Search for new phenomena in events with two Z bosons and missing transverse momentum in pp[over ¯] collisions at sqrt[s]=1.96 TeV

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Phys. Rev. D **85**, 011104 — Published 26 January 2012

DOI: 10.1103/PhysRevD.85.011104

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We present a search for new phenomena in events with two reconstructed Z bosons and large missing transverse momentum, sensitive to processes $p\bar{p} \to X_2X_2 \to ZZX_1X_1$, where X_2 is an unstable particle decaying as $X_2 \to ZX_1$ and X_1 is undetected. The particles X_1 and X_2 may be, among other possibilities, fourth generation neutrinos or supersymmetric particles. We study the final state in which one Z boson decays to two charged leptons and the second decays hadronically. In data corresponding to an integrated luminosity of 4.2 fb^{-1} from proton-antiproton collisions recorded by the CDF II detector at the Tevatron, with center-of-mass energy of 1.96 TeV, we find agreement between data and standard-model backgrounds. We calculate 95% confidence level upper limits on the cross section of the process $p\bar{p} \to X_2X_2 \to ZZX_1X_1$ ranging from 50 fb to 1 pb, depending on the masses of X_1 and X_2.

PACS numbers: 12.60.-i, 13.85.Rm, 14.65.-q, 14.80.-j

A natural extension to the standard model of particle physics is a fourth generation of quarks and leptons. The inclusion of a fourth generation provides a source of CP violation in B_s decays and can accommodate a heavy Higgs boson [1, 2]. Searches for fourth generation quarks at the Fermilab Tevatron have constrained the mass of up-type quarks (u_4), that decay as $u_4 \to Wq$, where q is a generic down-type quark, to be $m_{u_4} > 340$ GeV/c^2 at 95% confidence level (CL) [3], while limits on the mass of down-type quarks (d_4) decaying via $d_4 \to Wt$ are $m_{d4} >$ 372 GeV/c^2 at 95% CL [4].

Following the trend of mass hierarchy in the standard model, the least massive and therefore most accessible particle of this fourth generation may be the neutrino. Such a neutrino need not be solely a Dirac or Majorana state, but may be a mixture of the two [5]. This leads to two mass eigenstates N_1 and N_2, where N_2 is the unstable heavy eigenstate and N_1 is the stable and least massive eigenstate of the fourth generation neutrinos. These particles would partially evade the neutrino mass constraints

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from Z width studies at LEP [6].

The dominant production mechanism of N_1 would be via a Drell-Yan process, $p\bar{p} \to Z/\gamma^* \to N_2 N_2 \to N_1 Z N_1 Z$, giving a final state of two Z bosons and large missing transverse momentum. This signature is shared by several other interesting new physics processes, most notably supersymmetric production, $\chi_2^0\chi_2^0 \to Z\chi_1^0 Z\chi_1^0$, where χ_1^0 and χ_2^0 are neutralinos. We consider the mode in which one Z decays hadronically and the other decays leptonically, giving a detector signature of two charged leptons, two jets and large missing transverse momentum. For this search we use $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV corresponding to 4.2 fb^{-1} of integrated luminosity collected by the CDF II detector.

Events were recorded by CDF II [7, 8], a general-purpose detector designed to study collisions at the Fermilab Tevatron $p\bar{p}$ collider. The CDF II detector is composed of a charged-particle tracking system immersed in a 1.4 T magnetic field consisting of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers located outside the calorimeters detect muons.

The data acquisition system is triggered by e or μ candidates with transverse momentum p_T, greater than 18 GeV/c. We retain electron and muon candidates with pseudorapidity [8] $|\eta| < 1.1$, $p_T \geq 20$ GeV/c and that satisfy the standard CDF identification requirements [9]. For muons, the track fit χ^2 per degree of freedom is used to reject poorly fit tracks likely resulting from charged pion and kaon decays in flight. Electrons from photon conversions are suppressed by rejecting electron candidates with a nearly collinear intersecting reconstructed track. Jets are reconstructed in the calorimeter using the JETCLU [10] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space. Measured jet energies are corrected to account for η-dependent variations in detector response, calorimeter coverage, and the expected contribution from additional $p\bar{p}$ interactions in the same event [11]. Jets are selected if they have $p_T \geq 15$ GeV/c and $|\eta| < 2.4$. Missing transverse energy [12], $\not\!\!E_T$, is reconstructed using calorimeter and muon information including the corrections described above.

To isolate the ZZ signature, we require two opposite-charge, same-flavor lepton candidates (e or μ) with $p_T > 20$ GeV/c for which the lepton-pair invariant mass is consistent with decay from a Z boson: $m_{\ell\ell} \in [76, 106]$ GeV/c^2. Additionally, we require at least two jets, each with $p_T > 15$ GeV/c and $|\eta| < 2.4$, and without identified secondary vertices resulting from b-hadron decay [13]. The $ZZ + \not\!\!E_T$ signature has the further requirement of large $\not\!\!E_T$, varying with hypothetical N_1 and N_2 masses, as shown in Table II.

The dominant background in the resulting sample is production of a Z boson in association with two jets from initial state radiation. We model this background using ALPGEN [14] to describe the hard process and PYTHIA [15] for the showering and hadronization. This background is strongly suppressed in events with large missing transverse momentum, as shown in Figure 1 and Table I, and is distinguished from the signal by the lack of a resonance in the dijet mass, m_{jj}.

The second largest expected background is due to W boson production in association with three jets from initial state radiation, where one jet is wrongly reconstructed as a lepton. We model this using an independent sample of events containing jets likely to mimic leptons, following Ref. [16]. Additional backgrounds result from standard-model production of two gauge bosons, including ZZ, WW, and WZ, as well as $t\bar{t} \to WbWb$, which are all modeled using PYTHIA.

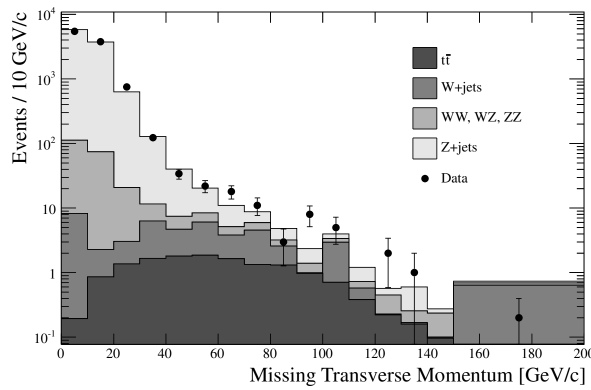

FIG. 1: Distribution of missing transverse momentum in events with the ZZ signature, for expected backgrounds and observed data.

TABLE I: Expected number of events for each source of background to the $ZZ \to \ell^+\ell^- jj$ and $ZZ + X_1X_1 \to \ell^+\ell^- jj + \not\!\!E_T$ signatures, as well as the observed event yield in data with 4.2 fb^{-1} of integrated luminosity. The threshold in $\not\!\!E_T$ is optimized as a function of the N_1, N_2 masses; one example ($N_1 = 125$ GeV/c^2, $N_2 = 225$ GeV/c^2) is shown here. Uncertainties shown include both systematic and statistical uncertainty added in quadrature.

Process	$\ell^+\ell^- jj$	$\ell^+\ell^- jj$ and $\not\!\!E_T > 36$ GeV
WW	4.4 ± 1.3	2.7 ± 0.8
$t\bar{t}$	14.8 ± 3.0	11.6 ± 2.3
W+jets	36.1 ± 16.7	21.7 ± 12.6
ZZ	99.4 ± 20.5	4.2 ± 0.9
WZ	105.6 ± 22.1	5.2 ± 1.1
Z+jets	10171 ± 4422	94.6 ± 38.5
Total	10432 ± 4485	140.0 ± 40.6
Data	10199	152

To isolate the double-resonance nature of the $ZZ + \not\!\!E_T$ signature, we calculate the distance from the Z boson reconstructed mass in the $m_{\ell\ell}$–m_{jj} mass plane, accounting for the relative difference in the resolutions between the leptons and jets as well as the observed bias in reconstructed m_{jj}, using the variable

$$\Delta m = \sqrt{\left(\frac{m_{\ell\ell} - m_{Z\to\ell\ell}}{g_{\ell\ell}}\right)^2 + \left(\frac{m_{jj} - m_{Z\to jj}}{g_{jj}}\right)^2}, \quad (1)$$

where $m_{\ell\ell}(m_{jj})$ is the reconstructed lepton (jet) pair mass, compared to the reference $m_{Z\to\ell\ell} = 91.6$ GeV/c^2 ($m_{Z\to jj} = 85.3$ GeV/c^2) found in simulated events. To account for the superior lepton resolution, the dilepton and dijet mass differences are scaled by factors related to the resolutions: $g_{\ell\ell} = 10$ GeV/c^2, $g_{jj} = 15$ GeV/c^2. The uncertainties of these reference values are small, and may be neglected. The distribution of Δm for data and simulated background and signal is shown in Figure 2.

We model the production of the N_2 signal and its subsequent decay into N_1 over a grid of masses in the (M_{N1}, M_{N2}) plane using MADGRAPH [17] with the CTEQ5L [18] parton distribution fuctions; PYTHIA [15] is used for the showering and hadronization. To suppress the large backgrounds expected from standard-model sources we require large $\not\!\!E_T$; as the expected magnitude of missing transverse momentum depends strongly on M_{N1} and M_{N2}, we vary the selection threshold of $\not\!\!E_T$ to optimize for sensitivity at each (M_{N1}, M_{N2}) pair considered, as seen in Table II. The acceptance for each mass point can be seen in Figure 3. For each point in the mass grid, we form template histograms as a function of Δm for the expected signal and background, as displayed in Figure 2.

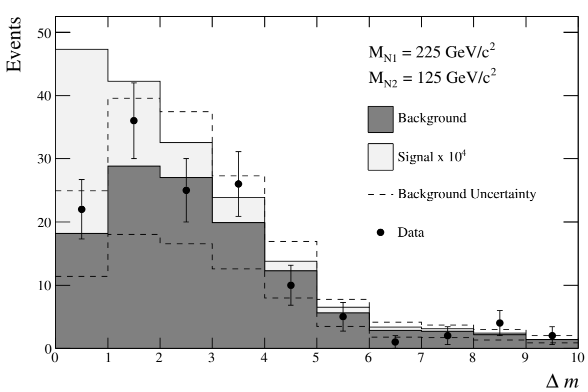

FIG. 2: Distribution of the variable Δm, defined in the text, for expected background, observed data and an example signal (scaled by 10^4) in data with 4.2 fb^{-1} of integrated luminosity. This example uses a missing transverse momentum threshold of $\not\!\!E_T > 36$ GeV, optimized for this (M_{N1}, M_{N2}) mass point; see Table II. Background uncertainties are statistical and systematic added in quadrature.

In addition to the templates formed for the nominal expectation, we form alternate templates that incorporate the effects of systematic uncertainties under $\pm 1\sigma$ variation. Fitting to these templates using the maximum likelihood method, we extract the best-fit signal cross section, σ_{N2}. Systematic uncertainties affecting the shapes of templates, including uncertainty in the jet energy scale [11], QCD radiation, PDFs, Q^2 (square of momentum transfer in the interaction) and uncertainty in lepton energy resolution, are accounted for as nuisance parameters in our likelihood. The dominant source of systematic uncertainty in this analysis is uncertainty in the jet energy scale (40%), which can significantly modify the number of jets in background processes that pass the p_T threshold, the location of the m_{jj} resonance in the signal process, and the measured $\not\!\!E_T$ in an event. The second largest systematic uncertainty is due to uncertainty on the theoretical normalization of the background rates (10%). Finally, we apply the unified ordering principle [19] for the Neyman construction to create confidence intervals in the true value of σ_{N2} for each N_2, N_1 mass point.

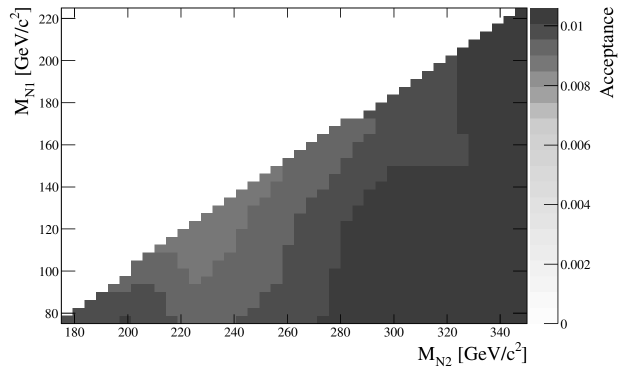

FIG. 3: Acceptance of the $ZZ + \not\!\!E_T$ signature, including BR$(ZZ \to \ell\ell qq)$, as a function of the masses of the fourth generation neutrinos, N_1 and N_2. The threshold in $\not\!\!E_T$ is optimized at each point on a grid in this plane. Linear interpolation is performed between the grid points. The apparent structure in the plot results from statistical fluctuation.

We find the candidate events in the data to be consistent with expected standard-model backgrounds and thus set upper limits at 95% CL on the cross section for $p\bar{p} \to N_2 N_2 \to N_1 Z N_1 Z$. Theoretical cross sections for each mass point are presented in Table II, along with their respective expected and observed limits in our data sample. The expected and observed cross section limits can be seen in Figure 4 and Table II.

In summary, we have performed the first search for new phenomena in events with two reconstructed Z bosons and large missing transverse momentum. This signature is sensitive to processes $p\bar{p} \to X_2 X_2 \to ZZX_1X_1$, where X_2 is an unstable particle decaying as $X_2 \to ZX_1$ and X_1 being undetected. The particles X_1 and X_2 may be, among other possibilities, fourth generation neutrinos or supersymmetric particles. A specific model in which X_2

TABLE II: Acceptance of the $ZZ + \not{E}_T$ selection for varying thresholds in $\not{E}_T$ optimized for each point in the M_{N1}, M_{N2} mass plane. Also shown are the median expected and observed 95% CL upper limits on the cross section (σ_{N2}) in data with 4.2 fb^{-1} of integrated luminosity, as well as the theoretical prediction [17, 20].

M_{N1}, M_{N2} [GeV/c^2]	$\not{E}_T$ Cut [GeV]	Acceptance [%]	σ_{N2} [fb] Theory	σ_{N2} [fb] Exp. /Obs. Limit
75, 175	37	0.99	0.51	511 / 702
75, 200	68	1.02	0.21	292 / 369
125, 225	36	0.85	0.16	684 / 1088
75, 225	92	0.93	0.081	156 / 273
75, 275	118	1.01	0.015	94 / 132
125, 300	119	1.06	0.013	99 / 138
175, 300	80	0.96	0.022	171 / 315
125, 350	156	1.05	0.003	75 / 48
225, 350	80	1.05	0.006	190 / 297
75, 350	167	1.06	0.001	71 / 55

and X_1 are fourth-generation neutrinos is used without loss of generality. In the final state in which one Z boson decays to two charged leptons and the second decays hadronically, we find agreement between the data and the standard-model expectation using data from proton-antiproton collisions with 4.2 fb^{-1} of integrated luminosity. Based on the results in Table II, we report 95% CL upper limits on the cross section of the process $p\bar{p} \rightarrow X_2X_2 \rightarrow ZZX_1X_1$ ranging from 50 fb to 1 pb depending on the masses of X_1 and X_2.

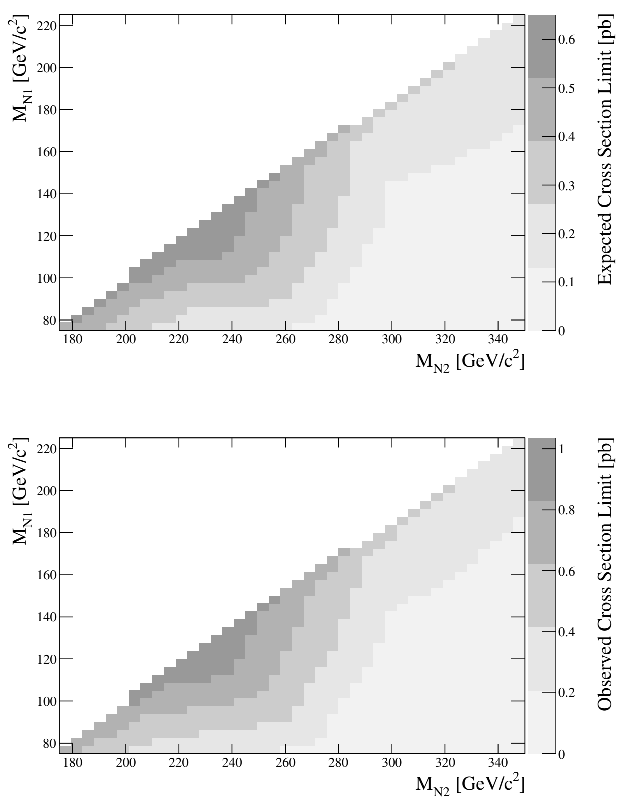

FIG. 4: Upper limit at 95% CL on the cross section of $p\bar{p} \rightarrow N_2N_2 \rightarrow N_1ZN_1Z$ in data with 4.2 fb^{-1} of integrated luminosity as a function of the masses of N_1 and N_2. Top shows median expected limits; bottom shows observed limits; see Table II.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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