Confinement, chiral symmetry breaking and the QCD phase diagram

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Institute for Theoretical Physics
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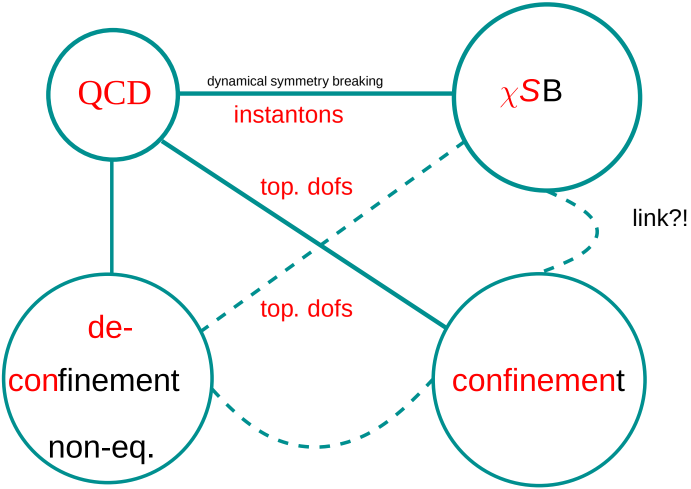
Quarks and Hadrons in strong QCD, St Goar, March 17th, 2008


QCD
dynamical symmetry breaking
instantons
χSB
top. dofs
link?!
top. dofs
de-
confinement
non-eq.
confinement

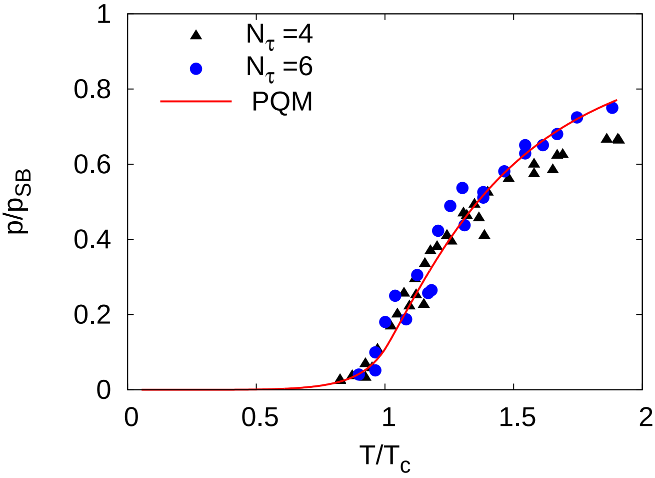
some questions

- chiral symmetry breaking
  - mechanism & critical temperature
  - bound state spectrum
- confinement-deconfinement
  - mechanism & critical temperature
  - spectrum, mass gap
- finite density
  - phase diagram & critical point
- dynamics

some answers: compute Green functions

- chiral symmetry breaking
  - $\langle q(x)\bar{q}(y)\rangle$, ...
- confinement-deconfinement
  - $\langle A(x)A(y)\rangle$, $\langle C(x)\bar{C}(y)\rangle$, ...
  - $\langle 1/N_c \,\mathrm{tr}\,\mathcal{P} \exp i \int_0^\beta dt\, A_0\rangle$, ...
- dynamics with functional methods
- gauge fixing is mostly a benefit, not a liability
  - Landau gauge & Polyakov gauge

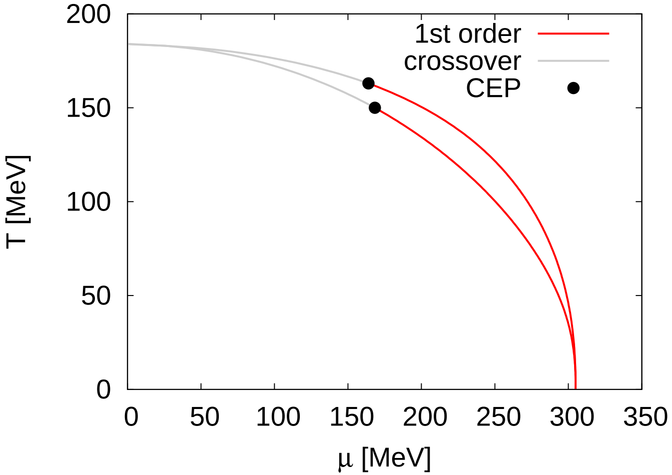
Schaefer, Pawlowski, Wambach, Phys. Rev. D **76** (2007) 074023



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

see talk of B.-J. Schaefer

Schaefer, Pawlowski, Wambach, Phys. Rev. D **76** (2007) 074023



see talk of B.-J. Schaefer

1. Functional RG
   - properties
   - topology
2. Landau gauge QCD
   - Signatures of confinement
   - Infrared asymptotics & finite volume effects
3. QCD at finite temperature
   - confinement-deconfinement phase transition

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$$k\partial_k \Gamma_k[\phi] = \frac{1}{2}\,\mathrm{Tr}\,\frac{1}{\Gamma_k^{(2)}[\phi] + k^2}\,2k^2$$

Wetterich, Phys. Lett. B **301** (1993) 90

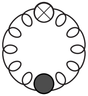
$$k\partial_k \Gamma_k[\phi] = \frac{1}{2} \mathrm{Tr} \frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)} k\partial_k R_k(p^2)$$

Wetterich, Phys. Lett. B **301** (1993) 90

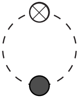
$$k\partial_k \Gamma_k[\phi] = \frac{1}{2}\,\mathrm{Tr}\,\frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)}\,k\partial_k R_k(p^2)$$

- in Yang-Mills theory

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



$$-$$



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$$k\partial_k \Gamma_k[\phi] = \frac{1}{2}\,\mathrm{Tr}\,\frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)}\,k\partial_k R_k(p^2)$$

- self-similarity, reparameterisation & projections
- fermions straightforward though 'physically' complicated
  - no sign problem numerics as in scalar theories!
  - chiral fermions reminder: Ginsparg-Wilson fermions from RG argument!
  - bound states via (re-)bosonisation effective field theory techniques applicable!

Wetterich, Phys. Lett. B **301** (1993) 90

$$k\partial_k \Gamma_k[\phi] = \frac{1}{2}\,\mathrm{Tr}\,\frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)}\,k\partial_k R_k(p^2)$$

- self-similarity, reparameterisation & projections
- fermions straightforward
- flows in Landau gauge QCD

Ellwanger, Hirsch, Weber '96
Bergerhoff, Wetterich '97
Pawlowski, Litim, Nedelko, von Smekal '03
Kato '04
Gies, Fischer '04
Pawlowski '05

Wetterich, Phys. Lett. B **301** (1993) 90

$$k\partial_k\Gamma_k[\phi] = \frac{1}{2}\,\mathrm{Tr}\,\frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)}\,k\partial_k R_k(p^2)$$

- self-similarity, reparameterisation & projections
- fermions straightforward
- functional methods in Landau gauge QCD (IR)
  - Dyson-Schwinger equations — von Smekal, Hauck, Alkofer '97
  - stochastic quantisation — Zwanziger '02
  - flows in Landau gauge QCD — Pawlowski, Litim, Nedelko, von Smekal '03
  - quark confinement from Landau gauge propagators — Braun, Gies, Pawlowski '07

topology ?

- tunneling in QM

Zappala, Phys. Lett. A **290** (2001) 35

- instanton-induced terms in QCD

Pawlowski, Phys. Rev. D **58** (1998) 045011

- $\mathcal{N} = 2$ susy Yang-Mills

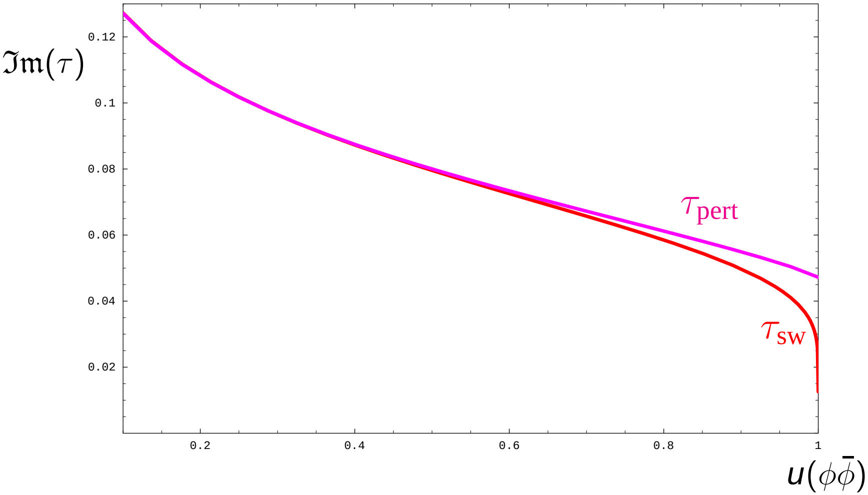
Dolan, Pawlowski, unpublished work

$$\tau = \frac{i}{g^2} + \frac{\theta}{8\pi^2} = \frac{i}{4\pi^2}\left(\ln\frac{\phi\bar{\phi}}{\Lambda^2_{\rm QCD}} + 3\right) + \text{top.}$$

- anomalies, solitons $\cdots$

Coupling τ in $\mathcal{N} = 2$ susy Yang-Mills (Seiberg-Witten)

Dolan, Pawlowski, unpublished work



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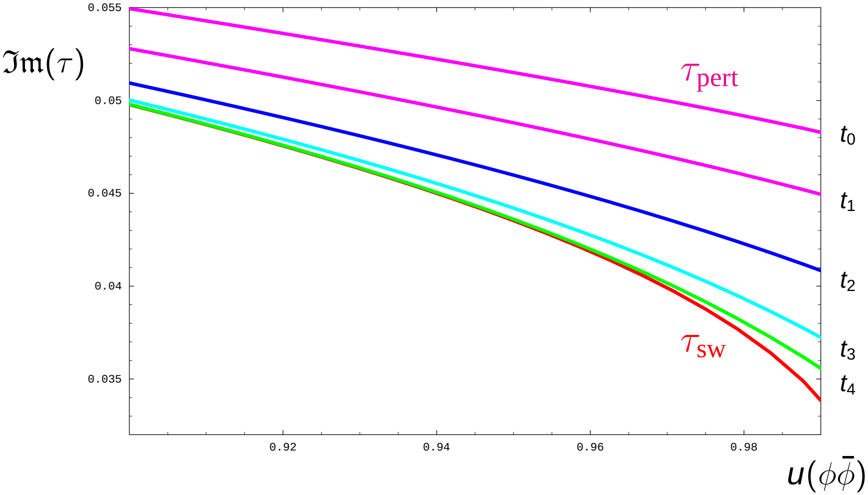

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2 Landau gauge QCD
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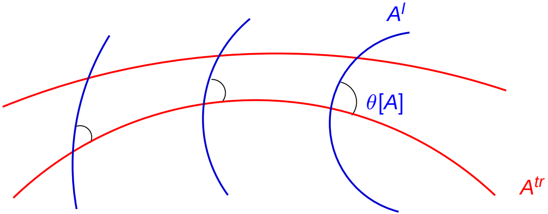
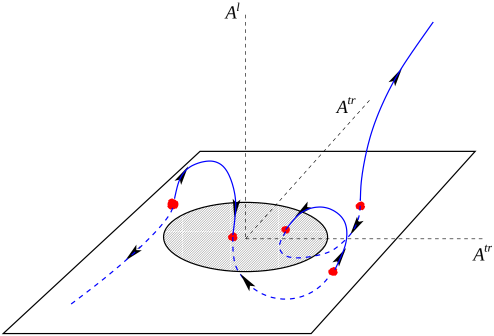
3 QCD at finite temperature
- confinement-deconfinement phase transition

$$S_{\rm cl} = \frac{1}{2}\int \mathrm{tr}\, F^2 = \frac{1}{2}\int A^a_\mu \left(p^2\delta_{\mu\nu} - p_\mu p_\nu\right) A^a_\nu + \cdots$$

gauge fixing ensures the existence of the gauge field propagator





Gribov problem

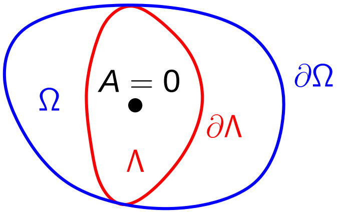
confinement scenario

$$\Omega = \{A \,|\, \partial_\mu A_\mu = 0,\ -\partial_\mu D_\mu \geq 0\}$$

- entropy

  $\int dA\ \det(-\partial D)\, e^{-S}$

- entropy ($\int dA$)
  - $\partial\Omega\,(\cap\partial\Lambda)$ dominates IR
  - ghost IR-enhanced
  - gluonic mass-gap: confined gluons



non-renormalisation of ghost-gluon vertex

confinement scenario

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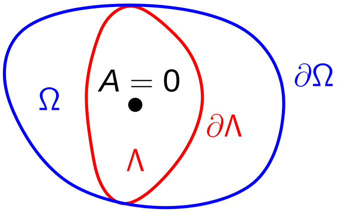

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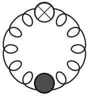
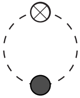
non-renormalisation of ghost-gluon vertex

- Kugo-Ojima (in BRST-extended configuration space)
  - gluonic mass-gap $+$ no Higgs mechanism

Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012

functional RG

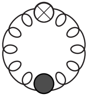
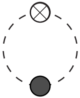
$\partial_t \Gamma_k[\phi] \; = \; \frac{1}{2}$  $-$ 

- mode cut-off

$$R_k(p^2) \propto \Gamma_0^{(2)}(p^2)\,\delta(p^2-k^2)$$

Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012

functional RG

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

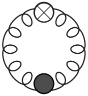
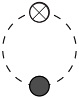
- mode cut-off

$$R_k(p^2) \propto \Gamma_0^{(2)}(p^2)\,\delta(p^2 - k^2)$$

  - physics unchanged

Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012

functional RG

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

- mode cut-off

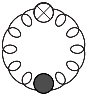
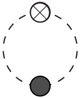
$$R_k(p^2) \propto \Gamma_0^{(2)}(p^2)\,\delta(p^2 - k^2)$$

  - physics unchanged
  - loop integration

$$\frac{1}{\Gamma_k^{(2)} + R_k}\,(k\partial_k R_k)\,\frac{1}{\Gamma_k^{(2)} + R_k} \simeq \frac{1}{\Gamma_0^{(2)}}\,k^2\delta'(p^2 - k^2)$$

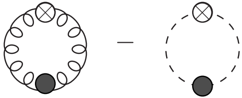
Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012

functional RG

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

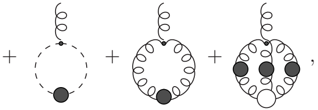
functional RG

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

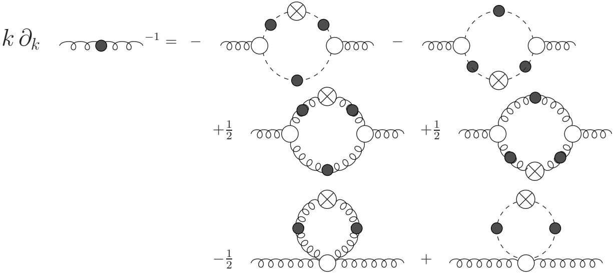


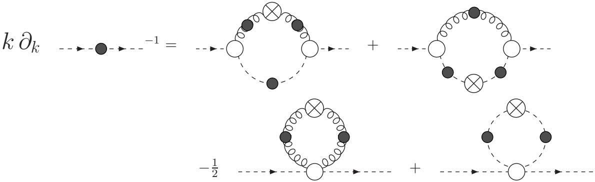
functional DSE

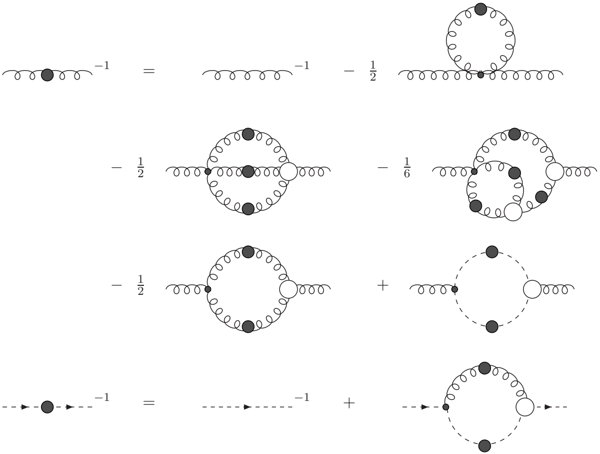
$$\frac{\delta \Gamma_k[\phi]}{\delta A} = \frac{\delta S[\phi]}{\delta A}$$



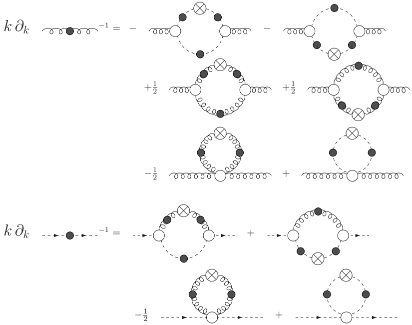
$$\frac{\delta \Gamma_k[\phi]}{\delta C} = \frac{\delta S[\phi]}{\delta C} +$$

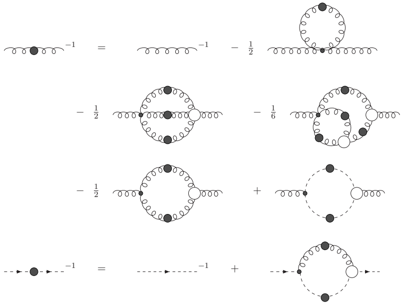

$k\,\partial_k$
$^{-1} = -$
$-$
$+\frac{1}{2}$
$+\frac{1}{2}$
$-\frac{1}{2}$
$+$


$k\,\partial_k$
$^{-1} =$
$+$
$-\frac{1}{2}$
$+$



Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012; work in progress





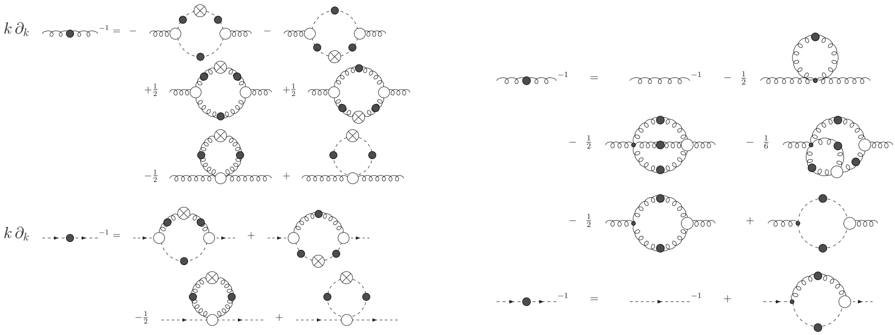
Unique infrared asymptotics in Landau gauge QCD

- conformal scaling

$$\Gamma^{(2n,m)}(\lambda p_1, \ldots, \lambda p_{2n+m}) = \lambda^{\kappa_{2n,m}} \Gamma^{(2n,m)}(p_1, \ldots, p_{2n+m})$$

- decoupling: $\kappa_{n,m} = 0$ & massive gluon   no confinement!?

Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012; work in progress



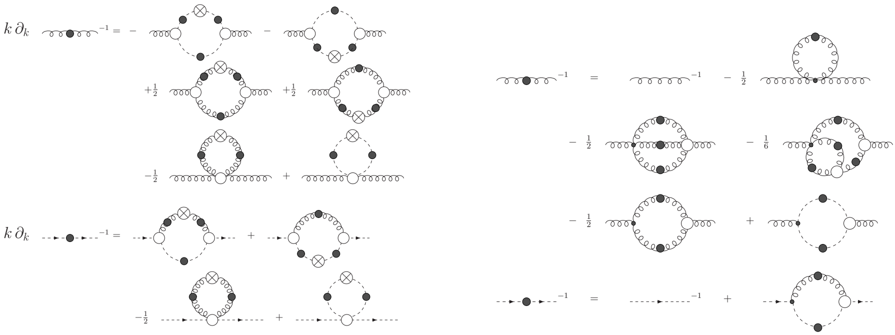
Unique infrared asymptotics in Landau gauge QCD

$$\Gamma^{(2n,m)} \sim p^{2(n-m)\kappa_C} \qquad \text{with} \qquad \kappa_C \geq 0$$

$\Gamma^{(2n,m)}$: vertex with n ghost and anti-ghost lines, m gluons

confirms Alkofer, Fischer, Llanes-Estrada, Phys. Lett. **B611** (2005) 279–288
see also Alkofer, Huber, Schwenzer '08

Fischer, Pawlowski, Phys. Rev. D **75** (2007) 025012; work in progress



Unique infrared asymptotics in Landau gauge QCD

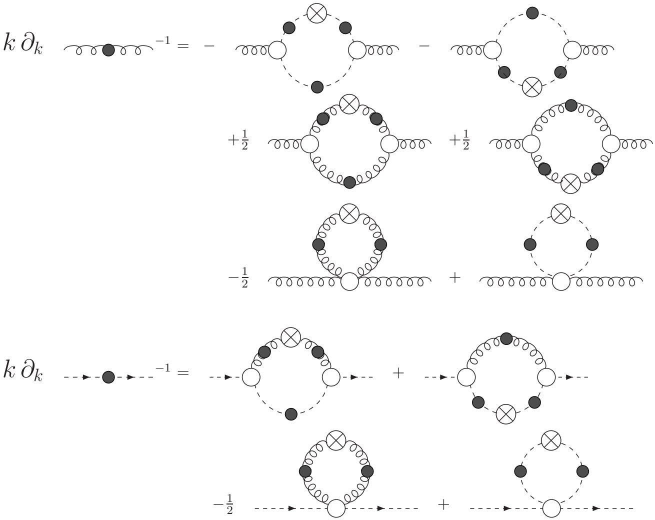
$$\Gamma^{(2n,m,\text{quarks})} \sim p^{2(n-m)\kappa_C+\text{quarks}}$$

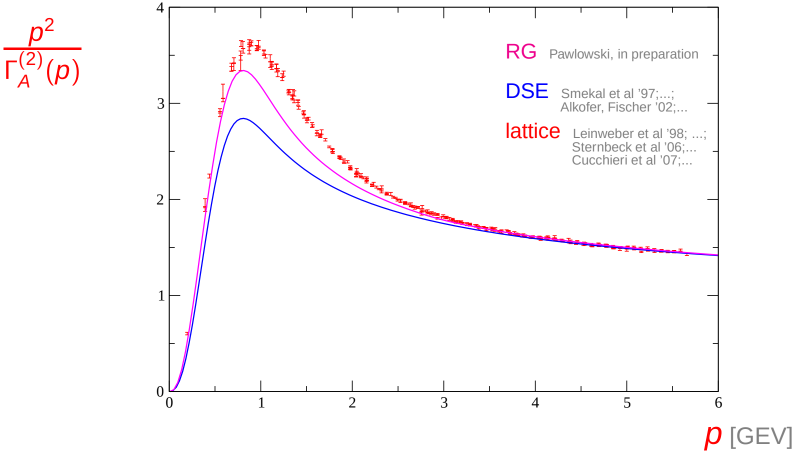
QCD: work in progress; QED_3: Nedelko,Pawlowski, in preparation

UV-IR flow

- full momentum dependence of propagators
- vertices momentum-dependent RG-dressing
- optimisation
- functional relations between diagrams

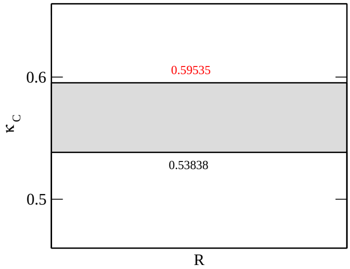
UV-IR flow





$\frac{p^2}{\Gamma_A^{(2)}(p)}$
4
3
2
1
0
0
1
2
3
4
5
6
RG Pawlowski, in preparation
DSE Smekal et al '97;...;
Alkofer, Fischer '02;...
lattice Leinweber et al '98; ...;
Sternbeck et al '06;...
Cucchieri et al '07;...
p [GEV]

$$p^2\langle A(p)A(-p)\rangle = \frac{p^2}{\Gamma_A^{(2)}(p)} \stackrel{p\to 0}{\longrightarrow} (p^2)^{-2\kappa_C} \qquad \stackrel{\text{DSE}}{=} \frac{D(p^2)}{p^2}$$



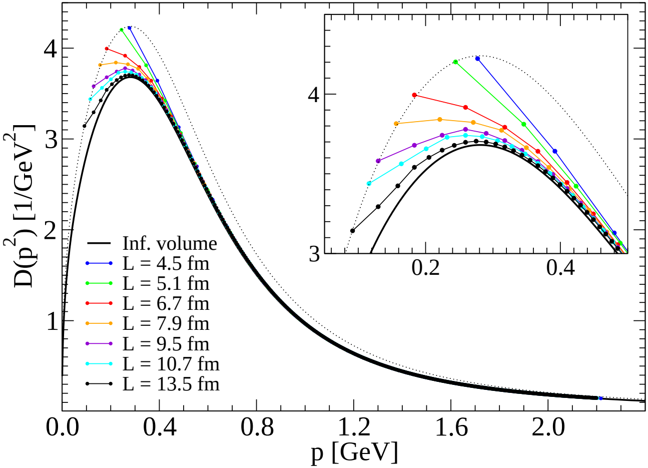
Pawlowski, Litim, Nedelko, von Smekal, Phys. Rev. Lett. **93** (2004) 152002

- optimisation: $\kappa_C = 0.59535\ldots, \quad \alpha_s = 2.9717\ldots$

equals DS/StochQuant-result: Lerche, von Smekal, Phys. Rev. D **65** (2002) '02
D. Zwanziger, Phys. Rev. D **65** (2002)
RG-confirmation: C. S. Fischer and H. Gies, JHEP **0410** (2004)

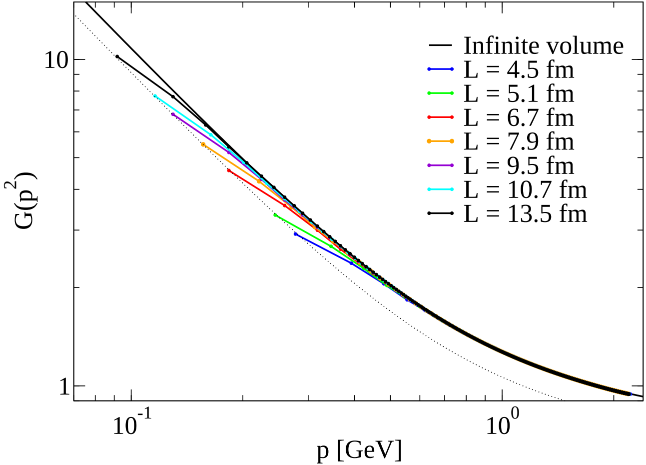
$$D(p^2) = \frac{1}{\Gamma_A^{(2)}(p)}$$

Fischer, Maas, Pawlowski, von Smekal, Annals Phys.322:2916-2944,2007



$$G(p^2) = \frac{p^2}{\Gamma_C^{(2)}(p)}$$

Fischer, Maas, Pawlowski, von Smekal, Annals Phys.322:2916-2944,2007



Functional methods–lattice puzzle

- lower dimensions
  - quantitative agreement in $d = 2$ Maas '07
  - qualitative agreement in $d = 3$ talk of A. Maas
- large volumes on the lattice
  - in $d = 4$ up to 128^4 at $\beta = 2.2$ Cucchieri et al '07
- gauge fixings
  - improved gauge fixing procedures Bogolubsky et al '07, von Smekal et al '07, talk of A. Maas
  - stochastic quantisation with D. Spielmann, I.O. Stamatescu
- $SU(2)$ versus $SU(3)$ Cucchieri et al '07, Sternbeck et al '07
- $\beta = 0$: evidence for gauge fixing/finite size problems talk of L. von Smekal

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Order parameter

- Polyakov loop $\Phi(\vec{x}) = \langle L[A_0] \rangle$

$$L[A_0](\vec{x}) = \frac{1}{N_c} \mathrm{tr} \mathcal{P} e^{i \int_0^\beta dt\, A_0}$$

with $\langle \Phi \rangle \simeq e^{-F_q}$

  - confinement: $F_q = \infty$
  - deconfinement: F_q finite

Order parameter

- Polyakov loop $\Phi(\vec{x}) = \langle L[A_0] \rangle$

$$L[A_0](\vec{x}) = \frac{1}{N_c} \mathrm{tr} \mathcal{P} e^{i \int_0^\beta dt\, A_0}$$

with $\langle \Phi \rangle \simeq e^{-F_q}$

  - confinement: $F_q = \infty$
  - deconfinement: F_q finite

- string tension

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

  - $\lim_{|\vec{x}-\vec{y}| \to \infty} F_{q\bar{q}}(\vec{x}-\vec{y}) \simeq \beta\sigma|\vec{x}-\vec{y}|$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

see also talk of H. Gies

- background field flow

$$k\partial_k\Gamma_k[\phi,A] = \frac{1}{2}\,\mathrm{Tr}\frac{1}{\Gamma_k^{(2,0)}[\phi,A] + R_k(\Gamma_k^{(2,0)}[0,A])}k\partial_k R_k(\Gamma_k^{(2,0)}[0,A])$$

  - fluctuation fields $\phi = (a, C, \bar{C})$
  - background field A
  - Landau-DeWitt gauge: $D_\mu(A)a_\mu = 0$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

- background field flow for effective potential $V_{\rm eff}[A_0] = \Gamma_k[0, A_0]$

$$k\partial_k V_{\rm eff}[A_0] = \frac{1}{2}\,\mathrm{Tr}\frac{1}{\Gamma_k^{(2,0)}[0,A_0] + R_k(\Gamma_k^{(2,0)}[0,A_0])} k\partial_k R_k(\Gamma_k^{(2,0)}[0,A_0])$$

  - vanishing fluctuation fields $\phi = 0$

$$\Gamma_{k,A}^{(2,0)} = \frac{\delta^2\Gamma_k}{\delta a^2} \neq \frac{\delta^2\Gamma_k}{\delta A^2}$$

- background field flow for effective potential $V_{\rm eff}[A_0] = \Gamma_k[0, A_0]$

$$k\partial_k V_{\rm eff}[A_0] = \frac{1}{2}\,\mathrm{Tr}\frac{1}{\Gamma_k^{(2,0)}[0,A_0] + R_k(\Gamma_k^{(2,0)}[0,A_0])} k\partial_k R_k(\Gamma_k^{(2,0)}[0,A_0])$$

- determination of propagator

$$\Gamma_k^{(2,0)}[0,A] = \Gamma^{(2)}_{k,\rm Landau}(p^2 \to -D^2) + O(F)$$

- background field flow for effective potential $V_{\text{eff}}[A_0] = \Gamma_k[0, A_0]$

$$k\partial_k V_{\text{eff}}[A_0] = \frac{1}{2}\,\mathrm{Tr}\frac{1}{\Gamma_k^{(2,0)}[0,A_0] + R_k(\Gamma_k^{(2,0)}[0,A_0])} k\partial_k R_k(\Gamma_k^{(2,0)}[0,A_0])$$

- determination of propagator

$$\Gamma_k^{(2,0)}[0,A] = \Gamma_{k,\text{Landau}}^{(2)}(p^2 \to -D^2) + O(F)$$

- Polyakov loop $\Phi(\vec{x}) = \langle L[A_0] \rangle$

$$L[A_0] = \frac{1}{N_c}\mathrm{tr}\mathcal{P}e^{i\int_0^\beta dt\, A_0}$$

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$$L[\langle A_0\rangle] \qquad \text{from} \qquad \left.\frac{\partial V_{\rm eff}[A_0]}{\partial A_0}\right|_{A_0=\langle A_0\rangle} = 0$$

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$$L[\langle A_0\rangle] \geq \langle L[A_0]\rangle$$

- full effective action

$$\Gamma_0[0,A] = \frac{1}{2}\,\mathrm{Tr}\ln\Gamma_0^{(2,0)}[0,A] + O(\partial_t\Gamma_k^{(2,0)}) + c.t.$$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

- full effective action

$$\Gamma_0[0,A] = \frac{1}{2}\,\mathrm{Tr}\ln\Gamma_0^{(2,0)}[0,A] + O(\partial_t\Gamma_k^{(2,0)}) + c.t.$$

- full effective potential in the deep infrared, $\Gamma_{0,A/C}^{(2,0)} \sim (-D^2)^{1+\kappa_{A/C}}$

$$V^{\mathrm{IR}}[\beta A_0] \simeq \left\{\frac{d-1}{2}(1+\kappa_A) + \frac{1}{2} - (1+\kappa_C)\right\}\frac{1}{\Omega}\mathrm{Tr}\ln\big(-D^2[A_0]\big)$$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

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- full effective potential in the deep infrared

$$V^{\mathrm{IR}}[\beta A_0] \simeq \left\{1 + \frac{(d-1)\kappa_A - 2\kappa_C}{d-2}\right\} V^{\mathrm{UV}}[\beta A_0]$$

- full effective action

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- confinement criterion with sum rule $\kappa_A = -2\kappa_C - \frac{4-d}{2}$

$$\kappa_C > \frac{d-3}{4}$$

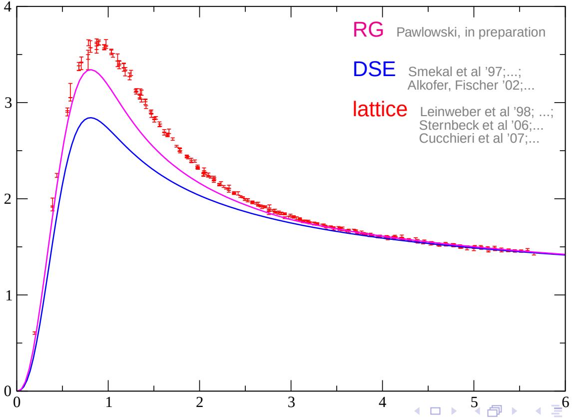
no confinement with background field propagators $\delta^2\Gamma_k/\delta A^2$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

- determination of $L(\langle A_0 \rangle)$

$$\Gamma_0[0,A] = \frac{1}{2}\,\mathrm{Tr}\ln \Gamma_0^{(2,0)}[0,A] + O(\partial_t \Gamma_k^{(2,0)}) + c.t.$$

$$\frac{p^2}{\Gamma_A^{(2)}(p)}$$

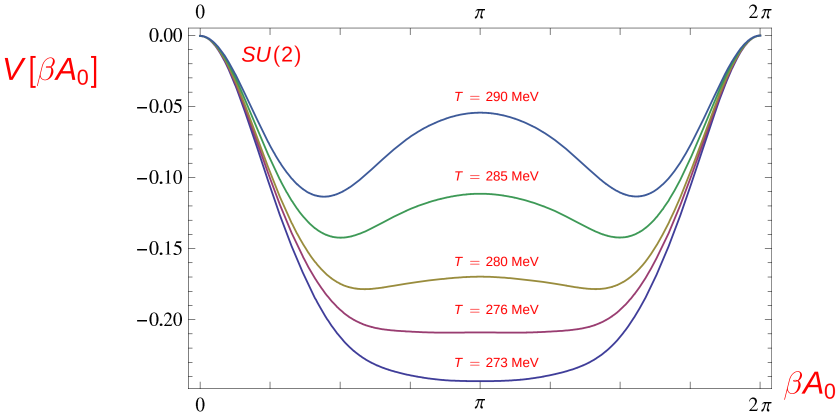


p [GEV]

Polyakov loop potential, $SU(2)$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

$T_c \simeq 276 \pm 10\text{MeV}$ $\quad T_c/\sqrt{\sigma} = 0.627 \pm 0.023$ $\quad$ lattice: $T_c/\sqrt{\sigma} = .709$



Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

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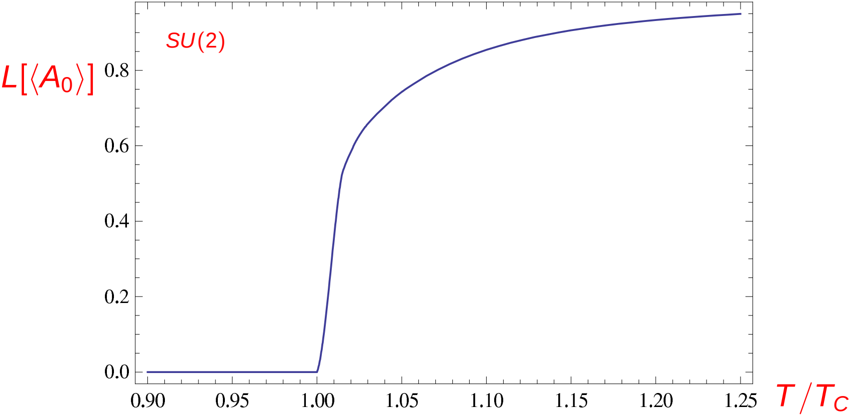
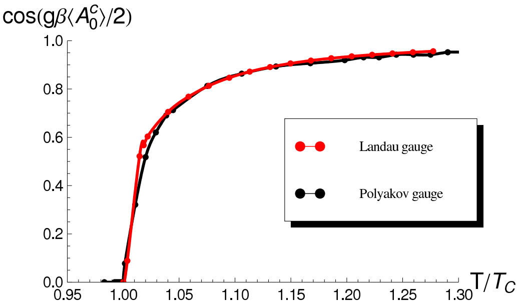


Marhauser, Pawlowski, in preparation

see talk of F. Marhauser

flow in Polyakov gauge: $A_0 = A_0(\vec{x})\sigma_3$

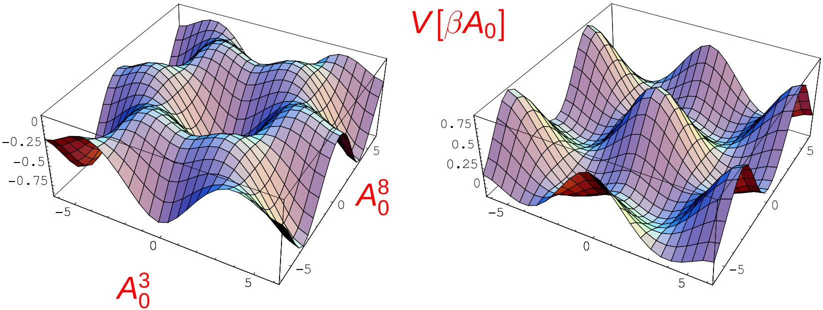


- ——: Polyakov gauge
- ——: Landau gauge propagators

Polyakov loop potential, $SU(3)$

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

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



Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

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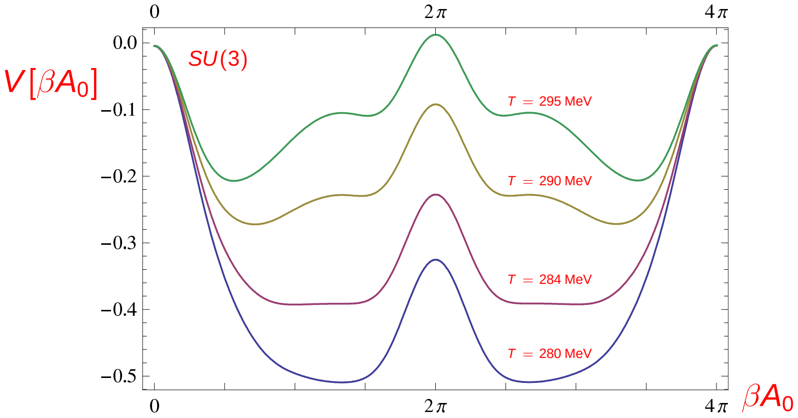

Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

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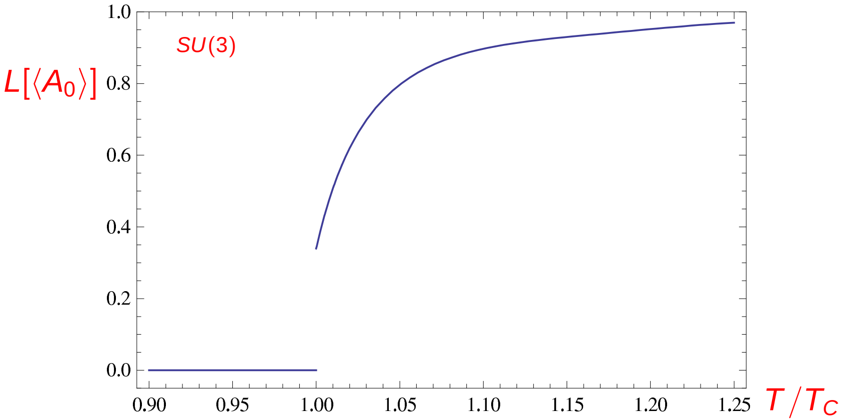

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  - confinement-decofinement phase transition from KO/GZ
  - dynamical chiral symmetry breaking   see talks of H. Gies, B.-J. Schaefer
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