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Can a light technipion be discovered at the Tevatron if it decays to two gluons?

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Abstract

In multiscale and topcolor–assisted models of walking technicolor, light, spin–one technihadrons can exist with masses of a few hundred GeV; they are expected to decay as $\rho_T \to W\pi_T$. For $M_{\rho_T} \simeq 200\,\mathrm{GeV}$ and $M_{\pi_T} \simeq 100\,\mathrm{GeV}$, the process $p\bar{p} \to \rho_T \to W\pi_T$ has a cross section of about a picobarn at the Tevatron. We demonstrate the detectability of this process with simulations appropriate to Run II conditions, for the challenging case where the technipion decays dominantly into two gluons.

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Color–singlet technipions, $\pi_T^\pm$ and π_T^0, are the pseudo–Goldstone bosons of multiscale technicolor [1] and topcolor–assisted technicolor [2, 3, 4, 5], and are expected to be the lightest particles associated with the new physics. These technipions couple to fermions in a similar fashion as the standard model Higgs boson, with a magnitude set by the technipion decay constant F_T, but have no tree level couplings to W or Z gauge bosons. Consequently, technipions can be produced singly at hadron colliders through tree–level quark annihilation or one–loop gluon fusion processes. If the quark annihilation process is dominant, then the production rate is feeble, and the signal is a dijet peak, maybe with heavy flavor. There is little hope of distinguishing this from QCD heavy flavor backgrounds. If gluon fusion is dominant, then the production rate can be large, but the signal is a digluon peak, with daunting backgrounds, or a rare $\gamma\gamma$ peak. It may be possible to observe the latter at the Large Hadron Collider (LHC) or possibly even the Tevatron, but this is still an open question.

On the other hand, technivector mesons also arise in technicolor models, and these can be produced at substantial rates through their mixing with gauge bosons [6, 7]. The technivector mesons in question are an isotriplet of color-singlet ρ_T and the isoscalar partner ω_T. Because techni-isospin is likely to be a good approximate symmetry, ρ_T and ω_T should have equal masses. The enhancement of technipion masses due to walking technicolor [8] suggests that the channels $\rho_T \to \pi_T\pi_T$ and $\omega_T \to \pi_T\pi_T\pi_T$ are kinematically closed. Thus, the decay modes $\rho_T \to W_L\pi_T$ and $Z_L\pi_T$, where W_L, Z_L are longitudinal weak bosons, and $\omega_T \to \gamma\pi_T$ may dominate [1]. In recent phenomenological analyses, it has been assumed that π_T^0 decays into $b\bar{b}$. The presence of heavy flavor, plus an isolated lepton or photon, provides clear signatures for these processes. It has been demonstrated that such signals can be easily detected in Run II of the Fermilab Tevatron [10], and experimental searches following this prescription have been carried out on the Run I dataset [11].

However, it is quite possible that light technipions contain colored technifermions, in which case the decay $\pi_T^0 \to gg$ may contribute significantly or dominate if the number of technicolors N_{TC} is large [12, 13]. In this case, the signature of technivector production is γ or $W + 2$ jets, and the backgrounds are correspondingly more severe. We present simulations of $\bar{p}p \to \rho_T^\pm \to W_L^\pm\pi_T^0$ for the Tevatron collider with $\sqrt{s} = 2\,\mathrm{TeV}$ and an inte-

grated luminosity of $2\,\mathrm{fb}^{-1}$, corresponding to that expected in Run II. We follow the previous analysis which studied $\pi_T^0 \to b\bar{b}$ [10] in using topological cuts to exploit the resonant production process and thus enhance the signal–to–background ratio. For the cross sections and cuts we use in this paper, the signal stands out well above the background. We would expect that the complementary channel $\bar{p}p \to \rho_T^0 \to Z_L \pi_T^0$ with $Z \to \ell^+\ell^-$ might add some sensitivity, but we have not considered this in detail. For the case of $Z \to \nu\bar{\nu}$, the fake $\not{E}_T$ background from QCD multijet production is likely to overwhelm the signal.

We have used PYTHIA 6.1 [14] to generate $\bar{p}p \to \rho_T^\pm \to W^\pm \pi_T^0$ and $\pi_T^0 \to gg$ at the Tevatron Collider with $\sqrt{s} = 2\,\mathrm{TeV}$. The cross section is calculated under the assumptions of [10]. The total production cross section times the branching ratio for the decay of the W–boson into electrons, $\sigma \cdot B(W^\pm \to e^\pm)$, is in the range 0.1–0.7 pb for $m_{\rho_T} \gtrsim 200$ GeV and $m_{\pi_T} \gtrsim 100$ GeV. The parameter dependence is illustrated in Fig. 1. For detailed studies we have focused on a typical point, with $m_{\rho_T} = 220\,\mathrm{GeV}$ and $m_{\pi_T} = 110\,\mathrm{GeV}$, where $\sigma \cdot B = 0.45\,\mathrm{pb}$.

The partial width for the decay $\pi_T^0 \to gg$ can be calculated using the (energy–dependent) expression

$$\Gamma(\pi_T \to gg) = \frac{1}{128\pi^3 F_T^2} \alpha_s^2 C_{\pi_T} N_{TC}^2 s^{3/2}, \tag{1}$$

while the competing decay has the width

$$\Gamma(\pi_T \to b\bar{b}) = \frac{1}{4\pi^2 F_T^2} 3 p_f C_f m_b^2. \tag{2}$$

In these expression, $\sqrt{s}$ is the resonance mass, p_f is the b–quark momentum in the resonance rest frame, and the constants C_{π_T} and C_f account for the flavor content of the technipion wave function. By comparing these expressions, we find that the $\pi_T^0 \to gg$ decay begins to dominate when $N_{TC} \gtrsim 3-4$. For the purposes of this study, we have forced the π_T^0 to decay always into the gg final state. Our final results refer to the quantity $\sigma \cdot B$ denoted above times the branching ratio for $\pi_T^0 \to gg$.

The dominant background, $W^\pm$ jet jet, was calculated in two ways: firstly

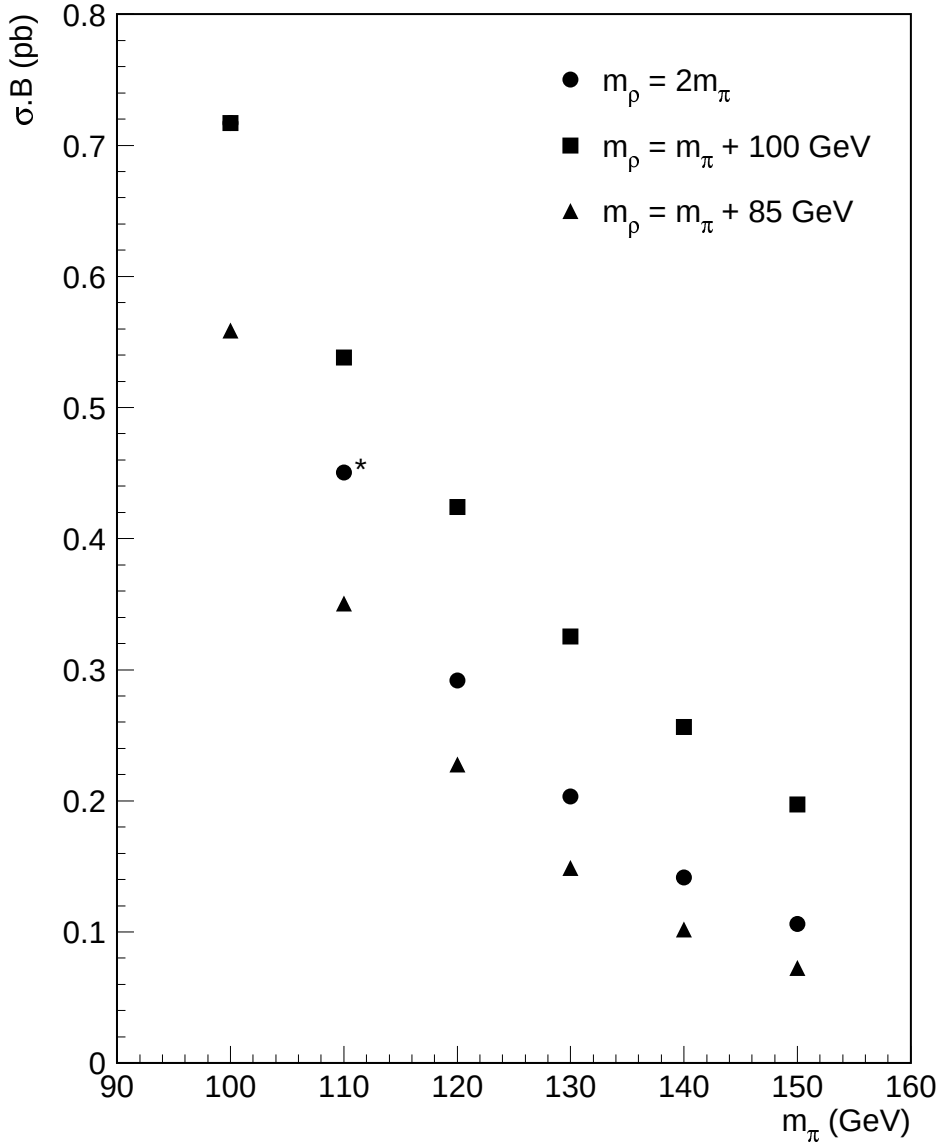

Figure 1: Production cross section for $p\overline{p} \to \rho_T \to \pi_T^0 W$, multiplied by $B(W \to e\nu) = 0.105$, for various masses of ρ_T and π_T. The asterisk denotes the point ($m_{\rho_T} = 220, m_{\pi_T} = 110$ GeV) which was studied in detail.

using the standard implementation of PYTHIA for the processes $qg \to Wq'$ and $q\overline{q}' \to Wg$ with a minimum W transverse momentum of 15 GeV/c; and secondly by interfacing the explicit "2 to 3" processes (*e.g.* $q\overline{q}' \to Wgg$, $qg \to Wq'g$ and others) with PYTHIA. In the latter case, the showering scale for initial state radiation is the same as the factorization scale $Q^2_{ISR} = m^2_W$, while for final state radiation it is the same as the invariant mass of the two final state partons, $Q^2_{FSR} = m^2_{jj}$. Representative color flows are used to connect the initial state to the final state. The two separate calculations are found to be in excellent agreement.

Jets were found using the clustering code provided in PYTHIA with a cell size of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, a cone radius $R = 0.7$ and a minimum jet E_T of 5 GeV. Cell energies were smeared using a calorimeter resolution σ_E of $0.5\sqrt{E(\mathrm{GeV})}$[9]. Missing transverse energy $\not\!\!E_T$ was estimated by taking the vector sum of the momenta of all clusters of energy found in the calorimeter with $E_T > 5\,\mathrm{GeV}$. In a previous study [10] this was found to give a reasonable representation of the $\not\!\!E_T$ resolution of the DØ detector.

Selected events were required to have an isolated electron, large missing energy, and two or more jets. The kinematic selections applied were:

- Electron: $E_T > 20\,\mathrm{GeV}$; pseudorapidity $|\eta| < 1.0$;
- Missing energy: $\not\!\!E_T > 20\,\mathrm{GeV}$;
- Two or more jets with $E_T > 20\,\mathrm{GeV}$; and $|\eta| < 1.25$, separated from the lepton by at least $\Delta R = 0.7$
- Leading jet $E_T > 40\,\mathrm{GeV}$.

Since the technipion was forced to decay into gluons, whose large color-charge leads to a high probability for final state radiation, the technipion mass was estimated by:

$$m_{jj(j)} = \begin{cases} \text{invariant mass}(jet_1, jet_2, jet_3) & \text{if } E_T(jet_3) > 15\,\mathrm{GeV} \\ \text{invariant mass}(jet_1, jet_2) & \text{otherwise} \end{cases}$$

This algorithm seeks to recombine some of the final state radiation. We have not worked extensively to optimize our algorithm, since the experimental situation will undoubtedly be more complicated than we have simulated. Our goal is to demonstrate that it is possible to achieve a better resolution than the naive dijet mass. Figure 2 shows that it gives a significantly improved technipion mass resolution compared with naively taking the invariant mass of the leading two jets, at the cost of introducing a high-side tail from initial-state radiation. The peak of the reconstructed mass is shifted downwards from its "true" value of 110 GeV by the cumulative effects of final state gluon radiation, fragmentation (particles emitted outside the cone), and muons and neutrinos within the jets. These effects also make the mass resolution much broader than the calorimetric energy resolution alone would imply.

A similar mass estimation technique might be applicable to the $b\bar{b}$ invariant mass in such cases as $H \to b\bar{b}$ searches. We note, however, that the requirement that there be displaced vertex tags within each of the candidate b jets already rejects much of the radiative contamination in the $b\bar{b}$ case. This is not, of course, possible for an object decaying to two gluon jets.

Requiring that the lepton and jets be central in pseudorapidity exploits the fact that the signal events will tend to be produced with larger center-of-mass scattering angles than the background.

Figure 3(a) shows the distribution of $m_{jj(j)}$ (as defined above) jets for signal events (dotted), background (dashed) and their sum (solid) passing these criteria for a luminosity of $2\,\mathrm{fb}^{-1}$.

The particular kinematics of $\rho_T \to W_L \pi_T$ suggests other cuts that can discriminate signal from the $W+$jets background. The small Q-value for the ρ_T decay causes the π_T (and the W_L) to have low longitudinal and transverse momenta, and the jets from the technipion decay to be similar in energy and to have a large opening azimuthal angle $\Delta\phi(jj)$. These expectations were borne out by simulated distributions in these variables. Cutting on these variables then helps to suppress the Wjj background to $\rho_T \to W_L \pi_T$.

Consequently, we have taken the selected events in Fig. 3(a) and applied additional topological cuts:

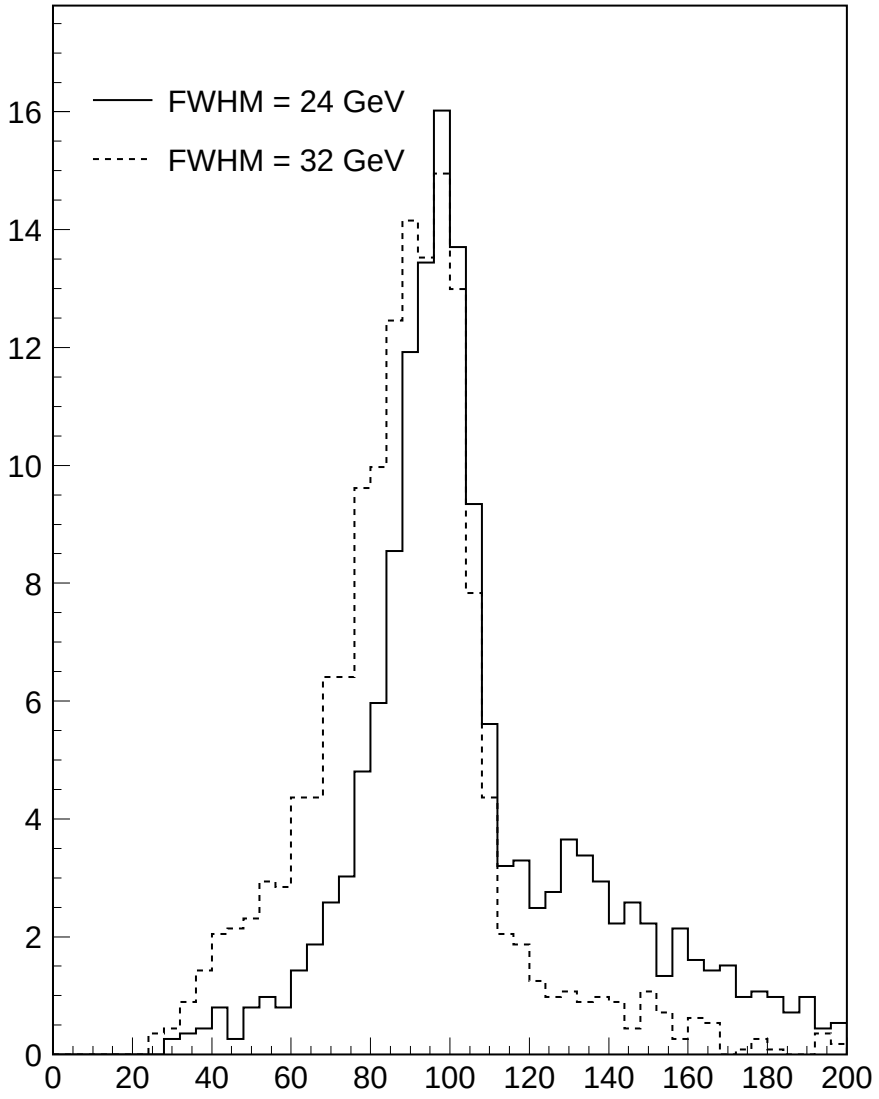

Figure 2: Technipion mass resolution in the decay $\pi_T^0 \to gg$, for signal events passing the kinematic cuts. The technipion mass was estimated firstly as the invariant mass of the two leading jets (dashed line) and secondly by $m_{jj(j)}$ as defined in the text (solid line). The full-width at half maximum is reduced from 32 to 24 GeV by the latter definition.

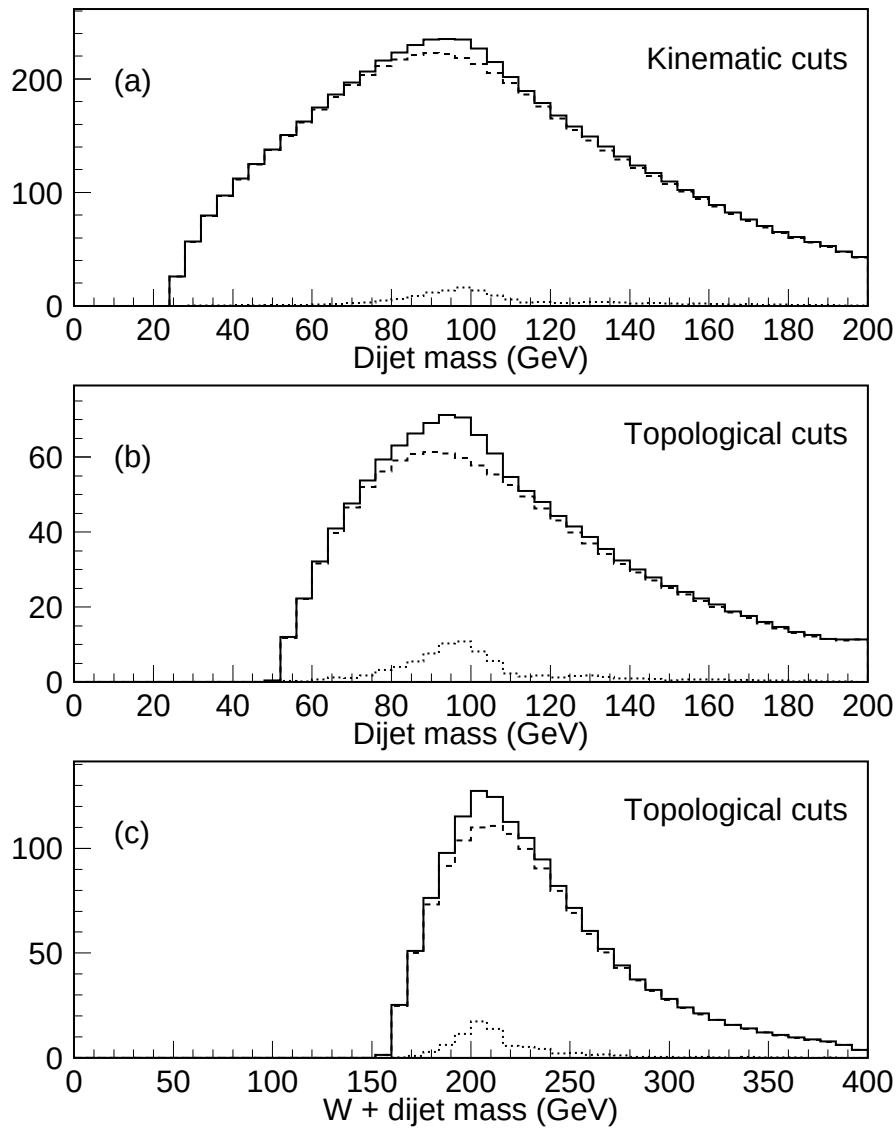

Figure 3: Invariant mass distributions for π_T^0 signal (dotted), Wjj background (dashed), and their sum (solid). The vertical scale is events per bin in 2 fb^{-1} of integrated luminosity. Plot (a) shows the dijet mass $m_{jj(j)}$ with kinematic selections only, (b) with the addition of topological selections, and (c) shows the invariant mass of the $W + \pi_T^0$ system for the same sample as (b).

- $35 < p_T^{jj(j)} < 65\,\mathrm{GeV}$;
- $|p_L^{jj(j)}| < 55\,\mathrm{GeV}$;
- $(E_T(jet_1) - E_T(jet_2))/(E_T(jet_1) + E_T(jet_2)) < 0.5$;
- $\Delta\phi(jj) > 90°$.

The dijet transverse momentum $p_T^{jj(j)}$ and longitudinal momentum $p_L^{jj(j)}$ are calculated from the leading three (two) jets if the third jet has E_T greater (less) than 15 GeV, just as is the invariant mass $m_{jj(j)}$. The precise numerical values in these cuts of course depend on the technirho and technipion masses and their difference. An experimental search would need to re-optimize the cut values for each point in parameter space, as was in fact done in [11].

The effects of the topological cuts are shown in Fig. 3(b). The signal-to-background at 100 GeV is improved from $\sim 1:12$ to $\sim 1:5$ by these cuts. A visible excess is apparent in this distribution, which corresponds to the π_T^0 mass. Also, the signal distribution peaks in a different mass bin than is expected for the background.

Fig. 3(c) shows the corresponding invariant mass distribution after topological cuts for the Wjj system, which corresponds roughly to the ρ_T mass. Here the W four-momentum was reconstructed from the lepton and $\not{E}_T$, taking the lower-rapidity solution in each case. Unfortunately, while the signal-to-background is also good in the peak region of this plot, the cuts have resulted in the signal and background shapes being similar. Unlike the previous figure a deviation from the expected background shape is not visible.

To estimate the significance of the signal, we counted signal S and background B events within ± 16 GeV of the peak. We find $S = 85$ and $B = 1716$ from Fig. 3(a), yielding $S/B = .05$ and $S/\sqrt{B} = 2.04$. From Fig. 3(b), we find $S = 54$ and $B = 467$, with $S/B = .12$ and $S/\sqrt{B} = 2.51$. Including the decays of the W into muons, and assuming the same efficiency as for electrons, the significance of the signal distribution in Fig. 3(b) is increased to 3.55. Therefore, if two experiments collect 2 fb^{-1} of data in Run II, then

a 5 sigma deviation might be observed in the combined data sets. Additionally, the nearly degenerate ω_T may produce a γgg signal of comparable significance.

In conclusion, we have shown that the low-scale technicolor signature $\rho_T \to W\pi_T$ can be discovered in Run II of the Tevatron for production rates as low as a few picobarns, even if the decay mode $\pi_T^0 \to gg$ dominates.

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