Strongly $\gamma$-Deformed $\mathcal{N}=4$ Supersymmetric Yang-Mills Theory as an Integrable Conformal Field Theory

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We demonstrate by explicit multiloop calculation that $\gamma$-deformed planar $\mathcal{N}=4$ supersymmetric Yang-Mills (SYM) theory, supplemented with a set of double-trace counterterms, has two nontrivial fixed points in the recently proposed double scaling limit, combining vanishing ’t Hooft coupling and large imaginary deformation parameter. We provide evidence that, at the fixed points, the theory is described by an integrable nonunitary four-dimensional conformal field theory. We find a closed expression for the four-point correlation function of the simplest protected operators and use it to compute the exact conformal data of operators with arbitrary Lorentz spin. We conjecture that both conformal symmetry and integrability should survive in $\gamma$-deformed planar $\mathcal{N}=4$ SYM theory for arbitrary values of the deformation parameters.

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Introduction.—The most general theory which admits an AdS$_3$ dual description in terms of a string $\sigma$-model [1,2] is believed to be $\gamma$-deformed $\mathcal{N}=4$ supersymmetric Yang-Mills (SYM) theory [3,4]. At the classical level, this $\sigma$ model is integrable and conformal. At the quantum level, it admits a solution in terms of the $\gamma$-deformed quantum spectral curve (QSC$_\gamma$) [5–9]. It is not obvious, however, that this solution yields the correct description of $\gamma$-deformed planar $\mathcal{N}=4$ SYM theory at any ’t Hooft coupling $g^2 = \gamma g_{YM} N_c$, since it automatically implies conformal symmetry and integrability of the theory. Both properties are highly debated, especially due to the loss of supersymmetry for the general deformation parameters $\gamma_1, \gamma_2, \gamma_3$, breaking the $R$ symmetry $SU(4) \rightarrow U(1)^3$.

The main danger for both conformality and integrability in this theory comes from the fact that $\gamma$-deformed $\mathcal{N}=4$ SYM theory is not complete at the quantum level [10–12]. Namely, in order to preserve renormalizability, it has to be supplemented with new double-trace counterterms of the kind $\text{tr}(\phi^* \phi_j) \text{tr}(\phi_k \phi^* \phi_i)$, with $j=1,2,3$ being a complex scalar field [10,13,14]. The corresponding coupling constants run with the scale, thus breaking the conformal symmetry. For example, for the double-trace interaction term $\alpha^2_{ji} \text{tr}(\phi_j \phi^*_i) \text{tr}(\phi^*_i \phi^*_j)$ the one-loop $\beta$ function is given by [11]

$$\beta_{\alpha^2_{ji}} = \frac{g^4}{\pi} \sin^2 \gamma_j^+ \sin^2 \gamma_j^- + \frac{\alpha^2_{jj}}{4\pi^2},$$

where $\gamma_j^+ = \mp \frac{1}{2}(\gamma_2 \pm \gamma_3), \gamma_j^- = \mp \frac{1}{2}(\gamma_3 \pm \gamma_1)$, and $\gamma_3^\pm = \mp \frac{1}{2}(\gamma_1 \pm \gamma_2)$. However, at weak coupling, the $\beta$ function has two fixed points $\beta_{\alpha^2_{ij}}(\alpha_{jj}) = 0$,

$$\alpha^2_{jj} = \pm 2i g^2 \sin \gamma_j^+ \sin \gamma_j^- + O(g^4).$$

At these fixed points, which should persist at arbitrary values of $g^2$ and arbitrary $N_c$, $\gamma$-deformed $\mathcal{N}=4$ SYM theory should be a genuine nonsupersymmetric conformal field theory (CFT). In addition, it is natural to conjecture that the QSC$_\gamma$ formalism gives the integrability description of this theory in the planar limit precisely at the fixed points.

To elucidate the role of the double-trace couplings we examine the scaling dimensions of the operators $\text{tr}(\phi^*_j)$. Such operators are protected in the undeformed theory but receive quantum corrections for nonzero deformation parameters $\gamma_j$. For $J \geq 3$ the contribution of the double-trace terms to their anomalous dimensions $\gamma_J$ is suppressed in the planar limit [15]. However, this is not the case for $J = 2$ for which $\gamma_{j=3}$ would diverge without the double-trace coupling contribution. At the fixed points (2), we get a finite but complex anomalous dimension
\[
\gamma_{j=2}(g) = \mp \frac{ig^2}{2\pi^2} \sin \gamma_j^+ \sin \gamma_j^- + O(g^4). \tag{3}
\]

This means that we deal with a nonunitary CFT.

In this Letter, we confirm explicitly, in the double scaling (DS) limit introduced in [15], that \(\gamma\)-deformed planar \(\mathcal{N}=4\) SYM theory does have a conformal fixed point parameterized by \(g^2\) and the three deformation parameters \(\gamma_1, \gamma_2, \gamma_3\). The existence of this fixed point was first discussed in [12] in the DS limit.

The double scaling limit of \(\gamma\)-deformed \(\mathcal{N}=4\) SYM theory [15] combines the \(g \to 0\) limit and large imaginary twists \(e^{-ir/2} \to \infty\), so that \(\xi_j = ge^{-ir/2}\) remain finite. In particular, for \(\xi_1 = \xi_2 = 0\) and \(\xi_3 = 4\pi \xi \neq 0\), one obtains a nonunitary, biscalar theory [15]

\[
L_\phi = N_c \text{tr} \left( \sum_{i=1,2} \partial^\mu \phi_i \partial_\mu \phi_i + (4\pi)^2 \xi \phi_i^\dagger \phi_i \phi_j \phi_k \phi_l \right). \tag{4}
\]

In this limit the double-trace counterterms become

\[
L_{\text{ct}}/(4\pi)^3 = \alpha_i^2 \sum_{i=1}^2 \text{tr}(\phi_i \phi_i) \text{tr}(\phi_j^\dagger \phi_j^\dagger) + \alpha_i^2 \text{tr}(\phi_i \phi_j) \text{tr}(\phi_j^\dagger \phi_i), \tag{5}
\]

where \(\alpha_i^2 \equiv \alpha_i^2/(4\pi)^2 = \alpha_i^2/(4\pi)^2\). In the DS limit, relations (2) and (3) simplify as \(\alpha_i^2 \approx \mp \xi^2/2\) and \(\gamma_{j=2} = \pm 2i\xi^2\) [12].

In this Letter, we compute the \(\beta\) functions for the double-trace couplings at seven loops, confirming that the biscalar theory with Lagrangian \(L_\phi + L_{\text{ct}}\) given by (4) and (5) is a genuine nonunitary CFT at any coupling \(\xi\). We examine the two-point correlation functions of the operators \(\text{tr}(\phi_i \phi_j)\) and \(\text{tr}(\phi_i \phi_j^\dagger)\) in this theory and find that they are protected in the planar limit. Moreover, we compute exactly, for any \(\xi\), the four-point function of such protected operators and apply the operator product expansion (OPE) to show that the scaling dimension of the operator \(\text{tr}(\phi_i \phi_j)\) satisfies the remarkably simple exact relation

\[
(\Delta - 4)(\Delta - 2)^2 \Delta = 16 \xi^4. \tag{6}
\]

Its solutions define four different functions \(\Delta(\xi)\). At weak coupling, the solutions \(\Delta = 2 \mp 2i\xi^2 + O(\xi^2)\) describe scaling dimensions of the operator \(\text{tr}(\phi_i \phi_j)\) (with \(i = 1, 2\)) at the two fixed points. The two remaining solutions, \(\Delta = 4 + \xi^4 + O(\xi^6)\) and \(\Delta = -\xi^4 + O(\xi^6)\), describe scaling dimensions of a twist-four operator, carrying the same \(U(1)\) charge \(J = 2\), and its shadow, respectively.

As another manifestation of integrability of the biscalar theory, relation (6) can be reproduced [16] by means of the QSC formalism [5–7] (see [17]).

Perturbative conformality of biscalar theory.—In order to compute the \(\beta\) functions for the double-trace couplings, we consider the following two-point correlation functions of dimension-2 operators:

\[
G_1(x) = \langle \text{tr}[\phi_i \phi_j(x)] \text{tr}[\phi_i^\dagger \phi_j^\dagger(0)] \rangle.
\]

\[
G_2(x) = \langle \text{tr}[\phi_i \phi_j(x)] \text{tr}[\phi_i^\dagger \phi_j^\dagger(0)] \rangle.
\]

\[
G_3(x) = \langle \text{tr}[\phi_i \phi_j^\dagger(x)] \text{tr}[\phi_i^\dagger \phi_j(0)] \rangle. \tag{7}
\]

The reason for this choice is that, in the planar limit, each \(G_i\) receives contributions from Feynman diagrams involving double-trace interaction vertices of one kind only. As a consequence, \(G_i\) depends only on two coupling constants, \(\xi\) and \(\alpha_i\). For arbitrary values of the couplings \(\alpha_i\), the renormalized correlation function \(G_i(x)\) satisfies the Callan-Symanzik evolution equation depending on the \(\beta\) function for the coupling \(\alpha_i\).

To compute the correlation functions (7) we employ dimensional regularization with \(d = 4 - 2\epsilon\). We start with \(G_7\) and \(G_8\). In the planar limit, they receive contributions from Feynman diagrams shown in Fig. 1 (left). They consist of a chain of scalar loops joined together through single- or double-trace vertices. In momentum space, their contribution to \(G_i\) forms a geometric progression. In configuration space, the bare correlation function is given by

\[
G_i/G_i^{(0)} = \sum_{\theta \geq 0} (\xi^2 - \alpha_i^2)^{\theta} (\pi x^2)^{\epsilon c} \times \frac{\Gamma((2 - (\ell + 1)\epsilon)) \Gamma^{\ell+1}(\epsilon) \Gamma^{2\ell}(1 - \epsilon)}{\Gamma((\ell + 1)\epsilon)) \Gamma^{\ell+1}(2 - 2\epsilon)}, \tag{8}
\]

where \(i = 2, 3\) and \(G_i^{(0)}\) denotes the Born-level contribution. To obtain a finite result for the correlation function, we have to replace bare couplings with their renormalized values

\[
\xi^2 \to \mu^2 \xi^2, \quad \alpha_i^2 \to \mu^{2\epsilon} \alpha_i^2 Z_i, \tag{9}
\]

and perform renormalization of the operators in (7) by multiplying \(G_i\) by the corresponding \(Z_i\) factor. Requiring \(Z_7 G_7, Z_8 G_8\) to be finite for \(\epsilon \to 0\) leads to the following expression for \(Z_i\) in the minimal subtraction scheme:

\[
Z_i = 1 - \frac{(\alpha_i^2 - \xi^2)^2}{\alpha_i^2(\alpha_i^2 - \xi^2 - \epsilon)} = \left( i = 2, 3 \right). \tag{10}
\]

In the standard manner, we use this relation to find the exact \(\beta\) function for the coupling \(\alpha_i\) (for \(i = 2, 3\))

\[
\beta_i = 2\epsilon \alpha_i^2 + \frac{d\alpha_i^2}{d\ln \mu} = -\alpha_i^2 \frac{d\ln Z_i}{d\ln \mu} = 2(\alpha_i^2 - \xi^2)^2. \tag{11}
\]

We deduce from this relation that the \(\beta\) functions vanish for \(\alpha_i^2 = \xi^2\), which also implies \(Z_i = 1\). As follows from (8), the correlation function at the fixed point is \(G_i = G_i^{(0)}\), so that the operators \(\text{tr}(\phi_i \phi_j)\) and \(\text{tr}(\phi_i \phi_j^\dagger)\) are protected.
The calculation of the correlation function $G_1$ is more involved. In the planar limit it receives contributions from Feynman diagrams shown in Fig. 1 (right) and those known as “wheel” diagrams [19]. In momentum space, their contribution to $G_1$ factorizes into a product of Feynman integrals $I_L$ that form a geometric progression,

$$\tilde{G}_1(p) = \int d^4x e^{ipx} G_1(x) = \sum_{\ell \geq 0} \sum_{L \geq 0} a_{\ell}^2 \left[ \sum_{i=0}^{\ell} a_{L}^i I_L(p) \right].$$  \hspace{1cm} (12)

Here the sum over $\ell$ runs over double-trace vertices and $I_L(p)$ denote $(2L + 1)$-loop scalar “wheel” integrals with $2L$ internal vertices shown in Fig. 1 (right).

In dimensional regularization, $I_L(p)$ takes the form $I_L(p^2) = (p^2)^{-(2L+1)c/2L+1}(c_0 + c_1 e + \cdots)$, with $L$-dependent coefficients $c_i$. Expressions for $I_L$ at $L = 0, 1$ are known in the literature [20]; we computed $I_L$ for $L = 2, 3$. Using the obtained expressions we determined the expression for the bare correlation function $G_1(x)$ up to seventh order in perturbation theory. Going through the renormalization procedure, we use (9) to express $G_1(x)$ in terms of renormalized coupling constants $\xi^2$, $\alpha^2$ and require $Z_G, G_1(x)$ to be finite for $e \rightarrow 0$. This fixes the coupling renormalization factor $Z_1$ and allows us to compute the corresponding $\beta$ function $\beta_1 = -\alpha^2 d\ln Z_1/d\ln \mu$.

For $\beta_1$ we obtained in the minimal subtraction scheme

$$\beta_1 = a(\xi) + \alpha^2 b(\xi) + \alpha^4 c(\xi),$$  \hspace{1cm} (13)

where the functions $a, b, c$ are given by

$$a = -\xi^4 + \xi^8 - \frac{4}{3} \xi^{12} + O(\xi^{16}),
$$

$$b = -4\xi^4 + 4\xi^8 - \frac{88}{5} \xi^{12} + O(\xi^{16}),
$$

$$c = -4 - 4\xi^4 + \frac{4}{3} \xi^8 + O(\xi^{12}).$$  \hspace{1cm} (14)

At weak coupling their expansion runs in powers of $\xi^4$. Similarly to (11), $\beta_1$ is a quadratic polynomial in the double-trace coupling $\alpha^2$. This property follows from the structure of irreducible divergent subgraphs of Feynman diagrams shown in Fig. 1. As a consequence, $\beta_1$ has two fixed points,

$$\alpha_1^2_{\pm} = -\frac{1}{2c} \left( b \pm \sqrt{b^2 - 4ac} \right)$$

$$= \pm \frac{i\xi^2}{2} - \frac{\xi^4}{2} \mp \frac{3i\xi^6}{4} + \xi^8 \pm \frac{65i\xi^{10}}{48} - \frac{19\xi^{12}}{10} + O(\xi^{14}).$$  \hspace{1cm} (15)

For these values of the double-trace coupling, the correlation function scales as $G_1(x) \sim 1/(x^2)^{\Delta}$, where the scaling dimension $\Delta_{\pm} = \Delta(\alpha_1^2, \pm)$ is given by [21]

$$\Delta_{\pm} = 2 \mp 2i\xi^2 \pm i\xi^6 \mp \frac{7i}{4} \xi^{10} + O(\xi^{14}).$$  \hspace{1cm} (16)

Notice that, in distinction from (15), the expansion of $\Delta_{\pm}$ runs in powers of $\xi^4$. It is straightforward to verify that $\Delta_{\pm}$ satisfy the exact relation (6).

Curiously, there exists the following relation between the functions (14) and the scaling dimensions at the fixed point:

$$b^2 - 4ac = 4(\Delta_{\pm} - 2)^2.$$  \hspace{1cm} (17)

It can be understood as follows. For generic complex $\xi$, we find using (13) that for $\mu \rightarrow 0$ and $\mu \rightarrow \infty$ the coupling $\alpha_1(\mu)$ flows into one of the fixed points $\alpha_1^2$. Then, in the vicinity of a fixed point, for $\mu \rightarrow \infty$, the Callan-Symanzik equation fixes the form of renormalized $\tilde{G}_1(p)$

$$\tilde{G}_1(p) \sim e^{4 \int_{\alpha(\mu)}^{\alpha_1(\mu)} [d\alpha(r)]/\beta_1(\alpha)}$$

$$\sim \left( \frac{\alpha_1^2(\mu) - \alpha_1^2_{\pm}}{\alpha_1^2(p) - \alpha_1^2_{\pm}} \right)^{2(\gamma(\alpha_1)/\sqrt{b^2 - 4ac})},$$  \hspace{1cm} (18)

where $\alpha_1^2(\mu), \alpha_1^2(p)$ are in the vicinity $\alpha_1^2$, and $\gamma(\alpha) = \Delta - 2$ is the anomalous dimension. We recall that the bare correlation function $\tilde{G}_1(p)$ is given by the geometric progression (12), so that as a function of $\alpha_1^2$ it has a simple pole at some $\alpha_1^2$. After the renormalization procedure, $\alpha_1^2$ is effectively replaced by a renormalized coupling constant defined at the scale $\mu^2 = p^2$. The requirement for $\tilde{G}_1(p)$ to have a simple pole in $\alpha_1^2(p)$ fixes the exponent on the left-hand side of (18) to be 1, leading to (17).

Thus, we demonstrated by explicit seven-loop calculation that the $\beta$ functions have two fixed points, $\alpha_1^2 = -\xi^2$, while $\alpha_1^2(\pm)(\xi)$ is given by (15). We therefore conclude that, in the planar limit, the biscalar theory (4) and (5) with appropriately tuned double-trace couplings is a genuine nonunitary CFT, at least perturbatively.

**Exact correlation function.**—We can exploit the conformal symmetry to compute exactly the four-point correlation function

$$G = \langle \text{tr}[\phi_1(x_1)\phi_1(x_2)]\text{tr}[\phi_1(x_3)\phi_1(x_4)] \rangle = \frac{G(u, v)}{x_{12}^2 x_{34}^2},$$  \hspace{1cm} (19)
which is obtained from the two-point function $G_1(x)$ defined in (7) by point splitting the scalar fields inside the traces. Here $G(u, v)$ is a finite function of cross-ratios $u = x_{12}^2x_{34}^2/(x_{13}^2x_{24}^2)$ and $v = x_{14}^2x_{23}^2/(x_{13}^2x_{24}^2)$, invariant under the exchange of points $x_1 \leftrightarrow x_2$ and $x_3 \leftrightarrow x_4$. It admits the conformal partial wave expansion

$$G(u, v) = \sum_{\Delta, S \in \mathbb{Z}^+} C^2_{\Delta, S} u^{(\Delta - S)/2} g_{\Delta, S}(u, v),$$

where the sum runs over operators with scaling dimensions $\Delta$ and even Lorentz spin $S$. Here $C_{\Delta, S}$ is the corresponding OPE coefficient and $g_{\Delta, S}(u, v)$ is the conformal block [22].

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$$\Delta \quad \text{and} \quad \text{Lorentz spin} \quad S.$$
of \((29)\) well defined. For finite \(\xi^4\), these poles provide a
vanishing contribution to \((29)\) but generate a branch-cut
\(\sqrt{-\xi^4} \) singularity of \(G(u, v)\).

At small \(u\), we close the integration contour in \((29)\) to the
lower half-plane and pick up residues at the poles located at
\[ h_{\Delta,S} = \xi^4 \] (30)
and satisfying \(\text{Re}\Delta > S\). The resulting expression for
\(G(u, v)\) takes the expected form \((20)\) with the OPE
coefficients given by
\[
C^2_{\Delta,S} = \frac{S + 1}{u^4((4 - \Delta)\Delta + S(S + 2) - 2)} \left( \Gamma(S - \Delta + 4) \Gamma(\frac{1}{2} (S + \Delta)) \right) \\
\times \Gamma^2(\frac{1}{2} (S - \Delta + 4)) \Gamma(S + \Delta - 1).
\] (31)

The relations \((30)\) and \((31)\) define exact conformal data of
operators that appear in the OPE of \(tr[\phi_1(x_1) \phi_4(x_2)]\). For
\(S = 0\) the relation \((30)\) leads to \((6)\). At weak coupling, \((30)\)
has the two solutions \(\Delta = S + 2 - 2\xi^4/[S(S + 1)] + O(\xi^8)\)
and \(\Delta = S + 4 + 2\xi^4/[S(S + 1) + S + 2] + O(\xi^8)\) describing
the operators of twist 2 and 4, respectively. The two
remaining solutions of \((30)\) have scaling dimensions
\(4 - \Delta\) and correspond to shadow operators. We verified
by explicit calculation that \((30)\) and \((31)\) correctly repro-
duce the weak coupling expansion of the anomalous
dimensions and the OPE coefficients for the operators of twist
2 and 4.

Conclusions.—We demonstrated by explicit multiloop
calculation that the strongly \(\gamma\)-deformed planar \(\mathcal{N} = 4\)
SYM has two nontrivial fixed points whose position depends
on the properly rescaled ’t Hooft coupling. We also provided evidence that, at the fixed points, it is
described by an integrable nonunitary four-dimensional
conformal field theory. Namely, we found a closed expres-
sion for the four-point correlation function of the simplest
protected operators and used it to compute the exact
conformal data (scaling dimensions and OPE coefficients)
of twist-2 and twist-4 operators with arbitrary Lorentz spin.
In general, correlation functions in this theory are dom-
ninated by fishnet graphs \([15,25]\) which admit a description
in terms of integrable noncompact Heisenberg spin chains
\([26-28]\). Following \([15,27,29]\), the integrability can be used
to compute these correlation functions and also the
amplitudes \([30,31]\).

We conjecture that both conformal symmetry and
integrability should survive in \(\gamma\)-deformed planar \(\mathcal{N} = 4\)
SYM theory for arbitrary values of the deformation
parameters \(\gamma_i\). The underlying integrable nonunitary
CFT can be studied using the QSC formalism \([5-8]\).

The integrable nonunitary CFTs of the kind considered
here also exist in lower or higher dimensions. The known
examples include a two-dimensional effective theory
describing the high-energy limit of QCD \([32]\), where
the two-dimensional fishnet graphs can also be studied \([33]\),
the three-dimensional strongly \(\gamma\)-deformed Aharony-
Bergman-Jafferis-Maldacena (ABJM) model \([29]\), and
a six-dimensional three-scalar model \([34]\) for which the
“mother” gauge theory is not known (see also \([35]\)).
According to \([34]\), the latter two theories are self-consistent
CFTs and do not require adding double-trace counterterms.
It would be interesting to find the dual string description
of the biscalar theory. It might be nontrivial due to the
tachyon in \(\gamma\)-deformed AdS\(_3 \times S^5\) \([37]\).

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