On the phase diagram of QCD

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Quark-Gluon-Plasma meets Cold Atoms - Episode II
Riezlern, August 4th 2009

Outline

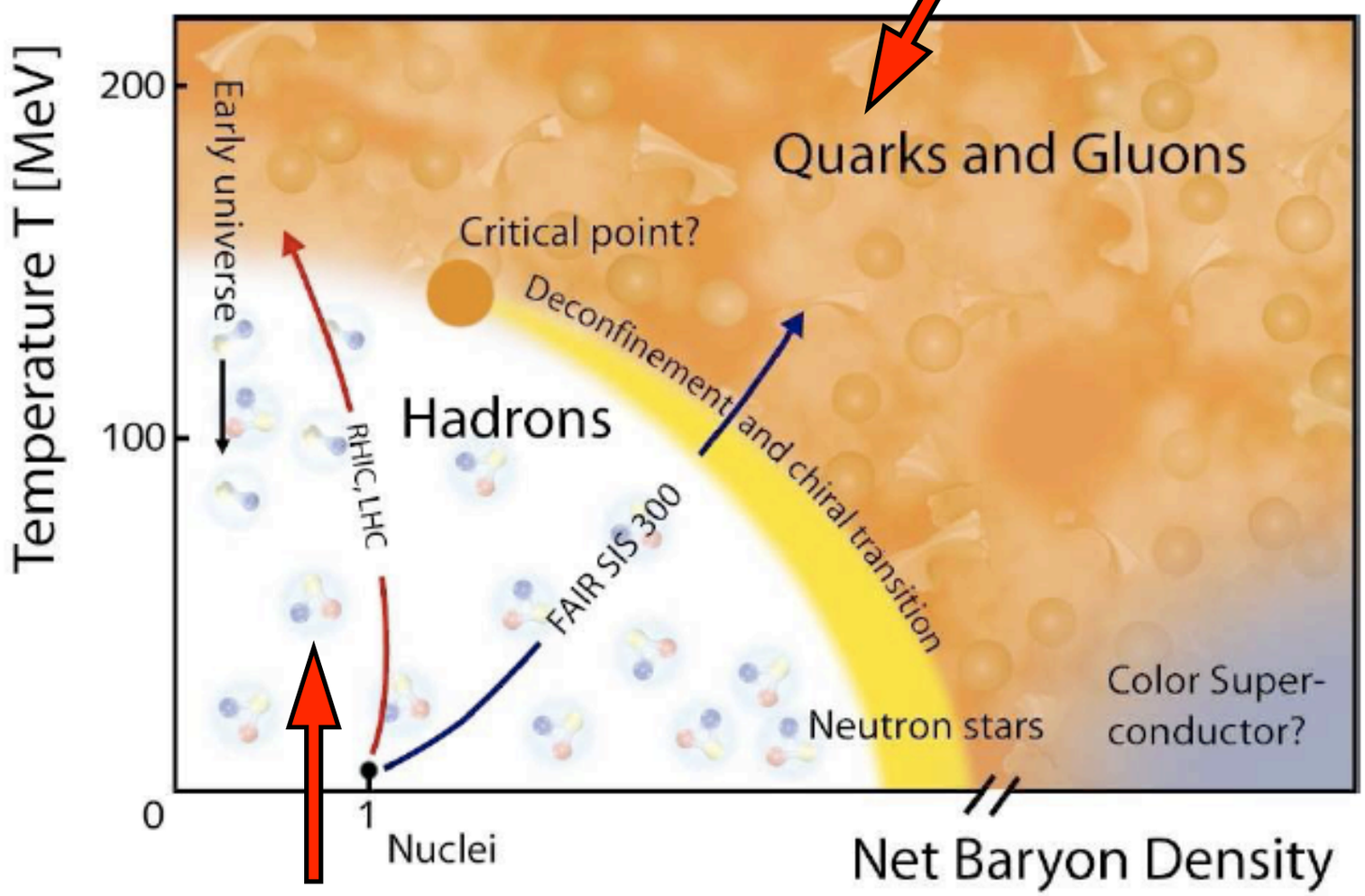
- Phase diagram of QCD: a short introduction
  - Confinement-Deconfinement phase transition
  - Chiral symmetry breaking
- Phase diagram of QCD: results
  - Quark confinement & chiral symmetry breaking
  - Chiral phase structure at finite density
- Summary and outlook

Phase diagram of QCD: a short introduction

Phasendiagram of QCD

massless quarks (chiral symmetry)

deconfinement



FAIR, www.gsi.de

hadronic phase

confinement & chiral symmetry breaking

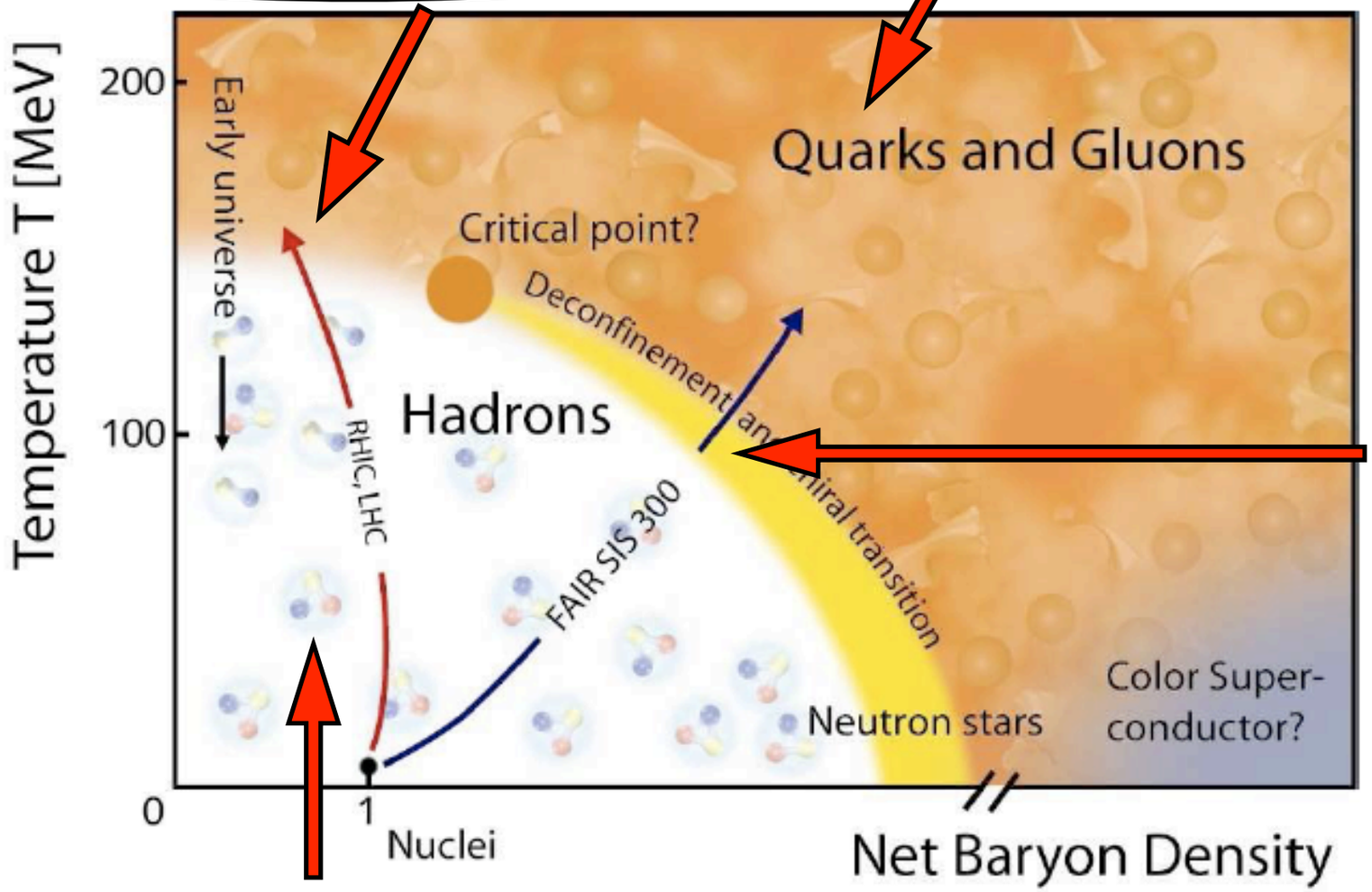
Phasendiagram of QCD

Strongly correlated quark-gluon-plasma

'RHIC serves the perfect fluid'

massless quarks (chiral symmetry)

deconfinement



FAIR, www.gsi.de

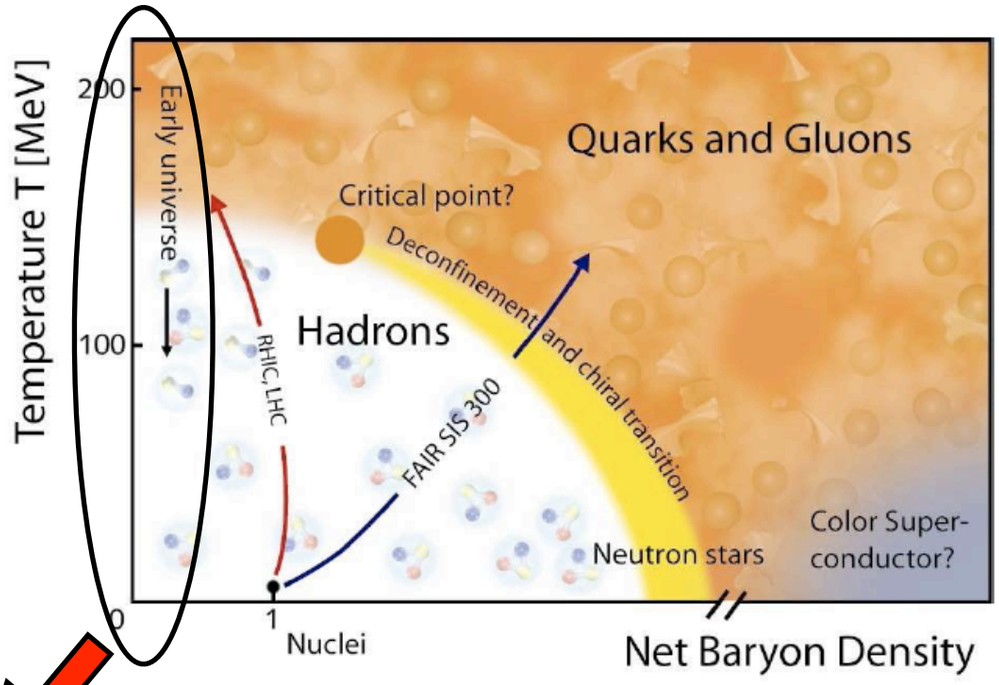
quarkyonic:

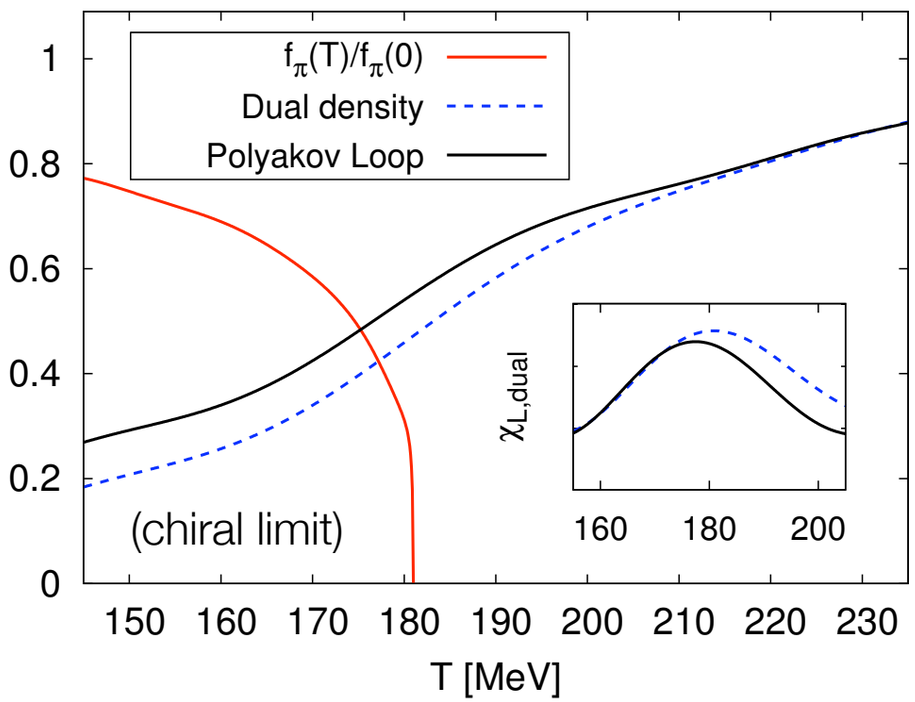
confinement & chiral symmetry

hadronic phase

confinement & chiral symmetry breaking

Phasendiagram of QCD

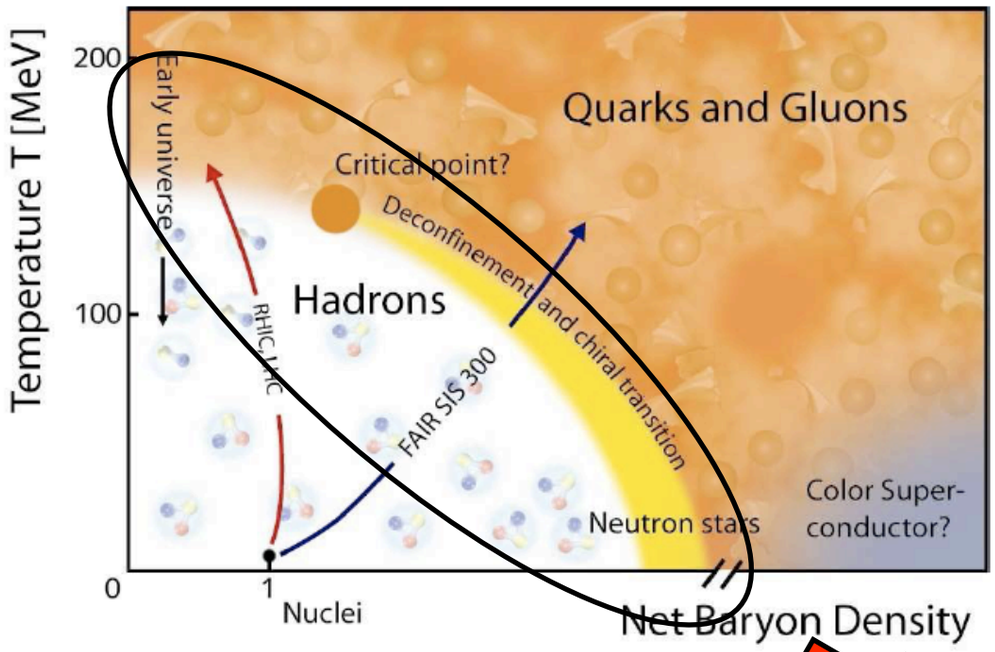




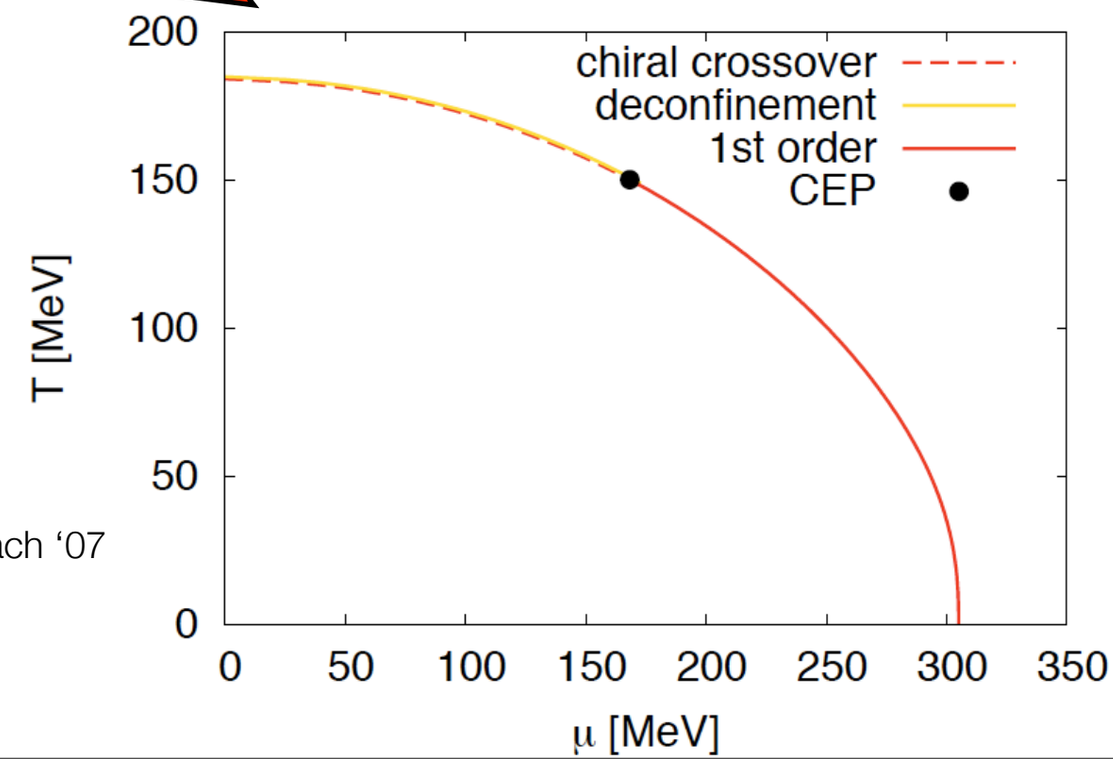
full dynamical 2 Flavour QCD

Braun, Haas, Marhauser,JMP '09

Phasendiagram of QCD

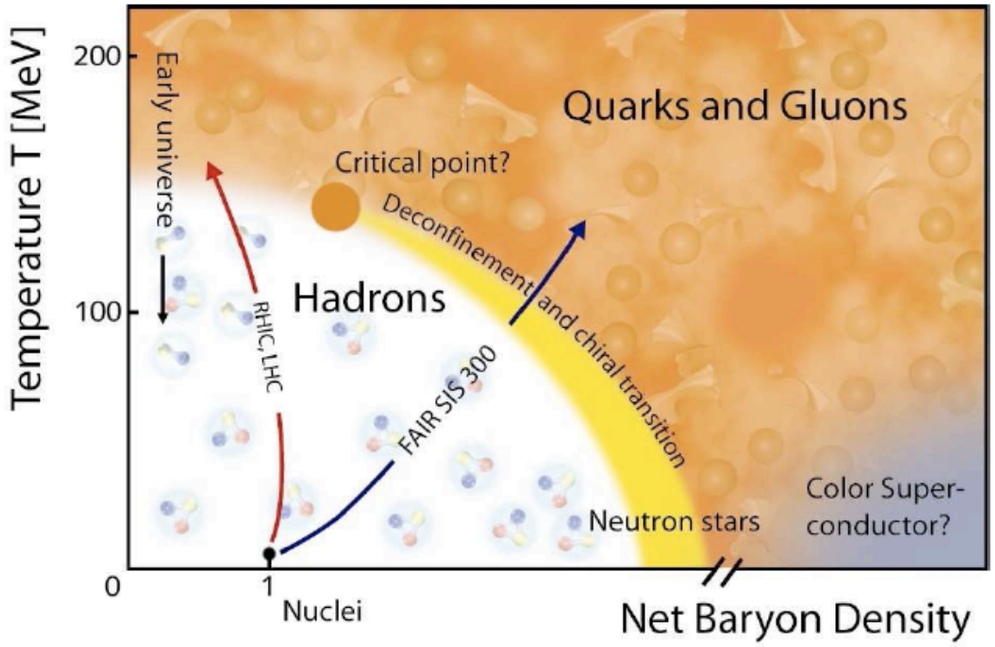


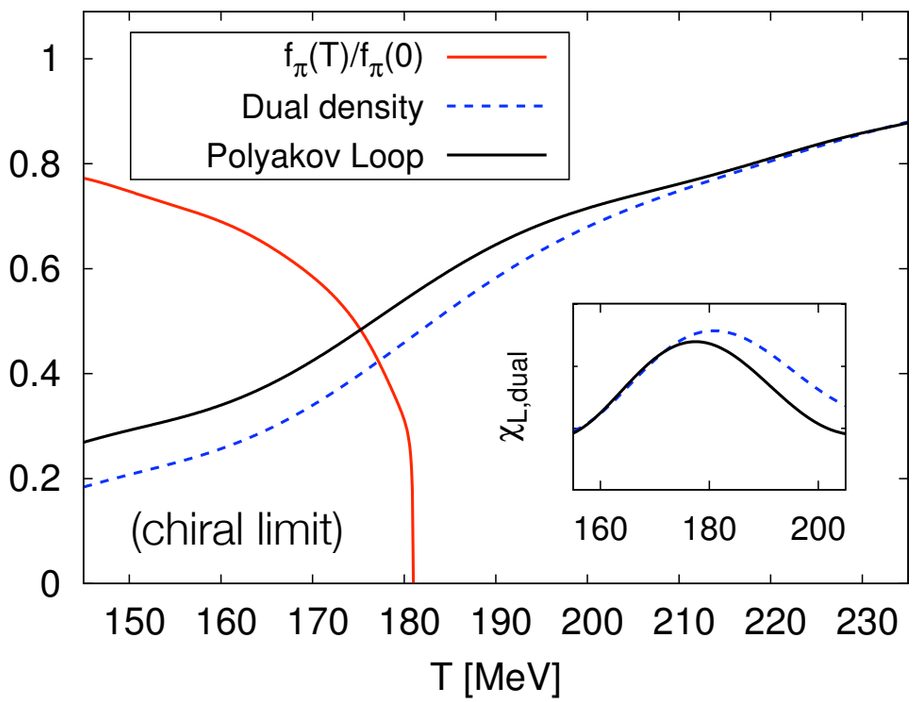
Polyakov - quark-meson model

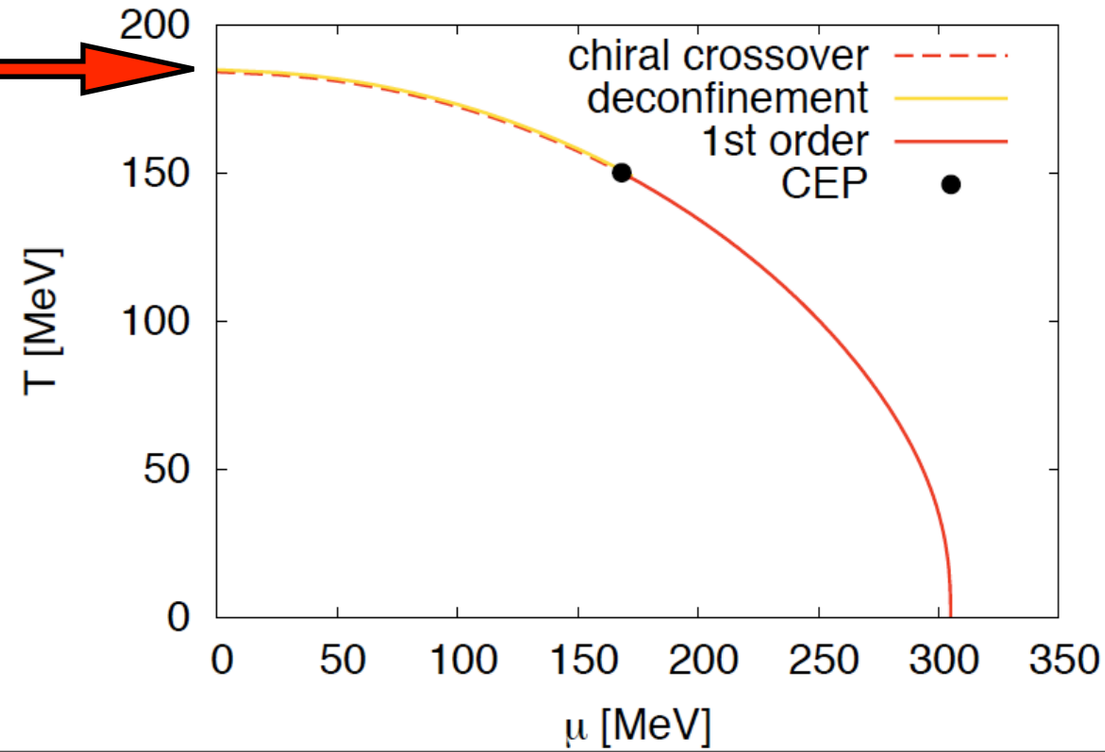


Schaefer, JMP, Wambach ‘07

Phasendiagram of QCD





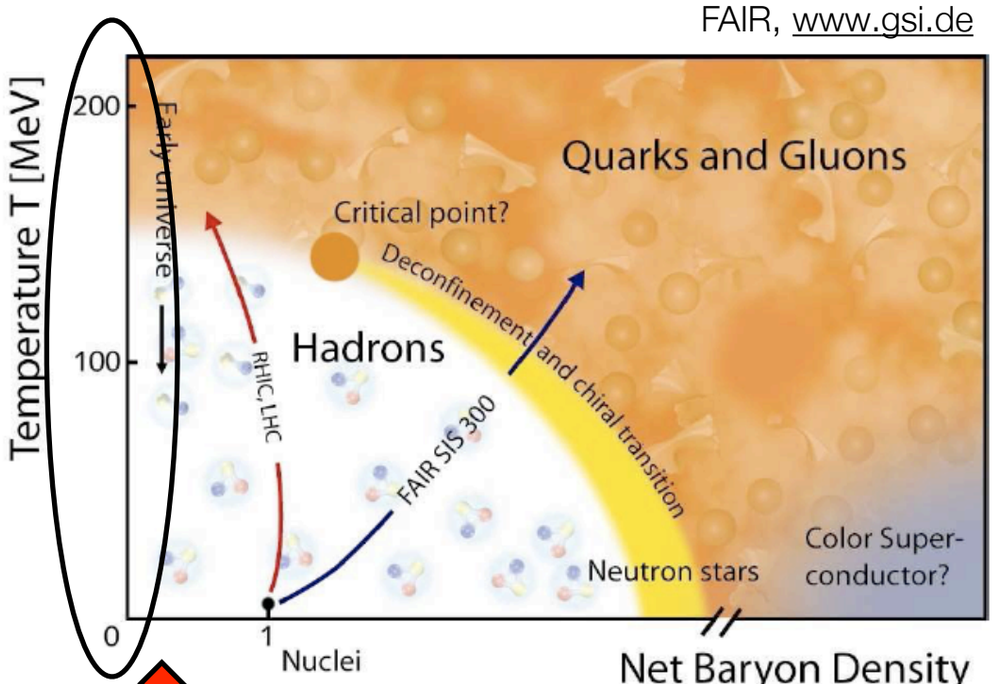


Quark-Gluon-Plasma meets Cold Atoms

QCD

Cold Atoms

FAIR, www.gsi.de



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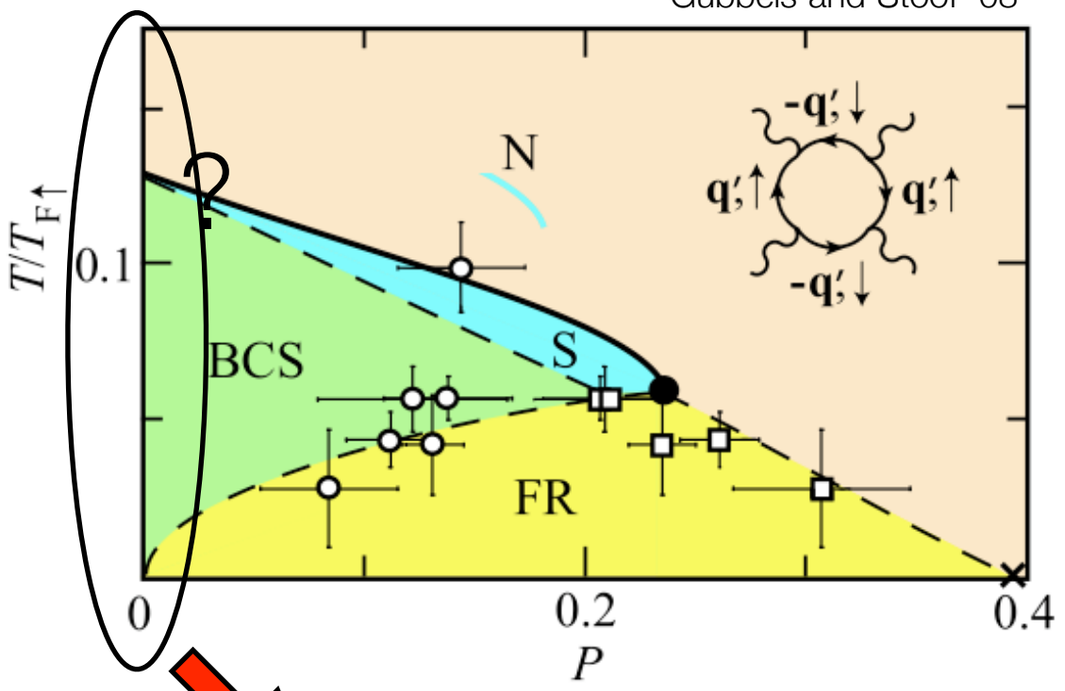
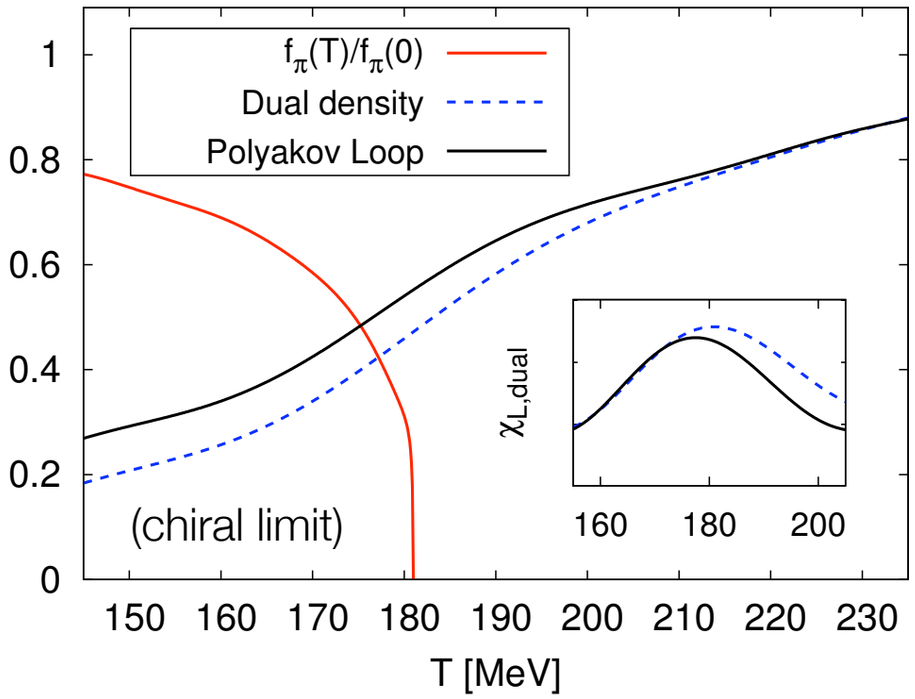
Gubbels and Stoof '08



Braun, Haas, Marhauser,JMP '09



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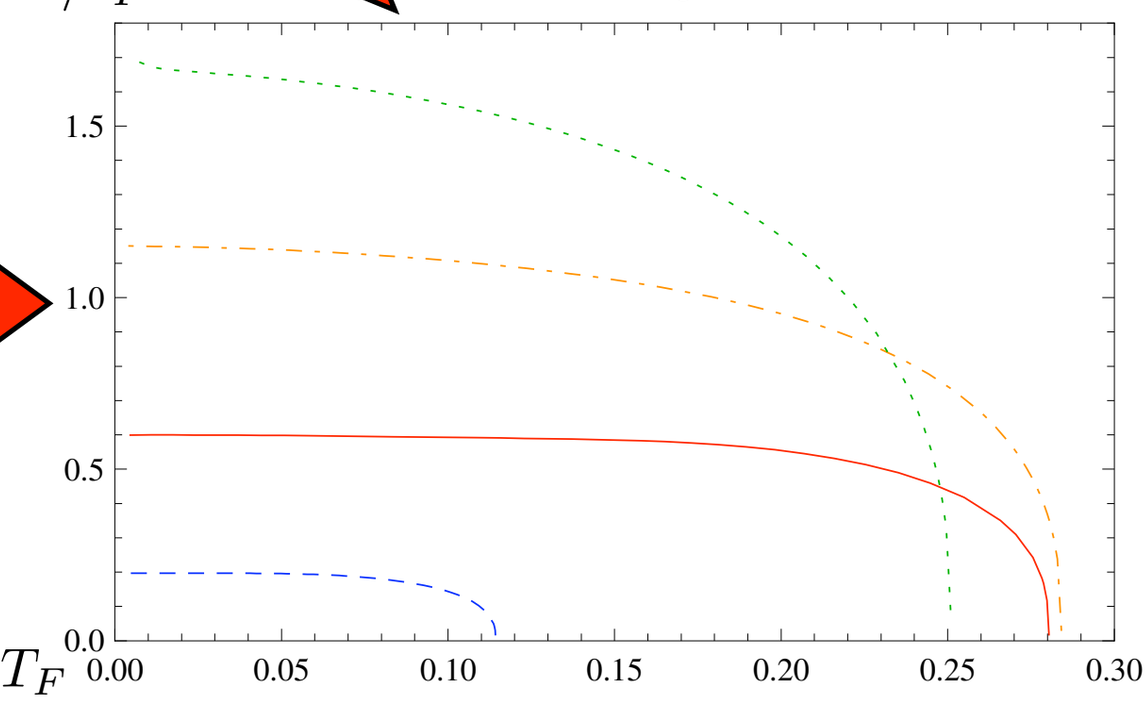
Diehl, Gies,JMP, Wetterich '07

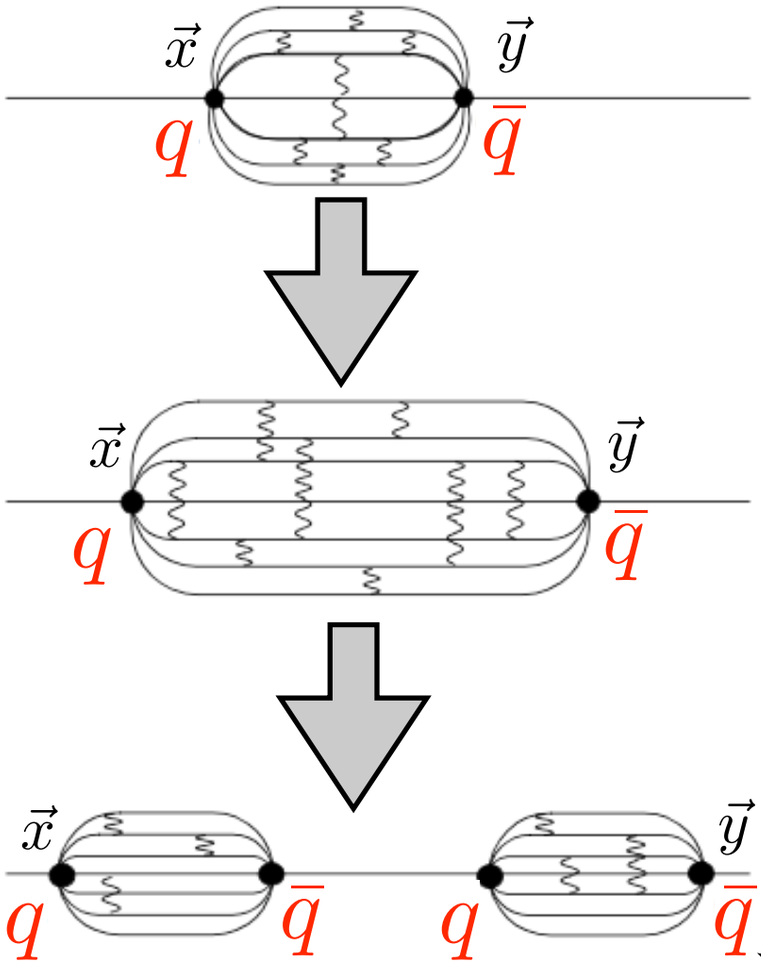
Diehl, Flörchinger, Gies,JMP, Wetterich '09



Confinement

Confinement

$$r = |\vec{x} - \vec{y}|$$



$$\langle q(\vec{x})\bar{q}(\vec{y})\rangle \simeq e^{-\beta F_{q\bar{q}}(r)}$$

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

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

$$F_{q\bar{q}} \simeq \sigma r_0$$

string breaking at $r \approx 1.1 fm$

Confinement

$$r = |\vec{x} - \vec{y}|$$

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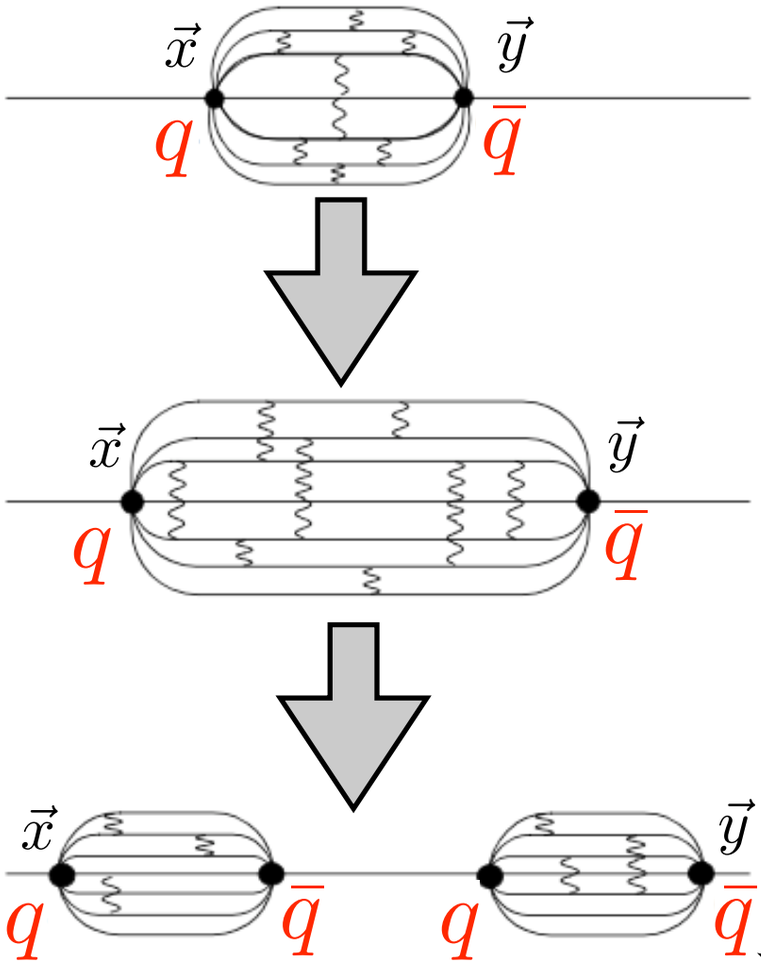

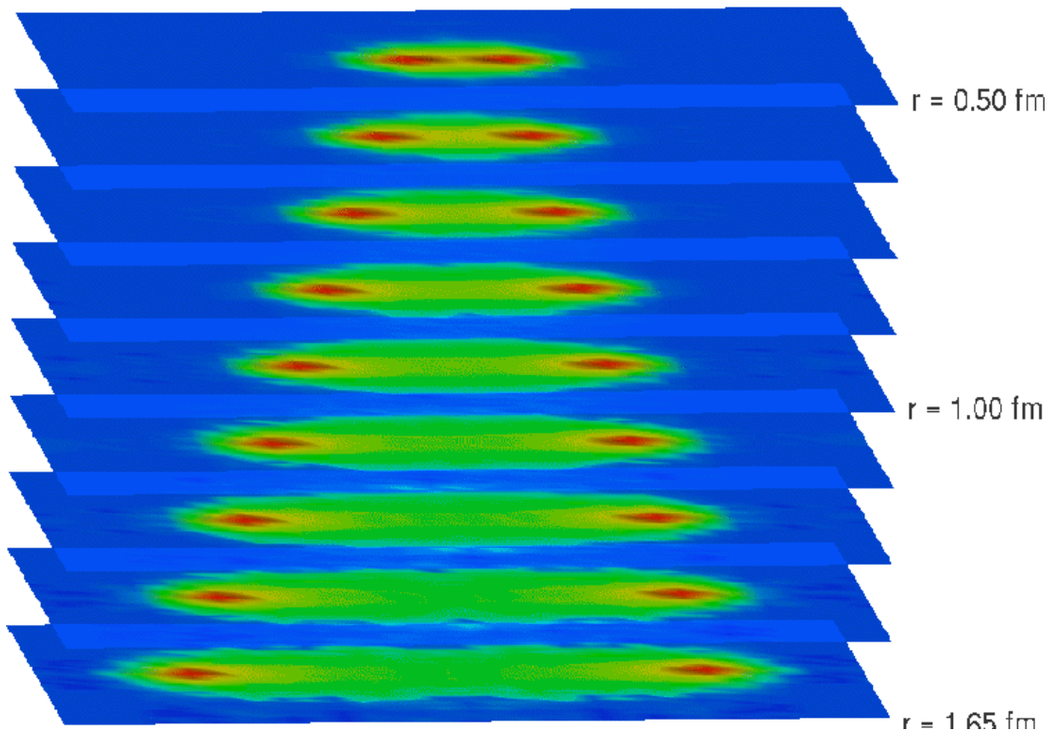

Bali et al. ‘94

string breaking at $r \approx 1.1 fm$

Confinement

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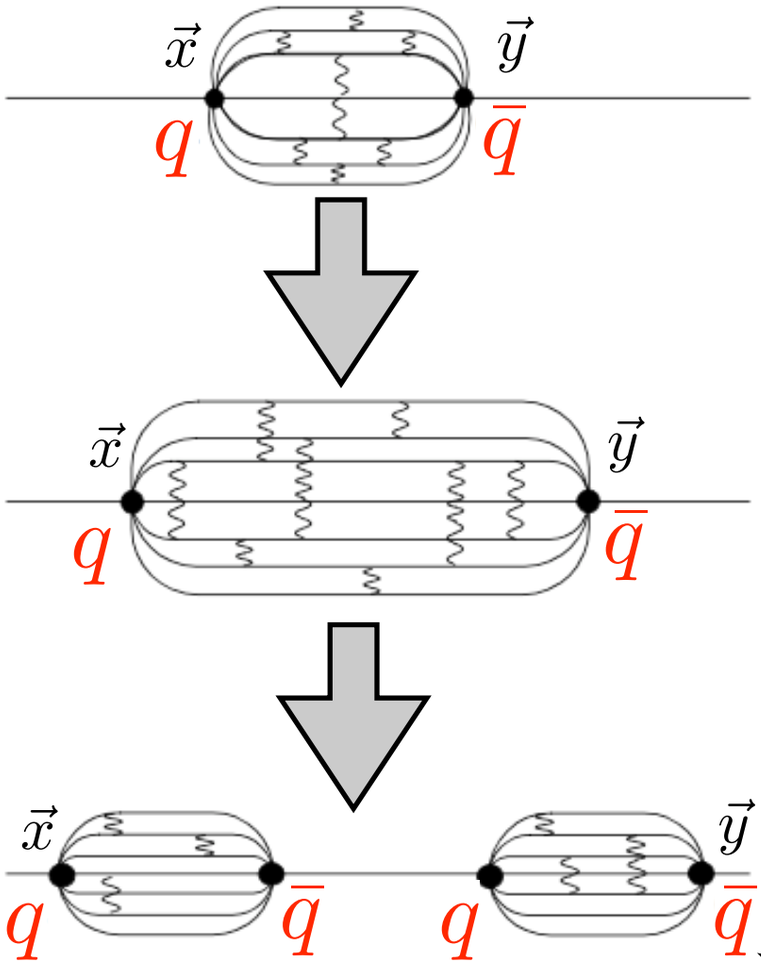
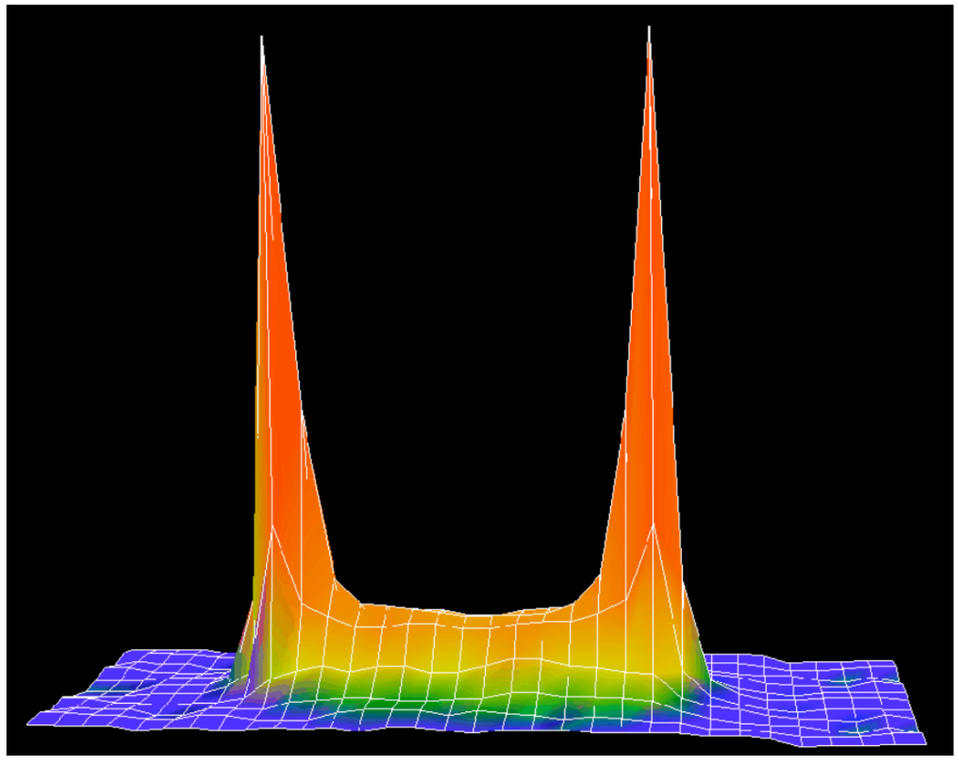


Energy density



Bali et al. ‘94

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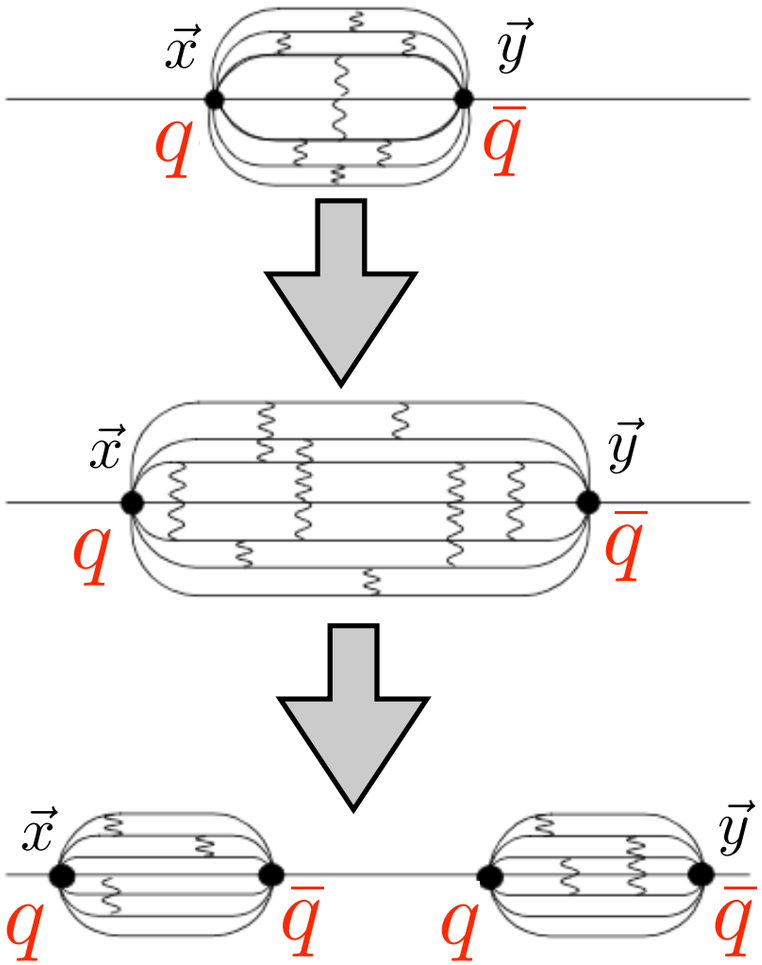


Order parameter $\sim \langle q \rangle'$

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

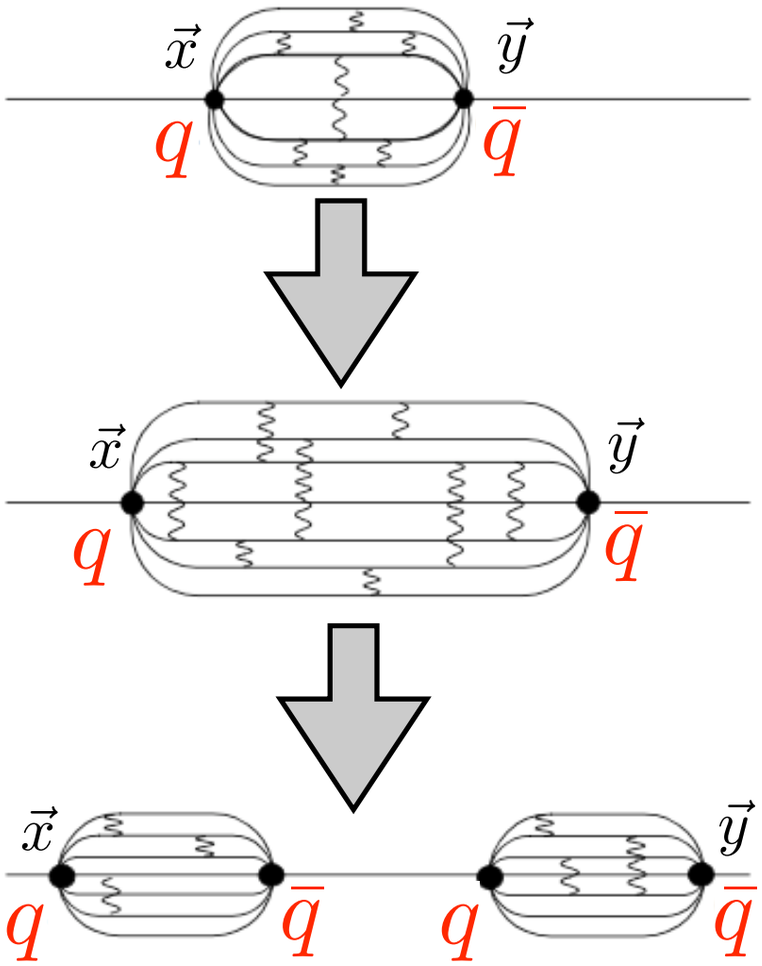
- Confinement: $\Phi = 0$
- Deconfinement: $\Phi \neq 0$

Φ Polyakov loop

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

Confinement

$$r = |\vec{x} - \vec{y}|$$



string breaking at $r \approx 1.1 fm$

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

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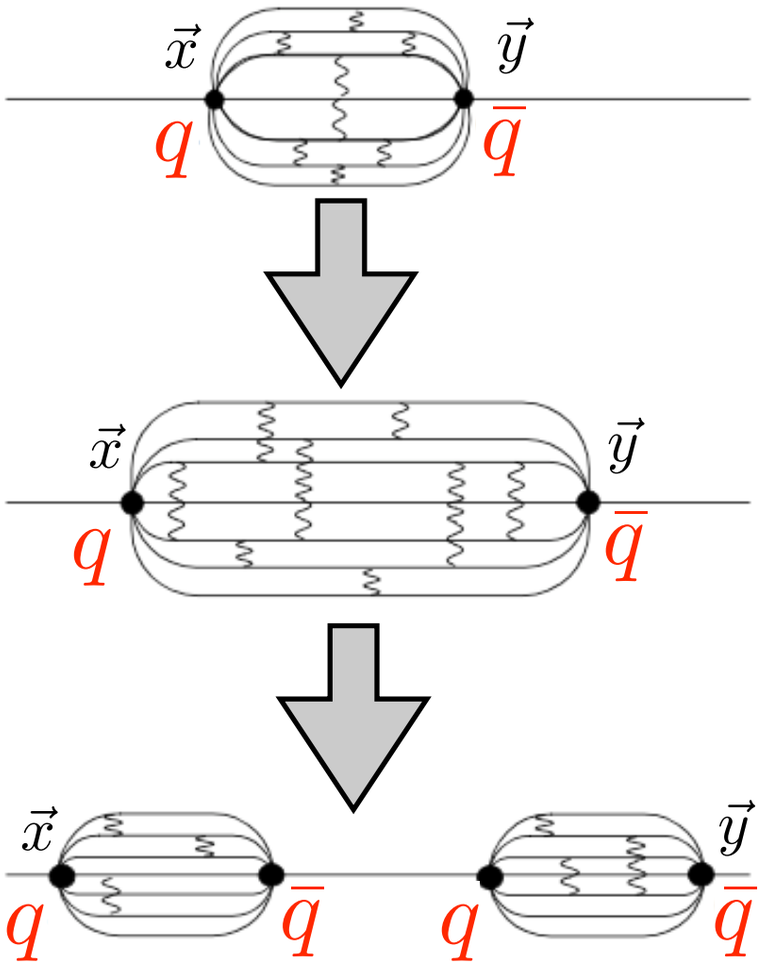
Symmetry

- Z_3 - symmetry: $q \rightarrow zq$
- broken by dynamical quarks

Confinement

$$r = |\vec{x} - \vec{y}|$$



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

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

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Mechanism?

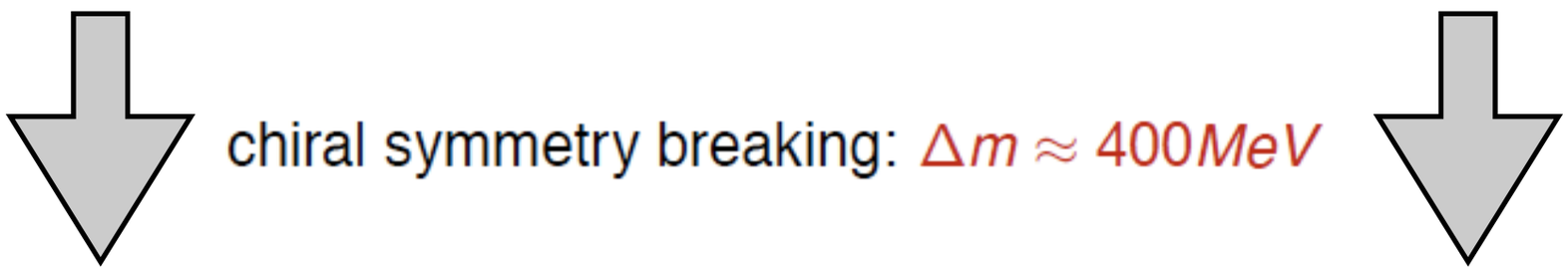
- not fully resolved

Chiral symmetry breaking

Chiral symmetry breaking

chiral symmetry

Generation	first	second	third	Charge
Mass [MeV]	1.5-4	1150-1350	170×10^3	
Quark	u	c	t	$\frac{2}{3}$
Quark	d	s	b	$-\frac{1}{3}$
Mass [MeV]	4-8	80-130	$(4.1\text{-}4.4)\times10^3$	



2 light flavours, one heavy flavour $2+1$

chiral symmetry breaking

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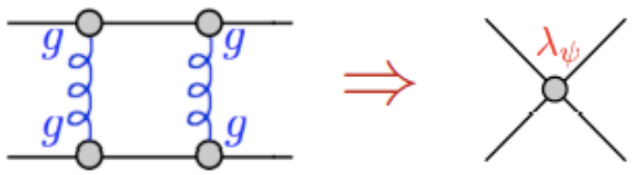
Chiral symmetry breaking



$\Rightarrow$

$\propto \alpha_s^2$

$$\int d^4x\, \lambda_\psi \left[(\bar{q}q)^2 - (\bar{q}\gamma_5 q)^2\right]$$

$$\langle \bar{q}q \rangle \neq 0$$

mass term: $\langle \bar{q}q \rangle\, \bar{q}q$

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chiral symmetry breaking: $\Delta m \approx 400 MeV$

2 light flavours, one heavy flavour $2+1$

Generation	first	second	third	Charge
Mass [MeV]	1.5-4	1150-1350	170×10^3	
Quark	u	c	t	$\frac{2}{3}$
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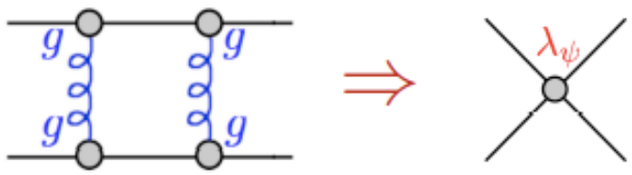
Chiral symmetry breaking



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mass term: $\langle \bar{q}q \rangle\, \bar{q}q$

Order parameter

$$\sigma = \langle \bar{q}q \rangle$$

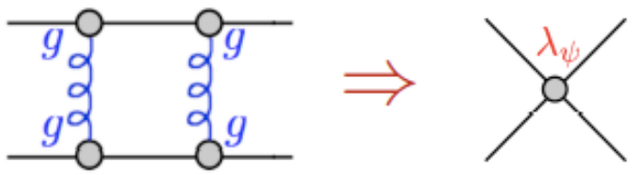
chiral condensate

- chiral symmetry: $\sigma = 0$
- symmetry breaking: $\sigma \neq 0$

Symmetry

- $SU_L(N_f) \times SU_R(N_f)$
- broken to $SU(N_f)$

Chiral symmetry breaking



$\Rightarrow$

$\propto \alpha_s^2$

$$\int d^4x \, \lambda_\psi \left[(\bar{q}q)^2 - (\bar{q}\gamma_5 q)^2 \right]$$

$\langle \bar{q}q \rangle \neq 0$

mass term: $\langle \bar{q}q \rangle \, \bar{q}q$

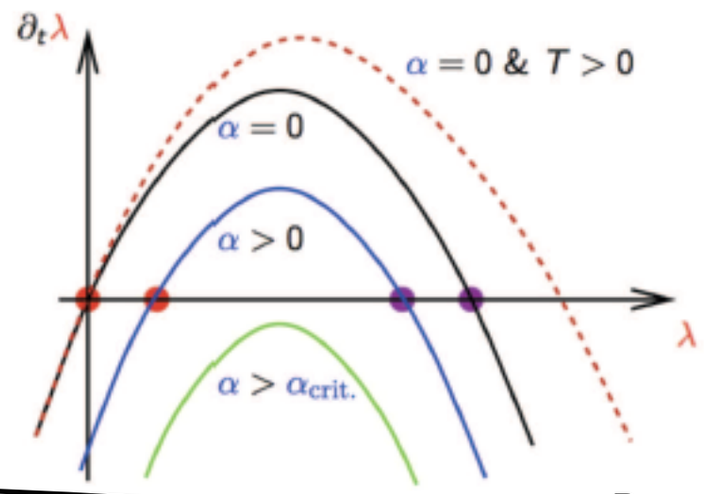
$\alpha_s > \alpha_{s,\mathrm{crit}}$

Order parameter

$$\sigma = \langle \bar{q}q \rangle$$

chiral condensate

- chiral symmetry: $\sigma = 0$
- symmetry breaking: $\sigma \neq 0$



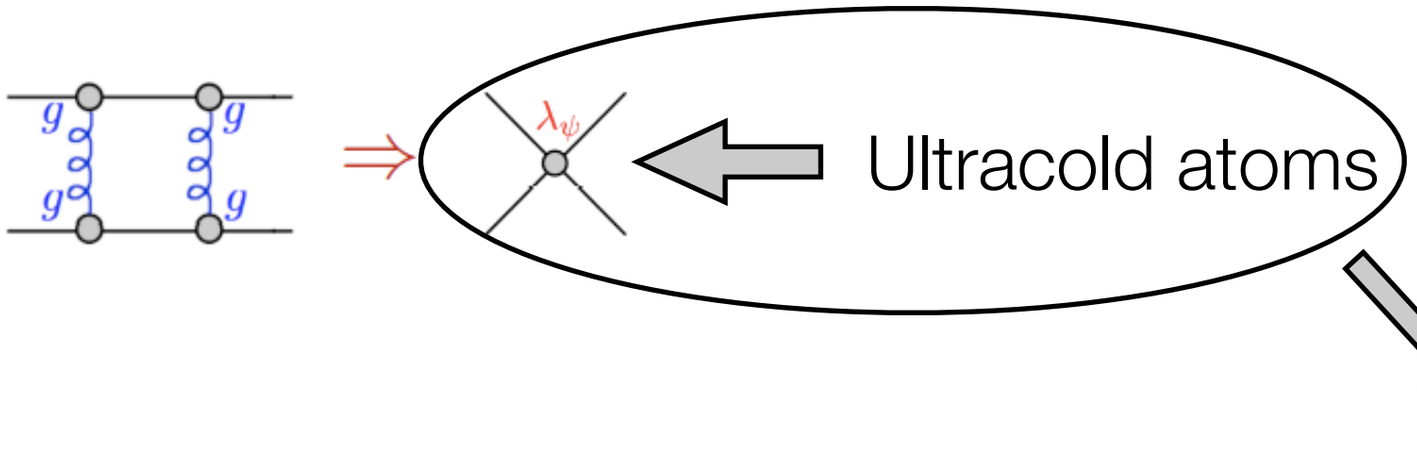
Braun, Gies ‘06

Chiral symmetry breaking directly sensitive to size of α_s

Quark-Gluon-Plasma meets Cold Atoms

Condensation phenomena

QCD | Cold Atoms



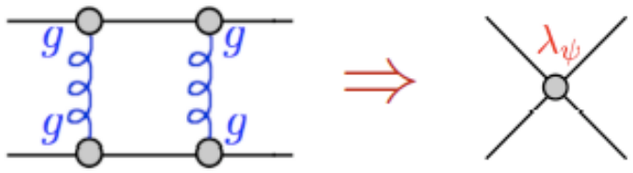
talks of Stefan Flörchinger
Richard Schmidt

Rapp et al ‘06

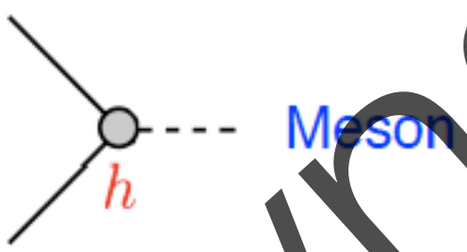
Quark-Gluon-Plasma meets Cold Atoms

Condensation phenomena ⟸ (functional RG-flows)

QCD | Cold Atoms



Hadronisation | Molecule formation



+Baryons and Glueballs | +Trions

Dynamical

Condensation

talks of Stefan Flörchinger
Richard Schmidt

Gies, Wetterich ‘01

JMP ‘05

Flörchinger, Wetterich ‘09

Phase diagram of QCD: Results

Quark confinement & chiral symmetry breaking

Continuum Methods

The Functional RG

- Introduction to Functional RG flows & some results in QCD (talks)
  - Integrals from differential equations: The FRG-idea in 0+0-dimensions
    http://www.thphys.uni-heidelberg.de/~pawlowsk/NPgauge/bonus/idea.pdf
  - Introduction to the Functional RG & QCD flows
    http://www.thphys.uni-heidelberg.de/~pawlowsk/talks/graz.pdf
  - Confinement & chiral symmetry breaking from Functional Methods
    http://www.thphys.uni-heidelberg.de/~pawlowsk/talks/berlin08.pdf

Confinement

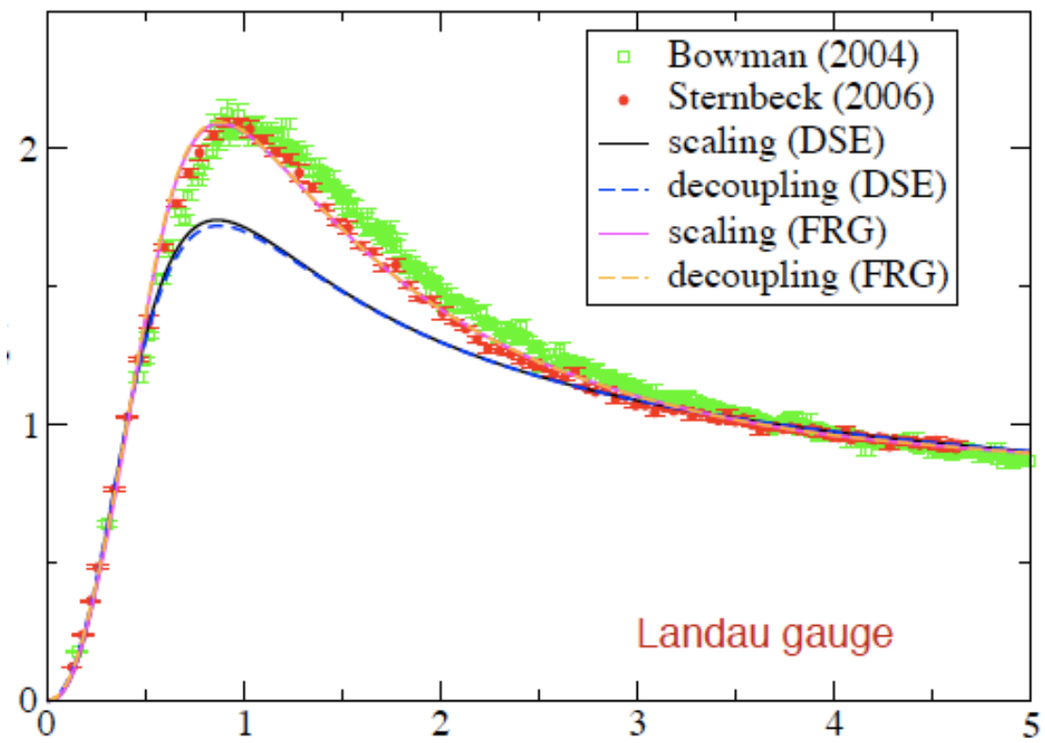
Continuum methods ⟸ (Functional RG-flows)

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

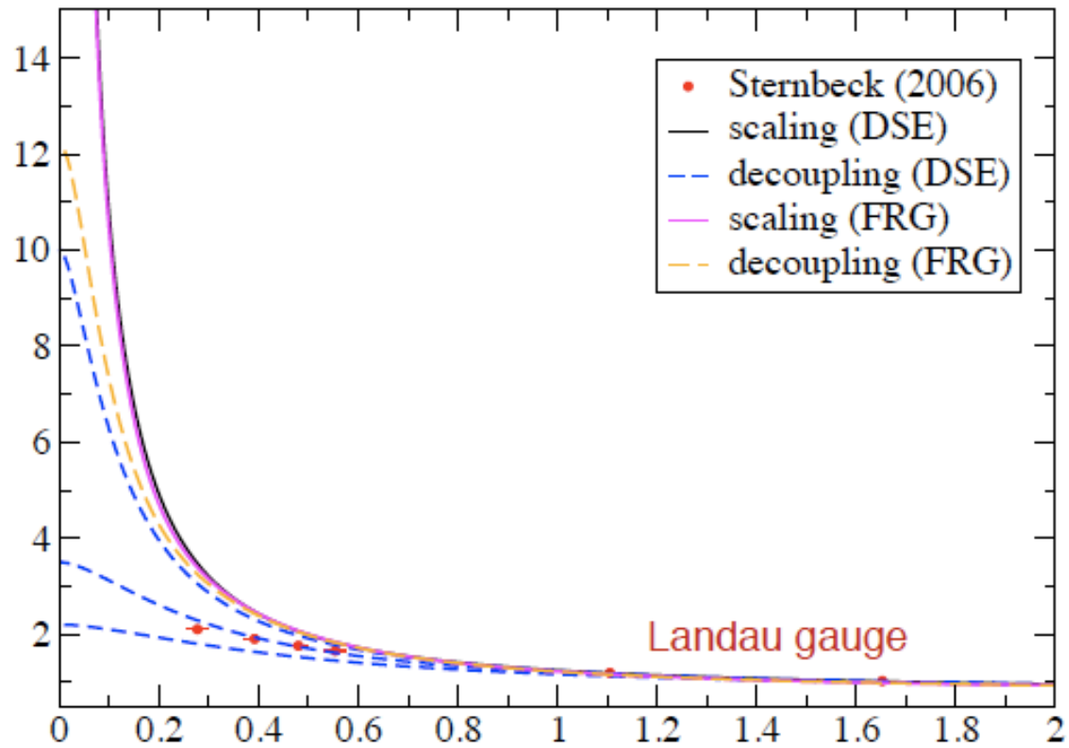
Braun, Gies, JMP '07

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

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



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



p [GeV]

Fischer, Maas, JMP '08

Confinement

Continuum methods

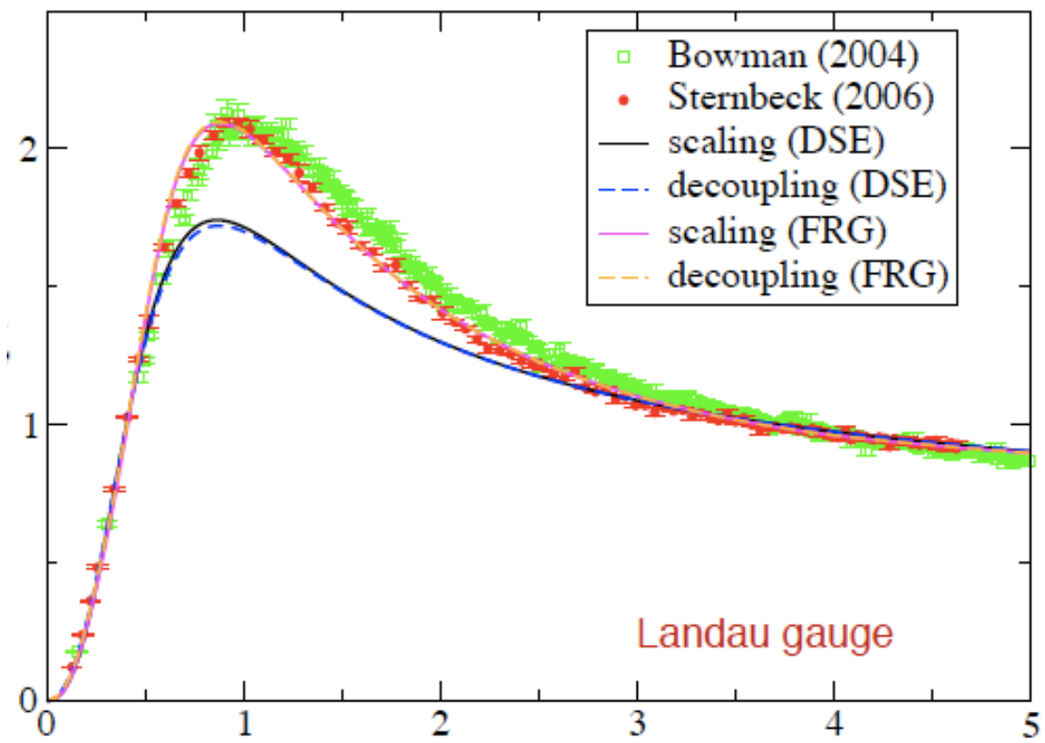
Braun, Gies, JMP '07

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

'Polyakov loop potential'

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

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



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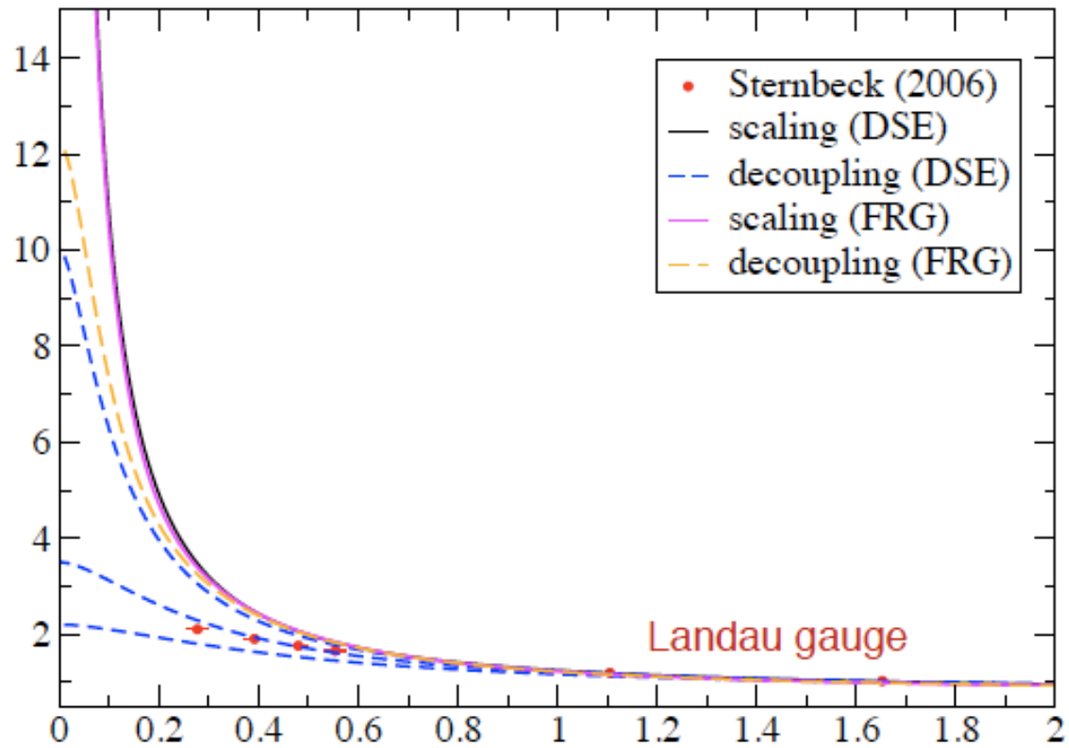
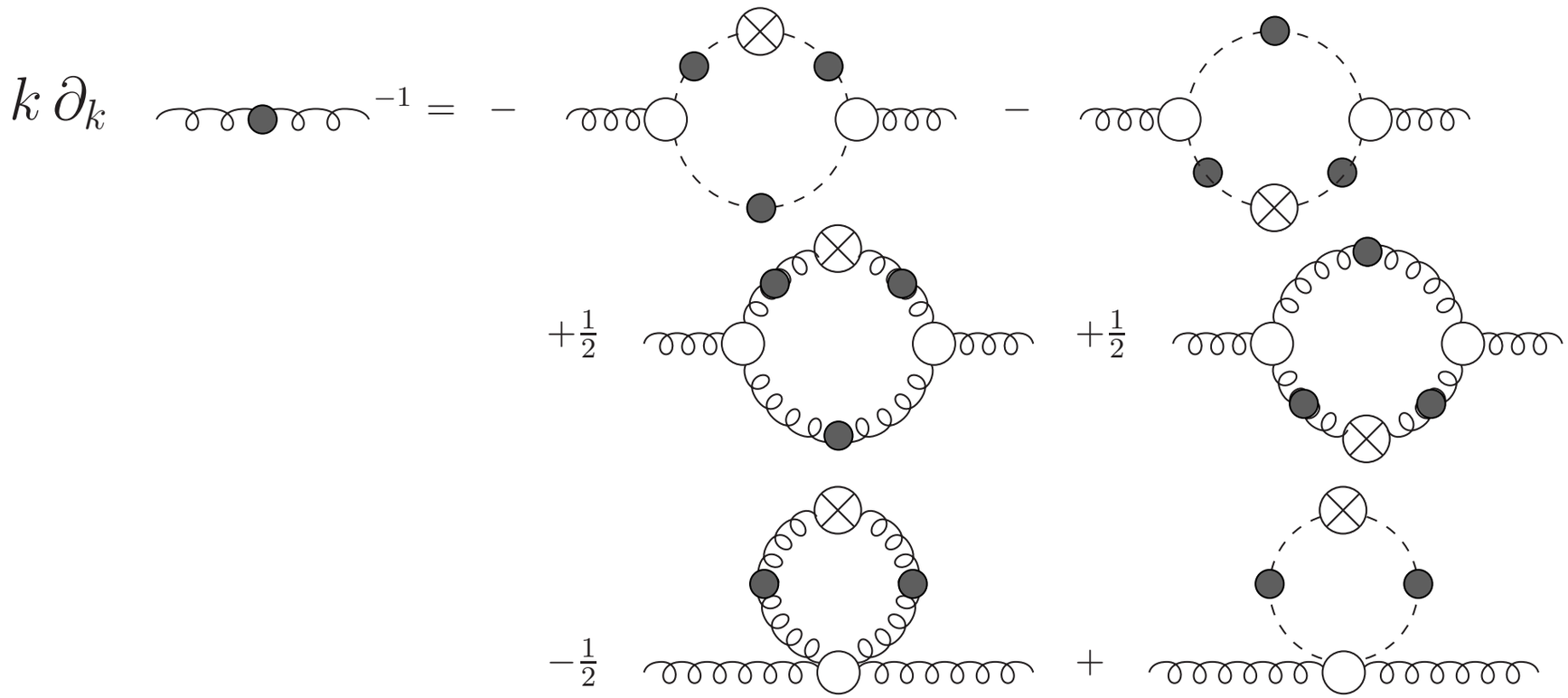


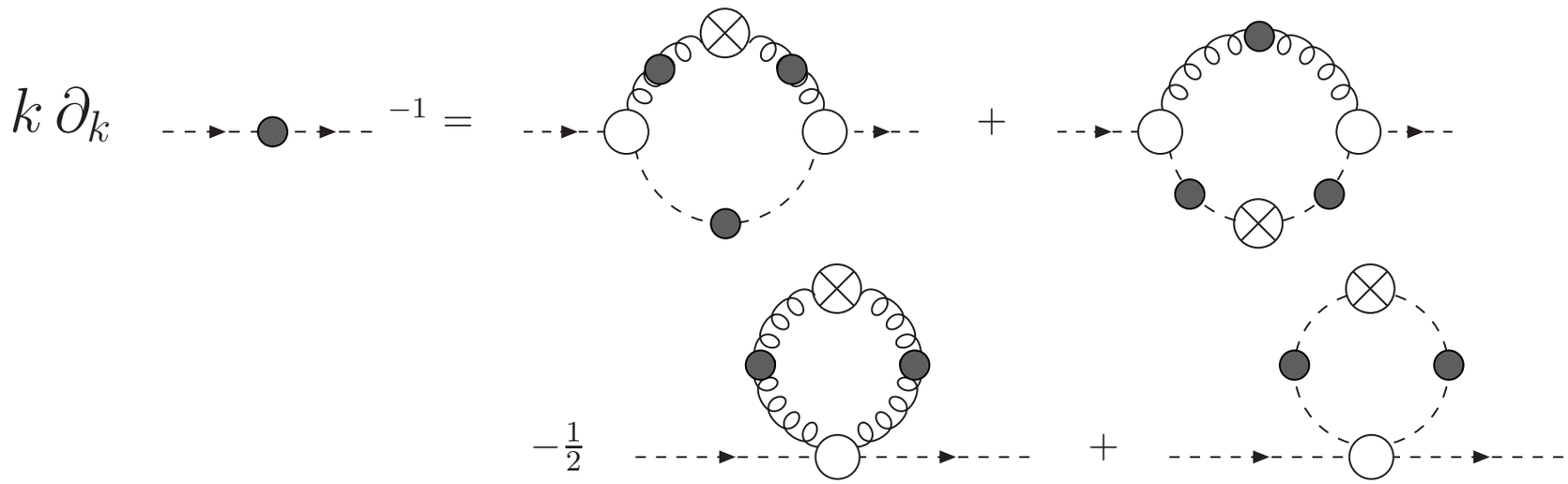
p [GeV]

Fischer, Maas, JMP '08

Confinement

Continuum methods

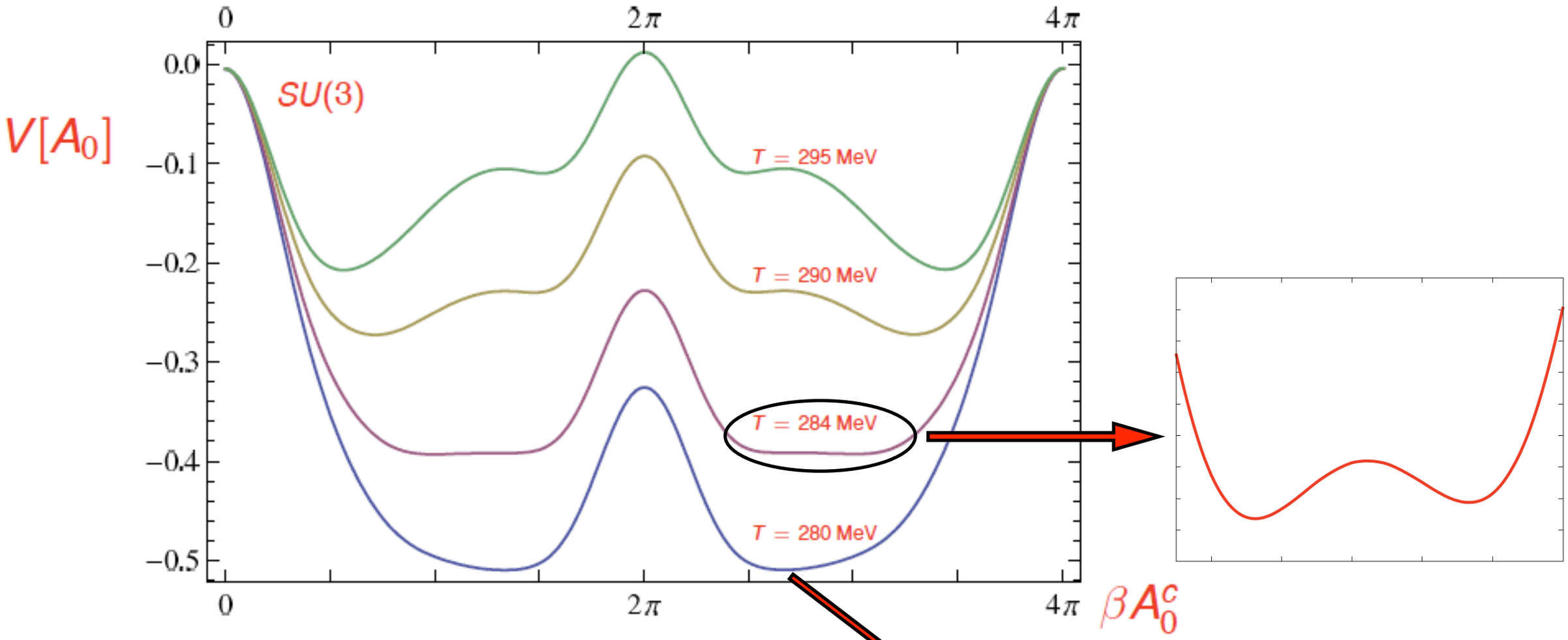




Confinement

Continuum methods

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



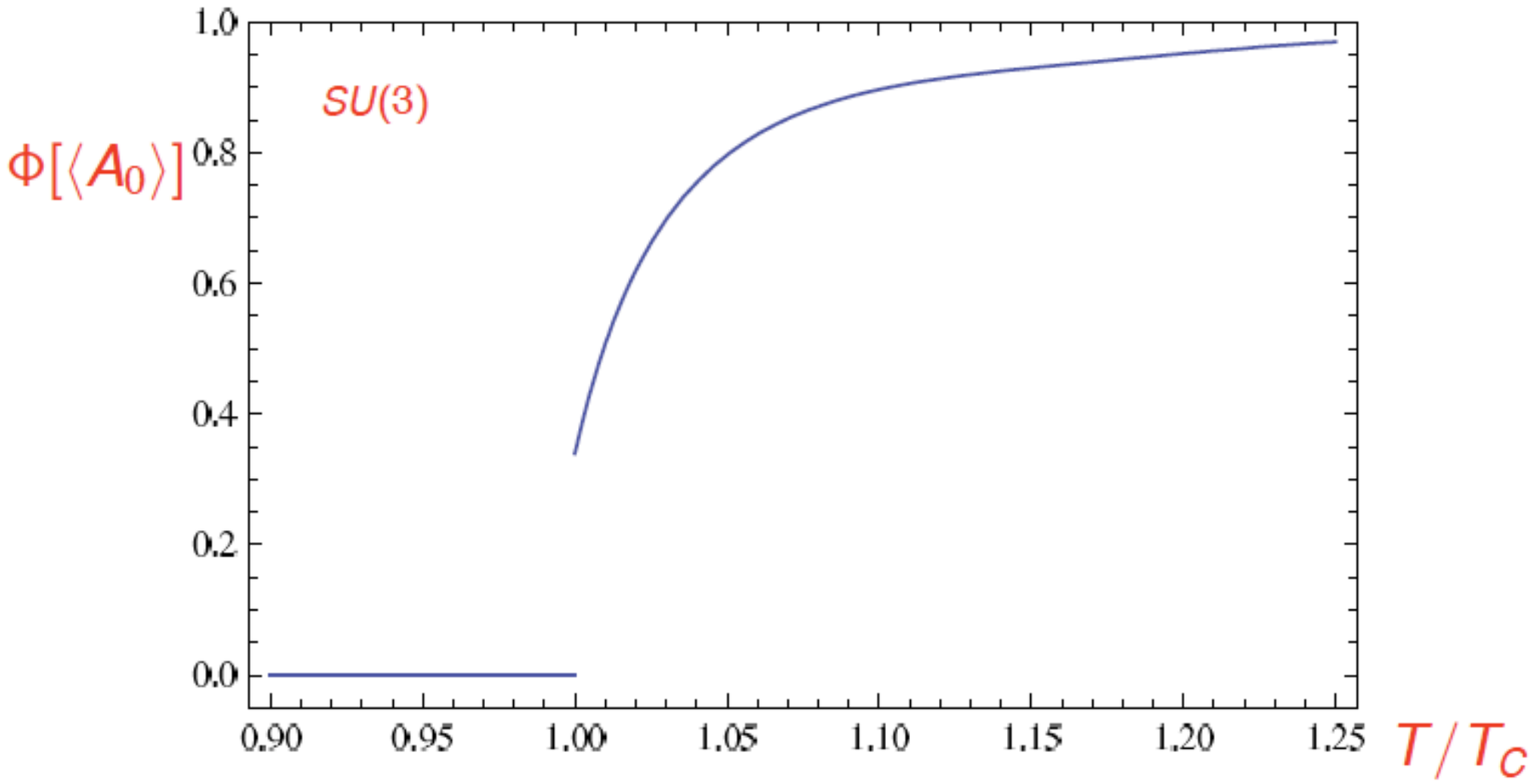
$$\Phi[A_0^c] = \frac{1}{3}(1 + 2\cos\frac{1}{2}\beta A_0^c) \longrightarrow \Phi[\frac{8}{3}\pi] = 0$$

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: $T_c/\sqrt{\sigma} = .646$



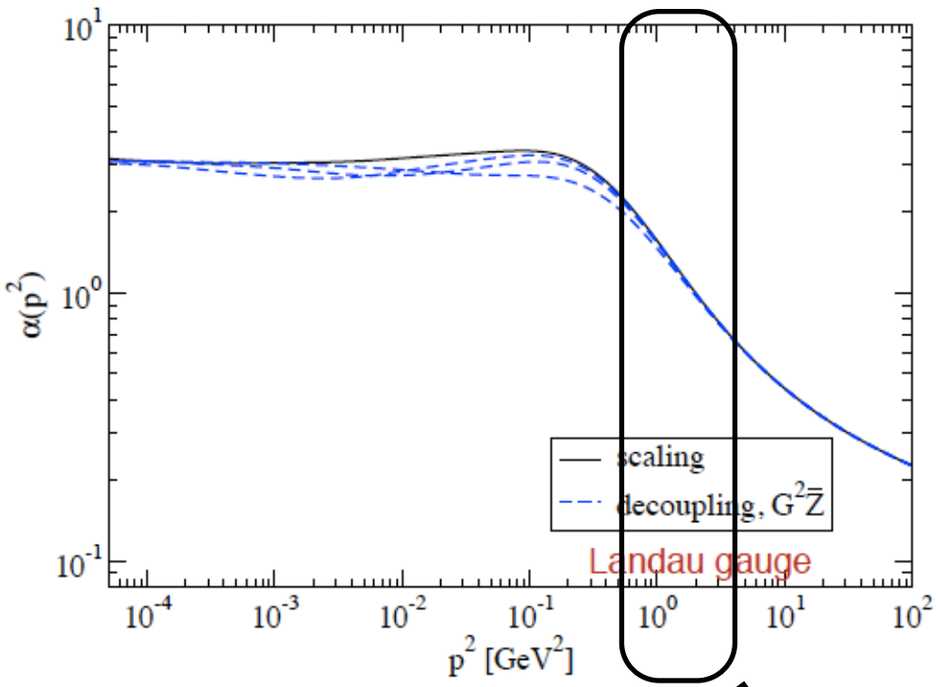
Braun, Gies, JMP ‘07

Confinement

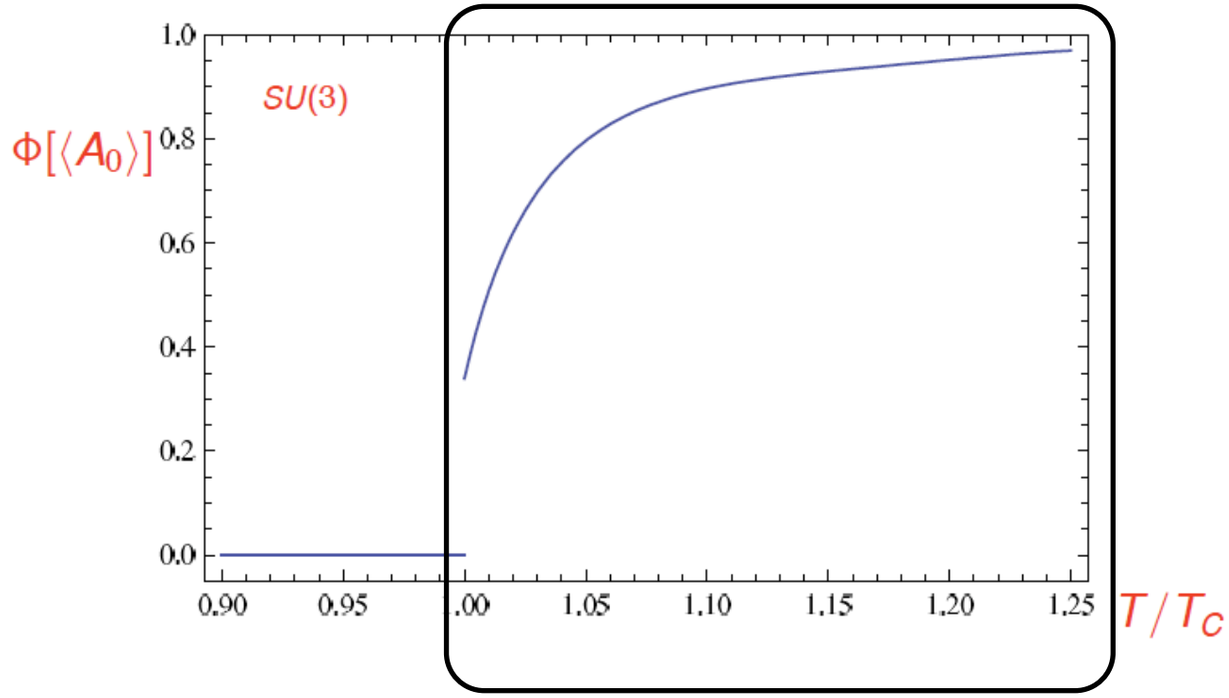
Continuum methods

$\alpha_s \sim p^6 \langle AA \rangle \langle C\bar{C} \rangle^2$

Fischer, Maas, JMP '08



Braun, Gies, JMP '07



$$p\frac{\partial \alpha_s}{\partial p} \simeq T\frac{\partial \alpha_s}{\partial T}$$

Confinement is sensitive to $T\partial_T \ln \alpha_s$, not to $\alpha_s \sim 1/N_c$

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 $\psi_\theta = e^{2\pi i\theta t/\beta}\psi$

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

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

Dual order parameter

Continuum methods ⟸ (Functional RG-flows)

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

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

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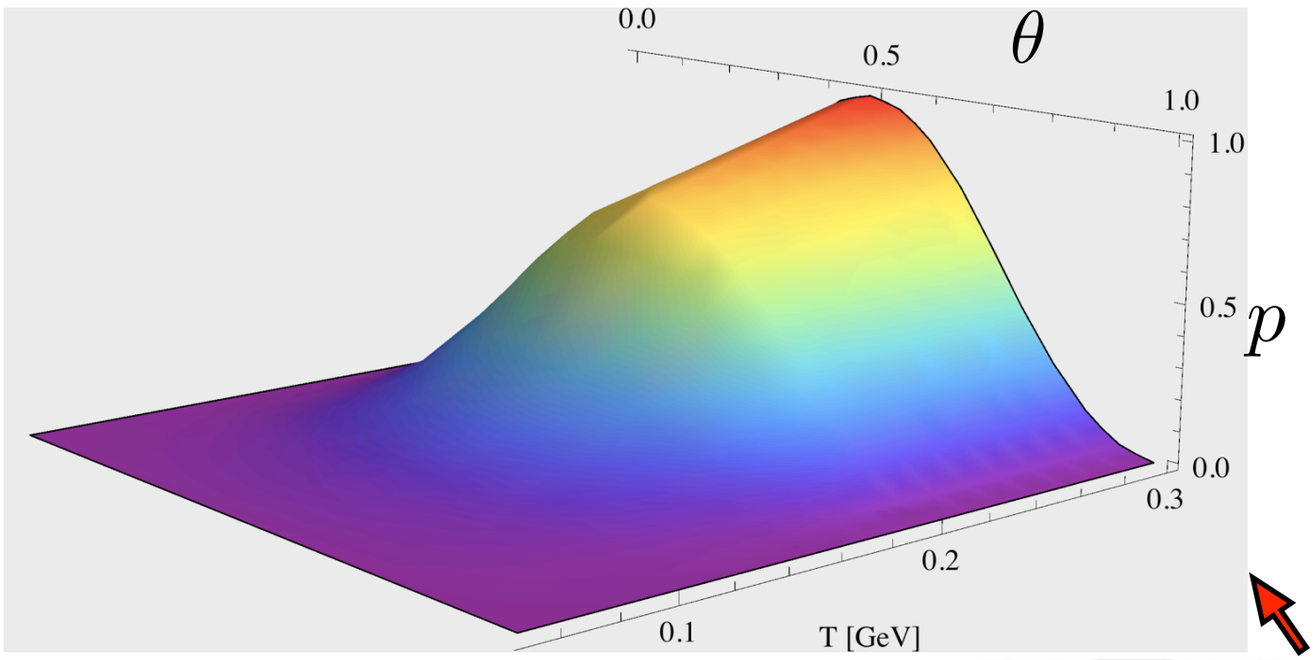
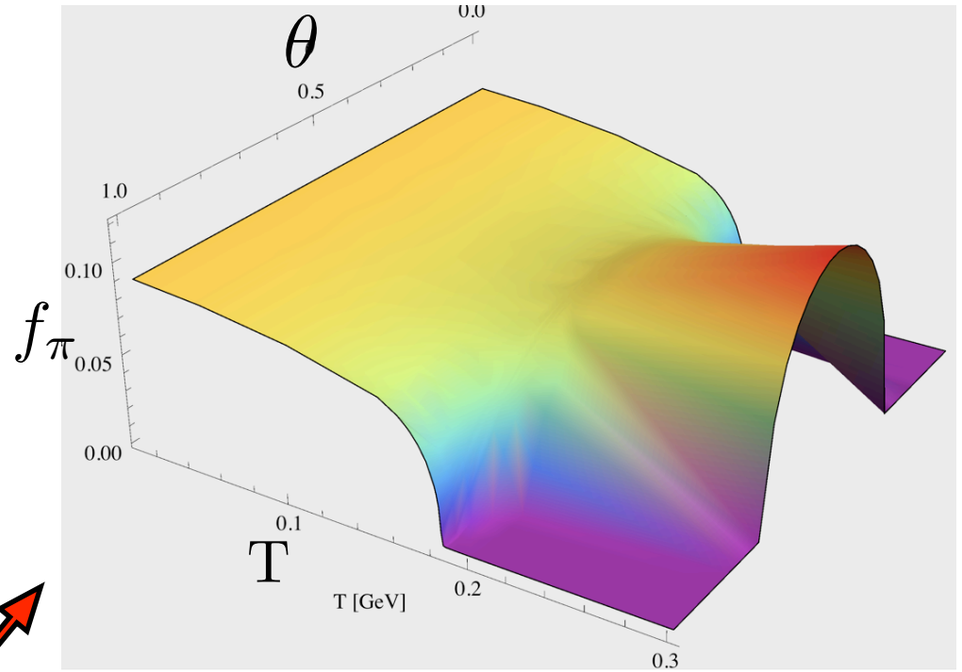
order parameter for confinement

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

$f_\pi(T,\theta)$





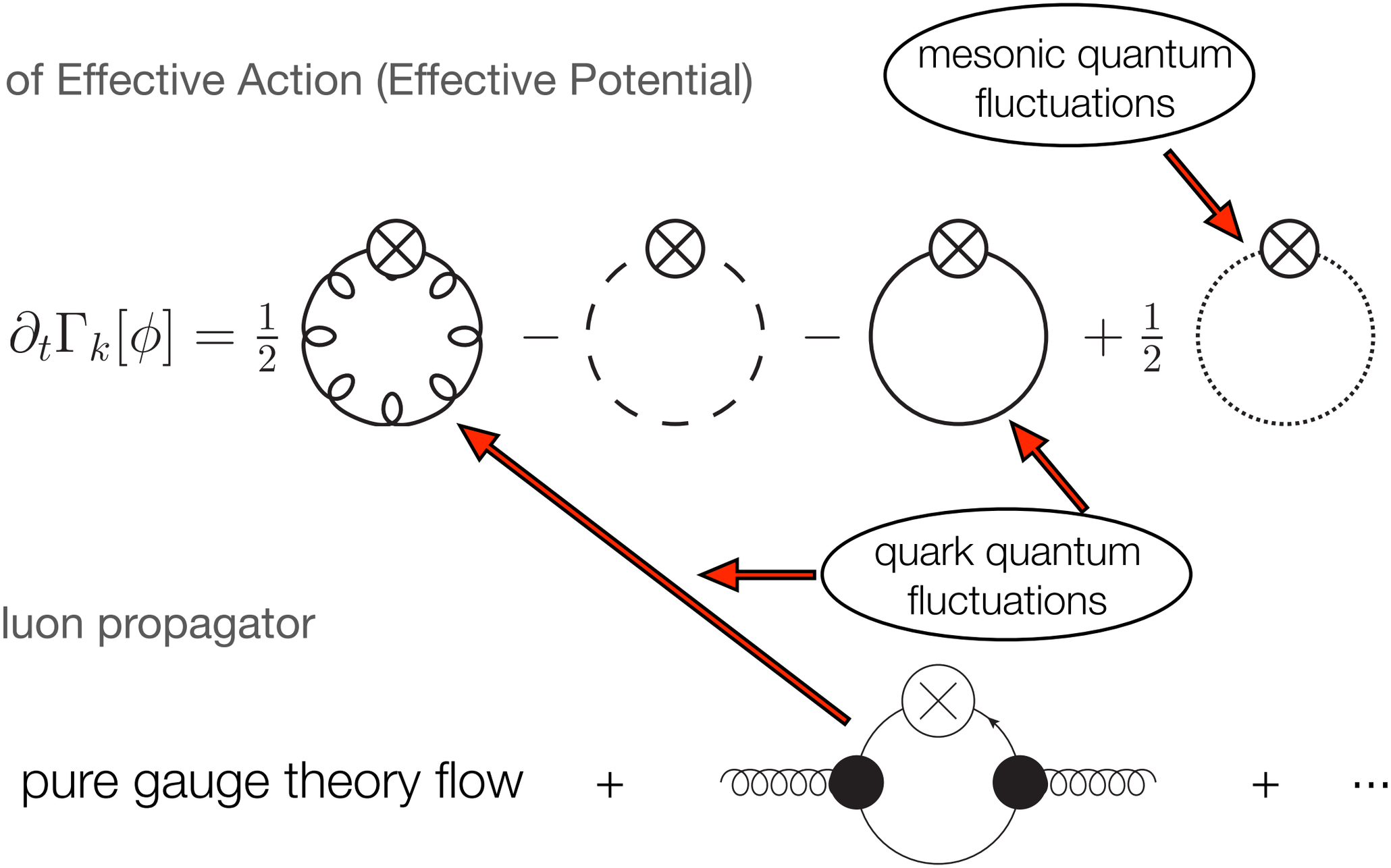
fixed A_0: no Roberge-Weiss periodicity

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)

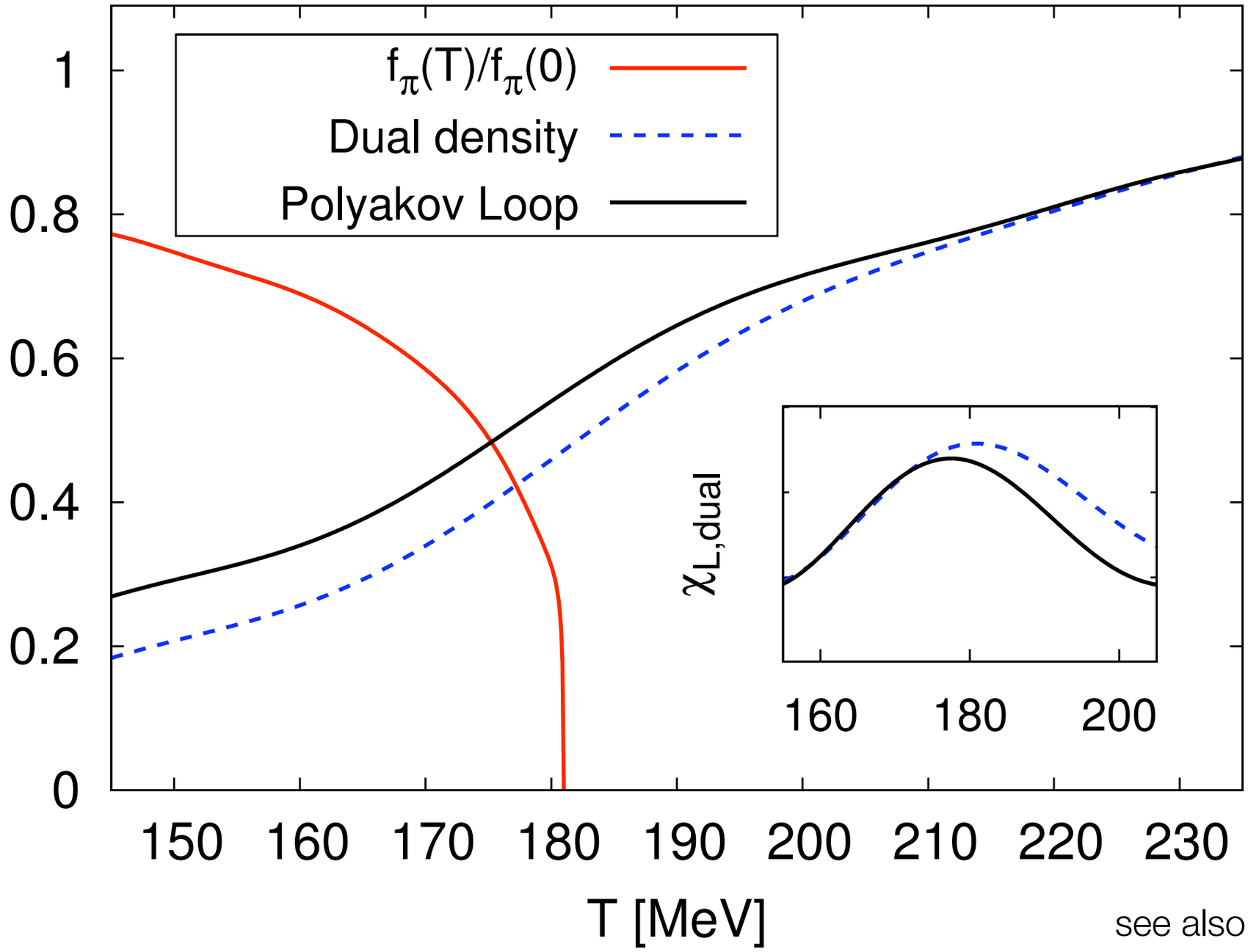


- flow of gluon propagator

pure gauge theory flow + + ...

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods



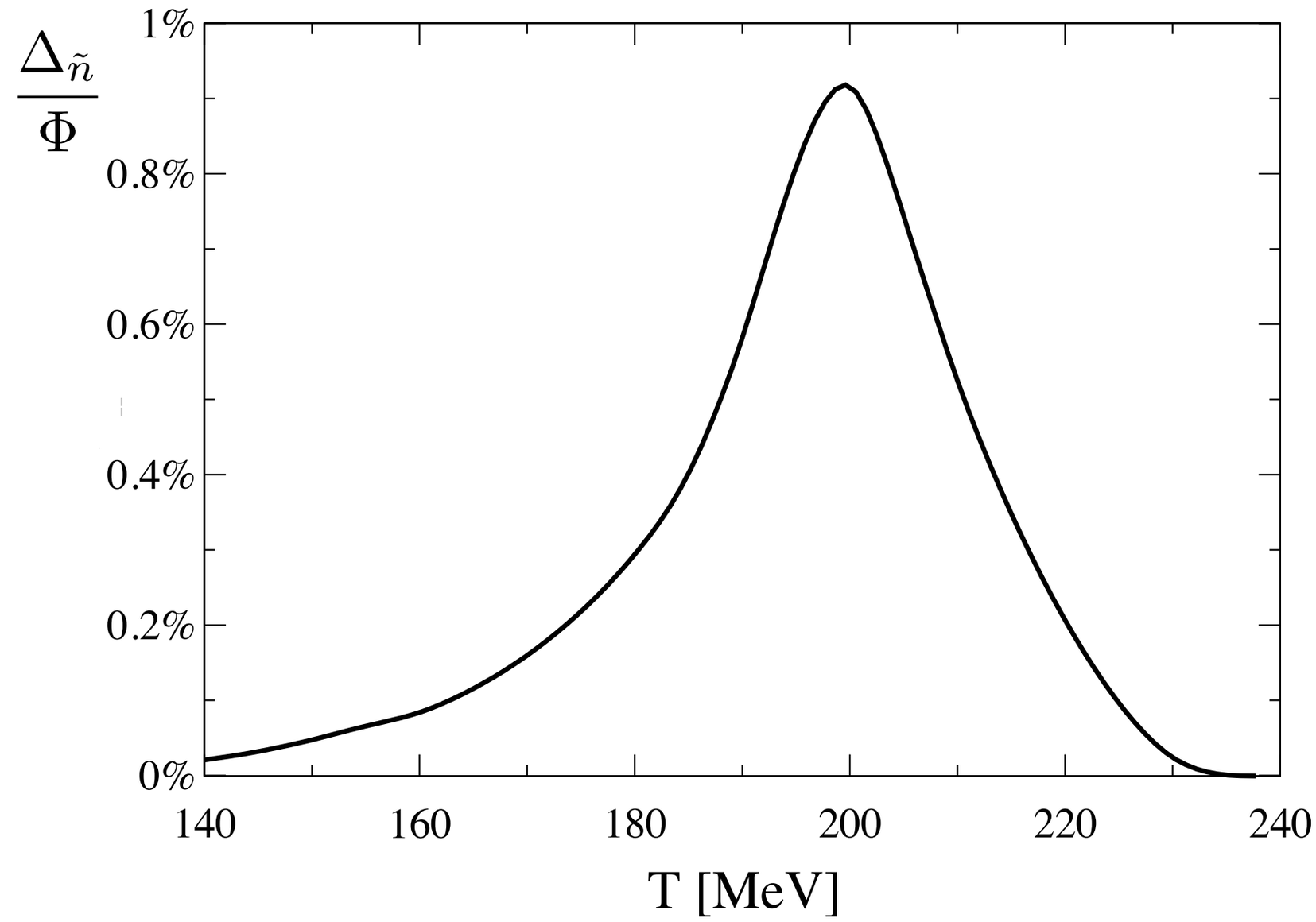
see also Poster by Lisa M. Haas

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

Braun, Haas, Marhauser, JMP ‘09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods

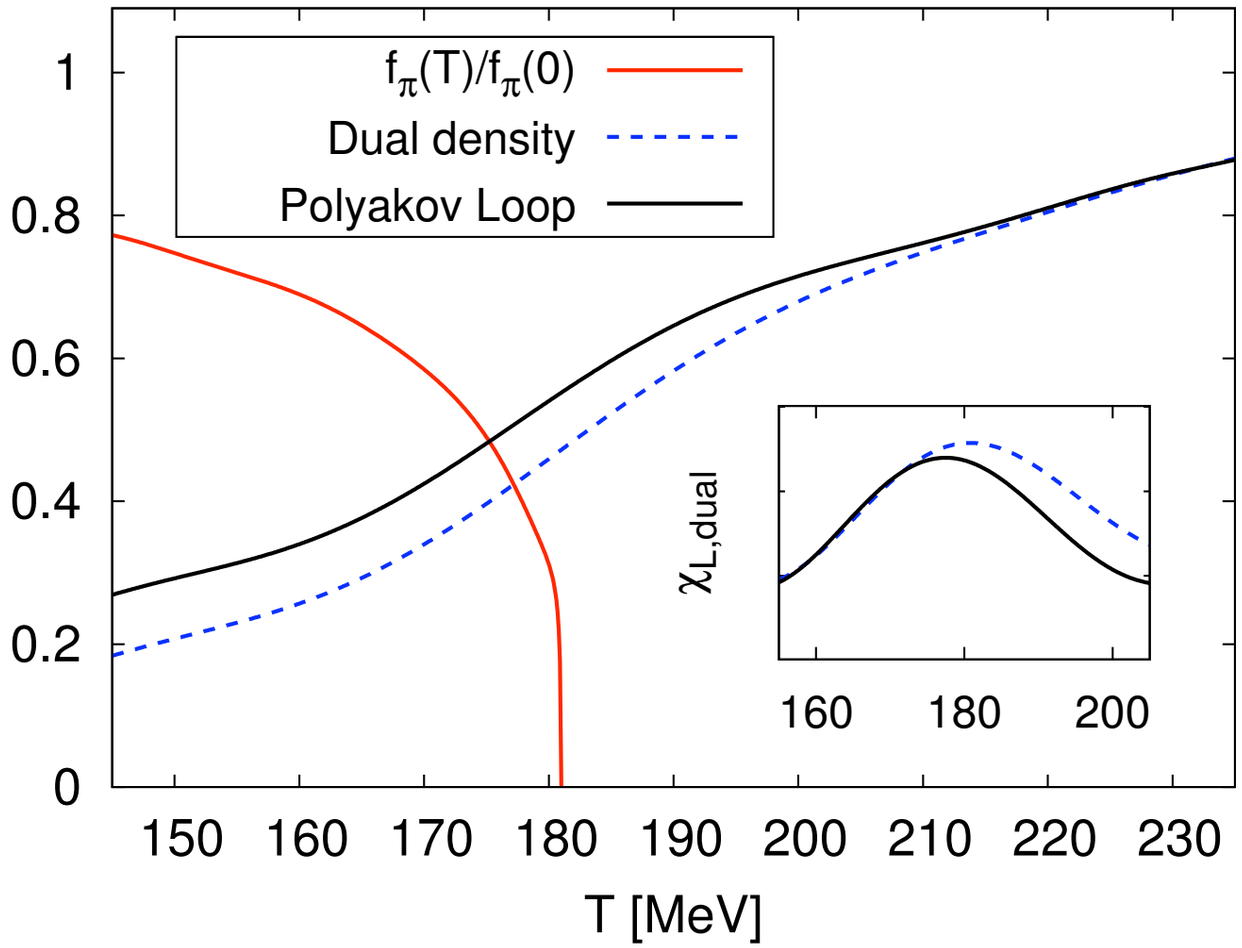


$\Delta_{\tilde{n}} = \frac{\tilde{n}[\langle A_0 \rangle]}{\tilde{n}[0]} - \Phi[\langle A_0 \rangle]$: Deviation of dual density from Polyakov loop

Braun, Haas, Marhauser, JMP ‘09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods & lattice



compatible with Karsch et al '08

$N_f = 2+1$

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

$N_f = 2$

compatible with Fodor et al '08?

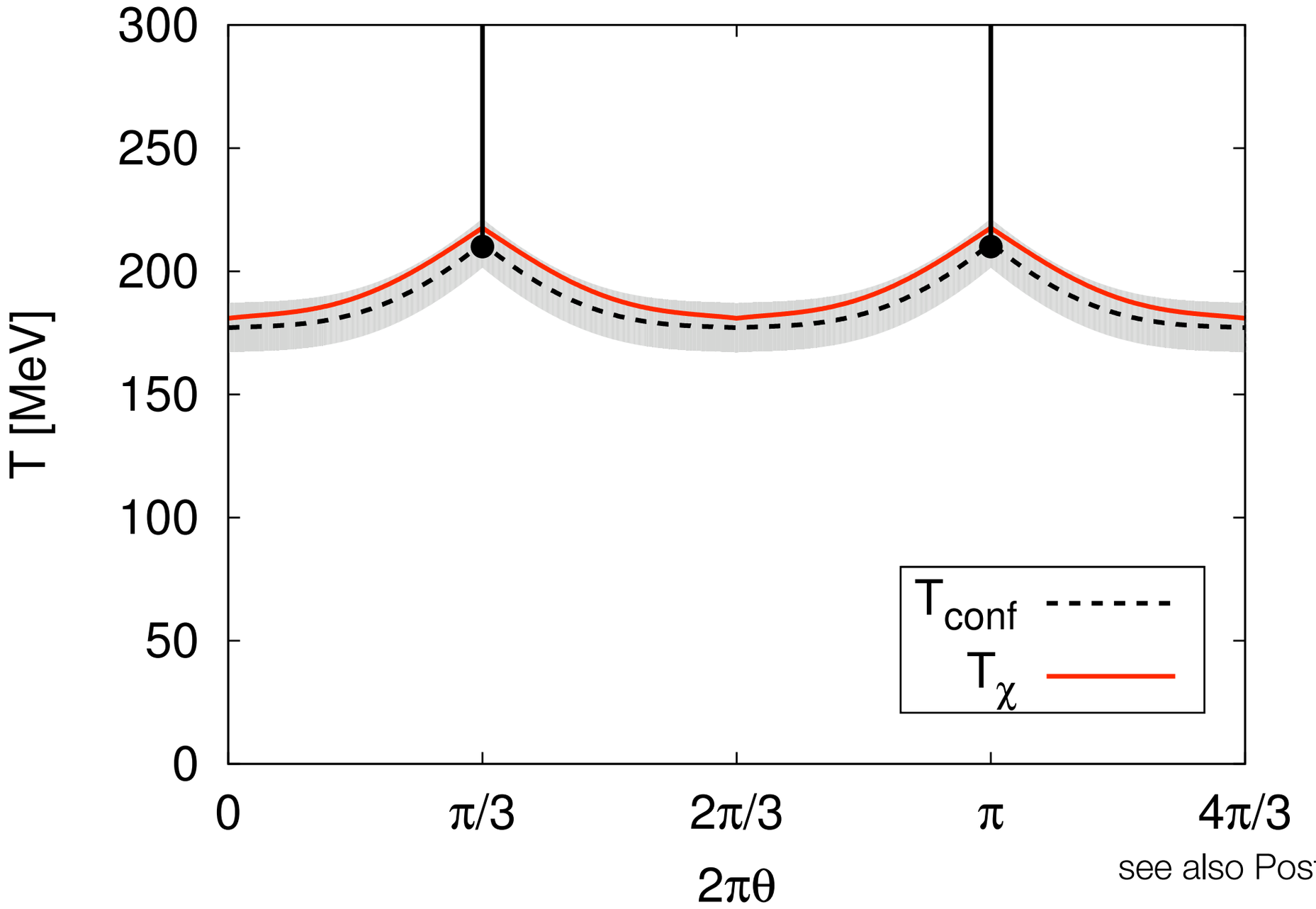
$175{\rm MeV} \simeq T_{c,{\rm conf}} > T_{c,\chi} \simeq 150{\rm MeV}$

$N_f = 2+1$

Braun, Haas, Marhauser, JMP '09

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods



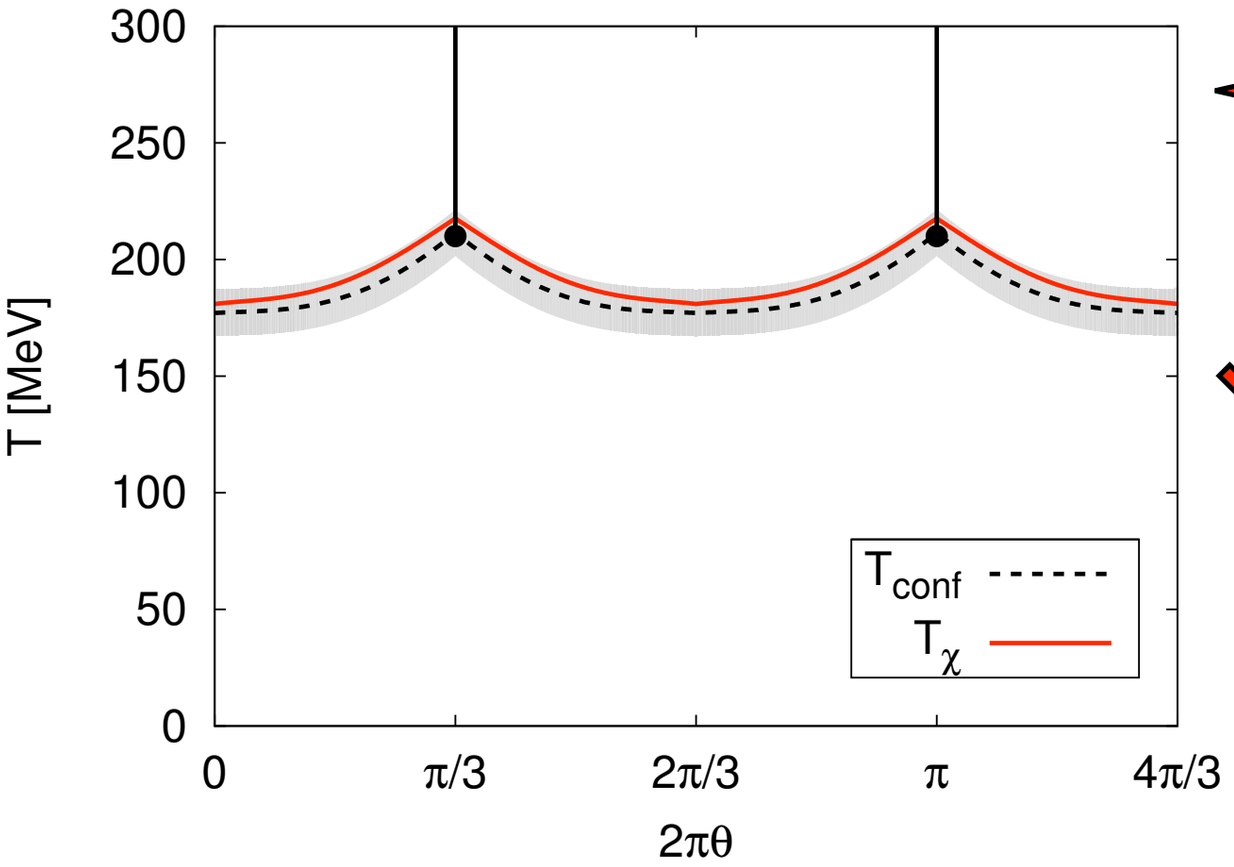
see also Poster by Lisa M. Haas

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

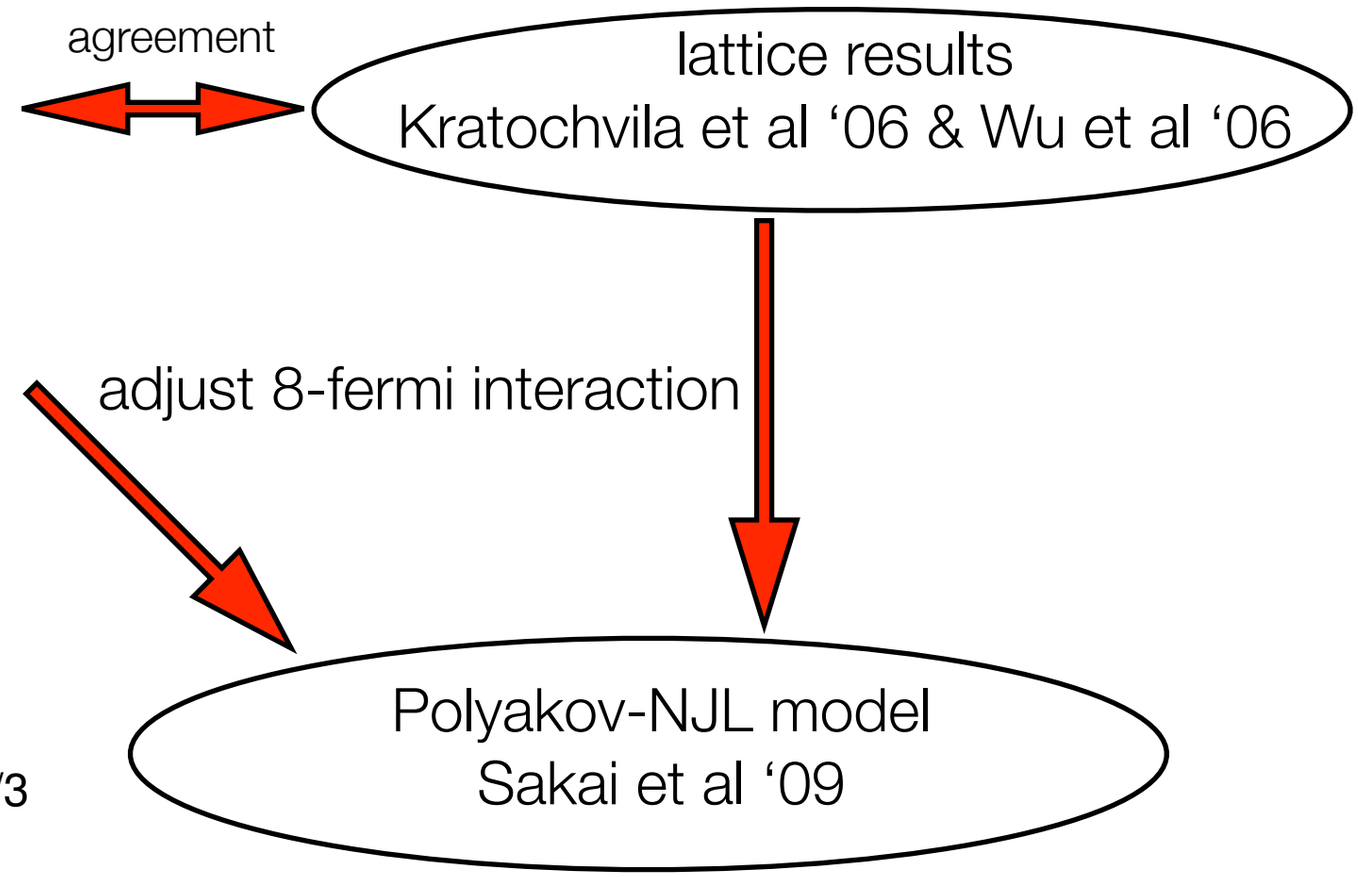
Braun, Haas, Marhauser, JMP '09

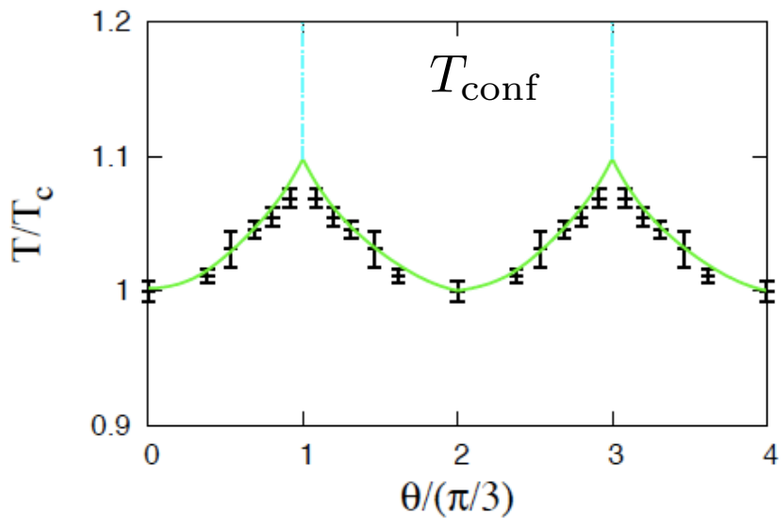
Full dynamical QCD: N_f = 2 & chiral limit

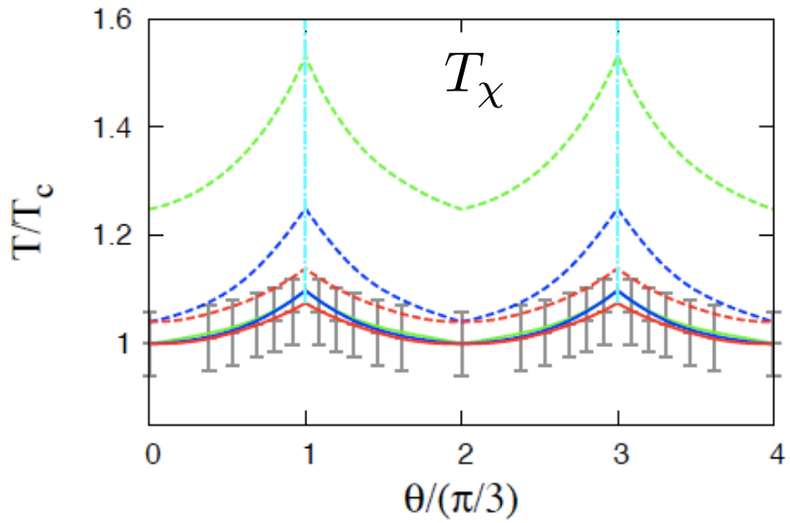
Continuum methods & lattice



Braun, Haas, Marhauser, JMP ‘09



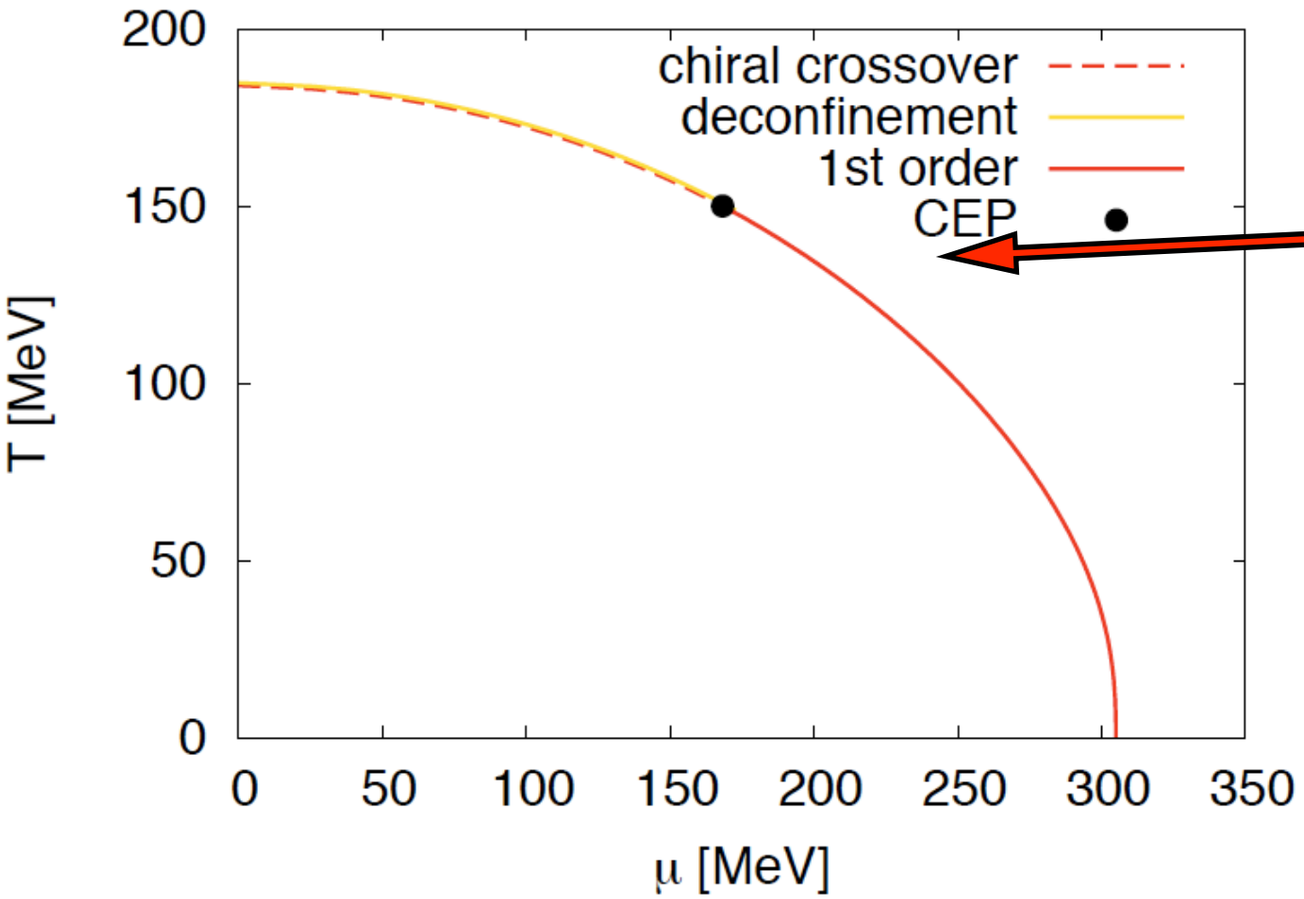




Chiral phase structure at finite density

Phase diagram of QCD

Polyakov - Quark-Meson model

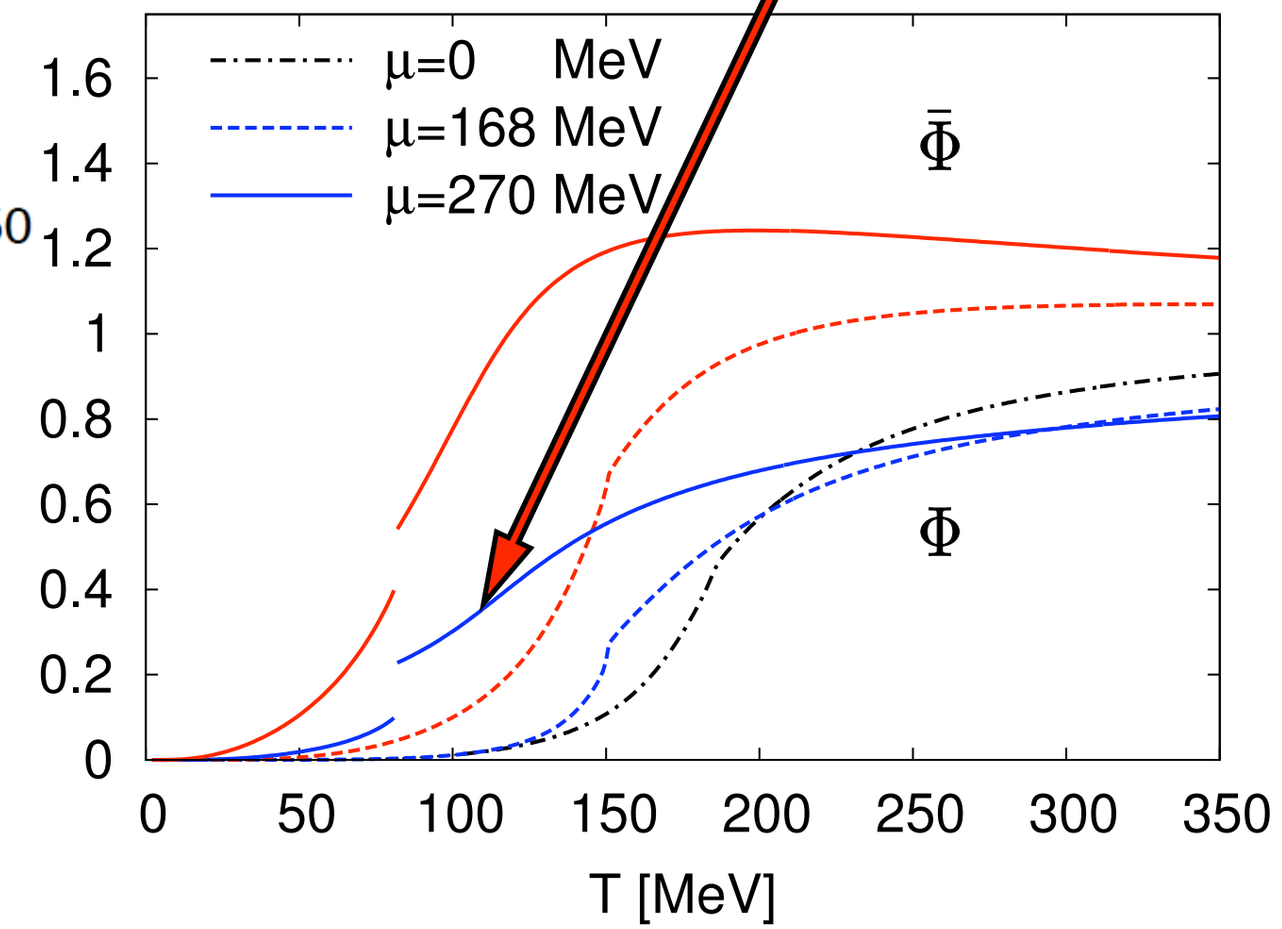


$N_f = 2$

Schaefer, JMP, Wambach ‘07

quarkyonic phase?

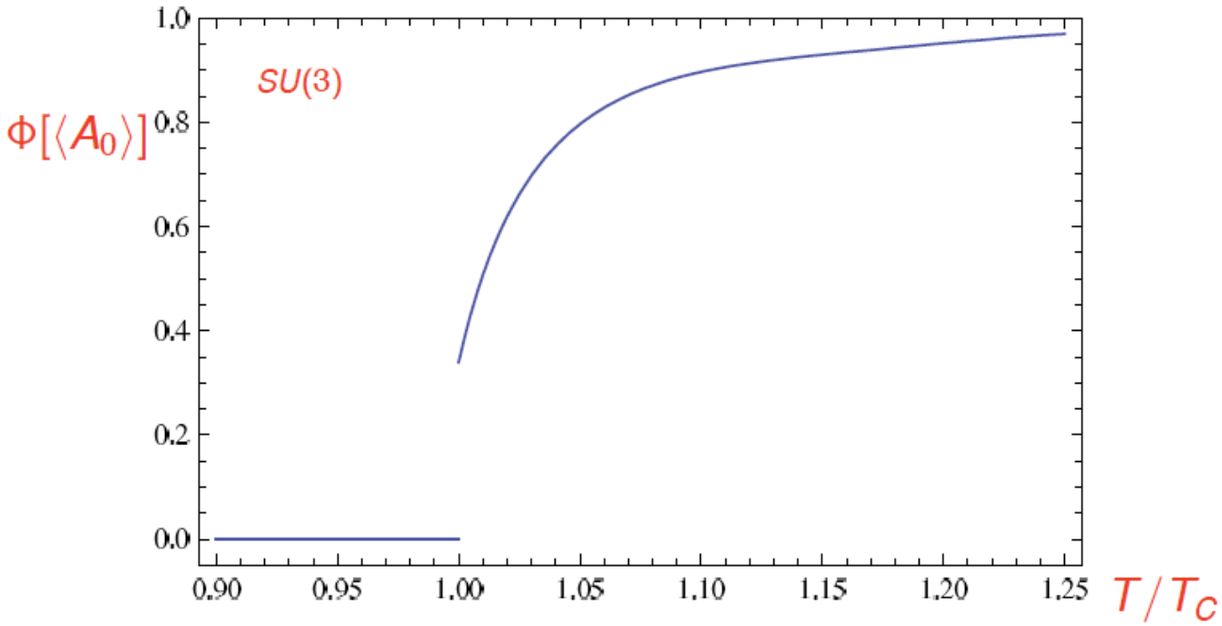
washed out by quantum fluctuations?

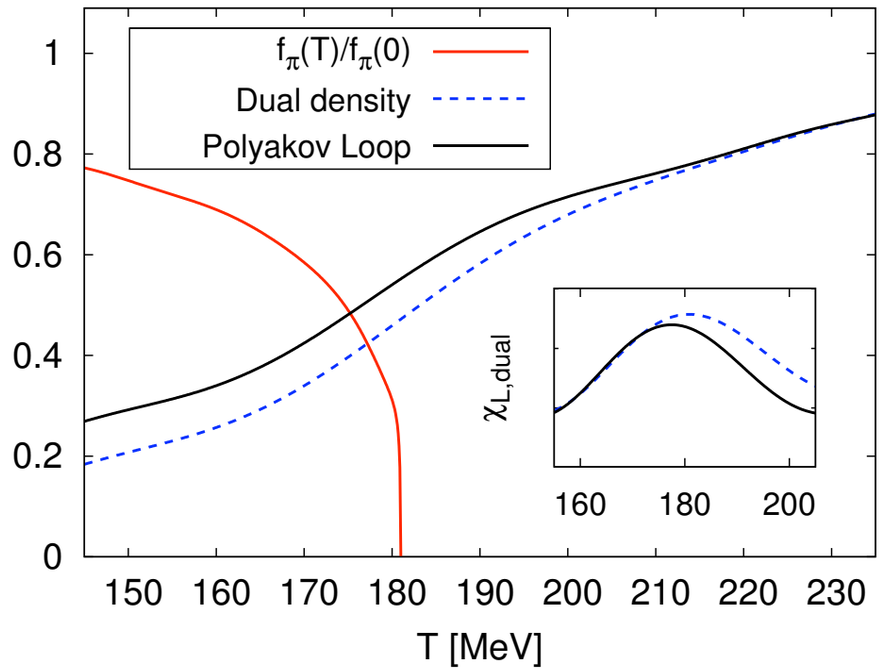


Summary & outlook

Summary & outlook

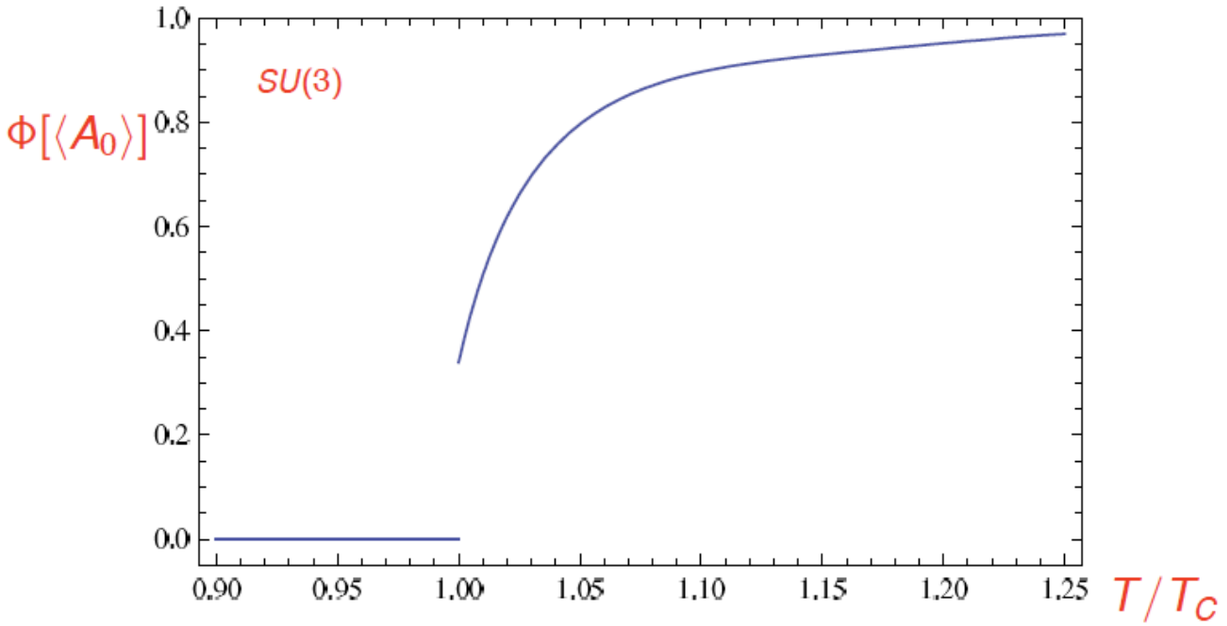
- Phase diagram of QCD
  - Confinement & chiral symmetry breaking at finite temperature

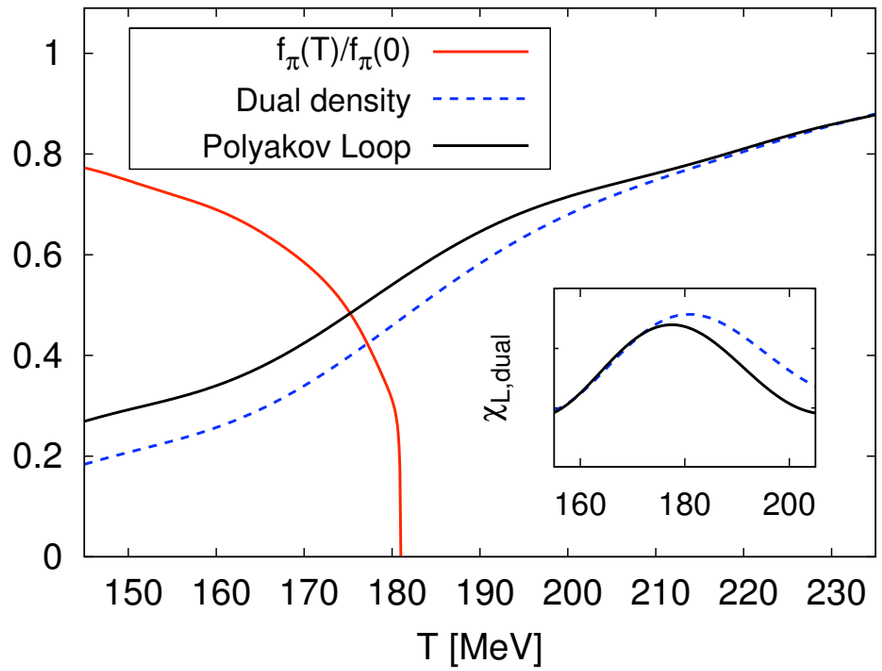




Summary & outlook

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





  - Dynamical hadronisation

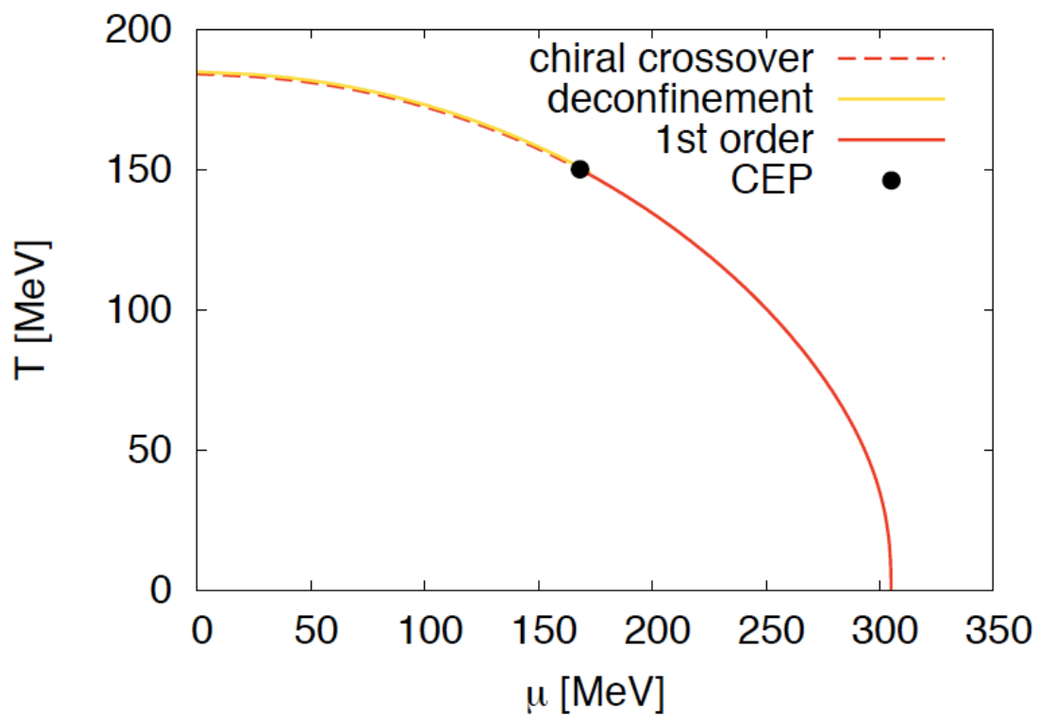
    QCD flows dynamically into hadronic effective theories

  - 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



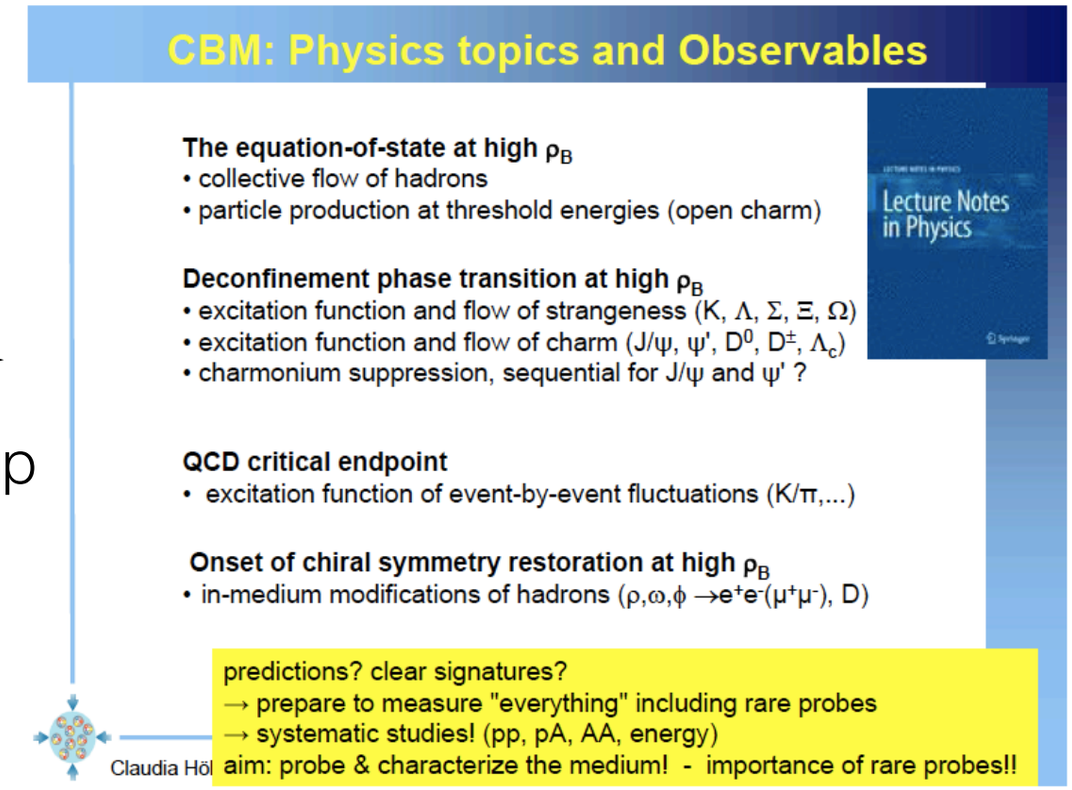
Summary & outlook

- 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



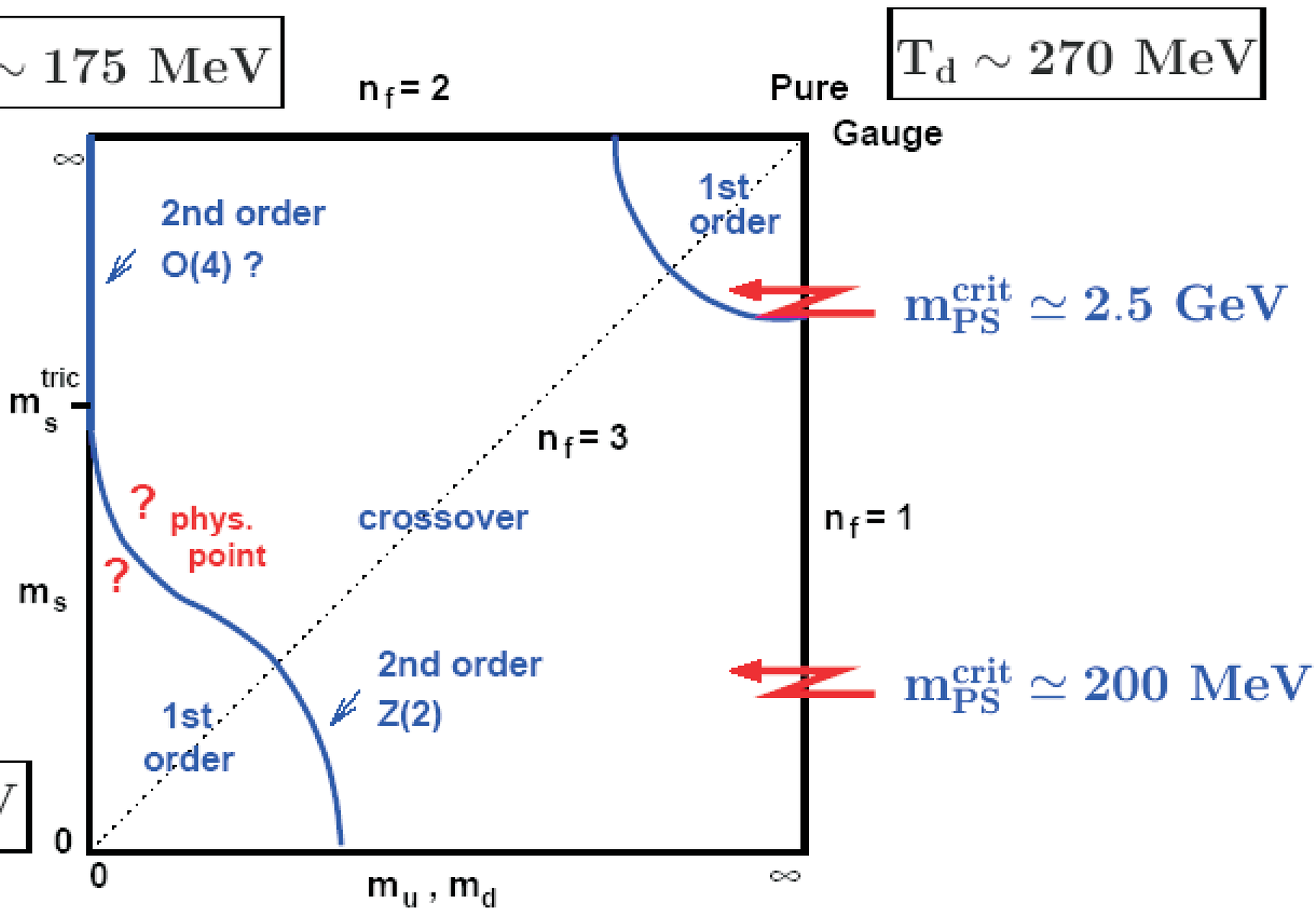
Summary & outlook

- 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
    - QGP meets Cold Atoms

Additional material
Chiral phase structure at finite density

Chiral phase diagram

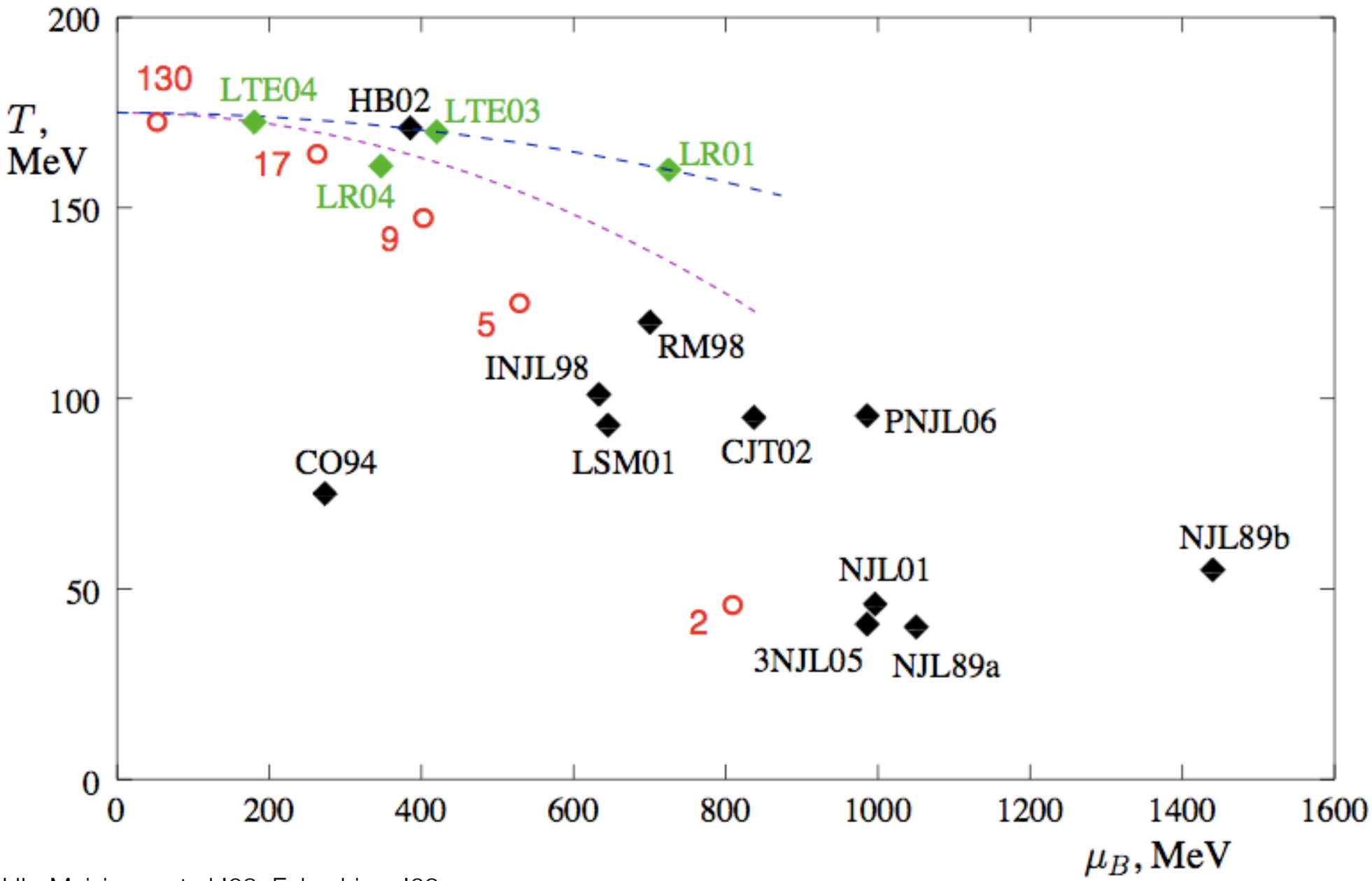
$T_\chi^{n_f=2} \sim 175$ MeV



$T_\chi^{n_f=3} \sim 155$ MeV

Karsch et al. ‘03

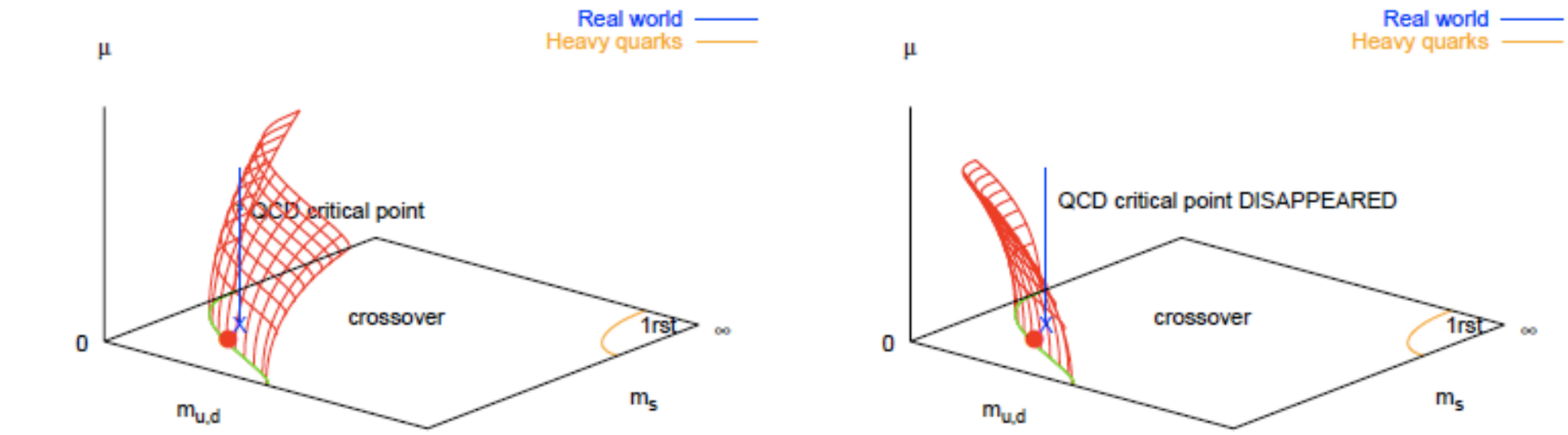
Critical point



PNJL: Meisinger et al ’03, Fukushima ’03,
Ratti et al ’06, Megias et al ’06, Sasaki et al ’06, ...

M. Stephanov ‘07

Critical point



Strategy: tune m_q for 2nd-order P.T. at $\mu = 0$, then turn on infinitesimal μ

Does the transition become 1rst-order (left) or crossover (right)?

Answer: little change ($\rightarrow$ surface almost vertical)

2007: measure δB_4 under $\delta\mu^2 \rightarrow$ crossover: $\frac{m_c(\mu)}{m_c(0)} = 1 - 3.3(5)\left(\frac{\mu}{\pi T}\right)^2$

de Forcrand et al '07

Phase diagram of QCD

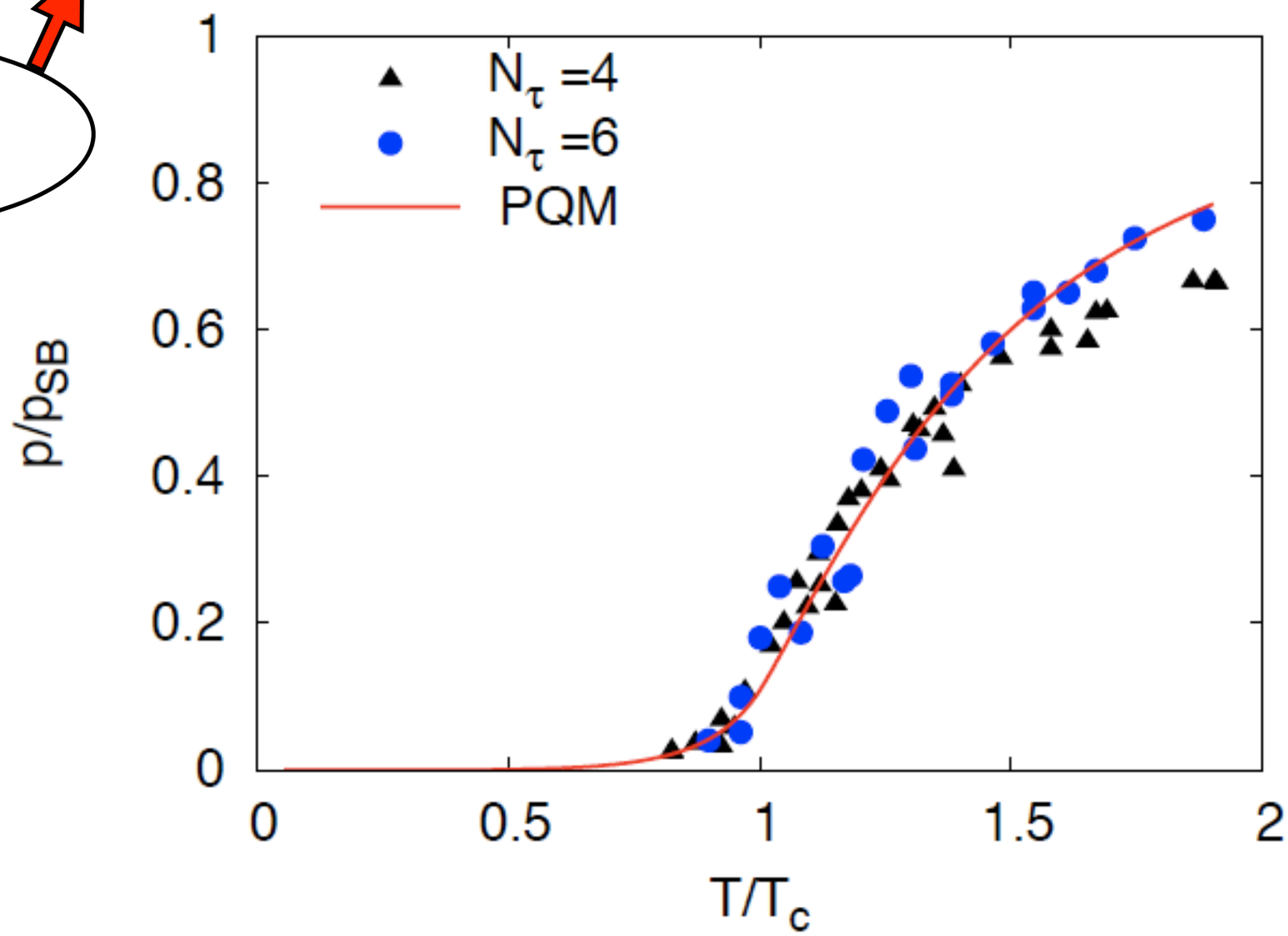
Polyakov - Quark-Meson model

Schaefer, JMP, Wambach '07

EoM of: $U[\Phi, \bar{\Phi}]$ $+V[\sigma, \vec{\pi}]$ $+\Omega_{\bar{q}q}(\Phi, \bar{\Phi}, \sigma)$

Polyakov loop | meson | fermionic determinant

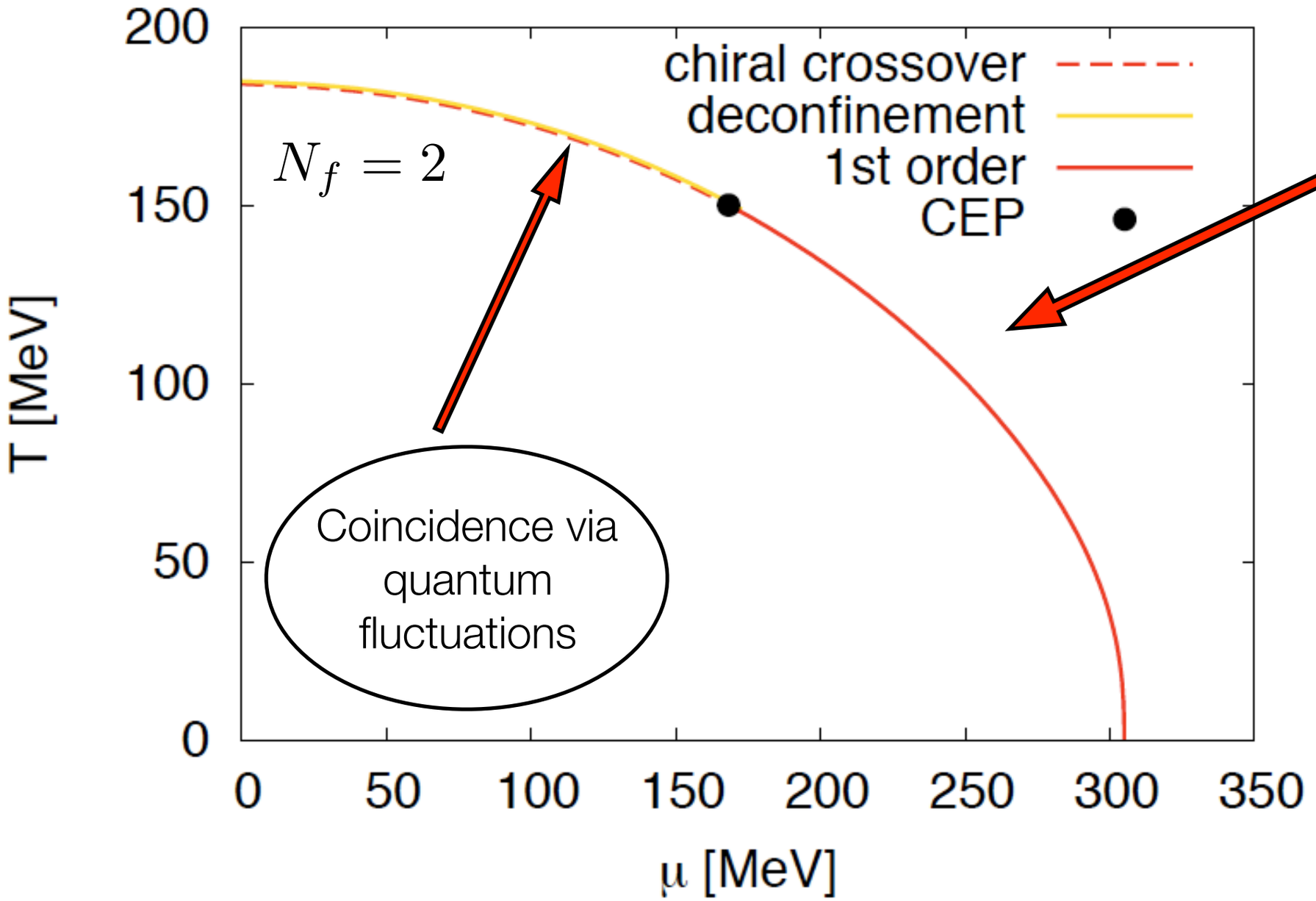
+ quantum fluctuations



lattice data taken from Ali Khan et al. (CP-PACS), Phys. Rev. D 64 (2001)

Phase diagram of QCD

Polyakov - Quark-Meson model



Schaefer, JMP, Wambach ‘07

Phase diagram of QCD

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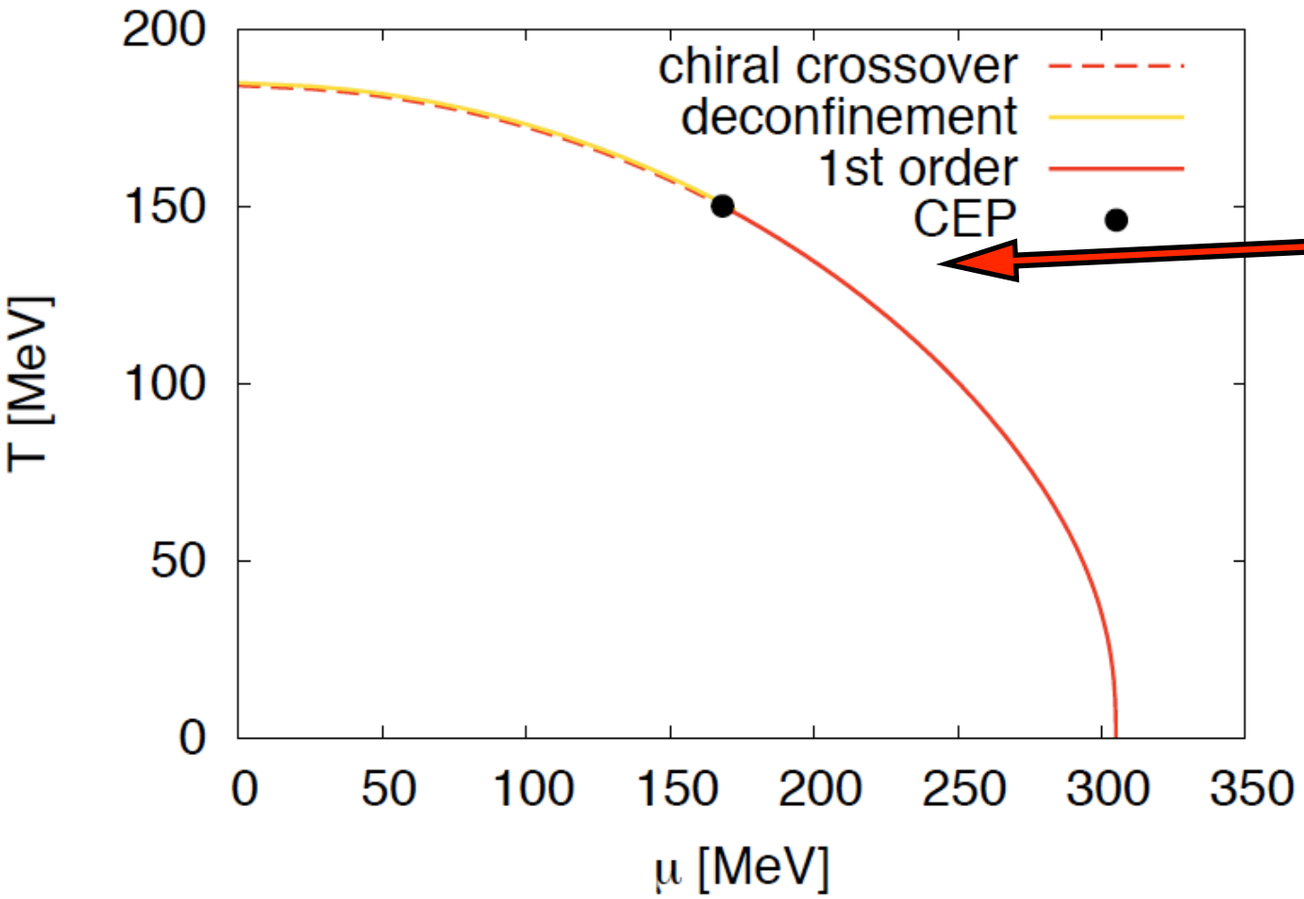

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