Measuring the Ratios W+Njets to Z+Njets As A Precision Test of the Standard Model

MadGraph Predictions

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See CDF Note 5963 version 1.1 by Erin Collins and Henry Frisch
Many thanks to Tim Stelzer, Steve Mrenna, Michelangelo Mangano, and John Campbell for their help.

Outline

- Motivation
- Brief Description of MadGraph
- Parameters and Selection Criteria
- MadGraph Cross Sections and Ratios for W+Jets and Z+jets
- Comparison to MCFM
- Comparison to ALPGEN
- Comparison to CDF Run I Data
- Further studies
- Conclusions

Why Study the Ratios (W+Jets)/(Z+Jets) ?

- The analyses of Run I data indicate that uncertainties in the cross sections for W+Njets and Z+Njets appear to increase rapidly with increasing N

N(Jets)	$\sigma \times$BR (pb)	Sys Unc (pb)	Sys Unc (%)
0	1896 pb	108 pb	5.7%
1	370 pb	49 pb	13%
2	83 pb	18 pb	22%
3	15.3 pb	4.9 pb	32%
4	2.9 pb	1.3 pb	44%
5	0.24 pb	0.28 pb	117%

Table 1:

Exclusive jet cross sections with their absolute and percentage uncertainties, (crudely) extracted from the inclusive cross sections in the D. Cronin-Hennessy, et al. *Measurement of* $W \rightarrow e\nu + N$ *Jet Cross Sections* for N$\geq$1; and from F. Abe, et al. *Measurement of* $\sigma B(W \rightarrow e\nu)$ *and* $\sigma(Z \rightarrow ee)$ for N=0.

Why Study the Ratios (W+Jets)/(Z+Jets) ?

- The sources of the uncertainty are as follows:

N(Jets)	Et_J Scale	Und Ev	QCD Bkgd	Mult Int	η_J	Acc	Oblit	Top
≥ 1	6.8%	5.8%	5.2%	3.2%	1.9%	0.8%	0.2%	0.05%
≥ 2	11%	9.8%	5.4%	7.2%	3.7%	1.0%	0.3%	0.3%
≥ 3	17%	16%	9.1%	9.8%	4.8%	1.8%	0.6%	1.3%
≥ 4	23%	21%	15.8%	14%	5.5%	3.5%	1.3%	0.5%

Table 2:

Percentage Systematic uncertainties for *Inclusive* W+N jet bins for N=1 to N=4. These are taken from Table 10 of the Duke analysis (D. Cronin-Hennessy, et al.); the upper error bar is used in all cases. Many of these uncertainties will partially cancel in the W/Z ratio.

- Taking the ratio W+Njets to Z+Njets may partially cancel some systematic uncertainty, thus giving a relatively smaller uncertainty for each N. The systematic uncertainties which may partially cancel include those associated with
  - Jet Energy Scale
  - Underlying Event
  - Multiple Interactions
  - Jet eta

Why Study the Ratios (W+Jets)/(Z+Jets) ?

- Suppose one could get systematics down to 1% uncertainty in the W/Z ratio: could the ratio method be useful in detecting/measuring new physics? Perhaps - see N=4 Jets: without top contribution, cross section corresponding to 1 sigma uncertainty in the predicted ratio is 230 fb; top contribution would add 8000 fb in the numerator and would cause the measured ratio to be very different from predicted, thus indicating the presence of the top quark. The method would work similarly for as-yet unknown physics.

Event and W Properties		W/Z Ratio Method Reach	
N(Jets)	σ_W	σ_{new} 2 fb^{-1}	σ_{new} 15 fb^{-1}
0	1896 pb	20 pb (1.0%)	20 pb (1.0%)
1	370 pb	4.4 pb (1.2%)	3.7 pb (1.0%)
2	83 pb	1.5 pb (1.8%)	0.9 pb (1.1%)
3	15 pb	0.5 pb (3.5%)	240 fb (1.6%)
4	3.1 pb	230 fb (7.5%)	95 fb (2.9%)

Table 3:

The cross section corresponding to a 1-sigma uncertainty in the W/Z ratio in 2 fb^{-1}, and in 15 fb^{-1} from the cross sections of Table 1. Note the number of $Z^0 \rightarrow e^+e^-$ events for each N is about a factor of 10 smaller than the number of W events. Using the $Z^0 \rightarrow \mu^+\mu^-$ channel one can gain approximately root-2 on these uncertainties.

DISCLAIMER: This is very much work in progress; please do not use the numbers presented in the following slides.

MadGraph Overview

MadGraph is a matrix element generator which calculates squared amplitudes to leading order using, as a default, the parton distribution function CTEQ5L.

The user inputs a process and parameters, and MadGraph outputs Feynman diagrams and cross sections for that process.

The user may specify a goal number of events to be generated or the percent accuracy desired for the cross section.

Note that MadGraph defines a jet to be any of u,d,s,c,g (the user must ask for t or b explicitly), and MadGraph defines a proton to be made only of the light quarks (again, no t or b quarks).

MadGraph - created by T. Stelzer and W. F. Long.
See Comput.Phys.Commun. 81 (1994) 357-371.

Parameters and Selection Criteria

- PDF CTEQ5L
- Beam Energy = 980 GeV
- $Q^2 = {W_{mass}}^2$
- Leptons:
  - $E_T > 25.0$ GeV
  - $|\eta| < 1.0$ for the first electron
  - $|\eta| < 2.5$ for other electrons
  - $|\eta| < 9.0$ for neutrinos
- Jets:
  - $E_T > 15.0$ GeV
  - $|\eta| < 2.5$
- $\Delta R > 0.4$ for pairs of outgoing particles

MadGraph W+Njets Cross Sections

W+Jets Cross Sections (pb)				
N jet	# b	(QCD, QED)	QCD W^++Jets	
0 j	0 b	(0,2)	341.5	$\pm$ 0.5
1 j	0 b	(1,2)	42.1	$\pm$ 0.3
2 j	0 b	(2,2)	8.28	$\pm$ 0.05
2 j	2 b	(2,2)	0.0917	$\pm$ 0.0008
3 j	0 b	(4,2)	1.68	$\pm$ 0.02
3 j	2 b	(4,2)	0.0307	$\pm$ 0.0003
4 j	0 b	(4,2)	0.357	$\pm$ 0.005
4 j	2 b	(4,2)	0.0095	$\pm$ 0.0003
4 j	4 b	(4,2)	(4.1	$\pm$ 0.1)E-5
5 j	0 b	(6,2)		
5 j	2 b	(6,2)	0.00261	$\pm$ 0.00004
5 j	4 b	(6,2)	(2.12	$\pm$ 0.05)E-5

Table 4:

A tabulation of LO SM predicted W+jet cross-sections and uncertainties, giving the cross sections for processes with one W^+.

MadGraph W+Njets Cross Sections - Plots

No b Jets   2 b Jets

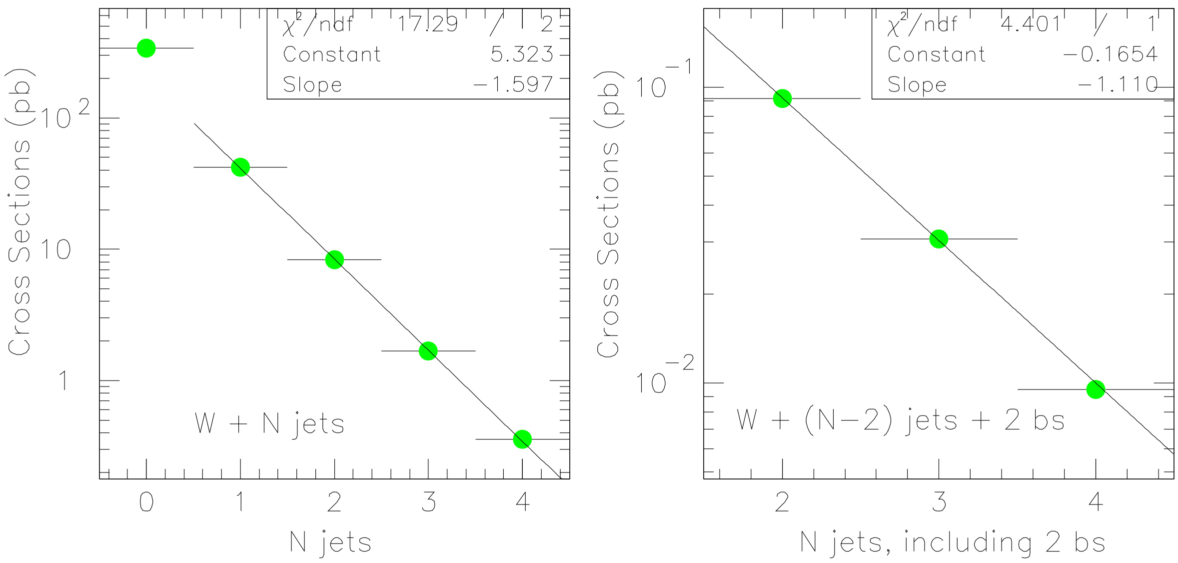


Figure 1:

$W^+(e^+ + \nu_e)$+Njets vs Njets where the N jets are u,d,s,c,g in the first case, and where 2 b jets are required and the remaining (N-2) jets are u,d,s,c,g in the second case.

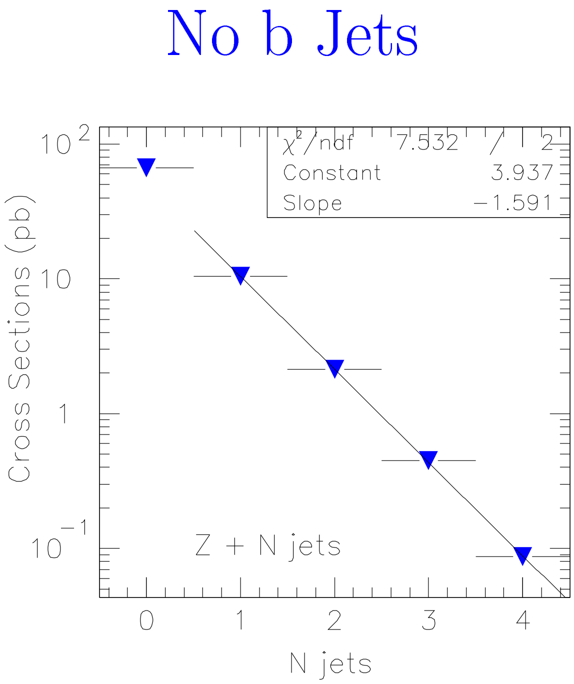
MadGraph Z+Njets Cross Sections

Z+Jets Cross Sections (pb)				
N jet	# b	(QCD, QED)	QCD Z^0+Jets	
0 j	0 b	(0,2)	67.0	± 0.2
1 j	0 b	(1,2)	10.45	± 0.01
2 j	0 b	(2,2)	2.13	± 0.03
2 j	2 b	(2,2)	0.0362	± 0.0002
3 j	0 b	(4,2)	0.448	± 0.006
3 j	2 b	(4,2)	0.0132	± 0.0002
4 j	0 b	(4,2)	0.087	± 0.001
4 j	2 b	(4,2)	(3.81	± 0.05)E-3
4 j	4 b	(4,2)	(1.76	± 0.04)E-5
5 j	0 b			
5 j	2 b			
5 j	4 b			

Table 5:

A tabulation of LO SM predicted Z+jet cross-sections and uncertainties, giving the cross sections for processes with one Z.

MadGraph Z+Njets Cross Sections - Plots



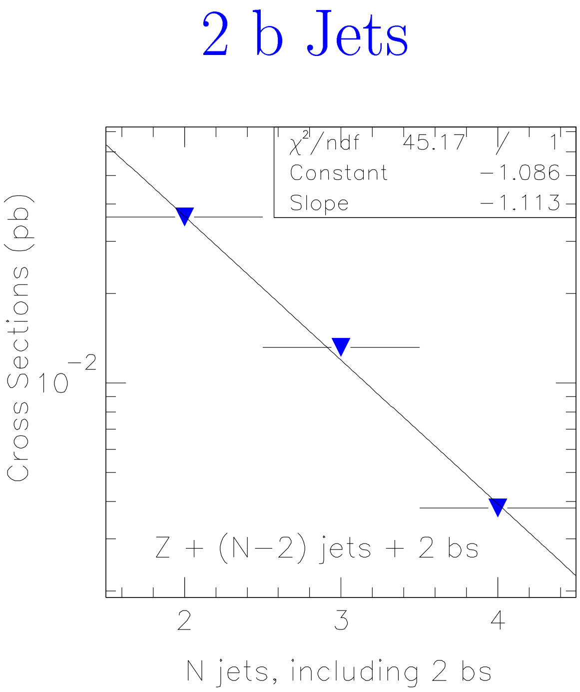


Figure 2:

$Z^0(e^+e^-)$ +Njets vs Njets where the N jets are u,d,s,c,g in the first case, and where 2 b jets are required and the remaining (N-2) jets are u,d,s,c,g in the second case.

MadGraph Ratio Boson+Njets / Boson+N+1Jets

(N Jets)/(N+1 Jets) for W *or* Z			
W+jets		**Z+jets**	
W+0j/W+1j	8.11 ± .06	Z+0j/Z+1j	6.41 ± .02
W+1j/W+2j	5.08 ± .05	Z+1j/Z+2j	4.91 ± .07
W+2j/W+3j	4.93 ± .07	Z+2j/Z+3j	4.75 ± .09
W+3j/W+4j	4.71 ± .09	Z+3j/Z+4j	5.15 ± .09
W+4j/W+5j		Z+4j/Z+5j	

Table 6:
Ratios of cross sections. (W^++Njets)/(W^++(N+1)jets) and (Z^0+Njets)/(Z^0+(N+1)jets).

- We want to understand why the W case is different from the Z case
- We want to understand why the ratios within Z+Njets vary as they do, as well as why the ratios within the W+Njets vary as they do
- Currently checking these numbers with other generators

MadGraph Ratio Boson+Njets / Boson+N+1Jets

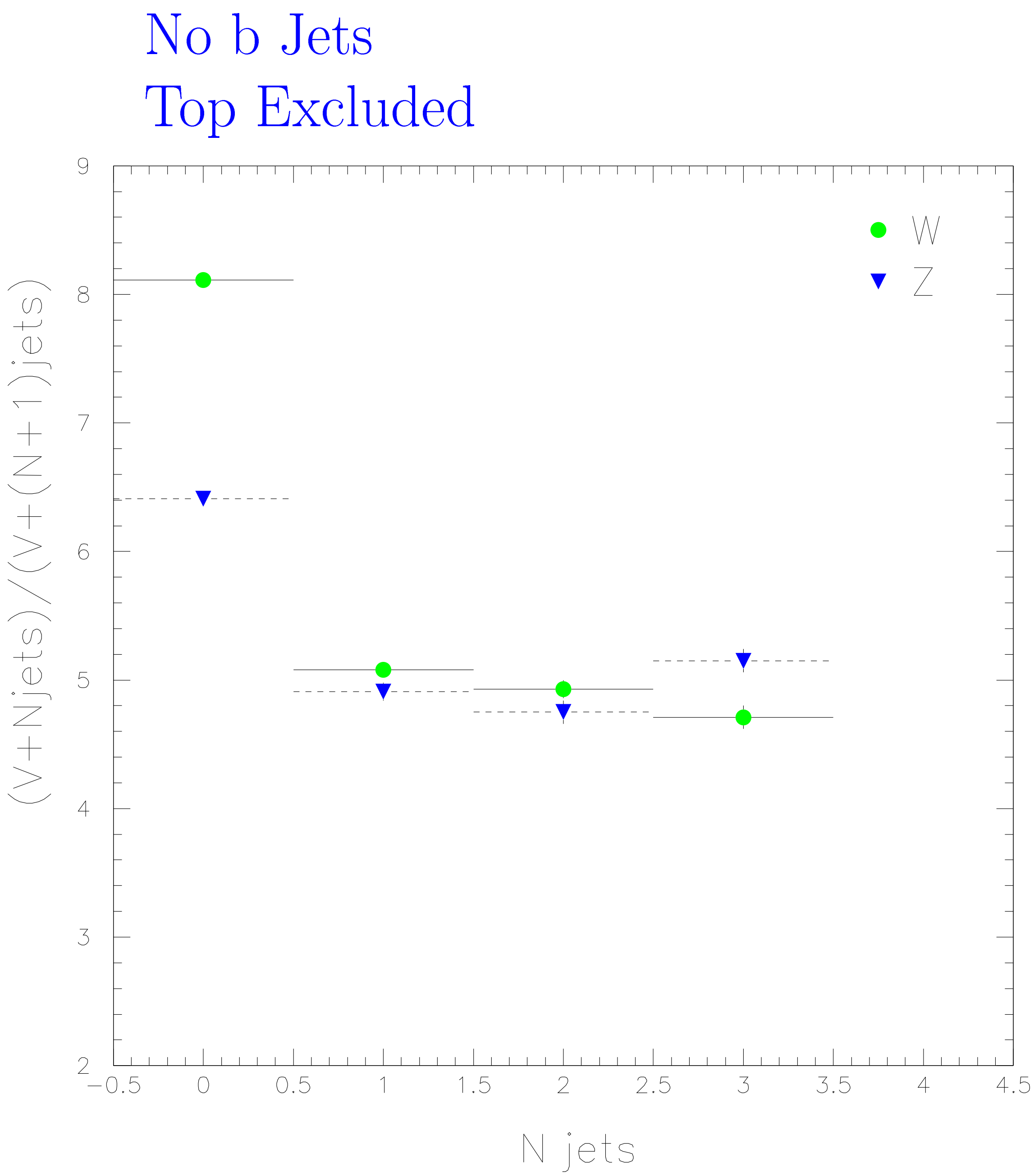


Figure 3:

Ratios of cross sections: N jets to N+1 jets for W or Z production.

MadGraph Ratio W+Njets / Z+NJets

$\sigma W^+/\sigma Z^0$			
N jet	# b	(QCD, QED)	$\sigma W^+/\sigma Z^0$
0 j	0 b	(0,2)	5.10 $\pm$ .02
1 j	0 b	(1,2)	4.03 $\pm$ .03
2 j	0 b	(2,2)	3.89 $\pm$ .06
3 j	0 b	(4,2)	3.75 $\pm$ .07
4 j	0 b	(4,2)	4.10 $\pm$ .07
5 j	0 b		
2 j	2 b	(2,2)	2.53 $\pm$ .03
3 j	2 b	(4,2)	2.33 $\pm$ .04
4 j	2 b	(4,2)	2.49 $\pm$ .09
5 j	2 b		
4 j	4 b	(4,2)	2.33 $\pm$ .08
5 j	4 b		

Table 7:
$\sigma W^+/\sigma Z^0$

We want to understand the pattern here - both for the ratios where no b jets are included and for the ratios where 2 b jets are included.

MadGraph Ratio W+Njets / Z+NJets - Plot

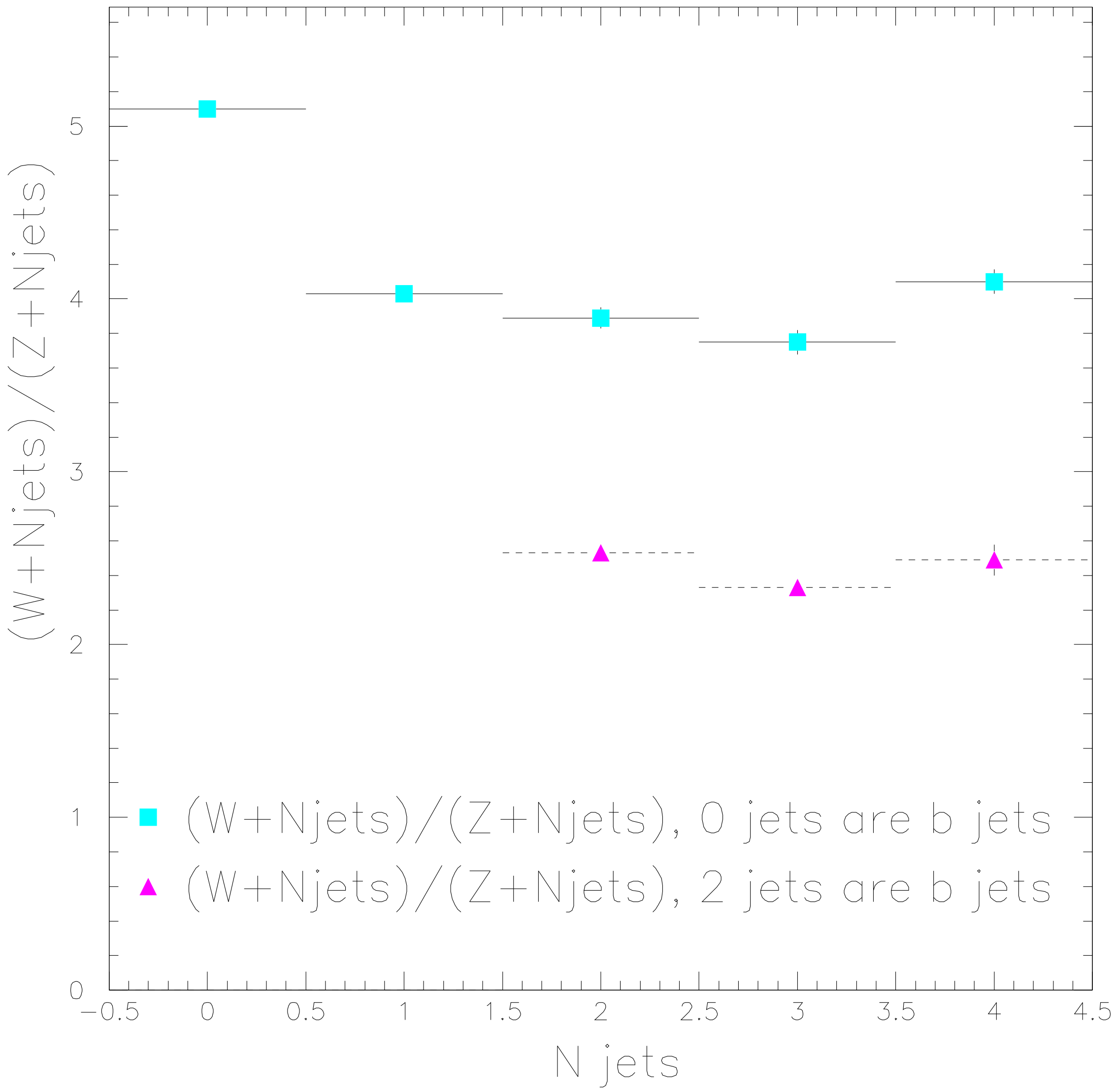


Figure 4:

The ratios of W+Njets to Z+Njets versus Njets.

MadGraph v. MCFM

MadGraph cross sections and ratios compared to those from MCFM. The parameters and selection criteria are as described above. Note that the MCFM Z cross sections do not include the photon interference. Thanks to John Campbell and Keith Ellis for providing these preliminary MCFM numbers as well as their expertise.

W+jets Cross Sections (pb) and Ratios				
	Cross Section (pb)		Ratio (W+Njets)/(W+N+1jets)	
N	MCFM	MadGraph	MCFM	MadGraph
0	344.4 ± 0.4	341.5 ± 0.5	7.04 ± 0.03	8.11 ± 0.06
1	48.9 ± 0.2	42.1 ± 0.3	4.57 ± 0.05	5.08 ± 0.05
2	10.7 ± 0.1	8.28 ± 0.05	5.35 ± 0.27	4.93 ± 0.07
3	2.0 ± 0.1	1.68 ± 0.02	-	4.71 ± 0.09
4	-	0.357 ± 0.005	-	-

Table 8: W^+

Z+jets Cross Sections (pb) and Ratios				
	Cross Section (pb)		Ratio (Z+Njets)/(Z+N+1jets)	
N	MCFM	MadGraph	MCFM	MadGraph
0	69.9 ± 0.1	67.0 ± 0.2	5.78 ± 0.05	6.41 ± 0.02
0	12.1 ± 0.1	10.45 ± 0.01	4.51 ± 0.04	4.91 ± 0.07
0	2.68 ± 0.01	2.13 ± 0.03	4.39 ± 0.02	4.75 ± 0.09
0	0.61 ± 0.01	0.448 ± 0.006	-	5.15 ± 0.09
0	-	0.087 ± 0.001	-	-

Table 9: Z^0

MadGraph v. MCFM: W Ratios

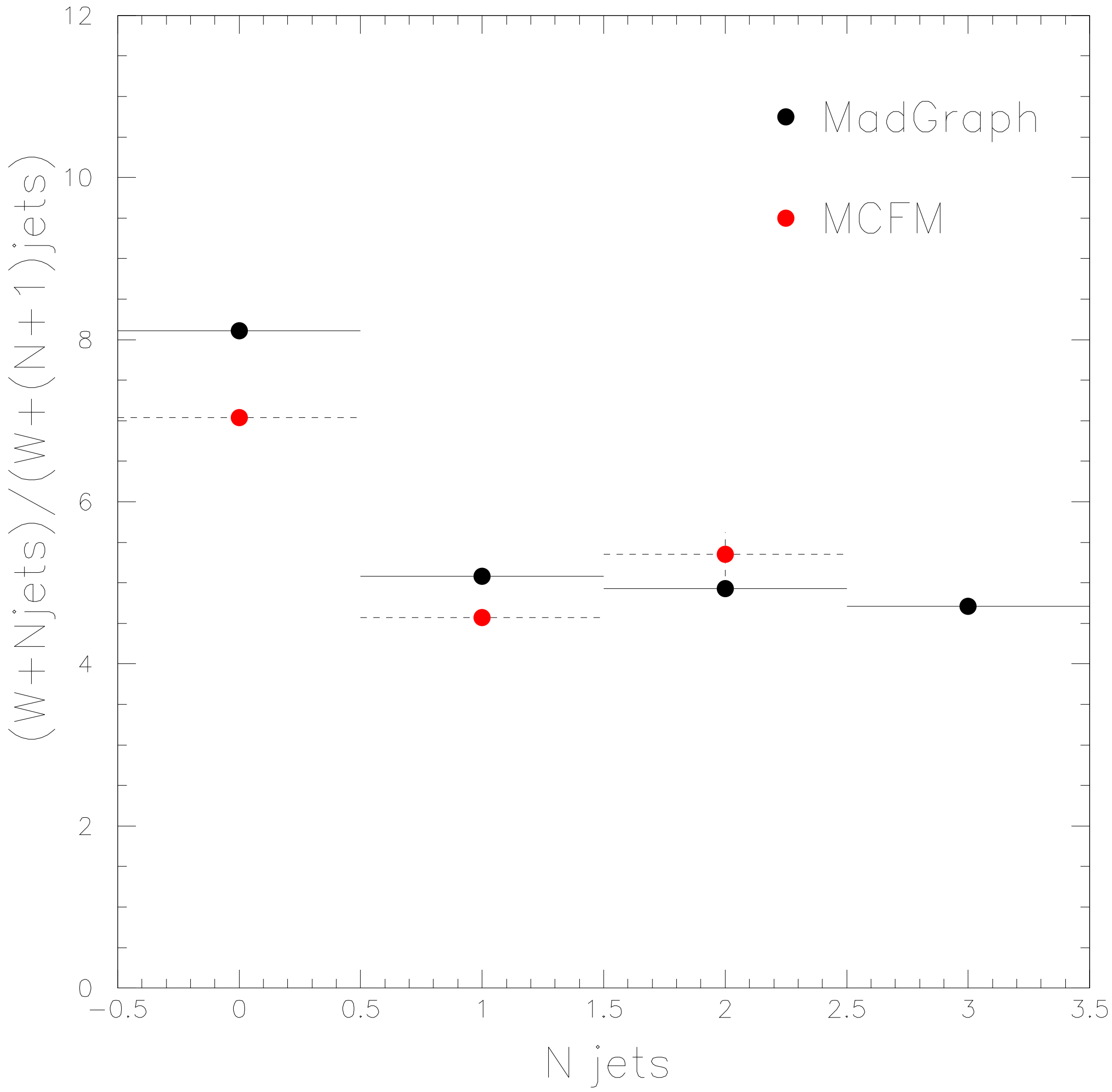


Figure 5:

(W+Njets) / (W+N+1jets) versus Njets for MadGraph and MCFM.

MadGraph v. MCFM: Z Ratios

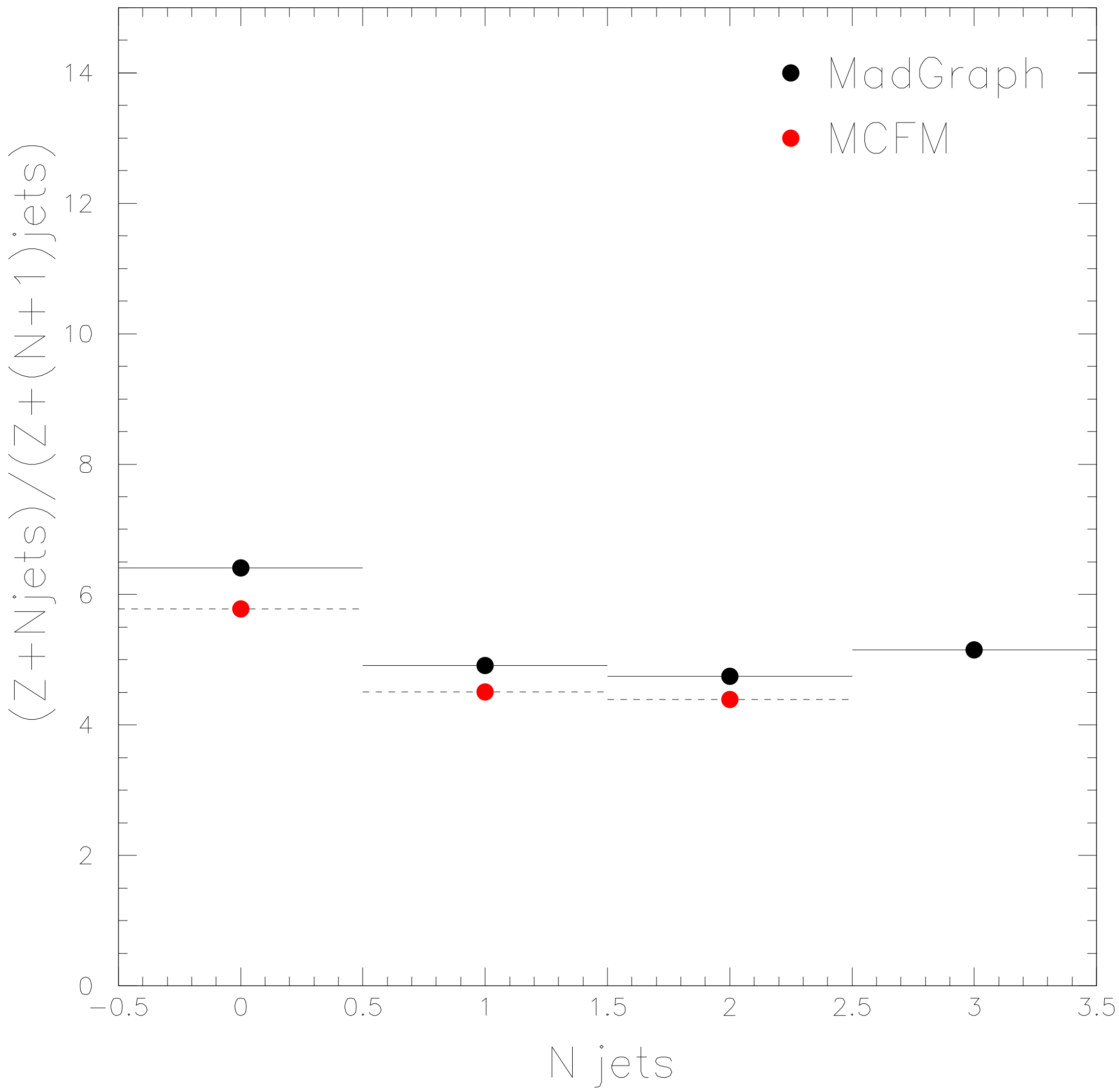


Figure 6:

(Z+Njets) / (Z+N+1jets) versus Njets for MadGraph and MCFM. Note that the MCFM Z cross sections do not include the photon interference.

MadGraph v. MCFM: W/Z Ratio

W+Njets / Z+Njets		
N jet	MCFM	MadGraph
0	$4.93 \pm .01$	$5.10 \pm .02$
1	$4.04 \pm .04$	$4.03 \pm .03$
2	$3.99 \pm .04$	$3.89 \pm .06$
3	$3.28 \pm .17$	$3.75 \pm .07$
4	-	$4.10 \pm .07$

Table 10:

A tabulation of MCFM and MadGraph predicted W/Z ratio. Note that the Z cross sections from MCFM do not include the photon interference.

MadGraph v. MCFM: W/Z Plot

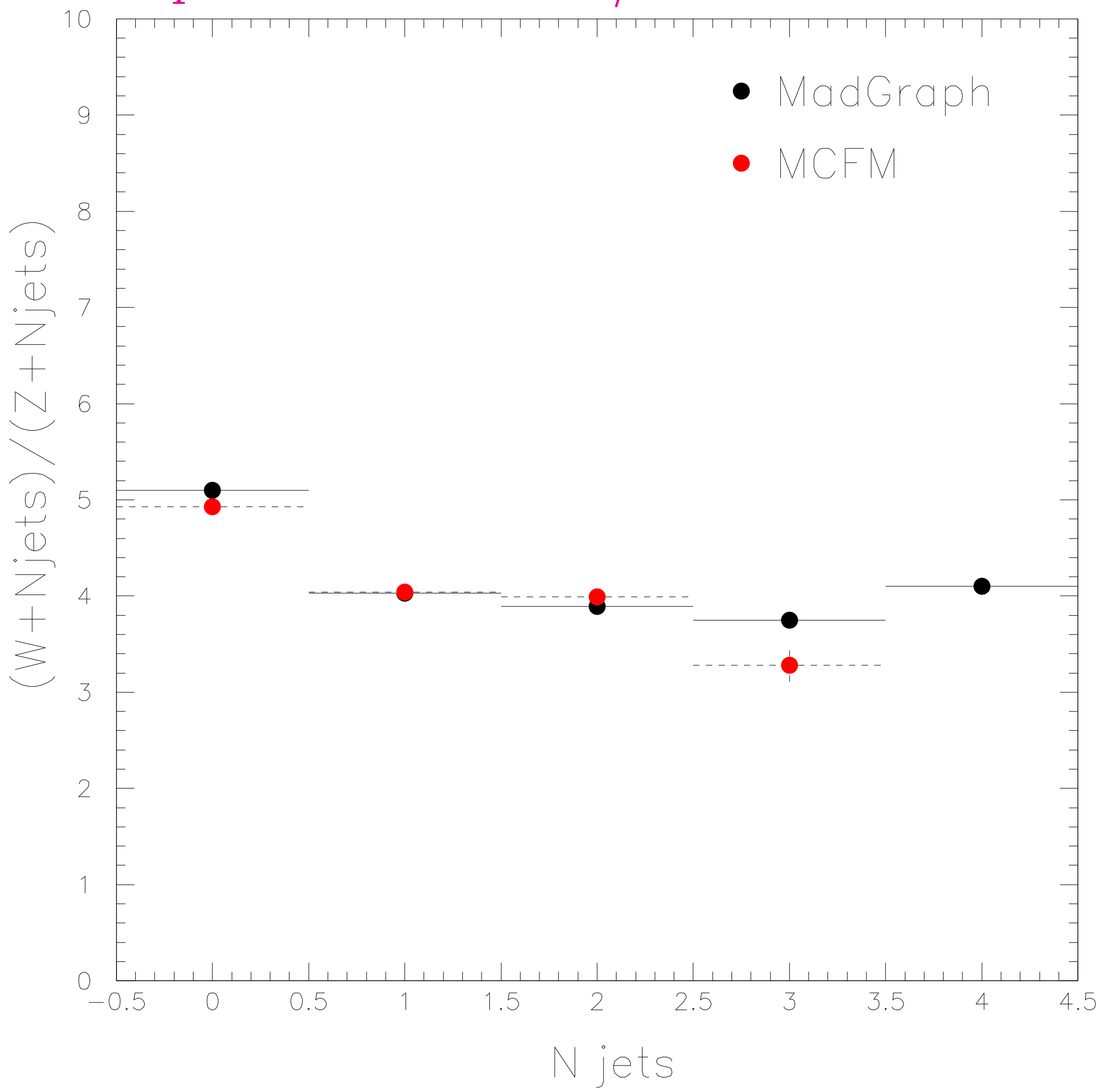


Figure 7:

(W+Njets) / (Z+Njets) versus Njets for MadGraph and MCFM. Again the photon interference is missing in the MCFM Z cross sections.

MadGraph v. ALPGEN: Selection Criteria

ALPGEN

Event generator that calculates matrix elements to leading order.

See Michelangelo Mangano, et al. hep-ph/0206293 - Many thanks to Michelangelo for his help with the ALPGEN numbers.

Selection criteria used to compare MadGraph to ALPGEN:

- PDF CTEQ5L (default)
- Beam Energy = 1000 GeV
- $\mathrm{Q}^2 = {\mathrm{W}_{\mathrm{mass}}}^2$ while in ALPGEN, $\mathrm{Q}^2 = {\mathrm{W}_{\mathrm{mass}}}^2 + {\mathrm{P}_{\mathrm{T,W}}}^2$ for W+jets, and $\mathrm{Q}^2 = {\mathrm{Z}_{\mathrm{mass}}}^2 + {\mathrm{P}_{\mathrm{T,Z}}}^2$ for Z+jets. This is the only major difference.
- $\mathrm{E_T} > 20.0$ GeV for jets
- $\mathrm{E_T} > 1.0$ GeV for leptons
- $|\eta| < 2.5$ for jets
- $|\eta| < 9.0$ for leptons
- $\Delta R > 0.4$ for pairs of jets in W and Z cases
- $\Delta R > 0.0$ for other particle pairs
- production of only W^+, the cross section will be doubled in the results, since ALPGEN's W cross sections include W^+ and W^-
- $80.0\ \mathrm{GeV} \leq \mathrm{m}_{\mathrm{e+e-}} \leq 100.0\ \mathrm{GeV}$ in Z case

Please note that this is very much work in progress.

MadGraph v. ALPGEN: Cross Sections and Ratios

W+jets Cross Sections (pb) and Ratios (MLM cuts)				
	Cross Section (pb)		Ratio (W+Njets)/(W+N+1jets)	
N	ALPGEN	MadGraph	ALPGEN	MadGraph
0	2093 ± 9	2090 ± 10	9.43 ± 0.09	10.00 ± 0.11
1	222 ± 2	209 ± 2	5.56 ± 0.06	5.90 ± 0.09
2	39.9 ± 0.2	35.4 ± 0.4	5.61 ± 0.05	5.80 ± 0.12
3	7.11 ± 0.05	6.1 ± 0.1	4.72 ± 0.04	5.87 ± 0.15
4	1.506 ± 0.006	1.04 ± 0.02	6.10 ± 0.10	
5	0.247 ± 0.004		-	-

Table 11: W

Z+jets Cross Sections (pb) and Ratios (MLM cuts)				
	Cross Section (pb)		Ratio (Z+Njets)/(Z+N+1jets)	
N	ALPGEN	MadGraph	ALPGEN	MadGraph
0	145.24 ± 0.09	171.9 ± 0.9	8.40 ± 0.05	8.75 ± 0.05
1	17.3 ± 0.1	19.64 ± 0.06	5.81 ± 0.03	5.86 ± 0.07
2	2.98 ± 0.00	3.35 ± 0.04	5.75 ± 0.07	5.88 ± 0.12
3	0.518 ± 0.006	0.57 ± 0.01	5.95 ± 0.10	
4	0.087 ± 0.001		6.35 ± 0.16	
5	0.0137 ± 0.0003		-	-

Table 12: Z

The W cross sections and ratios are in fair agreement except for the 3 and 4 jet numbers; the ALPGEN Z cross sections are systematically lower than the corresponding MadGraph numbers.

MadGraph v. ALPGEN: W Ratios

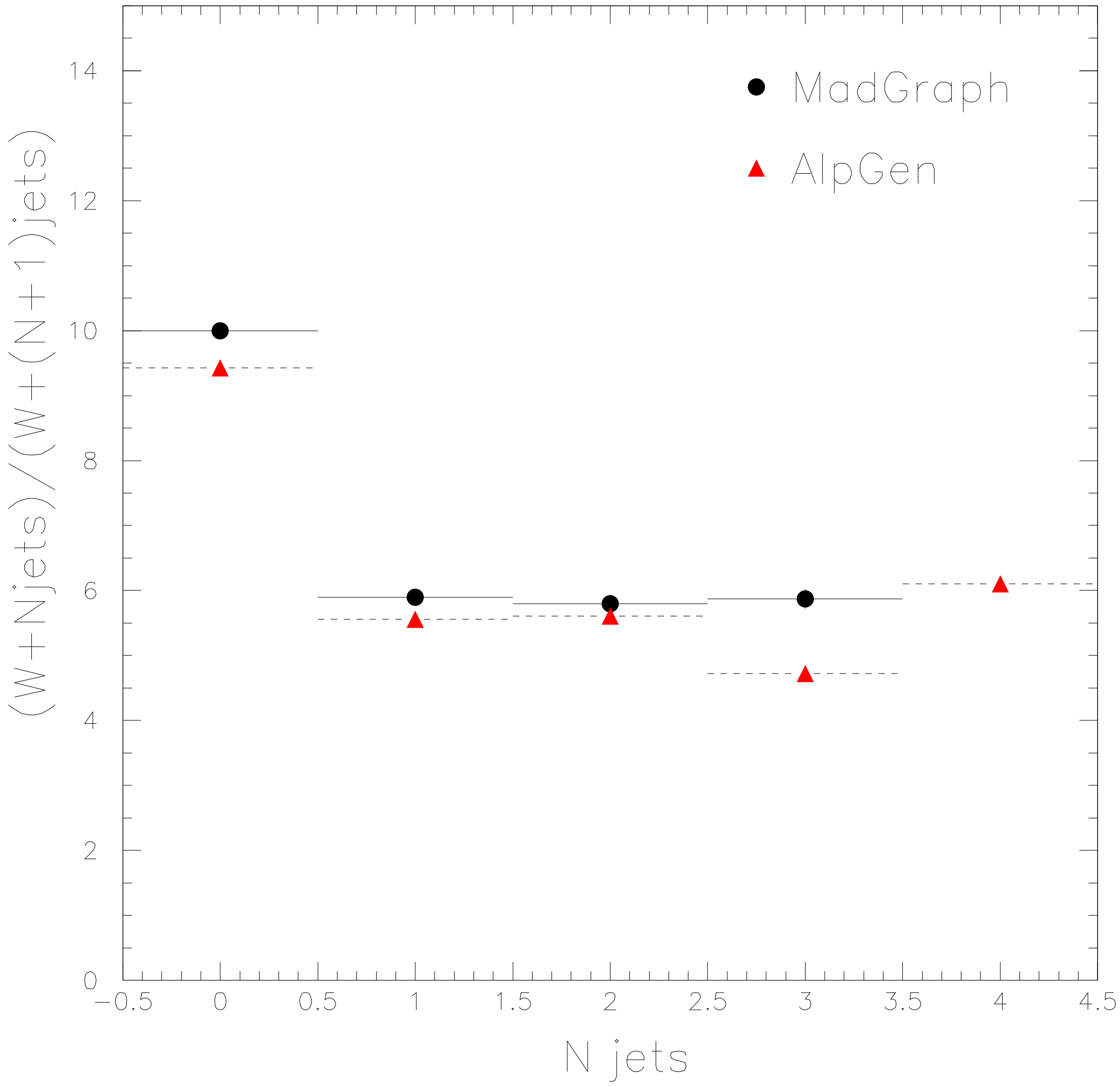


Figure 8:

(W+Njets) / (W+N+1jets) versus Njets for MadGraph and ALPGEN.

MadGraph v. ALPGEN: Z Ratios

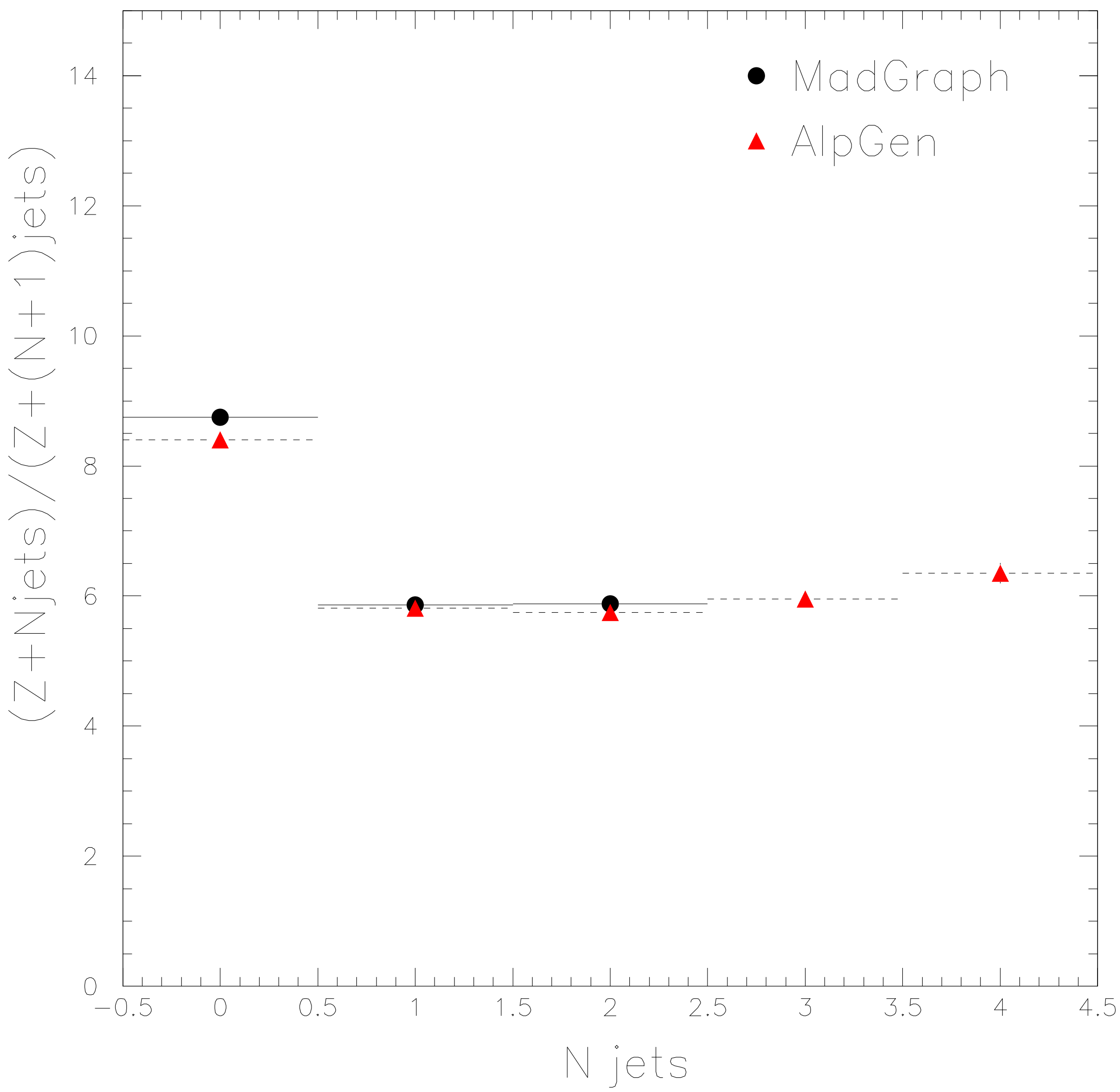


Figure 9:

(Z+Njets) / (Z+N+1jets) versus Njets for MadGraph and ALPGEN.

MadGraph v. ALPGEN: W/Z Ratio

W+Njets / Z+Njets (MLM cuts)		
N jet	ALPGEN	MadGraph
0	14.41 ± 0.06	12.16 ± 0.09
1	12.83 ± 0.14	10.64 ± 0.11
2	13.39 ± 0.07	10.57 ± 0.17
3	13.73 ± 0.19	10.70 ± 0.26
4	17.31 ± 0.21	$\pm$
5	18.03 ± 0.49	$\pm$

Table 13:

A tabulation of ALPGEN and MadGraph predicted W/Z ratio.

We are working to understand these numbers; the ALPGEN ratio seems to increase beginning at 4 jets. The corresponding MadGraph numbers are still running - it will be interesting to see if the MadGraph ratios follow the same pattern.

MadGraph v. ALPGEN: W/Z Plot

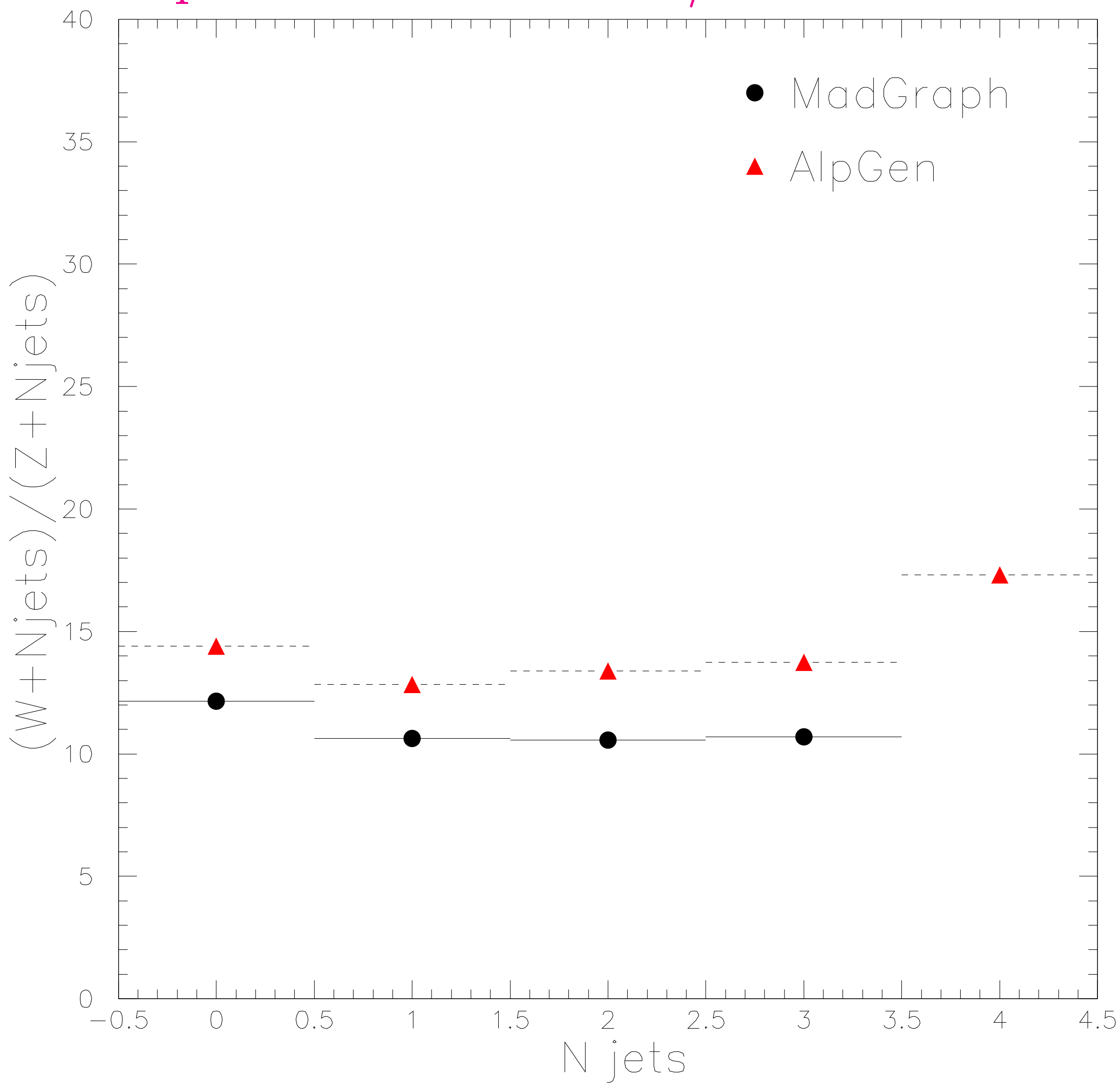


Figure 10:

(W+Njets) / (Z+Njets) versus Njets for MadGraph and ALPGEN. This plot pointed to a bug in ALPGEN.

MadGraph v. Data

The data from Run I, at $\sqrt{s} = 1.8$ TeV, were extracted from the Duke studies.

N	σ_{W+Nj}	σ_{Z+Nj}	$\sigma_{W+Nj} / \sigma_{Z+Nj}$	$\sigma_{W+Nj} / \sigma_{W+N+1j}$	$\sigma_{Z+Nj} / \sigma_{Z+N+1j}$
0	2019 $\pm$ 108	185.8 $\pm$ 11.1	5.43 $\pm$ 0.44	5.46 $\pm$ 0.78	5.23 $\pm$ 0.87
	$\pm$ 68	$\pm$ 6.7	$\pm$ 0.27	$\pm$ 0.53	$\pm$ 0.60
1	370 $\pm$ 48.8	35.5 $\pm$ 5.5	5.21 $\pm$ 1.06	4.46 $\pm$ 1.10	4.55 $\pm$ 1.26
	$\pm$ 34	$\pm$ 3.9	$\pm$ 0.75	$\pm$ 0.81	$\pm$ 0.93
2	83 $\pm$ 17.3	7.8 $\pm$ 1.8	5.32 $\pm$ 1.65	5.42 $\pm$ 1.98	4.88 $\pm$ 1.97
	$\pm$ 12.9	$\pm$ 1.34	$\pm$ 1.23	$\pm$ 1.30	$\pm$ 1.46
3	15.3 $\pm$ 4.6	1.6 $\pm$ 0.53	4.78 $\pm$ 2.14	5.28 $\pm$ 4.48	3.72 $\pm$ 1.92
	$\pm$ 2.8	$\pm$ 0.39	$\pm$ 1.46	$\pm$ 3.77	$\pm$ 1.73
4	2.9 $\pm$ 2.3	0.43 $\pm$ 0.17	3.37 $\pm$ 2.99		
	$\pm$ 2.0	$\pm$ 0.17	$\pm$ 2.68		
5					

Table 14: The cross sections times branching ratio for W+Njets and Z+Njets production (first two columns) extracted from the CDF measurements versus the number of jets, at $\sqrt{s} = 1.8$ TeV. These are used to calculate the ratios of the W+Njet to Z+Njets jet cross section times branching ratio (third column). Also shown are the (less robust) ratios of W+Njets to W+N+1jets and Z+Njets to Z+N+1jets. The first uncertainty given is the uncorrelated error, while the second is the correlated error.

MadGraph v. Data - W Ratios

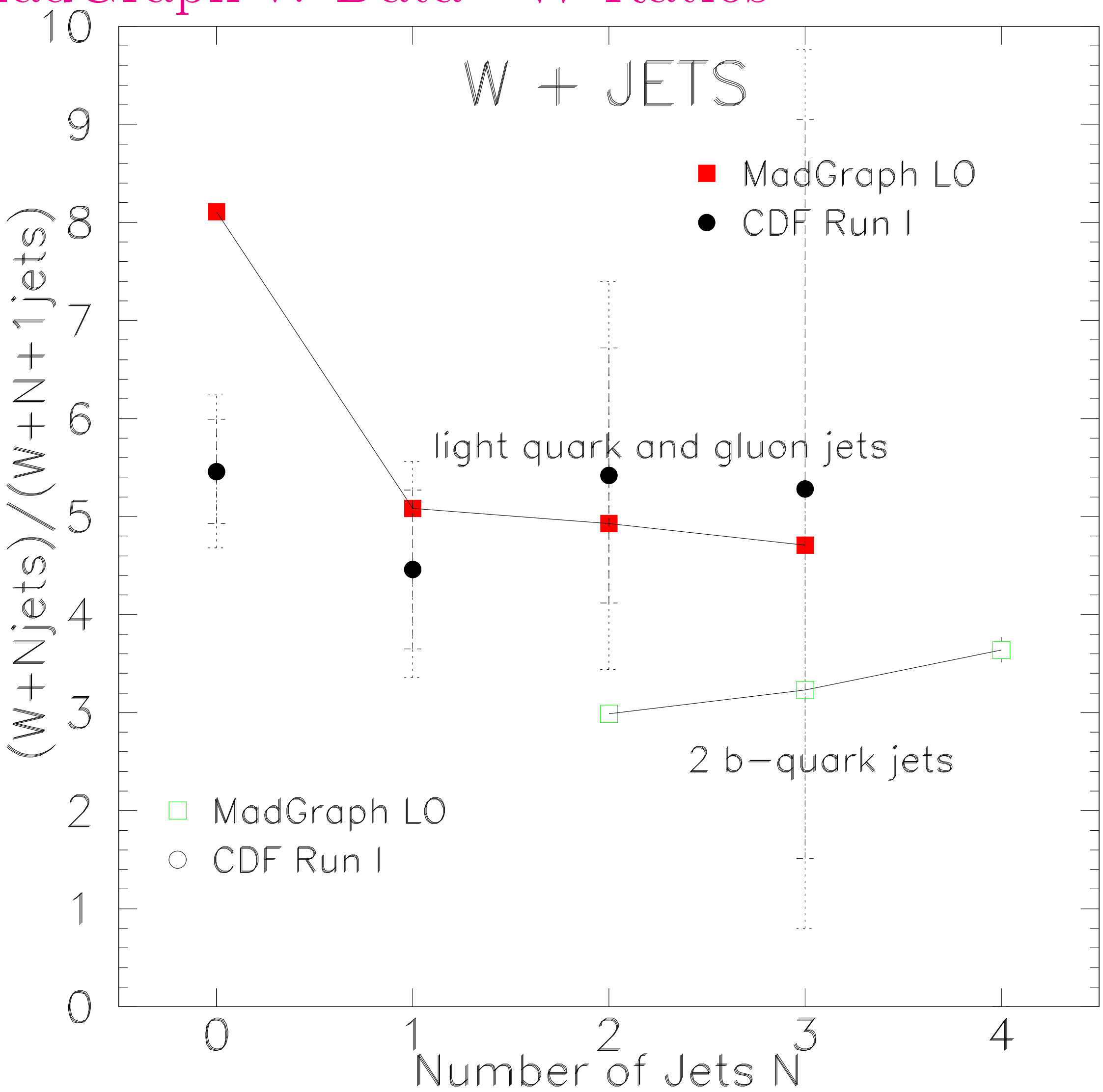


Figure 11:

The ratio (W+Njets)/(W+N+1jets) versus N for both MadGraph and CDF data (with error bars for both correlated and uncorrelated errors).

MadGraph v. Data - Z Ratios

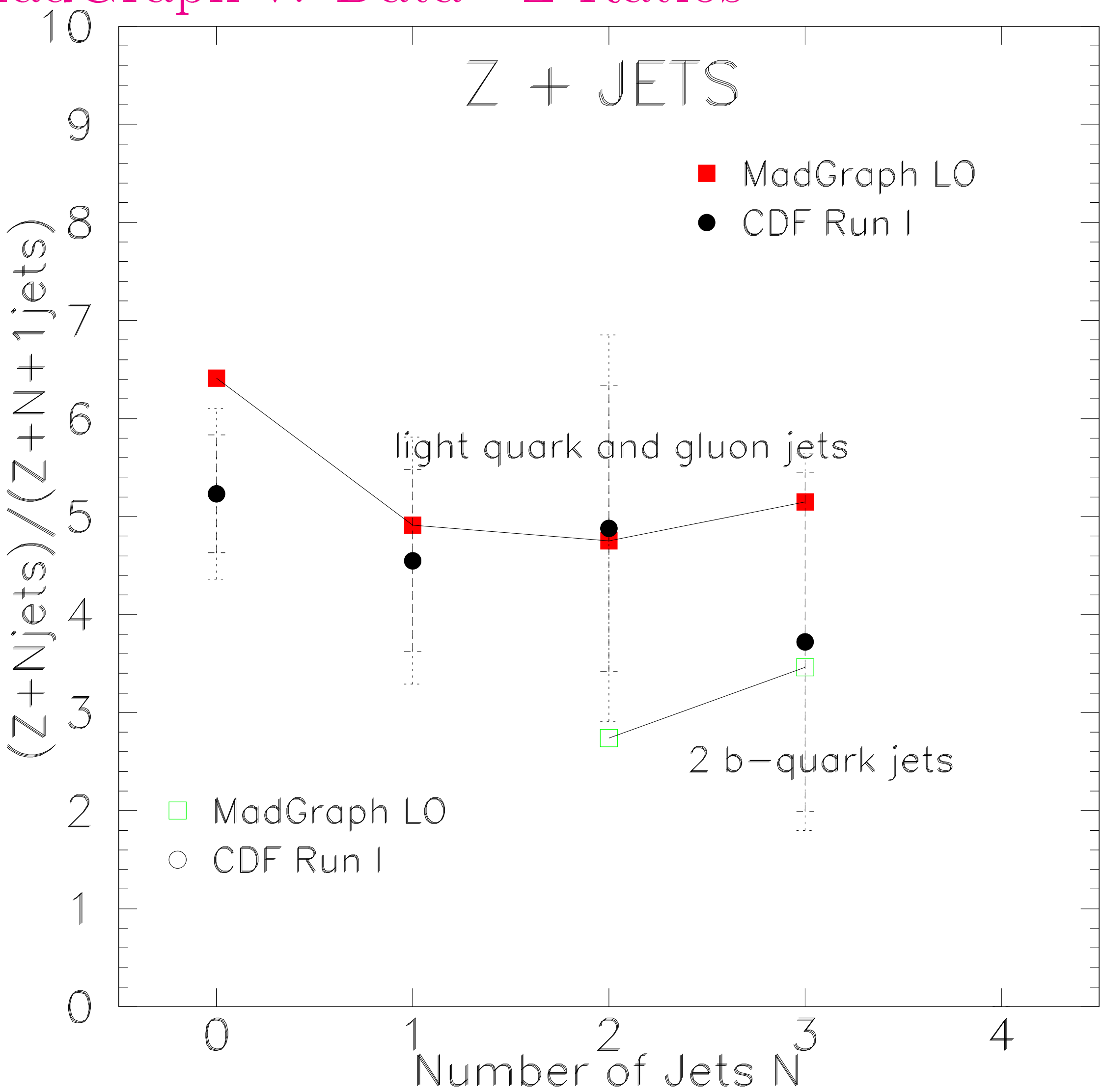


Figure 12:

The ratio (Z+Njets)/(Z+N+1jets) versus N for both MadGraph and CDF data (with error bars for both correlated and uncorrelated errors).

MadGraph v. Data - W/Z Plot

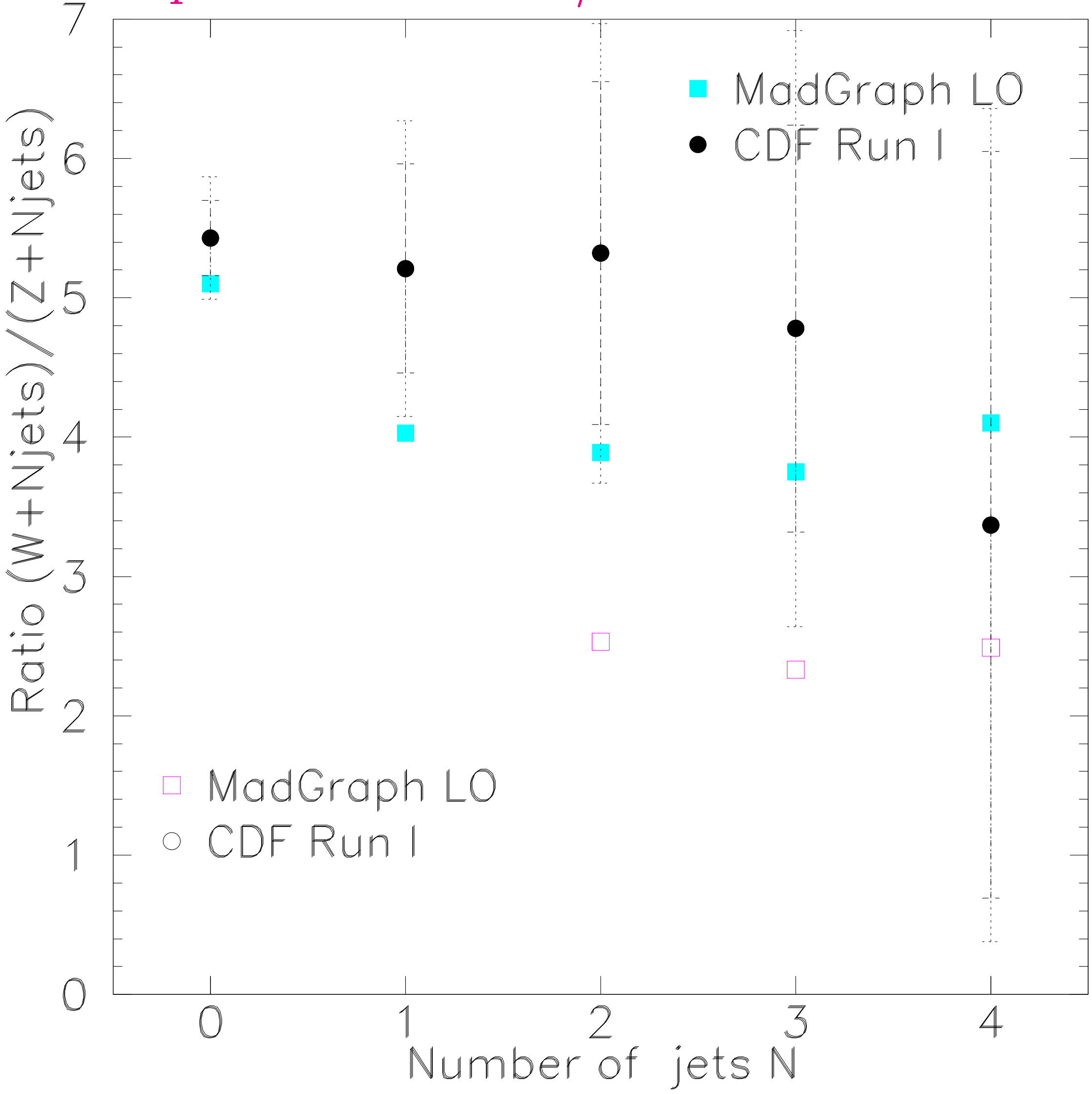


Figure 13:

The ratio (W+Njets)/(Z+Njets) versus N for both MadGraph and CDF data (with error bars for both correlated and uncorrelated errors).

Other studies in progress

- Q^2 scale study - the scale in MadGraph can be changed. How do the W/Z ratios depend on the scale? Currently, we are calculating W+jets and Z+jets cross sections with $Q^2 = {V_{mass}}^2 + {P_{T,V}}^2$, keeping all the other original MadGraph cuts to do a comparison. Some preliminary results are below.

W+Jets Cross Sections (pb)			
N jet # b	$Q^2 = {W_{mass}}^2$	$Q^2 = {W_{mass}}^2 + {P_{T,W}}^2$	$Q^2 = {W_{mass}}^2 + {P_{T,W}}^2 / Q^2 = {W_{mass}}^2$
0 j 0 b	341.5 ± 0.5	343 ± 2	1.004 ± 0.006
1 j 0 b	42.1 ± 0.3	45.4 ± 0.3	1.078 ± 0.010
2 j 0 b	8.28 ± 0.05	9.26 ± 0.09	1.118 ± 0.013
3 j 0 b	1.68 ± 0.02	1.99 ± 0.03	1.185 ± 0.023
4 j 0 b	0.357 ± 0.005	0.428 ± 0.007	1.199 ± 0.026
Z+Jets Cross Sections (pb)			
N jet # b	$Q^2 = {W_{mass}}^2$	$Q^2 = {Z_{mass}}^2 + {P_{T,Z}}^2$	$Q^2 = {Z_{mass}}^2 + {P_{T,Z}}^2 / Q^2 = {W_{mass}}^2$
0 j 0 b	67.0 ± 0.2	67.1 ± 0.3	1.001 ± 0.005
1 j 0 b	10.45 ± 0.01	11.0 ± 0.1	1.053 ± 0.010
2 j 0 b	2.13 ± 0.03	2.24 ± 0.03	1.052 ± 0.020
3 j 0 b	0.448 ± 0.006	0.468 ± 0.006	1.045 ± 0.019
4 j 0 b	0.087 ± 0.001	0.099 ± 0.001	1.138 ± 0.017

Table 15:

A comparison of W,Z cross sections for different Q^2 scales.

Plot - Ratio of different Q^2 scales for W and Z

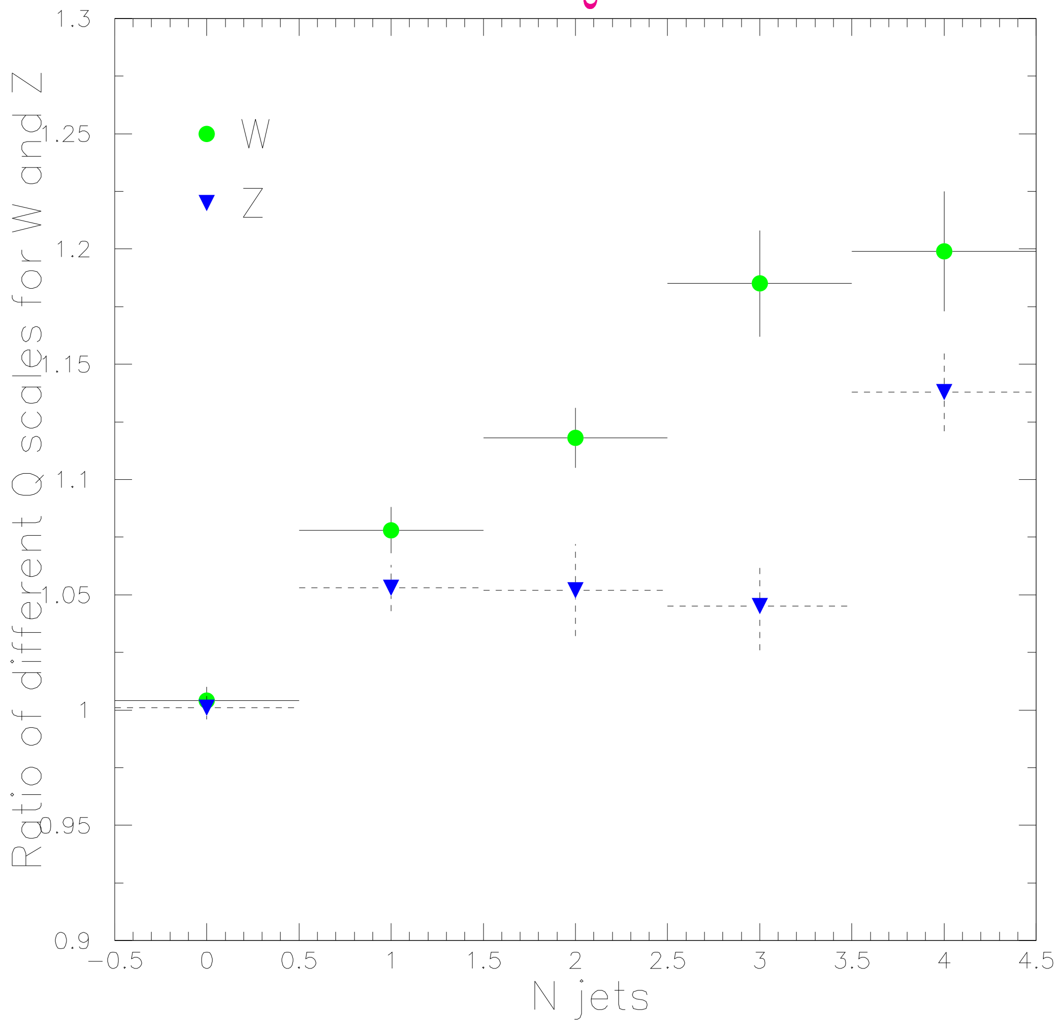


Figure 14:

The ratio of W+Njet cross sections where $Q^2 = {W_{mass}}^2$ to W+Njet cross sections where $Q^2 = {W_{mass}}^2 + {P_{T,W}}^2$ versus N jets (green dots). The ratio of Z+Njet cross sections with $Q^2 = {W_{mass}}^2$ to Z+Njet cross sections with $Q^2 = {Z_{mass}}^2 + {P_{T,Z}}^2$ versus N jets (blue triangles).

Other studies in progress

- We have a new version of MCFM that we can use to make predictions for different Q^2 scales - we can then compare the MCFM predictions to those from MadGraph.

- We want to understand any discrepancies among the predicted cross sections and ratios for MadGraph, ALPGEN, CompHep, and MCFM before moving on to anything more complicated - such as adding showering, etc.

- PDF study - MadGraph can be modified to use structure functions other than CTEQ5L. How do the W/Z ratios depend on the pdf used?