

Spatial String Tension and Its Effects on Screening Correlators in a Thermal QCD Plasma

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We calculate the spatial Wilson line correlator for $2 + 1$ flavor QCD using highly improved staggered quark discretization for fermions and in quenched QCD for a wide range of temperatures, from the chiral crossover temperature $T_{pc} \simeq 156$ MeV or the deconfinement temperature $\simeq 300$ MeV, respectively, up to 2 GeV. Extracting the spatial string tension for different lattice cutoffs and by performing a continuum extrapolation of this observable, we show that the soft (magnetic) gluons interact nonperturbatively even at temperatures $\gtrsim 1$ GeV. We provide incriminating evidences to demonstrate that dimensionally reduced effective theories can describe these soft quark and gluon quasi-particles for both quenched and $2 + 1$ flavor QCD, at temperatures $T \gtrsim 5T_{pc}$. We also show for the first time the imprints of the nonperturbative pseudopotential in the properties of mesonic screening masses for temperatures ranging from 0.8 to 164 GeV in the quark-gluon plasma.

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Introduction—Quantum chromodynamics (QCD) has a rich set of nonperturbative properties at finite temperatures [1,2]. There is a transition from a phase of color-singlet degrees of freedom to a phase where color charges are deconfined when the temperature is increased, which occur through a first order phase transition [3] or a smooth crossover [4], respectively, in QCD without and in the presence of dynamical quarks. *Ab initio* lattice field theory calculations have demonstrated this and also determined the corresponding transition temperature, which is $T_d r_0 = 0.7457(45)$ [5] for QCD without quarks [pure SU(3) gauge theory or quenched QCD], whereas it is $T_{pc} \simeq 156$ MeV [6–9] in presence of two degenerate light quarks and one strange quark flavor. In the deconfined phase of QCD with a gauge coupling g , two more scales apart from the temperature T are dynamically generated; the electric gT and the magnetic scale $g^2 T / \pi$, which correspond to the inverse correlation lengths of the color-electric and color-magnetic degrees of freedom, respectively. When these scales are well separated, i.e., $g^2 T / \pi \ll gT \ll \pi T$, the gauge and fermion fields with typical momenta $\sim \pi T$ can be integrated out [10] resulting in dimensionally reduced effective theory known as electrostatic QCD (EQCD) [11,12]. Within this effective field theory the temporal component of the gauge field A_0 appear as a static adjoint scalar field and the parameters of this theory, i.e.,

the couplings g_E, λ_E and the Debye mass m_D can be calculated using perturbation theory to all orders in g [12,13]. The high temperature phase in QCD correspond to the confined phase in a three-dimensional adjoint Higgs theory [13,14]. The confinement scale of this theory corresponds to the magnetic scale in QCD, which is inherently nonperturbative and gives rise to infrared divergences which cannot be tamed through perturbative resummations [15]. At higher temperatures, the A_0 fields become massive and can be integrated out from the QCD partition function, giving rise to an effective theory called magnetostatic QCD (MQCD) which is a three-dimensional pure gauge theory [12,16,17]. However, it is not clear *a priori* at what temperatures such a clean separation of scales would occur to justify the validity of these effective theories to describe QCD [18,19].

The nonperturbative magnetic sector in high temperature QCD can be directly accessed through the calculation of the spatial Wilson loop [20,21]. Earlier lattice calculations have demonstrated the area-law behavior of the spatial Wilson loop, further extracting the spatial string tension σ_s from the linearly rising pseudopotential at large distance scales in SU(3) without dynamical quarks [22–26] as well as in $2 + 1$ flavor QCD with a heavier than physical light quark mass [27]. An agreement with the estimate of σ_s in dimensional reduced theory was observed at $\gtrsim 2 T_{pc}$, and agreement between the EQCD calculations and lattice QCD data of different thermodynamic quantities like the quark number susceptibilities are typically observed at temperatures $\gtrsim 3 T_{pc}$ [28].

In this Letter, we revisit the calculation of the σ_s using sophisticated lattice QCD techniques to convincingly address the question *what temperature range herald the*

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onset of the dimensional reduction in QCD? By performing a careful continuum extrapolation of the pseudopotential extracted out of spatial Wilson line correlators calculated at two(three) different lattice cutoffs for a temperature range $\sim 0.2\text{--}1(2.7)$ GeV for QCD with(without) dynamical physical quarks, we demonstrate the onset of dimensional reduction at temperatures $\gtrsim 5 T_{\text{pc}}$ from a detailed understanding of its properties. We show for the first time that this nonperturbative potential describing the magnetic modes can remarkably explain the deviation of the screening masses of mesonlike long-distance excitations at high temperatures $0.8\text{--}164$ GeV from the perturbative EQCD prediction. We further quantify the spin splitting between the vector and the pseudoscalar screening excitations which cannot be addressed within the leading order perturbative EQCD framework [29].

Theoretical and numerical framework—In this Letter we extract the *confining* pseudopotential and, subsequently, σ_s by measuring the correlation between two spatial Wilson lines $W(R, L)$ in modified-Coulomb gauge, each of which are of length L along the z direction separated by a transverse distance R in the x - y plane. We use spatial Wilson line correlators in modified-Coulomb gauge instead of the spatial Wilson loops because these have a much better signal to noise ratio and lead to the same pseudopotential. This approach is often used to obtain the static potential in zero temperature QCD [30–34], and results in the same potential as the calculations using Wilson loops, see, e.g., Ref. [35]. We implement the Wilson lines on a four-dimensional Euclidean lattice with N sites along each spatial direction and N_τ sites along the temporal direction, τ and at each time slice. We consider $N = 32, 40$ for $2 + 1$ flavor QCD and $N = 32, 48, 64$ for pure SU(3) with $N_\tau = N/4$ for each temperature $T = 1/(N_\tau a)$ which is varied between $0.16\text{--}1$ GeV and $0.3\text{--}2.7$ GeV, respectively. The pseudopotential $V(R)$ can be extracted from the ratio of expectation values of the spatial Wilson line correlators of length $z = La$ and $z = (L + 1)a$, where $L \lesssim N$ from the relation,

$$V(R)a = \lim_{L \rightarrow \infty} \ln \left[\frac{\langle W(R, L) \rangle}{\langle W(R, L + 1) \rangle} \right]. \quad (1)$$

The expectation values are calculated typically over 200–2400 gauge configurations in QCD with and without dynamical fermions, details of which are mentioned in the Supplemental Material [36]. Because of finite statistics the right side of Eq. (1) is dominated by the gauge noise for large distances $L > 5\text{--}10$ due to which a clear plateau-like feature is not visible in this observable. This is due to finite lattice size as well as contamination from the excited states. Hence we use an ansatz $m(L, R) = V(R) + be^{-V_1 L}$ in order to extract the ground state energy $V(R)$ reliably at each R by removing the contamination due to the first excited state energy V_1 . We have varied the fit range between $L \in [1, 4]$ for $T \lesssim 4 T_c$ and $L \in [1, 8]$ at $T \gtrsim 4 T_c$.

The pseudopotential is extracted for each jackknife bin and the statistical errors are estimated from the variance among such bins. For the highest temperatures we have studied, the spatial volumes are small leading to contamination from the excited states leading to larger errors in the extracted pseudopotential.

The pseudopotential $V(R)$ has an additional divergence in the continuum due to the self energy of quark and anti-quark pair. We have renormalized $V(R)$ using the same renormalization factor (C_Q) [37] which is extracted from the static potential between a quark–antiquark pair at $T = 0$. This is allowed since no new ultraviolet divergences appear at finite temperatures. Further details on our procedure to extract the pseudopotential and the results for pseudopotentials at different temperatures and lattice sizes are discussed and shown in Fig. 1 in the Supplemental Material [36].

Spatial string tension and the onset of dimensional reduction—Once the renormalized pseudopotential is measured, we extract the spatial string tension using the ansatz $V(r) = V_0 + \sigma_s r - \alpha_c/r$. We also extract the coupling α_c as a result of the fit. The Coulomb term in the above ansatz could have two possible origins. It could come from the short distance perturbative part, in which case we have $\alpha_c = \alpha_p = (4/3)g^2/(4\pi)$ at leading order. Alternatively, the Coulomb term can arise from the fluctuations of the color flux tube along the transverse direction [38–41], in which case $\alpha_c = \alpha_L = (D - 2)(\pi/24)$, with D being the spacetime dimension. This is the so-called Lüscher term and the above description applies at relatively large distances. When dimensional reduction sets in $D = 3$, otherwise we have $D = 4$. One would expect that for $r < (\pi T)^{-1}$ the perturbative α_p/r term will dominate the pseudopotential, whereas for intermediate distances $(\pi T)^{-1} < r < (g^2 T/\pi)^{-1}$ the Lüscher term determined by α_L will be relevant. At large distances $r > (g^2 T/\pi)^{-1}$, one would expect the largest contribution coming from the term containing σ_s . Indeed we observe that the α_c extracted from our fits are close to α_L at intermediate distances $rT \in [0.5, 1.2]$ and eventually tending towards zero at larger distances.

The results for the extracted α_L is compiled in Fig. 1. The average values of α_L are consistent with $\pi/12$ for $T \lesssim 5 T_c(2 T_c)$ but beyond $T \gtrsim 5 T_c(3 T_c)$, these values approach $\pi/24$ indicating the onset of dimensional reduction beyond this temperature for QCD with (without) dynamical quarks. Henceforth T_c correspond to $T_{\text{pc}}(T_d)$ for SU(3) with (without) dynamical quarks. To ensure the robustness of our extraction method for α_L we have compared our results with a previous lattice study [26] in SU(3) gauge theory with $N_f = 0$. We observe a good agreement with the earlier results. However going to finer $N_\tau = 12, 16$ lattice spacings is important to precisely demonstrate that the value of α_L approaches $\pi/24$ at temperatures $T \gtrsim 4 T_c$. From these observations, we thus held the coefficient of $1/r$ term to a fixed value depending upon the temperature and extract $\sqrt{\sigma_s}/T$ from a two-parameter fit to the pseudopotential for

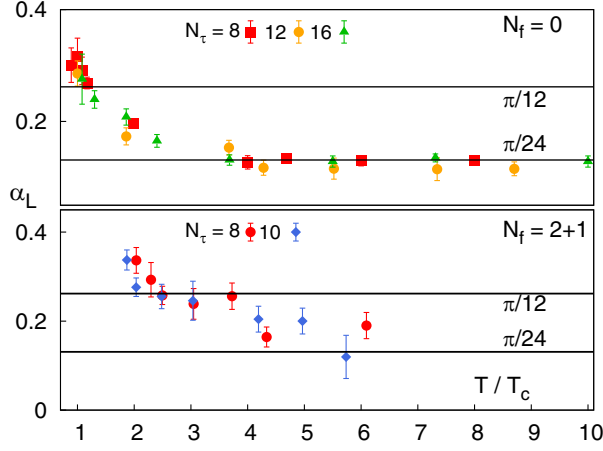


FIG. 1. The coefficient of the Coulomb term extracted from the fit to $V(r)$ at intermediate distances $(\pi T)^{-1} < r < (g^2 T/\pi)^{-1}$ for $N_f = 0$ and $N_f = 2 + 1$ flavor QCD for a range of temperatures between 1–10 T_c . The red, blue, orange, and green points correspond to lattice size $N_\tau = 8, 10, 12$, and 16 , respectively.

SU(3) gauge theory with and without dynamical quarks as a function of T/T_c , results of which are shown in Fig. 2. We observe that $\sqrt{\sigma_s}/T$ has a strong temperature dependence for $T < 4 T_c$, beyond which it is mildly dependent of temperature for $N_f = 0$ case, whereas for $N_f = 2 + 1$, a slow variation with T/T_c persist till $\sim 5 T_c$. This coincides with the onset of dimensional reduction and the three-dimensional effective theory being confining with the scale characterized by $\sqrt{\sigma_s}$.

We next interpret the temperature dependence of the spatial string tension in QCD. The extracted spatial string tension for $2 + 1$ flavor QCD, for different lattice spacings or equivalently different $N_\tau = 8, 10$ for the entire temperature range we have studied, is shown in physical units in

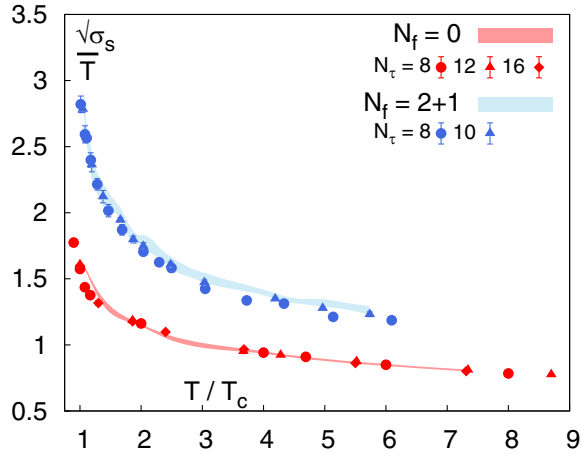


FIG. 2. The comparison of the continuum extrapolated values of $\sqrt{\sigma_s}/T$ as a function of T/T_c for quenched (red band) and $2 + 1$ flavor QCD (blue band). The lattice data for cutoff corresponding to $N_\tau = 8, 10, 12$, and 16 are shown as circle, triangle, box and diamond symbols, respectively.

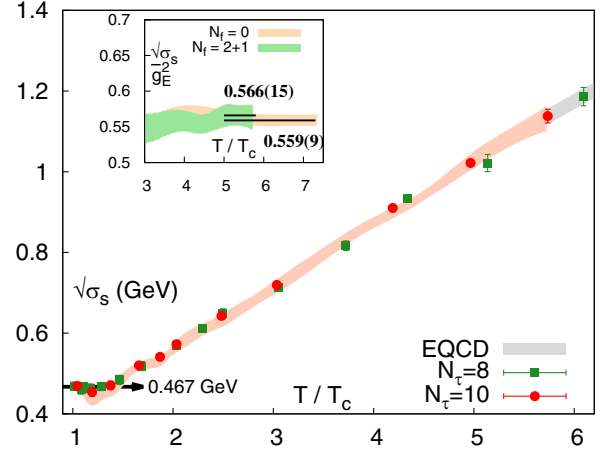


FIG. 3. The variation of $\sqrt{\sigma_s}$ with T/T_c for different lattice cutoffs corresponding to $N_\tau = 8, 10$ along with its continuum estimates (orange band). The continuum estimates are close to EQCD prediction at $T \gtrsim 5 T_c$, shown as gray band. The black line in lower left corner denotes $\sqrt{\sigma} = 0.467$ GeV at $T = 0$ from Ref. [34]. The variation of the continuum estimate for $\sqrt{\sigma_s}/g_E^2$ with T/T_c is shown in the inset for SU(3) (yellow band) and $2 + 1$ flavor QCD (green band), respectively.

Fig. 3. The data for $\sqrt{\sigma_s}$ do not show a significant lattice cutoff dependence as evident from the good agreement between $N_\tau = 8$ and $N_\tau = 10$ data. Nevertheless we perform a cubic splines interpolation of the data as a function of temperature and for each N_τ and then perform a continuum extrapolation, which is shown as a red band in Fig. 3. We observe that at $T < 260$ MeV the value of $\sqrt{\sigma_s}$ is in excellent agreement with the string tension, $\sqrt{\sigma} = 0.467$ GeV extracted from the temporal Wilson line correlator [34] at $T = 0$ [22]. At temperatures $\gtrsim 260$ MeV the electric scale gT starts to separate from the hard scale πT resulting in the onset of linear temperature dependence of $\sqrt{\sigma_s}$.

At higher temperatures $\sqrt{\sigma_s}$ rises with increasing temperatures and we would like to quantify this trend. To compare with the literature, the variation of $\sqrt{\sigma_s}/g_E^2$ with temperature is shown in the inset of Fig. 3. The three-dimensional EQCD coupling g_E^2 is calculated up to two-loop in g^2 [42]. It is evident from the plot that the dependence of $\sqrt{\sigma_s}/g_E^2$ on temperature (or equivalently the four-dimensional gauge coupling g) is mild for $T > 5 T_c$, again reinforcing the validity of an effective three-dimensional description as also observed in the data for the Lüscher term. The other couplings within EQCD, i.e., m_D, λ_E have an even milder dependence on g [42] hence fitting the data for $\sqrt{\sigma_s}/g_E^2$ with a constant function for the range of temperatures between 5–5.8 T_c , we obtain $\sqrt{\sigma_s} = 0.566(15) g_E^2$. Extrapolating our EQCD inspired fit to higher temperatures, shown as a gray band in Fig. 3, we observe that it perfectly accommodates for the lattice data at a cutoff corresponding to $N_\tau = 8, T/T_c \sim 6$, which was not used in the fit. Our results are consistent with

the first extensive study in $2 + 1$ flavor QCD performed with a different staggered fermion discretization [27], where lattice data for $\sqrt{\sigma_s}$ was found to match with $0.54(1)g_E^2$, albeit with a large uncertainty, at temperatures $T \gtrsim 1.5 T_c$, where $T_c \sim 200$ MeV. As already discussed in Ref. [27] major sources of uncertainties in such a direct comparison with the prediction from dimensionally reduced theory are due to errors in the determination of spatial string tension and the coupling g_E in a three-dimensional SU(3)-Higgs model. We have instead changed the strategy and extracted the dependence of the spatial string tension with g_E^2 with a constant fit to our data for $\sqrt{\sigma_s}/g_E^2$ in a temperature range where we observe hints of the onset of dimensional reduction.

We have also performed the same analysis for SU(3) gauge theory without dynamical quarks but for a wider temperature range, which allows us to observe the onset of dimensional reduction more carefully. Since our continuum extrapolated data for $\sqrt{\sigma_s}/g_E^2$ in SU(3) shows almost no temperature or, equivalently, the four-dimensional gauge coupling dependence in the range $5 < T/T_c < 7.3$, hence it can be parametrized as $0.559(9)g_E^2$ in this range and beyond as shown in the inset in Fig. 3. The coefficient which characterizes the variation of $\sqrt{\sigma_s}$ with g_E^2 is in perfect agreement with our observation in $2 + 1$ flavor QCD. This confirms the fact that indeed the dynamical fermions do not affect such observables at $T \gtrsim 5T_c$, since it is most sensitive to the magnetic gluons which interact nonperturbatively even at asymptotically high temperatures. Our result agrees with and improves upon the previous lattice study [26] in four-dimensional SU(3) gauge theory which reported $\sqrt{\sigma_s} = 0.566(13)g_E^2$, where the tree-level matching $g_E^2 = g^2(T)T$ was used in the fit but no continuum extrapolation was carried out.

Within three-dimensional SU(3) gauge theory characterized by a coupling g_3 , two independent lattice studies have reported the variation of $\sqrt{\sigma_s}$ as $\sim 0.553(2)g_3^2$ [43] and $\sim 0.554(4)g_3^2$ [25], whereas a Hamiltonian-based approach in [44] parametrized it as $\sim 0.564g_3^2$. In the temperature range $5 < T/T_c < 7.3$ we find that for $N_f = 0$ case, the $\sqrt{\sigma_s}/g_3^2 = 0.557(7)$ has no noticeable dependence on temperature, which also alludes to the onset of dimensional reduction. Here we have taken $g_3^2 = g^2T$. We would similarly expect that the MQCD effective theory will start to describe the $2 + 1$ flavor QCD data at these high temperatures as well.

Consequences: Screening mass at high temperatures— Having established the nonperturbative nature of the spatial Wilson line correlators and the associated pseudopotential and determined the value of the spatial string tension the next question we ask is what are the corresponding consequences? In order to address this question one has to choose observables which are most sensitive to the magnetic scale. One of them is the spatial meson correlation function [45]. The long distance behavior of these correlators is governed

by the meson screening masses. Temperature dependence of the spatial meson correlators thus describes the transition from hadronlike to quarklike excitations due to the melting of mesons [46–48] because these are related to the corresponding spectral functions [46,49,50]. Furthermore, there is a close connection between screening masses and real-time rates of photon and dilepton production in the deconfined plasma [51]. Thus a precise understanding of the properties of screening masses and their sensitivity to the magnetic scale is of utmost importance.

The continuum extrapolated spatial screening mass of pseudoscalar isotriplet mesonlike excitations in $2 + 1$ flavor QCD measured using HISQ discretization shows a significant deviation from the perturbative EQCD prediction [29] at $T \lesssim 1$ GeV [52–54] and more recently this deviation is observed to persist even at $T \lesssim 164$ GeV [55]. More interestingly there exists a clear difference in the magnitude of the vector and pseudoscalar meson screening masses at such high temperatures [55] which cannot be explained within the EQCD effective theory at $\mathcal{O}(g^2)$.

In an attempt to understand these puzzles, we recall that at high enough temperatures quark excitations acquire an effective mass $M = \pi T + g^2 T C_F / 8\pi + \mathcal{O}(g^4)$, and the spatial correlation function represent nonrelativistic bound states of these heavy quarks in $2 + 1$ dimensions. The screening mass can thus be determined from the lowest eigenvalue of a two-dimensional Schrödinger equation with a static potential which until now, has been derived from a systematic $1/(\pi T)$ expansion of the heavy quark propagator in presence of magnetic gluons by resumming gluon-exchange ladder diagrams within EQCD [29]. In order to include the effects of nonperturbatively interacting magnetic gluons we propose a more general procedure to determine the potential by matching to the perturbative potential in the region $r < m_D^{-1}$ to the continuum extrapolated potential $V(r)$ extracted in the previous section at $r \sim m_D^{-1}$. Further details of this matching procedure can be found in the Supplemental Material [36]. The nonperturbative interactions also affect the effective mass M . Hence we determine them by fitting the screening mass $2M + \delta m_{\text{scr}}$ obtained by solving the Schrödinger equation for the zero angular momentum state,

$$\left[-\frac{1}{M} \left(\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} \right) + V(r) \right] \psi_0(r) = \delta m_{\text{scr}} \psi_0(r), \quad (2)$$

for different trial values of M , to the lattice data on the spin-averaged values of the continuum extrapolated screening mass in $2 + 1$ flavor QCD [55] in the temperature range $T \in [1, 164]$ GeV. This is necessary due to the fact that the pseudoscalar and vector screening masses are not degenerate, and split evenly due to spin-spin interaction [56,57] between a heavy quark–antiquark pair which we will derive within the NRQCD framework starting from EQCD Lagrangian. The results for $M/(\pi T)$ as a function

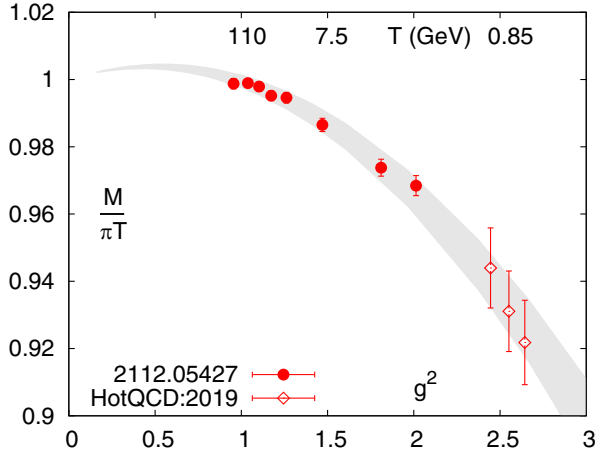


FIG. 4. The results for the mass M that goes into Eq. (2), obtained by performing a fit to the spin-averaged data for screening mass from Ref. [55] at $T \in [1, 164]$ GeV (filled points). The fit extrapolated to lower values of temperature provides a good match to the lattice data (open points) from Ref. [52].

of g^2 is shown in Fig. 4 which we could parametrize using $M/(\pi T) = 1 + 0.0159(15)g^2 - 0.0165(10)g^4$ with a $\chi^2/\text{d.o.f.} = 0.53$. The coupling g was estimated at the scale $2\pi T$ using the five-loop beta function with $\Lambda_{\overline{\text{MS}}}^{(3)} = 0.339(12)$. The coefficient of the $\mathcal{O}(g^2)$ term is consistent with the perturbative estimate (0.01688) [29] but non-perturbative interactions which contribute at $\mathcal{O}(g^4)$ is also of the same magnitude with opposite sign. At asymptotically high temperatures M goes over to πT as expected.

To check the robustness of our procedure we have used this parametrization to estimate spin-averaged screening masses temperatures lower than 1 GeV, which are in good agreement with available lattice QCD results [52] up to $T \gtrsim 5T_c$, where we earlier observed the onset of dimensional reduction. We have also derived the spin dependent potential, $V_s(r) = (\pm \frac{1}{4})(4g^2 T/3M^2)\delta^2(r)$ for vector and pseudoscalar states, respectively, at $\mathcal{O}(g^2)$, details of which are given in the Supplemental Material [36]. Since this term is subdominant compared to our matched potential $V(r)$, one can treat it as a perturbation. This leads to a correction to the ground state energy of Eq. (2) given by an amount $\delta m_{\text{scr}}^{(1)}(T) = (\pm \frac{1}{4})(2/3\pi)(g^2 T/M^2)|\psi_0(0)|^2$, for vector and pseudoscalar states, respectively, and depends on the ground state wave function ψ_0 at the origin. We could then estimate the corresponding screening mass $2M + \delta m_{\text{scr}}(T) + \delta m_{\text{scr}}^{(1)}(T)$ normalized by $2\pi T$, which is shown in Fig. 5.

Our calculated values are in excellent agreement with the lattice QCD data [52,58], within 1σ at $T \gtrsim 5T_c$, but more importantly the correct g^2 dependence is achieved over a large temperature range which could not be explained earlier. At lower temperatures, where dimensional reduction is not valid, we do not expect this spin potential to accurately describe the data.

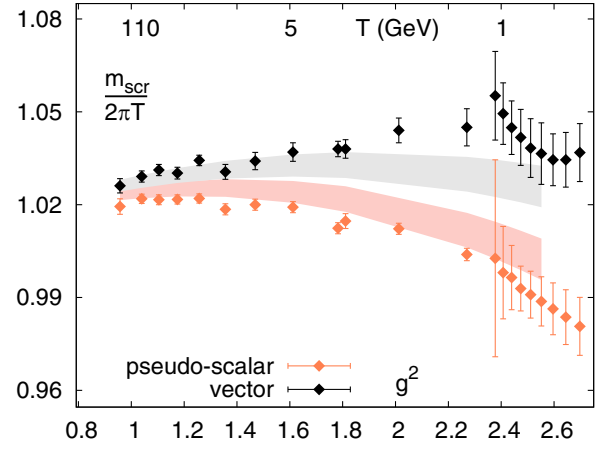


FIG. 5. The splitting between the pseudoscalar and vector screening masses, shown as red and gray bands, respectively, predicted using the spin-spin interaction term derived perturbatively. Our results are compared with lattice QCD data from Refs. [52,55]. The bands were drawn by performing a simple interpolation of the data points in the entire range of temperatures $\gtrsim 5T_c$.

Summary and outlook—In this Letter, we explain an important feature of the strongly interacting quark gluon plasma, i.e., the deviation of the screening mass corresponding to the long-wavelength excitations of the plasma from its perturbative EQCD prediction by including nonperturbative interactions of the magnetic gluons quantified by the spatial string tension. By performing a careful continuum extrapolation of $\sqrt{\sigma_s}$ and studying its temperature dependence we estimate the temperature regime $T \gtrsim 5T_c$ where QCD can be described by a dimensionally reduced effective theory. In this regime we calculate the *effective* potential that enters into the determination of the screening masses by matching the nonperturbative potential (at long distances) with the EQCD potential (valid at short distances) at the Debye scale. Remarkably the ground state wave function obtained using this potential can be used to explain the spin-splitting that exist between the pseudoscalar and vector screening masses for a wide range of temperatures up to $T \gtrsim 5T_c$, without any additional parameter tuning. As a follow-up we will like to extend our formalism to explain the large spin-splitting that persist in the screening masses in QCD closer to T_c and further quantify how nonperturbative interactions at the magnetic scale enter into dynamical properties of the quark-gluon plasma, e.g., the soft dilepton and photon rates [51], directly measurable in experiments. Our Letter is thus very general and can be adapted to study melting of baryons in QGP using inputs from [59], dark matter bound-state formation in electroweak plasma in the early universe, see for, e.g., [60] or understanding collective excitations in, for example, holographic plasmas, superconductivity.

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Data availability—The data that support the findings of this Letter and used in preparing the figures presented can be found in Ref. [62].

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