The phase diagram of two flavour QCD

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Quarks, Gluons and the Phase Diagram of QCD
St. Goar, September 2nd 2009

Outline

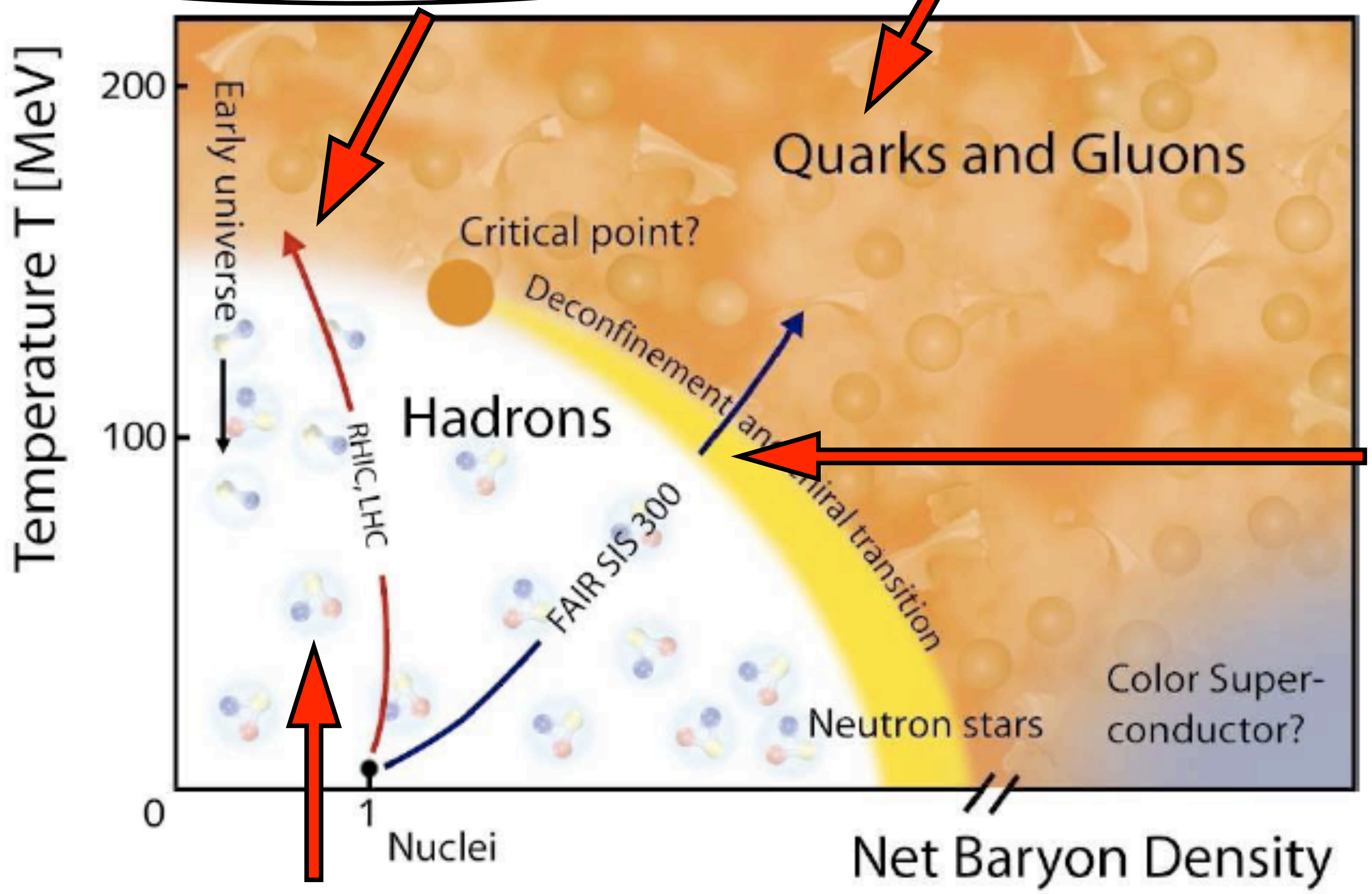
- Phase diagram of two flavour QCD
- Quark confinement & chiral symmetry breaking
- Chiral phase structure at finite density
- Summary and outlook

Phase diagram of QCD

Phase diagram of QCD

Strongly correlated quark-gluon-plasma
'RHIC serves the perfect fluid'

massless quarks (chiral symmetry)
deconfinement



FAIR, www.gsi.de

quarkyonic:
confinement & chiral symmetry

hadronic phase
confinement & chiral symmetry breaking

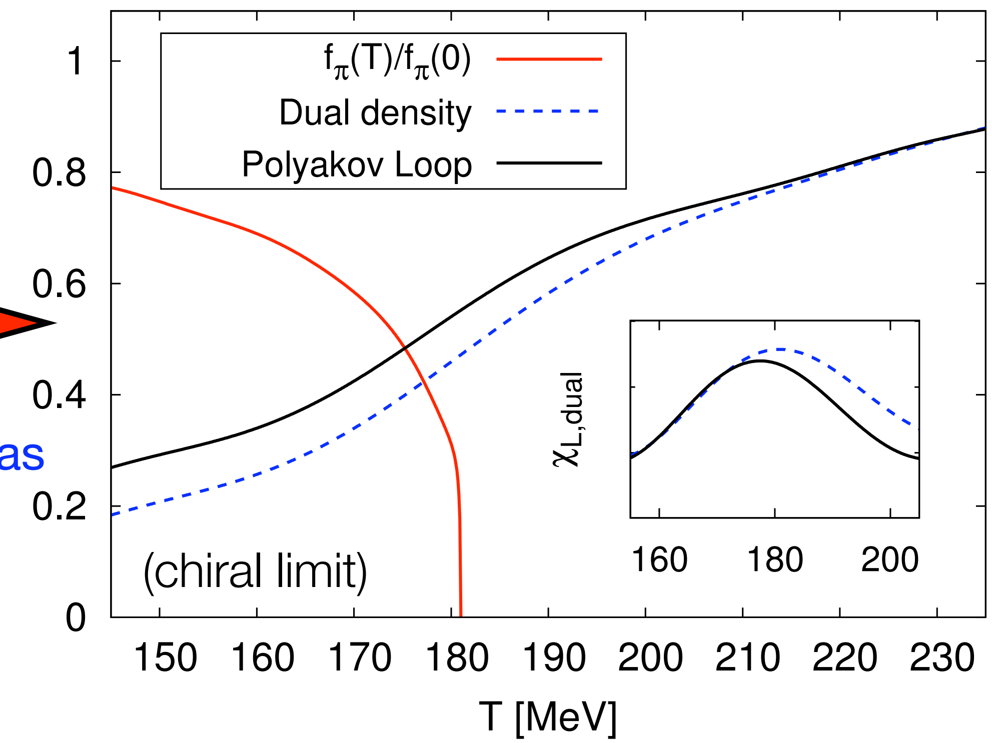
Phase diagram of two flavour QCD

Continuum methods

RG-flows in QCD

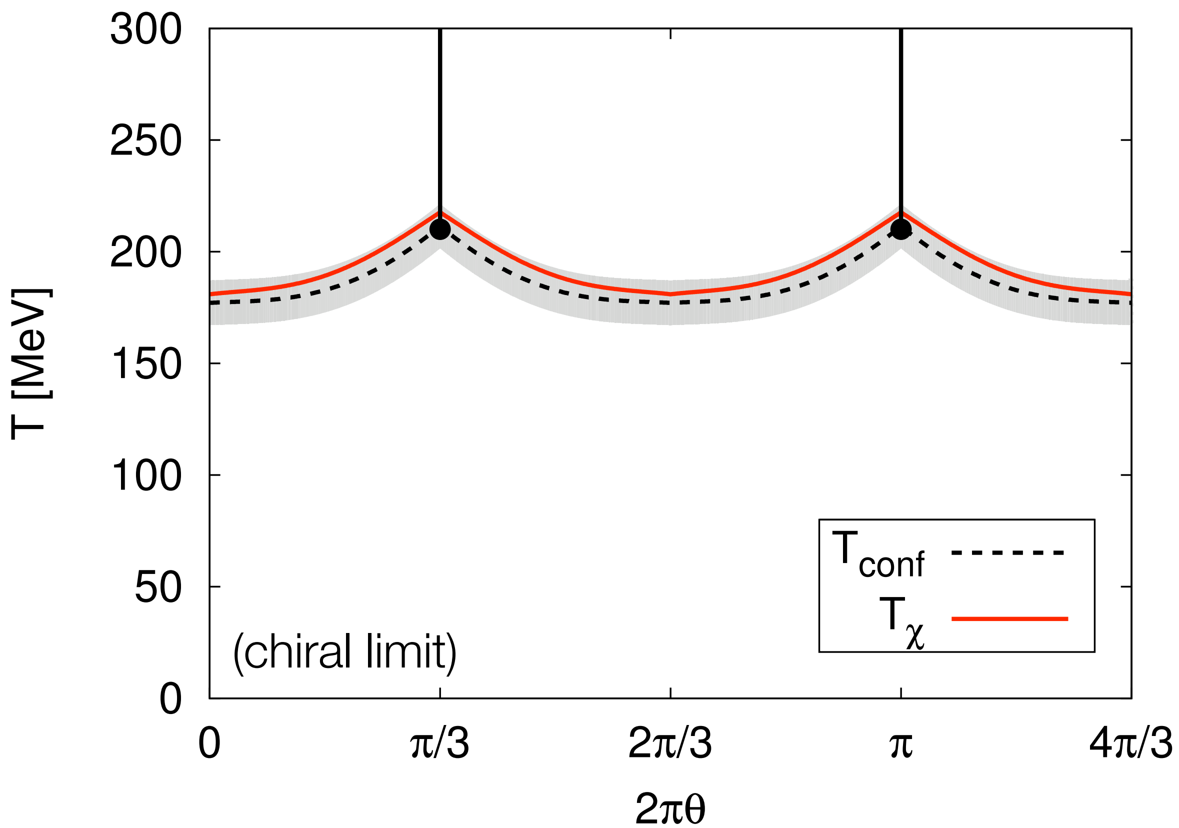
Braun, Haas, Marhauser,JMP ’09

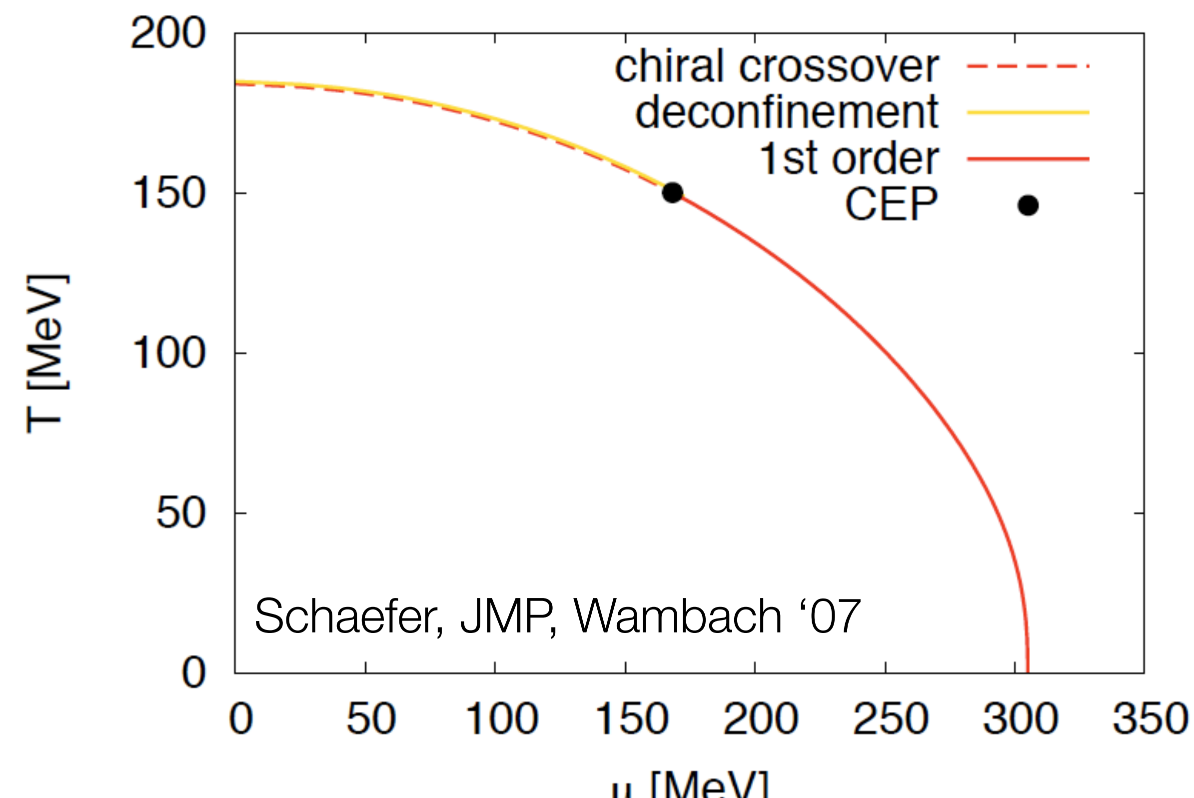
cf. talks by J. Braun & L. Haas



PNJL & PQM model

cf. talks by K. Fujushima
W. Weise
B.-J. Schaefer





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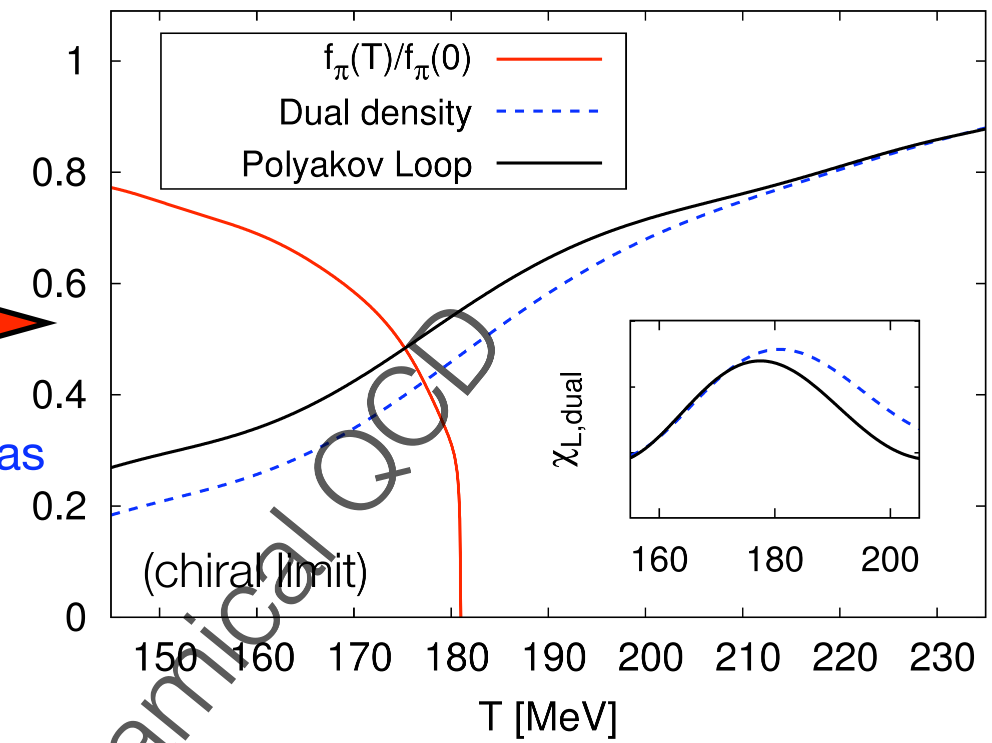

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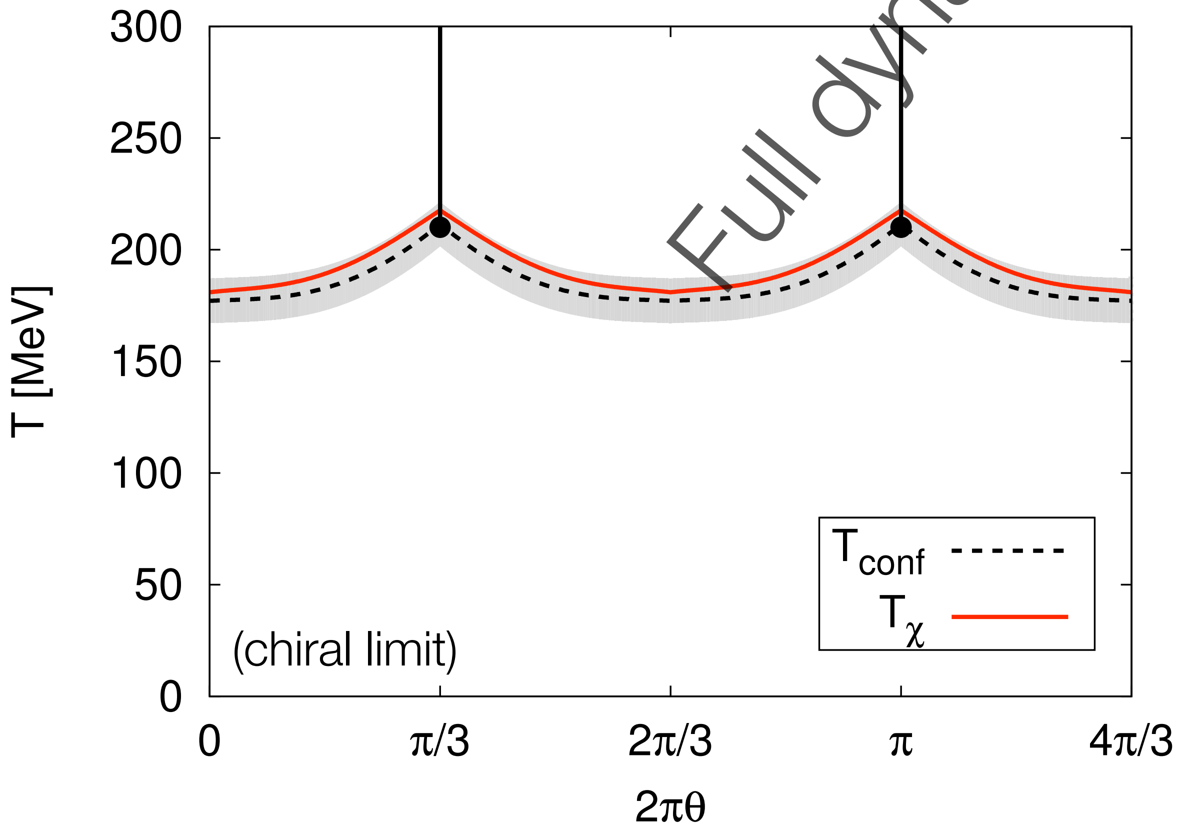
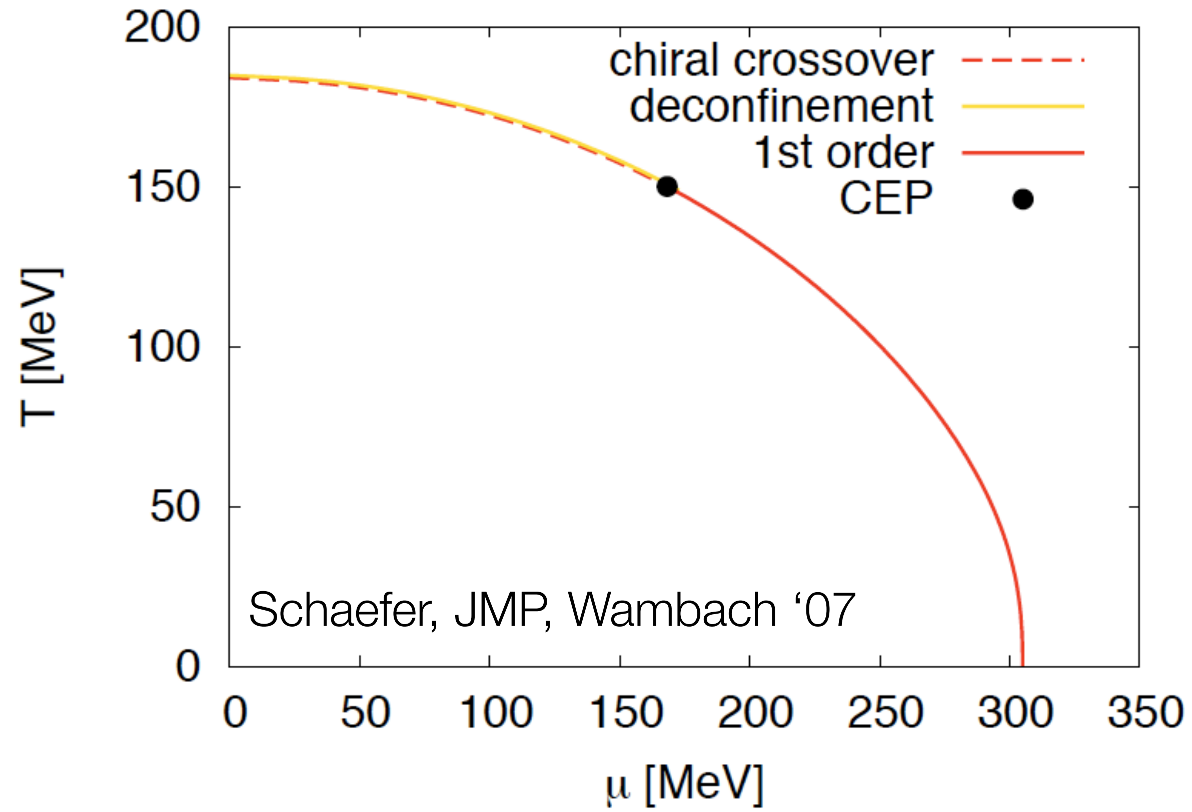




Quark confinement & chiral symmetry breaking

Confinement

Continuum methods ⟵ (Functional RG-flows)

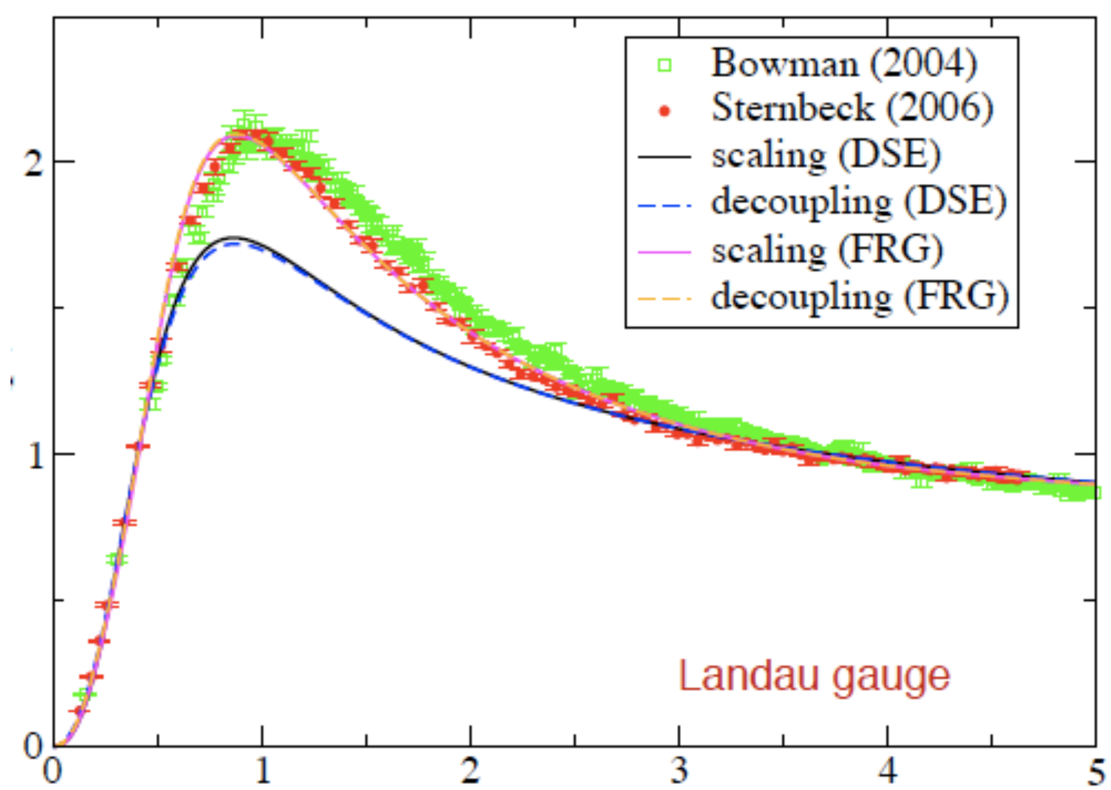
RG-scale k: $t = \ln k$

Braun, Gies, JMP '07

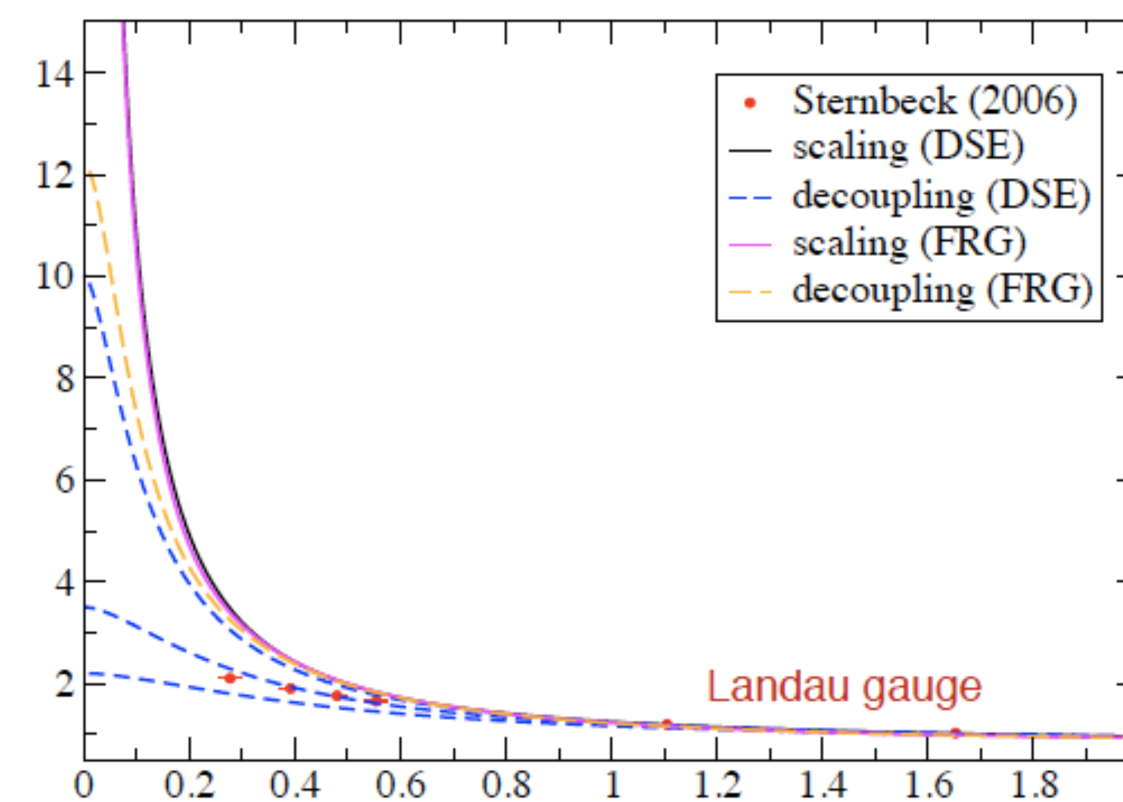
$$V[A_0] = -\frac{1}{2}\mathrm{Tr}\log\langle AA\rangle[A_0] + O(\partial_t\langle AA\rangle) - \mathrm{Tr}\log\langle C\bar{C}\rangle[A_0] + O(\partial_t\langle C\bar{C}\rangle) + O(V''[A_0])$$

$$p_0 \to 2\pi T n - g A_0$$

$p^2\langle A\,A\rangle(p^2)$



$p^2\langle C\,\bar{C}\rangle(p^2)$



p [GeV]

Fischer, Maas, JMP '08

JMP, in preparation

Confinement

Continuum methods

Braun, Gies, JMP '07

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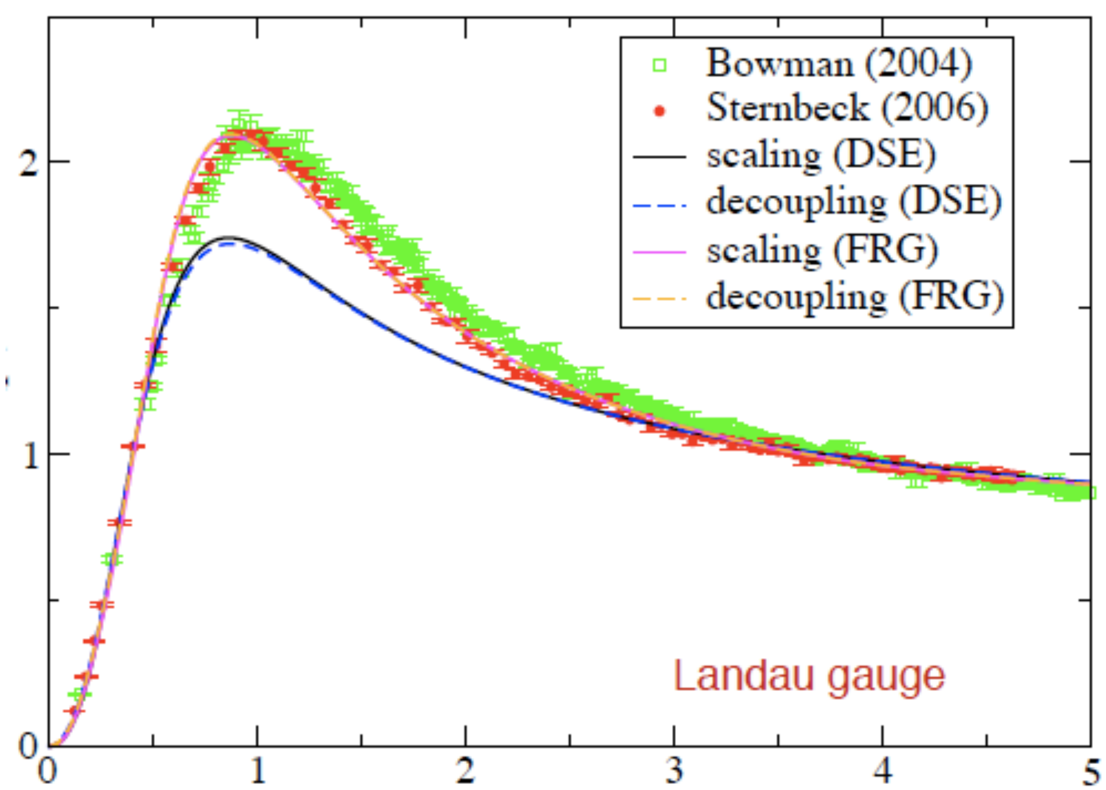
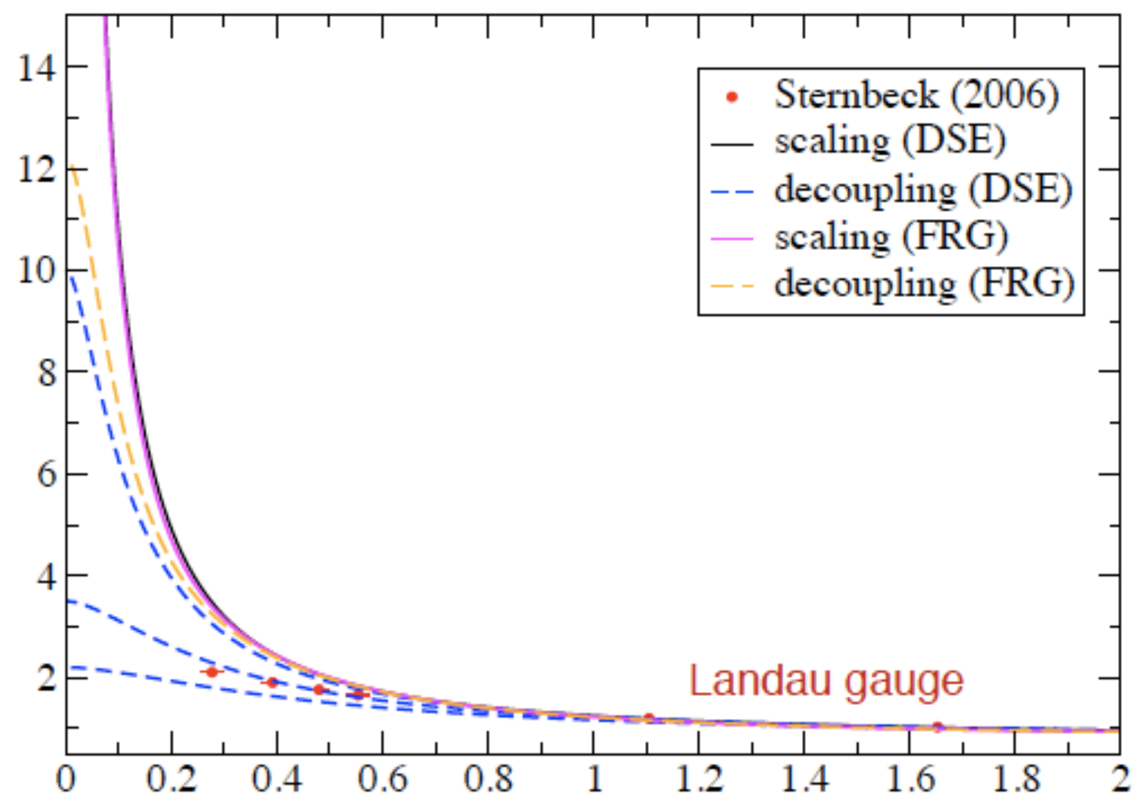
'Polyakov loop potential'

subleading for $T_{c,\mathrm{conf}}$

$p^2\langle A\,A\rangle(p^2)$



$p^2\langle C\,\bar{C}\rangle(p^2)$



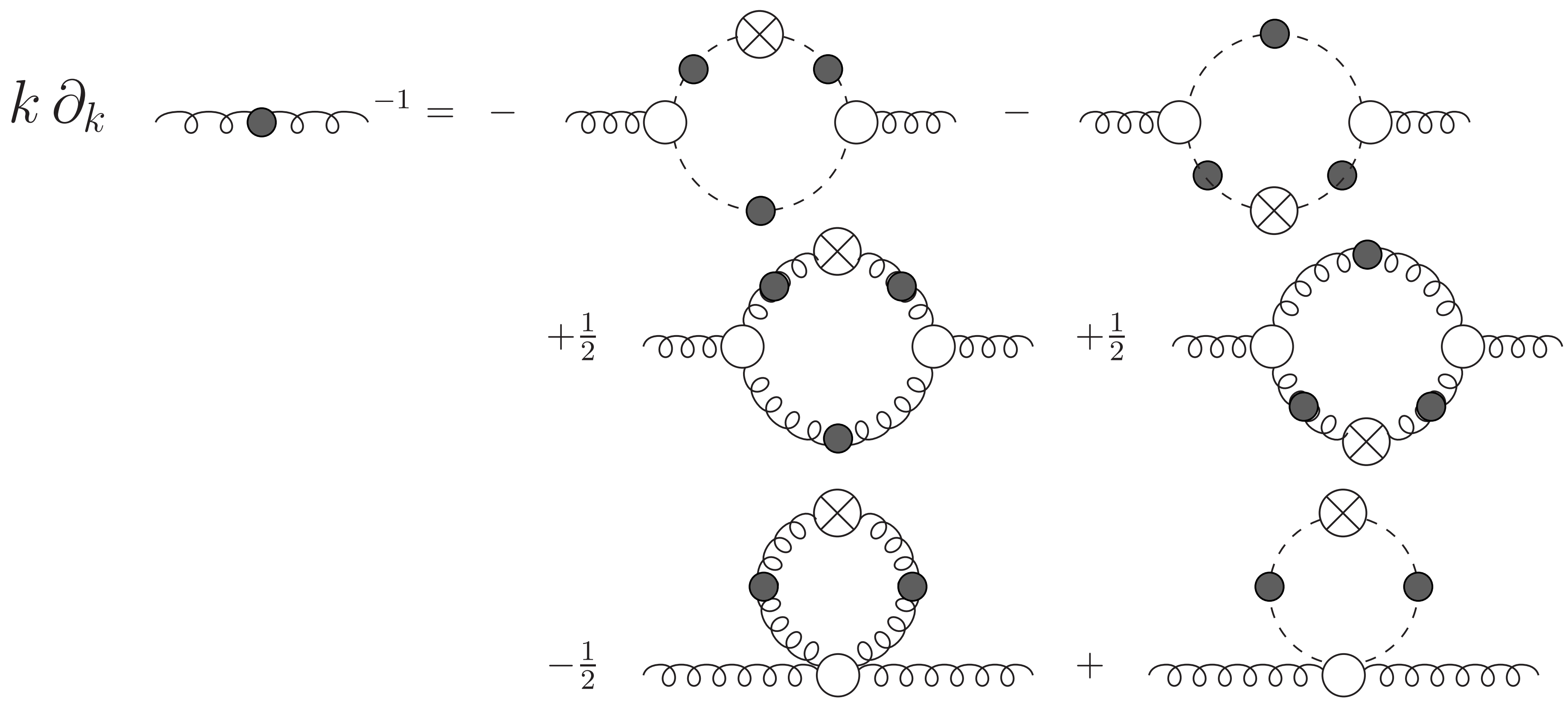
$p\ [\mathrm{GeV}]$

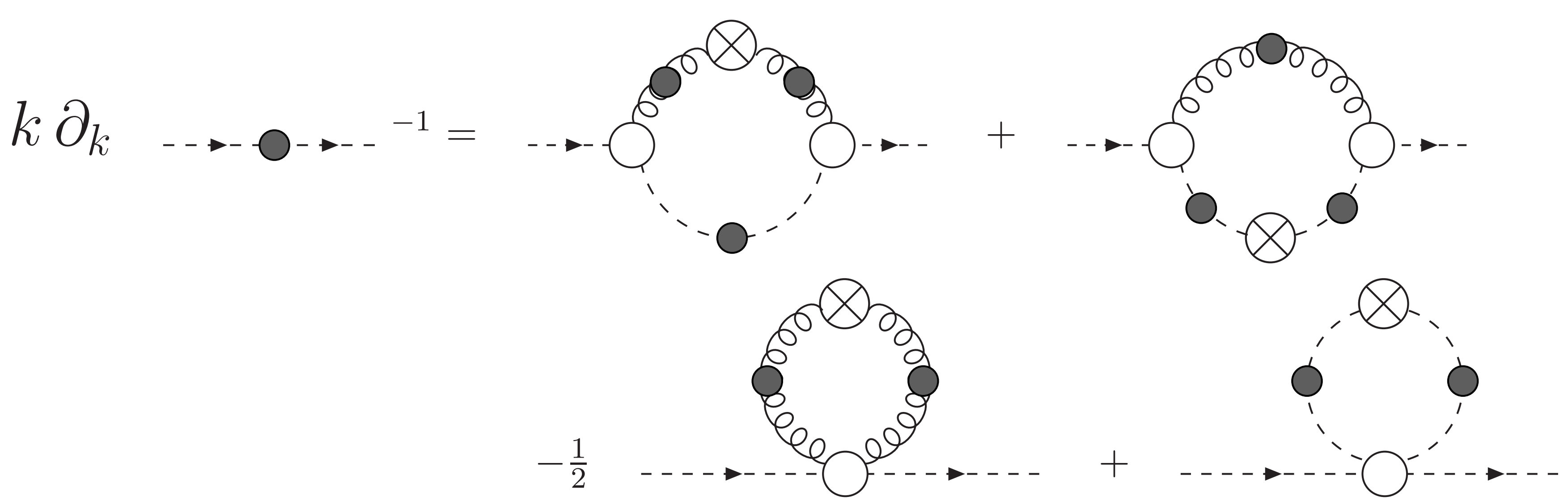
Fischer, Maas, JMP '08

JMP, in preparation

Confinement

Continuum methods

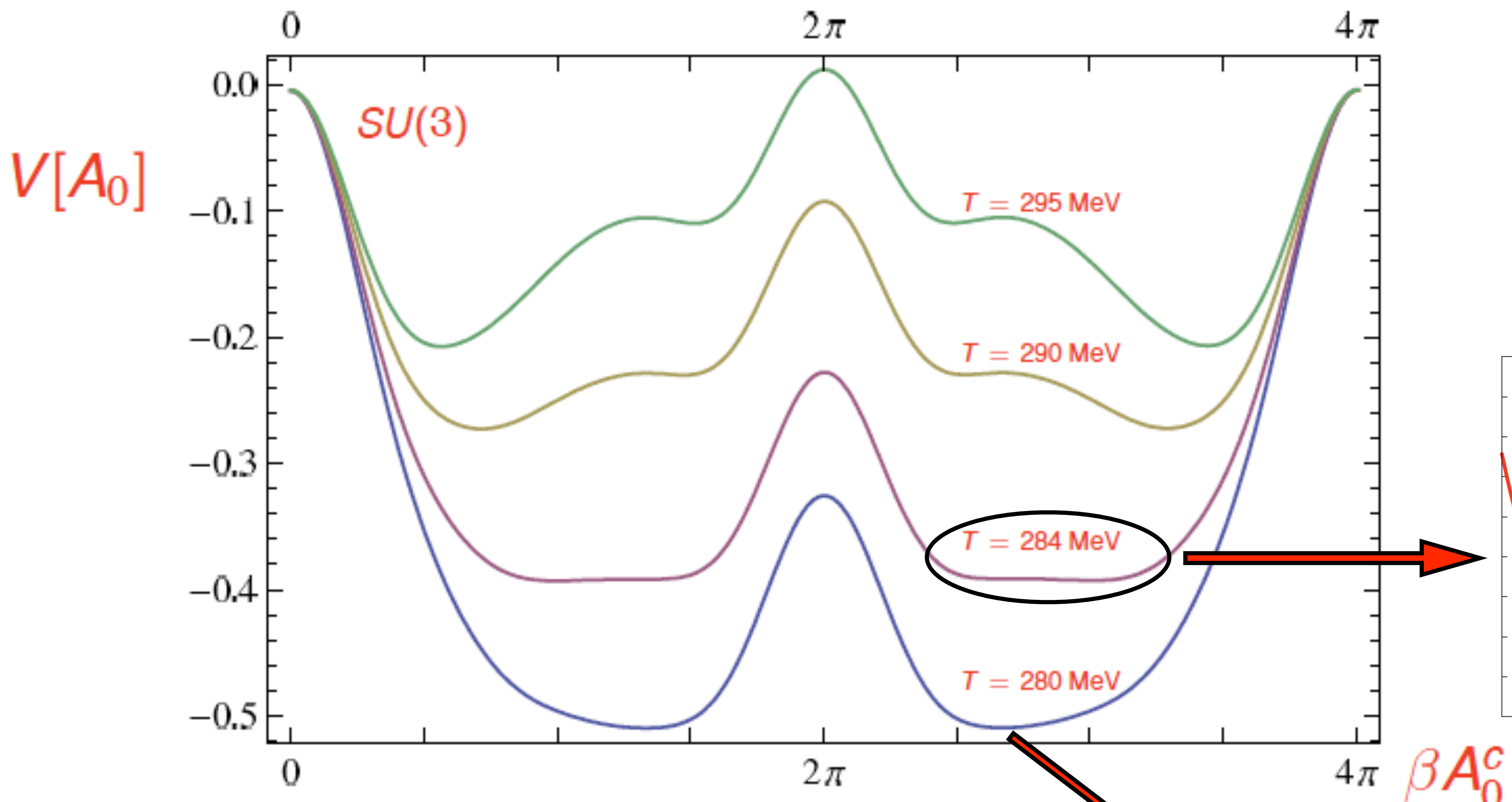


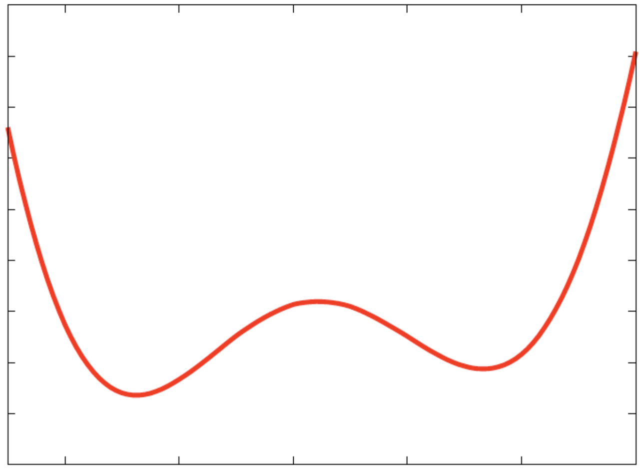


Confinement

Continuum methods

$T_c \simeq 284 \pm 10\text{MeV}$ $\qquad$ $T_c/\sqrt{\sigma} = 0.646 \pm 0.023$ $\quad$ lattice: $T_c/\sqrt{\sigma} = .646$





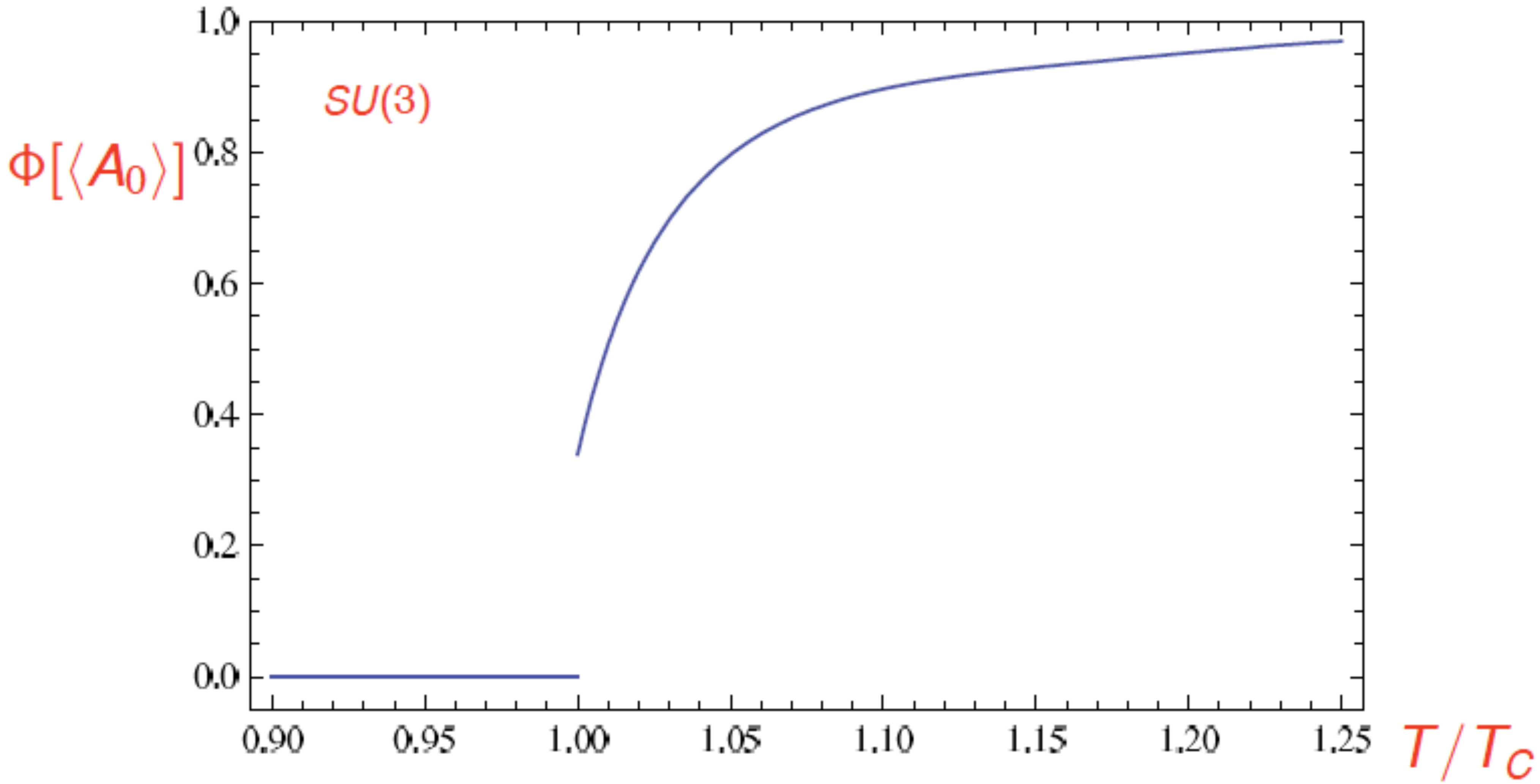
$$\Phi[A_0^c] = \frac{1}{3}(1 + 2\cos\frac{1}{2}\beta A_0^c) \longrightarrow \Phi[\frac{8}{3}\pi] = 0$$

Braun, Gies, JMP '07

Confinement

Continuum methods

$T_c \simeq 284 \pm 10\text{MeV}$ $T_c/\sqrt{\sigma} = 0.646 \pm 0.023$ lattice: $T_c/\sqrt{\sigma} = .646$



for SU(N), G(2), Sp(2) cf. talk by Jens Braun

Braun, Gies, JMP '07

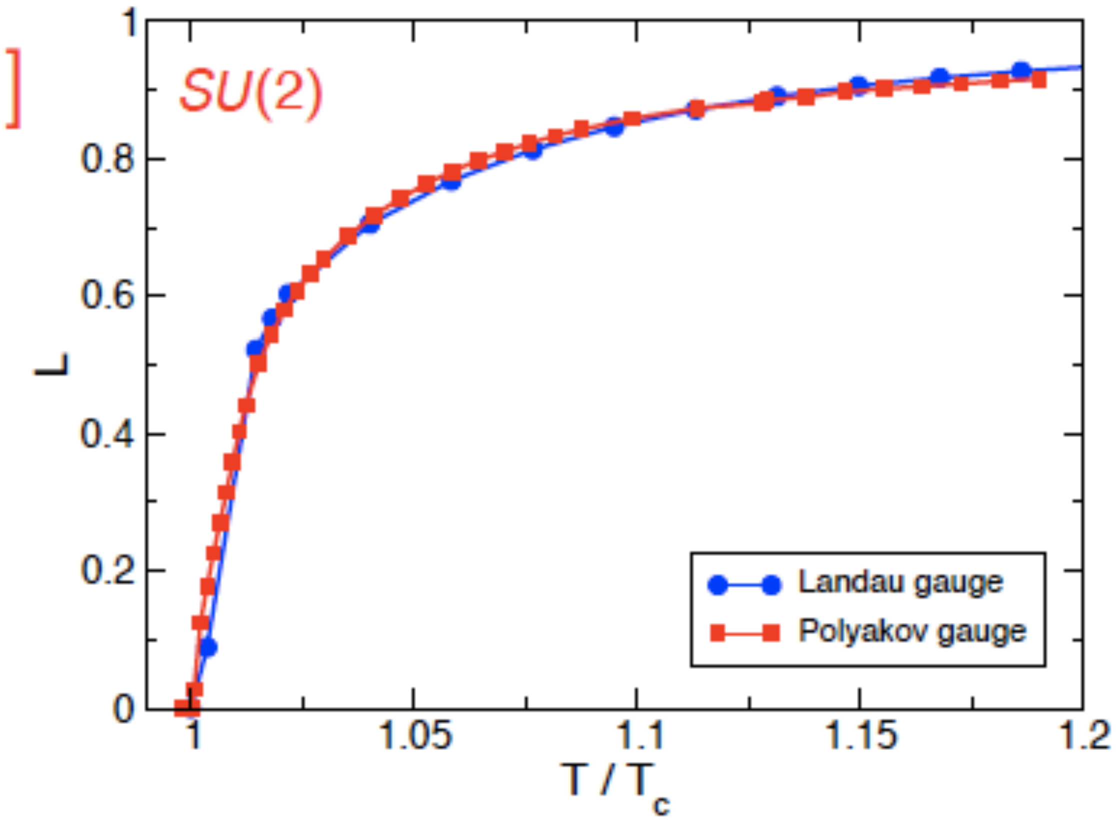
Universal properties & gauge independence

Continuum methods

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

RG-flow : $V[A_0] = -\int dt\, \mathrm{flow}[V''[A_0]\,,\,\alpha_s]$

$\Phi[\langle A_0\rangle]$



T/T_c

- ——: Polyakov gauge: crit. exp. $\nu = 0.65$ $\nu_{\rm Ising} = 0.63$
- ——: Landau gauge propagators

JMP, Marhauser '08

Imaginary chemical potential

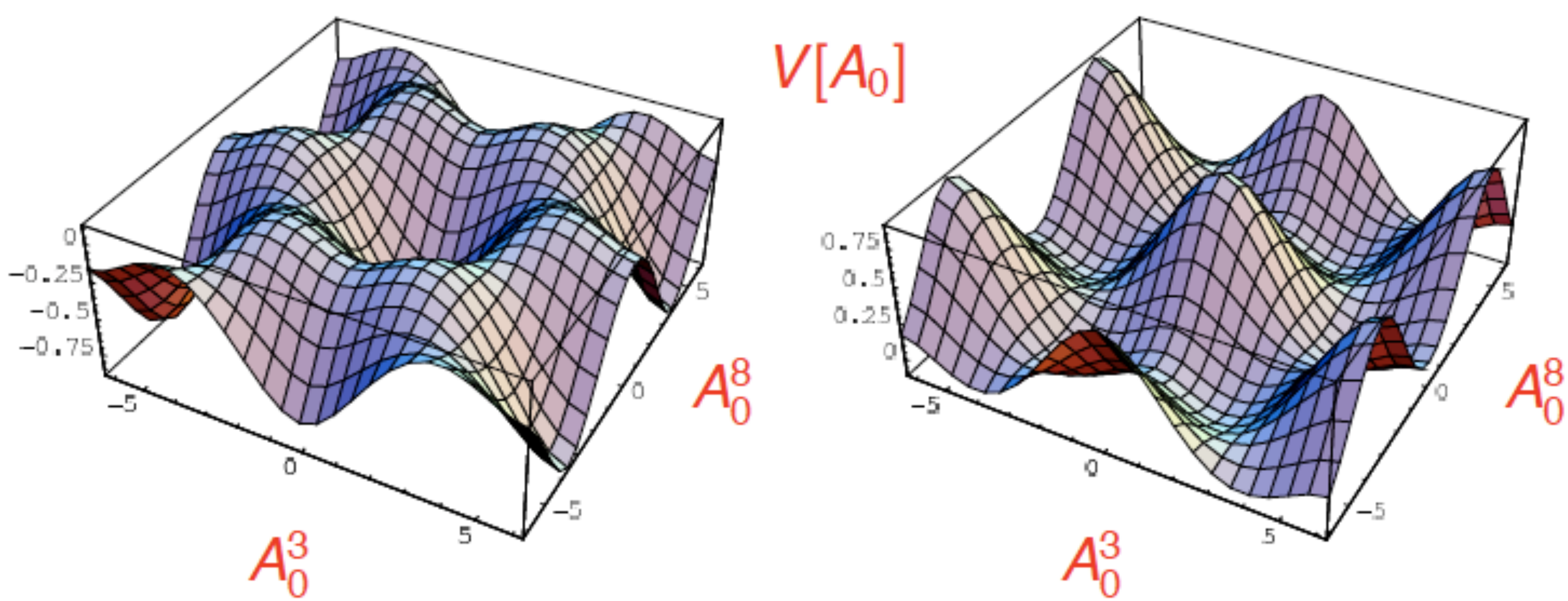
Lattice & Continuum QCD

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

- Roberge-Weiss symmetry

$$Z_\theta = Z_{\theta+1/3}$$

deconfining confining



Dual order parameter

Lattice & Continuum QCD

$$\mathcal{O}_\theta = \langle O[e^{2\pi i\theta t/\beta}\psi]\rangle \qquad \text{with} \qquad \psi_\theta(t+\beta,\vec{x}) = -e^{2\pi i\theta}\psi_\theta(t,x)$$

imaginary chemical potential $\mu = 2\pi i\theta/\beta$ for $\psi_\theta = e^{2\pi i\theta t/\beta}\psi$

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

order parameter for confinement

Dual order parameter

- Lattice
  - Gattringer '06
  - Synatschke, Wipf, Wozar '08
  - Bruckmann, Hagen, Bilgici, Gattringer '08
- Continuum
  - Fischer, '09; Fischer, Mueller '09
  - Braun, Haas, Marhauser, JMP '09 ← imaginary chemical potential

cf. talks by J. Braun, C. Fischer, L. Haas, A. Wipf

Dual order parameter

Lattice & Continuum QCD

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

- no imaginary chemical potential (lattice studies):

DSE: 4 loop and more → $\tilde{\mathcal{O}}$ ← FRG: 3 loop and more

- imaginary chemical potential I: evaluated at equations of motion

$\tilde{\mathcal{O}}[\langle A_0\rangle_\theta] \equiv 0$ ← Roberge-Weiss

- imaginary chemical potential II: evaluated at a fixed background

standard FRG & DSE → $\tilde{\mathcal{O}}[\langle A_0\rangle_\theta] \neq 0$ ← breaking of Roberge-Weiss

Dual order parameter

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Dual order parameter

Continuum methods ⟸ (Functional RG-flows)

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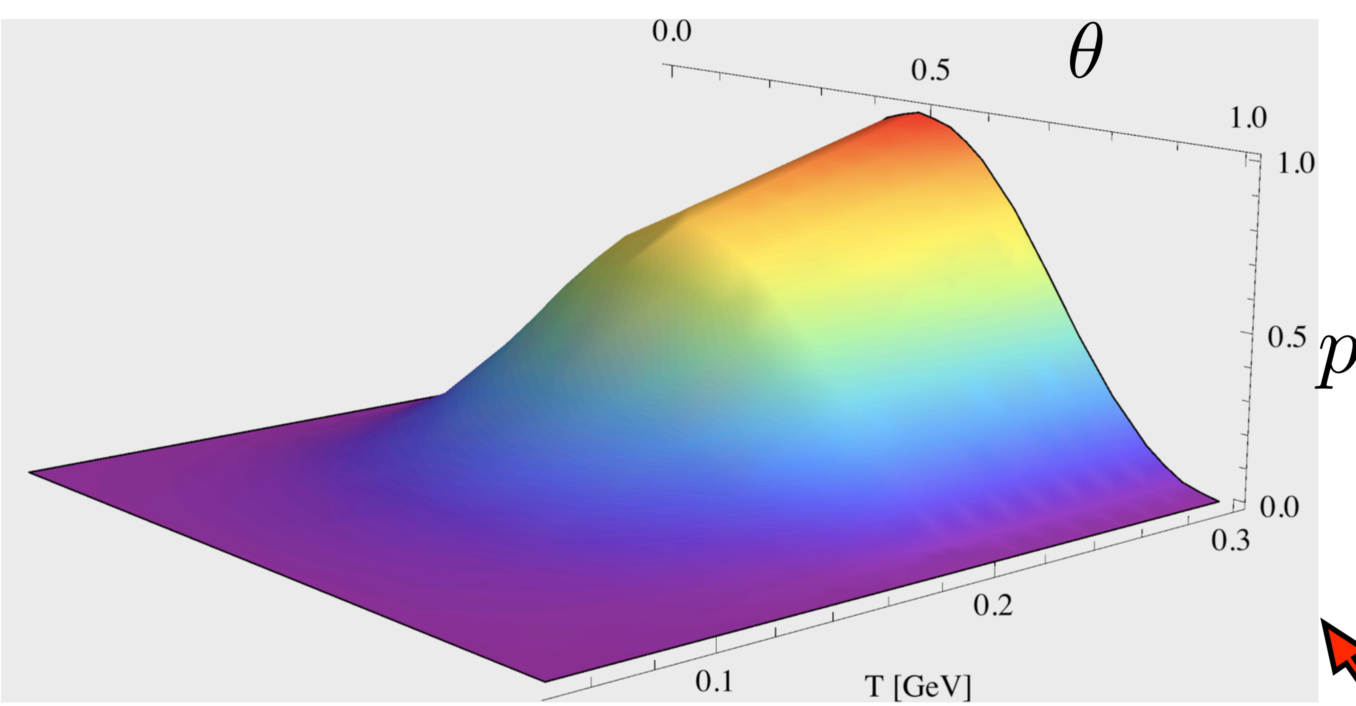
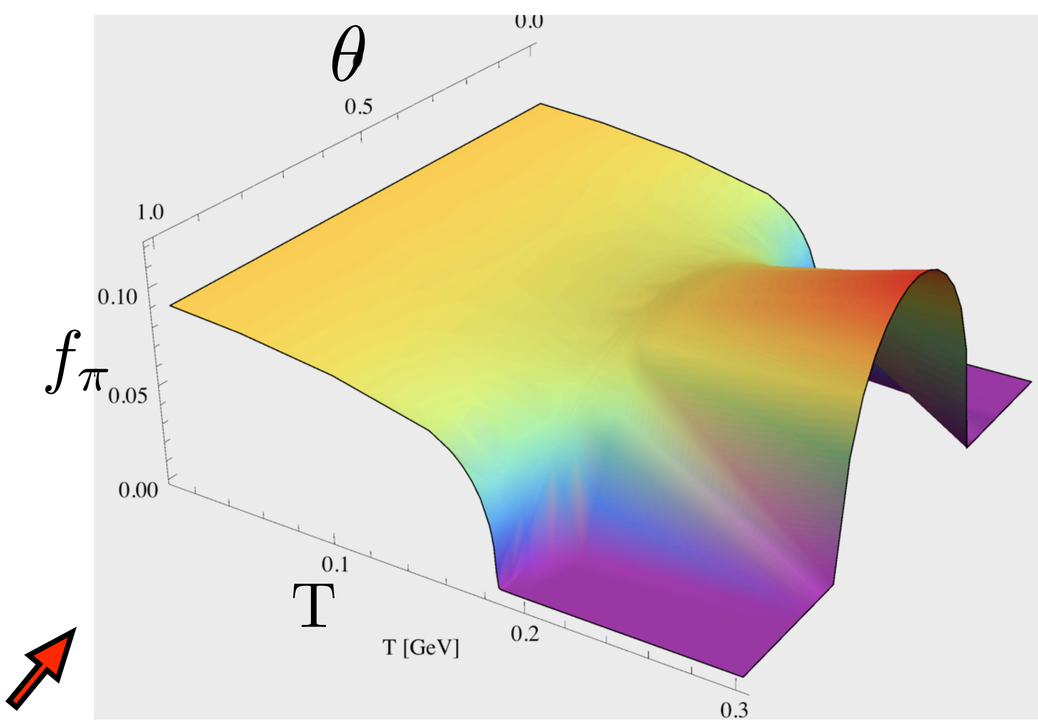
$$z = e^{2\pi i\theta_z} \longrightarrow \int_0^1 d\theta\, \mathcal{O}_\theta e^{-2\pi i\theta}$$

order parameter for confinement

'fermionic pressure difference' $p(T,\theta) \simeq P(T,\theta) - P(T,0)$



$f_\pi(T,\theta)$



fixed A_0: no Roberge-Weiss periodicity

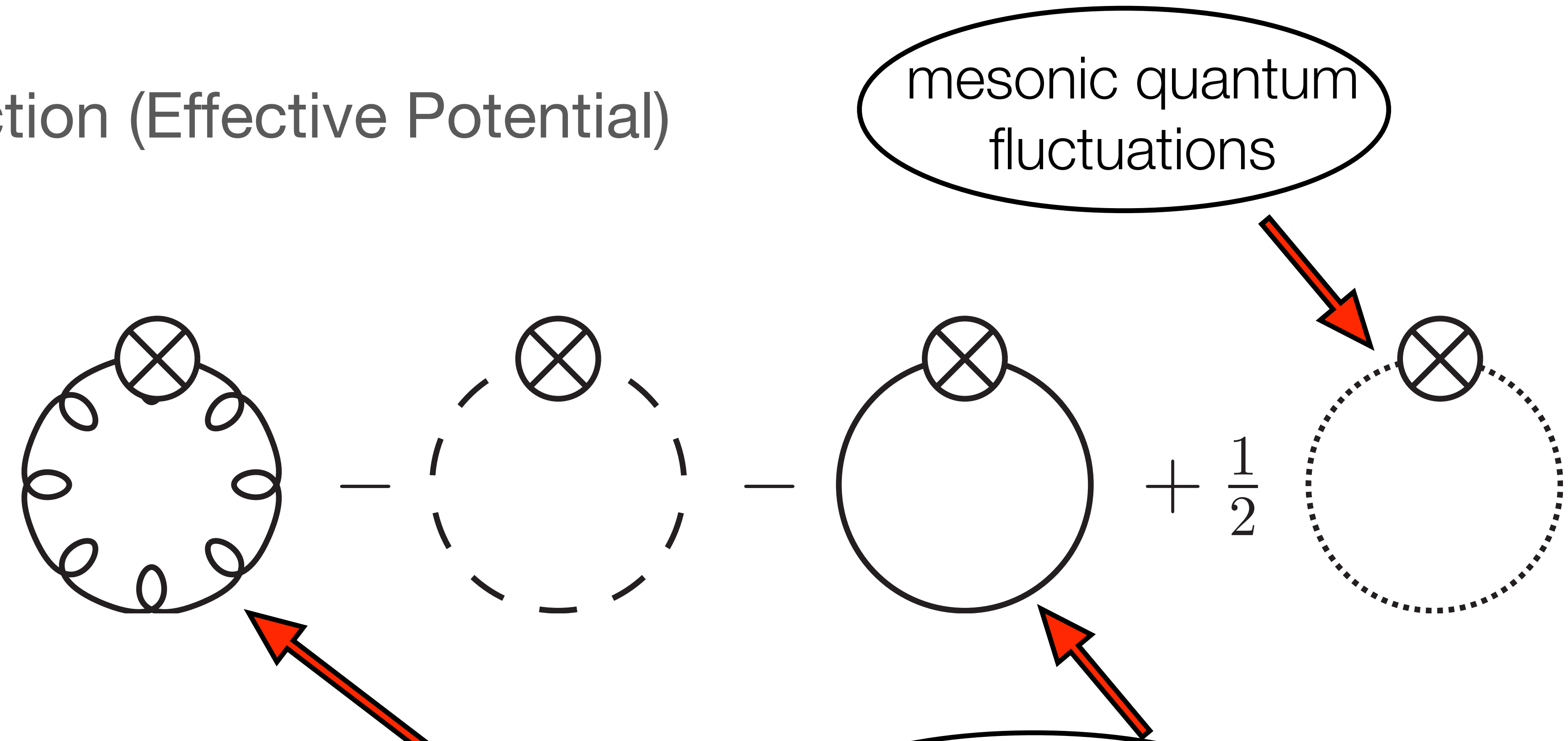
Braun, Haas, Marhauser, JMP '09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods ⟸ (Functional RG-flows)

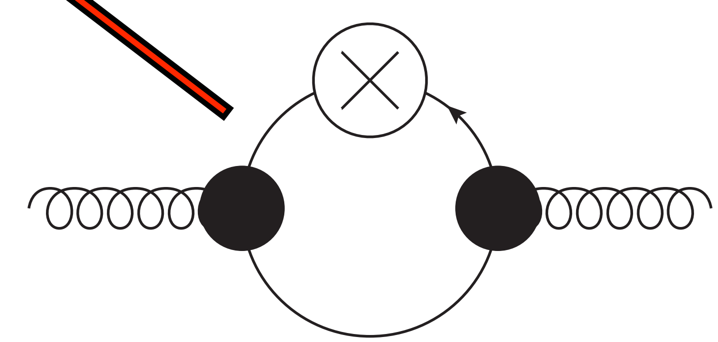
- RG-flow of Effective Action (Effective Potential)

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



- flow of gluon propagator

pure gauge theory flow $+$

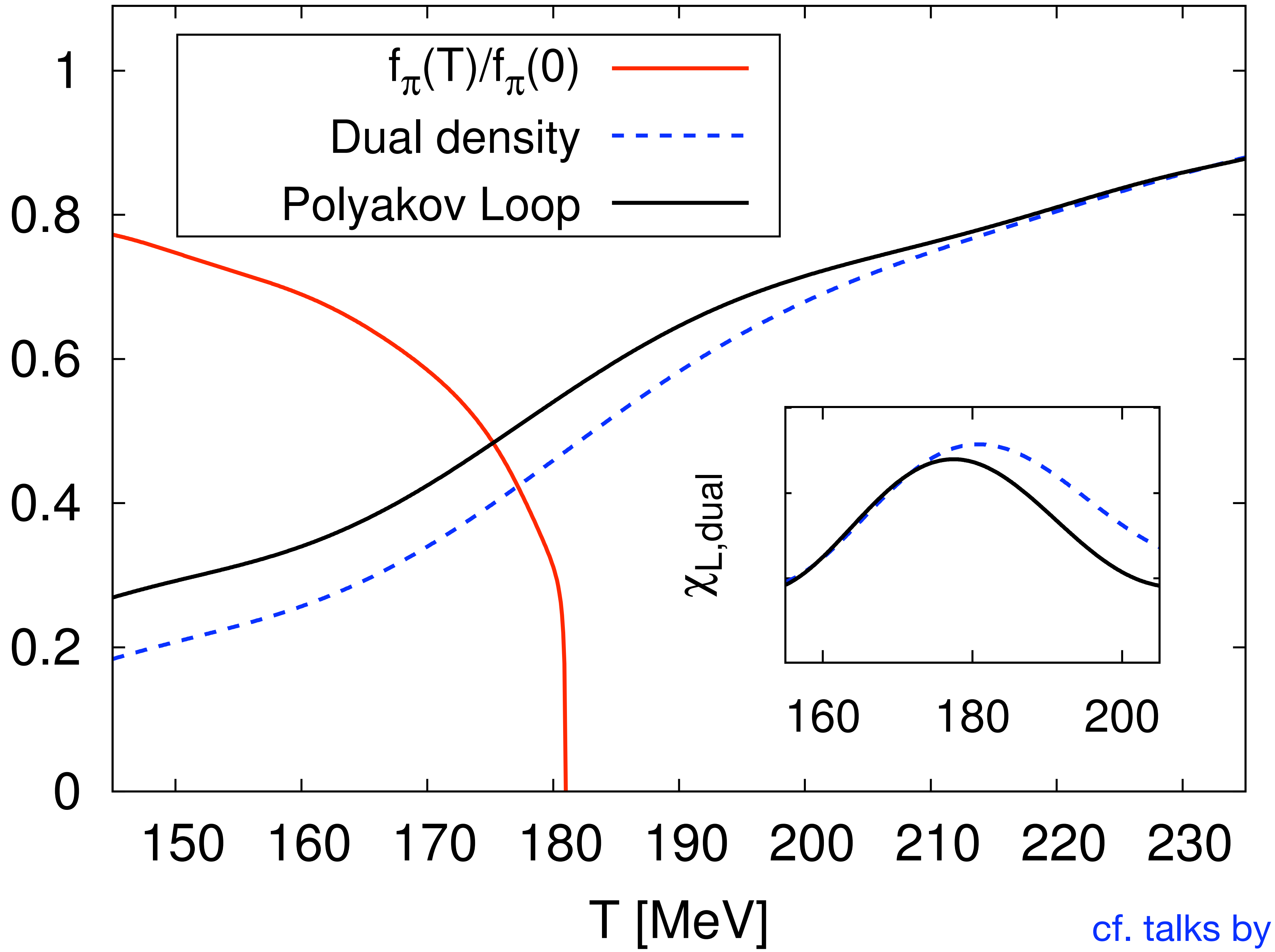


$+ \ \cdots$

cf. talk by L. Haas

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods



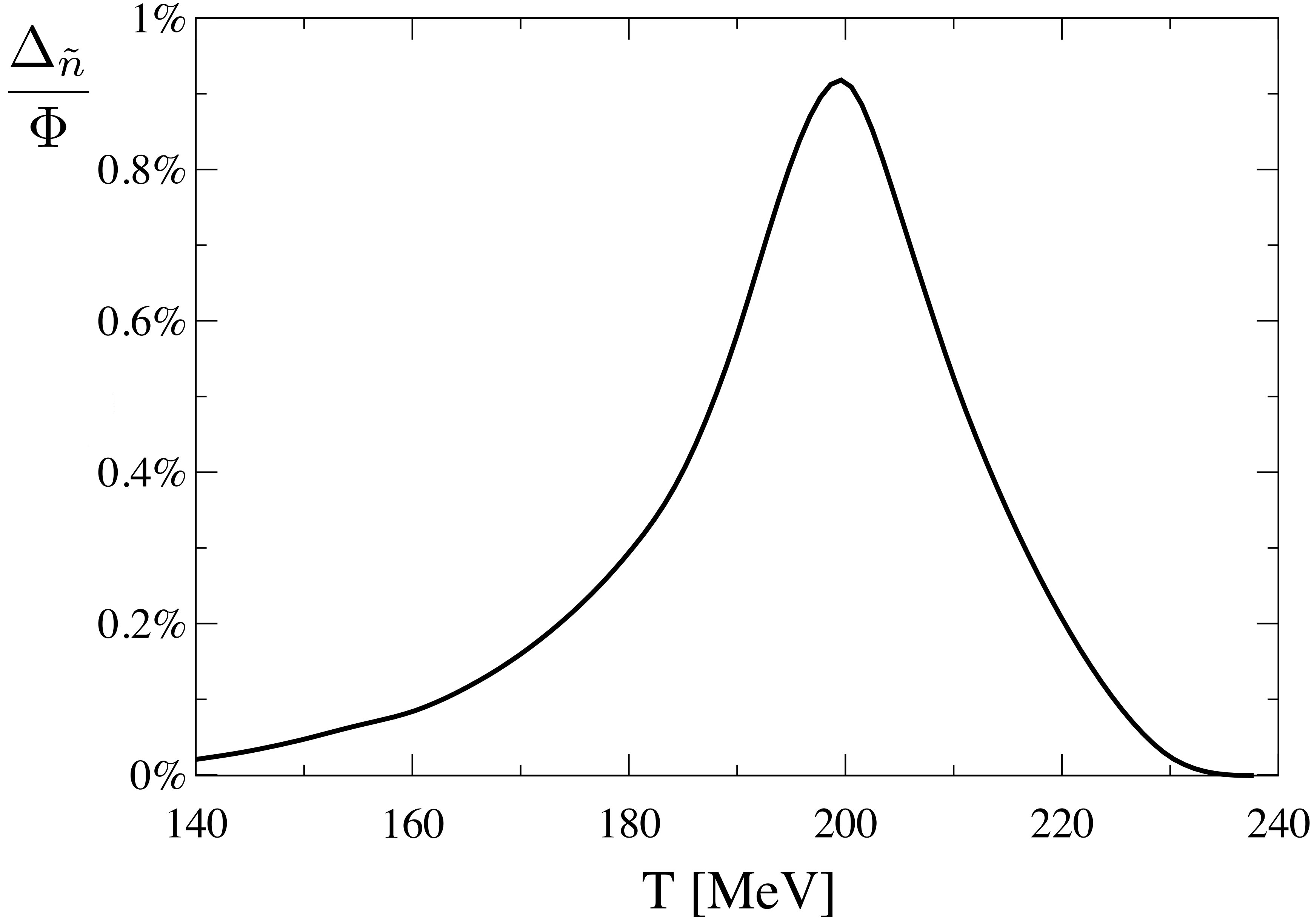
cf. talks by J. Braun & L. Haas

$$T_\chi = T_{\mathrm{conf}} \simeq 180\mathrm{MeV}$$

Braun, Haas, Marhauser, JMP '09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods

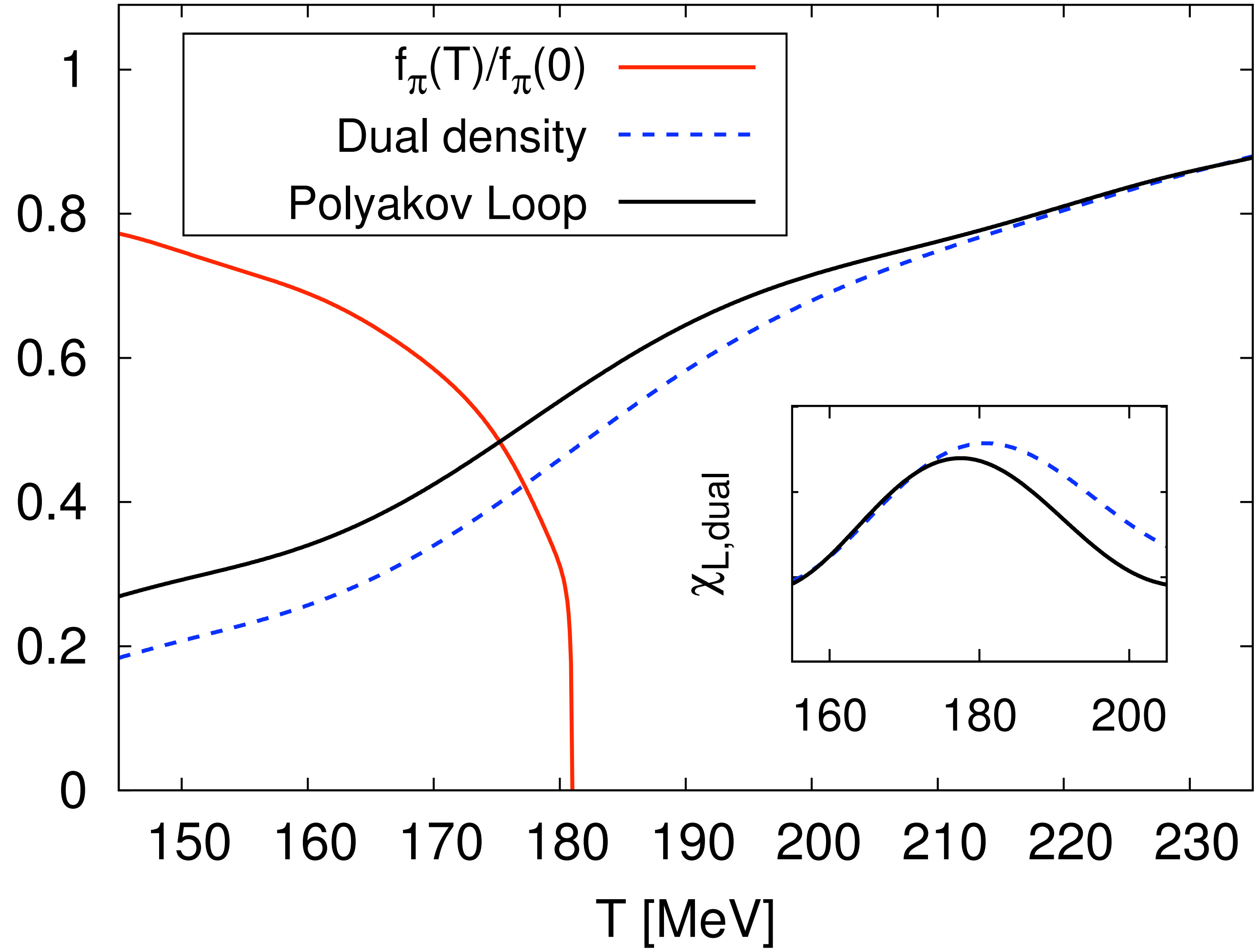


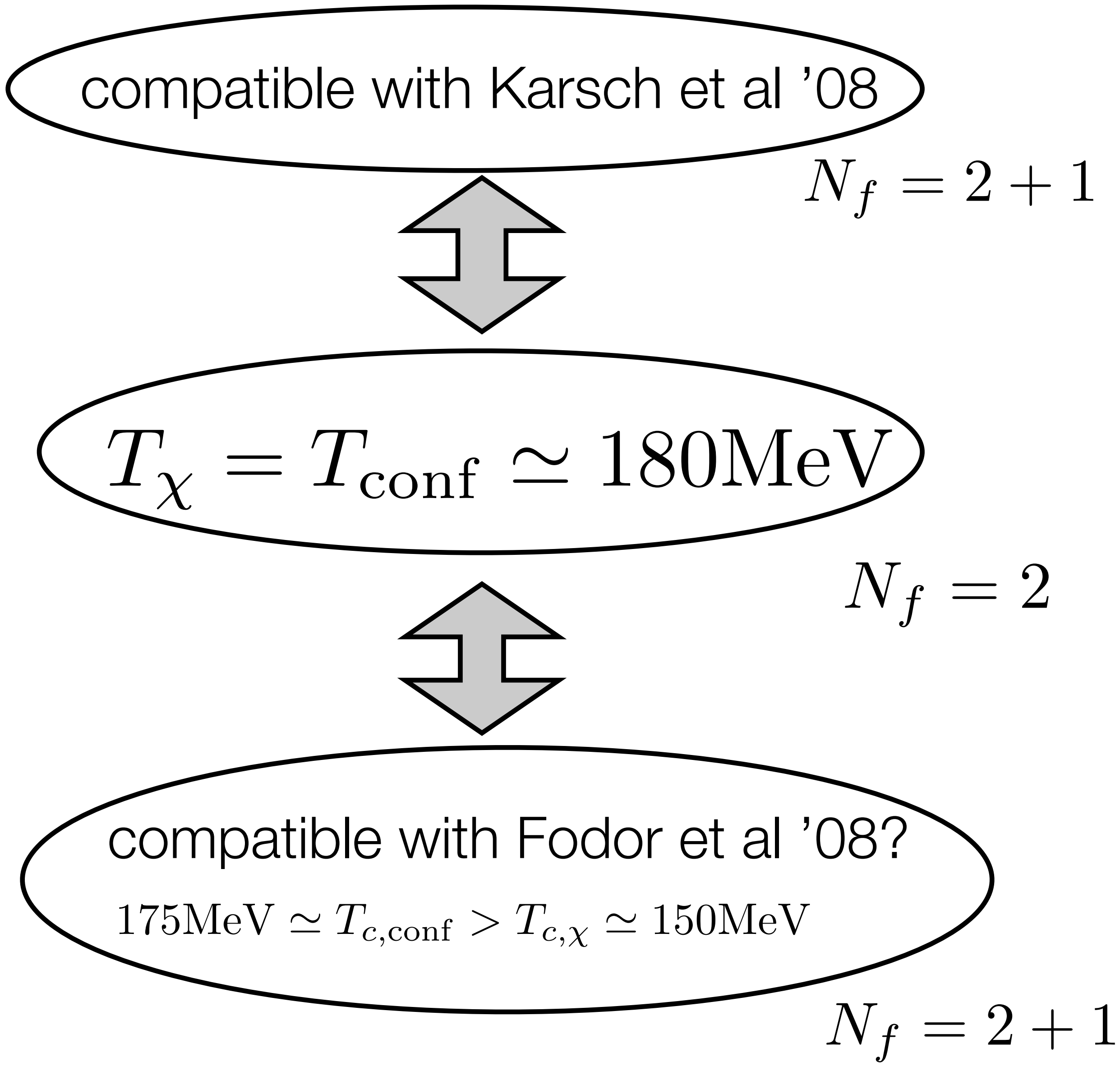
$$\Delta_{\tilde{n}} = \frac{\tilde{n}[\langle A_0 \rangle]}{\tilde{n}[0]} - \Phi[\langle A_0 \rangle] :$$ Deviation of dual density from Polyakov loop

Braun, Haas, Marhauser, JMP '09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods & lattice





Braun, Haas, Marhauser, JMP '09

Full dynamical QCD: N_f = 2 & chiral limit

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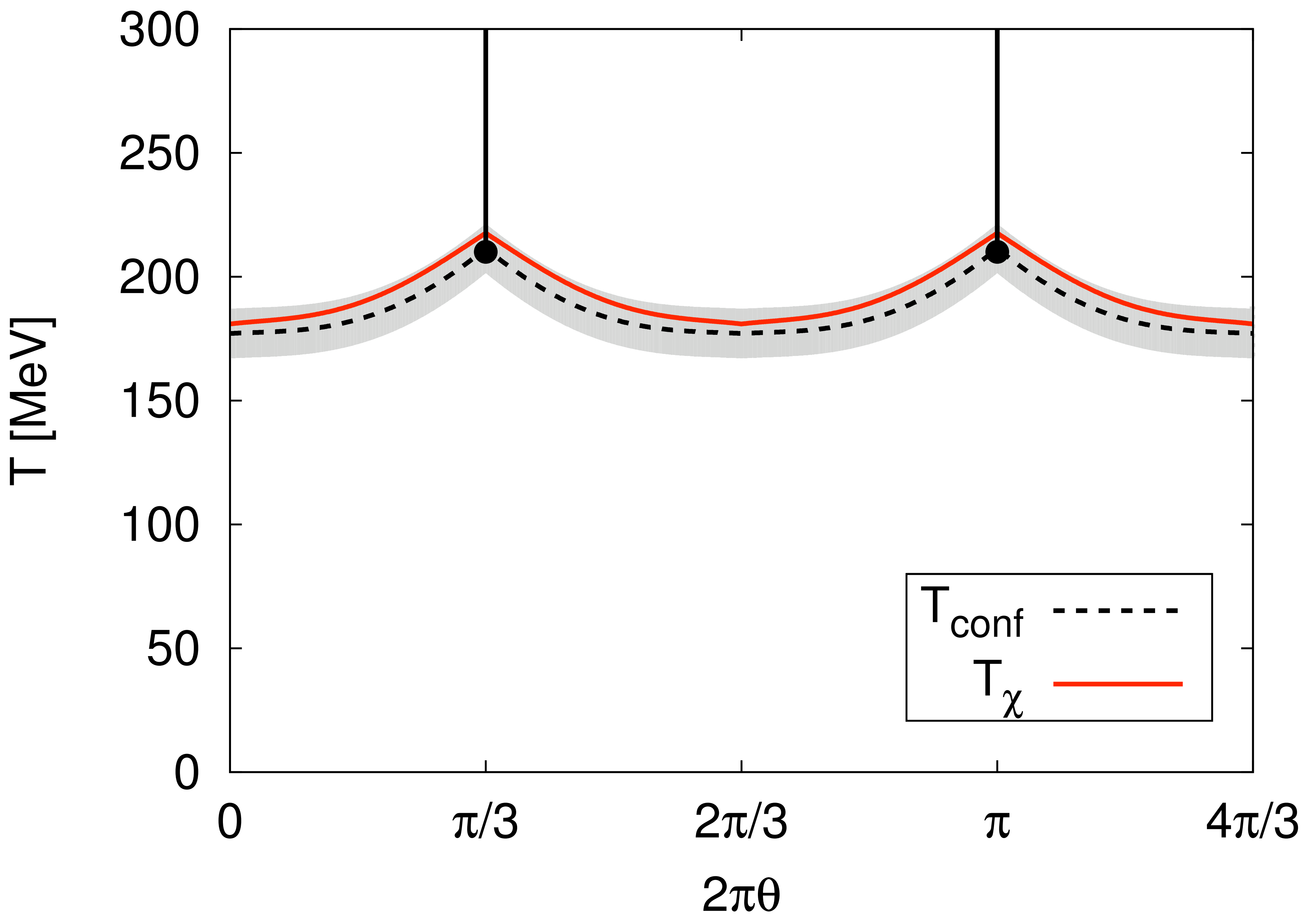
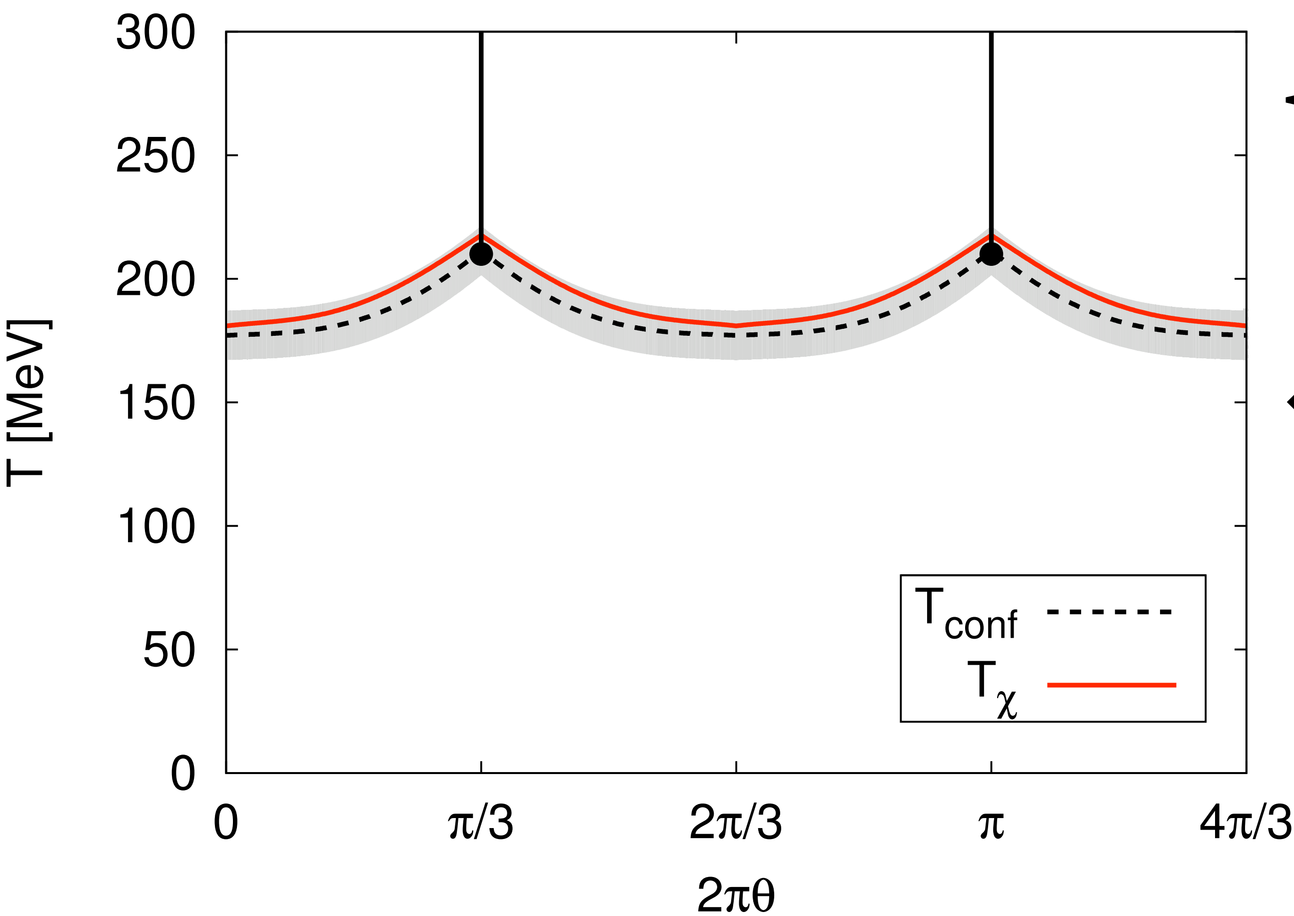


chemical potential : $\mu = 2\pi i\, T\, \theta$

Braun, Haas, Marhauser, JMP '09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods & lattice



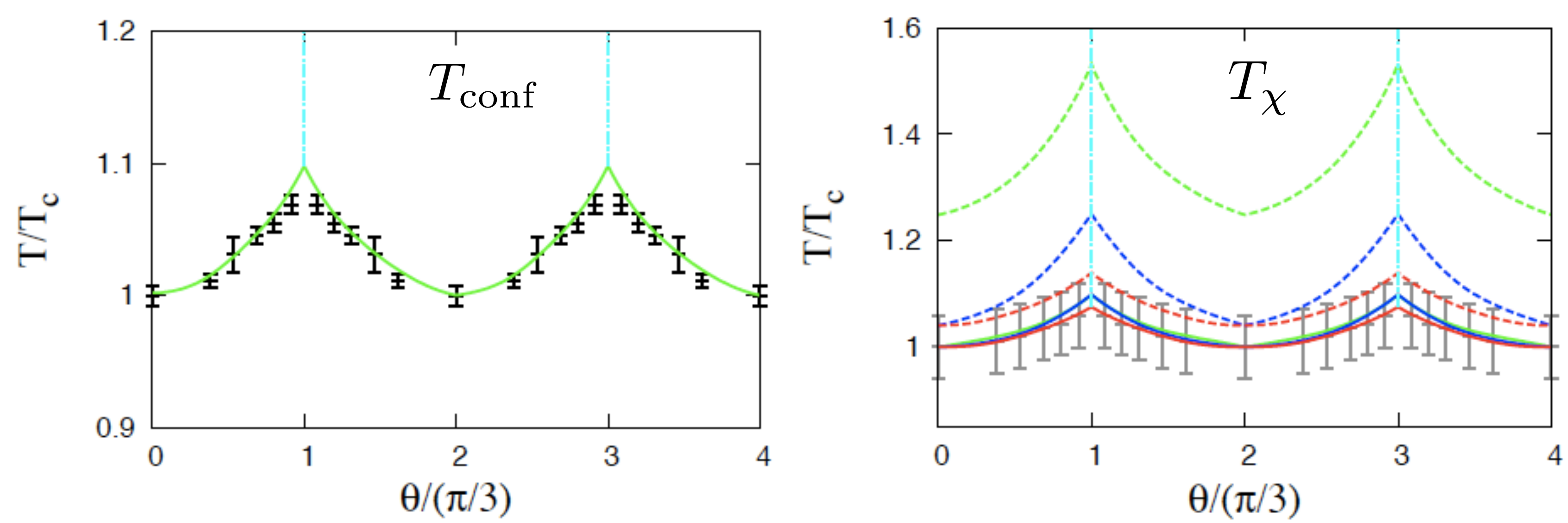
Braun, Haas, Marhauser, JMP '09

agreement

lattice results
Kratochvila et al '06 & Wu et al '06

adjust 8-fermi interaction

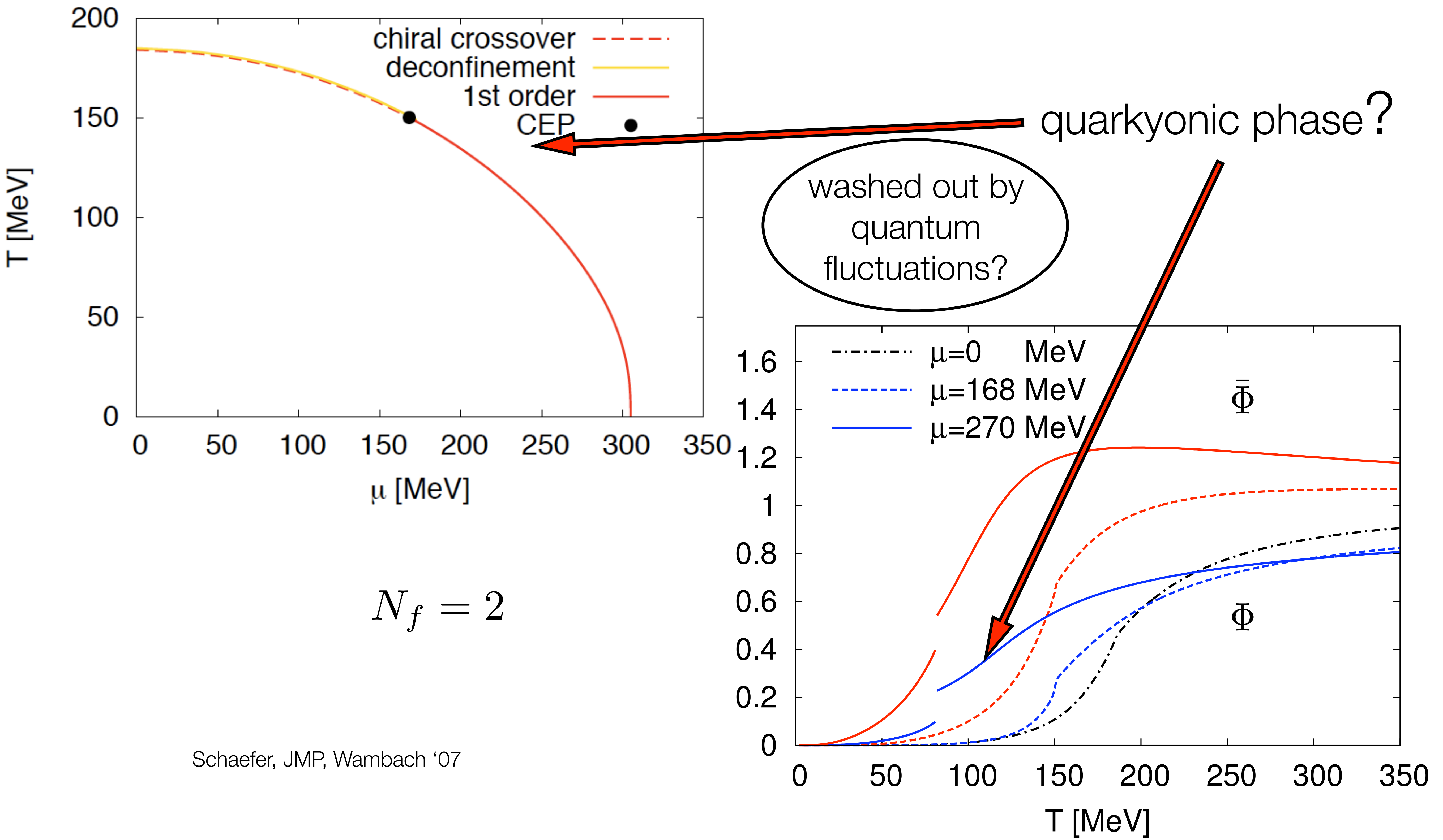
Polyakov-NJL model
Sakai et al '09



Chiral phase structure at finite density

Phase diagram of QCD

Polyakov - Quark-Meson model



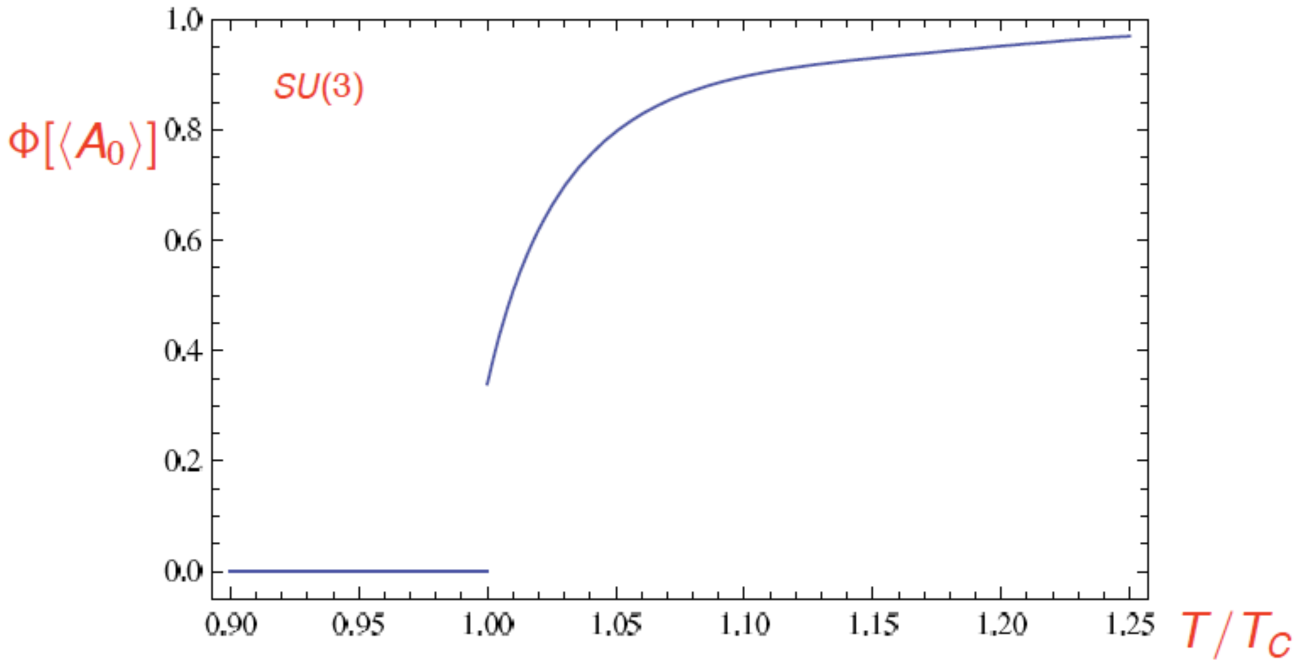
$N_f = 2$

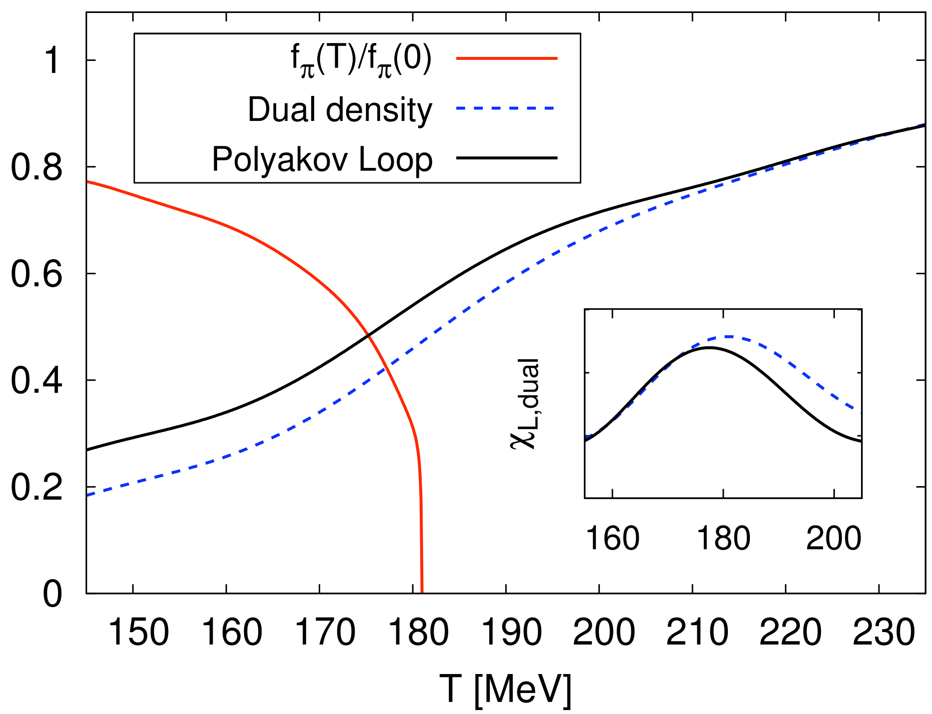
Schaefer, JMP, Wambach '07

Summary & Outlook

Summary & outlook

- Phase diagram of QCD
    - Confinement & chiral symmetry breaking at finite temperature





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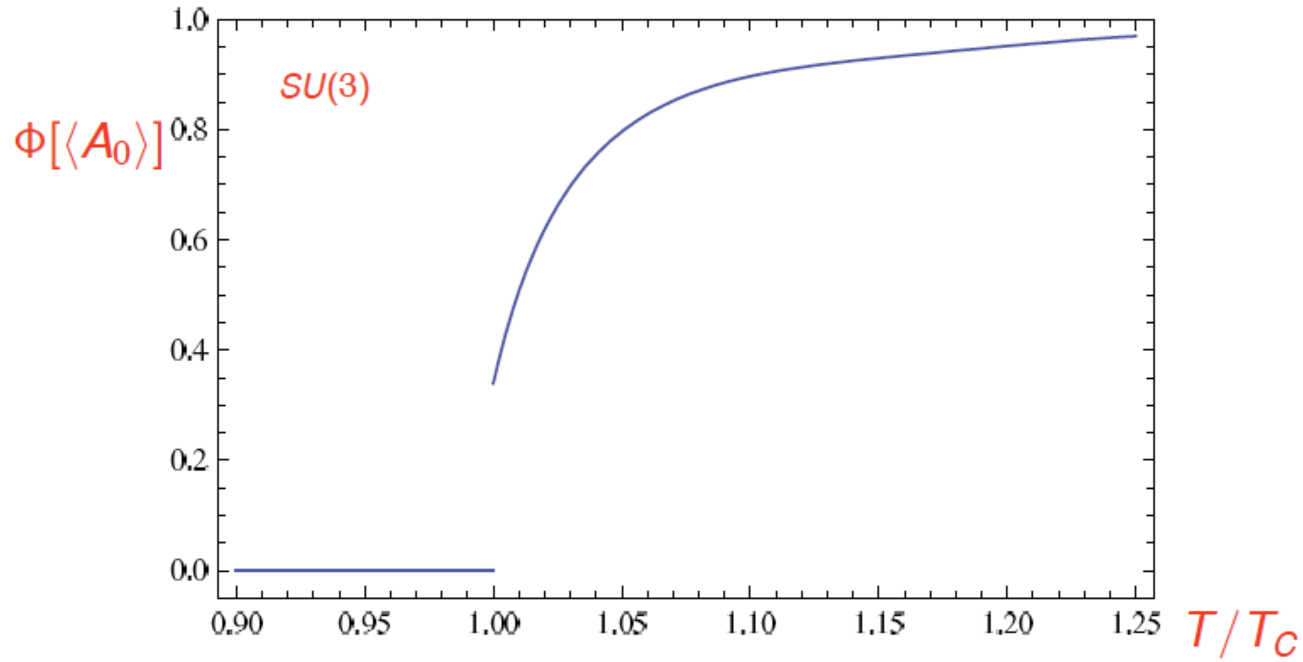
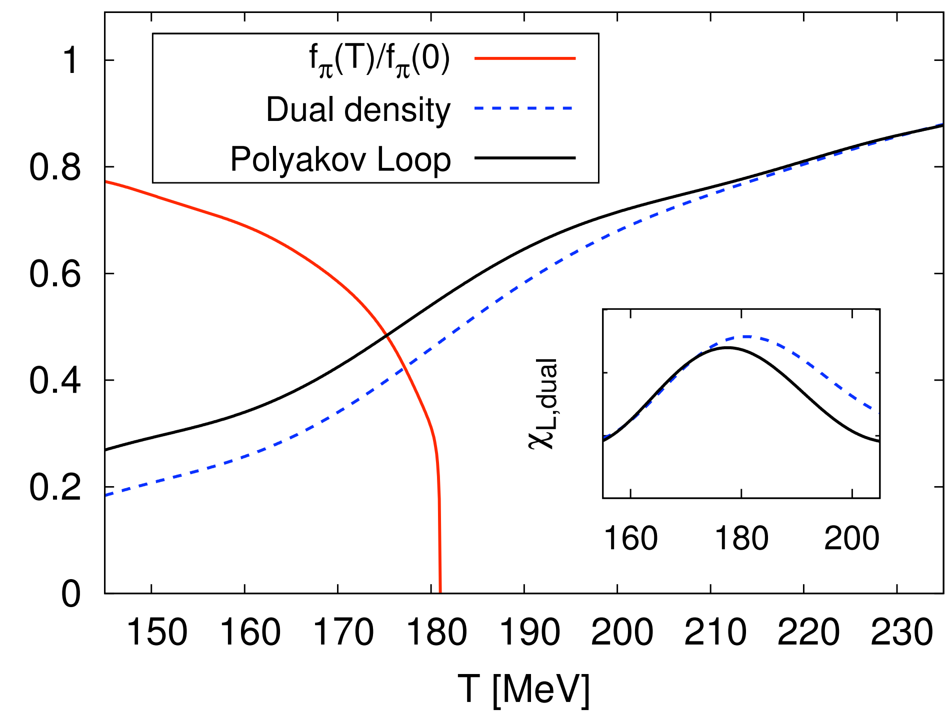




- Dynamical hadronisation

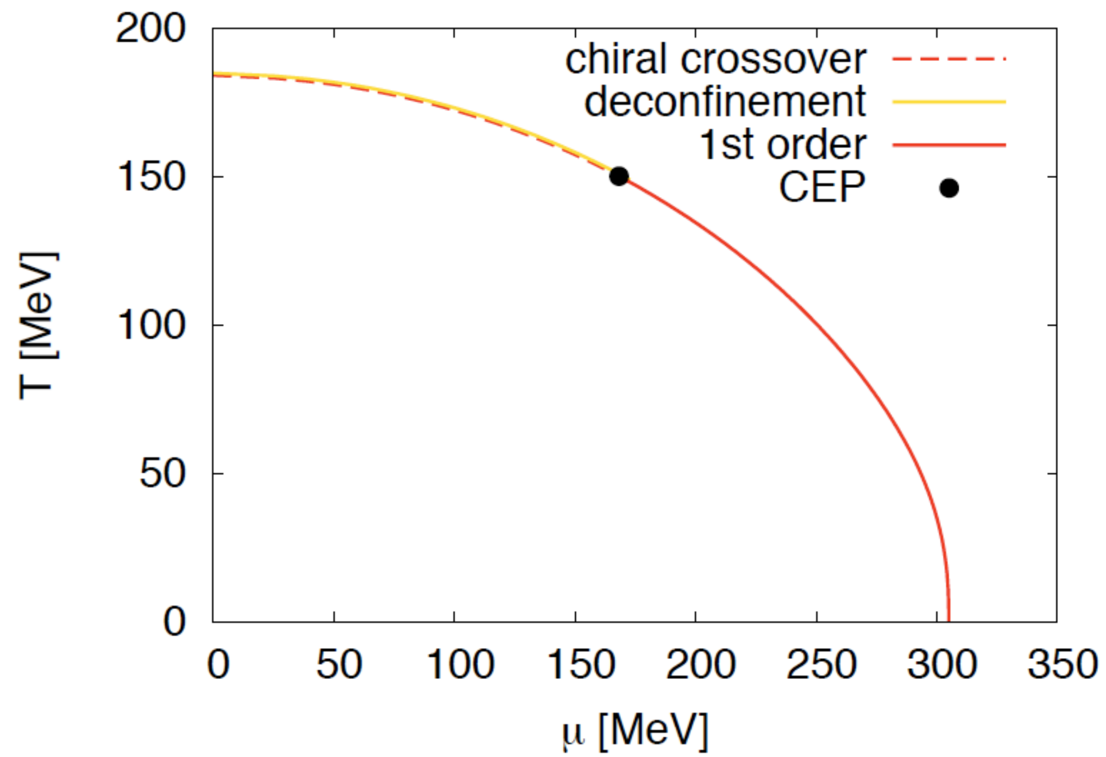
QCD flows dynamically into hadronic effective theories

- Next steps: real chemical potential & 2+1 flavours

work in progress

Summary & outlook

- Phase diagram of QCD
    - Confinement & chiral symmetry breaking at finite temperature
        - Dynamical hadronisation
    - critical point and phase lines in effective theories



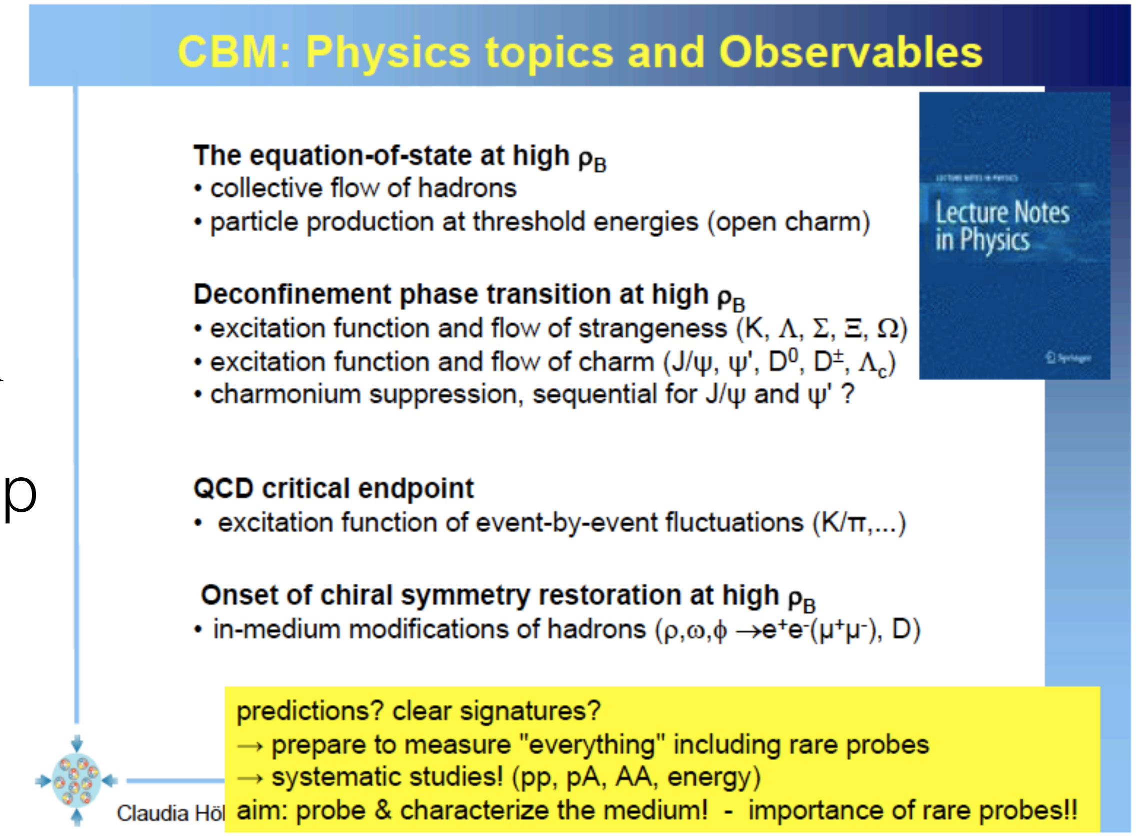
Summary & outlook

- Phase diagram of QCD
  - Confinement & chiral symmetry breaking at finite temperature
    - Dynamical hadronisation
  - critical point and phase lines in effective theories
    - Hadronic properties
  - Next step

e.g.

Top-down meets bottom-up

Refine effective hadronic theories



Summary & outlook

- Phase diagram of QCD
    - Confinement & chiral symmetry breaking at finite temperature
        - Dynamical hadronisation
    - critical point and phase lines in effective theories
        - Hadronic properties
    - non-equilibrium physics