How much nonperturbative is the infrared regime of QCD?

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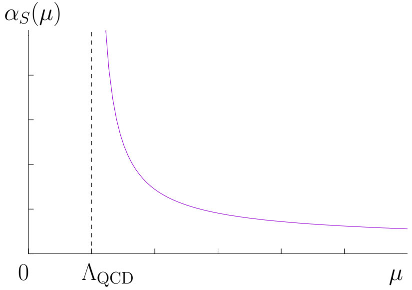
Introduction

Perturbative calculations in QCD predicts

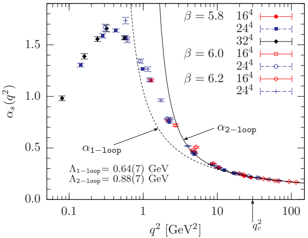
- a decrease of the strong interaction at high energy: asymptotic freedom;
- a divergence at some finite momentum scale: Λ_{QCD}: Landau pole.



The IR regime is inaccessible to perturbation theory.

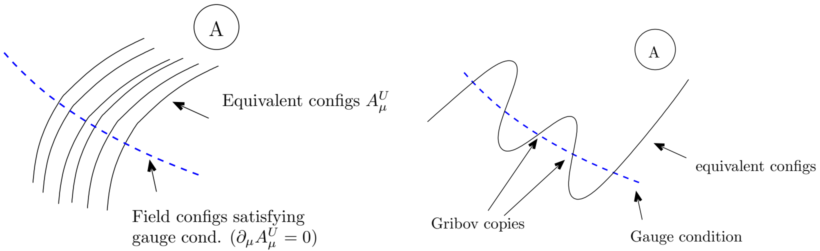
However...

- Lattice simulation lead to different results. In the quenched approximation:



- Perturbative calculations are performed within the Faddeev-Popov framework, which disregards the issue of Gribov ambiguities. This is ok at high energy but may be problematic in the IR.

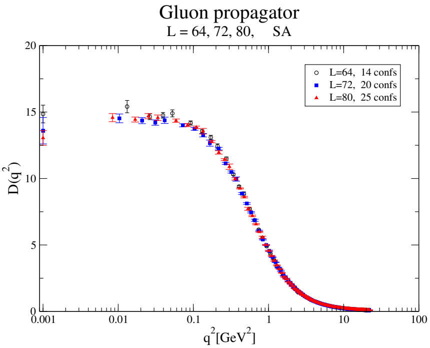
Gribov issue



At the light of Gribov copies, the Faddeev-Popov construction is not a well-defined gauge-fixing procedure at the nonperturbative level (Neuberger zero problem).

Other surpirize

- Lattice simulations (in Landau gauge) show clear evidence of a massive behavior for the gluon propagator: Decoupling solution



- Not expected within the Faddeev-Popov approach, where all fields are massless.

A phenomenological model

- The mass generation is a difficult issue (presence of a condensate? nonperturbative effect? related with Gribov ambiguity?) Once we are convinced it exists, how much physics can we understand?
- Introduce a mass for the gluon by hand in the (gauge-fixed) Lagrangian:

$$\mathcal{L} = \frac{1}{4}(F_{\mu\nu}^a)^2 + \partial_\mu \bar{c}^a (D_\mu c)^a + h^a \partial_\mu A_\mu^a + \frac{1}{2} m^2 \left(A_\mu^a\right)^2$$

(Here, we make the assumption that no extra field is needed)

- This is one particular representative of the Curci-Ferrari lagrangian.

Overview

- Motivate the interest of this phenomenological model.
- Systematic comparison with Lattice correlation functions.

Nice properties of the model

- UV ($p \gg m$) properties are unaffected by the gluon mass.
- In particular, the theory is renormalizable to all orders (De Boer et al). (gluon mass softly breaks the BRST symmetry)
- the (running) gluon mass tends to zero in the ultraviolet ($m(\mu) \propto g^{\alpha}(\mu)$ with $\alpha > 0$).
- Feynman rules are identical to usual ones, except for the massive gluon propagator:

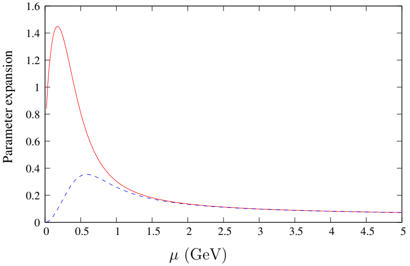
$$\langle A_\mu A_\nu \rangle_0(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) \frac{1}{p^2 + m^2}$$

  perturbation calculations are easy to perform.
- Low momentum physics regularized by the gluon mass.

Infrared behavior

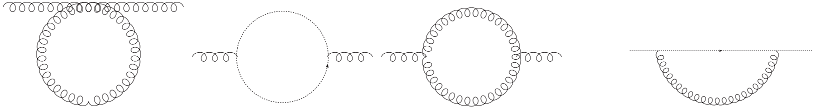
At very low momenta, gluons are frozen. Ghost loop dominates.

- $\Gamma_{A^a_\mu A^b_\nu} \sim \text{Const} + p^{d-2}$
  - in $d = 4$, leads to log divergences, hard to see...
  - in $d = 3$, gluon propag $cte + |p|$
- $\Gamma_{A^a_\mu A^b_\nu A^c_\rho} \sim -f^{abc}(ip_\mu \delta_{\nu\rho} + \cdots)p^{d-4}$. Leads to a change of sign, consistent with lattice data.
- Interaction between ghosts is mediated by heavy gluons (see also Weber). Effective interaction is suppressed by some positive power of p at low momentum.



Ghost and gluon propagators

Need to compute 4 Feynman diagrams



Define $\langle A_\mu A_\nu \rangle(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) G(p)$ $\qquad \langle c\bar{c}\rangle(p) = \frac{1}{p^2} F(p)$.

Introduce 4 renormalization parameters and you get ($s = p^2/m^2$.):

$$G^{-1}(p)/m^2 = s + 1 + \frac{g^2 N}{384\pi^2} s \Big\{ 111 s^{-1} - 2 s^{-2} + (2 - s^2)\log s$$

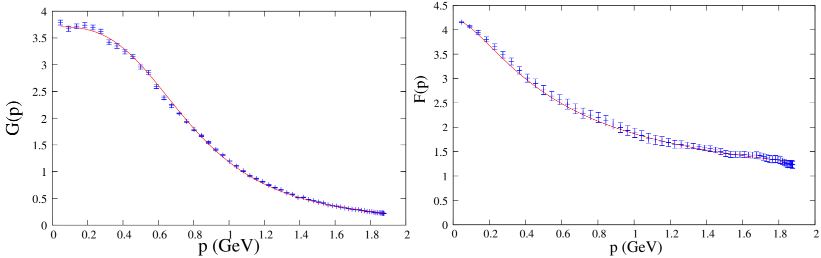
$$+ (4s^{-1} + 1)^{3/2}\left(s^2 - 20s + 12\right)\log\left(\frac{\sqrt{4+s} - \sqrt{s}}{\sqrt{4+s} + \sqrt{s}}\right)$$

$$+ 2(s^{-1} + 1)^3\left(s^2 - 10s + 1\right)\log(1+s) - (s \to \mu^2/m^2)\Big\},$$

$$F^{-1}(p) = 1 + \frac{g^2 N}{64\pi^2}\Big\{ - s\log s + (s+1)^3 s^{-2}\log(s+1) - s^{-1} - (s \to \mu^2/m^2)\Big\}$$

Comparison with lattice data

For SU(2) (Cucchieri, Mendes '08)



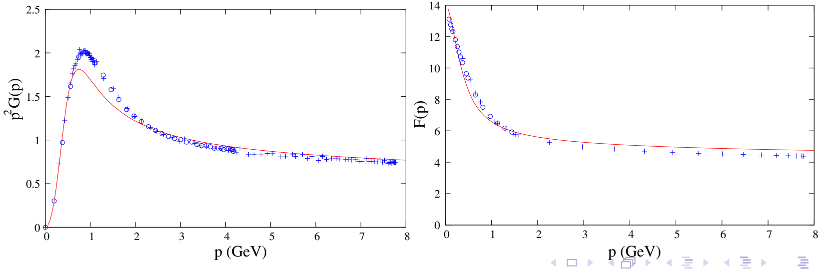
Renormalization-group flow

From renormalization factors, deduce a set of coupled β functions for g and m:

In the UV ($\mu \gg m$) $\beta_g \simeq -\frac{g^3 N}{16\pi^2}\frac{11}{3}$

In the IR ($\mu \ll m$) $\beta_g \simeq +\frac{g^3 N}{16\pi^2}\frac{1}{6}$

For SU(3) (Bogolubsky '09, Dudal '10)

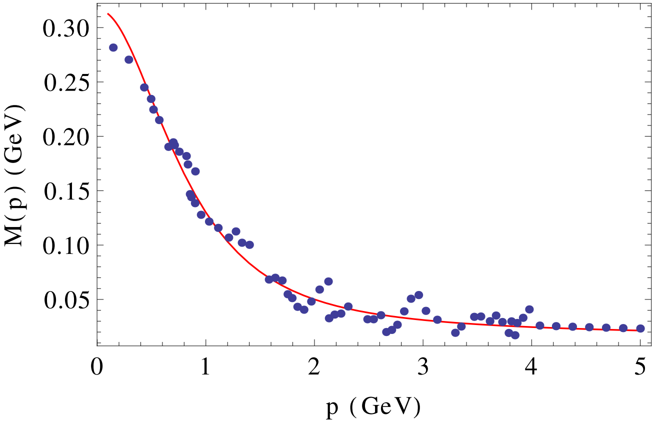


Other correlation functions

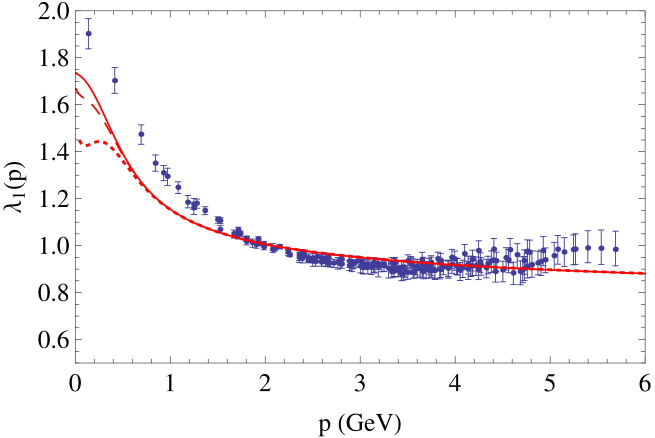
- By the same technique, we have computed (all tensorial components) and compared with lattice data, when available:
  - 3 gluon vertex and ghost-gluon vertex;
  - quark propagator;
  - quark-gluon vertex;
- Agreement (Maximal error of 15-20%) in the quenched approximation.
- In unquenched calculations (Skullerud et al), still ok, but less precise, because the quark-gluon vertex is larger (typically the double of the ghost-gluon vertex).
- 1-loop compares badly to lattice for the quark renormalization factor and for one of the structure tensors of the quark-gluon vertex (λ_2).

Quark mass

The quark mass is enhanced in the infrared. But no chiral symmetry breaking.



Quark-gluon vertex



Limitations of the method

We have a nice and simple way of describing the infrared behavior of correlation functions. However:

- We have a phenomenological parameter that must be fixed by comparison with lattice data, or experimental values.
- The mass term breaks BRST symmetry. There is actually a BRST symmetry which is however not nilpotent.
- We cannot define the physical subspace, and prove unitarity in the textbook way (this problem common to all approaches beyond pert. theory).
- The quark-gluon coupling constant is larger. The approach as it stands is not fully justified

Beyond correlation functions

- By the same approaches we studied the phase diagram of Yang-Mills and of QCD with heavy quarks.
- We try to deal with the quark-gluon interaction and reproduce the spontaneous chiral symmetry breaking.
- Can we control the generation of the gluon mass?