DØ- CONF note 4579

A Search for Techniparticle Production in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV in the Mode $\rho_T \rightarrow W(\rightarrow e\nu) + \pi_T$

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URL: http://www-d0.fnal.gov

(Dated: August 26, 2004)

A study of $e\nu + b\overline{Q}$ production, where $\overline{Q} = \overline{b}, \overline{c}$-quark, at DØ using e + jets events in 238 pb^{-1} of integrated luminosity is presented. We select events with $b-$quark jets by identifying secondary vertices in the jets. We interpret our findings in terms of limits on the production of particles predicted by extended technicolor models and in particular for the production decay chain $\rho_T \rightarrow W(\rightarrow e\nu) + \pi_T$. In the absence of an excess over standard model background, we compute a 95% C.L. upper limit on the techniparticle production cross section for the mass combination, $m(\rho_T) = 200$ GeV and $m(\pi_T) = 105$ GeV of 6.4 pb. For certain values of the model parameters, we can rule out this mass combination for a range of the mass parameter M_V between 200 and 500 GeV.

Prepared for 2004 Summer Conferences

I. INTRODUCTION

Events with $e\nu + b\overline{Q}$, where $\overline{Q} = \overline{b}, \overline{c}$-quark, in the final state are of interest because they can be produced by several proposed mechanisms of electroweak symmetry breaking. The standard model Higgs boson could be produced in $p\overline{p}$ collisions at the Tevatron in association with a W boson. For $m_H < 130$ GeV, the Higgs boson decays predominantly into $b\overline{b}$ and the W boson decays to $e\nu$ with a branching fraction of about 1/9. Extended technicolor models [1] predict the existence of a large number of new particles, e.g. technirho (ρ_T) and technipion (π_T), some of which may have masses as low as a few hundred GeV. One process to produce them at the Tevatron is $p\overline{p} \to \rho_T \to W + \pi_T$ followed by π_T decaying to $b\overline{b}$ or $b\overline{c}$[1].

Known standard model processes can also produce $e\nu b\overline{b}$ final states. The dominant process is production of W bosons in association with a $b\overline{b}$ pair. Other processes are various top quark decay modes.

Events that contain a high-p_T electron and two jets are relatively easy to trigger on using the electron signature. However such a sample is dominated by $W+$ jets production, in which most of the jets originate from the fragmentation of gluons and/or light quarks. Thus the identification of jets from the fragmentation of b-quarks is a crucial tool to identify $e\nu + b\overline{Q}$ events and remove the dominant backgrounds. In this analysis, we use the property that b-hadrons have a relatively large lifetime. We reconstruct the secondary vertex from the decay of the long-lived b-hadrons using tracks in jets which have a large impact parameter with respect to the primary $p\overline{p}$ interaction vertex.

A. Signal

Technihadrons at the Tevatron are predicted to be produced in association with an Electroweak Gauge Boson. In this note we study the properties of $W\pi_T$ events produced in $p\overline{p}$ collisions via the ρ_T resonance: $p\overline{p} \to \rho_T \to W\pi_T$, where $W \to e\nu$. and $\pi_T^0 \to b\overline{b}$(or $\pi_{\mathrm{T}}^+ \to \mathrm{c\overline{b}}$)(or $\pi_{\mathrm{T}}^- \to \mathrm{b\overline{c}}$) (Fig. 1). We chose two different mass combinations for π_T and ρ_T for simulating the signal samples. Table I lists the assumed masses, which are chosen such that the first set is at the edge of the excluded region by CDF and LEP-II[2] and the second set lies in the open search region and within the sensitivity region for searches during Run II. The corresponding production cross sections are calculated with PYTHIA V6.224 [3]. However, the previously published searches by CDF for technicolor particles [2] use older calculations. When comparing limits this must be taken into account.

While computing the cross sections we use baseline values for the various model parameters:

- The symmetry group is SU(N_{TC}) with N_{TC} set to 4.
- The number of technidoublets $N_D = 9$
- $Q_U + Q_D = \frac{4}{3}$, where Q_D and Q_U are the charges of T_U and T_D techniquarks.
- Sin(χ) = 1/3, where χ is the mixing angle between π_T and W_L, the longitudinal component of the W boson.

Since the cross section is calculated at LO, we account for NLO effects by scaling the cross sections by a constant K-factor of 1.3 [4]. In the TCSM-2 model [1] branching ratios for the processes $\pi_T^0(\to b\overline{b})$ and $\pi_T^+(\to c\overline{b})$ are 0.88 and 0.91 respectively. These are included in the values shown in Table I. The dependence of the cross sections on the mass parameter M_V is also shown in the table. The amplitude of the decay of a color singlet vector meson to a transversely polarized gauge boson and a technipion is made of axial and vector currents. They are inversely dependent on two parameters called M_A and M_V respectively. We set $M_V = M_A$ as suggested in [1]. M_V controls the decay into transversely polarized bosons vs. longitudinal ones. So for instance, for small values of M_V, $\rho_T \to \gamma\pi_T$ increases and $\rho_T \to W\pi_T$ decreases. We also use B($W \to e\nu$) = 0.1068 for the final limit calculation in this channel.

B. Background

The sources of background to the technicolor signals are the standard model processes $Wb\overline{b}$, Wbj, Wcj, $Wc\overline{c}$ production, $t\overline{t}$ decays, events with single top quark production, and di-boson production events.

Some of the sources of backgrounds which are considered in this analysis are listed with their cross sections in Table II. The sample labeled as $Wjj(+HF\ b-\mathrm{tag})$ predominantly contains Wjj, Wbj, Wcj, Wcc events. We rely on this sample to estimate the Wbj, Wcj, Wcc backgrounds. We do not use the Wjj events from this MC, but rather derive this component of the background from our data sample. $Wb\overline{b}$ background is estimated separately. All MC samples were generated via the full DØ Monte Carlo simulation, including processing via DØGeant and the DØ reconstruction software.

TABLE I: Cross Sections for two different Technicolor mass combinations as a function of the mass parameter M_V.

$m(\rho_T)$	$m(\pi_T)$	M_V	cross section $\times$ B(pb) $\rho_T \to W + \pi_T$		Total (pb)
			$\pi_T^{\pm}(\to c\bar{b})$ or $(\pi_T^{-} \to b\bar{c})$	$\pi_T^{0}(\to b\bar{b})$	
175 GeV	85 GeV	100	3.0	2.3	5.3
175 GeV	85 GeV	200	3.3	2.3	5.7
175 GeV	85 GeV	300	3.3	2.5	5.8
175 GeV	85 GeV	500	3.7	2.3	6.0
200 GeV	105 GeV	100	2.9	2.2	5.1
200 GeV	105 GeV	200	3.7	2.9	6.6
200 GeV	105 GeV	300	4.0	3.3	7.3
200 GeV	105 GeV	500	4.5	3.3	7.8

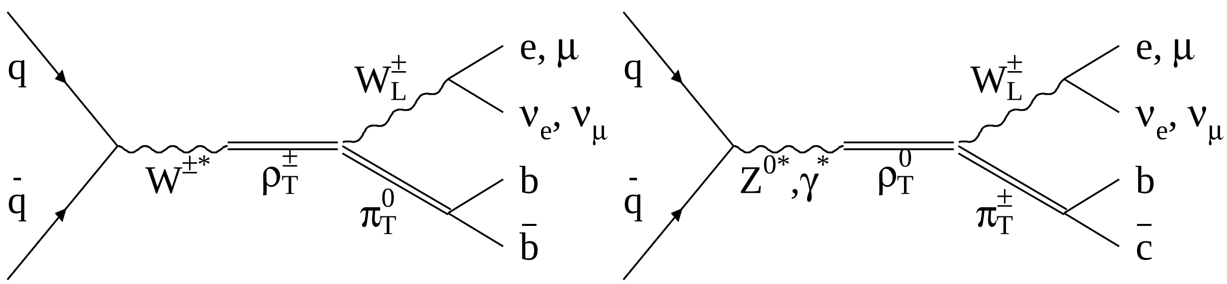

FIG. 1: Feynman Diagram for technirho production and decay.

Production of W+jets with one of the light quarks misidentified as a b-jet also contributes to the background. In addition, there is a contribution to the background from QCD multijet events, where one of the jets is misidentified as an electron and either a jet in the event is mistagged as a b-quark, or a real b-jet is found. The heavy flavor content for this process is not negligible. These two "instrumental backgrounds" are determined from our data sample. The W+jets mistag background is determined by convoluting the jets in the W+jets event sample with the probability for being mis-identified as a b-jet. The QCD multijet events background is determined by using events with low missing E_T which have a jet tagged as a b-jet using the secondary vertexing algorithm.

TABLE II: Physics Background Processes. We list their cross sections along with the generator (PYTHIA [3] OR ALPGEN [5]) USED.

process	generator	cross section (in pb)
$t\bar{t} \to \ell\nu\ b\bar{b}\ q\bar{q}$	pythia	2.95
$t\bar{t} \to \ell^{+}\nu\ell^{-}\nu\ b\bar{b}$	pythia	0.695
$W^{*} \to tb \to (e\nu + \tau\nu)bb$	pythia	0.115
$qtb \to q\ (e\nu + \tau\nu)bb$	pythia	0.258
$W(\to e\nu) + b\bar{b}$	alpgen	3.35
$Wjj(+HF\ b-\text{tag})$	alpgen	287.3
$W(\to e + \nu)$	pythia	2684
$W(\to \tau + \nu)$	pythia	2684
$WZ \to \ell + \nu\ b\bar{b}$	pythia	0.0542
$Z/\gamma \to e^{+}e^{-}(15 < m_{\ell\ell} < 60\ \text{GeV})$	pythia	528
$Z/\gamma \to e^{+}e^{-}(60 < m_{\ell\ell} < 130\ \text{GeV})$	pythia	245.7
$Z(\to e^{+}e^{-}) + b\bar{b}$	pythia	0.539

II. EVENT SAMPLE SELECTION

To select the event sample for the techniparticle search, we first identify events which have an electron with high transverse momentum accompanied by substantial missing E_T, indicative of a W boson in the final state. We require electron candidates to have transverse momentum $p_T > 20$ GeV, and pseudorapidity $|\eta| < 1.1$. The event is required to have a minimum missing E_T of 20 GeV. In addition we require that the transverse mass, $M_T(W)$, constructed from the electron and missing E_T be greater than 30 GeV. Only those events which have at least 2 jets with $p_T > 20$ GeV and $|\eta_{det}| < 0.9$ or $1.2 < |\eta_{det}| < 2.5$ are kept.

Events with π_T in the final state contain two b-jets or a b and c-jet, while at this stage of event selection, the dominant source of background is the production of a W boson accompanied by several light-quark and gluon jets. We can enhance the signal events in the sample by requiring that one of the jets in the event be identified as originating from a b-quark. We utilize the secondary vertex algorithm to identify b-quark jets. This algorithm is based on reconstruction of the location of the b-quark decay by using the Kalman Filter (KF) technique [6]. As a starting step this algorithm selects tracks with large transverse impact parameters and finds all two-track seed vertices from the selected tracks in the jet. Additional tracks are attached to the seeds according to the resulting chisquared contribution to the vertex based on the KF algorithm, until all tracks in the jet are exhausted. These vertices are then classified as secondary vertices based on their decay length, collinearity angle and the chisquared. The jet is considered b-tagged, if it has at least one secondary vertex with a large value of decay length significance S, where the S is defined as the decay length of the secondary vertex divided by its uncertainty. To determine the b-quark jet identification efficiency, we use a μ+jet data sample. This sample is expected to be rich in heavy flavor jets. We apply a correction derived from Monte Carlo (MC) to obtain the inclusive b-tagging efficiency. We parameterize the b-tagging efficiency as a function of jet p_T and η. The c-quark tagging efficiency is obtained by scaling the b-tagging efficiency derived from data by the ratio observed in $Z \to b\bar{b}$ and $Z \to c\bar{c}$ MC.

In order to understand the standard model backgrounds to the $e\nu b\overline{Q}$ final state, we need to understand the rate for misidentifying a jet from light quark or gluon fragmentation as a b-jet. To obtain the mistag rate, we use the jets with negative decay length significance in the jet trigger data (corrected for a small heavy flavor contamination and an asymmetry between positive and negative tags as observed in the light quark MC). The light quark mistag rate is parameterized as a function of the p_T and η of the jet. For this analysis, we use a b-jet definition which gives a b-jet efficiency of ~35% for a 0.25% light quark jet mistag rate.

Another, smaller, source of background is from multijet events with one of the jets is misidentified as an electron (e.g. a π^0 overlapping with the track of a charged particle) and significant p_T imbalance due to detector resolution. These mis-identification background sources are minimized by requiring that $E_T^W = |E_T(\text{ele})| + |\not{E}_T| > 65$ GeV.

The sample corresponds to an integrated luminosity of $\approx 238\text{pb}^{-1}$. This value is obtained by normalizing the observed inclusive $W \to e\nu$ sample to the number of expected events per pb^{-1}, determined from the physics processes listed in Table II, after subtracting instrumental backgrounds. The major contribution to the uncertainty on this quantity comes from the $W \to e\nu$ inclusive cross section and is estimated by studying the difference between NLO and NNLO MCFM cross sections [7].

III. SELECTION CUTS AND OPTIMIZATION FOR ρ_T AND π_T SEARCH

As noted earlier, the technirho (ρ_T) decays to a W boson accompanied by a technipion (π_T). The charged technipion (π_T^+) is expected to decay predominantly into $\bar{b}c$ quarks, while the neutral technipion decays most of the times to $b\bar{b}$ quarks. Therefore, we select events in which there is an electron and a neutrino, indicative of a W boson and at least one jet tagged as originating from a b-quark. We also restrict the number of jets in the event to two. We show distribution of basic kinematical quantities for this set of events in Figs. 2 and 3. At this stage of the analysis, the technipion signal is swamped by backgrounds from W+heavy flavor, mistags, $t\bar{t}$ and single top backgrounds.

In order to optimize the technipion signal over background, we study several topological variables. In particular, we optimize the following variables:

- $\Delta\phi(jj)$: the difference in ϕ between the two jets.
- $p_T(jj)$: the transverse momentum for the same dijet system.
- H_T^e: the scalar sum of p_T of the electron, and all the selected good jets in the event.

Figure 4, shows the distributions of the topological variables $\Delta\phi$, the $p_T(jj)$, and H_T^e. We find that the following values of the cuts on these various variables give us the best signal sensitivity for the mass combination $m(\rho_T) = 200$ GeV and $m(\pi_T) = 105$ GeV:

- $\Delta\phi(jj) > 2.2$
- $p_T(jj) < 75$ GeV
- $H_T^e <$ 200 GeV

Technicolor particles, ρ_T and π_T are expected to have narrow widths ($\sim$ 1 GeV/c^2). In addition to correlations between the two jets from the π_T decay, we expect these particle to be seen in the distributions of dijet invariant mass, $m(jj)$ and the invariant mass of the W-dijets, $m(Wjj)$.

To reconstruct the dijet invariant mass, $m(jj)$, the jets are chosen with the criteria described earlier. The $m(jj)$ distribution corresponds to the reconstructed π_T mass.

The invariant mass $m(Wjj)$ is the invariant mass of the dijet system combined with the W (reconstructed from the electron and missing p_T in the event). This is equivalent to reconstructing the mass of the technirho resonance (ρ_T). While computing $m(Wjj)$, we reconstruct the W boson four vectors from the electron and the missing p_T using the W mass constraint to solve for the p_z of the neutrino. Out of the two possible solutions for the neutrino p_z, we take the smaller value, and in the case of a complex solution, we take the real part of the solution.

In Fig. 5, we plot the distributions of $m(jj)$, and $m(Wjj)$ for events with 2 jets (including one with a b-tag). We expect to observe two narrow simultaneous resonances corresponding to the production of ρ_T and π_T in the $m(jj)$ and $m(Wjj)$ distributions. We plot $m(Wjj)$ against $m(jj)$ in Fig. 6 after applying the selection on the topological variables. If the techniparticles are produced, then we expect a clustering of events as shown in the bottom right plot of this figure. This clustering corresponds to $m(\rho_T) = 200$ GeV and $m(\pi_T) = 105$ GeV. For the final event selection, we impose a mass window cut which corresponds to the requirement: $72.5 < m(jj) < 125$ and $160 < m(Wjj) < 240$ GeV.

Event yields as a function of various selection criteria are listed in Table III along with the expected background, and signal events.

TABLE III: Event Yields, Expected Background and Signal Events as a function of Event Selection Criteria.

Selection Criterion	DATA	Expected number of Background Events	Expected number of Signal Events
$M_T(W) + E_T^W$+1 b-tag	74	73.4	9.1
$M_T(W) + E_T^W$+1 b-tag+$\Delta\phi(jj)$	28	28.3	7.5
$M_T(W) + E_T^W$+1 b-tag+$\Delta\phi(jj)$+$p_T(jj)$	22	24.7	7.4
$M_T(W) + E_T^W$+1 b-tag+$\Delta\phi(jj)$+$p_T(jj)$+H_T^e	17	18.3	7.2
$M_T(W) + E_T^W$+1 b-tag+$\Delta\phi(jj)$+$p_T(jj)$+H_T^e+mass window	4	6.6	6.2

IV. SYSTEMATIC UNCERTAINTY

The dominant source of background after the final cuts are $Wb\bar{b}$, W+mistagged light quark jets, and W+HF processes. Consequently the largest systematic uncertainties arise from the jet energy scale corrections, jet energy resolution differences between data and Monte Carlo, the b-tagging efficiency, and the electron reconstruction efficiency in multijet events. The level of contributions from these sources are listed in Table IV. Combining all of these effects we obtain a total systematic error of 25%.

For the $W + \pi_T$ signal, we also expect that the dominant systematic uncertainties are from the same sources as for the backgrounds. They are listed in Table IV, leading to a total systematic uncertainty of $\sim$ 15%.

TABLE IV: Sources of Systematic Uncertainty.

Source	Background	Signal
Jet Energy Scale	13.5%	5%
Jet Resolution	19%	7%
b-tagging	8%	8%
Electron Reconstruction	5%	5%

TABLE V: Summary of the Analysis.

	Number of Events	Systematic Uncertainty
DATA	4	
Expected Background	6.6	25%
Signal Efficiency	3.7%	15%
Luminosity	238 pb^{-1}	7%

V. LIMIT ON THE $\rho_T \to W + \pi_T$ PRODUCTION CROSS SECTION

The event yields, after the final selection cuts for DATA, expected background events, the signal efficiency, and the luminosity along with the systematic errors are summarized in Table V. We note that, after all of the cuts, the observed data agree well with the background expectation from standard model processes. In the absence of a techniparticle signal, we proceed to compute an upper limit on the cross section for production of such particles. A standard Bayesian limit-setting procedure [8] with the signal and background systematics discussed previously is applied.

We find that for the combination, $m(\rho_T) = 200$ GeV and $m(\pi_T) = 105$ GeV the 95% C.L. upper limit on the process $\rho_T \to W(\to e\nu) + \pi_T(\to b\overline{Q})$ is 0.681 pb. Accounting for B($W \to e\nu$)=0.1068, this translates to a 95% C.L. upper limit on the process $\rho_T \to W + \pi_T$ of 6.4 pb. Given the theory cross sections listed in Table I, we can rule out this mass combination for a range of mass parameter M_V between 200 and 500 GeV.

VI. CONCLUSION

We have performed an analysis of the DØ Run II data to search for techniparticle production in the mode $\rho_T \to W(\to e\nu) + \pi_T(\to b\overline{Q})$. We have compared the properties of the events that pass our selection cuts with expectation from standard model background sources and find good agreement. In the absence of a signal, we compute the 95% C.L. upper limit on the production cross section for $m(\rho_T) = 200$ GeV and $m(\pi_T) = 105$ GeV to be 6.4 pb. We rule out the existence of this techniparticle mass combination for a range of the mass parameter M_V between 200 and 500 GeV.

Acknowledgments

We thank Ken Lane and Stephen Mrenna for various helpful discussions and cross checks regarding the details of their technicolor model. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à l'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry of Education and Science, Agency for Atomic Energy and RF President Grants Program (Russia), CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), Departments of Atomic Energy and Science and Technology (India), Colciencias (Colombia), CONACyT (Mexico), KRF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), Natural Sciences and Engineering Research Council and WestGrid Project (Canada), BMBF and DFG (Germany), A.P. Sloan Foundation, Civilian Research and Development Foundation, Research Corporation, Texas Advanced Research Program, and the Alexander von Humboldt Foundation.

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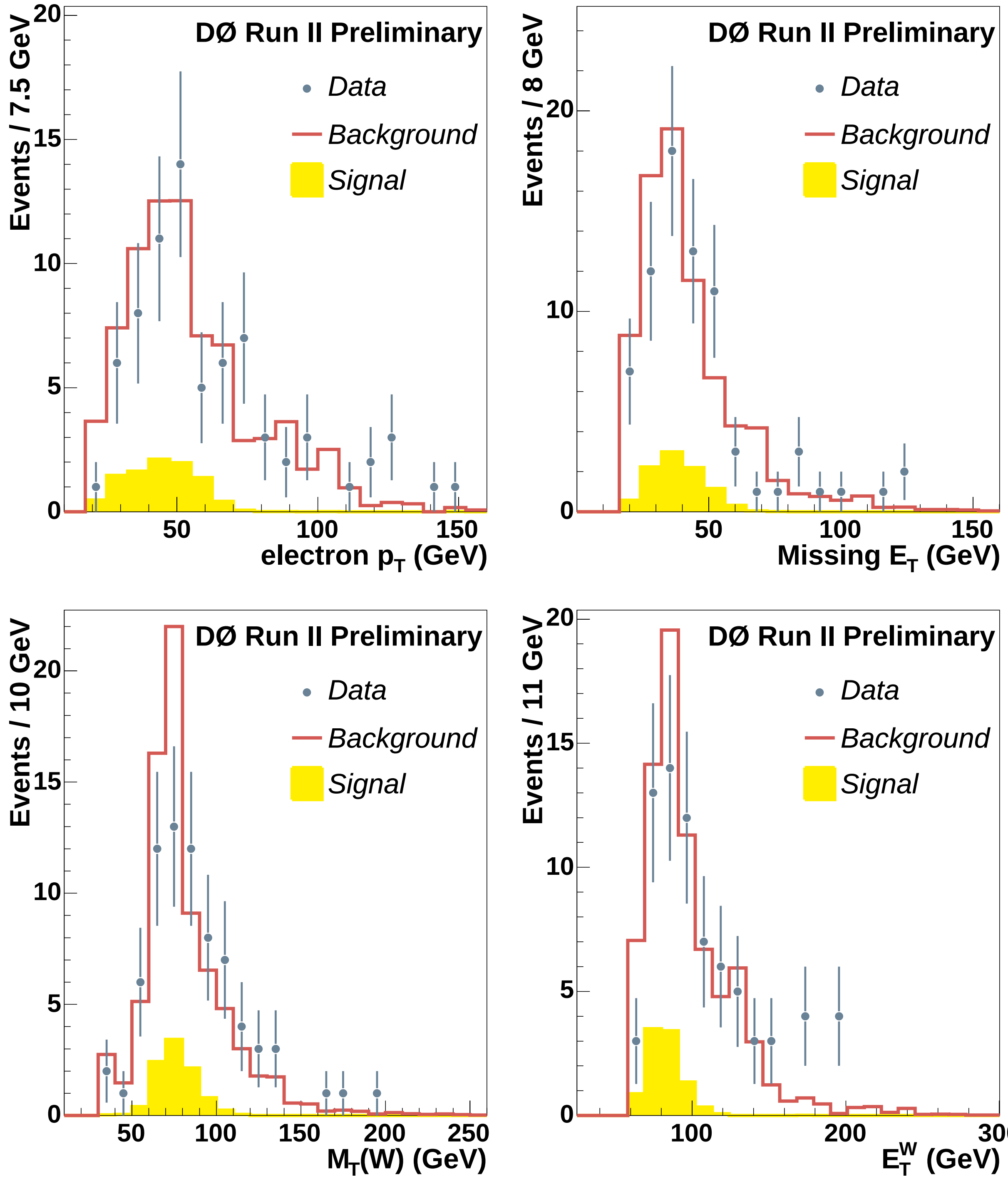

FIG. 2: Distributions of electron p_T (top left), missing p_T (top right), W boson transverse mass (bottom left) and the E_T^W (bottom right) for $e + \nu$+2jets with at least one $b-$tagged jet in the event and passing the E_T^W requirement.

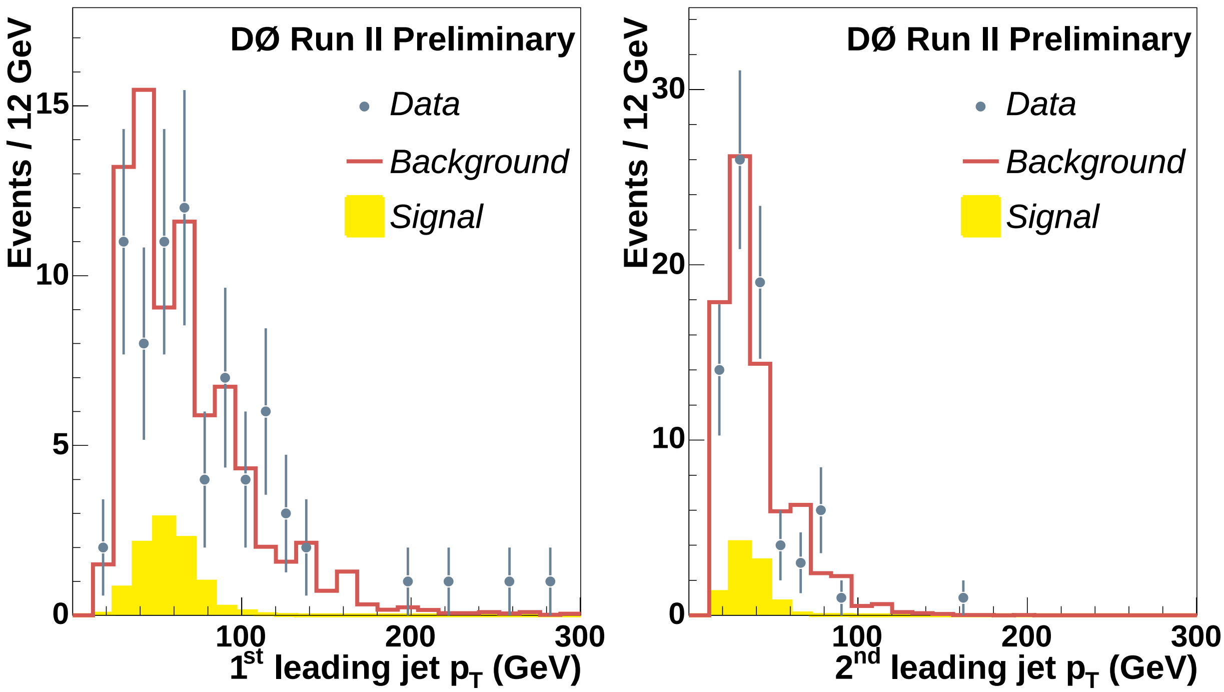

FIG. 3: Distributions of leading and second jet p_T for $e+\nu$+2jets with at least one $b-$tagged jet in the event and passing the E_T^W requirement.

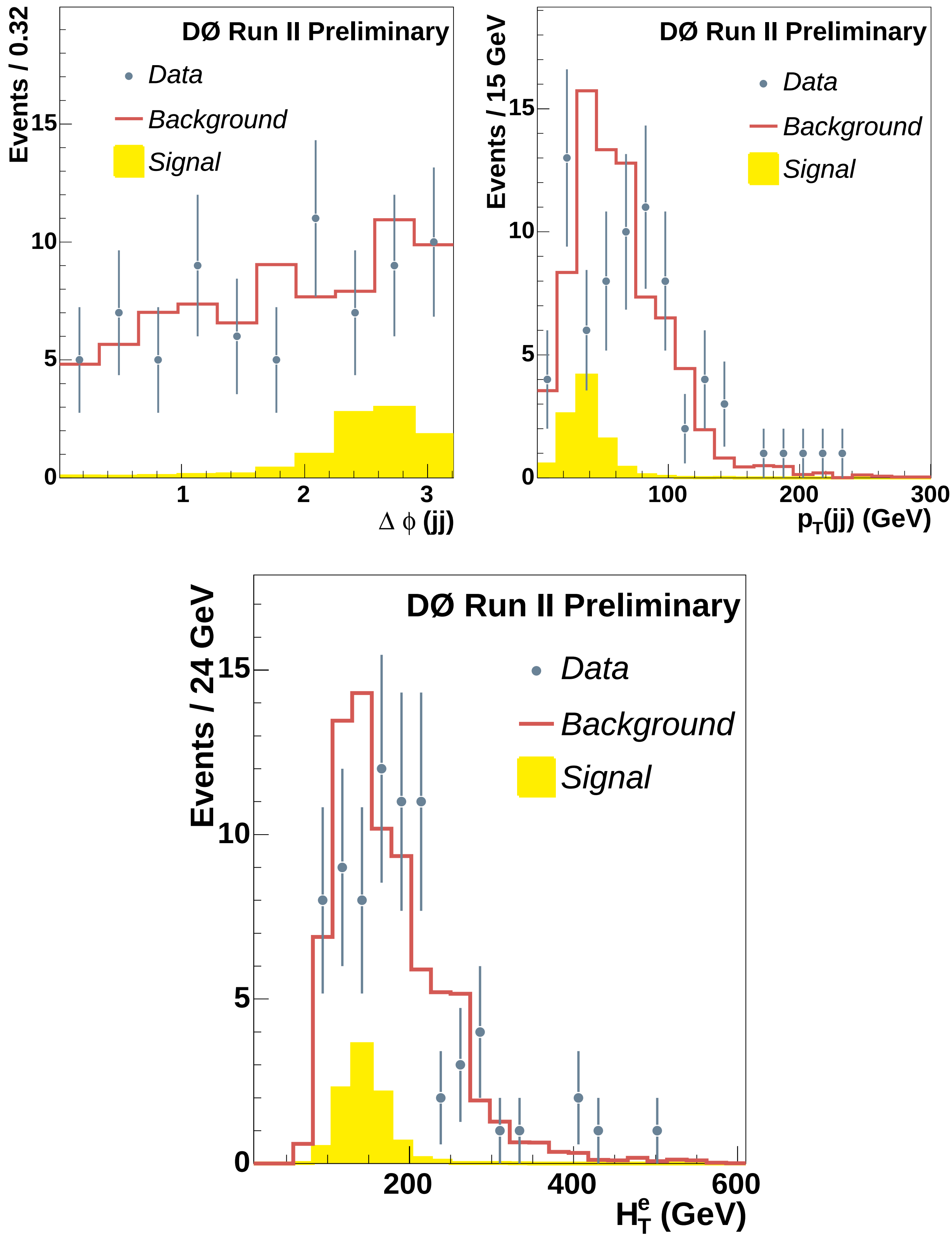

FIG. 4: Distributions of $\Delta\phi(jj)$ (top left), p_T (top right), and H_T^e (bottom plot) of the dijet system in events with $e+\nu$+2jets with at least one $b-$tagged jet and passing the E_T^W requirement.

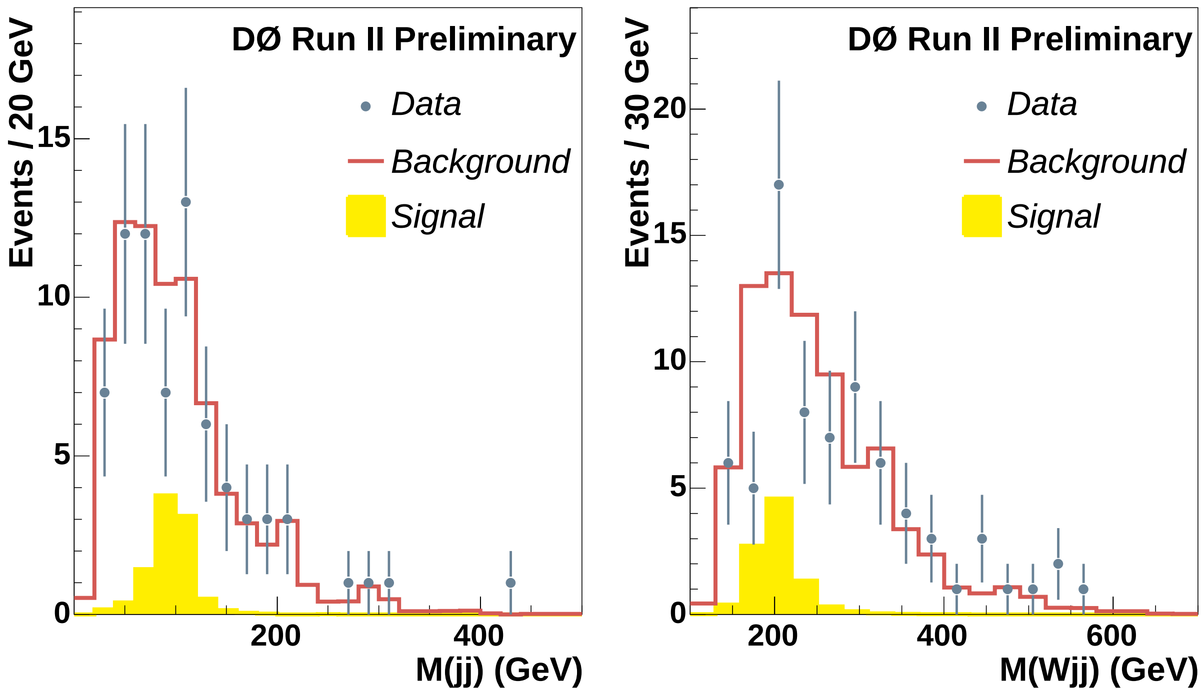

FIG. 5: Distribution of the invariant mass $m(jj)$ (left) and the invariant mass of the W boson and the dijets $m(Wjj)$ (right) for events with $e+\nu$+2jets with at least one $b-$tagged jet and passing the E_T^W requirement.

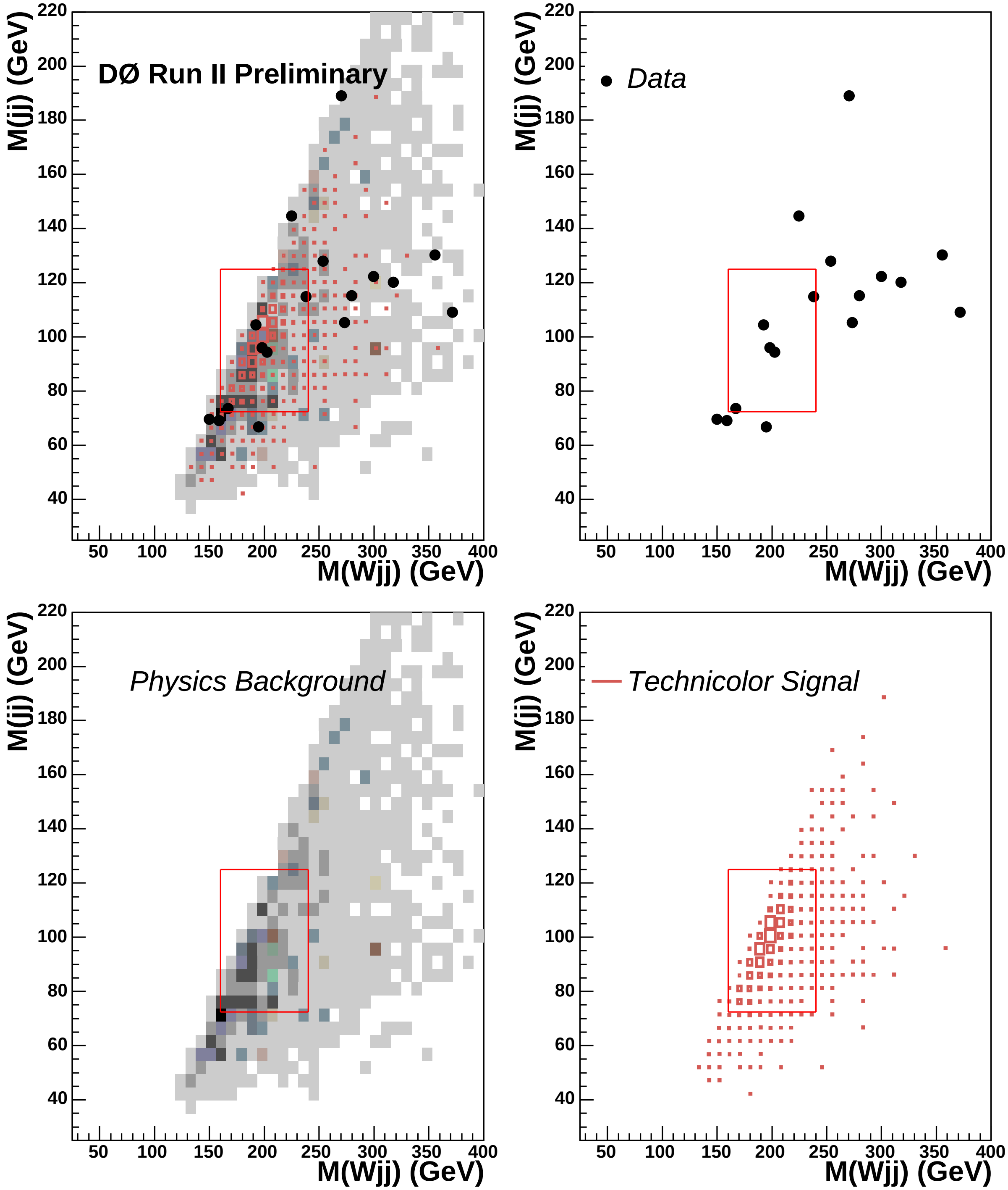

FIG. 6: Invariant mass of W+dijets (ρ_T) vs the dijet invariant mass (π_T) in events with $e+\nu$+2jets (with one $b-$tagged jet) for the backgrounds (bottom left), the expected signal (bottom right) and the data sample (top right). The top left plot is the overlay of all other three plots. Cuts on H_T^e, $\Delta\phi(jj)$, $p_T(jj)$ have been applied.