A NEW PARADIGM FOR QCD IN THE INFRARED?

Urko Reinosa*

(based on various collaborations with N. Barrios, D. M. van Egmond, J. A. Gracey, M. Peláez, M. Tissier, J. Serreau and N. Wschebor)

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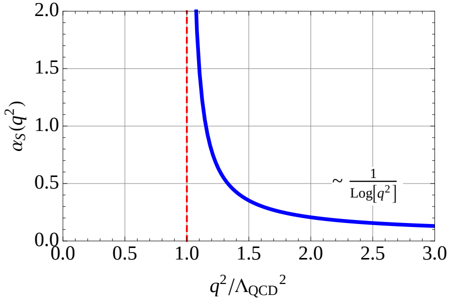
May 10, 2023, Laboratoire Charles Coulomb, Montpellier.

QCD is weakly coupled in the UV and strongly coupled in the IR:

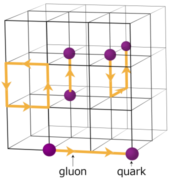


Any serious account of its low energy properties
requires non-perturbative methods.

This view will not be challenged in this talk
but refined in some sense.

To date, the only really first-principle non-perturbative approach is based on lattice QCD. The (Euclidean) QCD functional integral

$$\int \mathcal{D}[A\psi\bar{\psi}]\, e^{-S_{\rm QCD}[A,\psi,\bar{\psi}]} \longrightarrow$$



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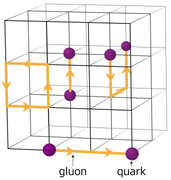
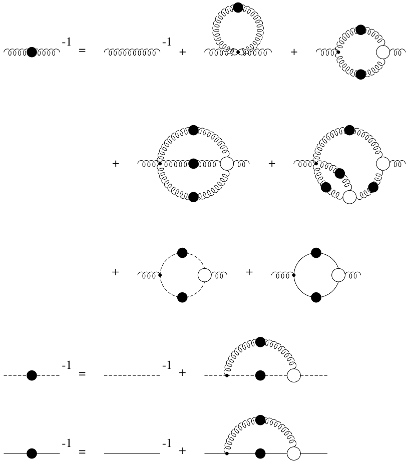


is discretized and evaluated via Monte-Carlo importance-sampling which relies on a probabilistic interpretation.

The method looses its predictive power whenever the probabilistic interpretation fails: finite baryonic density, real-time processes, …

To overcome these limitations, non-perturbative continuum methods have been developed. The QCD functional integral is replaced by infinite hierarchies of equations (DS, FRG, NPI, . . .):



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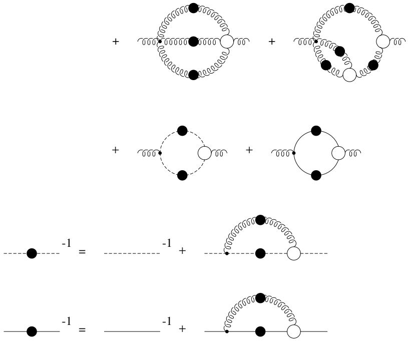

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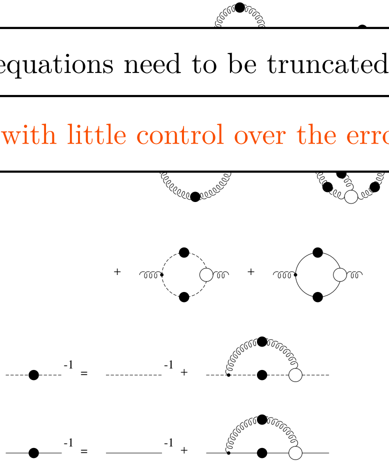

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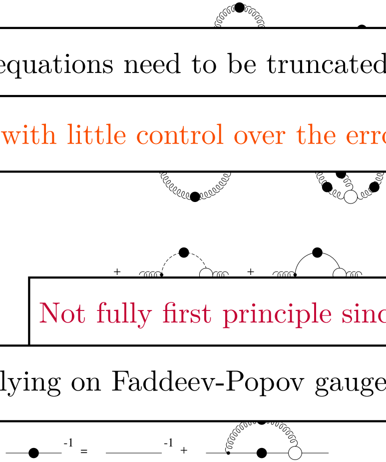

These equations need to be truncated in practice

with little control over the error ...

Not fully first principle since

relying on Faddeev-Popov gauge-fixing

Could one imagine a third possible way into infrared QCD that allows one to circumvent some of the limitations of the lattice while providing a systematic control over the error?

We believe that some of the results obtained over these past 20 years within Landau gauge-fixed lattice simulations point at that possibility.

This talks aims at reporting our progresses towards this goal ...
[M. Peláez, U. Reinosa, J. Serreau, M. Tissier, N. Wschebor, Rept. Prog. Phys. 84 (2021)]

OUTLINE

I. Motivation ✓

II. Quarks and Gluons in the infrared

III. The Curci-Ferrari (CF) model

IV. Benchmarking the CF model:

  a. Pure glue case;
  b. Glue + Heavy quarks;
  c. Glue + Light quarks;

V. Probing the QCD phase structure from the CF model

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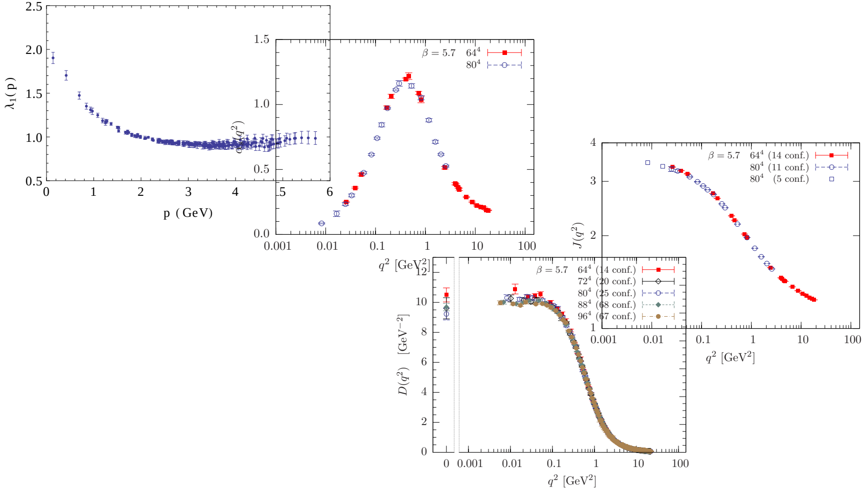
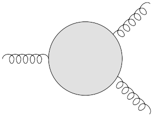
LANDAU-GAUGE-FIXED LATTICE SIMULATIONS

Over the past 20 years, Landau-gauge-fixed lattice simulations have allowed us to refine our understanding of the dynamics of colored fields in the infrared while revealing unexpected features:

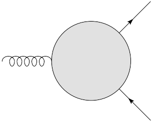


NON-UNIVERSALITY OF THE STRONG INTERACTION IN THE INFRARED

We all learn that the strong interaction is universal:



$\sim \sqrt{\alpha_S^{\mathrm{glue}}}$

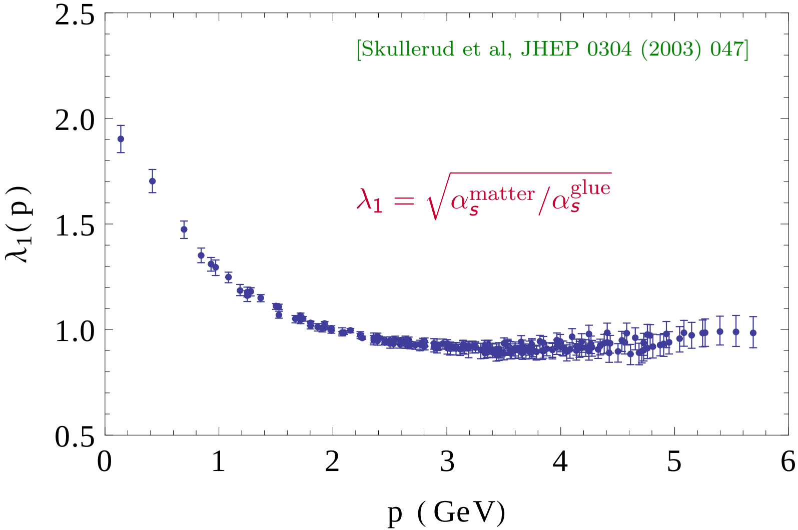


$\sim \sqrt{\alpha_S^{\mathrm{matter}}}$

$$\Rightarrow \quad \boxed{\alpha_S^{\mathrm{glue}} = \alpha_S^{\mathrm{matter}}}$$

However, this is a UV result which is not true anymore in the IR.

NON-UNIVERSALITY OF THE STRONG INTERACTION IN THE INFRARED



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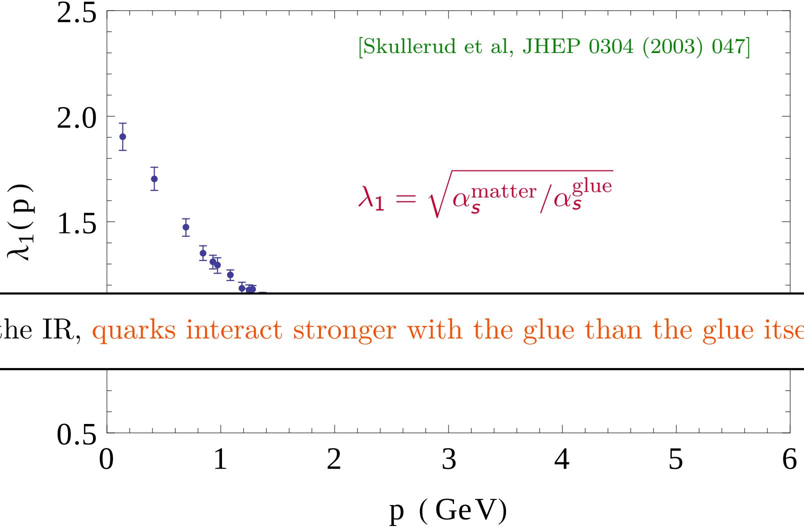

In the IR, quarks interact stronger with the glue than the glue itself!

GLUE COUPLING

Since there is a hierarchy of couplings in the infrared, it is interesting to look at the smallest of them, $\alpha_s^{\rm glue}$. Here comes a second surprise:

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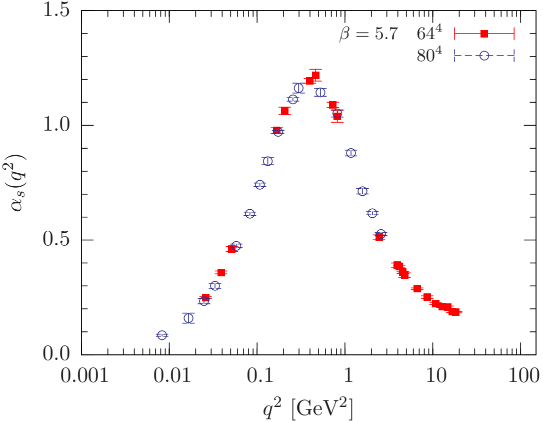

[I. L. Bogolubsky, E. M. Ilgenfritz, M. Müller-Preussker, A. Sternbeck, PLB 676, 69 (2009)]

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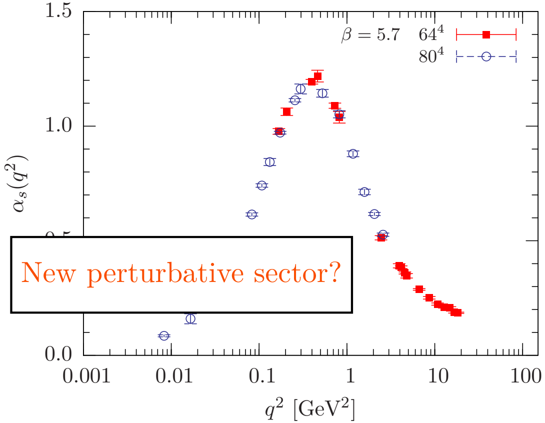

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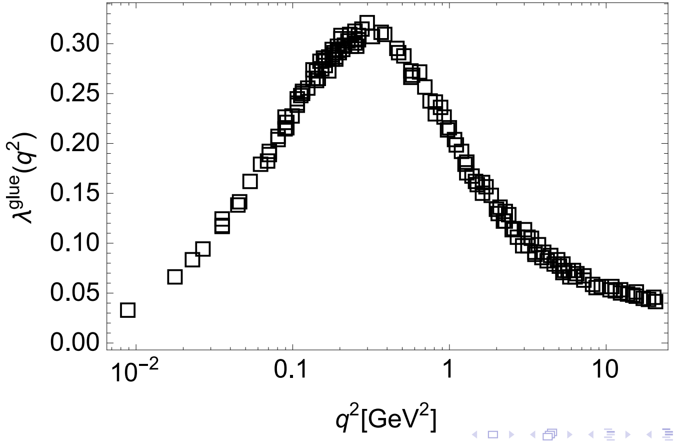
GLUE COUPLING

In fact, the natural expansion parameter of perturbation theory in the glue sector is not $\alpha_s^{\rm glue}$ but rather

$$\lambda^{\rm glue} \equiv \frac{g^2 N_c}{16\pi^2} = \frac{N_c}{4\pi}\alpha_s^{\rm glue}$$



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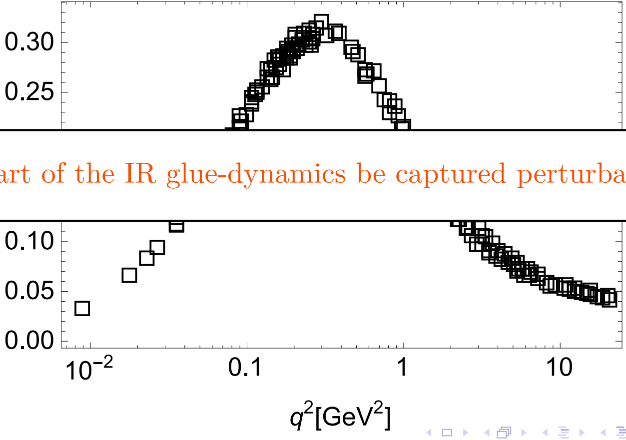

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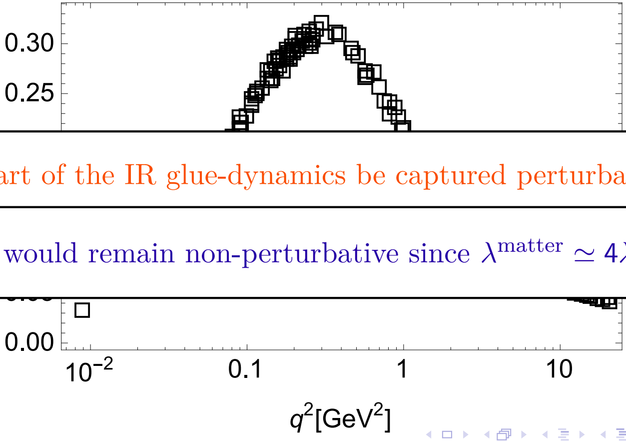

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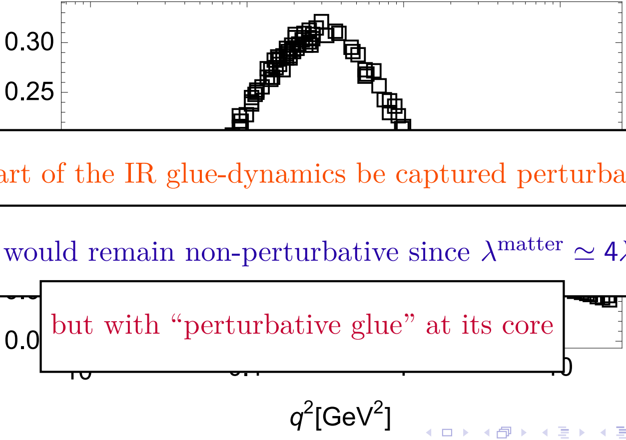


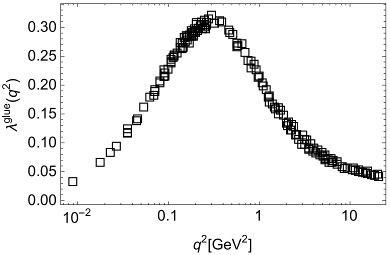
Could part of the IR glue-dynamics be captured perturbatively?

QCD would remain non-perturbative since $\lambda^{\rm matter} \simeq 4\lambda^{\rm glue}$

but with “perturbative glue” at its core

BUT WAIT ...

We have two seemingly contradictory pictures for the glue sector:



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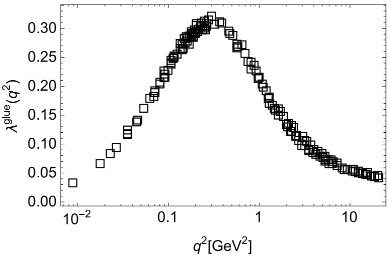

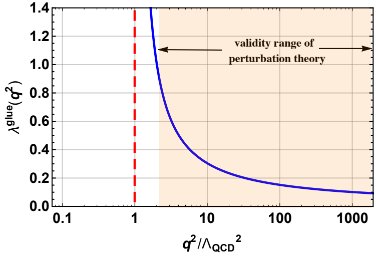

According to the first, perturbation theory is valid over all scales.

According to the second, perturbation theory predicts its own failure.

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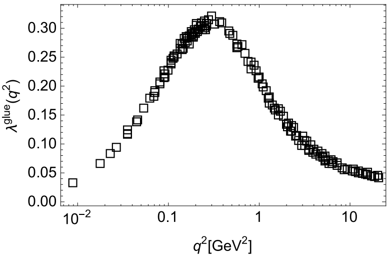

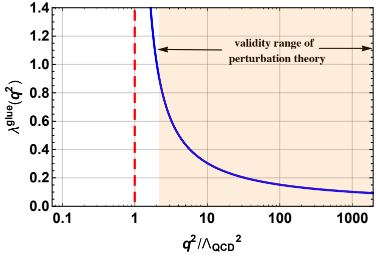

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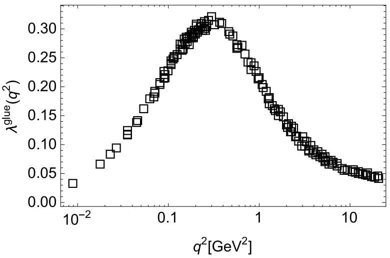
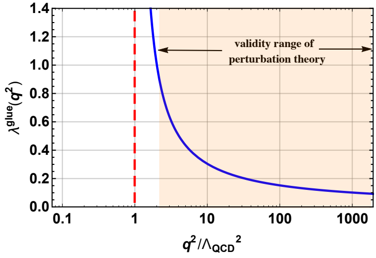




Yet, the first is the outcome of a first-principle lattice calculation.

The second results instead from an (uncontrolled) extrapolation of the Faddeev-Popov procedure.

GAUGE FIXING AND FADDEEV-POPOV ACTION

To set up a perturbative expansion we should in principle consider:

$$S_{YM}[A] \quad \text{with} \quad \partial_\mu A_\mu^a = 0 \quad \text{[Landau gauge]}$$

In practice, however, we use:

$$S_{FP} = S_{YM} + \int_x \left\{ i h^a \partial_\mu A_\mu^a + \bar{c}^a \partial_\mu D_\mu c^a \right\} \quad \text{[Faddeev-Popov]}$$

These two ways of proceeding are often thought to be equivalent.

GAUGE FIXING AND FADDEEV-POPOV ACTION

However, the equivalence is known to rely on a mathematically incorrect assumption ("Gribov copy problem").

In fact:

– At high energies, the equivalence is seen to hold.
– At low energies, we have tangible evidence that it does not.

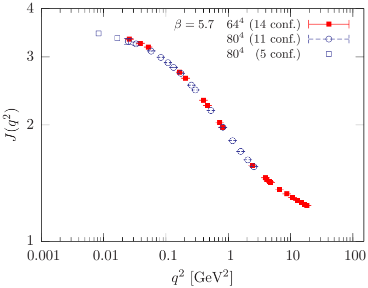
SCALING VS DECOUPLING SOLUTIONS

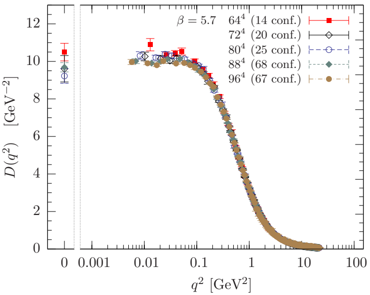
Kugo and Ojima: when the FP action is taken seriously at all scales, one deduces a specific behavior of the correlation functions in the IR

$$\Rightarrow \text{“scaling” solution} \left\{ \begin{array}{l} J(q^2) \equiv q^2 \langle c(-q)\bar{c}(q)\rangle \to \infty \text{ as } q \to 0 \\ \\ D(q^2) \equiv P^{\perp}_{\mu\nu}(q)\langle A_\mu(-q)A_\nu(q)\rangle \to 0 \end{array} \right.$$

SCALING VS DECOUPLING SOLUTIONS

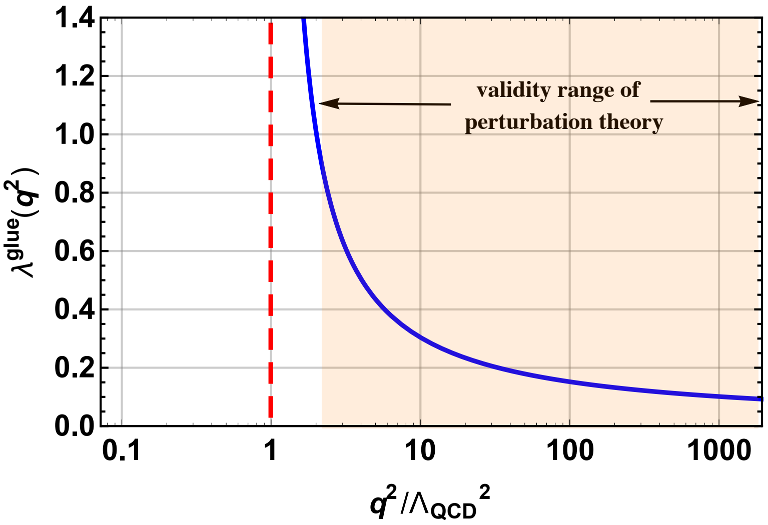
At odds with the "decoupling" solution found on the lattice (which does not rely on FP):





[I. L. Bogolubsky, E. M. Ilgenfritz, M. Müller-Preussker, A. Sternbeck, PLB 676, 69 (2009)]

PERTURBATIVE GLUE SCENARIO



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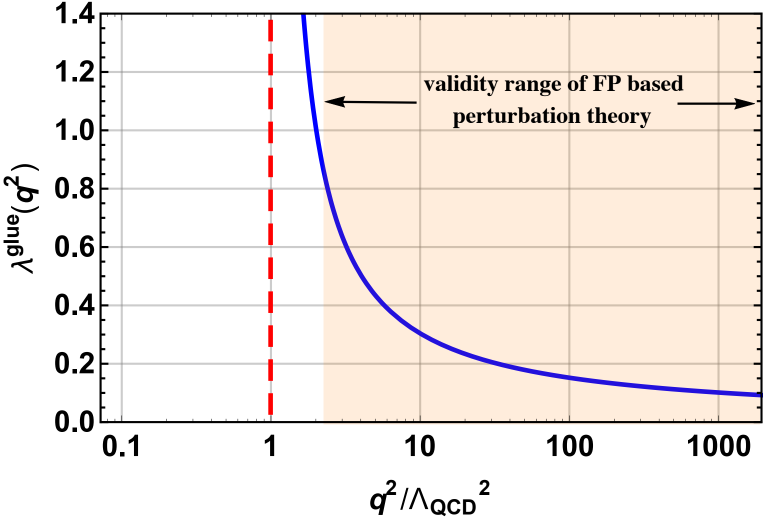

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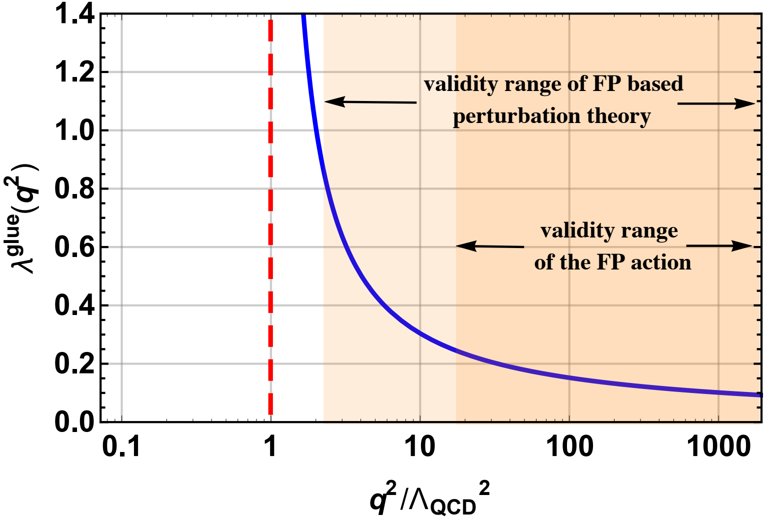

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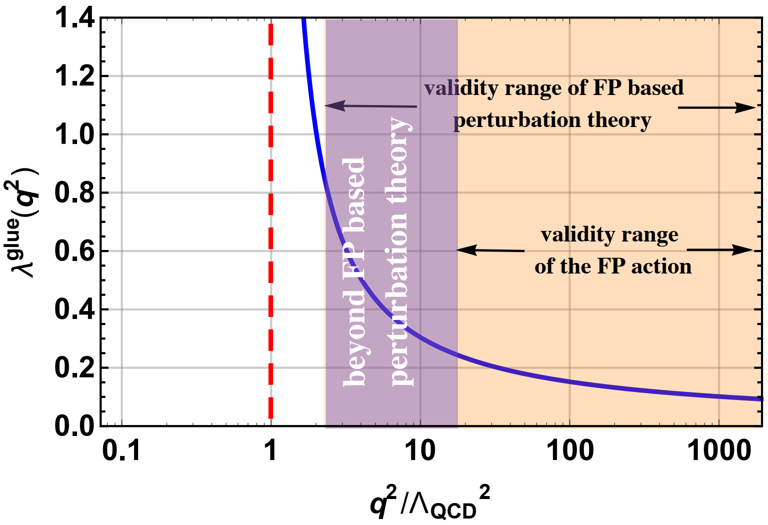

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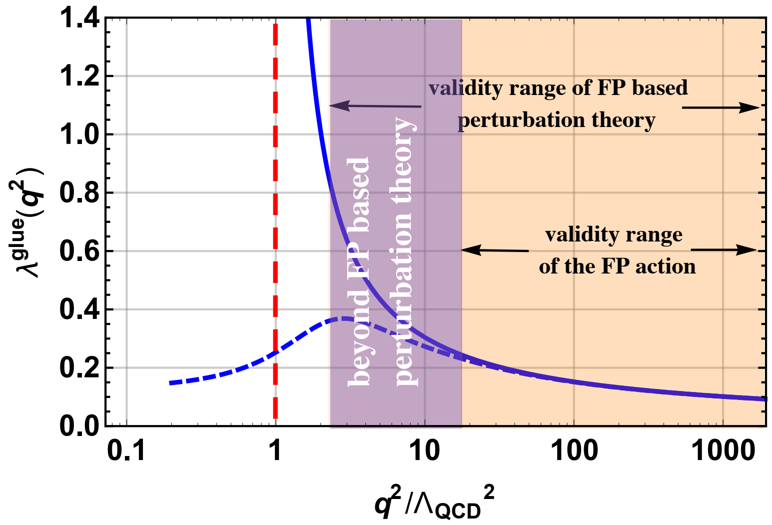


BEYOND THE FADDEEV-POPOV ACTION

In order to implement this perturbative glue scenario, we need to find how the FP action is modified in the infrared

$$S_{FP} \longrightarrow S_{FP} + \delta S$$

How to find the appropriate extension δS?

- first-principle approach: not known;
- semi-first-principle approach: Gribov-Zwanziger;
- phenomenological approaches: add new operators to S_{FP} and try to constrain their couplings, or even discard them, using experiments/lattice simulations.

THE CURCI-FERRARI MODEL

The Curci-Ferrari (CF) model is one example of such an extension:

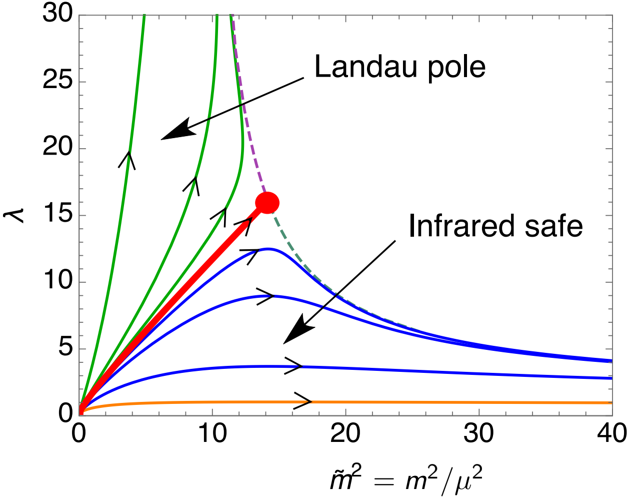
$$S_{CF} = \underbrace{\int_x \left\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \partial_\mu \bar{c}^a D_\mu c^a + i h^a \partial_\mu A^a_\mu \right\}}_{\text{incomplete FP gauge-fixing, valid in the UV only a priori}} + \underbrace{\int_x \frac{m^2}{2} A^a_\mu A^a_\mu}_{\text{IR pheno term}}$$

Please, bear in mind that this is a phenomenological approach motivated by the decoupling behavior in the Landau gauge. No claim that our approach is first principle.

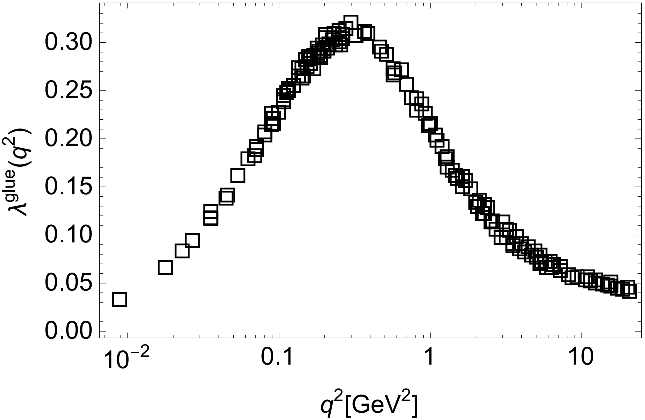
However: the model is renormalizable. So it relies on only one additional parameter m^2 that can be fixed by comparison to gauge-fixed lattice simulations in the Landau gauge.

FLOW DIAGRAM OF THE CF MODEL

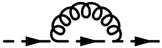
The main interest of the CF model lies in its flow diagram :



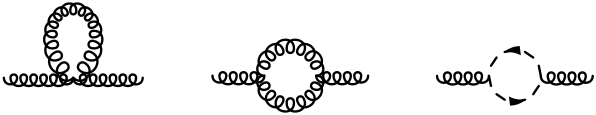
PURE GLUE EXPANSION PARAMETER



A perturbative expansion within the CF model should suffice.

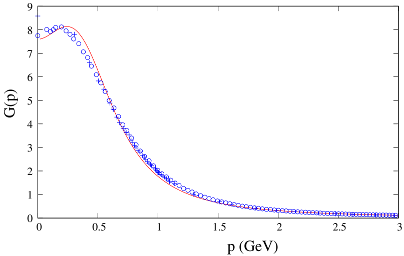


ONE-LOOP TWO-POINT FUNCTIONS

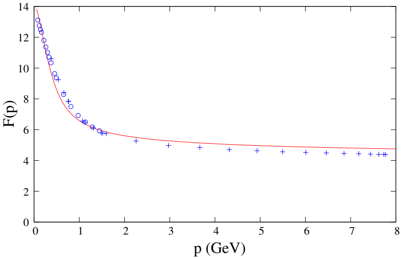


FITS TO THE LATTICE

$G(p) \equiv D(p)$



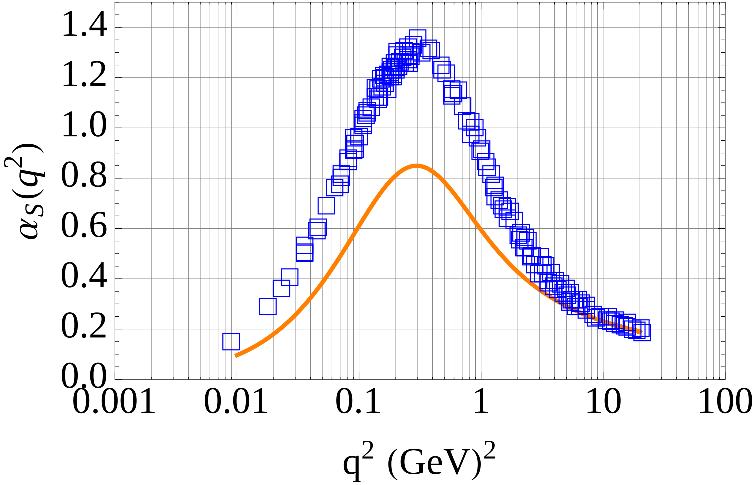
$F(p) \equiv J(p)$

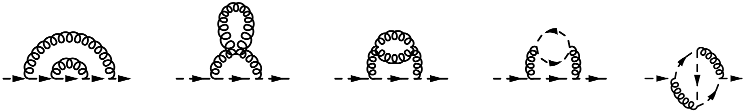


Tissier and Wschebor, Phys. Rev. D82 (2010) & Phys. Rev. D84 (2011).

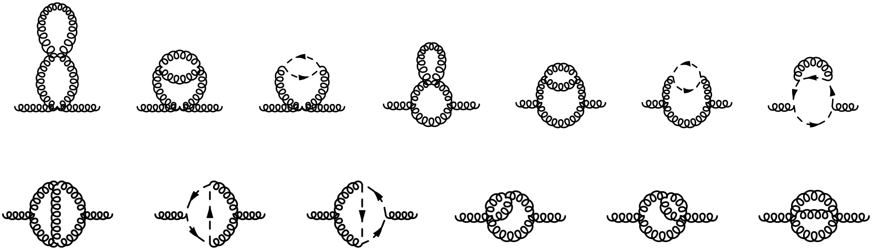
$m_0 \simeq 500\,\mathrm{MeV}$

RUNNING COUPLING





TWO-LOOP TWO-POINT FUNCTIONS

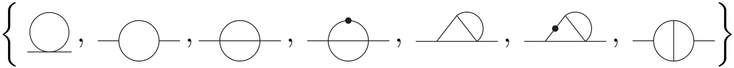


REDUCTION TO MASTER INTEGRALS

1. We use Laporta algorithm to decompose the two-loop two-point functions into a basis of (scalar) master integrals

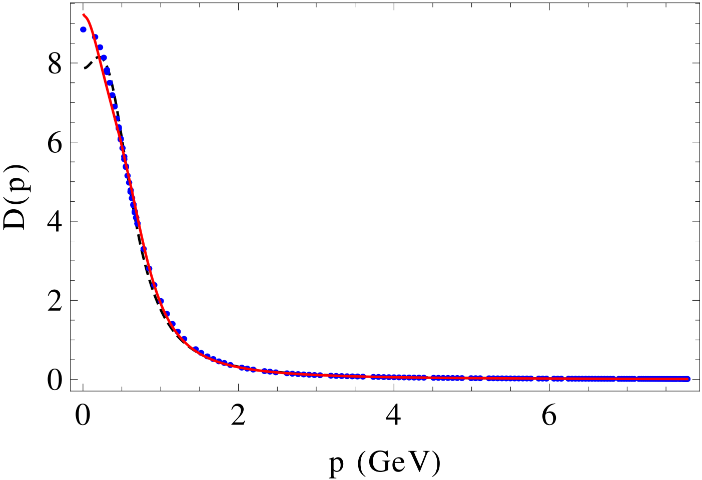
$$\begin{aligned}\Gamma^{(2)}_{AA}(p) &= p^2 + m^2 + \sum_{D\in\mathcal{M}} \mathcal{R}_{AA}(D)\,\mathcal{I}(D)\\ \Gamma^{(2)}_{c\bar{c}}(p) &= p^2 + \sum_{D\in\mathcal{M}} \mathcal{R}_{c\bar{c}}(D)\,\mathcal{I}(D)\end{aligned}$$

where $\mathcal{R}_{AA}(D)$ and $\mathcal{R}_{c\bar{c}}(D)$ are rational functions of p^2 and m^2, and $\mathcal{I}(D)$ is a master Feynman integral, with D among

$D \in \mathcal{M} =$ 

2. We then evaluate each of the masters using the TSIL package.
[https://www.niu.edu/spmartin/TSIL/]

IMPROVED FITS TO THE LATTICE



[J.A. Gracey, M. Peláez, U. Reinosa, M. Tissier, Phys. Rev. D100 (2019)]

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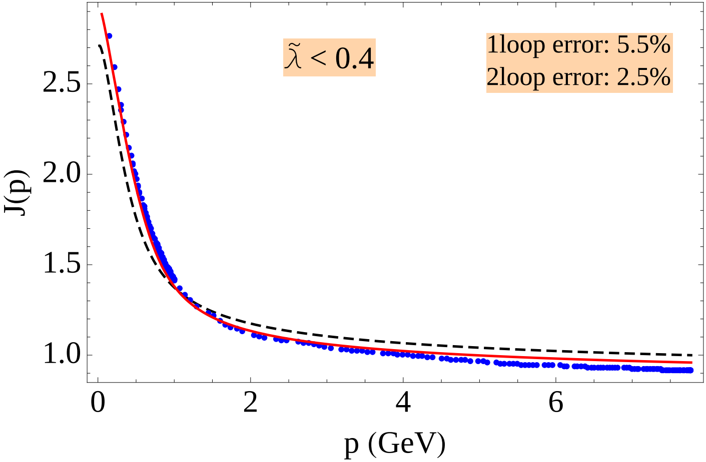

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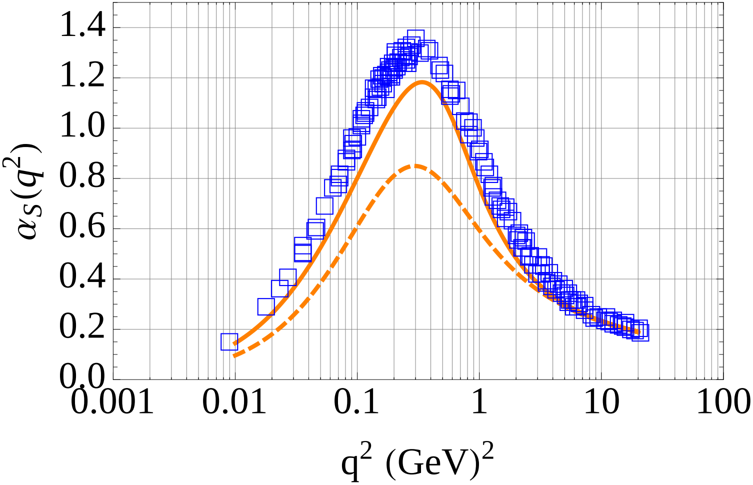
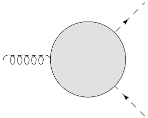
IMPROVED RUNNING COUPLING



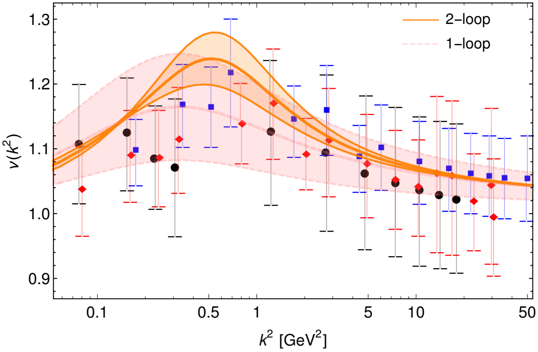
ONE-LOOP AND TWO-LOOP THREE-POINT FUNCTIONS

GHOST-ANTIGHOST-GLUON VERTEX

We have evaluated the ghost-antighost-gluon vertex

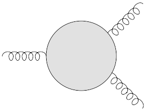


- at one-loop for any configuration of the external momenta;
- at two-loop in the vanishing gluon momentum configuration.

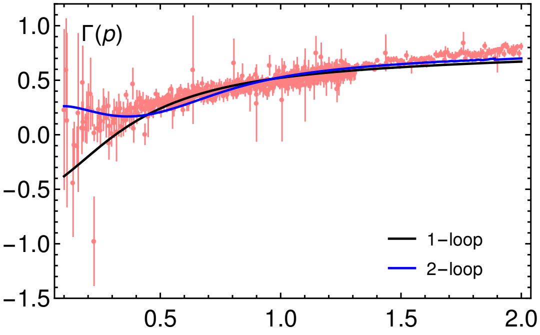


[N. Barrios, M. Peláez, U. Reinosa, N. Wschebor, Phys. Rev. D102 (2020)]

THREE-GLUON VERTEX

Similarly, we have evaluated the three-gluon vertex 

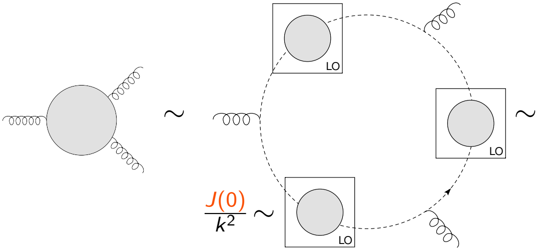
- at one-loop for any configuration of the external momenta;
- at two-loop in the one-vanishing-momentum configuration.



[N. Barrios, M. Peláez, U. Reinosa, Phys. Rev. D106 (2022)]

ZERO-CROSSING?

Using the decoupling of gluons and Smirnov's IR expansion (analog of Weinberg's UV expansion), one finds that the leading behavior is given by an effective one-ghost-loop:



$$\sim \frac{g^3 N_c}{384\pi^2} \ln \frac{k^2}{\mu^2} \times J^3(0)$$

[N. Barrios, M. Peláez, U. Reinosa, Phys. Rev. D106 (2022)]

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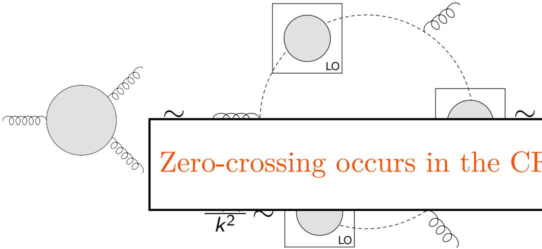

$\sim \dfrac{g^3 N_c}{\ldots} \ln \dfrac{k^2}{\mu^2} \times J^3(0)$

Zero-crossing occurs in the CF model

[N. Barrios, M. Peláez, U. Reinosa, Phys. Rev. D106 (2022)]

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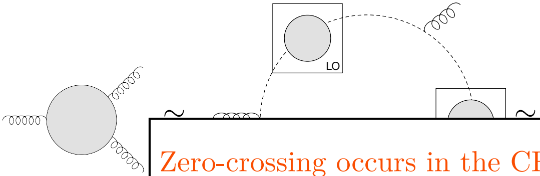


$$\sim \frac{g^3 N_c}{} \ln \frac{k^2}{\mu^2} \times J^3(0)$$

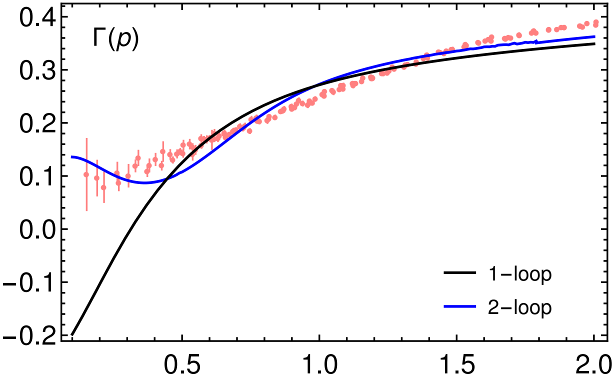
Zero-crossing occurs in the CF model

and more generally in YM + decoupling

[N. Barrios, M. Peláez, U. Reinosa, Phys. Rev. D106 (2022)]

ZERO-CROSSING?

We find a small zero-crossing scale at two-loop order (a few MeV) compatible with some recent lattice data in the IR:



[N. Barrios, M. Peláez, U. Reinosa, Phys. Rev. D106 (2022)]

I. Motivation ✓

II. Quarks and Gluons in the infrared ✓

III. The Curci-Ferrari (CF) model ✓

IV. Benchmarking the CF model:

a. Pure glue case; ✓
b. Glue + Heavy quarks;
c. Glue + Light quarks;

V. Probing the QCD phase structure from the CF model

HEAVY QCD

Before heading to QCD, it is interesting to investigate a formal regime where all quarks are considered heavy (although not infinitely massive).

This “heavy QCD” regime is a good testing ground for any new method on the market.

The expansion parameter is similar to that of pure glue, so the perturbative CF should work here as well.

THE QUARK PROPAGATOR

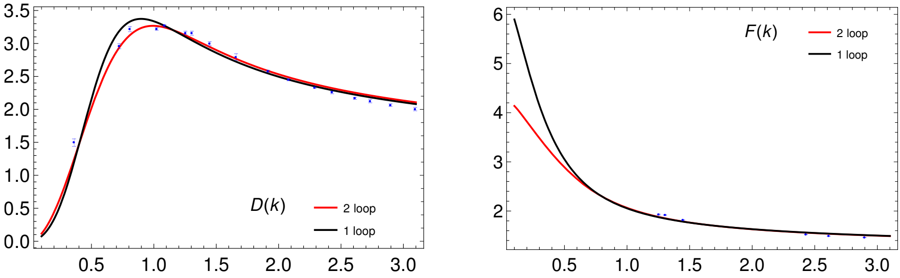
In addition to the ghost and gluon propagators, we have now the form factors of the quark propagator:

$$S(q) = \langle \psi \bar{\psi} \rangle = \frac{Z(q^2)}{i\not{q} + M(q^2)}$$

We evaluate the quark dressing function $Z(q^2)$ and the quark mass function $M(q^2)$ at one- and two-loop order of the perturbative CF expansion.

RESULTS

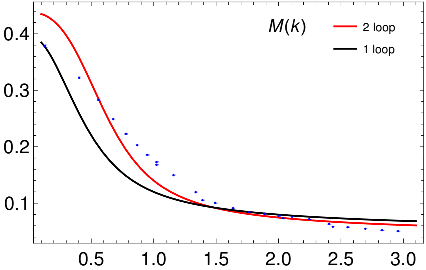
The pure glue sector is still very well described by the pert. CF model:

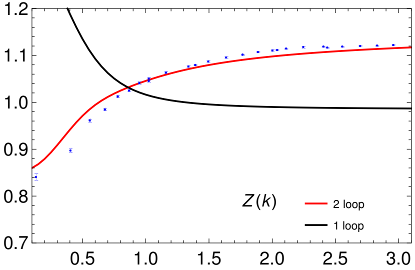


[N. Barrios, J. A. Gracey, M. Peláez, U. Reinosa, Phys. Rev. D104 (2021)]

RESULTS

The pert. CF model also accounts for the quark form factors:





[N. Barrios, J. A. Gracey, M. Peláez, U. Reinosa, Phys. Rev. D104 (2021)]

N.B.: the quark dressing Z is completely off at one-loop. This is due to an accidental symmetry that makes the one-loop correction abnormally small in the UV.

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QCD WITH LIGHT QUARKS

The perturbative CF model is doomed to fail for at at least two reasons:

– no perturbative treatment can account for chiral symmetry breaking (responsible for most of the quark mass function);

– even though $\lambda^{\rm glue} < 0.3$ is perturbative, $\lambda^{\rm matter} \sim 4\lambda^{\rm glue} \lesssim 1.2$ and thus reaches non-perturbative values.

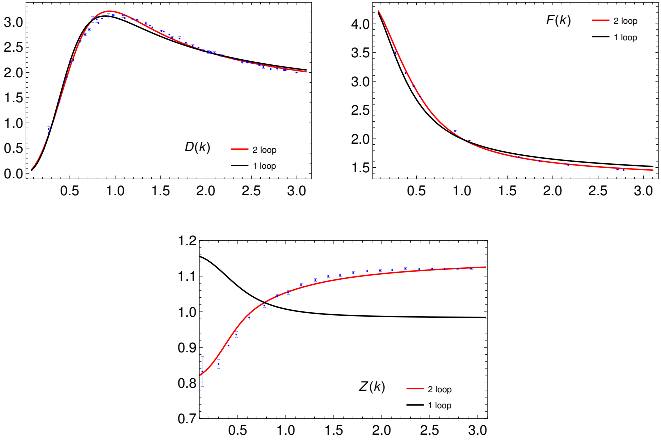
This does not mean that the CF model should be abandoned, however, since:

– quantities that are little sensitive to chiral symmetry breaking could still be correctly accounted by the perturbative CF model;

– quantities that are governed by chiral symmetry breaking could still be accounted by the CF model beyond perturbation theory.

PERTURBATIVE RESULTS

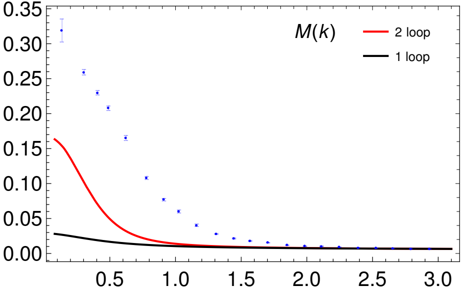
The perturbative CF model is still quite good at describing quantities that are not directly impacted by chiral symmetry breaking:



[N. Barrios, J. A. Gracey, M. Peláez, U. Reinosa, Phys. Rev. D104 (2021)]

THE QUARK MASS FUNCTION

On the other hand, the perturbative CF model performs poorly on the quark mass function (as expected):



[N. Barrios, J. A. Gracey, M. Peláez, U. Reinosa, Phys. Rev. D104 (2021)]

Need to go beyond perturbation theory. But then, what is difference with the standard continuum non-perturbative approaches?

CONTROLLED NON-PERTURBATIVE SET-UP

The problem with the non-perturbative approaches based on FP is that the truncations are ad-hoc, with little control over the error.

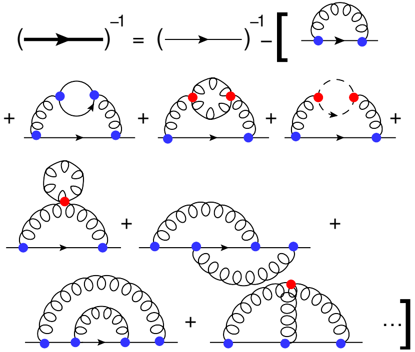
One can try invoking an expansion in $1/N_c$ but the calculations are prohibitively difficult.

Within the CF model, however, one can invoke a second small expansion parameter $\lambda^{\mathrm{glue}} < 0.3$.

The combination of both expansions in $1/N_c$ and λ^{glue} seems to be the winning horse.

CONTROLLED NON-PERTURBATIVE SET-UP

Example of the quark propagator:



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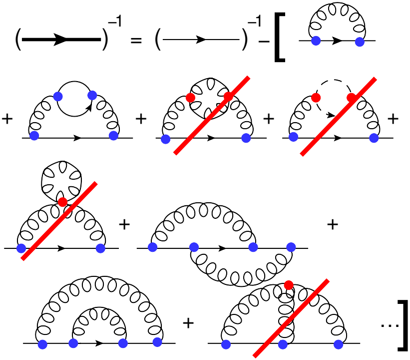

$\boxed{\text{suppressed by } \lambda^{\text{glue}}}$

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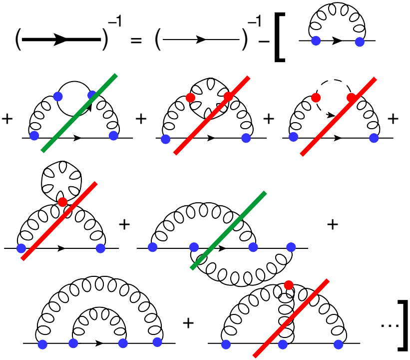
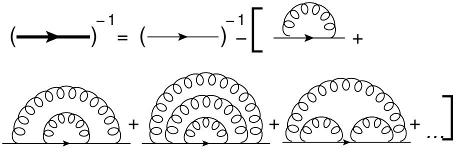


suppressed by λ^{glue}

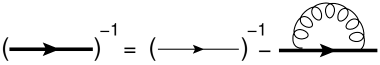
suppressed by $1/N_c$

RAINBOW EQUATION

At leading-order, the double expansion in λ^{glue} and $1/N_c$ leads to the family of diagrams



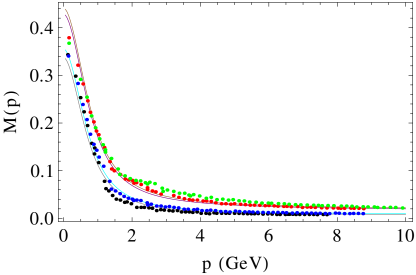
which can be resummed into

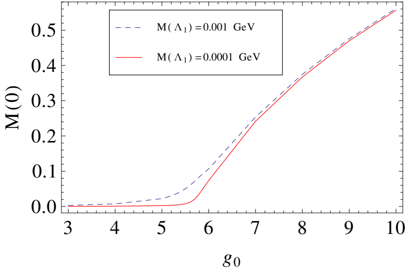


This is nothing but the well known Rainbow equation derived not from ad-hoc approximations but from a systematic expansion controlled by two small parameters.

BACK TO THE QUARK MASS FUNCTION

Good account of chiral symmetry breaking:

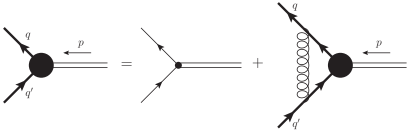




[M. Peláez, U. Reinosa, J. Serreau, M. Tissier, N. Wschebor, Phys. Rev. D96 (2017)]

THE PION DECAY CONSTANT

Other vertex functions sensible to chiral symmetry breaking can be computed in a similar way. At LO the quark-antiquark-pion vertex is given by the well known Rainbow-Ladder equation:



As a first application, we were able to predict a value for the pion decay constant in the chiral limit in agreement with the expected value of 86 MeV.

[M. Peláez, U. Reinosa, J. Serreau, N. Wschebor, Phys. Rev. D107 (2023)]

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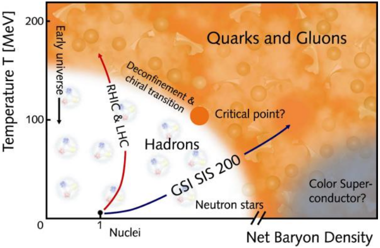
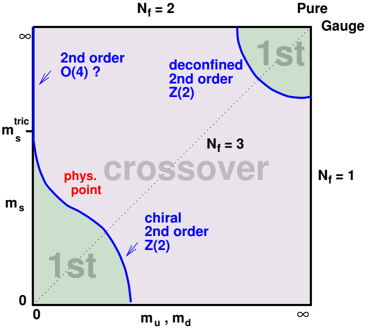
QCD PHASE STRUCTURE

What are the predictions of the CF model regarding the confinement/deconfinement transition and chiral symmetry breaking?

[U. Reinosa, Lecture Notes in Physics (2023)]



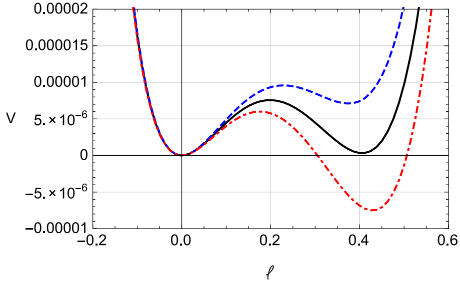


Order parameters:

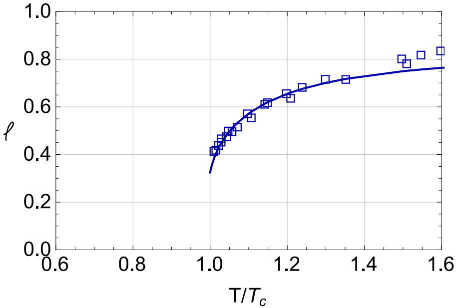
$$\ell \equiv \frac{1}{N_c}\left\langle \mathrm{tr}\, P \exp\left\{ig\int_0^\beta d\tau\, A_0\right\}\right\rangle \quad \text{and} \quad \sigma \equiv \langle\bar{\psi}\psi\rangle$$

PURE GLUE RESULTS

We have computed the Polyakov loop potential at one-loop order of the perturbative CF expansion. It does already a pretty good job in reproducing known features of the YM phase structure:



$T_c^{CF} \sim 268\,\mathrm{MeV}$
(vs $270\,\mathrm{MeV}$ on the lattice)

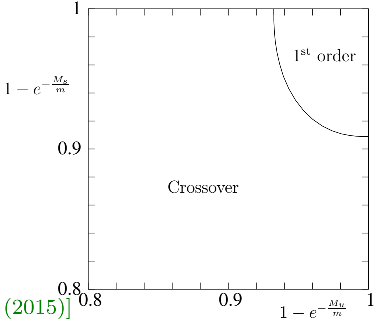


[D. M. van Egmond, U. Reinosa, J. Serreau, M. Tissier, SciPost Phys. 12 (2022).]

HEAVY QUARK QCD

It does also a pretty good job in retrieving the phase structure in the heavy quark sector:

M_c/T_c	$N_f = 1$	$N_f = 2$	$N_f = 3$
Lattice	7.23	7.92	8.33
CF	6.74	7.59	8.07
Matrix	8.04	8.85	9.33
DSE	1.42	1.83	2.04



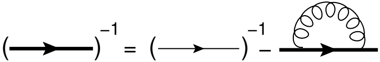
[U. Reinosa, J. Serreau, M. Tissier, Phys. Rev. D92 (2015)]

Two-loop corrections improve the results further.

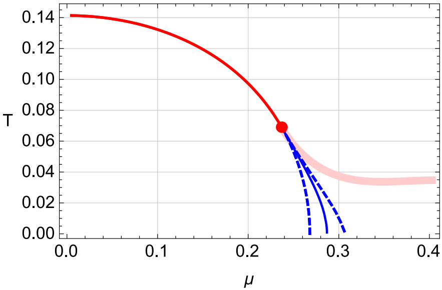
[J. Maelger, U. Reinosa, J. Serreau, Phys. Rev. D97 (2018)]

QCD WITH LIGHT QUARKS

The light quark sector calls again for the use of the Rainbow equation at finite temperature/density:



A preliminary (qualitative) study leads to the presence of a CEP in the phase diagram:



[J. Maelger, U. Reinosa, J. Serreau, Phys. Rev. D101 (2020)]

CONCLUSIONS

- Over the past 20 years, lattice simulations of Landau-gauge correlation functions have revealed unexpected aspects of the dynamics of quarks and gluons in the infrared.

- This allows one to contemplate a new path into QCD that treats the pure glue interactions perturbatively, while dealing with the remaining interactions via a well tested $1/N_c$-expansion.

- These ideas cannot be put in practice via the standard perturbative set-up since the latter relies on the FP Landau gauge-fixed action, valid only in the ultraviolet.

CONCLUSIONS

– Lattice results for the gluon propagator suggest to model the unknown part of the Landau gauge-fixed action in the infrared via the Curci-Ferrari model.

– Within this model, the new strategy appears to be well under control and allows one to reproduce a number of lattice QCD results (correlators, phase structure, . . .).

– These results point to the idea that a better understanding of the gauge fixing in the infrared could open new pathways into infrared QCD.

THANK YOU!

BACKUP

A FREQUENT CONFUSION

The Curci-Ferrari model is often confused with massive Yang-Mills a.k.a. Proca theory which amounts to adding a mass term prior to fixing any gauge:

$$S_{Proca} \equiv S_{YM} + \int_x \frac{m^2}{2} A_\mu^a A_\mu^a \quad \text{vs} \quad S_{CF} \equiv S_{FP} + \int_x \frac{m^2}{2} A_\mu^a A_\mu^a$$

Quite different models actually:

- S_{Proca} is non-renormalizable while S_{CF} is renormalizable;
- S_{Proca} breaks gauge invariance while in S_{CF} it is already explicitly broken by the gauge fixing provided by S_{FP};
- S_{Proca} is an explicit modification of a fundamental theory S_{YM}, while S_{CF} aims at modelling the incomplete gauge fixing S_{FP}.