DIBOSON PRODUCTION AT THE TEVATRON

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For the CDF and D0 Collaborations

The CDF and D0 detectors at the Tevatron Collider are being used to measure WW, WZ and ZZ production as well as $W\gamma$ and $Z\gamma$ production in order to study Trilinear Gauge Couplings. Improved limits on nonstandard coupling parameters are given and prospects for further improvement are discussed.

1 Introduction

1.1 Motivation and Notation

Deviations from the minimal standard model may become apparent in the coupling of a W boson to a γ or Z. Assuming CP conservation, this coupling is described by the Lagrangian[1]

$$\begin{aligned} i\mathcal{L}_{WWV} = \\ g_{WWV}[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) \\ +\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ +(\lambda_V/m_W^2)W^\dagger_{\lambda\mu}W^\mu_\nu V^{\nu\lambda}] \end{aligned} \qquad (1)$$

where V means γ or Z. The factor $g_{WW\gamma}$ is e, g_{WWZ} is $e \times cot(\theta_W)$ and g_1^γ is 1. In the standard model, the coupling g_1^Z is 1, κ_γ and κ_Z are 1, and λ_γ and λ_Z are 0. The classical moments of the W are given by

$$\mu_W = e/2M_W(1+\kappa+\lambda) \qquad (2)$$

$$Q_W^e = -e/2M_W^2(\kappa-\lambda). \qquad (3)$$

Nonstandard couplings increase cross section at high E_T. To prevent implicit violation of unitarity, deviations from standard model couplings are taken with a form factor Λ^2_{FF} so, *eg.*, $\Delta\kappa$ is $(\kappa-1)/(1+\hat{s}/\Lambda^2_{FF})^2$. The new physics causing the nonstandard coupling gives the scale of Λ_{FF}. The equivalent CP violating couplings, like the CP conserving ones, tend to increase high E_T cross section.

Note that some analyses use assumptions which may or may not be reasonable to reduce the number of parameters. CP conservation gives five parameters. Assuming that γ and Z couplings are the same gets down to three parameters. The HISZ assumptions[2] leave two parameters. Reasonable assumptions about the new physics causing the non standard couplings predict values less than 0.05,[3] less than Tevatron or even LEP2 will be probing. Limits on individual parameters assume that the others are at standard model values.

1.2 Measurements

The Tevatron run of 1992/93, denoted "1a," produced data samples of about 20 pb^{-1} for CDF and 14 pb^{-1} for D0. In 1994/95 each detector collected about 90 pb^{-1}, denoted "1b," and an additional small sample in 1995/96 is denoted "1c." The results presented are updates of earlier analyses. Production of pairs of IVBs (W or Z) are denoted as leptonic if both IVBs decay to electron or muon and semileptonic if one decays to electron or muon and the other to hadrons (jet pair).

Production of photons accompanying Ws has been used to study these couplings and production of photons accompanying Zs studies similar but differently defined nonstandard couplings for Zs.[4] Similar to the W case an excess of events at high E_T would signal nonstandard coupling.

2 Leptonic IVB Pairs

Electron or muon decays of both IVBs should provide a clean enough signature so that with sufficient statistics a signal for pairs can be isolated. The D0 analysis of 1a data found 1 WW candidate with about half an event of background and half an event signal expected.[5] Assuming γ and Z couplings the same, this gives $-2.6 < \Delta\kappa < 2.8$ and $-2.2 < \lambda < 2.2$ at 95% CL for $\Lambda_{FF} = 0.9$ TeV.

CDF,[6] for the 108 pb^{-1} for run 1, has found five leptonic WW candidates, 3 $e\mu$, 2 ee and no $\mu\mu$, where expectation is roughly 2:1:1. Cutting against jets in the events eliminates background from top. The remaining background is 0.4 ± 0.2

Figure 1: CDF four muon ZZ candidate. Three muons are identified by track stubs in chambers behind the central calorimeter (CMU) and two of these are further identified by stubs behind steel walls (CMP). The fourth muon candidate is a track exiting the tracker endplate, identified only by tracking and the calorimeter.

events from Drell Yan, 0.4 ± 0.2 from fake leptons, 0.2 ± 0.1 from $Z \to \tau\tau$, and 0.1 from WZ for a total background expectation of 1.2 ± 0.3 events. The cross section for W pair production in $\bar{p}p$ collisions at 1.8 TeV is measured to be $10.2^{+6.5}_{-5.1} \pm 1.6$ pb, where the systematic error is from luminosity and acceptance. This agrees well with the NLO QCD predicted cross section of 9.5 pb.[7] The parameter limits, as above, are $-1.1 < \Delta\kappa < 1.3$ and $-0.8 < \Delta\kappa < 0.9$ for $\Lambda_{FF} = 1$ TeV. Both sets of limits use only the cross section and not E_T information from the leptons.

CDF has one three electron WZ candidate with 0.6 events expected for run 1, and in the 1c data a four muon ZZ candidate was found with about 0.1 expected. The ZZ candidate is shown in Fig. 1. Such events in LHC detectors should be both interesting and common.

3 Semileptonic IVB Pairs

The background from W plus jets makes it difficult to isolate a signal for IVB pairs when one of the IVBs is reconstructed as a jet pair, but non-standard couplings tend to populate production at high IVB p_T where W plus jets background is much reduced.

D0 has analyzed the 1a sample.[8] CDF has extended the 1a analysis[9] to the full 110 pb^{-1}. D0 uses jet cone radius of 0.3 in $\eta\phi$ space to give good acceptance for jet pairs out to $p_T(W)$ of 350 GeV/c while CDF uses 0.4 and acceptance falls off above about 300 GeV/c. D0 uses electronic Ws with a 25 GeV threshold on leptons while CDF uses both electrons and muons and both Ws and Zs with 20 GeV leptonic thresholds. The hadronic IVB is selected with a mass window of 50-110 or 60-110 GeV/c^2 for D0 and CDF.

CDF sets its limits by cutting to p_T(IVB)$>$ 200 GeV/c which should eliminate W plus jets background. No events are found. D0 makes up somewhat for what should be a factor 16 less exposure by doing a detailed background calculation and fitting the $p_T(W)$ spectrum to background plus nonstandard production. The semileptonic IVB pair channel is quite good for sensitivity to all parameters and the limits are given it Table 1. These limits could be combined between experiments and also for different channels, as D0 has done for 1a analyses, but a start would be to evaluate the limits using the same Λ_{FF}.

4 $W\gamma$ Production

The 1a analyses for both collaborations have been published.[10] CDF has no update to the 67 pb^{-1} sample shown last summer.[11] These use central e, μ and γ, $|\eta| < 1$ with a γ E_T threshold of 7 GeV. D0 has added 75 pb^{-1} of 1b data to the 1a analysis. Thresholds of 25 GeV are used for electron Ws with the electron in the range $|\eta| < 1.1$ or $1.5 < |\eta| < 1.5$. For muon Ws the thresholds are 15 GeV and the muon must be within $|\eta| < 1$. The η range for the photon is the same as for electrons and the E_T threshold is 10 GeV. For electron events, the γ candidate must have no tracker hits associated. In both cases the photon is required to be separated from the lepton by at least 0.7 in $\eta\phi$ space (ΔR). This 75 pb^{-1} 1b sample is compared to the CDF sample in Table 2.

Table 1: IVB semileptonic (jet pair) analysis lower and upper bounds at 95% CL with all other couplings fixed as standard. CDF bounds are preliminary. Λ_{FF} is in TeV.

Coupling	limits	Λ_{FF}	Exp.
g_1^Z	0.09, 2.05	1.0	CDF
	0.39, 1.68	2.	CDF
$\Delta\kappa_\gamma$	-2.8, 3.3	1.	D0
λ_γ	-2.5, 2.5	1.	D0
	-1.7, 1.7	1.	CDF
$\Delta\kappa_Z$	-0.95, 1.01	1.	CDF
	-1.1, 1.3	1.5	D0
	-0.58, 0.68	2.	CDF
λ_Z	-0.60, 0.58	1.	CDF
	-0.7, 0.7	1.5	D0
	-0.37, 0.40	2.	CDF
$\Delta\kappa_{\gamma=Z}$	-0.67, 0.85	1.	CDF
	-0.9, 1.1	1.5	D0
	-0.49, 0.54	2.	CDF
$\lambda_{\gamma=Z}$	-0.51, 0.51	1.	CDF
	-0.6, 0.7	1.5	D0
	-0.35, 0.32	2.	CDF
$\Delta\kappa_\gamma$ (HISZ)	-0.83, 1.02	1.	CDF
	-1.0,1.3	1.5	D0
	-0.61, 0.67	2.	CDF
λ_γ (HISZ)	-0.51, 0.52	1.	CDF
	-0.6, 0.7	1.5	D0
	-0.34, 0.33	2.	CDF

Table 2: D0 1b 75 pb^{-1} $W\gamma$ sample compared to the CDF 67 pb^{-1} sample shown last summer.

	D0 1b e	D0 1b μ	CDF e, μ
Events	46	58	109
Backg.	13.2 ± 2.3	23.0 ± 4.6	26.4 ± 2.6
σ/σ_{SM}	$0.90^{+0.24}_{-0.21}$	$1.09^{+0.38}_{-0.31}$	1.11 ± 0.24

Table 3: D0 1b 89 pb^{-1} $Z\gamma$ sample for standard and tight selection compared to the CDF 67 pb^{-1} sample shown last summer.

	D0 Stand.	D0 Tight	CDF
Events	21	14	31
Backg.	4.0 ± 1.2	1.6 ± 0.5	1.4 ± 0.2
SM	16.7 ± 1.7	12.1 ± 1.2	24.9 ± 1.7
Expected	20.7 ± 2.1	13.7 ± 1.3	27.7 ± 1.7

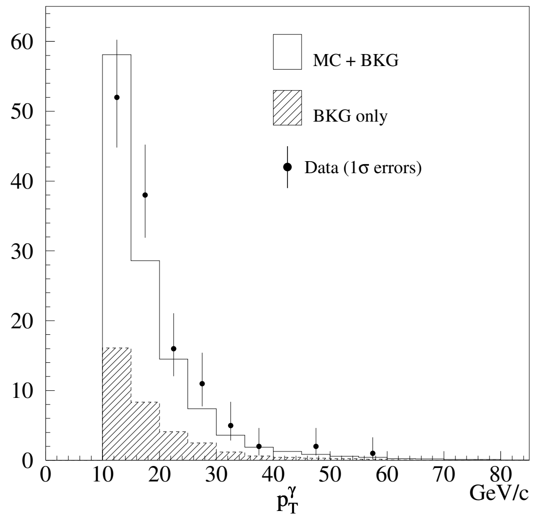

Figure 2: D0 photon E_T spectrum for the preliminary combined 1a-1b $W\gamma$ analysis showing background, SM expectation and data.

D0 obtains coupling limits by combining the 1b sample with the their 1a sample for a combined 89 pb^{-1} analysis. The photon E_T spectrum is shown in Fig. 2. The individual preliminary limits are $-0.97 < \Delta\kappa_\gamma < 0.99$ and $-0.33 < \lambda_\gamma < 0.31$ and the two are shown correlated in Fig. 3, which also shows a CLEO limit from $b \to s\gamma$.[12]

5 $Z\gamma$ Production

Both 1a analyses have been published[13] and CDF has not updated the 67 pb^{-1} shown last summer.[11] D0 has a new analysis of 89 pb^{-1} of 1b data in the electron mode. The selection is similar to that for electron $W\gamma$. Three events appear with photon E_T between 70 and 90 GeV so a tighter selection on tracker hits was tried. These two selections are compared to the CDF sample in Table 3. The tighter selection keeps 2/3 of the events and 2 of the 3 events between 70 and 90 GeV. The CDF highest E_T photons are at 39 and 64 GeV but there is an event not yet included at 182 GeV.

The new D0 preliminary limits (95% CL) are $-1.8 < h_{30}^Z < 1.8$, $-0.38 < h_{40}^Z < 0.38$, $-1.8 < h_{30}^\gamma < 1.9$ and $-0.38 < h_{40}^\gamma < 0.38$. These are not much different from the D0 1a analysis or the CDF analysis.

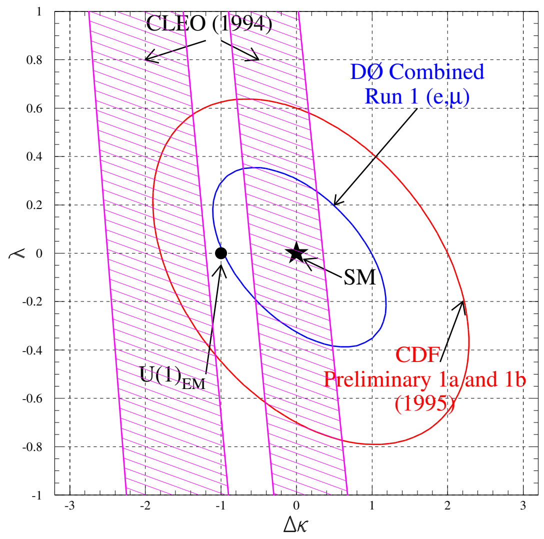

Figure 3: D0 and CDF coupling limits from preliminary combined 1a-1b $W\gamma$ analyses.

6 Outlook

The production of $W\gamma$ and of pairs of IVBs in 1.8 TeV $\bar{p}p$ collisions seems to be well described by the standard model. Coupling parameter limits are typically in the range of a few tenths.

The Tevatron Collider will be off for several years for fixed target running and upgrades to the injector and the detectors. For the immediate future we need to consider what more information there is in the existing data. In general, a factor of 10 in luminosity should improve a given limit by a factor of 2.

In the $W\gamma$ and $Z\gamma$ analyses, more than a factor of 2 in luminosity is available as both colaborations complete the analysis of the full datasets and the results are combined between experimets. The $W\gamma$ charge asymmetry and radiation zero analyses need to be completed. In $Z\gamma$ the neutrino decays of the Z can be used.

For semileptonic IVB pair production, in effect a factor of 4 in luminosity is available as D0 analyzes 1b, the CDF analysis becomes more sophisticated and the two results are combined.

During the Tevatron Collider hiatus the LEP2 program should measure enough IVB pairs to set coupling parameter limits of order 0.1. Eventually the Tevatron Collider program will resume and samples of about 2 fb^{-1} per experiment are expected by perhaps 2002. At that point Tevatron results should again be competitive. Studies at LHC or perhaps a linear collider may be needed to become sensitive to parameter regions of specific interesting new physics reach.

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References

1. K. Hagiwara, K. Hikasa, R. D. Peccei and D. Zeppenfeld, *Nucl. Phys.* B **282**, 253 (1987), K. Gaemers and G. Gounaris, *Z. Phys.* C **1**, 259 (1979).
2. K. Hagiwara, S. Ishihara, R. Szalapssky and D. Zeppenfeld, *Phys. Rev.* D **48**, 21 (1993).
3. I. Hinchliffe in *International Symposium on Vector Boson Self Interactions*, ed. U. Bauer, S. Errede and T. Muller (AIP Press, 1996) p 335.
4. U. Bauer and E. L. Berger, *Phys. Rev.* D **44**, 1476 (1990).
5. S. Abachi *et al.* (D0), *Phys. Rev. Lett.* **75**, 1023 (1995).
6. F. Abe *et al.* (CDF), subm. *Phys. Rev. Lett.*, FERMILAB-PUB-96/311-E.
7. J. Ohnemus, *Phys. Rev.* D **44**, 1403 (1991), J. Ohnemus, *Phys. Rev.* D **44**, 3477 (1991), U. Bauer, T. Han and J. Ohnemus, *Phys. Rev.* D **51**, 3381 (1995).
8. S. Abachi *et al.* (D0), subm. *Phys. Rev. Lett.*, FERMILAB-PUB-96/115-E.
9. F. Abe *et al.* (CDF), *Phys. Rev. Lett.* **75**, 1017 (1995).
10. F. Abe *et al.* (CDF), *Phys. Rev. Lett.* **74**, 1936 (1995), S. Abachi *et al.* (D0), *Phys. Rev. Lett.* **75**, 1034 (1995).
11. D. Benjamin in *Proceedings of the Tenth Topical Workshop on proton antiproton Collider Physics*, ed. R. Raja and J. Yoh, (AIP Press, 1995) p. 370.
12. S. M. Playfer in *International Symposium on Vector Boson Self Interactions*, ed. U. Bauer, S. Errede and T. Muller (AIP Press, 1996) p 124.
13. F. Abe *et al.* (CDF), *Phys. Rev. Lett.* **74**, 1941 (1995), S. Abachi *et al.* (D0), *Phys. Rev. Lett.* **75**, 1028 (1995).