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Predicted Cross sections for Wγ, W$\gamma\gamma$, Zγ, and Z$\gamma\gamma$ Channels for the Photon-Lepton+X Search

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Abstract

To have confidence in the expected number of events with a high-p_T lepton and photon + other objects requires comparing predictions from several monte carlo generators. We have used COMPHEP and MADGRAPH to make data samples, tabulate SM cross-sections,and, make distributions for the production of a W or Z boson and a high E_T photon. With MADGRAPH we have also done the same for two-photon production with a W or Z boson, and have used COMPHEP samples prepared for us to compare. Integral cross sections at generator level in kinematic variables such as the E_T of the photon are also presented, giving the number of events expected in the lepton+photon channels above a given threshold. The datasets are available to be simulated.

1 Introduction

The SM makes precise predictions for the higher-order electroweak production of the W and Z bosons with accompanying high-p_T photons. In Run I there a number of events in signatures with high-p_T leptons and photons that are rare in the SM [1, 2, 3, 4]. We have observed the $ee\gamma\gamma\not\!\!E_t$ and $\mu\mu\gamma\gamma jj$ events, as well as the high 200 GeV Z event recoiling against a photon, which looks very similar to a 200 GeV-p_T Z event from Run 0. In addition, we have found a statistical excess in the $\ell\gamma\not\!\!E_T$ sample. We are preparing for the long-promised larger data sets in Run II to see if the anomalous events continue.

At present we are working at the generator level to compare predictions from different generators and to get confidence in the new tools. These generators also generate events, and these can be simulated and re-simulated (as the simulation improves) and used to predict the numbers of background events in specific channels. In this note we present cross sections for Wγ and Zγ, and W$\gamma\gamma$ and Zgg, production using the COMPHEP [5] and MadGraph [6] Monte Carlo generators.

One important note on what we call a 'Z' is in order. The 'Tight' cuts described below have a mass window cut around the Z^0 mass. The production in the charged dilepton channels (e.g. e^+e^-) proceeds through two s-channel amplitudes, the γ and Z^0 poles. While the Z^0 pole dominates for the selection criteria used here ($\sim$ 96%), both amplitudes contribute, so that everywhere here when we say 'Z' we mean both amplitudes, as the source of an event in the resulting final state cannot be untangled experimentally.

2 Monte Carlo Generation Parameters

We are interested in having three data sets with three sets of parameters for each physics process in order to get the total production cross-section and also the 'visible' CDF cross-section before and after parton-fragmentation and radiation by the shower Monte Carlos. These are analysis-level cuts. The parameters for the three analysis cases are listed in Table 1.

Particle	Total			Wide			Tight		
	Et	η	ΔR	Et	η	ΔR	Et	η	ΔR
'First' Lepton	1.0	6.0	0.2	12.0	2.5	0.2	25.0	1.0	0.4
Additional Leptons	1.0	6.0	0.2	6.0	2.5	0.2	12.0	2.5	0.4
Neutrinos	1.0	6.0	0	6.0	6.0	0	$\not\!\!E_t > 25.0$	6.0	0
'First' Photon	6.0	6.0	0.2	6.0	2.5	0.2	25.0	1.0	0.4
Additional Photons	6.0	6.0	0.2	6.0	2.5	0.2	12.0	2.5	0.4

Table 1: The 'Analysis cuts' used on the generator output to produce Table 11. The cuts labeled 'Total' are used to generate an approximation of the the total cross section, and can be used to calculate acceptances (however for processes with a photon pole a mass cut may be necessary). The cuts labeled 'Wide' are 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. The cuts labeled 'Tight' correspond to cuts we plan to use in analyses, and are used to make plots and calculate rates at generator level.

In the Wide and Tight cases where there are two identical particles in the final state that are selected with asymmetric cuts , such as $Z^0 \rightarrow e^+e^-$ decay with (at least) one electron being required to be central, we have to 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 1 in a routine that reads the generator output file. The data samples are made with these 'Sample cuts', which are listed in Table 2.

Particle	Sample_Total			Sample_Wide			Sample_Tight		
	Et	η	ΔR	Et	η	ΔR	Et	η	ΔR
'First' Lepton	1.0	6.0	0.2	6.0	2.5	0.2	12.0	2.5	0.4
Additional Leptons	1.0	6.0	0.2	6.0	2.5	0.2	12.0	2.5	0.4
Neutrinos	1.0	6.0	0	6.0	6.0	0	$\not\!\!E_t > 25.0$	6.0	0
'First' Photon	6.0	6.0	0.2	6.0	2.5	0.2	12.0	2.5	0.4
Additional Photons	6.0	6.0	0.2	6.0	2.5	0.2	12.0	2.5	0.4

Table 2: The 'Sample cuts' used at generator level to produce the data samples. Note that for the Wide and Tight samples these are not the cuts used at analysis level for calculating cross sections, which correspond to a subset of these samples, as described in the text.

The first set of numbers, labeled 'Sample_Total', is with cuts which accept basically all events that could possibly be detected by CDF. This sample can be used as the 'denominator' to calculate acceptances. However, for channels with multiple photons such as $W\gamma\gamma$, the fraction of all events that pass the tight cuts is very small, and so using a 'Total' sample for detailed studies of the detector is impractical.

The second set, labeled 'Sample_Wide', has E_T and η cuts which are far enough below the 'Tight' analysis thresholds so that the sample contains those events that could be 'promoted' into the sample by smearing of E_T due to initial state radiation and/or smearing of η due to the vertex distribution. For example, in the Run I $\ell\gamma$ analysis, in order to get the total contribution from $W\gamma$ events with a photon with $E_T > 25$ GeV it was necessary to generate events with values of E_T down to 10 GeV or so. However, the thresholds for leptons can be set low without much loss of efficiency, as there is not much cross section for low-p_T leptons from decays of W's and Z's.

The third set, labeled 'Sample_Tight', corresponds to the cuts used in previous analyses, in some cases modified slightly by changes to the detector. These are used to make samples from which we make plots of generator-level distributions corresponding to final plots of data. However, in those cases of two identical particles with asymmetric cuts, these samples are made with the lower of the two thresholds, and the final cuts are made on the ntuples from the samples.

The generators are run at a center-of-mass energy of 1.96 TeV; we use CTEQ5L structure functions, with 4 flavors contributing. The renormalization and factorization scales are set by default to be equal to M_Z in both programs. The relevant electroweak parameters are the default ones in MadGraph at present: Table 3 gives these as well as the July 2002 LEP Electroweak Working Group values [7] and CDF6063 [8]. We also give the default values for Comphep, used for the comparisons below. We have left both the MadGraph and Comphep values at their defaults for the present. As seen below, the agreement between the two is within 10% over many decades in cross section even without any tuning of parameters.

All uncertainties quoted below are statistical only.

Parameter	LEPEWKWG	CDF6063	MadGraph	COMPHEP
M_Z	91.1874	91.1880	91.1880	91.1884
M_W	80.403	80.41	79.955	(80.343)
Γ_Z	2.4952	2.445	2.4950	2.4944
sin^2_W	0.2226	0.2224	0.2312	0.2237
$1/\alpha$	128.90	132.4	128.90	128.90
g_{Weak}	(0.6643)	0.6532	0.6494	(0.6601)

Table 3: The input electroweak parameters for MadGraph and COMPHEP. Also shown are the current values (July 2002) from the LEP Electroweak Working Group [7] and from CDF6063 [8]. Note that not all of these variables are independent- some are basic inputs while others are derived internally in the programs. Quantities we derived from the tree-level EWK relations are shown in parentheses.

3 Wgamma

The $W\gamma$ channel is the main SM contributor to the $\ell\gamma\not{E}_t$ signature with the Run I cuts. In the Run I analysis, $W\gamma$ was expected to contribute 1.93 ± 0.26 events to the $e\gamma\not{E}_t$ channel, out of a total of 3.41 ± 0.34, and 1.99 ± 0.27, out of a total of 4.23 ± 0.46 for the $\mu\gamma\not{E}_t$ channel. Having a reliable prediction of this signature is thus crucial.

We have generated samples in this channel using COMPHEP and MadGraph. Table 4 presents the integrated cross-section versus the $\mathrm{E_T}$ of the highest-$\mathrm{E_T}$ photon for the 'Tight' cuts of Table 1 (for photon $\mathrm{E_T} < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon $\mathrm{E_T}$- these are calculated from the Wide sample). Note that since this is at LO the $\mathrm{E_T}$ of the photon is the same as the $\mathrm{p_T}$ of the $e\nu$ pair, as there are only 3 particles in the final state and the initial state has zero transverse momentum. Figure 1 shows the integrated cross section versus $\mathrm{E_T}$ of the photon. Figures 2 and 3 show kinematic distributions from the tight sample.

One can see that there is agreement within statistics between MadGraph and Comphep in the Wγ predictions. We have used default input parameters for each of the programs as the agreement is good enough for the purposes of our exotics searches.

$W\gamma$ $\mathrm{E_T^e} > 25, \lvert\eta\rvert^e < 1.0, \lvert\eta\rvert^\gamma < 1.0, \not{E}_t > 25$			
$\mathrm{E_T}^{gamma_1}$	σ (fb)		
(GeV)	MadGraph	CompHep	Ratio (M/C)
6	838 ± 29	—	—
10	316 ± 18	319 ±10	0.99±0.06
20	40.0 ± 6.4	41.3±3.7	0.97±0.18
25	22.1 ± 0.4	22.4±0.2	0.99 ± .02
30	14.9 ± 0.1	14.8±0.1	1.01 ± .01
40	7.81 ± 0.08	7.80±0.09	1.00 ± .02
50	4.84 ± 0.06	4.80±0.07	1.01 ± .02
60	3.19 ± 0.05	3.27±0.06	0.98 ± .02
80	1.67 ± 0.04	1.64±0.04	1.02 ± .03
100	0.979 ± 0.029	0.930±0.030	1.05 ± .05
120	0.588 ± 0.023	0.548±0.023	1.05 ± .05
140	0.346 ± 0.017	0.330±0.018	1.05 ± .08
160	0.222 ± 0.014	0.224±0.015	0.99 ± .09
180	0.140 ± 0.011	0.126±0.011	1.11 ± .13
200	0.087 ± 0.009	0.091±0.009	0.95 ± .14

Table 4: The integral cross-sections in fb for $e\nu\gamma$ production at 1.96 GeV versus the gamma $\mathrm{E_T}$. The cross sections are given for the 'Tight' cuts as described in Table 1. For photon $\mathrm{E_T} < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon $\mathrm{E_T}$ and are calculated from the Wide samples.

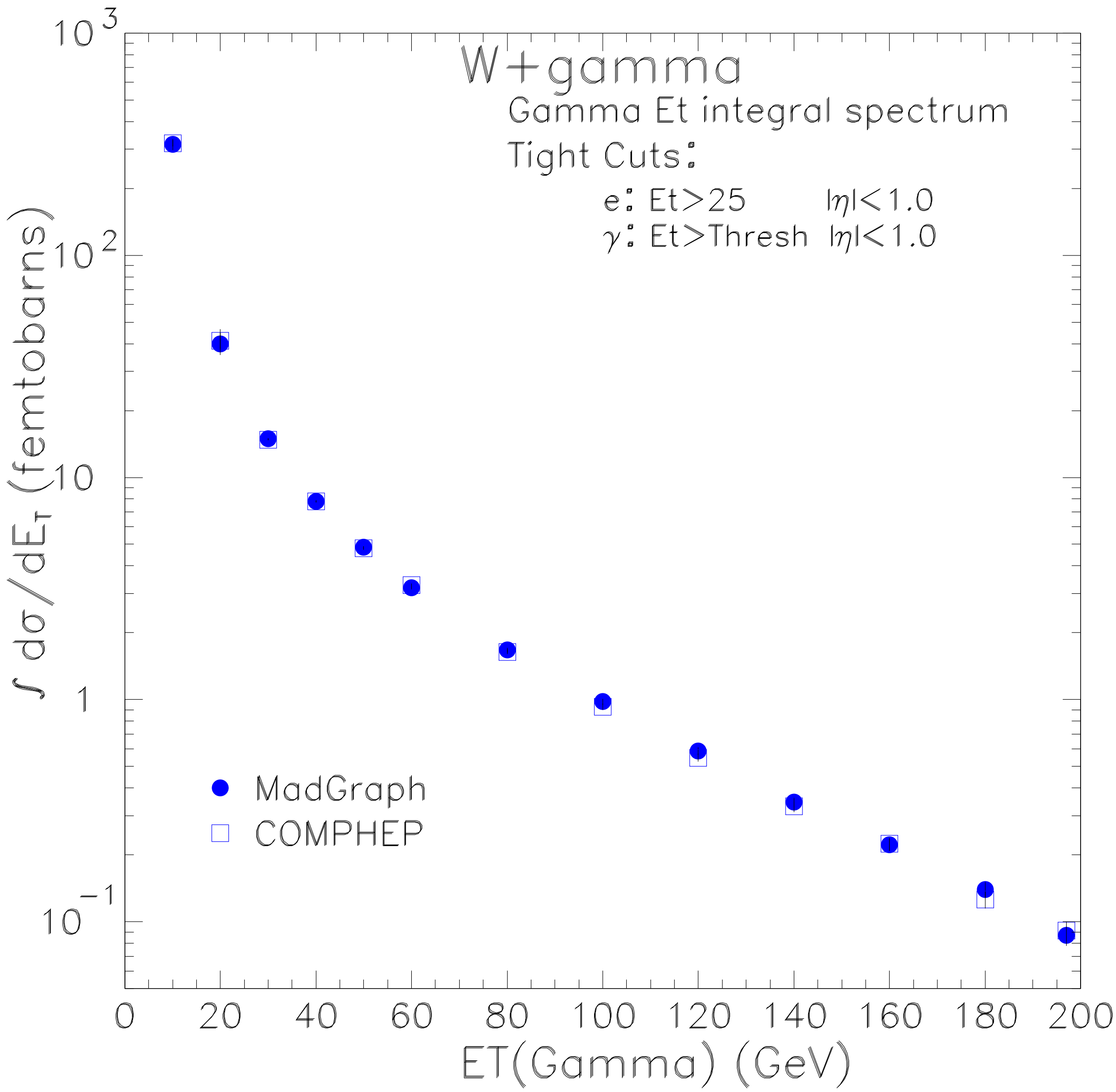

Figure 1: The integral cross-sections in fb from MadGraph and COMPHEP for $e\nu\gamma$ production at 1.96 GeV versus the gamma E_T for the 'Tight' cuts as described in Table 1. For photon $E_T < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon E_T and are calculated from the Wide sample.

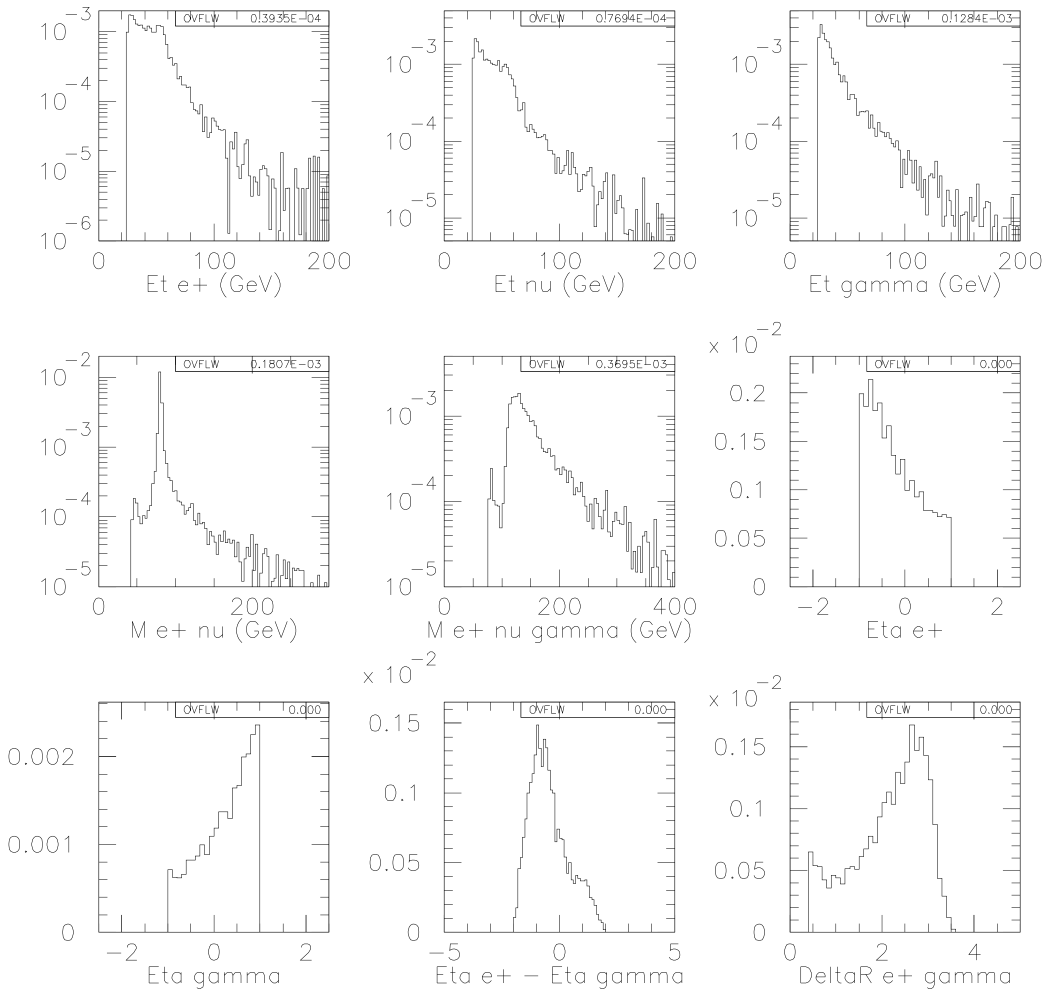

Figure 2: Kinematic distributions for the e^+, ν, and γ from the MadGraph $W\gamma$ sample with 'Tight' cuts.

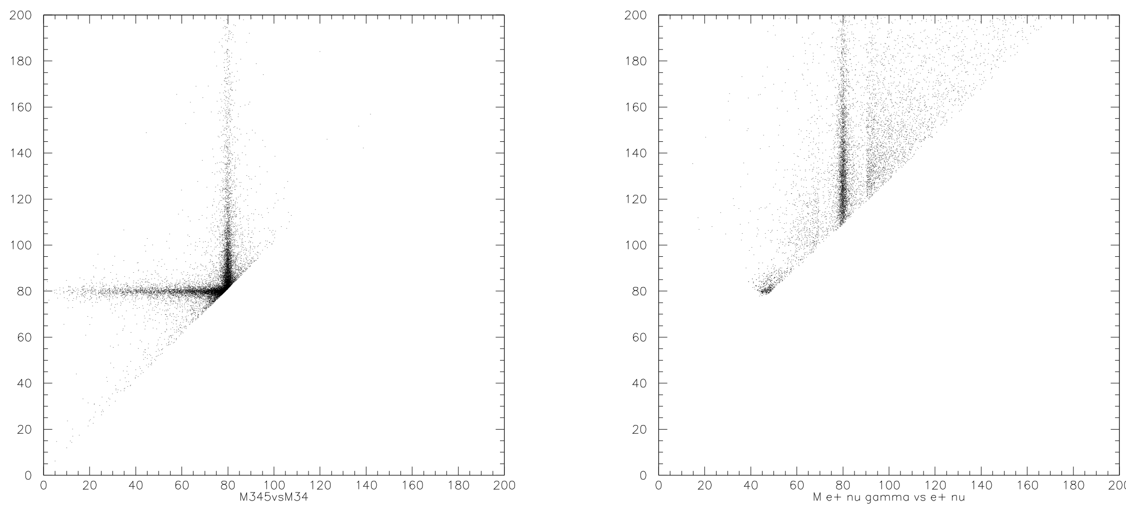

Figure 3: The invariant mass of the $e\nu\gamma$ system plotted versus the invariant mass of the $e\nu$ system for cuts of $E_T > 1$ and $\eta < 6$ for all three particles (left-hand plot) and the 'Tight' cuts (right-hand plot) from the MadGraph $W\gamma$ samples.

4 Zgamma

We have observed two events with a Z^0 with transverse momentum of 200 GeV balanced by, in one case, a photon[1, 2, 3, 4], and in the other two jets with an invariant mass consistent with a W. Reliable predictions for high $\mathrm{E_T}$ $Z\gamma$ events versus the $\mathrm{E_T}$ of the gamma (which at LO is the same as the $\mathrm{p_T}$ of the Z) are thus of high priority.

The process $\bar{p}p \rightarrow Z^0\gamma$ is also one of the major SM backgrounds for the lepton+ photon+X searches. It is the largest contributor to the inclusive multi-body category in the Run I search, with expected contributions in 86 $\mathrm{pb}^{-1}$of 5.01 ± 0.54 events in the $e\gamma$ mode and $4.60{\pm}0.54$ in the $\mu\gamma$ mode [9] It is also significant in the $\ell\gamma\not{E}_t$ channel, especially for muons, as one muon can be missed inducing $\not{E}_t$. The expected contributions for these the electron and muon channels in Run I were 0.32 ± 0.5 and 0.96 ± 0.15 events, respectively, smaller than the $W\gamma$ contributions, but still significant, with a total $(e + \mu)$ of 1.27 ± 0.17 out of the 7.64 ± 0.71 events expected in 86 pb^{-1}.

Table 5 shows the integrated spectrum in fb for the production of an e^+e^- pair satisfying the tight cuts versus the $\mathrm{E_T}$ threshold for the photon from both MadGraph and COMPHEP. The numbers are generated using the Tight sample for photon $\mathrm{E_T} > 25$ GeV; for $\mathrm{E_T} < 25$ GeV the tight cuts are applied to the Wide sample. There is good ($\sim 1\%$) agreement between the Tight and Wide samples. The samples run out of statistics at the highest values of $\mathrm{E_T}$, and the simple (Gaussian) method of calculating the statistical uncertainties probably underestimates them; we consequently are not bothered by the apparent 2.8σ discrepancy above 180 GeV (note also that the 180 and 200 GeV points are highly correlated, as this is an integral spectrum). The integral cross sections are plotted in Figure 4.

Lastly, one can estimate an upper limit on the number of events with a central-central Z^0 and a 200 GeV photon, as in our famous Run 1 event [2, 3]. The average of the MadGraph and Comphep cross sections is $\sigma_{200} = 0.185 \pm 0.002$ fb (185 attobarns). Without including acceptance or efficiencies, in 100 pb^{-1}(0.1 fb^{-1}), we would expect 0.0185 events with $\mathrm{E}_\mathrm{T}^{\gamma} > 200$ GeV. This estimate is lower than the $0.0451{\pm}0.0026$ events expected with $M_{\ell\ell\gamma} > 400$ GeV quoted in Ref [3], perhaps because it is not the same quantity that is being selected (the selection here is on Et^{γ}, rather than on system mass). We expect that including the acceptance and efficiencies will lower this by approximately a factor of 2-3.

Z+Central Gamma Cross Sections (femtobarns)						
E_T^{gamma}	$E_T^1 > 25$, $\lvert\eta\rvert^1 < 1.0$,$E_T^2 > 12$, $\lvert\eta\rvert^2 < 2.5$			$E_T^1 > 25$, $\lvert\eta\rvert^1 < 1.0$,$E_T^2 > 25$, $\lvert\eta\rvert^2 < 1.0$		
(GeV)	MadGraph	CompHep	Mad/Com Ratio	MadGraph	CompHep	Mad/Com Ratio
6	1200 ± 20	—	—			
10	739 ± 16	—	—			
20	261 ± 9	—	—			
25	150 ± 1.4	156 ±1.8	0.96±0.01	27.8± 0.6	29.4± 0.8	0.95±0.03
30	83.2 ± 1.0	86.0 ±1.4	0.97±0.02	18.7± 0.5	19.1± 0.6	0.98±0.04
40	33.7 ± 0.6	34.9 ±0.9	0.97±0.03	10.7± 0.4	11.4± 0.5	0.94±0.05
50	19.5 ± 0.5	20.7 ±0.7	0.94±0.04	6.98± 0.30	7.41± 0.4	0.94±0.06
60	13.3 ±0.13	14.1 ±0.2	0.94±0.02	4.72± 0.04	5.03± 0.05	0.94±0.01
80	6.76 ±0.09	7.18 ±0.12	0.93±0.02	2.60± 0.03	2.74± 0.04	0.95±0.02
100	3.71 ±0.07	3.94 ±0.09	0.94±0.03	1.56± 0.02	1.65± 0.03	0.95±0.02
120	2.17 ±0.05	2.30 ±0.07	0.94±0.04	0.97± 0.02	1.03± 0.02	0.94±0.03
140	1.31 ±0.04	1.35 ±0.05	0.97±0.05	0.64± 0.02	0.63± 0.02	1.02±0.05
160	0.79 ±0.03	0.85 ±0.04	0.93±0.06	0.41± 0.01	0.41± 0.02	1.00±0.05
180	0.48 ±0.03	0.54 ±0.03	0.89±0.07	0.27± 0.01	0.27± 0.01	1.00±0.05
200	0.29 ±0.02	0.35 ±0.03	0.83±0.09	0.18± 0.01	0.19± 0.01	0.95±0.07

Table 5: The integral cross-sections in fb for $e^+e^-\gamma$ production at 1.96 GeV versus the gamma E_T. The cross sections are given for the 'Tight' cuts as described in Table 1. For photon $E_T < 25$ GeV the cross sections are for all cuts being 'Tight' except that on the photon E_T, and are calculated from the Wide sample. The 'Tight' cuts require one electron to be central ($\lvert\eta\rvert < 1.0$) with $E_T > 25$ GeV, and the other to be within $\lvert\eta\rvert < 2.5$ with $E_T > 12$ GeV. The right-most columns give the cross sections in fb requiring both electrons to be central with $E_T > 25$ GeV. To get enough statistics at large photon E_T additional datasets were made with a photon threshold of 60 GeV; this causes the discontinuities in the uncertainties at 60 GeV.

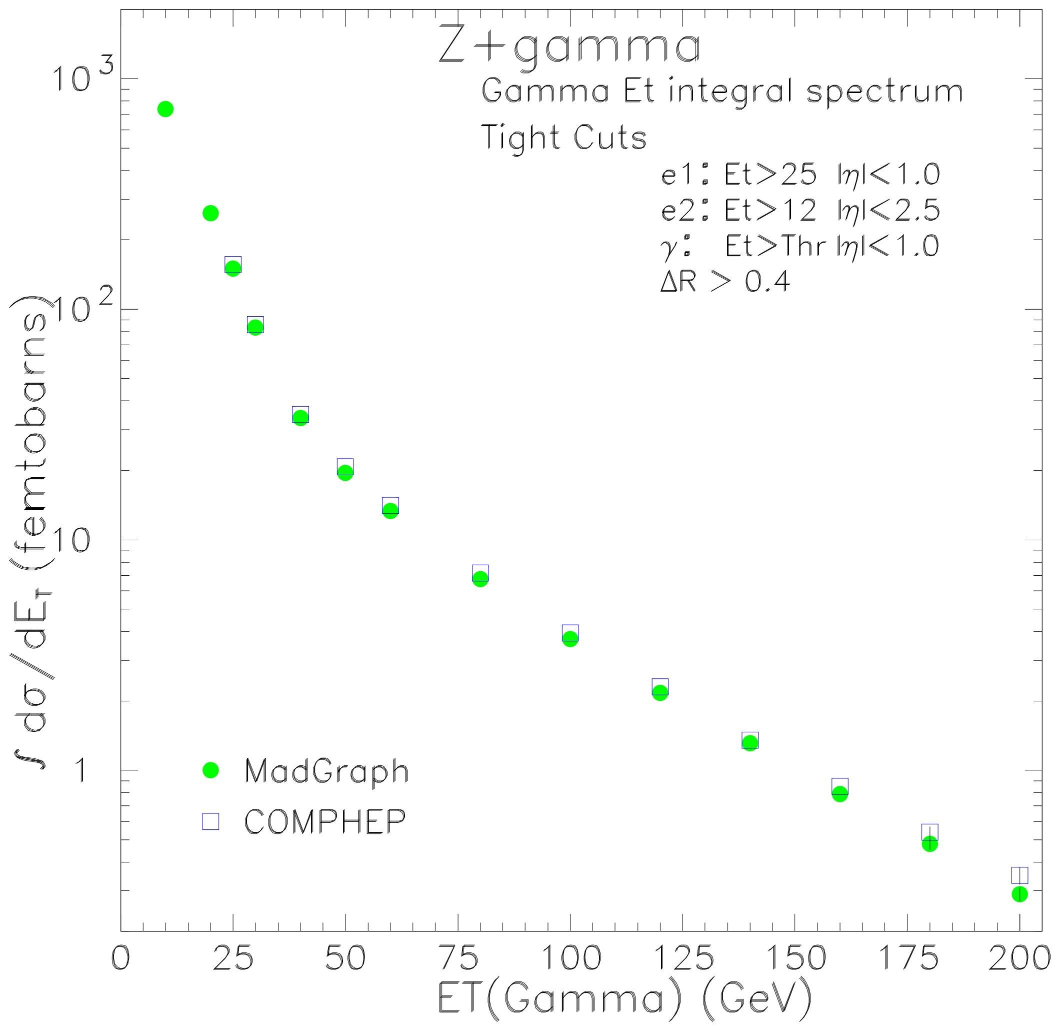

Figure 4: The integral cross-sections in fb from MadGraph and COMPHEP for $e^+e^-\gamma$ production at 1.96 GeV versus the gamma $\mathrm{E_T}$ for the 'Tight' cuts as described in Table 1. For photon $\mathrm{E_T} < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon $\mathrm{E_T}$ and are calculated from the Wide sample. The agreement is statistically reasonable (see Table 5.)

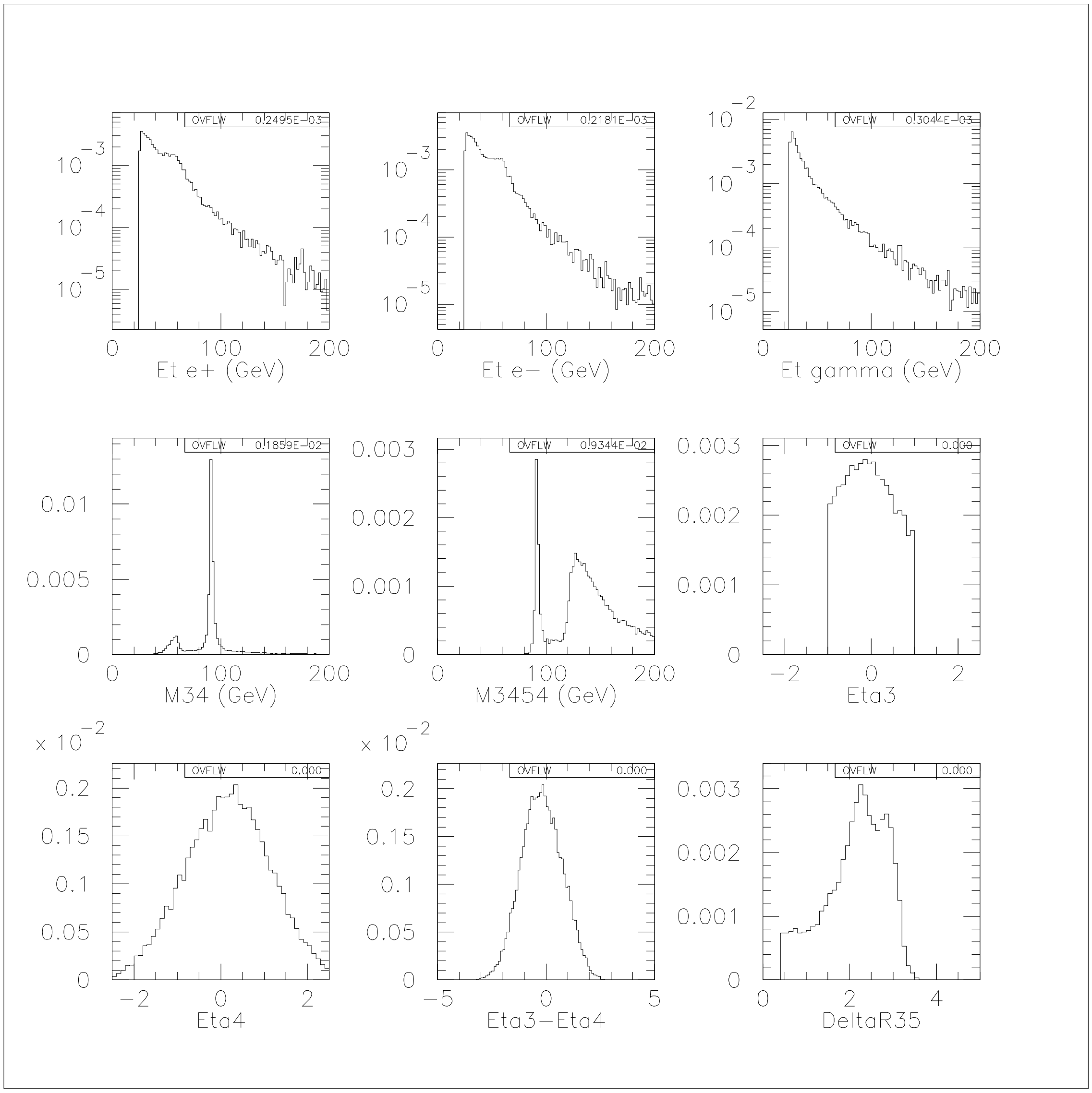

Figure 5: Kinematic distributions for the e^+, e^-, and γ from the MadGraph $Z\gamma$ sample. Particles 3,4, and 5 are the e^+, e^-, and γ respectively.

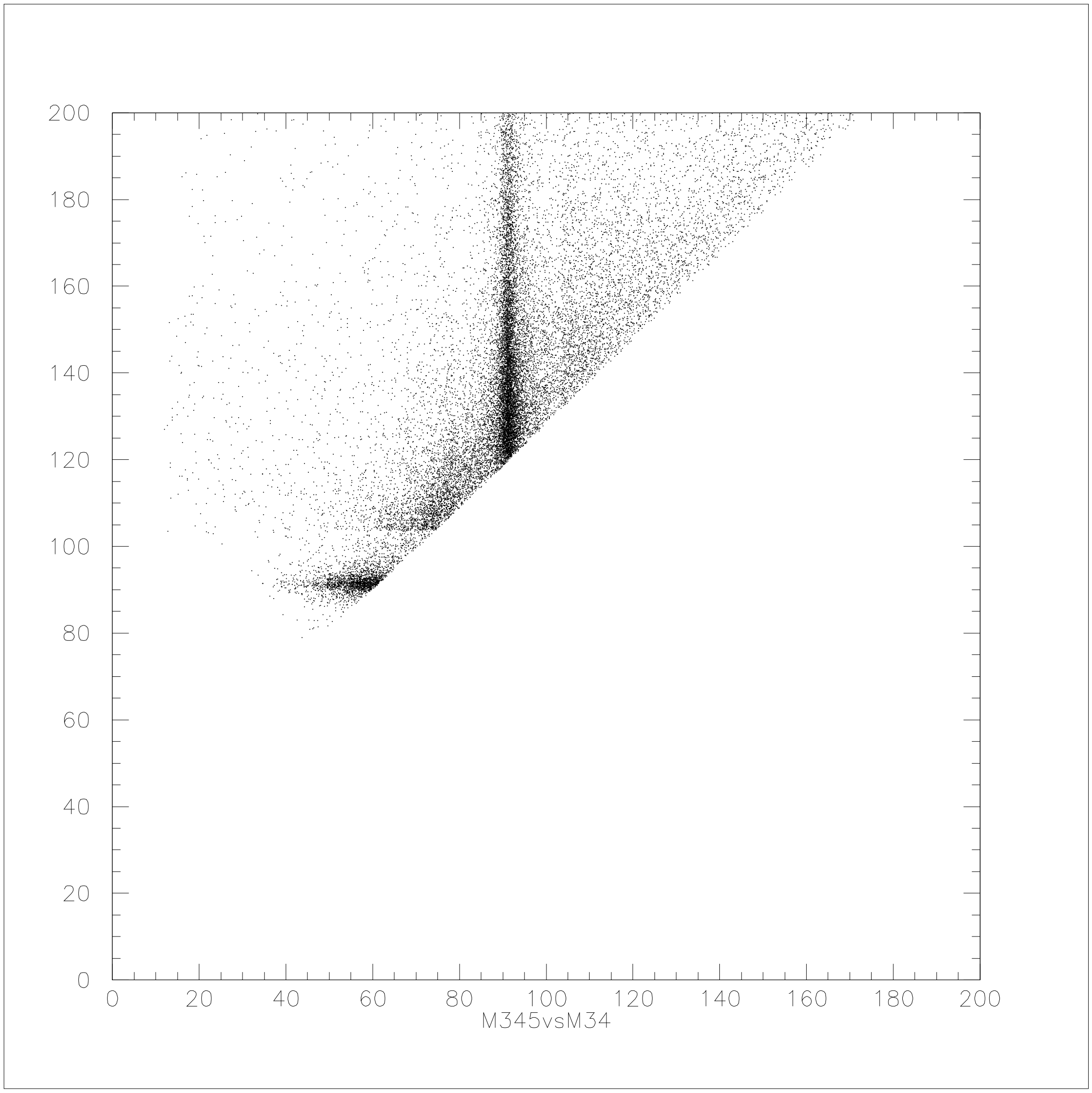

Figure 6: The three-body $e^+e^-\gamma$ mass vs the two-body e^+e^- mass from the MadGraph $Z\gamma$ sample. One can clearly see the two cases where a Z is made with an external gamma or decays to $e^+e^-\gamma$.

5 Wgammagamma

The final state of one lepton and two photons, $\ell\nu\gamma\gamma$, is produced in the SM through the W intermediate state, with radiation off of any of the charged lines in the diagrams. The radiation from the electron produces a 'knee' in the photon $\mathrm{E_T}$ spectrum around 40 GeV, as the electron spectrum cuts off there. We denote the final state of $\ell\nu\gamma\gamma$ as 'Wgammagamma' for convenience, although the W is virtual and the kinematics of the final state are more complicated than the name would suggest.

We have already observed an event with the $\ell\nu\gamma\gamma$ final state in the Run II data [10]. This event has $\mathrm{E}_\mathrm{T}^e = 47$ GeV, $\not{E}_t = 39$ GeV, $\mathrm{E}_\mathrm{T}^{\gamma 1} = 91$ GeV, $\mathrm{E}_\mathrm{T}^{\gamma 2} = 24$ GeV, and has a $\mathrm{p_T}$ of the $e\nu$ pair of 71 GeV.

The integral cross sections for the production $\ell\nu\gamma\gamma$ events satisfying the 'Tight' cuts are presented in Table 6 versus the minimum $\mathrm{p_T}$ of the $e\nu$ pair and the $\mathrm{E_T}$ of each of the two photons independently. Figure 7 displays the integrated cross-sections for the $\mathrm{p_T}$ of the $e\nu$ (W) system, the highest-Pt photon, and the second photon. [1]

W+γ+γ Cross Sections (attobarns) vs W $\mathrm{p_T}$			
p_T^W	$\mathrm{E}_\mathrm{T}^1 > 25$, $\lvert\eta\rvert^1 < 1.0$; $\mathrm{E}_\mathrm{T}^2 > 12$, $\lvert\eta\rvert^2 < 2.5$		
(GeV)	MadGraph	CompHep	Mad/Comp
0	109±4	116±7	0.94±0.07
10	103±4	110±7	0.94±0.07
20	82.3±3.8	90.6±5.9	0.91±0.07
30	60.4±3.3	70.4±5.2	0.86±0.08
40	46.5±2.9	50.2±4.4	0.93±0.10
50	34.5±2.5	35.0±3.7	0.99±0.13
60	25.5±2.1	23.7±3.0	1.08±0.16
80	13.0±1.5	12.8±2.2	1.02±0.21
100	8.3±1.2	6.6±1.6	1.26±0.35
120	4.6±0.9	5.1±1.4	0.90±0.30
140	2.8±0.7	3.1±1.1	0.90±0.39
160	0.7±0.4	3.1±1.1	0.23±0.15
180	0.4±0.3	2.0±0.9	0.20±0.17
200	0.2±0.2	1.2±0.7	0.17±0.19

Table 6: The integral cross-sections in attobarns (10^{-3} fb or 10^{-6} pb) for $\ell\nu\gamma\gamma$ production at 1.96 TeV vs. the $\mathrm{p_T}$ of the $\ell\nu$ pair. All events are required to pass the 'Tight' cuts of Table 1, i.e. the electron has to have $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$, $\not{E}_t > 25$ GeV, one of the two photons has to satisfy $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$, and the other $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$. Note that in the highest bins the Gaussian uncertainties underestimate the true Poisson uncertainty, as there are only one or two events in each sample, and so the apparent disagreement at very high p_T^W isn't real (and the cross sections are already smaller than an attobarn!).

[1] MadGraph does not order the photons in $\mathrm{E_T}$; we have reordered them for these results.

Figures 9,10, and 11 show the kinematic distributions for the e^+, ν, γ_1, and γ_2 for the Madgraph $W\gamma\gamma$ sample. The 2D plots are a little misleading, as these are weighted events, but for these plots a dot is made independent of the weight. However one can see the trends. The 1D plots are made with the weights. One can see the effects of radiation from the electron as well as from the other internal lines.

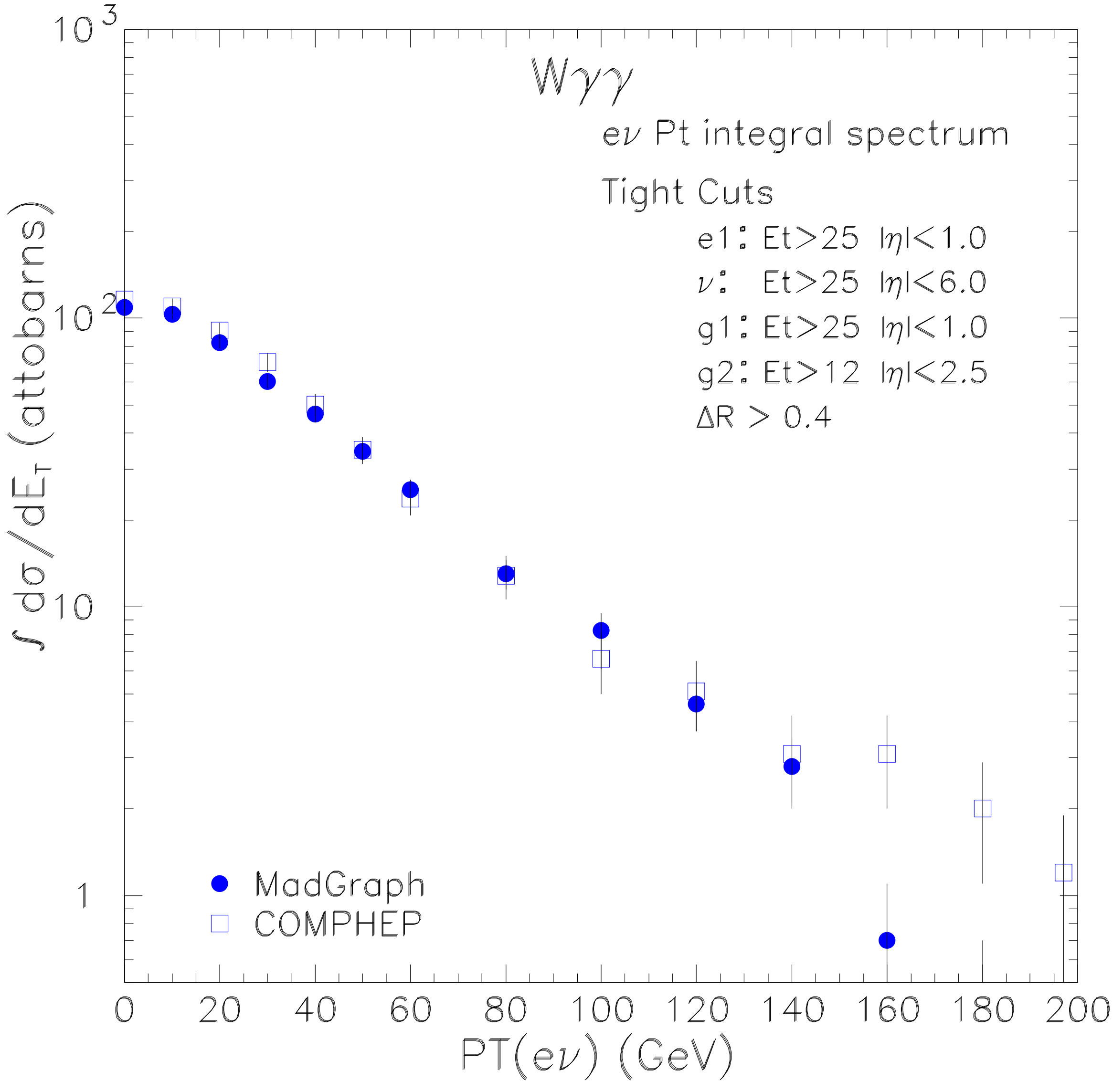

Figure 7: The integrated cross section above a threshold in attobarns ((10^{-3} fb or 10^{-6} pb) from MadGraph and CompHep W-gamma-gamma samples vs the W p_T. The leptons and photons are required to pass the 'Analysis_Tight' cuts of Table 1.

$\mathrm{E}_{\mathrm{T}}^{gamma}$ (GeV)	W+Gamma+Gamma Cross Sections (attobarns) vs $\mathrm{E}_{\mathrm{T}}^{gamma}$					
	$\mathrm{E}_{\mathrm{T}}^{1} > 25,\ \lvert\eta\rvert^{1} < 1.0;\ \ \mathrm{E}_{\mathrm{T}}^{2} > 12,\ \lvert\eta\rvert^{2} < 2.5$					
	MadGraph		CompHep		Mad/Com Ratio	
	1st Photon	2nd Photon	1st Photon	2nd Photon	1st Photon	2nd Photon
0	—	—	—	–	—	–
10	—	—	—	–	—	–
20	—	60.8±3.3	—	58.4±4.8	—	1.04±0.10
25	109±4	44.6±2.8	116±7	43.2±4.1	0.94±0.07	1.03±0.12
30	89.5±4.0	26.1±2.1	93.4±6.0	23.7±3.0	0.96±0.07	1.10±0.17
40	61.1±3.3	12.0±1.5	63.4±5.0	11.7±2.1	0.96±0.09	1.03±0.22
50	44.0±2.8	7.4±1.1	44.0±4.1	7.0±1.7	1.00±0.11	1.06±0.30
60	34.4±2.5	4.8±0.9	35.0±3.7	4.3±1.3	0.98±0.13	1.11±0.42
80	19.6±1.9	1.8±0.6	19.5±2.8	2.7±1.0	1.01±0.17	0.67±0.33
100	12.7±1.5	0.7±0.4	12.1±2.2	1.6±0.8	1.05±0.23	0.44±0.33
120	8.1±1.2	0.5±0.3	7.4±1.7	1.2±0.7	1.09±0.30	0.42±0.35
140	4.1±0.8	0.4±0.3	4.3±1.3	0.4±0.4	0.95±0.34	1.0±1.3
160	2.5±0.7	0.2±0.2	3.5±1.2	0.4±0.4	0.71±0.32	0.5±0.7
180	1.6±0.5	—	2.7±1.0	0.4±0.4	—	—
200	0.5±0.3	—	2.0±0.9	—	—	—

Table 7: The integral cross-sections in **attobarns** (10^{-3} fb or 10^{-6} pb) for $\ell\nu\gamma\gamma$ production at 1.96 TeV vs. the p_{T} of the first and second photons. All events are required to pass the 'Tight' cuts of Table 1, i.e. the electron has to have $\mathrm{E}_{\mathrm{T}} > 25$ GeV and $|\eta| < 1.0$, $\not\!\!E_t > 25$ GeV, one of the two photons has to satisfy $\mathrm{E}_{\mathrm{T}} > 25$ GeV and $|\eta| < 1.0$, and the other $\mathrm{E}_{\mathrm{T}} > 12$ GeV and $|\eta| < 2.5$. The threshold in the left-hand column applies one at a time to each photon (i.e. the other has to pass only the tight cuts.).

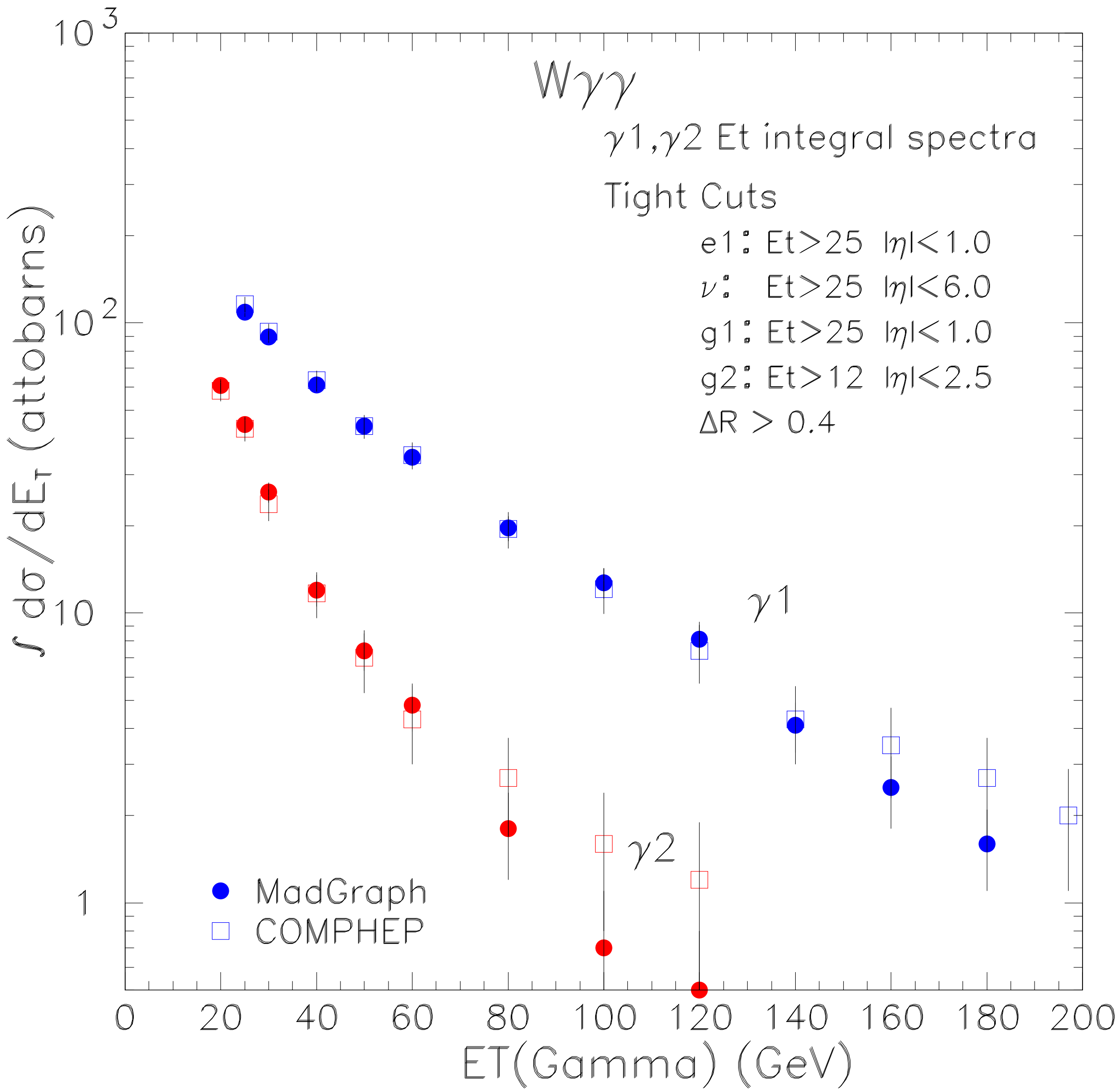

Figure 8: The integrated cross section in attobarns ((10^{-3} fb or 10^{-6} pb) for W-gamma-gamma production. The leptons and photons are required to pass the 'Analysis_Tight' cuts of Table 1; then the further requirement that the E_T of one photon pass the threshold is imposed. The cross section for the highest-E_T photon to be above the threshold is in blue; and the 2nd photon is in red.

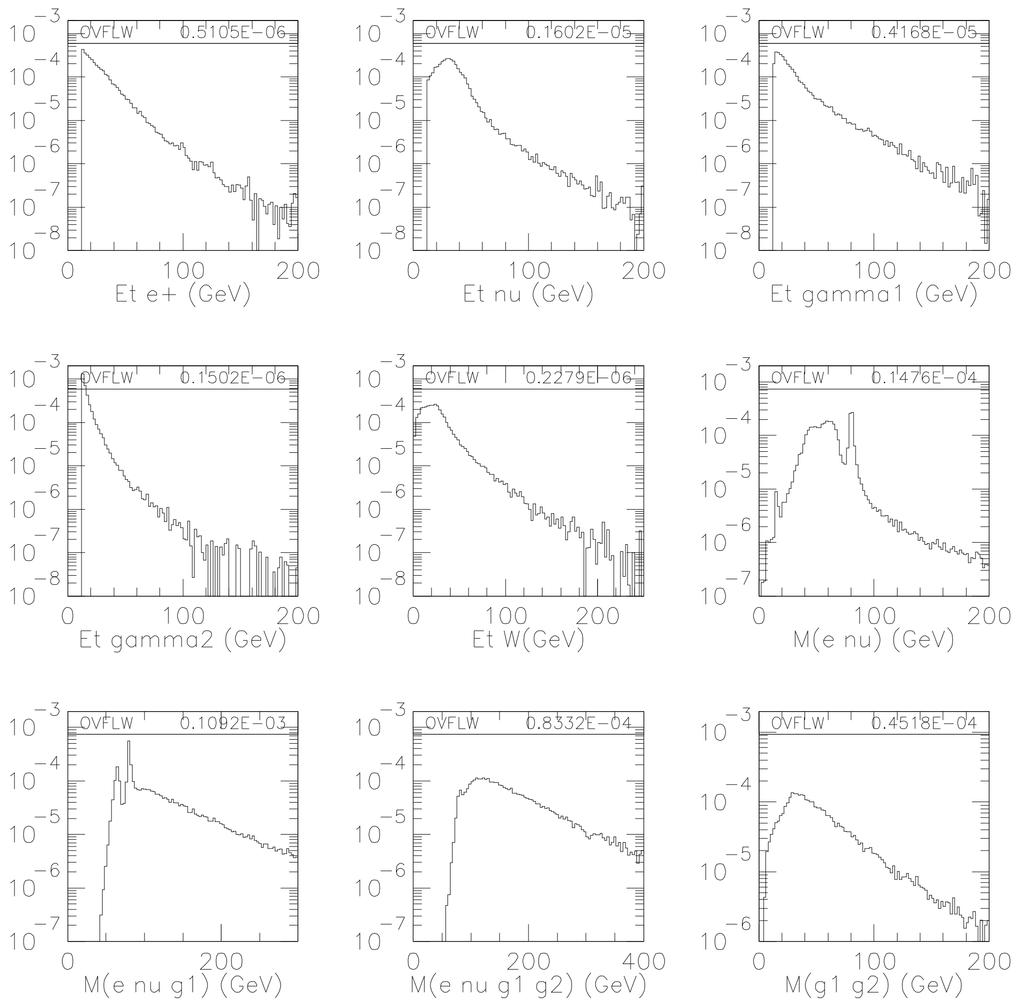

Figure 9: Kinematic distributions for the MadGraph W-gamma-gamma sample.

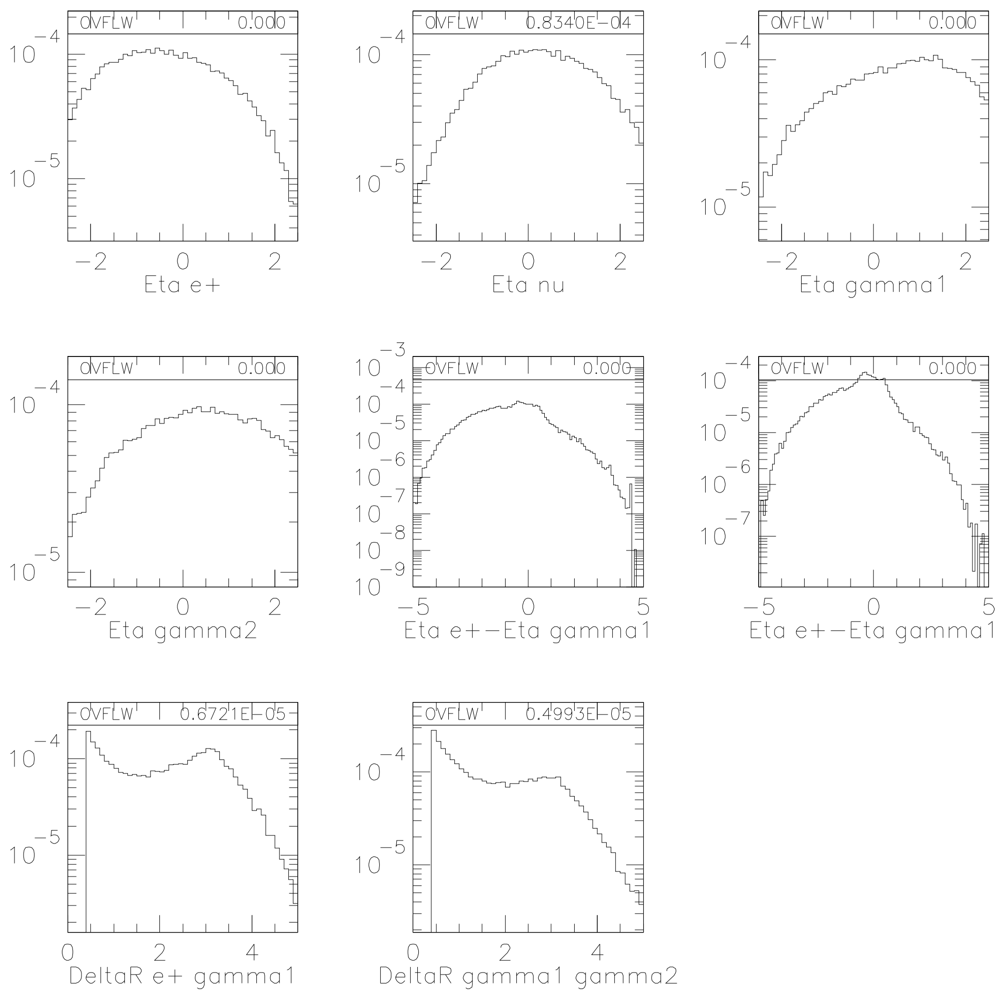

Figure 10: More kinematic distributions for the MadGraph W-gamma-gamma sample.

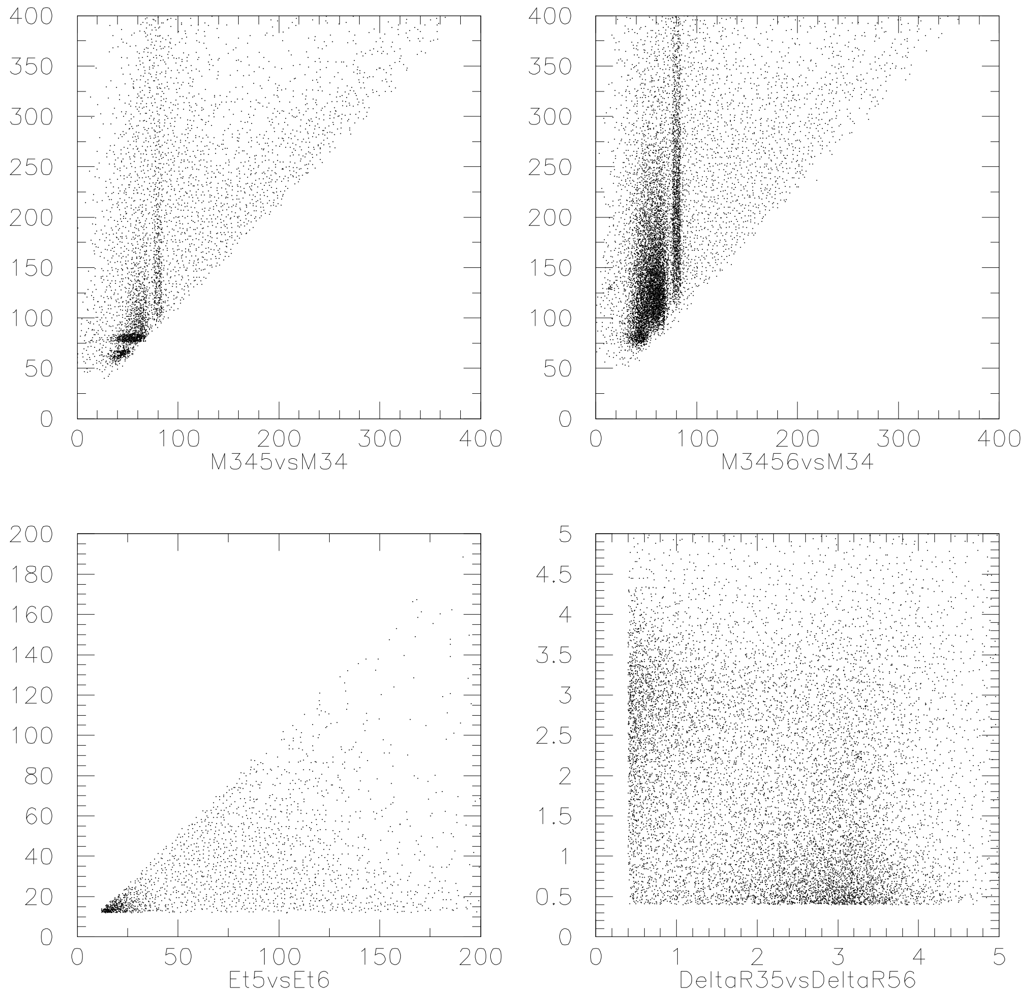

Figure 11: Correlations among kinematic distributions for the MadGraph W-gamma-gamma sample.

6 Zgammagamma

The final state of two leptons and two photons, $\ell\bar{\ell}\gamma\gamma$, is generated through the intermediate photon and Z^0 states, with radiation off of any of the charged lines in the diagrams. We denote this as 'Zgammagamma' for convenience, but the two amplitudes modify the mass spectra and angular distributions, and so are both important.

This process is one of the SM mechanisms that could produce the $\mu\mu\gamma\gamma jj$ event (although with an extra two jets), and is of interest in the dilepton-diphoton searches as a background. As one can see below the SM cross sections are small, typically one femtobarn or less.

In the Run II search we plan to use both a 12 GeV and a 25 GeV threshold on the second lepton and photon much as was done in the diphoton search in Run I [11].

The LO cross sections calculated using both Madgraph and CompHep for finding a lepton pair with $\mathrm{p_T}$ greater than a given threshold for events with two electrons and two photons satisfying the Tight cuts of Table 1 are given versus the $\mathrm{p_T}$ of the pair in Table 8. The tight cuts require one electron to have $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$, and the other $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$, and similarly one of the two photons has to satisfy $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$, and the other $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$. Also given is the ratio of the MadGraph to the CompHep prediction for each $\mathrm{p_T}$; the agreement both in shape and normalization is quite good, with the MadGraph predictions being 8-9% lower, not unexpected since no effort was made to make the input parameters identical.

The MadGraph and CompHep cross sections versus the $\mathrm{p_T}$ of the pair are also shown in Figure 12.

Figure 13 shows the integral cross sections versus the Et of the two photons. The photons are ordered according to $\mathrm{E_T}$, with the highest $\mathrm{E_T}$ photon being γ_1. As above, one of the two leptons and one of the two photons (N.B.- not necessarily γ_1) has to have $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$, and the other lepton and other photon $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$. These cross sections are tabulated in Table 9 versus the respective thresholds.

Z+γ+γ Cross Sections (attobarns) vs Z p_T			
p_T^Z	$E_T^1 > 25$, $\|\eta\|^1 < 1.0$; $E_T^2 > 12$, $\|\eta\|^2 < 2.5$		
(GeV)	MadGraph	CompHep	Mad/Comp
0	1250±17	1369±10	0.913±0.014
10	1210±17	1320±10	0.917±0.015
20	986±15	1070±9	0.921±0.016
30	741±13	810±8	0.915±0.018
40	530±11	582±6	0.911±0.021
50	356±9	388±5	0.918±0.026
60	246±8	267±4	0.921±0.033
80	127±5	133±3	0.955±0.043
100	66.0±3.9	73.0±2.3	0.90 ±0.06
120	35.8±2.8	39.7±1.7	0.90 ±0.08
140	20.2±2.2	23.1±1.3	0.87 ±0.11
160	10.7±1.6	13.2±1.0	0.82 ±0.14
180	5.6±1.1	7.8±0.7	0.72 ±0.16
200	3.4±0.8	4.8±0.6	0.71 ±0.19

Table 8: The integral cross-sections in attobarns (10^{-3} fb or 10^{-6} pb) for $e^+e^-\gamma\gamma$ production at 1.96 TeV vs. the p_T of the e^+e^- pair. All events are required to pass the 'Tight' cuts of Table 1, i.e. one electron has to have $E_T > 25$ GeV and $|\eta| < 1.0$, and the other $E_T > 12$ GeV and $|\eta| < 2.5$, and similarly one of the two photons has to satisfy $E_T > 25$ GeV and $|\eta| < 1.0$, and the other $E_T > 12$ GeV and $|\eta| < 2.5$. Note that in the highest bins the Gaussian uncertainties underestimate the true Poisson uncertainty, as there are only one or two events in each sample, and so the apparent disagreement at very high p_T^W isn't real (and the cross sections are attobarns!).

E_T^{gamma} (GeV)	Z+Gamma+Gamma Cross Sections (attobarns) vs E_T^{gamma}					
	$E_T^1 > 25$, $\|\eta\|^1 < 1.0$; $E_T^2 > 12$, $\|\eta\|^2 < 2.5$					
	MadGraph		CompHep		Mad/Com Ratio	
	1st Photon	2nd Photon	1st Photon	2nd Photon	1st Photon	2nd Photon
0	—	—	—	–	—	–
10	—	—	—	–	—	–
20	—	591±12	—	647±7	—	0.913±0.021
25	1250±17	378±9	1360±10	428±6	0.919±0.014	0.883±0.024
30	937±15	231±5	1020±9	255±4	0.918±0.017	0.906±0.024
40	582±12	100±5	634±7	108±3	0.918±0.021	0.93±0.05
50	402±10	50.1±3.5	434±6	51.7±1.9	0.927±0.026	0.97±0.08
60	292±8	30.2±2.7	312±5	28.5±1.4	0.936±0.030	1.06±0.11
80	152±6	11.3±1.6	166±3	9.6±0.8	0.92±0.04	1.18±0.19
100	86.0±4.5	4.8±1.2	92.1±2.6	3.9±0.5	0.93±0.06	1.23±0.35
120	46.0±3.4	2.0±0.8	50.7±1.9	1.8±0.4	0.91±0.08	1.11±0.51
140	25.9±2.5	1.2±0.8	30.6±1.5	0.9±0.3	0.85±0.09	1.33±0.99
160	13.7±1.9	—	17.5±1.1	—	0.78±0.12	—
180	8.8±1.6	—	10.3±0.9	—	—	—
200	4.4±1.1	—	5.6±0.6	—	—	—

Table 9: The integral cross-sections in **attobarns** (10^{-3} fb or 10^{-6} pb) for $e^+e^-\gamma\gamma$ production at 1.96 TeV vs. the p_T of the first and second photons. All events are required to pass the 'Tight' cuts of Table 1, i.e. one electron and one photon have to have $E_T > 25$ GeV and $|\eta| < 1.0$, and the other lepton and photon have to satisfy $E_T > 12$ GeV and $|\eta| < 2.5$. The threshold in the left-hand column applies one at a time to each photon (i.e. the other has to pass only the tight cuts.).

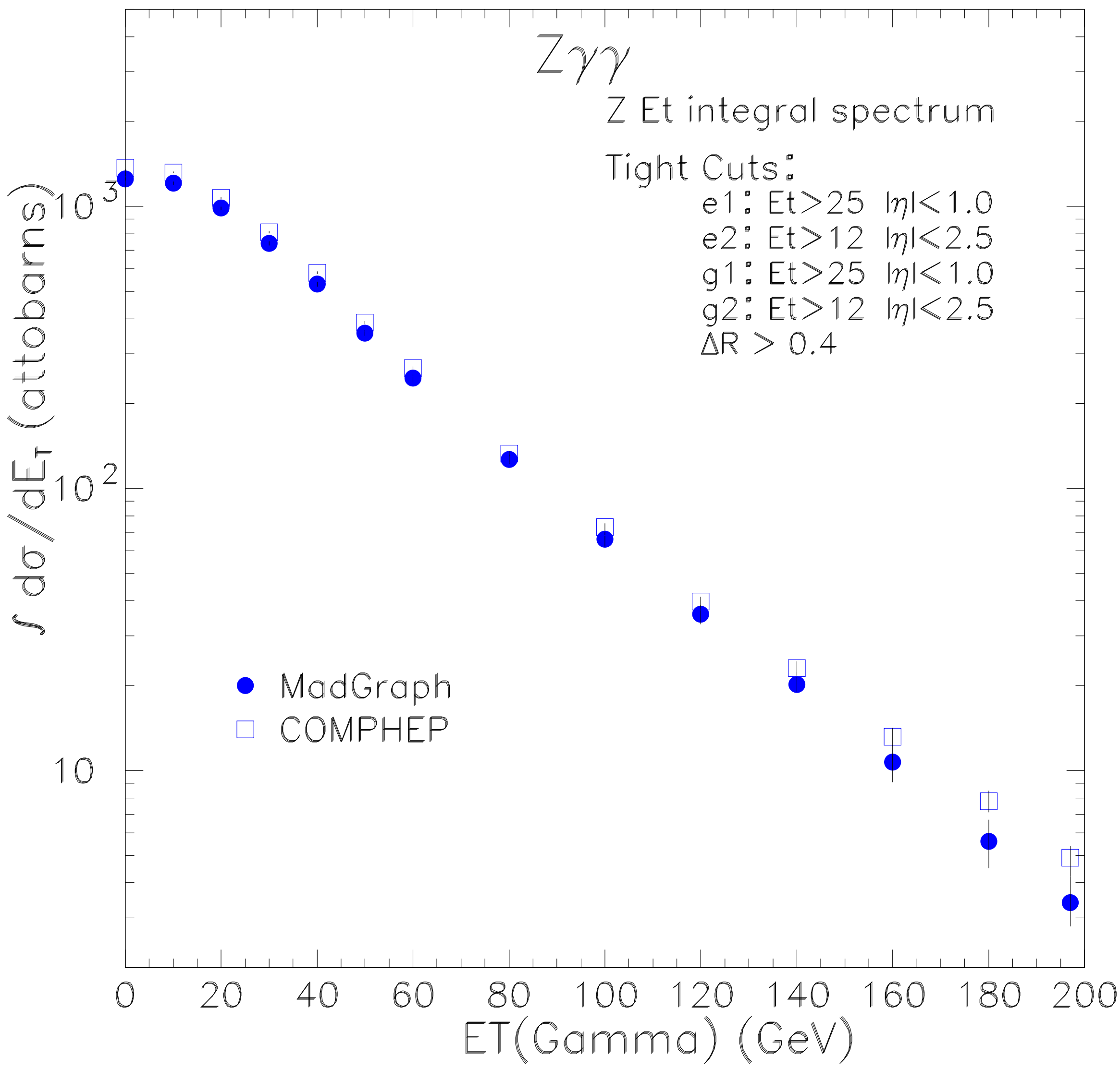

Figure 12: The integrated cross section above a threshold in attobarns (10^{-3} fb or 10^{-6} pb) from MadGraph and CompHep Z-gamma-gamma samples. In each case all particles are required to pass the 'Tight Analysis' cuts of Table 1; then the further requirement that the variable (e.g. E_T of γ_1) pass the threshold is imposed.

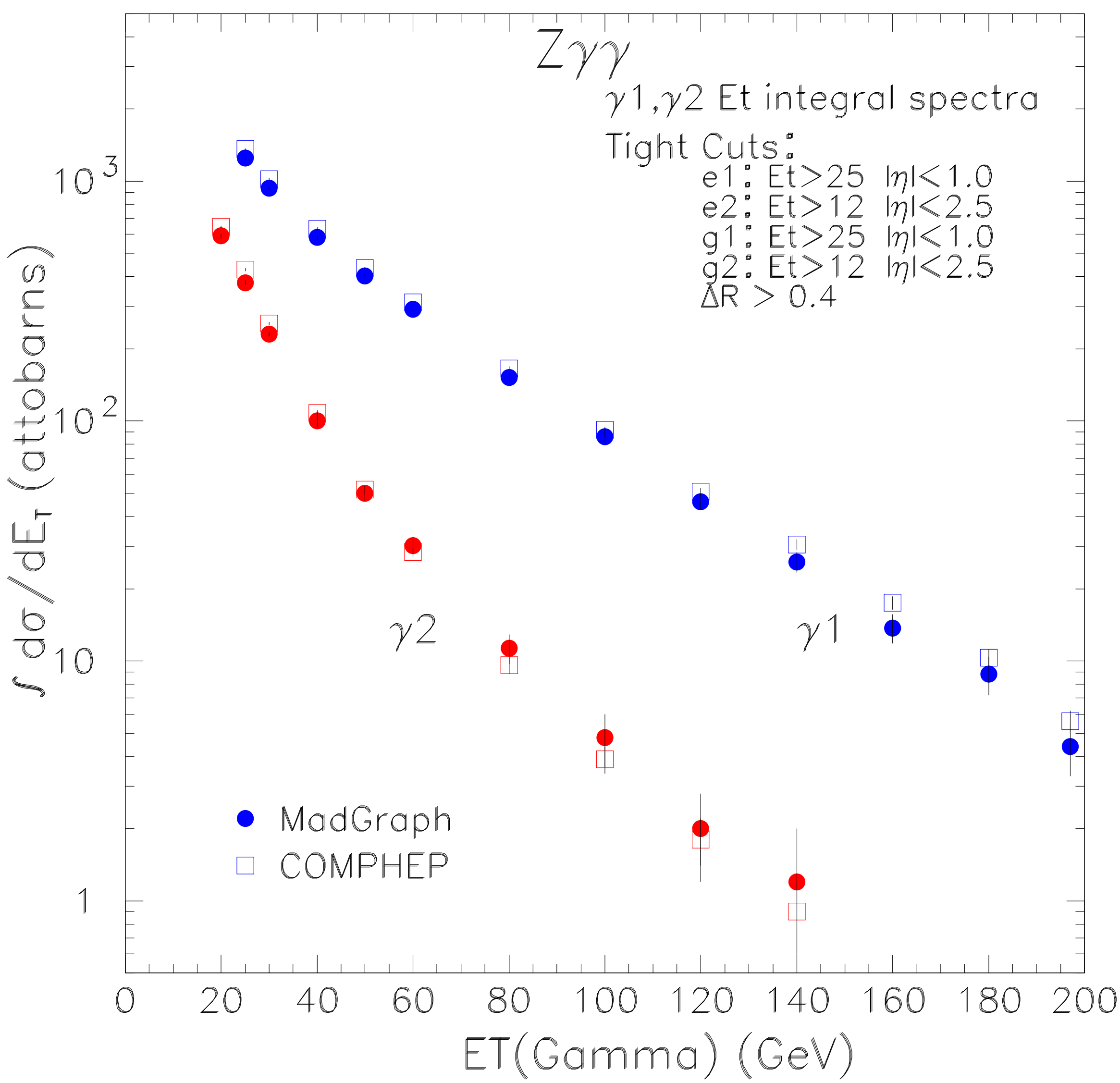

Figure 13: The integrated cross section above a threshold for each of the photons in attobarns (10^{-3} fb or 10^{-6} pb) from MadGraph and CompHep $e^+e^-\gamma\gamma$ samples. In each case all particles are required to pass the 'Tight Analysis' cuts of Table 1; then the further requirement that the variable (e.g. E_T of γ_1) pass the threshold is imposed.

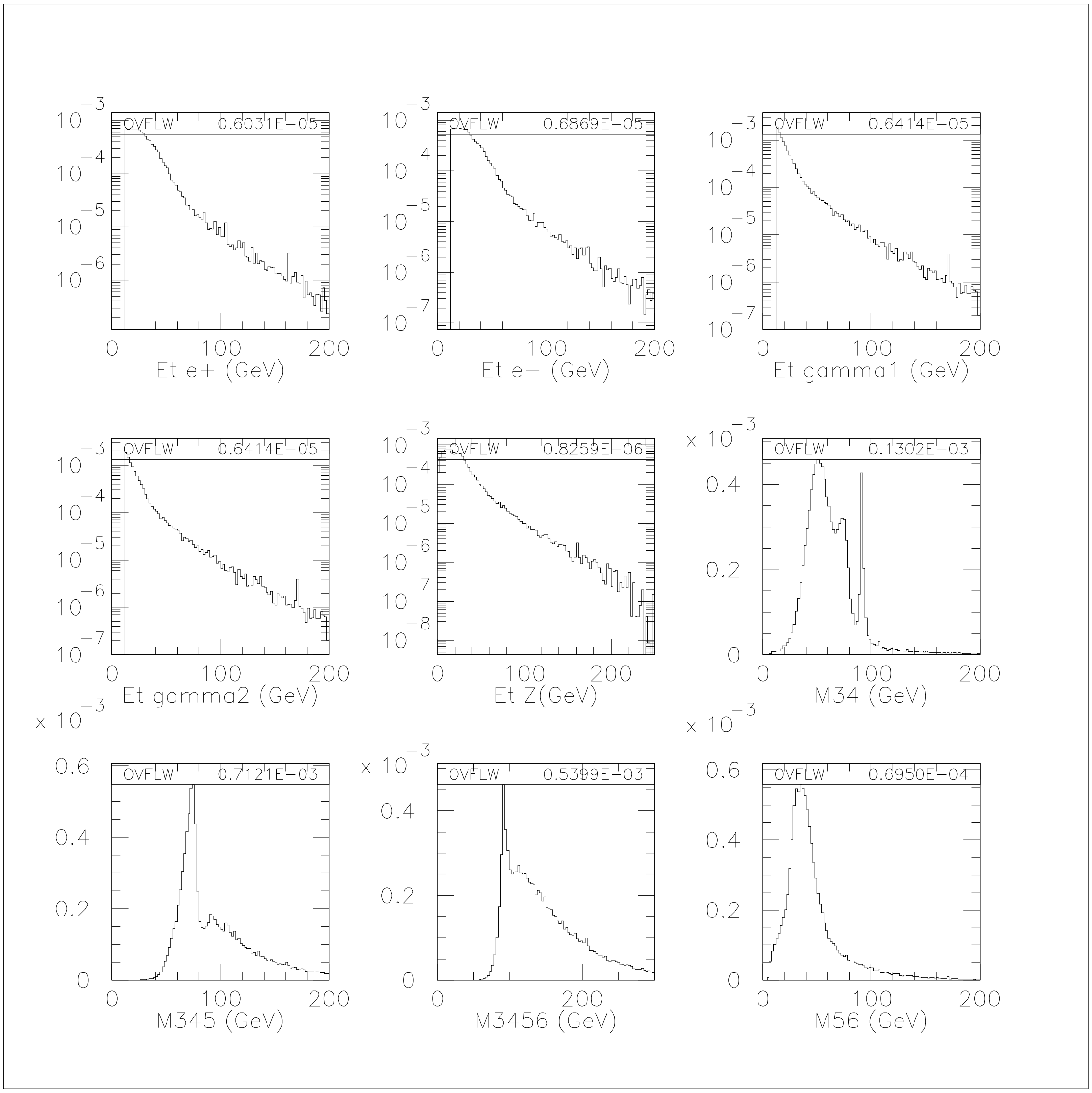

Figure 14: Kinematic distributions for the MadGraph Z-gamma-gamma sample. Particles 3,4,5, and 6 are the e^+, e^-, γ_1,and γ_2, respectively.

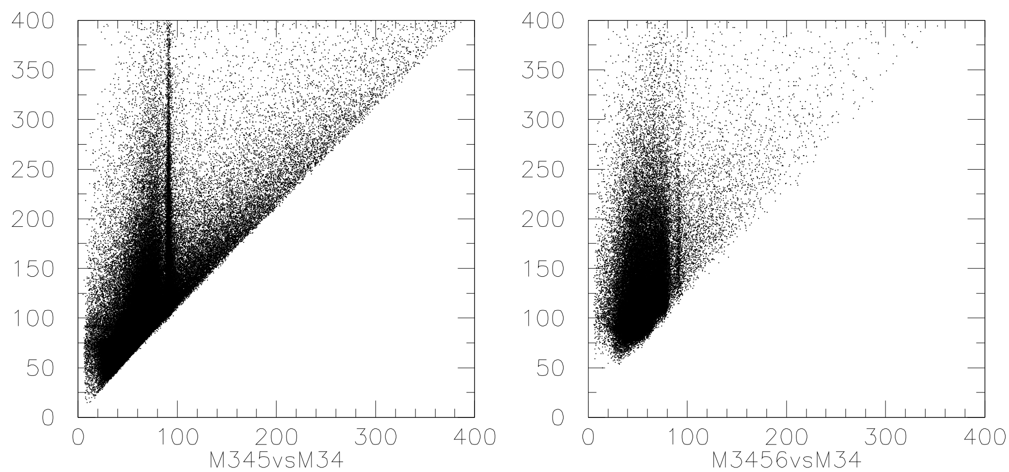

Figure 15: More kinematic distributions for the MadGraph Z-gamma-gamma sample. Particles 3,4,5, and 6 are the e^+, e^-, γ_1,and γ_2, respectively.

7 W+0jet and Z+0jet LO Crossections for Normalization

We use the inclusive W and Z cross sections to normalize these channels so that rather than measure the absolute $W\gamma$, $W\gamma\gamma$, $Z\gamma$, and $Z\gamma\gamma$ cross sections, we measure the more precise ratio of cross sections (e.g. $W/W\gamma)^2$. This ratio should be less sensitive to the uncertainties in parameters relating to W production, such as the PDF's, choice of Q^2 scale, contributions from NLO in α_s, etc. than the cross sections themselves, and hence provides a better test of the Standard Model (see Ref [12] for a quantitative example).

The MadGraph and CompHep LO crossections for W and Z with 0 jets are summarized in Table 10. They agree well, with the difference being due to the input parameters. The LO ratio $R \equiv (W^+ + W^-)/Z$ is ~ 7; this differs from the canonical value of 10.2 or so because there is no mass window cut, and the $\mathrm{p_T}$ cut on the second leg is lower than usual.

W and Z + 0jet LO Cross Sections (picobarns)					
Channel	Et_1, $\lvert\eta\rvert_1$	Et_2, $\lvert\eta\rvert_2$	MadGraph	CompHep	Mad/Comp
$\mathrm{W}^\pm \to e^\pm\nu$	25, 1.0	25, 6.0	341.2±0.6	350.6±5.3	0.973±0.015
$\mathrm{Z}^0 \to e^+e^-$	25, 1.0	25, 1.0	34.7±0.6	36.6±0.6	0.948±0.022
$\mathrm{Z}^0 \to e^+e^-$	25, 1.0	12, 2.5	99.1±1.1	105.0±1.1	0.944±0.014
$\mathrm{Z}^0 \to e^+e^-$	12, 2.5	12, 2.5	178.8±1.5	186.7±1.4	0.958±0.011

Table 10: The LO cross-sections in picobarns for W+0jet and Z+0jet production at 1.96 TeV. Events are required to pass the 'Tight' cuts of Table 1, i.e. one electron has to have $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$. In the W case we require $\not{E}_t > 25$ GeV. For the Z crossections there give three cases: electron has to satisfy $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$, and the other $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$. , both electrons satisfying $\mathrm{E_T} > 25$ GeV and $|\eta| < 1.0$ ('Central-central'), and (an exception to the tight cuts), both electrons satisfying $\mathrm{E_T} > 12$ GeV and $|\eta| < 2.5$ (corresponding to the generated samples).

8 Summary of Cross Sections

We summarize the crossections for heavy boson plus one or two photons in Table 11 below. There is excellent agreement (within 10% or within statistics) between MadGraph and CompHep in all channels. As the two generators are really different in technique, this gives us confidence in the predictions.

9 Ratios

Measurements of the set of ratios $(\mathrm{W}^\pm \to e^\pm\nu{+}\gamma)/(\mathrm{W}^\pm \to e^\pm\nu)$, $(\mathrm{Z}^0 \to e^+e^-{+}\gamma)/(\mathrm{Z}^0 \to e^+e^-)$, $(\mathrm{W}^\pm \to e^\pm\nu{+}\gamma\gamma)/(\mathrm{W}^\pm \to e^\pm\nu)$, $(\mathrm{Z}^0 \to e^+e^-{+}\gamma\gamma)/(\mathrm{Z}^0 \to e^+e^-)$,etc. provide a more precise

[2]Ratios greater than 1.0 seem easier to remember, so we prefer quoting the ratios this way.

Signature	Process	$\sigma_{MadGraph}$			$\sigma_{CompHep}$			Ratio
$e^+\nu$	W	341	$\pm$	0.6 picob	351	$\pm$	5 pb	0.973$\pm$0.015
$e^+\nu\gamma$	Wγ	22.1	$\pm$	0.4 femtob	22.4	$\pm$	0.1 fb	0.99$\pm$0.02
$e^+\nu\gamma\gamma$	W$\gamma\gamma$	109	$\pm$	4 attob	116	$\pm$	7 ab	0.94$\pm$0.07
e^+e^-	Z	99.1	$\pm$	1.1 picob	105	$\pm$	1 pb	0.944$\pm$0.014
$e^+e^-\gamma$	Zγ	150	$\pm$	1.4 femtob	156	$\pm$	2 fb	0.96$\pm$0.01
$e^+e^-\gamma\gamma$	Z$\gamma\gamma$	1250	$\pm$	17 attob	1369	$\pm$	10 ab	0.913$\pm$0.014

Table 11: The cross sections for the 'Tight Analysis' cuts of Table 1 from MadGraph and Comphep for the production times BR of states with multiple bosons and photons. The intermediate state denoted by 'Z' includes both the γ and Z^0 poles everywhere. As this is before showering there is no intrinsic k_T smearing. The cross sections are also given for W and $Z\gamma$ production to normalize the photon processes. Note that the cross sections range from picobarns (pb) to femtobarns (fb) to attobarns (ab). Uncertainties are statistical only.

test of the standard model than those of the absolute cross sections, as many of the systematics should cancel to a fairly high order [12] In particular, the efficiencies and acceptances for the triggering electron (first leg) should be close to the same. In addition, the second lepton, whether neutrino or photon, should also be treated similarly, as the additional photon or photons are well-measured, and so the missing Et or the second electron should not be much affected. The quantitative understanding of how well we can measure these ratios will take the full analysis. Theoretical uncertainties, such as those from the PDF's, also at least partially cancel, as can be seen from Table 11. We make this explicit in Table 12 below.

Signature	Process	MadGraph Ratio	CompHep Ratio	R_M/R_C
$e^+\nu/e^+\nu\gamma$	W/Wγ	(15.43$\pm$0.07)E+3	(15.67$\pm$0.23)E+3	0.98$\pm$0.05
$e^+\nu/e^+\nu\gamma\gamma$	W/W$\gamma\gamma$	(3.13$\pm$0.11)E+6	(3.03$\pm$0.19)E+6	1.03$\pm$0.07
$e^+\nu\gamma/e^+\nu\gamma\gamma$	Wγ/W$\gamma\gamma$	(0.203$\pm$0.008)E+3	(0.193$\pm$0.012)E+3	1.05$\pm$0.08
$e^+e^-/e^+e^-\gamma$	Z^0/Zγ	(0.66$\pm$0.01)E+3	(0.67$\pm$0.01)E+3	0.98$\pm$0.02
$e^+e^-/e^+e^-\gamma\gamma$	Z^0/Z$\gamma\gamma$	(0.0793$\pm$0.0014)E+6	(0.0767$\pm$0.0009)E+6	1.03$\pm$0.02
$e^+e^-\gamma/e^+e^-\gamma\gamma$	Zγ/Z$\gamma\gamma$	(0.120$\pm$0.0020)E+3	(0.114$\pm$0.0017)E+3	1.05$\pm$0.02

Table 12: The ratios of cross sections for the 'Tight Analysis' cuts of Table 1 from MadGraph and Comphep for the production times BR of states with multiple bosons and photons. Uncertainties are statistical only.

10 Expected Numbers for Observed High-$\mathrm{E_T}$ Photon Events

The $ee\gamma\gamma \not{E}_t$ event sparked interest in signatures involving high-$\mathrm{E_T}$ electroweak gauge bosons, in particular photons. In Run I there were a number of 'unusual' such events; in Run II so far we have observed one, an event with $\mathrm{E_T}$, a high $\mathrm{p_T}$ electron, and two central photons, one of which has an $\mathrm{E_T}$ of 90 GeV[10]. What is new in Run II in terms of tools that are better than those of Run I is that we have multiple general MC generators to generate processes with more particles in the final state.

To summarize briefly some of the interesting events with high p_T photons (there are others, but this gives a flavor for why we want more Run II data now that we have established the cuts):

1. The $ee\gamma\gamma\not{E}_t$ event [11];
2. The $\mu\mu\gamma\gamma jj$ event [11, 1];
3. The $t\bar{t}\gamma$ event [13];
4. The $e\gamma\not{E}_t jet_{fat}$ event [1];
5. The 200-GeV γZ^0 event [2, 3];
6. The Run II $W\gamma\gamma$ event [10].

The SM predictions for the signatures of the last two of these have been calculated here. For the 200-GeV γZ^0 event, the cross section for producing events with p_T for the Z above the value observed can be read off of Figure 4, and is < 0.3 fb. Similarly, the cross section for a two-photon event satisfying the tight cuts with one photon with E_T above 90 GeV is around 15 attobarns (see Table 7 and Figure 8.). We await a large enough sample to see if these events are fluctuations or something new.

11 Conclusions

The predicted cross sections from MadGraph and COMPHEP for high-E_T single and pair photon production in association with a W or Z^0 boson have similar shapes and agree to better than 10% over many decades. We have confidence in the predictions.

12 Acknowledgments

We would like to thank Sasha Belyaev, Edward Boos, Lev Dudko, Steve Mrenna, Sasha Sherstnev, and Tim Stelzer, for sharing some of their expertise with Comphep, MadGraph, and Pythia, and for many physics discussions. The critical $W\gamma\gamma$ and $Z\gamma\gamma$ COMPHEP data sets were generated by Sasha Belyaev and Sasha Sherstnev, respectively.

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