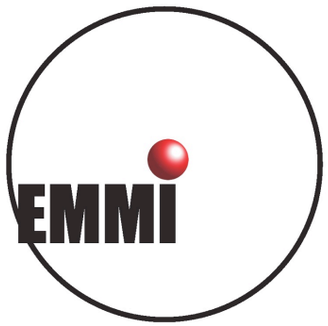
On the QCD phase diagram

Lisa Marie Haas
University of Heidelberg

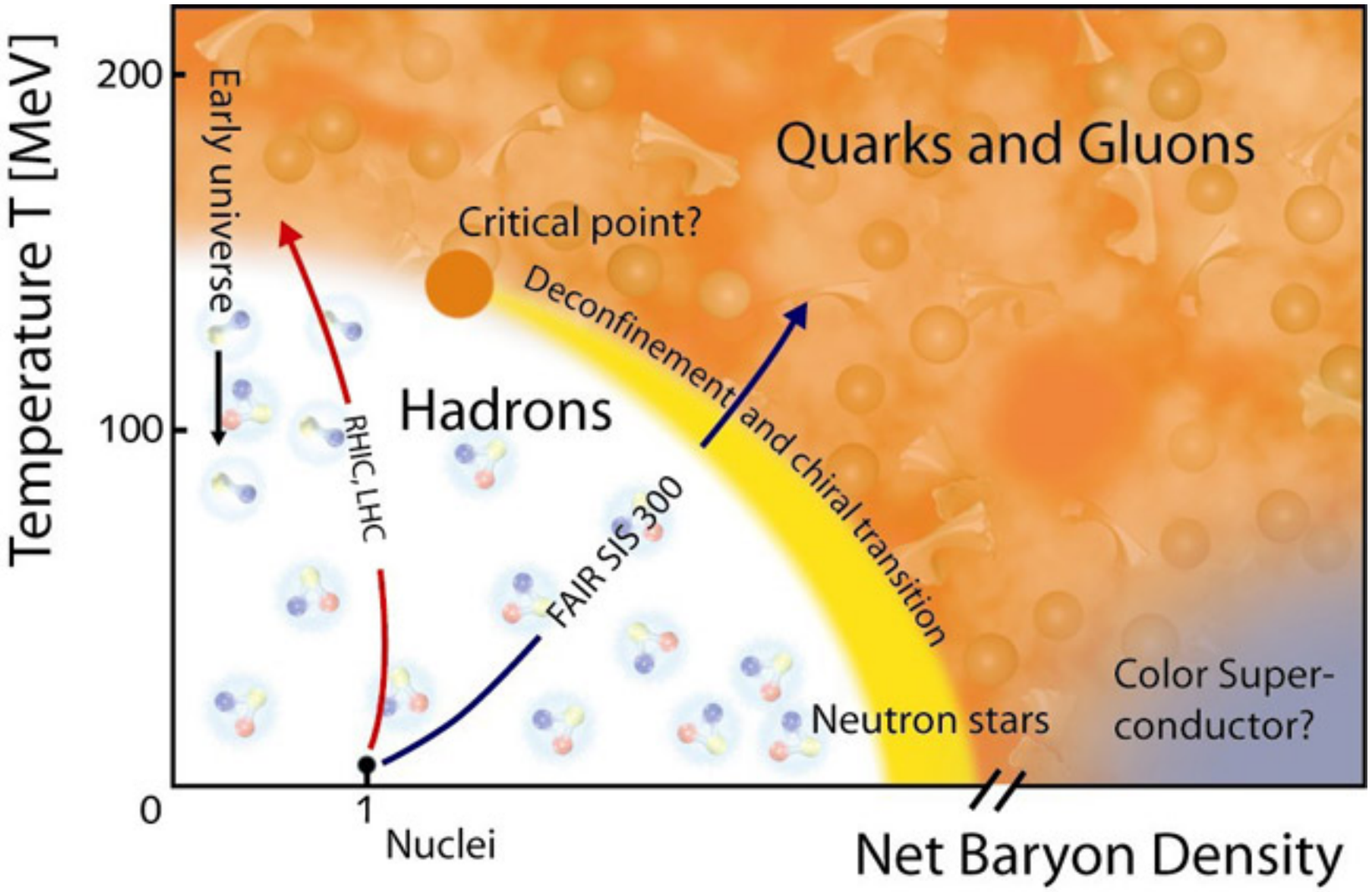
arXiv:0908.0008 [Braun, LMH, Marhauser, Pawlowski],
work in progress [Braun, LMH, Pawlowski]

ERG 2010, Corfu



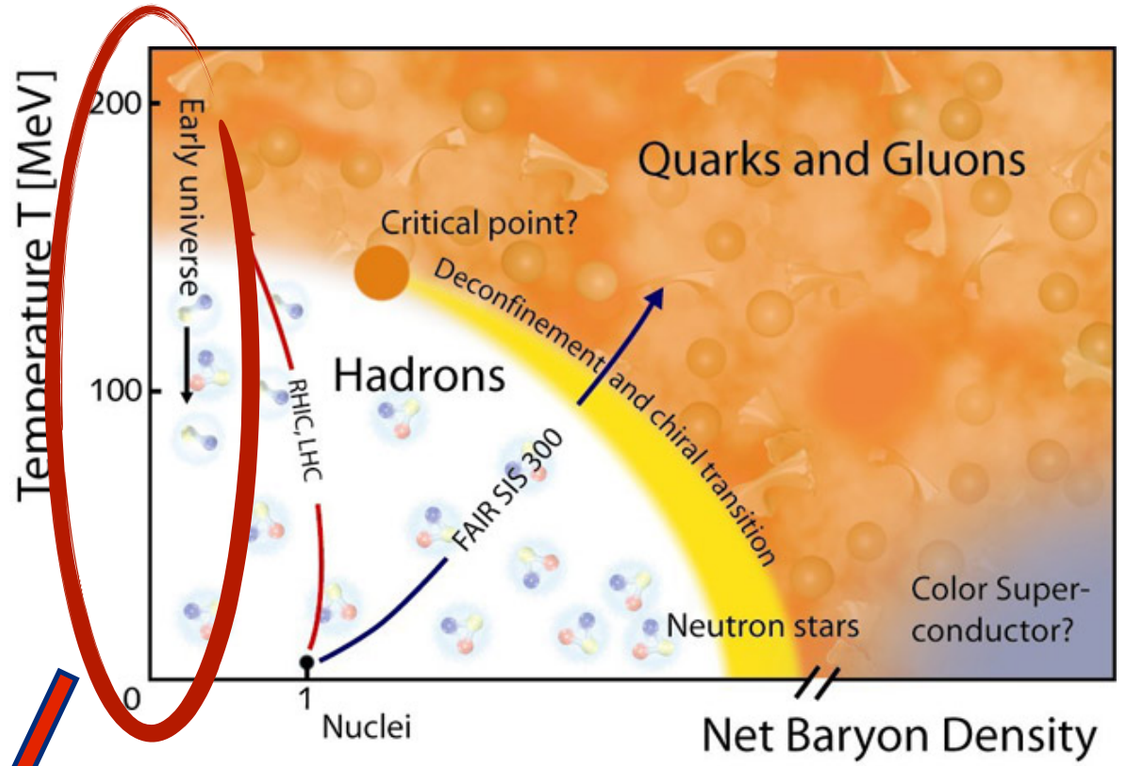
Motivation & Results

Motivation



credits: GSI Darmstadt

The QCD phase diagram $N_f=2$



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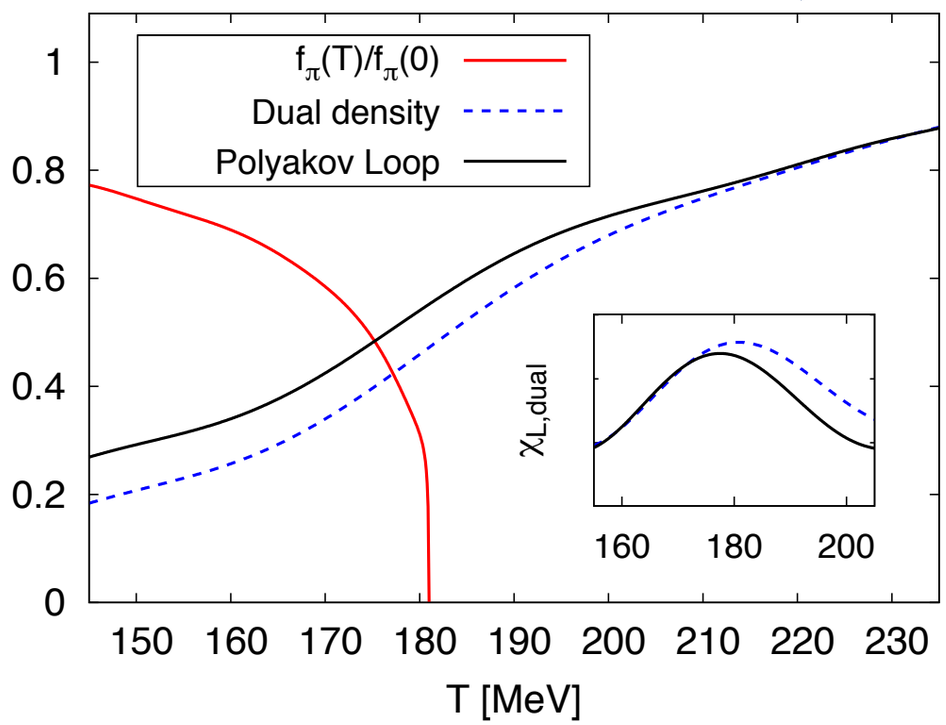

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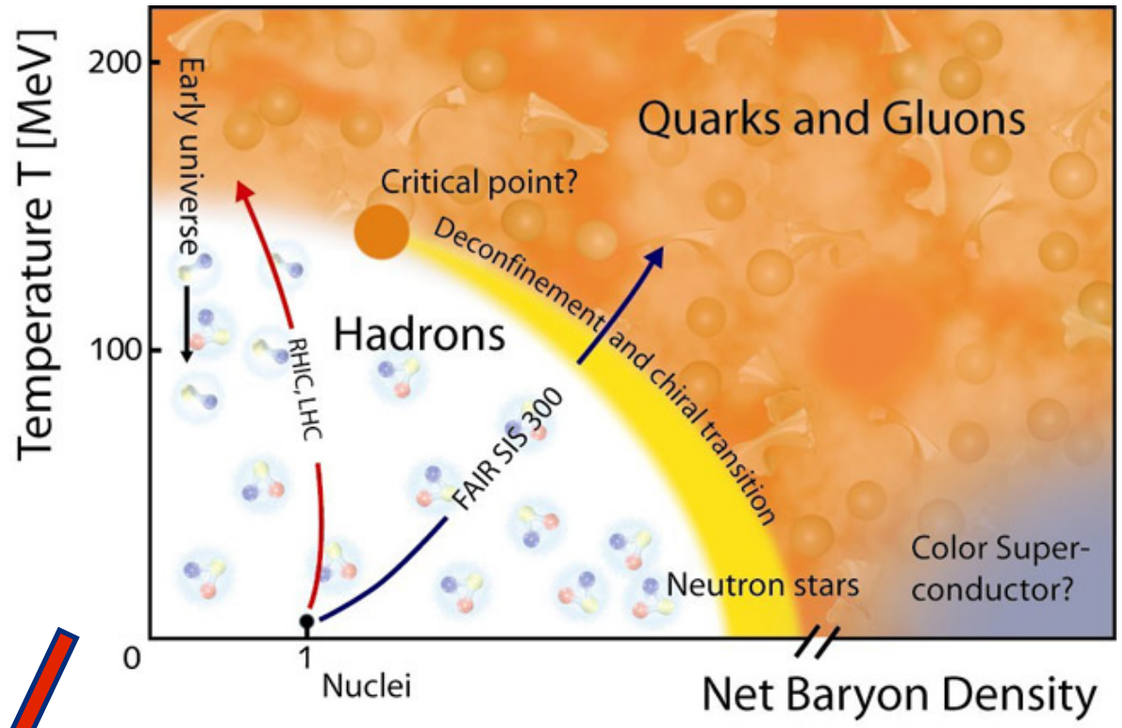

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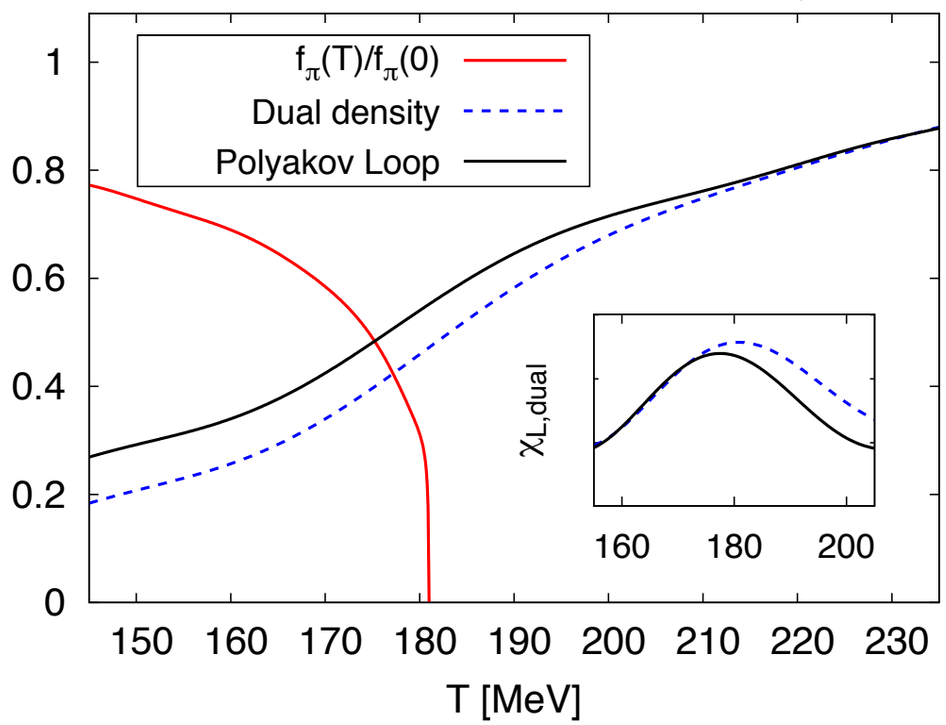

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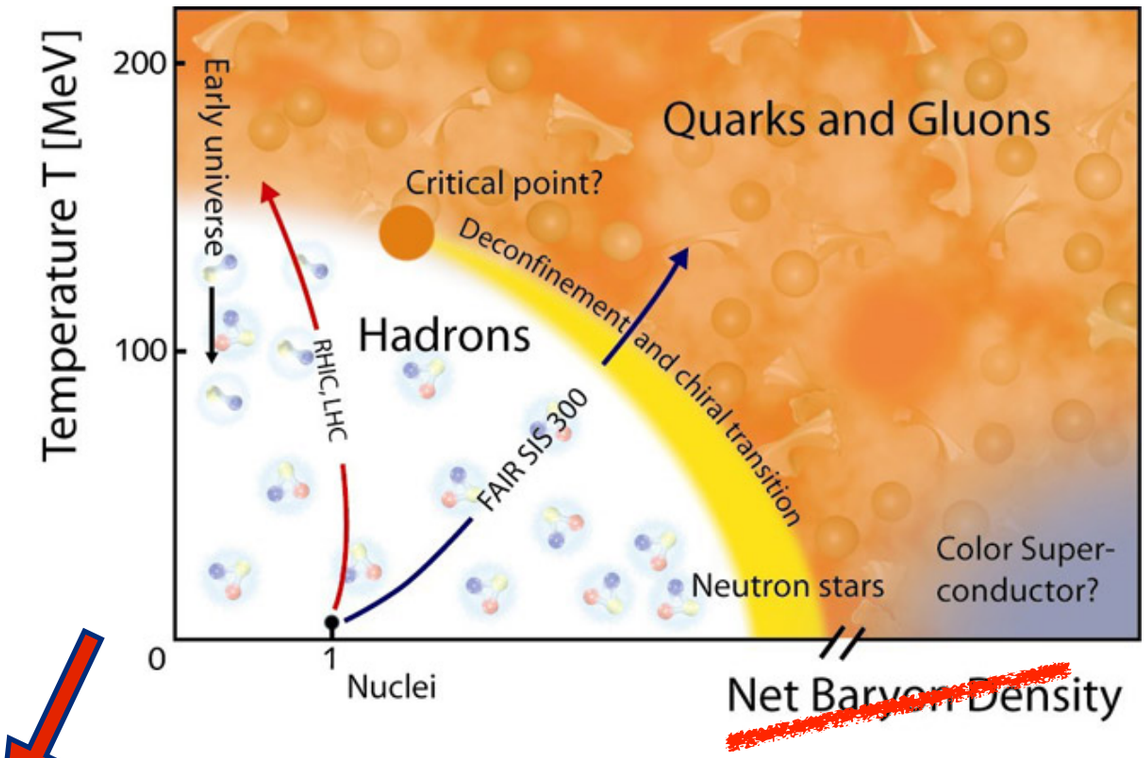

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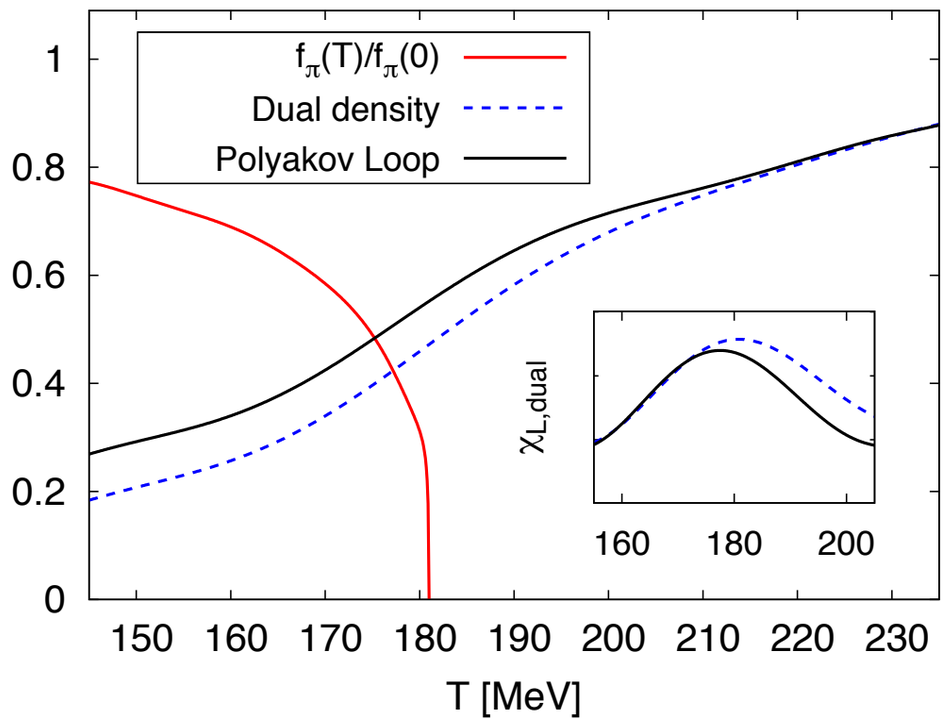

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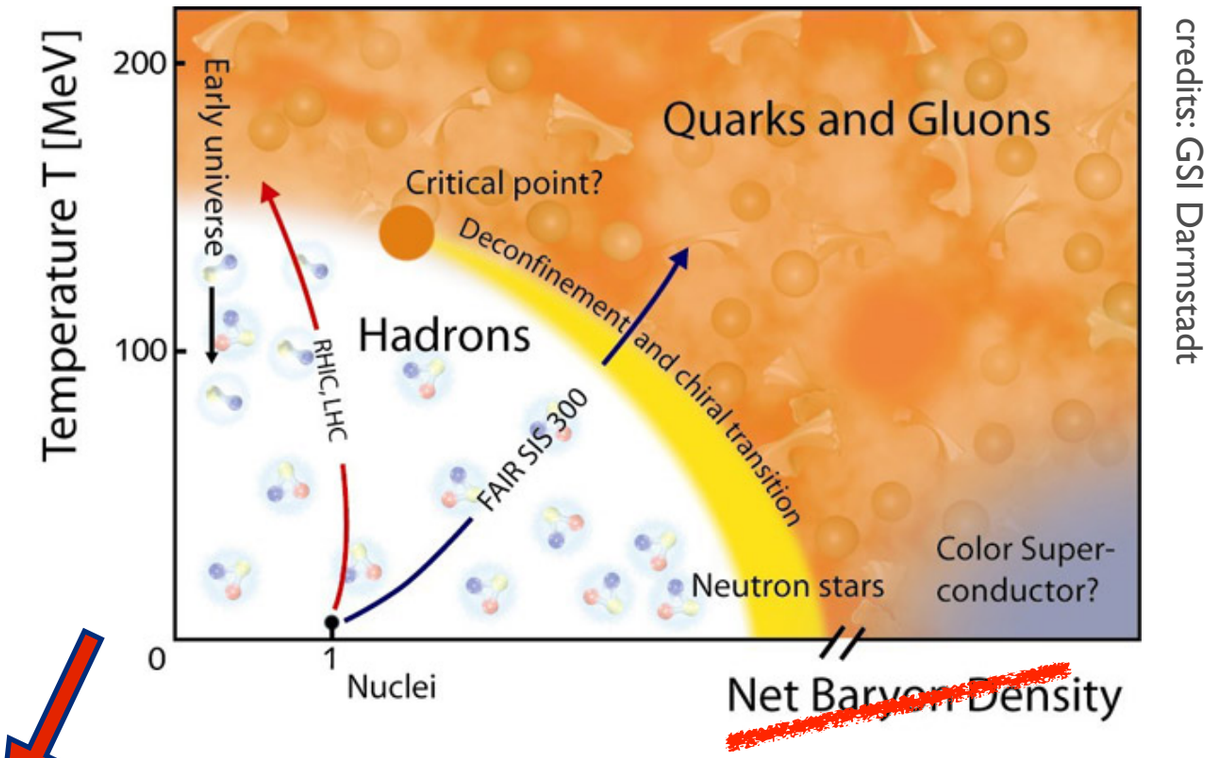

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(quark chemical potential)^2

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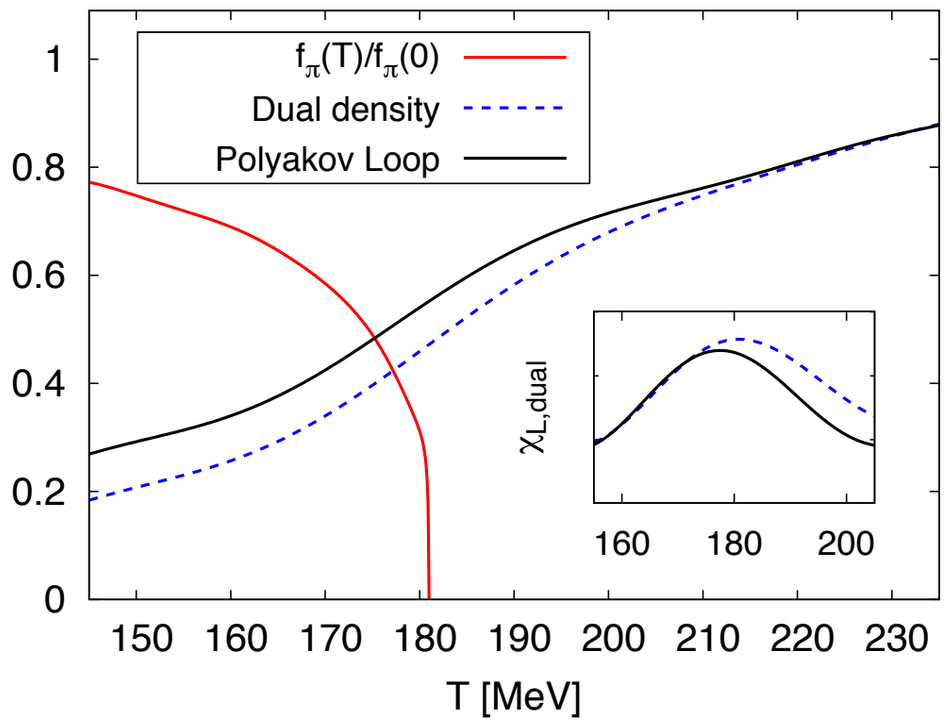

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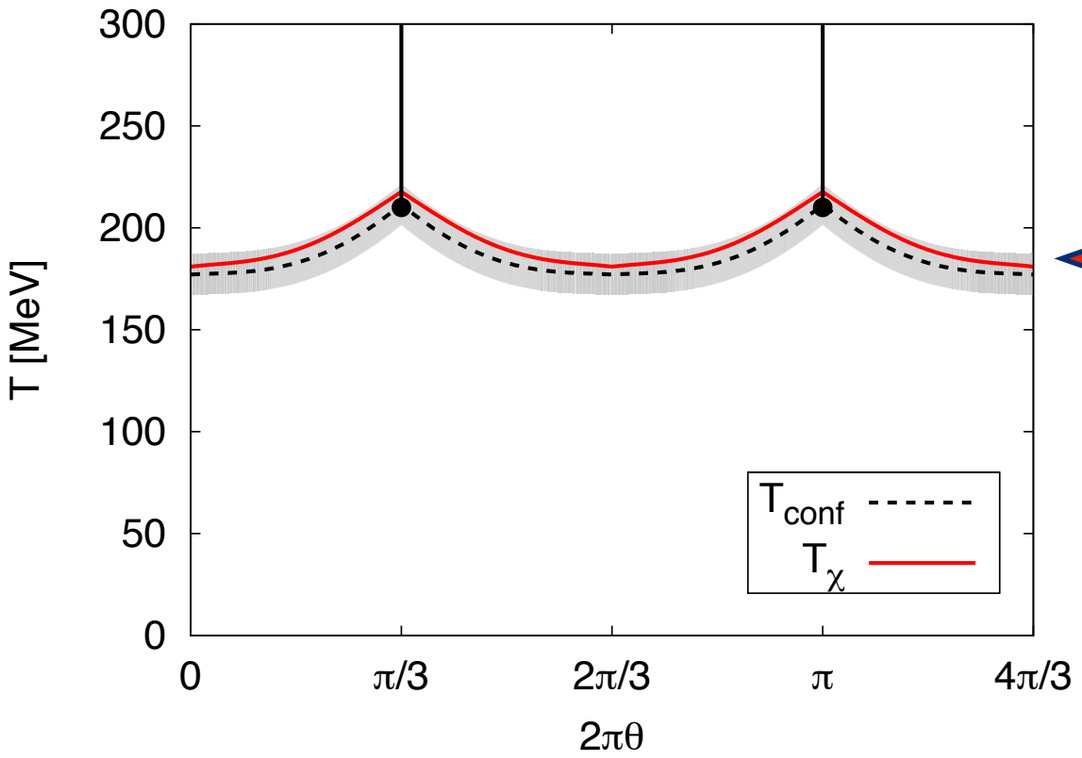

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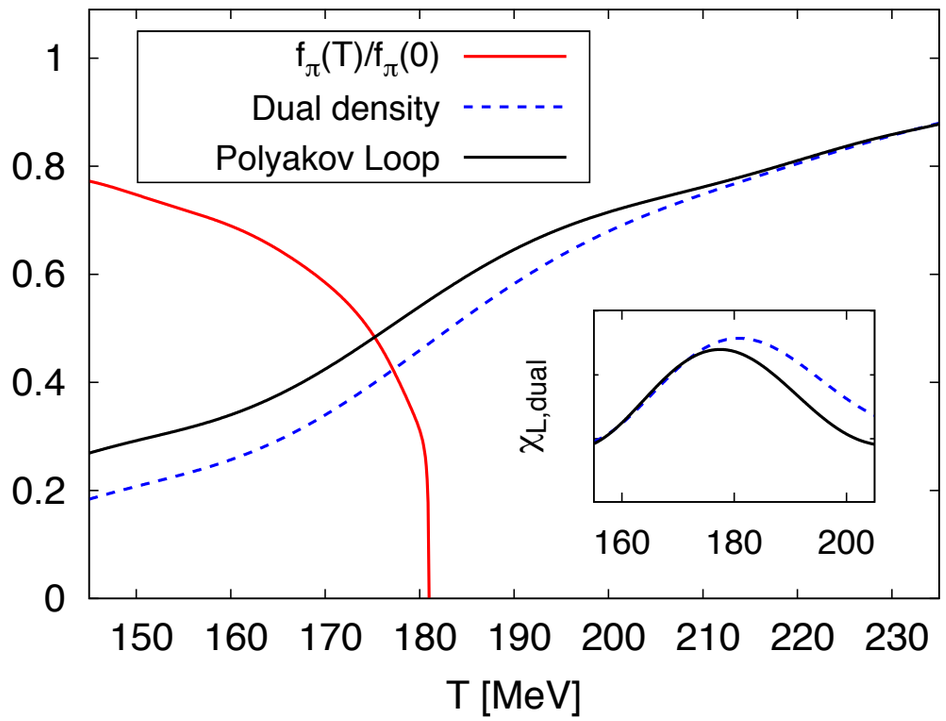

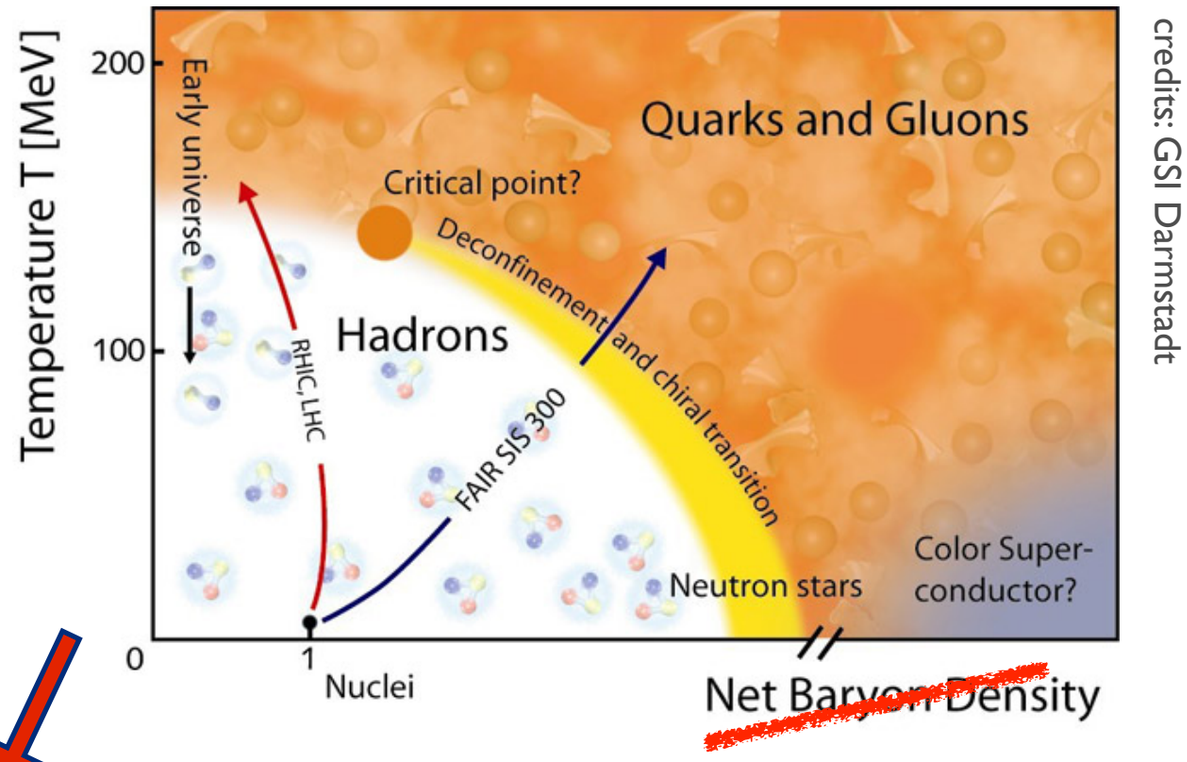

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$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$

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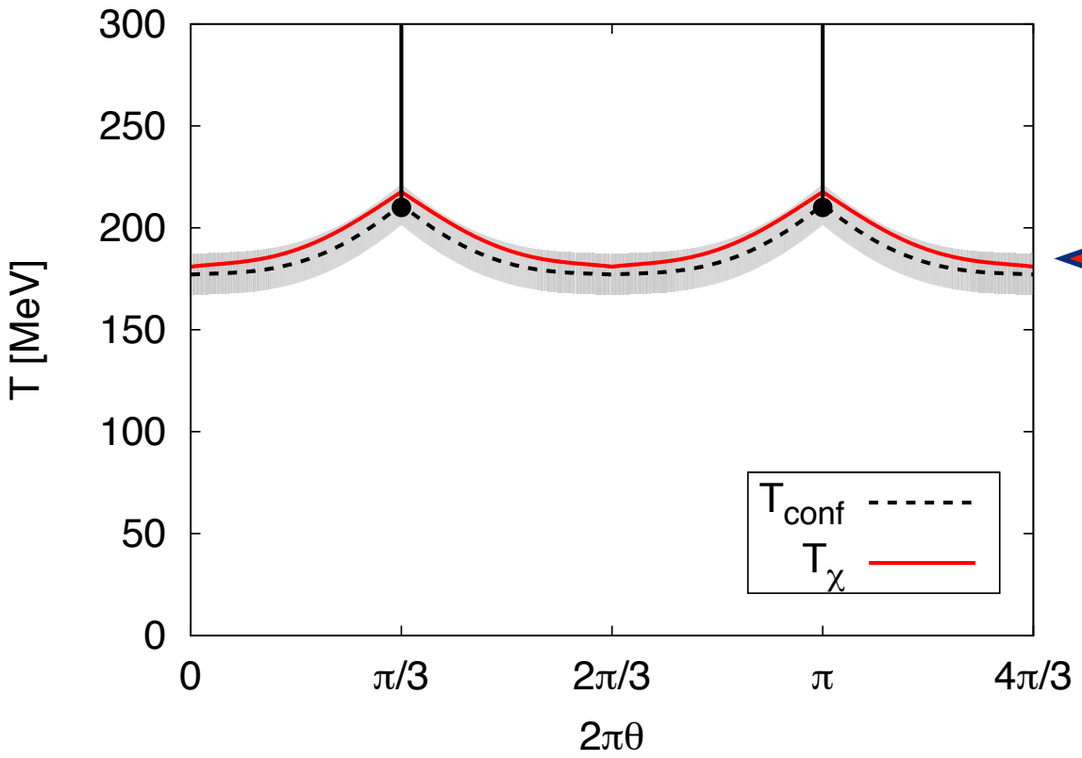

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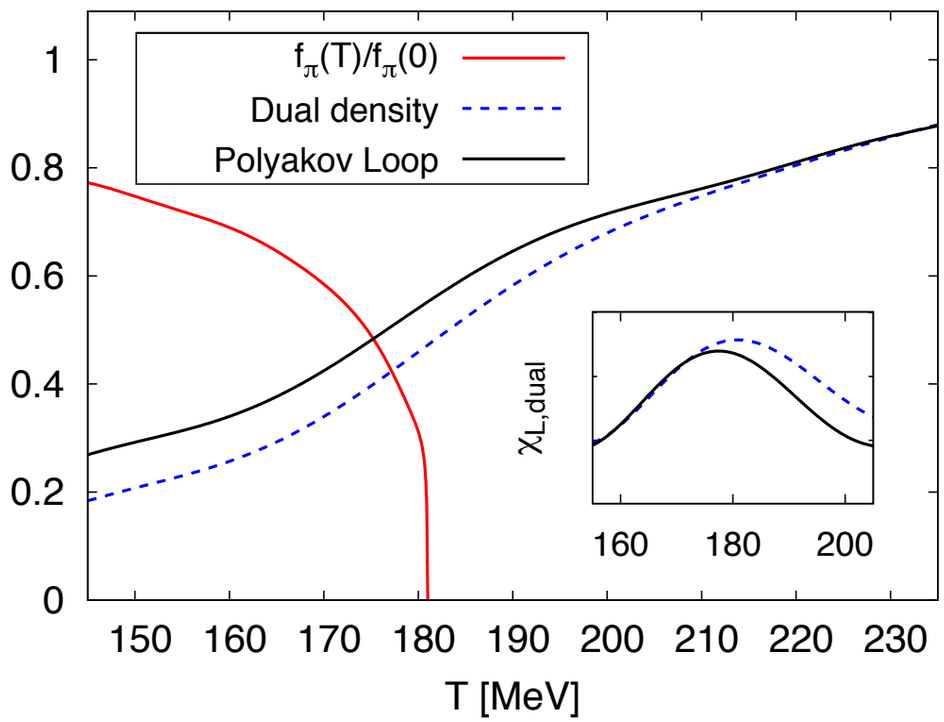

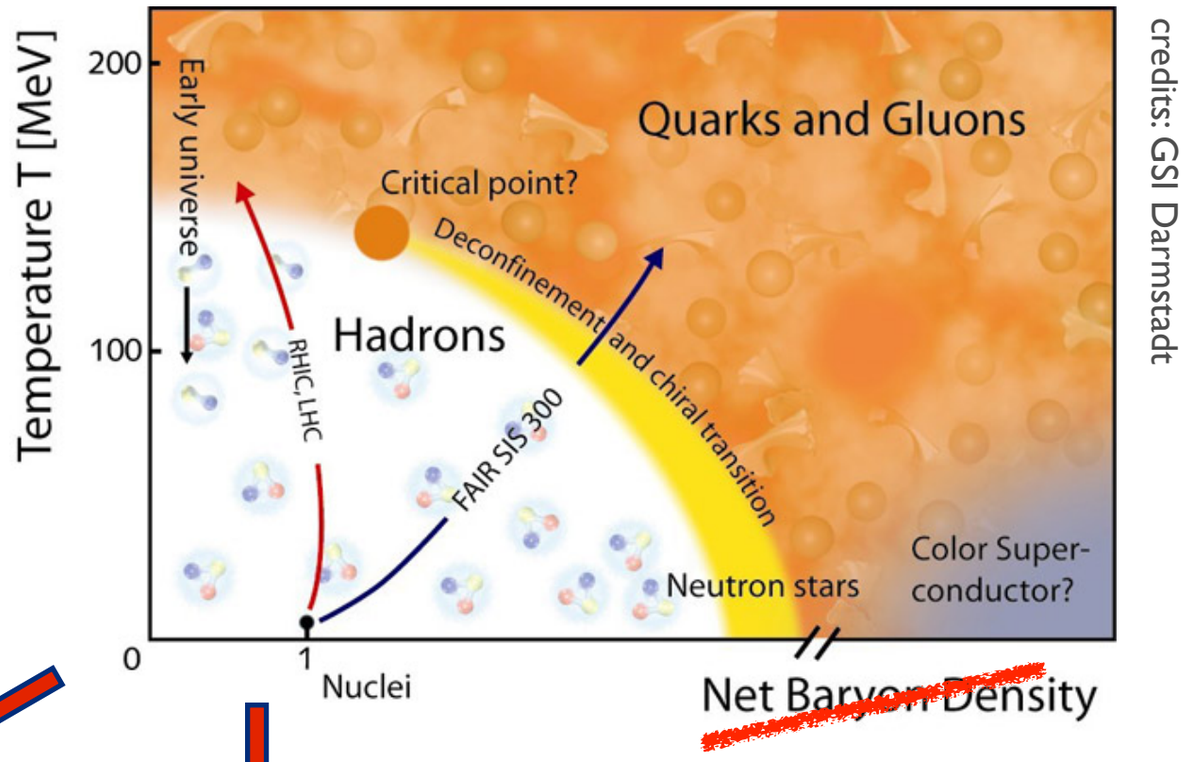

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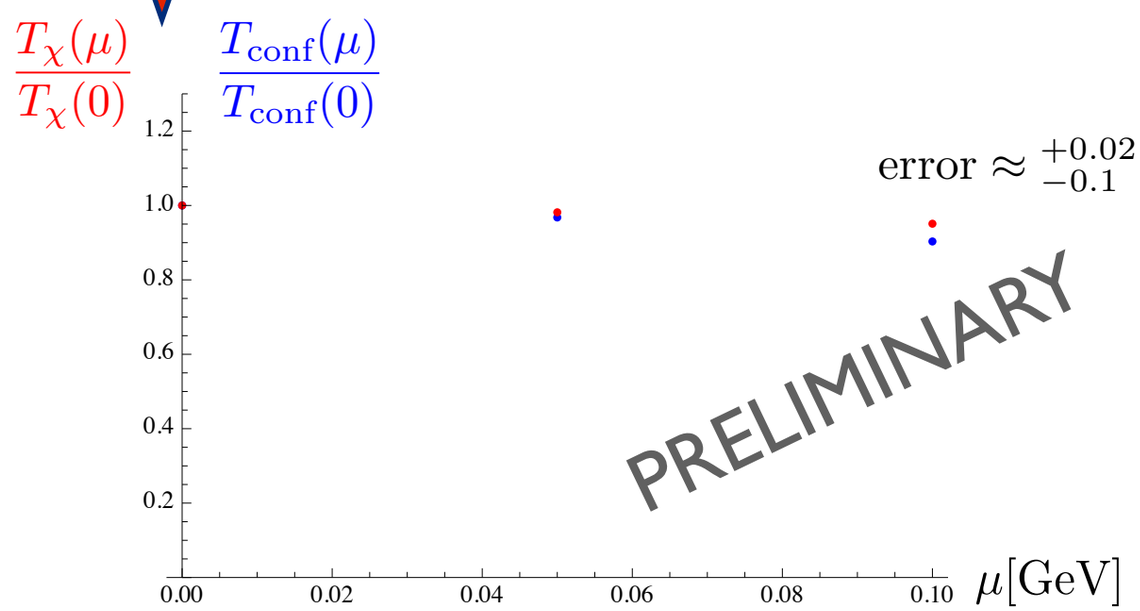
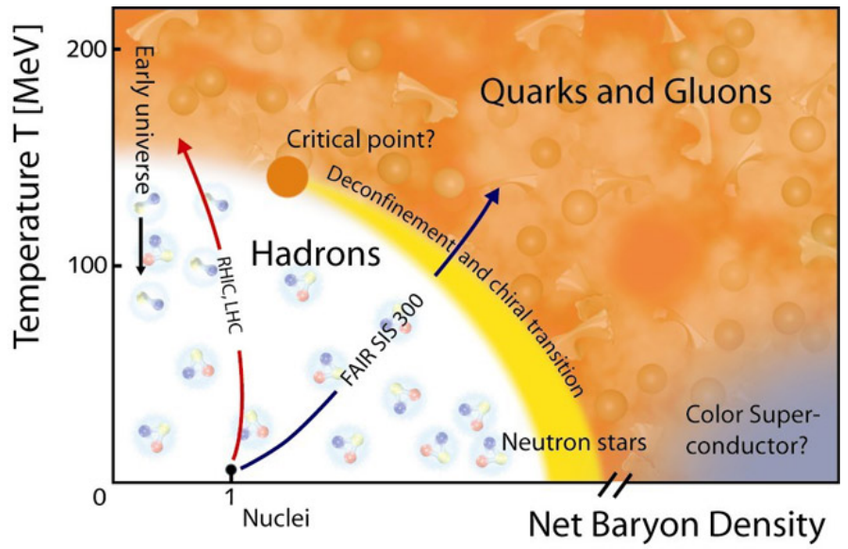


J. Braun, LMH, J. M. Pawlowski, work in progress

Method

Renormalisation Group flows

- continuum formulation
- incorporate full dynamics
- fermions straightforward
  - no sign problem
  - chiral fermions
- bound states via dynamical hadronisation



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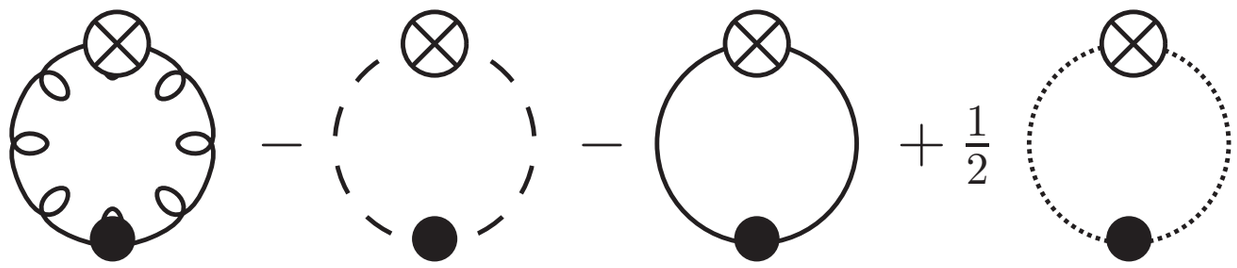
$\longrightarrow$ complementary to lattice

functional RG flow: $\partial_t \Gamma_k[\phi] = \frac{1}{2}$ 

Quark confinement & chiral symmetry breaking at imaginary μ

Chiral phase transition

macroscopic states

dofs: hadrons

broken χ symmetry

phase

transition

microscopic states

dofs: q, $\bar{q}$, g

χ symmetry

symmetry of matter sector of QCD for $m_q = 0$

order parameter: chiral condensate $\langle \bar{\psi}\psi \rangle$

$$\langle \bar{\psi}\psi \rangle = \begin{cases} 0 & T > T_{c,\chi} \\ > 0 & T < T_{c,\chi}. \end{cases}$$

Deconfinement phase transition

Symmetry of gauge sector of QCD:

center symmetry Z_3 for SU(3)

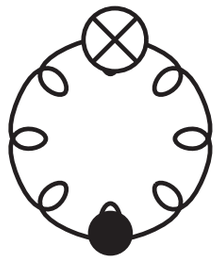
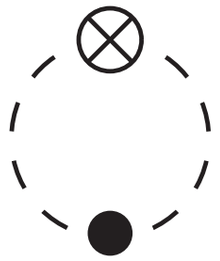
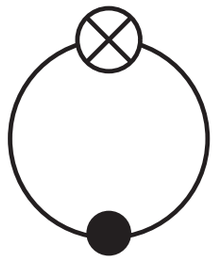
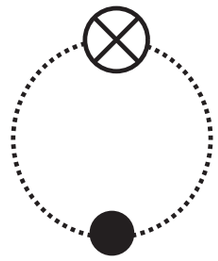
symmetry present in the limit of static quarks ($m_q \to \infty$)

order parameter: Polyakov loop ϕ

$$\phi = \frac{1}{N_c} \mathrm{Tr}\, \mathcal{P}\, e^{i \int_0^{1/T} dt\, \langle A_0 \rangle} = \begin{cases} > 0 & T > T_{c,\mathrm{conf}} \\ 0 & T < T_{c,\mathrm{conf}}. \end{cases}$$

Approximation

imaginary chem. pot. $\theta = -\mathrm{i}\mu/2\pi T$, $N_f = 2$, **chiral limit**

$$\partial_t \Gamma_k[\phi] = \tfrac{1}{2}$$  $-$  $-$  $+\tfrac{1}{2}$ 

gluon gauge quark meson

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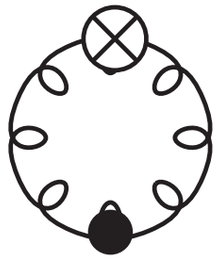
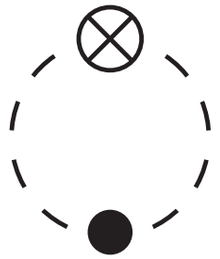
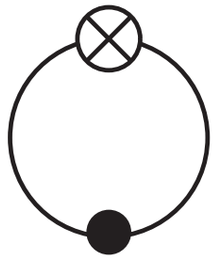
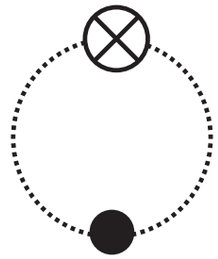
$$\partial_t \Gamma_k[\phi] = \tfrac{1}{2}$$  $-$  $-$  $+\tfrac{1}{2}$ 

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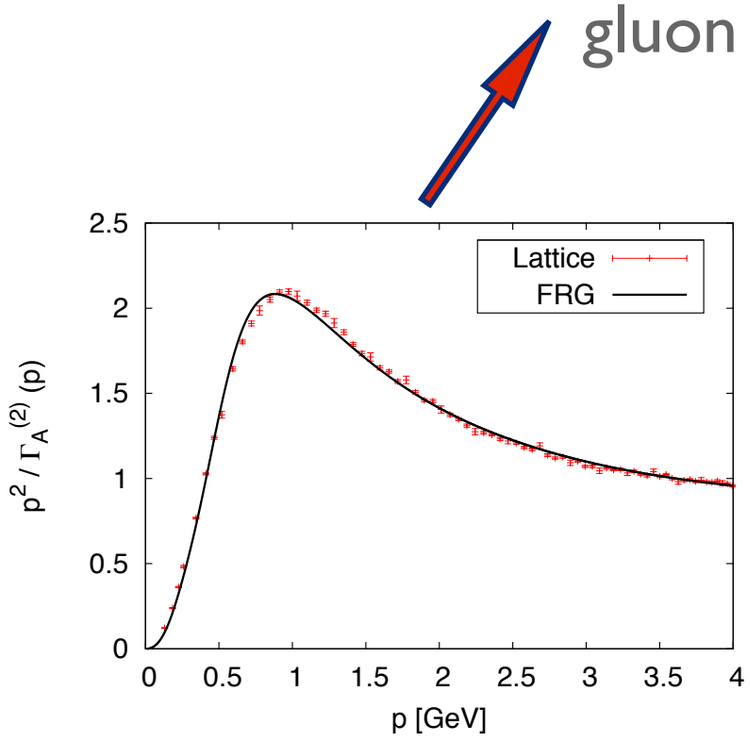

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J. M. Pawlowski, in preparation

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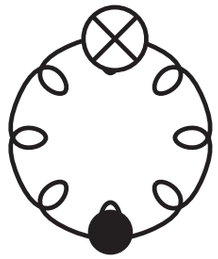
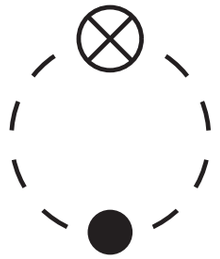
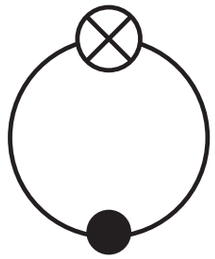
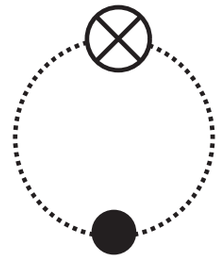
$$\partial_t \Gamma_k[\phi] = \tfrac{1}{2}$$  $$-$$  $$-$$  $$+\tfrac{1}{2}$$ 

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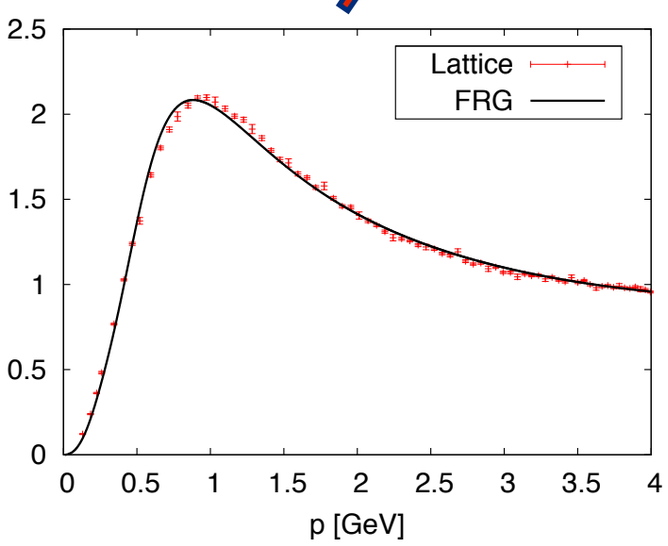

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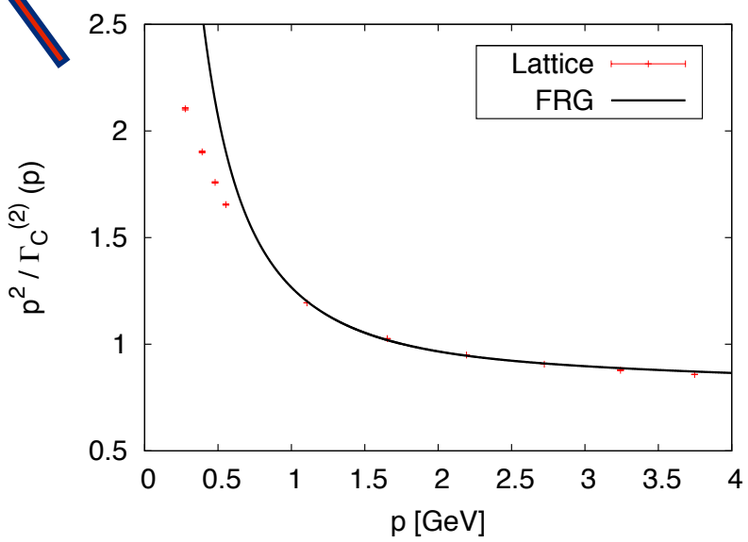

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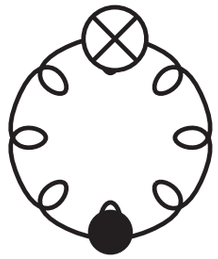
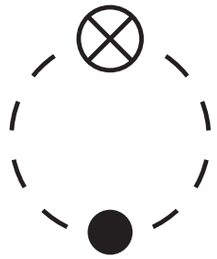
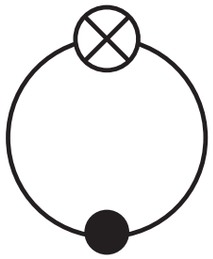
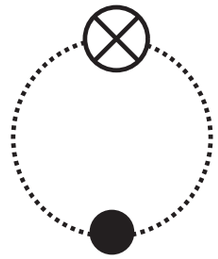
$$\partial_t \Gamma_k[\phi] = \tfrac{1}{2}$$  $-$  $-$  $+\tfrac{1}{2}$ 

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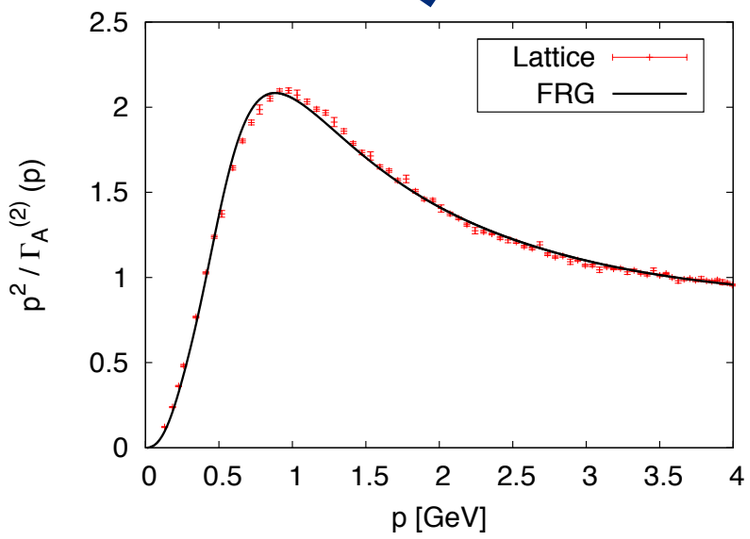
mesonic quantum fluctuations



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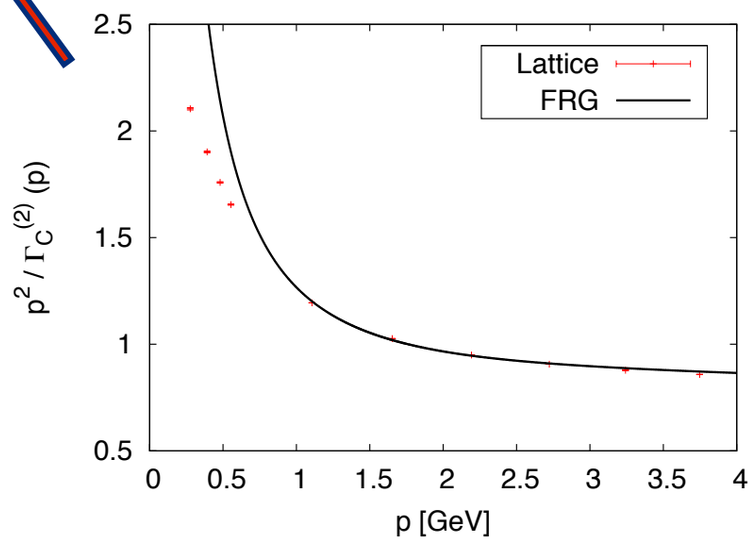

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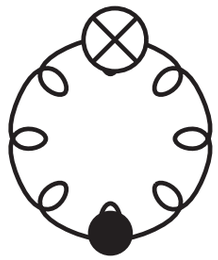
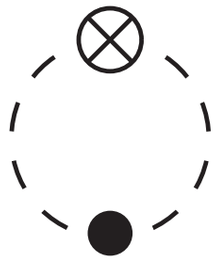
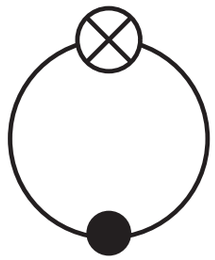
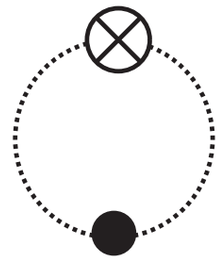
$$\partial_t \Gamma_k[\phi] = \tfrac{1}{2}$$  $-$  $-$  $+\tfrac{1}{2}$ 

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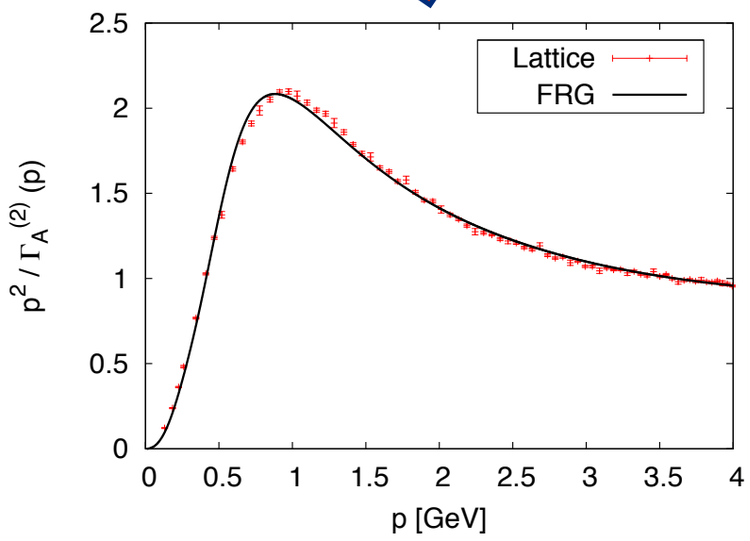

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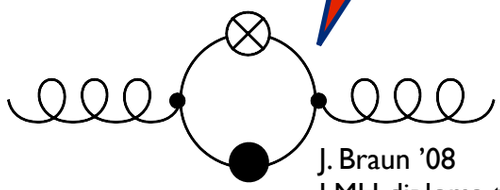

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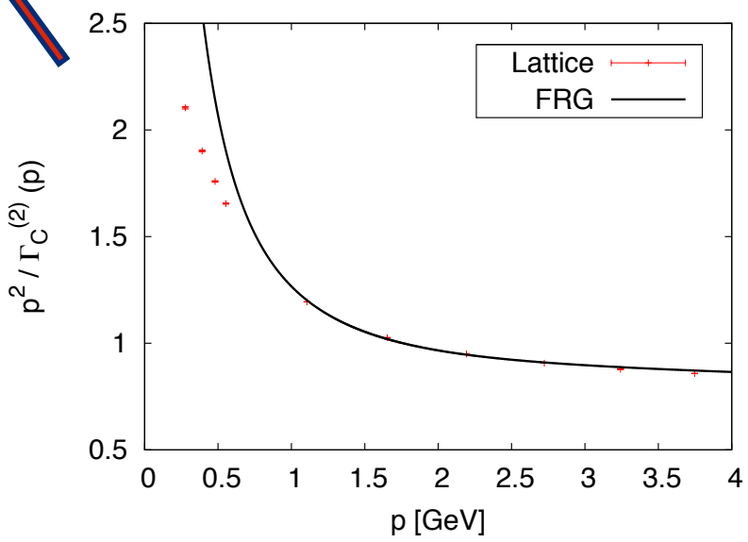
LMH diploma thesis '08



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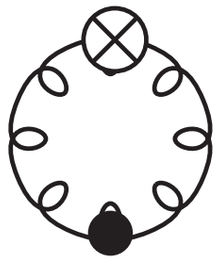
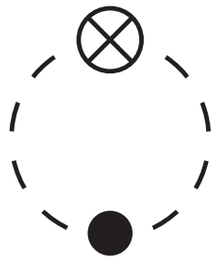
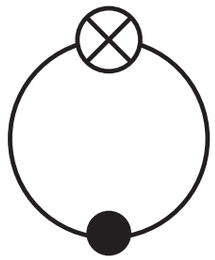
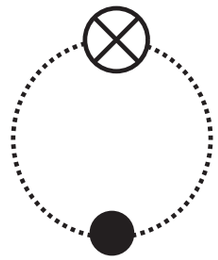
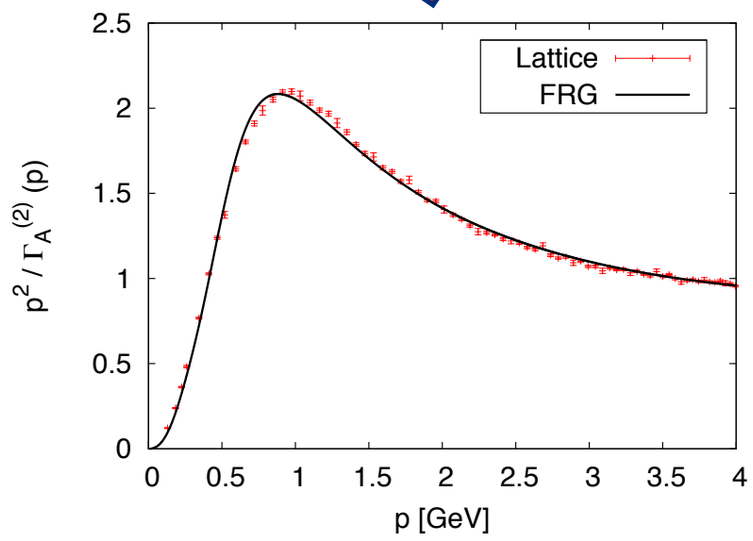
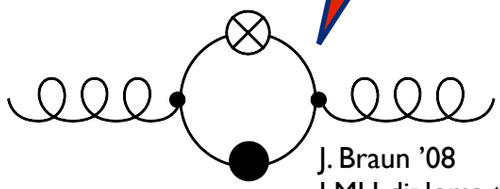
$$\partial_t \Gamma_k[\phi] = \tfrac{1}{2}$$  $-$  $-$  $+\tfrac{1}{2}$ 

gluon gauge quark meson

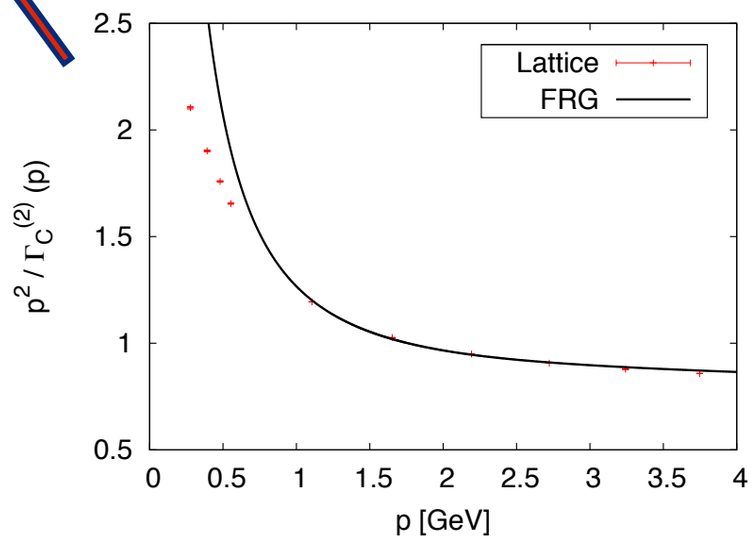


C.S. Fischer, A. Maas, J. M. Pawlowski, '08
J. M. Pawlowski, in preparation



J. Braun '08
LMH diploma thesis '08

mesonic quantum fluctuations



C.S. Fischer, A. Maas, J. M. Pawlowski, '08
J. M. Pawlowski, in preparation

J. Braun, H. Gies, J. M. Pawlowski '07

confining properties: full momentum dependence of ghost & gluon propagator

Polyakov loop potential

J. Braun, H. Gies, J. M. Pawlowski '07

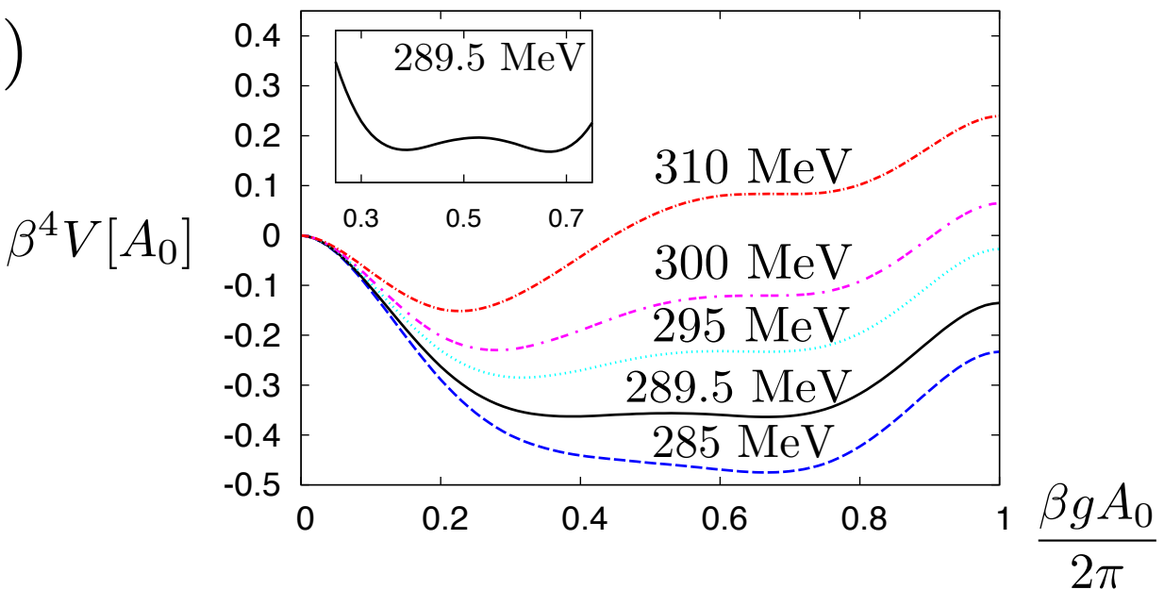
incorporates information of glue flux in QCD & fermionic contributions

$$V_{\text{eff, QCD}}[A_0] = V_{\text{glue}}[A_0] + V_{\text{ferm}}[A_0]$$

glue flux in QCD

full backcoupling included

$SU(3)$



slice in A_0^8 - direction

$T_c = 289.5 \pm 10$ MeV

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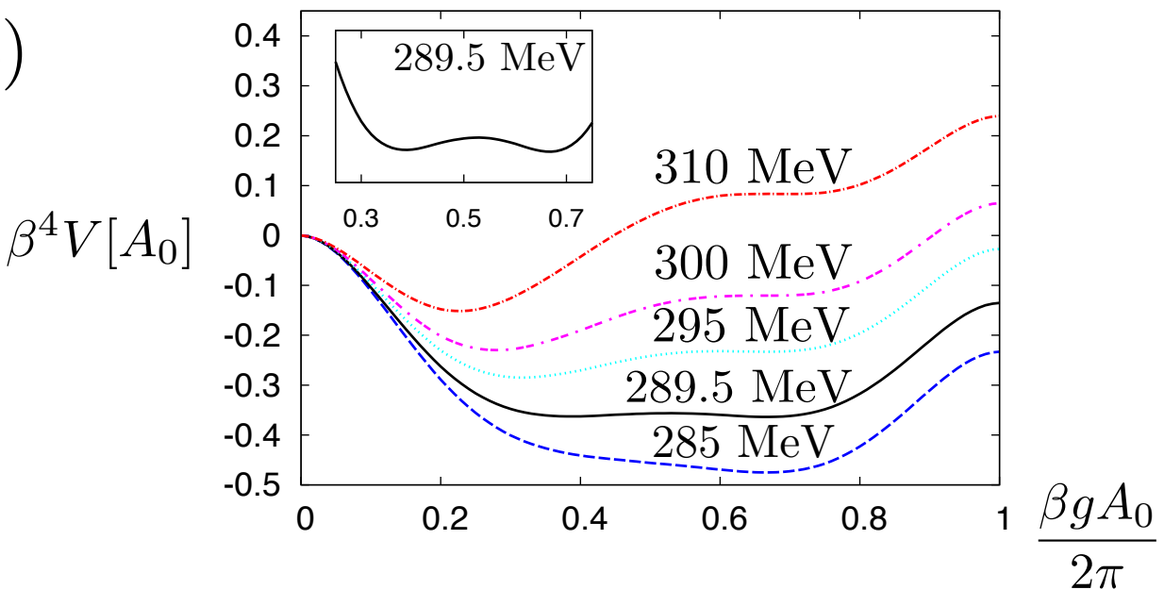

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recent upgrade for SU(N), Sp(2), E(7): J. Braun, A. Eichhorn, H. Gies, J. M. Pawlowski '10

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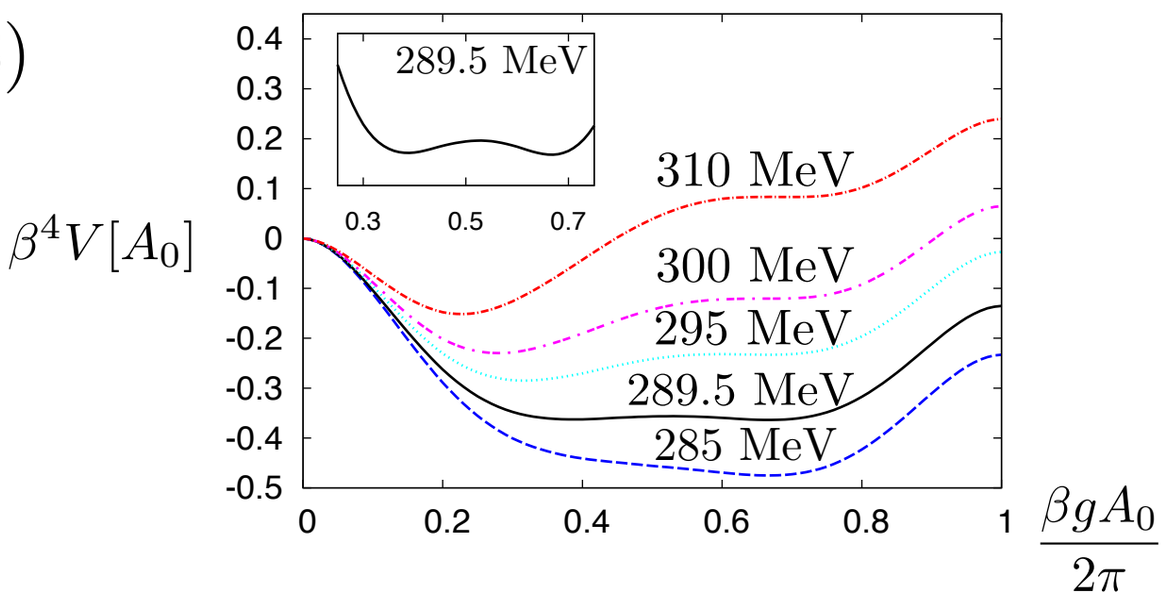

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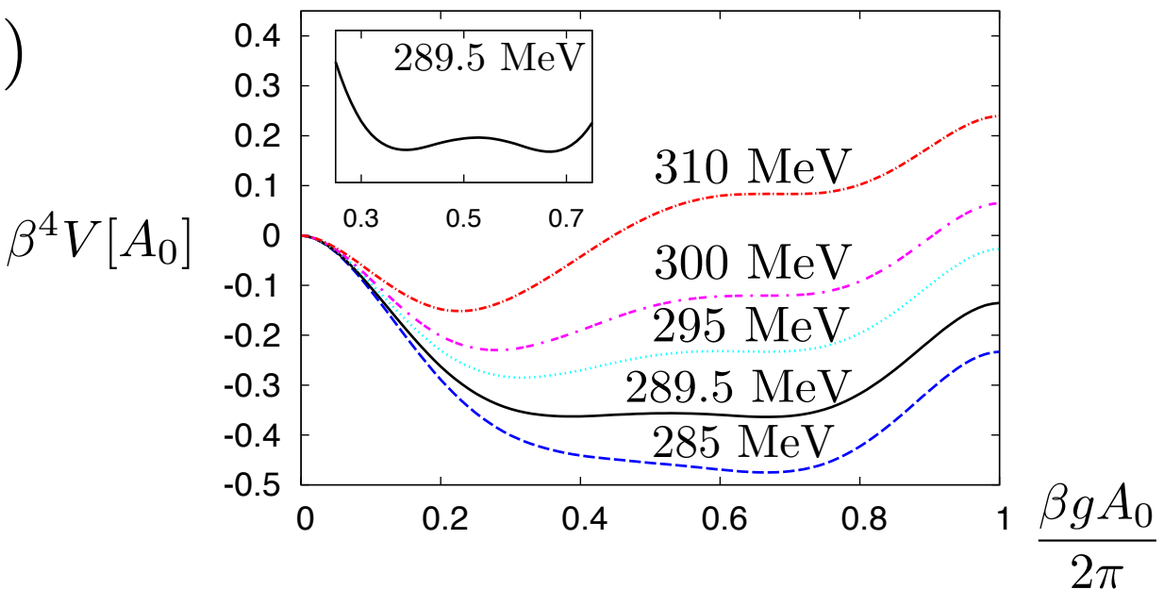
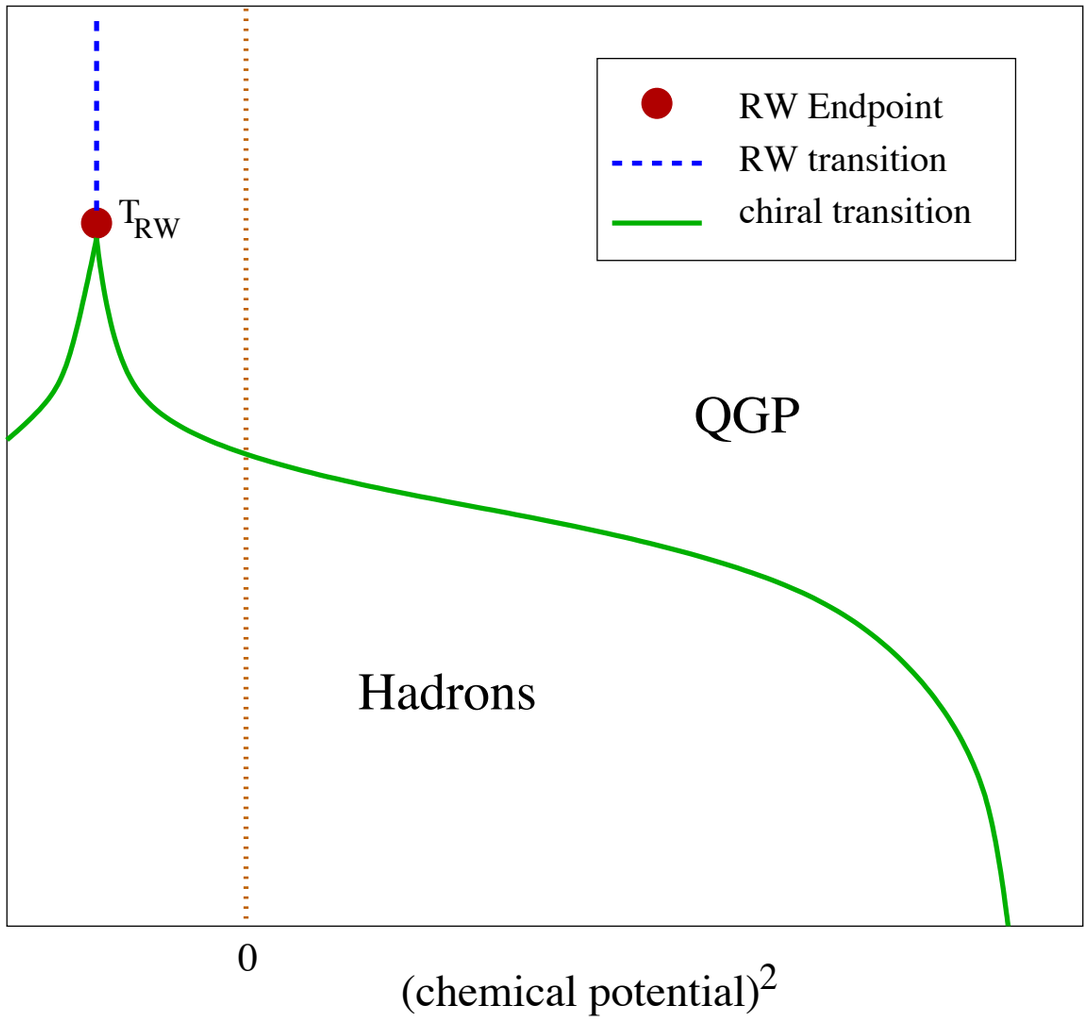


slice in A_0^8 - direction

$T_c = 289.5 \pm 10 \text{ MeV}$

→ see talk of J. M. Pawlowski

Roberge-Weiss periodicity & p.t.



$\theta = -\mathrm{i}\mu/2\pi T$:

$$\mathrm{QCD}_\theta = \mathrm{QCD}_{\theta+\theta_z} \quad \text{periodic}$$

where $\theta_z = 0, 1/3, 2/3$ for SU(3)

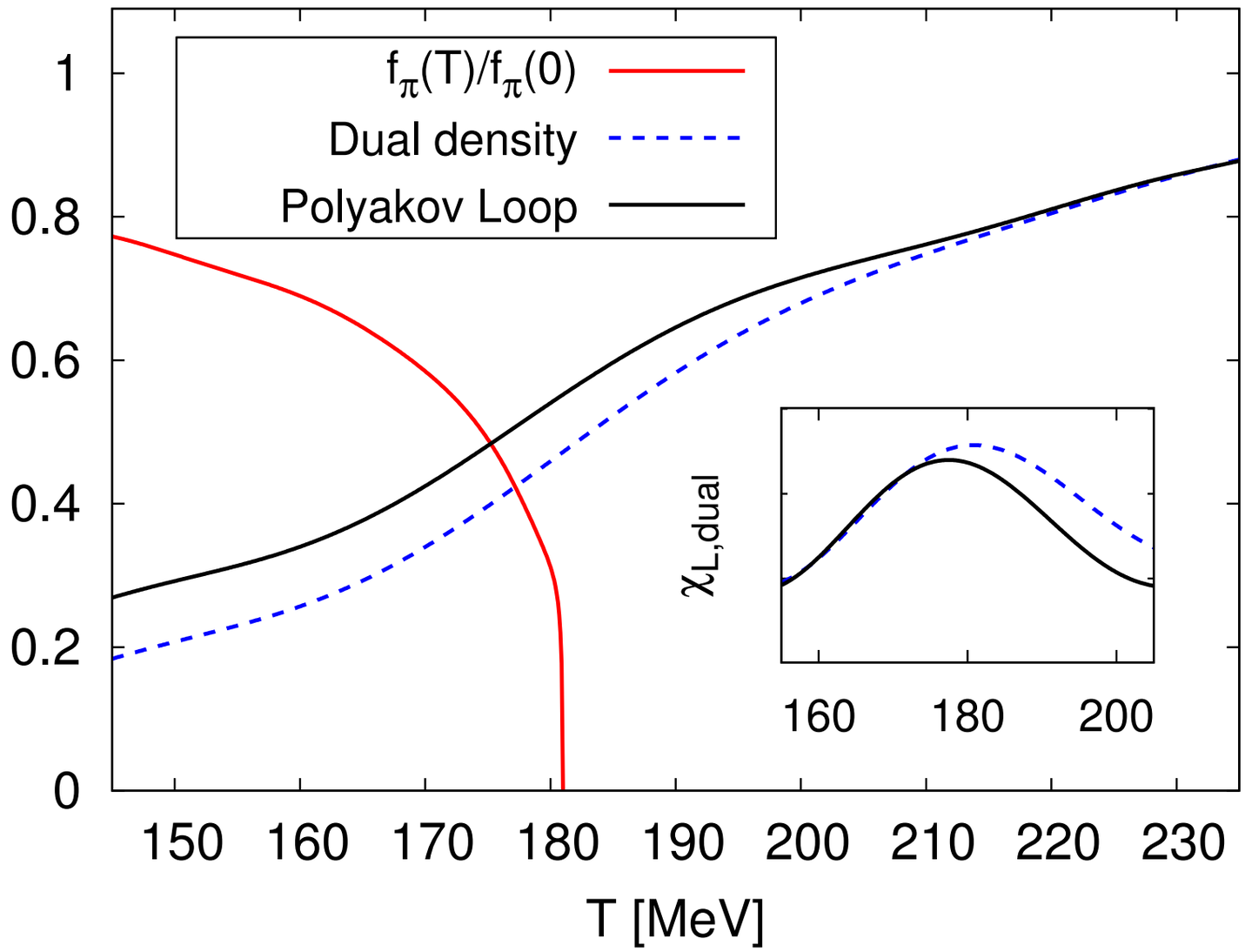
quantities related to effective action: show same periodicity (RW periodicity) e.g. $\langle\bar{\psi}\psi\rangle$

QCD_θ : smooth until $\theta = 1/6$, then shows discontinuity: Polyakov loop RW phase transition

Order parameters

J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

$\theta = 0$:



$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$

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J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

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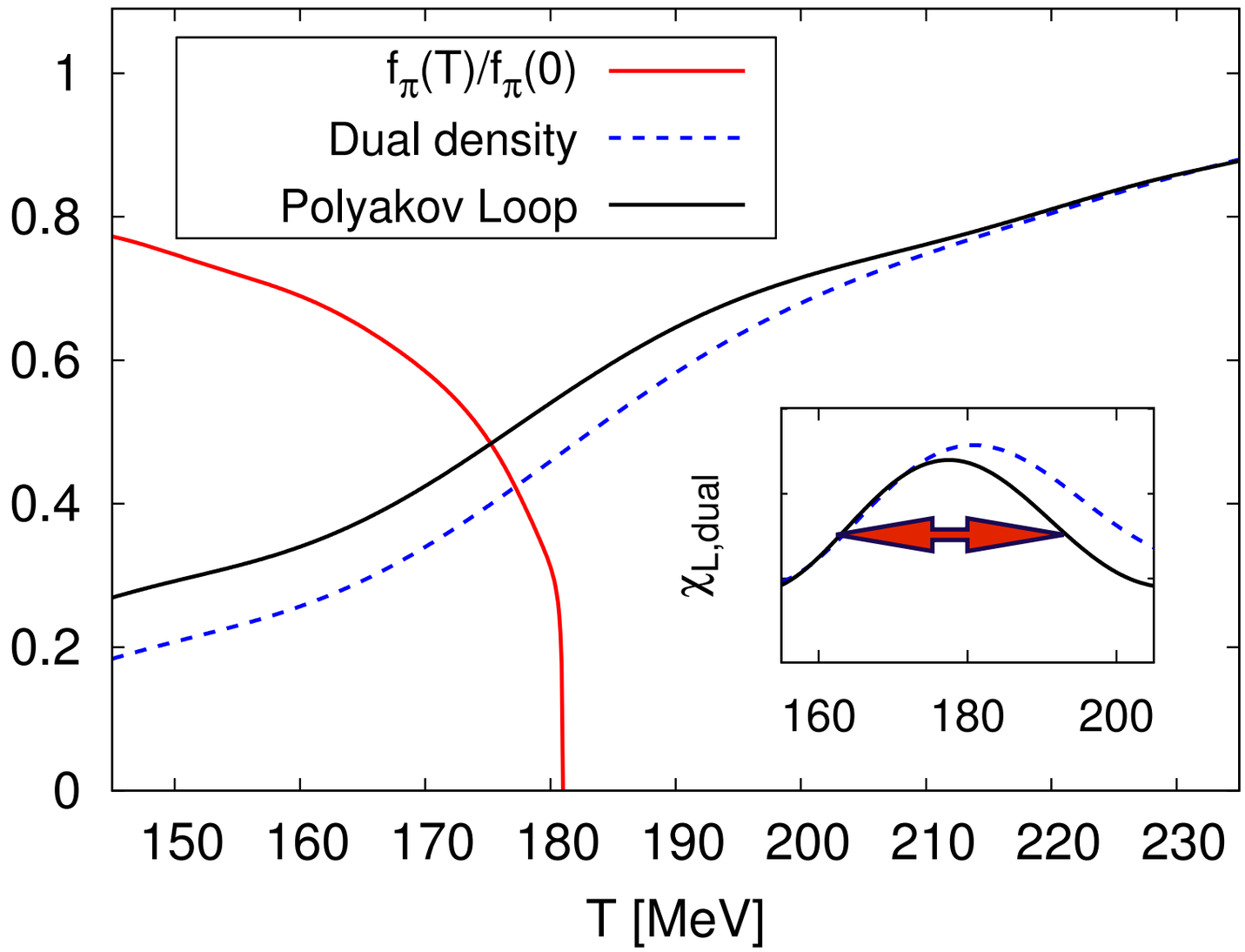
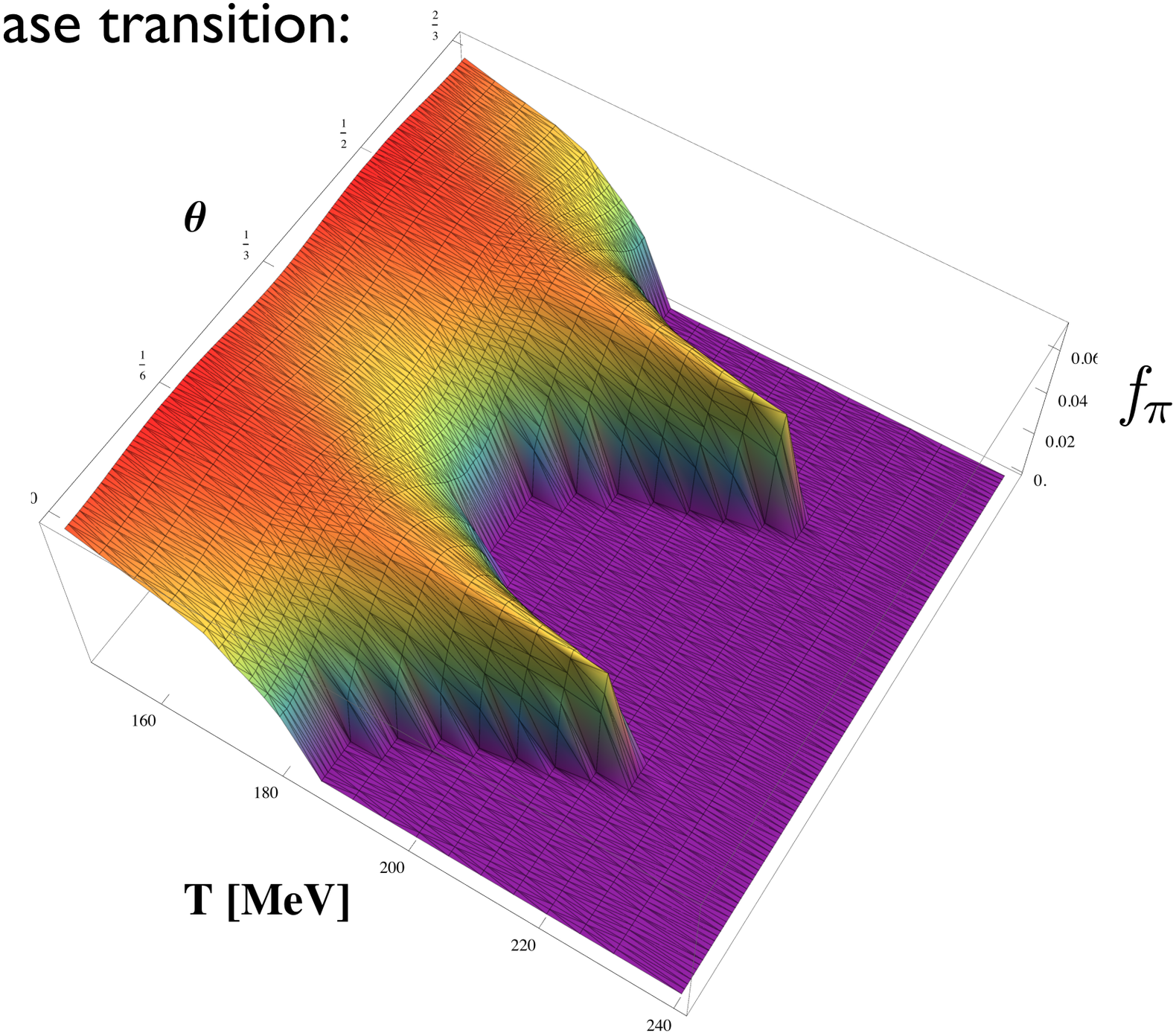


$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$

Phase diagram for imaginary μ

J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

chiral phase transition:



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J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

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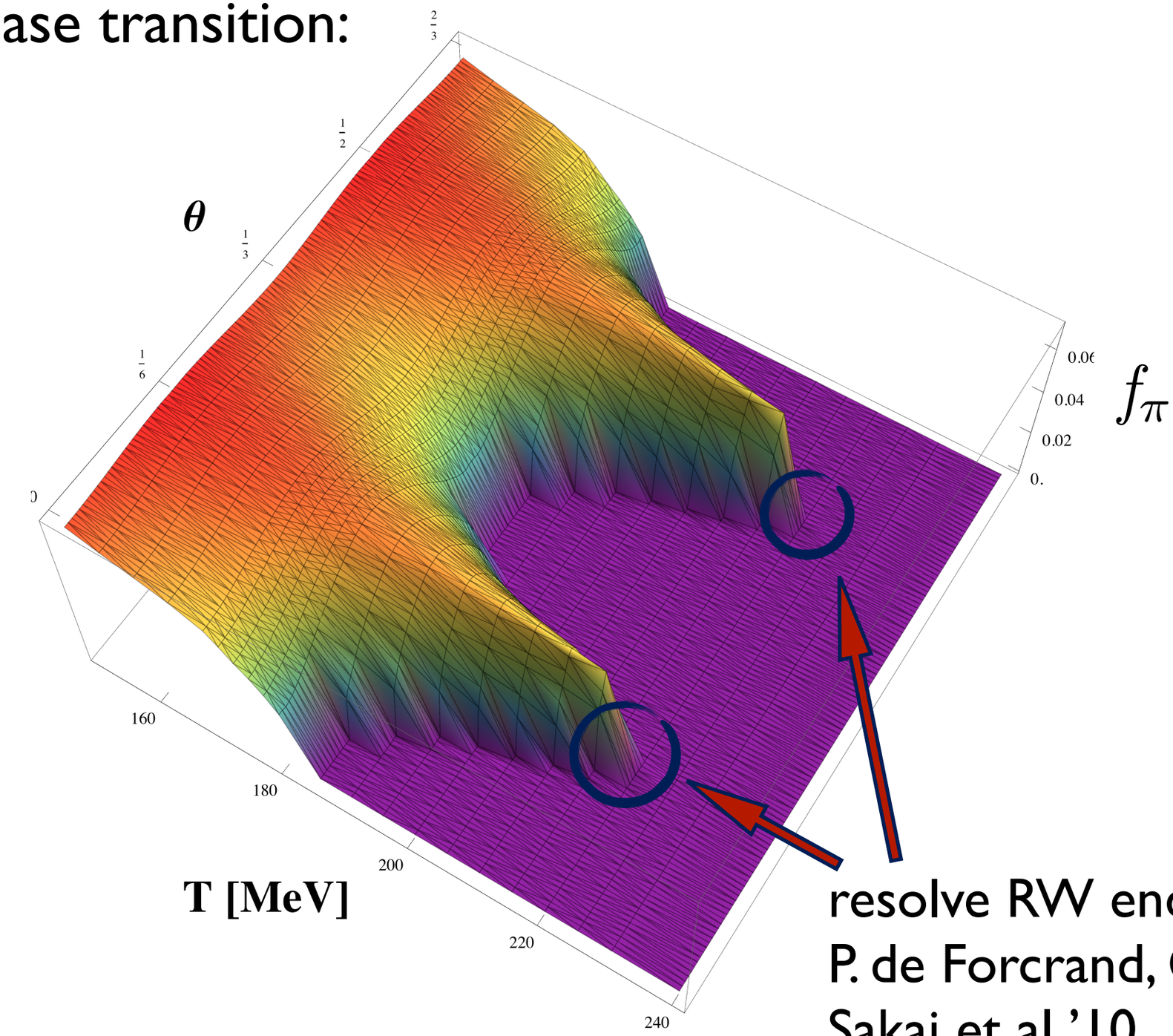
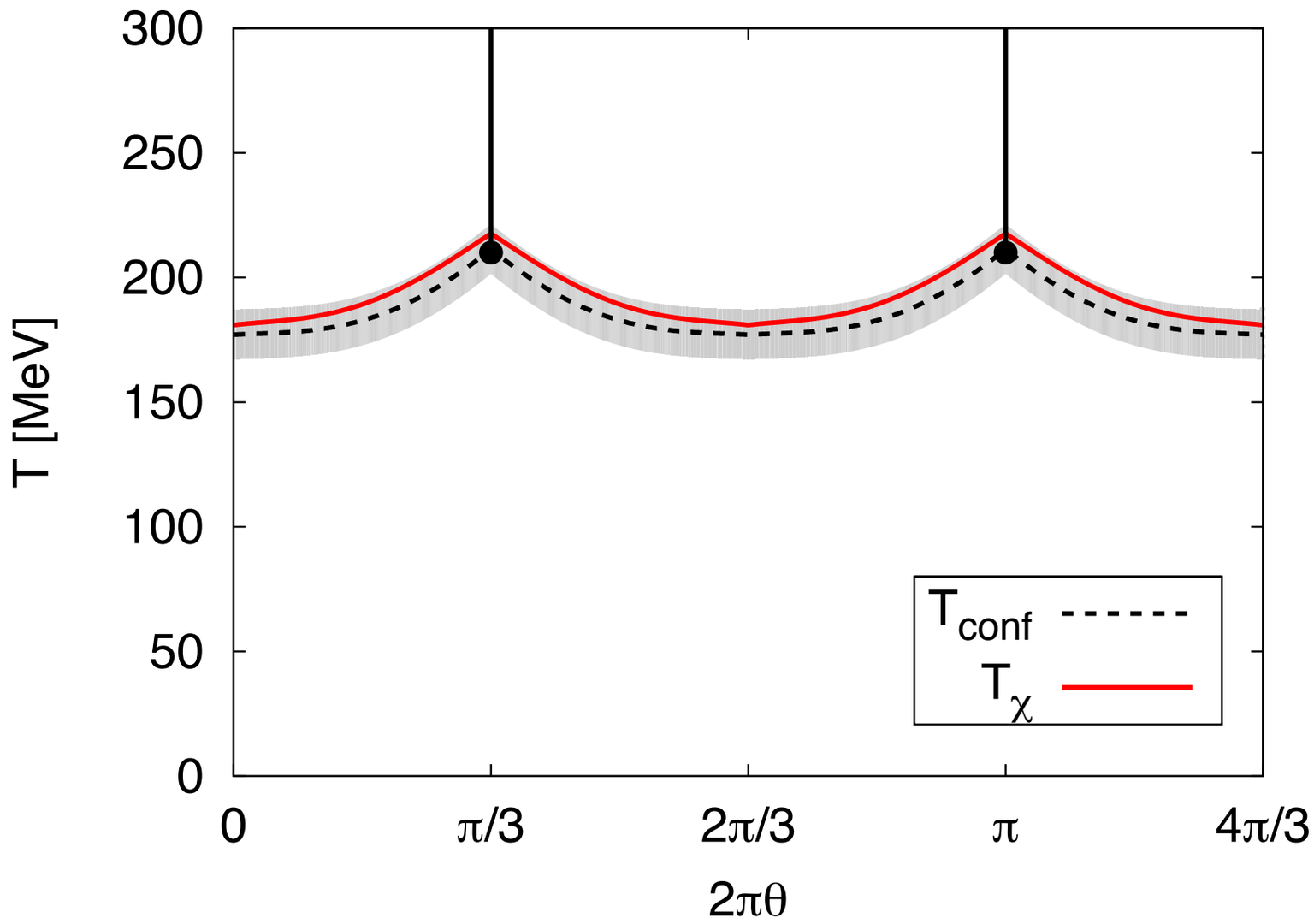


resolve RW endpoint:
P. de Forcrand, O. Phillipsen '10
Sakai et al '10

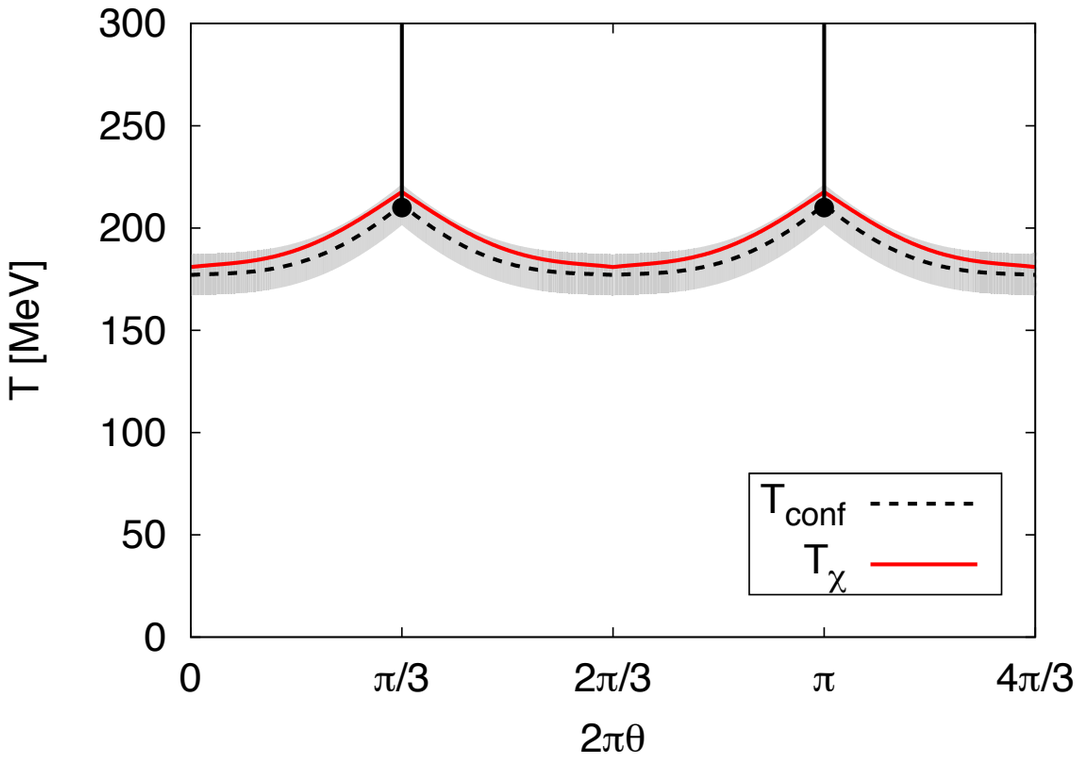
Phase diagram for imaginary μ

J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09



T_{conf} and T_χ lie close together, end in critical point (RW phase transition)

Phase diagram for imaginary μ



J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

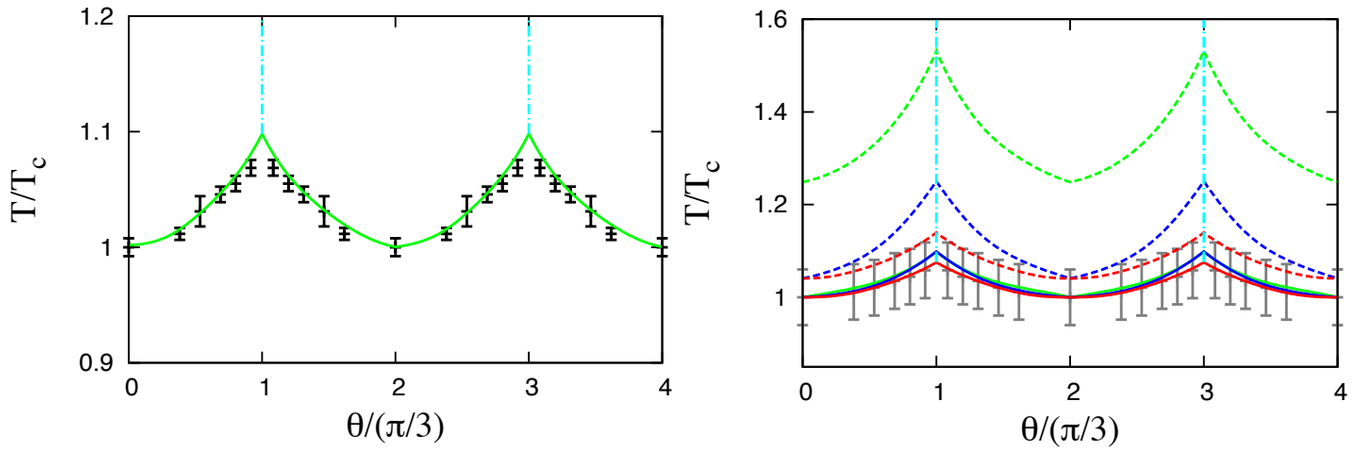
coinciding T_{cr} result from interplay of quantum fluctuations & are not adjusted by hand

compatible with lattice:

Kratochvila et al '06;
Wu et al '06

PNJL model agrees if 8-quark interaction is adjusted:

Sakai et al '08



Dual order parameters

imaginary chemical potential ⟶

C. Gattringer '06;
F. Synatschke, A. Wipf, C. Wozar '07;
F. Bruckmann, C. Hagen, C. Gattringer '08;
C. S. Fischer '09; C. S. Fischer, J. Mueller '09;
J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

Observable $\mathcal{O}_\theta$: transforms non-trivially under center transformations $z = e^{2\pi i \theta_z}$ with $\theta_z = 0, 1/3, 2/3$ for SU(3)

is an oder parameter for confinement

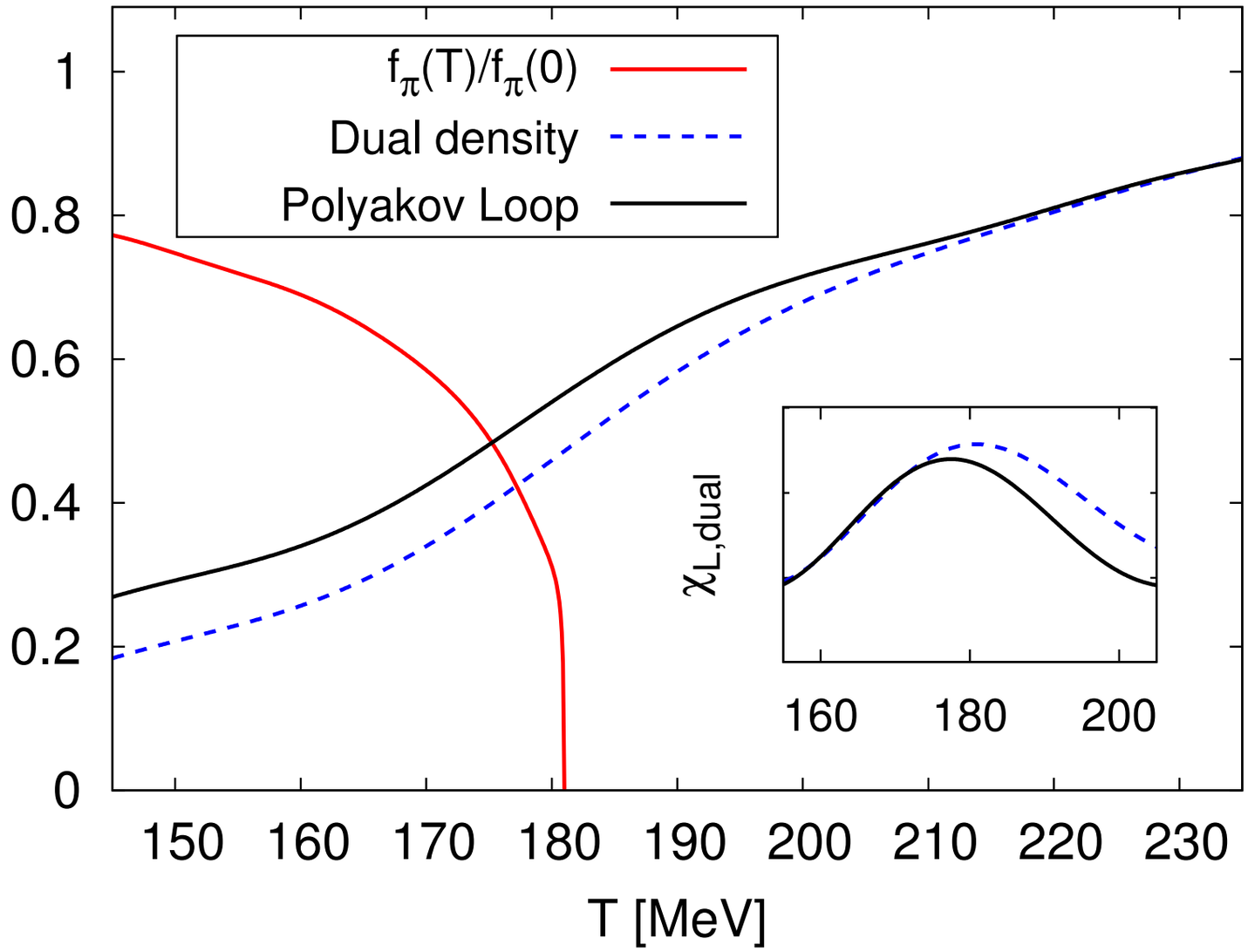
$$\tilde{\mathcal{O}} = \int_0^1 d\theta \, e^{-2\pi i \theta} \mathcal{O}_\theta$$

$\tilde{\mathcal{O}}$ sensitive w.r.t. center transformations $\tilde{\mathcal{O}} \to z\tilde{\mathcal{O}}$

e.g. dual density $n_\theta \sim \int \langle \bar{\psi} \gamma_0 \psi \rangle_\theta$

Order parameters

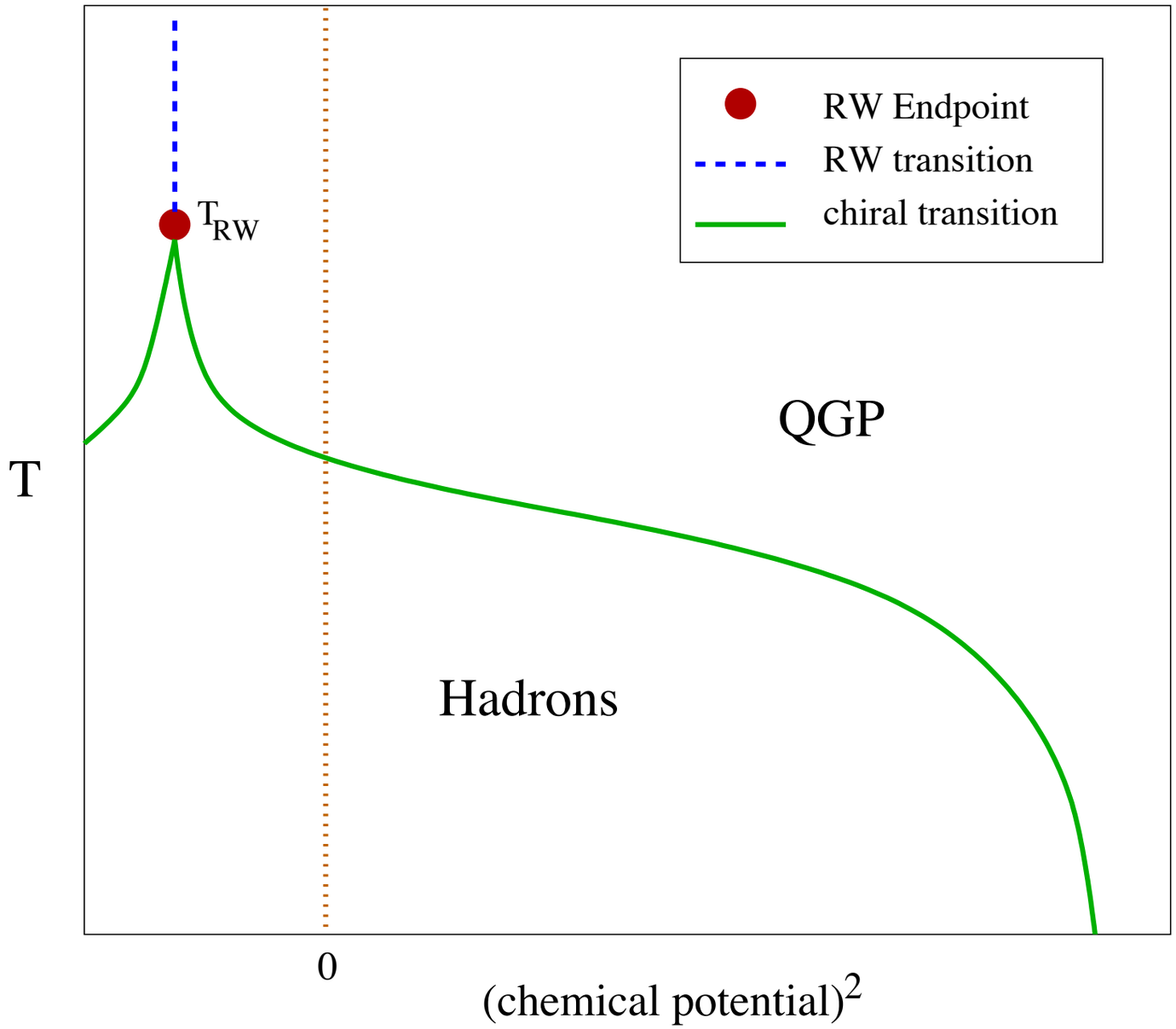
J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09



$$T_{\mathrm{conf},\Phi} = T_{\mathrm{conf},\tilde{n}} \longrightarrow \textbf{consistency check}$$

Quark confinement & chiral symmetry breaking at real μ

The phase diagram $N_f=2$, chiral limit



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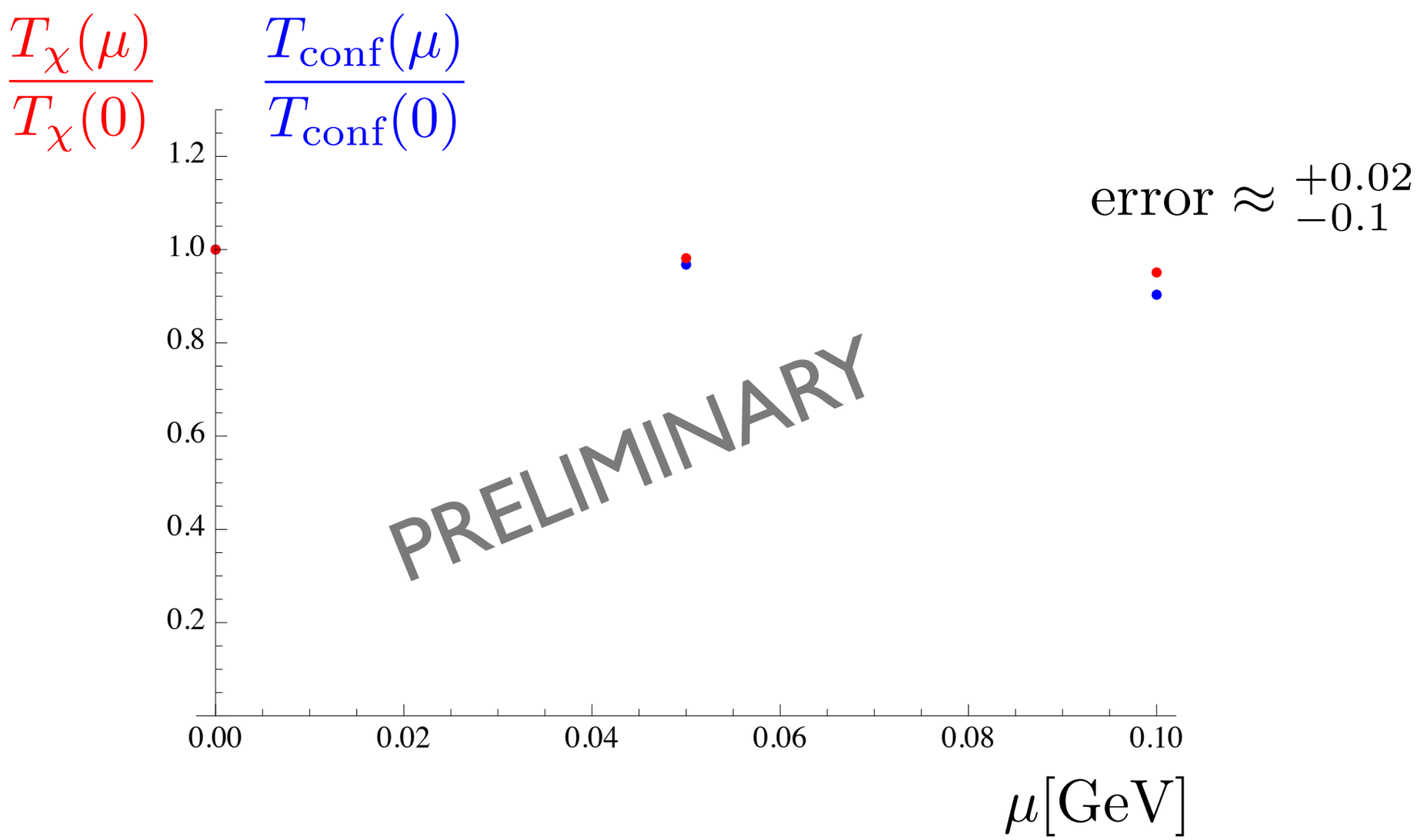
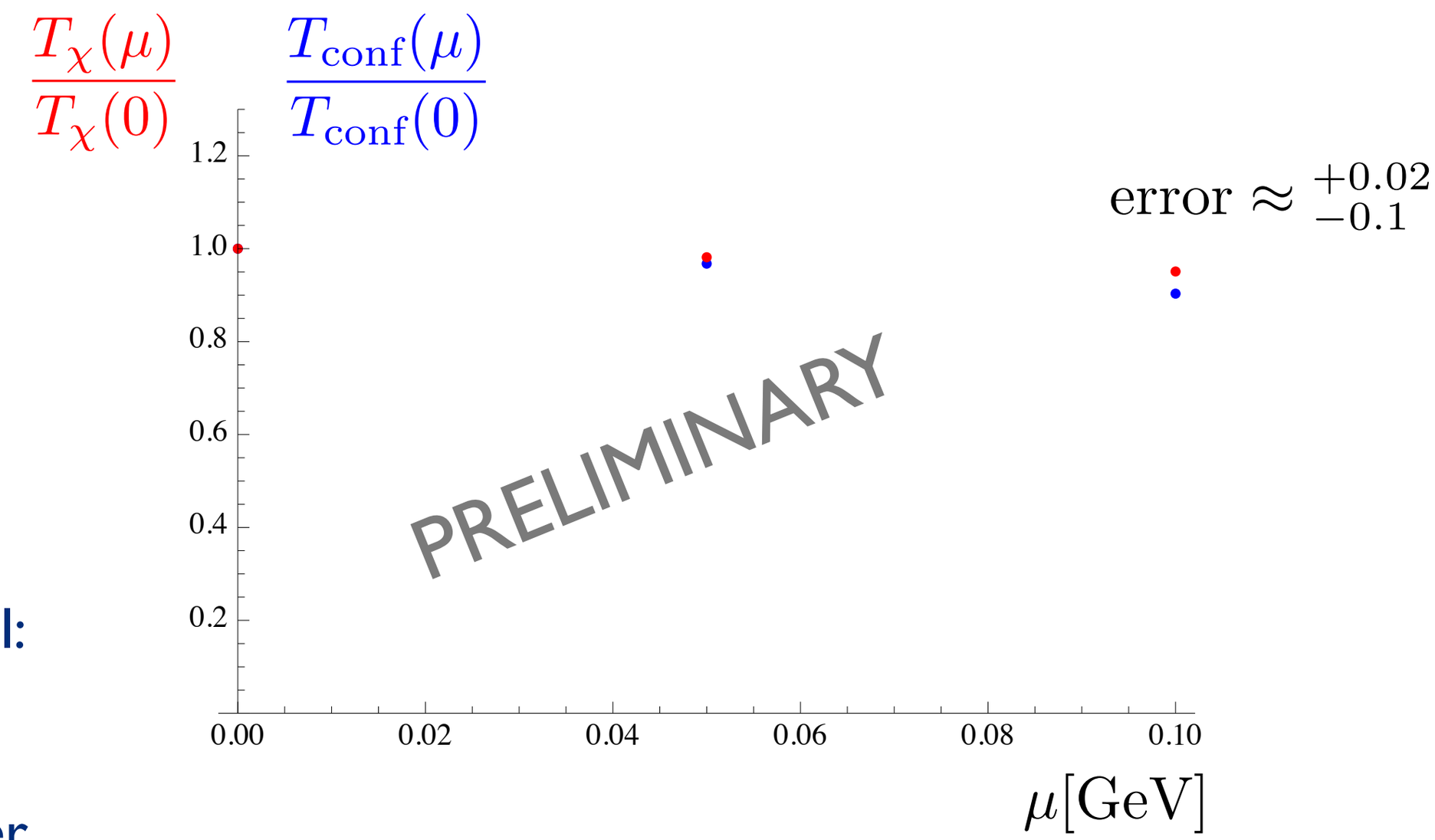


J. Braun, LMH, J. M. Pawlowski, work in progress

The phase diagram $N_f=2$, chiral limit



PQM model:
see talk of
T. Herbst
B.-J. Schaefer

J. Braun, LMH, J. M. Pawlowski, work in progress

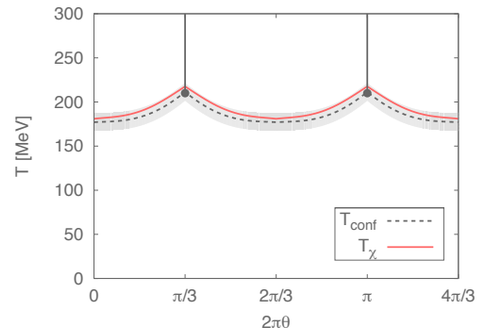
Summary & Outlook

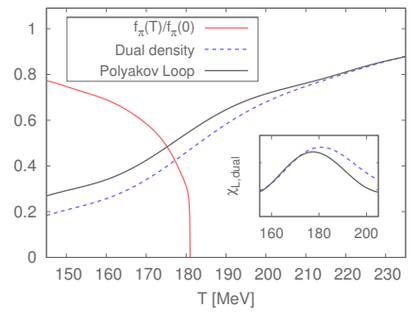
Summary

phase diagram $N_f = 2$: imaginary chemical potential

Roberge-Weiss periodicity

$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$





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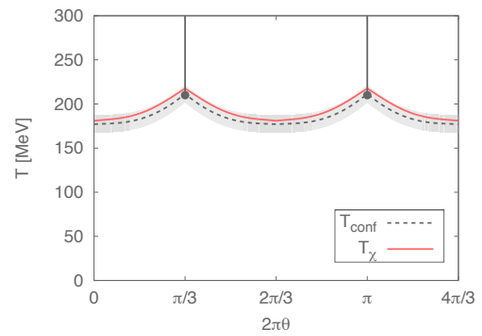
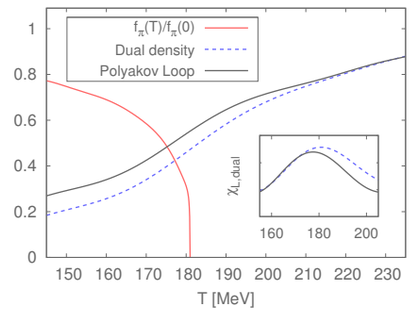
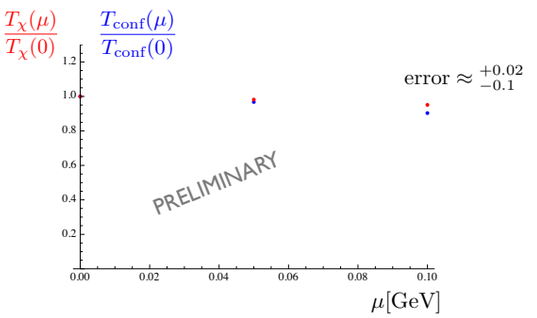




phase diagram $N_f = 2$: real chemical potential



Summary & Outlook

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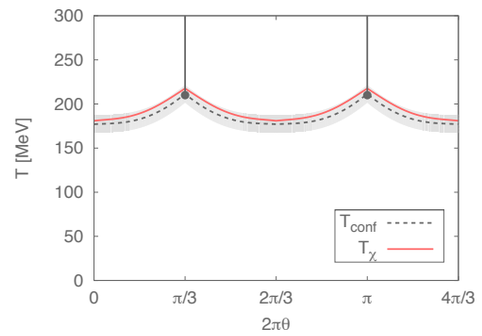
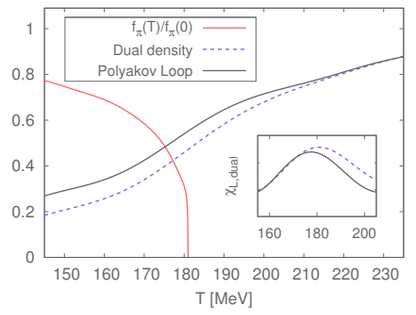
$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$





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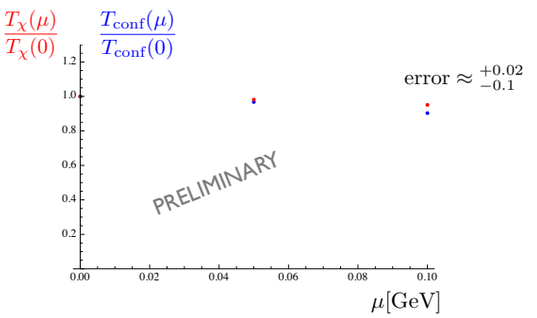


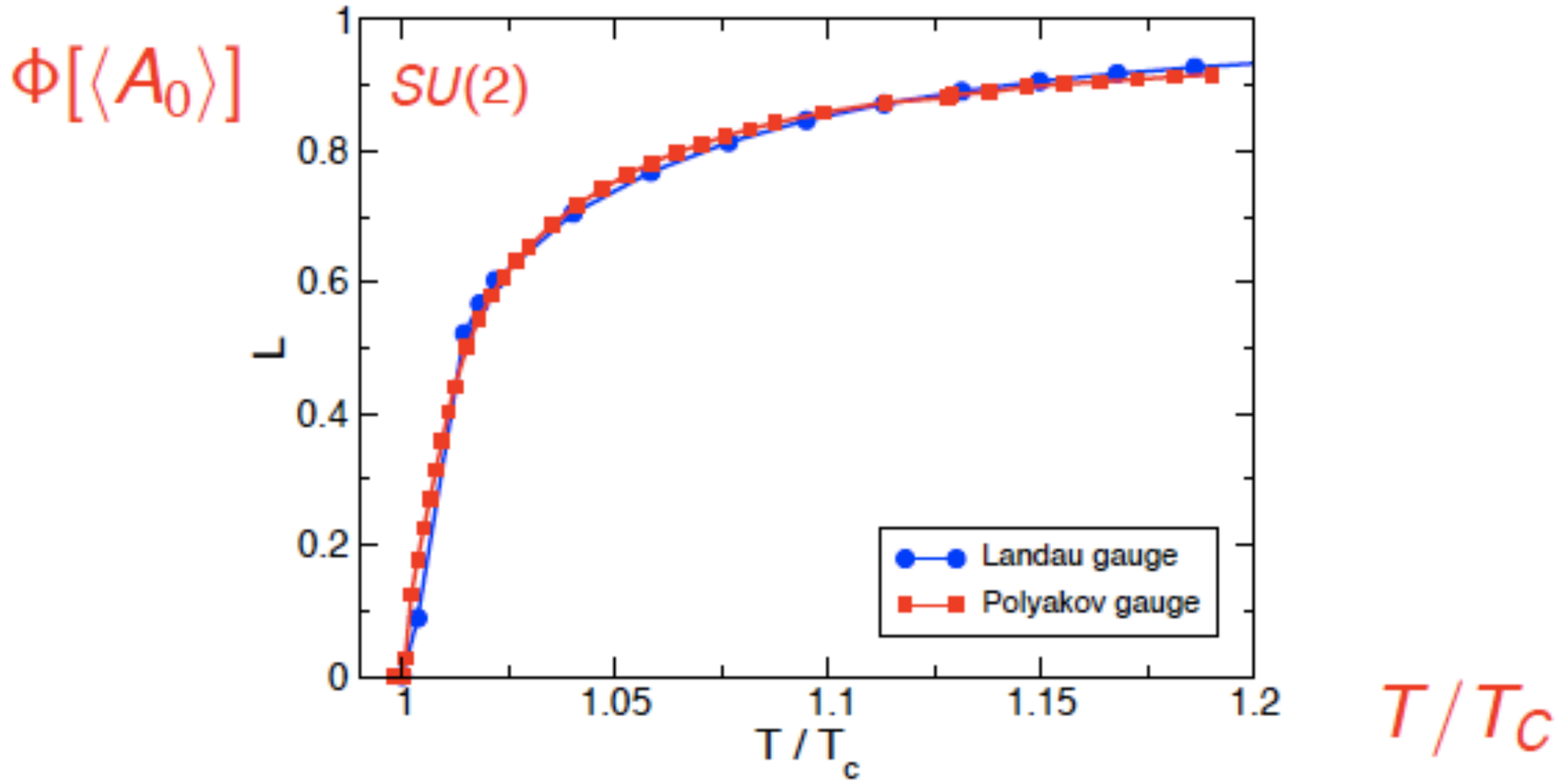
Outlook

extend to $N_f = 2 + 1$: real chemical potential

Additional slides

Gauge invariance

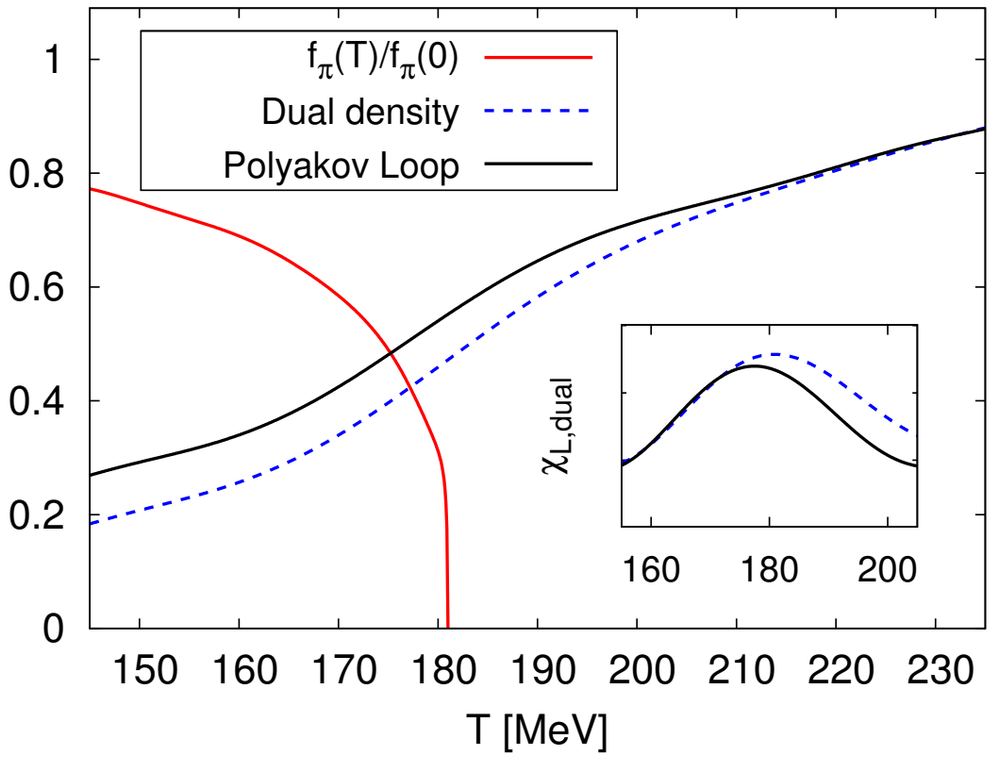
F. Marhauser, J. M. Pawlowski '08



Polyakov gauge: $A_0 = A_0^c(\vec{x})\sigma_3$

Critical temperatures

$N_f = 2$



J. Braun, LMH, F. Marhauser, J. M. Pawlowski '09

$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$

$N_f = 2 + 1$

compatible with Karsch et al '08

$$T_{\mathrm{conf},cr} \simeq T_{\chi,cr}$$

compatible with Fodor et al '08

$$175\,\mathrm{MeV} \simeq T_{\mathrm{conf},cr} > T_{\chi,cr} \simeq 150\,\mathrm{MeV}$$