Search for $ZX \rightarrow \nu \bar{\nu} b \bar{b}$

Events in the D0 Detector

B. Abbott et al.
The D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1997

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Distribution

Approved for public release; further dissemination unlimited.
Search for $ZX \to \nu \bar{\nu} b \bar{b}$ Events in the DØ Detector

The DØ Collaboration *

Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(July 18, 1997)

Abstract

We report on a search for a new particle, X, decaying via $X \to b \bar{b}$, made through associated production with a Z boson. We use data collected with the DØ detector operating at the Fermilab Tevatron $p\bar{p}$ collider with $\sqrt{s} = 1.8$ TeV. We utilize muon-tagged jets to identify $b$-quarks and the $\nu\bar{\nu}$ channel to detect Z bosons. Preliminary results on cross section limits for X masses between 90 GeV/$c^2$ and 180 GeV/$c^2$ are presented.


(DØ Collaboration)
1 Universidad de los Andes, Bogotá, Colombia
2 University of Arizona, Tucson, Arizona 85721
3 Boston University, Boston, Massachusetts 02215
4 Brookhaven National Laboratory, Upton, New York 11973
5 Brown University, Providence, Rhode Island 02912
6 Universidad de Buenos Aires, Buenos Aires, Argentina
7 University of California, Davis, California 95616
8 University of California, Irvine, California 92697
9 University of California, Riverside, California 92521
10 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11 CINVESTAV, Mexico City, Mexico
12 Columbia University, New York, New York 10027
13 Delhi University, Delhi, India 110007
14 Fermi National Accelerator Laboratory, Batavia, Illinois 60510
15 Florida State University, Tallahassee, Florida 32306
16 University of Hawaii, Honolulu, Hawaii 96822
17 University of Illinois at Chicago, Chicago, Illinois 60607
18 Indiana University, Bloomington, Indiana 47405
19 Iowa State University, Ames, Iowa 50011
20 Korea University, Seoul, Korea
21 Kyungsung University, Pusan, Korea
22 Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
23 University of Maryland, College Park, Maryland 20742
24 University of Michigan, Ann Arbor, Michigan 48109
25 Michigan State University, East Lansing, Michigan 48824
26 Moscow State University, Moscow, Russia
27 University of Nebraska, Lincoln, Nebraska 68588
28 New York University, New York, New York 10003
29 Northeastern University, Boston, Massachusetts 02115
30 Northern Illinois University, DeKalb, Illinois 60115
31 Northwestern University, Evanston, Illinois 60208
32 University of Notre Dame, Notre Dame, Indiana 46556
33 University of Oklahoma, Norman, Oklahoma 73019
34 University of Panjab, Chandigarh 16-00-14, India
35 Institute for High Energy Physics, 142-284 Protvino, Russia
36 Purdue University, West Lafayette, Indiana 47907
37 Rice University, Houston, Texas 77005
38 Universidade do Estado do Rio de Janeiro, Brazil
39 University of Rochester, Rochester, New York 14627
40 CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, Gif-sur-Yvette, France
41 Seoul National University, Seoul, Korea
42 State University of New York, Stony Brook, New York 11794
43 Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India
44 University of Texas, Arlington, Texas 76019
45 Texas A&M University, College Station, Texas 77843
We have searched for the production of a new particle, X, in association with a Z boson using the signatures \( Z \to \nu \bar{\nu} \) and \( X \to b \bar{b} \). The b-quarks are identified through their decays to muons while missing energy in the detector indicates the presence of neutrinos. The final state particles, \( \nu \bar{\nu} b \bar{b} \), are identical to that in our charge 1/3 third generation leptoquark search. We use the same data samples and event selection for the ZX search reported here [1]. This paper gives preliminary limits on production cross section times \( \beta \), the branching ratio for \( X \to b \bar{b} \), for masses of X (\( M_X \)) between 90 GeV/c^2 and 180 GeV/c^2.

The data used for this search was collected by the DØ detector operating at the Fermilab Tevatron during the 1993-1996 period with \( p \bar{p} \) collisions at \( \sqrt{s} = 1.8 \) TeV. The DØ detector, described in detail elsewhere [2], is composed of three major systems: an inner detector for tracking charged particles, a uranium-liquid argon calorimeter for measuring electromagnetic and hadronic showers, and a muon spectrometer. The calorimeter has 0.1 segmentation in both pseudorapidity \( \eta \) and azimuth \( \phi \) and measures the energy of jets with a resolution of approximately \( \sigma/E = 0.8/\sqrt{E} \) (E in GeV) [3]. The muon spectrometer consists of three layers of proportional drift tubes with a magnetized iron toroid between the first two layers. This provides a measurement of muon momentum with a resolution of \( \delta p/p = \left( \frac{0.18(p-2)}{p} \right)^2 + (0.003p)^2 \right)^{1/2} \) (p in GeV/c). The total thickness of the calorimeter plus the toroid varies from 13 to 15 interaction lengths and reduces the hadron punchthrough to a negligible level. The presence of neutrinos in the final state is inferred from missing transverse energy \( (\not{E}_T) \). This is defined as the negative of the vector sum of the calorimeter cell transverse energies and the \( p_T \) of detected muons.

Candidate ZX events were collected using three triggers, each requiring at least one muon in the trigger [4]. A dimuon sample required two muons at both hardware and software trigger levels, with \( p_T > 3.5 \) GeV/c. The second trigger required a muon with \( p_T > 1.0 \) GeV/c and a calorimeter hardware-only jet trigger with an \( E_T \) threshold of 10 GeV. The third trigger required a muon with \( p_T > 15 \) GeV/c and a jet with \( E_T > 15 \) GeV. Integrated luminosities of 60.1 pb\(^{-1}\), 19.5 pb\(^{-1}\), and 92.4 pb\(^{-1}\) respectively were collected with these three triggers.

B-quark decay is indicated by the presence of a muon associated with a jet. The offline analysis required muon tracks in the pseudorapidity range \( |\eta| < 1.0 \) and \( p_T > 3.5 \) GeV/c, Muon trajectories are required to be consistent with the reconstructed vertex position and have at least 1 GeV energy deposition in the calorimeter. For events with either single muon trigger, the muon is required to have hits in all three layers of the muon detector, a matching track in the central detector, and a good fit when these elements are combined. At least one of the muons in dimuon trigger events must satisfy these additional requirements. Jets are reconstructed using a cone algorithm with \( R = 0.7 \) where \( R = \sqrt{(d\phi)^2 + (d\eta)^2} \) about the jet’s direction. Each jet was required to satisfy the following quality criteria: (1) 0.05 < electromagnetic fraction of the jet \( E_T < 0.90 \), (2) the ratio of the highest cell energy to the next highest < 10, and (3) the fraction of \( E_T \) deposited in the outermost calorimeter layer < 0.4. To reduce multi-jet QCD and top backgrounds, events with 6 or more jets \( (E_T > 10 \) GeV) are rejected. For the dimuon trigger, we require the dimuon invariant mass be greater than 8 GeV/c^2 thereby rejecting low mass resonances, and that both muons have a unique jet with \( \Delta R(\mu - \text{jet}) < 0.5 \) and \( E_T > 10 \) GeV. The remaining events are dominated by \( b \bar{b} \) decays [5]. Single muon triggers require a jet be associated with the muon using the
same $\Delta R$ and and $E_T$ requirements. Single muon events must have an additional jet, with $E_T > 25$ GeV and $|\eta| < 1.5$. Events with only a single muon-tagged jet have contributions from $W$+jet events where $W \rightarrow \mu\nu$ [6]. Due to the neutrino, $W$ decays have significant $E_T$, and therefore can contribute to our signal. To reduce the $W$ acceptance, we use two variables to improve the b-quark identification.

We define $Z_\mu = pT_\mu/H_T$ with $H_T$ being the scalar sum of the $E_T$ of the jets and muons in the event. $Z_\mu$ will be large if the muon energy dominates the event. A requirement that $Z_\mu < 0.20$ removes about 90% of the $W \rightarrow \mu\nu$ events with a signal efficiency of about 82%. We also use the pattern of energy deposition around the muon to reduce the $W$ contribution.

We define $E_{46} = E(R_\mu \leq 0.4)/E(R_\mu \leq 0.6)$ as the ratio of energy in a R-cone of 0.4 about the muon’s direction to that in a R-cone of 0.6. $B$-decays will have the majority of their hadronic energy well-associated with the muon. A requirement that $E_{46} > 0.80$ removes about 84% of the $W \rightarrow \mu\nu$ events with a signal efficiency of about 80%.

The high-$p_T$ muon trigger channel has a significant contribution from $t\bar{t}$ events. The scalar sum of jet $E_T$, $H_T$, was used to identify the top quark [8]. In this analysis, we use $H_T$, including muon energies, to reduce the top contribution. We require $H_T < 240$ GeV for those events satisfying the high-$p_T$ muon trigger; this removes about one-third of $t\bar{t}$ events with an efficiency of about 93% for signal channels.

We use the missing energy in the event to identify neutrinos. Fig. 1 gives the $E_T$ distributions with $M_X = 90$ GeV/c$^2$; it is essentially the $p_T$ of the $Z$. To aid in eliminating events where the $E_T$ is mismeasured, we reject events where the azimuthal angular separation between the missing energy direction and the nearest jet, $d\phi$, is less than 0.7. We also reject events where the vector sum of the jet and muon transverse energies is consistent with zero; these events were found to have significant contributions to the missing energy from the part of calorimeter near the main ring of the accelerator, and from individual calorimeter cells. The resulting $E_T$ distribution combining all three trigger channels is given in Fig. 2. A requirement that $E_T > 35$ GeV leaves 2 events.

We have considered background contributions from $t\bar{t}$ production, $W$ and $Z$ bosons, and QCD-produced $b\bar{b}$ and $c\bar{c}$ events. Top events have multiple b-quarks and $E_T$, but with extra, energetic jets. We use Monte Carlo, and a production cross section of $5.5 \pm 1.8$ pb [9], to estimate that $t\bar{t}$ contributes 1.5 ± 0.5 events to our sample. $W$ and $Z$ events produce $E_T$ through the decays $W \rightarrow l\nu$ and $Z \rightarrow \nu\nu$. Also, either a prompt muon has to overlap a jet or a jet itself needs to fragment into a muon usually by a $c$-quark or a $\pi$/K decay. We again use Monte Carlo to calculate their contributions, with production cross sections of $21.2 \pm 1.3$ nb and $6.5 \pm 0.5$ nb [10] yielding $1.0 \pm 0.5$ W events and $0.1 \pm 0.1$ Z events in our sample. QCD-produced $b\bar{b}$ and $c\bar{c}$ events do not have energetic neutrinos and are effectively eliminated by the $E_T$ and $d\phi$ cuts. Estimates of their contribution using data and Monte Carlo are imprecise but consistent with 0, and we use a value of 0 from this source in our limit calculation as it gives the most conservative results. Our total background estimate is therefore 2.6 ± 0.7 events.

We calculate the acceptances for $ZX$ events by assuming that the X particle has identical properties to the Higgs boson. The use of a central muon to tag $b$-decays limits the acceptance to values under 3%. We combine the three trigger channels to set limits. Errors on the acceptance include contributions from trigger and reconstruction efficiency, effects of muon momentum resolution and jet energy scale, our understanding of the $E_{46}$ cut, and
Monte Carlo statistics. The three trigger channels have different systematic errors since their selection criteria and average muon $p_T$ differ, but most errors are correlated. The total systematic error on the combined acceptance for the preliminary results reported here is about 14%. We anticipate this being lowered to about 10% in the near future.

The 95% confidence level (C.L.) limits on the production cross section are obtained using a Bayesian approach [11] and include the systematic uncertainties on the acceptance and a 5.3% uncertainty on the integrated luminosity. Preliminary limits on the cross section times $\beta$, the branching ratio for $X \rightarrow b\bar{b}$, as a function of $M_X$ are shown in Fig. 3. Limits range from 84 pb for $M_X = 90 \text{ GeV}/c^2$ to 37 pb for $M_X = 180 \text{ GeV}/c^2$.

We thank the staffs at Fermilab and collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à l’Energie Atomique (France), State Committee for Science and Technology and Ministry for Atomic Energy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).
FIG. 2. The distribution of $E_T$ for data events after all other requirements.

REFERENCES

* Visitor from IHEP, Beijing, China.
† Visitor from Universidad San Francisco de Quito, Quito, Ecuador.

[1] Leptoquark Searches at DØ, paper contributed to this conference.
FIG. 3. 95% CL cross section limit for ZX production versus $M_X$.