

On the thermodynamics and phase structure of QCD

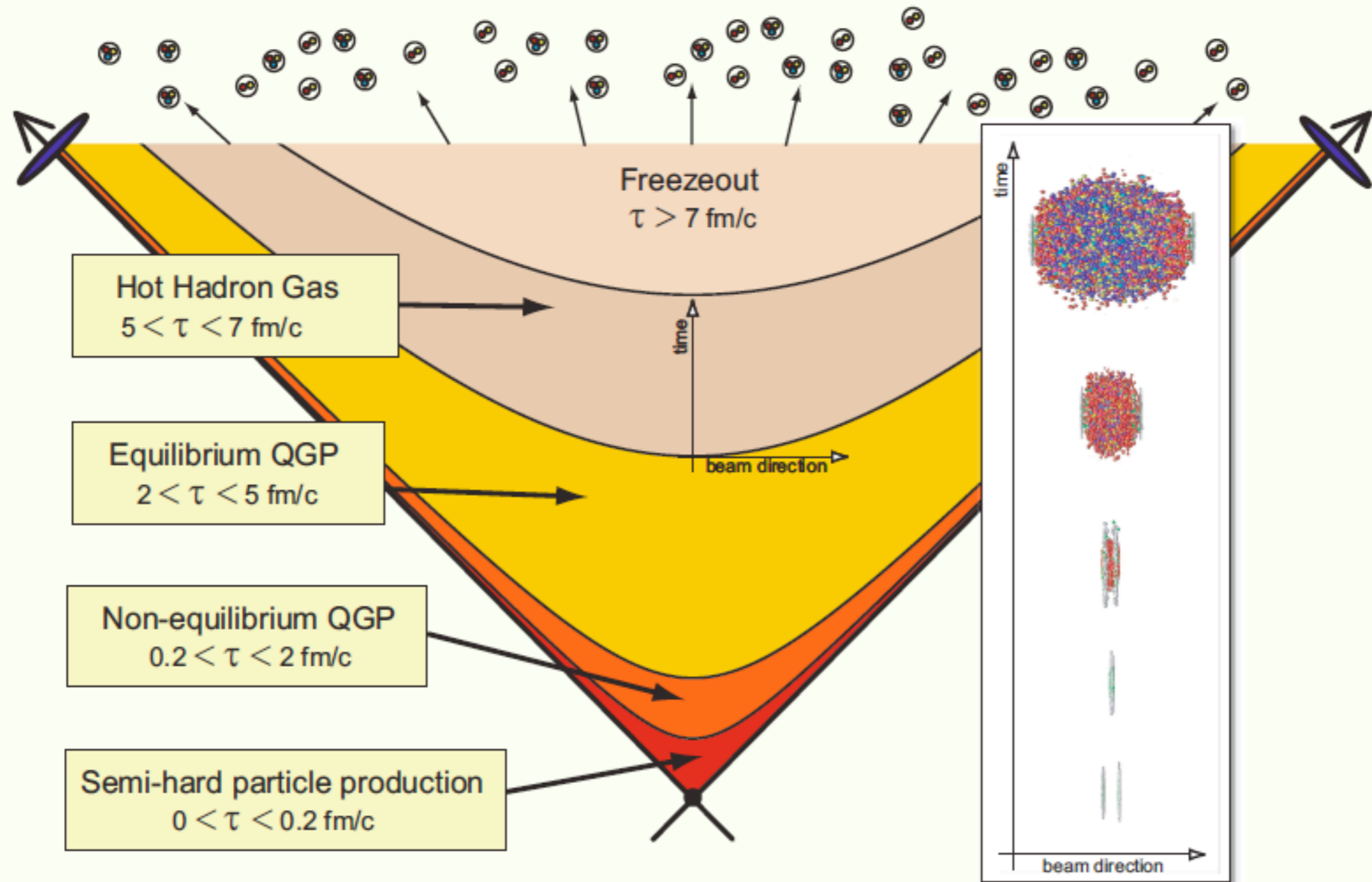
Jan M. Pawłowski
Universität Heidelberg & ExtreMe Matter Institute

Hirschegg, January 17th 2012



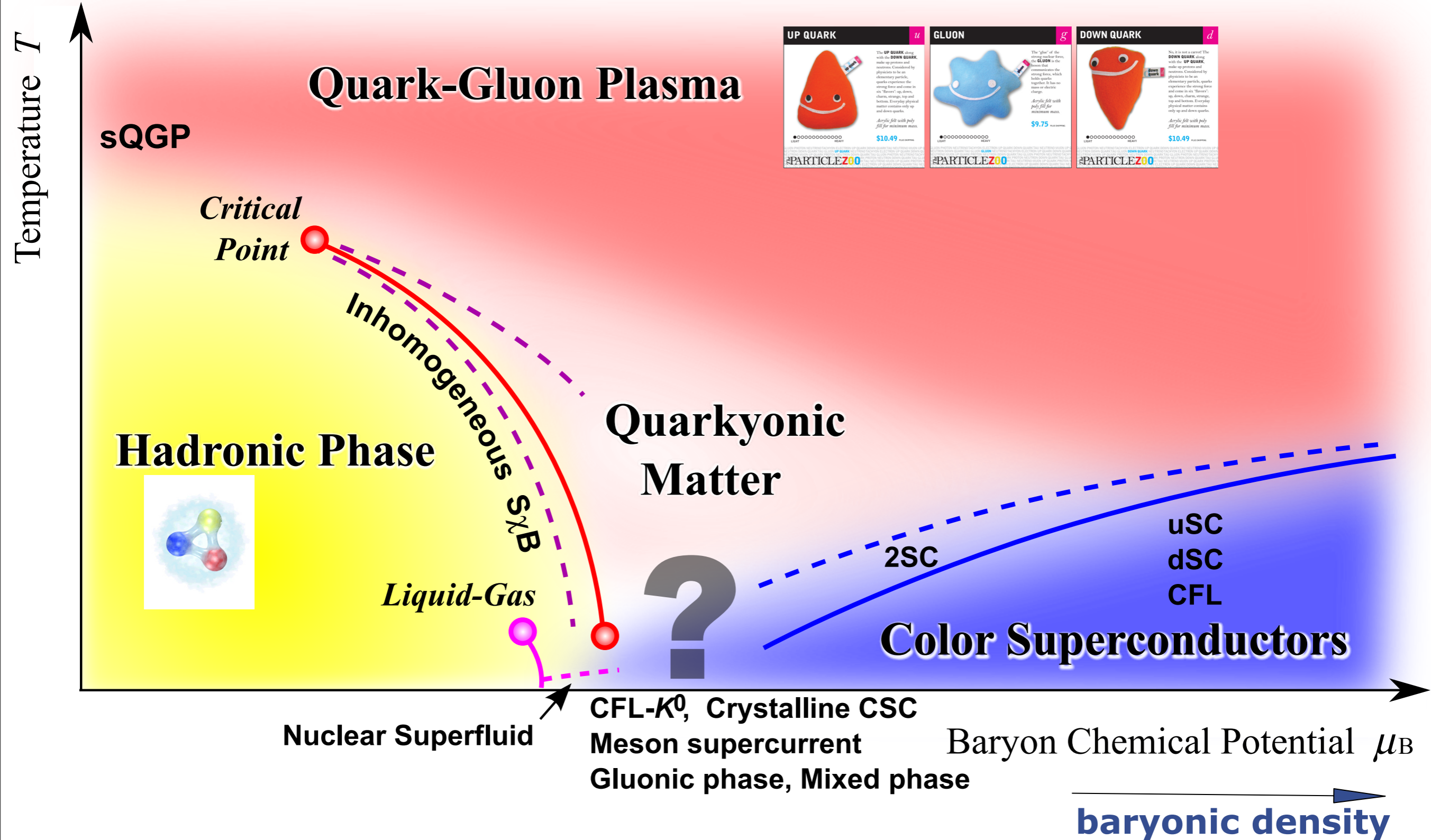
Heavy ion collisions

Heavy-ion collision timescales and “epochs” @ RHIC

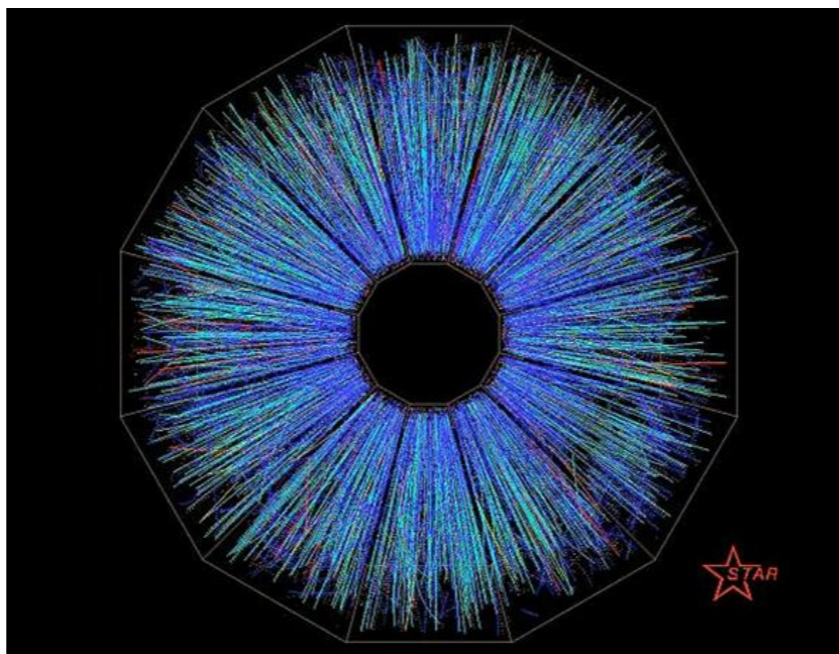


*1 fm/c $\simeq 3 \times 10^{-24}$ seconds

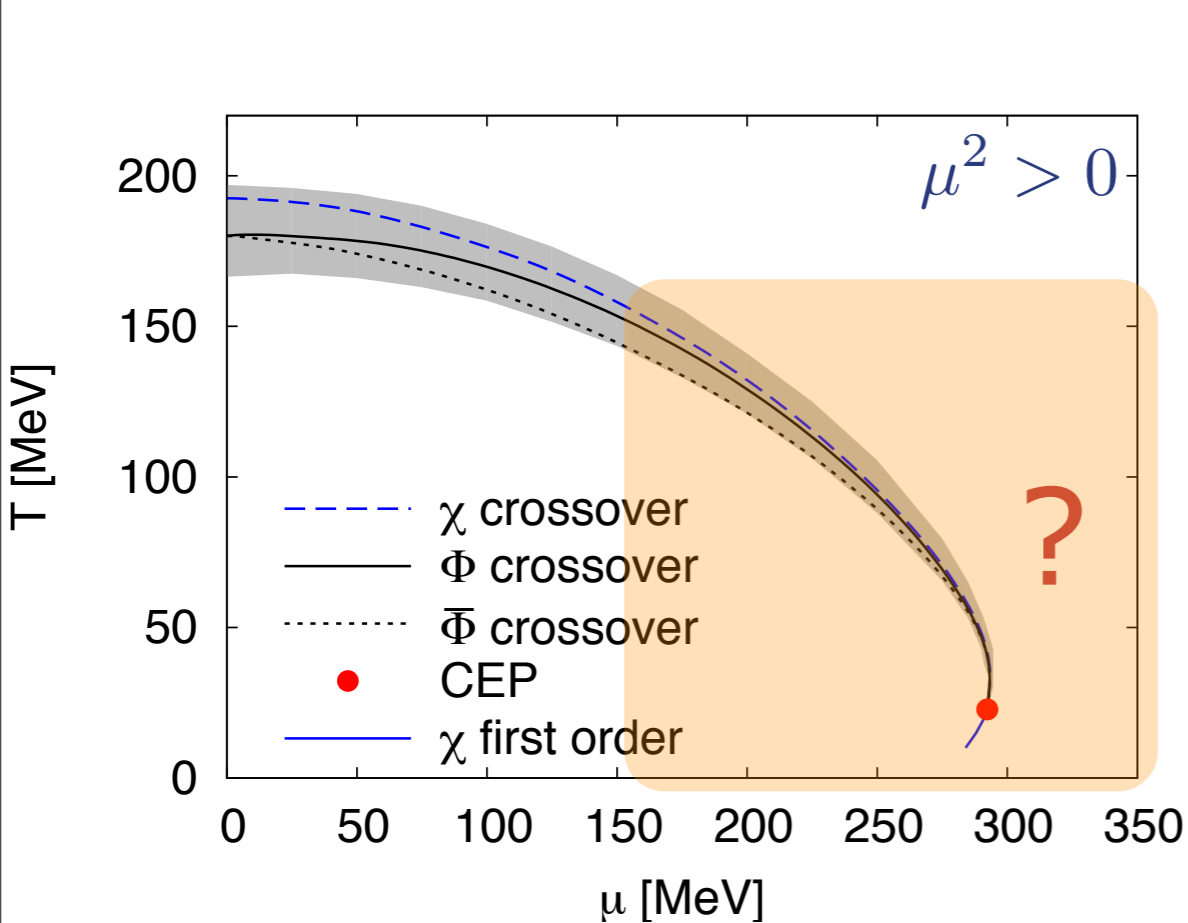
Phase diagram of QCD



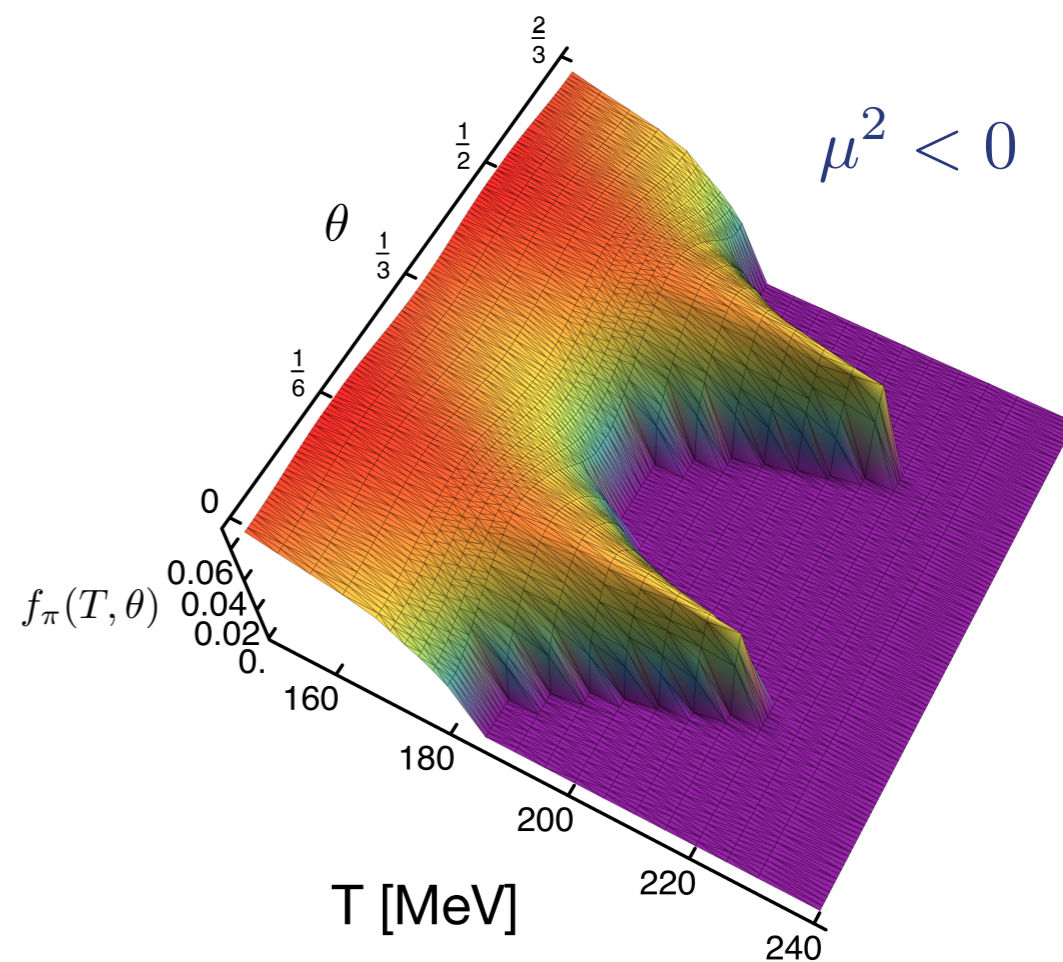
<p>UP QUARK u</p> <p>The "glu" of the strong nuclear force, the UP QUARK, makes up protons and neutrons. Considered by physicists to be an elementary particle, quarks experience the strong force and come in six "flavors": up, down, charm, strange, top and bottom. Everyday physical matter contains only up and down quarks.</p> <p>Acrylic felt with poly fill for maximum mass.</p> <p>\$10.49</p>	<p>GLUON g</p> <p>The "glu" of the strong nuclear force, the GLUON is the boson that communicates the strong force, which binds quarks together. It has no mass or electric charge.</p> <p>Acrylic felt with poly fill for maximum mass.</p> <p>\$9.75</p>	<p>DOWN QUARK d</p> <p>No, it is not a carrot! The DOWN QUARK, along with the UP QUARK, makes up protons and neutrons. Considered by physicists to be an elementary particle, quarks experience the strong force and come in six "flavors": up, down, charm, strange, top and bottom. Everyday physical matter contains only up and down quarks.</p> <p>Acrylic felt with poly fill for maximum mass.</p> <p>\$10.49</p>
---	---	---



From the quark-gluon plasma to the hadron gas



Results



Functional Methods for QCD

for a short review see JMP, arXiv:1012.5075

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \left[\text{glue quantum fluctuations} - \text{quark quantum fluctuations} + \frac{1}{2} \text{hadronic quantum fluctuations} \right]$$

free energy

glue quantum fluctuations

quark quantum fluctuations

hadronic quantum fluctuations

RG-scale k : $t = \ln k$

The diagram illustrates the decomposition of the time derivative of the effective action, $\partial_t \Gamma_k[\phi]$, into three components. On the left, the equation is written as $\partial_t \Gamma_k[\phi] = \frac{1}{2} [\dots]$. The first component, 'glue quantum fluctuations', is shown in an orange box and consists of a solid circle with eight small circles on its perimeter and a solid black dot at the bottom, minus a dashed circle with the same features. The second component, 'quark quantum fluctuations', is shown in a blue box and consists of a solid circle with a solid black dot at the bottom. The third component, 'hadronic quantum fluctuations', is shown in a purple box and consists of a dotted circle with a solid black dot at the bottom. The entire expression is multiplied by $\frac{1}{2}$. Below the diagram, the text 'free energy' is on the left, and 'RG-scale k : $t = \ln k$ ' is on the right.

- **Gluons have cost us decades**

- **Fermions are straightforward** though 'physically' complicated

- no sign problem
- chiral fermions

- **bound states via dynamical hadronisation**

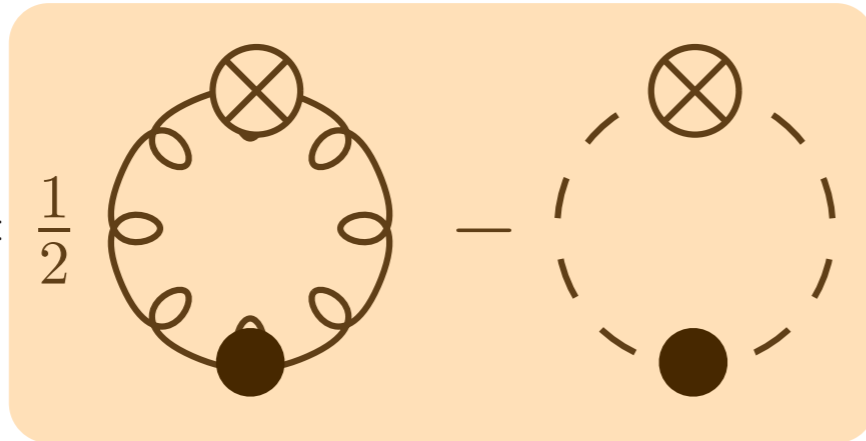
Complementary to lattice!

e.g. finite volume scaling: Braun, Klein, Piasecki, Schaefer '10-11

Functional Methods for QCD

glue
quantum fluctuations

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}$$



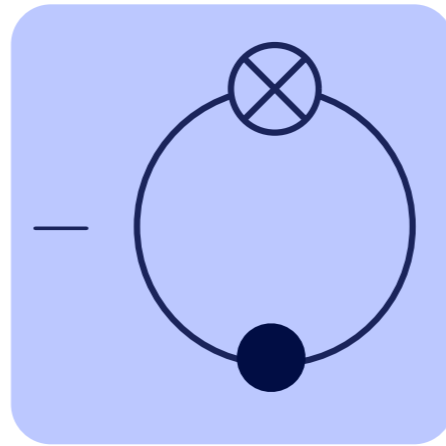
free energy

Yang-Mills theory

Functional Methods for QCD

$$\partial_t \Gamma_k[\phi] =$$

free energy



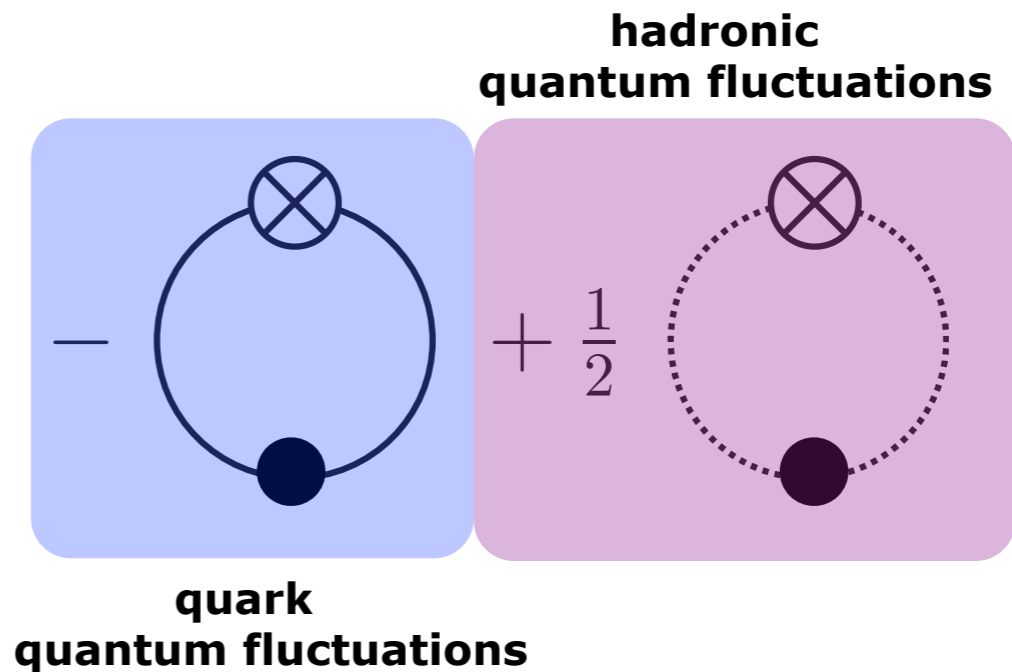
quark
quantum fluctuations

NJL/PNJL model

Functional Methods for QCD

$$\partial_t \Gamma_k[\phi] =$$

free energy



Quark-hadron/PQH models

- **bound states via dynamical hadronisation**

Functional Methods for QCD

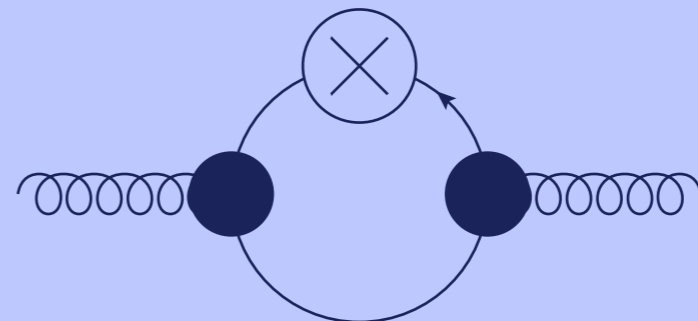
$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \left[\text{glue quantum fluctuations} - \text{quark quantum fluctuations} + \frac{1}{2} \text{hadronic quantum fluctuations} \right]$$

free energy

flow of gluon propagator

pure gauge theory flow

+



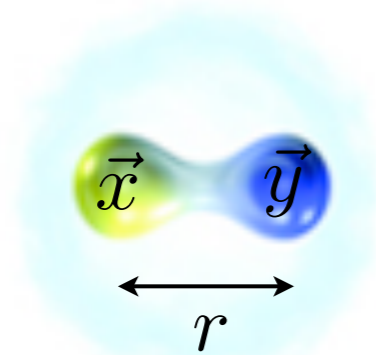
+

...

Naturally incorporates PQM/PNJL models as specific low order truncations

Confinement

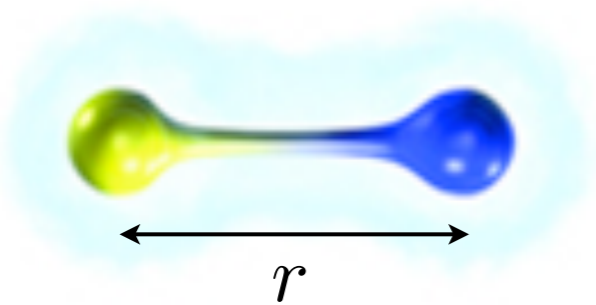
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



$$F_{q\bar{q}} \simeq -\frac{1}{r}$$

Order parameter $\sim \langle q \rangle'$

$$\Phi = e^{-\frac{1}{2T} F_{q\bar{q}}(\infty)}$$

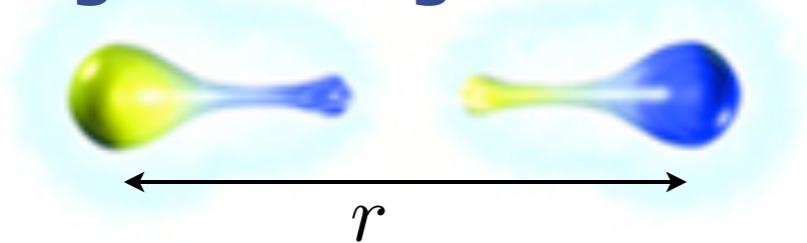


$$F_{q\bar{q}} \simeq \sigma r$$

▪ **Confinement** $\Phi = 0$

▪ **Deconfinement** $\Phi \neq 0$

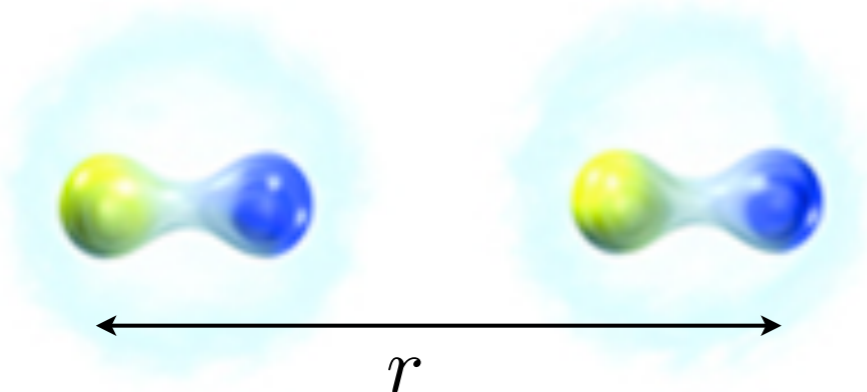
string breaking at $r \approx 1\text{fm}$

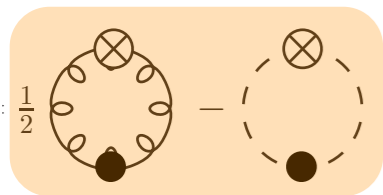


$$F_{q\bar{q}} \simeq \text{const.}$$

Polyakov loop

$$\Phi = \frac{1}{3} \langle \text{Tr } \mathcal{P} \exp \{ ig \int_0^{1/T} dx_0 A_0 \} \rangle$$





Confinement

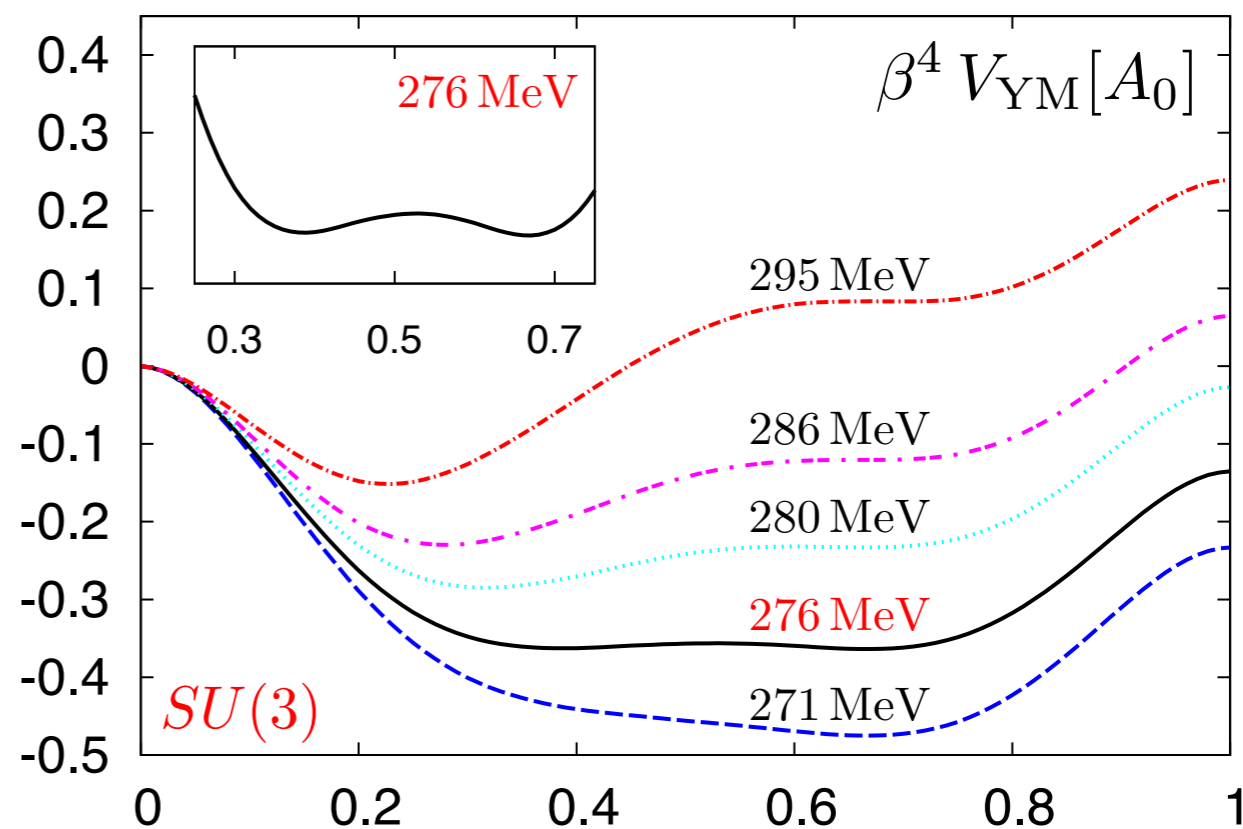
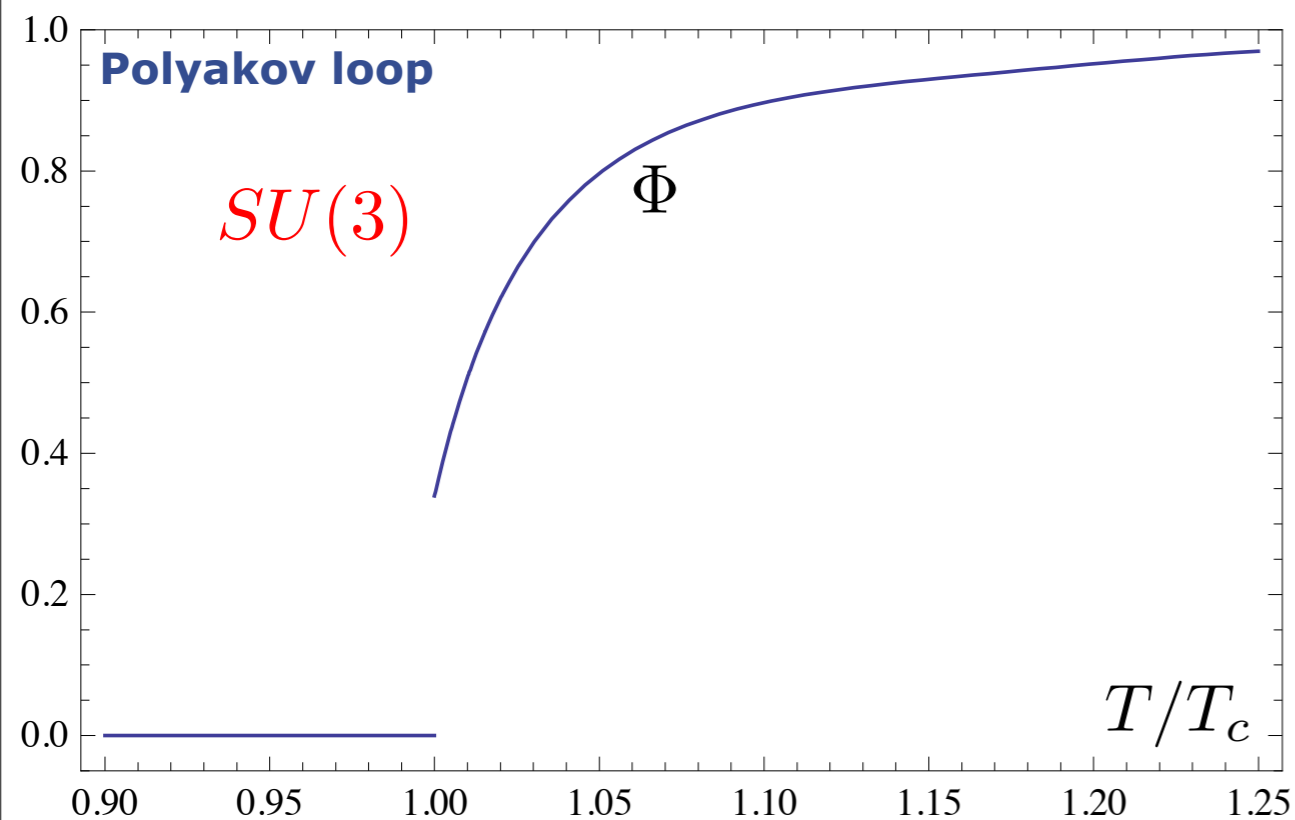
Order parameter

Braun, Gies, JMP '07

$$T_c = 276 \pm 10 \text{ MeV}$$

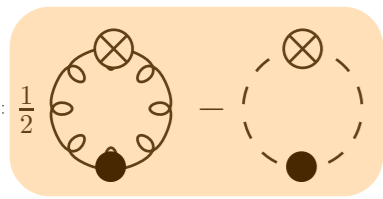
$$T_c/\sqrt{\sigma} = 0.658 \pm 0.023$$

$$\text{lattice : } T_c/\sqrt{\sigma} = 0.646$$



$$\Phi[A_0] = \frac{1}{3} \left(1 + 2 \cos \frac{1}{2} \beta g A_0 \right)$$

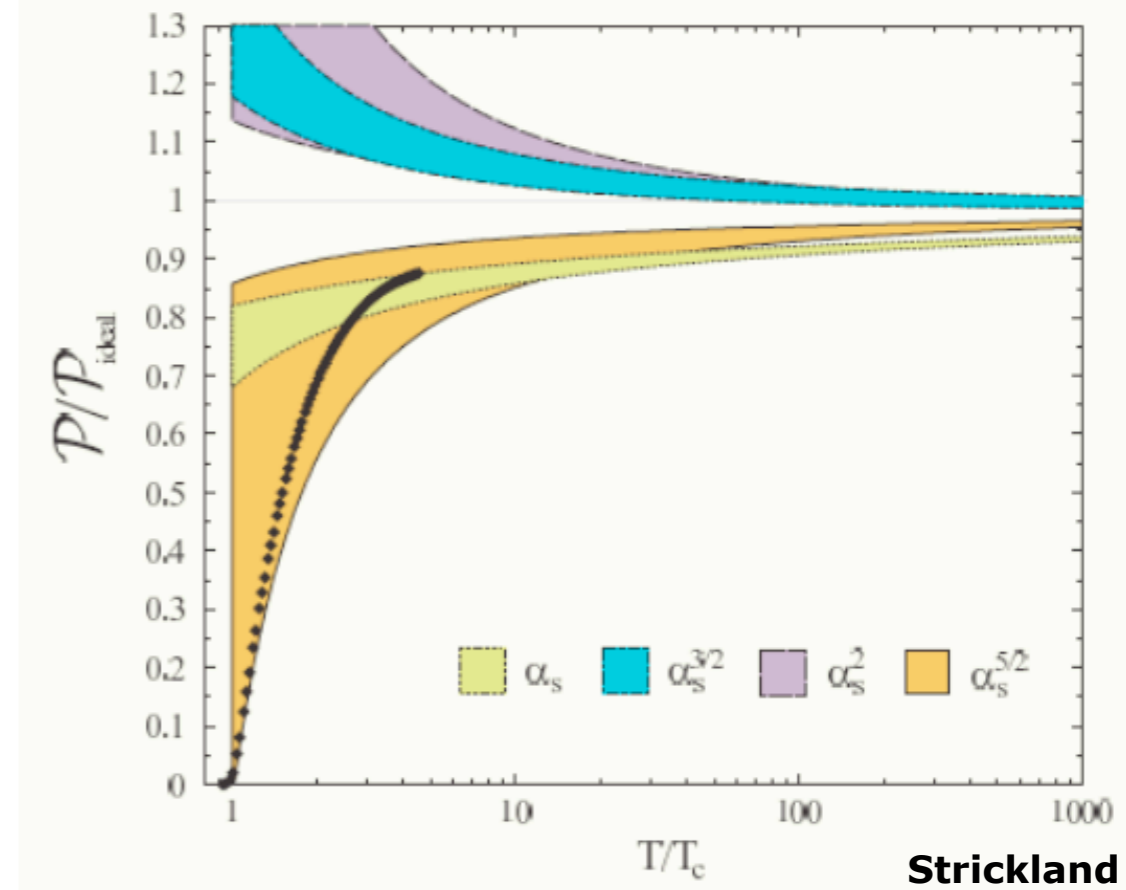
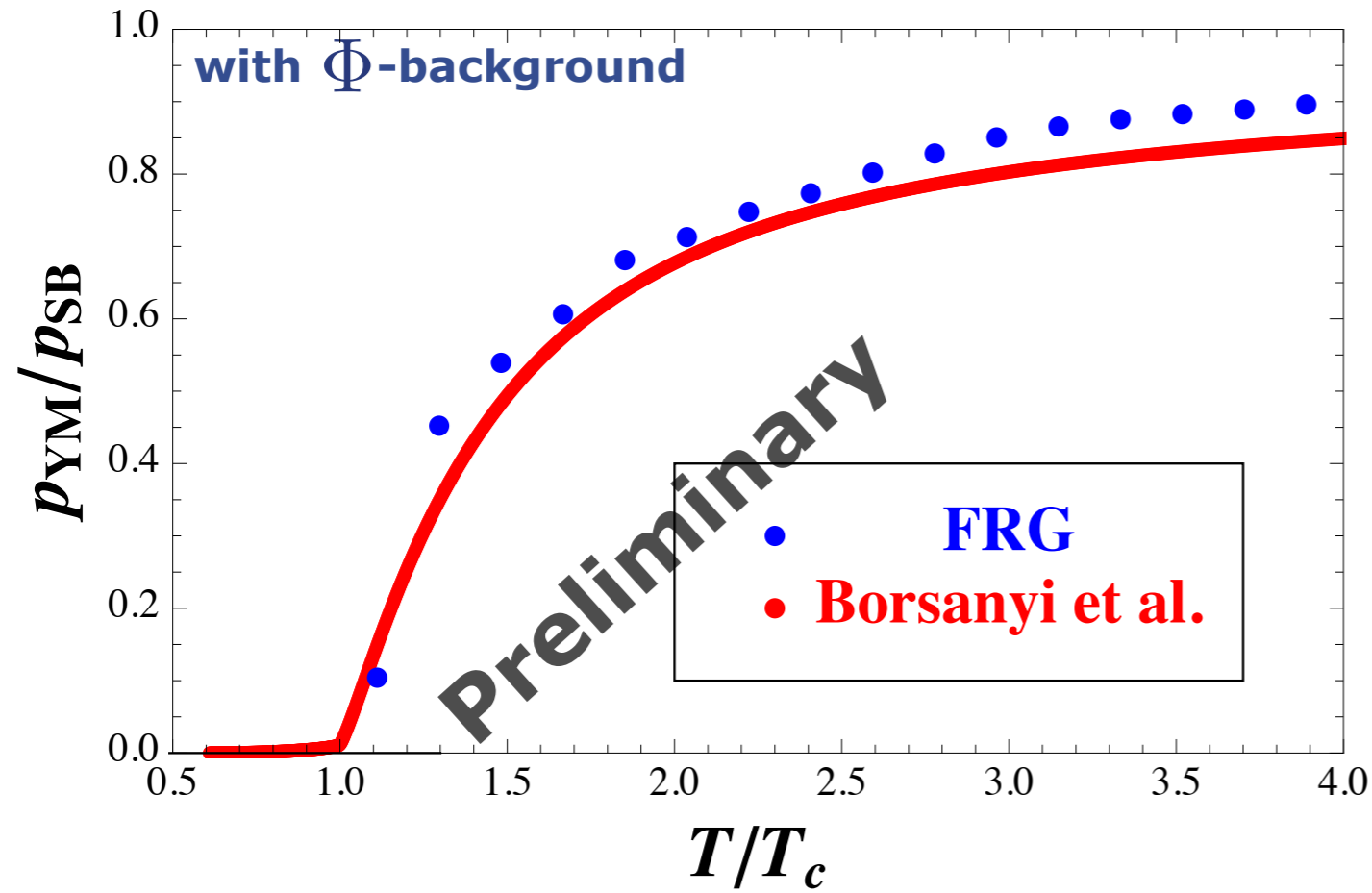
$$\Phi \left[\frac{4}{3} \pi \frac{1}{\beta g} \right] = 0 \quad \frac{\beta g A_0}{2\pi}$$



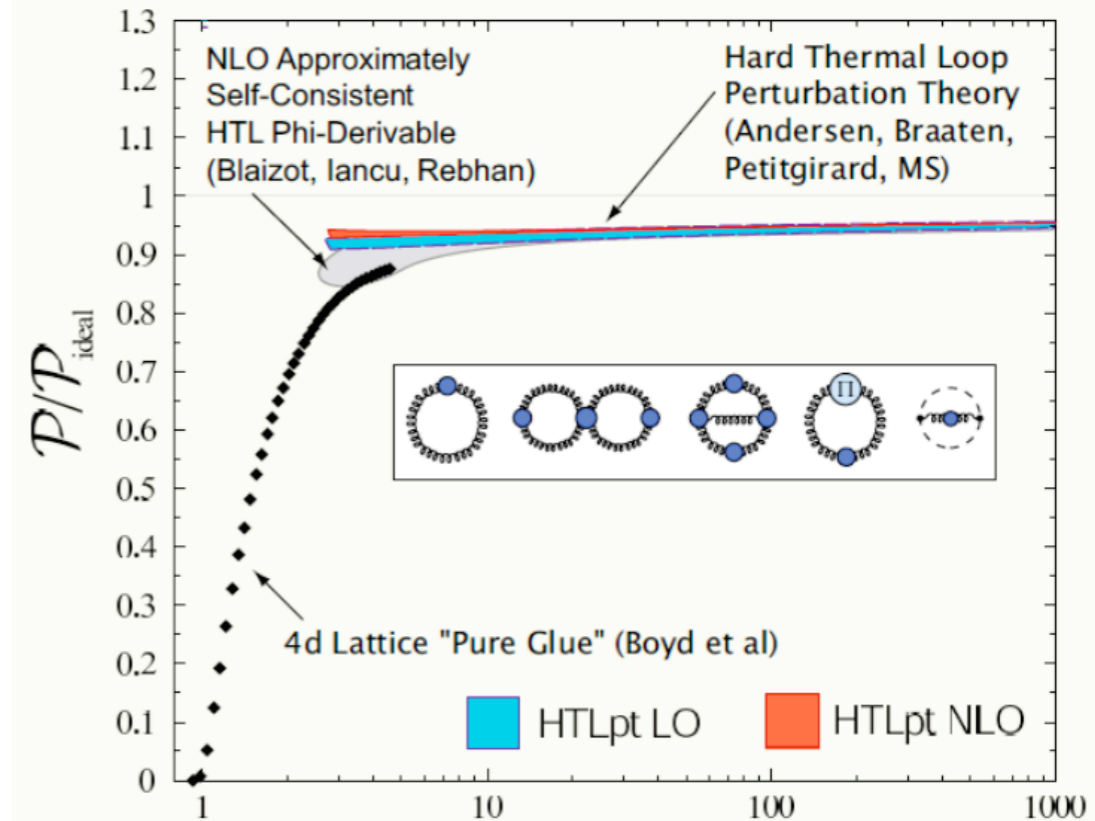
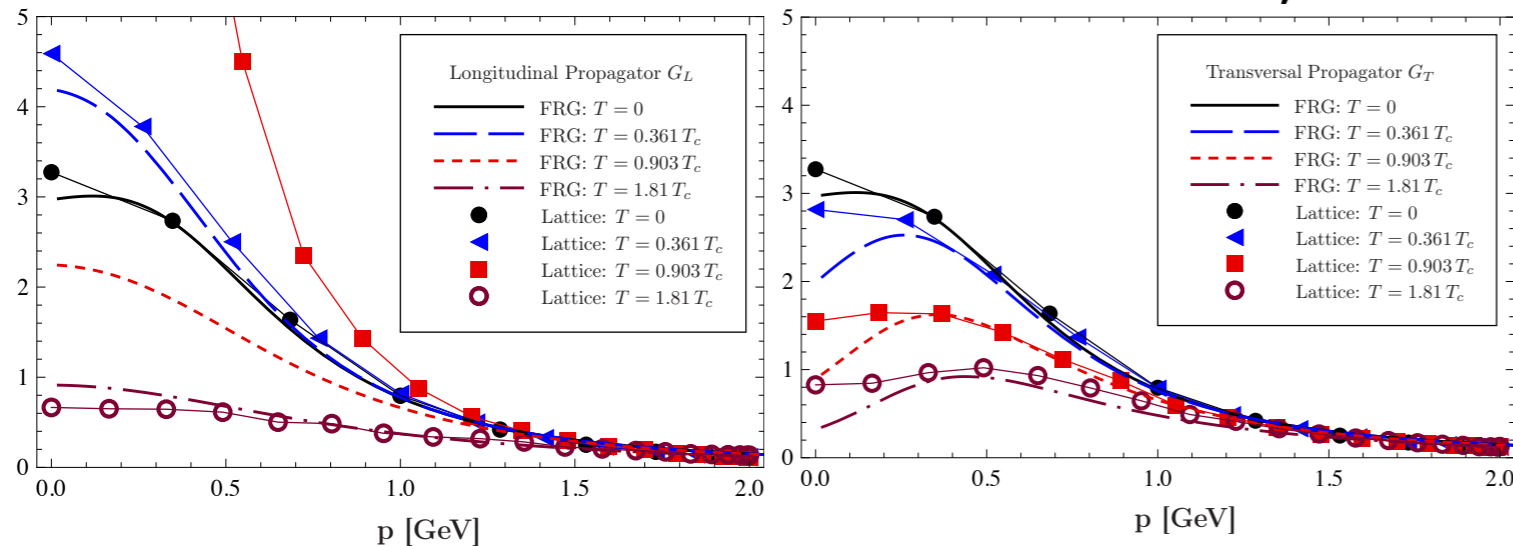
thermodynamics

Yang-Mills pressure

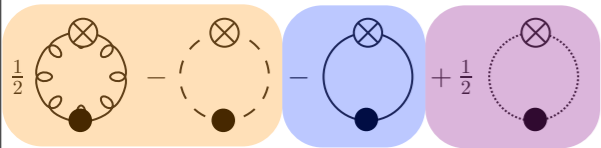
Fister, JMP



Fister, JMP '11

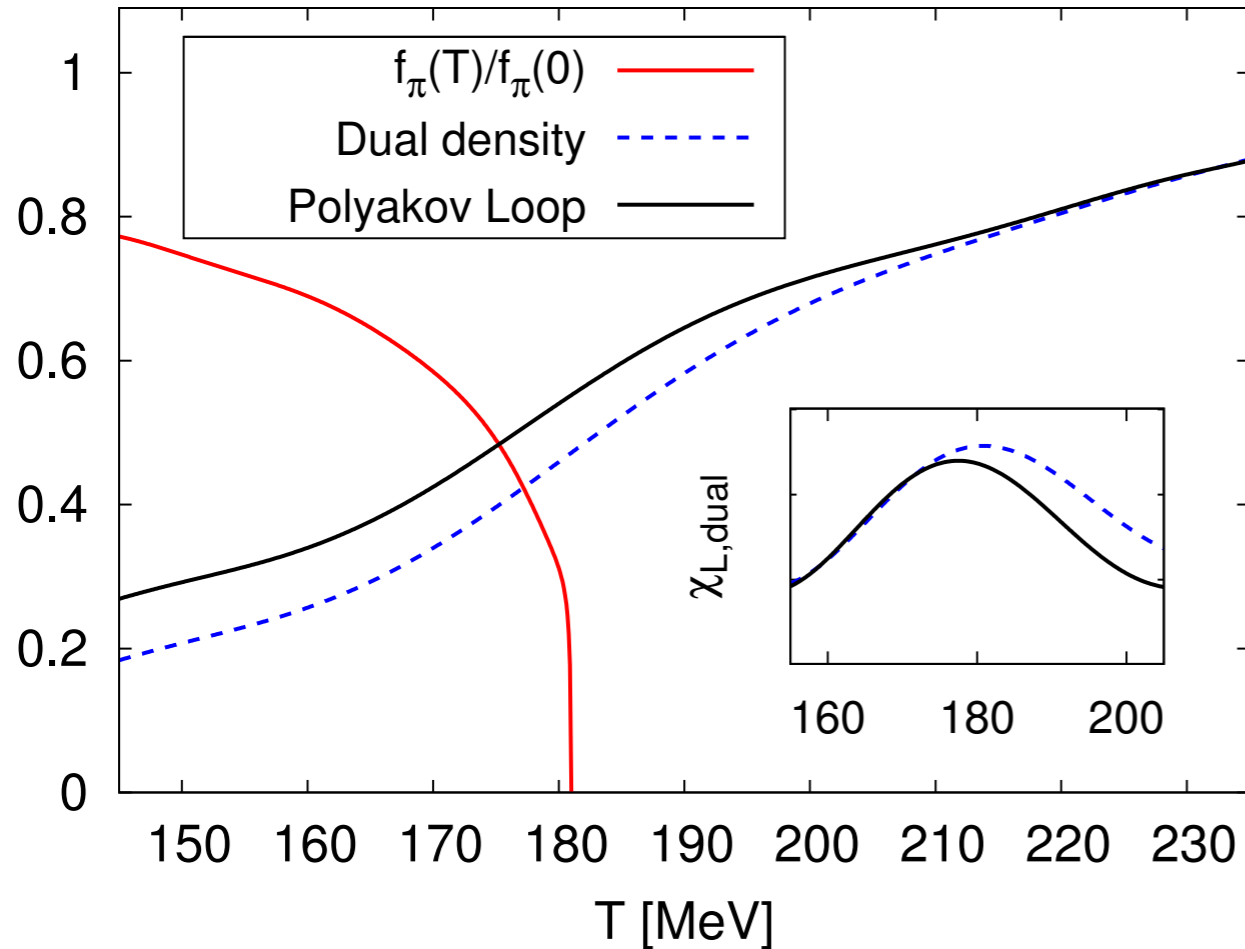


Full dynamical QCD: $N_f = 2$ & chiral limit



Phase structure

Braun, Haas, Marhauser, JMP '09

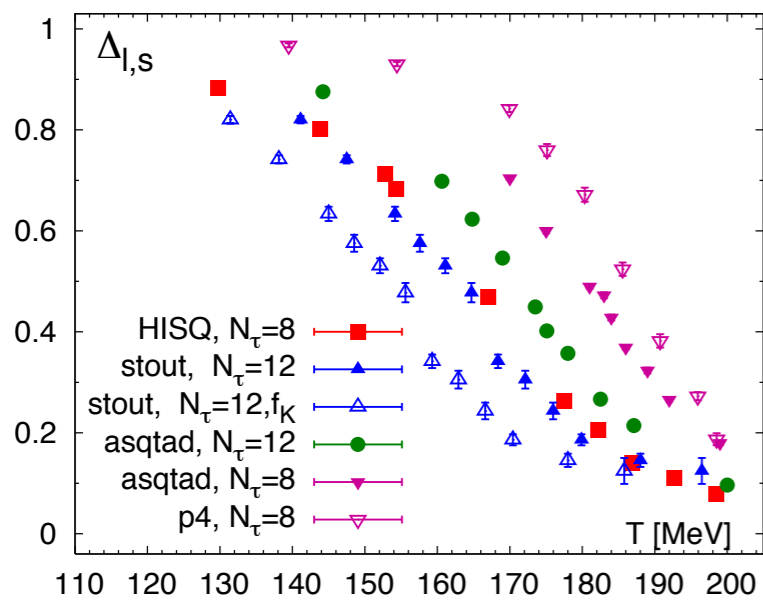


- $T_\chi \simeq T_{\text{conf}} \simeq 180 \text{ MeV}$

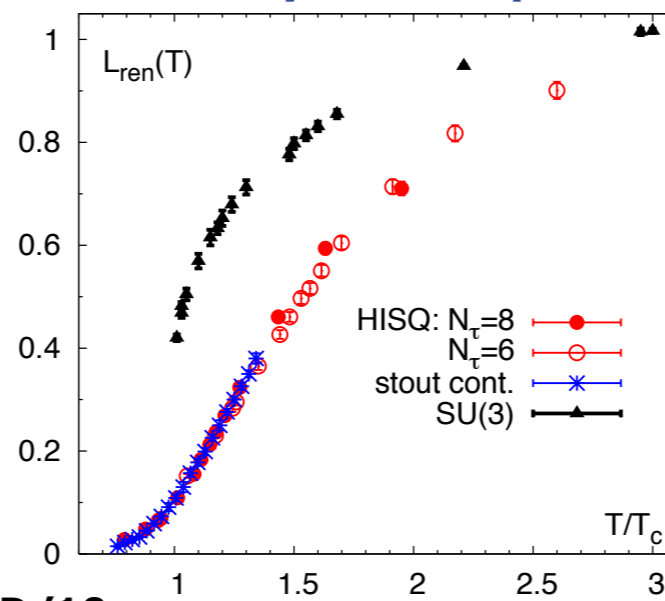
- Width** $\Delta T_{\text{conf}} \simeq \pm 20 \text{ MeV}$

- $T_{\text{conf,FRG}} \lesssim T_{\text{conf,lattice}}$

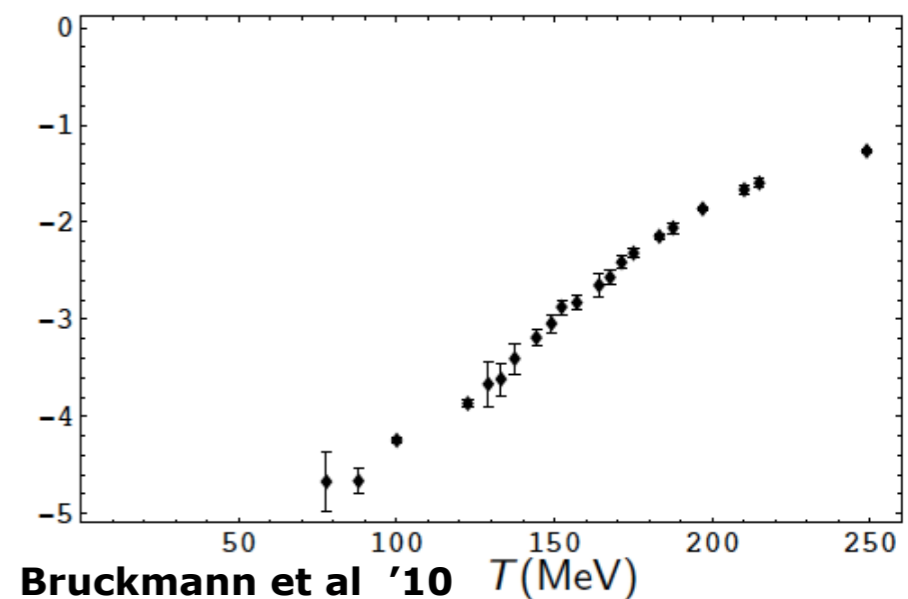
Chiral condensate



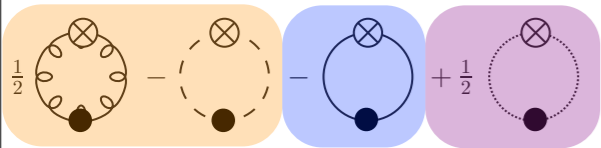
Polyakov loop



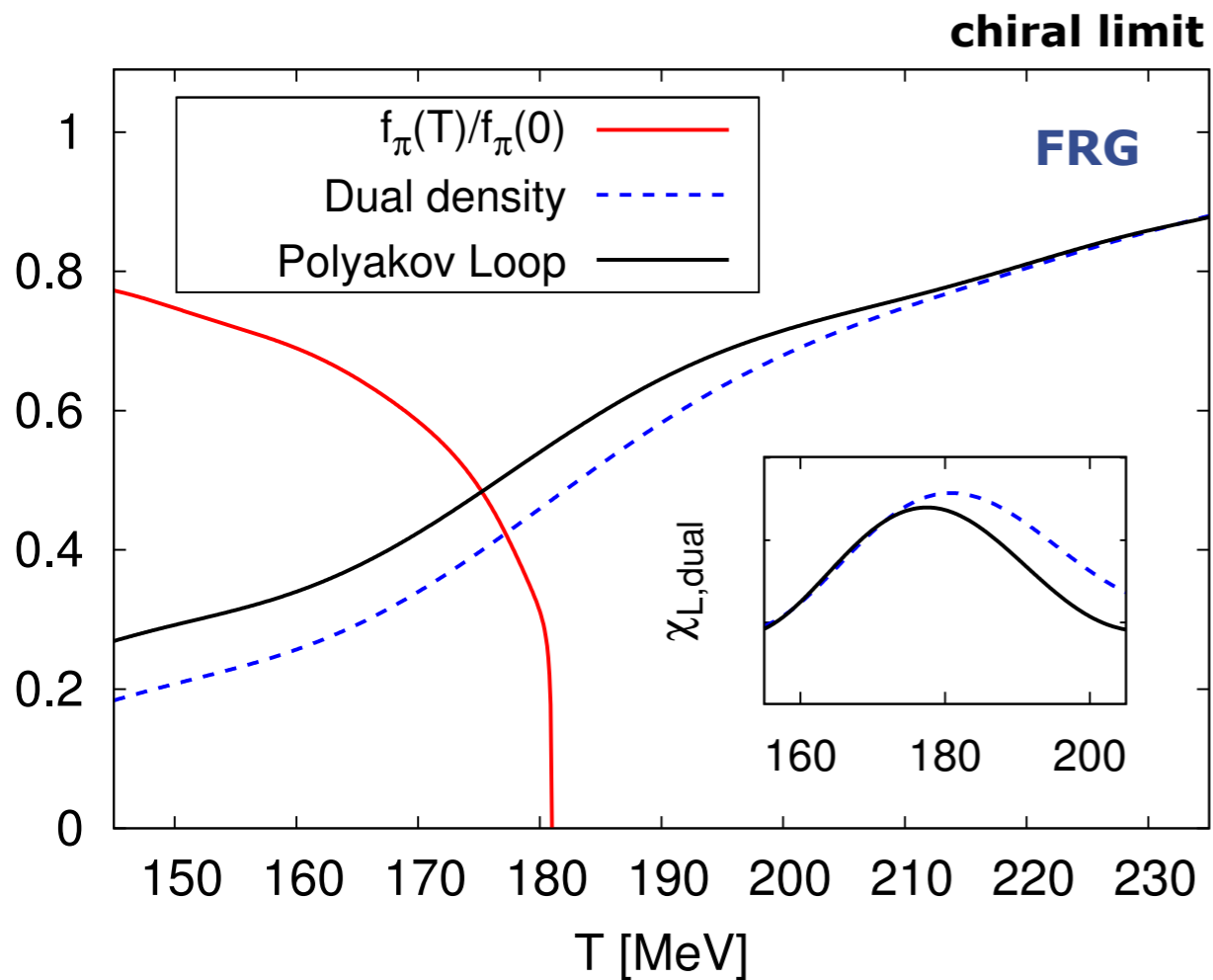
Log of dual condensate, $m=60 \text{ MeV}$



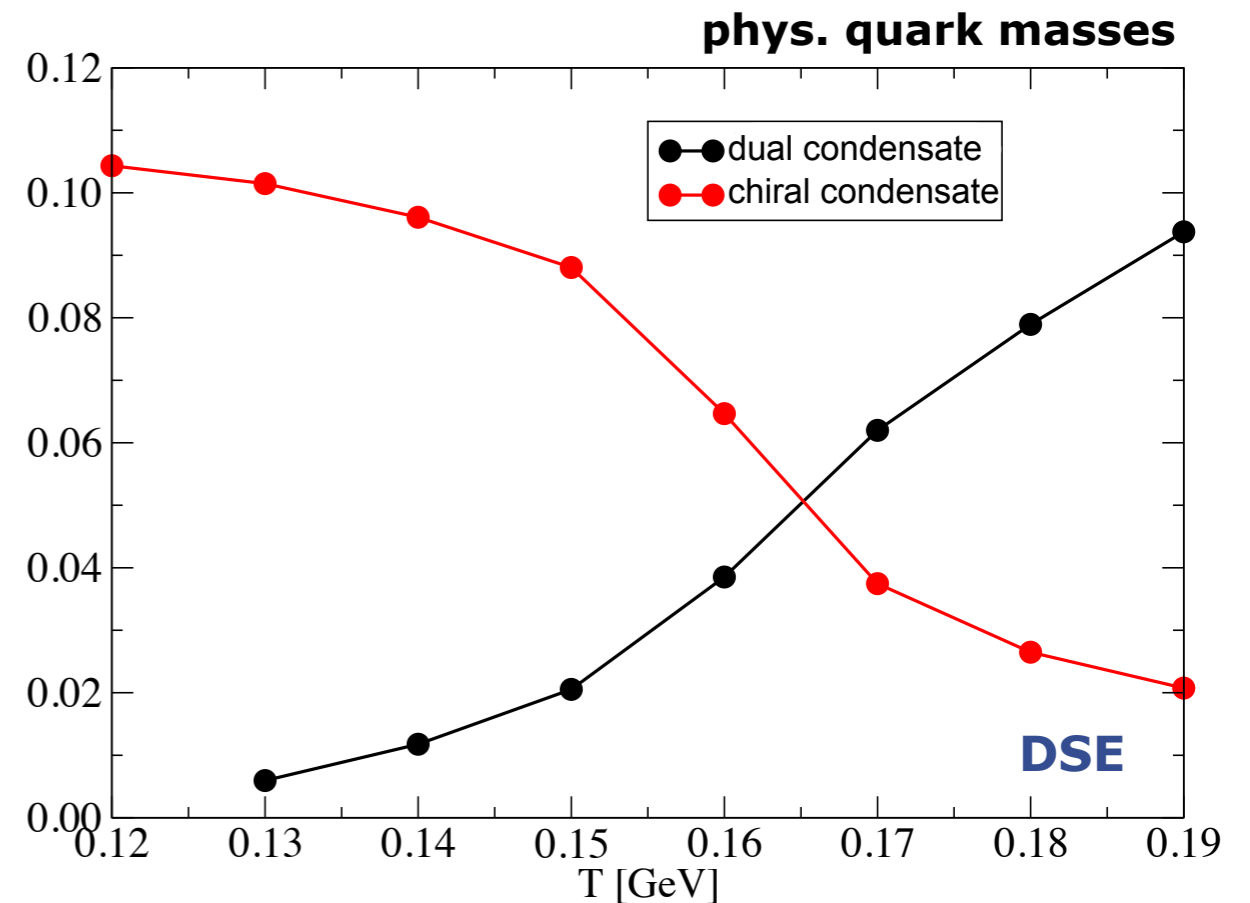
Full dynamical QCD: $N_f = 2$ & chiral limit



Phase structure



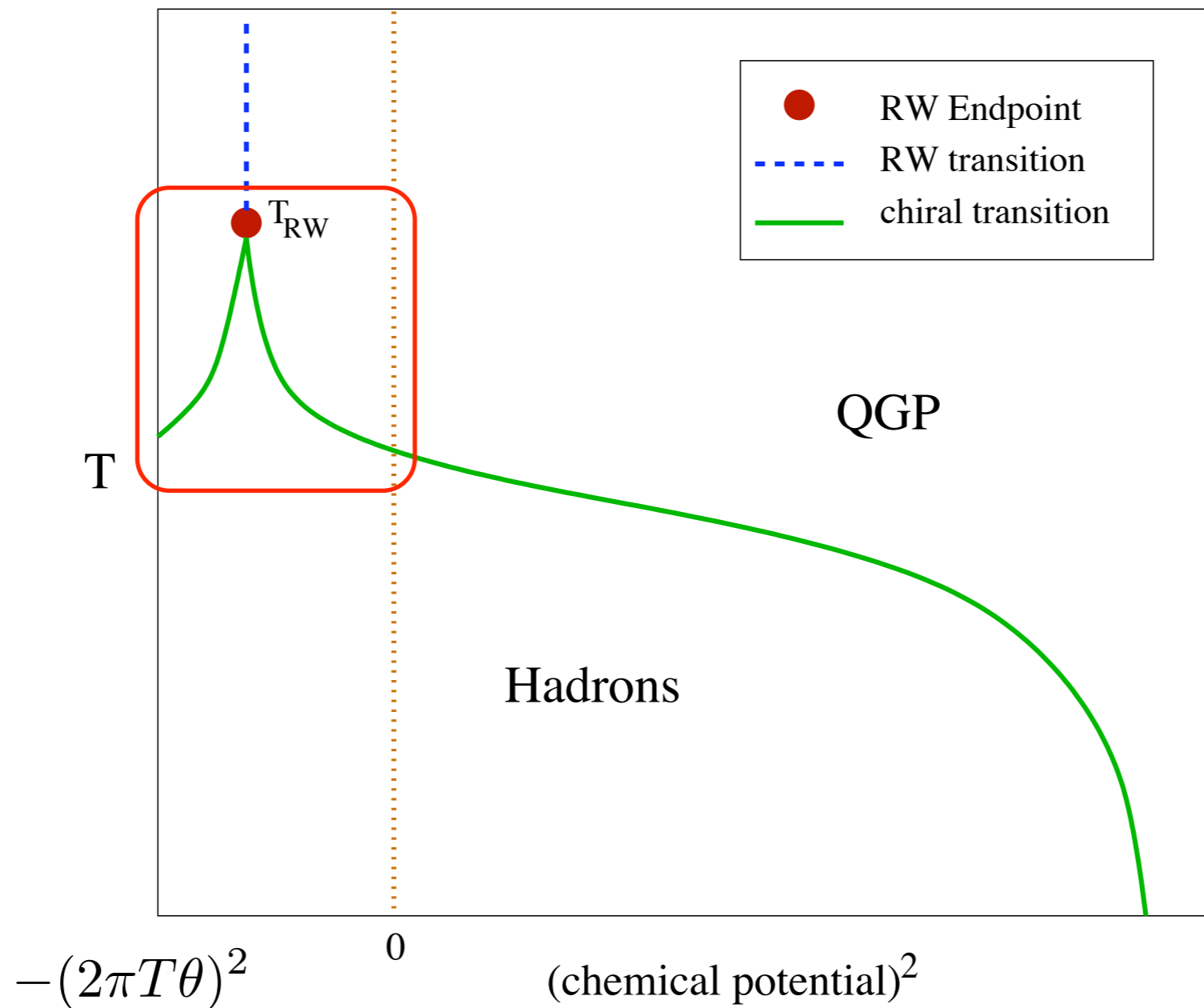
Braun, Haas, Marhauser, JMP '09



Fischer, Lücker, Mueller '11

Imaginary chemical potential

$$\psi_\theta(t + \beta, \vec{x}) = -e^{2\pi i \theta} \psi_\theta(t, x) \quad \text{with} \quad \mu = 2\pi i T \theta$$



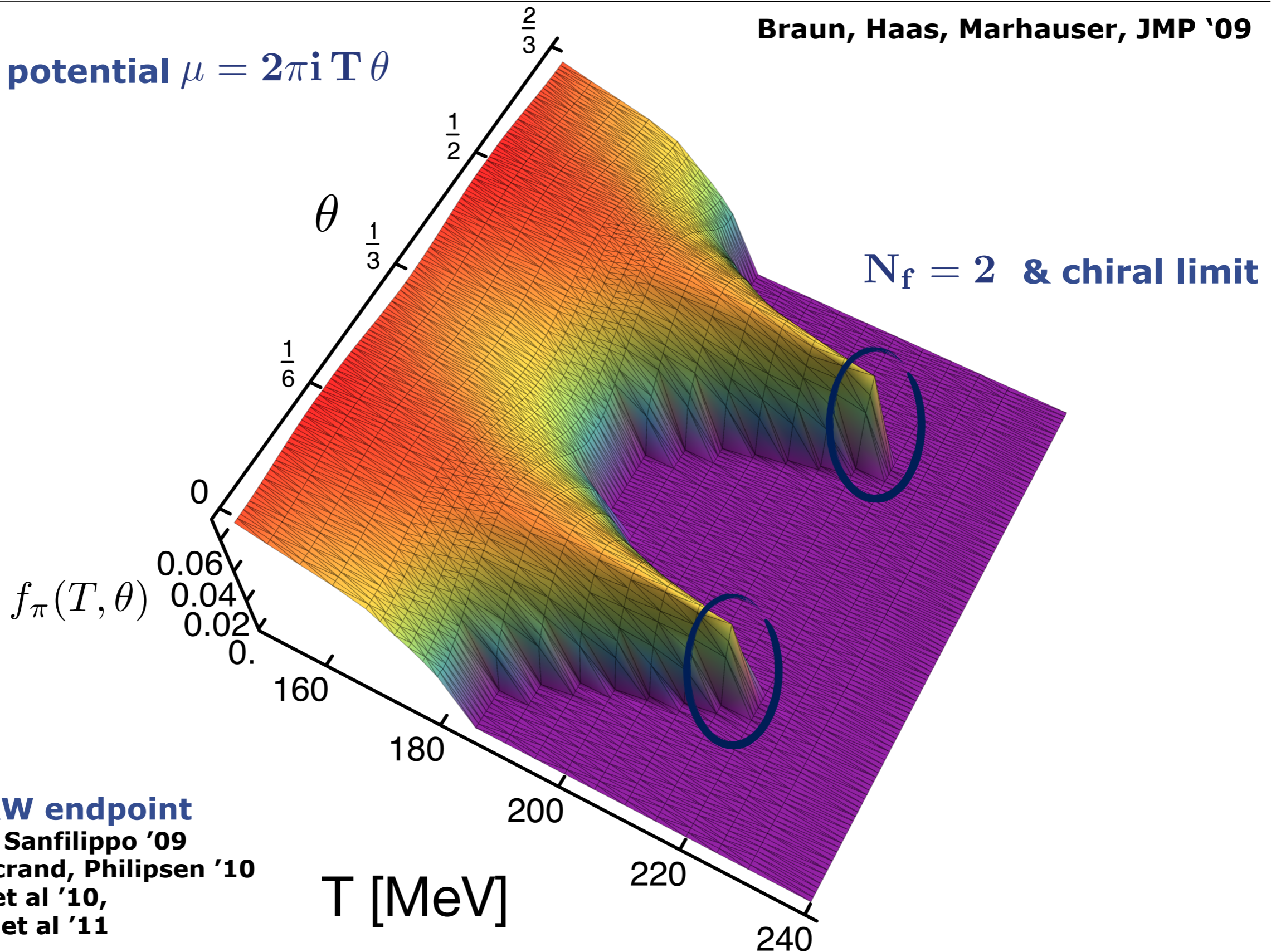
Roberge-Weiss symmetry: $\theta \rightarrow \theta + 1/3$

Imaginary chemical potential

Chiral phase structure

Braun, Haas, Marhauser, JMP '09

chemical potential $\mu = 2\pi i T \theta$



Nature of RW endpoint

lattice: D'Elia, Sanfilippo '09

de Forcrand, Philipsen '10

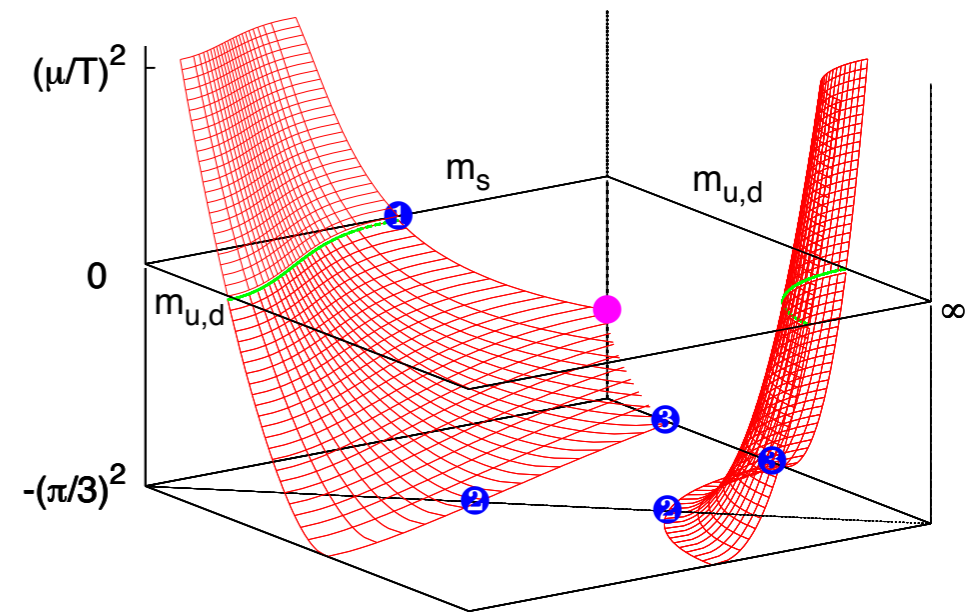
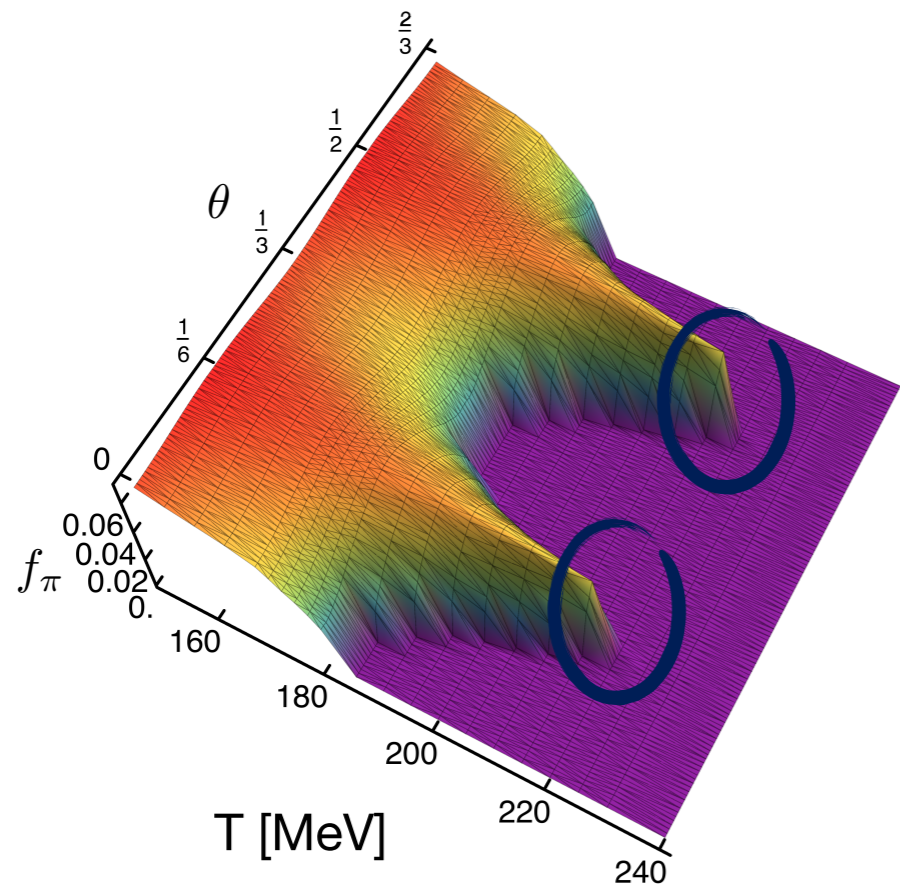
PNJL: Sakai et al '10,

Morita et al '11

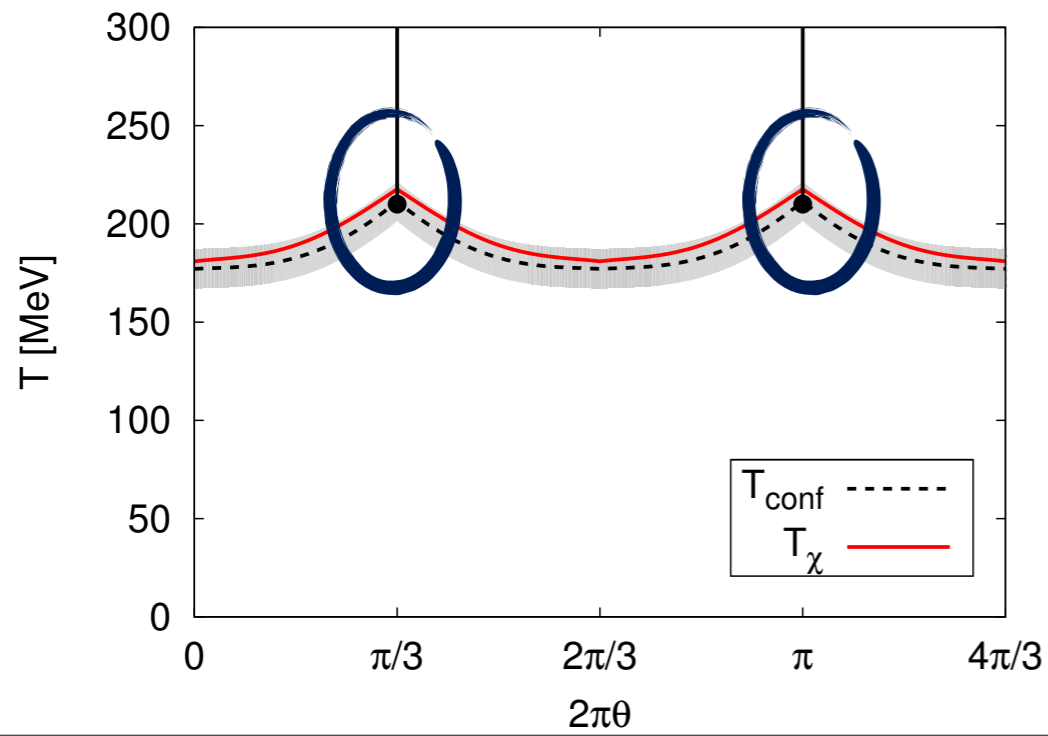
Imaginary chemical potential

Nature of the RW endpoint

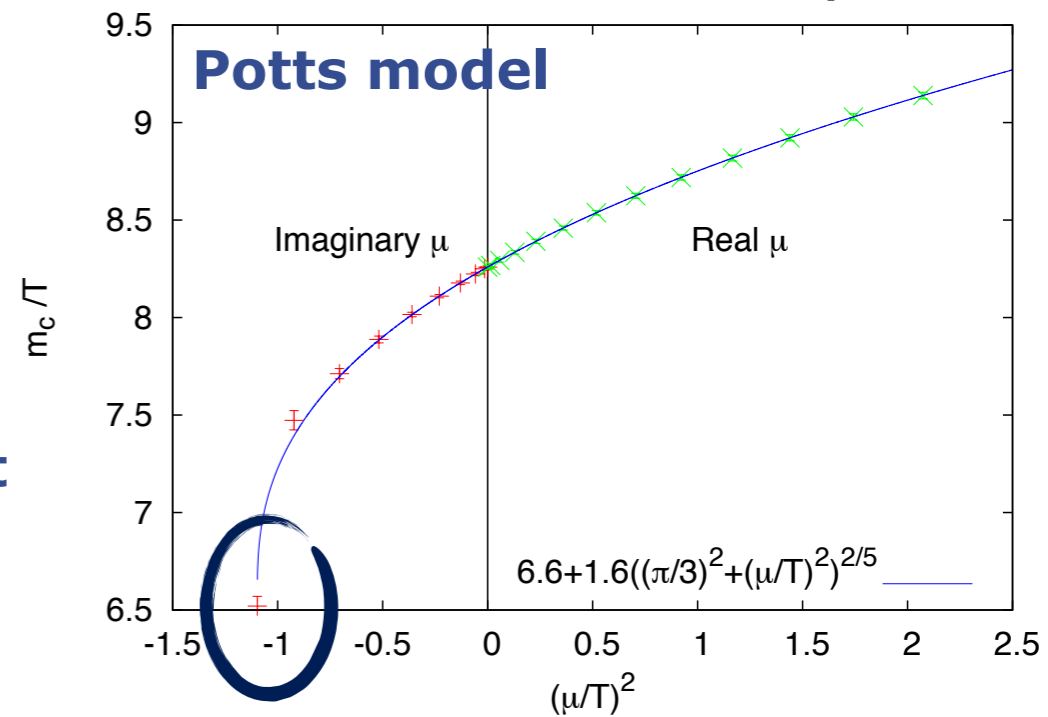
chemical potential $\mu = 2\pi i T \theta$



O. Philipsen '11



RW endpoint

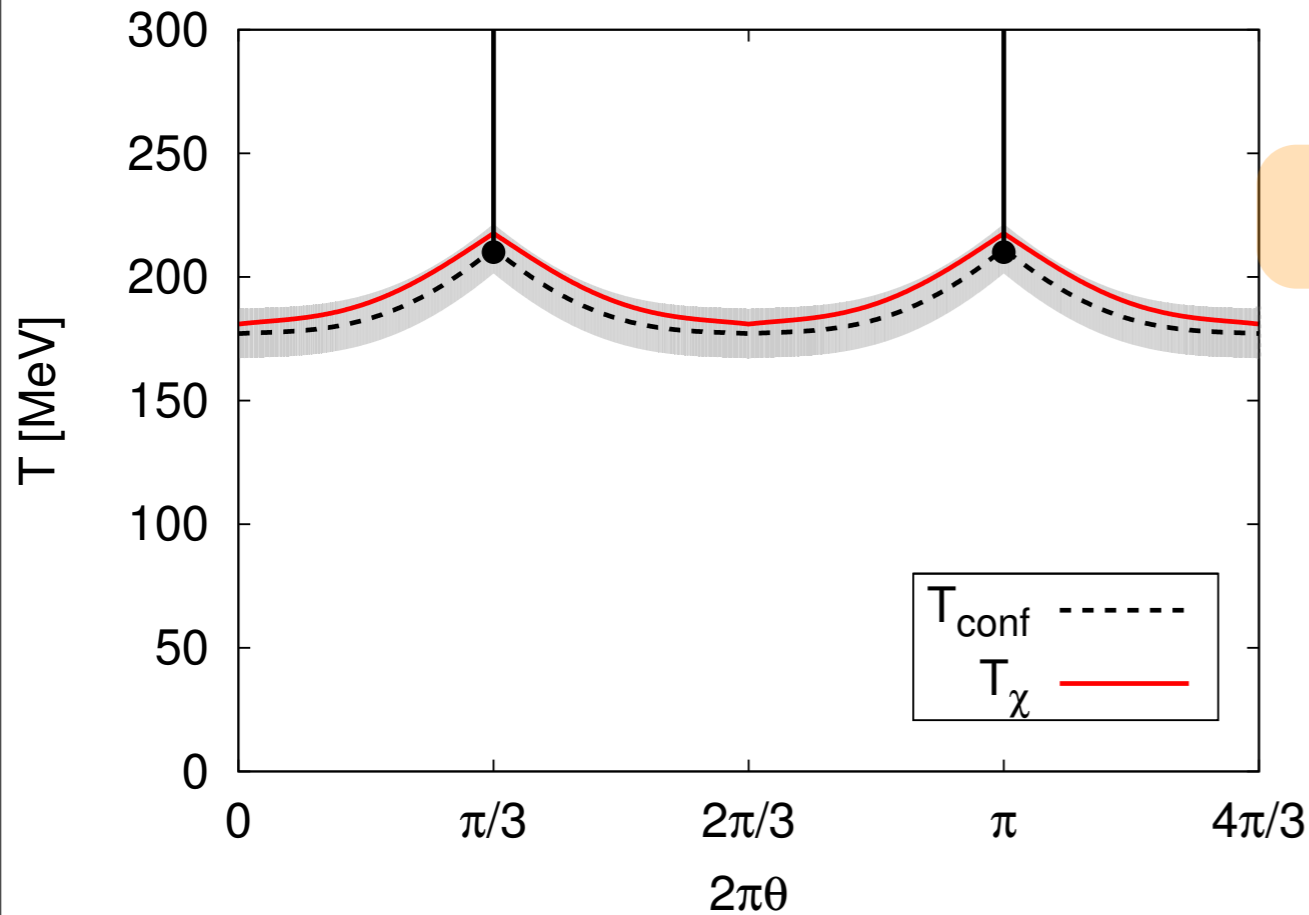


Imaginary chemical potential

Phase structure

chemical potential $\mu = 2\pi i T \theta$

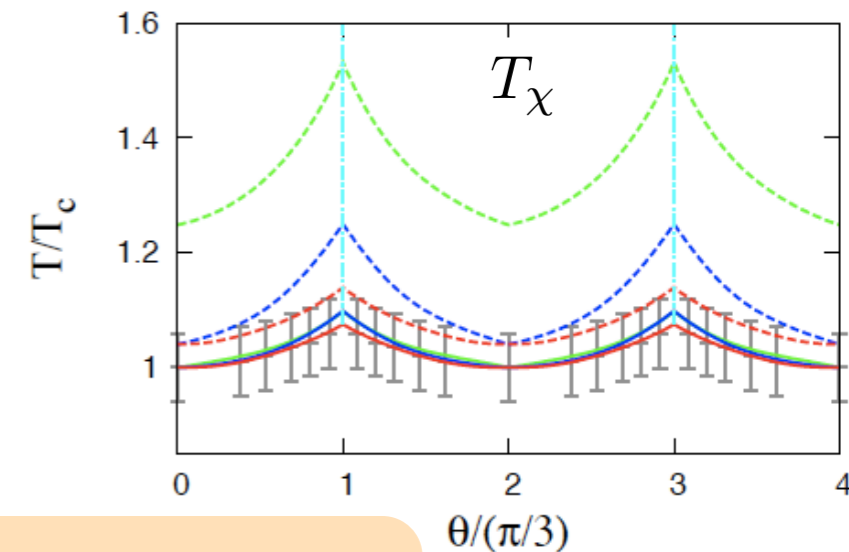
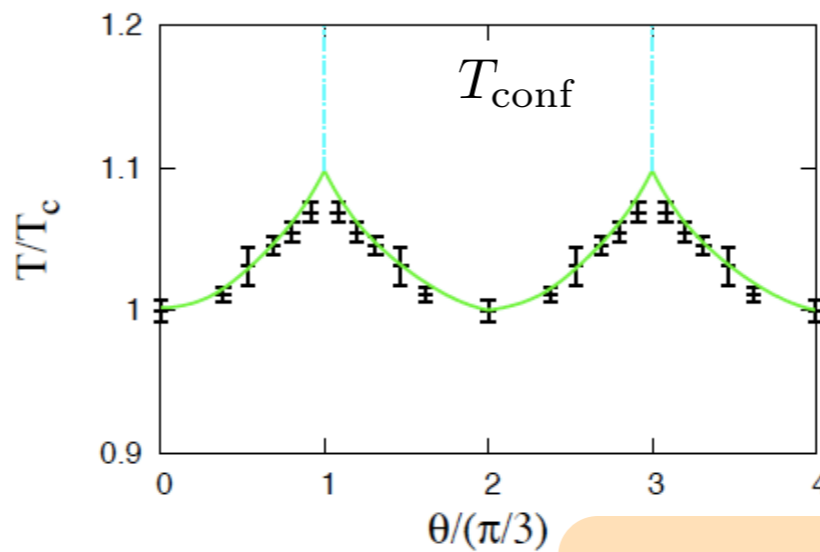
Braun, Haas, Marhauser, JMP '09



compatibility

lattice results, e.g.
Kratochvila et al '06,
Wu et al '06,
D'Elia et al '07,

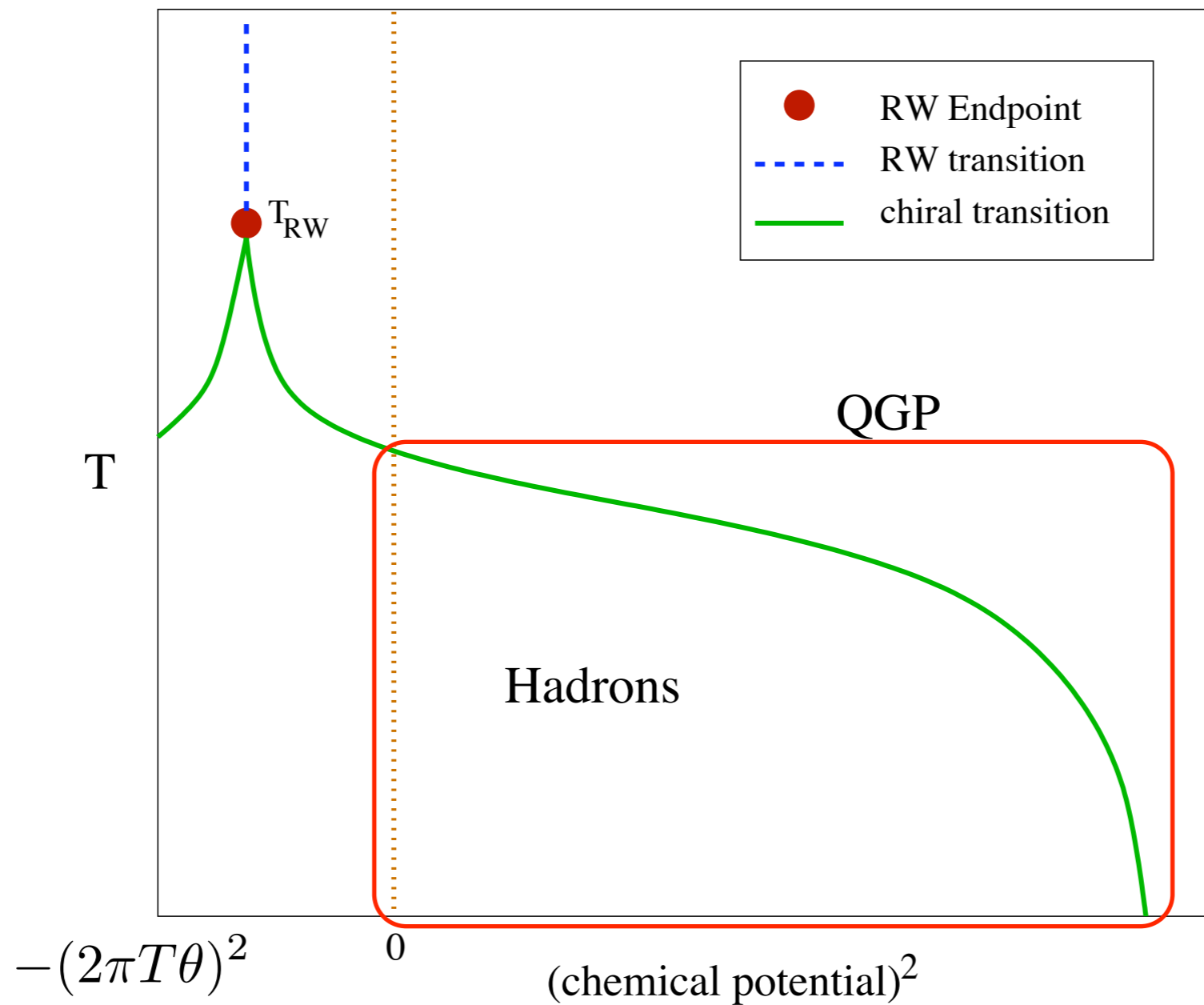
Polyakov-NJL model
Sakai et al '09, ...



adjust 8-fermi interaction

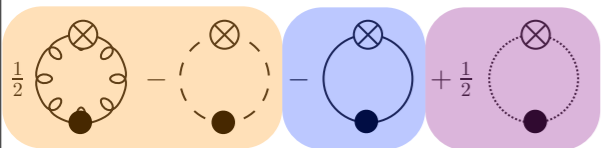
Real chemical potential

$$\psi_\theta(t + \beta, \vec{x}) = -\psi(t, x)$$

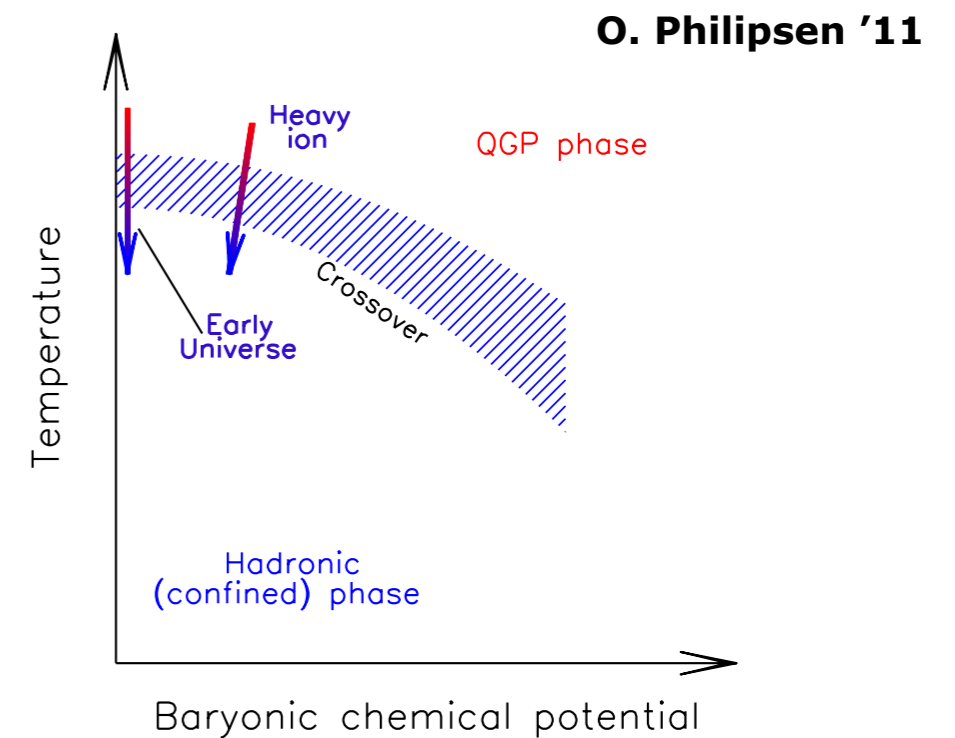
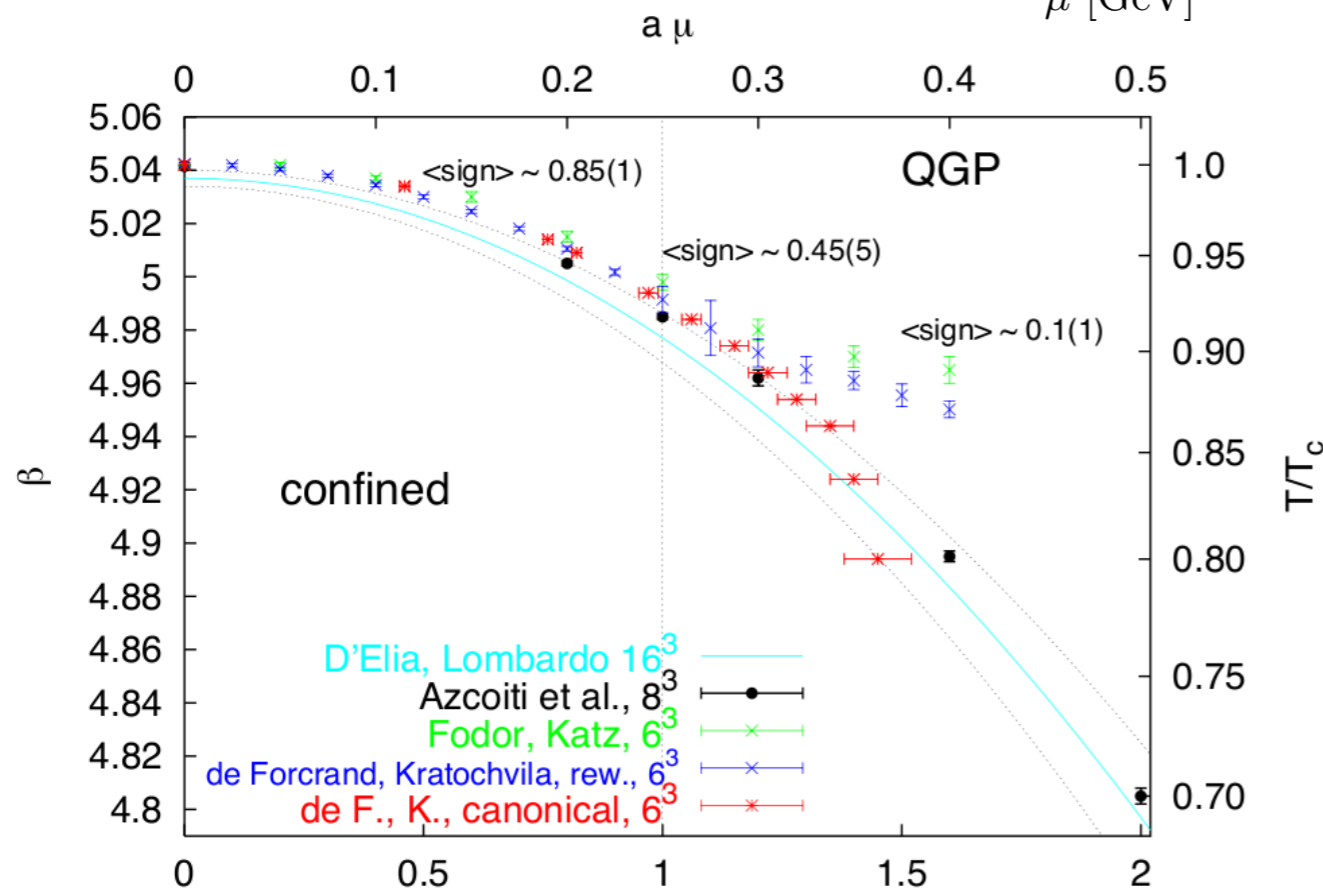
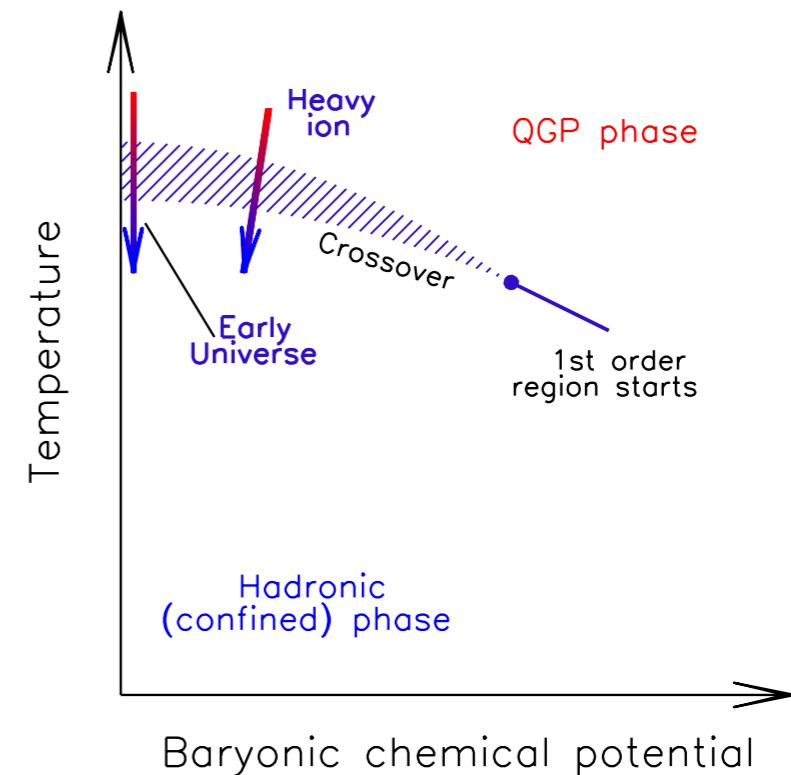
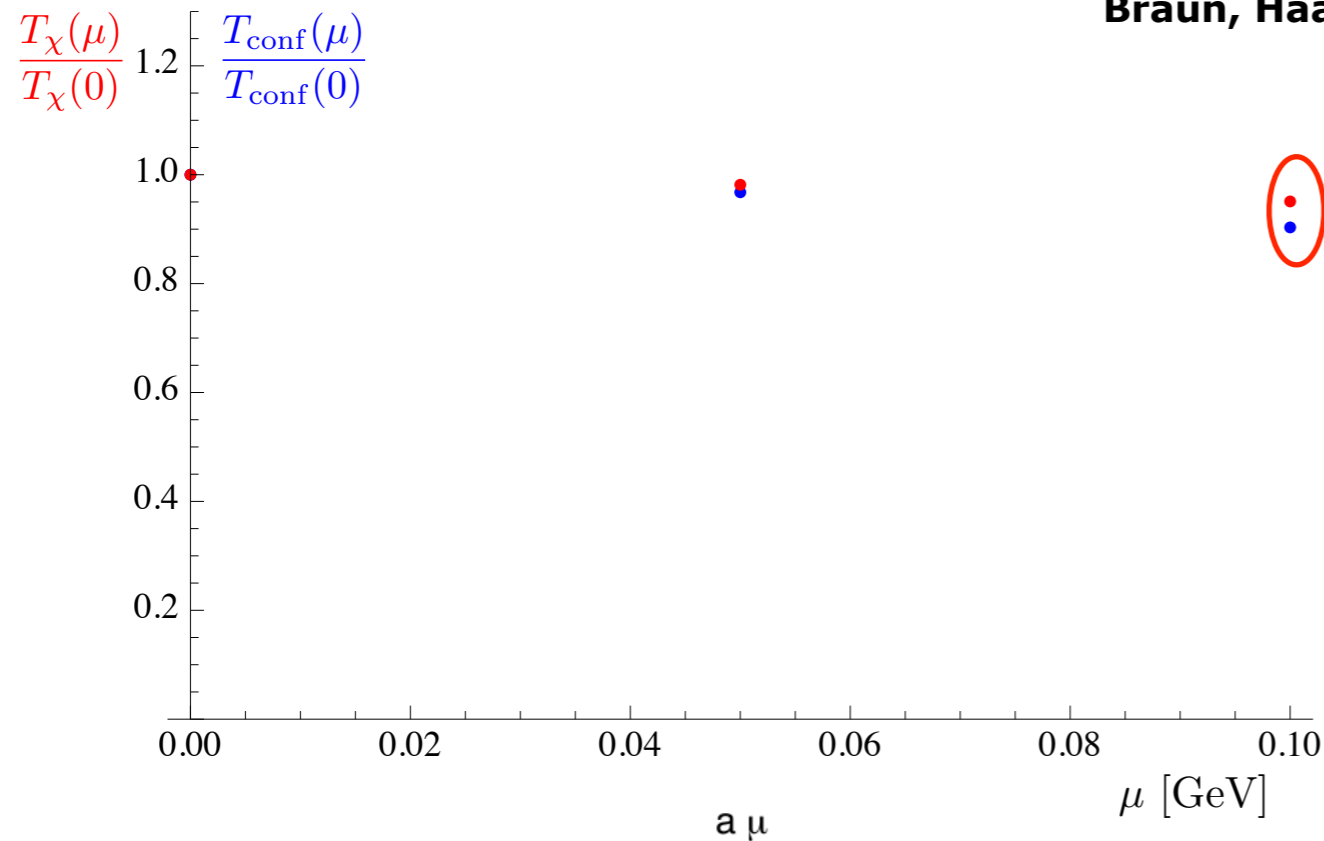


Real chemical potential

Full dynamical QCD

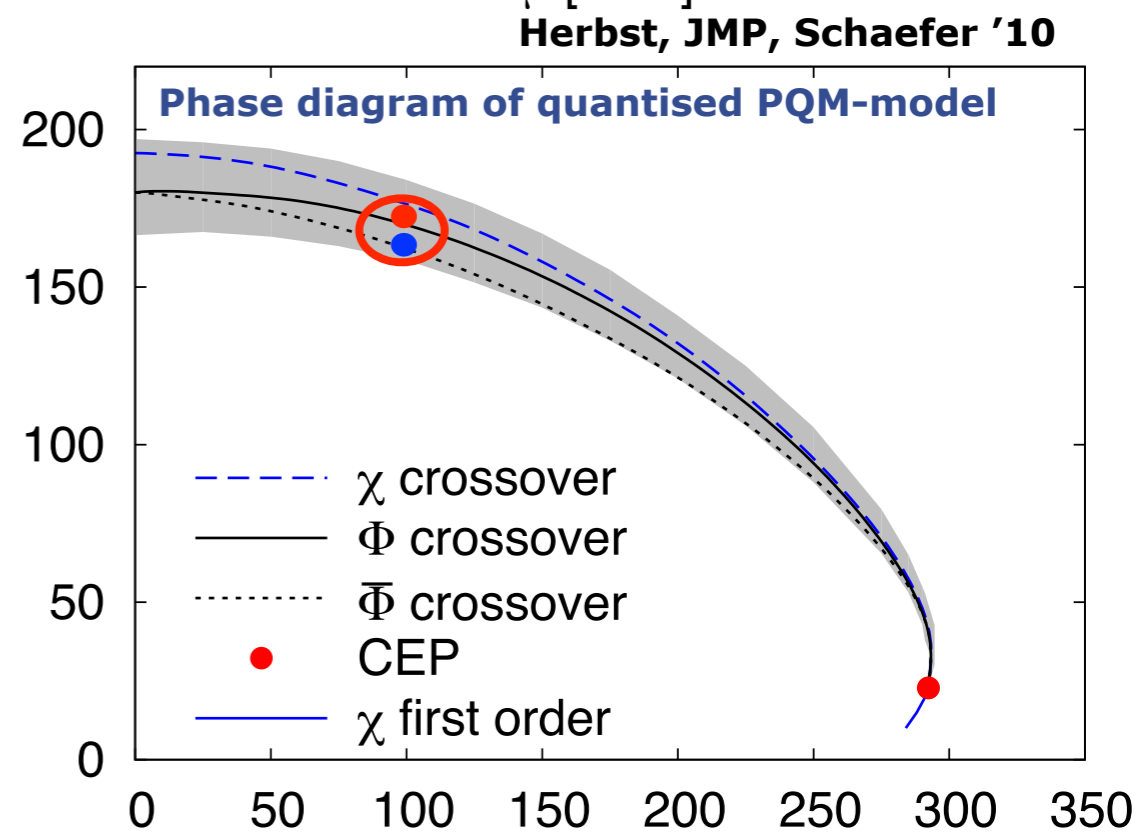
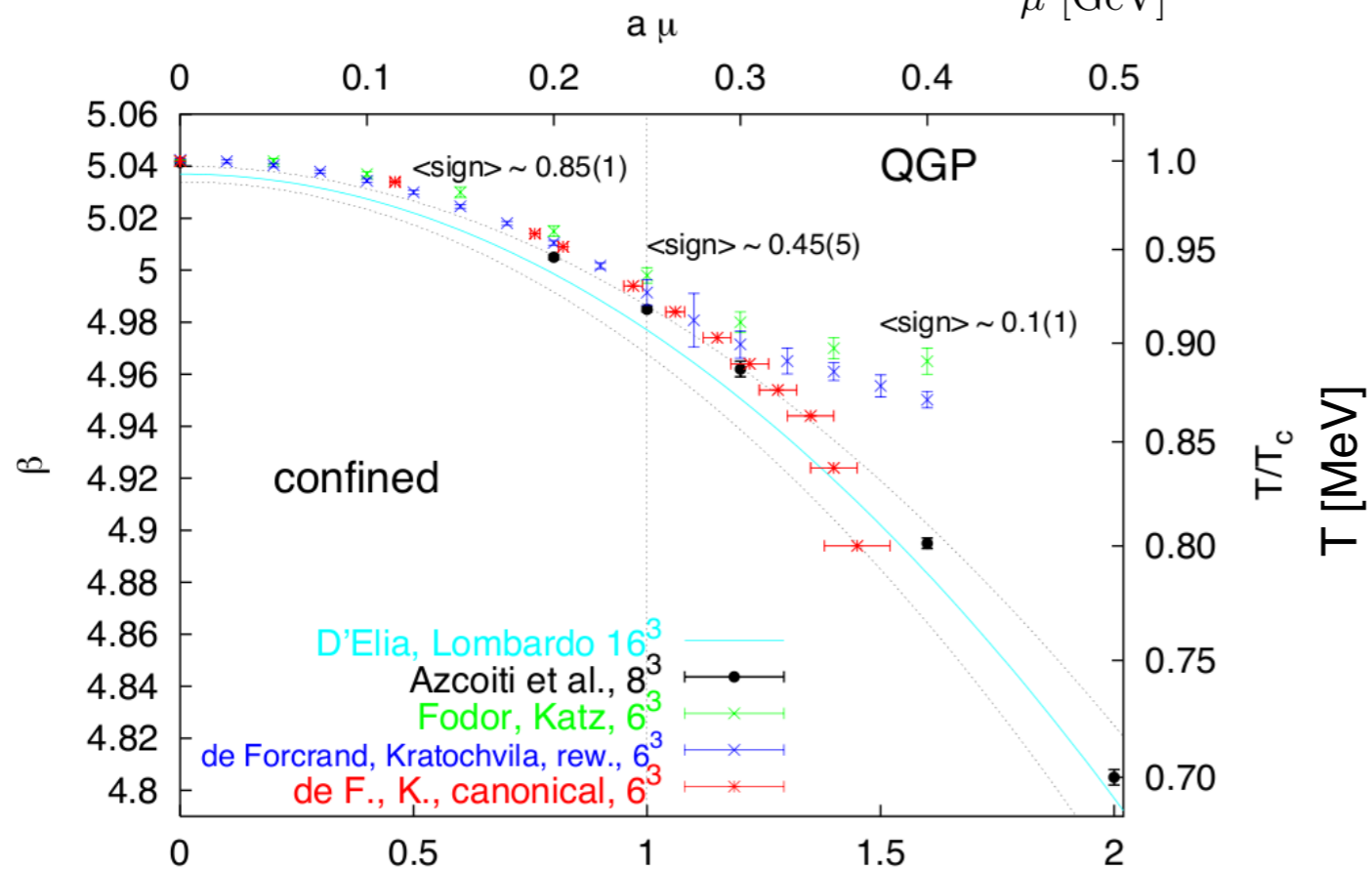
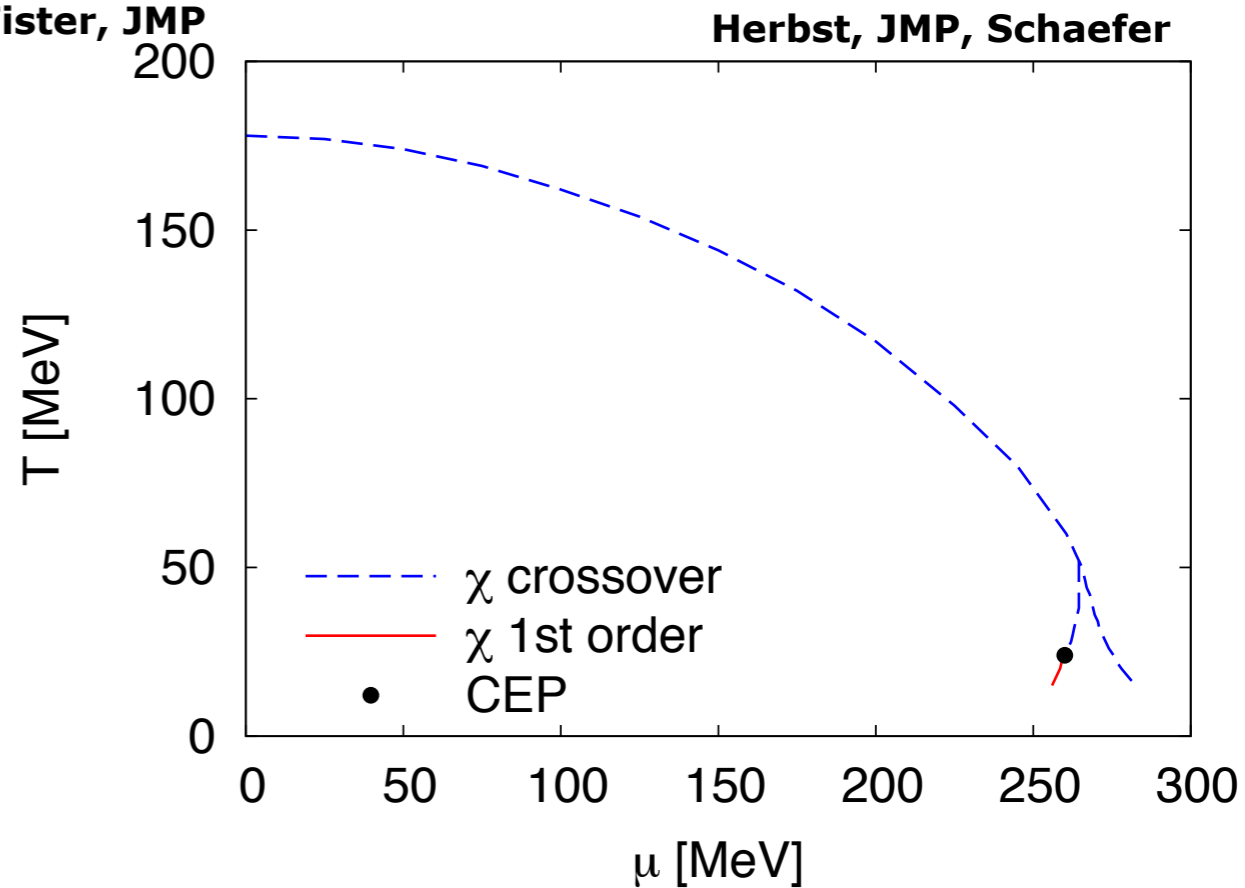
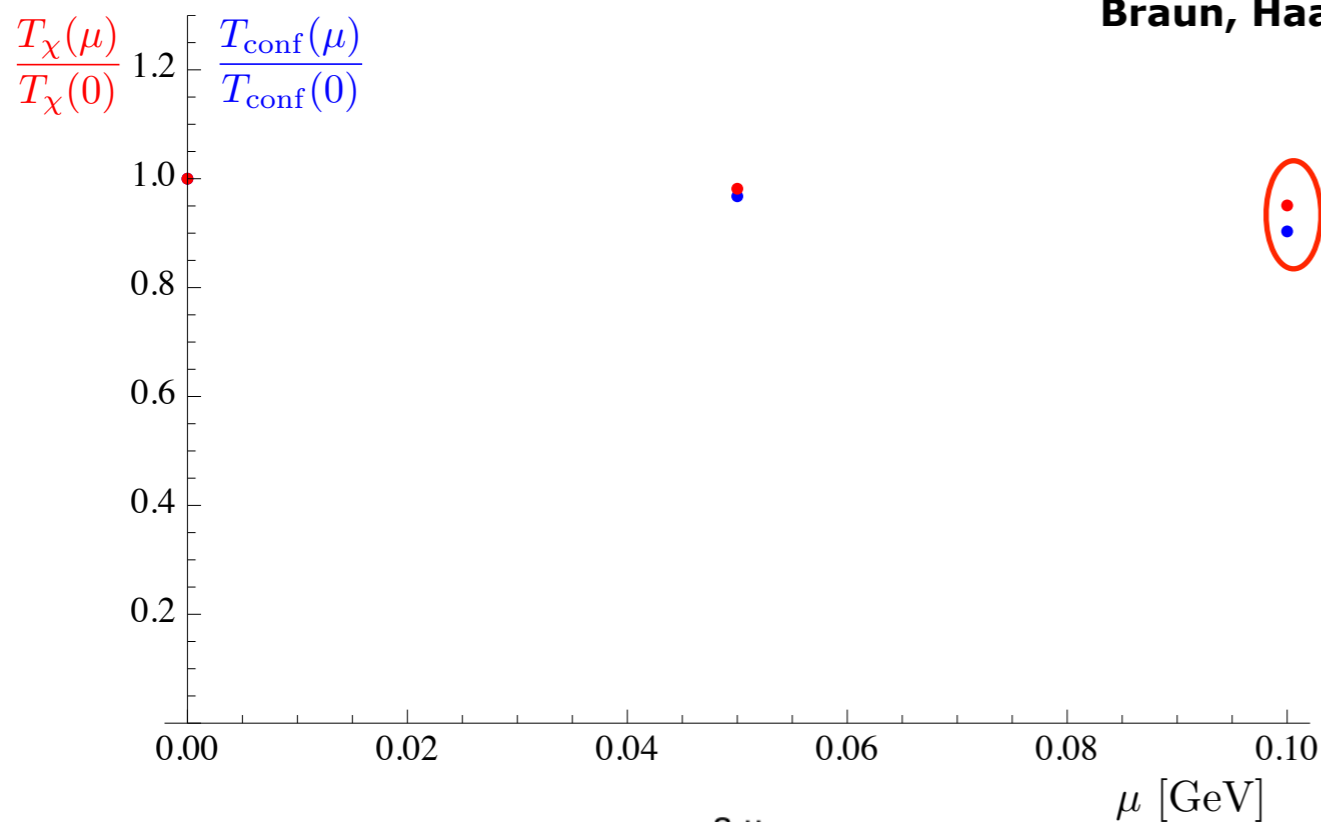


Braun, Haas, Fister, JMP



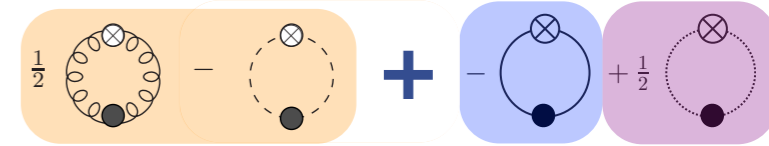
Real chemical potential

Full dynamical QCD

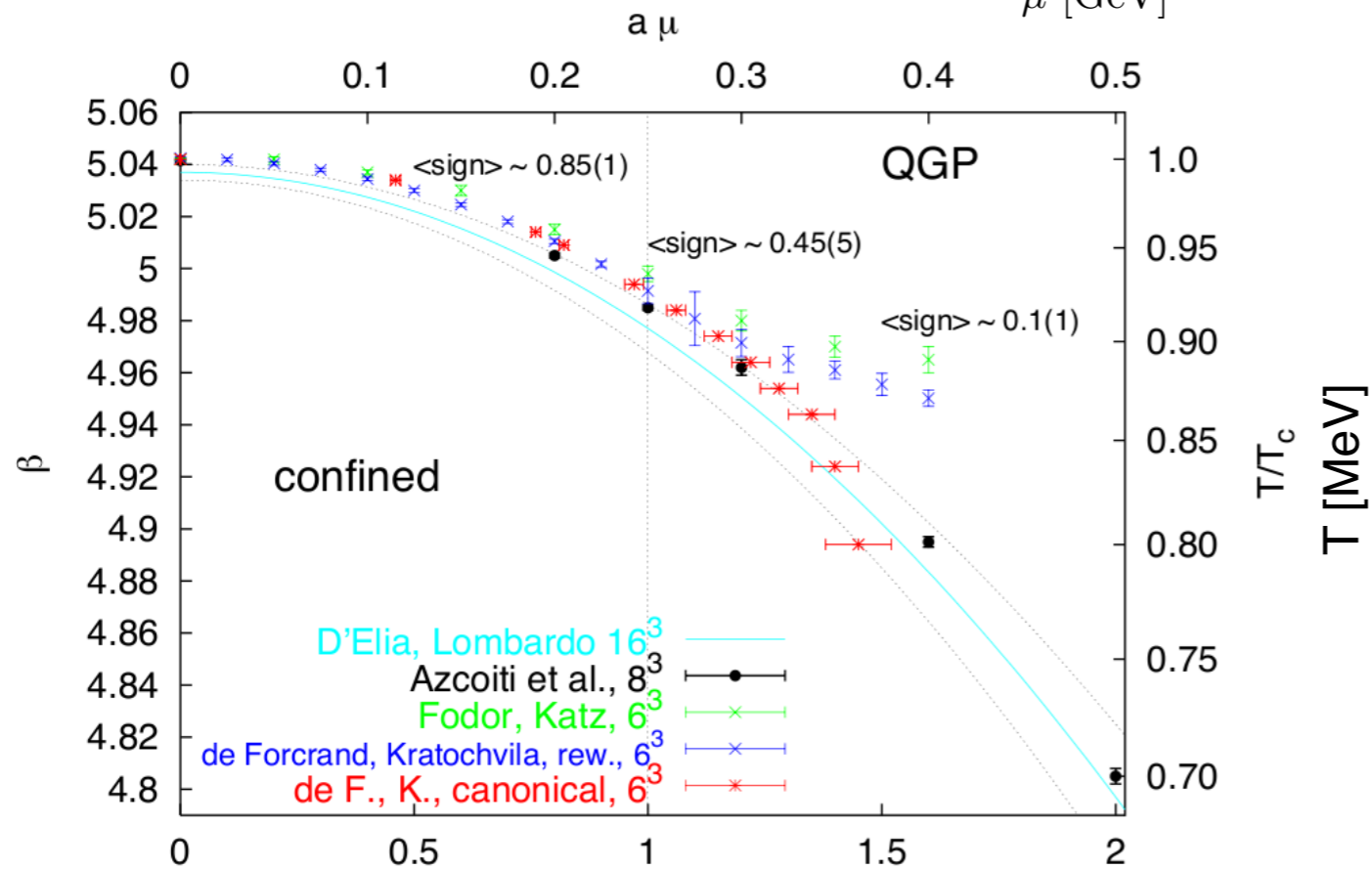
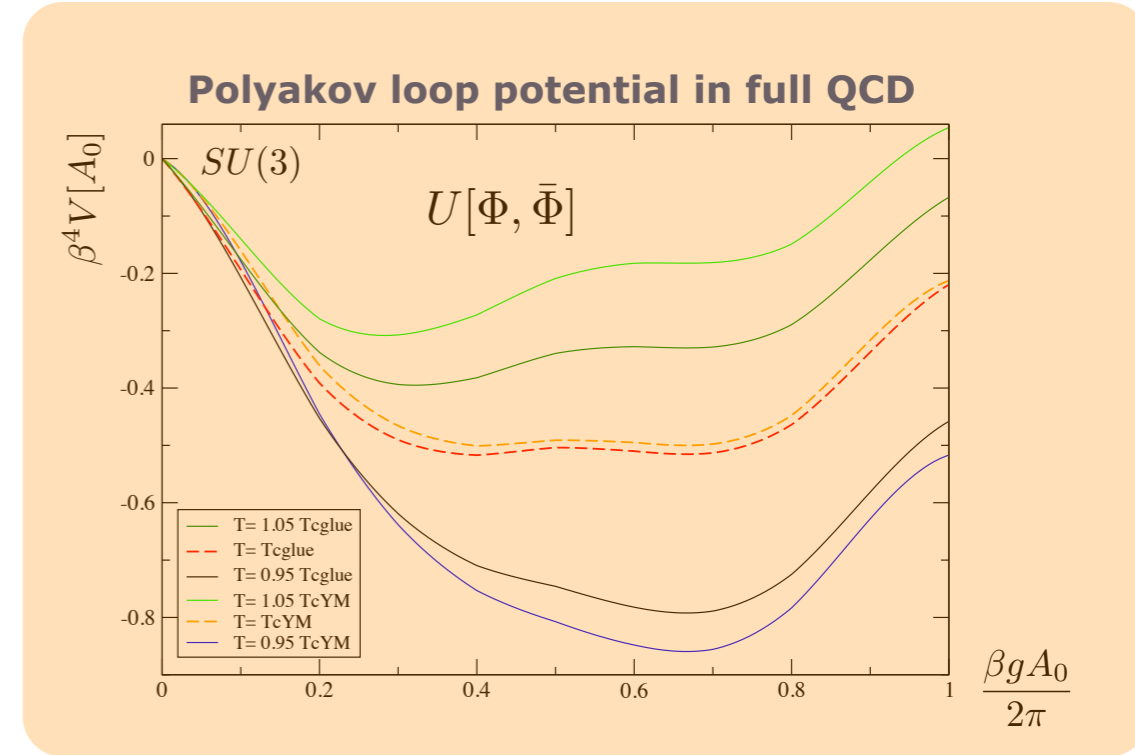
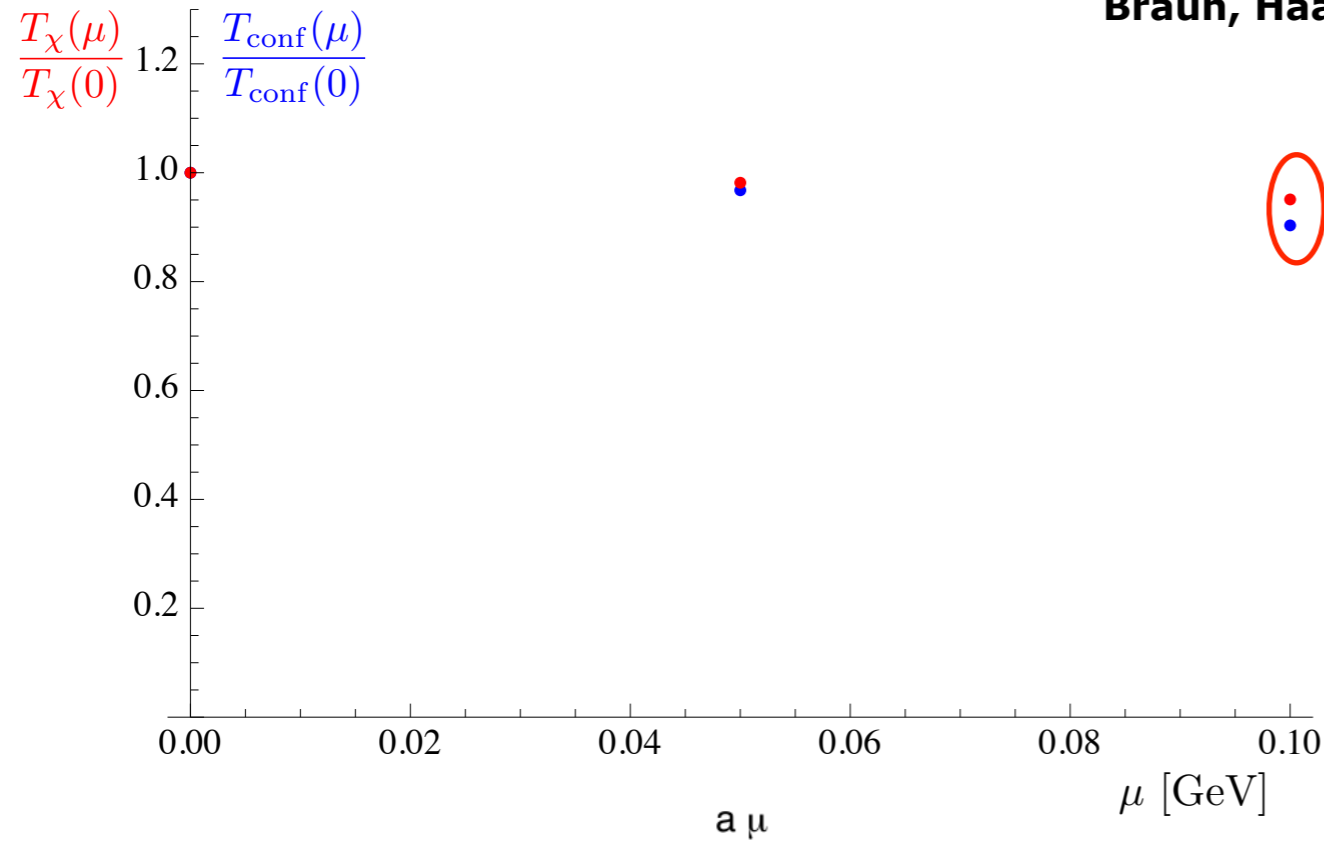


Real chemical potential

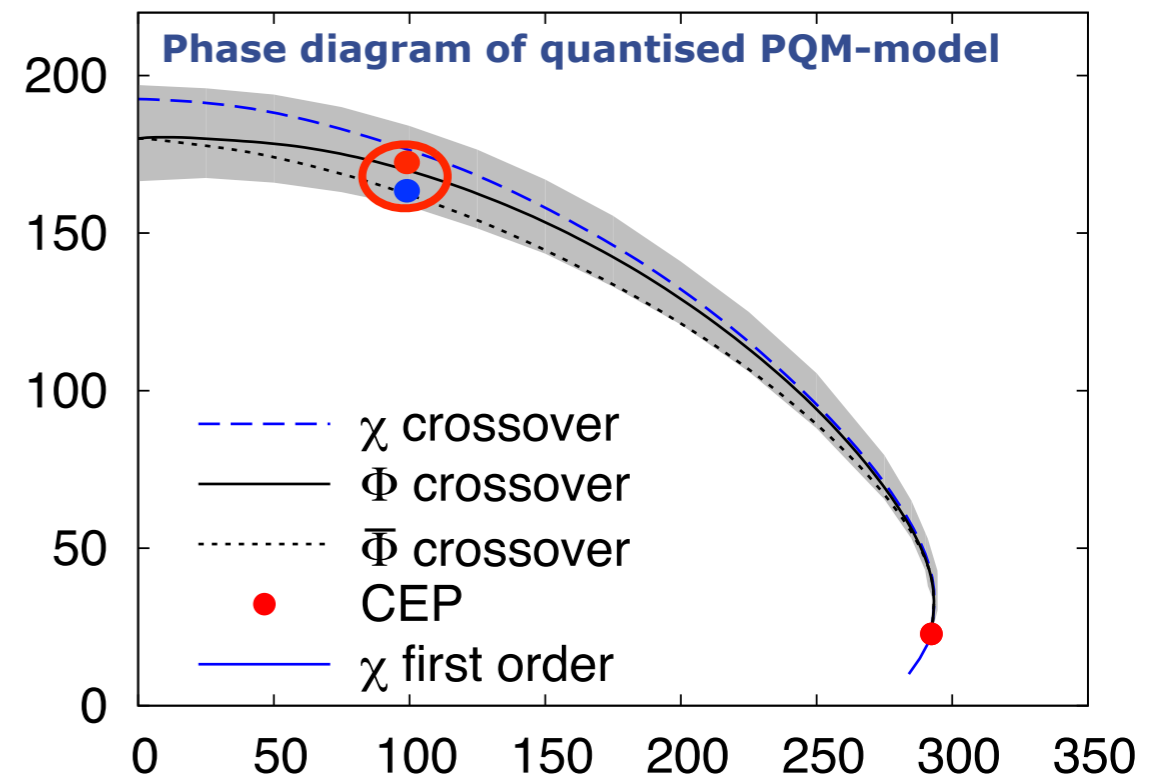
Full dynamical QCD



Braun, Haas, Fister, JMP

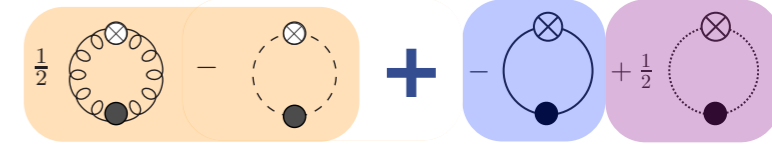


Herbst, JMP, Schaefer '10



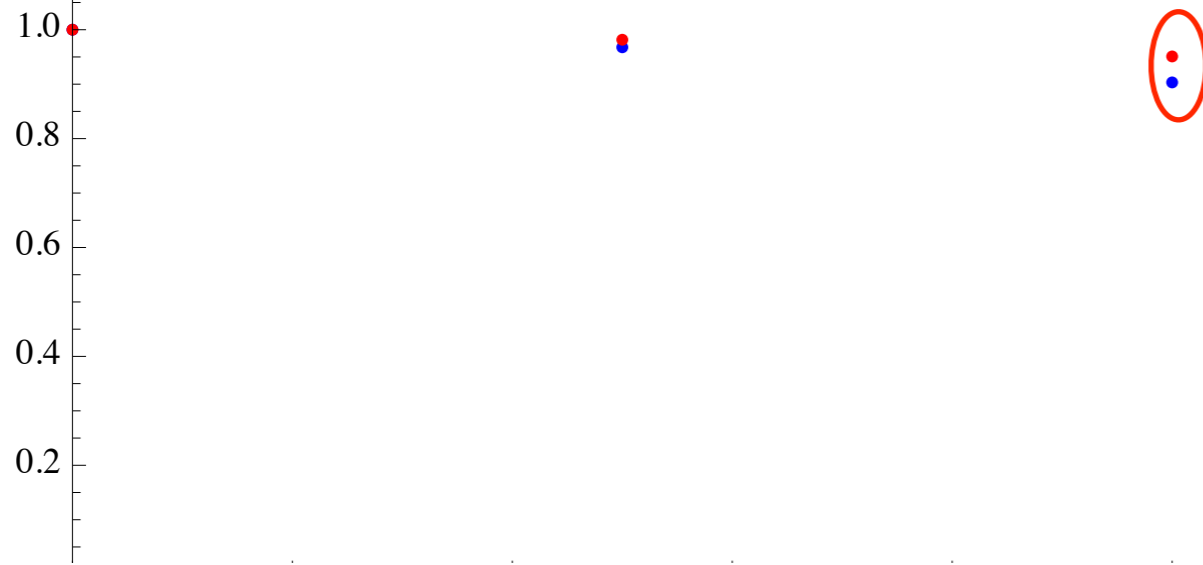
Real chemical potential

Full dynamical QCD

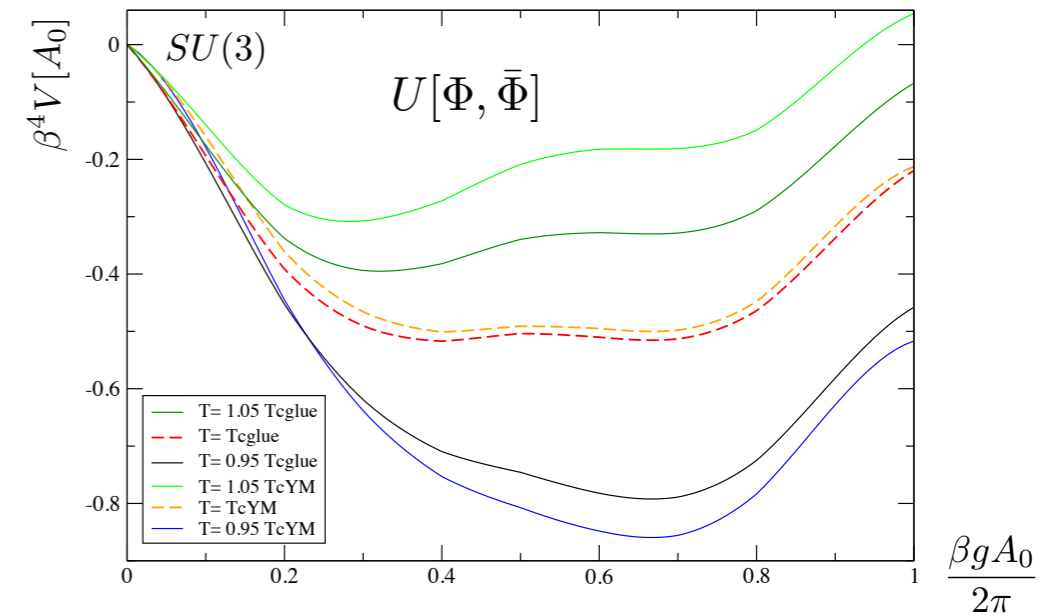


Braun, Haas, Fister, JMP

$$\frac{T_\chi(\mu)}{T_\chi(0)} = \frac{T_{\text{conf}}(\mu)}{T_{\text{conf}}(0)}$$

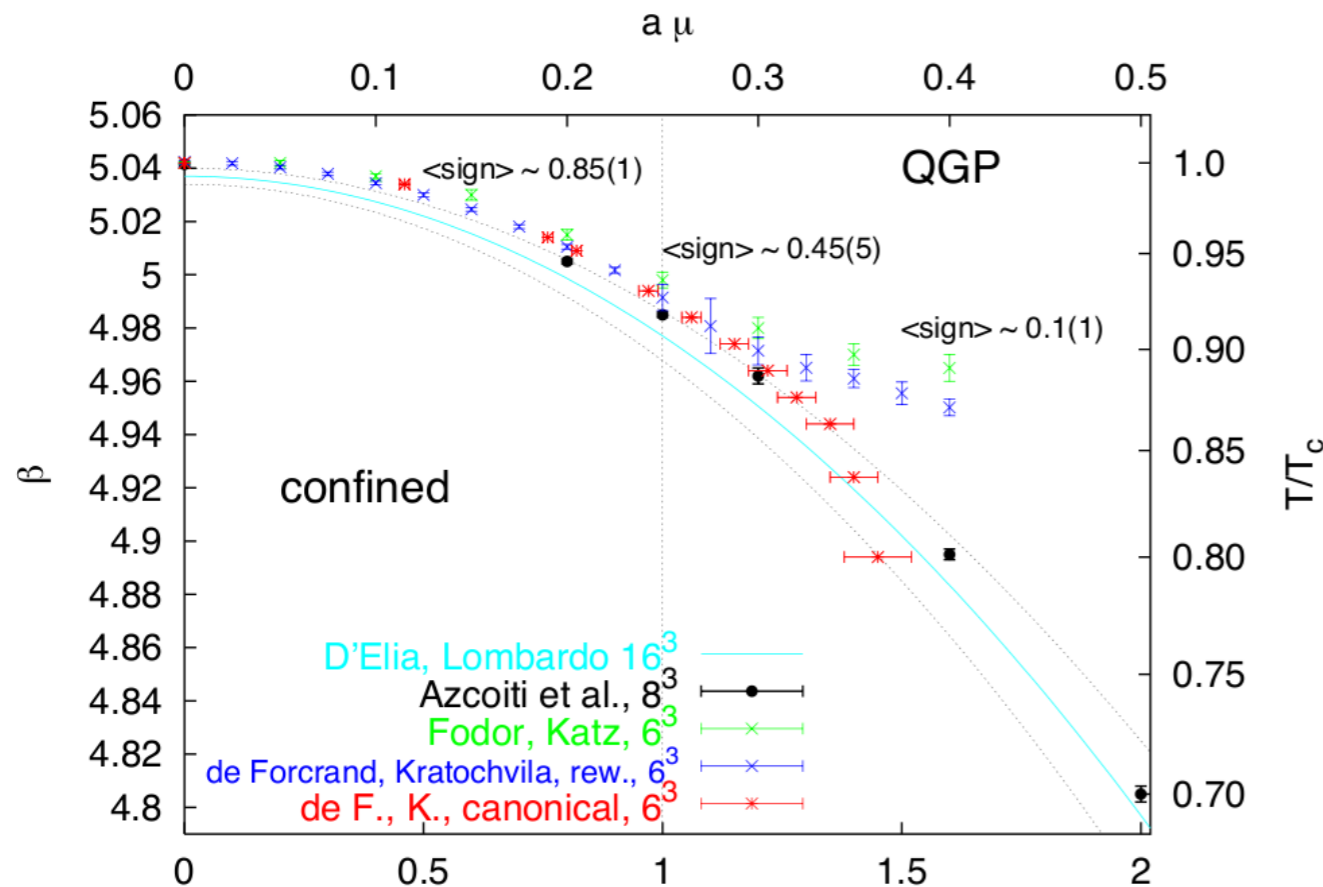


Polyakov loop potential in full QCD

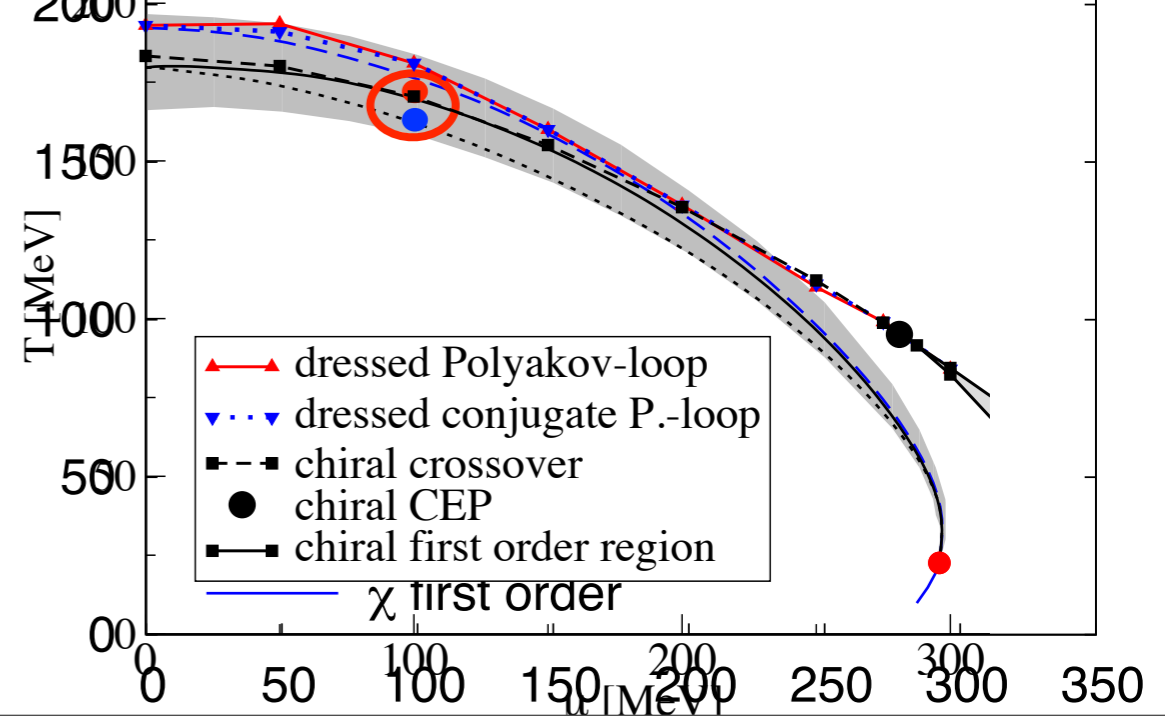


DSE: Fischer, Lueker, Mueller '11

Herbst, JMP, Schaefer '10



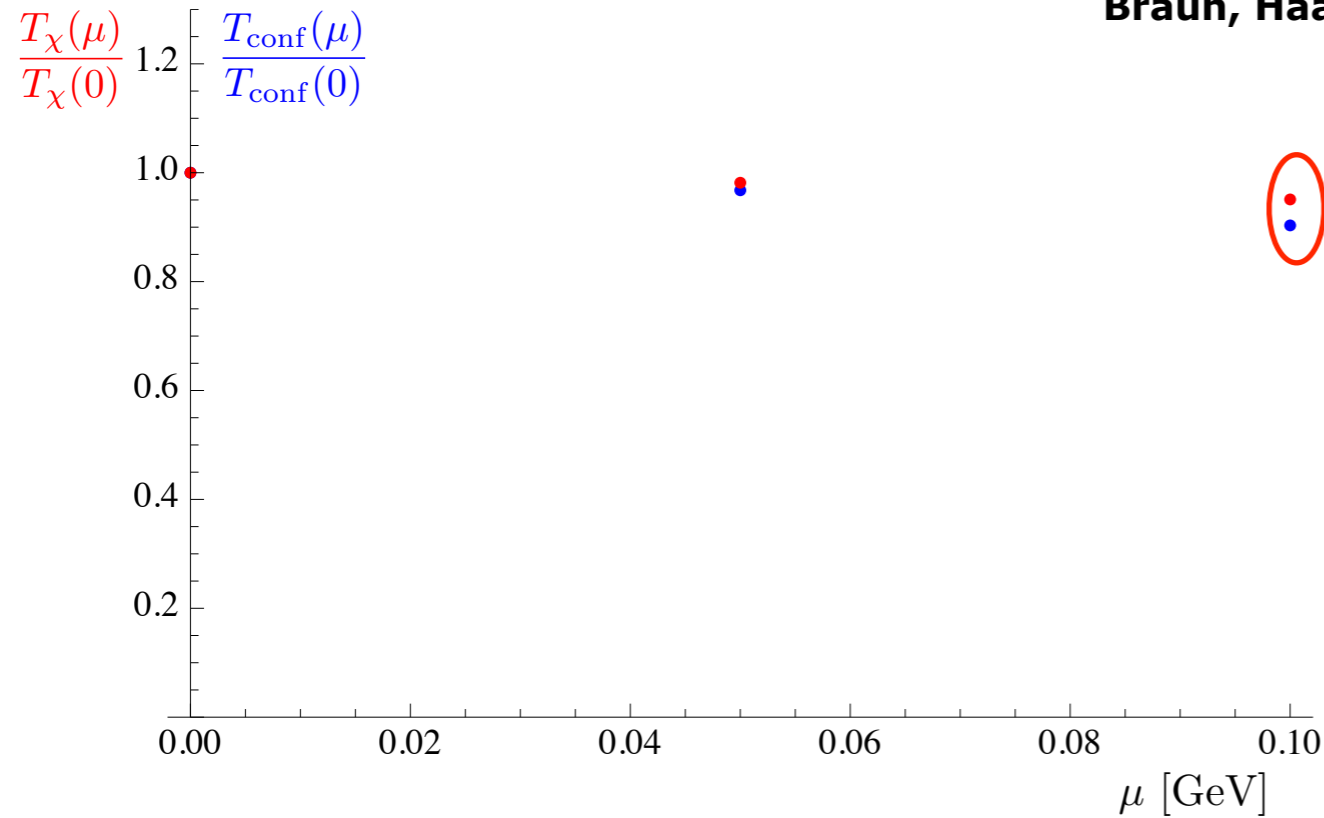
Phase diagram of quantised PQM-model



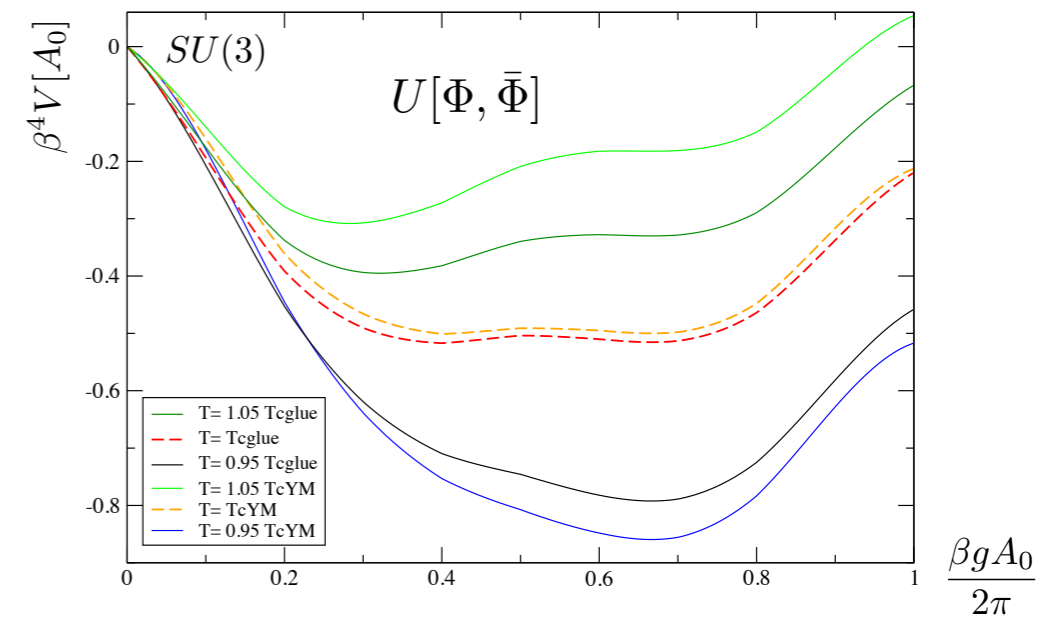
Real chemical potential

Full dynamical QCD

Braun, Haas, Fister, JMP



Polyakov loop potential in full QCD

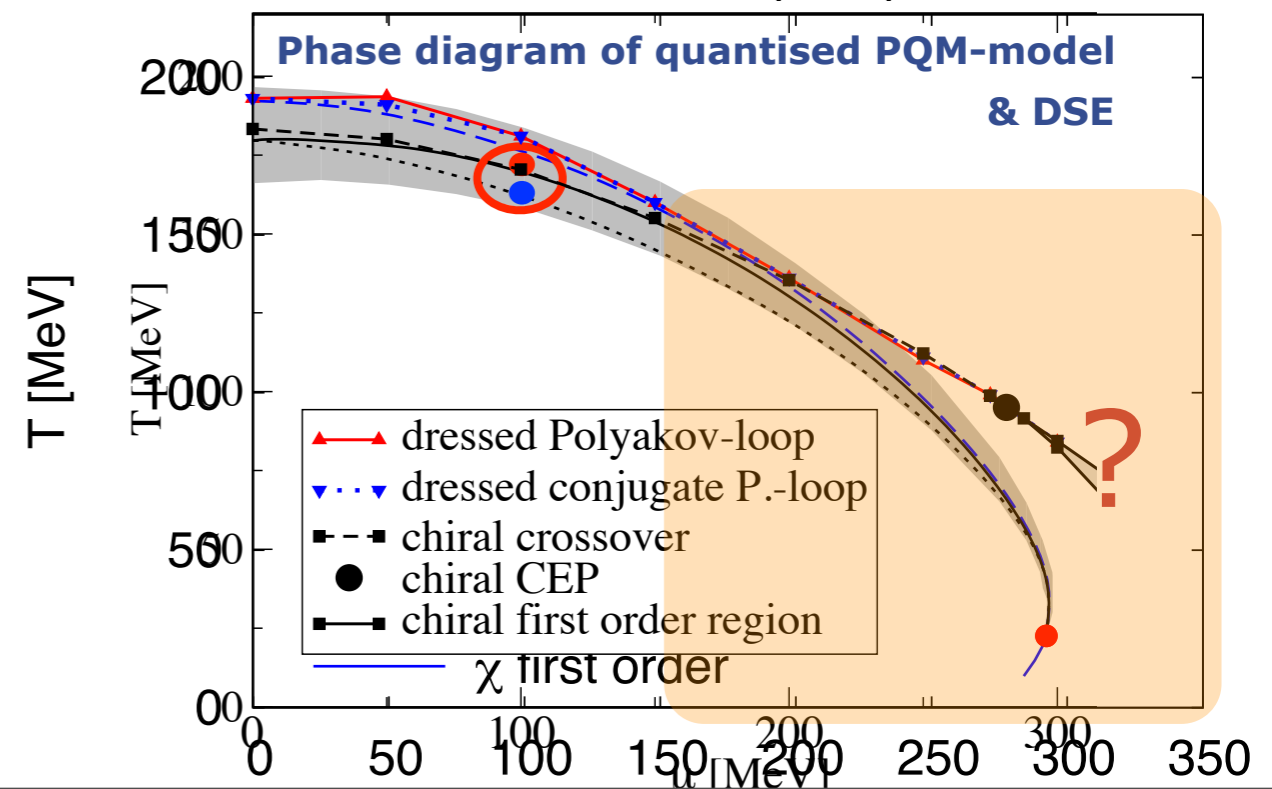


DSE: Fischer, Lücker, Mueller '11

Herbst, JMP, Schaefer '10

Critical point unlikely for

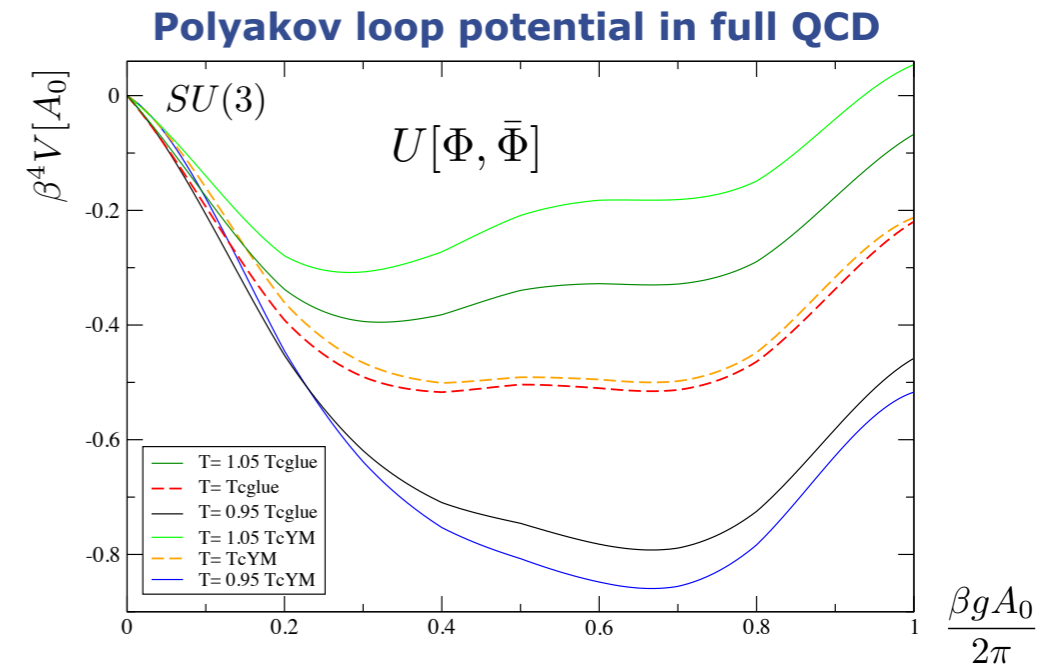
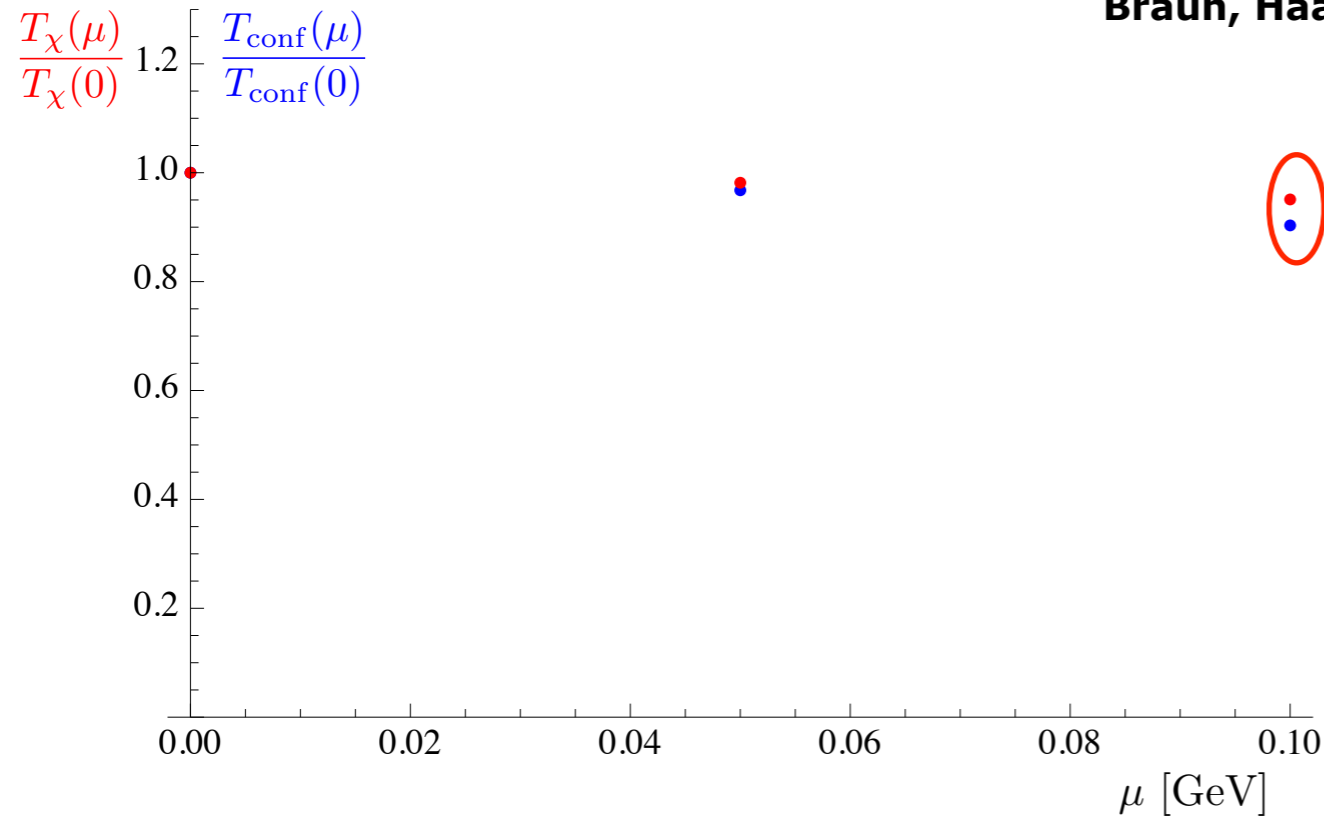
$$\frac{\mu_B}{T} < 2$$



Real chemical potential

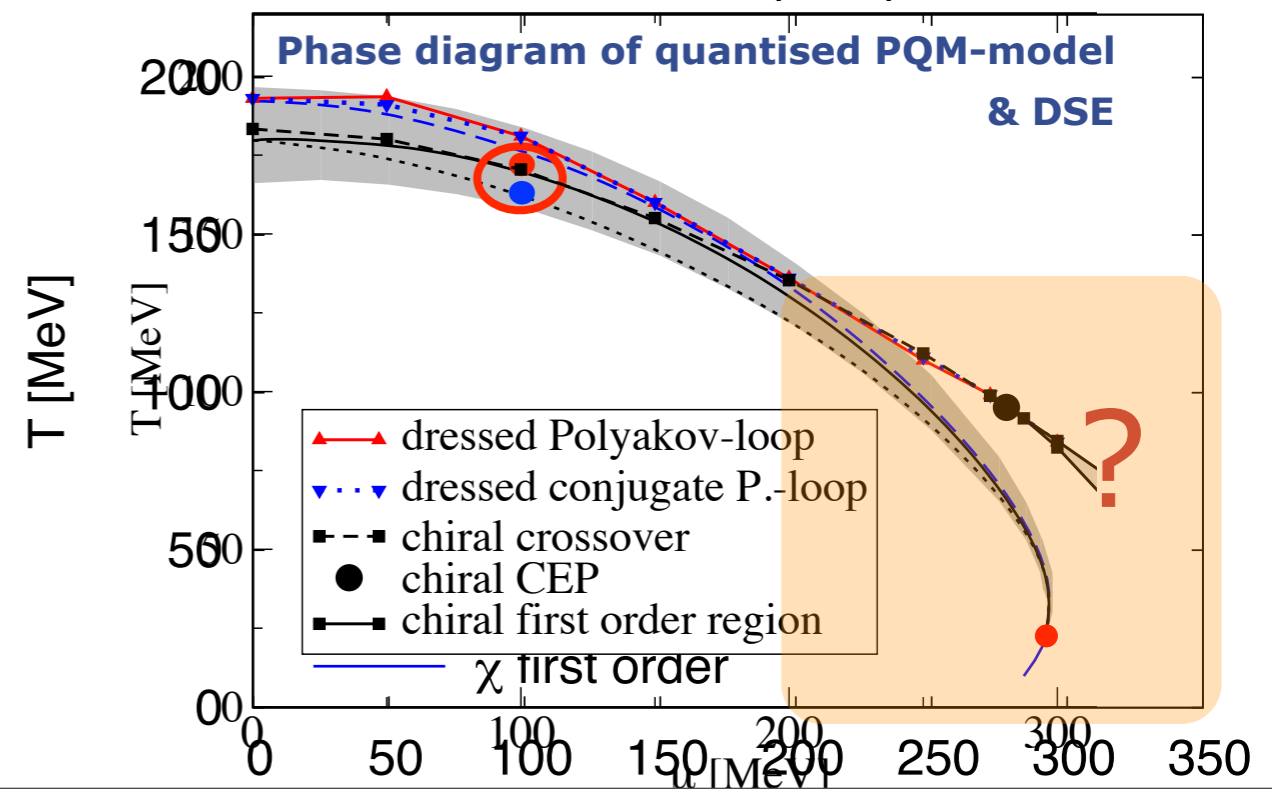
Full dynamical QCD

Braun, Haas, Fister, JMP



DSE: Fischer, Lücker, Mueller '11

Herbst, JMP, Schaefer '10



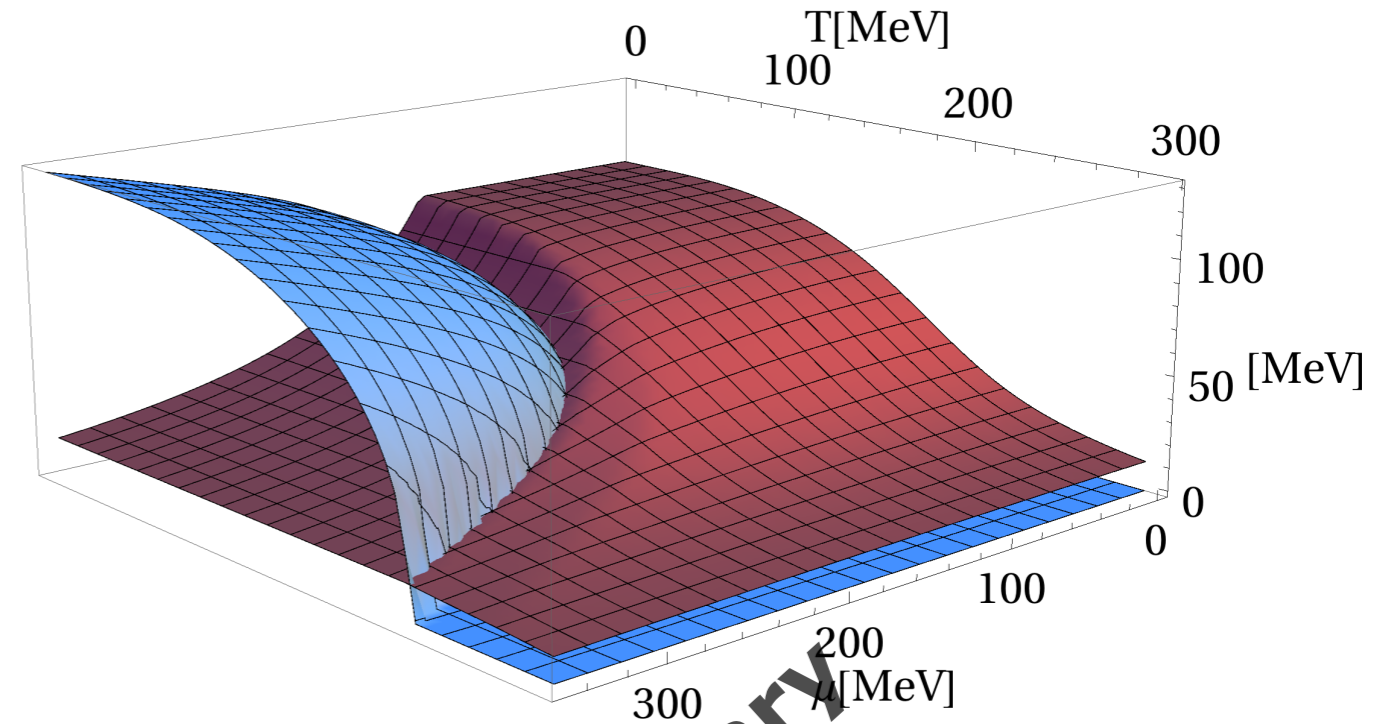
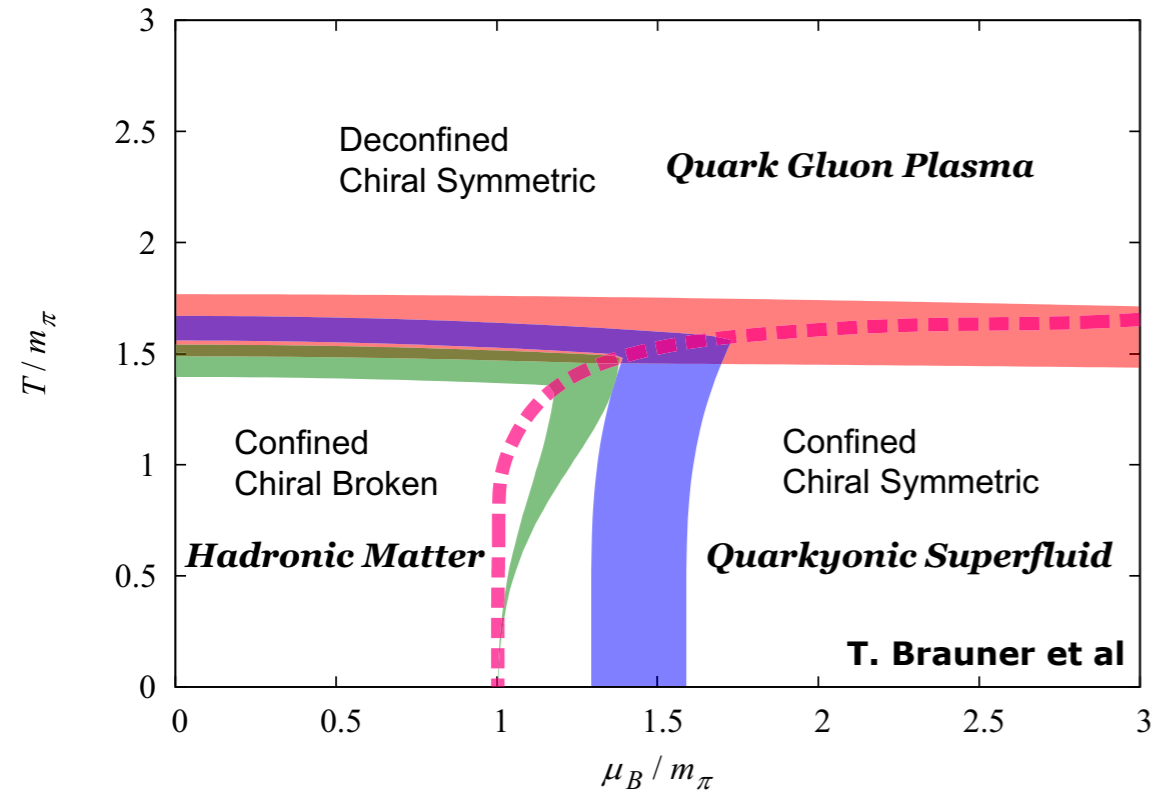
Critical point unlikely for

$$\frac{\mu_B}{T} < 4.5$$

Real chemical potential

a glimpse at baryons

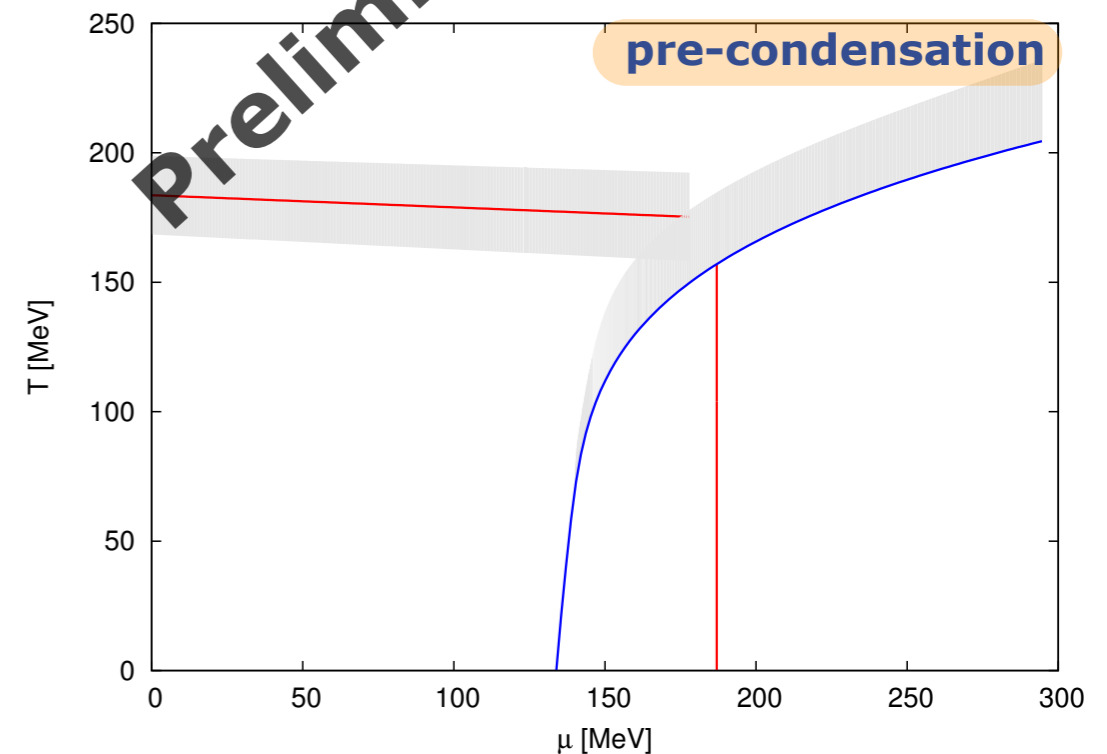
Haas, Khan, JMP, Rennecke, Scherer



two colour QCD

..., Ratti et al '04, ..., Brauner et al '08,

see talk of Lorenz von Smekal

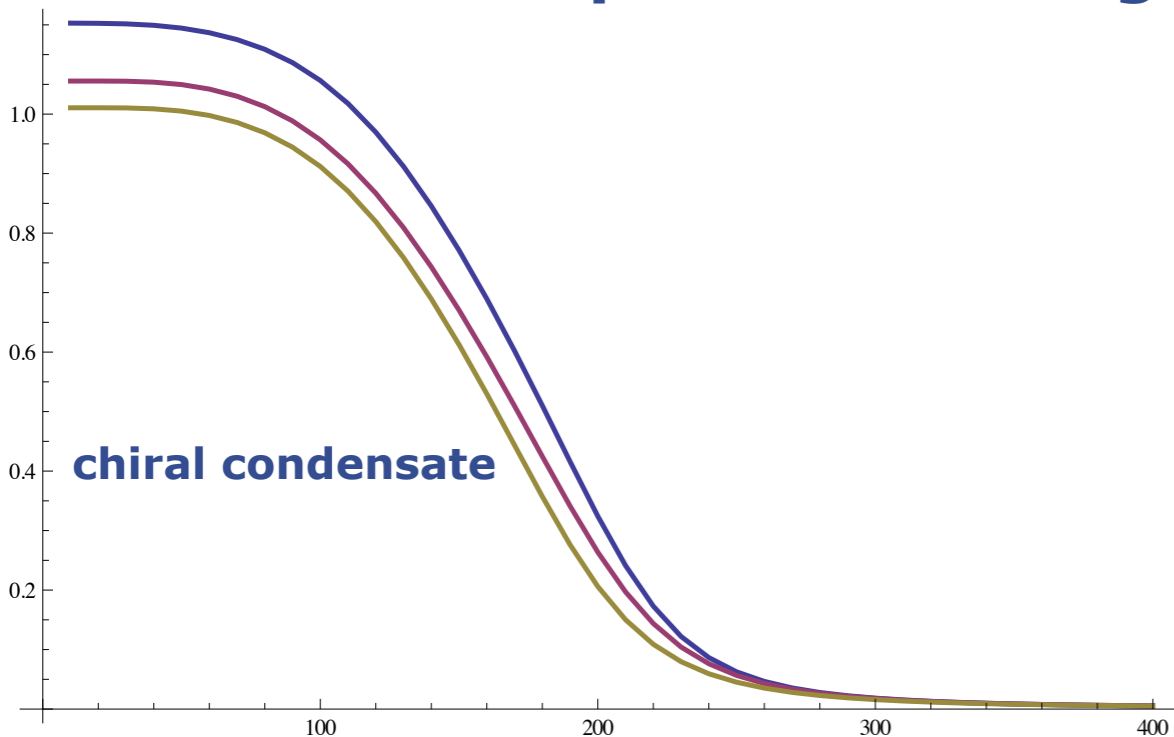


Real chemical potential

a glimpse at multi-scatterings

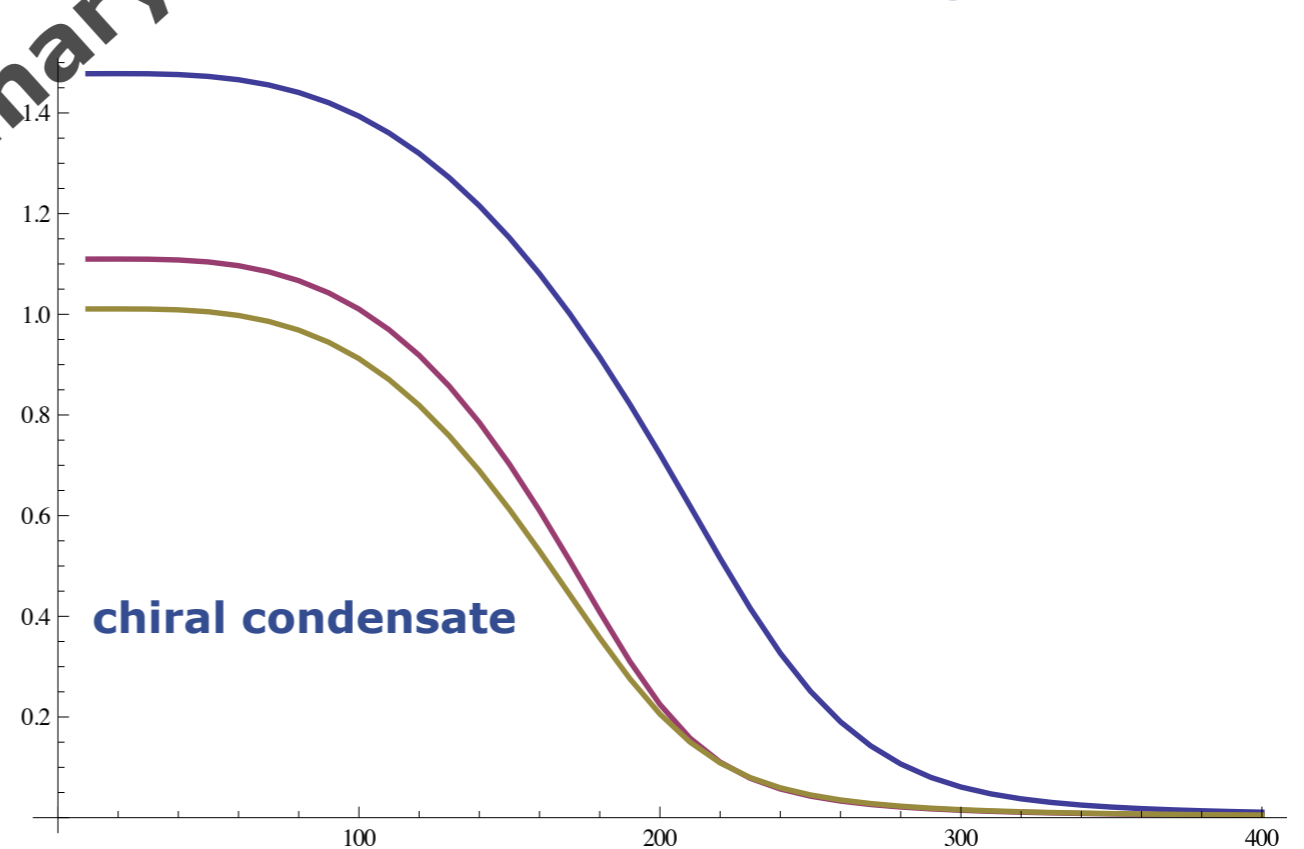
JMP, Rennecke

Multi-meson-quark scatterings



chiral condensate

Multi-meson scatterings



chiral condensate

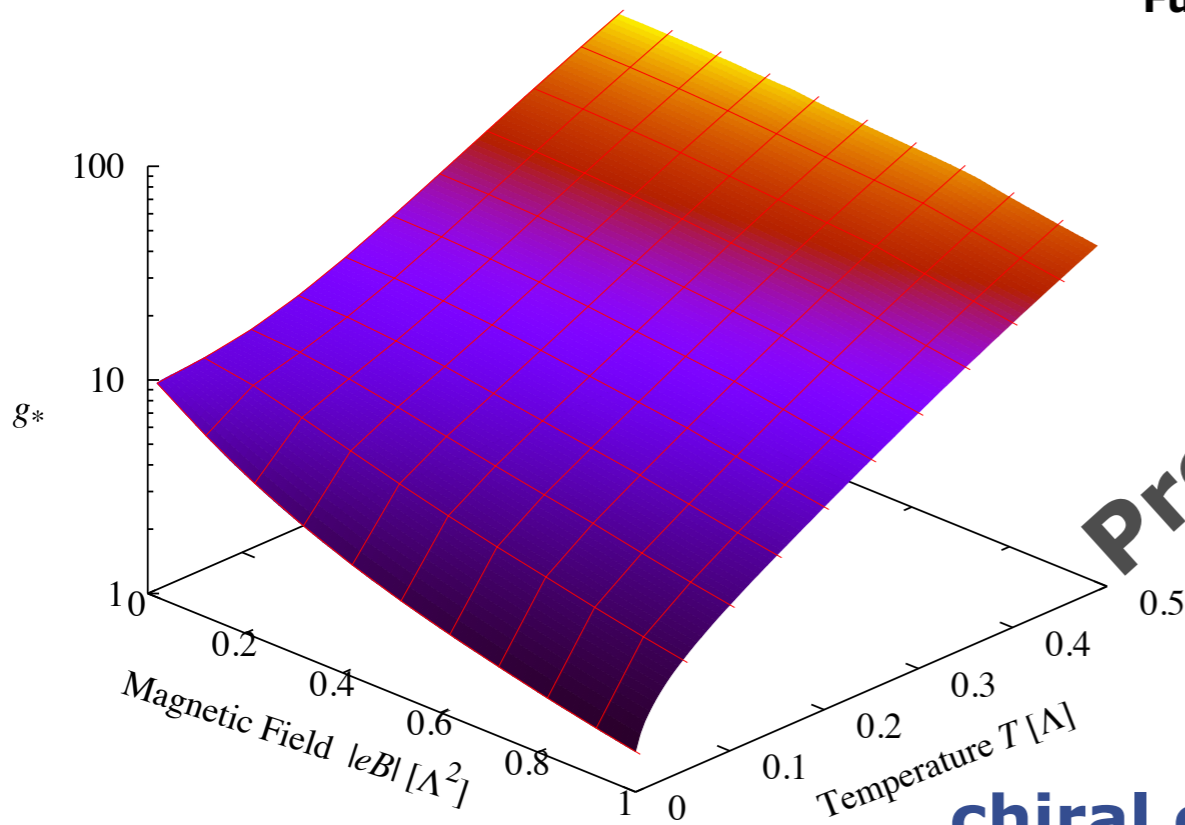
PQM model

Preliminary

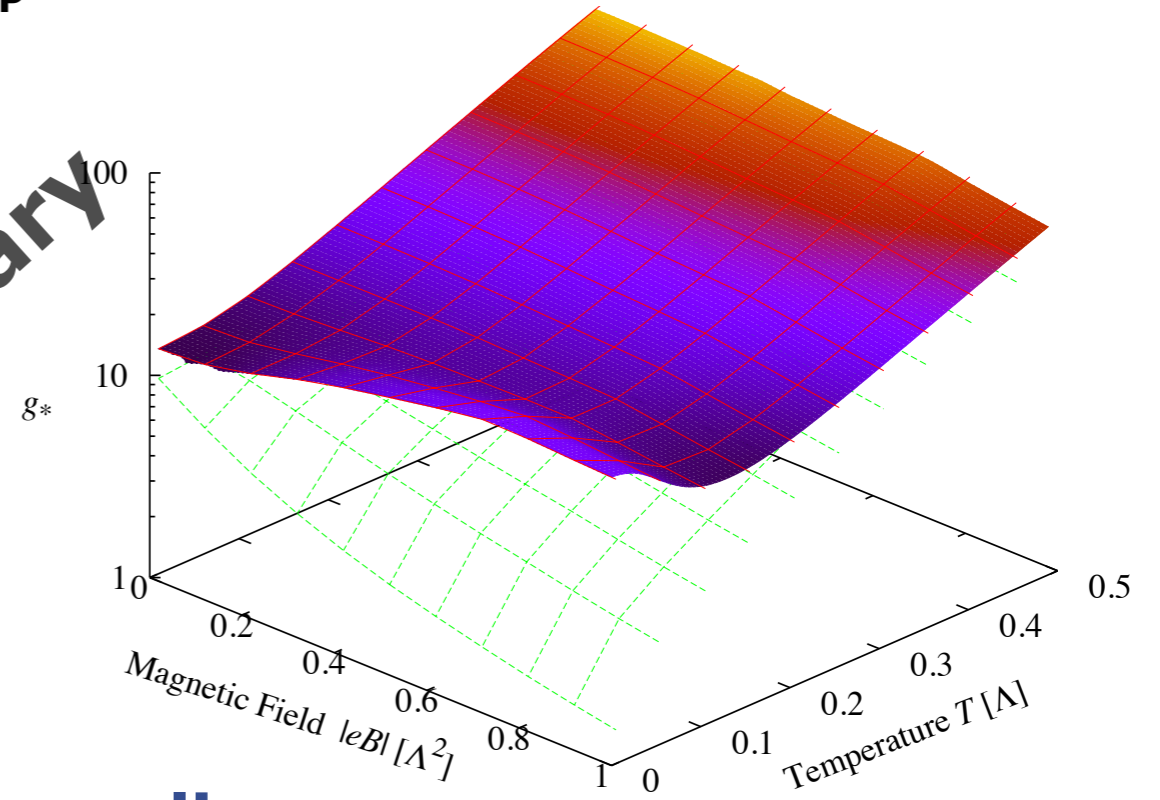
Real chemical potential

a glimpse at strong magnetic fields

Fukushima, JMP

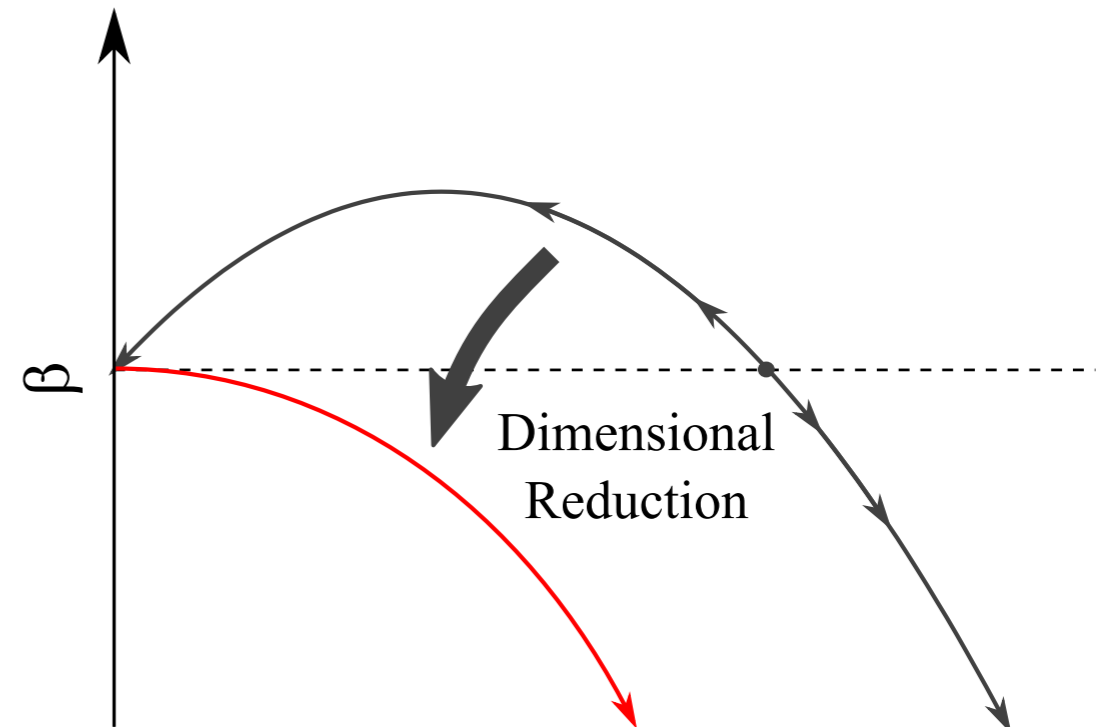


Preliminary



chiral critical coupling

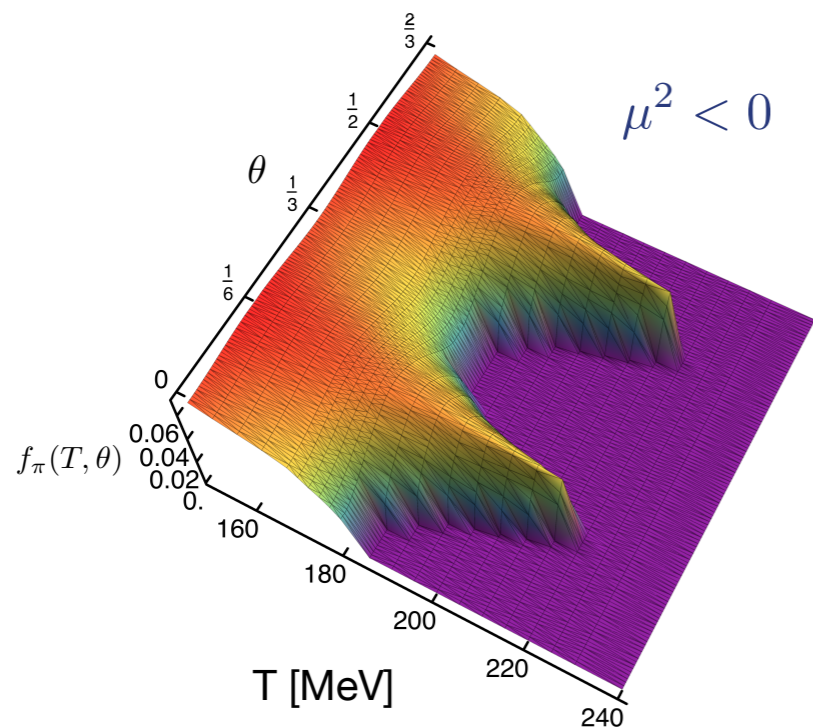
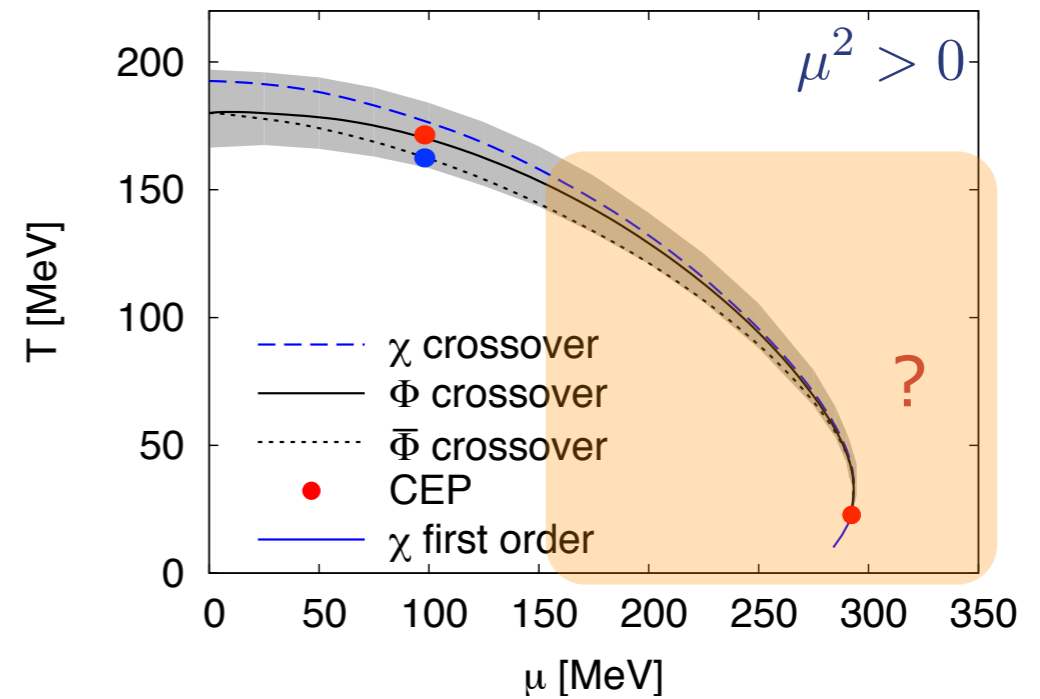
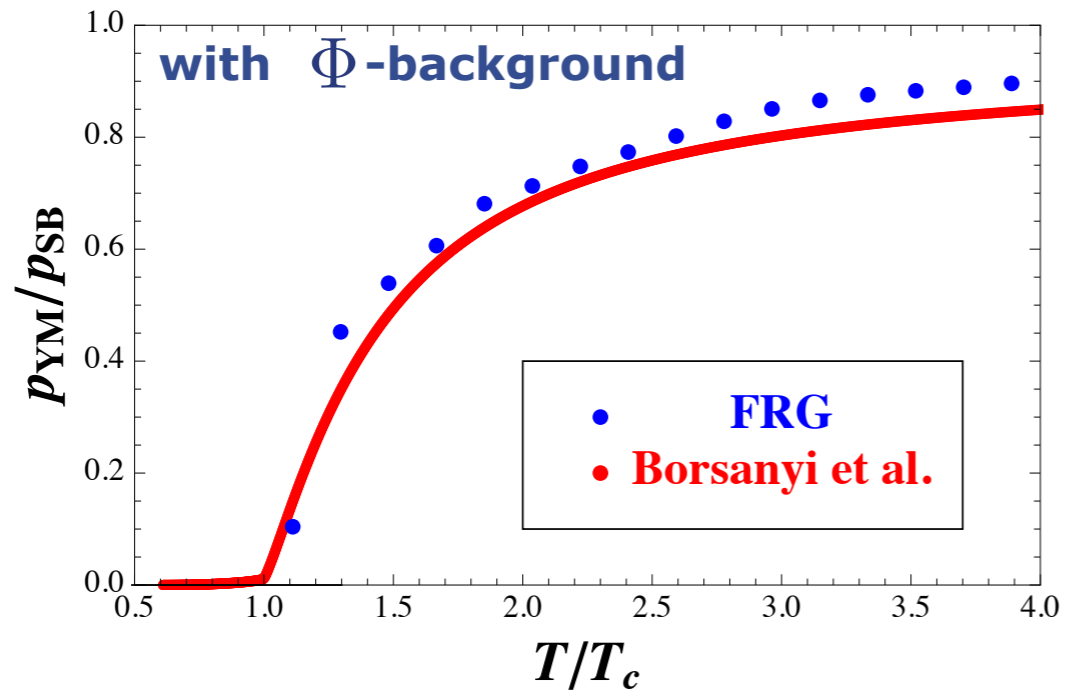
Matter sector



Summary & outlook

Phase diagram of QCD

Phase structure and thermodynamics at finite T & μ



Critical point unlikely for

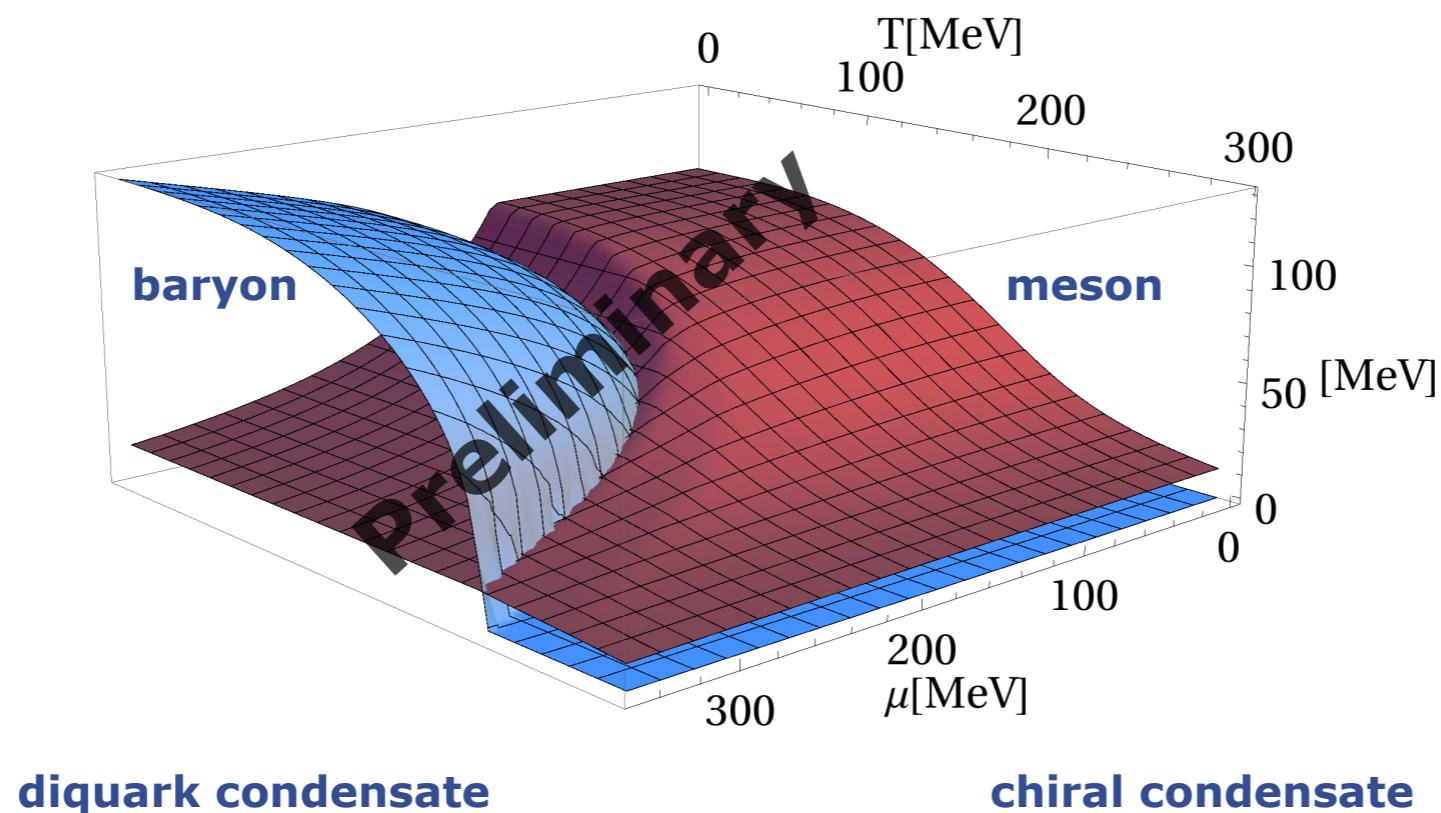
$$\frac{\mu_B}{T} < 2$$

Summary & outlook

▪ Phase diagram of QCD

- Phase structure and thermodynamics at finite T & μ
- 2+1 flavours, **baryons**, phenomenology, dynamics
- QCD meets cold quantum gases: two-colour QCD

Haas, Khan, JMP, Rennecke, Scherer



Summary & outlook

- **Phase diagram of QCD**

- **Phase structure and thermodynamics at finite T & μ**
- **2+1 flavours, baryons, phenomenology, dynamics**
- **QCD meets cold quantum gases: two-colour QCD**

EpisodeIII: QGP meets ultracold atoms (Hirscheegg August 25th -31st)

- **Hadronic properties**

- **dynamical hadronisation**
- **dynamics**