The infrared fixed points of QCD and their physics

Kai Schwenzer
Washington University in St. Louis

based on:
R. Alkofer, M. Huber & K. S, arXiv:0801.2862,
R. Alkofer, C.S. Fischer, F. Llanes-Estrada & K. S.,
arXiv:0804.3042, Annals Phys. 324, 106 (2009) &
K.S., arXiv:0811.3608,

Feb 25. 2010

Introduction

Strong interaction

- Described by QCD

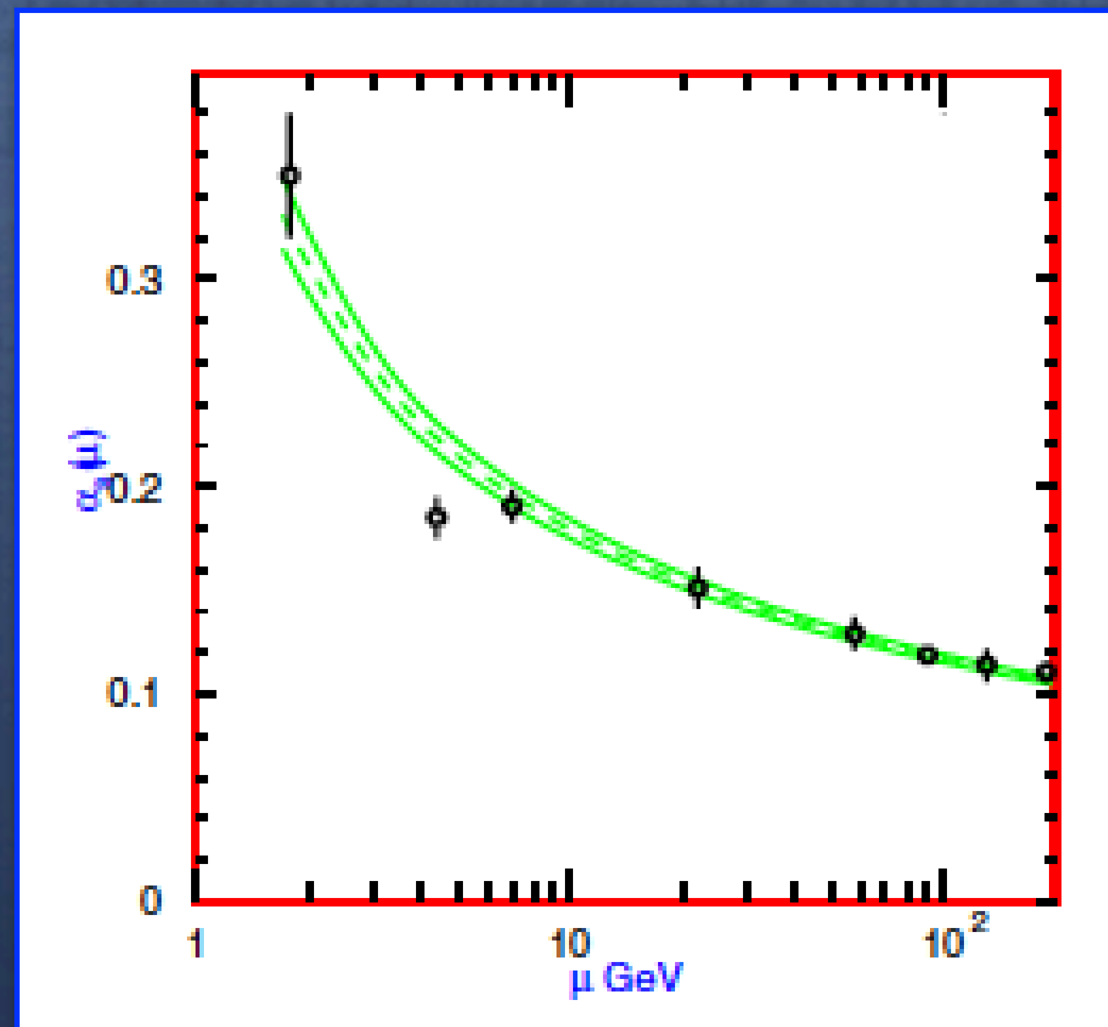
$$Z_{QCD} = \int \mathcal{D}[A,c,q] \exp\left(\int \bar{q}(i\not{D} - m)q - \frac{1}{4}(F^a_{\mu\nu})^2 + \frac{(\partial_\mu A^a_\mu)^2}{2\zeta} + \bar{c}^a(-\partial_\mu D_\mu)c^a \right)$$

  - Landau gauge $\partial_\mu A_\mu = 0$

- UV regime simple due to asymptotic freedom

- IR regime becomes strongly coupled - no small parameter

- Description via local degrees of freedom could break down ...



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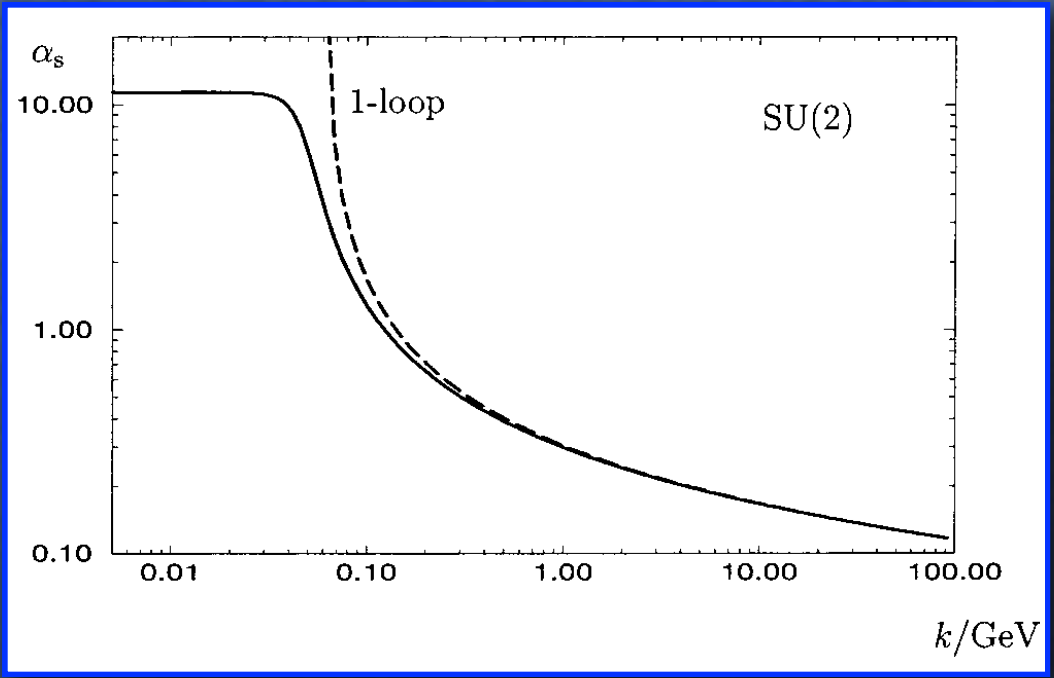


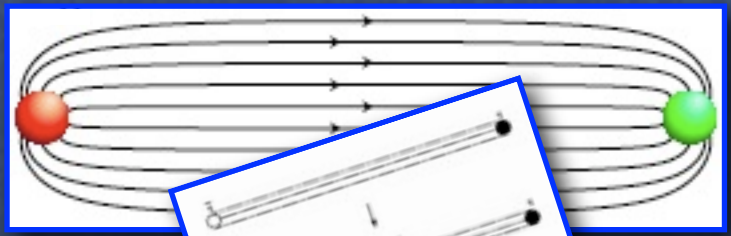
H. Gies, Phys. Rev. D 66 (2002) 025006

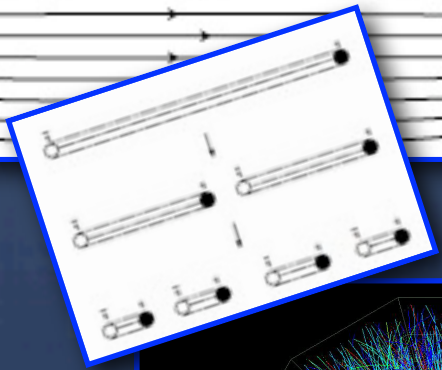
... but the dynamics can prevent this

Aspects of confinement

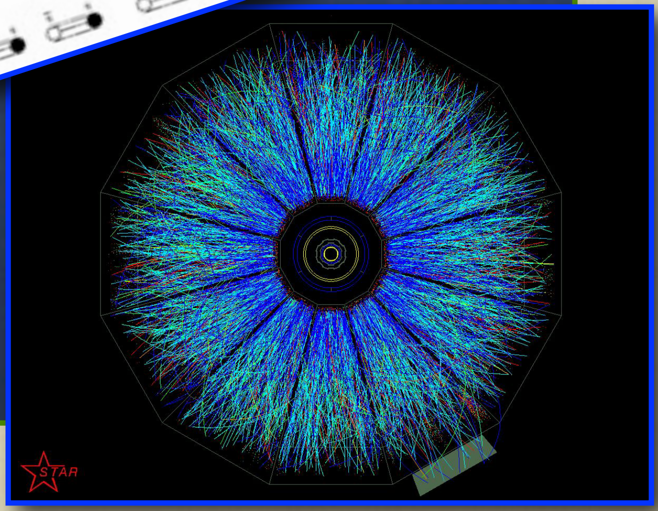
- No colored particles measured (i.e. no fractional electric charge): quarks / nucleon $\lesssim 10^{-28}$
- Static / "non-relativistic" aspects:
  - Area-law behavior of large Wilson loops in the strong coupling limit of lattice gauge theory

    K. G. Wilson, PRD 10 (1974) 2445
  - Stringy behavior / flux-tube





- Dynamic / Relativistic aspects:
  - Production of new hadrons when the system is sufficiently excited
  - String breaking / hadronization



Description of matter

- The Physical degrees of freedom of matter at low scales ...

Hadrons

... are quite different from the underlying building blocks

Landau gauge: quarks, transverse gluons & ghosts

- It would be very desirable to have a direct connection of the physical observables to the dynamics of the fundamental local constituents

- Some kind of Construction manual ...

Functional methods & IR-analysis

Dyson-Schwinger eq´s

- Idea: An average should not depend on the way the sum is performed: (in YM theory $\phi \equiv (A, \bar{c}, c)$)

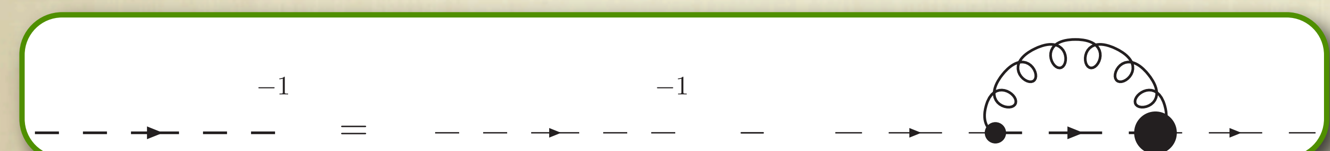
$$\delta \left\langle \mathrm{e}^{J\cdot\phi} \right\rangle = \int D\phi \frac{\delta}{\delta\phi} \mathrm{e}^{-S[\phi]+J\cdot\phi} = 0$$

- Formulation in terms of the effective action Γ:

$$\frac{\delta\Gamma}{\delta\Phi_i} = \frac{\delta S}{\delta\phi_i}\bigg|_{\phi_i \to \Phi_i + \Delta_{ij}\frac{\delta}{\delta\Phi_j}}$$

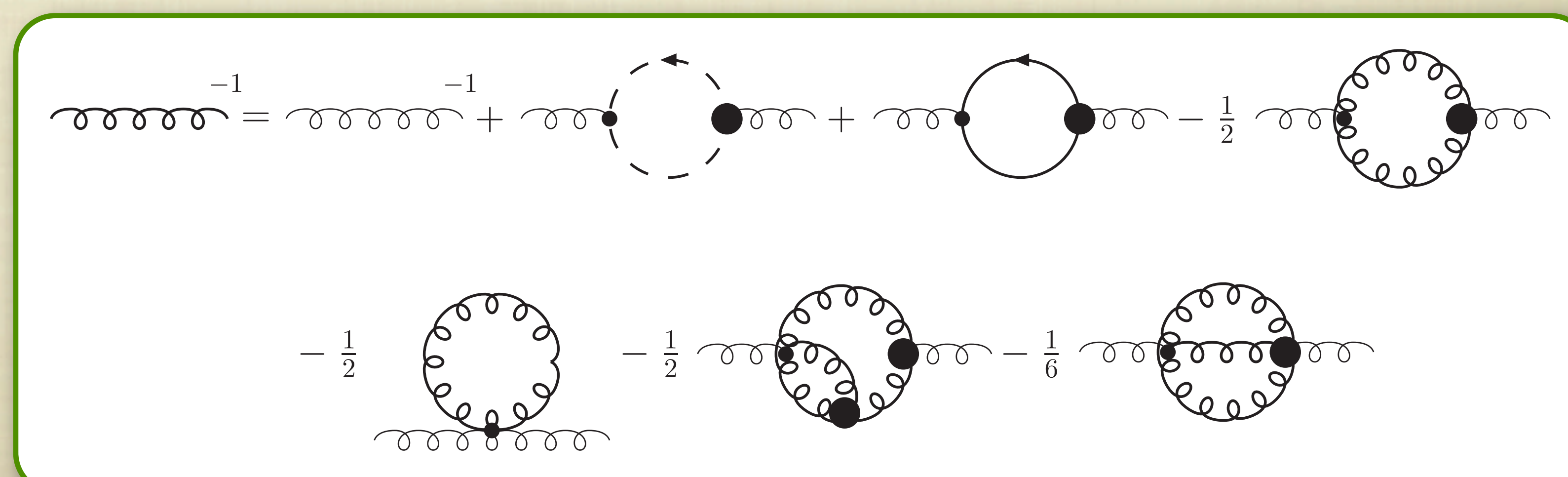
- DSEs for arbitrary Green functions of a theory can be obtained algorithmically

R. Alkofer, M. Huber and K. S., Comp. Phys. Comm. 180 (2009) 965



Ghost Propagator

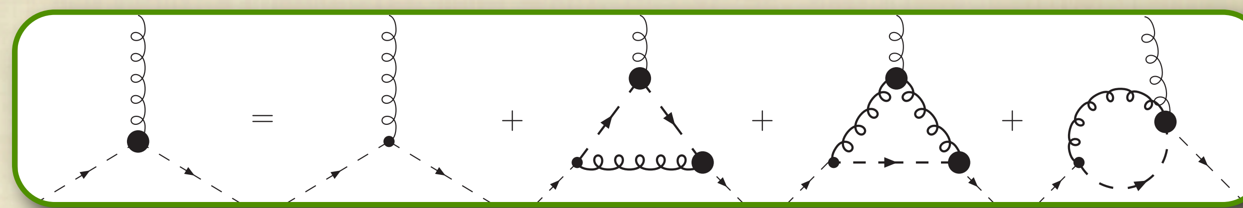
Gluon Propagator



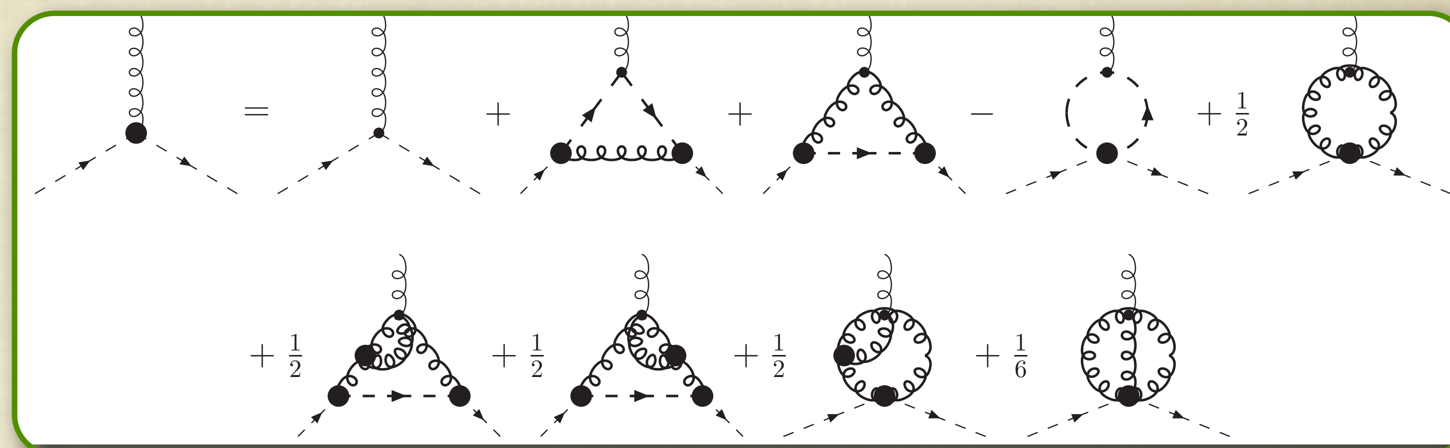
Coupled Nonlinear integral equations for the propagators

Vertex DSEs

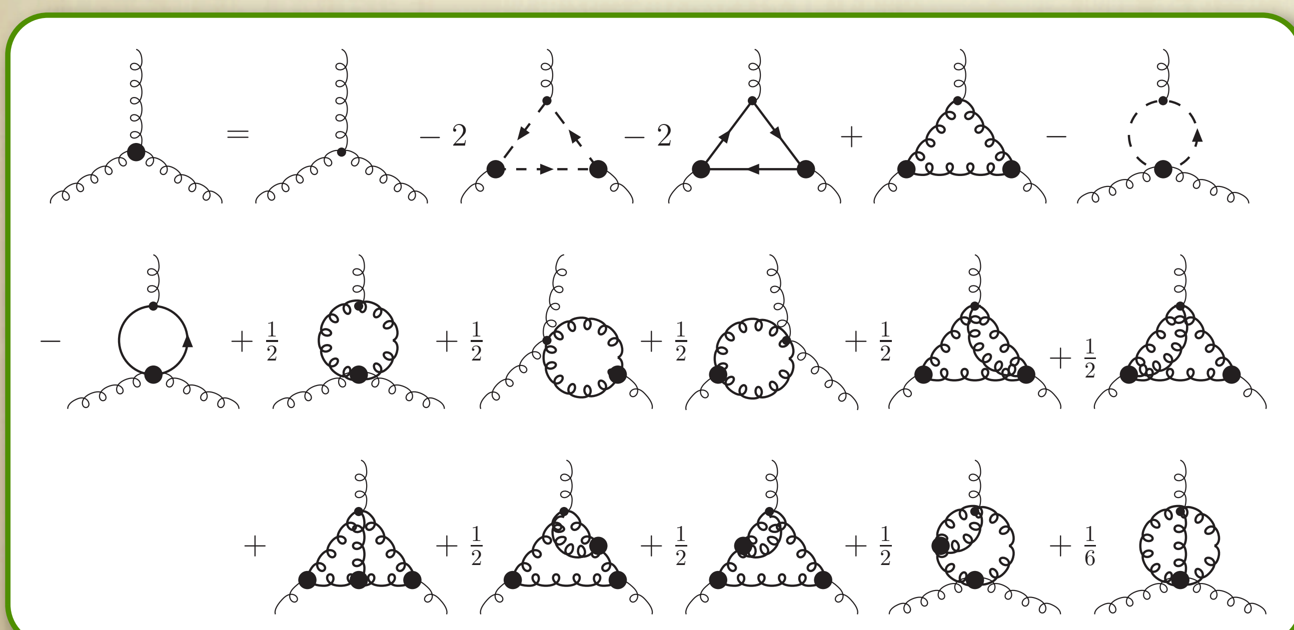
- Propagator DSEs involve the vertices
- Infinitely coupled system of equations
- In general no controlled Approximation scheme

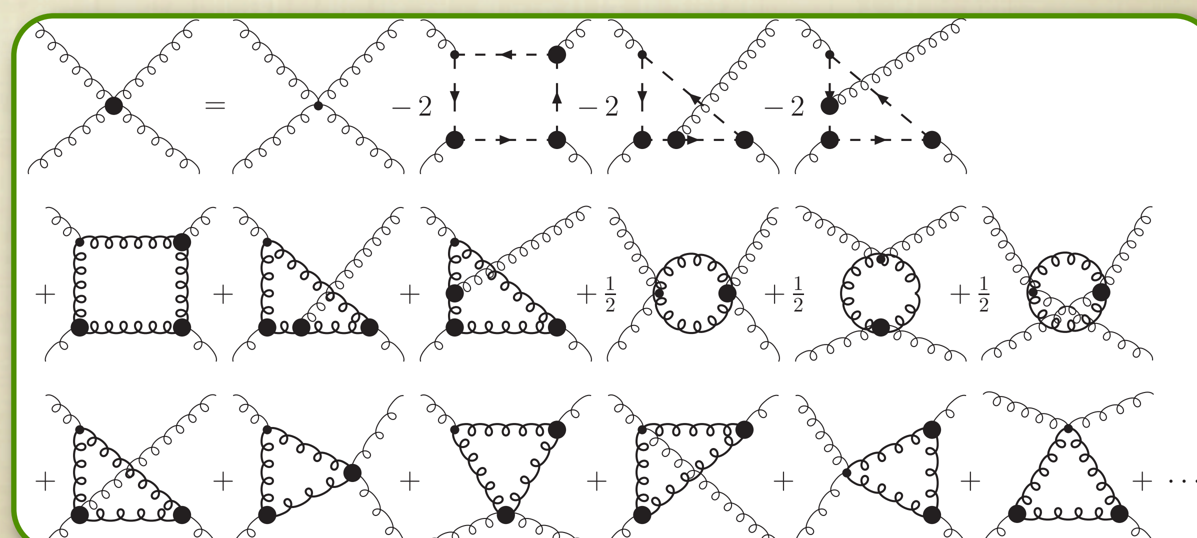


Ghost-gluon vertex (V1 & 2)



3-gluon vertex



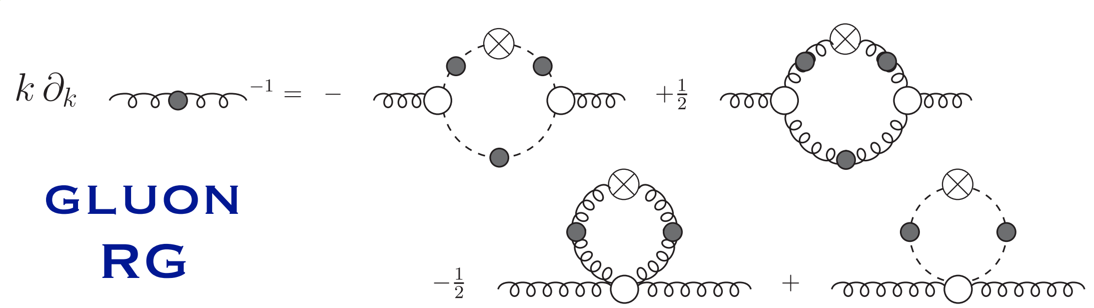


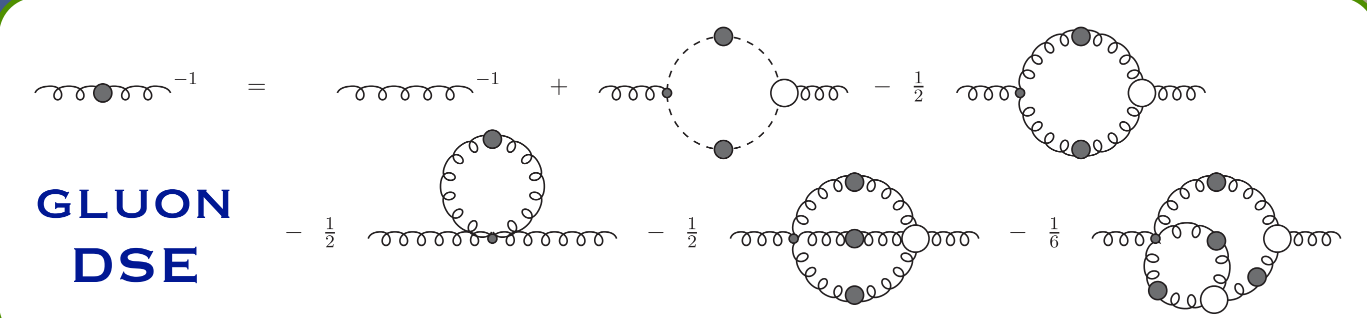
4-gluon vertex

Functional hierarchies

- The functional equations look quite similar ... but the dynamics is resummed rather differently:

RG	DSE
Infinite tower of coupled functional equations for the local Green functions of the theory	
involves cutoff, successive mode elim.	unconstr. integration, modes are mixed
only 1-loop graphs & only dressed vertices	up to 2-loop graph (4D) & one bare vertex
all graphs scale identically (conf. case)	suppressions due to bare vertex



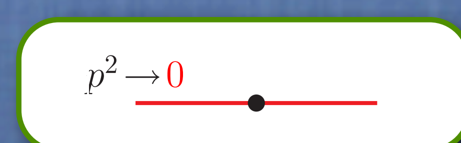


IR-Analysis

- **Confinement** is a long range / **IR phenomenon**

- Classical Yang-Mills theory is "conformal" but quantum Fluctuations induce a scale Λ_{QCD}

- Renormalization group (**assumption**): far below this scale Greens functions are described by scaling



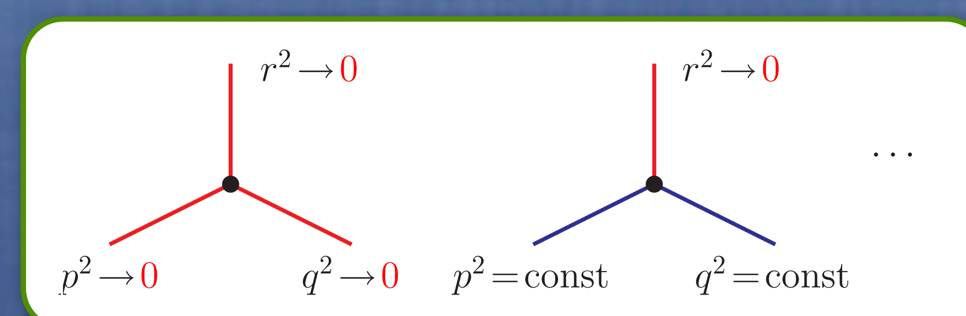
$$\sim \left(\frac{p^2}{\Lambda_{QCD}^2}\right)^{\delta-1}$$

canonical & anomalous IR-exponent

characteristic momentum

- For vertices Kinematic IR divergences are possible
  ... and also realized

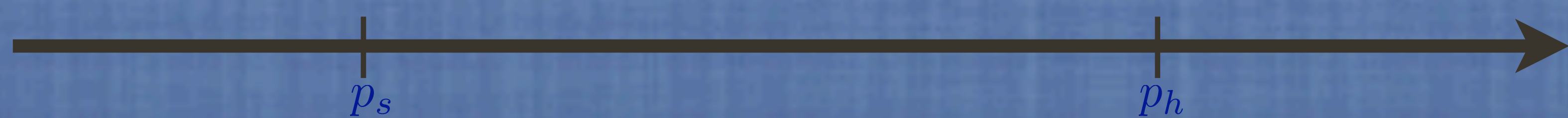
  R. Alkofer, M. Q. Huber and K. S., arXiv:0812.4045



uniform soft

IR sensitive regions

- When both hard p_h and soft p_s external momenta are present ($p_s \ll p_h, \Lambda_{QCD}, M$) ...
  - Loop momenta k of the order of all external scales contribute: $I_3(p_s,p_h) = \int \frac{d^dk}{(2\pi)^d} \frac{1}{(k+p_s)^{2\alpha}} \frac{1}{(k-p_h)^{2\beta}} \frac{1}{k^{2\gamma}}$
- Divide integral into various IR sensitive regions:



- Decomposed integrals depend on a single scale

IR sensitive regions

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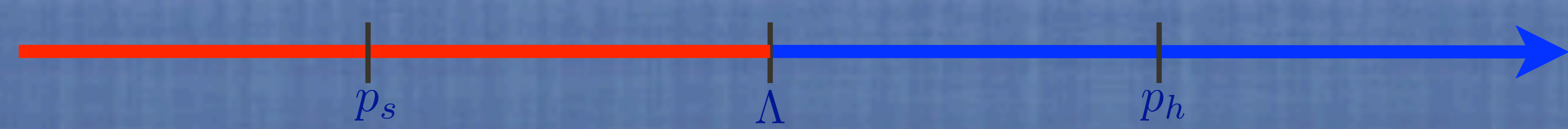

$p_s \ll \Lambda \ll p_h$

- Decomposed integrals depend on a single scale

IR sensitive regions

- When both **hard** p_h and **soft** p_s external momenta are present ($p_s \ll p_h, \Lambda_{QCD}, M$) ...
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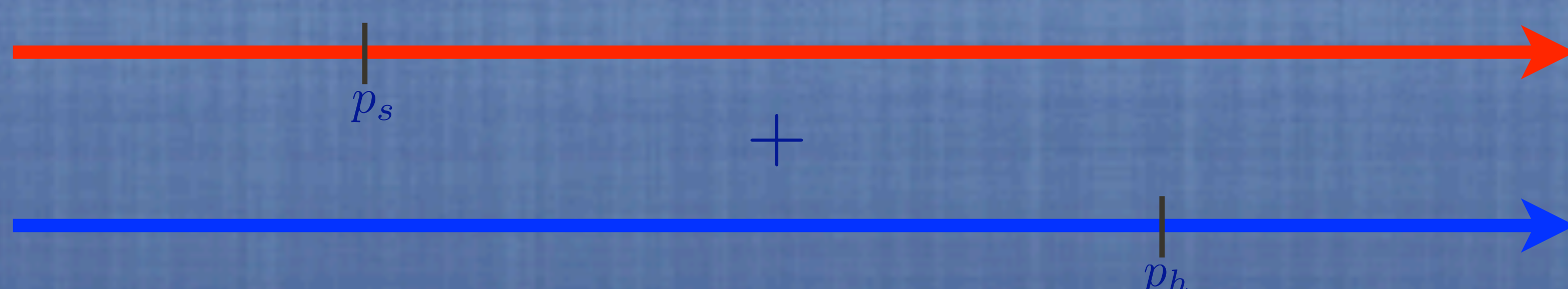
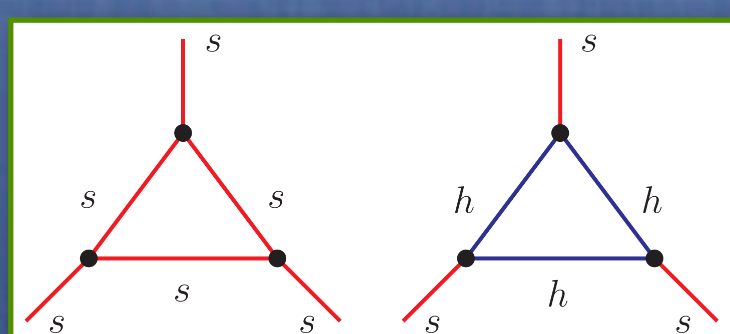
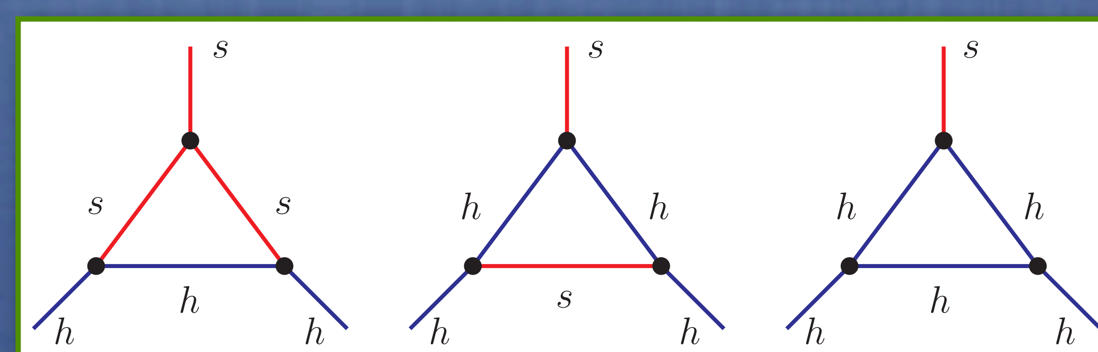


$$+O\left(\frac{p_s}{p_h}\right)$$

- Decomposed integrals depend on a **single** scale



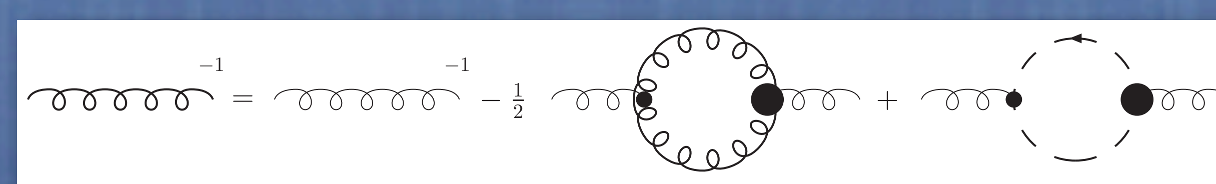
UNIFORM



SOFT

Power counting

- The parametric IR-dependence of the integrals on a single external scale can be obtained via a power counting analysis
  - Without numerically solving the DSEs
- Leading loop correction & leading tensor structure dominates and determines scaling of the vertex --> algebraic equations for exponents
- E.g. Gluon DSE



$$\left(p^2\right)^{1-\delta_{gl}} = \max\left(p^2, p^4\left(p\left(p^2\right)^{\delta_{3g}}\right)p\left(p^{-2}\left(p^2\right)^{\delta_{gl}}\right)^2, p^4\left(p\left(p^2\right)^{\delta_{gg}}\right)p\left(p^{-2}\left(p^2\right)^{\delta_{gh}}\right)^2\right)$$

$$\Rightarrow \quad -\delta_{gl} = \min\left(0, \delta_{3g} + 2\delta_{gl}, \delta_{gg} + 2\delta_{gh}\right)$$

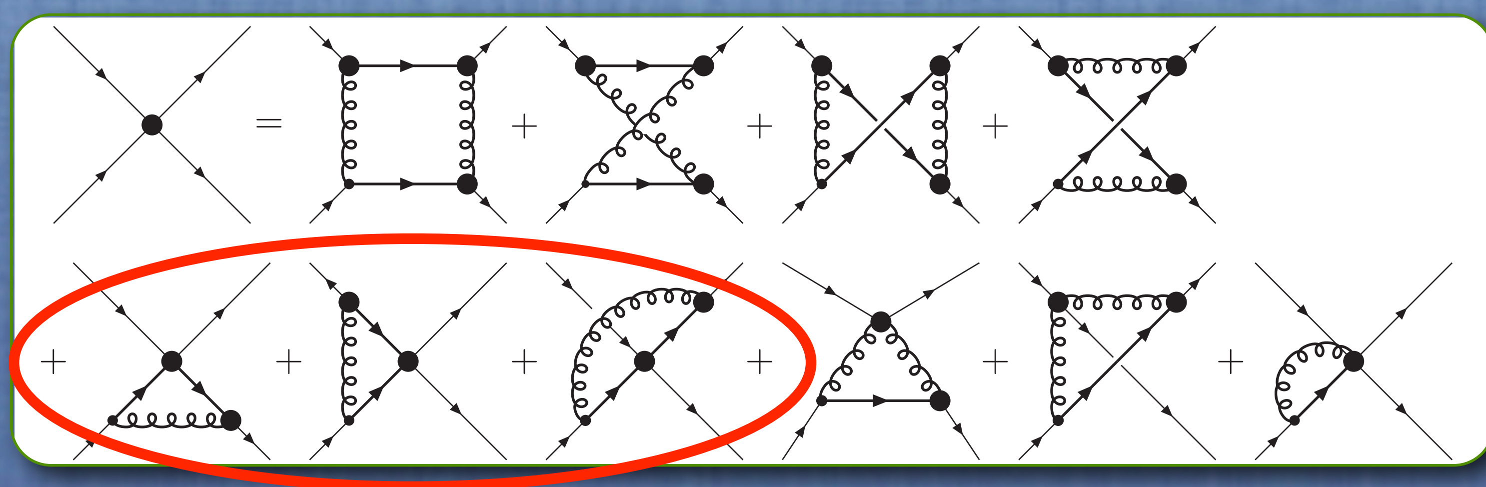
- System of such algebraic equations

IR truncation

- DSEs for higher order vertices do not involve bare "driving terms"

n	3	4	> 4
$k_{max}^{(L=2,n_0=4)}$	3	2	1
$k_{max}^{(L=1,n_0=3)}$	2	1	1
$k_{max}^{(L=1,n_0=4)}$	1	1	1

- ... and are even linear!



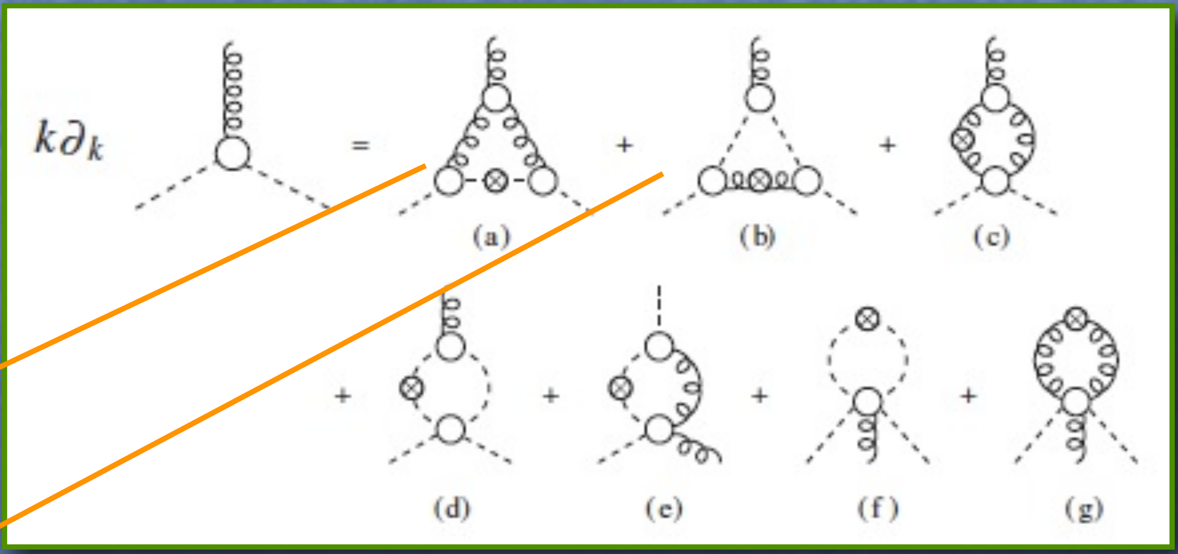
- Cannot self-consistently induce non-trivial IR power law solutions $\delta_n \leq \delta_n + X \Rightarrow X \geq 0$

- The IR fixed point structure is determined by the primitively divergent Greens functions

Functional constraints

- The functional **Renormalization group** forms a **distinct tower of equations** that involve the same green functions

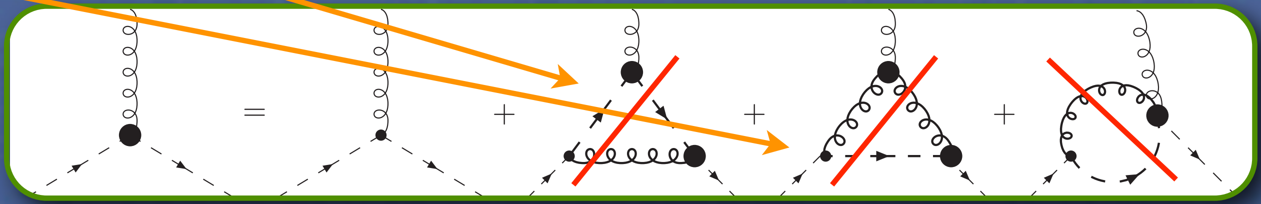
C.S.Fischer & J.M.Pawlowski, PRD 75 (2007) 025012; PRD 80 (2009) 025023



- But: **All** arising vertices are **dressed**

- The l.h.s. is given by the leading term on the r.h.s., e.g. :

$$\delta_{gg} \leq 2\delta_{gg} + \delta_{3g} + \delta_{gh} + 2\delta_{gl} \qquad \delta_{gg} \leq 3\delta_{gg} + 2\delta_{gh} + \delta_{gl}$$

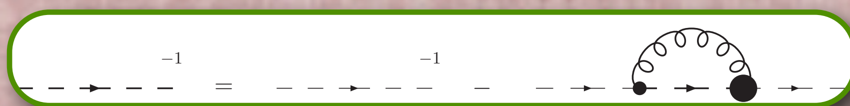


- Yields important constraints for the DSE system!

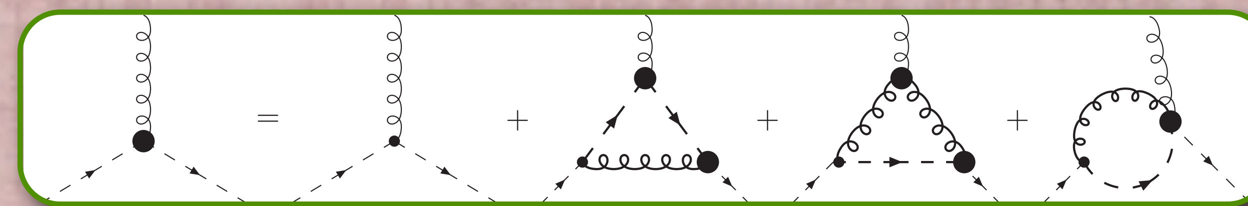
--> ghost-gluon vertex not IR enhanced

Gauge sector
& gluon confinement

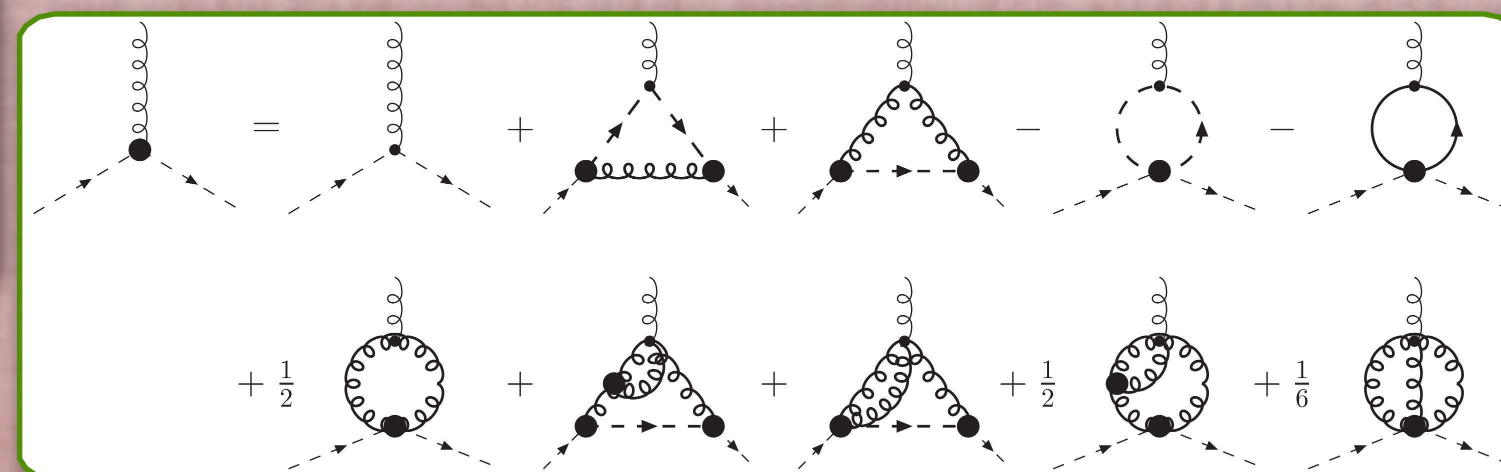
Yang-Mills sector

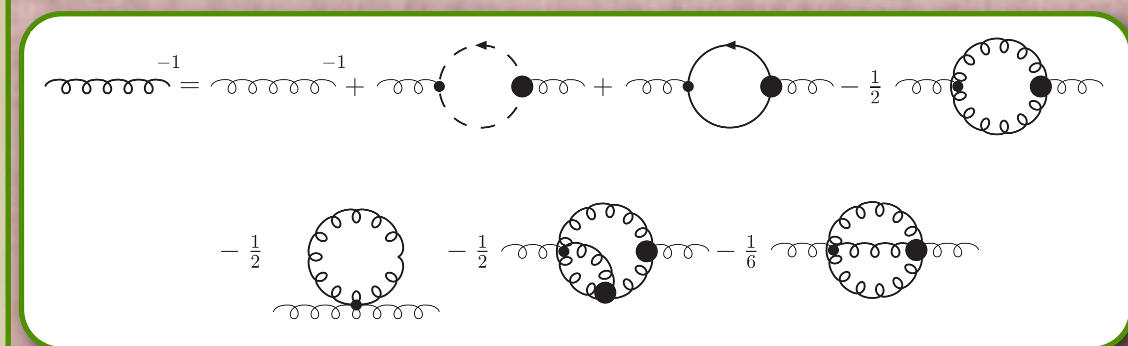


GHOST PROPAGATOR



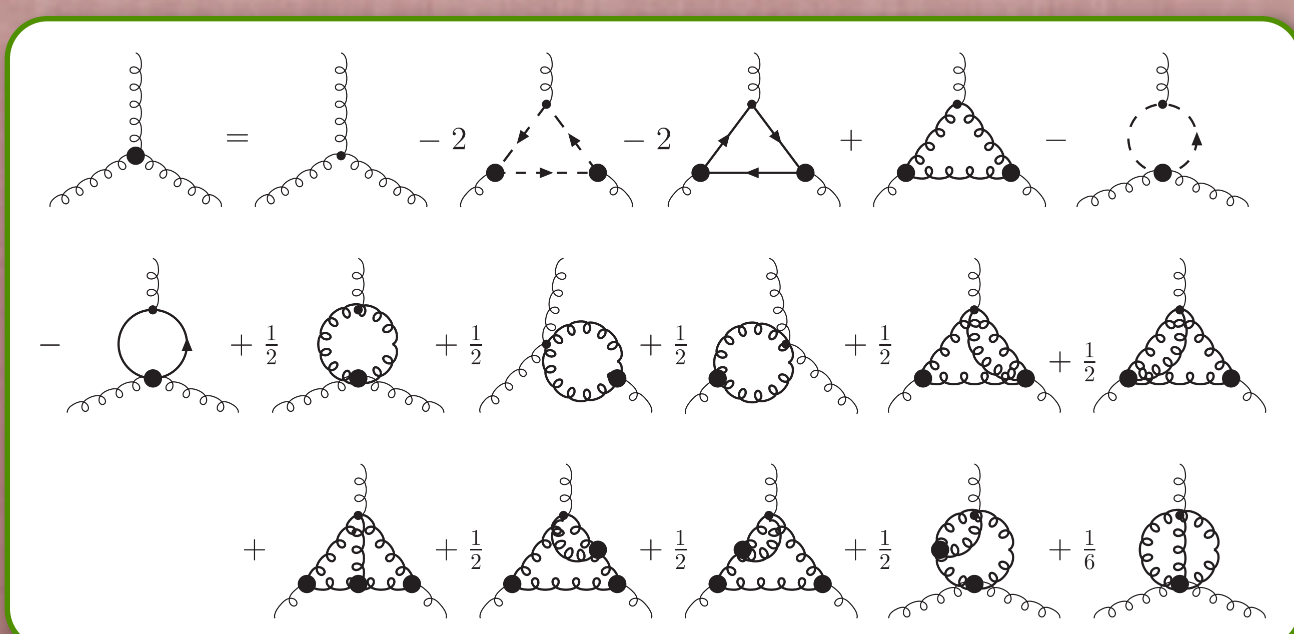
GHOST-GLUON VERTEX (V1 & 2)

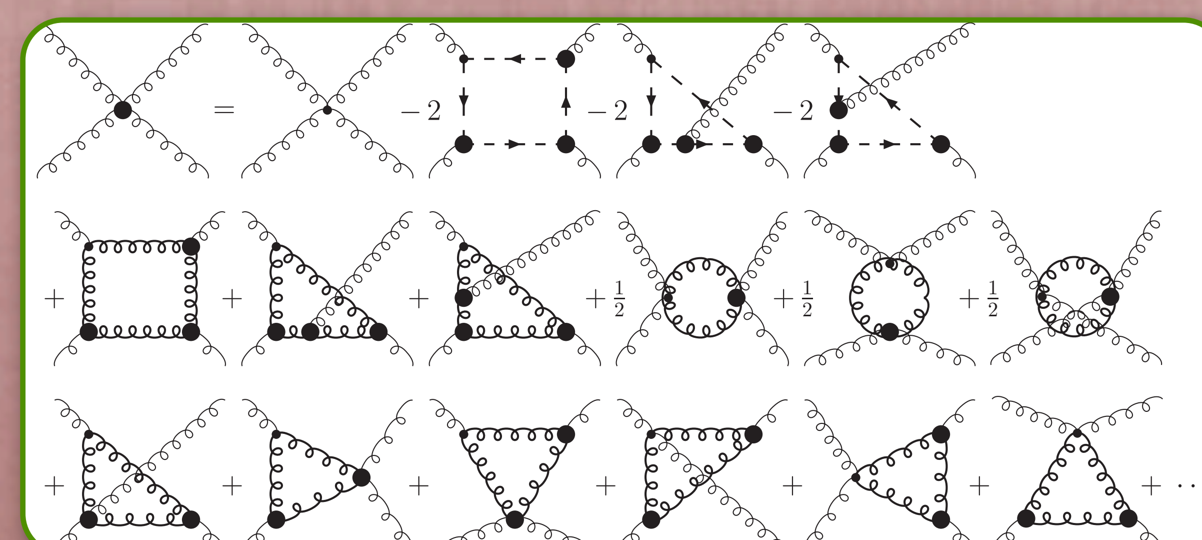




GLUON PROPAGATOR

3-GLUON VERTEX





4-GLUON VERTEX

IR analysis

- The DSE system for the uniform IR exponents ...

$$
\begin{aligned}
-\delta_{gh} &= \min\left(0, \delta_{gg} + \delta_{gh} + \delta_{gl}\right) \ , \\
-\delta_{gl} &= \min\left(0, \delta_{3g} + 2\delta_{gl}, \delta_{gg} + 2\delta_{gh}, 2\delta_{3g} + 4\delta_{gl}, \delta_{4g} + 3\delta_{gl}\right) \\
\delta_{gg} &= \min\left(0, 2\delta_{gg} + 2\delta_{gh} + \delta_{gl}, \delta_{3g} + \delta_{gg} + \delta_{gh} + 2\delta_{gl}\right) \\
\delta_{3g} &= \min\left(0, 2\delta_{gg} + 3\delta_{gh}, 2\delta_{3g} + 3\delta_{gl}, \delta_{3g} + 2\delta_{gl}, \delta_{4g} + 2\delta_{gl}, 3\delta_{3g} + 5\delta_{gl}, \delta_{4g} + \delta_{3g} + 4\delta_{gl}\right) \ , \\
\delta_{4g} &= \min\left(0, 3\delta_{gg} + 4\delta_{gh}, 3\delta_{3g} + 4\delta_{gl}, \delta_{4g} + 2\delta_{gl}, 2\delta_{3g} + 3\delta_{gl}, \delta_{4g} + \delta_{3g} + 3\delta_{gl}, 4\delta_{3g} + 6\delta_{gl}, \delta_{4g} + 2\delta_{3g} + 5\delta_{gl}
\end{aligned}
$$

$$
\begin{aligned}
-\delta_{gh} &= \min\left(0, \delta_{gh} + \delta_{gl}\right) \ , \\
-\delta_{gl} &= \min\left(0, 2\delta_{gh}\right) \ , \\
\delta_{gg} &= 0 \ , \\
\delta_{3g} &= \min\left(0, 3\delta_{gh}\right) \ , \\
\delta_{4g} &= \min\left(0, 4\delta_{gh}, 3\delta_{3g} + 4\delta_{gl}\right)
\end{aligned}
$$

... simplifies considerably!

- Unique scaling solution of the DSE system

R.Alkofer, C.S.Fischer and F.J.Llanes-Estrada, Phys. Lett. B 611 (2005) 279;
C.S.Fischer and J.Pawlowski, Phys. Rev. D 75 (2007) 025012

Yang-Mills fixed points

- Two qualitatively different IR solutions - depending on the boundary conditions:

	δ_{gh}	δ_{gl}	δ^u_{gg}	δ^u_{3g}	δ^u_{4g}	δ^{gh}_{gg}	δ^{gl}_{gg}	δ^{gl}_{3g}
scaling	$-\kappa$	2κ	0	-3κ	-4κ	0	$\min\left(0, \frac{3}{2} - 2\kappa\right)$	$\min(0, 1 - 2\kappa)$
decoupling	0	1	0	0	0	0	0	0

$\kappa \approx 0.595$

R. Alkofer, M. Huber & K. S, arXiv:0801.2862

- Decoupling scenario

P.Boucaud, et.al., JHEP 0806 (2008) 012;
A.C.Aguilar, D.Binosi, J.Papavassiliou, PRD 78 (2008) 025010;
C.S.Fischer, A. Maas & J. Pawlowski, arXiv:0810.1987

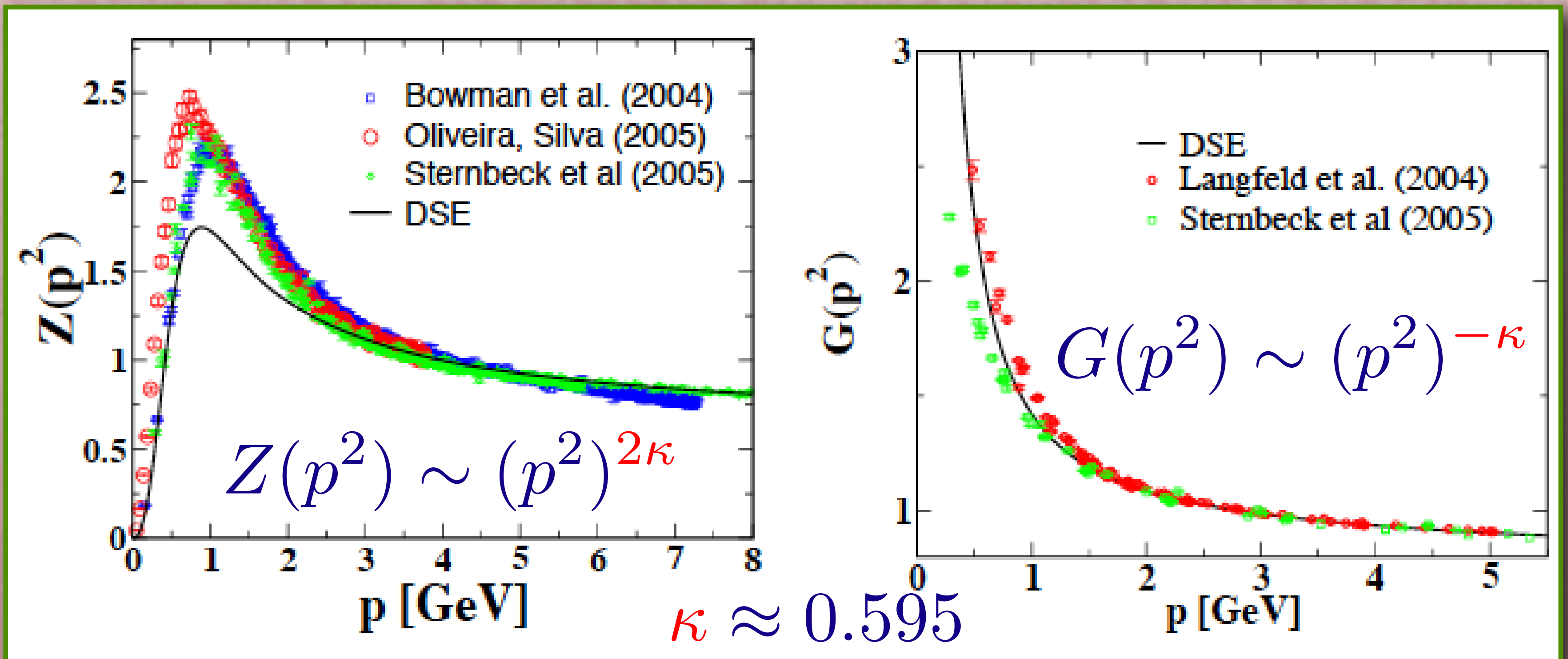
  - massive IR gluon propagator
  - IR regime is entirely suppressed!

- Scaling solution L. v. Smekal, A. Hauck & R. Alkofer, PRL 79 (1997) 3591;
J. M. Pawlowski, et. al., PRL 93 (2004) 152002; ...

  - strong IR enhancement via ghost dynamics 
  - Gluon confinement via Kugo-Ojima mechanism

Scaling solution

- Results compared to quenched lattice data



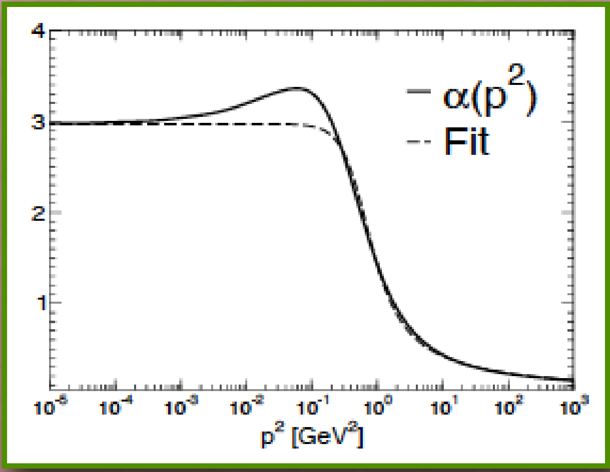
Reasonable qualitative agreement - but new lattice data available ...

C. S. Fischer and R. Alkofer, PLB 536 (2002) 177

- Ghost-dominance

  L. v. Smekal, A. Hauck & R. Alkofer, PRL 79 (1997) 3591

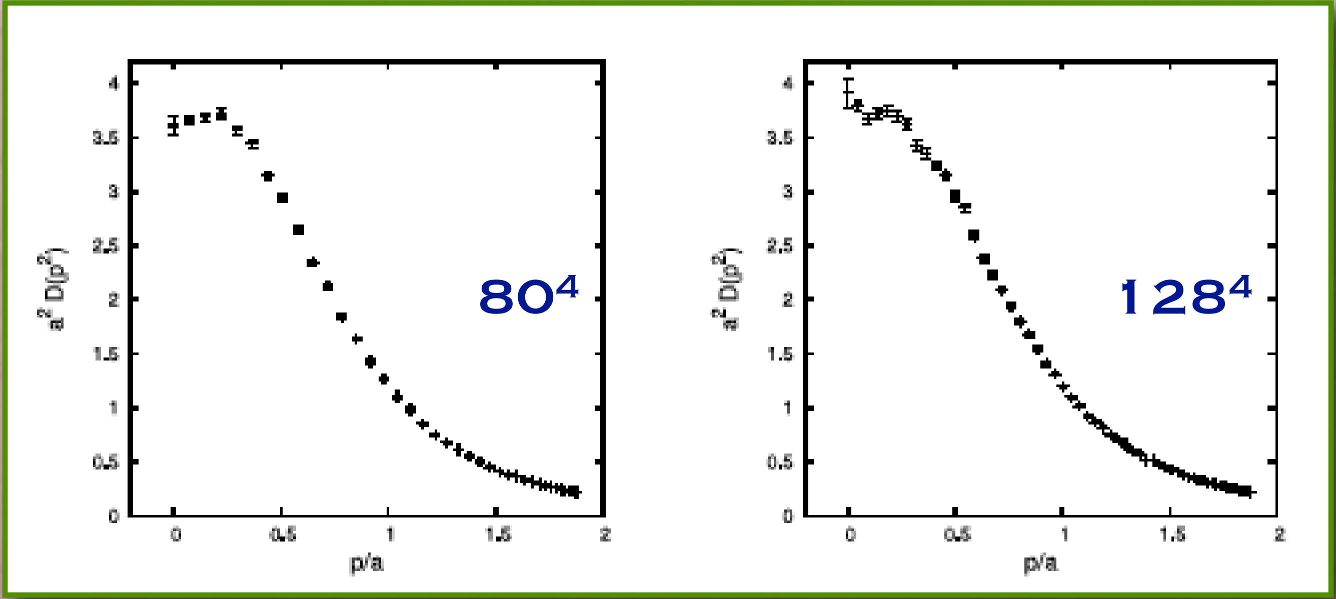
- Finite IR limit of the coupling



- Kugo-Ojima confinement scenario

Recent lattice data

- Challenging recent data on large lattices



A. Cucchieri, T. Mendes, arXiv:0710.0412

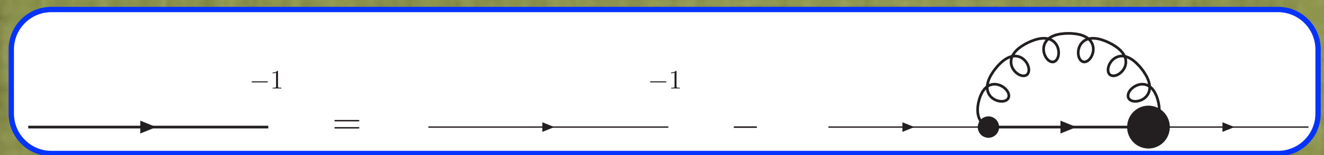
Where is the long-range interaction?

- Gluon becomes IR finite and ghost roughly bare
  - problems with Gribov copies? Axel Maas, PRD 79 (2009) 014505
  - Problems with the gauge definition? A. Sternbeck, L. von Smekal, arXiv:0811.4300
- Apparently no problem with Gribov ambiguity in continuum framework M. Huber, R.Alkofer and S. P. Sorella, arXiv:0910.5604

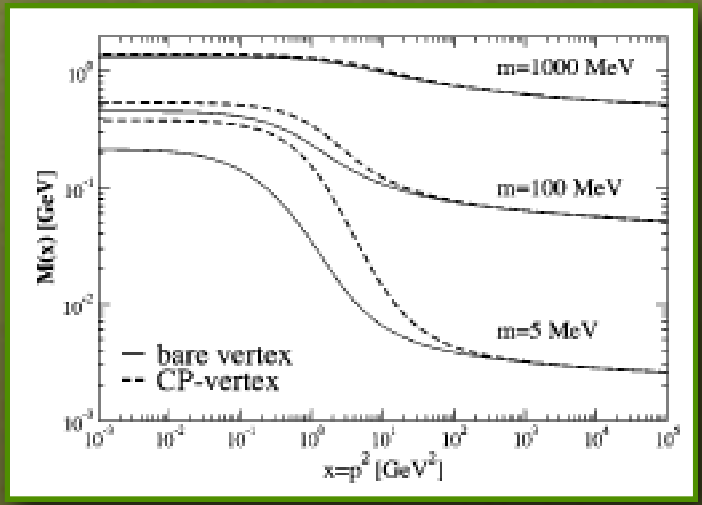
Quenched QCD & Quark confinement

Quark propagator

- Only DSE for the quark propagator considered



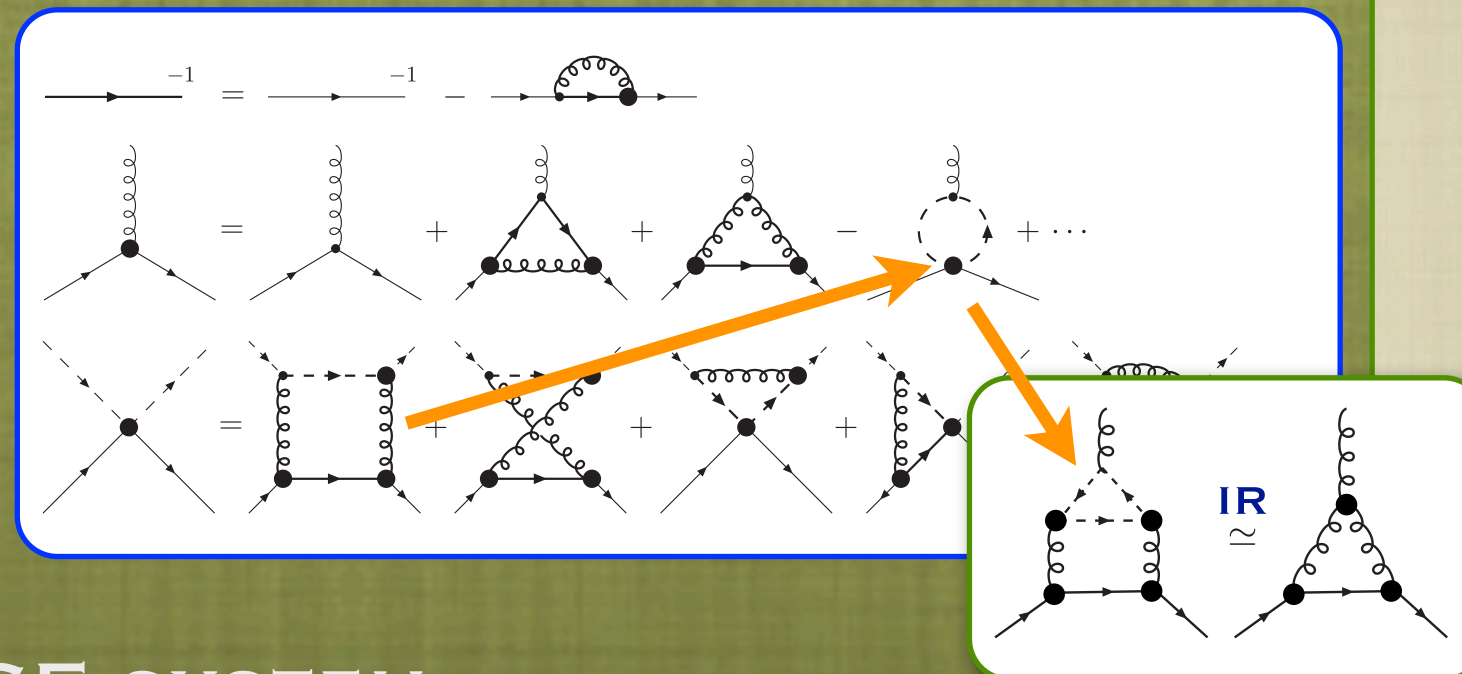
- Two different tensor structures in the IR regime
  - Vector part $\sim \dfrac{\not p}{M^2}$ & scalar part $\sim \dfrac{1}{M}$
- Dynamical Spontaneous chiral symmetry breaking in the propagator
- But: No positivity violations and no strong gluonic dynamics that induce quark confinement



R. Alkofer & C. Fischer
Phys. Rev. D 67 (2003) 094020

DSEs in Quark sector

- System in the **matter sector:**
- In quenched approximation: gauge results as an input

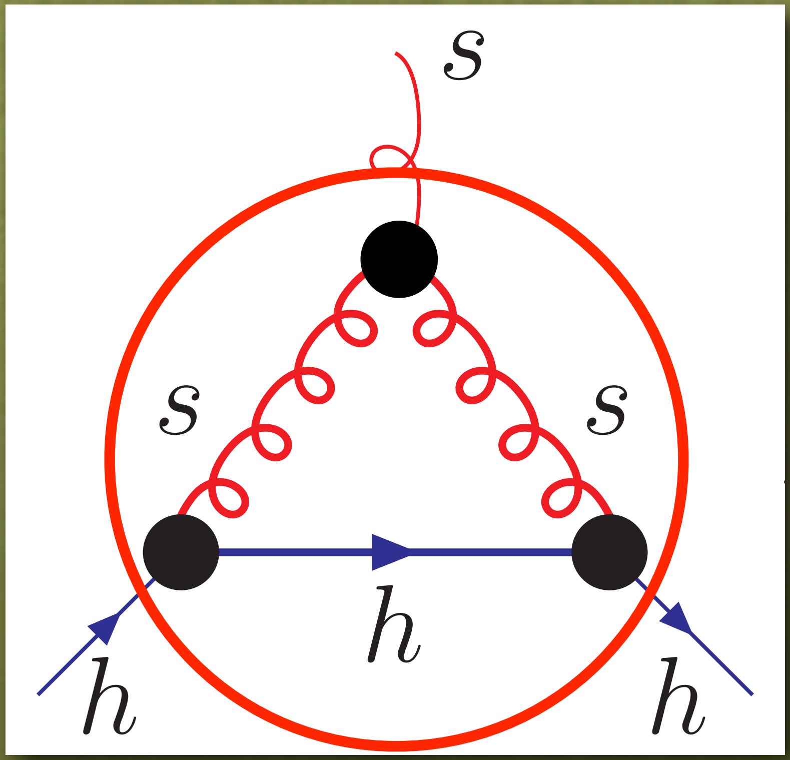


- Peculiarity of the DSE system:
  - one bare vertex in each DSE
  - quarks & ghosts don't couple at tree level
- Quark-ghost DSE has to be included
- Effectively dressed non-Abelian graph as in RG

Dynamical Vertices

- The non-Abelian graph induces a non-linearity in the quark-gluon vertex DSE
  --> self-consistent enhancement

R.Alkofer, C.S.Fischer & F.J.Llanes-Estrada, Mod. Phys. Lett. A 23 (2008) 1105



- IR singularity of the quark-gluon vertex:

$$\Gamma_{qg} \sim (p^2)^{\delta_{qg}} \qquad \delta_{qg} = -\frac{1}{2} - \kappa$$

- Same strong IR-Singularity in the soft gluon limit for arbitrary quark kinematics

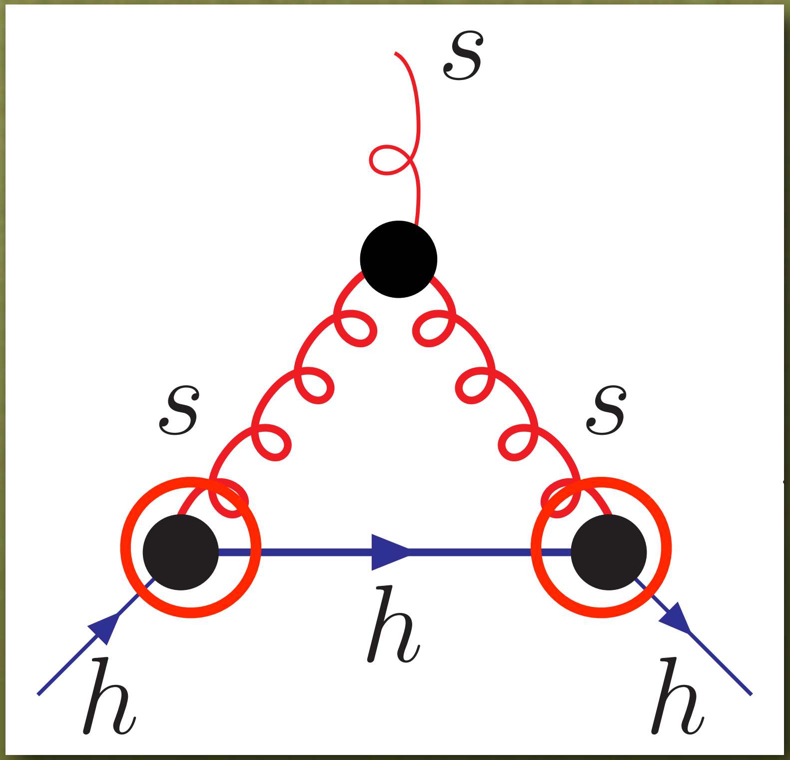
R. Alkofer R. Alkofer, C.S. Fischer, F. Llanes-Estrada & K. S., Annals Phys. 324, 106 (2009)

$$(p^2)^{\delta_{qg}} \sim (p^2)^{2+2\delta_{qg}-3\kappa+2(2\kappa-1)}$$

Dynamical Vertices

- The non-Abelian graph induces a non-linearity in the quark-gluon vertex DSE
  --> self-consistent enhancement

R.Alkofer, C.S.Fischer
& F.J.Llanes-Estrada,
Mod. Phys. Lett. A 23 (2008) 1105



- IR singularity of the quark-gluon vertex:

$$\Gamma_{qg} \sim (p^2)^{\delta_{qg}} \qquad \delta_{qg} = -\frac{1}{2} - \kappa$$

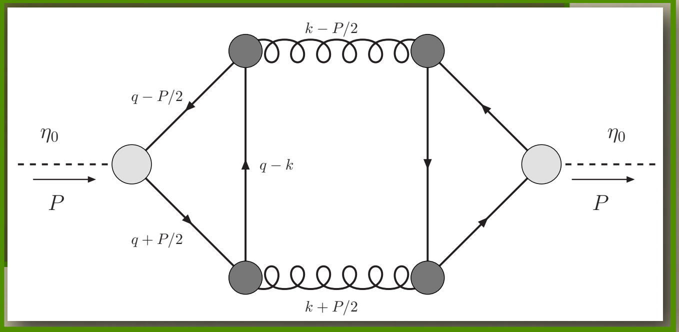
- Same **strong** IR-Singularity in the soft gluon limit for arbitrary quark kinematics

R. Alkofer R. Alkofer, C.S. Fischer, F. Llanes-Estrada & K. S.,
Annals Phys. 324, 106 (2009)

$$(p^2)^{\delta_{qg}} \sim (p^2)^{2+2\delta_{qg}-3\kappa+2(2\kappa-1)}$$

- Soft singularity provides mechanism for $U_A(1)$ anomaly & $\eta\,/\,\eta'$ mass splitting

R. Alkofer, C. S. Fischer & R. Williams, EPJ A 38 (2008) 53



Quenched solution

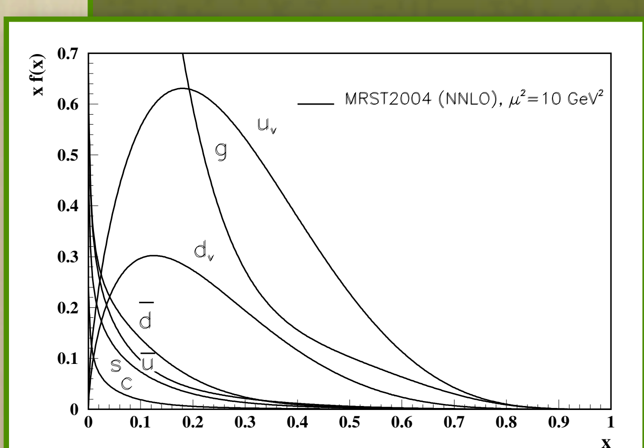
- IR fixed points of quenched QCD:

δ_{gh}	δ_{gl}	δ_q	δ^u_{gg}	δ^u_{3g}	δ^u_{qg}	δ^{gh}_{gg}	δ^{gl}_{gg}	δ^{gl}_{3g}	δ^q_{gg}	δ^{gl}_{qg}
$-\kappa$	2κ	0	0	-3κ	$-\frac{1}{2}-\kappa \vee 0$	0	0	$1-2\kappa$	0	$-\frac{1}{2}-\kappa \vee 0$

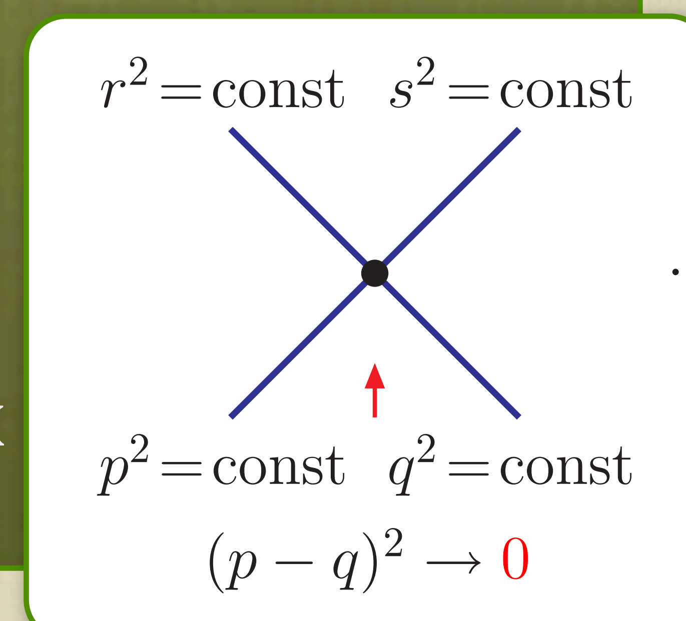
- ☆ **Strong, self-consistently enhanced singularities** in the quark-gluon vertex - **even when only the gluon momentum vanishes**!

- Second solution without enhanced vertex

- Kinematic case important because:

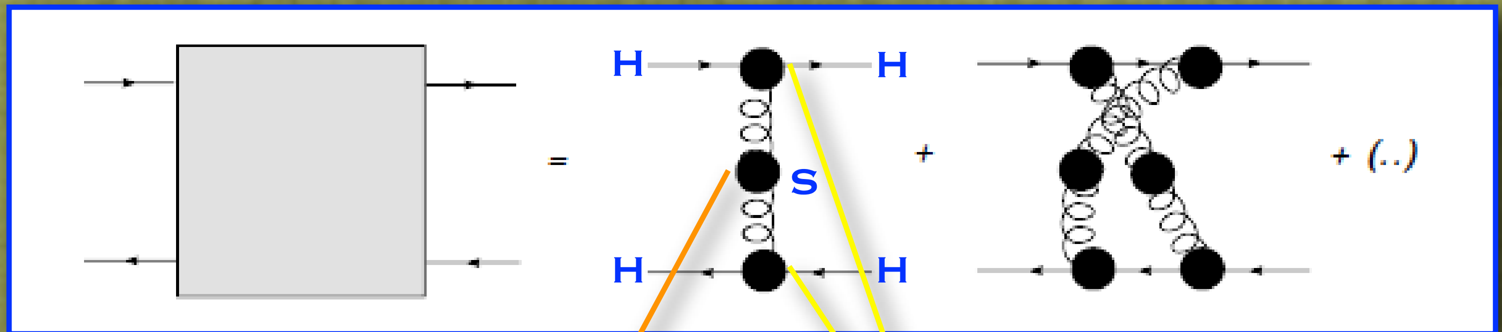


Valence quarks in a hadrons have finite momenta ... → only IR sensitive quark-quark interaction



Static Confinement

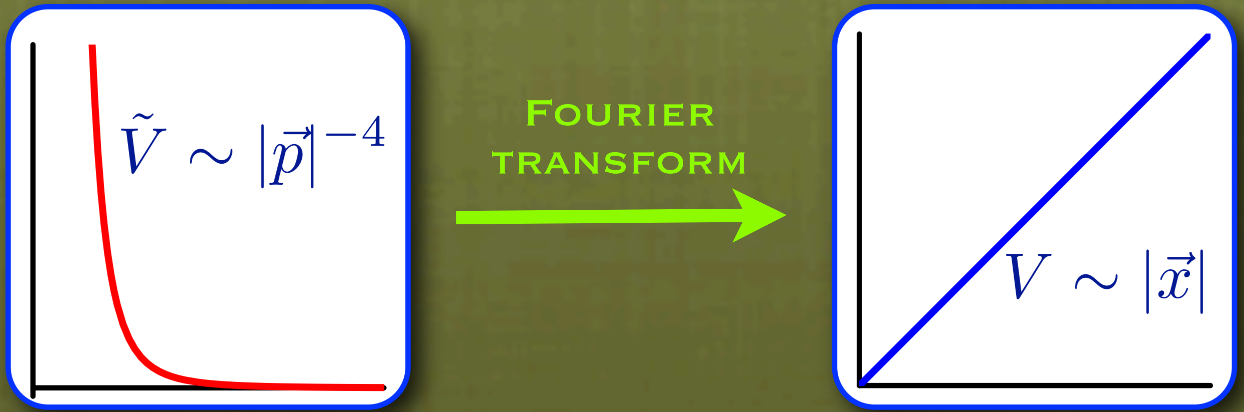
- Quark-gluon vertex induces strongly singular quark-quark interaction



$$\Gamma_{4q} \sim (p^2)^{2\kappa-1+2(-1/2-\kappa)} = p^{-4}$$

- 4-quark vertex lowest order in the expansion of the gauge invariant correlator including a Wilson line

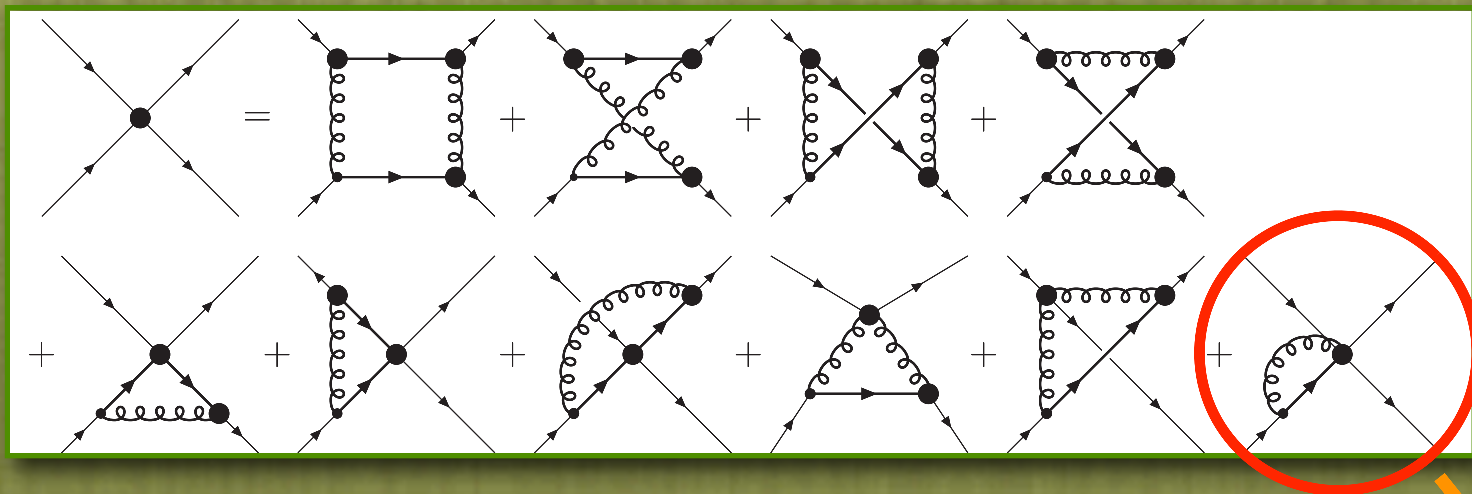
- Quark confinement due to Linear potential whenever the static quarks are far apart and the gluon is soft



- IR slavery: different mechanism than for gluons

Realization in 1PI DSE

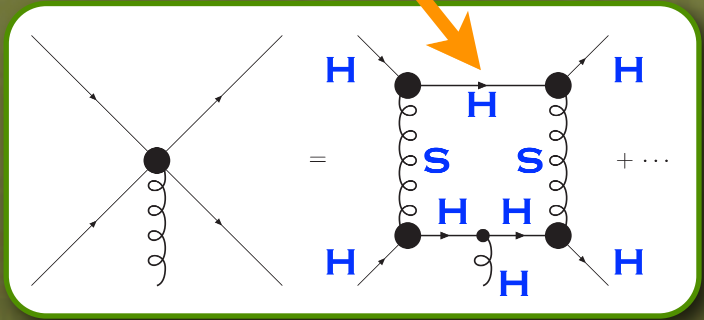
- 4-quark DSE should encode meson confinement



- 1-loop gluon exchange is suppressed since there is always one bare vertex

$$\sim (p^2)^{2+3\left(-\frac{1}{2}-\kappa\right)+2(-1+2\kappa)} = p^{-3+2\kappa}$$

  - but ... the 2-loop contribution from the higher order DSE is more IR singular



$$\sim (p^2)^{2+4\left(-\frac{1}{2}-\kappa\right)+2(-1+2\kappa)} = p^{-4}$$

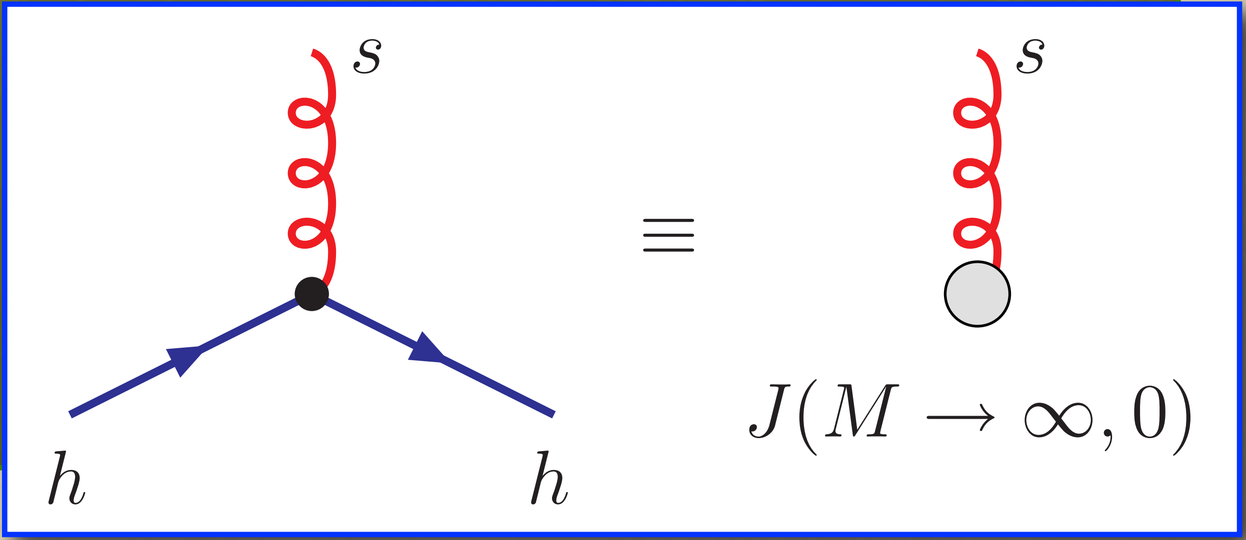
- strong IR-divergence in accordance to NPI / RG

Universal mechanism

- Quenched QCD provides confining potential
  - Fermion determinant entirely neglected in quenched lattice studies - No quark dynamics ...
  - ... yet, quarks are present in the DSE treatment
- Same result for a theory where the matter fields are fundamentally charged scalars

L. Fister, R. Alkofer & K. S.

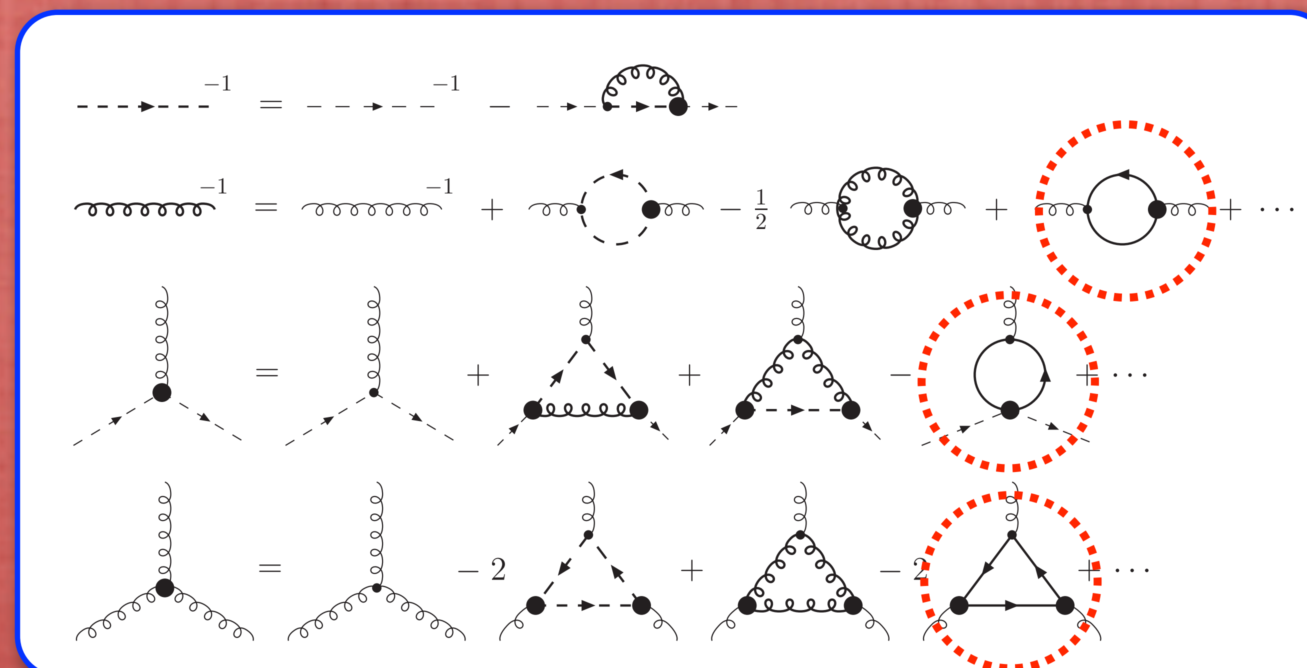
  - much simpler theory (model system) --> lattice
  - The Confinement mechanism is a property of the gauge dynamics and not of the matter sector!

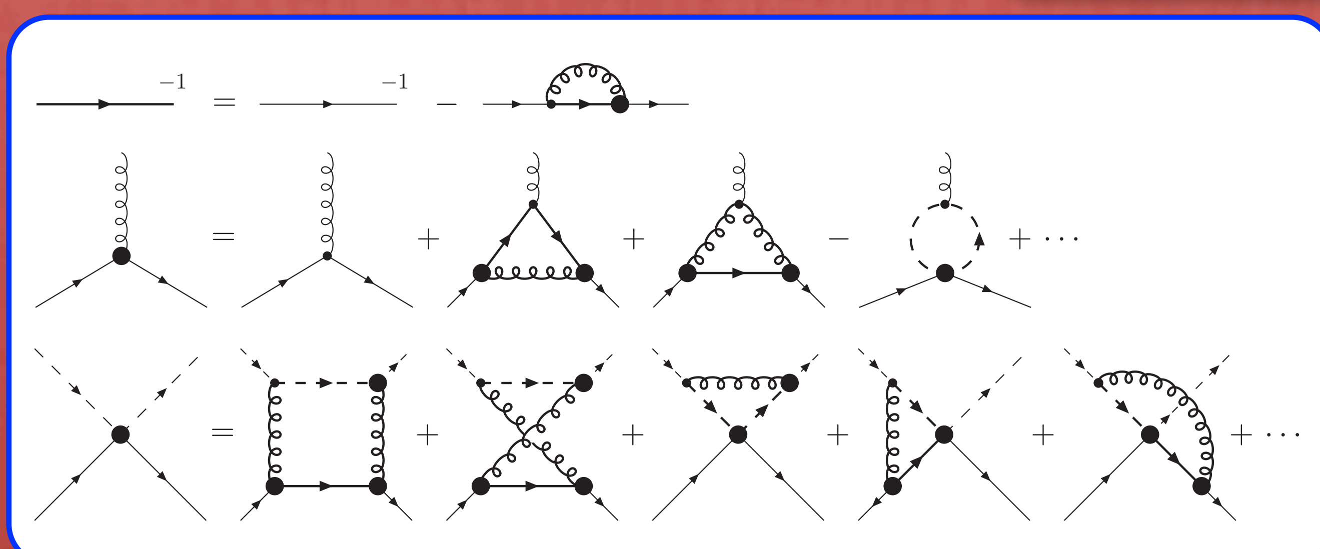


Dynamical QCD & Screening

Unquenched QCD

- Coupled system of equations of the gauge and matter sector
  - Unquenching effects via closed quark loops
  - introduce the quark masses m_i

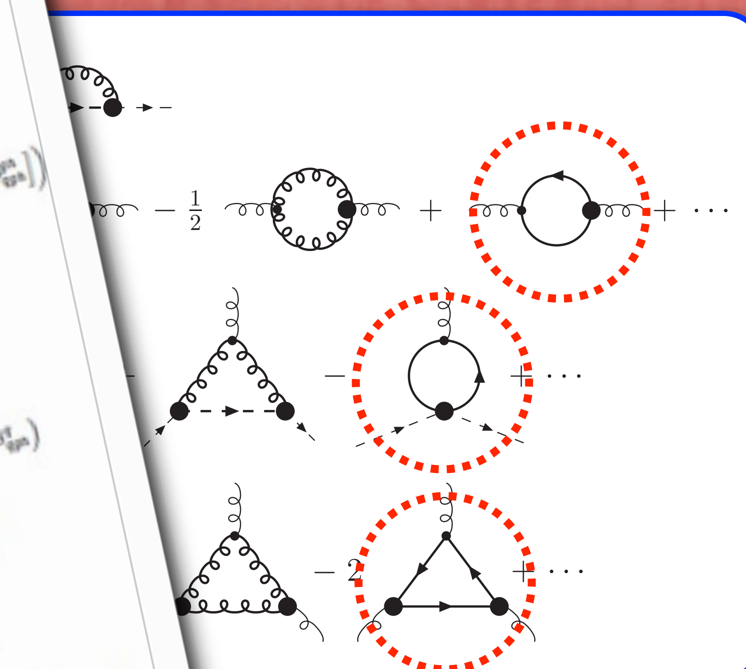


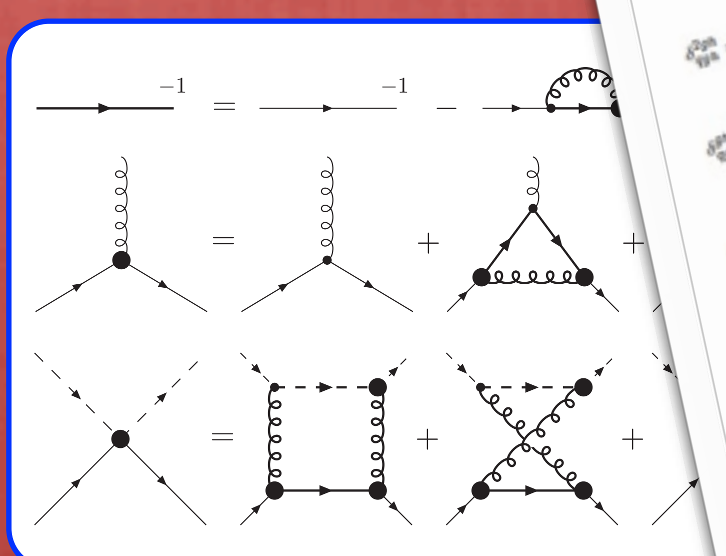


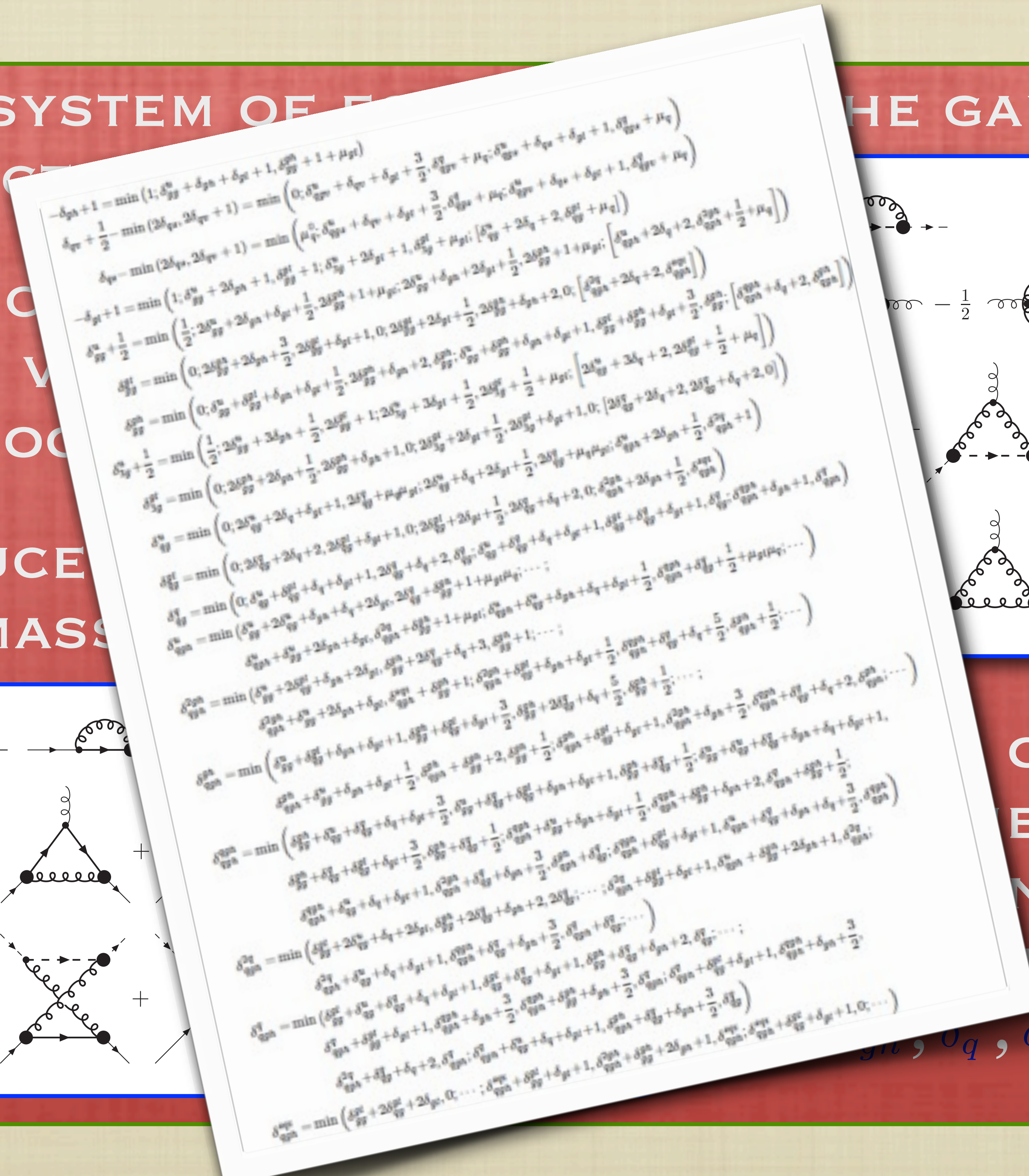
- System of coupled non-linear equations for 18 IR exponents: δ_{gl}, δ_{gh}, δ_q, δ_{qg}^{u}, δ_{qg}^{gl}, ...

Unquenched QCD

- Coupled system of E… …he gauge and matter sec…
  - Unquenc… effects v… quark loo…
  - introduce… quark mass…



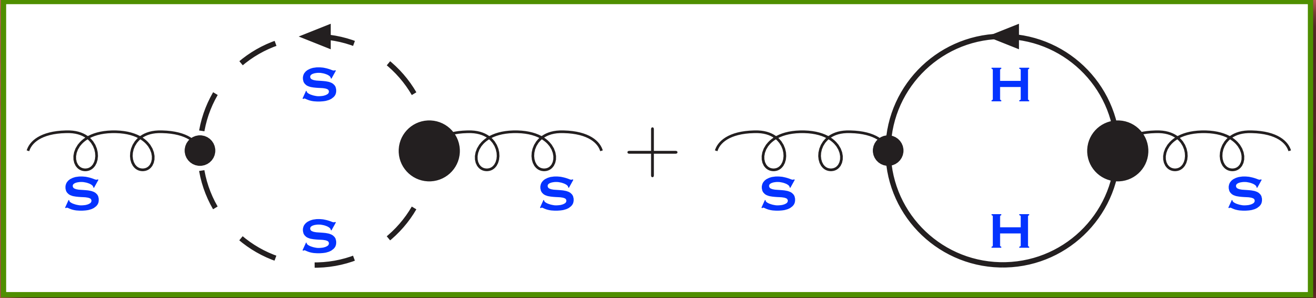




… of coupled …ear …ns for 18 …ents: … δ_{gh}, δ_q, δ^{u}_{qg}, δ^{gl}_{qg}, …

Dynamical Screening

- A Strong soft divergence is not compatible with the Yang-Mills scaling solution
  - it would contribute in the unquenching diagrams even for large loop momenta of the order of the quark mass and dominate over the leading ghost loop
  - signalizes screening of the interaction



$$\left(p^2\right)^{2+2(-1-\kappa)+2\frac{1}{2}} < \left(p^2\right)^{-\frac{1}{2}-\kappa}$$

- Finite mass QCD cannot be asymptotically confining but only as long as the energy of the system is far below the quark masses

Fixed points of QCD

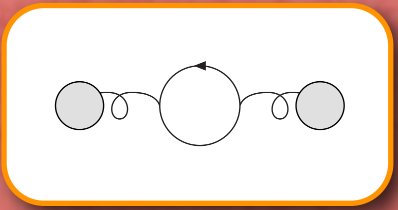
- Fixed point structure depends on the quark mass:

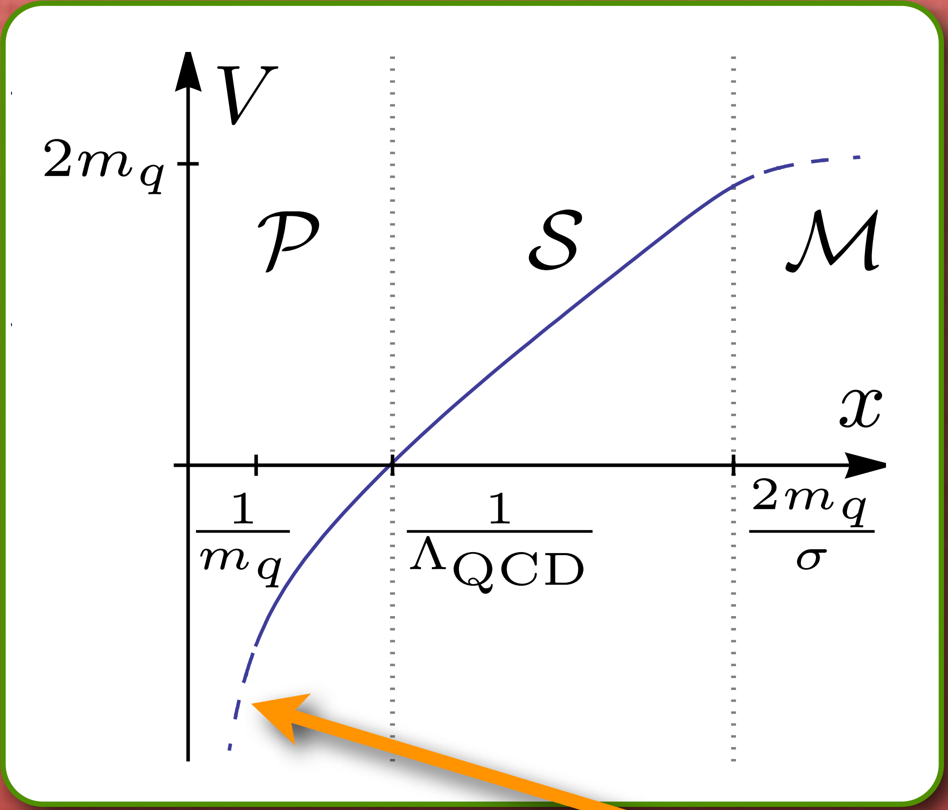
		δ_{gh}	δ_{gl}	δ_q	δ^u_{gg}	δ^{gl}_{gg}	δ^{gh}_{gg}	δ^u_{3g}	δ^{gl}_{3g}	δ^u_{qg}	δ^{gl}_{qg}	δ^q_{qg}
scaling	static ($m_q \to \infty$) / quenched	$-\kappa$	2κ	- / 0	0	0	0	-3κ	$\min(0, 1-2\kappa)$	- / $-\frac{1}{2}-\kappa \vee 0$	$-\mathbf{\frac{1}{2}}-\kappa \vee 0$	0
	massive ($m_q > 0, m_q^0 \geq 0$)	$-\kappa$	2κ	0	0	0	0	-3κ	$\min(0, 1-2\kappa)$	$-\frac{1}{2}-\kappa \vee 0$	**0**	0
	chiral ($m_q = m_q^0 = 0$)	$-\kappa$	2κ	$-\frac{1}{2}$	0	0	0	-3κ	$\min(0, 1-2\kappa)$	$-\kappa \vee 0$	**0**	0
decoupling	($\forall\, m_q$)	0	1	$-\frac{1}{2} \vee 0$	0	0	0	0	0	0	**0**	0
perturbative	($\forall\, m_q$, both IR & UV)	0	0	$-\frac{1}{2} \vee 0$	0	0	0	0	0	0	**0**	0

- Gauge sector is unchanged by the quark dynamics
- No strong kinematic singularity of the quark-gluon vertex in dynamical QCD
  - Confining interaction is screened precisely at scales of the order of the quark mass
  - has the Potential to describe string breaking & hadronization ... but color can still be

Heavy quark potential

$(\Lambda_{QCD} \ll m_q < \infty)$





K. S., arXiv:0811.3608

- For $p_g \gtrsim m_q \Rightarrow x \lesssim 1/m_q$ heavy quark picture not valid

Heavy quark potential

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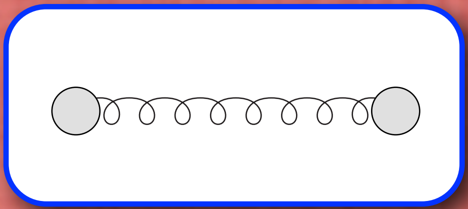

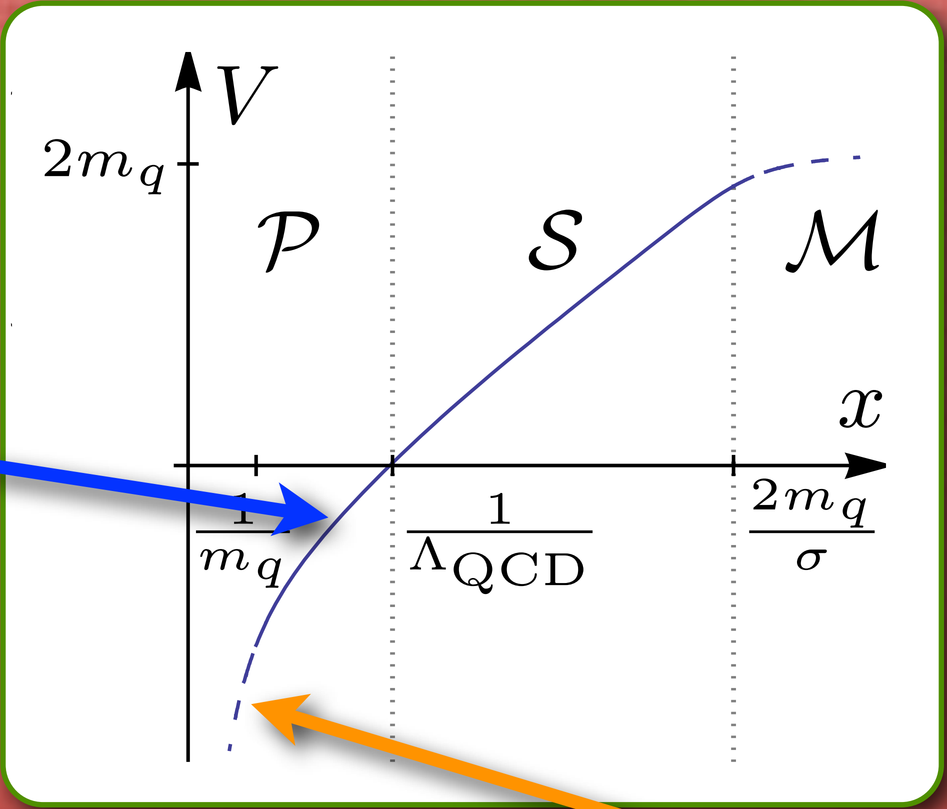

K. S., arXiv:0811.3608

- **Perturbative UV fixed point:**
  applies for $x \ll 1/\Lambda_{QCD}$
  Coulomb part
  (1-gluon exchange)
- For $p_g \gtrsim m_q \Rightarrow x \lesssim 1/m_q$ heavy quark picture NOT VALID

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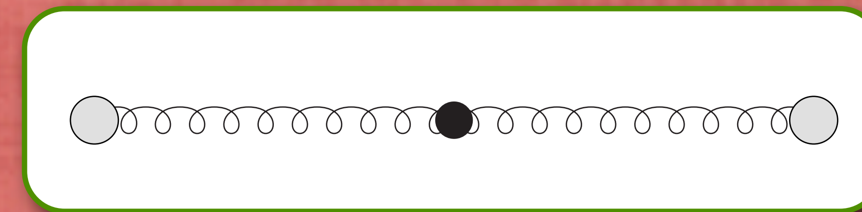

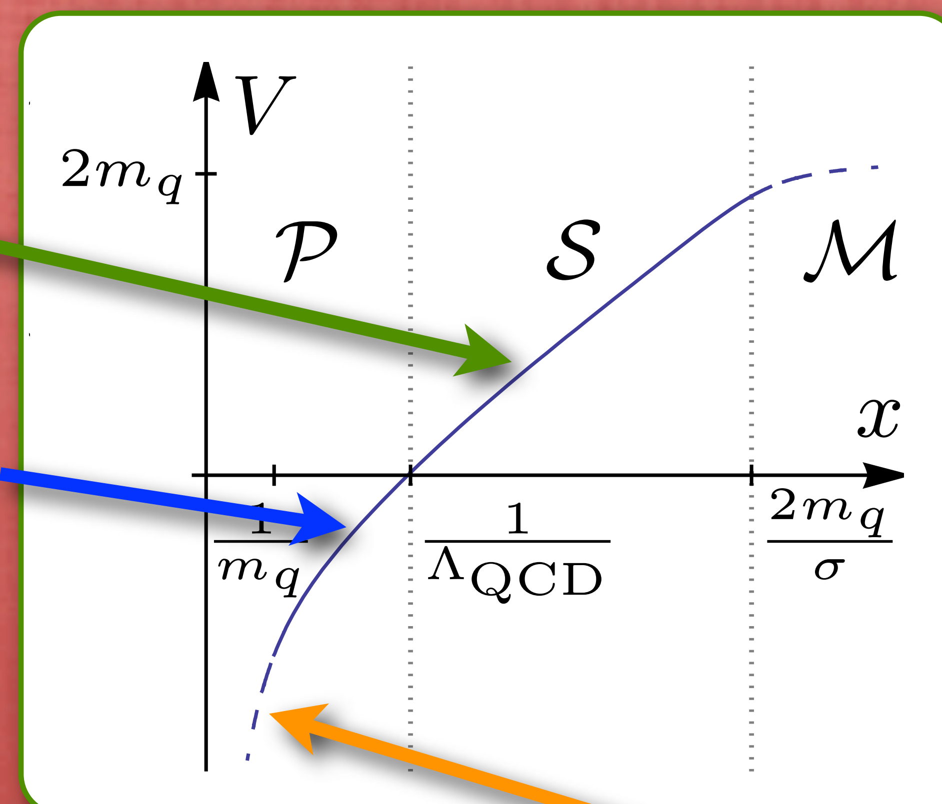

K. S., arXiv:0811.3608

- **Static IR fixed point:**
  valid for $V \sim \sigma x \ll 2m_q$
  linear confining potential
- **Perturbative UV fixed point:**
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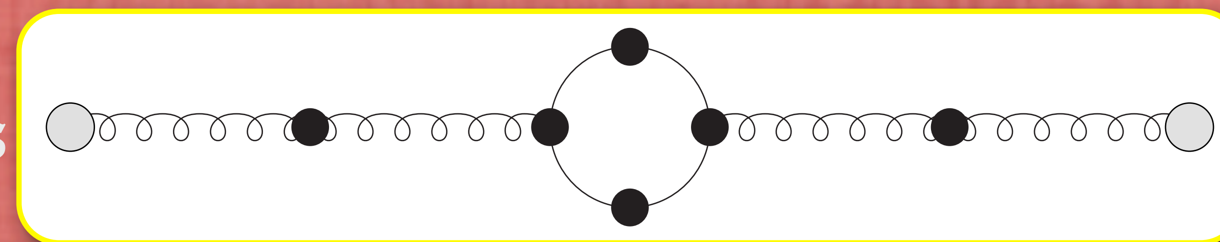
- For $p_g \gtrsim m_q \Rightarrow x \lesssim 1/m_q$ heavy quark picture NOT VALID

Heavy quark potential

$(\Lambda_{QCD} \ll m_q < \infty)$

- Massive IR fixed point:
  Screened by quark loops
  potential breaks down



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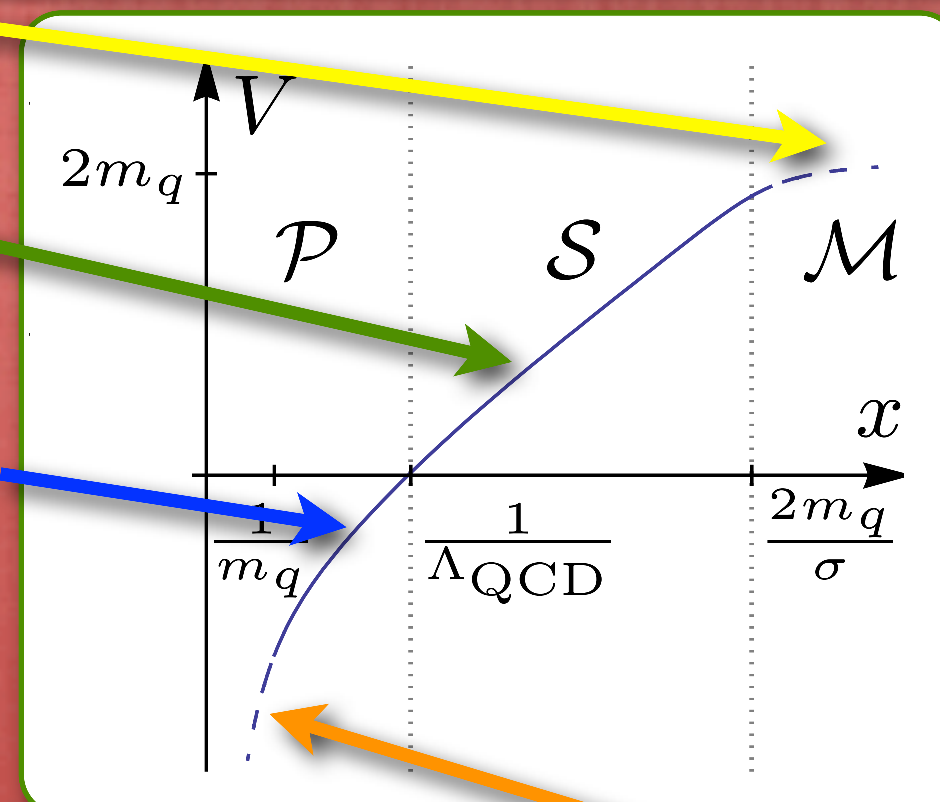

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K. S., arXiv:0811.3608

- For $p_g \gtrsim m_q \Rightarrow x \lesssim 1/m_q$ heavy quark picture not valid

★ Fixed points determine complete qualitative form analytically and beyond the strong coupling limit

Conclusion & Outlook

- Simple dynamical mechanism for quark confinement in Landau gauge QCD based on IR-scaling fixed points
  - relies on soft-gluon singularities of vertex
  - explains both static and relativistic aspects
- Coherent picture of the QCD vacuum
  - chiral symmetry breaking & confinement
  - spontaneous & anomalous mass generation
- Goal: Bound states & color confinement
- How to do the same within an RG-analysis?