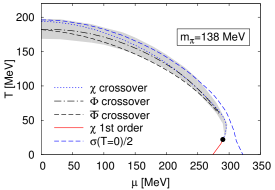
On the Phase Structure and Thermodynamics of QCD

Tina Katharina Herbst

In Collaboration with J. M. Pawlowski and B.-J. Schaefer

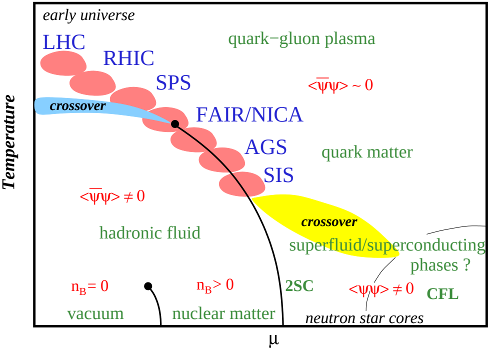


Delta Meeting 2013

Heidelberg, Germany

January 11th - 12th, 2013

Expected QCD Phase Structure & Open Questions:



[picture from Schaefer, Wagner (2008)]

- Chiral and Deconfinement Transitions:
  - ▷ Coincidence at $\mu > 0$?
  - ▷ Quarkyonic Phase ?
- Critical Endpoint:
  - ▷ Existence ?
  - ▷ Location ?
  - ▷ Properties ?
  - ▷ Additional CEPs ?
- Additional Phases ?
- Beyond Mean-Field Approximation: Impact of Fluctuations ?
- ...

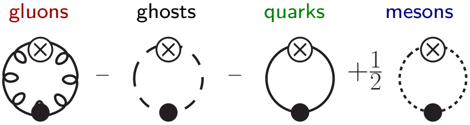
Talk Outline

From QCD to Polyakov-Loop Extended Chiral Models

FRG Flow for 2-Flavour QCD

Including **Fluctuations** by the Functional Renormalisation Group

$\partial_t \Gamma_k[A, C, \psi, \phi] = \frac{1}{2}$



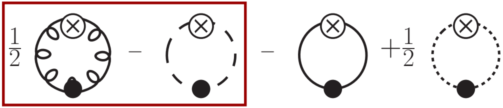
[Braun et al., (2011)]

FRG Flow for 2-Flavour QCD

Including **Fluctuations** by the Functional Renormalisation Group

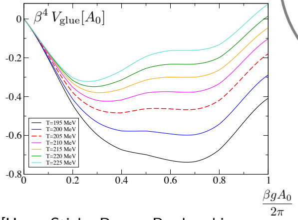
gluons ghosts quarks mesons

$$\partial_t \Gamma_k[A, C, \psi, \phi] = \frac{1}{2}\ \ldots\ -\ \ldots\ -\ \ldots\ +\frac{1}{2}\ \ldots$$



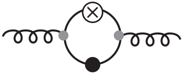
[Braun et al., (2011)]

QCD Glue Potential



[Haas, Stiele, Braun, Pawlowski, Schaffner-Bielich in prep.]

fully coupled system !

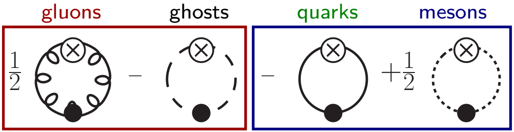


A Low-Energy Effective Description

Integrate out gluon degrees of freedom

more

$\partial_t \Gamma_k[A, C, \psi, \phi] =$



Glue Potential
$\mathcal{U}_{\mathrm{glue}}(\Phi, \bar{\Phi}; T_0)$

Quark-Meson Model
coupled to Φ

Polyakov–Quark-Meson Model

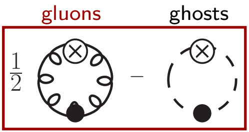
$$\mathcal{L}_{\mathrm{PQM}} = \bar{q}\left[\not{D}(\Phi) + h(\sigma + i\gamma_5\vec{\tau}\vec{\pi}) + \mu\gamma_0\right] q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + U(\sigma, \vec{\pi}) + \mathcal{U}(\Phi, \bar{\Phi}; T_0)$$

A Low-Energy Effective Description

Usually: Polyakov-loop potential fitted to Yang-Mills lattice data

[e.g. Ratti, Thaler, Weise (2006)]

$\partial_t \Gamma_k[A, C] =$



Polyakov-Loop Potential

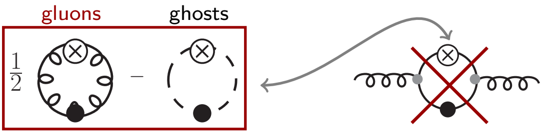
$\mathcal{U}_{\mathrm{YM}}(\Phi, \bar{\Phi}; T_0)$

A Low-Energy Effective Description

Usually: Polyakov-loop potential fitted to Yang-Mills lattice data

[e.g. Ratti, Thaler, Weise (2006)]

$$\partial_t \Gamma_k[A, C] =$$



Polyakov-Loop Potential

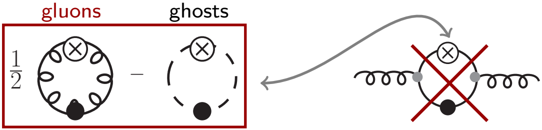
$\mathcal{U}_{\mathrm{YM}}(\Phi, \bar{\Phi}; T_0)$

A Low-Energy Effective Description

Usually: Polyakov-loop potential fitted to Yang-Mills lattice data

[e.g. Ratti, Thaler, Weise (2006)]

$\partial_t \Gamma_k[A, C] =$



Polyakov-Loop Potential

$\mathcal{U}_{\mathrm{YM}}(\Phi, \bar{\Phi}; T_0)$

Include the Matter Backreaction

account for the Silver-Blaze Property

$$T_0(N_f, T, \mu) = T_\tau e^{-\frac{1}{\alpha_0 b(N_f, T, \mu)}}$$

$$b(N_f, T, \mu) = \frac{11N_c - 2N_f}{6\pi} - b_\mu \frac{\mu^2}{(\hat{\gamma} T_\tau)^2} \Theta_T(\mu - m_q)$$

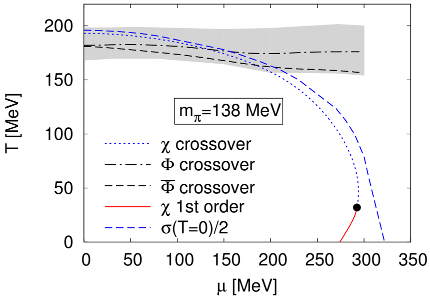
▸ more

Mass Sensitivity of the Phase Structure

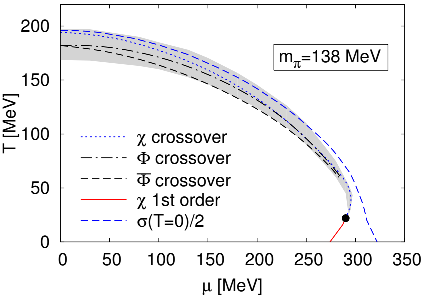
Physical Masses $m_\pi = 138$ MeV

[TKH, Pawlowski, Schaefer, (2010, 2012)]

w/o $T_0(\mu)$



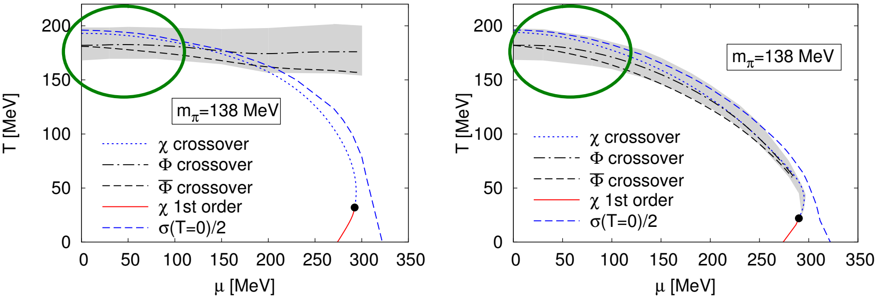
incl. $T_0(\mu)$



Physical Masses $m_\pi = 138$ MeV

[TKH, Pawlowski, Schaefer, (2010, 2012)]

w/o $T_0(\mu)$ | **incl.** $T_0(\mu)$

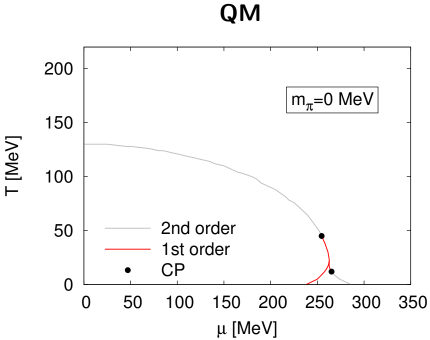


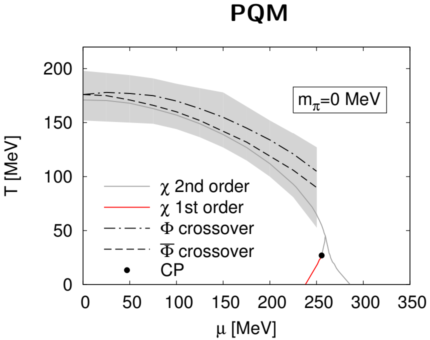
Curvature: $\kappa = -0.1434(39)$ $\qquad$ $\kappa = -0.2889(47)$

- ▷ 2-flavour DSE: $\kappa = -0.23$ (HTL) [Fischer, Luecker, (2012)]
  $\kappa = -0.37$ (w/o HTL)
- ▷ (2+1)-flavour lattice: $\kappa = -0.059(2)(4)$ [Kaczmarek et al., (2011)]

Chiral Limit $m_\pi = 0$ MeV

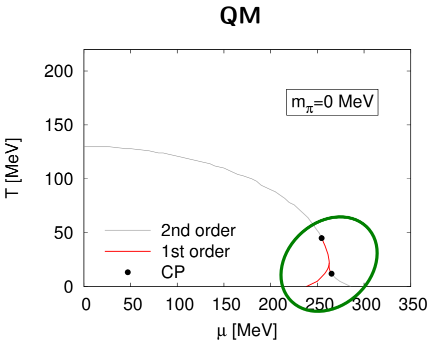
[TKH, Pawlowski, Schaefer in prep.]

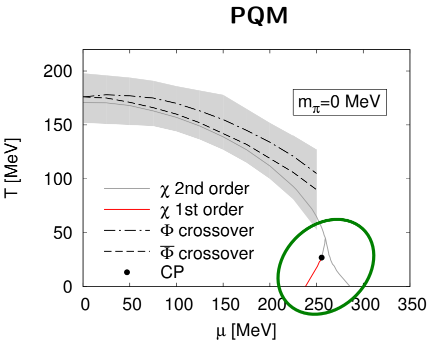




Chiral Limit $m_\pi = 0$ MeV

[TKH, Pawlowski, Schaefer in prep.]

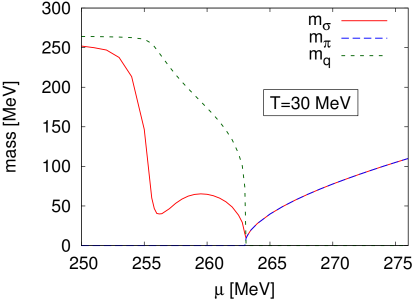


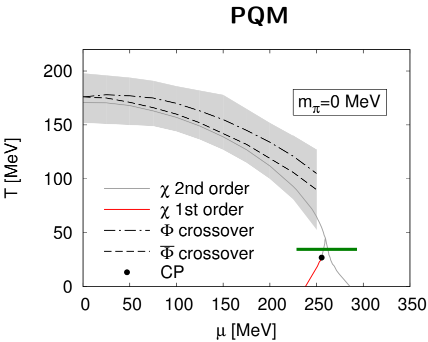


- 2 CEPs in QM, only 1 in PQM
- Splitting in the chiral transition line

Chiral Limit $m_\pi = 0$ MeV

[TKH, Pawlowski, Schaefer in prep.]



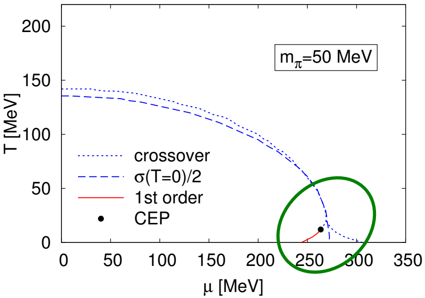


- 2 CEPs in QM, only 1 in PQM
- Splitting in the chiral transition line
- Splitting also seen in sigma-meson mass

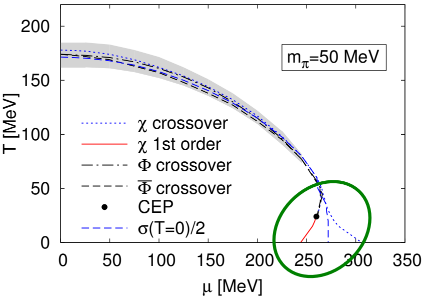
Small Masses $m_\pi = 50$ MeV

[TKH, Pawlowski, Schaefer in prep.]

QM



PQM

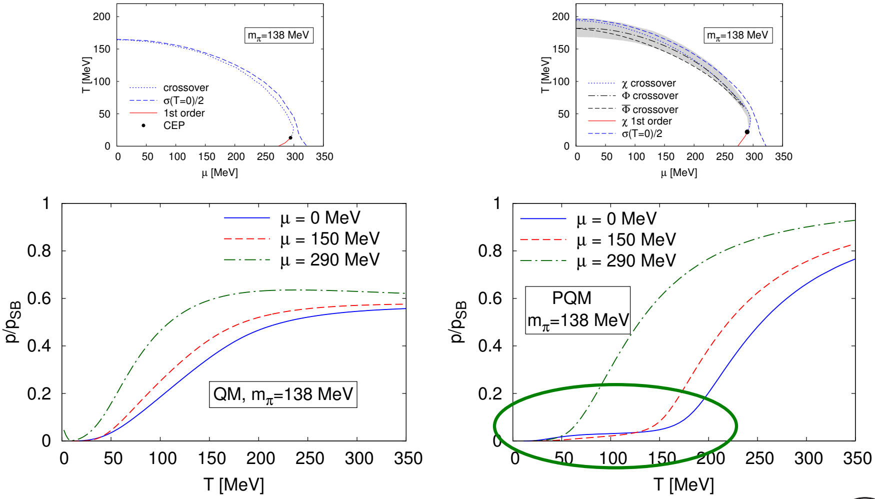


- Splitting persists
- only 1 CEP in QM & PQM
- outer transition branch weakened with increasing m_π

Thermodynamics

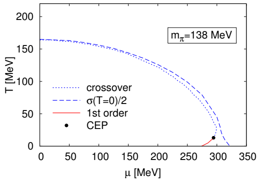
Pressure at the Physical Mass Point

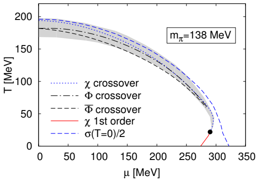
[TKH, Pawlowski, Schaefer in prep.]

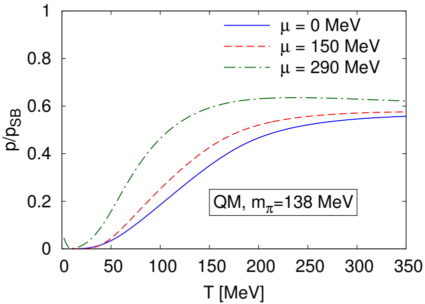


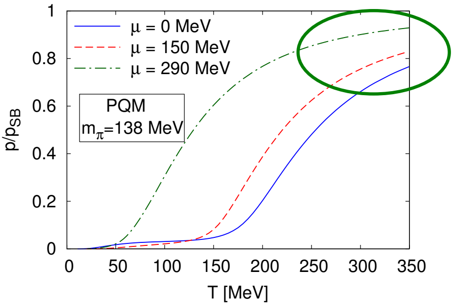
Pressure at the Physical Mass Point

[TKH, Pawlowski, Schaefer in prep.]





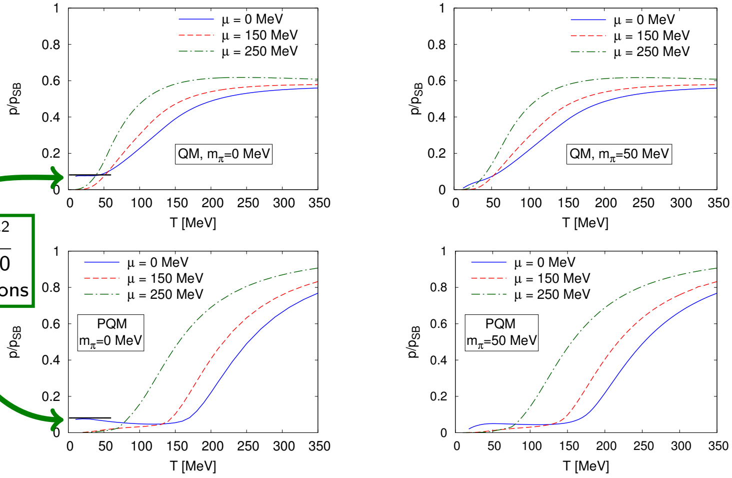




Pressure at Smaller Masses

[TKH, Pawlowski, Schaefer in prep.]

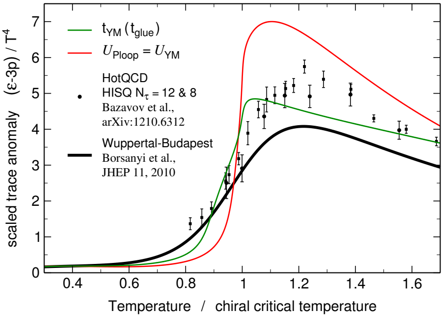
$m_\pi = 0$ **MeV** $\qquad m_\pi = 50$ **MeV**



$$\frac{p}{T^4} = 3\frac{\pi^2}{90}$$

massless pions

Interaction Measure at $\mu = 0$



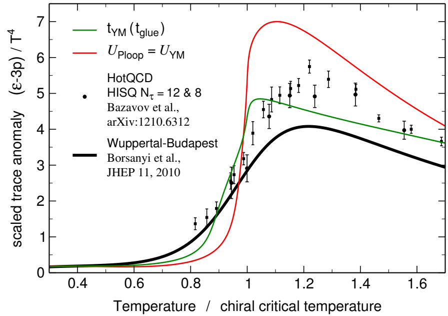
solid coloured lines:
(2+1)-flavour PQM in MFA

[Haas, Stiele, Braun, Pawlowski, Schaffner-Bielich in prep.]

red: standard Polyakov-loop potential $\mathcal{U}_{\mathrm{YM}}$

green: augmented Polyakov-loop potential using QCD input:

Interaction Measure at $\mu = 0$

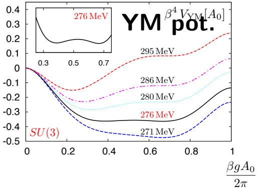


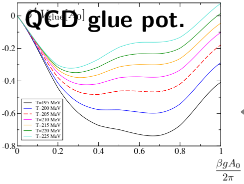
solid coloured lines:
(2+1)-flavour PQM in MFA
[Haas, Stiele, Braun, Pawlowski, Schaffner-Bielich in prep.]

red: standard Polyakov-loop potential $\mathcal{U}_{\rm YM}$

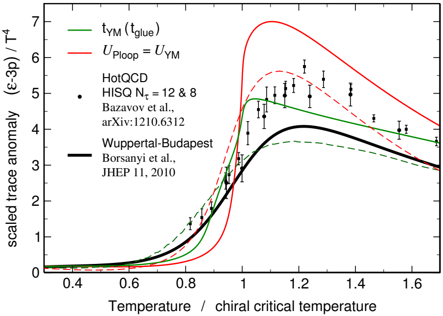
green: augmented Polyakov-loop potential using QCD input:

$$\mathcal{U}_{\rm glue}(T) = \mathcal{U}_{\rm YM}(T_{\rm YM}(T))$$





Interaction Measure at $\mu = 0$



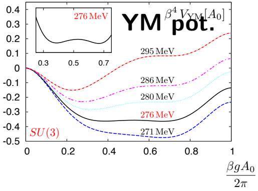
solid coloured lines:
(2+1)-flavour PQM in MFA
[Haas, Stiele, Braun, Pawlowski, Schaffner-Bielich in prep.]

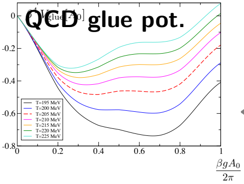
dashed lines: 2-flavour PQM with FRG [(2+1)-flavour: work in progress]
[TKH, Stiele, Pawlowski, Schaefer in prep.]

red: standard Polyakov-loop potential $\mathcal{U}_{\mathrm{YM}}$

green: augmented Polyakov-loop potential using QCD input:

$$\mathcal{U}_{\mathrm{glue}}(T) = \mathcal{U}_{\mathrm{YM}}(T_{\mathrm{YM}}(T))$$





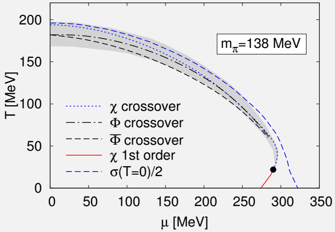
Summary & Outlook

QCD Phase Structure and TD via 2-flavour PQM truncation

- Important Feature: Matter Backreaction to Gluonic Sector

  $$T_0 \rightarrow T_0(N_f, T, \mu)$$

- Modifications of the Phase Structure
  - ▷ fluctuations push CEP downwards
  - ▷ no CEP for $\mu/T < 1$
  - ▷ $T_0(\mu)$: chiral and deconfinement transitions coincide
  - ▷ $\rightsquigarrow$ quarkyonic phase shrinks



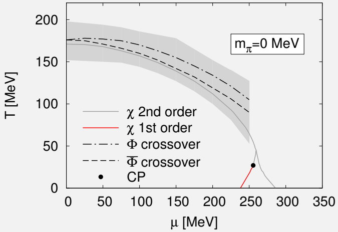
Summary & Outlook

QCD Phase Structure and TD via 2-flavour PQM truncation

- Important Feature: Matter Backreaction to Gluonic Sector

  $T_0 \to T_0(N_f, T, \mu)$

- Modifications of the Phase Structure
  - fluctuations push CEP downwards
  - no CEP for $\mu/T < 1$
  - $T_0(\mu)$: chiral and deconfinement transitions coincide
  - $\rightsquigarrow$ quarkyonic phase shrinks
- Mass Sensitivity
  - splitting in chiral transition at small T weakened for physical m_π



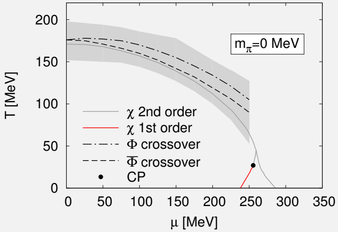
Summary & Outlook

QCD Phase Structure and TD via 2-flavour PQM truncation

- Important Feature: Matter Backreaction to Gluonic Sector

  $$T_0 \to T_0(N_f, T, \mu)$$

- Modifications of the Phase Structure
  - fluctuations push CEP downwards
  - no CEP for $\mu/T < 1$
  - $T_0(\mu)$: chiral and deconfinement transitions coincide
  - $\rightsquigarrow$ quarkyonic phase shrinks
- Mass Sensitivity
  - splitting in chiral transition at small T weakened for physical m_π
- QCD input to Polyakov-loop potential
  - good agreement with lattice results for, e.g., the interaction measure



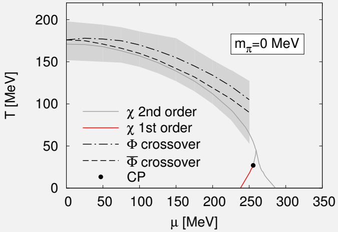
Summary & Outlook

QCD Phase Structure and TD via 2-flavour PQM truncation

- Important Feature: Matter Backreaction to Gluonic Sector

$$T_0 \to T_0(N_f, T, \mu)$$

- Modifications of the Phase Structure
  - fluctuations push CEP downwards
  - no CEP for $\mu/T < 1$
  - $T_0(\mu)$: chiral and deconfinement transitions coincide
  - $\rightsquigarrow$ quarkyonic phase shrinks
- Mass Sensitivity
  - splitting in chiral transition at small T weakened for physical m_π
- QCD input to Polyakov-loop potential
  - good agreement with lattice results for, e.g., the interaction measure
- high μ/low T region
  - baryons not included here
- Next step: (2+1)-flavours beyond MFA



Backup I: The Polyakov–Quark-Meson Model

Polyakov–Quark-Meson Truncation

$$\Gamma_k = \int d^4x \left\{ \bar{q}\left(\not{D} + \mu\gamma_0 + ih(\sigma + i\gamma_5\vec{\tau}\vec{\pi})\right) q + \frac{1}{2}(\partial_\mu\phi)^2 + \Omega_k[\sigma,\vec{\pi},\Phi,\bar{\Phi}] \right\}$$

at initial scale Λ: $\Omega_\Lambda[\sigma,\vec{\pi},\Phi,\bar{\Phi}] = \mathcal{U}(\Phi,\bar{\Phi}) + U(\sigma,\vec{\pi}) + \Omega_\Lambda^\infty[\sigma,\vec{\pi},\Phi,\bar{\Phi}]$

$\phi = (\sigma,\vec{\pi})$ . . . meson field ($N_f = 2$)

$\not{D}(\Phi) = \gamma_\mu\partial_\mu - i\,g\gamma_0 A_0(\Phi)$

g . . . gauge coupling

h . . . Yukawa coupling

- Polynomial Polyakov-Loop Potential

$$\frac{\mathcal{U}(\Phi,\bar{\Phi};T_0)}{T^4} = -\frac{b_2(T;T_0)}{2}\Phi\bar{\Phi} - \frac{b_3}{6}\left(\Phi^3 + \bar{\Phi}^3\right) + \frac{b_4}{4}\left(\Phi\bar{\Phi}\right)^2$$

- Ω_Λ^∞: T & μ dependent initial condition

back

Backup II: $T_0(N_f, T, \mu)$

[Schaefer, Pawlowski, Wambach (2007)]

[TKH, Pawlowski, Schaefer (2011)]

- $T_0 \longleftrightarrow \Lambda_{QCD}$
- perturbative 1-loop estimate:

$$\beta(\alpha) = -b(N_f)\,\alpha^2 + \mathcal{O}(\alpha^3)$$

- $\mu \neq 0$: HDL/HTL

$$b(N_f) \to b(N_f, \mu)$$

  - ▷ at T=0: Silver-Blaze Property

$$\Gamma(T=0, \mu) \sim \Theta(\mu - m_q)$$

  - ▷ at $T > 0$: $\Theta(\mu - m_q) \to \Theta_T(\mu - m_q)$
  - ▷ $b(N_f, \mu) \to b(N_f, T, \mu)$

$$T_0(N_f, T, \mu) = T_\tau e^{-1/(\alpha_0 b(N_f, T, \mu))}$$

back