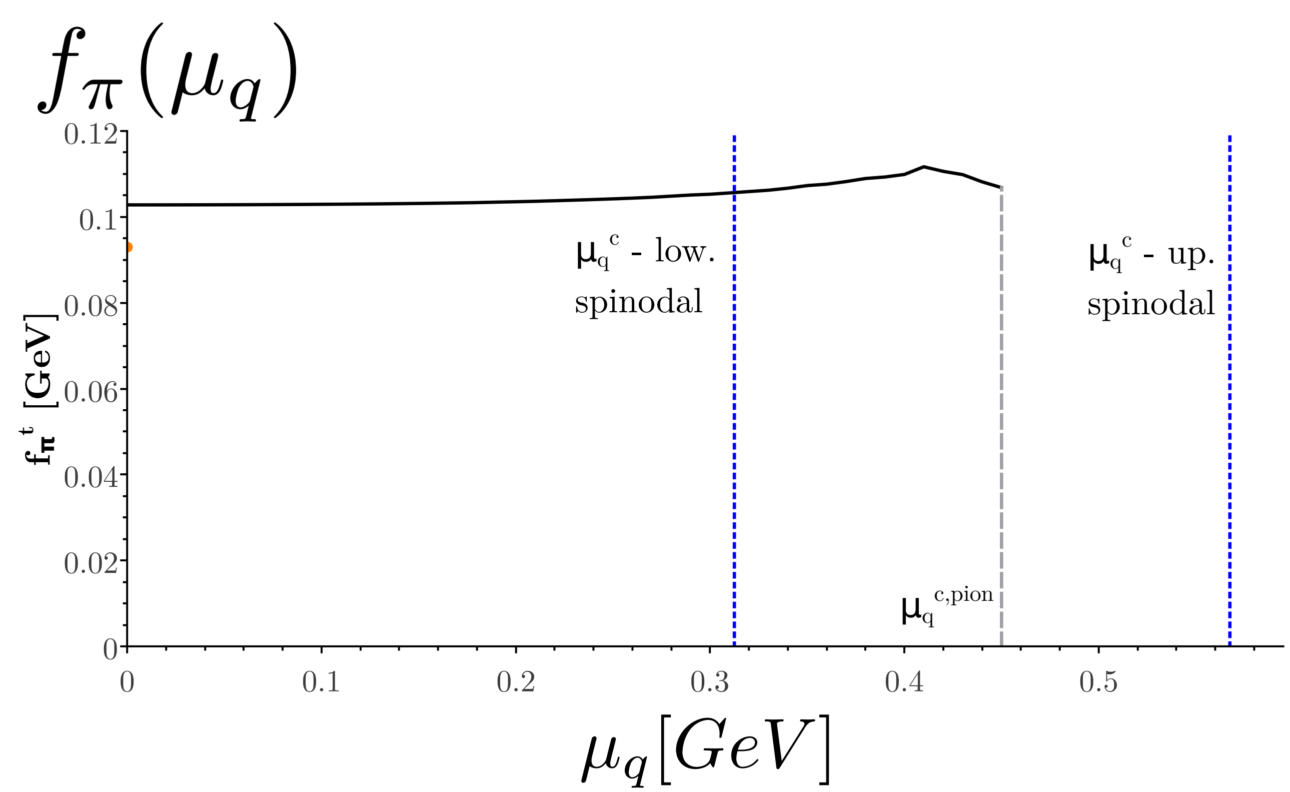
CF and Mueller, PRD 84 (2011) 054013

Pion properties at finite chemical potential









P. Gunkel, CF, work in progress

- **Silver blaze satisfied** T. D. Cohen, PRL 91 , 222001 (2003) cf. also D. Mueller, PhD-thesis, TU Darmstadt 2013

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. Phillip Isserstedt

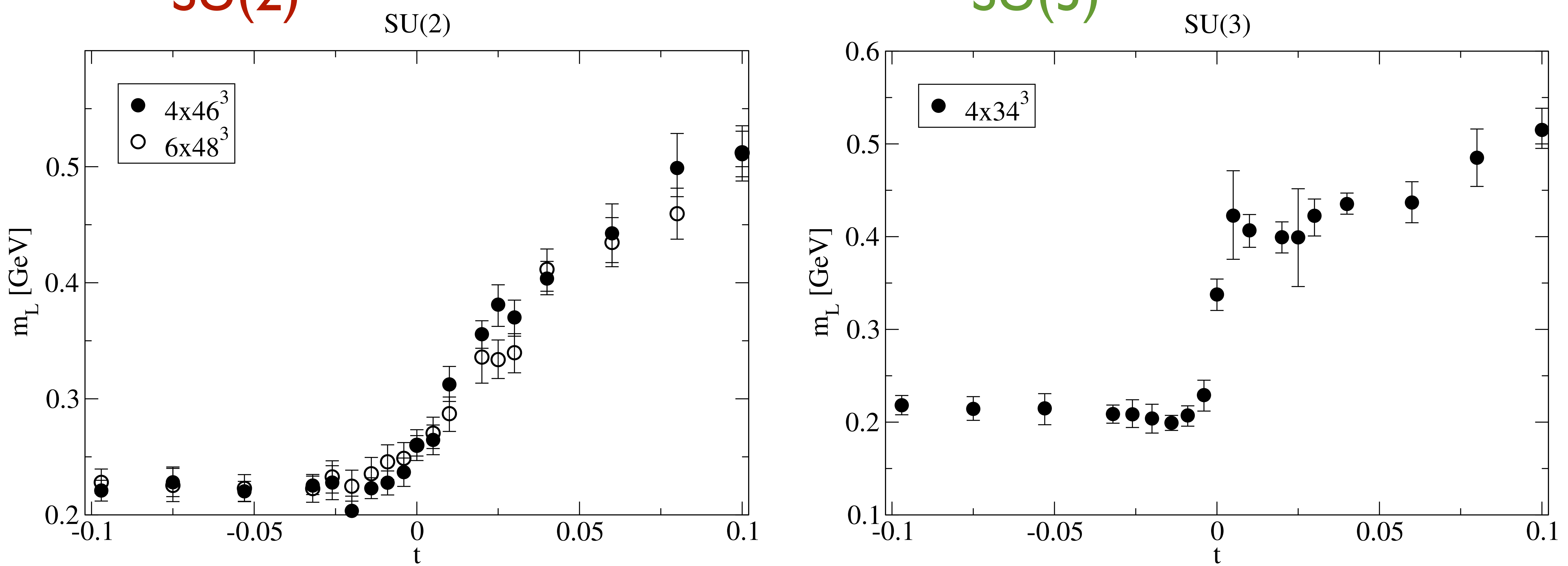
- quark spectral functions

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

Backup

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

SU(2) SU(3)



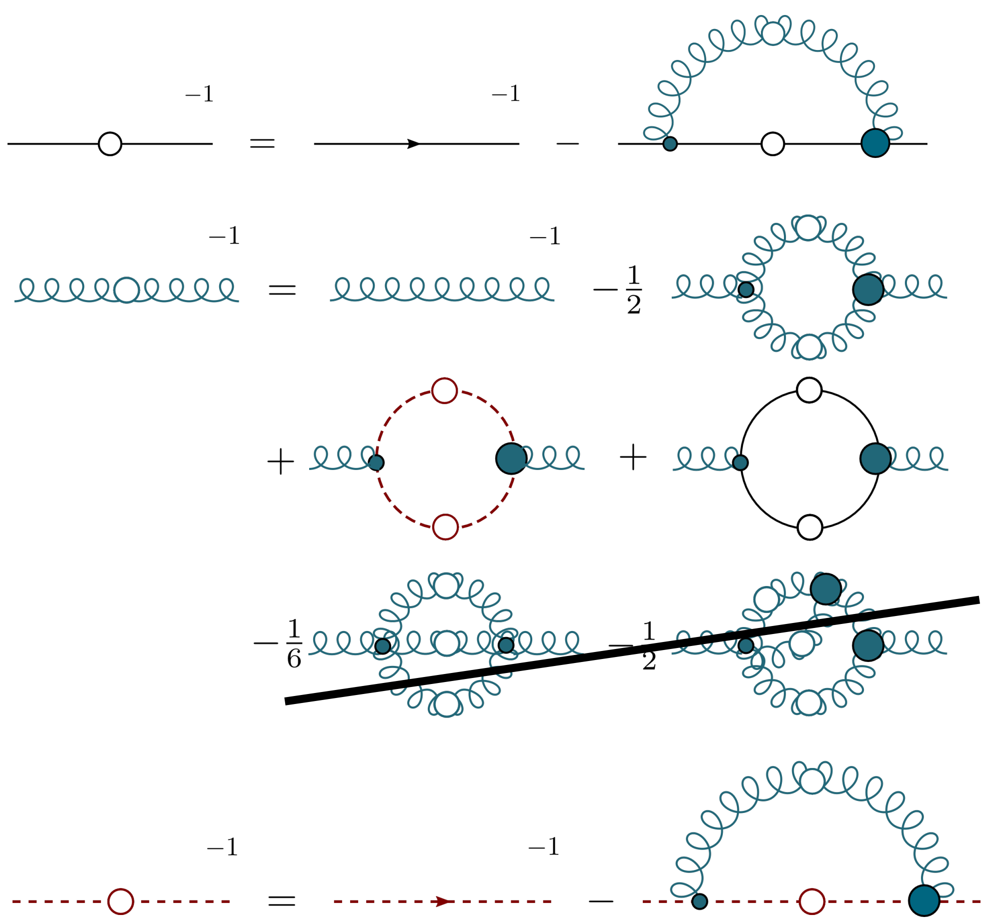
Maas, Pawlowski, Smekal, Spielmann, PRD 85 (2012) 034037
CF, Maas, Mueller, EPJC 68 (2010)

$t = (T-T_c)/T_c$

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

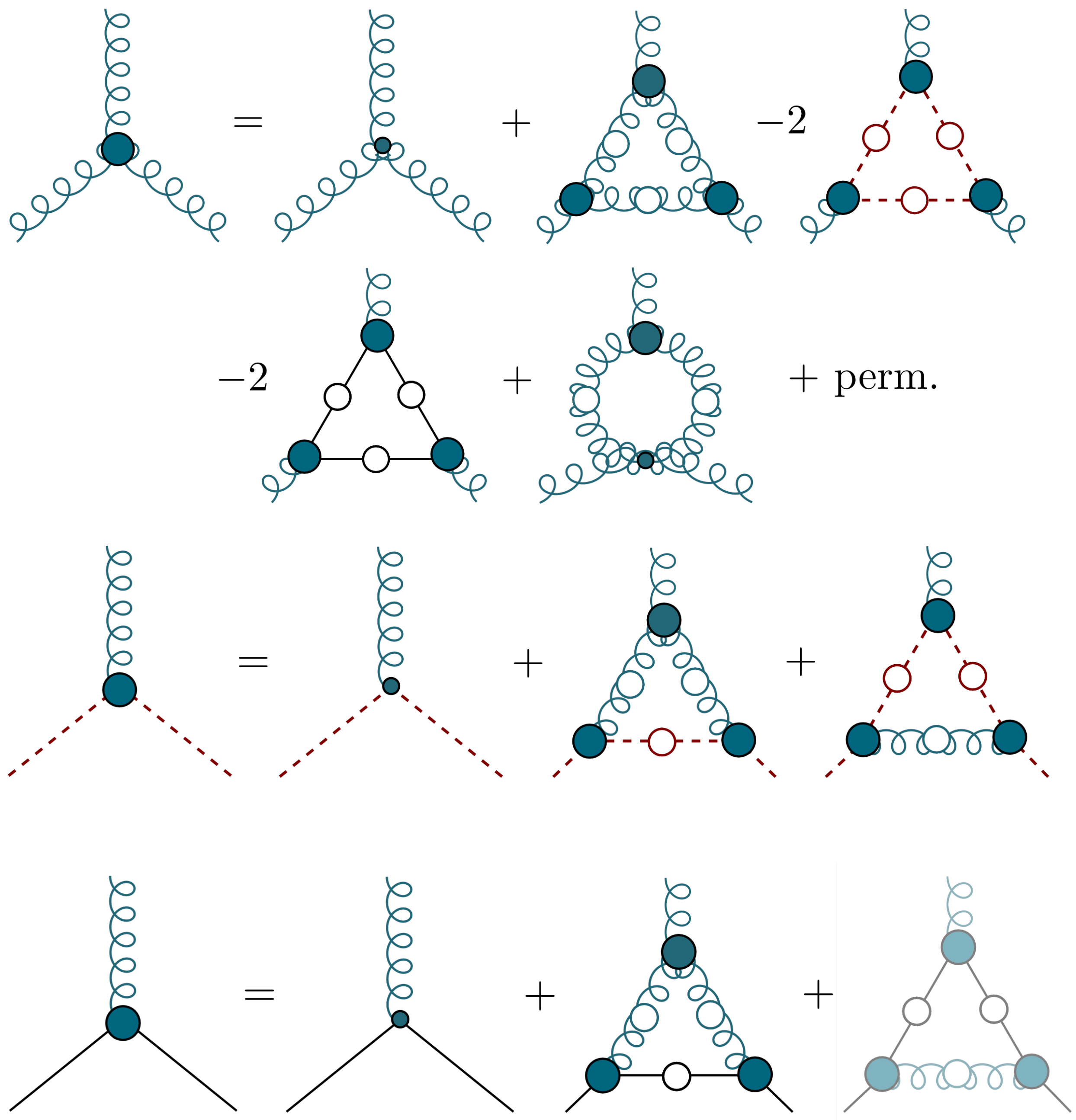
3PI-truncation

propagators



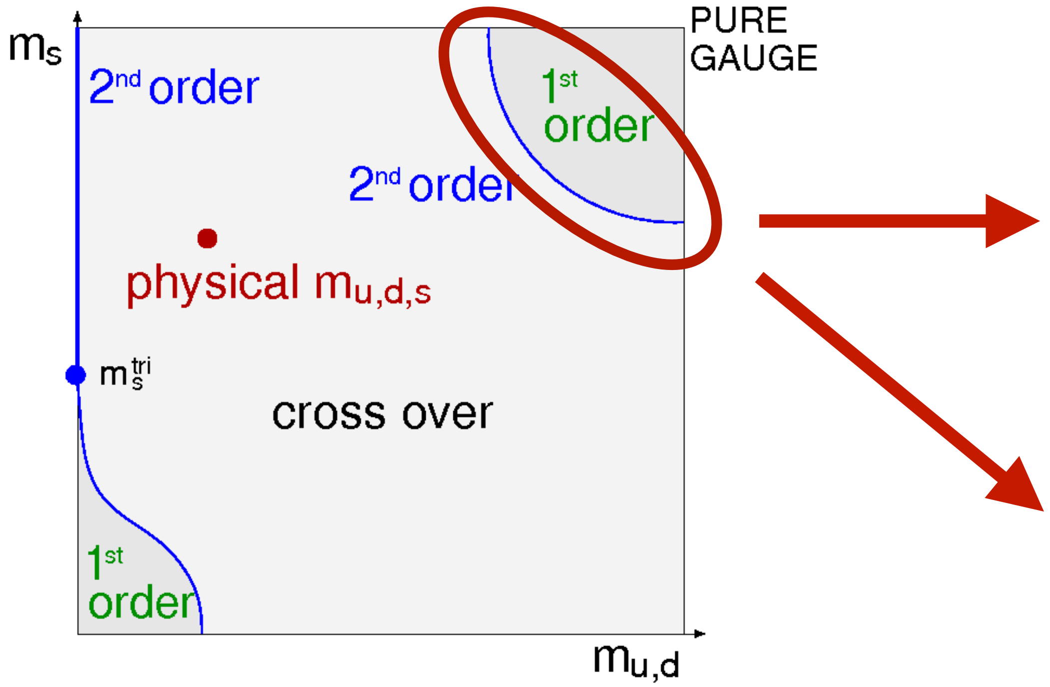
for different BRL approaches see work of
Aguilar, Alkofer, Binosi, Blum, Chang, Cyrol, Eichmann, Fister, Huber, Maas, Mitter, Papavassiliou, Pawlowski, Roberts, Smekal, Strodthoff, Vujinovic, Watson, Williams…

vertices

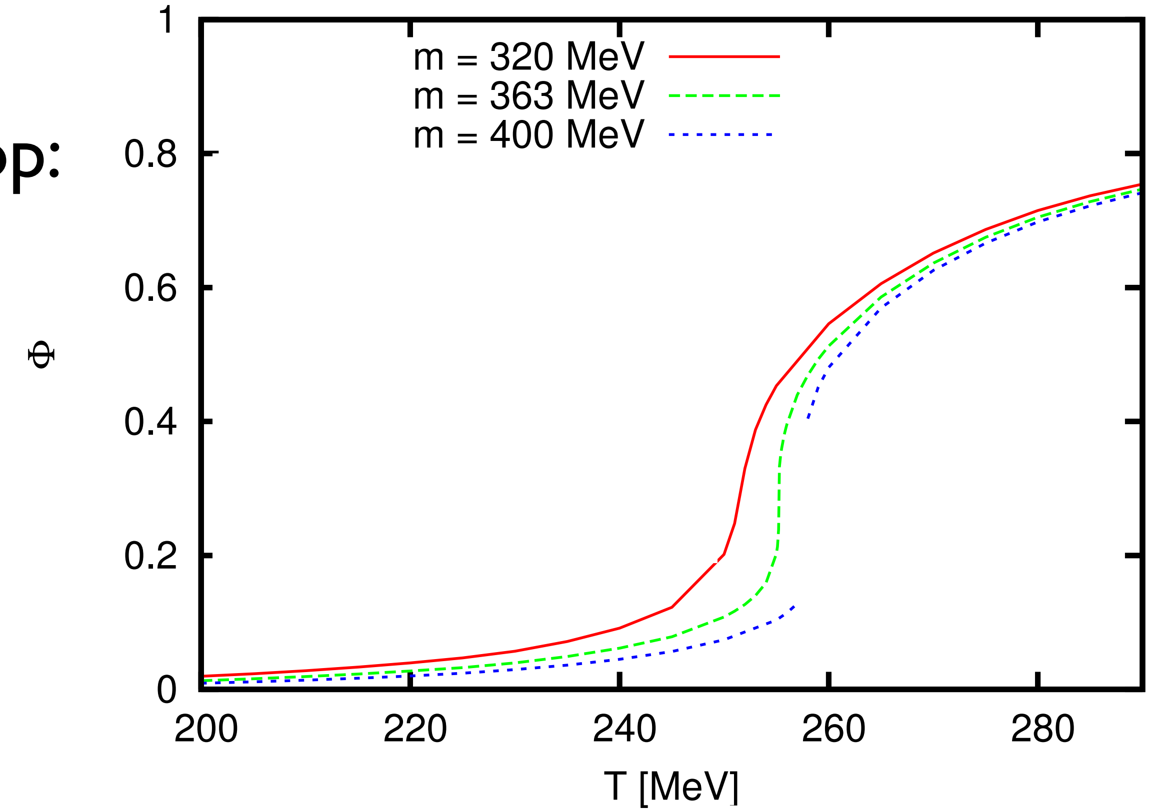


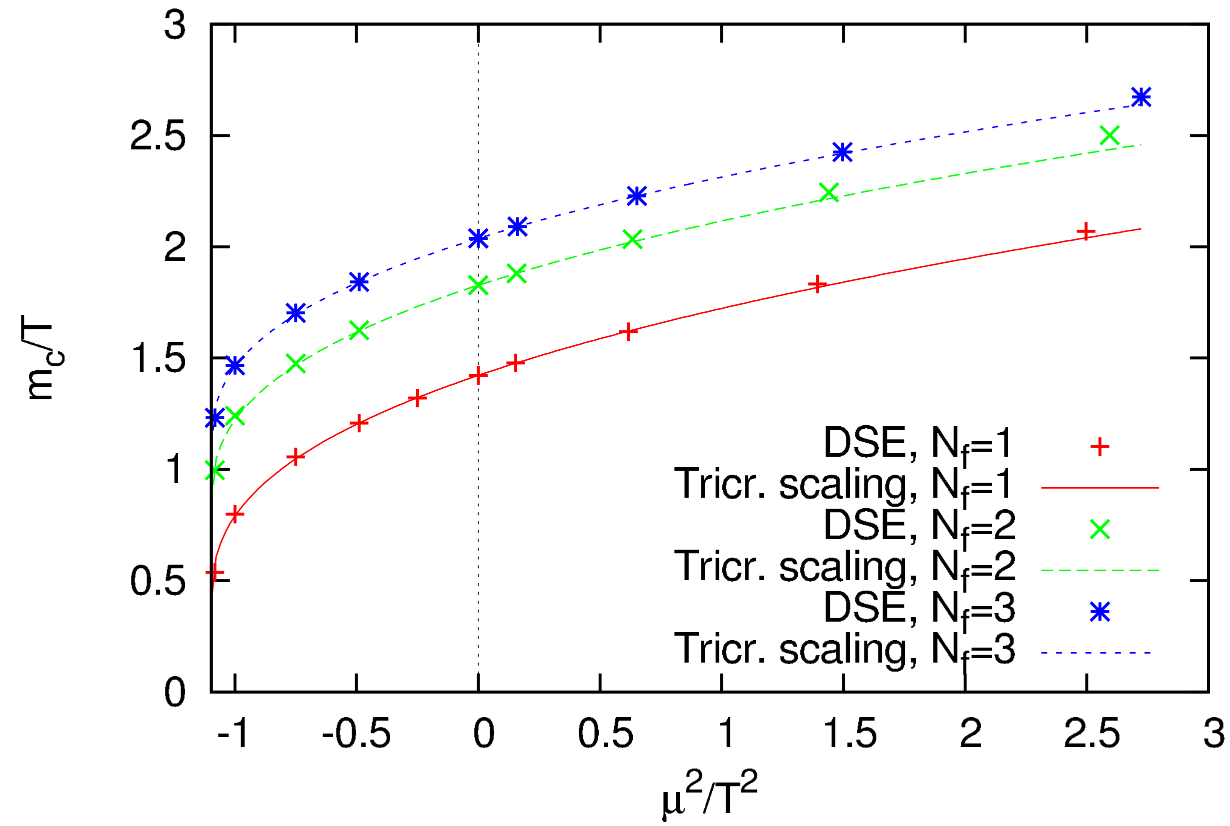
Williams, CF, Heupel, PRD 93 (2016) 034026
CF, Williams, PRL 103 (2009) 122001

Critical line/surface for heavy quarks



Polyakov Loop:



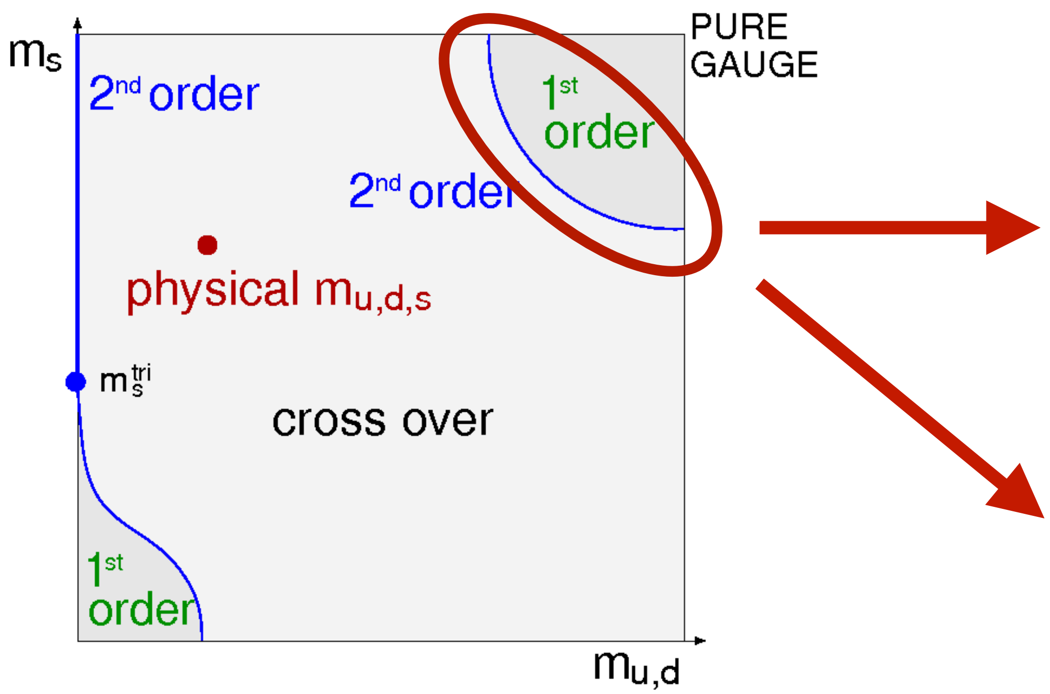


- Deconfinement transition in agreement with lattice QCD
- Correct tricritical scaling
- Roberge-Weiss-transition seen

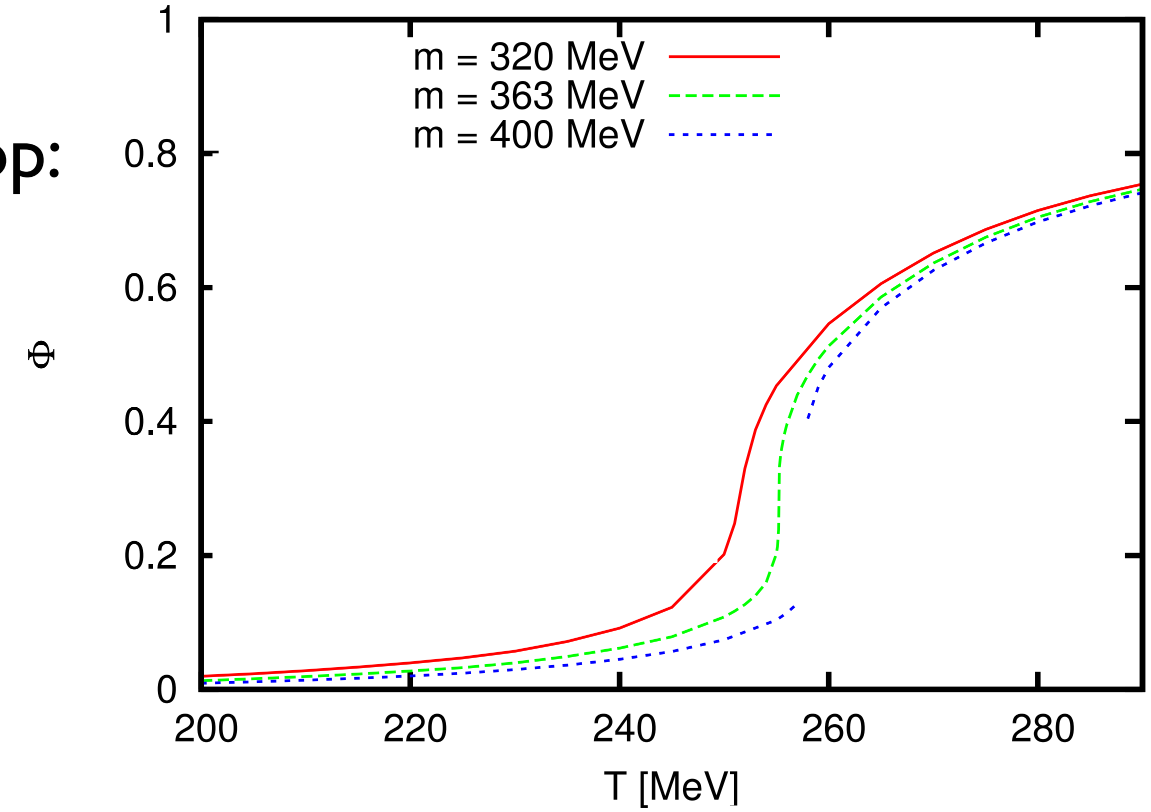
Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

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

Critical line/surface for heavy quarks



Polyakov Loop:



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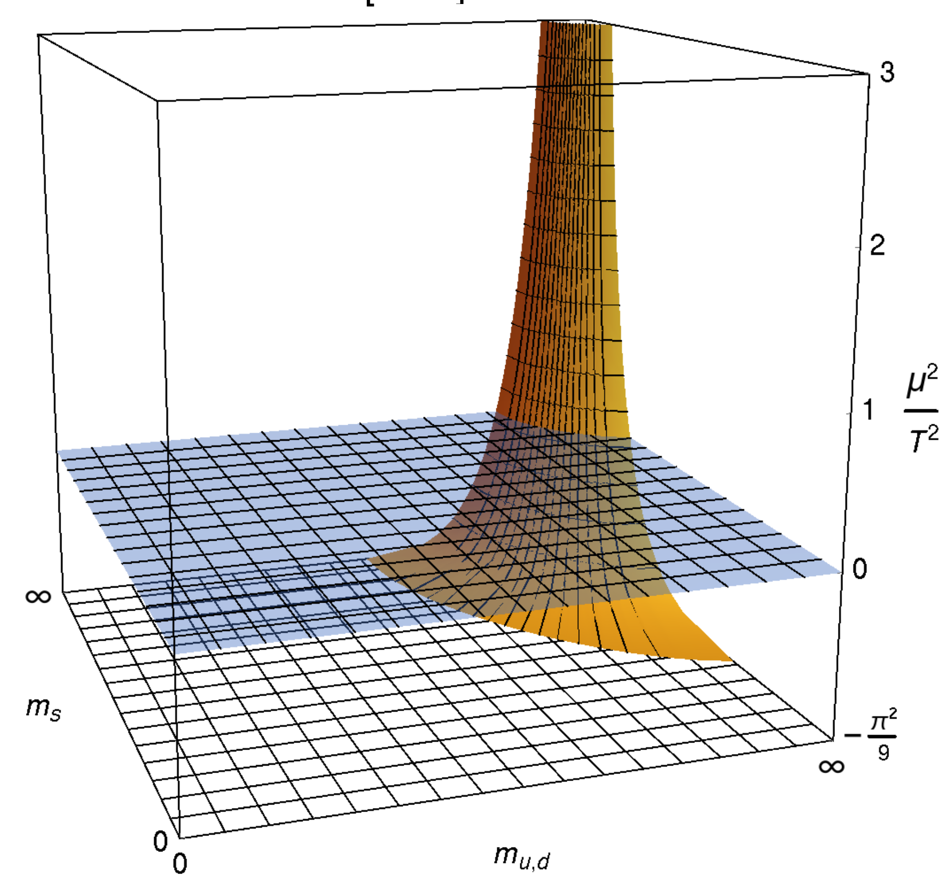
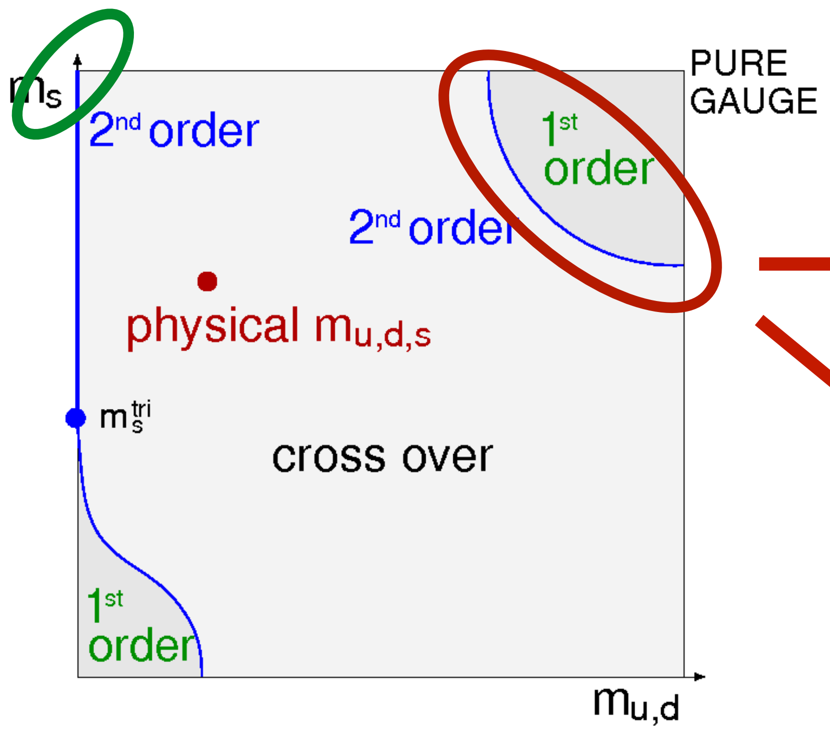


Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

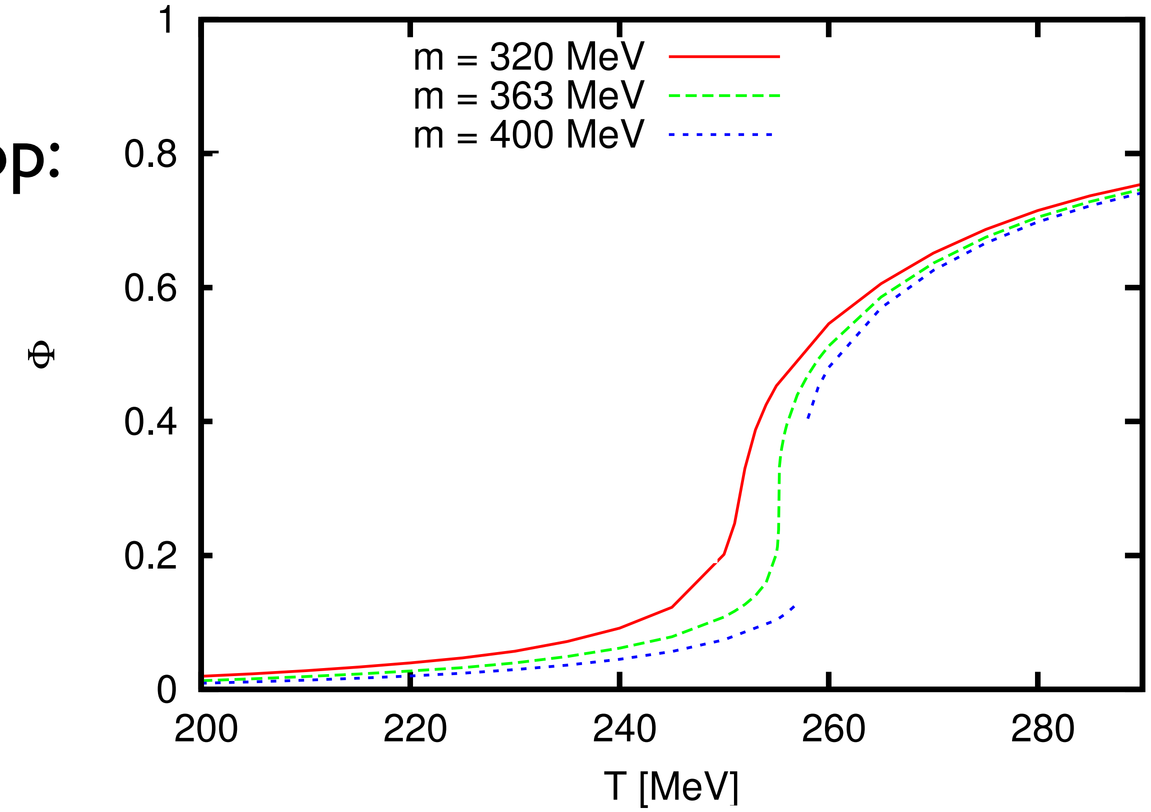
CF, Luecker, Pawlowski, PRD 91 (2015) 1

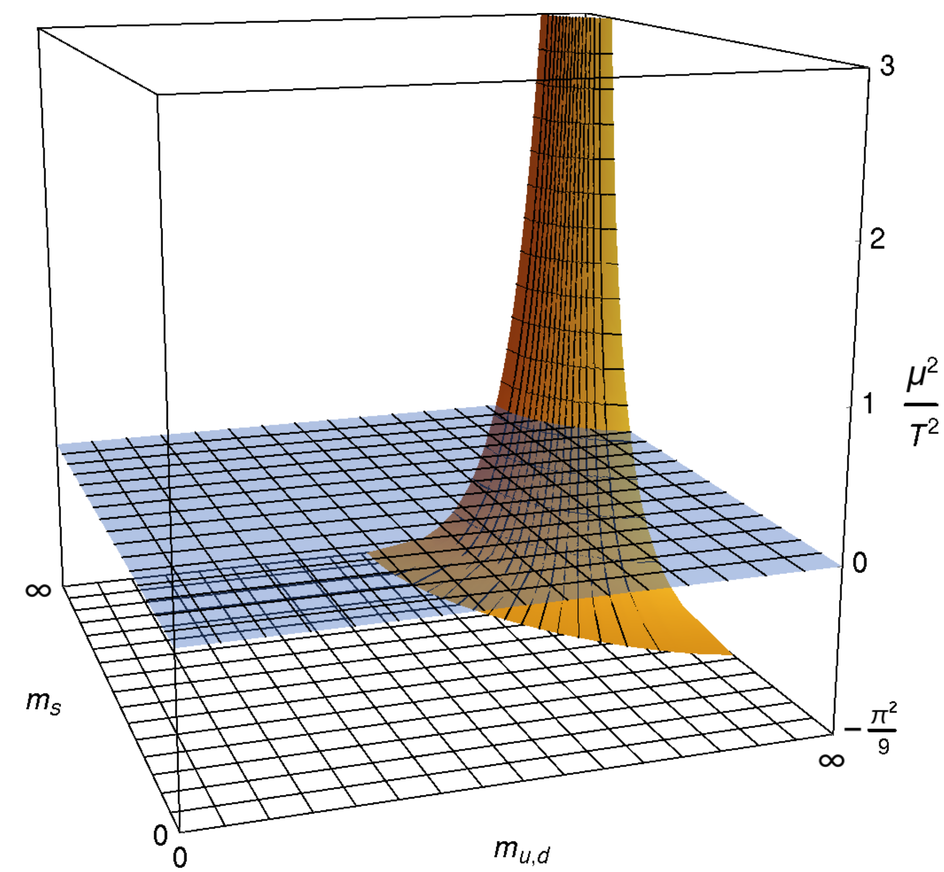
Critical line/surface for heavy quarks

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



Polyakov Loop:





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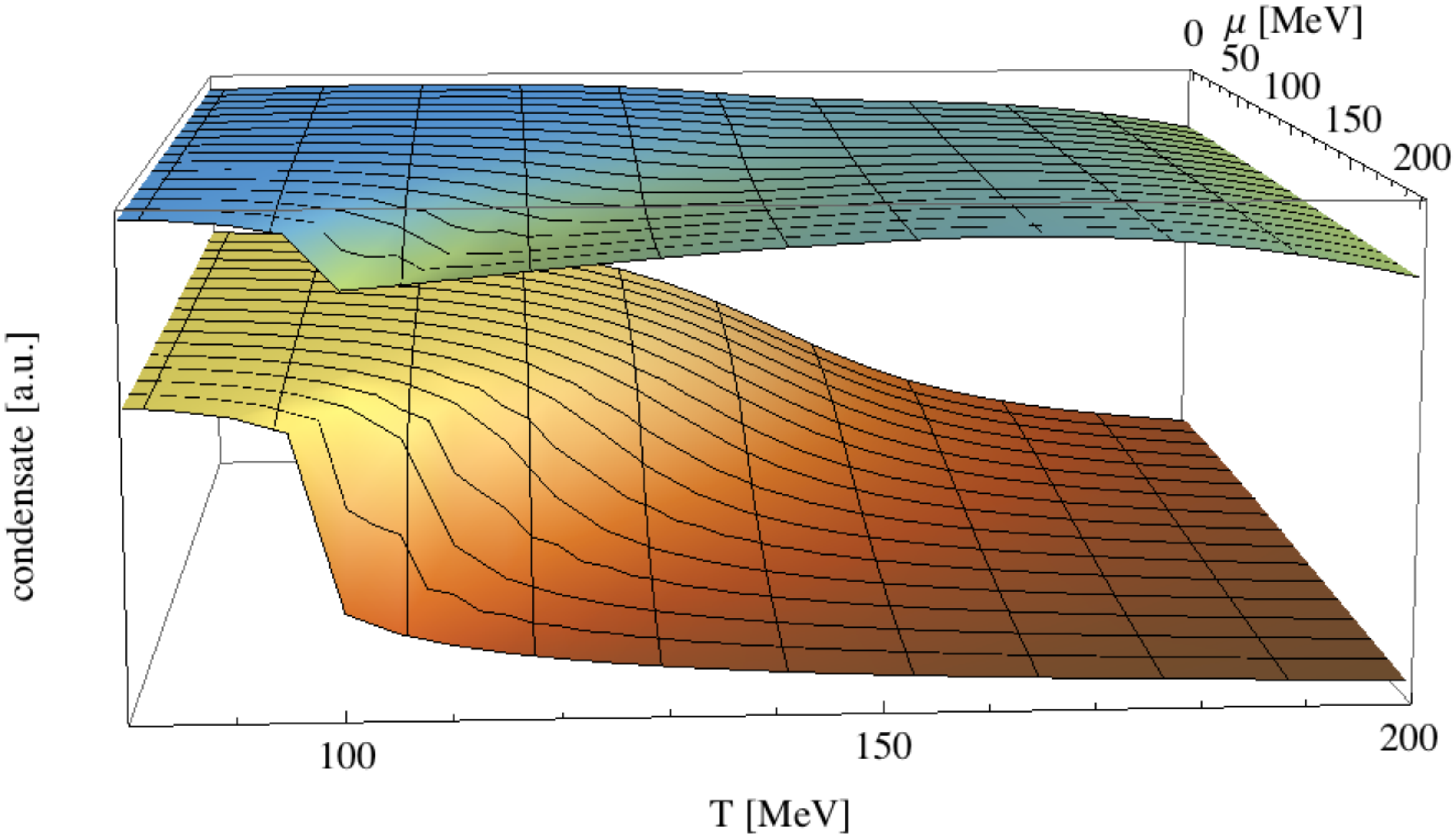
Lattice:
Fromm, Langelage, Lottini, Philipsen, JHEP 1201 (2012) 042

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

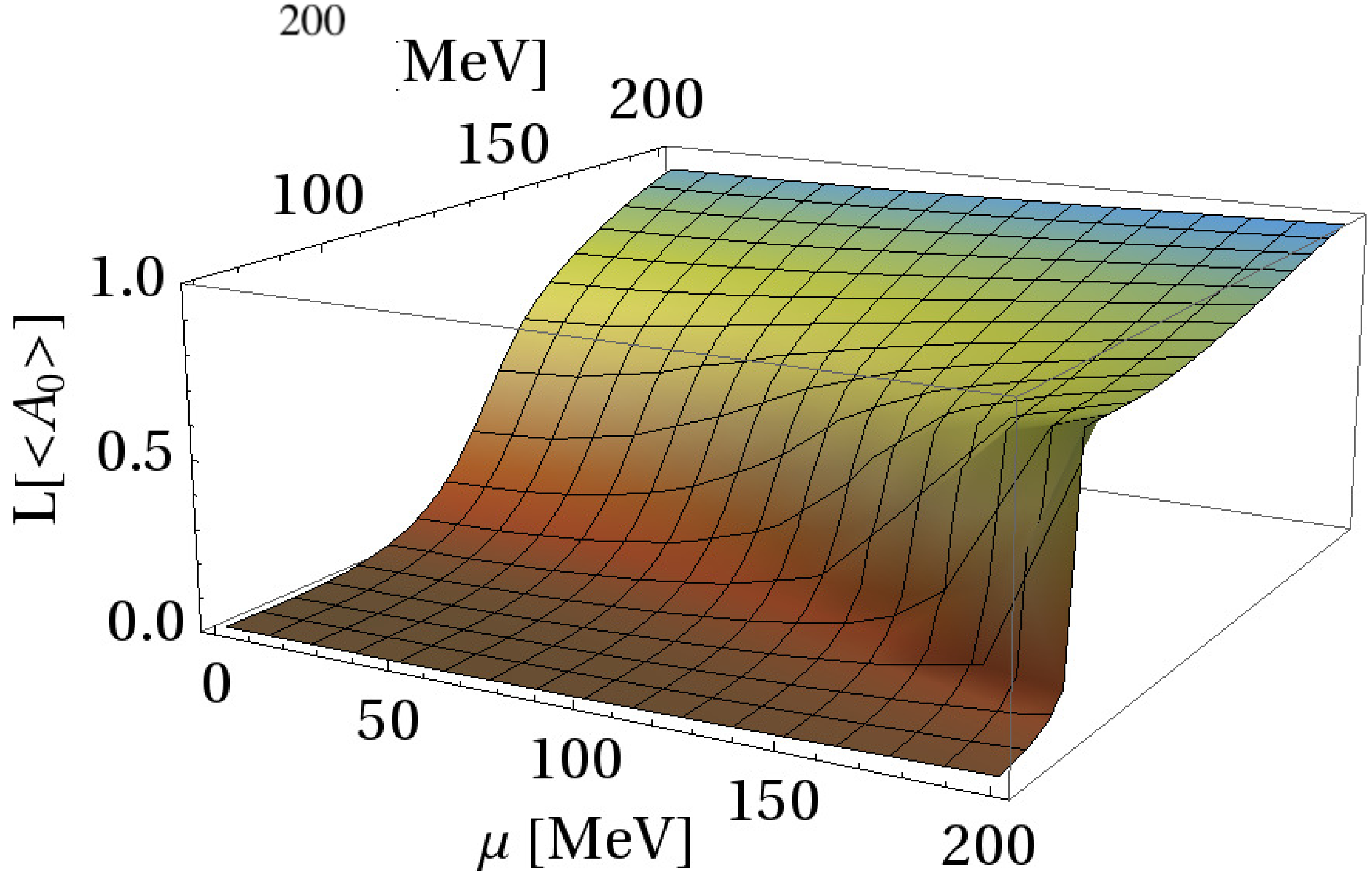
Nf=2+1: Condensate and dressed Polyakov Loop



Quark condensate

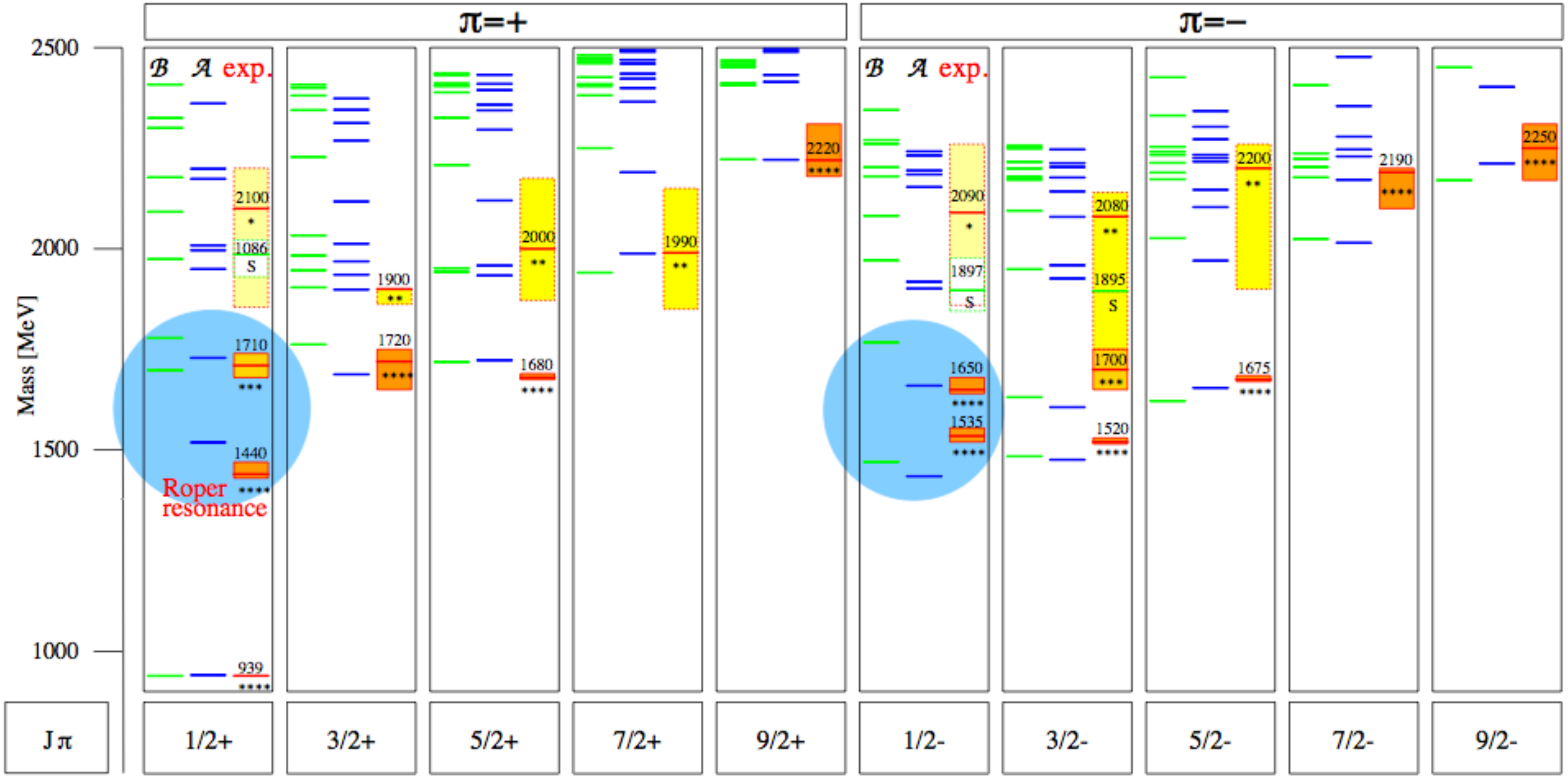
Polyakov-Loop

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



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

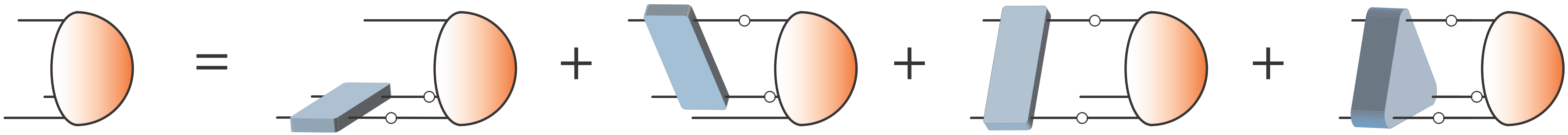
Baryons: Quark model



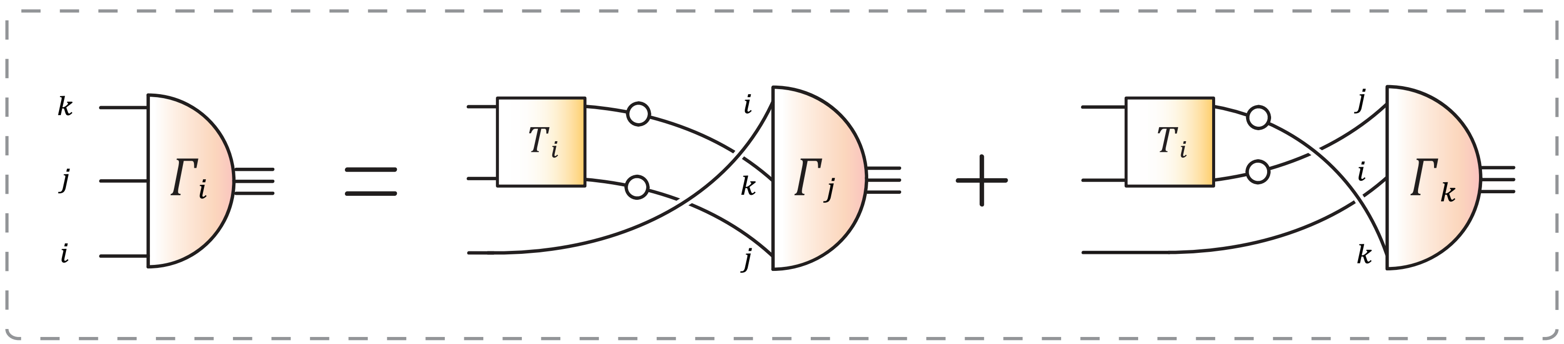
Loring, Metsch, Petry, EPJA 10 (2001) 395

- ‘missing resonances’ - three-body vs. quark-diquark
- level ordering: $N\frac{1}{2}^{\pm}$ vs. $\Lambda\frac{1}{2}^{\pm}$

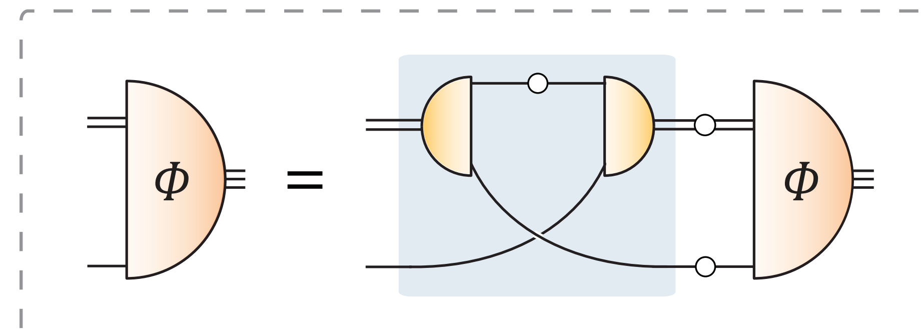
BSE for baryons (derived from equation of motion for G)



Faddeev equation (no three-body forces)

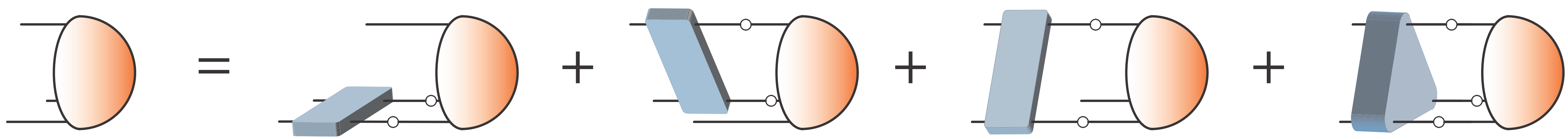


Diquark-quark



Vacuum: Baryons from BSEs

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



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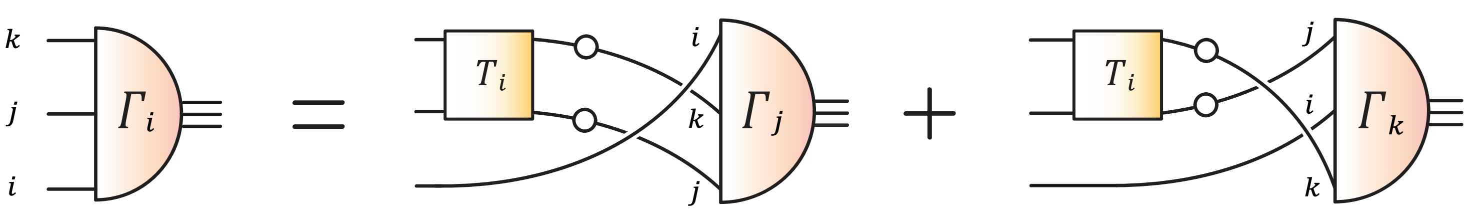
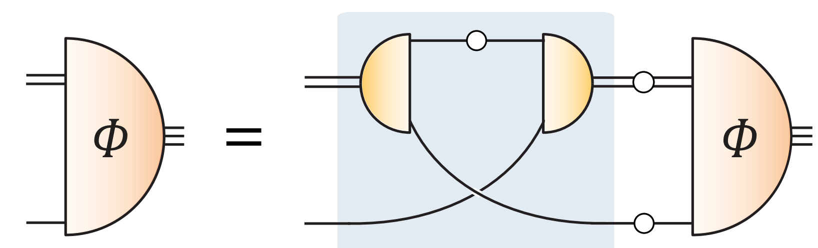
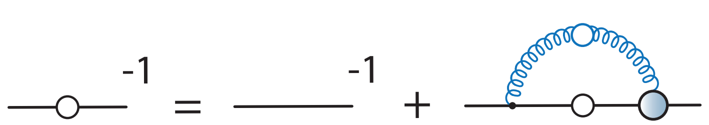
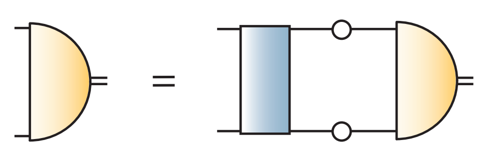
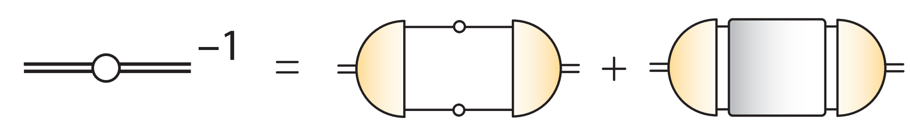


Diquark-quark









Vacuum: Baryons from BSEs

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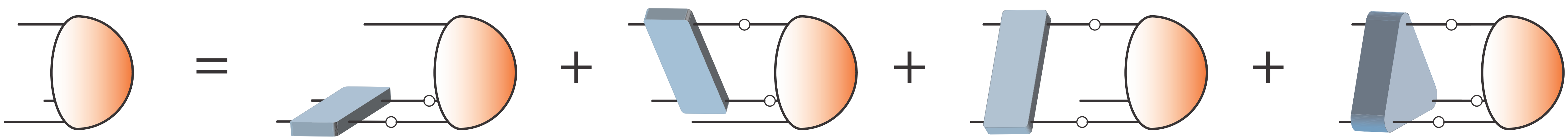

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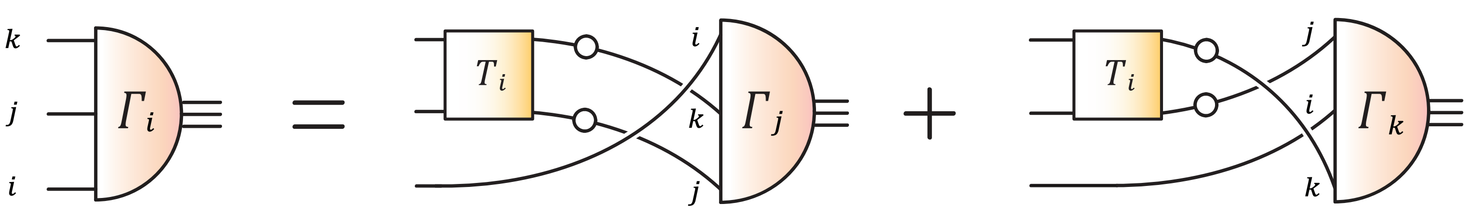
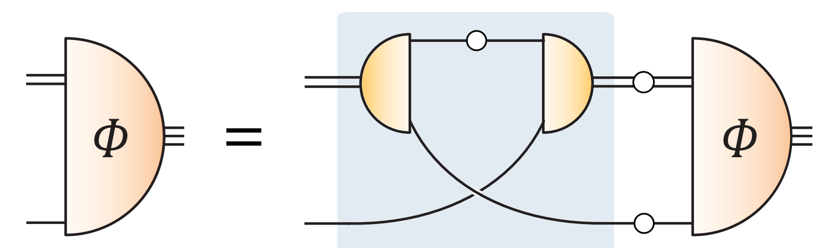
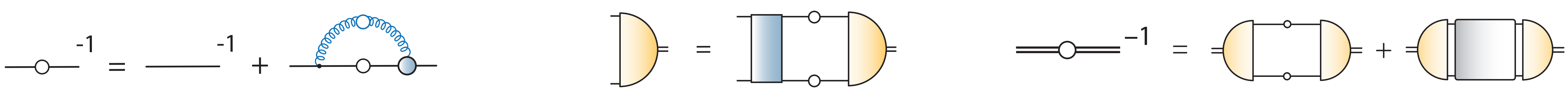
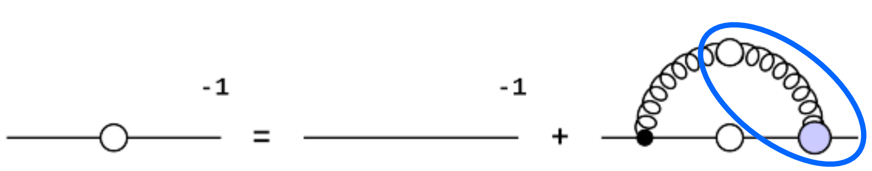


Diquark-quark



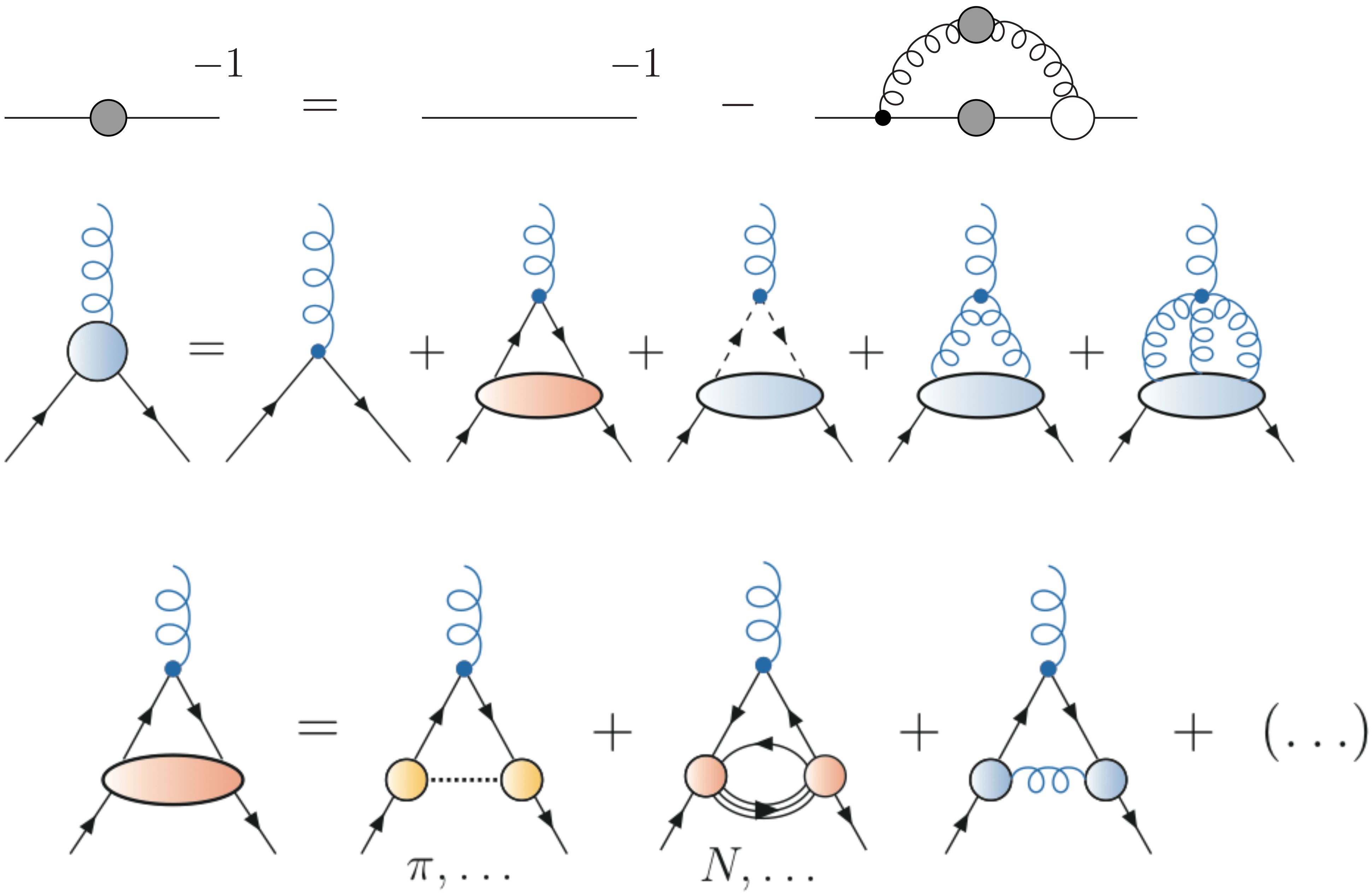


- Input: Non-perturbative quark, quark-gluon interaction (RL)



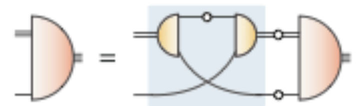
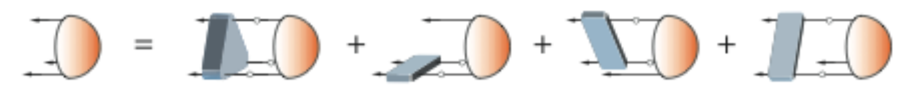
$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

Baryon effects onto quark I

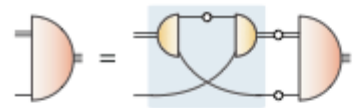


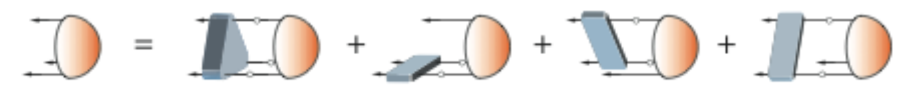
- ‘Off-shell baryons’ do affect quark condensate…

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	√	√		$\dots$		
$N \to N^*\gamma$	√	√		$\dots$		
$N^*(1535), \dots$	$\dots$	$\dots$		$\dots$	$\dots$	
$N \to N^*\gamma$	$\dots$	$\dots$				
	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





	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	√	√		$\dots$		
$N \to N^*\gamma$	√	√		$\dots$		
$N^*(1535), \dots$	$\dots$	$\dots$		$\dots$	$\dots$	
$N \to N^*\gamma$	$\dots$	$\dots$				
	Roberts et al	Oettel, Alkofer Roberts, Bloch Segovia et al.	Eichmann, Alkofer Nicmorus, Krassnigg	Eichmann, Alkofer Sanchis-Alepuz, CF	Sanchis-Alepuz, CF Williams	

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Approximation for Quark-Gluon interaction

- T,μ,m-dependent vertex:

Abelian WTI

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

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

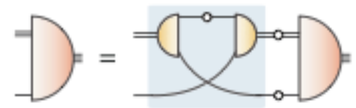
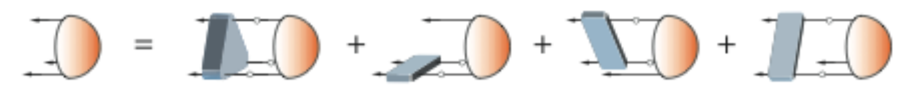
perturbation theory

Infrared ansatz:

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

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**
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Roper	√	√		$\dots$		
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$N^*(1535), \dots$	$\dots$	$\dots$		$\dots$	$\dots$	
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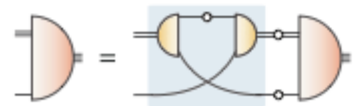
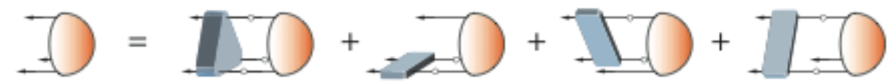
Eichmann, N*-Workshop, Trento 2015

DSE/Faddeev landscape (T=μ=0)

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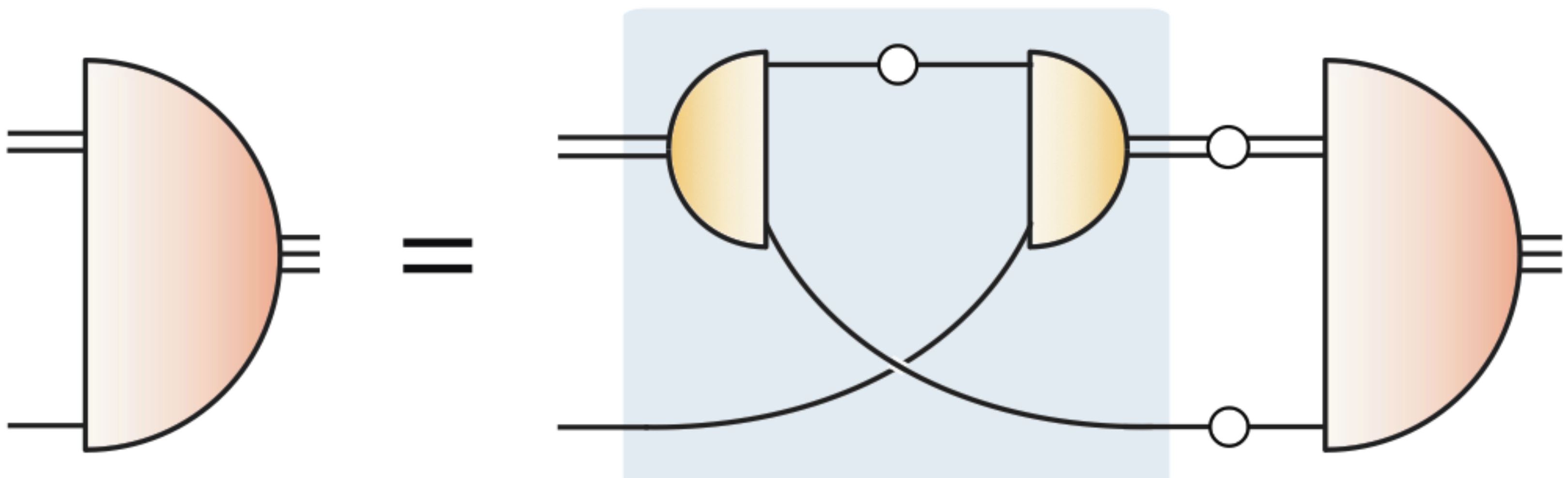

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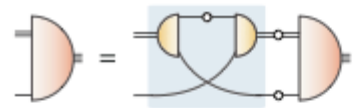
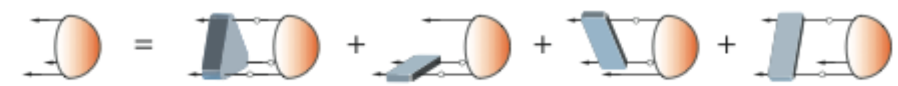
DSE/Faddeev landscape (T=μ=0)

	Quark-diquark 			Three-quark 		
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$N^*(1535), \dots$	$\dots$	$\dots$		$\dots$	$\dots$	
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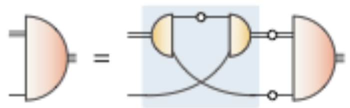
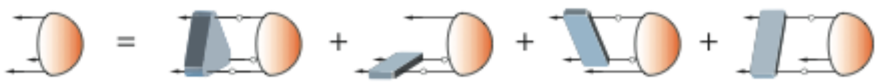
Eichmann, N*-Workshop, Trento 2015

DSE/Faddeev landscape (T=μ=0)

	Quark-diquark 			Three-quark 		
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N, Δ em. FFs	√	√	√	√		
$N \to \Delta\gamma$	√	√	√	...		
Roper	√	√		...		
$N \to N^*\gamma$	√	√		...		
$N^*(1535), \ldots$	...	...		...	...	
$N \to N^*\gamma$	...	...				

Contact interaction	QCD-based model	DSE (RL)	RL	bRL
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