Accessing the topological susceptibility via the Gribov horizon

Caroline Felix

caroline.felix@kuleuven.be

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Kopaonik-Serbia

Outline

The $U_A(1)$ problem is well known, one solution for this was was offered by 't Hooft by means of instanton calculus, but another way to understand the anomalous η' mass was, independently, worked out by Veneziano and Witten,

The $U_A(1)$ problem is well known, one solution for this was was offered by 't Hooft by means of instanton calculus, but another way to understand the anomalous η' mass was, independently, worked out by Veneziano and Witten,

$$m_{\eta'}^2 = \frac{4N_f}{f_\pi^2} \chi_{\theta=0, N_f=0}^4 = \mathcal{O}(1/N) \tag{1}$$

where θ is the vacuum angle, f_π the pion decay constant and χ is the topological susceptibility.

The relation (1) thus explains the relatively large η' mass, given that $\chi_{\theta=0, N_f=0}^4 \equiv \chi^4$ is sufficiently large. Filling in the numbers requires $\chi^4 \sim (200 \text{ MeV})^4$, not far from the lattice $SU(3)$ estimates.

In a recent paper[1], an explicit relationship between the Veneziano ghost and color confinement was proposed, via the dynamics of this Veneziano ghost (so topological susceptibility) and Gribov copies. However, this analysis is incompatible with BRST symmetry.

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[1]D. E. Kharzeev and E. M.Levin, Phys. Rev. Lett. **114** (2015) 242001.

The better attempt is to investigate the topological susceptibility, χ^4, in $SU(3)$ and $SU(2)$ Euclidean Yang-Mills theory using an appropriate Padé approximation tool and a non-perturbative gluon propagator, within a BRST invariant framework and by taking into account Gribov copies in a general linear covariant gauge.
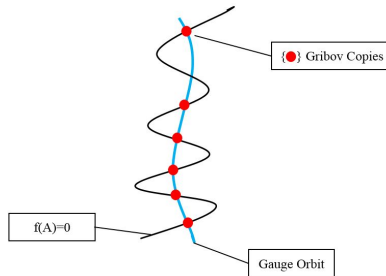
Why does Kharzeev and Levin's procedure break the BRST symmetry?

Before to answer this question, it is good to refresh our memory about the Gribov copies, BRST symmetry and topological susceptibility....

Gribov problem

▶ Gribov[2] showed that the Faddeev-Popov construction is not valid at the non-perturbative level.

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[2]V. N. Gribov, Nucl. Phys. B **139** (1978) 1.

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- ▶ we are overcounting equivalent gauge configurations, since we have more than one configuration for each gauge orbit,
- ▶ the Faddeev-Popov measure is ill-defined, since there are zero-modes of the Faddeev-Popov operator when considering the infinitesimal copies (*det M = 0*).

Gribov region

The main idea of the Gribov method is to restrict the functional integral to a certain region Ω in field space, called the Gribov region, which is defined as

$$\Omega = \{A_\mu^a; \ \partial_\mu A_\mu^a = 0, \quad \mathcal{M}^{ab}(A) = -\partial_\mu D_\mu^{ab}(A) > 0\}. \tag{2}$$

[3]G. Dell'Antonio and D. Zwanziger, Nucl. Phys. B **326** (1989) 333.

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- ▶ Landau gauge, $\partial_\mu A_\mu^a = 0$,
- ▶ Hermitian Faddeev-Popov operator,

$$\mathcal{M}^{ab}(A) = -\delta^{ab}\partial^2 + gf^{abc}(A)_\mu^c \partial_\mu, \tag{3}$$

  is positive. Inside the Gribov region, there are no infinitesimal copies, since $\mathcal{M}^{ab}(A) > 0$;
- ▶ it is convex, bounded and intersected by each gauge orbit[3]
- ▶ Its boundary, $\partial\Omega$, is called the first Gribov horizon and there, the first null eigenvalue of $\mathcal{M}^{ab}(A)$ (i.e. the first zero-mode of Faddeev-Popov operator) appears.

[3]G. Dell'Antonio and D. Zwanziger, Nucl. Phys. B **326** (1989) 333.

Ω + the formation of the dimension two condensates, $\langle A_\mu^a A_\mu^a \rangle$ and $\langle \bar{\varphi}_\mu^{ab} \varphi_\mu^{ab} - \bar{\omega}_\mu^{ab} \omega_\mu^{ab} \rangle$ + extension to the linear covariant gauges, our action is given by

$$S = S_{YM} + S_{FP} + S_{RGZ} + S_\tau, \qquad (4)$$

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whereby

$$S_\tau = \int d^4x \, \tau^a \, \partial_\mu (A^h)_\mu^a \tag{5}$$

implements, through the Lagrange multiplier τ, the transversality of the composite operator $(A^h)_\mu^a$, $\partial_\mu (A^h)_\mu^a = 0$; S_{YM} is the Yang-Mills action,

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$$S_{YM} = \frac{1}{4} \int d^4x F_{\mu\nu}^a F_{\mu\nu}^a, \tag{6}$$

S_{FP} is the Faddeev-Popov action,

$$S_{FP} = \int d^4x \left(\frac{\alpha}{2} b^a b^a + i b^a \, \partial_\mu A_\mu^a + \bar{c}^a \partial_\mu D_\mu^{ab}(A) c^b \right), \tag{7}$$

The RGZ action is [4] [5] [6]

[4] D. Dudal, S. P. Sorella, N. Vandersickel and H. Verschelde, Phys. Rev. D **77** (2008) 071501.

[5] D. Dudal, J. A. Gracey, S. P. Sorella, N. Vandersickel and H. Verschelde, Phys. Rev. D **78** (2008) 065047.

[6] D. Dudal, S. P. Sorella and N. Vandersickel, Phys. Rev. D **84** (2011) 065039.

Refined Gribov-Zwanziger (RGZ) action

The RGZ action is [4] [5] [6]

$$S_{RGZ} = \int d^4x \left[\bar{\varphi}^{ac}_\mu \partial_\nu D^{ab}_\nu \varphi^{bc}_\mu - \bar{\omega}^{ac}_\mu \partial_\nu (D^{ab}_\nu \omega^{bc}_\mu) - g(\partial_\nu \bar{\omega}^{an}_\mu) f^{abc} D^{bm}_\nu c^m \varphi^{cn}_\mu \right]$$

$$- \gamma^2 g \int d^4x \left[f^{abc} (A^h)^a_\mu \varphi^{bc}_\mu + f^{abc} (A^h)^a_\mu \bar{\varphi}^{bc}_\mu + \frac{d}{g}(N_c^2 - 1)\gamma^2 \right]$$

$$+ \frac{m^2}{2} \int d^4x (A^h)^a_\mu (A^h)^a_\mu + M^2 \int d^4x (\bar{\varphi}^{ab}_\mu \varphi^{ab}_\mu - \bar{\omega}^{ab}_\mu \omega^{ab}_\mu). \tag{8}$$

[4] D. Dudal, S. P. Sorella, N.Vandersickel and H. Verschelde, Phys. Rev. D **77** (2008) 071501.

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So what is A_μ^h in S_{RGZ} and $S_\tau = \int d^4x \, \tau^a \, \partial_\mu (A^h)_\mu^a$?

The local gauge invariance of A_μ^h

The configuration A_μ^h is a non-local power series in the gauge field, obtained by minimizing the functional $f_A[u]$ along the gauge orbit of A_μ [7] [8] [9] , with

$$
\begin{aligned}
f_A[u] &\equiv \min_{\{u\}} \mathrm{Tr} \int d^4x\, A_\mu^u A_\mu^u, \\
A_\mu^u &= u^\dagger A_\mu u + \frac{i}{g} u^\dagger \partial_\mu u.
\end{aligned}
\tag{9}
$$

One finds that a local minimum is given by

$$
\begin{aligned}
A_\mu^h &= \left(\delta_{\mu\nu} - \frac{\partial_\mu \partial_\nu}{\partial^2} \right) \phi_\nu , \qquad \partial_\mu A_\mu^h = 0 , \\
\phi_\nu &= A_\nu - ig \left[\frac{1}{\partial^2} \partial A, A_\nu \right] + \frac{ig}{2} \left[\frac{1}{\partial^2} \partial A, \partial_\nu \frac{1}{\partial^2} \partial A \right] + O(A^3).
\end{aligned}
\tag{10}
$$

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[7] G. Dell'Antonio and D. Zwanziger, Nucl. Phys. B **326** (1989) 333.

[8] P. van Baal, Nucl. Phys. B **369** (1992) 259.

[9] M. Lavelle and D. McMullan, Phys. Rept. **279** (1997) 1.

The local gauge invariance of A_μ^h

To get a local theory, we introduce of an auxiliary localizing Stueckelberg field ξ^a, whose role is to give, for each gauge field A_μ, its corresponding configuration that minimizes the functional A^2, i.e., A_μ^h. This is most naturally implemented by defining a field h which effectively acts on A_μ as a gauge transformation would act, in order to provide the minimizing configuration A^h, that is

$$A_\mu^h = (A^h)_\mu^a T^a = h^\dagger A_\mu h + \frac{i}{g} h^\dagger \partial_\mu h, \tag{11}$$

while

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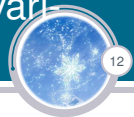
while

$$h = e^{ig\,\xi^a T^a}. \tag{12}$$

The local gauge invariance of A_μ^h under a gauge transformation $v \in SU(N)$ with

$$h \to v^\dagger h, \quad h^\dagger \to h^\dagger v, \quad A_\mu \to v^\dagger A_\mu v + \frac{i}{g} v^\dagger \partial_\mu v. \tag{13}$$

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BRST symmetry is very important to quantize a gauge theory and to construct a covariant canonical formulation.

The action $S = S_{YM} + S_{FP} + S_{RGZ} + S_\tau$ enjoys an exact nilpotent BRST invariance, $sS = 0$, if we define the following BRST transformation rules to all fields,

$$
\begin{aligned}
sA_\mu^a &= -D_\mu^{ab} c^b, \quad sc^a = \frac{g}{2} f^{abc} c^b c^c, \\
s\bar{c}^a &= ib^a, \quad sb^a = 0. \\
sh^{ij} &= -igc^a (T^a)^{ik} h^{kj} \\
s\varphi_\mu^{ab} &= 0, \quad s\omega_\mu^{ab} = 0, \\
s\bar{\omega}_\mu^{ab} &= 0, \quad s\bar{\varphi}_\mu^{ab} = 0, \\
s\tau^a &= 0.
\end{aligned}
\tag{14}
$$

Gluon propagator

The general form of the gluon propagator, based on the BRST invariance, is given by

$$D_{\mu\nu}(p) = D(p)P_{\mu\nu}(p) + L(p)\frac{p_\mu p_\nu}{p^2}, \tag{15}$$

with the transverse form factor $D(p)$ (at tree level, this factor stems from the quadratic part of the action $S = S_{YM} + S_{FP} + S_{RGZ} + S_\tau$),

$$D(p) = \frac{p^2 + M^2}{p^4 + (M^2 + m^2)p^2 + M^2 m^2 + \lambda^4}. \tag{16}$$

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containing all non-trivial information, for the longitudinal part, we have

$$L(p) = \frac{\alpha}{p^2}, \tag{17}$$

with

$$P_{\mu\nu}(p) = \delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}, \qquad L_{\mu\nu}(p) = \frac{p_\mu p_\nu}{p^2} \tag{18}$$

the transversal and longitudinal projectors.

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The **topological susceptibility** χ^4 measures fluctuations of the topological charge in the QCD vacuum and it is defined by

$$\chi^4 = -\lim_{p^2 \to 0} p_\mu p_\nu \langle K_\mu K_\nu \rangle \geq 0. \qquad (19)$$

whereby K_μ is the topological Chern-Simons current,

$$K_\mu = \frac{g^2}{16\pi^2} \epsilon_{\mu\nu\rho\sigma} A_{\nu,a} \left(\partial^\rho A^{\sigma,a} + \frac{g}{3} f^{abc} A_b^\rho A_c^\sigma \right). \qquad (20)$$

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This current is related to the topological charge density,

$$Q(x) = \partial_\mu K_\mu = \frac{g^2}{32\pi^2} F_{\mu\nu} \tilde{F}_{\mu\nu}. \qquad (21)$$

The "glost" of Kharzeev-Levin

Kharzeev and Levin interpreted the current correlator,

$$K_{\mu\nu}(p) = i \int d^4x \, e^{ipx} \langle K_\mu(x) K_\nu(0) \rangle \overset{p^2 \sim 0}{\sim} -\frac{\chi^4}{p^2} g_{\mu\nu}, \tag{22}$$

as resulting from an effective interaction between the gluon (in Feynman gauge $\alpha = 1$) and the Veneziano ghost. An effective ghost-gluon-gluon vertex $\Gamma_\mu(q,p)$ was postulated, and then they found that a dynamically corrected gluon propagator (the "glost"),

$$\mathcal{G}_{\mu\nu}(p^2) = \frac{p^2}{p^4 + \chi^4} \delta_{\mu\nu}, \tag{23}$$

solves the Dyson-Schwinger equation, when using only this coupling[10] in the deep infrared. However, if we compare (23) and (15),

$$D_{\mu\nu}(p) = D(p) P_{\mu\nu}(p) + L(p) \frac{p_\mu p_\nu}{p^2},$$

we notice that there is an inconsistency between these equations, indicating that the propagator (23) is incompatible with BRST symmetry.

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[10] D. E. Kharzeev and E. M. Levin, Phys. Rev. Lett. **114** (2015) 24, 242001. & D. Dudal and M. S. Guimaraes, Phys. Rev. D **93** (2016) no.8, 085010.

Can we obtain, by using Gribov type propagators, a reasonable "semi-non-perturbative" estimate for the topological susceptibility χ^4, without the new effective vertices?

Källén-Lehmann spectral density and χ^4

The topological susceptibility is given by

$$\chi^4 = -\lim_{p^2 \to 0} p_\mu p_\nu \langle K_\mu K_\nu \rangle .$$

We may in general set, using the Källén-Lehmann spectral density,

$$
\begin{aligned}
\langle K_\mu(p) K_\nu(-p) \rangle &= \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) \mathcal{K}_\perp(p^2) + \frac{p_\mu p_\nu}{p^2} \mathcal{K}_\parallel(p^2) \\
&\equiv \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) \int_0^\infty d\tau \frac{\rho_\perp(\tau)}{\tau + p^2} + \frac{p_\mu p_\nu}{p^2} \int_0^\infty d\tau \frac{\rho_\parallel(\tau)}{\tau + p^2}, \quad (24)
\end{aligned}
$$

based on Euclidean invariance. So,

$$-\chi^4 = \lim_{p^2 \to 0} p^2 \mathcal{K}_\parallel(p^2) = \lim_{p^2 \to 0} p^2 \int_0^\infty d\tau \frac{\rho_\parallel(\tau)}{\tau + p^2}. \qquad (25)$$

From dimensional analysis, we only need 2 subtractions ($\rho_\parallel(\tau) \sim \tau$ for $\tau \to \infty$), so a finite result is guaranteed from

$$\mathcal{K}_\parallel(p^2) = b_0 + b_1 p^2 + p^4 \int_0^\infty d\tau \frac{\rho_\parallel(\tau)}{(\tau + p^2)\tau^2}$$

and thus

$$- \chi^4 = \lim_{p^2 \to 0} p^2 \left(b_0 + b_1 p^2 + p^4 \int_0^\infty d\tau \frac{\rho_\parallel(\tau)}{(\tau + p^2)\tau^2} \right), \qquad (26)$$

with $b_{0,1}$ subtraction constants. Obviously, we can rewrite (26) as

$$- \chi^4 = \lim_{p^2 \to 0} p^6 \int_0^\infty d\tau \frac{\rho_\parallel(\tau)}{(\tau + p^2)\tau^2}. \qquad (27)$$

The RGZ gluon propagator can be rewritten as

$$D(p^2) = \frac{p^2 + M_1^2}{p^4 + M_2^2 p^2 + M_3^4}, \tag{28}$$

we obtain

$$\rho_{||}(\tau) = -2A_+ A_- \frac{g^4(N^2-1)}{2^{2d+5}\pi^{7/2}\Gamma(\frac{d-1}{2})} \frac{(\tau^2 - 4b^2 - 4a\tau)^{(d-1)/2}}{\tau^{d/2}}, \tag{29}$$

for $\tau \geq \tau_c = 2(a + \sqrt{a^2 + b^2})$, where

$$a = \frac{M_2^2}{2}, \qquad b = \frac{\sqrt{4M_3^4 - M_2^4}}{2}. \tag{30}$$

In MOM scheme:

$$D(p^2 = \mu^2) = \frac{1}{\mu^2}. \tag{31}$$

The proper renormalization factor Z is thus given by, at scale μ,

$$D(p^2) = Z \frac{p^2 + M_1^2}{p^4 + M_2^2 p^2 + M_3^4}, \qquad (32)$$

with

$$Z = \frac{1}{\mu^2} \frac{\mu^4 + M_2^2 \mu^2 + M_3^4}{\mu^2 + M_1^2}. \qquad (33)$$

The gluon propagator we will use is to be renormalized in MOM scheme at scale μ, so the g^2 becomes

$$g^2(\mu) = \frac{1}{\beta_0 \log\left(\frac{\mu^2}{\Lambda_{\text{MOM}}^2}\right)}, \qquad \beta_0 = \frac{11}{3}\frac{N}{16\pi^2}. \qquad (34)$$

We use $\Lambda_{\text{MOM}}^{N=2} \approx 628$ MeV and $\Lambda_{\text{MOM}}^{N=3} \approx 425$ MeV [11].

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[11] P. Boucaud, F. De Soto, J. P. Leroy, A. Le Yaouanc, J. Micheli, O. Pene, J. Rodriguez-Quintero, Phys. Rev. **D79** (2009) 014508.

Padé approximation

▶ The MOM strong coupling expansion parameter is effectively very small, an indication that a perturbative treatment makes sense in the considered momentum region, after which we "extrapolate" to the deep infrared using the described Padé analysis.

▶ We approximated

$$p^6 \int_0^\infty d\tau \frac{\rho_\parallel(\tau)}{(\tau + p^2)\tau^2}, \tag{35}$$

with an $[\mathcal{M} + 2, \mathcal{M}]$ Padé rational function in variable p^2, which are the ones having the same large p^2 behavior, viz. $\mathcal{O}(p^4)$.

▶ We opted to do the Padé approximation around $p^2 = \mu^2$.

▶ With this, we can study the function $\chi(\mu^2)$ using the previous ingredients and search for optimal values, in the sense of minimal dependence, on the scale μ^2.

For $N = 3$, the spectral density is

$$\rho_{||}(\tau) = -2A_+A_- \frac{g^4(\mu)Z^2}{2^9\pi^4} \frac{\left(\tau^2 - 4b^2 - 4a\tau\right)^{3/2}}{\tau^2}. \quad (36)$$

Using the lattice obtained values $M_1^2 = 4.473 \pm 0.021$ GeV^2; $M_2^2 = 0.704 \pm 0.029$ GeV^2; $M_3^4 = 0.3959 \pm 0.0054$ GeV^4 [12], we get

$$a = 0.352\,\text{GeV}^2\,, \qquad b = 0.522\,\text{GeV}^2\,, \qquad 2A_+A_- = 31.719. \quad (37)$$

[12] O. Oliveira and P. J. Silva, Phys. Rev. D **86** (2012) 114513.
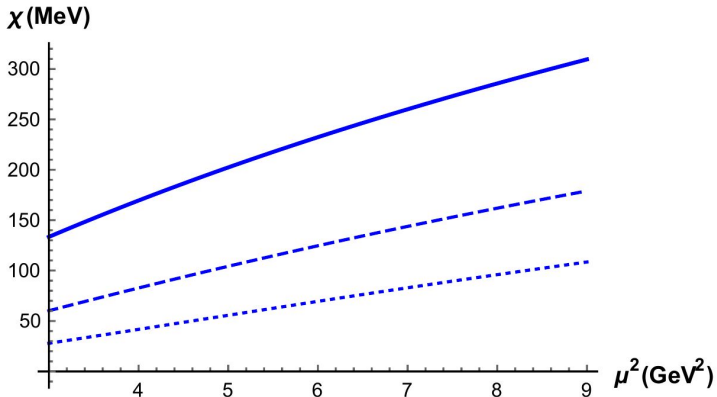
FIG. 1: The $SU(3)$ topological susceptibility χ for variable μ^2 for $\mathcal{M} = 1, 2, 3$ (full, dashed, dotted).

To get an error estimation from the uncertainty on $\vec{x} \equiv (M_1^2, M_2^2, M_3^4)$, we the followed relation:

$$\sigma_\chi(\mu^2) = \sqrt{\sum_i \left(\frac{\partial \chi}{\partial x_i}\right)^2 \sigma_{x_i}^2}. \tag{38}$$
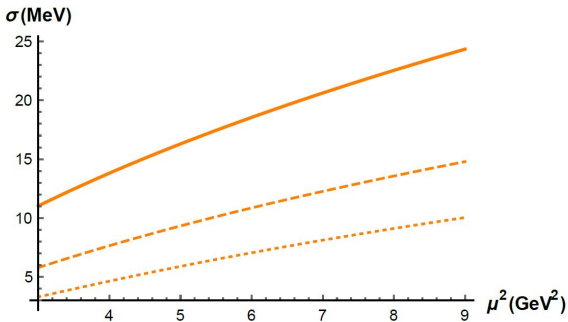
FIG. 2: Estimated error on χ for $SU(3)$ due to the uncertainty on the fitting parameters for variable μ^2 for $\mathcal{M} = 1, 2, 3$ (full, dashed, dotted).

For $N = 2$, the spectral density is

$$\rho_{||}(\tau) = -2A_+A_- \frac{3g^4(\mu)Z^2(\mu)}{2^{12}\pi^4} \frac{\left(\tau^2 - 4b^2 - 4a\tau\right)^{3/2}}{\tau^2}. \tag{39}$$

Here, we used $M_1^2 = 2.508 \pm 0.078$ GeV^2; $M_2^2 = 0.590 \pm 0.026$ GeV^2; $M_3^4 = 0.518 \pm 0.013$ GeV^4 [13] , yielding

$$a = 0.295 \text{ GeV}^2, \qquad b = 0.657 \text{ GeV}^2, \qquad 2A_+A_- = 6.176. \tag{40}$$

[13] A. Cucchieri, D. Dudal, T. Mendes and N. Vandersickel, Phys. Rev. D **85** (2012) 094513
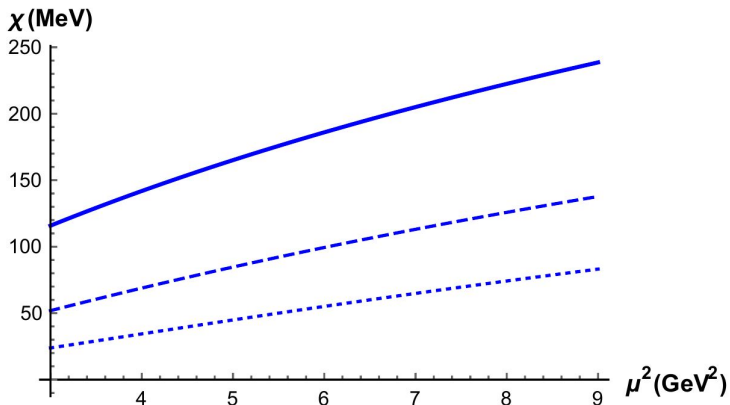
FIG. 3: The $SU(2)$ topological susceptibility χ for variable μ^2 for $\mathcal{M} = 1, 2, 3$ (full, dashed, dotted).
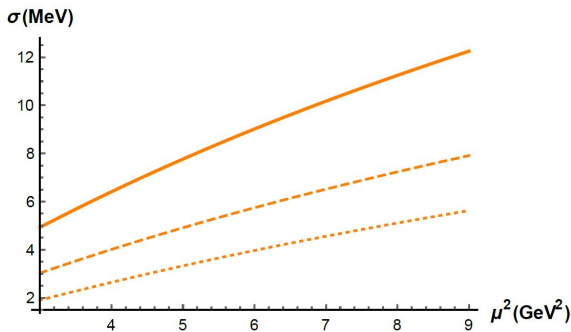
FIG. 4: Estimated error on χ for $SU(2)$ due to the uncertainty on the fitting parameters for variable μ^2 for $\mathcal{M} = 1, 2, 3$ (full, dashed, dotted).

Conclusion

- We have analyzed the topological susceptibility, χ^4, in $SU(2)$ and $SU(3)$ Euclidean Yang-Mills theory in a generic linear covariant gauge taking into account the Gribov ambiguity.

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▶ We have analyzed the topological susceptibility, χ^4, in $SU(2)$ and $SU(3)$ Euclidean Yang-Mills theory in a generic linear covariant gauge taking into account the Gribov ambiguity.

▶ To get estimates for the χ^4, we developed a particular Padé rational function approximation based on the Källén-Lehmann spectral integral representation of the topological current correlation function.

Conclusion

- ▶ We have analyzed the topological susceptibility, χ^4, in $SU(2)$ and $SU(3)$ Euclidean Yang-Mills theory in a generic linear covariant gauge taking into account the Gribov ambiguity.

- ▶ To get estimates for the χ^4, we developed a particular Padé rational function approximation based on the Källén-Lehmann spectral integral representation of the topological current correlation function.

- ▶ In order to improve upon this crude estimates, we plan to include the next order correction in future work. Notice this will be computationally challenging, thanks to the significantly enlarged set of vertices in the now considered Gribov-Zwanziger action for the linear covariant gauge.

Thank You

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