Tevatron Potential for Technicolor Search with Prompt Photons.

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Abstract

We perform a detailed study of the process of single color octet isoscalar $\eta_T$ production at the Tevatron with $\eta_T \to \gamma + g$ decay signature, including a complete simulation of signal and background processes. We determined a set of optimal cuts from an analysis of the various kinematical distributions for the signal and backgrounds. As a result we show the exclusion and discovery limits on the $\eta_T$ mass which could be established at the Tevatron for some technicolor models.

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I. INTRODUCTION

The Standard Model has been extensively tested and it is a very successful description of the weak interaction phenomenology. Nevertheless, the electroweak symmetry breaking sector has essentially remained unexplored. In the Standard Model, the Higgs boson plays a crucial rôle in the symmetry breaking mechanism. However, the presence of such a fundamental scalar at the 100 GeV scale gives rise to some theoretical problems, such as the naturalness of a light Higgs boson and the triviality of the fundamental Higgs self-interaction. These problems lead to the conclusion that the Higgs sector of the Standard Model is in fact a low energy effective description of some new Physics at a higher energy scale.

Three main avenues for the new Physics have been proposed: low-scale supersymmetry \cite{1}, large extra dimensions at TeV scale \cite{2} and dynamical symmetry breaking \cite{3,4}. A common prediction of all these extensions of the Standard Model is the appearance of new particles in the range of some hundred GeV to a few TeV.

We focus on the issue of the technicolor models of dynamical symmetry breaking which predict new particles such as Pseudo-Nambu-Goldstone-Bosons (PNGB) and vector resonances. Many of these models include colored technifermions and hence some PNGB’s can be color-triplet or even color-octet particles. These color-octet scalars can be copiously produced at a hadron collider and they are the subject of this paper.

The main contribution to the color-octet PNGB masses comes from QCD. If it is assumed that technicolor dynamics scales from QCD, this contribution is in the range of 200 –
400 GeV, but their masses can be different in models with non-QCD-like dynamics \cite{5}.

Production of technicolor particles has been studied at various present and future colliders such as Tevatron \cite{1}, LEP \cite{2}, NLC \cite{3} and the Muon Collider \cite{4}. The impact of PNGB on rare K meson decays induced through the exchange of color-singlet $\pi_1^T$ and color-octet $\pi_8^T$ technipions has been recently studied \cite{10} in the context of multiscale technicolor \cite{11} where typical limits of the order of $m_{\pi_8^T} \geq 250$ GeV were obtained.

Of special interest is the case of the isoscalar color-octet PNGB, the so-called technieta ($\eta_T$), since it can be produced via gluon fusion through the heavy quark loop. In the near future, the upgraded 2 TeV Tevatron collider will be the most promising machine for technieta search. The channel $p\bar{p} \rightarrow \eta_T \rightarrow t\bar{t}$ was initially studied by Appelquist and Triantaphylou \cite{12} in the context of the one family technicolor model \cite{13}. More recently Eichten and Lane \cite{14} have studied the same channel in the context of walking technicolor. They concluded that a technieta with mass in the range $M_{\eta_T} = 400 - 500$ GeV doubles the top quark production cross section at Tevatron and hence it is excluded in this mass range.

In our study we would like to concentrate on the search of technieta with mass below the $t\bar{t}$ threshold, which is not constrained by the $t\bar{t}$ production process.

The $p\bar{p} \rightarrow \eta_T \rightarrow gg$ and $p\bar{p} \rightarrow \eta_T \rightarrow g\gamma$ processes were studied in the early eighties by Hayot and Napoly \cite{15} in the framework of the one family technicolor model. They showed that, due to the signal-to-background ratio, the gluon-photon channel is preferable. Nevertheless, theirs results must be taken only as qualitative since no complete and detailed analysis were made.

In this letter we perform a complete realistic study of the $p\bar{p} \rightarrow \eta_T \rightarrow \gamma + \text{jet}$ process in order to understand Tevatron potentials for $\eta_T$ search with the mass below the $t\bar{t}$ thresh-
old. We consider three different scenarios: the one family model \[14\], top-color assisted technicolor (TC2) \[17\] and multiscale technicolor \[12\].

**II. EFFECTIVE COUPLINGS**

The color-octet technieta couples to gluons and photons through the Adler-Bell-Jackiw anomaly \[18\]. This effective coupling can be written as:

\[
A(\eta_T \rightarrow B_1 B_2) = \frac{S_{\eta_T B_1 B_2}}{4\pi^2 \sqrt{2} F_Q} \epsilon_{\mu \nu \alpha \beta} \epsilon_1^\mu \epsilon_2^\nu k_1^\alpha k_2^\beta
\]

where \( \epsilon_i^\mu \) and \( k_i^\mu \) represents the polarization and momentum of the vector boson \( i \). In our case the factors \( S_{\eta_T B_1 B_2} \) are given by \[19\] :

\[
S_{\eta_T g g} = g_s^2 d_{abc} N_{TC}
\]

and

\[
S_{\eta_T g \gamma} = \frac{g_s e}{3} \delta_{ab} N_{TC}
\]

where \( g_s = \sqrt{4\pi\alpha_s}, \ e = \sqrt{4\pi\alpha} \) and \( \alpha \) and \( \alpha_s \) are the electromagnetic and strong coupling constant, and \( N_{TC} \) is the number of technicolors (we take \( N_{TC} = 4 \))

The technieta coupling to quarks can be written as:

\[
A(\eta_T \rightarrow q \bar{q}) = \frac{m_q}{F_Q} \bar{u}_q \gamma^5 \frac{\lambda_a}{2} v_q.
\]

With these couplings we can compute the technieta partial widths:

\[
\Gamma(\eta_T \rightarrow gg) = \frac{5g_s^2 N_{TC} M_{\eta_T}^3}{384\pi^3 F_Q^2},
\]

\[
\Gamma(\eta_T \rightarrow g\gamma) = \left( \frac{N_T e g_s}{4\pi F_Q} \right)^2 \frac{M_q^3}{576\pi}
\]
\[ \Gamma(\eta_T \rightarrow q\bar{q}) = \frac{m_q^2 M_{\eta_T} \beta_q}{16\pi F_Q^2} \]  

(7)

where

\[ \beta_q = \sqrt{1 - \frac{4m_q^2}{M_{\eta_T}^2}}, \]

(8)

\( m_q \) is the quark mass and \( M_{\eta_T} \) is the technieta mass.

These expressions were used to calculate the technieta total width. From equations (3) and (8) we can see that:

\[ \frac{\Gamma(\eta_T \rightarrow \gamma g)}{\Gamma(\eta_T \rightarrow gg)} = \frac{2\alpha_s}{15\alpha_s} = 8.7 \times 10^{-3}. \]

(9)

Hence, the decay channel \( \eta_T \rightarrow g\gamma \) is suppressed, but due to the more manageable background it is expected to provide a larger statistical significance.

The constant \( F_Q \) that appears in the couplings is the PNGB decay constant. Its value is model-dependent. In this work we consider three values for \( F_Q \): \( F_Q = 125 \text{ GeV} \) for the one family technicolor model, \( F_Q = 80 \text{ GeV} \) for top-color assisted technicolor and \( F_Q = 40 \text{ GeV} \) for multiscale technicolor.

Some typical values of the technieta partial and total widths are shown in Table I for \( \alpha_s = 0.119 \) and \( M_{\eta_T} = 250 \text{ GeV} \).

III. SIGNAL AND BACKGROUND RATES

With the couplings discussed in the previous section we can show that the partonic cross section for the process \( gg \rightarrow \eta_T \rightarrow \gamma g \) can be written as:

\[ \hat{\sigma} = \frac{5\hat{s}^3 \pi^3}{384} \left( \frac{N_T e g_s}{12\sqrt{2\pi} F_Q} \right)^2 \left( \frac{N_T \alpha_s}{\sqrt{2\pi} F_Q} \right)^2 \frac{1}{(\hat{s} - M_{\eta_T}^2)^2 + \Gamma_{\eta_T}^2 M_{\eta_T}^2} \]

(10)
We wrote a Fortran code in order to convolute the above partonic cross section with the CTEQ4M partonic distribution functions (with $Q^2 = M^2_{\eta_T}$). Because the technieta coupling with quarks is proportional to the quark mass, we neglect the technieta production via $q\bar{q}\eta_T$ interaction. In the case of gluon fusion we only take into account the $s$-channel contribution, which is dominant at the resonance. It must be noted that gauge invariance is preserved due to the Levi-Civita tensor present in equation (3). Table II shows the cross section (in pb) calculated for different values of $M_{\eta_T}$ and $F_Q$ at $\sqrt{s} = 2000$ GeV with a cut in the transverse photon and jet momentum $p_{T\gamma,j} > 10$ GeV. These values for the cross section agree, with a precision of one percent, with a narrow width approximation. The cross section becomes sizeable for low values $M_{\eta_T}$ and $F_Q$, being of the order of a picobarn. However, the cross section for the background $p\bar{p} \rightarrow \gamma g$ and $p\bar{p} \rightarrow \gamma q$ processes is $\sigma_{\text{back}} = 2.14 \times 10^4$ pb, which is a factor of $10^4$ larger than the signal. This situation clearly shows that a detailed kinematical analysis is necessary to work out the strategy to suppress the background as strongly as possible in order to extract the signal.

**IV. COMPLETE SIMULATION OF SIGNAL AND BACKGROUND**

In order to perform a complete signal and background simulation we use the PYTHIA 5.7 generator. Effects of jet fragmentation, initial and final state radiation (ISR+FSR) as well as smearing of the jet and the photon energies have been taken into account. Since the process $\eta_T \rightarrow \gamma g$ was absent in PYTHIA we created a generator for $gg \rightarrow \eta_T \rightarrow \gamma g$ process and linked it to PYTHIA as an external user process.

In our simulation we have used CTEQ4M structure function and have chosen $Q^2 = M^2_{\eta_T}$ for the signal.
In this framework we study, for both signal and background, distributions of the transverse photon momentum, transverse jet momentum, rapidity and invariant mass in order to find the optimal kinematical cuts for signal subtraction. These distributions are shown in Fig. 1. We can see that the ISR+FSR and energy smearing effects make the mass distribution (Fig. 1(a)) quite broad. Notice the difference in $p_t$ distribution for photons (Fig. 1(b)) and jets (Fig. 1(c)). The fact that the distribution for jets is wider than for photons is due to initial and final state radiation.

We have found the following optimal set of kinematical cuts:

\begin{align}
 p_{t\gamma,jet} &> \frac{M_{\eta T}}{2} - 40 \text{ GeV} \\
 M_{\eta T} - \frac{M_{\eta T}}{10} &\leq M_{\gamma,jet} \leq M_{\eta T} + 10 \text{ GeV}
\end{align}  

To take into account the detector pseudorapidity coverage we have chosen the following cuts for $\eta_{\gamma}$ and $\eta_{jet}$:

\begin{align}
 |\eta_{\gamma}| &\leq 1.5, \quad |\eta_{jet}| < 3
\end{align}  

Table III shows the signal and background cross sections after those cuts have been applied. It is interesting to look at the values of the significance which is written as $\frac{\sqrt{L_{\sigma_{\text{signal}}}}}{\sqrt{L_{\sigma_{\text{back}}}}}$ and characterizes the statistical deviation of the number of the observed events from the predicted background. The significance as a function of the $M_{\eta T}$ for different technicolor models is shown in (Fig. 3(a), where we have assumed a luminosity of $L = 2000 \text{ pb}^{-1}$ for the Tevatron Run II. For multiscale technicolor ($F_Q = 40 \text{ GeV}$), the significance is above the $2\sigma$ 95% CL exclusion limit for technieta mass less than 350 GeV while for a $5\sigma$ discovery criteria one obtains $M_{\eta T} > 266 \text{ GeV}$ mass limit. For the top-color assisted technicolor model
(\(F_Q = 80\) GeV) one can establish only a 95% CL exclusion limit \(M_{\eta_T} > 175\) GeV. For the one family technicolor model the significance is too small to establish any limits on \(M_{\eta_T}\).

In our study we compared results based on PYTHIA simulation and results obtained using MADGRAPH [21] and HELAS [22] without taking into account ISR+FSR and the energy smearing effects. The corresponding significance for this case is shown in Fig.3(b). One can see that for this ideal case respective values of significance is about 2.5 times higher than in the case when we model the realistic situation using PYTHIA. The differences between Fig.3 (a) and (b) clearly shows the importance of the complete simulation of the signal and background in order to obtain realistic results.

Finally it is worth pointing out that the study of the \(b\bar{b}\) signature would lead to similar bounds on the \(\eta_T\) mass. This is because the signal for \(b\bar{b}\) final state will be roughly increased by a factor 10 (see Table [1]) but the background will be about two orders higher than that for \(\gamma + jet\) signature. This would lead to the same values of the significance as for \(\gamma + jet\) final state. However, one should take into account also the efficiency of b-tagging which will decrease the significance.

**CONCLUSIONS**

We have studied the potential of the upgraded Tevatron collider for the \(\eta_T\) search with \(\eta_T \rightarrow \gamma + g\) decay signature and mass below the \(t\bar{t}\) threshold. Results have been obtained for the one family model, top-color assisted technicolor and multiscale technicolor.

We found that for multiscale technicolor model, Tevatron can exclude \(M_{\eta_T}\) up to 350 GeV at 95%CL, while the 5\(\sigma\) discovery limit for \(\eta_T\) is 266 GeV. For the top-color assisted technicolor model one can only put a 95%CL lower limit on \(\eta_T\) mass equal to 175 GeV while
for one family technicolor model the significance is too small to establish any limit at all. Study of $b\bar{b}$ final state signature is not expected to give better limits on the $\eta_T$ mass.

We have performed a complete simulation of the signal and background and have shown the importance of taking into account the effects of jet fragmentation, initial and final state radiation, as well as smearing of the jet and the photon energies.

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### TABLES

| $\Gamma \setminus F_Q$ | 40 GeV | 80 GeV | 125 GeV |
|----------------------|--------|--------|---------|
| $\eta_T \to ag$     | 0.008  | 0.002  | $8 \times 10^{-4}$ |
| $\eta_T \to gg$     | 0.929  | 0.232  | 0.095   |
| $\eta_T \to bb$     | 0.078  | 0.019  | 0.008   |
| $\eta_T \to \text{all}$ | 1.015  | 0.254  | 0.104   |

**TABLE I.** Partial widths (in GeV) for $M_{\eta_T} = 250$ GeV.

| $M_{\eta_T} \setminus F_Q$ | 40 GeV | 80 GeV | 125 GeV |
|-----------------------------|--------|--------|---------|
| 150 GeV                     | 6.00   | 1.50   | 0.62    |
| 200 GeV                     | 2.58   | 0.65   | 0.27    |
| 250 GeV                     | 1.17   | 0.29   | 0.12    |
| 300 GeV                     | 0.55   | 0.14   | 0.06    |
| 340 GeV                     | 0.31   | 0.08   | 0.03    |

**TABLE II.** Total cross section in pb for the process $pp \rightarrow \eta_T \rightarrow g\gamma$ with $\sqrt{s} = 2000$ GeV.
| $M_{\eta r} \backslash F_Q$ | 40 GeV | 80 GeV | 125 GeV | Background |
|--------------------------|--------|--------|---------|------------|
| 150 GeV                  | 1.53   | 0.38   | 0.16    | 60.72      |
| 200 GeV                  | 0.63   | 0.16   | 0.06    | 15.51      |
| 250 GeV                  | 0.26   | 0.07   | 0.03    | 4.53       |
| 300 GeV                  | 0.11   | 0.03   | 0.01    | 1.72       |
| 340 GeV                  | 0.06   | 0.01   | $6 \times 10^{-3}$ | 0.94       |

TABLE III. Signal and background cross sections in pb for $\sqrt{s} = 2000$ GeV after cuts.
FIG. 1. Distributions of invariant mass (a), photon transverse momentum (b), jet transverse momentum (c), photon rapidity (d) and jet rapidity (e) for signal (dashed line) and background (solid line) before any cut. We have assumed $M_{\eta_T} = 250 \text{ GeV}$ and $F_Q = 40 \text{ GeV}$. 
FIG. 2. Invariant mass distribution for signal (dashed line) and background (solid line) after cuts, $M_{\eta_T} = 250$ GeV and $F_Q = 40$ GeV.

FIG. 3. Significance as a function of $M_{\eta_T}$ for multiscale technicolor (solid line), top-color assisted technicolor (dashed line) and one family technicolor (dotted line), based on results obtained with (a) and without (b) taking into account ISR+FSR and energy smearing effects.