Study of Diboson Production at DØ

The DØ Collaboration[1]

(July 1996)

The results from the direct measurements of the trilinear gauge boson couplings are reported using the data taken with the DØ detector at Fermilab. The limits on the anomolous coupling parameters were obtained at the 95% CL from three processes, WW/WZ production with the subsequent W boson decay to an electron and a neutrino and the second W or Z boson decay to two jets and $W\gamma$ and $Z\gamma$ productions with the subsequent W and Z boson decays to electron and muon channels.

S. Abachi,[14] B. Abbott,[28] M. Abolins,[25] B.S. Acharya,[43] I. Adam,[12] D.L. Adams,[37] M. Adams,[17] S. Ahn,[14] H. Aihara,[22] J. Alitti,[40] G. Álvarez,[18] G.A. Alves,[10] E. Amidi,[29] N. Amos,[24] E.W. Anderson,[19] S.H. Aronson,[4] R. Astur,[42] R.E. Avery,[31] M.M. Baarmand,[42] A. Baden,[23] V. Balamurali,[32] J. Balderston,[16] B. Baldin,[14] S. Banerjee,[43] J. Bantly,[5] J.F. Bartlett,[14] K. Bazizi,[39] J. Bendich,[22] S.B. Beri,[34] I. Bertram,[37] V.A. Bezzubov,[35] P.C. Bhat,[14] V. Bhatnagar,[34] M. Bhattacharjee,[13] A. Bischoff,[9] N. Biswas,[32] G. Blazey,[14] S. Blessing,[15] P. Bloom,[7] A. Boehnlein,[14] N.I. Bojko,[35] F. Borcherding,[14] J. Borders,[39] C. Boswell,[9] A. Brandt,[14] R. Brock,[25] A. Bross,[14] D. Buchholz,[31] V.S. Burtovoi,[35] J.M. Butler,[3] W. Carvalho,[10] D. Casey,[39] H. Castilla-Valdez,[11] D. Chakraborty,[42] S.-M. Chang,[29] S.V. Chekulaev,[35] L.-P. Chen,[22] W. Chen,[42] S. Choi,[41] S. Chopra,[24] B.C. Choudhary,[9] J.H. Christenson,[14] M. Chung,[17] D. Claes,[42] A.R. Clark,[22] W.G. Cobau,[23] J. Cochran,[9] W.E. Cooper,[14] C. Cretsinger,[39] D. Cullen-Vidal,[5] M.A.C. Cummings,[16] D. Cutts,[5] O.I. Dahl,[22] K. De,[44] M. Demarteau,[14] N. Denisenko,[14] D. Denisov,[14] S.P. Denisov,[35] H.T. Diehl,[14] M. Diesburg,[14] G. Di Loreto,[25] R. Dixon,[14] P. Draper,[44] J. Drinkard,[8] Y. Ducros,[40] S.R. Dugad,[43] D. Edmunds,[25] J. Ellison,[9] V.D. Elvira,[42] R. Engelmann,[42] S. Eno,[23] G. Eppley,[37] P. Ermolov,[26] O.V. Eroshin,[35] V.N. Evdokimov,[35] S. Fahey,[25] T. Fahland,[5] M. Fatyga,[4] M.K. Fatyga,[39] J. Featherly,[4] S. Feher,[14] D. Fein,[2] T. Ferbel,[39] G. Finocchiaro,[42] H.E. Fisk,[14] Y. Fisyak,[7] E. Flattum,[25] G.E. Forden,[2] M. Fortner,[30] K.C. Frame,[25] P. Franzini,[12] S. Fuess,[14] E. Gallas,[44] A.N. Galyaev,[35] T.L. Geld,[25] R.J. Genik II,[25] K. Genser,[14] C.E. Gerber,[14] B. Gibbard,[4] V. Glebov,[39] S. Glenn,[7] J.F. Glicenstein,[40] B. Gobbi,[31] M. Goforth,[15] A. Goldschmidt,[22] B. Gómez,[1] G. Gomez,[23] P.I. Goncharov,[35] J.L. González Solís,[11] H. Gordon,[4] L.T. Goss,[45] N. Graf,[4] P.D. Grannis,[42] D.R. Green,[14] J. Green,[30] H. Greenlee,[14] G. Griffin,[8] N. Grossman,[14] P. Grudberg,[22] S. Grünendahl,[39] W.X. Gu,[14,*] G. Guglielmo,[33] J.A. Guida,[2] J.M. Guida,[5] W. Guryn,[4] S.N. Gurzhiev,[35] P. Gutierrez,[33] Y.E. Gutnikov,[35] N.J. Hadley,[23] H. Haggerty,[14] S. Hagopian,[15] V. Hagopian,[15] K.S. Hahn,[39] R.E. Hall,[8] S. Hansen,[14] R. Hatcher,[25] J.M. Hauptman,[19] D. Hedin,[30] A.P. Heinson,[9] U. Heintz,[14] R. Hernández-Montoya,[11] T. Heuring,[15] R. Hirosky,[15] J.D. Hobbs,[14] B. Hoeneisen,[1,†] J.S. Hoftun,[5] F. Hsieh,[24] Tao Hu,[14,*] Ting Hu,[42] Tong Hu,[18] T. Huehn,[9] S. Igarashi,[14] A.S. Ito,[14] E. James,[2] J. Jaques,[32] S.A. Jerger,[25] J.Z.-Y. Jiang,[42] T. Joffe-Minor,[31] H. Johari,[29] K. Johns,[2] M. Johnson,[14] H. Johnstad,[29] A. Jonckheere,[14] M. Jones,[16] H. Jöstlein,[14] S.Y. Jun,[31] C.K. Jung,[42] S. Kahn,[4] G. Kalbfleisch,[33] J.S. Kang,[20] R. Kehoe,[32] M.L. Kelly,[32] L. Kerth,[22] C.L. Kim,[20] S.K. Kim,[41] A. Klatchko,[15] B. Klima,[14] B.I. Klochkov,[35] C. Klopfenstein,[7] V.I. Klyukhin,[35] V.I. Kochetkov,[35] J.M. Kohli,[34] D. Koltick,[36] A.V. Kostritskiy,[35] J. Kotcher,[4]

[1]Submitted to the 28$^{\rm th}$ International Conference on High Energy Physics, Warsaw, Poland, 25-31 July 1996.

J. Kourlas,[28] A.V. Kozelov,[35] E.A. Kozlovski,[35] M.R. Krishnaswamy,[43] S. Krzywdzinski,[14] S. Kunori,[23] S. Lami,[42] G. Landsberg,[14] J-F. Lebrat,[40] A. Leflat,[26] H. Li,[42] J. Li,[44] Y.K. Li,[31] Q.Z. Li-Demarteau,[14] J.G.R. Lima,[38] D. Lincoln,[24] S.L. Linn,[15] J. Linnemann,[25] R. Lipton,[14] Y.C. Liu,[31] F. Lobkowicz,[39] S.C. Loken,[22] S. Lökös,[42] L. Lueking,[14] A.L. Lyon,[23] A.K.A. Maciel,[10] R.J. Madaras,[22] R. Madden,[15] L. Magaña-Mendoza,[11] S. Mani,[7] H.S. Mao,[14,*] R. Markeloff,[30] L. Markosky,[2] T. Marshall,[18] M.I. Martin,[14] B. May,[31] A.A. Mayorov,[35] R. McCarthy,[42] T. McKibben,[17] J. McKinley,[25] T. McMahon,[33] H.L. Melanson,[14] J.R.T. de Mello Neto,[38] K.W. Merritt,[14] H. Miettinen,[37] A. Mincer,[28] J.M. de Miranda,[10] C.S. Mishra,[14] N. Mokhov,[14] N.K. Mondal,[43] H.E. Montgomery,[14] P. Mooney,[1] H. da Motta,[10] M. Mudan,[28] C. Murphy,[17] F. Nang,[5] M. Narain,[14] V.S. Narasimham,[43] A. Narayanan,[2] H.A. Neal,[24] J.P. Negret,[1] E. Neis,[24] P. Nemethy,[28] D. Nešić,[5] M. Nicola,[10] D. Norman,[45] L. Oesch,[24] V. Oguri,[38] E. Oltman,[22] N. Oshima,[14] D. Owen,[25] P. Padley,[37] M. Pang,[19] A. Para,[14] C.H. Park,[14] Y.M. Park,[21] R. Partridge,[5] N. Parua,[43] M. Paterno,[39] J. Perkins,[44] A. Peryshkin,[14] M. Peters,[16] H. Piekarz,[15] Y. Pischalnikov,[36] V.M. Podstavkov,[35] B.G. Pope,[25] H.B. Prosper,[15] S. Protopopescu,[4] D. Pušeljić,[22] J. Qian,[24] P.Z. Quintas,[14] R. Raja,[14] S. Rajagopalan,[42] O. Ramirez,[17] M.V.S. Rao,[43] P.A. Rapidis,[14] L. Rasmussen,[42] S. Reucroft,[29] M. Rijssenbeek,[42] T. Rockwell,[25] N.A. Roe,[22] P. Rubinov,[31] R. Ruchti,[32] J. Rutherfoord,[2] A. Sánchez-Hernández,[11] A. Santoro,[10] L. Sawyer,[44] R.D. Schamberger,[42] H. Schellman,[31] J. Sculli,[28] E. Shabalina,[26] C. Shaffer,[15] H.C. Shankar,[43] R.K. Shivpuri,[13] M. Shupe,[2] J.B. Singh,[34] V. Sirotenko,[30] W. Smart,[14] A. Smith,[2] R.P. Smith,[14] R. Snihur,[31] G.R. Snow,[27] J. Snow,[33] S. Snyder,[4] J. Solomon,[17] P.M. Sood,[34] M. Sosebee,[44] M. Souza,[10] A.L. Spadafora,[22] R.W. Stephens,[44] M.L. Stevenson,[22] D. Stewart,[24] D.A. Stoianova,[35] D. Stoker,[8] K. Streets,[28] M. Strovink,[22] A. Sznajder,[10] P. Tamburello,[23] J. Tarazi,[8] M. Tartaglia,[14] T.L. Taylor,[31] J. Thompson,[23] T.G. Trippe,[22] P.M. Tuts,[12] N. Varelas,[25] E.W. Varnes,[22] P.R.G. Virador,[22] D. Vititoe,[2] A.A. Volkov,[35] A.P. Vorobiev,[35] H.D. Wahl,[15] G. Wang,[15] J. Warchol,[32] G. Watts,[5] M. Wayne,[32] H. Weerts,[25] A. White,[44] J.T. White,[45] J.A. Wightman,[19] J. Wilcox,[29] S. Willis,[30] S.J. Wimpenny,[9] J.V.D. Wirjawan,[45] J. Womersley,[14] E. Won,[39] D.R. Wood,[29] H. Xu,[5] R. Yamada,[14] P. Yamin,[4] C. Yanagisawa,[42] J. Yang,[28] T. Yasuda,[29] P. Yepes,[37] C. Yoshikawa,[16] S. Youssef,[15] J. Yu,[14] Y. Yu,[41] Q. Zhu,[28] Z.H. Zhu,[39] D. Zieminska,[18] A. Zieminski,[18] E.G. Zverev,[26] and A. Zylberstejn[40]

[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 92717
[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 77251
[38] Universidade Estadual do Rio de Janeiro, Brazil
[39] University of Rochester, Rochester, New York 14627
[40] CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, 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, Bombay 400005, India
[44] University of Texas, Arlington, Texas 76019
[45] Texas A&M University, College Station, Texas 77843

INTRODUCTION

The gauge boson self-interactions are a direct consequence of the non-Abelian $SU(2) \times U(1)$ gauge symmetry of the Standard Model (SM). The trilinear couplings appear as three gauge boson vertices and can be measured by studying the gauge boson pair production processes. The measurement of the coupling parameters is one of a few remaining crucial tests of the SM. Deviations of the couplings from the SM values signal new physics.

The $WWV(V=\gamma$ or $Z)$ vetrtices are described by a general effective Lagrangian (1) with two overall couplings ($g_{WW\gamma}=-e$ and $g_{WWZ}=-e\cdot cot\theta_W$) and six dimensionless coupling parameters g_1^V, κ_V and λ_V, where $V=\gamma$ or Z, after imposing C, P and CP invariance. g_1^γ is restricted to unity by electromagnetic gauge invariance. The general Lagrangian is reduced to the SM Lagrangian by setting $g_1^\gamma = g_1^Z$, $\kappa_V = 1(\Delta\kappa_V \equiv \kappa_V - 1 = 0)$ and $\lambda_V = 0$. The cross section with the non-SM coupling parameters grows with $\hat{s}$. In order to avoid unitarity violation, the coupling parameters are modified as form factors with a scale Λ; $\lambda_V(\hat{s}) = \frac{\lambda_V}{(1+\hat{s}/\Lambda^2)^2}$ and $\Delta\kappa_V(\hat{s}) = \frac{\Delta\kappa_V}{(1+\hat{s}/\Lambda^2)^2}$.

The $Z\gamma V(V=\gamma$ or $Z)$ vertices are described by a general vertex function (2) with eight dimensionless coupling parameters $h_i^V(i=1,4\,;V=\gamma$ or $Z)$. In the SM, all of h_i^V's are zero. The form factors for these vertices, which are required to constrain the cross sections within the unitarity limit, are $h_i^V(\hat{s}) = \frac{h_{i0}^V}{(1+\hat{s}/\Lambda^2)^n}$, where $n=3$ for $i=1,3$ and $n=4$ for $i=2,4$.

In this report, measurements of trilinear gauge boson coupling parameters are presented based on the data taken with the DØ detector during the Tevatron collider runs 1A (1992 - 1993) and 1B (1994 - 1995) at Fermilab. Limits on the anomolous coupling parameters were obtained at a 95% CL from three processes, WW/WZ production with the subsequent W

boson decay to an electron and a neutrino and the second W or Z boson decay to two jets and $W\gamma$ and $Z\gamma$ productions with the subsequent W and Z decays to electron and muon channels.

WW/WZ PRODUCTION

The WW/WZ candidates were obtained by searching for events containing an isolated electron with high $E_T(E_T > 25$ GeV), large missing transverse energy $\not{E}_T(\not{E}_T > 25$ GeV) and two high E_T jets from ~ 14 pb^{-1} of data taken during 1992 - 1993 Tevatron collider run (Run 1A). The transverse mass of the electron and neutrino system was required to be consistent with a W boson decay ($M_T > 40$ GeV/c^2). The invariant mass of two jet system was required to be $50 < m_{jj} < 110$ GeV/c^2, as expected for a W or Z boson decay. The number of events that satisfied all of the requirements was 84. The gauge bosons produced from anomolous self-interactions tend to have high p_T. Two jets from such a high p_T W or Z boson may not be well-separated in space. In order to maximize the detection efficiency of W and Z bosons with high p_T, a small jet cone size of $\Delta R = 0.3$ was used in this analysis. The detection efficiency of W and Z boson in two jet decay mode was estimated as a function of p_T of $W(Z)$ boson $p_T^{W(Z)}$ using ISAJET (3) and PYTHIA (4) event generators and a GEANT (5) based detector simulation program. The detection efficiency stayed constant at approximately 60% up to $p_T = 350$ GeV/c. There were two major sources of background for this process, QCD multijet events with a jet misidentified as an electron and W boson production associated with two jets. Total number of background events was estimated to be 75.5 ± 13.3. The SM predicted 3.2 ± 0.6 events for the above requirements and thus no significant deviation from the SM prediction was seen. A maximum likelihood fit to the p_T^W spectrum, calculated from the E_T of electron and missing E_T, was performed to set limits on the anomolous couplings. Assuming the WWZ couplings and the $WW\gamma$ couplings are equal and using $\Lambda = 1.5$ TeV, the following limits at a 95% confidence level were obtained, as shown in Fig. 1a:

$$-0.9 < \Delta\kappa < 1.1(\lambda = 0)\ ;\ -0.6 < \lambda < 0.7(\Delta\kappa = 0)$$

Different assumptions for the relationship between the WWZ couplings and the $WW\gamma$ couplings were examined. The limits in Fig. 1b were obtained using the HISZ (6) relations. In Fig. 1c limits on the WWZ couplings are shown under the assumption that the $WW\gamma$ couplings take the SM values. In Fig. 1d limits on the $WW\gamma$ couplings are shown with the assumption that the WWZ couplings take the SM values. These plots indicate that this analysis is more sensitive to WWZ couplings as expected from the larger overall couplings for WWZ than $WW\gamma$ and that it is complementary to the $W\gamma$ production process which is sensitive to the $WW\gamma$ couplings only.

COMBINED FIT FROM RUN 1A $WW\gamma/WWZ$ COUPLINGS MEASUREMENTS

The limits on $WW\gamma$ couplings were reported previously from a fit to the photon E_T spectrum in $W\gamma$ production using the Run 1A data (7). The limits on $WW\gamma$ and WWZ couplings were also reported previously from an upper limit on the WW production cross section and decay in dilepton channels (8). Since these two previous results and the above WW/WZ analysis measured the same couplings, a combined fit to all three data sets was performed, yielding a significantly improved limits from the individual analyses;

$$-0.71 < \Delta\kappa < -0.89(\lambda = 0)\ ;\ -0.44 < \lambda < 0.44(\Delta\kappa = 0),$$

where it was assumed that the WWZ couplings and the $WW\gamma$ couplings were equal. The contour is shown in Fig. 2.

$W\gamma$ PRODUCTION

The $W(\ell\nu)\gamma$ candidates were selected by searching for events containing an isolated lepton with high E_T, large missing transverse energy, $\not\!\!E_T$, and an isolated photon from $\sim 75\text{pb}^{-1}$ of data taken during 1994 - 1995 Tevatron collider run (Run 1B). For the electron channel, the events were required to have an electron with $E_T > 25$ GeV in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$ and to have $\not\!\!E_T > 25$ GeV. A requirement on the transverse mass $M_T > 40$ GeV/c^2 was applied to insure the detection of a W boson. For the muon channel, the events were required to have a muon with $p_T > 15$ GeV/c in the fiducial region of $|\eta| < 1.0$ and to have $\not\!\!E_T > 15$ GeV. The requirement for the photon was common to both the channels. The candidate event was required to have a photon with $E_T > 10$ GeV in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. In addition, the separation in $\eta - \phi$ space between a photon and a lepton ($\mathcal{R}_{\ell\gamma}$) had to be greater than 0.7. This requirement suppressed the contribution of the radiative W decay process, and minimized the probability for a photon cluster to merge with a nearby calorimeter cluster associated with an electron or a muon. An additional cut for photon in the electron channel, which required that there be no statistically significant tracking chamber hits in a narrow road pointing the EM cluster, was imposed in order to reduce background from $p\bar{p} \to eeX$ type events, such as $Z\gamma \to ee\gamma$ and $t\bar{t} \to eeX$. The above selection criteria yielded 46 $W(e\nu)\gamma$ and 58 $W(\mu\nu)\gamma$ candidates.

The backgrounds were estimated from the Monte Carlo simulation and data. The estimated total backgrounds were 13.2 ± 2.3 for the electron channel and 23.0 ± 4.6 for the muon channel, respectively. The kinematic and geometrical acceptance was estimated as a function of coupling parameters using the Monte Carlo program of Baur and Zeppenfeld (9). The MRSD_$'$ parton distribution functions (10) were used. The p_T distribution of the $W\gamma$ system was simulated using the observed spectrum of the W in the inclusive $W(e\nu)$ sample. The $W\gamma$ cross section times the leptonic branching ratio $Br(W \to \ell\nu)$ (for photons with $E_T^\gamma > 10$ GeV and $\mathcal{R}_{\ell\gamma} > 0.7$) was obtained for the electron and muon channel separately using the acceptance for the SM couplings and the measured trigger and selection efficiencies:

$$\sigma_{W\gamma} \cdot Br(W \to e\nu) = 11.2^{+2.7}_{-2.3}(stat) \pm 0.6(syst) \pm 0.6(lum)\ \text{pb}$$
$$\sigma_{W\gamma} \cdot Br(W \to \mu\nu) = 13.6^{+3.4}_{-2.9}(stat) \pm 2.1(syst) \pm 0.7(lum)\ \text{pb}$$

The results agree with the SM prediction of $\sigma_{W\gamma} \cdot Br(W \to \ell\nu)^{SM} = 12.5 \pm 1.0$ pb within errors.

To set limits on the anomolous coupling parameters, a binned maximum likelihood fit was performed on the E_T spectrum of photon for each of the $W(e\nu)\gamma$ and $W(\mu\nu)\gamma$ samples. A dipole form factor with a scale $\Lambda = 1.5$ TeV was used in the Monte Carlo event generation. The 95% CL limits on the coupling parameters are

$$-1.4 < \Delta\kappa_\gamma < 1.4\ (\lambda_\gamma = 0)\ ;\ -0.5 < \lambda_\gamma < 0.5\ (\Delta\kappa_\gamma = 0)\quad (e-channel)$$
$$-1.95 < \Delta\kappa_\gamma < 1.95\ (\lambda_\gamma = 0)\ ;\ -0.52 < \lambda_\gamma < 0.52\ (\Delta\kappa_\gamma = 0)\quad (\mu-channel)$$

for $\hat{s} = 0$. A combined fit to all of the $W\gamma$ data sets including the electron and muon data from Run 1A was performed, yielding the following limits on the anomolous couplings, as shown in Fig. 3:

$$-0.97 < \Delta\kappa_\gamma < 0.99 \ (\lambda_\gamma = 0) \ ; \ -0.33 < \lambda_\gamma < 0.31 \ (\Delta\kappa_\gamma = 0)$$

Figure 3 also shows the results from CDF collaboration (11) and CLEO collaboration (12). The $U(1)$ only couplings of the W boson to a photon, which lead to $\kappa_\gamma = 0$ ($\Delta\kappa_\gamma = -1$) and $\lambda_\gamma = 0$ are excluded at a 95% CL.

$Z\gamma$ PRODUCTION

The $Z\gamma$ candidates were selected by searching for events containing two isolated electrons with high transverse energy E_T and an isolated photon from $\sim$ 89 pb^{-1} of data taken during 1994 - 1995 Tevatron collider run. Two electrons with $E_T > 25$ GeV were required. The requirements for photon selection were similar to the $W\gamma$ analysis. It was required that the transverse energy of photon be greater than 10 GeV and that the separation between a photon and a lepton ($\mathcal{R}_{\ell\gamma}$) be greater than 0.7. Two analysis methods were used, motivated by a few events with a high E_T photon that were unexpected by the SM. ***Standard*** selection required (i) at least one electron candidate has an associated track, (ii) the second electron may or may not have an associated track, and (iii) the photon candidate must not have an associated track. On the other hand, ***Tight*** selection required that (i) at least one electron candidate has an associated track as in ***Standard*** selection, (ii) the second electron candidate must have at least a significant number of hits in a narrow road pointing the energy cluster in the calorimeter and (iii) the photon candidate must not have a statistically significant number of hits associated with it. The above selection yielded 21 (Standard) and 14 (Tight) $Z(ee)\gamma$ candidates.

The backgrounds were estimated from the Monte Carlo simulation and data. The estimated total background events were 4.0 ± 1.2 for the Standard selection and 1.6 ± 0.5 for the Tight selection. The kinematic and geometrical acceptance as a function of coupling parameters were estimated using the Monte Carlo program of Baur and Berger (2). The MRSD$_'$ parton distribution functions were used. The trigger and electron selection efficiencies were derived from data. The SM predicts 16.7 ± 1.7 (Standard) and 12.0 ± 1.2 (Tight) events.

To set the limits on the anomolous coupling parameters, the observed E_T spectrum of the photon was fitted using an unbinned maximum likelihood method. The results from two analyses were consistent with each other. The following 95% CL limits on the *CP*-conserving $ZZ\gamma$ and $Z\gamma\gamma$ couplings with the form factor scale $\Lambda = 500$ GeV (under the assumption that all couplings except one have the SM values, *i.e.* zeros) were obtained:

$$-1.8 < h^Z_{30} < 1.8; -0.38 < h^Z_{40} < 0.38$$
$$-1.8 < h^\gamma_{30} < 1.9; -0.38 < h^\gamma_{40} < 0.38.$$

The limit contour is shown in Fig. 4. Limits on the *CP*-violating couplings h^V_{i0} ($i = 1, 2$; $V = \gamma$ or Z) were numerically the same as those for *CP*-conserving couplings.

CONCLUSIONS

A search for anomolous WW and WZ production was carried out using the electron plus jets decay modes on $\sim$ 14 pb^{-1} of data. The measured p_T spectrum of W boson was consistent with the SM prediction and the estimated backgrounds. Limits on the anomolous couplings were obtained by a maximum likelihood fit to the p_T spectrum of W boson. The limits on the anomolous couplings were improved when a combined fit to three Run 1A data sets of gauge boson pair production processes was performed, assuming that the WWZ couplings and the $WW\gamma$ couplings are equal:

$$-0.71 < \Delta\kappa < -0.89(\lambda = 0)\ ;\ -0.44 < \lambda < 0.44(\Delta\kappa = 0).$$

Measurements of p_T spectrum of photon in the $W\gamma$ production followed by leptonic W boson decay with $\sim 75\ \mathrm{pb}^{-1}$ of data resulted in new limits on the anomolous $WW\gamma$ couplings. After combining with the previously published Run 1A results, further improved limits were obtained on the couplings:

$$-0.97 < \Delta\kappa_\gamma < 0.99\ (\lambda_\gamma = 0)\ ;\ -0.33 < \lambda_\gamma < 0.31\ (\Delta\kappa_\gamma = 0).$$

Also a measurement of p_T spectrum of photon in the $Z\gamma$ production followed by Z boson decay to ee channel with $\sim 89\ \mathrm{pb}^{-1}$ of data resulted in slightly improved limits on the anomolous $ZZ\gamma$ and $Z\gamma\gamma$ couplings compared to the previous measurement (13):

$$-1.8 < h_{30}^Z < 1.8; -0.38 < h_{40}^Z < 0.38$$
$$-1.8 < h_{30}^\gamma < 1.9; -0.38 < h_{40}^\gamma < 0.38.$$

The final Run 1 limits will be obtained when all of the possible analyses using $90-100\ \mathrm{pb}^{-1}$ of data from Run 1A and Run 1B are completed and combined fits performed.

ACKNOWLEDGMENTS

We thank the staffs at Fermilab and the collaborating institutions for their contributions to the success of this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L'Energie Atomique (France), Ministries for Atomic Energy and Science and Technology Policy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), and the A.P. Sloan Foundation.

REFERENCES

* Visitor from IHEP, Beijing, China.

† Visitor from Univ. San Francisco de Quito, Ecuador.

1. K. Hagiwara, R.D. Peccei, D. Zeppenfeld and K. Hikasa, *Nucl. Phys.* B **282**, 253 (1987)
2. U. Baur and E.L. Berger, *Phys. Rev.* D **41**, 1476 (1990).
3. F. Paige and S. Protopopescu, BNL Report No. BNL-38034, 1986 (unpublished), release V6.49.
4. T. Sjöstrand, Computer Physics Commun. bf 82, 74 (1994).
5. F. Carminati *et al* "GEANT Users Guide," CERN Program Library, 1991 (unpublished).
6. K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, *Phys. Rev.* D **48**, 2182 (1993).
7. S. Abachi *et al*, *Phys. Rev. Lett.* **75**, 1034 (1995).
8. S. Abachi *et al*, *Phys. Rev. Lett.* **75**, 1023 (1995).
9. U. Baur and D. Zeppenfeld, *Nucl. Phys.* B **308**, 127 (1988).
10. A.D. Martin, R.G. Roberts and W.J. Sterling, *Phys. Rev.* D **47**, 867 (1993).

11. D. Benjamin, "$W\gamma$ and $Z\gamma$ Production at the Tevatron," in 10th Topical Workshop on Proton-Antiproton Collider Physics, edited by R. Raja and J. Yoh, AIP Press (1996) p. 370.
12. S.M. Playfer, "Rare b Decays and Anomolous Couplings," in International Symposium on Vector Boson Interactions, edited by U. Baur, S. Errede, T. Müller, AIP Press (1996) p. 124.
13. S. Abachi *et al*, *Phys. Rev. Lett.* **75**, 1028 (1995).

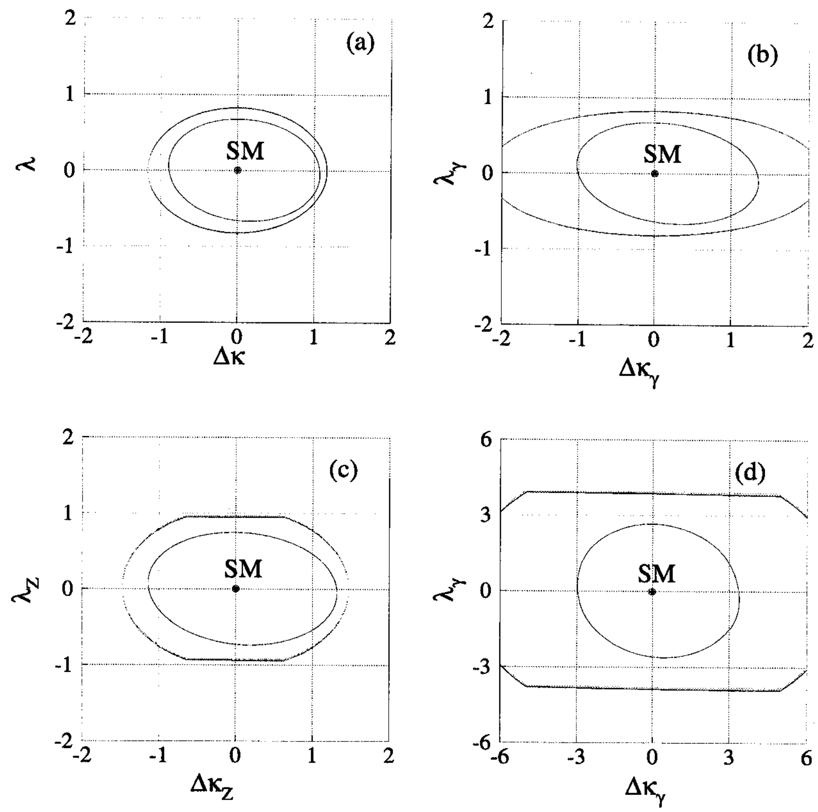

FIG. 1. Contour limits on anomolous coupling parameters at the 95% CL (inner curves) and limits from S-matrix unitarity (outer curves), assuming (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z, \lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations; (c) SM $WW\gamma$ couplings, and (d) SM WWZ couplings. $\Lambda = 1.5$ TeV is used for (a), (b) and (c); $\Lambda = 1.0$ TeV is used for (d).

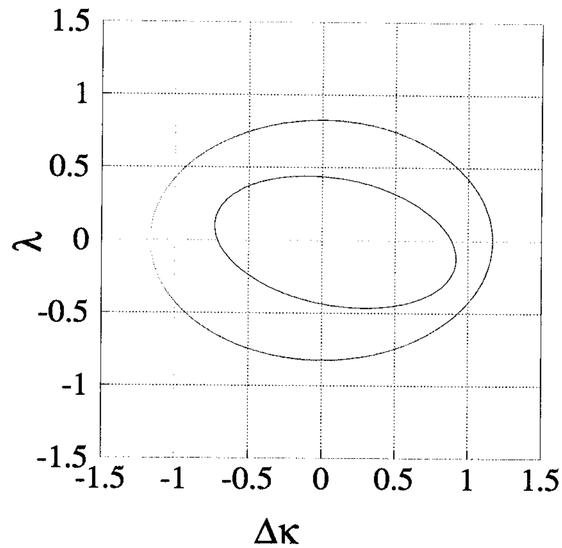

FIG. 2. Combined contour limits on anomolous coupling parameters at the 95% CL, using $\Lambda = 1.5$ TeV: the inner curve is the result from combined fit to three data sets from Run 1A; the outer contour is the unitarity constraint.

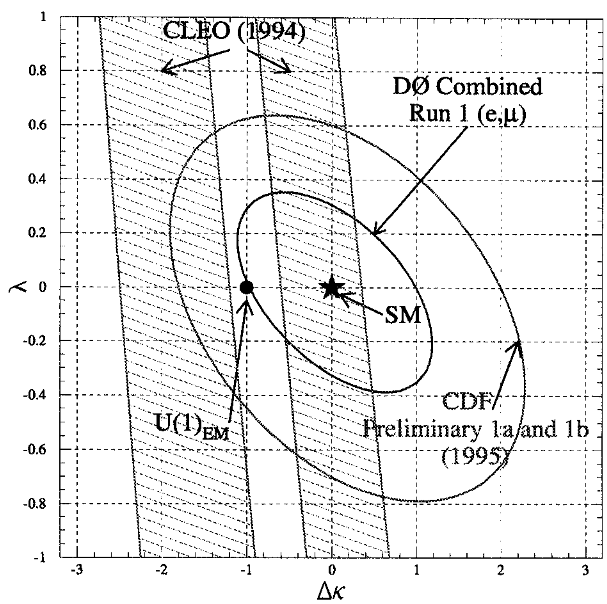

FIG. 3. Contour limits on anomolous coupling parameters at the 95% CL: the inner curve is the result from combined fit to Run 1A and Run 1B $W\gamma$ data sets; the outer contour is the result from CDF collaboration; the shaded areas are the allowed regions from $b \to s\gamma$ measurement by CLEO collaboration.

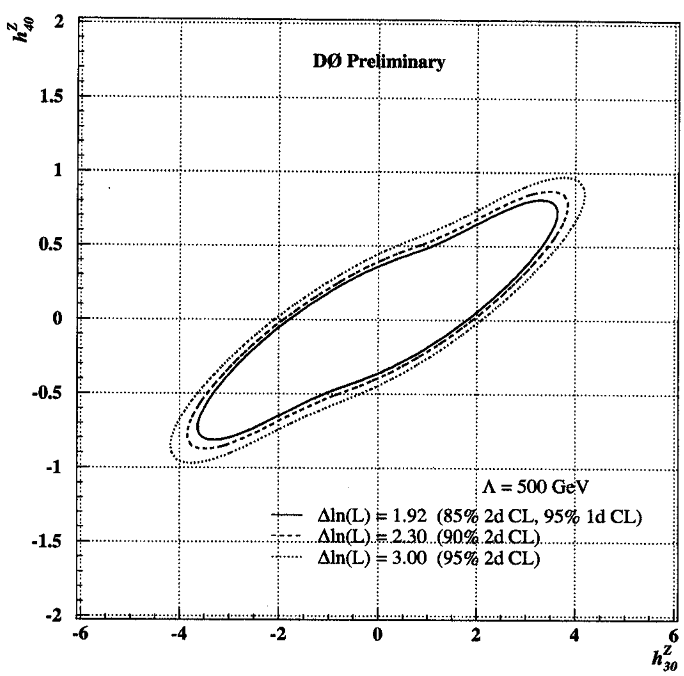

FIG. 4. Contour limits on anomolous coupling parameters at the 85%, 90% and 95% CLs from a maximum likelihood fit to the p_T spectrum of photon in the $Z\gamma$ production.