Eur. Phys. J. C 49, 1077–1081 (2007)
DOI 10.1140/epjc/s10052-006-0184-4

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

Consequences of partial vector meson dominance for the phenomenology of colored technihadrons

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Received: 16 May 2006 / Revised version: 2 November 2006 /

Abstract. In this paper we address the question: do the limits on technirho production at the Tevatron mean what we think they do? These limits are based on calculations that rely on vector meson dominance (VMD). VMD was invented in order to describe the interaction of electrons with hadrons (the rho meson and pions). The method has been used also as a tool in the study of technicolor phenomenology. Nevertheless there is evidence in the sense that, even in its original context, VMD is not completely realized. In this work we investigate the consequences of a deviation from complete VMD for the phenomenology of colored technihadrons. We focus specially on the production of the color octet technirho and color triplet technipions. We found that a relatively small direct coupling of the proto-technirho to quarks is enough to suppress or even eliminate the interaction among quarks and the physical technirho. On the other hand, it is possible to suppress the coupling of the physical technirho to technipions, but in this case a large interaction among the technipions and the proto-gluon must be introduced. The consequences for the limits on the mass of the color octet technirho and colored triplets technipions are also investigated.

PACS. 12.40.Vv; 12.60.Nz

1 Introduction

We do not know what mechanism has been chosen by Nature to break the electroweak symmetry. There is a general agreement in the sense that the Higgs sector of the standard model is incomplete and new physics must exist at the TeV scale in order to explain the origin of electroweak symmetry breaking. An appealing possibility is that a new strong interaction breaks the electroweak symmetry through the formation of a condensate of new fermions which is not a singlet of the electroweak symmetry group. This hypothetical new interaction is generally called technicolor; for recent reviews see [1, 2]. In general, technicolor models have a rich spectrum of composite pseudoscalar and vector states. Some non-minimal models predict the existence of colored technihadrons such as color octet technirhos and color triplet technipions. They are the focus of this work.

Because technicolor is a strongly coupled theory, it is necessary to use effective methods in order to study its phenomenology. In general, the methods that have been proved useful in the description of the properties and interactions of usual hadrons are also used in the study of technihadrons. One of such methods is vector meson dominance (VMD); for a modern review of VMD, see [3]. A related, but perhaps more elegant, method for describing such interactions is the so called hidden symmetry. A realization of this technique applied to a strong electroweak sector is known as the BESS model; for a review, see [4].

VMD was invented in order to describe the interaction of electrons with hadrons (the rho meson and pions). In this scheme the electron interacts directly only with the (proto-) photon while the pion interacts directly only with the (proto-) rho meson. The interaction between electrons and pions is made possible by a mixing of the (proto-) photon with the (proto-) rho. In a similar way, it is assumed that the normal fermions interacts with technihadrons through mixing of the standard model gauge bosons with the vector technimesons.

Nevertheless, some deviations from complete VMD occur in its original context [5, 6]. For example, it has been claimed that the decay of the usual (QCD) $\rho(770)$ into a pair of leptons is better described if a direct coupling of the leptons to the ρ is introduced [5]. On the other hand, in [6] it is shown that the introduction of a direct coupling of the photon to the charged pions allows one to abandon the universality condition in order to obtain a correct pion form factor. Moreover, we know that technicolor dynamics is not like QCD. All these circumstances motivate us to ask about the meaning of the limits on technirho production at the Tevatron when the departure from traditional VMD is considered.

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In this work we investigate the consequences of deviations from complete VMD (which we will call partial VMD) for the production of a color octet technirho and a pair of color triplet technipions.

2 General framework

The first studies of the color octet technirho phenomenology [7, 8] were done using a version of VMD (generalized to the color interaction) based on non-diagonal propagators. In this work, we start with a version of VMD which is equivalent to the previous one but is formulated in terms of mass-mixing terms.

As it was previously shown [9], the mixing of the color octet technirho with the gluon can be described by the Lagrangian:

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}\tilde{G}^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{1}{4}\tilde{\rho}^a_{\mu\nu}\tilde{\rho}^{a\mu\nu} + \frac{1}{2}M_G^2\tilde{G}^2 \\ &+ \frac{1}{2}M_{\tilde{\rho}}^2\tilde{\rho}^2 - \frac{\tilde{g}}{g'}M_{\tilde{\rho}}^2\tilde{G}\tilde{\rho}\,, \end{aligned} \tag{1}$$

where

$$\begin{aligned}\tilde{G}^a_{\mu\nu} &= \partial_\mu\tilde{G}^a_\nu - \partial_\nu\tilde{G}^a_\mu - \tilde{g}f^{abc}\tilde{G}^b_\mu\tilde{G}^c_\mu \\ \tilde{\rho}^a_{\mu\nu} &= \partial_\mu\tilde{\rho}^a_\nu - \partial_\nu\tilde{\rho}^a_\mu - g'f^{abc}\tilde{\rho}^b_\mu\tilde{\rho}^c_\mu\,.\end{aligned}$$

This Lagrangian is invariant under $SU(3)_C$ provided that the fields transform as

$$\begin{aligned}\delta\tilde{G}^a &= -f^{abc}\tilde{G}^b\Lambda^c - \frac{1}{\tilde{g}}\partial\Lambda^a\,, \\ \delta\tilde{\rho}^a &= -f^{abc}\tilde{\rho}^b\Lambda^c - \frac{1}{g'}\partial\Lambda^a.\end{aligned} \tag{2}$$

Notice that the fields $\tilde{G}$ and $\tilde{\rho}$ are not physical fields, because they are not mass eigenstates. We call them the proto-gluon and the proto-technirho, respectively. The physical fields can be written as

$$\begin{aligned}G^a_\mu &= \tilde{G}^a_\mu\cos\alpha + \tilde{\rho}^a\sin\alpha \\ \rho^a_\mu &= -\tilde{G}^a_\mu\sin\alpha + \tilde{\rho}^a_\mu\cos\alpha\,,\end{aligned} \tag{3}$$

where α is given by

$$\sin\alpha = \frac{\tilde{g}}{\sqrt{g'^2+\tilde{g}^2}}\,. \tag{4}$$

As usual, we estimate the value of α scaling up the mixing between the photon and the usual rho meson obtained in normal VMD:

$$\sin\alpha = \frac{g}{\sqrt{2\pi}}\frac{1}{\sqrt{2.97\times 3/N_{\mathrm{TC}}}}\,, \tag{5}$$

where N_{TC} is the number of technicolors. As usual, we set $N_{\mathrm{TC}} = 4$.

When the Lagrangian (1) is written in terms of the physical fields, we find that there is no coupling between a color octet technirho and two gluons [9]. Nevertheless, it has been shown [10] that an operator with dimension six exists that restores this coupling. This operator may be written as

$$\mathcal{L} = \mathrm{i}\frac{c_2}{4\pi\Lambda^2_{\mathrm{TC}}}f^{abc}\rho^{a\mu\nu}G^{b\gamma}_\mu G^c_{\nu\gamma}\,. \tag{6}$$

Of course we do not know the value of the constant c_2 and hence an important uncertainty exists about the contribution of this operator. For simplicity, we work in the pessimistic limit assuming that the constant c_2 is small enough to make this contribution negligible. In fact, at the Tevatron this term is not important due to the low gluon luminosity at large partonic center-of-mass energies [11]. However, this term is crucial for the study of the color octet technirho phenomenology at the LHC. In this case, a reliable estimation of c_2 based on dynamical calculations would be very valuable, but this analysis is beyond the scope of this work.

3 Color octet technirho coupling to quarks

Now we want to couple these fields to quarks. In normal VMD, this is done assuming that the quarks only interacts with the proto-gluon. Nevertheless, because both the proto-gluon and the proto-technirho, transform like gauge fields, it is possible to write a covariant derivative with both fields:

$$\mathcal{L} = \bar{\psi}\mathrm{i}\gamma^\mu\left[\partial_\mu - \mathrm{i}(1-x)\tilde{g}\tilde{G}^a_\mu\frac{\lambda^a}{2} - \mathrm{i}xg'\tilde{\rho}^a_\mu\frac{\lambda^a}{2}\right]\psi\,. \tag{7}$$

In this way, we introduce a direct coupling between the quarks and the proto-technirho the strength of which is measured by the parameter x. This kind of direct coupling can be produced by extended technicolor although in this case it must be proportional to the quark mass and, hence, must be small. Nevertheless, because we do not know exactly all the properties of the underlying (extended) technicolor theory, we cannot ignore the possibility that a more important coupling can be generated.

When Lagrangian (7) is written in terms of physical fields we obtain

$$\begin{aligned}\mathcal{L} = &\mathrm{i}\bar{\psi}\gamma^\mu\partial_\mu\psi + g\bar{\psi}\gamma^\mu G^a_\mu\frac{\lambda^a}{2}\psi \\ &+ g\tan\alpha\left(\frac{x}{\sin^2\alpha} - 1\right)\bar{\psi}\gamma^\mu\rho^a_\mu\frac{\lambda^a}{2}\psi\,,\end{aligned} \tag{8}$$

where $g = \tilde{g}\cos\alpha = g'\sin\alpha$ is the usual QCD coupling constant. Notice that the coupling of the gluon to quarks is the usual one and it is independent of x. On the other hand, the coupling of the physical color octet technirho not only depends on x; it vanishes for $x = \sin^2\alpha$. That means that a relative small deviation from normal VMD can produce the decoupling of the physical technirho from quarks. Of course this effect has important consequences for the present mass limits obtained at the Tevatron.

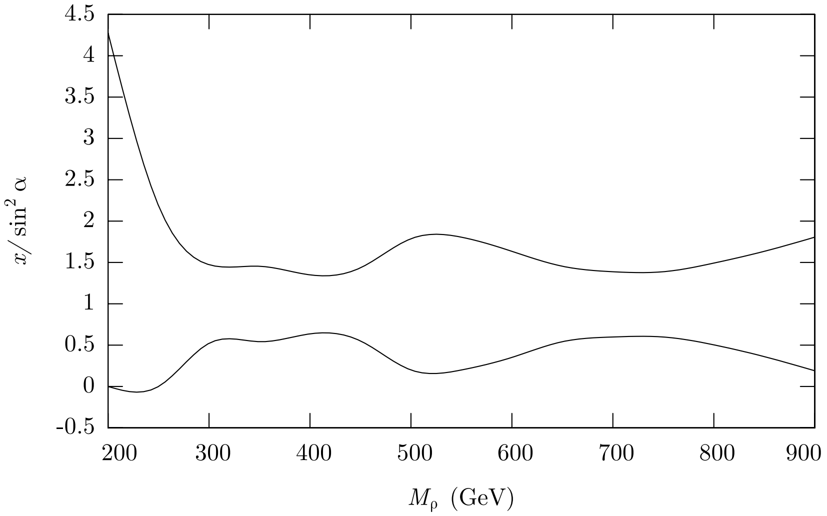

Fig. 1. Limits on the x parameter. The region between the lines is allowed

4 Dijet production at the Tevatron

In order to evaluate the effects on the technirho phenomenology of such a modification of the technirho–quark interaction, we compute (with the help of LanHEP [12–15] and CalcHEP [16]) the cross section for the resonant production of dijets at the Tevatron and we compare it with the experimental limits obtained by the CDF Collaboration for a luminosity of $106\,\mathrm{pb}^{-1}$ (Run I) [17]. We use the CTEQ6L [18] parton distribution function, $\sqrt{s} = 1800$ GeV and we implement the following kinematical cuts:

$$|\eta| < 2.0 \quad \text{for both jets} \tag{9}$$

and

$$|\cos\theta^*| = \left|\tanh\left(\frac{\eta_1 - \eta_2}{2}\right)\right| < \frac{2}{3}\,, \tag{10}$$

where η is the jet pseudo-rapidity.

As we have already said, we work in the limit where the color octet technirho does not couple to two gluons, hence it is produced only by quark fusion. For this reason, we do not interpret the experimental results as limits on the color octet technirho mass, but as limits on the x parameter. The results are shown in Fig. 1. The curves represent the 95% C.L. limits on $x/\sin^2\alpha$ and the region between them is allowed.

The color octet technirho remains invisible in this channel if $x/\sin^2\alpha \approx 1 \pm 0.5$. For the value of $\sin\alpha$ given by (5), we obtain that the value of x needed in order to explain the non-observability of the color octet technirho at the Tevatron is $x \approx 0.11 \pm 0.05$. This value of x seems too high, because it implies that ETC would produce unacceptable big masses for the u and d quarks. Nevertheless, this numerical result depends of the expression of $\sin\alpha$ shown in (5) that was scaled up from QCD. This procedure is highly dangerous because we know that technicolor's dynamics is not QCD-like. Of coure, we can ask whether, in a realistic model, the mixing angle can be small enough in order to have an $x \approx \sin^2\alpha$ compatible with the u and d quarks. To our knowledge, this is an open question.

On the other hand, in the context of the top quark production in the so called extended BESS model [19] it has been considered a direct coupling of a color octet vector resonance (equivalent to our color octet technirho) to quarks of the same order of magnitude as the lower bound of our x.

Let us turn again our attention to the color octet technirho production by gluon fusion, governed by the dimension six operator shown in (6). We have already said that this process is subdominant at the Tevatron due to the low gluon luminosity at large partonic center-of-mass energies. Nevertheless, it is necessary to study its contribution when the coupling of the technirho to quarks is suppressed. In this case we compute the production cross section using $\Lambda_{\mathrm{TC}} = 1$ TeV, and we compare our results with the experimental limits on the production of a color octet technirho, in order to obtain limits on the parameter c_2. The results are shown in Fig. 2. The region below the curve is allowed.

Notice that even for large values of c_2 the color octet technirho remains invisible in the dijet spectrum. We recall that, on the ground of dimensional analysis, the natural value of c_2 is of order $O(1)$.

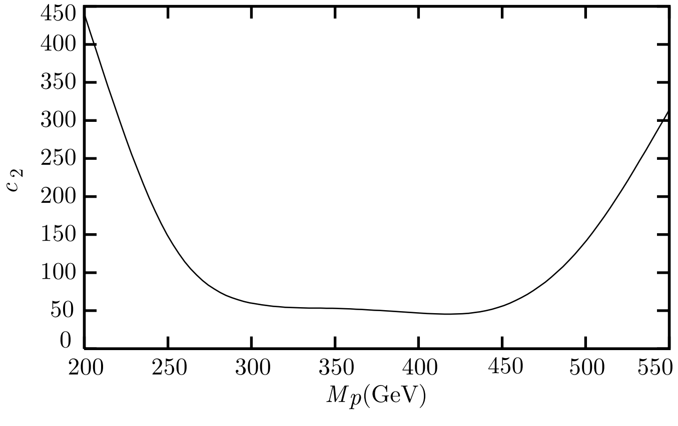

Fig. 2. Limits on the c_2 parameter. The region below the curve is allowed

5 Technipion pair production

Another interesting process is the production of colored technipions. In this section we focus on the production of the color triplet ones. In the one family technicolor model, there are four color triplet technipions which we denote generically by π_3. We assume that they have the same mass. In an exact analogy with the previous case, the Lagrangian may be written in terms of our extended covariant derivative:

$$\mathcal{L} = D_\mu \pi_3 \left(D^\mu\right)^\dagger \bar{\pi}_3 - M_\pi^2 \pi_3 \bar{\pi}_3 \,, \tag{11}$$

where

$$D_\mu = \partial_\mu - (1-y)\mathrm{i}g' \frac{\lambda^a}{2} \tilde{\rho}^a_\mu - y\mathrm{i}\tilde{g} \frac{\lambda^a}{2} \tilde{G}^a_\mu \,. \tag{12}$$

In this case, the parameter y measures the strength of the direct coupling between the proto-gluon and the color triplet technipion. The relevant Feynman rules for the technipion pair production, written in terms of the physical fields, are shown in Table 1.

Notice that the couplings of the physical gluon to technipions are independent of y and are exactly the same ones as we would obtain in scalar QCD. On the other hand, the coupling of the physical technirho depends on y, but it is suppressed only if $y \approx \cos^2 \alpha$. That is, a large proto-gluon to technipions coupling is needed, which, in principle, seems unnatural.

Table 1. Feynman rules relevant for the technipion pair production

Fields in the vertex				Variational derivative of Lagrangian
$G_{\mu p}$	$\bar{\pi}_{3q}$	π_{3r}		$g \frac{\lambda^p_{qr}}{2} \left(p_3^\mu - p_2^\mu\right)$
$G_{\mu p}$	$G_{\nu q}$	$\bar{\pi}_{3r}$	π_{3s}	$g^2 g^{\mu\nu} \left(\frac{\lambda^p_{rt}}{2} \frac{\lambda^q_{ts}}{2} + \frac{\lambda^q_{rt}}{2} \frac{\lambda^p_{ts}}{2} \right)$
$\rho_{\mu q}$	$\bar{\pi}_{3p}$	π_{3r}		$\frac{g}{\cos\alpha \sin\alpha} \left(\cos^2\alpha - y\right) \frac{\lambda^q_{pr}}{2} \left(p_3^\mu - p_2^\mu\right)$

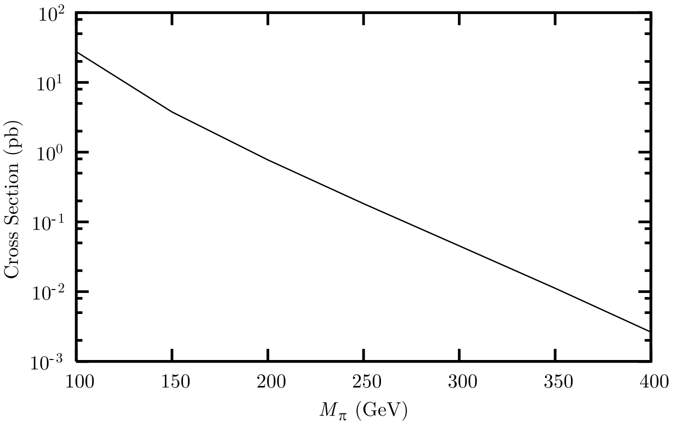

Fig. 3. Non-resonant color triplet technipion pair production cross section as a function of the technipion mass for $\sqrt{s} = 1800$ GeV and $y = 0$

Of course, the technirho production still can be suppressed by the mechanism discussed in the previous section, and then the technipion pair production would become non-resonant. Under these conditions, we compute the technipion pair production cross section for $\sqrt{s} = 1800$ GeV as a function of the technipion mass. The result is shown in Fig. 3. In general, the present limit for the production cross section of a pair of color triplet technipions is $\sigma(p\bar{p} \to \pi_3\bar{\pi}_3) < 0.5$ pb [20], and our results satisfy this limit for $M_\pi \geq 200$ GeV. Of course, the same result (i.e. Fig. 3) would be obtained, without any assumption on the parameter x, if $M_\rho < 2M_\pi$ or if the ρ is too heavy to be produced.

6 Searching the color octet technirho at the LHC

Let us turn, for a moment, our attention to the LHC. As we have seen in the previous sections, the production of a color octet technirho suffers of significant theoretical uncertainties. But the LHC will offer a center-of-mass energy and a luminosity big enough to consider other channels like the production of a pair of color octet technirhos. The Feynman diagrams for this process are shown in Fig. 4. The last four diagrams (from e to h) depend on the mixing angle, c_2 and the x parameter, in contrast to the first four diagrams (a to d) which are model independent. In fact, the only couplings that participate in the first four diagrams of Fig. 4 are (except for the usual QCD) $G\rho\rho$ and $GG\rho\rho$ and they are dictated by gauge invariance. The Feynman rules for these couplings can be obtained from the Lagrangian (1) and are presented in Table 2.

We estimate the pair production of color octet technirhos using only diagrams a, b and d of Fig. 4, because we expect that the dominant contribution to this process, at the LHC, comes from gluon fusion. The result is shown in Fig. 5. It is expected that LHC will have a luminosity of $\mathcal{L} = 10^4\ \mathrm{pb}^{-1}/\mathrm{yr}$, so the color octet technirhos must be abundantly produced (between 10^8 and 10^4 events per year in the whole possible mass range) at the LHC. Of course, a more detailed analysis taking into account realistic detector effects and background must be done, but such a work is beyond the scope of this paper.

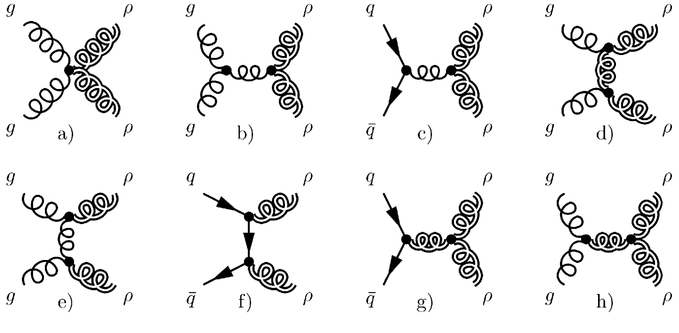

Fig. 4. Feynman diagrams for the production of a pair of color octet technirhos at the LHC

Table 2. Feynman rules relevants for the technirho pair production

Fields in the vertex	Variational derivative of Lagrangian
$G_{\mu p}$ $R_{\nu q}$ $R_{\rho r}$	$g f_{pqr} \big(p_1^{\rho} g^{\mu\nu} - p_3^{\mu} g^{\nu\rho} + p_3^{\nu} g^{\mu\rho}$ $- p_1^{\nu} g^{\mu\rho} + p_2^{\mu} g^{\nu\rho} - p_2^{\rho} g^{\mu\nu}\big)$
$G_{\mu p}$ $G_{\nu q}$ $R_{\rho r}$ $R_{\sigma s}$	$g^2 \big(g^{\mu\rho} g^{\nu\sigma} f_{pqt} f_{rst} + g^{\mu\nu} g^{\rho\sigma} f_{prt} f_{qst}$ $- g^{\mu\sigma} g^{\nu\rho} f_{prt} f_{qst} - g^{\mu\sigma} g^{\nu\rho} f_{pqt} f_{rst}$ $+ g^{\mu\nu} g^{\rho\sigma} f_{pst} f_{qrt} - g^{\mu\rho} g^{\nu\sigma} f_{pst} f_{qrt}\big)$

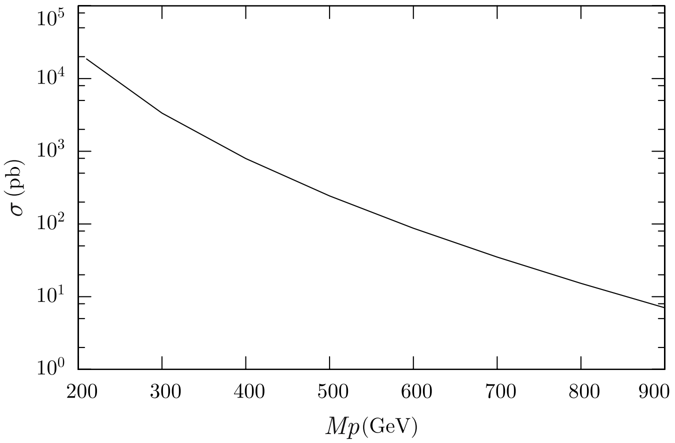

Fig. 5. Pair production of color octet technirhos at the LHC through gluon fusion. Remark that we use $c_2 = 0$

7 Conclusion

We have written down the more general Lagrangian (using operators with dimension up to four) that describes the interaction of the color octet technirho with quarks, gluons and colored technipions. Our Lagrangian deviates from the usual implementation of vector meson dominance because it includes a direct coupling of the technirho to quarks. We found that the coupling of the physical technirho to quarks is modified in such a way that it can be significantly suppressed with respect to the usual expectations of normal VMD. In fact, we compared our predictions to the experimental data from the CDF Collaboration, and we found that a relative small direct coupling can render the color octet technirho invisible. This effect has consequences also for the pair production of colored technipions, which becomes non-resonant. Nevertheless, the data obtained at the Tevatron exclude the existence of color triplet technipions for $M_\pi < 200$ GeV. Finally, we propose to pay attention to the pair production of color octet technirhos as a viable discovery channel at the LHC.

Acknowledgements. The author received support from Universidad Austral de Chile (DID grant S-2006-28).

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