Limits on anomalous trilinear gauge couplings from $WW \to e^+e^-, WW \to e^\pm e^\pm$, and $WW \to \mu^+\mu^-$ events from $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV

V.M. Abazov, B. Abbott, M. Abolins, B.S. Acharya, M. Adams, T. Adams, M. Agelou, S.H. Ahn, M. Ahsan, G.D. Alexeev, et al.

FERMILAB-PUB-06-268-E

Limits on anomalous trilinear gauge couplings from $WW \to e^+e^-$, $WW \to e^\pm\mu^\mp$, and $WW \to \mu^+\mu^-$ events from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

V.M. Abazov,[36] B. Abbott,[76] M. Abolins,[66] B.S. Acharya,[29] M. Adams,[52] T. Adams,[50] M. Agelou,[18] S.H. Ahn,[31] M. Ahsan,[60] G.D. Alexeev,[36] G. Alkhazov,[40] A. Alton,[65] G. Alverson,[64] G.A. Alves,[2] M. Anastasoaie,[35] T. Andeen,[54] S. Anderson,[46] B. Andrieu,[17] M.S. Anzelc,[54] Y. Arnoud,[14] M. Arov,[53] A. Askew,[50] B. Åsman,[41] A.C.S. Assis Jesus,[3] O. Atramentov,[58] C. Autermann,[21] C. Avila,[8] C. Ay,[24] F. Badaud,[13] A. Baden,[62] L. Bagby,[53] B. Baldin,[51] D.V. Bandurin,[60] P. Banerjee,[29] S. Banerjee,[29] E. Barberis,[64] P. Bargassa,[81] P. Baringer,[59] C. Barnes,[44] J. Barreto,[2] J.F. Bartlett,[51] U. Bassler,[17] D. Bauer,[44] A. Bean,[59] M. Begalli,[3] M. Begel,[72] C. Belanger-Champagne,[5] L. Bellantoni,[51] A. Bellavance,[68] J.A. Benitez,[66] S.B. Beri,[27] G. Bernardi,[17] R. Bernhard,[42] L. Berntzon,[15] I. Bertram,[43] M. Besançon,[18] R. Beuselinck,[44] V.A. Bezzubov,[39] P.C. Bhat,[51] V. Bhatnagar,[27] M. Binder,[25] C. Biscarat,[43] K.M. Black,[63] I. Blackler,[44] G. Blazey,[53] F. Blekman,[44] S. Blessing,[50] D. Bloch,[19] K. Bloom,[68] U. Blumenschein,[23] A. Boehnlein,[51] O. Boeriu,[56] T.A. Bolton,[60] G. Borissov,[43] K. Bos,[34] T. Bose,[78] A. Brandt,[79] R. Brock,[66] G. Brooijmans,[71] A. Bross,[51] D. Brown,[79] N.J. Buchanan,[50] D. Buchholz,[54] M. Buehler,[82] V. Buescher,[23] S. Burdin,[51] S. Burke,[46] T.H. Burnett,[83] E. Busato,[17] C.P. Buszello,[44] J.M. Butler,[63] P. Calfayan,[25] S. Calvet,[15] J. Cammin,[72] S. Caron,[34] W. Carvalho,[3] B.C.K. Casey,[78] N.M. Cason,[56] H. Castilla-Valdez,[33] D. Chakraborty,[53] K.M. Chan,[72] A. Chandra,[49] F. Charles,[19] E. Cheu,[46] F. Chevallier,[14] D.K. Cho,[63] S. Choi,[32] B. Choudhary,[28] L. Christofek,[59] D. Claes,[68] B. Clément,[19] C. Clément,[41] Y. Coadou,[5] M. Cooke,[81] W.E. Cooper,[51] D. Coppage,[59] M. Corcoran,[81] M.-C. Cousinou,[15] B. Cox,[45] S. Crépé-Renaudin,[14] D. Cutts,[78] M. Ćwiok,[30] H. da Motta,[2] A. Das,[63] M. Das,[61] B. Davies,[43] G. Davies,[44] G.A. Davis,[54] K. De,[79] P. de Jong,[34] S.J. de Jong,[35] E. De La Cruz-Burelo,[65] C. De Oliveira Martins,[3] J.D. Degenhardt,[65] F. Déliot,[18] M. Demarteau,[51] R. Demina,[72] P. Demine,[18] D. Denisov,[51] S.P. Denisov,[39] S. Desai,[73] H.T. Diehl,[51] M. Diesburg,[51] M. Doidge,[43] A. Dominguez,[68] H. Dong,[73] L.V. Dudko,[38] L. Duflot,[16] S.R. Dugad,[29] D. Duggan,[50] A. Duperrin,[15] J. Dyer,[66] A. Dyshkant,[53] M. Eads,[68] D. Edmunds,[66] T. Edwards,[45] J. Ellison,[49] J. Elmsheuser,[25] V.D. Elvira,[51] S. Eno,[62] P. Ermolov,[38] H. Evans,[55] A. Evdokimov,[37] V.N. Evdokimov,[39] S.N. Fatakia,[63] L. Feligioni,[63] A.V. Ferapontov,[60] T. Ferbel,[72] F. Fiedler,[25] F. Filthaut,[35] W. Fisher,[51] H.E. Fisk,[51] I. Fleck,[23] M. Ford,[45] M. Fortner,[53] H. Fox,[23] S. Fu,[51] S. Fuess,[51] T. Gadfort,[83] C.F. Galea,[35] E. Gallas,[51] E. Galyaev,[56] C. Garcia,[72] A. Garcia-Bellido,[83] J. Gardner,[59] V. Gavrilov,[37] A. Gay,[19] P. Gay,[13] D. Gelé,[19] R. Gelhaus,[49] C.E. Gerber,[52] Y. Gershtein,[50] D. Gillberg,[5] G. Ginther,[72] N. Gollub,[41] B. Gómez,[8] A. Goussiou,[56] P.D. Grannis,[73] H. Greenlee,[51] Z.D. Greenwood,[61] E.M. Gregores,[4] G. Grenier,[20] Ph. Gris,[13] J.-F. Grivaz,[16] S. Grünendahl,[51] M.W. Grünewald,[30] F. Guo,[73] J. Guo,[73] G. Gutierrez,[51] P. Gutierrez,[76] A. Haas,[71] N.J. Hadley,[62] P. Haefner,[25] S. Hagopian,[50] J. Haley,[69] I. Hall,[76] R.E. Hall,[48] L. Han,[7] K. Hanagaki,[51] K. Harder,[60] A. Harel,[72] R. Harrington,[64] J.M. Hauptman,[58] R. Hauser,[66] J. Hays,[54] T. Hebbeker,[21] D. Hedin,[53] J.G. Hegeman,[34] J.M. Heinmiller,[52] A.P. Heinson,[49] U. Heintz,[63] C. Hensel,[59] K. Herner,[73] G. Hesketh,[64] M.D. Hildreth,[56] R. Hirosky,[82] J.D. Hobbs,[73] B. Hoeneisen,[12] H. Hoeth,[26] M. Hohlfeld,[16] S.J. Hong,[31] R. Hooper,[78] P. Houben,[34] Y. Hu,[73] Z. Hubacek,[10] V. Hynek,[9] I. Iashvili,[70] R. Illingworth,[51] A.S. Ito,[51] S. Jabeen,[63] M. Jaffré,[16] S. Jain,[76] K. Jakobs,[23] C. Jarvis,[62] A. Jenkins,[44] R. Jesik,[44] K. Johns,[46] C. Johnson,[71] M. Johnson,[51] A. Jonckheere,[51] P. Jonsson,[44] A. Juste,[51] D. Käfer,[21] S. Kahn,[74] E. Kajfasz,[15] A.M. Kalinin,[36] J.M. Kalk,[61] J.R. Kalk,[66] S. Kappler,[21] D. Karmanov,[38] J. Kasper,[63] P. Kasper,[51] I. Katsanos,[71] D. Kau,[50] R. Kaur,[27] R. Kehoe,[80] S. Kermiche,[15] N. Khalatyan,[63] A. Khanov,[77] A. Kharchilava,[70] Y.M. Kharzheev,[36] D. Khatidze,[71] H. Kim,[79] T.J. Kim,[31] M.H. Kirby,[35] B. Klima,[51] J.M. Kohli,[27] J.-P. Konrath,[23] M. Kopal,[76] V.M. Korablev,[39] J. Kotcher,[74] B. Kothari,[71] A. Koubarovsky,[38] A.V. Kozelov,[39] J. Kozminski,[66] D. Krop,[55] A. Kryemadhi,[82] T. Kuhl,[24] A. Kumar,[70] S. Kunori,[62] A. Kupco,[11] T. Kurča,[20,*] J. Kvita,[9] S. Lammers,[71] G. Landsberg,[78] J. Lazoflores,[50] A.-C. Le Bihan,[19] P. Lebrun,[20] W.M. Lee,[53] A. Leflat,[38] F. Lehner,[42] V. Lesne,[13] J. Leveque,[46] P. Lewis,[44] J. Li,[79] Q.Z. Li,[51] J.G.R. Lima,[53] D. Lincoln,[51] J. Linnemann,[66] V.V. Lipaev,[39] R. Lipton,[51] Z. Liu,[5] L. Lobo,[44] A. Lobodenko,[40] M. Lokajicek,[11] A. Lounis,[19] P. Love,[43] H.J. Lubatti,[83] M. Lynker,[56] A.L. Lyon,[51] A.K.A. Maciel,[2] R.J. Madaras,[47] P. Mättig,[26] C. Magass,[21] A. Magerkurth,[65] A.-M. Magnan,[14] N. Makovec,[16] P.K. Mal,[56] H.B. Malbouisson,[3] S. Malik,[68] V.L. Malyshev,[36] H.S. Mao,[6] Y. Maravin,[60] M. Martens,[51] R. McCarthy,[73] D. Meder,[24] A. Melnitchouk,[67] A. Mendes,[15] L. Mendoza,[8] M. Merkin,[38] K.W. Merritt,[51] A. Meyer,[21] J. Meyer,[22] M. Michaut,[18] H. Miettinen,[81] T. Millet,[20] J. Mitrevski,[71] J. Molina,[3] N.K. Mondal,[29] J. Monk,[45] R.W. Moore,[5] T. Moulik,[59] G.S. Muanza,[16] M. Mulders,[51] M. Mulhearn,[71]

L. Mundim,[3] Y.D. Mutaf,[73] E. Nagy,[15] M. Naimuddin,[28] M. Narain,[63] N.A. Naumann,[35] H.A. Neal,[65] J.P. Negret,[8] P. Neustroev,[40] C. Noeding,[23] A. Nomerotski,[51] S.F. Novaes,[4] T. Nunnemann,[25] V. O'Dell,[51] D.C. O'Neil,[5] G. Obrant,[40] V. Oguri,[3] N. Oliveira,[3] N. Oshima,[51] R. Otec,[10] G.J. Otero y Garzón,[52] M. Owen,[45] P. Padley,[81] N. Parashar,[57] S.-J. Park,[72] S.K. Park,[31] J. Parsons,[71] R. Partridge,[78] N. Parua,[73] A. Patwa,[74] G. Pawloski,[81] P.M. Perea,[49] E. Perez,[18] K. Peters,[45] P. Pétroff,[16] M. Petteni,[44] R. Piegaia,[1] J. Piper,[66] M.-A. Pleier,[22] P.L.M. Podesta-Lerma,[33] V.M. Podstavkov,[51] Y. Pogorelov,[56] M.-E. Pol,[2] A. Pompoš,[76] B.G. Pope,[66] A.V. Popov,[39] C. Potter,[5] W.L. Prado da Silva,[3] H.B. Prosper,[50] S. Protopopescu,[74] J. Qian,[65] A. Quadt,[22] B. Quinn,[67] M.S. Rangel,[2] K.J. Rani,[29] K. Ranjan,[28] P.N. Ratoff,[43] P. Renkel,[80] S. Reucroft,[64] M. Rijssenbeek,[73] I. Ripp-Baudot,[19] F. Rizatdinova,[77] S. Robinson,[44] R.F. Rodrigues,[3] C. Royon,[18] P. Rubinov,[51] R. Ruchti,[56] V.I. Rud,[38] G. Sajot,[14] A. Sánchez-Hernández,[33] M.P. Sanders,[62] A. Santoro,[3] G. Savage,[51] L. Sawyer,[61] T. Scanlon,[44] D. Schaile,[25] R.D. Schamberger,[73] Y. Scheglov,[40] H. Schellman,[54] P. Schieferdecker,[25] C. Schmitt,[26] C. Schwanenberger,[45] A. Schwartzman,[69] R. Schwienhorst,[66] J. Sekaric,[50] S. Sengupta,[50] H. Severini,[76] E. Shabalina,[52] M. Shamim,[60] V. Shary,[18] A.A. Shchukin,[39] W.D. Shephard,[56] R.K. Shivpuri,[28] D. Shpakov,[51] V. Siccardi,[19] R.A. Sidwell,[60] V. Simak,[10] V. Sirotenko,[51] P. Skubic,[76] P. Slattery,[72] R.P. Smith,[51] G.R. Snow,[68] J. Snow,[75] S. Snyder,[74] S. Söldner-Rembold,[45] X. Song,[53] L. Sonnenschein,[17] A. Sopczak,[43] M. Sosebee,[79] K. Soustruznik,[9] M. Souza,[2] B. Spurlock,[79] J. Stark,[14] J. Steele,[61] V. Stolin,[37] A. Stone,[52] D.A. Stoyanova,[39] J. Strandberg,[41] S. Strandberg,[41] M.A. Strang,[70] M. Strauss,[76] R. Ströhmer,[25] D. Strom,[54] M. Strovink,[47] L. Stutte,[51] S. Sumowidagdo,[50] A. Sznajder,[3] M. Talby,[15] P. Tamburello,[46] W. Taylor,[5] P. Telford,[45] J. Temple,[46] B. Tiller,[25] M. Titov,[23] V.V. Tokmenin,[36] M. Tomoto,[51] T. Toole,[62] I. Torchiani,[23] S. Towers,[43] T. Trefzger,[24] S. Trincaz-Duvoid,[17] D. Tsybychev,[73] B. Tuchming,[18] C. Tully,[69] A.S. Turcot,[45] P.M. Tuts,[71] R. Unalan,[66] L. Uvarov,[40] S. Uvarov,[40] S. Uzunyan,[53] B. Vachon,[5] P.J. van den Berg,[34] R. Van Kooten,[55] W.M. van Leeuwen,[34] N. Varelas,[52] E.W. Varnes,[46] A. Vartapetian,[79] I.A. Vasilyev,[39] M. Vaupel,[26] P. Verdier,[20] L.S. Vertogradov,[36] M. Verzocchi,[51] F. Villeneuve-Seguier,[44] P. Vint,[44] J.-R. Vlimant,[17] E. Von Toerne,[60] M. Voutilainen,[68,†] M. Vreeswijk,[34] H.D. Wahl,[50] L. Wang,[62] M.H.L.S Wang,[51] J. Warchol,[56] G. Watts,[83] M. Wayne,[56] M. Weber,[51] H. Weerts,[66] N. Wermes,[22] M. Wetstein,[62] A. White,[79] D. Wicke,[26] G.W. Wilson,[59] S.J. Wimpenny,[49] M. Wobisch,[51] J. Womersley,[51] D.R. Wood,[64] T.R. Wyatt,[45] Y. Xie,[78] N. Xuan,[56] S. Yacoob,[54] R. Yamada,[51] M. Yan,[62] T. Yasuda,[51] Y.A. Yatsunenko,[36] K. Yip,[74] H.D. Yoo,[78] S.W. Youn,[54] C. Yu,[14] J. Yu,[79] A. Yurkewicz,[73] A. Zatserklyaniy,[53] C. Zeitnitz,[26] D. Zhang,[51] T. Zhao,[83] B. Zhou,[65] J. Zhu,[73] M. Zielinski,[72] D. Zieminska,[55] A. Zieminski,[55] V. Zutshi,[53] and E.G. Zverev[38]
(DØ Collaboration)

[1] *Universidad de Buenos Aires, Buenos Aires, Argentina*
[2] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3] *Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[4] *Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[5] *University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada*
[6] *Institute of High Energy Physics, Beijing, People's Republic of China*
[7] *University of Science and Technology of China, Hefei, People's Republic of China*
[8] *Universidad de los Andes, Bogotá, Colombia*
[9] *Center for Particle Physics, Charles University, Prague, Czech Republic*
[10] *Czech Technical University, Prague, Czech Republic*
[11] *Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[12] *Universidad San Francisco de Quito, Quito, Ecuador*
[13] *Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France*
[14] *Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[15] *CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France*
[16] *IN2P3-CNRS, Laboratoire de l'Accélérateur Linéaire, Orsay, France*
[17] *LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France*
[18] *DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[19] *IPHC, IN2P3-CNRS, Université Louis Pasteur, Strasbourg, France, and Université de Haute Alsace, Mulhouse, France*
[20] *Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, Université Claude Bernard, Villeurbanne, France*
[21] *III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany*
[22] *Physikalisches Institut, Universität Bonn, Bonn, Germany*
[23] *Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[24] *Institut für Physik, Universität Mainz, Mainz, Germany*
[25] *Ludwig-Maximilians-Universität München, München, Germany*
[26] *Fachbereich Physik, University of Wuppertal, Wuppertal, Germany*

[27]Panjab University, Chandigarh, India
[28]Delhi University, Delhi, India
[29]Tata Institute of Fundamental Research, Mumbai, India
[30]University College Dublin, Dublin, Ireland
[31]Korea Detector Laboratory, Korea University, Seoul, Korea
[32]SungKyunKwan University, Suwon, Korea
[33]CINVESTAV, Mexico City, Mexico
[34]FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
[35]Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
[36]Joint Institute for Nuclear Research, Dubna, Russia
[37]Institute for Theoretical and Experimental Physics, Moscow, Russia
[38]Moscow State University, Moscow, Russia
[39]Institute for High Energy Physics, Protvino, Russia
[40]Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[41]Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
[42]Physik Institut der Universität Zürich, Zürich, Switzerland
[43]Lancaster University, Lancaster, United Kingdom
[44]Imperial College, London, United Kingdom
[45]University of Manchester, Manchester, United Kingdom
[46]University of Arizona, Tucson, Arizona 85721, USA
[47]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
[48]California State University, Fresno, California 93740, USA
[49]University of California, Riverside, California 92521, USA
[50]Florida State University, Tallahassee, Florida 32306, USA
[51]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[52]University of Illinois at Chicago, Chicago, Illinois 60607, USA
[53]Northern Illinois University, DeKalb, Illinois 60115, USA
[54]Northwestern University, Evanston, Illinois 60208, USA
[55]Indiana University, Bloomington, Indiana 47405, USA
[56]University of Notre Dame, Notre Dame, Indiana 46556, USA
[57]Purdue University Calumet, Hammond, Indiana 46323, USA
[58]Iowa State University, Ames, Iowa 50011, USA
[59]University of Kansas, Lawrence, Kansas 66045, USA
[60]Kansas State University, Manhattan, Kansas 66506, USA
[61]Louisiana Tech University, Ruston, Louisiana 71272, USA
[62]University of Maryland, College Park, Maryland 20742, USA
[63]Boston University, Boston, Massachusetts 02215, USA
[64]Northeastern University, Boston, Massachusetts 02115, USA
[65]University of Michigan, Ann Arbor, Michigan 48109, USA
[66]Michigan State University, East Lansing, Michigan 48824, USA
[67]University of Mississippi, University, Mississippi 38677, USA
[68]University of Nebraska, Lincoln, Nebraska 68588, USA
[69]Princeton University, Princeton, New Jersey 08544, USA
[70]State University of New York, Buffalo, New York 14260, USA
[71]Columbia University, New York, New York 10027, USA
[72]University of Rochester, Rochester, New York 14627, USA
[73]State University of New York, Stony Brook, New York 11794, USA
[74]Brookhaven National Laboratory, Upton, New York 11973, USA
[75]Langston University, Langston, Oklahoma 73050, USA
[76]University of Oklahoma, Norman, Oklahoma 73019, USA
[77]Oklahoma State University, Stillwater, Oklahoma 74078, USA
[78]Brown University, Providence, Rhode Island 02912, USA
[79]University of Texas, Arlington, Texas 76019, USA
[80]Southern Methodist University, Dallas, Texas 75275, USA
[81]Rice University, Houston, Texas 77005, USA
[82]University of Virginia, Charlottesville, Virginia 22901, USA
[83]University of Washington, Seattle, Washington 98195, USA

(Dated: August 4, 2006)

Limits are set on anomalous $WW\gamma$ and WWZ trilinear gauge couplings using $W^+W^- \rightarrow e^+\nu_e e^-\bar{\nu}_e$, $W^+W^- \rightarrow e^\pm\nu_e\mu^\mp\nu_\mu$, and $W^+W^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ events. The data set was collected by the Run II DØ detector at the Fermilab Tevatron Collider and corresponds to approximately

250 pb^{-1} of integrated luminosity at $\sqrt{s} = 1.96$ TeV. Under the assumption that the $WW\gamma$ couplings are equal to the WWZ couplings and using a form factor scale of $\Lambda = 2.0$ TeV, the combined 95% C.L. one-dimensional coupling limits from all three channels are $-0.32 < \Delta\kappa < 0.45$ and $-0.29 < \lambda < 0.30$.

Within the standard model (SM), interactions between the bosons of the electroweak interaction are entirely determined by the gauge symmetry. Any deviation from the SM couplings is therefore evidence of new physics.

The most general Lorentz invariant effective Lagrangian which describes the triple gauge couplings has fourteen independent coupling parameters, seven for each of the $WW\gamma$ and WWZ vertices [1]. With the assumption of electromagnetic gauge invariance and C and P conservation, the number of independent couplings is reduced to five, and the Lagrangian takes this form:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda} \quad (1)$$

where $V = \gamma$ or Z, W^μ is the W^- field, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, and $g_1^\gamma = 1$. The overall couplings are $g_{WW\gamma} = -e$ and $g_{WWZ} = -e\cot\theta_W$.

The five remaining parameters are g_1^Z, κ_Z, κ_γ, λ_Z, and λ_γ. In the SM, $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ and $\lambda_Z = \lambda_\gamma = 0$. The couplings g_1^Z, κ_Z, and κ_γ are often written in terms of their deviation from the SM values as $\Delta g_1^Z = g_1^Z - 1$, and similarly for $\Delta\kappa_Z$ and $\Delta\kappa_\gamma$.

One effect of introducing anomalous coupling parameters into the SM Lagrangian is an increase of the cross section for the $q\bar{q} \to Z/\gamma \to W^+W^-$ process, particularly as parton center-of-mass energies rise to infinity. Thus, constant finite values of the anomalous couplings produce unphysically large cross sections, violating unitarity. To keep the cross section from diverging, the anomalous coupling must vanish as $s \to \infty$. This is done by introducing a dipole form factor for an arbitrary coupling α (g_1^Z, κ_V, or λ_V from Eq. 1):

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \hat{s}/\Lambda^2)^2} \quad (2)$$

where the form factor scale Λ is set by new physics. For a given value of Λ, there is an upper limit on the size of the coupling, beyond which unitarity is exceeded.

Limits on the $WW\gamma$ and WWZ anomalous couplings are set using the data, event selection, and background calculations from the recent WW cross section analysis published by the DØ Collaboration [2]. The cross section analysis measures the $p\bar{p} \to WW$ cross section to be $13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{syst}) \pm 0.9(\text{lum})$ pb, compared with a SM next-to-leading order prediction of $13.0 - 13.5$ pb [3].

The leptonic channels $WW \to \ell^+\nu\ell^-\bar{\nu}$ ($\ell = e,\ \mu$) were used to measure the cross section, with integrated luminosities of 252 pb^{-1} for the e^+e^- channel, 235 pb^{-1} for the $e^\pm\mu^\mp$ channel, and 224 pb^{-1} for the $\mu^+\mu^-$ channel. Table I summarizes the predicted numbers of signal and background events and the number of observed candidate events in each channel. Details of selection cuts and efficiencies can be found in Ref. [2].

Channel	Signal	Background	Candidates
e^+e^-	3.26 ± 0.05	2.30 ± 0.21	6
$e^\pm\mu^\mp$	10.8 ± 0.1	3.81 ± 0.17	15
$\mu^+\mu^-$	2.01 ± 0.05	1.94 ± 0.41	4

TABLE I: Predicted numbers of signal and background events, with statistical error, and number of candidate events for each decay channel.

Four anomalous coupling relationships are considered. In the first relationship, the $WW\gamma$ parameters are equal to the WWZ parameters: $\Delta\kappa_\gamma = \Delta\kappa_Z$ and $\lambda_\gamma = \lambda_Z$. The second relationship, the HISZ parameterization [4], imposes SU(2)×U(1) symmetry upon the coupling parameters. For the final two relationships, either the SM $WW\gamma$ or WWZ interaction is fixed, while the other parameters are allowed to vary. In all cases, parameters which are not constrained by the coupling relationships are set to their SM values.

Anomalous coupling limits must be set for a given coupling relationship and form factor scale. Setting limits on a pair of anomalous couplings simultaneously requires a grid of Monte Carlo (MC) events, generated specifically for that coupling relationship and form factor scale. The likelihood of getting the actual measured events is calculated at each of the grid points and the limits for the couplings are then extracted from a fit to the likelihood distribution across the grid.

The leading order MC generator by Hagiwara, Woodside, and Zeppenfeld (HWZ) [1] is used to generate events for a grid in $(\Delta\kappa, \lambda)$ space. The central area of each grid has a finer spacing of generated coupling parameters to ensure that the likelihood surface is well defined inside the area where limits are expected to be set.

The generated events for each grid point are passed through a parameterized simulation of the DØ detector that is tuned using Z boson events. The outputs for each grid point are the simulated p_T spectra for the two leptons in the event scaled to match the luminosity of the data. Eight p_T bins are used to calculate the likelihood at each grid point: three bins plus an overflow bin for each of the two leptons. Figure 1 shows the data for the leading lepton in the $e^\pm\mu^\mp$ channel with MC estimations for the SM and two sample anomalous coupling grid points.

The simulated signal from the HWZ generator and the

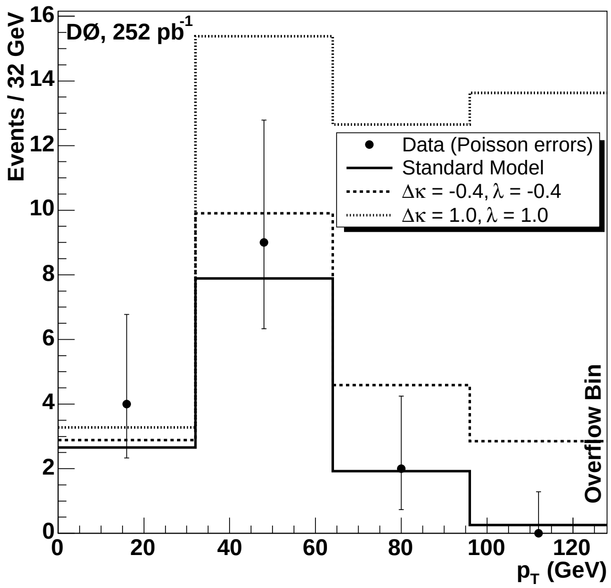

FIG. 1: Leading lepton p_T distributions for data (points), SM MC (solid line), and two anomalous coupling MC scenarios (dashed lines), from the $WW \to e^{\pm}\mu^{\mp}$ channel, binned as used to calculate likelihood.

background, taken from the cross section analysis, are compared to the p_T distribution of the data by calculating a bin-by-bin likelihood. Each bin is assumed to have a Poisson distribution with a mean equal to the sum of the signal and background. The uncertainties on the signal and background distributions are accounted for by weighting with Gaussian distributions. Correlations between the signal and background uncertainties for each channel are small, so they are handled separately. The uncertainty on the luminosity is 100% correlated, and so varies the same way for all channels. The likelihood, L, is calculated as

$$L = \int \mathcal{G}_{f_l} P_{ee}(f_l) P_{e\mu}(f_l) P_{\mu\mu}(f_l) df_l \qquad (3)$$

$$P_{\ell\ell}(f_l) = \int \mathcal{G}_{f_n} \int \mathcal{G}_{f_b} \prod_{i=1}^{N_{\rm bins}} \mathcal{P}\left[N^i_{\ell\ell}; (f_l f_n n^i_{\ell\ell} + f_l f_b b^i_{\ell\ell})\right] df_n df_b \qquad (4)$$

where $\mathcal{P}(a;\alpha)$ is the Poisson probability of obtaining a events if the mean expected number is α; $n^i_{\ell\ell'}$ and $b^i_{\ell\ell'}$ are the simulated numbers of signal and background events for the $\ell\ell'$ channel in bin i; $N^i_{\ell\ell'}$ is the measured number of events for this channel in this bin; and f_l, f_n, and f_b are the luminosity, signal, and background weights drawn from the Gaussian distributions $\mathcal{G}_{f_l}$, $\mathcal{G}_{f_n}$, and $\mathcal{G}_{f_b}$ respectively.

Coupling		95% C.L. Limits	Λ (TeV)
$WW\gamma = WWZ$	λ	$-0.31, 0.33$	1.5
	$\Delta\kappa$	$-0.36, 0.47$	
$WW\gamma = WWZ$	λ	$-0.29, 0.30$	2.0
	$\Delta\kappa$	$-0.32, 0.45$	
HISZ	λ	$-0.34, 0.35$	1.5
	$\Delta\kappa_\gamma$	$-0.57, 0.75$	
SM $WW\gamma$	λ_Z	$-0.39, 0.39$	2.0
	$\Delta\kappa_Z$	$-0.45, 0.55$	
SM WWZ	λ_γ	$-0.97, 1.04$	1.0
	$\Delta\kappa_\gamma$	$-1.05, 1.29$	

TABLE II: One-dimensional limits at the 95% C.L. with various assumptions relating the $WW\gamma$ and WWZ couplings at various values of Λ. Parameters which are not constrained by the coupling relationships are set to their SM values.

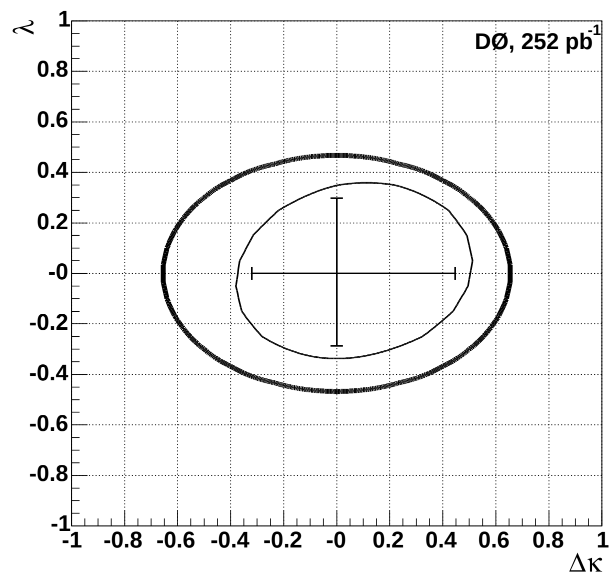

FIG. 2: One- and two-dimensional 95% C.L. limits when WWZ couplings are equal to $WW\gamma$ couplings, at $\Lambda = 2.0$ TeV. The bold curve is the unitarity limit, the inner curve is the two-dimensional 95% C.L. contour, and the ticks along the axes are the one-dimensional 95% C.L. limits.

To extract the limits, a 6th order polynomial is fitted to the grid of negative log likelihood values. The one- and two-dimensional 95% C.L. limits are determined by integrating the likelihood curve or surface, respectively. In the one-dimensional case, the 95% C.L. limits represent the pair of points of equal likelihood that bound 95% of the total integrated area between the ends of the MC grid. The two-dimensional 95% C.L. countour line is the set of points of equal likelihood that bound a region containing 95% of the total integrated volume between the MC grid boundaries.

One-dimensional 95% C.L. limits are summarized in

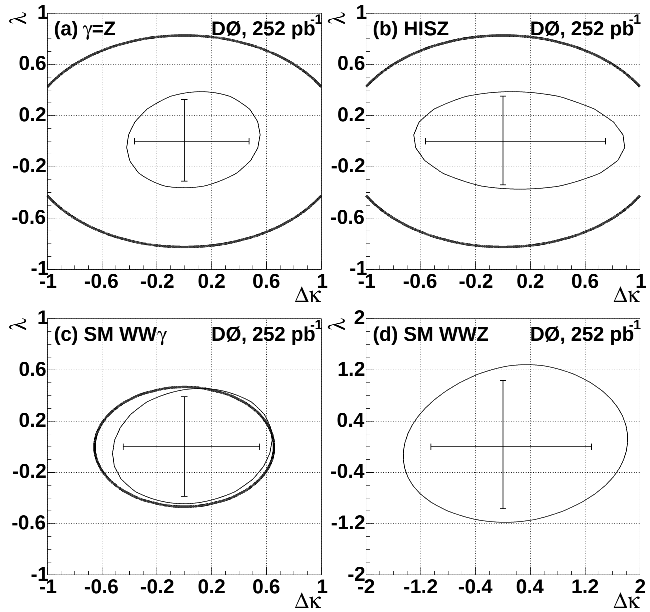

FIG. 3: One- and two-dimensional 95% C.L. limits for (a) $WW\gamma = WWZ$ at Λ=1.5 TeV, (b) HISZ at Λ=1.5 TeV, (c) SM $WW\gamma$ at Λ=2.0 TeV, and (d) SM WWZ at Λ=1.0 TeV. The bold curve is the unitarity limit (where it fits within the plot boundaries), the inner curve is the two-dimensional 95% C.L. contour, and the ticks along the axes are the one-dimensional 95% C.L. limits.

Table II, and two-dimensional 95% C.L. contours are shown in Figs. 2 and 3. Under the assumption that the $WW\gamma$ and WWZ couplings are equal and using a form factor scale of $\Lambda = 2.0$ TeV, the 95% C.L. limits obtained are $-0.32 < \Delta\kappa < 0.45$ and $-0.29 < \lambda < 0.30$. This significantly improves upon the previous limits from the DØ Collaboration, $-0.62 < \Delta\kappa < 0.77$ and $-0.53 < \lambda < 0.56$, set in Run I at the Fermilab Tevatron Collider for the same channels under the same assumption using an integrated luminosity of 100 pb^{-1} [5]. Although the combined anomalous coupling limits from the CERN e^+e^- Collider (LEP) collaborations are tighter [6], the hadronic collisions at the Fermilab Tevatron Collider explore a range of parton center-of-mass energies not explored at LEP.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); Research Corporation; Alexander von Humboldt Foundation; and the Marie Curie Program.

[1] K. Hagiwara, J. Woodside, and D. Zeppenfeld, Phys. Rev. D **41**, 2113 (1990).

[2] V. M. Abazov *et al.* (DØ Collaboration), Phys. Rev. Lett. **94**, 151801, hep-ex/0410066 (2005).

[3] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006, hep-ph/9905386 (1999).

[4] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Rev. D **48**, 2182 (1993), the coupling relationships used are $\Delta\kappa_Z = \Delta\kappa_\gamma(1 - \tan^2\theta_W)$, $\Delta g_1^Z = \Delta\kappa_\gamma/(2\cos^2\theta_W)$, and $\lambda_Z = \lambda_\gamma$.

[5] B. Abbott *et al.* (DØ Collaboration), Phys. Rev. D **58**, 031102, hep-ex/9803017 (1998).

[6] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP TGC Working Group, LEPEWWG/TGC/2005-01 (2005).