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Cross Sections and Samples for SM Backgrounds to Multiple Gauge Boson Events:
Top Dilepton,$WWb\bar{b}$, WZ^0/γ^*+Jet, and WW+Jet Production at LO Parton Level

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Abstract

The MadGraph-II Monte Carlo event generator is used to generate datasets, and to calculate cross sections and acceptances, for SM background processes that produce high-p_T dilepton events: $t\bar{t}$, WW+jets, WZ+jets, $Z^0 \to \tau^+\tau^-$+jets, etc. The thresholds have been set low (7 GeV for jets, 1 GeV for leptons from W's, etc.) in order for the samples to be useful after 'smearing' by the shower Monte Carlos. The samples have full spin correlations, including transmitting the W spins to tau decays. Both the Z and gamma poles with no invariant mass cut are included where relevant.

1 Introduction

The Run I sample of 'top' dilepton events has a number of events that are 'untop-like'. The most striking of these is an event that has three isolated high-pt leptons, consistent with three W's [1]; other events have either too many jets, do not fit the top mass well, or kinematics that are expected to be rare in the SM.

The dilepton signature is one of the search modes for many models of new physics, including a heavy new fourth generation that decays into top and or W's or Z's [2, 3, 4], extra spatial dimensions [5], and SUSY [6]. Both the production and the decay of the top can be nonstandard, as the top can be produced in the decay of heavier new particles or can decay to new lighter ones [6]. Several of these models produce more than heavy bosons (W's or Z's), either through the decay into W's [5] or through the production of a pair of tops and a pair of W's [3]. Multiple W's will give same-sign lepton and trilepton events.

This note documents samples produced, using the MadGraph (MadEvent) program [12], of the major standard model processes producing dilepton events: top di-leptonic decays, WW+jets, including $WWb\bar{b}$, WZ^0/γ^*+jets, and Drell-Yan+jets. The results presented here are purely at generator level, and do not have either showering, ISR, or detector simulation; the resulting cross sections may provide a baseline for qualitative understanding of the which are the important backgrounds and fake rates. We then have gone on to run these through Pythia and CdfSim, and then through CDF reconstruction [7].

The results described here have been generated with MadGraph version 3.00 or 3.20. This version of MadGraph produces output with the particle helicity information and event-by-event Q^2 information to allow a correct accounting for spin correlations in tau decays and jet matching in the shower monte-carlos.

The crossections quoted are at Leading Order (LO) with scales $Q^2 = M_Z^2$. A k-factor determined from more sophisticated calculations for each process should be applied [8], which will depend on the Q^2 scale. But the whole procedure used here is pretty crude: a better treatment (in the works) would use a more appropriate Q^2 scale, and jet matching [14], and then normalize to the NLO predictions.

2 Monte Carlo Generation Parameters

The data sets have been generated with the cuts shown in Table 1. The thresholds have been set very low compared to the analysis cuts in order for the samples to be useful after the inclusion of initial state radiation by the shower Monte Carlos. In cases where there are two identical particles in the final state that are selected with asymmetric cuts , such as $Z^0 \to e^+e^-$ decay with one electron being required to be central, we generate with both particles with the looser cuts of the two (e.g. at a lower threshold or wider η) and then later impose the analysis cuts of Table 2 in a routine that reads the generator output file, taking the 'OR' of the cases where one or other lepton is central *and* over threshold. Gluon splitting to c-quark pairs required a Delta-R cut to converge; however splitting to b-quark pairs converged without the cut and so it was omitted, as the cases where the b's could intermingle can be relevant.

Particle	E_T	η	ΔR
Charged Leptons	1.0	6.0	0.1
Leptons from e^+e^- pairs	6.0	6.0	0.1
Neutrinos	1.0	6.0	0.
Jets	7.0	3.0	0.1
c-quarks	7.0	3.0	0.1
c-quarks from gluon split	7.0	3.0	0.1
b-quarks	7.0	3.0	0.1
b-quarks from gluon split	7.0	3.0	0.
W-bosons (before decaying)	0.0	6.0	0.

Table 1: The 'Sample cuts' used at generator level to make the samples. The cuts are intended to be loose enough so that the smearing in E_T and η in Pythia or Herwig can reach down below threshold and find those events that will be promoted over threshold. In the case that leptons are made in pairs the thresholds have been raised to be far from the large cross sections caused by the photon pole.

The samples are then made into ntuples [15], and further cuts, the 'Analysis cuts', are applied. The cuts are listed in Table 2. These cuts require one lepton to be central with $E_T > 20$ GeV; the other lepton is required to have $E_T > 12$ GeV and $|\eta| < 2.5$. Either of the two leptons is allowed to satisfy the cuts on the ''first' lepton [16].

The lower threshold on the 2nd lepton is the result of studies on acceptances in W+jets and Z+jets channels. It results in a higher acceptance in top decays, and, from the studies below, should still have acceptable levels of background. The dilepton channel suffers from low statistics but in general (particularly for $e\mu$, but also for ee and $\mu\mu$ if there are b-tags or large Ht) has less background than the other channels and hence moving toward higher acceptance is possible.

Jets are defined to be gluons and the 4 flavors of lighter quarks (u,d,s, and c); b-quarks and t-quarks are tabulated separately (however when a $c\bar{c}$ is explicitly called out in the final state the resulting crossection is a (small) subset of the generic jet crossection). The eta cut on jets of 2.5 is set as a reasonable choice for b-quarks from top decay.

Missing Et ($\not{E}_t$) is calculated from all neutrinos in the process. As the calculations in MadGraph are LO and there are no further decays of particles and no smearing of any kind neutrinos are the only source of $\not{E}_t$.

Particle	E_T	η	ΔR
First Lepton	20.0	1.0	0.4
Additional Leptons	12.0	2.5	0.4
Missing Et	20.0	—	0.
Jets	10.0	2.5	0.4
b,c-quarks	10.0	2.5	0.4

Table 2: The 'Analysis cuts' used to calculate acceptances. No delta-R cuts are applied between any neutrino and any other particle.

3 Samples and Crossections

Table 3 lists the crossections-times-branching-ratio ($\sigma\cdot$BR) for diboson production followed by specific decays. The W bosons are decayed either to all three lepton flavors or the two lighter quark flavors.

In all cases where a Z^0 boson is involved both the Z^0 and photon amplitudes are included (and of course the interference). No cut on the invariant mass of the lepton pair has been applied; this allows the production of lower mass pairs with individual p_T's over threshold. Note that in some modes, for example $Z^0/\gamma^* Z^0/\gamma^* \rightarrow \ell^+\ell^-\ell^+\ell^-$, an intermediate photon makes a significant contribution with these low p_T thresholds.

The output files contain the helicities of each particle, which are used throughout the intermediate steps of production and the decay chain.

4 WW+jets; e, μ, τ Dilepton Final States

WW production followed by the leptonic decay of both W's is both a good reference channel and also a SM background for top dilepton decay. MadGraph V3.00, which outputs the W helicities, was used to generate WW+Njet samples. Each W was then decayed with the

Crossections and DataSets for DiBoson Processes			
Process/Decay	Name	Sigma·BR	Comment
$W^+Z^0/\gamma^* \to \ell^+\nu e^+e^-$	Wee0jet_ll	0.01885 pb	W into e,mu,tau
	Wee0jet_qq	0.03998 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu e^+e^-$+1 jet	Wee1jet_ll	0.01231 pb	W into e,mu,tau
	Wee1jet_qq	0.02613 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu e^+e^-$+2 jets	Wee2jet_ll	0.00806 pb	W into e,mu,tau
	Wee2jet_qq	0.01710 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu e^+e^- + b\bar{b}$	Weebbbar_ll	0.00008 pb	W into e,mu,tau
	Weebbbar_qq	0.00017 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu e^+e^- + c\bar{c}$	Weeccbar_ll	0.00013 pb	W into e,mu,tau
	Weeccbar_qq	0.00027 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \mu^+\mu^-$	Wmumu0jet_ll	0.01885 pb	W into e,mu,tau
	Wmumu0jet_qq	0.03998 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \mu^+\mu^-$+1 jet	Wmumu1jet_ll	0.01239 pb	W into e,mu,tau
	Wmumu1jet_qq	0.02630 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \mu^+\mu^-$+2 jets	Wmumu2jet_ll	0.00806 pb	W into e,mu,tau
	Wmumu2jet_qq	0.01710 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \mu^+\mu^- + b\bar{b}$	Wmumubbbar_ll	0.00008 pb	W into e,mu,tau
	Wmumubbbar_qq	0.00017 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \mu^+\mu^- + c\bar{c}$	Wmumuccbar_ll	0.00013 pb	W into e,mu,tau
	Wmumuccbar_qq	0.00027 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \tau^+\tau^-$	Wtautau0jet_ll	0.01893 pb	W into e,mu,tau
	Wtautau0jet_qq	0.04014 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \tau^+\tau^-$+1 jet	Wtautau1jet_ll	0.01208 pb	W into e,mu,tau
	Wtautau1jet_qq	0.02562 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \tau^+\tau^-$+2 jets	Wtautau2jet_ll	0.00785 pb	W into e,mu,tau
	Wtautau2jet_qq	0.01664 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \tau^+\tau^- + b\bar{b}$	Wtautaubbbar_ll	0.00008 pb	W into e,mu,tau
	Wtautaubbbar_qq	0.00017 pb	W into u,d,c,s
$W^+Z^0/\gamma^* \to \ell^+\nu \tau^+\tau^- + c\bar{c}$	Wtautauccbar_ll	0.00012 pb	W into e,mu,tau
	Wtautauccbar_qq	0.00026 pb	W into u,d,c,s
$Z^0/\gamma^*Z^0/\gamma^* \to \ell^+\ell^-\ell^+\ell^-$	ZZ_ll_ll	0.01085 pb	Z1,Z2 to e, μ, τ
$Z^0/\gamma^*Z^0/\gamma^* \to \ell^+\ell^-\nu\bar{\nu}$	ZZ_ll_nunu	0.02152 pb	Z1 to $e\mu\tau$; Z2 to ν's

Table 3: Diboson samples and the cross-section for each process including the decay, i.e. σ·BR. The W bosons are decayed either to all 3 lepton flavors or the 3 light quark flavors. In all cases where a Z^0 boson is involved both the Z^0 and photon amplitudes are included. No cut on the invariant mass of the lepton pair has been applied. The helicities of all particles are used in the production and decays.

MadGraph routine decay_event.f into the three lepton types, e, μ, and τ, producing a file that has the 9 combinations of dileptons.

The total crossection found for $W^+W^- + 0$ jets is 8.745±0.035 pb. This is 15% lower than the 10.3 pb found at LO by Campbell and Ellis [8] at 2 TeV, using a slightly lower Q^2 ($= M_W^2$) and the same PDF (CTEQ5). Campbell and Ellis find a K-factor of 1.3, which should be applied to the numbers below.

Some caveats: the τ's from W decay are not decayed at this pre-HEPG/TAUOLA stage, so that the tau decay contributions to e, μ, final states are not included in the tabulated results. The calculation is LO, with $Q^2 = M_Z^2$; no k-factor has been applied (these two factors are in opposite directions and so tend to cancel, as shown in the case of $t\bar{t}$ production in Table 10).

4.1 Rates: Events per 100 pb^{-1}

The numbers of dilepton+jet events [22] per 100 pb^{-1} passing the analysis cuts of Table 2 are given in Table 4. The rows correspond to the matrix-element used; the columns give the number of events which pass the cuts inclusively; i.e., ≥ 0 jets has no jet requirement but only the lepton and met requirements, ≥ 1 jets has in addition the requirement of at least 1 jet with $E_T > 10$ Gev, etc.

Note that the 0,1, and 2 jet inclusive $\geq$ 0-jet rates have a very large overlap (i.e. double-counting), and thus cannot be simply summed. This is not unexpected, as the jet threshold is low compared to the Q^2 of the process[14].

WW + N Jet Events per 100 pb^{-1}								
M.E. Process	Order		$E_T^{2nd lepton} > 12$ GeV			$E_T^{2nd lepton} > 20$ GeV		
($\rightarrow \ell^+\ell^- + ...$)	α_s	α	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets
$WW + 0\ jets$	0	99	5.13±.07	N/A	N/A	4.33±.07	N/A	N/A
$WW + 1\ jet$	99	99	3.45±.05	2.40±.04	N/A	2.85±.05	2.00±.04	N/A
$WW + 2\ jets$	99	99	2.18±.03	2.02±.03	0.88±.02	1.80±.03	1.67±.03	0.72±.02
$WW + bb$	99	99	.026±.001	.025±.001	.015±.001	.021±.001	.020±.001	.013±.001
$WW + c\bar{c}$	99	99	.039±.001	.036±.001	.016±.001	.032±.001	.030±.001	.013±.001

Table 4: The number of e^+e^- *or* $\mu^+\mu^-$ events per 100 pb^{-1} predicted at LO and generator-level to satisfy the criteria of: one central lepton (e.g. e^+ or e^-) with $E_T > 20$ GeV and $|\eta| < 1.0$; a second (e.g. e^- or e^+) with $E_T > 12$ GeV and $|\eta| < 2.5$ (columns 2-4), or $E_T > 20$ GeV and $|\eta| < 2.5$ (columns 5-7); $\not{E}_t > 20$ GeV; and $\geq$ 0, 1, or 2 jets satisfying $E_T > 10$ GeV and $|\eta| < 2.5$. A ΔR cut of > 0.4 has been applied to all parton pairs counted in a given column. For cross-generation dilepton final states such as $e\mu$ or $\mu\tau$, these numbers should be multiplied by 2 to account for the two possible charge combinations; thus the total number of standard CDF 'dilepton' events produced into this kinematic acceptance is 4 times these numbers. The row labeled "$WW + b\bar{b}$" has neither the large s-channel $t\bar{t}$ pair production nor the much smaller virtual top diagrams included (ie. what one would get if the top did not exist). A summary of $t\bar{t}$ crossections is given in Table 10.

4.2 WW+Heavy Flavor

When one requests $WWb\bar{b}$ from MadGraph with any number of QCD vertices allowed, the dominant contribution is from top pair production, although there are also small contributions from diagrams with virtual tops in them as well (see below). One can explicitly turn off top production in MadGraph to get the contributions from gluon splitting. A number of caveats are in order [9], but the contribution from non-top processes is tiny compared to that from top as shown in Table 4. This is discussed in more detail in the next section. The $WWc\bar{c}$ contribution is also very small.

4.3 Conclusions on WW

1. There is a gain of about 20% in acceptance for a 12 GeV threshold over that for a 20 GeV threshold (this will be larger when the tau decays are taken into account).
2. The LO-generator-level crossection from the 0-jet matrix element corresponds to the production of 20.5 $e^+e^-, \mu^+\mu^-$, and $e^\pm\mu^\pm$ events per 100 pb-1 with one central lepton with $Et > 20$, the other with $\mathrm{E_T} > 12$ GeV, and $\not{E}_t > 20$ GeV from WW decays, not including the contribution from tau leptonic decays(see Table 4).
3. The LO-generator-level crossection from the 2-jet matrix element corresponds to the production of 3.5 e^+e^-+2 jet,$\mu^+\mu^-$+2 jet, and $e^\pm\mu^\pm$+2 jet events per 100 pb-1 with one central lepton with $Et > 20$ and the other with $\mathrm{E_T} > 12$ GeV, and $\not{E}_t > 20$ GeV and 2 jets, not including the contribution from tau leptonic decays. The jets are required to have $\mathrm{E_T} > 10$ GeV and $|\eta| < 2.5$(see Table 4).
4. The matrix-element crossection as a function of the number of jets, N, falls slowly with N for the chosen generation parameters; requiring (parton-level) jets with $\mathrm{E_T} > 10$ GeV the factor is about 1.5 for 1jet/0jet, and 1.6 for 2jet/1jet. We need to implement the jet-matching for the diboson samples.
5. Only 70% of the W+1jet-ME generated events have 1 jet passing the analysis cuts. For W+2 jet events, 40% have 2 jets that pass, but 93% have at least 1 such jet.
6. Heavy flavor production in conjunction with W pairs is minuscule; basically any b-quarks are due to top.

5 $Z^0/\gamma^* \to \tau^+\tau^-$+Jet Crossections

The production of tau pairs through an intermediate Z^0 or photon followed by the leptonic decay of both taus will produce all four of the electron/muon dilepton combinations with some amount of $\not{E}_t$ due to the 4 neutrinos in the two tau decays, and so is a source of, for example, $e\mu$ events with intrinsic $\not{E}_t$.

Samples were generated of $Z^0/\gamma^* \to \tau^+\tau^-$+ 0, 1, 2 and 3 jets, and also with $b\bar{b}$ and $c\bar{c}$. The production includes both the gamma and Z intermediate states, and the cuts (see Table 2) allow the case where the invariant mass of the tau pair is low, but the $\mathrm{p_T}$ of the pair recoiling against 1 or more jets is substantial (often cut out by an $\hat{s}$ cut on the pair in many MC samples). The spins of the tau's are in the data format output; the MadGraph decay routine thus takes into account the spin correlations and the spin structure of the Z

$Z^0/\gamma^* \to \tau^+\tau^- +$ N Jet Events per 100 pb^{-1}: No Met Cut						
M.E. Process	$E_T^{2ndlepton} > 12$ GeV			$E_T^{2ndlepton} > 20$ GeV		
$(DY + NJets)$	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets
$DY + 0\ jets$	50.1±3.6	N/A	N/A	20.9±2.3	N/A	N/A
$DY + 1\ jet$	21.9±1.2	12.7±0.9	N/A	10.5±0.9	5.8±0.6	N/A
$DY + 2\ jets$	11.4±0.6	10.4±0.6	4.7±0.4	5.1±0.4	4.4±0.4	2.1±0.3
$DY + b\bar{b}$	0.14±.01	0.13±.01	0.08±.01	0.06±.01	0.06±.01	0.04±.01
$DY + c\bar{c}$	0.19±.01	0.18±.01	0.08±.01	0.08±.01	0.08±.01	0.04±.01

Table 5: The number of e^+e^- *or* $\mu^+\mu^-$ events per 100 pb^{-1} predicted at LO and generator-level to satisfy the criteria of: one central lepton (e.g. e^+ or e^-) with $E_T > 20$ GeV and $|\eta| < 1.0$; a second (e.g. e^- or e^+) with $E_T > 12$ GeV and $|\eta| < 2.5$ (columns 2-4), or $E_T > 20$ GeV and $|\eta| < 2.5$ (columns 5-7); and ≥ 0, 1, or 2 jets satisfying $E_T > 10$ GeV and $|\eta| < 2.5$. A ΔR cut of > 0.4 has been applied to all parton pairs counted in a given column. The missing Et cut is **not** applied. For cross-generation dilepton final states such as $e\mu$ or $\mu\tau$, these numbers should be multiplied by 2 to account for the two possible charge combinations; thus the total number of standard CDF 'dilepton' events produced into this kinematic acceptance is 4 times these numbers.

production, decay, and the subsequent tau decays. As the tau decay is 3-body, the lepton p_T spectrum is soft, and so taking into account the spin correlations is important.

The decay of a Z^0 or γ^* into a tau pair has intrinsic $\not\!\!E_t$ due to the four neutrinos in the two tau decays. However, because the tau's are typically back-to-back, the missing-Et spectrum is quite steep in the zero-jet case, and the 20 GeV requirement consequently reduces the rate by an order-of-magnitude at generator level. The 1-jet and 2-jet samples have broader $\not\!\!E_t$ spectra, and the effect is less dramatic. But the rates are very sensitive to the detector performance and so generator-level studies are less useful. The rates below both before and after the $\not\!\!E_t$ cut are listed in Tables 5 and 6, respectively.

5.0.1 Rates before the $\not\!\!E_t$ cut

Table 5 gives the number of events passing all the dilepton event selection cuts except the $\not\!\!E_t$ cut.

5.0.2 Rates after the $\not{E}_t$ cut

The number of events per 100 pb^{-1} passing the selection cuts including the $\not{E}_t$ cut is shown in Table 6. The generator-level numbers are very similar to those from the WW channel.

$Z^0/\gamma^* \to \tau^+\tau^- +$ N Jet Events per 100 pb^{-1}						
M.E. Process	$E_T^{2ndlepton} > 12$ GeV			$E_T^{2ndlepton} > 20$ GeV		
$(DY + NJets)$	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets
$DY + 0\ jets$	5.8±1.2	N/A	N/A	1.0±0.4	N/A	N/A
$DY + 1\ jet$	5.0±0.6	3.6±0.5	N/A	1.6±0.4	1.4±0.3	N/A
$DY + 2\ jets$	5.3±0.4	5.2±0.4	2.3±0.3	2.0±0.3	1.9±0.3	0.8±0.2
$DY + bb$	0.07±.007	0.06±.006	0.05±.005	0.02±0.04	0.02±.004	0.02±.003
$DY + c\bar{c}$	0.07±.007	0.07±.007	0.03±.005	0.03±.004	0.03±.004	0.02±.003

Table 6: The number of e^+e^- *or* $\mu^+\mu^-$ events per 100 pb^{-1} predicted at LO and generator-level to satisfy the criteria of: one central lepton (e.g. e^+ or e^-) with $E_T > 20$ GeV and $|\eta| < 1.0$; a second (e.g. e^- or e^+) with $E_T > 12$ GeV and $|\eta| < 2.5$ (columns 2-4), or $E_T > 20$ GeV and $|\eta| < 2.5$ (columns 5-7); $\not{E}_t > 20$ GeV; and ≥ 0, 1, or 2 jets satisfying $E_T > 10$ GeV and $|\eta| < 2.5$. A ΔR cut of > 0.4 has been applied to all parton pairs counted in a given column. For cross-generation dilepton final states such as $e\mu$ or $\mu\tau$, these numbers should be multiplied by 2 to account for the two possible charge combinations; thus the total number of standard CDF 'dilepton' events produced into this kinematic acceptance is 4 times these numbers.

5.1 Conclusions on $Z^0/\gamma^* \to \tau^+\tau^-$+Jet Crossections

1. There is a gain (for better or worse) of a factor of 2.4 (!) in acceptance for a 12 GeV threshold over that for a 20 GeV threshold for $Z^0/\gamma^* \to \tau^+\tau^-$+0 Jets with no $\not{E}_t$ cut at LO (no kt-smearing).
2. The increase in acceptance becomes much larger with the $\not{E}_t$ cut, being a factor of 5.8 ± 2.6 (the statistics are poor due to the severity of the $\not{E}_t$ cut). The true number is very sensitive to simulation and may prove credible only with detailed comparisons of spectra.
3. The LO-generator-level crossection from the 0-jet matrix element corresponds to the production of 200±14 $e^+e^-, \mu^+\mu^-$, and $e^\pm\mu^\pm$ events per 100 pb-1 with one central lepton with $Et > 20$, the other with $E_T > 12$ GeV, before the met cut(see Table 5
4. Adding the $\not{E}_t$ cut to the lepton selection gives 23±5 dilepton events per 100 pb-1 at generator-level (no $\not{E}_t$ smearing at all).
5. The LO-generator-level crossection from the 2-jet matrix element corresponds to the production of 46±2 e^+e^-+2 jet,$\mu^+\mu^-$+2 jet, and $e^\pm\mu^\pm$+2 jet events per 100 pb-1 with one central lepton with $Et > 20$ and the other with $E_T > 12$ GeV, and 2 jets. The jets are required to have $E_T > 10$ GeV and $|\eta| < 2.5$(see Table 5).
6. The $\not{E}_t > 20$ GeV cut, although the numbers are unreliable at generator-level, cuts severely: 23±5 0-jet and 9±1 2-jet events pass all dilepton cuts per 100 pb-1.

7. Drell-Yan tau-pair $+b\bar{b}$ production gives 0.32 ±0.04 2-jet events per 100 pb-1 before the met cut. Charm pair production is comparable (see Table 5). The met cut reduces these to 0.2±0.02 and 0.12±0.02 events per 100 pb-1, respectively.

6 WZ^0/γ^*+ Jet Crossections

Dilepton and trilepton events can come from the production of WZ^0 or $W\gamma^*$ followed by the decay of the Z^0 or virtual photon into a lepton pair. The W will sometimes decay leptonically, resulting in a trilepton event; when the W decays hadronically the signature is dilepton plus (usually) two jets. This channel is often called 'WZ', but the virtual photon contribution is not negligible, particularly for high-Pt pairs. A lower limit on the pair mass thus is not be applied in the generation. The leptonic W decay case is interesting as it forms trilepton events with $\not\!\!E_t$; the hadronic case generates Z+2-jet events with no $\not\!\!E_t$, which will be embedded in a large QCD background.

Six separate samples were made for each value of Njet (Njet=0,1,2, and $b\bar{b}$ and $c\bar{c}$) to get the Z^0 and γ^* contributions including the interference terms for the e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ final states. For each of the three flavors of the lepton pair two sets were made, one with the W decaying into $c\bar{s}$ and $u\bar{d}$, and the other into the three leptonic e,μ, and τ modes

Table 7 shows the parton-level dilepton crossections only for the Wee0jet_ll and Wee0jet_qq samples [20]. The tabulated numbers are for the sum of $(W^+ + W^-)$; they should be doubled to include both Wmumu and Wee production (there will also be a smaller Wtautau contribution which will increase the sum). The numbers of events per 100 pb^{-1} with at least two leptons satisfying the selection criteria (any combination of the three from the e^+e^- pair from the Z^0/γ^* and the e, μ, or τ from the W decay) are:

WZ^0/γ^* + N Jet Events per 100 pb^{-1}			
M.E. Process	met cut	$E_T^{2ndlepton} > 12$ GeV	$E_T^{2ndlepton} > 20$ GeV
$Wee + 0\ jets \rightarrow (e, \mu, \tau) + e^+e^-$	yes	2.16±.02	1.99±.02
$Wee + 0\ jets \rightarrow (ud, c\bar{s}) + e^+e^-$	no	4.14±.005	3.76±.05

Table 7: The number of e, μ dilepton events per 100 pb^{-1} from the production of a W^+ or W^- boson plus an e^+e^- pair (aka 'WZ'), followed by the lepton (e, μ, or τ). Both the Z and photon poles are included. The events are required at generator-level to satisfy the criteria of: one central lepton (e.g. $e^\pm$ or $\mu^\pm$) with $E_T > 20$ GeV and $|\eta| < 1.0$; a second with $E_T > 12$ GeV and $|\eta| < 2.5$ (column 2, or $E_T > 20$ GeV and $|\eta| < 2.5$ (column 3); and for the leptonic decay of the W, $\not\!\!E_t > 20$ GeV. A ΔR cut of > 0.4 has been applied to all accepted lepton pairs. The analogous qq and ll samples in $W\mu^+\mu^-$ and $W\tau^+\tau^-$ have not been tabulated but are available. The total dilepton rate (e and μ) will be double this from the $W\mu^+\mu^-$, not counting the $W\tau^+\tau^-$ contribution.

7 $Z^0/\gamma^* Z^0/\gamma^*$ Production

A sample was generated of the diboson production of Z^0/γ^* pairs, followed by the decay of each Z^0/γ^* into an e, μ, or τ. Table 8 gives the rate for one flavor, e.g. e^+e^-, satisfying the dilepton cuts except the $\not{E}_t$ cut (at generator level for these decays there is no $\not{E}_t$).

A sample in which one Z^0/γ^* is allowed to decay to neutrinos and the other to the three lepton flavors was also generated, and the dilepton rate for a single flavor is also listed in Table 8. In this case a $\not{E}_t$ cut has been applied.

$Z^0/\gamma^* Z^0/\gamma^*$ Events per 100 pb^{-1}			
M.E. Process	Met Cut	$\mathrm{E_T}^{2ndlepton} > 12$ GeV	$\mathrm{E_T}^{2ndlepton} > 20$ GeV
$ZZ + 0\ jets \rightarrow (e, \mu, \tau) + (e, \mu, \tau)$	no	0.201±.002	0.193±.002
$ZZ + 0\ jets \rightarrow (e, \mu, \tau) + (\nu_e, \nu_\mu, \nu_\tau)$	yes	0.88±.01	0.79±.01

Table 8: The number of e^+e^-events per 100 pb^{-1} from the production of a a $Z^0/\gamma^* Z^0/\gamma^*$ boson pair predicted at LO and generator-level to satisfy the criteria of: one central lepton (e.g. e^+ or e^-) with $\mathrm{E_T} > 20$ GeV and $|\eta| < 1.0$; a second (e.g. e^- or e^+) with $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$ (column 2), or $\mathrm{E_T} > 20$ GeV and $|\eta| < 2.5$ (column 3). A ΔR cut of > 0.4 has been applied to all accepted lepton pairs. In the 4-lepton case no met cut has been applied. In the case where both Z's go to leptons the standard e/mu combinations will be 4 times this rate; in the case where one Z goes to neutrinos there are only e^+e^- and $\mu^+\mu^-$ combinations so the total is only twice the quoted e^+e^- rate.

8 Top +jets and $WWb\bar{b}$ +jets Crossections

The two largest SM contributors to two leptons plus intrinsic missing Et with b-quark jets are $t\bar{t}$ and $\mathrm{W^+W^-}b\bar{b}$ production. MadGraph allows us to generate samples of these with additional jets, and in addition outputs the helicities from the decay chains so that the HEPG bank momenta correctly take the spin correlations of the tops and the W's (as well as the b-quarks) into account.

Table 9 shows the MadGraph crossections, expressed as the number of events per 100 pb^{-1}, for $\bar{p}p \rightarrow \mathrm{W^+W^-}b\bar{b}$+0,1, or 2 jets. In MadGraph one can control the number of QCD and EWK vertices used in the Feynman diagrams; columns 2 and 3 give the maximum number allowed. One can also explicitly require that there be no diagrams with a t or tbar at the gluon-quark-quark vertex (there are small contributions from virtual tops with weak couplings in more complex diagrams, but they are negligible); this process is labeled 'no top' in the table. The row labeled 'g,A,Z s-channel only' has only the 3 s-channel diagrams with an intermediate gluon, photon, or Z^0.

These top crossections, calculated at LO with $Q^2 = m_Z^2$ and CTEQ5L PDF's, correspond to a total top production crossection of 8.46± 0.06 pb. A comparison of this with NLO and NNLO predictions follows in Section 8.1.

Dilepton + N Jet Events per 100 pb^{-1}								
Process	Order		$E_T^{2nd lepton} > 12$ GeV			$E_T^{2nd lepton} > 20$ GeV		
$(\to \ell^+\ell^- + ...)$	α_s	α	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets	≥ 0 Jets	≥ 1 Jet	≥ 2 Jets
TOP								
$WW + b\bar{b}$	99	99	6.61±.03	6.59±.03	5.91±.03	5.53±.03	5.51±.03	4.96±.02
$WW + b\bar{b}$ g, A, Z s − channel only	99	99	6.35±.13	6.33±.13	5.68±.12	5.30±.12	5.29±.12	4.76±.11
TOP + JETS								
$WW + b\bar{b}$ 2nd order α, α_s only	2	2	6.55±.11	6.53±.11	5.85±.11	5.53±.11	5.52±.11	4.96±.10
$WW + b\bar{b} + j$ 2nd order α only	3	2	8.49±.15	8.48±.15	6.51±.13	7.06±.13	7.05±.13	5.47±.12
$WW + b\bar{b} + 2j$ 2nd order α only	4	2	6.58±.17	6.58±.17	6.48±.16	5.49±.15	5.49±.15	5.41±.15
EWK Diboson WW + $b\bar{b}$								
$WW + b\bar{b}$ no top	99	99	.026±.001	.025±.001	.015±.001	.021±.001	.020±.001	.013±.001
$WW + c\bar{c}$	99	99	.039±.001	.036±.001	.016±0.001	.032±.001	.030±.001	.013±.001

Table 9: The number of e^+e^- *or* $\mu^+\mu^-$ events per 100 pb^{-1} predicted at LO and generator-level to satisfy the criteria of: one central lepton (e.g. e^+ or e^-) with $E_T > 20$ GeV and $|\eta| < 1.0$; a second (e.g. e^- or e^+) with $E_T > 12$ GeV and $|\eta| < 2.5$ (columns 2-4), or $E_T > 20$ GeV and $|\eta| < 2.5$ (columns 5-7); $\not{E}_t > 20$ GeV; and ≥ 0, 1, or 2 jets satisfying $E_T > 10$ GeV and $|\eta| < 2.5$. A ΔR cut of > 0.4 has been applied to all parton pairs counted in a given column. For cross-generation dilepton final states such as $e\mu$ or $\mu\tau$, these numbers should be multiplied by 2 to account for the two possible charge combinations; thus the total number of standard CDF 'dilepton' events produced into this kinematic acceptance is 4 times these numbers. The row labeled "$WW + b\bar{b}$/notop" has neither the large s-channel $t\bar{t}$ pair production nor the much smaller virtual top diagrams included (ie. what one would get if the top did not exist). The row labeled '2nd order only' has only diagrams up to 2nd order in α_s and in α, which kills off all of the virtual top diagrams except for one, gluon to $b\bar{b}$ followed by a virtual top.

8.1 Theoretical cross-section Predictions: LO, NLO, and NNLO

To predict the number of SM dilepton and multi-boson events we need to normalize the LO MadGraph samples. One standard practice is to normalize the LO predictions to NLO predictions; another is to use a 'K-factor'. Table 10 compares the MadGraph crossections for $t\bar{t}$ production to theoretical predictions from the literature.

These top crossections, calculated at LO with $Q^2 = m_Z^2$ and CTEQ5L PDF's, correspond to a total top production crossection of 8.46± 0.06 pb. As shown in Table 10, this is a little above a NNLO prediction. Using a Q^2 scale that is more appropriate (m_{top}^2) gives a cross section at LO of 6.21±0.06 pb, not too far from (the lower of) the predictions for the NLO crossection shown in Table 10.

Theoretical $t\bar{t}$ Cross Section Predictions						
Authors	hep-ph	Date	Order/Resum	PDF	$\sqrt{s} = 1.8$	$\sqrt{s} = 1.96$
Kidonakis+Vogt	0309045	Sep 03	NNLO/yes	CTEQ6M	5.24±.31	6.77±.42
Mangano,Nason, Cacciari,Frixione, +Ridolfi	0303075	Mar 03	NLO/yes	CTEQ6M	$5.9^{+.052}_{-.0.68}$	$6.70^{+.71}_{-.88}$
Kidonakis	0010002	May 01	NNLO/yes NLO/yes	CTEQ5M CTEQ5M	$6.3^{+.1}_{-.4}$ 5.2	$8.1^{+.13}_{-.52}$[10] —
PDG (Mangano)	PRD66: 010001	Jun 02	—	—	—	5.13±.38
Bonciani,Catani, Mangano,+Nason	9801375	Mar 98	NLO/yes NLO/no	MRS2 MRS2	$5.06^{+.13}_{-.36}$ $4.87^{+.30}_{-.56}$	$6.53^{+.17}_{-.46}$[10] $6.28^{+.39}_{-.72}$[10]
Berger+Contopanagos	9603326	Mar 96	NLO/yes	CTEQ3	$5.52^{+.17}_{-.42}$	$7.17^{+.09}_{-.54}$[10]
Laenen,Smith +Van Neerven	9310233	Oct 93	NLO/yes	MRSD$'_{-}$	$4.95^{+.70}_{-.42}$	$6.39^{+.90}_{-.54}$[10]
MadGraph	This note		LO:$Q^2 = M_t^2$	CTEQ5L	—	6.21±0.02
MadGraph	This note		LO:$Q^2 = M_Z^2$	CTEQ5L	—	8.46±0.06

Table 10: A selection of top cross-section predictions. Those numbers tagged by Ref [10] have been scaled up to 1.96 TeV from 1.8 TeV by a factor of 1.29 (in many cases the 2.0 TeV crossections are given, but not 1.96). Note that the MadGraph numbers, described in this note, are higher than the NLO and NNLO calculations, which in turn are higher than the 2002 PDG value. This is due to the Q^2 scales, which are M_Z^2 everywhere in this note. Changing the Q^2 scales to M_{top}^2 lowers the crossection to be a little lower than the latest NNLO/NLL calculations.

9 Normalizing to the W and Z: W+0jet and Z+0jet

As a reference the $W^{\pm} \to e^{\pm}\nu$ and '$Z^0 \to e^+e^-$' crossections were calculated using the same MadGraph version and inputs (e.g. Q^2, couplings, and PDF's). For the W case no cut on E_T for the leptons is made. For the Z case a minimum E_T of 6 GeV was required [23]; a mass window cut of $66 < M_{e^+e^-} < 116$ GeV was then imposed. In both cases the leptons are required to have $\eta < 6.0$ and $\Delta R < 0.2$ (this last cut makes no difference). The $Z^0 \to e^+e^-$ cross section includes both the photon and Z^0 amplitudes. The resulting crossections are 2085 ± 2 pb ($W^+ + W^-$)and 186 ± 1 pb, for the $W^{\pm} \to e^{\pm}\nu$ and $Z^0\gamma \to e^+e^-$ channels, respectively. The W crossection is lower than the NLO prediction of 2687 ± 54 pb [24] by a factor of 1.29, which is a typical K-factor. The $Z/gamma^*$ crossection (which is what we see before correcting for the photon amplitude) is lower than the prediction for pure Z-exchange [24] of 251.3± 5.0 pb by a factor of 1.39. The MadGraph calculation using only the Z amplitude gives 183.9 ± 0.4 pb, which is lower than the Stirling NLO prediction by a factor of 1.37. The ratio $R = (W^+ + W^-)/Z^0$ from MadGraph with CTEQ5L is 11.3, somewhat higher than other predictions [25].

10 Summary

Samples of SM processes that will be backgrounds to multiple gauge boson production have been generated with MadGraph, and the parton-level crossections tabulated. The generation parameters are described in the note. All helicities and both the Z^0 and γ poles, where relevant, have been included. The samples have been simulated and produced with 4.11.2.

The generator-level rates form a 'denominator' for efficiencies and a sanity check with which one can compare rates after simulation and production. To get the n-jets channels correct will take jet matching. A summary of the rates, in units of events per 100 pb-1, for the zero jet channels for the e^+e^-, $\mu^+\mu^-$,and $e^+\mu^-$ and $e^-\mu^+$ dilepton selection is given in Table 11.

Dilepton Events (e^+e^-, $\mu^+\mu^-$,$e^+\mu^-$,$e^-\mu^+$) per 100 pb^{-1}			
M.E. Process	Met Cut	$\mathrm{E_T^{2nd lepton}} > 12$ GeV	$\mathrm{E_T^{2nd lepton}} > 20$ GeV
$WW + 0\ jets \to (e,\mu,\tau) + (e,\mu,\tau)$	yes	20.52±.28	17.32±.28
$WW + 2\ jets \to (e,\mu,\tau) + (e,\mu,\tau)$	yes	3.52±.08	2.88±.08
$WW + b\bar{b}\ jets \to (e,\mu,\tau) + (e,\mu,\tau)$	yes	0.060±.004	0.052±.004
$WW + c\bar{c}\ jets \to (e,\mu,\tau) + (e,\mu,\tau)$	yes	0.064±.004	0.052±.004
$WZ^0/\gamma^* + 0\ jets \to (e,\mu,\tau) + 2e, e\mu, 2\tau$	yes	4.32±.04	3.98±.04
$ZZ + 0\ jets \to (e,\mu,\tau) + (e,\mu,\tau)$	no	0.805±.007	0.772±.007
$ZZ + 0\ jets \to (e,\mu,\tau) + (\nu_e,\nu_\mu,\nu_\tau)$	yes	1.76±.02	0.79±.01
$Z^0/\gamma^* + 0jets \to \tau^+\tau^-$	no	200±14	83.6±9.2
$Z^0/\gamma^* + 2jets \to \tau^+\tau^-$	no	18.8±1.6	8.4±1.2
$Z^0/\gamma^* + 0jets \to \tau^+\tau^-$	yes	23.2±4.8	4.0±1.6
$Z^0/\gamma^* + 2jets \to \tau^+\tau^-$	yes	9.2±1.2	3.2±0.8
$t\bar{t} \to (e,\mu,\tau) + (e,\mu,\tau) + b\bar{b}$	yes	23.64±.12	19.84±.08

Table 11: The number of dilepton events (e^+e^-, $\mu^+\mu^-$,$e^+\mu^-$, or $e^-\mu^+$)) per 100 pb^{-1} predicted at LO and generator-level to satisfy the criteria of: one central lepton (e.g. e^+ or e^-) with $\mathrm{E_T} > 20$ GeV and $|\eta| < 1.0$; a second (e.g. e^- or e^+) with $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$ (column 2), or $\mathrm{E_T} > 20$ GeV and $|\eta| < 2.5$ (column 3). Jets, if present in the matrix element, are required to satisfy $\mathrm{E_T} > 10$ GeV and $|\eta| < 2.5$. A ΔR cut of > 0.4 has been applied to all accepted lepton and lepton-jet pairs. In the cases with no intrinsic met no met cut has been applied.

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[3] J.D. Bjorken, S. Pakvasa, and S.F. Tuan, SLAC-PUB-9212; hep-ph/0206116

[4] , D. E.Morrissey and C. E. M. Wagner, Phys. Rev. D69, p.53001, 2004; hep-ph/0308001",

[5] K. Agashe, G. Servant ANL-HEP-PR-04-19, EFI-04-06; hep-ph/0403143

[6] G. L. Kane, S. Mrenna Phys.Rev.Lett.77:3502-3505,1996; hep-ph/9605351

[7] The samples are (of course) available on request.

[8] J.M. Campbell and R.K. Ellis, Phys.Rev.D60:113006,1999; hep-ph/9905386 The numbers in this note are being recalculated and the new LO number is in good agreement (John Campbell, private communication).

[9] For example, 'turning off' diagrams kills off both the direct contributions and any interference contributions; which are not taken into account in the book-keeping of the separate pieces (but are in the whole).

[10] These calculations are done at 2 TeV and not the actual 1.96 Tev. Also Q^2 is M_W^2 and not M_Z^2 as in the MadGraph calculations.

[11] The samples are named Wee0jet_ll (W to leptons, e,mu, and tau, plus $Z^0/\gamma^* \to ee$, with 0 jets), Wee0jet_qq (same but W decay to the 2 lighter quark families, etc.).

[12] For a complete description of the techniques MadGraph uses, see: T. Stelzer and W. F. Long.
Comput.Phys.Commun. 81, 357 (1994); F. Maltoni and T. Stelzer, ILL-(TH)-02-9 For instructions and practical information see the (excellent) MadGraph web site at http://madgraph.hep.uiuc.edu/.

[13] "COMPHEP: A PACKAGE FOR EVALUATION OF FEYNMAN DIAGRAMS AND INTEGRATION OVER MULTIPARTICLE PHASE SPACE." By A. Pukhov, E. Boos, M. Dubinin, V. Edneral, V. Ilyin, D. Kovalenko, A. Kryukov, V. Savrin (Moscow State U.), S. Shichanin (Serpukhov, IHEP), A. Semenov (Dubna, JINR). INP-MSU-98-41-542, Aug 1999. 126pp. User's manual for version 33. e-Print Archive: hep-ph/9908288; E.E. Boos, M.N. Dubinin, V.A. Ilyin, A.E. Pukhov, and V.I. Savrin, INP MSU 94-36/358 and SNUTP-94-116, hep-ph/9503280; P. Baikov *et al.*, in Proc. of the Xth Int. Workshop on High Energy Physics and Quantum Field Theory, QFTHEP-95, ed. by B. Levtchenko and V. Savrin, (Moscow, 1995), p. 101.

[14] Steve Mrenna has implemented matrix element-parton shower matching using MadGraph and Pythia. This gives us the ability to generate samples with the correct mix of 0,1,2,3, and 4 jets. See: http://cepa.fnal.gov/personal/mrenna/ME-PS_Matching.html

[15] See Chadd Smith's web page at http://hep.uchicago.edu/cdf/mcinfo/chadd_kumac_howto.html

[16] MadGraph was run on the process $\bar{p}p \to e^+e^-$ with Et thresholds of (20,12) and a Delta-R cut of 0.2 for eta ranges on both leptons of $|\eta| < 2.5$ and for $|\eta| < 6.0$. The crossections increase from 145.4 0.3(pb) to 171.5 0.5(pb), an increase of 18%.

[17] The LEP Electroweak Working Group:
http://lepewwg.web.cern.ch/LEPEWWG/stanmod/summer2002_ results. We use the 'y5' set of numbers, corresponding to all data except that from NuTeV.

[18] CDF Note CDF/PHYS//PUBLIC/6063; S. Cabrera, E. Collins, S. Carron, C. Ferretti, H. Frisch, D. Gerdes, G. Gomez, A. Messina, T. Rodrigo, R. Roser, S. Sarkar, M. Soderberg, E. Thomson, S. Tsuno, R. Vilar, C. Wolfe; *Standardized Comparison of Matrix Element Monte Carlo Event Generators*

[19] E. Collins and H. Frisch, *The Ratio of W+N-jets To Z+N-jets Versus N As a Precision Test of the Standard Model*,
CDF Note: CDF/PHYS/ELECTROWEAK/PUBLIC/5963, Date: 5/12/02

[20] Fabio Maltoni has now modified the routine decay.f to give all modes of the W as a choice.

[21] G. Manca, CDFnote 6521, June 2003.

[22] I use 'accepted' events/100 pb^{-1} instead of quoting a cross section in pb after cuts as it's easier to remember. They are trivially related.

[23] The calculated cross section is the same to better than 0.2% asking only for $\hat{s}_{min}(e^+e^-) >$ 20 GeV and $\Delta R_{e^+e^-} > 0.2$.

[24] See D. Acosta et al. (the CDF Collaboration), hep-ex/04068078, and A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, hep-ph/0308087.

[25] See Ref. [19]. Changing from M_Z^2 to M_W^2 for the W channel has no measurable effect.