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Predicted Cross sections for Z^0+Photon and W+Photon Channels

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Abstract

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. Integral cross sections 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.

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]. 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 can now *a priori* define these as interesting channels, and get ready for the 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 used to predict the numbers of background events in specific channels. In this note we present cross sections for Wγ and Zγ production using the COMPHEP [5] and MadGraph [4] Monte Carlo generators, and W$\gamma\gamma$, and Zgg using MadGraph.

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 'smearing' by the shower Monte Carlos. These are analysis-level cuts. The parameters for the three analysis cases are listed in Table 1.

In the Wide and Tight cases where there are two identical particles in the final state that are selected with asymmetric cuts , such as $Z^0 \to e^+e^-$ decay with one electron being

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 9. 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.

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.

We chose the center-of-mass energy to be 1.96 GeV; we use CTEQ5L structure functions, with 4 flavors contributing. 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 [6] and CDF6063 [7]. 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.

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 [6] and from CDF6063 [7]. 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 W+0jet and Z+0jet

We plan on using the inclusive W and Z cross sections to normalize these channels so that rather than measure cross sections we measure the ratio of cross sections (e.g. $W + \gamma)/W$). 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.

One important note on what we call a 'Z' is in order. The 'Tight' cuts 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.

The Madgraph W cross section for $W^+ + 0$ jets with the tight cuts of Table 1 is

$$\sigma_{W^+} = 341.2 \pm 0.6 \text{ picobarns.} \quad (1)$$

The Madgraph Z cross section for $Z + 0$ jets with the tight cuts of Table 1 is

$$\sigma_Z = 99.4 \pm 0.7 \text{ picobarns.} \quad (2)$$

The ratio $R \equiv (W^+ + W^-)/Z$ is thus 6.84; this differs from the canonical value of 10.2 or so because there is no mass window cut, the p_T cut on the second leg is lower than usual, and the rapidity range for the second leg is wider than usual.

4 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 a sample of 128,003 weighted events using MadGraph using the 'Sample Wide' cuts of Table 2, and a sample of 48519 events corresponding to the 'Tight' cuts of Table 1. The cross sections corresponding to these cuts are:

- Sample_Wide: 10.40 ± 0.07 pb
- Analysis_Tight: 25.62 ± 0.05 fb.

Table 4 presents the integrated cross-section versus the E_T of the highest-E_T photon for the 'Tight' cuts of Table 1 (for photon $E_T < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon E_T- these are calculated from the Wide sample). Note that since this is at LO the E_T of the photon is the same as the 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 E_T of the photon. Figures 2 and 3 show kinematic distributions from the tight sample.

$E_T^{gamma_1}$ (GeV)	σ (fb)		
	MadGraph	CompHep	Ratio
6	1060	—	—
10	414	—	—
20	43.8	—	—
25	25.6	22.4	1.14
30	17.2	16.1	1.07
40	9.29	8.27	1.12
50	5.79	5.03	1.15
60	3.96	3.40	1.16
80	2.08	1.69	1.23
100	1.16	0.967	1.20
120	0.686	0.560	1.23
140	0.431	0.344	1.25
160	0.249	0.230	1.08
180	0.155	0.126	1.23
200	0.093	0.092	1.01

Table 4: The integral cross-sections in fb for $e\nu\gamma$ 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 the photon E_T and are calculated from the Wide sample

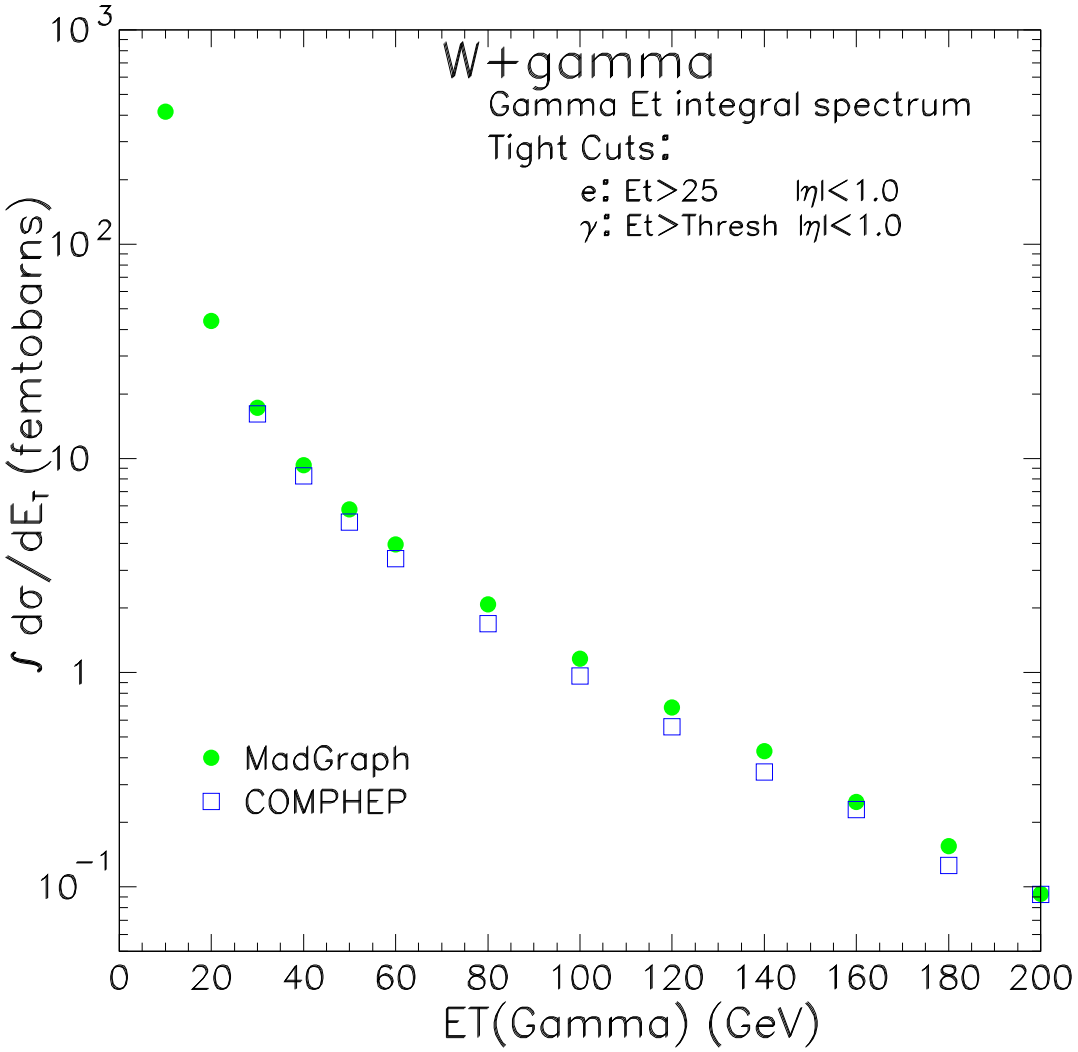

Figure 1: The integral cross-sections in fb from MadGraph and COMPHEP for $e\nu\gamma$ production at 1.96 GeV versus the gamma E_T for the 'Tight' cuts as described in Table 1. For photon $E_T < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon E_T and are calculated from the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

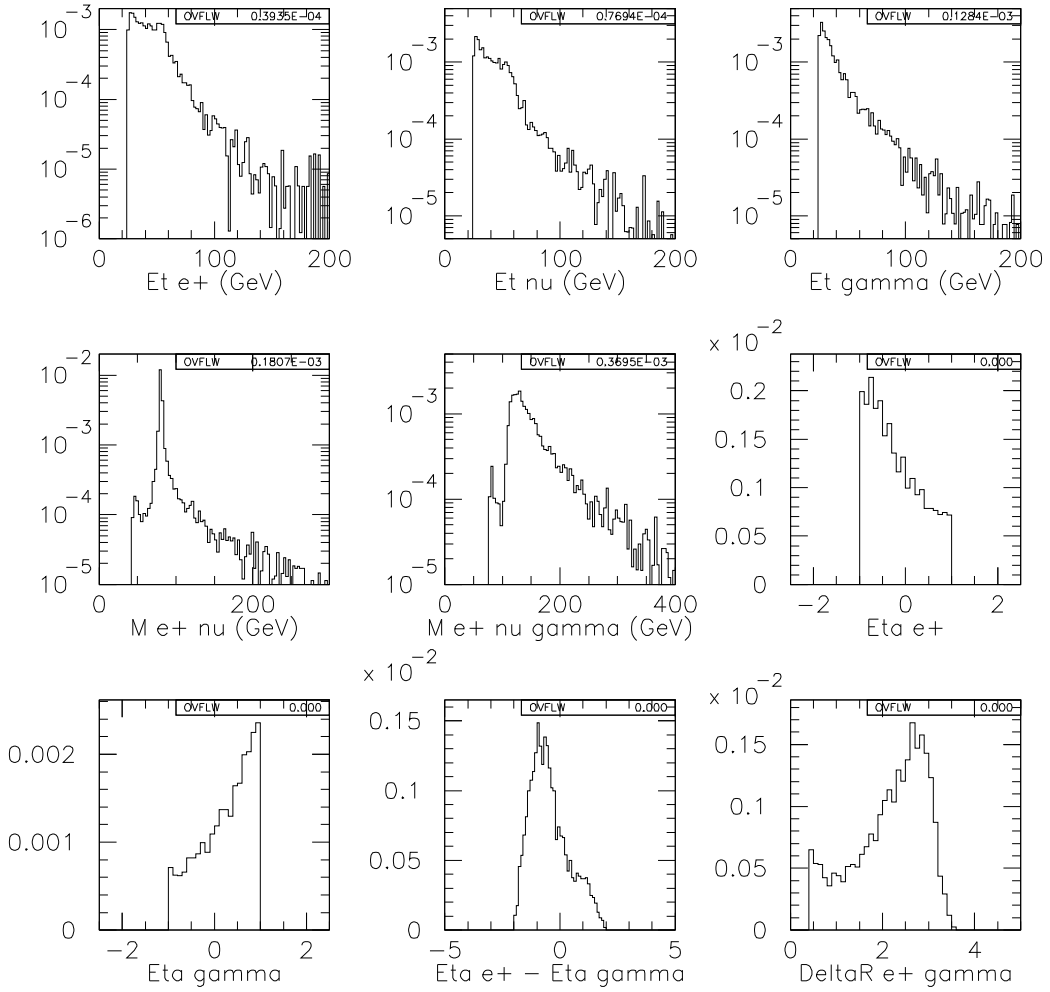

Figure 2: Kinematic distributions for the e^+, ν, and γ from the MadGraph $W\gamma$ sample with 'Tight' cuts.

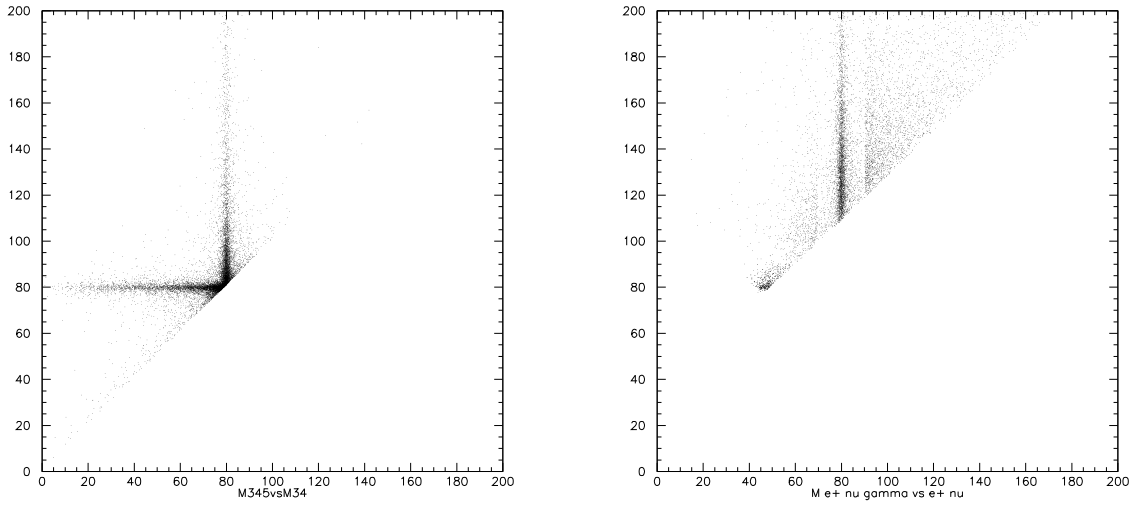

Figure 3: The invariant mass of the $e\nu\gamma$ system plotted versus the invariant mass of the $e\nu$ system for cuts of $\mathrm{E_T} > 1$ and $\eta < 6$ for all three particles (left-hand plot) and the 'Tight' cuts (right-hand plot) from the MadGraph $W\gamma$ samples.

5 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], and in the other two jets with an invariant mass consistent with a W. Reliable predictions for high E_T $Z\gamma$ events versus the E_T of the gamma (which at LO is the same as the p_T of the Z) are thus of high priority.

The process $\bar{p}p \to Z^0\gamma$ 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 pb^{-1}of 5.01 $\pm$ 0.54 events in the $e\gamma$ mode and 4.60$\pm$0.54 in the $\mu\gamma$ mode [8] 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}.

We have used MadGraph with the 'Sample_Tight' cuts to generate a Tight sample of 130,085 events, corresponding to an integrated luminosity of 498 fb^{-1}, and using the 'Analysis_Wide cuts', a sample of 282,726 events, corresponding to 49 fb^{-1}. The respective sample cross sections are 261 and 5722 fb. With COMPHEP the numbers are 249,562 (Tight) and 24,985 (Wide) events, corresponding to 1055.4 fb^{-1} and 4.69 fb^{-1}. The respective COMPHEP cross sections are 236.5 and 5328 fb.

Table 5 shows the integrated spectrum in fb for the production of an e^+e^- pair satisfying the tight cuts versus the E_T threshold for the photon from both MadGraph and COMPHEP. The numbers are generated using the Tight sample for photon $E_T > 25$ GeV; for $E_T < 25$ GeV the tight cuts are applied to the Wide sample. There is good but not perfect ($\sim 1\%$) agreement between the two samples at the matching point of 25 GeV, possibly due to statistics. The same numbers are plotted in Figure 4. The MadGraph and Comphep values for the integrated cross sections for the 'Tight Analysis' cuts of Table 1 are 177.3$\pm$ 0.7 and 181$\pm$ xx femtobarns, respectively.

$E_T^{gamma_1}$ (GeV)	σ (fb)		
	MadGraph	CompHep	Ratio
6	1460	—	—
10	884	—	—
20	306	—	—
25	177	181	0.98
30	96.4	102	0.95
40	37.6	39.9	0.94
50	22.3	22.9	0.97
60	15.2	15.0	1.01
80	7.86	7.28	1.08
100	4.35	3.81	1.14
120	2.50	2.05	1.22
140	1.50	1.18	1.27
160	0.936	0.692	1.35
180	0.551	0.411	1.34
200	0.348	0.242	1.44

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

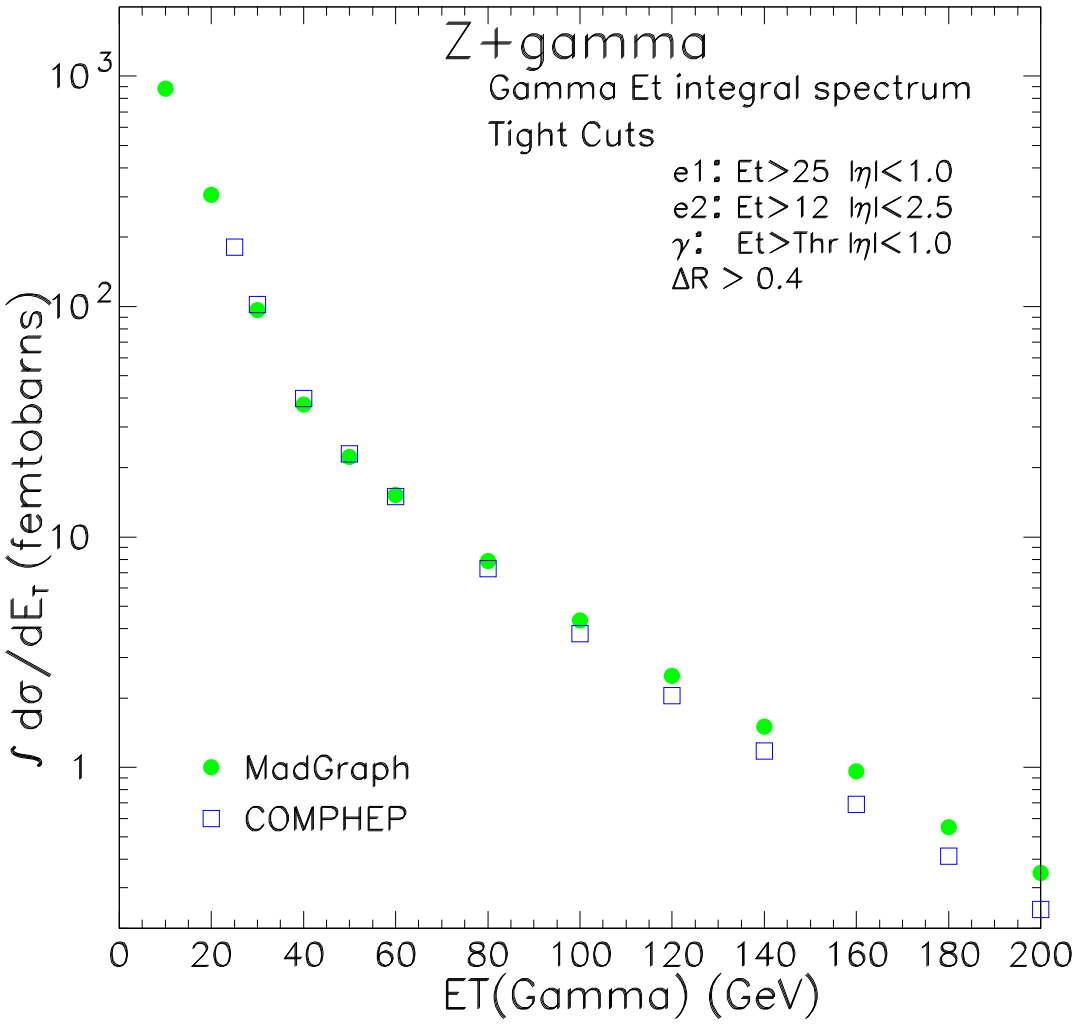

Figure 4: The integral cross-sections in fb from MadGraph and COMPHEP for $e^+e^-\gamma$ production at 1.96 GeV versus the gamma E_T for the 'Tight' cuts as described in Table 1. For photon $E_T < 25$ GeV the cross sections are for all cuts being 'Tight' except the photon E_T and are calculated from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

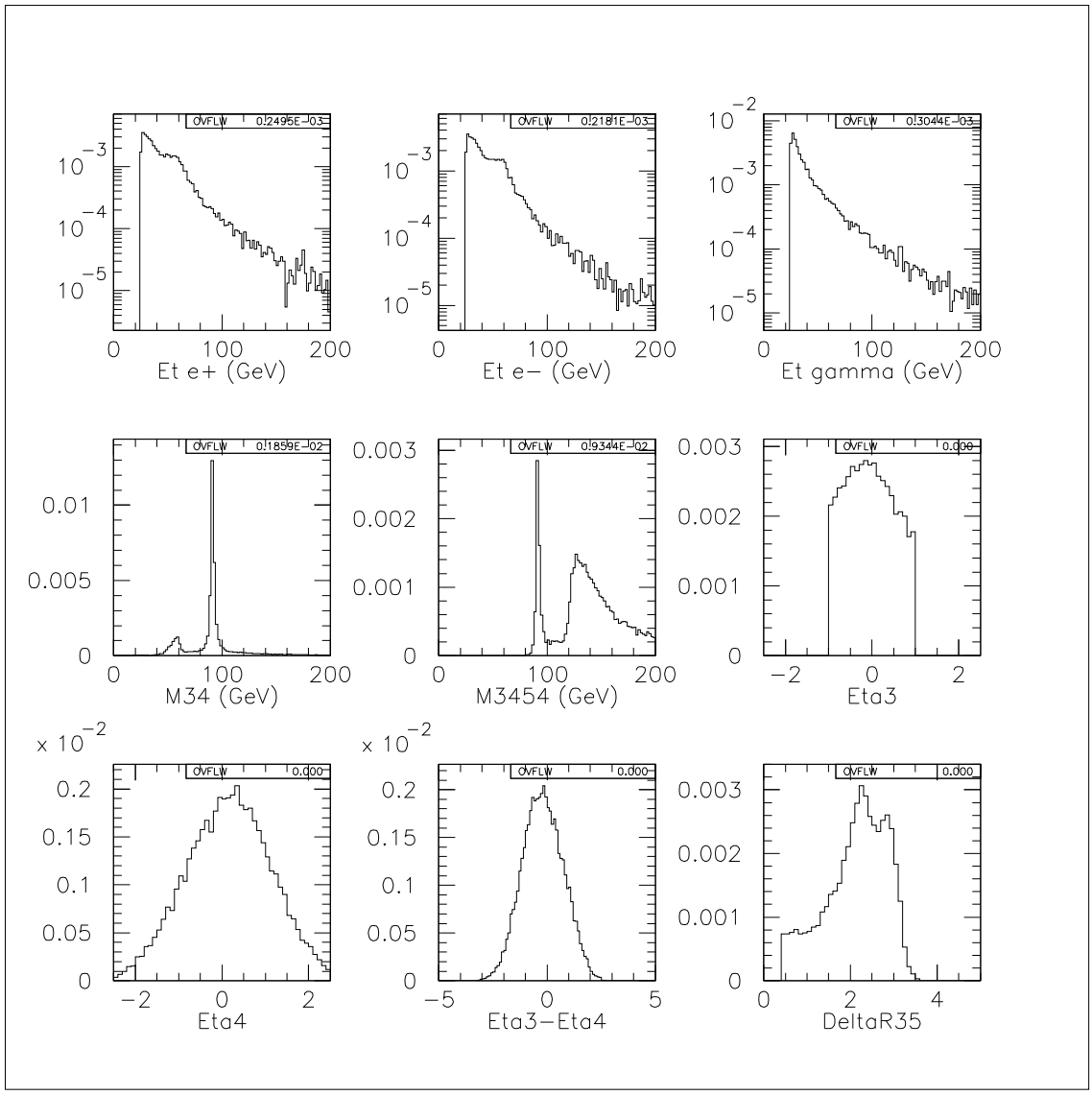

Figure 5: Kinematic distributions for the e^+, e^-, and γ from the MadGraph $Z\gamma$ sample. Particles 3,4, and 5 are the e^+, e^-, and γ respectively.

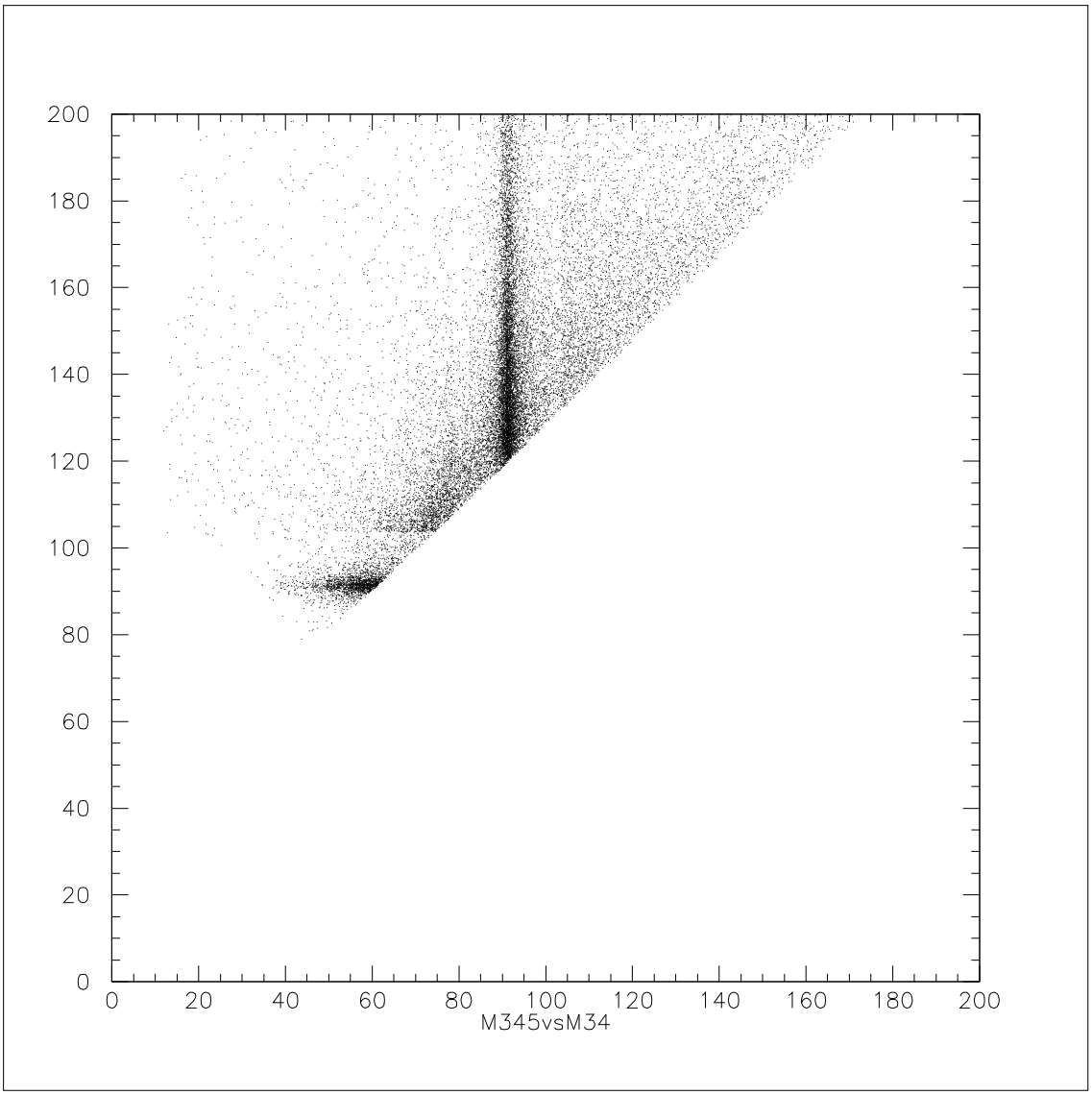

Figure 6: The three-body $e^+e^-\gamma$ mass vs the two-body e^+e^- mass from the MadGraph $Z\gamma$ sample. One can clearly see the two cases where a Z is made with an external gamma or decays to $e^+e^-\gamma$.

6 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 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 [9]. This event has $E_T^e = 47$ GeV, $\not\!\!E_t = 39$ GeV, $E_T^{\gamma 1} = 91$ GeV, $E_T^{\gamma 2} = 24$ GeV, and has a p_T of the $e\nu$ pair of 71 GeV. The cross-section for an event with a p_T of the $e\nu$ pair above 70 GeV, with the 'Tight' cuts[1], is 23×10^{-6} pb, meaning that in 10 pb^{-1}we expect 2.3×10^{-4} events, assuming 100% efficiency.

We have generated a sample of 59,996 weighted events using MadGraph [2]. The cuts at generation were different from those of Table 1, being 12 GeV in E_T for all 4 final state particles, and $|\eta| < 2.5$ for all except the neutrino, for which we required $|\eta| < 9.0$. A separation of $\Delta R < 0.4$ between all pairs not involving the neutrino was also required. The cross section for the cuts for this sample is 3.393 ± 0.007 fb. The 'Tight' cuts were then applied to the ntuple.

The resulting integral cross sections for the production $\ell\nu\gamma\gamma$ events satisfying the 'Tight' cuts are presented in Table 6 versus the minimum p_T of the $e\nu$ pair and the E_T of each of the two photons independently. Figure 7 displays the integrated cross-sections for the p_T of the $e\nu$ (W) system, the highest-Pt photon, and the second photon. [3]

Figures 8,9, and 10 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.

[1] This event actually has both photons in the Central (tighter than the 'Tight' cuts) and has all particles significantly above the 'Tight' thresholds of 25 and 12 GeV.

[2] The requested luminosity was 30,000 fb^{-1}, and the returned number of events listed on results.html was 6152K, but after event generation we see the smaller number.

[3] MadGraph does not order the photons in E_T; we have reordered them for these results.

Threshold (GeV)	$p_T(e\nu)$	$E_T(\gamma 1)$	$E_T(\gamma 2)$
0	123.	—	–
10	116.	—	–
20	95.5	—	57.9
25	—	123.	36.6
30	74.3	94.6	22.6
40	54.5	62.7	11.3
50	38.5	46.9	6.58
60	28.7	36.0	3.00
80	16.8	21.0	1.50
100	9.91	13.6	0.99
120	6.04	8.76	0.52
140	3.75	5.69	0.34
160	2.75	3.85	0.20
180	1.70	2.64	0.07
200	1.20	1.80	0.02

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 p_T of the $\ell\nu$ pair, the E_T of the highest E_T photon, and the E_T of the second-highest E_T photon. All events are required to pass the 'Tight' cuts of Table 1.

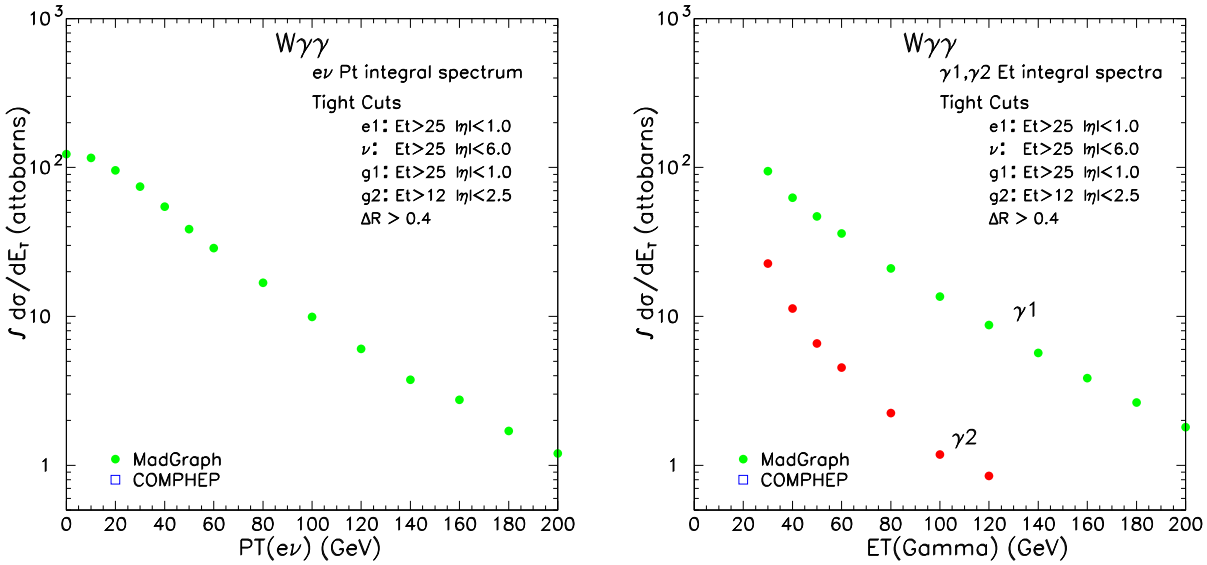

Figure 7: The integrated cross section above a threshold in attobarns (((10^{-3} fb or 10^{-6} pb) from MadGraph W-gamma-gamma samples. In each plot the leptons and photons are required to pass the 'Analysis_Tight' cuts of Table 1; then the further requirement that the variable (e.g. E_T of γ_1) pass the threshold is imposed. The left-hand plot shows the cross section for the highest-E_T photon (green) and the 2nd photon (red) to be above the threshold; the right-hand plot requires the Z-boson p_T to be above the threshold.

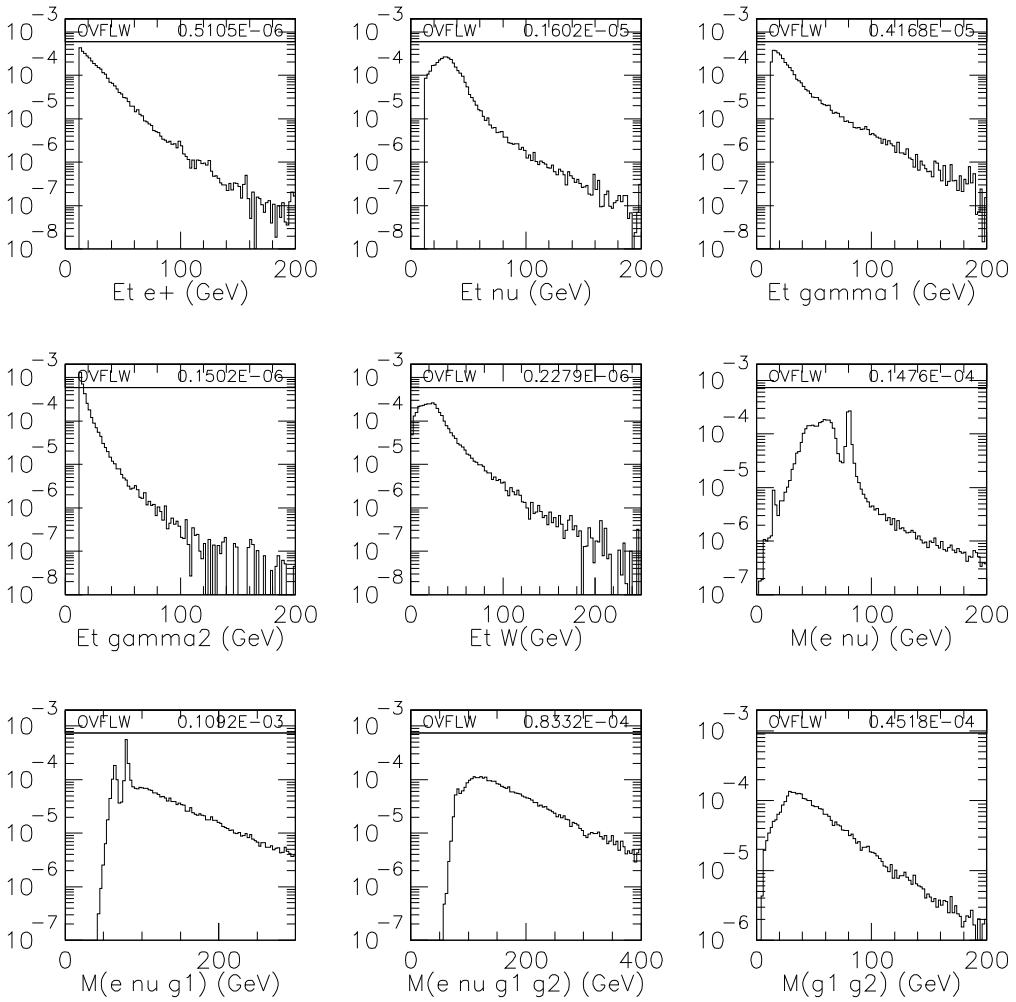

Figure 8: Kinematic distributions for the MadGraph W-gamma-gamma sample.

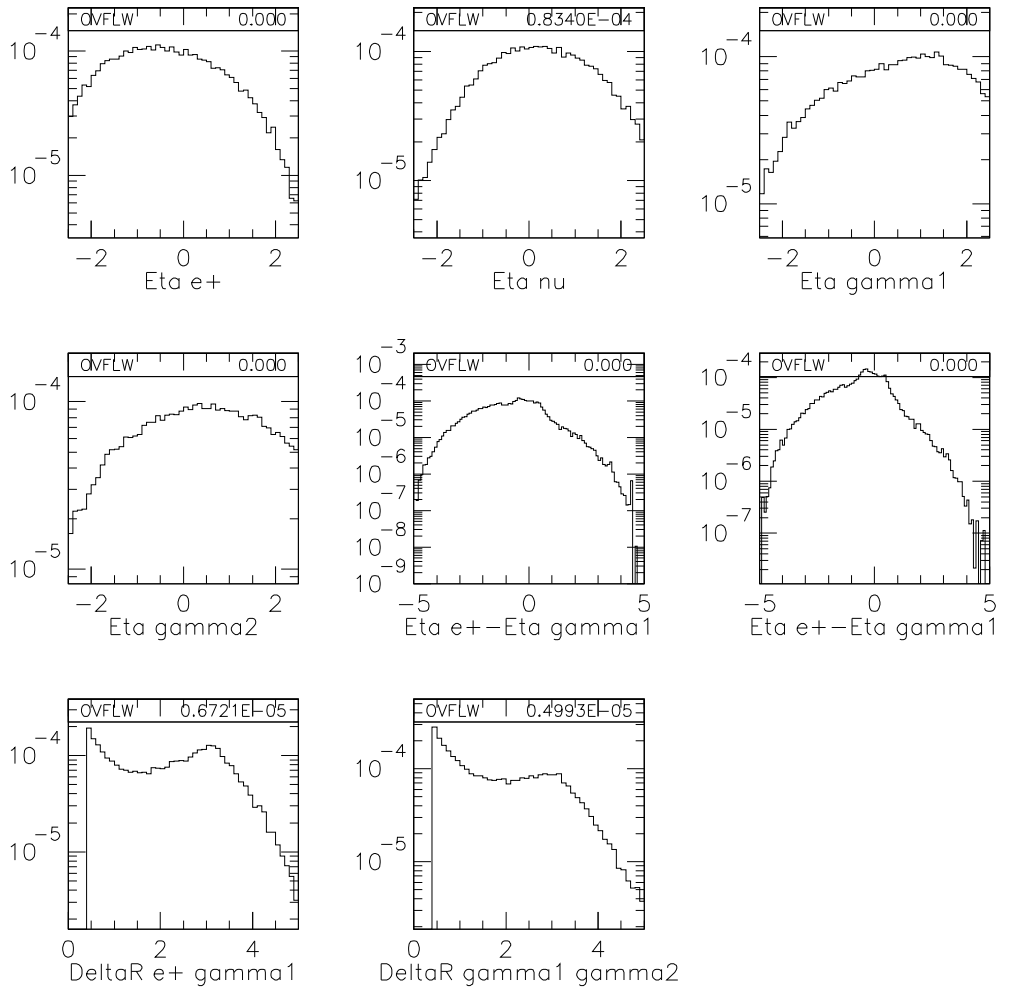

Figure 9: More kinematic distributions for the MadGraph W-gamma-gamma sample.

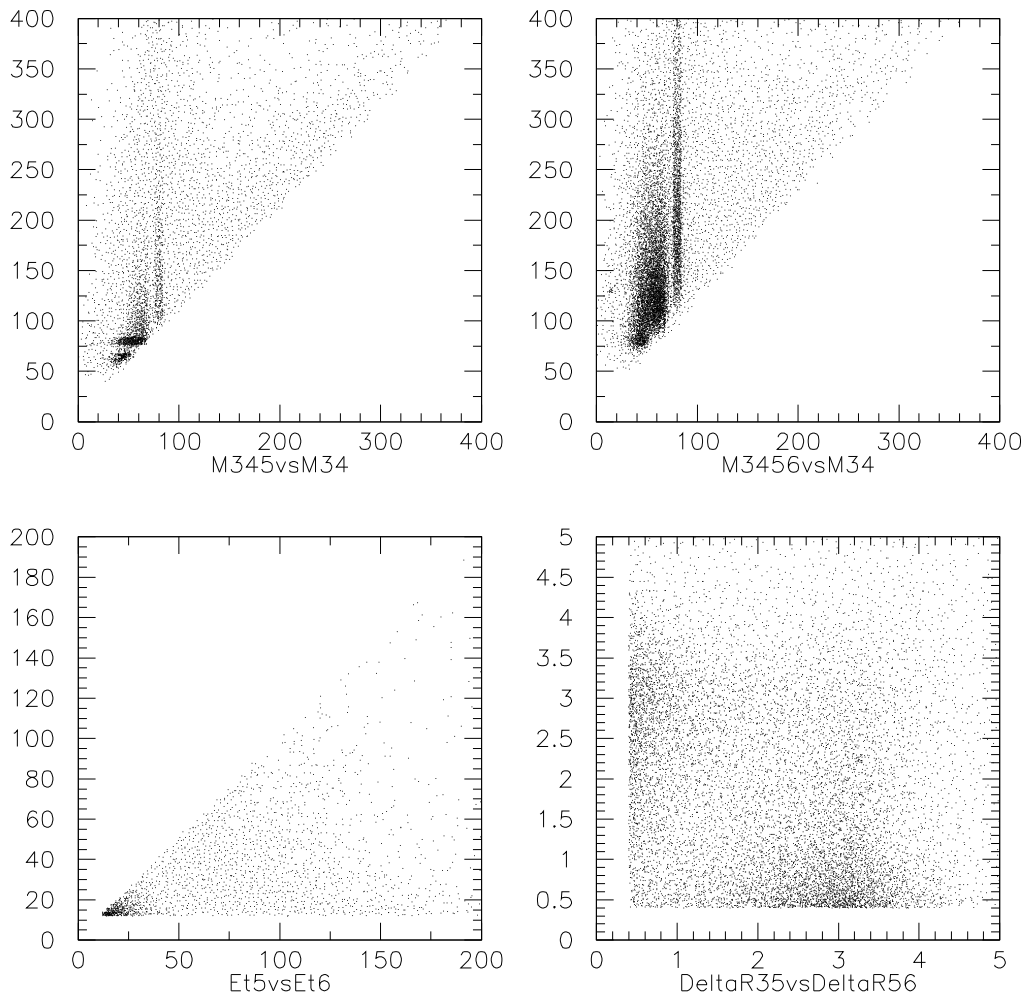

Figure 10: Correlations among kinematic distributions for the MadGraph W-gamma-gamma sample.

7 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 [10].

The cross sections for finding a lepton pair with p_T greater than a given threshold for events with two central leptons and two central photons, all with $E_T > 25$ GeV are also shown in Figure 11. The photons are ordered according to E_T, with the highest E_T photon being γ_1.

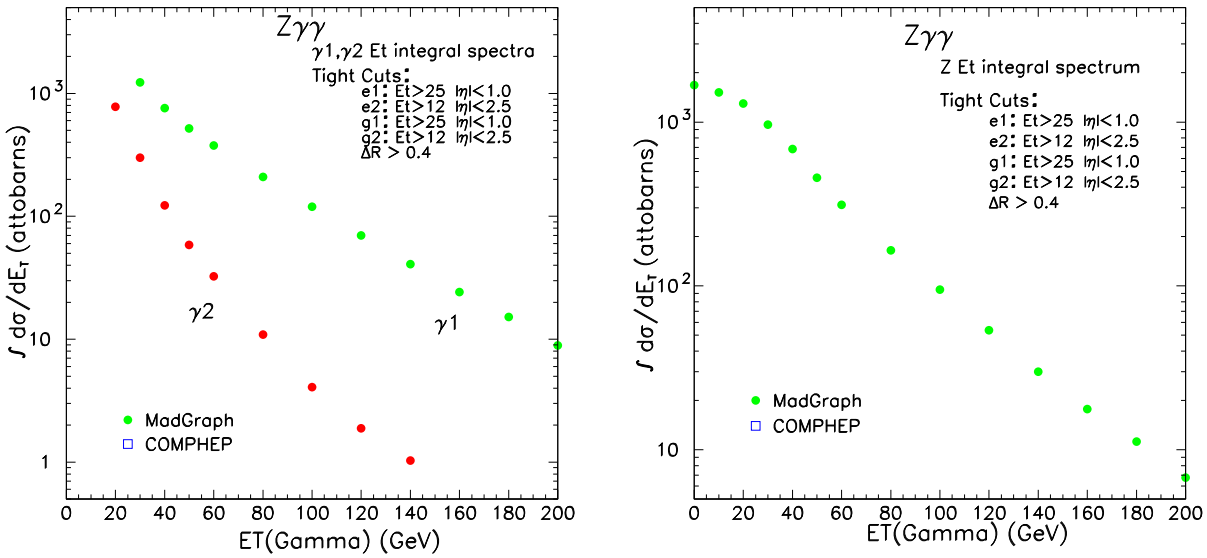

Figure 11: The integrated cross section above a threshold in attobarns (10^{-3} fb or 10^{-6} pb) from MadGraph Z-gamma-gamma samples. In each case all particles are required to pass the 'Tight Analysis' cuts of Table 1; then the further requirement that the variable (e.g. E_T of γ_1) pass the threshold is imposed.

Threshold (GeV)	$p_T(e^+e^-)$	$E_T(\gamma 1)$	$E_T(\gamma 2)$
0	1680	–	—
10	1620	–	—
20	1300	–	779
30	964	1230	300.
40	685	759	123.
50	458	520	58.5
60	313	378	32.4
80	165	209	10.9
100	94.9	120	4.07
120	53.6	69.9	1.88
140	29.9	40.9	1.03
160	17.7	24.2	0.221
180	11.2	15.2	0.072
200	6.75	8.91	0.028

Table 7: The integral cross-sections from MadGraph 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, the E_T of the highest E_T photon, and the E_T of the second-highest E_T photon. All events are required to pass the 'Tight' cuts of Table 1.

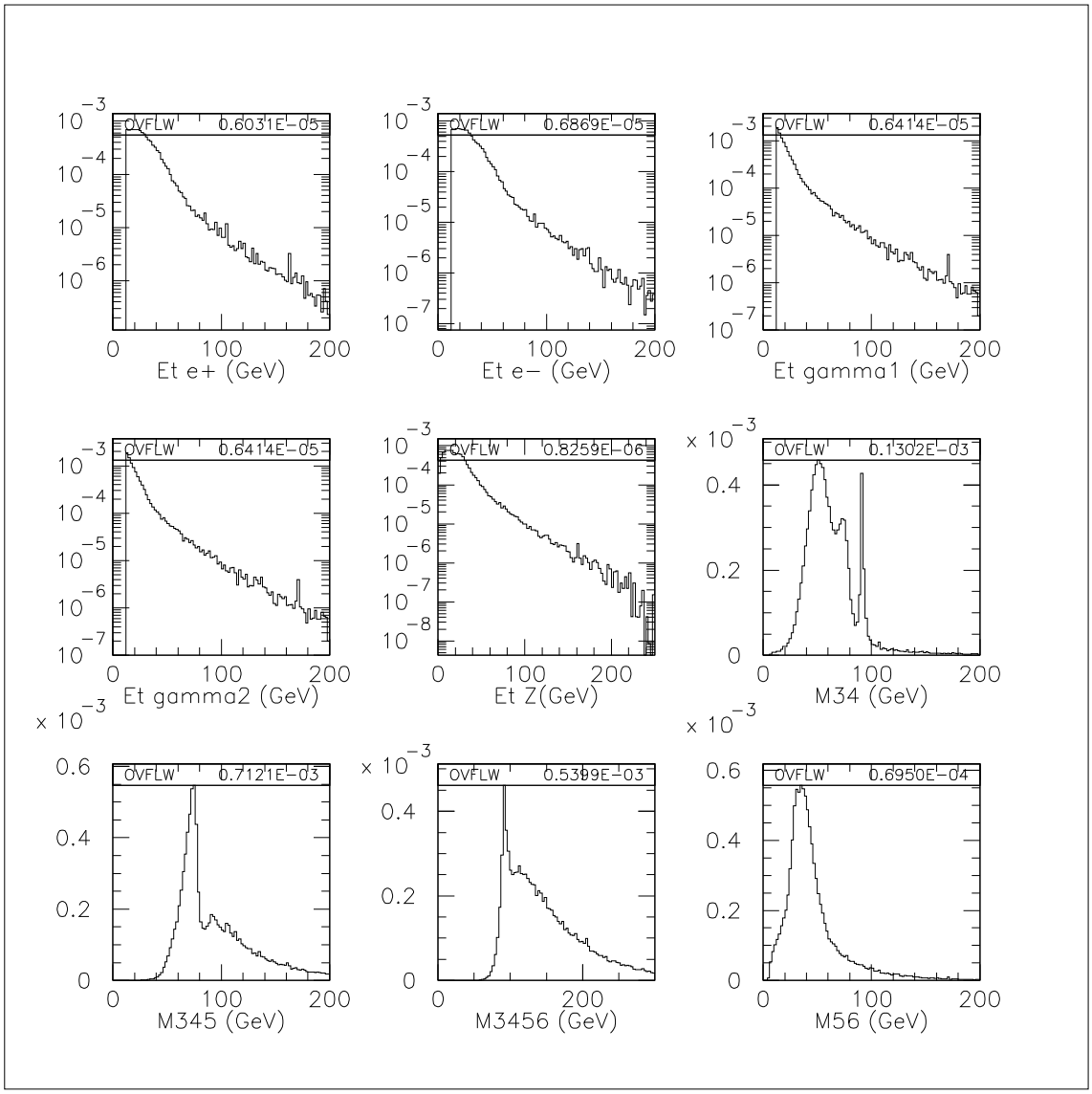

Figure 12: Kinematic distributions for the MadGraph Z-gamma-gamma sample. Particles 3,4,5, and 6 are the e^+, e^-, γ_1,and γ_2, respectively.

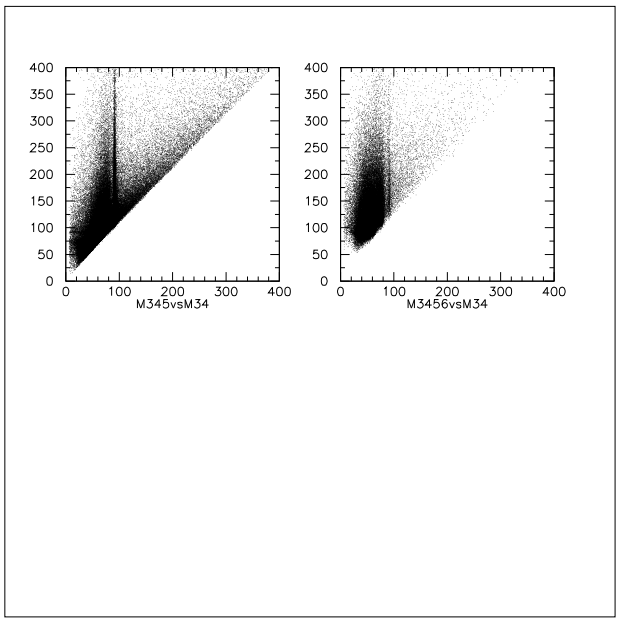

Figure 13: More kinematic distributions for the MadGraph Z-gamma-gamma sample. Particles 3,4,5, and 6 are the e^+, e^-, γ_1,and γ_2, respectively.

Table 8 contains the cross-sections from MadGraph for $\ell\ell\gamma\gamma$ production vs the p_T of the $\ell\ell$ pair.

$E_T^{\ell\ell}$	$\eta^{2nde} < 2.5$	$\eta^{2nde} < 1.0$
0	1.68	0.95
10	1.62	0.92
20	1.30	0.71
30	0.96	0.51
40	0.69	0.36
50	0.46	0.24
60	0.31	0.17
80	0.17	0.093
100	0.095	0.059
120	0.054	0.035
140	0.030	0.020
160	0.018	0.013
180	0.011	0.008
200	0.007	0.005

Table 8: The integral cross-sections in femtobarns for $\ell\ell\gamma\gamma$ production at 1.96 TeV vs. the $\ell\ell$ E_T. The cross sections are given for 'Tight' analysis cuts of Table 1; the cross sections are also quoted for when the second electron is required to be within $|\eta| < 1.0$ (all other cuts, including the photon cuts, are unchanged, e.g. the 2nd photon can still be in the plug).

8 Tabulated Cross Sections

Signature	Process	$\sigma_{MadGraph}$	$\sigma_{CompHep}$	Ratio
$e^+\nu$	W	341 $\pm$ 0.6 picob	xx $\pm$ xx pb	
$e^+\nu\gamma$	Wγ	25.6 $\pm$ 0.1 femtob	22.4 $\pm$ 0.1 fb	
$e^+\nu\gamma\gamma$	W$\gamma\gamma$	123 $\pm$ 2 attob	—	—
e^+e^-	Z	99.4 $\pm$ 0.7 picob	181 $\pm$ 1 pb	
$e^+e^-\gamma$	Zγ	177.3 $\pm$ 0.7 femtob	180.9 $\pm$ 4.1 fb	0.98
$e^+e^-\gamma\gamma$	Z$\gamma\gamma$	1670 $\pm$ 30 attob	—	—

Table 9: 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).

9 Conclusions

The predicted cross sections from MadGraph and COMPHEP for single high-E_T photon production in association with a W boson have similar shapes and agree to better than 20% over many decades, with MadGraph giving the higher cross-section. While this is good news in that it gives us some confidence that the fundamental calculations are sound, given that the two programs work in quite different ways, we need to understand the differences. The Zγ cross sections differ in shape and have a larger discrepancy, with the MadGraph predictions being about 5% lower at lower photon E_T and growing to about 30-40% higher at very high E_T; the two cross sections cross near E_T = 60 GeV. Work is continuing to understand some of the theoretical subtleties in the input parameters and assumptions in the calculations. However we expect that the predictions should be good enough to calculate the expected numbers of rare events in both the Wγ and Zγ single-photon channels and also in the diphoton W$\gamma\gamma$ and Z$\gamma\gamma$ channels in the meantime.

10 Acknowledgments

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