Strong correlations in gauge theories

Jan Martin Pawlowski

Institute for Theoretical Physics
Heidelberg University

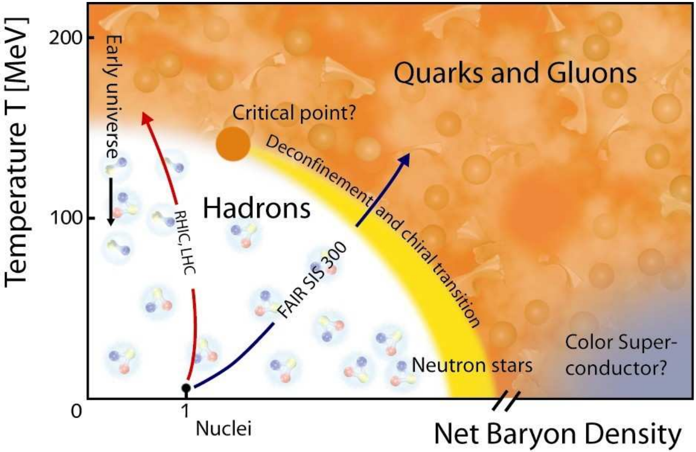
ERG 08, Heidelberg, July 4th, 2008

outline

outline

1. Introduction
2. Landau gauge QCD
   - Signatures of confinement
   - Infrared asymptotics & finite volume effects
3. QCD at finite temperature
   - Polyakov loop potential
   - confinement-deconfinement phase transition

QCD phase diagram



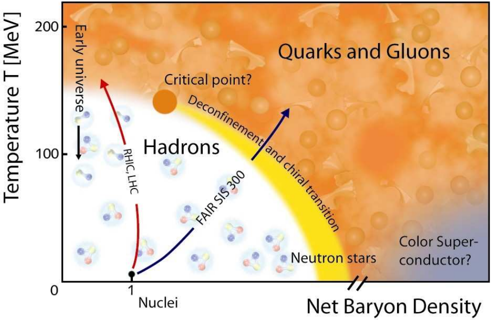
QCD phase diagram

- chiral phase transition

  $SU_L(N_f) \times SU_R(N_f)$

  order parameter:

$$\langle \bar{q}\, q \rangle = \begin{cases} 0, & T > T_{c,\chi} \\ > 0, & T < T_{c,\chi} \end{cases}$$



talks of J. Braun, B.-J. Schaefer

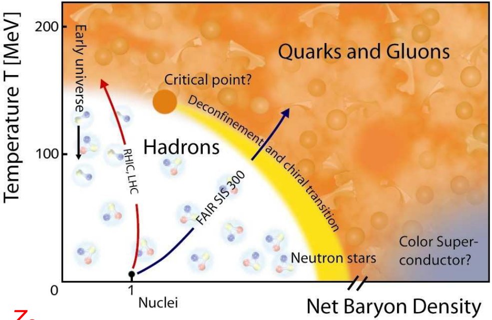
QCD phase diagram

- chiral phase transition:

  $SU_L(N_f) \times SU_R(N_f)$

  order parameter:

  $$\langle \bar{q}\, q \rangle = \begin{cases} 0, & T > T_{c,\chi} \\ > 0, & T < T_{c,\chi} \end{cases}$$



- confinement-deconfinement: Z_3

  order parameter:

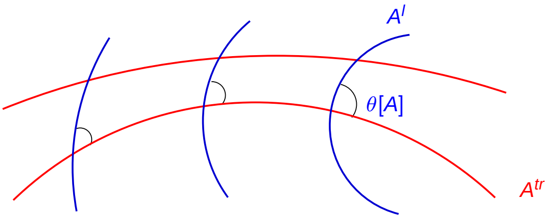
  $$\Phi = \langle \frac{1}{N_c} \mathrm{tr}\, \mathcal{P} e^{i \int_0^\beta dt\, A_0} \rangle = \begin{cases} > 0, & T > T_{c,\mathrm{conf}} \\ 0, & T < T_{c,\mathrm{conf}} \end{cases}$$

  $\Phi = e^{-F_q}$ relates to a static quark state.

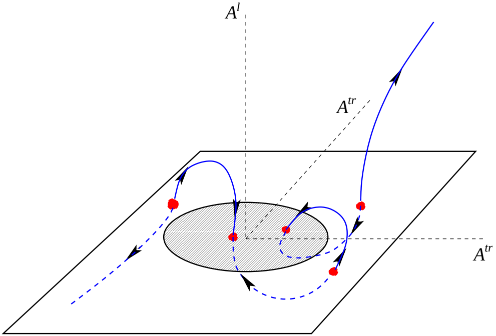
outline

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

gauge fixing ensures the existence of the gauge field propagator



Landau gauge $\xi = 0 : A^l = \partial_\mu A_\mu = 0$



Gribov problem

- Observables in Yang-Mills theory: $\mathcal{O}[A^g] = \mathcal{O}[A]$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA \, \mathcal{O}[A] \, e^{-S_{YM}[A]}$$

with $S_{YM} = \frac{1}{2} \int \mathrm{tr} \, F^2$ and $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$

- Observables in Yang-Mills theory: $\mathcal{O}[A^g] = \mathcal{O}[A]$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA\, \delta[\partial_\mu A_\mu]\, |\det(-\partial_\mu D_\mu)|\, \mathcal{O}[A]\, e^{-S_{YM}[A]}$$

Faddeev-Popov

- Observables in Yang-Mills theory: $\mathcal{O}[A^g] = \mathcal{O}[A]$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA\, \delta[\partial_\mu A_\mu]\, |\det(-\partial_\mu D_\mu)|\, \mathcal{O}[A]\, e^{-S_{YM}[A]}$$

Faddeev-Popov

- BRST: $|\det(-\partial_\mu D_\mu)| \to \det(-\partial_\mu D_\mu)$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA\, dC d\bar{C}\, \delta[\partial_\mu A_\mu]\, \mathcal{O}[A]\, e^{-S_{YM}[A] - \int \bar{C} \partial_\mu D_\mu C}$$

physical Hilbert space $\leftrightarrow$ nilpontency of BRST transformation s.

- Observables in Yang-Mills theory: $\mathcal{O}[A^g] = \mathcal{O}[A]$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA \, \delta[\partial_\mu A_\mu] \, |\det(-\partial_\mu D_\mu)| \, \mathcal{O}[A] \, e^{-S_{YM}[A]}$$

Faddeev-Popov

- BRST: $|\det(-\partial_\mu D_\mu)| \to \det(-\partial_\mu D_\mu)$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA \, dC d\bar{C} \, \delta[\partial_\mu A_\mu] \, \mathcal{O}[A] \, e^{-S_{YM}[A] - \int \bar{C} \partial_\mu D_\mu C}$$

but

$$\int dA \, \delta[\partial_\mu A_\mu] \, \frac{\det(-\partial_\mu D_\mu)}{|\det(-\partial_\mu D_\mu)|} = 0$$

- Observables in Yang-Mills theory: $\mathcal{O}[A^g] = \mathcal{O}[A]$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA \, \delta[\partial_\mu A_\mu] \, |\det(-\partial_\mu D_\mu)| \, \mathcal{O}[A] \, e^{-S_{YM}[A]}$$

Faddeev-Popov

- BRST: $|\det(-\partial_\mu D_\mu)| \to \det(-\partial_\mu D_\mu)$

$$\langle \mathcal{O}[A] \rangle = \frac{1}{\mathcal{N}} \int dA \, dC d\bar{C} \, \delta[\partial_\mu A_\mu] \, \mathcal{O}[A] \, e^{-S_{YM}[A] - \int \bar{C} \partial_\mu D_\mu C}$$

Remedies:

- weighting of copies: loss of BRST-invariance — loss of nilpotency
- topological gauge fixing — Witten index

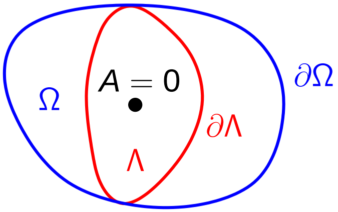
confinement scenario

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

- entropy

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

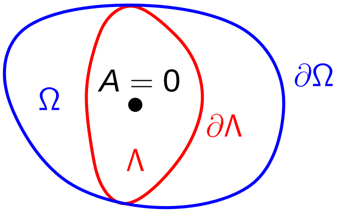
- entropy ($\int dA$)
  - $\partial\Omega\,(\cap\partial\Lambda)$ dominates IR
  - ghost IR-enhanced
  - gluonic mass-gap: confined gluons
    - violation of reflection positivity



non-renormalisation of ghost-gluon vertex

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

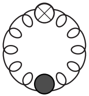
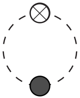
non-renormalisation of ghost-gluon vertex

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

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: $\phi = (A, C, \bar{C})$

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

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

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

- 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 though 'physically' complicated
- gauge invariance Ellwanger '94, Bonini et al '94, ...
  - loss of BRST-nilpotency
  - flow of modified Slavnov-Taylor identity $\mathcal{W}_k$

$$\partial_t\mathcal{W}_k = -\tfrac{1}{2}\mathrm{Tr}\left(\frac{1}{\Gamma_k^{(2)} + R_k}\partial_t R\,\frac{1}{\Gamma_k^{(2)} + R_k}\,\frac{\delta^2}{\delta\phi^2}\right)\mathcal{W}_k$$

Ellwanger '94, D'Attanasio, Morris '96, Litim, Pawlowski '98, 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 though 'physically' complicated
- gauge invariance

talks of Y. Igarashi, E. Itou, H. Sonoda

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
- gauge invariance
- 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

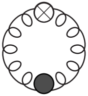
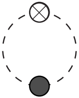
Wetterich, Phys. Lett. B **301** (1993) 90

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

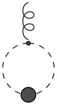
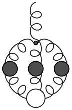
- self-similarity, reparameterisation & projections
- fermions straightforward
- functional methods in Landau gauge QCD (IR)
  - Dyson-Schwinger equations — von Smekal, Hauck, Alkofer '97
  - stochastic quantisation — Zwanziger '02
  - flows in Landau gauge QCD — Pawlowski, Litim, Nedelko, von Smekal '03
  - quark confinement from Landau gauge propagators — Braun, Gies, Pawlowski '07
  - analytic perturbation theory (fixed point for coupling) — Shirkov, Solovtsov '96

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

functional RG

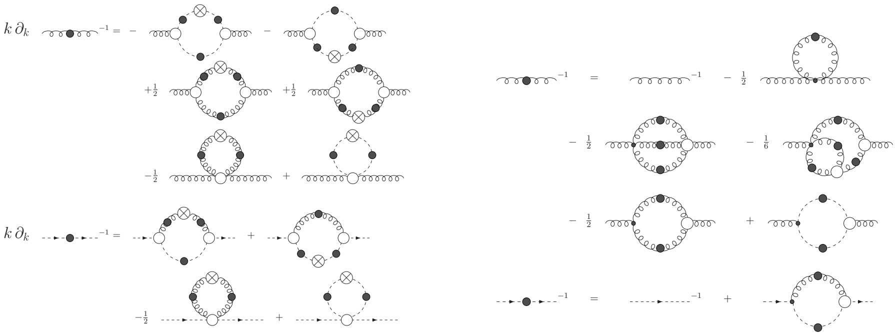
$$\partial_t \Gamma_k[\phi] \;=\; \frac{1}{2}$$  $$-$$ 

functional DSE

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

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

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



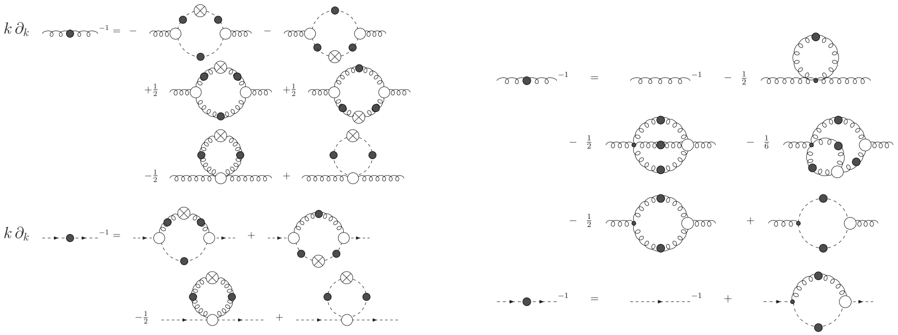
Unique infrared asymptotics in Landau gauge QCD

- conformal scaling

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

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

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



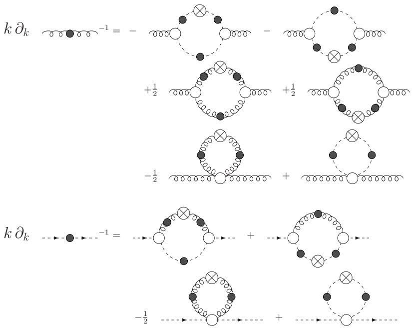
Unique infrared asymptotics in Landau gauge QCD

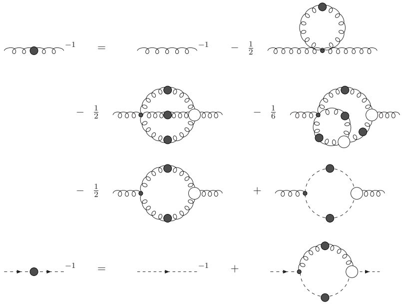
- conformal scaling

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

- decoupling: $\kappa_{2n,m} = 0$ & massive gluon   no confinement!?

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





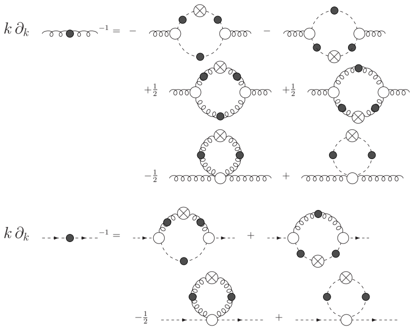
Unique infrared asymptotics in Landau gauge QCD

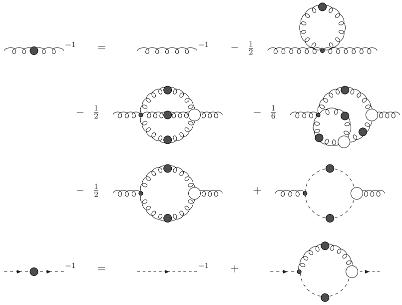
$$\Gamma^{(2n,m)} \sim p^{2(n-m)\kappa_C} \qquad \text{with} \qquad \kappa_c \geq 0$$

$\Gamma^{(2n,m)}$: 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

Truncation

- full momentum dependence of propagators
- vertices momentum-dependent RG-dressing
- optimisation   Litim '00, Pawlowski '05

Truncation

- full momentum dependence of propagators
- vertices momentum-dependent RG-dressing
- optimisation J. M. Pawlowski, Annals Phys. **322** (2007) 2831
  - RG-invariance: $D_\mu \Gamma_k = 0$ from $D_\mu \Gamma = 0$ Pawlowski '00,'02

$$(D_\mu + 2\gamma_\phi) R_k \stackrel{!}{=} 0 \qquad \rightarrow \qquad R_k = \Gamma_k^{(2)} r(x/k^2)$$

with $D_\mu x = 0$, e.g. $x = p^2$, $x = \Gamma_k^{(2)}/Z$.

Truncation

- full momentum dependence of propagators
- vertices momentum-dependent RG-dressing
- optimisation J. M. Pawlowski, Annals Phys. **322** (2007) 2831
  - RG-invariance
  - functional optimisation Pawlowski '05

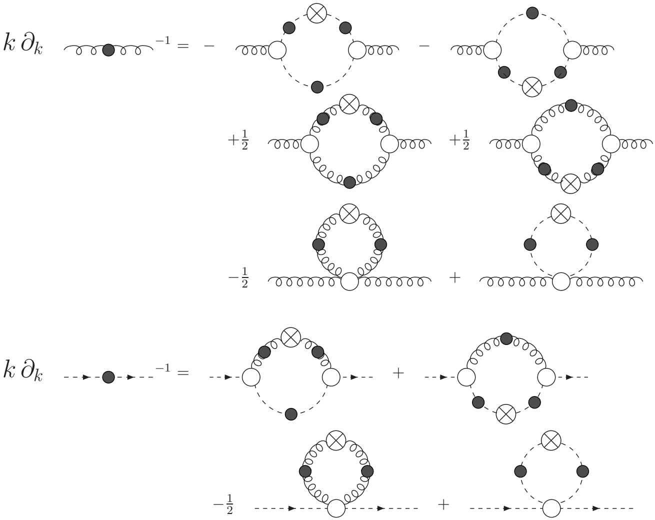
$$R_{\rm opt} \simeq (\Gamma_0^{(2)} - \Gamma_k^{(2)})\theta(\Gamma_0^{(2)} - \Gamma_k^{(2)})$$

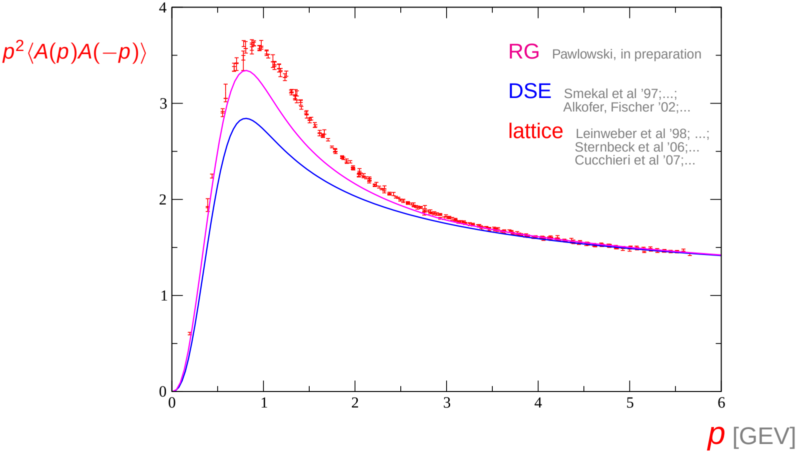
Truncation

- full momentum dependence of propagators
- vertices momentum-dependent RG-dressing
- optimisation
- functional relations between diagrams: Flow=Flow(DSE)

$$\Rightarrow k\partial_k \Gamma^{(2)}_{k,A/C}(p^2) = \mathrm{Flow}_k[\Gamma^{(2)}_{k,A/C}\,,\,\Gamma^{(3)}_k\,,\,\Gamma^{(4)}_k]$$

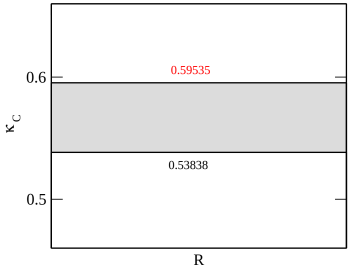
UV-IR flow





Improvement on FRG & DSE results: J. M. Pawlowski '08, Fischer '08

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



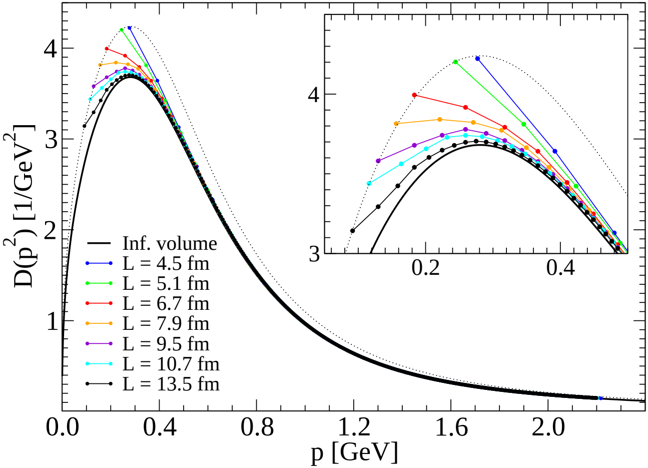
Pawlowski, Litim, Nedelko, von Smekal, Phys. Rev. Lett. **93** (2004) 152002

- functional 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)

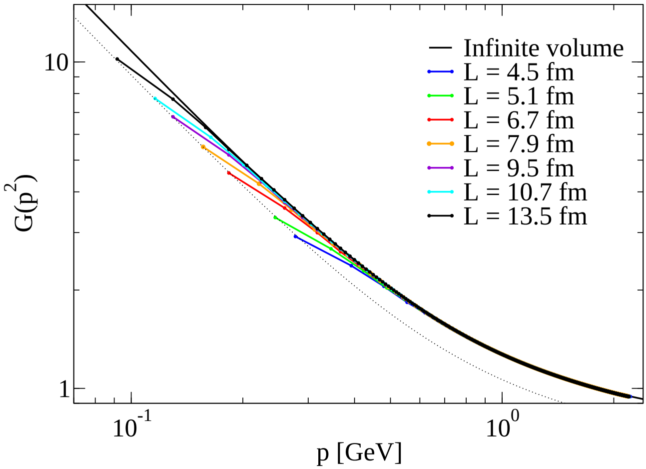
$$D(p^2) = \frac{1}{\Gamma_A^{(2)}(p)}$$

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 $d = 3$ A. Maas (St Goar '08)
- large volumes on the lattice
  - in $d = 4$ up to 128^4 at $\beta = 2.2$ Cucchieri et al '07
- gauge fixings
  - improved gauge fixings Bogolubsky et al '07, von Smekal et al '07, Maas (St Goar '08)
  - 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 von Smekal (St Goar '08)

outline

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 $\Phi \simeq e^{-F_q}$

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

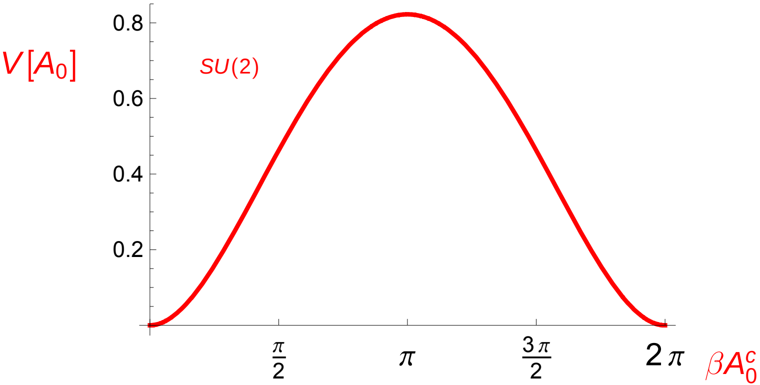
- string tension

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

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

Weiss potential

$$V^{\mathrm{UV}}[A_0] = \frac{1}{2\Omega}\,\mathrm{Tr}\ln S^{(2)}_{AA}[A_0] - \frac{1}{\Omega}\mathrm{Tr}\ln S^{(2)}_{C\bar{C}}[A_0]$$



$SU(2)$: $L[A_0] = \cos\frac{1}{2}\beta A_0^c$ with $A_0 = A_0^c\sigma_3$

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

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

- determination of fluctuation propagator   in Landau-DeWitt gauge

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

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

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

- determination of fluctuation propagator in Landau-DeWitt gauge

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

- Polyakov loop $L[\langle A_0\rangle] \geq \langle L[A_0]\rangle$

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

- full effective action

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

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

- full effective action

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

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

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

- full effective action

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

- full effective potential in the deep infrared

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

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

- full effective action

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

- full effective potential in the deep infrared

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

- 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

- full effective action

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

- full effective potential in the deep infrared

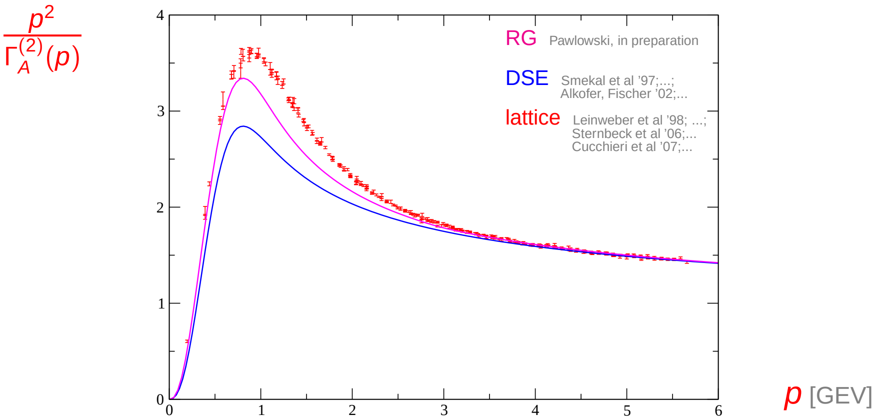
$$V^{\mathrm{IR}}[A_0] \simeq \left\{1 + \frac{(d-1)\kappa_A - 2\kappa_C}{d-2}\right\} V^{\mathrm{UV}}[A_0]$$

- bounds on κ_C in $d = 4$ Eichhorn, Gies, Pawlowski, poster

$$\frac{1}{4} < \kappa_C < \frac{41}{42}$$

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

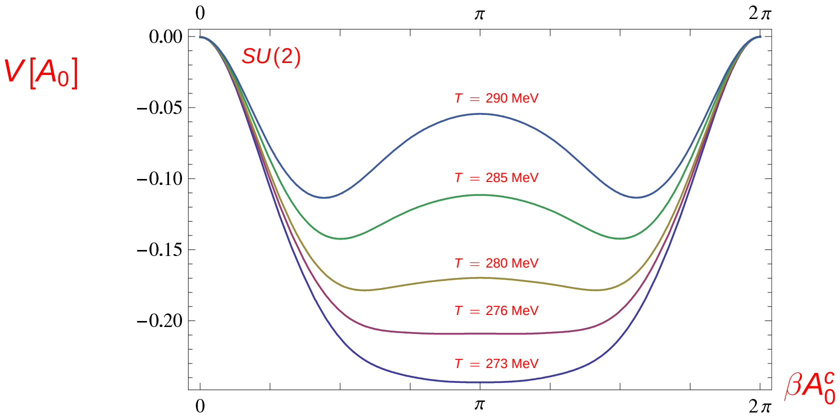
- determination of $L(\langle A_0 \rangle)$



Polyakov loop potential: $SU(2)$

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

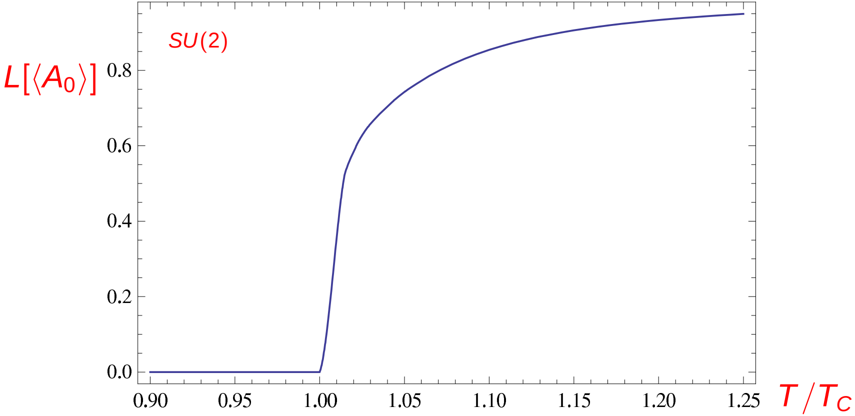
$T_c \simeq 276 \pm 10\text{MeV}$ $\qquad T_c/\sqrt{\sigma} = 0.627 \pm 0.023$ $\qquad$ lattice: $T_c/\sqrt{\sigma} = .709$



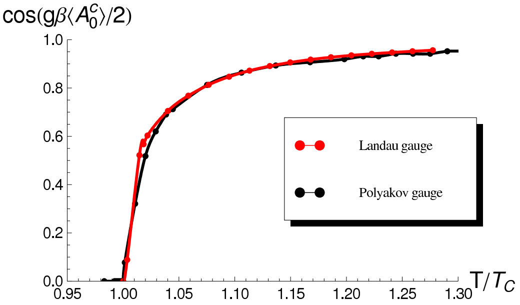
$$L[A_0] = \cos \tfrac{1}{2}\beta A_0^c$$

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: $T_c/\sqrt{\sigma} = .709$



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

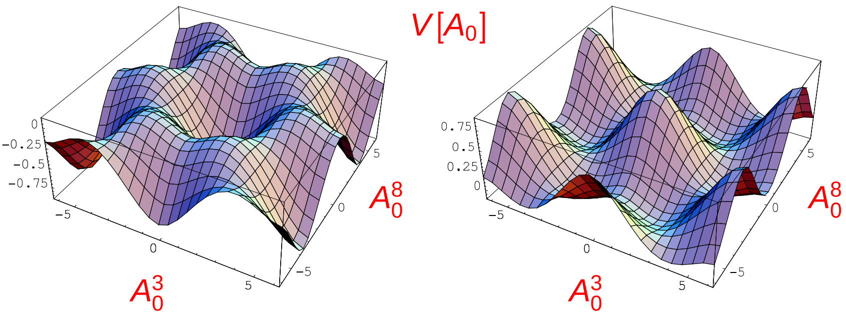


- ——: Polyakov gauge: crit. exp. $\nu = 0.65$ $\qquad \nu_{\text{Ising}} = 0.63$
- ——: Landau gauge propagators

Polyakov loop potential: $SU(3)$

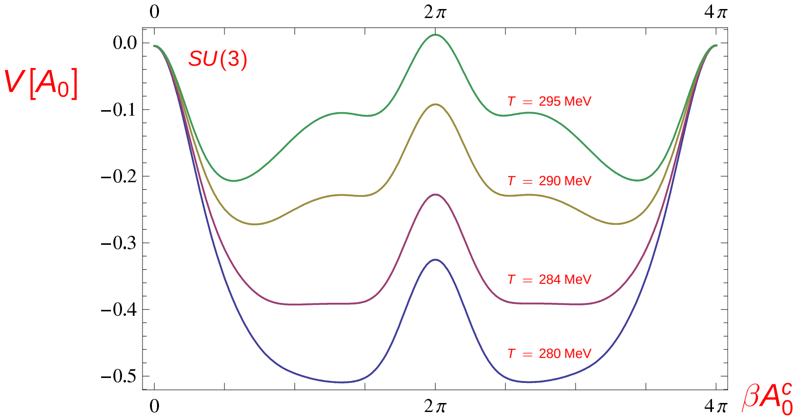
Braun, Gies, Pawlowski, arXiv:0708.2413 [hep-th]

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



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

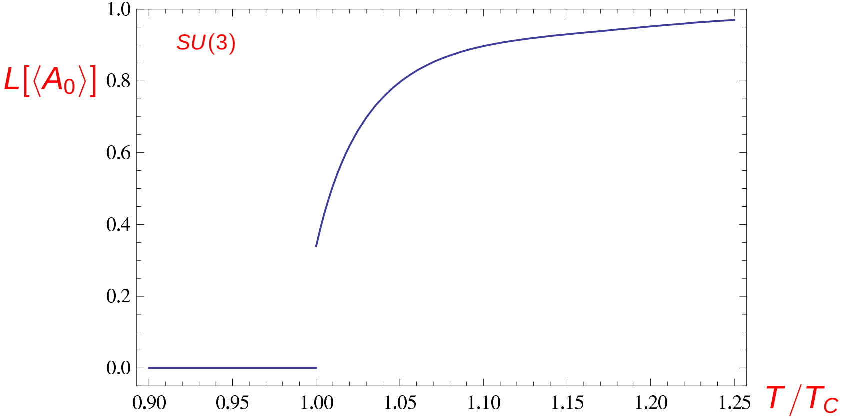
$T_c \simeq 284 \pm 10\text{MeV}$ $\qquad T_c/\sqrt{\sigma} = 0.646 \pm 0.023$ $\quad$ lattice: $T_c/\sqrt{\sigma} = .646$



$$L[\beta A_0^c = \tfrac{4}{3}\pi] = 0$$

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



- results
  - support for Kugo-Ojima/Gribov-Zwanziger scenario
  - confinement-deconfinement phase transition from KO/GZ
  - dynamical chiral symmetry breaking
  - ’QCD phase diagram’ from models
- challenges
  - full QCD
  - flow of Wilson loops & Polyakov loops: area law
  - QCD at finite temperature & density

- results
  - support for Kugo-Ojima/Gribov-Zwanziger scenario
  - confinement-decofinement phase transition from KO/GZ
  - dynamical chiral symmetry breaking
  - ’QCD phase diagram’ from models
- challenges
  - full QCD
  - flow of Wilson loops & Polyakov loops: area law
  - QCD at finite temperature & density

thanks to J. Braun, A. Eichhorn, C. Fischer, H. Gies, D. Litim, A. Maas, F. Marhauser, S. Nedelko, B.-J. Schaefer, L. von Smekal, J. Wambach