Triple Photon Production at the Tevatron in Technicolor Models.

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Abstract

We study the process $p\bar{p} \rightarrow \gamma\gamma\gamma$ as a signal for associated photon-technipion production at the Tevatron. This is a clean signature with relatively low background. Resonant and non-resonant contributions are included and we show that technicolor models can be effectively probed in this mode.
1 Introduction

The origin of fermion masses and mixings is one of most important issues in particle physics. Unfortunately, these parameters are inputs in the well-tested Standard Model (SM). Fermion masses are possibly related to the electroweak symmetry breaking mechanism, which is not known at the moment and is the top priority of present and future experiments. In the SM, a scalar electroweak doublet with self-interactions described by an *ad hoc* quartic potential is responsible for the symmetry breaking, leaving a scalar physical boson, the Higgs boson ($J^{PC} = 0^{++}$), as a remnant. Favorite extensions of the SM, like the minimal supersymmetric standard model (MSSM) [1], also predict the existence of a heavy pseudoscalar boson ($J^{PC} = 0^{-+}$), in addition to a light scalar boson.

Another interesting possibility is that the electroweak symmetry breaking is triggered by some new strong interaction, generally called technicolor, and in this case the lightest boson could be a pseudoscalar, like a pion, named technipion. In fact, in these models of dynamical symmetry breaking a whole new set of resonances related to the technicolor sector is predicted [2].

It is important to find experimental signatures that can distinguish these different models of symmetry breaking. A compilation of experimental signatures for different technicolor models, like multiscale and top-color assisted walking technicolor, can be found in [3].

In this letter we focus on the signature arising from associated photon-technipion production. This is analogous to the associated gauge-higgs boson production. The process $p\bar{p} \rightarrow \Pi_T^{(o)}(\gamma, Z, W^\pm)$, where $\Pi_T^{(o)}$ is a isospin triplet (singlet) technipion, can be enhanced by low-lying technicolor resonances like the techni-rho and the techni-omega. These processes have been studied in [4] and the importance of the process involving the final state photon has been stressed in [3].

The process $e^+e^- \rightarrow \gamma\Pi_T^{(o)}$ was analysed for LEP and future linear colliders in [6]. Recently, Lane *et al.* [7] re-studied this process taking into account both continuum and resonance contributions, but concentrating on the dominant $b\bar{b}$ decay mode.
In this letter we study the possibility of using the process $p\bar{p} \rightarrow \gamma \Pi_T^{(t)} \rightarrow \gamma\gamma\gamma$, which is a clean signature with relatively low background even in a hadronic environment, to put some constraints in some technicolor models. We also include both resonant and non-resonant contributions in our analysis and perform a simulation of the significance level of this signature.

2 The Model

The coupling of the technipion to two gauge bosons is mediated by the Adler-Bell-Jackiw anomaly \cite{8} arising from a techniquark triangle. The $\Pi_T^{(t)}B_1B_2$ coupling can be parametrized as:

$$A_{\Pi_T B_1 B_2} = \frac{S_{\Pi_T B_1 B_2}}{4\sqrt{2}\pi^2 F_{\Pi_T}} \epsilon_{\mu\nu\alpha\beta} \epsilon_{1}^{\mu}\epsilon_{2}^{\nu}k_{1}^{\alpha}k_{2}^{\beta}, \quad (1)$$

where $\epsilon_{1,2}$ and $k_{1,2}$ are the polarization vectors and momenta of the gauge bosons $B_{1,2}$ respectively. $F_{\Pi_T}$ is the technipion decay constant, which is related to the technipion coupling to the axial current. The group-theoretical factor $S_{\Pi_T B_1 B_2}$ is given by \cite{9}:

$$S_{\Pi_T B_1 B_2} = g_1 g_2 \text{Tr} \left( Q_{\Pi_T} \{Q_1, Q_2\} \right) / 2 \quad (2)$$

where $g_1$ and $g_2$ are the corresponding gauge coupling constants and $Q_1$, $Q_2$ and $Q_{\Pi_T}$ are the charges under the gauge groups and isospin respectively of the technifermions circulating in the loop. For our purposes we will be concerned only with the $\Pi_T^{(t)}\gamma\gamma$ and $\Pi_T^{(t)}\gamma Z$ couplings, since they provide the only contributions to the process $p\bar{p} \rightarrow \gamma \Pi_T^{(t)}$, shown in Figure \cite{1} and the corresponding group-theoretical factors, for a one-family technicolor model with gauge group $SU(N_{TC})$, are given by:

$$S_{\Pi_T \gamma\gamma} = \frac{4e^2}{\sqrt{6}}N_{TC}, \quad S_{\Pi_T \gamma Z} = 2e^2 \frac{1 - 4\sin^2\theta_w}{2\sin 2\theta_w}N_{TC} \quad (3)$$
\[ S_{\Pi_{T}\gamma\gamma} = -\frac{4e^2}{3\sqrt{6}} N_{TC} \] , \[ S_{\Pi_{T}\gamma Z} = \frac{4e^2 \tan \theta_{W}}{3\sqrt{6}} N_{TC} \] (4)

Consequently, the decay of neutral techni-pions into two photons is induced entirely by the anomaly. In contrast, the associated production of a photon with a neutral techni-pion is mediated by both \( \Pi_{T}(\gamma\gamma) \) and \( \Pi_{T}(\gamma Z) \) anomalous vertices, as well as by possible \( s \)-channel vector resonances, the isosinglet techni-omega (\( \omega_{T} \)), and the isotriplet techni-rho (\( \rho_{T} \)). These further contributions are depicted in Figure 2 and can be treated as a generalization of vector meson dominance.

From the viewpoint of perturbation theory, the anomalous couplings appear only at the one-loop level. The resonances, considered as techniquark bound states, are a sum to all orders in technicolor interactions and therefore include one-loop effects. However, no ambiguity of double-counting arises when we consider both the anomaly and resonance contributions, as these are due to very different energy scales, the former being a low-energy effect and therefore is not important at the resonance mass scale.

In the absence of isospin violation, the techni-omega mixes with the isoscalar part of the electroweak current, the \( B_{\mu} \) field, whereas the techni-rho mixes with the isotriplet part, the \( W_{\mu}^{3} \) field. In terms of the physical fields of the photon and the Z-boson, the mixing strengths are given by:

\[ g_{\omega_{T}-\gamma} = \sqrt{\frac{\alpha}{\alpha_{T}}} (Q_{U} + Q_{D}) \] , \[ g_{\omega_{T}-Z} = -\sqrt{\frac{\alpha}{\alpha_{T}}} (Q_{U} + Q_{D}) \tan \theta_{W} \] (5)

and

\[ g_{\rho_{T}-\gamma} = \sqrt{\frac{\alpha}{\alpha_{T}}} \] , \[ g_{\rho_{T}-Z} = \sqrt{\frac{\alpha}{\alpha_{T}}} \cot 2\theta_{W} \] (6)

where \( \alpha \) is the fine structure constant and \( \alpha_{T} \) is related to the technicolor coupling constant \( g_{T} \) and can be estimated by a naïve scaling from QCD:

\[ \alpha_{T} = \frac{g_{T}^{2}}{4\pi} = 2.9 \left( \frac{3}{N_{TC}} \right) \] (7)
Finally, the relevant amplitudes for the decays $\rho_T, \omega_T \rightarrow \gamma \Pi_T^{(j)}$ are given by, in the notation of [3]:

$$M \left( V_T(q) \rightarrow G(p_1)\Pi_T^{(j)}(p_2) \right) = \frac{eV_T G_{\Pi_T}^j}{M_V} \varepsilon^{\mu \alpha \beta \gamma} \varepsilon^\gamma_{
u}(q) q^\alpha p_1^\beta$$

(8)

where $M_V$ is a mass parameter usually taken to be 200 GeV and

$$V_{\omega_T \gamma \Pi_T} = \cos \chi, \quad V_{\omega_T \gamma \Pi_T'} = (Q_U + Q_D) \cos \chi', \quad V_{\rho_T \gamma \Pi_T} = (Q_U + Q_D) \cos \chi, \quad V_{\rho_T \gamma \Pi_T'} = \cos \chi'.$$

(9)

In the equation above $\chi$ and $\chi'$ are mixing angles between the isospin eigenstates and the mass eigenstates. In our computations we use a value of $\sin \chi = \sin \chi' = 1/3$ and $Q_U + Q_D = 5/3$ [3]. In order to compute the fermionic widths of the techni-pions we use the coupling constant $g_{\Pi_T f \bar{f}} = m_f/F_{\Pi_T}$.

3 Simulation of the process

The inputs to our codes are the relevant masses of $\Pi_T^{(j)}$, $\omega_T$, $\rho_T$, the technipion decay constant $F_{\Pi_T}$ and the resonance widths $\Gamma_{\rho_T}$ and $\Gamma_{\omega_T}$. In order to reduce the number of parameters, we will use in our calculations the reference set of values $m_{\Pi_T^{(j)}} = 110$ GeV and $m_{\omega_T} = m_{\rho_T}$. We also adopt $N_{TC} = 4$ and $F_{\Pi_T} = 82$ GeV, as appropriate in multiscale walking technicolor, but the results are relatively insensitive to this choice since the couplings of the vector resonances and the branching ratio $BR(\Pi_T^{(j)} \rightarrow \gamma \gamma)$ are independent of $F_{\Pi_T}$. The vector resonance widths were obtained from Pythia version 6.125 [10].

We used the parton distribution function CTEQ6 [11] with both momentum and factorization scales set at $\sqrt{s}$ and a total center-of-mass energy of $\sqrt{s} = 2000$ GeV. We convoluted the relevant parton distribution functions with the amplitudes described above. Total luminosities of 2 fb$^{-1}$ (Run 2a) and 30 fb$^{-1}$ (optimistic Run 2b) were considered.

The irreducible background was generated using the program CalcHEP 2.1 [12]. The main irreducible contribution comes from $u\bar{u}, d\bar{d} \rightarrow \gamma \gamma \gamma$. 

4
A gaussian smearing for the final state photon energy with $\sigma_E/E = 0.20/\sqrt{E}$ [13] was applied to both signal and background.

4 Results

In Figures 3 and 4 we show for illustrative purposes the differential cross sections for signal and background as a function of the 2-photon and 3-photon invariant mass respectively for $m_{\omega_T} = m_{\rho_T} = 350$ GeV and $m_{\Pi^T} = 110$ GeV. In both figures one can clearly see a signal that stands out above the background. The 2-photon distribution in Fig. 3 shows a peak centered around the techni-pion mass (which we chose at 110 GeV). Since this is a two-photon invariant mass distribution in three-photon events, the width of the peak does not correspond to the techni-pion width, but it contains also the combinatoric error from the selection among the three photons. Indeed, for a technipion much narrower than the techni-vector meson, the widths in both figures are comparable. The three-photon distribution in Fig. 4 shows a peak centered around the techni-vector meson mass. In this case, the width in the histogram reflects the resonance width together with the photon energy resolution that we use in the simulation. In addition, the distribution away from the peak is dominated by the anomaly contribution. As it is comparable to the background, the non-resonant contribution cannot be detected.

In order to further suppress the background, the following cuts were used:

\begin{align*}
M_{\gamma\gamma\gamma} &\in \left[ M_{\omega_T} - \frac{M_{\omega_T}}{10}, M_{\omega_T} + 20 \text{ GeV} \right] \\
M_{\gamma\gamma} &\in \left[ M_{\Pi^T} - \frac{M_{\Pi^T}}{10}, M_{\Pi^T} + 10 \text{ GeV} \right] \\
p_{T\gamma} &\geq 70 \text{ GeV} 
\end{align*} 

(10)

In Table I we present our results for the total number of 3-photon events for a given techni-resonance mass and for 2 different integrated luminosities, namely $L = 2$ fb$^{-1}$ and 30 fb$^{-1}$.

We can see that resonances up to 350 GeV can be found at the 5σ level even with $L = 2$ fb$^{-1}$. For an accumulated luminosity of $L = 30$ fb$^{-1}$, resonances as heavy as 550
| $m_{\omega_T,\rho_T}$ (GeV) | $\sigma$ (fb) | Events | S/B | Significance |
|---------------------------|--------------|--------|-----|--------------|
| 210                       | 18.22        | 12 - 175 | 38.6 | 21.2 - 82.3 |
| 250                       | 9.22         | 9 - 135 | 19.0 | 13.1 - 50.7 |
| 300                       | 4.83         | 4.3 - 64.7 | 13.1 | 7.5 - 29.1 |
| 350                       | 2.70         | 2.6 - 38.8 | 10.3 | 5.2 - 20.0 |
| 400                       | 1.83         | 0.92 - 13.8 | 5.0 | 2.2 - 8.4 |
| 450                       | 1.06         | 0.8 - 12.2 | 7.8 | 2.5 - 9.8 |
| 500                       | 1.00         | 0.2 - 3.3 | 3.5 | 0.9 - 3.4 |
| 550                       | 0.78         | 0.2 - 3.4 | 3.5 | 0.9 - 3.5 |
| 600                       | 0.52         | 0.06 - 0.9 | 1.6 | 0.3 - 1.2 |

Table 1: Cross sections (before cuts), number of events (after cuts), signal/background ratio and significance of the signal for $\mathcal{L} = 2$ fb$^{-1}$ and 30 fb$^{-1}$ (first and second figures respectively) for different techni-resonance masses.

GeV can be detected at the 3$\sigma$ level. In Figure 5 we show the statistical significance of the signal as a function of the techni-resonances for the two luminosities.

5 Conclusions

In this paper we have examined the triple photon production at the Tevatron as a signature for technicolor models. We have included both resonant and non-resonant contributions, but the former are dominant in a hadron machine, where the center-of-mass energy of the process is not fixed. The relatively low background enables one to obtain large significance levels. We found that technicolor models can be effectively probed in this mode and, with an accumulated luminosity of $\mathcal{L} = 30$ fb$^{-1}$, resonances as heavy as 550 GeV can be detected or excluded at the 3$\sigma$ level. Using this mode we can have information on both the techni-vectors as well as the techni-pion masses from the 3$-$ and 2$-$ photon invariant mass distributions respectively.
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**Table captions**

Table I: Cross sections, number of events, signal/background ratio and significance of the signal for $\mathcal{L} = 2 \text{ fb}^{-1}$ and $30 \text{ fb}^{-1}$ (first and second figures respectively) for different techni-resonance masses.

**Figure captions**

Figure 1: Triangle anomaly giving the continuum contribution to the $p\bar{p} \rightarrow \Pi_T \gamma$ process.

Figure 2: Feynman diagrams for the process $e^+e^- \rightarrow \tau^+\tau^-\nu\bar{\nu}$.

Figure 3: 2-photon invariant mass distribution for signal (upper histogram) and background (lower histogram) for $m_{\omega_T} = m_{\rho_T} = 350 \text{ GeV}$ and $m_{\Pi_T^{(r)}} = 110 \text{ GeV}$ for $\mathcal{L} = 30 \text{ fb}^{-1}$. The bin size used in these histograms is 0.43 GeV.

Figure 4: 3-photon invariant mass distribution for signal (upper histogram) and background (lower histogram) for $m_{\omega_T} = m_{\rho_T} = 350 \text{ GeV}$ for $\mathcal{L} = 30 \text{ fb}^{-1}$. The bin size used in these histograms is 1.1 GeV.

Figure 5: Statistical significance of signal for $\mathcal{L} = 30 \text{ fb}^{-1}$ (dots) and $\mathcal{L} = 2 \text{ fb}^{-1}$ (solid line) as a function of the masses of the techni-resonances.
Figure 1: Triangle anomaly giving the continuum contribution to the $p\bar{p} \rightarrow \Pi_T^{(0)} \gamma$ process.

Figure 2: Techni-omega and techni-rho contributions to the $p\bar{p} \rightarrow \Pi_T^{(0)} \gamma$ process.
Figure 3: 2-photon invariant mass distribution for signal (upper histogram) and background (lower histogram) for $m_{\omega_T} = m_{\rho_T} = 350$ GeV and $m_{\Pi_T'} = 110$ GeV for $\mathcal{L} = 30$ fb$^{-1}$. The bin size used in these histograms is 0.43 GeV.
Figure 4: 3-photon invariant mass distribution for signal (upper histogram) and background (lower histogram) for $m_{\omega_T} = m_{\rho_T} = 350$ GeV for $\mathcal{L} = 30$ fb$^{-1}$. The bin size used in these histograms is 1.1 GeV.
Figure 5: Statistical significance of signal for $\mathcal{L}=30$ fb$^{-1}$ (dots) and $\mathcal{L}=2$ fb$^{-1}$ (solid line) as a function of the masses of the techni-resonances.
