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Two-gluon coupling and collider phenomenology of color-octet technirho mesons

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Abstract

It has recently been suggested that gauge invariance forbids the coupling of a massive color-octet vector meson to two gluons. While this is true for operators in an effective Lagrangian of dimension four or less, we demonstrate that dimension six interactions will lead to such couplings. In the case of technicolor, the result is a technirho-gluon-gluon coupling comparable to the naive vector meson dominance estimate, but with a substantial uncertainty. This has implications for several recent studies of technicolor phenomenology.

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Modern technicolor [1, 2] theories[1] incorporate many technifermions in order to produce a theory in which the technicolor coupling runs very slowly, or "walks". Such a behavior can produce an enhancement of the technicolor condensate [6, 7, 8, 9, 10, 11] and ordinary fermion masses, thereby mitigating potentially dangerous flavor-changing neutral currents from extended technicolor interactions [12, 13]. In such a theory the technicolor scale and, in particular, the lightest technivector meson resonances (the analogs of the ρ and ω in QCD) may be much lighter than 1 TeV [14, 15, 16, 17, 18].

If some of the technifermions carry color, we expect that there will be color-octet technivector mesons. An analysis based on vector meson dominance [19, 15, 16, 17] suggests that the dominant production mechanism for a color-octet technirho at the Tevatron collider would be through gluon fusion. While several decay mechanisms are possible, a coupling of the technirho to pairs of gluons would give rise to a substantial branching ratio to two jets. CDF has searched for color-octet vector mesons decaying to dijets [20, 21] and $b\bar{b}$ [22], and (at the 95% CL) excludes ρ_T^8 with masses in the range 260 – 480 GeV/c^2 for dijet decays and in the range 350 – 440 GeV/c^2 for decays to $b\bar{b}$. Also based on vector meson dominance, CDF excludes color-octet technirho mesons decaying to third-generation leptoquark technipions [23, 24] in the mass range approximately 200 and 700 GeV, depending on the technipion mass.

Zerwekh and Rosenfeld [25] have recently suggested that gauge invariance forbids the coupling of a massive color-octet vector meson to two gluons[2]. On this basis, they have studied the Tevatron's prospects of finding a color-octet technirho produced by quark/anti-quark annihilation and decaying to dijets [27] and of observing pair production of color-octet techni-eta's [25].

The analysis presented by Zerwekh and Rosenfeld implicitly uses the "hidden local symmetry" formulation [28] which is most appropriate for a massive vector meson that is light compared to the fundamental dynamical scale of the underlying theory. The result is slightly more general, however, as can be seen by considering the terms of dimension four or less in an effective Lagrangian describing the couplings of a color-octet technirho ρ^μ $(= \rho^{a\mu}\lambda^a$, where λ^a are the generators of $SU(3)_C$) to gluons G^ν $(= G^{a\nu}\lambda^a)$

$$\begin{aligned}\mathcal{L}_4 &= \frac{-1}{2g^2}\,\mathrm{Tr}\,G^2_{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\rho^2_{\mu\nu} + \epsilon\,\mathrm{Tr}\,G^{\mu\nu}\rho_{\mu\nu} \\ &\quad + i\alpha\,\mathrm{Tr}\,[\rho_\mu,\rho_\nu]\rho^{\mu\nu} + i\beta\,\mathrm{Tr}\,[\rho_\mu,\rho_\nu]G^{\mu\nu} + \gamma\,\mathrm{Tr}\,[\rho_\mu,\rho_\nu]^2\ . \qquad (1)\end{aligned}$$

In this expression, g is the QCD coupling, the QCD covariant derivative is $D^\mu =$

[1] For recent reviews of theories of dynamical electroweak symmetry breaking, see [3, 4, 5] and references therein.

[2] Results on the production of color-octet quarkonia at hadron colliders imply that this coupling also vanishes to leading order in a non-relativistic "techniquark" model of the technirho meson [26]. The coupling does not, however, vanish at higher order in the non-relativistic expansion, nor is there any reason to believe that a technirho meson would be well described as a non-relativistic bound state.

$\partial^\mu + iG^\mu$,

$$G^{\mu\nu} \equiv \frac{1}{i}[D^\mu, D^\nu] \quad , \quad \rho^{\mu\nu} \equiv D^\mu \rho^\nu - D^\nu \rho^\mu \ , \tag{2}$$

and α, β, and γ real-valued couplings in the effective Lagrangian. The kinetic energy terms are normalized such that, under an $SU(3)$ QCD gauge transformation $U(x)$,

$$G^\mu(x) \to U(x) G^\mu(x) U^\dagger(x) - iU(x)\partial U^\dagger(x) \ , \tag{3}$$

and

$$\rho^\mu(x) \to U(x)\rho^\mu(x)U^\dagger(x) \ . \tag{4}$$

Note that we have chosen a basis in which the ρ^μ transforms homogeneously, and hence there is no mass-mixing between the ρ and the gluon.

The term proportional to ϵ in eqn. (1) appears to give rise to the gluon-ρ mixing [29] which is integral to calculations inspired by vector meson dominance [19, 15, 16, 17]. However, as demonstrated by Zerwekh and Rosenfeld [25], this coupling is illusory. Consider the field redefinition

$$G^\mu \to G^\mu + \epsilon g^2 \rho^\mu \ . \tag{5}$$

Such a redefinition, which is consistent with the gauge symmetry of eqns. (3) & (4), eliminates the kinetic energy mixing. In the new basis, it is clear that there is no direct coupling between the ρ and two properly defined gluons, although the constants $\alpha - \gamma$ are modified. In addition a coupling of the ρ to quarks is introduced which is, on shell, identical to that predicted by vector meson dominance [29]. Note that the elimination of the two-gluon coupling has nothing to do with "universality" of the ρ couplings, and is therefore independent of any assumption of hidden local symmetry.

There is no reason, however, to restrict the analysis to terms of dimension 4. As the technirho is a composite state in a strongly-coupled theory, contributions of higher-dimensions operators may be expected to contribute. In analogy with the analysis of anomalous gluon self-interactions [30, 31], we find there are only two independent and potentially relevant operators with dimension 6:

$$\begin{aligned} \mathcal{L}_6 = c_1 \mathcal{O}_1 \quad &+ \quad c_2 \mathcal{O}_2 \\ \mathcal{O}_1 \quad &= \quad \frac{1}{4\pi\Lambda^2} D^\alpha \rho_{\alpha\beta} D_\gamma G^{\gamma\beta} \\ \mathcal{O}_2 \quad &= \quad \frac{i}{4\pi\Lambda^2} f^{ABC} \rho^{\alpha\beta A} G_\alpha^{\gamma B} G_{\beta\gamma}^C \ . \end{aligned} \tag{6}$$

Here we have normalized the unknown couplings so that the coefficients $c_{1,2}$ are expected to be $\mathcal{O}(1)$ by naive dimensional analysis [32, 33, 34] and Λ characterizes the scale of the underlying strong technicolor interactions. As in the case of anomalous gluon couplings, application of the equations of motion shows that the first interaction gives rise only to couplings of on shell ρ particles to quarks. The second interaction in eqn. (6) does give rise to nonvanishing on-shell couplings of a color-octet vector meson to two gluons. Applying the analysis of [31] shows that the contributions of operators with $d \geq 8$ to the $\rho q\bar{q}$ and ρGG vertices are identical in form to the contributions from the $d = 6$ operators, but are multiplied by powers of m_ρ^2/Λ^2.

To compare the effects of the dimension-six interactions with our expectations from vector meson dominance, we calculate the partial decay width of the ρ into a pair of gluons. The operator $\mathcal{O}_2$ yields the partial decay width

$$\Gamma_6(\rho \to GG) = \frac{c_2^2 g^4}{16\pi(4\pi)^2} \frac{m_\rho^5}{\Lambda^4} \ . \tag{7}$$

In the vector meson dominance calculation, one assumes [35] a ρ - G coupling

$$\mathcal{L}_{VMD} = \frac{g m_\rho^2}{g_\rho} \rho^{\mu A} G_\mu^A \tag{8}$$

where g_ρ is analog of the $\rho \to \pi\pi$ coupling constant in QCD. This coupling yields the partial decay width [36]

$$\Gamma_{VMD}(\rho \to GG) = \frac{g^4}{16\pi g_\rho^2} m_\rho \ . \tag{9}$$

Comparing these expressions we find

$$\frac{\Gamma_6}{\Gamma_{VMD}} = c_2^2 \left(\frac{g_\rho}{4\pi}\right)^2 \left(\frac{m_\rho}{\Lambda}\right)^4 \ . \tag{10}$$

In terms of dimensional analysis, which implies $g_\rho = \mathcal{O}(4\pi)$, $|c_2| = \mathcal{O}(1)$, and $m_\rho = \mathcal{O}(\Lambda)$, we see that these two estimates agree in order of magnitude. Consistent with (8) above, we can estimate the technirho coupling from QCD [3] as previous phenomenological studies [19, 15, 16, 17] have done

$$\frac{g_\rho^2}{4\pi} \approx 2.97 \ . \tag{11}$$

In this case we see that the ratio above is approximately $c_2^2/4$, for $m_\rho \simeq \Lambda$.

Turning to phenomenology, the major point of interest is the ρ_T^8 production cross section at the Tevatron collider [20, 21, 23, 24, 22]. For a relatively narrow ρ_T^8, the gluon fusion cross section is proportional to the two-gluon partial width calculated above. If $|c_2|$ is of order one, we see that the production through the operator $\mathcal{O}_2$ is about one quarter of the naive vector meson dominance estimate. On the other hand, for $|c_2|$ even as large as 2, the two estimates are comparable.

[3] One can include "large-N_{TC}" scaling [37] estimates as well, in which case $g_\rho = \mathcal{O}(1/\sqrt{N_{TC}})$ and $\Gamma(\rho \to GG)/m_\rho = \mathcal{O}(N_{TC})$. The N_{TC}-counting, however, is the same for decays mediated by O_2 or by vector meson dominance.

At this point, we should mention that the strength of the $\rho - G$ mixing used in ref. [15] is a factor of $\sqrt{2}$ too large; this translates into dijet decay widths and ρ_8 production cross-sections which are a factor of two too large. As a result, the calculated theoretical cross-sections which CDF used to set limits on color-octet technirhos decaying to dijets [20, 21], b-jets [22], or leptoquarks [23, 24] correspond to the predictions of the $d = 6$ operator with coefficient $c_2 \approx 3$ rather than to the predictions of vector meson dominance ($c_2 \approx 2$).

An additional contribution to technirho production comes from quark/anti-quark annihilation. As mentioned earlier, the field redefinition of eqn. (5) induces couplings of ρ_T^8 to quarks

$$\frac{g^2}{\sqrt{g_\rho^2 - g^2}}\ \bar{\psi}\rho\psi \quad . \tag{12}$$

Using the QCD-based estimate (11) of g_ρ, ref. [27] shows that the $p\bar{p}$ cross-section at the Tevatron collider for producing a technirho from quark/anti-quark annihilation is about one quarter as large as the estimate from gluon fusion with $c_2 = 3$ in the mass range $200\,\mathrm{GeV} < m_\rho < 500\,\mathrm{GeV}$. On the other hand, if we take $g_\rho \approx 4\pi$, the cross-section from $q\bar{q}$ would be reduced by another factor of six. Given that walking technicolor models are expected to contain light technirho's precisely because their dynamics differ from those of QCD, we should be mindful of the uncertainty in our estimate of g_ρ.

Overall, then, we expect the total production cross section for a color-octet technirho at the Tevatron to be comparable to the naive vector meson dominance estimate, but with an uncertainty of approximately an order of magnitude. This has implications for several recent phenomenological studies. In searches for technirhos decaying to dijets or $b\bar{b}$, a reduced production rate would decrease the Tevatron's reach, but Tevatron run IIb with 10-20fb^{-1} of data would still be sensitive to the presence of light technirhos. In searches for leptoquark technipions decaying primarily to third-generation fermions, production without resonant enhancement by color-octet technirhos yields [38] a lower bound of $M_{LQ} \geq 148$ GeV. The resonant contribution of color-octet technirhos (corresponding to $c_2 \approx 3$) was found to increase sensitivity [23, 24, 15]; a reduced technirho contribution would presumably yield a result intermediate between the two. Finally, [25] found the rate of pair-production of color-octet techni-etas in the absence of a ρGG coupling to lie below the threshold of visibility; including the ρGG coupling might bring light techni-eta's over that threshold.

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