Studying mass generation in Landau-gauge Yang-Mills theory

GE, Pawlowski, Silva, 2107.05352
(accepted for publication in PRD)

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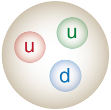
XIII International Workshop on High-Energy Physics
“Hard Problems of Hadron Physics: Non-Perturbative QCD & Related Quests”

Nov 11, 2021

Motivation

Three current quarks
do not make a proton:

$2m_u + m_d$ ~ 10 MeV << 1 GeV ?



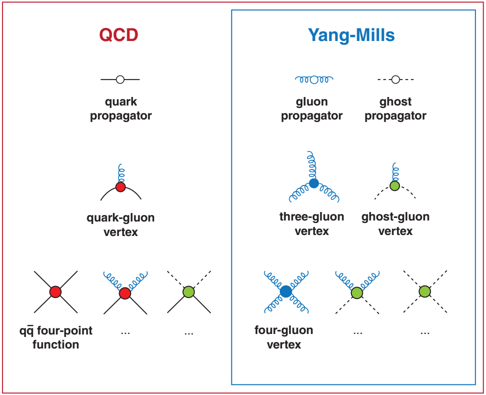
u	d	s	c	b	t
3	5	100	1000	4000	175000
350	350	350	350	350	350

[MeV]

QCD's n-point functions

QCD is determined by its **n-point correlation functions:**

$$S_{\text{QCD}} = \int d^4x \left[\bar{\psi}\,(\not{D} + M)\,\psi + \tfrac{1}{4}\,F^a_{\mu\nu}\,F^{\mu\nu}_a + \mathcal{L}_{\text{GF}} \right]$$



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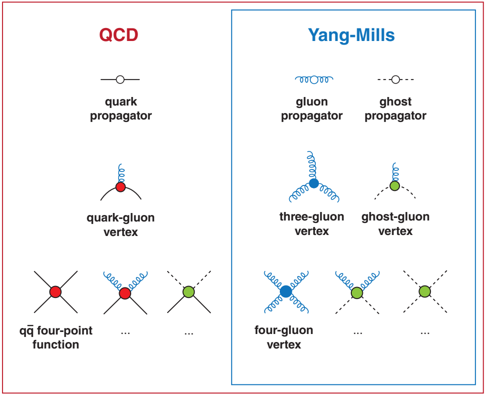
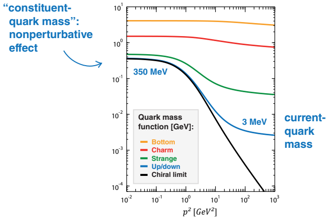
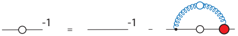


- **Mass generation for quarks:**
  Dynamical chiral symmetry breaking



- Outcome of
  Dyson-Schwinger equations (DSEs),
  functional renormalization group (FRG),
  lattice QCD



- Relies on underlying mass generation for **gluons**

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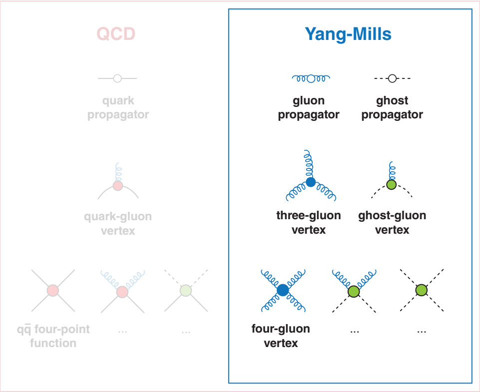

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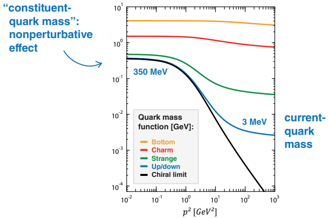

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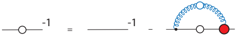


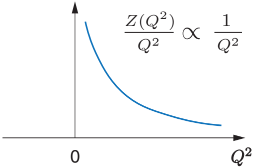
- Relies on underlying mass generation for **gluons**

Mass generation for gluons?

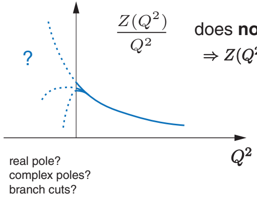
Gluon propagator:

$$D^{\mu\nu}(Q) = \underbrace{\frac{Z(Q^2)}{Q^2}}_{= D(Q^2)} \left(\delta^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2}\right) + \xi \, \frac{\overbrace{L(Q^2)}^{=1}}{Q^2} \, \frac{Q^\mu Q^\nu}{Q^2}$$

- **Perturbation theory:**
  Massless pole in gluon propagator



- **Nonperturbative calculations:**
  Massless pole disappears



does **not** diverge at $Q^2 = 0$
$\Rightarrow Z(Q^2 \to 0) = 0$

$$\lim_{r\to\infty} \int \frac{d^3Q}{(2\pi)^3} \frac{Z(\boldsymbol{Q}^2)}{\boldsymbol{Q}^2} \, e^{i\,\boldsymbol{x}\cdot\boldsymbol{Q}} \propto e^{-m_{\text{gap}}\,r}$$

Mass generation for gluons?

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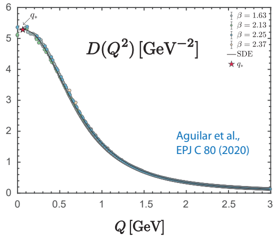
- **Massive (decoupling, "DC") solution of DSEs & FRG**

$$D(Q^2 \to 0) \sim \frac{1}{m^2} \quad \Leftrightarrow \quad \frac{1}{Z(Q^2)} \xrightarrow{Q^2 \to 0} \frac{m^2}{Q^2}$$

- **Lattice QCD:**



Aguilar, De Soto, Ferreira, Papavassiliou, Rodriguez-Quintero, Zafeiropoulos, EPJ C 80 (2020)

Duarte, Oliveira, Silva, PRD 94 (2016)

Maas, Phys. Rept. 524 (2013)

Bogolubsky, Ilgenfritz, Müller-Preussker, Sternbeck, PLB 676 (2009)

Cucchieri, Maas, Mendes, PRD 77 (2008)

...

Mass generation for gluons?

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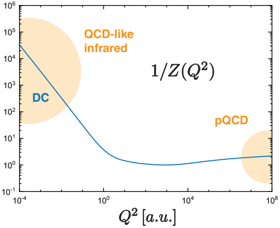

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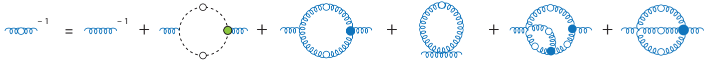
- For **gluon DSE,** this means somewhere on the r.h.s. there **must** be a $1/Q^2$ pole → where?



- **PT-BFM** (Pinch-technique/background-field method): massless bound states in three-gluon vertex
  Aguilar, Binosi, Papavassiliou, PRD 78 (2008), Aguilar, Papavassiliou, PRD 91 (2015)

Mass generation for gluons?

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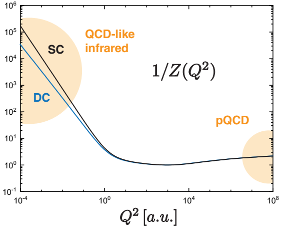
- **Scaling ("SC") solution of DSEs & FRG:**

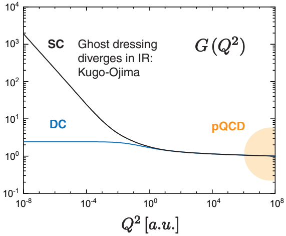
  n-point functions scale with IR power laws:
  $Z \sim (Q^2)^{2\kappa}$, $G \sim (Q^2)^{-\kappa}$, $\dots$, $\kappa \sim 0.59$
  Smekal, Hauck, Alkofer, Ann. Phys. 267 (1998), Lerche, Smekal, PRD 65 (2002), Fischer, Alkofer, PLB 536 (2002), PRD 70 (2004), Zwanziger, PRD 67 (2003)

  $q\bar{q}$ four-point function ~ $1/Q^4$
  
  Alkofer, Fischer, Llanes-Estrada, Mod. Phys. Lett. A 23 (2008)

  DSEs, FRG: family of DC solutions with scaling solution as endpoint
  Boucaud, Leroy, Yaouanc, Micheli, Pène, Rodríguez-Quintero, JHEP 06 (2008)
  Fischer, Maas, Pawlowski, Ann. Phys. 324 (2009),
  Reinosa, Serreau, Tissier, Wschebor, PRD 96 (2017)

  Not seen on lattice (but different DC solutions?)
  Cucchieri, Mendes, PRD 88 (2013), Sternbeck, Müller-Preussker, PLB 726 (2013)

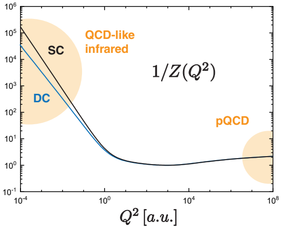




Mass generation for gluons?

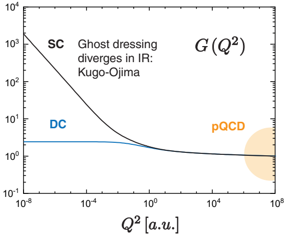
Options:

- Only DC solution is physical? (Lattice, PT-BFM)
- Only SC solution is physical? (Kugo-Ojima, $1/Q^4$)
- All solutions are physically equivalent?
  (Hadron physics, T > 0, ...)



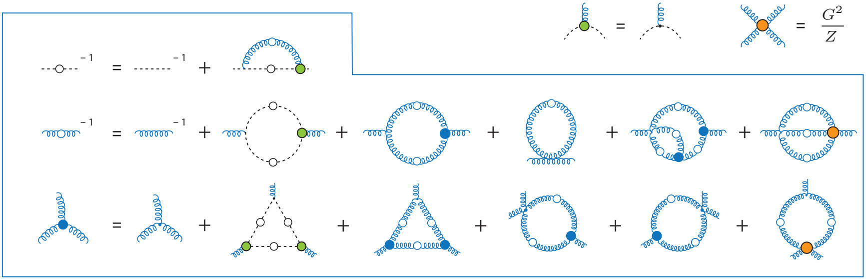
Questions:

- What actually distinguishes SC and DC?
- Where does the singularity in 1/Z come from?
- How is a gluon “mass” compatible with
  gauge invariance?



DSEs

This is what we solve:



Higher n-point functions:

DSEs & nPI: Huber, PRD 101 (2020) 114009

FRG: Cyrol, Fister, Mitter, Pawlowski, Strodthoff, PRD 94 (2016), PRD 97 (2018)

Binosi, Ibañez, Papavassiliou, JHEP 09 (2014)
Gracey, Pelaez, Reinosa, Tissier, PRD 100 (2019),
. . .

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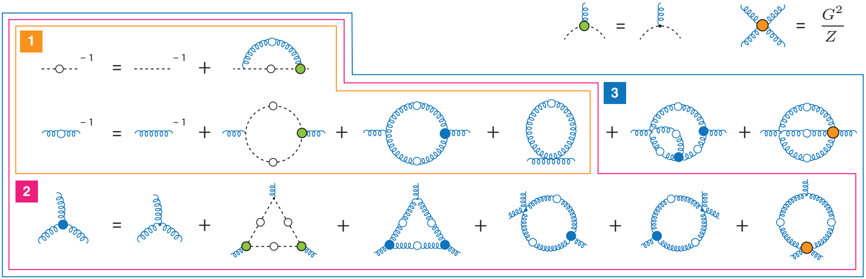

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...

Different truncations do not change qualitative features.
Internal way to quantify **truncation error** (deviation from STI):

1 c ~ 0.4
2 c ~ 0.9
3 c ~ 0.96 → 4% error (Full: c = 1)

Mass generation

Gluon has T + L component, L = trivial.

$$(D^{-1})^{\mu\nu}(Q) = (D_0^{-1})^{\mu\nu}(Q) + \Pi^{\mu\nu}(Q)$$

$$\Pi(Q^2)\,(Q^2\delta^{\mu\nu} - Q^\mu Q^\nu) + \widetilde{\Pi}(Q^2)\,\delta^{\mu\nu}$$

- mass dimension 2
- violates gauge invariance → must vanish
- vanishes in perturbation theory (dim. reg.), but not with cutoff → quadratic divergences

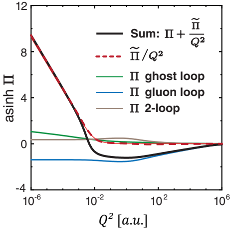
$$\Rightarrow \quad Z(Q^2)^{-1} = Z_A + \Pi(Q^2) + \frac{\widetilde{\Pi}(Q^2)}{Q^2}$$

$$L(Q^2)^{-1} = 1 + \xi\,\widetilde{\Pi}(Q^2)$$

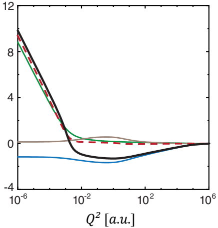
Usually:
drop longitudinal equation
($\widetilde{\Pi}(Q^2)$ must be zero anyway),
solve transverse equation.

But is it zero in practice? No ...
Actually, this term is responsible for **mass generation** → ??

Decoupling:
$\widetilde{\Pi}(Q^2)$ generates mass?



Scaling:
ghost loop dominance



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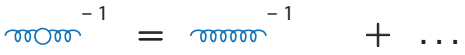


Expand self-energy in overcomplete basis:

$$\Delta_T(Q^2)\,(Q^2\delta^{\mu\nu} - Q^\mu Q^\nu) + \Delta_0(Q^2)\,\delta^{\mu\nu} + \Delta_L(Q^2)\,Q^\mu Q^\nu$$

Δ_0: contains **quadratic divergences,** need to be subtracted

Δ_L: must contain **longitudinal massless poles**

$$\Delta_L = -\frac{\Delta_0}{Q^2}$$

Mass generation must come from here!

$$Z(Q^2)^{-1} = Z_A + \Delta_T + \frac{\Delta_0}{Q^2}$$

$$L(Q^2)^{-1} = 1 + \xi \left[\Delta_L + \frac{\Delta_0}{Q^2}\right]$$

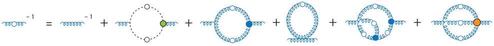
$$\left[\Delta_L + \frac{\Delta_0}{Q^2}\right] \stackrel{!}{=} 0$$

$$\Pi = \Delta_T - \Delta_L$$

$$\frac{\widetilde{\Pi}}{Q^2} = \frac{\Delta_0}{Q^2} + \Delta_L \stackrel{!}{=} 0$$

Two possibilities:

- **Scenario A:** $\Delta_L = 0 \;\Rightarrow\; \Delta_0$ must be artifact (from hard cutoff and/or truncation)
- **Scenario B:** $\Delta_L \neq 0 \;\Rightarrow$ Longitudinal consistency condition, requires longitudinal massless poles in the vertices (where?), does not affect transverse equation



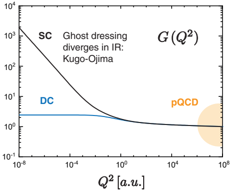
What distinguishes SC and DC solutions?

Renormalization

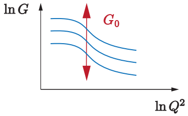
Boundary condition on ghost:

$G(0) \to \infty$

$G(0)$ finite



But $G(0) = G_0$ should only renormalize propagator...?



- n-point functions are related to bare ones by **renormalization constants:**

$$
\begin{aligned}
G^{(B)} &= Z_c\, G\,, & \Gamma_{\text{gh}} &= \widetilde{Z}_\Gamma\, \Gamma^{(B)}_{\text{gh}}\,,\\
Z^{(B)} &= Z_A\, Z\,, & \Gamma_{3g} &= Z_{3g}\, \Gamma^{(B)}_{3g}\,,\\
g^{(B)} &= Z_g\, g\,, & \Gamma_{4g} &= Z_{4g}\, \Gamma^{(B)}_{4g}\,,
\end{aligned}
$$

- In Landau gauge, can set $\widetilde{Z}_\Gamma = 1$

  $\Rightarrow$ all ren. constants related to $Z_A,\ Z_c$

$$
Z_g = \frac{1}{Z_A^{1/2}\, Z_c}\,, \qquad Z_{3g} = \frac{Z_A}{Z_c}\,, \qquad Z_{4g} = \frac{Z_A}{Z_c^2}\,.
$$

- Renormalization conditions for the propagators eliminate Z_A, Z_c in favor of $Z(\mu^2) = Z_\mu,\ G(\nu^2) = G_\nu\,,$ can always renormalize ghost at $\nu = 0$

$\Rightarrow$ YM eqs. depend on 3 “parameters”: $g,\ Z_\mu,\ G_0$

$$
\begin{aligned}
G(Q^2)^{-1} &= G_0^{-1} + \Sigma(Q^2) - \Sigma(0)\,,\\
Z(Q^2)^{-1} &= Z_\mu^{-1} + \mathbf{\Pi}(Q^2) - \mathbf{\Pi}(\mu^2)\,, \qquad \mathbf{\Pi} = \Delta_T + \frac{\Delta_0}{Q^2}\\
F_{3g}(Q^2) &= Z_{3g} + \mathcal{M}(Q^2)\,.
\end{aligned}
$$

Keep g & Z_μ fixed $\Rightarrow$ G_0 distinguishes SC & DC

Renormalization

- $\Delta_0(Q^2)$ contains quadratic divergences which must be subtracted. Arbitrariness in subtraction compensated by parameter β:

$$\Delta_0(Q^2) \to \Delta_0(Q^2) - \Delta_0(Q_0^2) + \frac{g^2}{4\pi}\, G_0^2\, \beta \mu^2$$

This introduces effective **mass term** into eqs:

$$\frac{\Delta_0}{Q^2} \to (\dots) + (\dots)\, \beta\, \frac{\mu^2}{Q^2}$$

- $g,\ Z_\mu,\ G_0$ are actually not independent, but only appear in **combination:**

$$\alpha = Z_\mu G_0^2\, \frac{g^2}{4\pi} \in \mathbb{R}_+$$

To see this, redefine $Z(Q^2) \to \frac{Z(Q^2)}{Z_\mu}$, $G(Q^2) \to \frac{G(Q^2)}{G_0}$, same for $Z_A,\ Z_c,\ F_{3g},\ F_{4g}$

Furthermore: $G(x) \to \sqrt{\alpha}\, G(x)$, $x = \frac{Q^2}{\beta\mu^2}$

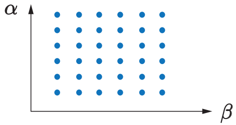
⇒ Yang-Mills eqs. depend on **two parameters** $\alpha,\ \beta$ (independent of truncation):

$$G(x)^{-1} = \frac{1}{\sqrt{\alpha}} + \Sigma(x) - \Sigma(0)$$
$$Z(x)^{-1} = 1 + \Pi(x) - \Pi(\tfrac{1}{\beta})$$
$$F_{3g}(x) = Z_{3g} + \mathcal{M}(x)$$

⇒ α only appears in ghost DSE: $G(0) = \sqrt{\alpha}$

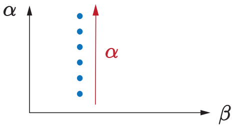
⇒ β only appears in subtraction point

⇒ Solve DSEs in $(\alpha,\ \beta)$ plane:



Family of solutions

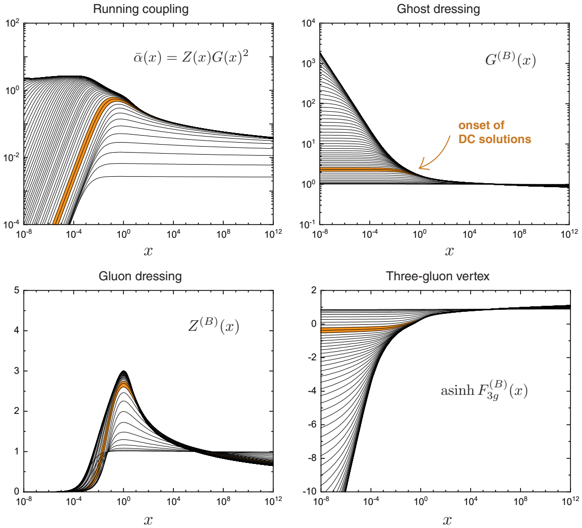
Fixed β, vary $\alpha \in (0, \infty)$:



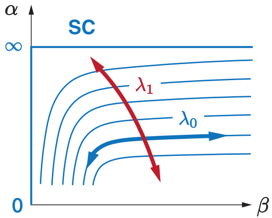
- **Running coupling** $\bar{\alpha}(x)$ is RG-invariant, sets scale (so far x is arbitrary)
- SC = envelope of DC solutions for $\alpha \to \infty$

$$Z \sim (Q^2)^{2\kappa}$$
$$G \sim (Q^2)^{-\kappa}$$
$$F_{3g} \sim (Q^2)^{-3\kappa}$$
$$\bar{\alpha} \sim \text{const.}$$

- Onset of DC solutions ↔ **lattice** solutions



Lines of constant physics

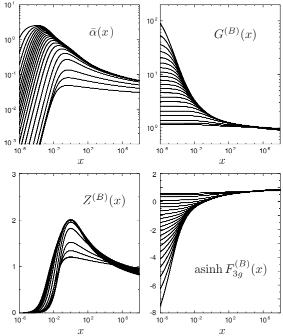


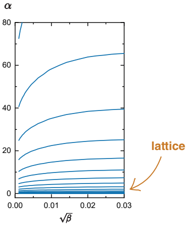
⇒ Two combinations of α and β determine solutions:

- $\lambda_0(\alpha,\beta)$ rescales system
- $\lambda_1(\alpha,\beta)$ distinguishes SC + DC

Family of solutions due to presence of **mass term!**

Solutions are identical along **lines of constant physics:** each curve is superposition of **30 curves** along trajectories:



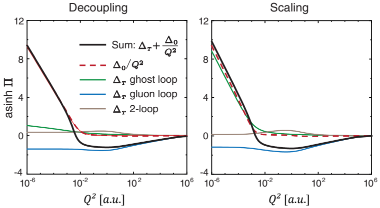


Where does the singularity in 1/Z come from?

Mass generation

$$\Pi(x) = \underbrace{\Delta_T(x)} + \underbrace{\frac{\Delta_0(x)}{x}}$$

DC:	ghost loop diverges logarithmically, other diagrams go to constant	diverges like 1/x: **mass generation**
SC:	diverges like $1/x^{2\kappa}$ (from ghost loop)	diverges like $1/x^{2\kappa}$ (from ghost loop)

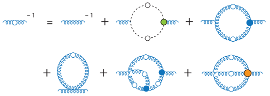


⇒ Need $\Delta_L \neq 0$ to satisfy longitudinal consistency condition

$$Z(Q^2)^{-1} = Z_A + \Delta_T + \frac{\Delta_0}{Q^2}$$

$$L(Q^2)^{-1} = 1 + \xi \underbrace{\left[\Delta_L + \frac{\Delta_0}{Q^2}\right]}_{\stackrel{!}{=}\,0}$$

⇒ requires **longitudinal massless poles** in either of the vertices

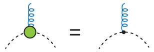


ghost-gluon vertex?
three-gluon vertex?

four-gluon vertex?

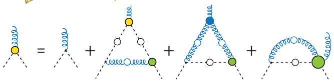
Longitudinal poles?

So far, we employed tree-level **ghost-gluon vertex:**

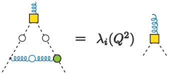


DSE for ghost-gluon vertex:

B term only appears here



This can be read as **inhomogeneous BSE** for B, to determine if B has pole, sufficient to solve **homogeneous BSE**



Bethe-Salpeter amplitude

$$\int dx'\, \mathcal{K}(x,x')\, \varphi(x') = \lambda_0\, \varphi(x)\,,$$

$$\mathcal{K}(x,x') = \frac{N_c}{(2\pi)^2}\, x\, G(x')^2 \int_{-1}^{1} dy\, (1-y^2)^{\frac{3}{2}}\, \frac{Z(w)}{w^2}$$

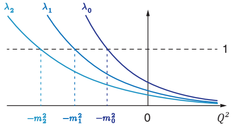
But general vertex has 2 tensors:

$$\Gamma^\mu_{\text{gh}}(p,Q) = -ig f_{abc}\left[(1+A)\, p^\mu + B\, Q^\mu\right]$$

$A(p^2, p\cdot Q, Q^2)$
$B(p^2, p\cdot Q, Q^2)$

- $(1+A)$: tree level
- A: small
- B: contributes to Δ_L, does it have a $1/Q^2$ pole?

Typical **eigenvalue spectrum** of a homogeneous BSE:



If $\lambda_0(Q^2 = 0) = 1 \;\Leftrightarrow$ **Ghost-gluon vertex has longitudinal massless pole**

Longitudinal poles?

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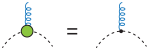

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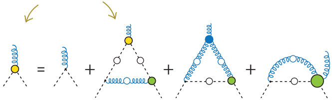

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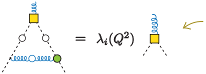

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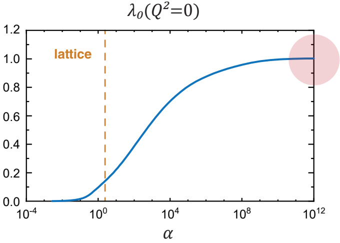


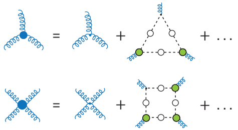
$\Rightarrow$ **Only SC solution** can satisfy consistency condition

If $\lambda_0(Q^2=0)=1$ $\Leftrightarrow$ **Ghost-gluon vertex has longitudinal massless pole**

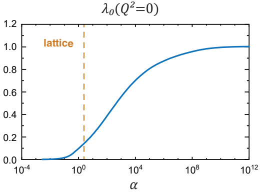
Longitudinal poles?

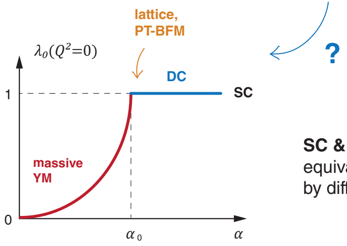
- But then what about lattice solutions?
- PT-BFM: longitudinal poles in 3-gluon vertex

  Aguilar, Ibanez, Mathieu, Papavassiliou, PRD 85 (2012),
  Aguilar, Binosi, Papavassiliou, PRD 95 (2017)
- Indeed, pole in ghost-gluon vertex would appear in any ghost loop



⇒ longitudinal poles in 3-gluon, 4-gluon vertex etc.





DC: 3-gluon vertex dominance

SC: ghost dominance

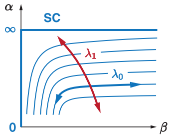
SC & DC physically equivalent, but generated by different mechanisms (?)

Summary

- Yang-Mills DSEs admit **family of solutions,** which depend on two parameters α, β

  $\lambda_0(\alpha,\beta)$ only rescales solutions

  $\lambda_1(\alpha,\beta)$ distinguishes SC + DC



- **Mass generation** through $\Delta_0 \Leftrightarrow \beta$, is entirely non-perturbative

$$Z(Q^2)^{-1} = Z_A + \Delta_T + \frac{\Delta_0}{Q^2}$$

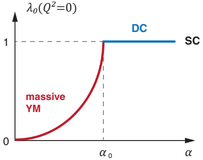
$$L(Q^2)^{-1} = 1 + \xi\left[\Delta_L + \frac{\Delta_0}{Q^2}\right]$$

$$\underbrace{\Delta_L + \frac{\Delta_0}{Q^2}}\stackrel{!}{=} 0$$

- Gauge consistency requires **longitudinal massless poles** in vertices

- Ghost-gluon vertex has longitudinal massless pole $\Rightarrow$ **SC solution consistent**

- Does not exclude consistency of DC solutions, if longitudinal poles in three-gluon vertex (PT-BFM)



Then presumably **all** solutions are physically equivalent (?)

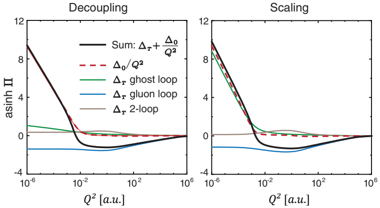
Thank you!

Backup slides

Mass generation

$$\Pi(x) = \Delta_T(x) + \frac{\Delta_0(x)-\Delta_0(x_0)}{x} + \frac{\beta}{x}$$

DC:	ghost loop diverges logarithmically, other diagrams go to constant	diverges like 1/x: **mass generation**
SC:	diverges like $1/x^{2\kappa}$ (from ghost loop)	diverges like $1/x^{2\kappa}$ (from ghost loop)



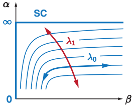
- **Scenario A:** Δ_0 is artifact from hard cutoff (like in QED) and/or truncation

→ Without this term, no QCD-like solutions

→ Take limit $\beta \to 0$:

$$\frac{\Delta_0(x)-\Delta_0(x_0)}{x} + \frac{\beta}{x} \longrightarrow \lim_{\beta\to 0} \frac{\beta}{x}$$

⇒ No DC solutions, **only SC solution**



However, singularity in 1/Z is triggered by β/x

⇒ could as well use arbitrary power β/x^{2n}

⇒ SC solution with infrared exponent $\kappa = n$

⇒ Ambiguity in SC solution, **disfavors Scenario A**

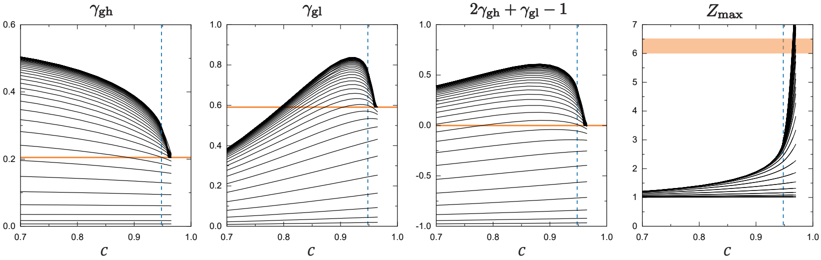
Truncation error

- Set $Z_{3g} \to c\, Z_{3g}$ ... quantifies deviation from STI (without truncation: $c = 1$),
  same effect from "over-renormalizing" 3-gluon vertex

- YM system only converges up to $c_{\text{max}} < 1$

- Anomalous dimensions reproduced for
  - 1 c ~ 0.4
  - 2 c ~ 0.9
  - 3 c ~ 0.96

  $\Rightarrow$ identifies "physical point" for each truncation

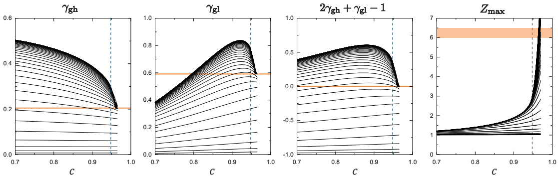


Truncation error

- Close to c_{max} , convergence is lost; strong curvature in gluon dressing
  ⇒ do not reach lattice directly

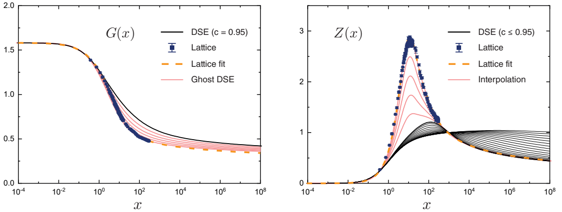
  Back-coupling of 3-gluon vertex sensitive to **4-gluon vertex**

  Workaround: solve nPI system (all internal vertices dressed)
  Huber, PRD 101 (2020) 114009



- Still, extrapolation **does** reproduce lattice peak for Z(x)

- Standalone **ghost DSE** at c_{max} with lattice gluon reproduces lattice ghost



⇒ **Lattice & DSE results match** for particular α (or generally λ_1) √

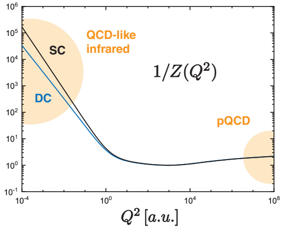
Mass generation for gluons?

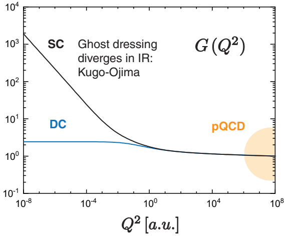
Options:

- Only DC solution is physical? (Lattice, PT-BFM)
- Only SC solution is physical? (Kugo-Ojima, $1/Q^4$)
- All solutions are physically equivalent?
  (Hadron physics, T > 0, ...)

Questions:

- What actually distinguishes SC and DC?
- Where does the singularity in 1/Z come from?
- How is a gluon "mass" compatible with gauge invariance?





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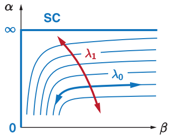

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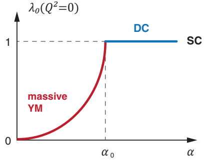

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