Infrared-suppressed gluon propagator in 4d Yang-Mills theory in a Landau-like gauge

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Abstract

The infrared behavior of the gluon propagator is directly related to confinement in QCD. Indeed, the Gribov-Zwanziger scenario of confinement predicts an infrared vanishing (transverse) gluon propagator in Landau-like gauges, implying violation of reflection positivity and gluon confinement. Finite-volume effects make it very difficult to observe (in the minimal Landau gauge) an infrared suppressed gluon propagator in lattice simulations of the four-dimensional case. Here we report results for the $SU(2)$ gluon propagator in a gauge that interpolates between the minimal Landau gauge (for gauge parameter $\lambda$ equal to 1) and the minimal Coulomb gauge (corresponding to $\lambda = 0$). For small values of $\lambda$ we find that the spatially-transverse gluon propagator $D_{tr}(0,|\vec{p}|)$, considered as a function of the spatial momenta $|\vec{p}|$, is clearly infrared suppressed. This result is in agreement with the Gribov-Zwanziger scenario and with previous numerical results in the minimal Coulomb gauge. We also discuss the nature of the limit $\lambda \to 0$ (complete Coulomb gauge) and its relation to the standard Coulomb gauge ($\lambda = 0$). Our findings are corroborated by similar results in the three-dimensional case, where the infrared suppression is observed for all considered values of $\lambda$.

Key words: Yang-Mills theory, Gluon propagator, Confinement, Interpolating gauge

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1 Introduction

The infrared behavior of the gluon propagator is linked to the confinement of gluons.\cite{1} In particular, the confinement scenario of Gribov and Zwanziger\cite{2,3,4,5,6,7,8} predicts a (transverse) gluon propagator vanishing at zero (Euclidean) momentum in Landau gauge and in Landau-like gauges (or \( \lambda \)-gauges). The latter class refers to gauges interpolating between the Landau and the Coulomb gauge\cite{9}, with a gauge condition (in \( d \) dimensions) given by

\[
\lambda \partial_0 A_0^a + \partial_1 A_1^a + \ldots + \partial_{d-1} A_{d-1}^a = 0, \tag{1}
\]

where the gauge parameter \( \lambda \) is between 1 and 0. Let us recall that an infrared (IR) null gluon propagator has far-reaching consequences. Indeed, such a particle cannot have a positive semi-definite spectral function\cite{10,11,12,13} or, as a consequence, a Källen-Lehmann representation. This is regarded as one possible manifestation of confinement,\cite{1,14,15} when considering Euclidean correlation functions\cite{1}.

The question of whether the Landau-gauge gluon propagator is indeed null at zero momentum is a long-standing one. Various continuum methods, based on functional approaches, yield a vanishing gluon propagator.\cite{1,6,7,8,16,17,18,19,20,21,22,23,24,25} This result is rather tightly constrained,\cite{25} i.e. it seems to be the only possible solution satisfying both Dyson-Schwinger equations and functional renormalization-group equations. At the same time, lattice calculations in four dimensions have obtained an IR-suppressed Landau-gauge gluon propagator \( D(p) \) only when using strongly-asymmetric lattices\cite{26} or a coupling constant in the strong-coupling regime.\cite{27} For lattice couplings in the scaling region and using symmetric lattices, one finds for the Landau-gauge gluon propagator an increase slower than \( 1/p^2 \) as one approaches the IR region\cite{28,29,30,31}, with a finite value for \( p = 0 \).\cite{32,33,34,35} The fact that a propagator decreasing at small momenta is not observed in the 4d case, even for volumes of almost \((10 \text{ fm})^4\),\cite{35} is probably due to very strong finite-size effects.\cite{32,33,34,35,36,37,38,39} This assumption is supported by numerical results in the 3d case, where much larger lattice sides are accessible. In this case, there is substantial evidence for an IR-suppressed gluon propagator in Landau gauge,\cite{40,41,42} in agreement with continuum calculations.\cite{6,43} However, also in this case, a reliable extrapolation of \( D(0) \) to the infinite-volume limit is still lacking.\cite{42} Finally, let us recall that lattice Landau calculations\cite{44,45,36,37} have also obtained direct evidence for the non-positivity of the gluon spectral function, both in the three- and in the four-dimensional cases.

The Gribov-Zwanziger confinement scenario applies also to Coulomb gauge.\cite{2,3,4,46,47,48,49,50} In this case it is important to observe that the standard Coulomb-gauge-fixing

\footnote{Thus, it is a sufficient condition for gluon confinement.\cite{1,15}}
condition $\partial_1 A_1^a + \ldots + \partial_{d-1} A_{d-1}^a = 0$ is not a complete one, due to the residual gauge degrees of freedom $g(t)$. On the other hand, a possible complete Coulomb gauge condition\[9\] can be obtained using the class of gauges defined in (1). Indeed, the parameter $\lambda$ interpolates between the Landau ($\lambda = 1$) and a complete Coulomb gauge, corresponding to the limit $\lambda \to 0$. Therefore, the complete Coulomb gauge condition is, by definition, a smooth limiting case of the interpolating gauge (1) while, of course, this is not the case for the standard Coulomb condition ($\lambda = 0$). Let us recall that the gauge condition (1) above can be obtained by minimizing the (lattice) functional\[3\]

$$E[g] = -\text{Tr} \sum_x \left[ \lambda U_0(x) + \sum_{i=1}^{d-1} U_i(x) \right], \quad (2)$$

where $U_\mu(x)$ indicates a lattice link variable in the $\mu$ direction. Then, the limiting case $\lambda \to 0$ corresponds to minimizing the following two functionals\[51\]

$$E_{\text{hor}}[g(\vec{x})] = -\text{Tr} \sum_x \sum_{i=1}^{d-1} U_i(x)$$

$$E_{\text{ver}}[g(t)] = -\text{Tr} \sum_x U_0(x). \quad (3)$$

The minimization of the first functional is equivalent to a Landau gauge condition fixed on each time slice, using $g(\vec{x})$ gauge transformations, i.e. it corresponds to the standard (incomplete) Coulomb gauge. The minimization of the second functional, considering only $g(t)$ gauge transformations, provides additional constraints, necessary to eliminate the residual gauge degrees of freedom. Note that we can also write $E_{\text{ver}}[g(t)] = -\text{Tr} \sum_t Q_0(t)$, with $Q_0(t) = \sum_{\vec{x}} U_0(t, \vec{x})$. Then, the minimization of $E_{\text{ver}}[g(t)]$ is like a one-dimensional Landau gauge fixing. Of course, quantities defined in terms of spatial link variables $U_i(x)$ are not affected by the residual gauge condition obtained by minimizing the functional $E_{\text{ver}}[g(t)]$.

Numerical studies in minimal Coulomb gauge have shown \[for the SU(2) case in 4d\] that the instantaneous transverse gluon propagator $D^{tr}(\vec{p})$ is indeed suppressed in the IR limit.\[51,52,53,54,55\] Also, in the infinite-volume limit, it has been found\[51,52,53\] that $D^{tr}(\vec{p})$ is well described by a Gribov-like propagator with a pair of purely imaginary poles $m^2 = \pm iy$. These results are in agreement with the Gribov-Zwanziger confinement scenario.\[2,3,4,46,47,48\] The fact that, for a given lattice size $L$ (in fm), one sees an IR-suppressed transverse gluon propagator in 4d-Coulomb gauge and in 3d-Landau gauge but not in 4d-Landau gauge may be related to a quantitatively different IR

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\[2\] Clearly, since the gauge fixing (1) is complete for any $\lambda \neq 0$, it is also a complete one when considering the limit $\lambda \to 0$.\[9\]

\[3\] A similar functional can be defined in the continuum.
suppression in the two cases. Indeed, functional methods\cite{6,43,56,57,58,59} predict a stronger suppression in 4d-Coulomb gauge and in 3d-Landau gauge than in 4d-Landau gauge, i.e. the so-called IR gluon exponent $\alpha_D$ should be larger for the 4d-Coulomb and the 3d-Landau cases.

One should note that, for any non-zero value of $\lambda$, the gauge condition (1) is essentially a \textit{deformed} Landau gauge, i.e. the IR exponents of the propagators do not depend on $\lambda$\cite{60}. In particular, calculations using Dyson-Schwinger equations suggest\cite{60} that, at momenta sufficiently small compared to a separation momentum $p_s$, the transverse gluon propagator behaves as in Landau gauge, i.e. all Lorentz and color components of the gluon propagator vanish at zero four-momentum. However, the limit $\lambda \to 0$ can also be thought of as sending to zero the momentum $p_s$, which separates Coulomb-gauge-like from Landau-gauge-like behavior. Indeed, for any finite value $\lambda \neq 0$ and given the Landau gauge condition $\partial_\mu A_\mu^a = 0$, we can obtain the gauge condition

$$\partial_0 A_0^a + \lambda^{-1} \left[ \partial_1 A_1^a + \ldots + \partial_{d-1} A_{d-1}^a \right] = 0 \tag{5}$$

by using the rescaling\footnote{In Ref. \cite{60}, a similar rescaling was used to show that Dyson-Schwinger equations for $\lambda$-gauges are equivalent to the Landau case for all $\lambda \neq 0$.} $x_i \to x_i/\lambda$ for $i \neq 0$. This implies, in momentum space, the rescaling $p_i \to \lambda p_i$. Thus, if we consider only spatial momenta, we find\footnote{Of course, this simple explanation is correct only at tree-level and can be modified by the renormalization of $\lambda$.} that $p_s$ is rescaled to $\lambda p_s$ and goes to zero when $\lambda \to 0$. As a consequence, one should expect that, for very small values of $\lambda$, all correlation functions would show a Coulomb-like behavior for momenta $p > p_s$, with $p_s$ very small. In particular, the correlation function that corresponds to the transverse (instantaneous) gluon propagator in Coulomb gauge should become more and more IR suppressed as the parameter $\lambda$ approaches zero. Investigating whether this is the case is the aim of this work.

2 Numerical results

Following Eqs. (8) and (9) of Ref. \cite{60}, we can consider on the lattice the three-dimensionally transverse gluonic correlation function

$$D^{tr}(p_0, |\vec{p}|) = \left( \delta_{ij} - \frac{p_i p_j}{\vec{p}^2} \right) \frac{A_i^a(p) A_j^a(-p)}{(N_c^2 - 1)(d - 2)V}. \tag{6}$$

At zero four-momentum one has

$$D^{tr}(0) = \delta_{ij} \frac{A_i^a(0) A_j^a(0)}{(N_c^2 - 1)(d - 1)V}. \tag{7}$$
Here, $N_c$ is the number of colors, $V$ is the $d$-dimensional lattice volume, Lorentz indices $i, j$ are summed only over the $d - 1$ spatial directions and $A_a^i(p)$ is the $d$-dimensional Fourier transform of the gluon field. Let us recall that, by considering only spatial momenta (i.e. $p_0 = 0$), the function $D^{\mu\nu}(0, |\vec{p}|)$ is predicted to be IR suppressed — and vanishing at zero momentum — for all non-zero values of $\lambda$ in three and in four dimensions.\[60] Also, when $\lambda$ is null, the above definition yields the instantaneous part of the three-dimensional transverse gluon propagator\[51]

$$D^{\text{inst}}(|\vec{p}|) = \sum_t \left( \delta_{ij} - \frac{p_i p_j}{\vec{p}^2} \right) \frac{< A_a^i(t, \vec{p}) A_a^j(t, -\vec{p}) >}{(N_c^2 - 1)(d - 2)V},$$

where now the Fourier transform of the gluon field is evaluated for each time slice. Indeed, when $\lambda$ is null, the gauge transformations $g(t)$ are independent of the gauge transformation $g(\vec{x})$ and the two sets of transformations commute. Then, the terms in Eqs. (6) that depend explicitly on $g(t)$ are averaged to zero and one is left with the expression above. Note that this explanation is valid whether the residual gauge freedom $g(t)$ is fixed or not.

Here we evaluate numerically $D^{\mu\nu}(0, |\vec{p}|)$ as a function of $|\vec{p}|$ for $SU(2)$ Yang-Mills theory in three and in four dimensions for several values of the parameter $\lambda$. Details of the simulations can be found in.\[42,61] Let us note that for $\lambda \neq 1$ the numerical gauge fixing is very similar to the usual Landau gauge fixing.\[41] On the other hand, when $\lambda$ goes to zero one sees\[62] that more iterations are needed in order to satisfy a given numerical accuracy for the gauge fixing, in agreement with a recent analytic study.\[63] This problem can be partially reduced by adding some extra gauge fixing sweeps in the $\mu = 0$ direction for each iteration of the gauge-fixing algorithm, i.e. by considering gauge transformations $g(t)$ that depend only on the $\mu = 0$ component of $x$.

Finally, we did not consider here possible systematic effects related to the breaking of rotational symmetry or to the existence of Gribov copies. The former type of effects can be parameterized by\[64] $a^2 p_4$, where $a$ is the lattice spacing and $p_4 = \sum_\mu p_\mu^4$. Therefore, this type of effects are not expected to play a significant role in the IR region, considered here. As for the latter type of effects, in the infinite-volume limit, averages taken over configurations belonging to the so-called Gribov region $\Omega$ should coincide\[8] with averages obtained by restricting the functional integral to the so-called fundamental modular region $\Gamma$, whose interior is free of Gribov copies.

Our results\[6] are reported in Figure 1. In three dimensions, a well-defined maximum (and thus an IR suppression) is visible for all values of $\lambda$. This includes also Landau gauge ($\lambda = 1$), confirming earlier results.\[40,41,42] As can be seen from the plot, the maximum value attained by the propagator seems to move to larger momenta with decreasing $\lambda$, going from about 400

\[6] Preliminary results have been presented in Ref. [65,66].
Fig. 1. The gluonic correlation function $D^\text{tr}(0, |\vec{p}|)$ in three (top figure) and four (bottom figure) dimensions. The spatial momenta $|\vec{p}|$ are chosen along a single axis. Circles indicate data for $\lambda = 1$ (Landau gauge), crosses are used for $\lambda = 1/2$, squares for $\lambda = 1/10$, triangles for $\lambda = 1/20$, stars for $\lambda = 1/100$ and upside-down triangles represent results at $\lambda = 0$ (Coulomb gauge). Data have been obtained at $\beta = 4.2$ in three dimensions and at $\beta = 2.2$ in four dimensions. The lattice size is $40^3 \approx (6.9 \text{ fm})^3$ in three dimensions and $22^4 \approx (4.6 \text{ fm})^4$ in four dimensions. In addition, in the bottom panel, diamonds correspond to a $40^4 \approx (8.4 \text{ fm})^4$ lattice at $\lambda = 1/100$. The physical scale has been set using Refs. [42,67]. Note that our error bars are smaller than the sizes of the symbols. Also, for $\lambda = 0$, we consider the standard (incomplete) Coulomb gauge.
MeV in the Landau case[42] to about 600 MeV for the Coulomb case. At the same time, as \( \lambda \) decreases, the maximum becomes more visible. In four dimensions, on the other hand, no discernible peak is visible in Landau gauge when considering the volume \( V = 22^4 \). Decreasing \( \lambda \), however, leads to a suppression of the propagator in the IR region. In particular, at the smallest value of \( \lambda \) considered, i.e. \( \lambda = 1/100 \) and for a lattice volume \( V = 40^4 \), a maximum is seen also in four dimensions. This maximum is as visible as the one in three dimensions in Landau gauge. Thus for small \( \lambda \), just as for Coulomb gauge,[51] one sees a maximum of the transverse gluon propagator already for
relatively small volumes.

A similar $\lambda$-dependence is also seen in the tensor component $D_{00}(0,|\vec{p}|)$. In particular, as $\lambda$ becomes small, this tensor component of the gluon propagator becomes enhanced for small (nonzero) values of $|\vec{p}|$ (see Fig. 2). Let us recall that, in Coulomb gauge, the $D_{00}$ component is IR divergent already at the perturbative level. Moreover, the instantaneous part of $D_{00}$ is related to the color Coulomb potential and should be diverging as $1/|\vec{p}|^4$ at small momenta.[46,47,48,51,52,53,54,55] Thus, from the discussion presented in the Introduction, one could expect to observe a $D_{00}$ component enhanced at intermediate momenta $p > p_s$ but still suppressed at small momenta. This is indeed the case and from the plots in Fig. 2 one clearly sees how this enhancement is developing for $|\vec{p}| \neq 0$ as the value of $\lambda$ decreases. Let us stress that the discontinuity in the behavior of the propagator at $|\vec{p}| \neq 0$ is observed since we are taking the limit $\lambda \to 0$. A similar discontinuity is also obtained when implementing the complete Coulomb gauge described in the Introduction. On the other hand, for the incomplete Coulomb gauge, $D_{00}$ is clearly a continuous function of $|\vec{p}|$ (see Fig. 2).

As said in the Introduction, the IR exponent $\alpha_D$ for the transverse correlator is predicted to show a discontinuity in the limit $\lambda \to 0$. This is not seen from our data. However, a reliable check of this prediction can only be obtained if one has control over the infinite-volume and the continuum limits, which we have not yet achieved. On the other hand, taking the limit $\lambda \to 0$ clearly induces a discontinuity in the behavior of the temporal component $D_{00}$.[60]

### 3 Conclusions

We have presented the first direct observation of an IR-suppressed gluonic correlation function on a symmetric 4d lattice in a Landau-like gauge, with gauge parameter $\lambda$ as in Eq. (1). (Landau gauge is obtained for $\lambda = 1$, while Coulomb gauge corresponds to $\lambda = 0$.) The suppression is seen for sufficiently small $\lambda$ when considering moderately small lattice volumes. Judging from the results shown for the 3d case, it is conceivable that a similar suppression might be observed for any $\lambda$ if a large enough lattice side is considered. Furthermore, since the limit $\lambda \to 1$ is smooth,[9,60] we expect to see an IR suppression for sufficiently large lattices also in Landau gauge. Moreover, we have obtained that the $D_{00}$ component of the gluon propagator gets enhanced in the IR region (for $|\vec{p}| \neq 0$) at small values of the interpolating parameter $\lambda$. These results clearly demonstrate the transformation of the correlation functions from Landau gauge towards Coulomb gauge when considering the limit $\lambda \to 0$. They

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This is a consequence of the minimization of $\mathcal{E}_{\text{ver}}[g(t)]$, defined in Eq. (4).
also provide additional support to the Gribov-Zwanziger scenario of confinement, establishing an IR suppression of gluonic correlation functions in four dimensions beyond Coulomb gauge. The use of the interpolating gauge thus constitutes a promising alternative to studies in Landau gauge, since finite-size effects are significantly smaller, allowing a more efficient investigation of the gauge dependence of correlation functions of confined objects.

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