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The Ratio of $W + N$-jets To $Z + N$-jets Versus N As a Precision Test of the Standard Model

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DRAFT

Abstract

Ratios of measured numbers allow the cancellation of systematic uncertainties. The production of heavy particles with quantum numbers conserved by the strong interaction will contribute to signatures with one or more electroweak bosons, and in many cases some number of accompanying jets. The W and Z bosons are relatively easy to detect, as they are heavy, and have leptonic decay modes. This note proposes an inclusive signature-based search for new physics by the precision measurement of the ratios (W+0 jet)/(Z+0 jet), (W+1 jet)/(Z+1 jet), (W+2 jets)/(Z+2 jets),... (W+N jets)/(Z+N jets), with N at least as large as 7, as a search mechanism for new physics, starting from the inclusive e and μ samples. These ratios can also be formed for the case where one more of the jets is tagged as a b or c quark. Among the systematics that at least partially cancel are the luminosity, good-run/file related issues, PDF's, detector acceptance and efficiencies, and systematics of jet finding and b-tagging. By analyzing all the N-jet channels at once, in a common framework, we can look for anomalies at each value of N, while using the others as control samples. In addition, the analysis will produce a measurement of the top cross-section normalized to the W cross section, a quantity that can be predicted free of the 10% uncertainty presently associated with the ratio to the total cross section. This method will be statistics-limited in Run IIa, and should continue to be viable in Run IIb and at the LHC.

1 Introduction

The W+jets signature is the signal for a number of highly interesting modes. One can go through the list of CDF notes and see how many of the significant and interesting analyses

have involved these channels. I list some of the past CDF analyses to show the scope covered by this signature, and hence the importance of robust theoretical predictions[1]. In many of these the identification of b-jets has been important, with two notable examples being the top discovery and the Higgs searches. We should be able to do both bottom and charm identification in Run II. In the future there may be newly predicted sources of W's or Z's with jets, or we may find that the current predictions do not agree with our Run II measurements and the source is something that was not yet predicted. The list below starts with searches for new physics, where the W and Z + jets channels are the SM backgrounds.
The W+2 jets channel has been used for the search for associated Higgs production, W+H [2, 3, 4, 5, 6, 7, 8, 9, 10, 11], for searches for W' decay into WZ [12, 13], for WW production[14], for searches for technicolored hadrons [15, 16] and leptoquarks LQ1 and LQ2 [17, 18, 19, 20], for single top production $t\bar{b}$ [21, 23, 25, 26, 27], and for light supersymmetric particles and/or an anomalously produced Higgs ('superjets') [28, 29, 30, 31]. The production of jets in both W and Z channels is an important background in the search for squarks and gluinos in the $\not\!\!E_{\mathrm{T}}+\geq$1 jets channel[32].
The semileptonic channels of W+ 3/4 jets followed by $\mathrm{W}^{\pm} \rightarrow e^{\pm}\nu$ or $\mathrm{W}^{\pm} \rightarrow \mu^{\pm}\nu$ have been the dominant channel for studies of the top quark [47, 48, 49, 50, 51].
The interest in the W/Z+ n jets channel extends up to large values of n, beyond what we have calculated so far. For example, the W+ 6 jets signature is the signature for associated Higgs production with a top quark pair [52], as well as a measure of QCD radiation in top quark pair production [53].
In addition to being the key to explicit searches for physics beyond the SM, the production of a W or a Z + jets has been studied to test QCD predictions[54, 55, 56]. These measurements include detailed analyses of the limiting systematic uncertainties as well as presenting the measured cross-sections (see Section 5).
The Duke studies have also been extended to include the case in which a photon is also produced in conjunction with the W or Z and the jets[57].
The idea of using the ratio of W/Z inclusive production as a precise method of determining the leptonic branching ratios of the W is due to Cabibbo [58]. There have been a number of measurements in CDF (each a PhD thesis) in both the electron [59, 60, 61] and muon [62] channels. The idea of measuring the W/Z ratio in each jet channel has been around for a while[63]; the first explicit measurement that I know of is in the context of the squark-gluino search of Ref. [32].
The production of heavy particles with quantum numbers conserved by the strong interaction will contribute to signatures with one or more electroweak bosons, and in many cases some number of accompanying jets. This note proposes a precision measurement of the ratios (W+0 jet)/(Z+0 jet), (W+1 jet)/(Z+1 jet), (W+2 jets)/(Z+2 jets),... (W+N jets)/(Z+N jets), for N between 0 and at least 7, as a search mechanism for new physics. The ratios can be measured using W and Z bosons identified with a common 'first leg', a charged e or μ, starting from the inclusive e and μ samples. These ratios can also be formed for the case where one more of the jets is tagged as a b or c quark. Among the systematics that at least partially cancel are the luminosity, good-run related issues, PDF's, detector acceptance and lepton identification efficiencies, and systematics of jet finding and b-tagging. In addition doing all values of N, from 0 to as high as we can expect to see events, with the same background samples, jet definitions, Monte Carlo parameters, etc., will allow a more

systematic treatment of 'feed-up' and 'feed-down' and other issues.
New physics, such as supersymmetry, extra dimensions, new gauge symmetries, technicolor, etc., would most likely populate W+ n jet channels differently from the corresponding Z+ n jet channels. In addition, it would most likely feed some set of n's differently from others. For example, a heavy W' could decay into WZ; while the signature has both a W and a Z, the branching ratios of the W and Z into leptons are very different (and the jet branching ratios are different too), so that the W/Z + 2 jet ratio would be different from the SM prediction at large values of jet E_T.
One comment on the notation 'Z' is in order. By 'Z' we mean the high-mass dilepton signature and thus include contributions from the photon pole as well as the Z pole. The definition of a Z will be such that it is dominated by the Z^0 pole (e.g. $m_{\ell\bar{\ell}} > 50$ GeV, for example, and will be open-ended on the high end so that contributions from new heavy Z-primes, for example, will enter into the table. However the dominant contributions to the table are expected to be from the Z^0 pole.

2 Theoretical Predictions: Current Status

The study of the production of jets associated with vector bosons has been an active field for some time, and has progressed enormously. A concise summary of the history is given in the introduction to Ref [33] and is partially repeated below. In addition to the progress in fundamental understanding and calculational techniques the availability of Monte Carlo (MC) codes that can produce unweighted events for input to detector simulations for direct comparison with data has also improved dramatically.
Leading order predictions that produce unweighted W or Z + jet events can be made with Herwig, Pythia, Isajet, Vecbos, and Resbos, among other programs. In addition there are generators such as Comphep, Grace and Madgraph, which are then interfaced through standard interfaces to shower monte carlos for fragmentation and radiation, and which take into account all relevant amplitudes and diagrams and keep track of the spins through the decay chain as well.
For the V (W or Z) + 1 jet channel, next-to-leading order (NLO) QCD predictions were made in references [40, 41, 42]. More recently, NLO predictions have been made both for heavy quark production and generic (any one of the 5 quark flavors u,d,c,s,b) jet production [35, 36]. The production of a single high-pt c-jet measures the strange content of the proton; that of a b-jet will constrain the fragmentation function of gluon splitting to $\bar{b}$ pairs. This channel should serve as a control sample for the W/Z ratio in the higher n-jet bins. Early calculations at NLO for the production of jets were
The production of W + 2 jets was calculated at LO in references [37, 38, 39]. Recently Campbell and Ellis have made calculations of both W and Z (including the photon amplitude) production at NLO [33]. In addition to the production of 'generic' jets, the paper calculates the production of two tagged b-jets [34]. This paper has many of the distributions relevant to the discussion of focusing on the *ratios* of numbers of events and distributions in each bin of N jets and M b-jets as the measured quantities[1].

[1]The distinction comes in how optimizes the measurement so that the uncertainties in the numerator and denominator cancel, and in how one calculates the correlated uncertainties, obviously.

The V+ 2-jet bin with 1 or 2 b-tags is the signal channel for single top and Higgs production in the SM, and for various new physics signatures such as $W' \to t\bar{b} \to Wb\bar{b}$, and similar decay modes in SUSY of charged Higgs bosons, for example. Of these, the Higgs (and any new particle that couples to both the W and the Z) will not change the ratio, but as it is a 2-body decay the maximum sensitivity will be by looking for a mass peak in the combined W and Z decay channels as has been done by CDF [5]. Single top production and new charged particles that decay into W's but not into Z's will change the ratio; as these are often 3-body decays, there is no narrow mass peak for which to hunt.
The production of V plus up to 4 jets has been calculated at LO in references [43, 44]. The calculation of V plus up to 6 jets in the more complex case in which 2 of the jets are a $\bar{b}$ pair (channels of very high interest) is described in Ref. [45].
Table 1 is a collection of various predictions for W and Z + jet production at the Tevatron. Tables 10 and 11, in contrast, would be a coherent effort (although only at LO) to make datasets of generated unweighted events with a uniform set of initial conditions (e.g. pdf's, eta ranges, pt cuts, b-tagging, etc.). It is these latter tables that we are now working to fill in with self-consistent LO predictions for $\sqrt{s}$ =1.96 TeV; the question of NLO is a harder one, for which we will need additional help.

Process	Ref	Order	$\sqrt{s}$	Lepton cuts	Jet cuts	b,c cuts	σ (pb)	
W+0j	[44]	LO	1.8	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	745	
W+1j	[44]	LO	1.8	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	120	
W+2j	[44]	LO	1.8	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	26	
W+3j	[44]	LO	1.8	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	4.8	
W+4j	[44]	LO	1.8	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	0.71	
W+2j	[39]	LO	1.8	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	17-27	
W+2j2b	[45]	LO	2.0	none	$E_T > 20; \|\eta\| < 2.5$	$\Delta R > 0.4$	0.360	2 b tags
W+3j2b	[45]	LO	2.0	none	$E_T > 20; \|\eta\| < 2.5$	$\Delta R > 0.4$	0.106	2 b tags
W+4j2b	[45]	LO	2.0	none	$E_T > 20; \|\eta\| < 2.5$	$\Delta R > 0.4$	0.027	2 b tags
W+5j2b	[45]	LO	2.0	none	$E_T > 20; \|\eta\| < 2.5$	$\Delta R > 0.4$	0.0058	2 b tags
W+6j2b	[45]	LO	2.0	none	$E_T > 20; \|\eta\| < 2.5$	$\Delta R > 0.4$	0.0011	2 b tags
W+2j	[33]	NLO	2.0	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	?	
W+2b	[33]	NLO	2.0	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	$\Delta R > 0.7$	?	
Z+2j	[33]	NLO	2.0	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	?	
Z+2b	[33]	NLO	2.0	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	$\Delta R > 0.7$	?	
W+0j	[46]	NLO	?	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	760	
W+1j	[46]	NLO	?	$E_T > 20; \|\eta\| < 1.0$	$E_T > 15; \|\eta\| < 2.0$	—	115	
W+2b	[35]	NLO	2.0?	none?	$E_T > 10; \|\eta\| < 3.0$	none?	9.1	1 b tag

Table 1: Some published predictions of the integrated cross section for W and Z+jet production measured in charged lepton decays at the Tevatron. Details and distributions are given in the references (before using any of these numbers one would have to read the reference!). Different PDF's and $\Delta - R$ cuts are used; see the references for precise details. W+charm jets is given in some references but not tabulated here.

3 Analysis Strategy and Data Sets

3.1 Overall Analysis Strategy: First and Second Legs

The previous CDF inclusive measurements [60, 59, 61, 62] of R, the ratio of W to Z production, have used the inclusive high-p_T electron and muon samples [64] as their starting point. The strategy was to select one high-p_T central lepton (the 'first leg') in a way common to both W's and Z's, and to select the second leg by $\not\!\!E_T$ for W's or a loose electron in central, plug, or forward for Z's, with thresholds so that the kinematics of the selection would be similar for W's and Z's. This way the efficiencies for the first leg largely cancel (there is a second-order effect because the Z has two chances to have a leg be central), and since the events are selected from the same data set the luminosities and book-keeping issues such as lost files etc. also cancel.

We propose to use the same strategy with respect to the starting samples: we will use the inclusive electron and muon high-p_T samples, fed by the ELECTRON_CENTRAL_18 and MUON_CMUP18 and MUON_CMUX18 (when it exists) triggers. The Express line triggers will be used for dataset.

The threshold in E_T on the first leg is 25 GeV. The Run 0 electron R analysis used a 20 GeV threshold on the first leg, but explored the higher thresholds of 25 and 30 GeV[65]. The Run Ia electron analysis[66] used 25 GeV as the first-leg threshold, which was close to the optimum found in Run 0.

The thresholds for the second electron leg in the plug need to be investigated; in Run I we used 20 GeV for a second central electron, 15 GeV for the (old) plug and 10 GeV for the forward calorimeter. For electrons in the central region we plan this time to have only a 'tight' selection, as the gain from a loose category is small. This will simplify efficiency calculations (this is also what the dilepton group has decided).

For the second leg of muons we expect an evolution as the tracking performance at larger values of η becomes understood. For now we expect to use only the region in η covered by the COT. In addition, given that the efficiency for a second tight muon may be small, we will probably want a looser selection, such as requiring only CMU, or possibly only an isolated CMIO. The muon R measurements have very different backgrounds and systematics; here we concentrate on electrons for now.

3.2 Jet Identification Criteria

Jets are identified using a cone of radius 0.4, within the rapidity region $|\eta| < 2.5$. The choice of E_T threshold is tricky, as there is an optimum for which 'feedup' (the promotion from the n-jet bin to the (n+1)-jet bin due to ISR/FSR, fragmentation, or jet-algorithm splitting), and 'feed-down' (the demotion from the n-jet bin to the (n-1)-jet bin due to merging of jets or the loss of a jet in reconstruction) effects are minimized with respect to the predictions of the LO generators. This is an active area of study [67]: for now we will take 15 GeV (corrected Et) as a first guess.

Quantity	Selection
Jet Et (corrected)	> 15 GeV
Jet $\|\eta\|$	< 2.5
Lepton-jet separation ΔR	>0.4
Jet-jet separation ΔR	>0.4
Not γ, e, μ, or τ	

Table 2: The jet selection criteria used in counting jets. The lepton-jet separation $\Delta - R$ is a place-holder before further study, as the isolation requirement on the leptons (cone of 0.4) forces an implicit separation of at least 0.4. Similarly, the jet-jet separation requirement should always be satisfied, but is listed explicitly for simple simulations.

3.3 B-Jet and C-jet Identification Criteria

B-jets and C-Jets will use whatever is the canonical (but non-NN) SVX b-tagging algorithm. The discrimination between b-jets and c-jets should use all the available information, including the longitudinal and transverse distributions of tracks in the jet, in a transparent way [68].

3.4 W Selection Criteria

The cuts for defining W events are given in Table 3. The lepton refers to the 'first leg' as discussed above, which is selected from the inclusive lepton samples just as the first leg is for the Z selection.

Quantity	Selection
Lepton 1 E_T (p_T)	>25 GeV
Lepton 1 $\|\eta\|$	<1.0
Neutrino Et ($\not\!\!E_T$)	>25 GeV
Neutrino $\|\eta\|$	<9.0

Table 3: The W sample selection. 'Lepton 1' refers to the first (and usually only) charged lepton leg. Additional leptons and/or photons in these events will be additionally counted in subsamples as was done for the $\gamma\gamma + X$ analysis.

3.5 Z Selection Criteria

The cuts for defining Z events are given in Table 4.

Quantity	Selection
Lepton 1 E_T (p_T)	>25 GeV
Lepton 1 $\|\eta\|$	<1.0
Lepton 2 E_T (p_T)	>25 GeV for $\|\eta\|$ <2.5

Table 4: The Z sample selection. 'Lepton 1' refers to the first charged lepton leg. Additional leptons and/or photons in these events will be additionally counted in subsamples as was done for the $\gamma\gamma + X$ analysis. A requirement of opposite-charge for the two leptons is made for the final counting, but not for the selection process.

4 Analysis Path: Data Sets and Flow Diagram

Figure 1 shows the analysis flow, starting with the inclusive electron and muon samples.

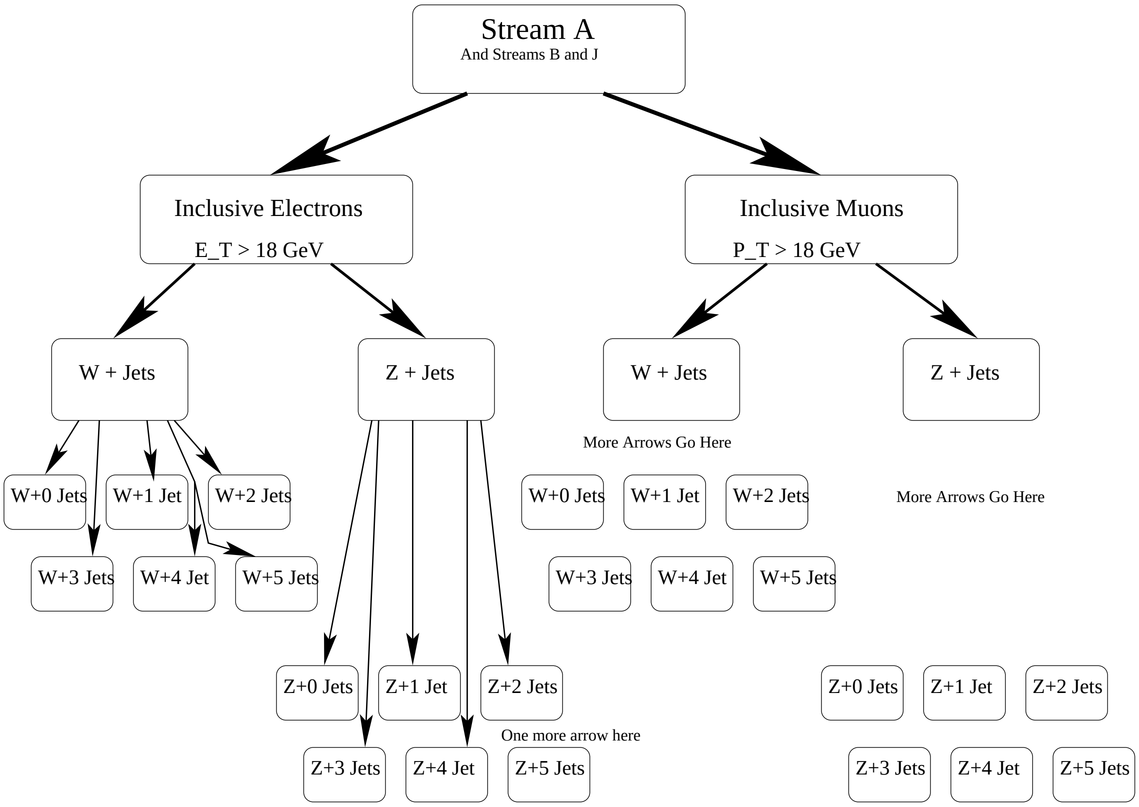

Figure 1: Schematic of the data flow. We will use Stream A as it contains the Level 3 banks and the inclusive leptons from Streams B and J. We hope to have predictions for up to 7 jets, although only 5 are shown for clarity. Not shown is the further subdivision into b-tags (and possibly even charm).

5 Systematic Uncertainties: Sensitivity to New Physics

I have used the cross sections and uncertainties measured in the Duke analysis [56] to make an initial estimate the achievable sensitivity in the W/Z ratio method. With the higher statistics of Run II and the improved theoretical tools it should be possible to improve on these numbers, but it will help to get a sense of how well one could do from the Run I numbers. Note that in the many cases where a b-quark is part of the signature, such as (one of the) Higgs or top, the cross-section limits will be much lower, as the percentage uncertainty is then on the cross section for N jets containing M b-jets [24].

Table 5 repeats the cross sections of Ref.s [56] and gives the percent uncertainties. These numbers are for the *inclusive* N-jet channels, i.e. for $\geq N$ jets for each N.

N(Jets)	$\sigma\times$BR (pb)	Sys Unc (pb)	Sys Unc (%)
$\geq$0	2490 pb	120 pb	4.8%
$\geq$1	471 pb	52 pb	11%
$\geq$2	101 pb	18 pb	18%
$\geq$3	18.4 pb	5.1 pb	28%
$\geq$4	3.1 pb	2.3 pb	42%
$\geq$5	0.2 pb	0.3 pb	117%

Table 5: The measured *inclusive* jet cross sections with their absolute and percentage uncertainties. The numbers for N$\geq$1 are from the Duke analysis [56]; the 0-jet bin is from Ref. [78] (S. Kopp et al.).

We can subtract off the sum of the higher N-jet bins to get the exclusive cross sections (that is, the cross section for W+ N jets, rather than for $\geq$ N.) To get the systematic, I have just subtracted in quadrature, as the largest systematics are the jet energy scale and the underlying event, as discussed below. This isn't quite fair, but I would guess it is not too bad an approximation for now.

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 6: *Exclusive* jet cross sections with their absolute and percentage uncertainties, (crudely) extracted from the inclusive cross sections. The numbers for N$\geq$1 are from the Duke analysis [56]; the 0-jet bin is from Ref. [78] .

5.1 Systematic Uncertainties in W+jets

The systematic uncertainties for the Duke analysis of W+jets are given in Table 10 of Ref [56], along with a discussion of the source of each uncertainty. The dominant uncertainties are from the jet energy scale, and from the contributions from the underlying event. For higher (≥ 4) jet multiplicities QCD backgrounds become comparable to each of the above.
Table 7 presents the percentage uncertainties from each of the systematic sources for the *inclusive* N-jet bins of the Duke W+jets analysis. One can see that in general the quoted systematic uncertainties grow rapidly with N.

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 7: 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 [56]; the upper error bar is used in all cases. Many of these uncertainties will (partially) cancel in the W/Z ratio.

5.2 Discussion of Systematics in the W Cross Section

The categories of systematic uncertainties as well as the estimated magnitudes listed in Table 7 come directly from Ref. [56]. In many cases these systematics should be very close to the same percentage in W+Njet and Z+Njet production for the same N, so that the systematic on the W/Z ratio is *much* smaller. It will take detailed studies, possibly including some consideration of higher-order effects, to make a quantitative estimate of the lack of perfect cancellation. I give a brief discussion [56] of each in turn here, largely to help identify contributing effects and also calculational strategies for the longer-term effort.

- **Jet Energy Scale:** Et_J This is the largest contributor for each of the values of N considered by the Duke group. Because both the W and the Z are color-singlets and therefore don't have any QCD final state radiation, there should be substantial cancellation in the ratio. The only differences are a (small) difference in $\hat{s}$ due to the W and Z mass difference (this is only a fraction of the total $\hat{s}$, and the dependence on $\hat{s}$ is only logarithmic), and the kinematic differences due to the production of Z's in $u\bar{u}$ and $d\bar{d}$ collisions vs the $u\bar{d}$ production of W's which will reflect the different x distributions of the u and d in the proton and the different couplings of the Z and the W. The strong dependence on N (growing rapidly with N) is presumably due to an accumulation of jets near threshold at larger N– it would be good to understand this better to better understand the cancellation in the ratio.
- **Underlying Event** This is the second-largest contributor. As in the case of the Jet Et Scale to first order the contributions in W and Z events should be the same, with the differences coming from the same considerations as above. I do not understand the rapid growth with N– it is presumably similar to the dependence on jet energy scale, in

that higher-N channels have a larger probability of having a jet close to the threshold where the addition of energy can change the N.

- **QCD Background** This is third-largest, and may be one of the hardest to get to cancel, as the backgrounds feeding the 'second leg' of either $\not{E}_t$ (the neutrino) or a high E_T electron are inherently different. The QCD background is complex enough that it is treated in a separate subsection below. I do not understand the strong dependence on N beyond the fact that one can have FSR in QCD events and not in EWK events, leading to a bigger relative cross section.
- **Jets from Multiple Interactions** This should cancel in entirety to first order, as the probability of having a jet from another interaction is independent of whether one has a W or Z in the event[2]. There will be a second-order effect due to 'Obliteration', which should be negligible. I am surprised by the strong dependence on N; I would think that adding another jet from an independent interaction is independent of N (to first order, at least).
- **Eta Cut for Jets** This uncertainty is described in Ref [56] as that due to the cut at $|\eta| = 2.4$ on jets. Because the Z and W are made with different distributions in longitudinal momentum there will be a second-order effect in the jet ηdistribution, calculable by Monte Carlo.
- **Kinematic and Geometric Acceptances** The analysis is designed to make the kinematics of the W and Z samples as close as possible; the acceptance for the first leg is the same, and the Et cuts for the ν and the second electron are similar. Using the bins for n<N to measure the PDF's should make this contribution small compared to the statistical uncertainty in bin N.
- **Obliteration** This refers to the case where an electron is 'obliterated' by a jet. It presumably can be measured well from the data, and checked by Monte Carlo. It shouldn't dominant in the W/Z ratio, just as it is not large in the W+N jets channel.
- **Top Quark** This 'background' is in fact one of the signals whose cross section we want to measure. Tagging one or more b-jets is critical to identifying this process; kinematic fitting to the W and top masses also will help. Separating out Z events from top dilepton events can be done using b-tagging, H_T, and $\not{E}_t$ and $\not{\phi}$ [69].
- The $Z^0 \to e^+e^-$, $Z^0 \to \tau^+\tau^-$ and $W^\pm \to \tau^\pm\nu$ Backgrounds to $W^\pm \to e^\pm\nu$

  Table 10 in Ref [56] does not list as a background the case in which one electron in a $Z^0 \to e^+e^-$ is lost completely, faking a $W^\pm \to e^\pm\nu$ decay (however this background isn't ignored in their analysis). This background is dangerous in the W/Z ratio, as it moves events from the (small) denominator into the (large) numerator. However it can be estimate well using the data for events in which a second track is seen, along with a combination of MC and data [65]. Similarly, the $W^\pm \to \tau^\pm\nu$ data can be estimated from the $W^\pm \to e^\pm\nu$ data and MC [65]. The $Z^0 \to \tau^+\tau^-$ contribution should be very small, and can be measured in the data from $e\mu$ decays and MC.

[2] It is not clear why it grows with N in the Duke numbers above.

5.3 Discussion of the QCD backgrounds to W+N jets

A detailed study of the sources of inclusive high E_T electrons was done in Ref. [65]. For a threshold of 20 GeV in E_T Kopp found that a sample of background electrons was consistent with a mix of 3 sources of comparable magnitudes: photon conversions $(41.5 \pm 2.2\%)$, Heavy Flavor (B's mostly) $((31.5 \pm 3.7\%)$, and isolated hadrons faking electrons $(27.0 \pm 4.4\%)$. Sacha also estimated his W sample had 6.5% background for 20/20 ($E_T/\not{E}_T$) GeV cuts; this dropped to 1.9% when the thresholds were raised to 25/25[3].

Taking the sources in order, photon conversions were the biggest QCD contributor in Run 1a, at 42% of 1.9%=0.8%. The efficiency for finding the second track of the conversion was found to be $(91 \pm 4\%)$ in Run 1a [65]; the efficiency (and unfortunately the rate, as there is more material) should be higher in Run II (the probability that one of the two tracks of a pair be above 25 GeV and the other below 400 MeV is less than a few %). This makes it small compared to the statistical uncertainty; if more rejection is needed, one can limit the amount of material that contributes to conversions by requiring L00 and/or L0 to have a hit on the electron track, and/or by cutting on pulse height against pairs in the SVX.

Heavy flavor production was estimated by Kopp to be a background at the 0.6% in the inclusive $W^{\pm} \to e^{\pm}\nu$ sample in Run I; using the better coverage, more layers, possibly track isolation, and the much-improved impact parameter resolution in Run II, should allow knocking this down below the statistical uncertainty, I believe (this depends critically on detector performance, so far not clear).

Lastly, the rate of fake electrons due to isolated hadrons can be measured directly from the data (provided we have the appropriate trigger).

6 Cancellation of Systematics in the W/Z ratio

How well we do in measuring and controlling the systematic uncertainties will depend critically on the performance of the detector, and in particular the performance of the silicon (the COT and calorimeters seem to be working well). The various components of the systematic uncertainties such as the QCD background can be measured from the data, along the lines of Kopp's treatment.

It is consequently hard to predict, but if the performance meets the TDR specifications, from the above considerations I expect the W/Z ratio measurement in Run IIa to be dominated by statistical uncertainties for N$\geq$3, and by systematic uncertainties for N=0,1,2. Kopp estimated that the systematic uncertainty in 1.0 fb^{-1} in Run II (see Table 9.3 of Ref. [65] would be 1.1%; I will just assume that with 2 fb^{-1} we can reach 1% systematic uncertainty in each of these three bins.

The reach in sensitivity to cross sections for new processes is calculated under these assumptions below, after a discussion of the statistical uncertainties.

[3]John Wahl, with similar ID cuts, except for the inclusion of the removal of conversions in the Run 1B sample, estimated 1.4%, 1.0%, and 0.7% for the QCD backgrounds for Et and $\not{E}_T$ cuts of 20/20, 25/25, and 30/30 GeV, respectively. If one removes the 42% conversions estimated by Kopp, his number becomes 1.1%, in excellent agreement with Wahl's.

7 Statistical Uncertainties

The statistical uncertainties set the scale for how well we have to beat down the systematics. A traditional rule-of-thumb is to get the systematic uncertainties down below 1/3 of the expected statistical uncertainty in a measurement; below that one doesn't gain much, and above that there is the danger that if the systematics are underestimated (they usually are) the total uncertainty is changed significantly. The expected statistical uncertainties in 2 fb^{-1} and 15 fb^{-1} are listed in Table 8. [4]

N(Jets)	N_{ev} 2 fb^{-1}	$\Delta(W/Z)$	N_{ev} 15 fb^{-1}	$\Delta(W/Z)$
0	95,000	0.3%	710,000	0.12%
1	19,000	0.7%	145,000	0.26%
2	4200	1.5%	32,000	0.56%
3	870	3.4%	6500	1.2%
4	180	7.4%	1400	2.7%
5	38	16%	283	5.9%
6	7.8	36%	59	13%
7	1.6	78%	12	29%
8	0.3	–%	2.6	63%

Table 8: The number of expected $Z^0 \to e^+e^-$+N jet events and the percentage statistical uncertainty in the W/Z ratio in 2 fb^{-1}, and in 15 fb^{-1}. The bins up through N=4 use the cross sections of Table 6, measured at 1.8 TeV; the N=5 and higher bins have been extrapolated using an exponential fit. Note that the number of $Z^0 \to e^+e^-$ events in each bin will be approximately a factor of 10 smaller than the corresponding number of W events. Using the $Z^0 \to \mu^+\mu^-$ channel one can gain approximately root-2 on these uncertainties. The higher energy also will improve these numbers.

7.1 Cross Section Reach

Using the systematic and statistical uncertainties above, we can estimate the sensitivity to new physics in each of the N-jet channels by multiplying the uncertainty times the respective W cross section. Table 9 presents the 1-sigma cross-section uncertainties on new physics measured using the predicted W/Z ratios. More sensitivity can come from comparing kinematic distributions or by looking for additional objects in the events (b-tagging being one obvious addition).

7.2 Balancing Statistical and Systematic Uncertainties

The achievable precision in the ratios of (W+Njets)/(Z+Njets) becomes dominated by the statistics of the Z events at large N, especially in the case where some of the jets are required

[4] There might seem to be no point in working too hard on channels for which the number of expected events is much less than one, but in the case where events are observed and few expected the mean number expected and its uncertainty are important in calculating the significance of the observation.

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%)
5	650 fb	100 fb (16%)	40 fb (6%)
6	140 fb	50 fb (36%)	18 fb (13%)
7	28 fb	20 fb (78%)	8 fb (29%)
8	6 fb	——	4 fb (63%)

Table 9: The cross section corresponding to a 1-sigma uncertainty in the W/Z ratio in 2 fb^{-1}, and in 15 fb^{-1}. The bins up through N=4 use the cross sections of Table 6; the N=5 and higher bins have been extrapolated using an exponential, with a factor of 4.8 for each successive jet. Note that the number of $Z^0 \to e^+e^-$ events in each bin will be approximately a factor of 10 smaller than the corresponding number of W events. Using the $Z^0 \to \mu^+\mu^-$ channel one can gain approximately root-2 on these uncertainties.

to be b-tagged. In these cases we would look for a 'hybrid' strategy in which we use other channels in the normalization to lower the statistical uncertainty to be comparable (e.g. a factor of 3 larger) to the systematic uncertainty, to optimize the precision. For example, one could fit the channels at lower N for Z+Njets.

8 MadGraph Generator-Level Predictions of the Ratios

For a first step, we have computed the cross sections at generator level at leading order (LO- i.e. tree level) to get precise predictions before initial-state radiation and fragmentation. These and detector-related effects will be done as a separate step. However it is very useful to see and understand the tree-level predictions before adding in complications. We will need to understand how these LO predictions depend on PDF's as well as comparing different generators.

8.1 A brief description of MadGraph

MadGraph is a matrix element generator[79] which calculates squared amplitudes to leading order using the HELAS library and using the parton distribution function CTEQ 5L. The user inputs a process, parameters (such as a beam energy of 980 GeV for the Tevatron), and selection criteria (such as E_T thresholds); MadGraph outputs Feynman diagrams as well as cross sections with errors for that process. Further, the user may specify the goal number of events to be generated or the desired percent accuracy for the cross section. Note that asking for a process with a jet (denoted 'j' in MadGraph) is equivalent to asking for any of u,d,s,c,g. The user must ask for a b or t specifically. Also, when asking for proton and antiproton as the incoming particles, note that these will only contain light quarks (no b or t quarks).

8.2 Selection criteria; Input parameters

The selection criteria used in generating these cross sections are as follows. For leptons, $E_T > 25.0$ GeV, and for jets, $E_T > 15.0$ GeV. The pseudorapidity cuts are $|\eta| < 1.0$ for the first outgoing electron, $|\eta| < 9.0$ for neutrinos, and $|\eta| < 2.5$ for all jets and electrons other than the first one. For pairs of outgoing particles, $\Delta R > 0.4$. The beam energy is 980 GeV and the Q^2 scale is set to the ${W_{mass}}^2$.

8.3 Predictions for W+jets, Z+jets

The LO predicted W+Njet cross-sections for final state particles satisfying the above selection criteria are listed in Table 10, and shown vs Njets in Figure 2. Table 11, and Figure 3 show the analogous quantities for Z+Njet production. In both figures the lines are a PAW fit of an exponential to the data points and their uncertainties.

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

Table 10: A tabulation of LO SM predicted W+jet cross-sections and uncertainties, giving the cross sections for processes with one W^+ satisfying the selection criteria in the text.

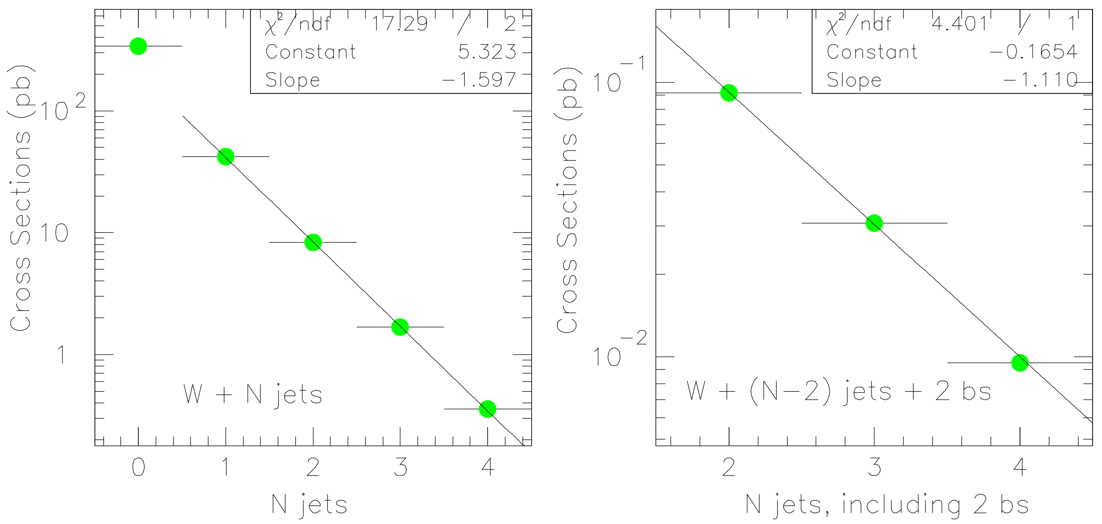

Figure 2: The MadGraph cross sections for $W^+(e^+ + \nu_e)$+Njets vs Njets where the N jets are u,d,s,c,g in the first case, and where 2 b jets are required and the remaining (N-2) jets are u,d,s,c,g in the second case. The positron is required to have $E_T > 25$ GeV and $|\eta| < 1.0$; the neutrino, $E_T > 25.0$ GeV and $|\eta| < 9.0$. The jets are required to have $E_T > 15$ GeV and $|\eta| < 2.5$. (other cuts)

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 11: A tabulation of LO SM predicted Z+jet cross-sections and uncertainties, giving the cross sections for processes with one Z satisfying the selection criteria in the text.

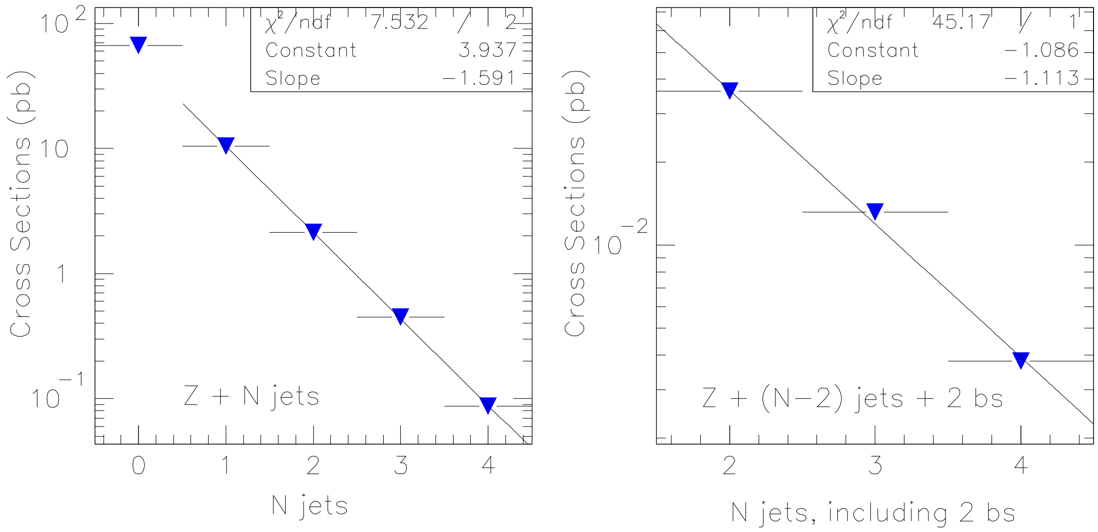

Figure 3: The MadGraph cross sections for $Z^0(e^+e^-)$ +Njets vs Njets where the N jets are u,d,s,c,g in the first case, and where 2 b jets are required and the remaining (N-2) jets are u,d,s,c,g in the second case. The positron is required to have E_T >25 GeV and $|\eta| < 1.0$; the electron, $E_T >$ 25.0 GeV and $|\eta|$ <2.5. The jets are required to have E_T >15 GeV and $|\eta| < 2.5$. (other cuts)

8.4 The Cost of Adding a Jet to a Boson+jet Event:Ratios of (V+n jets)/(V+n+1 jets), with no b-jets

It is well-known that each successive jet in a W+jet or Z+jet event roughly 'costs' a similar factor in cross-section, with the factor being between 3 and 6 depending on the Et threshold for the jet, as shown in Figures 2 and 3.
From the individual cross sections for each N jet channel in Tables 10 and 11, we can calculate the ratios of successive numbers of jets, e.g. (W+0jet)/(W+1jet), (Z+0jet)/(Z+1jet), etc., for up to 5 jets; these are tabulated in Table 12, and shown in Figure 4. Note that the W and Z channels behave quite differently; while we understand this is as yet only at LO, the differences are large and striking.

(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 12: Ratios of cross sections with no b jets included. (W^++Njets)/(W^++(N+1)jets) and (Z^0+Njets)/(Z^0+(N+1)jets)

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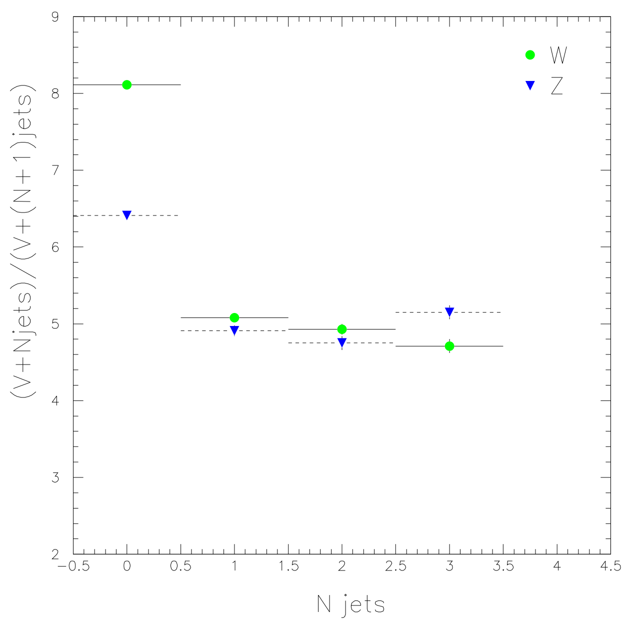

Figure 4: The ratios of cross sections for N jets to N+1 jets for W and Z production, with no b jets produced in the calculation.

8.5 The Cost of Adding a b-quark Pair to a Boson+jet Event:Ratios of (V+n jets)/($Vb\bar{b}$+n-2 jets)

Because so many of the signatures of new physics, the top quark, or of the Higgs boson involve b-quarks, the SM predictions for events with vector bosons and b-quark pairs are of high interest. Table 13 gives the ratio of the cross sections for the case where 2 of the jets are from $b\bar{b}$ pairs relative to the case where there are no b's. These ratios are shown in Figure 5.

(N jets)/($b\bar{b}$+(N-2) jets) for W *or* Z			
W+jets		**Z+jets**	
W+2j/W$b\bar{b}$+0j	90.29 ± .96	Z+2j/Z$b\bar{b}$+0j	58.84 ± .89
W+3j/W$b\bar{b}$+1j	54.72 ± .84	Z+3j/Z$b\bar{b}$+1j	33.94 ± .69
W+4j/W$b\bar{b}$+2j	37.58 ± 1.30	Z+4j/Z$b\bar{b}$+2j	22.83 ± .40
W+5j/W$b\bar{b}$+3j		Z+5j/Z$b\bar{b}$+3j	

Table 13: Ratios of N jets (including no b quarks) to N jets (including two b quarks for W or Z production.

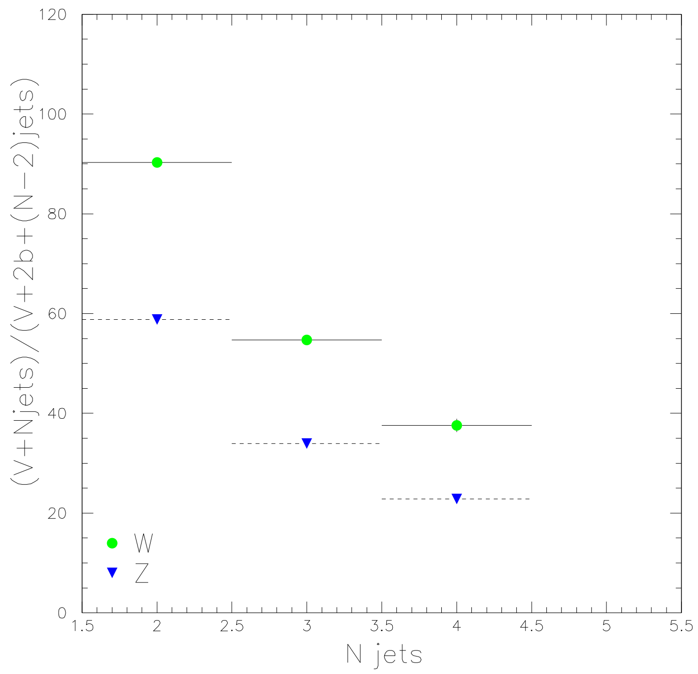

Figure 5: The ratios of cross sections for N jets to 2b+(N-2)jets for W and Z production.

8.6 The Cost of Adding a Jet to a Boson Event with a b-quark Pair: Ratios of (V$b\bar{b}$+n jets)/(V$b\bar{b}$+n+1 jets)

One can ask a different question– given a channel of W or Z with a b-quark pair, how often does one find another (generic) jet? Table 14 and Figure 6 show the ratios of ($Wb\bar{b}$+Njets)/($Wb\bar{b}$+N+1jets) and similarly for Z's.

($b\bar{b}$+Njets)/($b\bar{b}$+(N+1)jets) for W *or* Z			
W+jets		**Z+jets**	
W$b\bar{b}$+0j/W$b\bar{b}$+1j	2.99 ± .04	Z$b\bar{b}$+0j/Z$b\bar{b}$+1j	2.74 ± .04
W$b\bar{b}$+1j/W$b\bar{b}$+2j	3.23 ± .11	Z$b\bar{b}$+1j/Z$b\bar{b}$+2j	3.46 ± .07
W$b\bar{b}$+2j/W$b\bar{b}$+3j	3.64 ± .13	Z$b\bar{b}$+2j/Z$b\bar{b}$+3j	

Table 14: Ratios of W + Njets including 2 b jets to W + (N+1)jets including 2 b jets, and of Z + Njets including 2 b jets to Z + N+1jets including 2 b jets

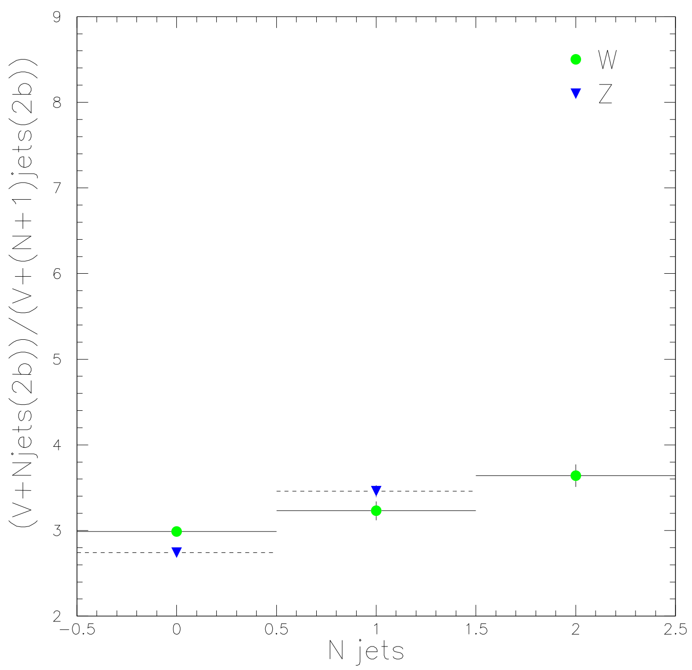

Figure 6: The ratios of cross sections for N jets (including 2 b jets) to N+1 jets (including 2 b jets) for W and Z production.

8.7 Top Pair and Single Top Production Cross Sections

MadGraph allows one to specify the intermediate state through which the final state particles are produced. For example, one can specify top dilepton production by specifying the input as:

$$\bar{p}p \to t\bar{t} \to e^+\nu_e e^-\nu_e b\bar{b} \tag{1}$$

This will create events with a pole at the top mass, but with the correct top width, and with the correct polarizations, which are then propagated down to the final particles.

8.7.1 Top Lepton+ Jets Production

W+Jets Cross Sections (pb) From $t\bar{t}$ and $t\bar{b}$ Int. States			
final state	(QCD, QED)	$t\bar{t}$	$t\bar{b}$
$e^+\bar{\nu_e} + b\bar{b}$			
$e^+\bar{\nu_e} + b\bar{b}$+1j			
$e^+\bar{\nu_e} + b\bar{b}$+2j			
$e^+\bar{\nu_e} + b\bar{b} + b\bar{b}$			

Table 15: This gives cross sections for top lepton+jet events. (This is still being filled in.)

8.7.2 Top Dilepton Production

W+Jets Cross Sections (pb) With Required Intermediate Particles		
final state	(QCD, QED)	$t\bar{t}$
$e^+\bar{\nu_e} + e^- + \nu_e + b\bar{b}$	(2,4)	.0238 ± .0003
$e^+\bar{\nu_e} + e^- + \nu_e + b\bar{b}$+1j		
$e^+\bar{\nu_e} + e^- + \nu_e + b\bar{b}$+2j		
$e^+\bar{\nu_e} + e^- + \nu_e + b\bar{b} + b\bar{b}$		

Table 16: This gives cross sections for top dilepton events. (This is still being filled in.)

8.8 Ratios of (W+n jets)/(Z+n jets), including b-jets

From the above numbers, we can calculate the predictions that we are proposing be the primary numbers that we test against. Table 17 gives the (current) LO predicted ratios for the 'CDF event' cuts described in Section 8.2.

$\sigma W^+/\sigma Z^0$			
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 17: $\sigma W^+/\sigma Z^0$

Figure 7 shows the ratios of W+Njets to Z+Njets versus Njets. For the cases where there are no b-quarks in the final state, one can see large departures from the zero-jet ratio of close to 5 for the 1-jet (high) and 2-and-higher jet bins (low).

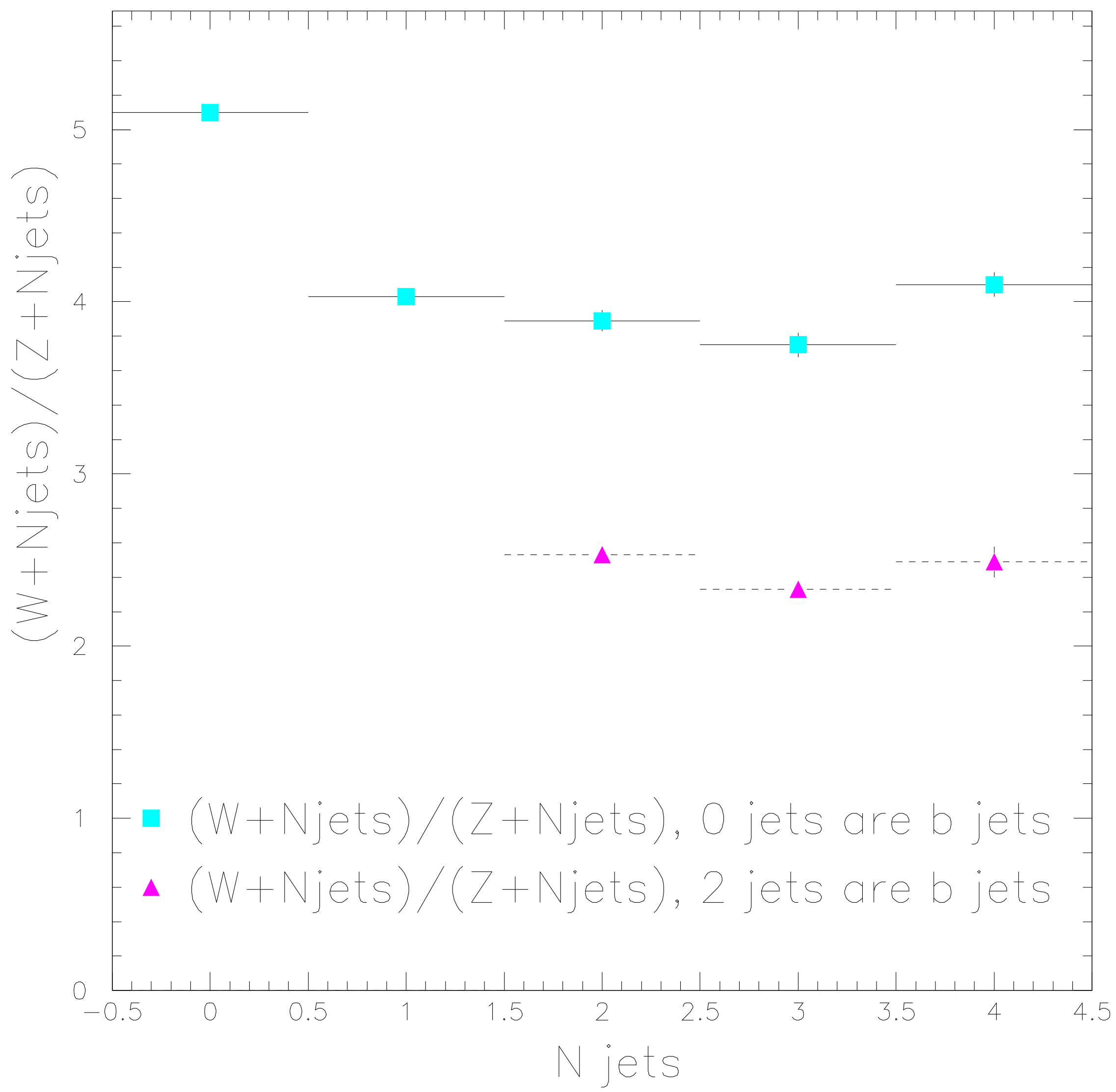

Figure 7: The ratios of W+Njets to Z+Njets versus Njets.

8.9 Summary Plots for W and Z

Figures 8 and 9 summarize some of the ratios for the W and Z processes. Shown are the ratio of V + Njets to V + (N+1)jets and the ratio of V + Njets (including 2 b jets) to V + (N+1)jets (including 2 b jets).

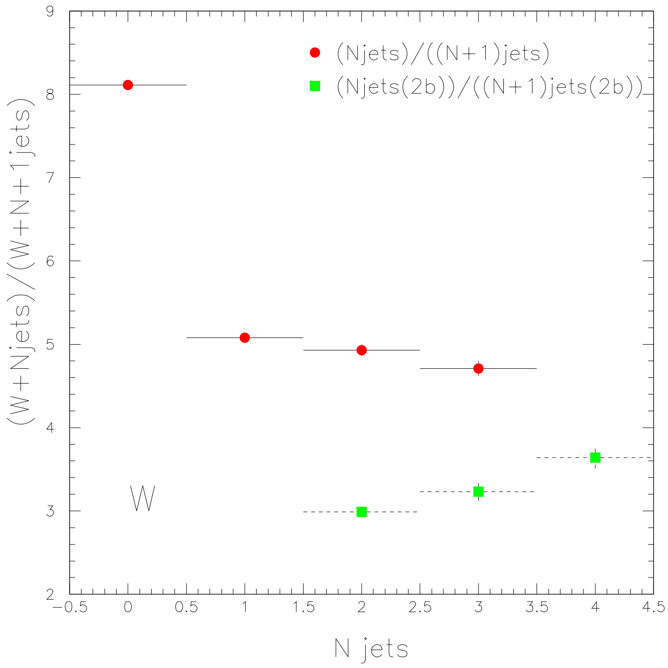

Figure 8: A summary of the ratios of Njets to N+1jets for W production.

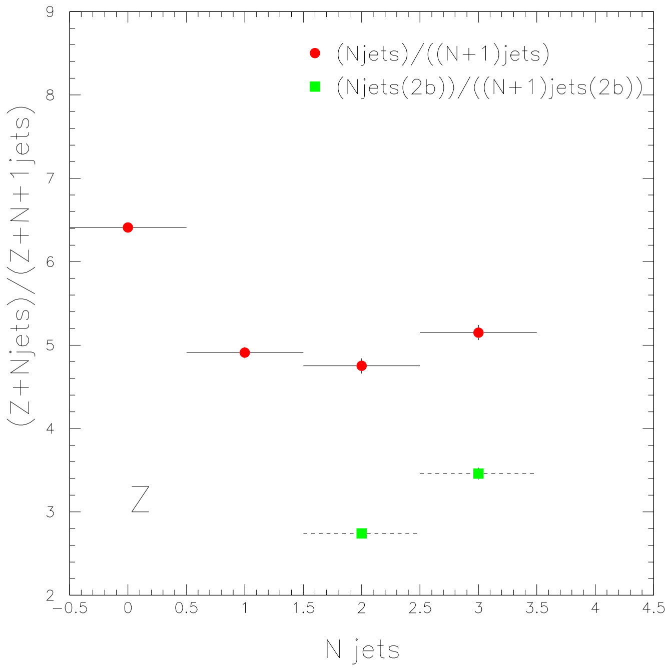

Figure 9: A summary of the ratios of Njets to N+1jets for Z production.

9 MadGraph Compared to AlpGen: Cross Sections and Ratios

One test of the MadGraph results is to compare the cross sections and ratios of cross sections to similar data found in [80], which was obtained using another LO matrix element generator, AlpGen.

9.1 Selection Criteria; Input Parameters

To make a direct comparison, we modify the selection criteria in MadGraph to match the criteria used in AlpGen as closely as possible. Both generators use the pdf CTEQ5L. MadGraph is modified to use the same beam energy and other selection criteria as AlpGen. The only major difference in the parameters used by AlpGen and those by MadGraph is the Q^2 scale as noted below. Here are the AlpGen criteria.

- PDF CTEQ5L (default)
- Beam Energy = 1000 GeV
- $\mathrm{Q}^2 = \mathrm{W_{mass}}^2 + \mathrm{P_{T,W}}^2$ for W+jets
- $\mathrm{Q}^2 = \mathrm{Z_{mass}}^2 + \mathrm{P_{T,Z}}^2$ for Z+jets
- $\mathrm{E_T} > 20.0$ GeV for jets
- $|\eta| < 2.5$ for jets
- $\Delta R > 0.4$ for pairs of jets in both W and Z cases
- $\Delta R > 0.0$ for other particle pairs
- production of both W^+ and W^-
- 80.0 GeV $\leq \mathrm{m_{e^+e^-}} \leq$ 100.0 GeV in Z case

The corresponding cuts in MadGraph are as follows:

- PDF CTEQ5L (default)
- Beam Energy = 1000 GeV
- $\mathrm{Q}^2 = \mathrm{W_{mass}}^2$
- $\mathrm{E_T} > 20.0$ GeV for jets
- $\mathrm{E_T} > 1.0$ GeV for leptons to approximate no $\mathrm{E_T}$ cut
- $|\eta| < 2.5$ for jets
- $|\eta| < 9.0$ for leptons to approximate no $|\eta|$ cut

- $\Delta R > 0.4$ for pairs of jets in both 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
- 80.0 GeV $\leq m_{e^+e^-} \leq$ 100.0 GeV in Z case

9.2 A Comparison of the Cross Sections and Ratios

The cross sections obtained from AlpGen and MadGraph for W+Njets and Z+Njets are given in Tables 18 and 19, respectively. Figures 10 and 11 show these cross sections and ratios for W. Figures 12 and 13 show these cross sections and ratios for Z. Note that the MadGraph Z cross sections are systematically higher than the AlpGen cross sections. At present, it is unclear why this is the case. Table 20 gives the ratios of W+Njets to Z+Njets for N = 0 to 5 and Figure 14 plots them.

W+jets Cross Sections (pb) and Ratios (MLM cuts)				
	Cross Section (pb)		Ratio (W+Njets)/(W+N+1jets)	
N jet	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 18: A tabulation of AlpGen and MadGraph predicted cross sections and ratios for W+jets.

Z+jets Cross Sections (pb) and Ratios (MLM cuts)				
	Cross Section (pb)		Ratio (Z+Njets)/(Z+N+1jets)	
N jet	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 19: A tabulation of AlpGen and MadGraph predicted cross sections and ratios for Z+jets.

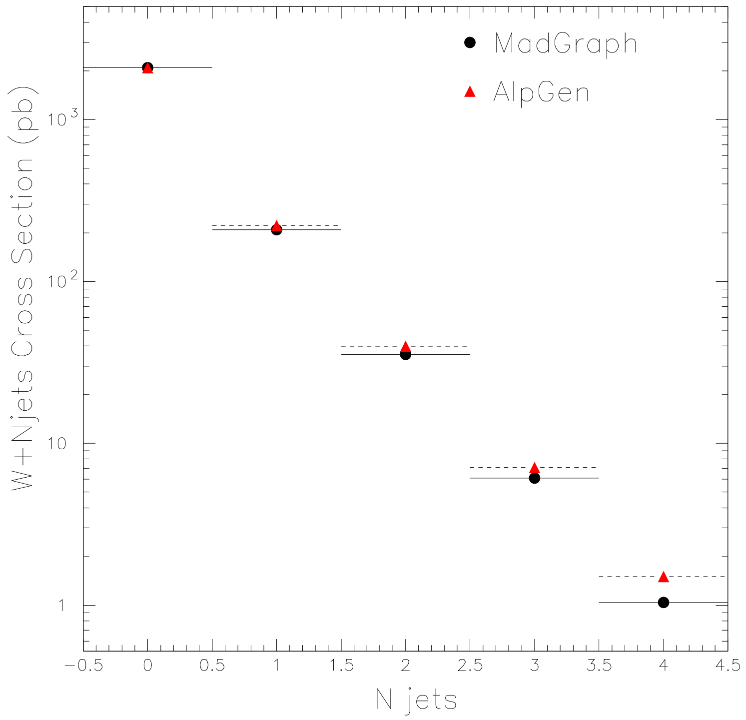

Figure 10: Cross Sections (pb) for W+Njets from MadGraph and ALPGEN.

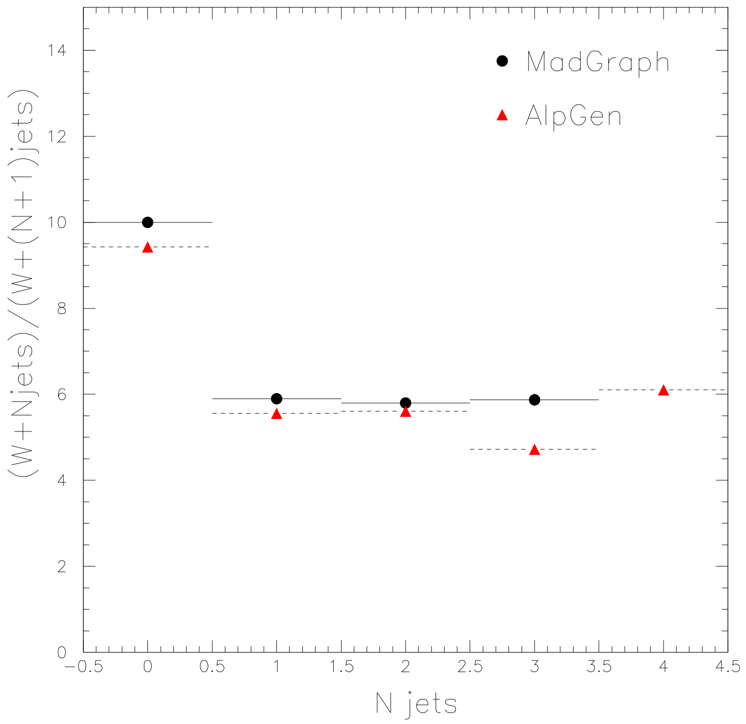

Figure 11: (W+Njets) / (W+N+1jets) versus Njets for MadGraph and ALPGEN.

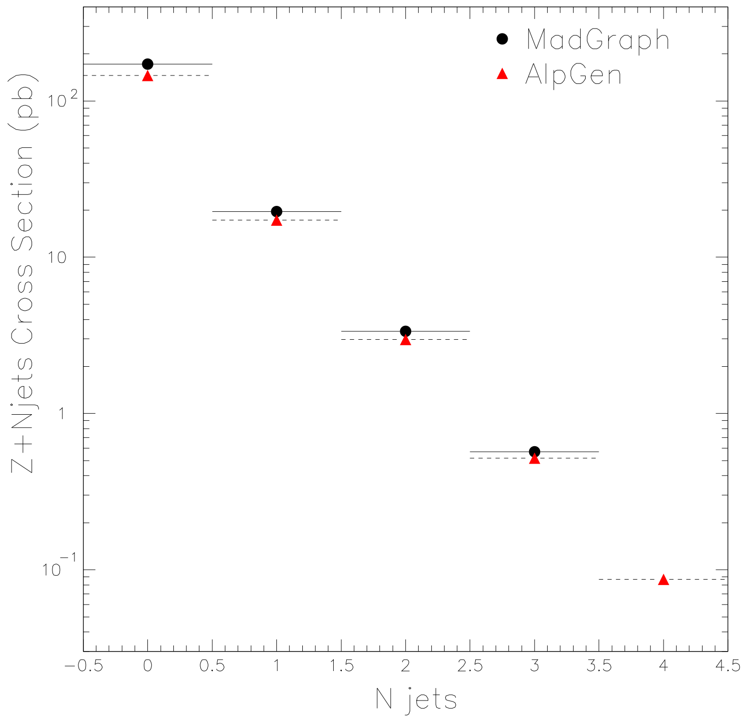

Figure 12: Cross Sections (pb) for Z+Njets from MadGraph and AlpGen.

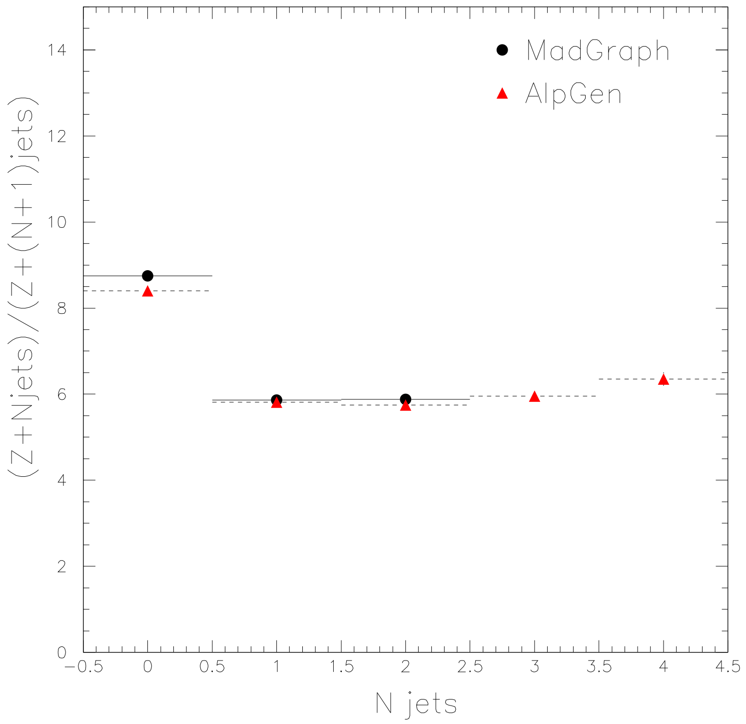

Figure 13: The ratios of Z+Njets to Z+N+1jets versus Njets for MadGraph and AlpGen.

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	±
5	18.03 ± 0.49	±

Table 20: A tabulation of ALPGEN and MadGraph predicted W/Z ratio.

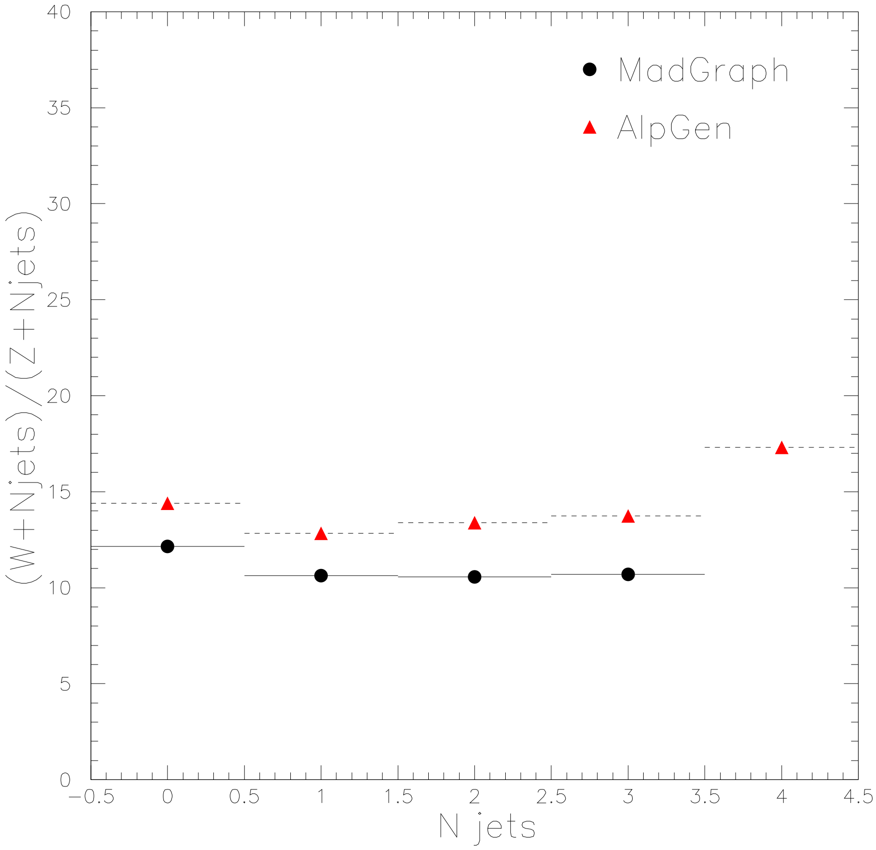

Figure 14: (W+Njets) / (Z+Njets) versus Njets for MadGraph and ALPGEN.

10 Q^2 Scale Study

It is possible to change the Q^2 scale in MadGraph. The default is $Q^2 = {W_{mass}}^2$. The cross sections and ratios in Section 8 correspond to this default scale. Another often used scale is $Q^2 = {V_{mass}}^2 + {P_{T,V}}^2$, where V is either Z or W. Modifying MadGraph to use this scale and using the selection criteria described in Section 8.2 for the remaining cuts, we obtain new cross sections as shown in Tables 21 and 22. The cross sections are plotted in Figures 15 and 16. Table 23 gives the ratios (W+Njets) / (Z+Njets) for the two different Q^2 scales, and Figure 17 plots them.

W+Jets Cross Sections (pb)

N jet	# b	(QCD, QED)	$Q^2 = {W_{mass}}^2$	$Q^2 = {W_{mass}}^2 + {P_{T,W}}^2$
0 j	0 b	(0,2)	341.5 ± 0.5	343 ± 2
1 j	0 b	(1,2)	42.1 ± 0.3	45.4 ± 0.3
2 j	0 b	(2,2)	8.28 ± 0.05	9.26 ± 0.09
3 j	0 b	(4,2)	1.68 ± 0.02	1.99 ± 0.03
4 j	0 b	(4,2)	0.357 ± 0.005	
2 j	2 b	(4,2)	0.0917 ± 0.0008	
3 j	2 b	(4,2)	0.0307 ± 0.0003	
4 j	2 b	(4,2)	0.0095 ± 0.0003	
4 j	4 b	(4,2)	(4.1 ± 0.1)E-5	

Table 21: A comparison of W+jet cross sections (for W^+ only) for $Q^2 = {W_{mass}}^2$ versus $Q^2 = {W_{mass}}^2 + {P_{T,W}}^2$, with other selection criteria as in the text.

Z+Jets Cross Sections (pb)

N jet	# b	(QCD, QED)	$Q^2 = {W_{mass}}^2$	$Q^2 = {Z_{mass}}^2 + {P_{T,Z}}^2$
0 j	0 b	(0,2)	67.0 ± 0.2	67.1 ± 0.3
1 j	0 b	(1,2)	10.45 ± 0.01	11.0 ± 0.1
2 j	0 b	(2,2)	2.13 ± 0.03	2.24 ± 0.03
3 j	0 b	(4,2)	0.448 ± 0.006	0.468 ± 0.006
4 j	0 b	(4,2)	0.087 ± 0.001	
2 j	2 b	(2,2)	0.0362 ± 0.0002	
3 j	2 b	(4,2)	0.0132 ± 0.0002	
4 j	2 b	(4,2)	(3.81 ± 0.05)E-3	
4 j	4 b	(4,2)	(1.76 ± 0.04)E-5	

Table 22: A comparison of Z+jet cross sections for $Q^2 = {W_{mass}}^2$ versus $Q^2 = {Z_{mass}}^2 + {P_{T,Z}}^2$, with other selection criteria as in the text.

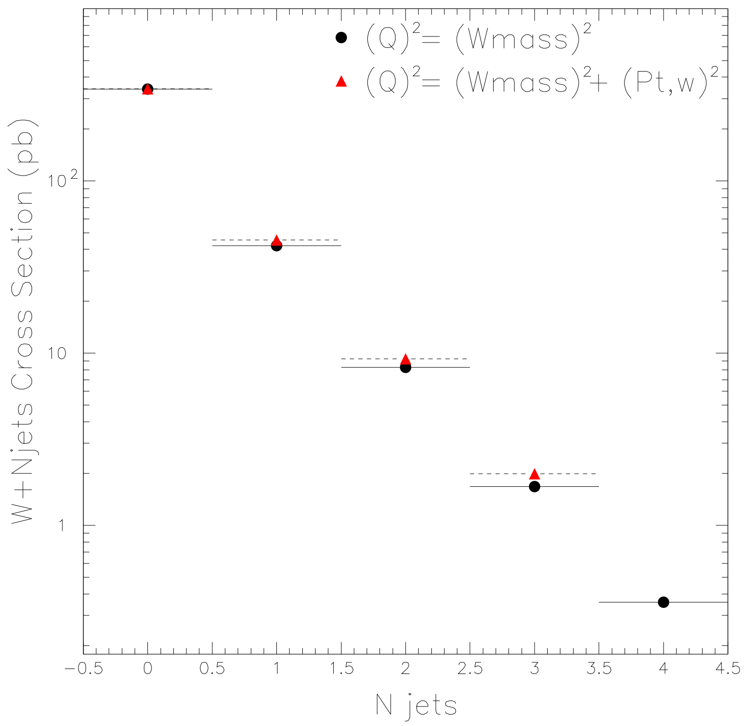

Figure 15: Cross Sections (pb) for W+Njets using different Q^2 scales in MadGraph.

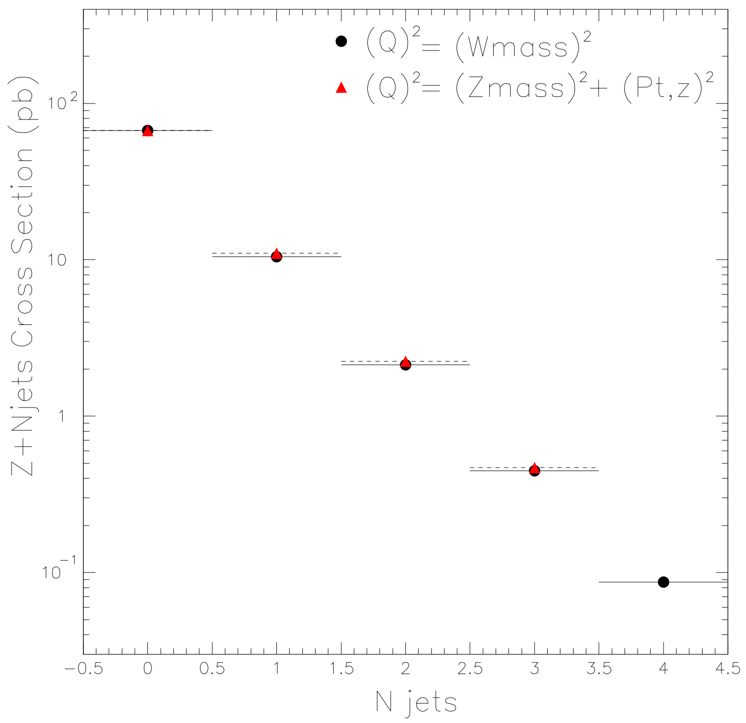

Figure 16: Cross Sections (pb) for Z+Njets using different Q^2 scales in MadGraph.

N jet	# b	(QCD, QED)	$Q^2 = {W_{mass}}^2$	$Q^2 = {V_{mass}}^2 + {P_{T,V}}^2$
0 j	0 b	(0,2)	5.10 ± .02	5.11 ± .04
1 j	0 b	(1,2)	4.03 ± .03	4.13 ± .05
2 j	0 b	(2,2)	3.89 ± .06	4.13 ± .07
3 j	0 b	(4,2)	3.75 ± .07	4.25 ± .08
4 j	0 b	(4,2)	4.10 ± .07	
5 j	0 b			
2 j	2 b	(2,2)	2.53 ± .03	
3 j	2 b	(4,2)	2.33 ± .04	
4 j	2 b	(4,2)	2.49 ± .09	
5 j	2 b			
4 j	4 b	(4,2)	2.33 ± .08	
5 j	4 b			

Table 23: $\sigma W^+/\sigma Z^0$

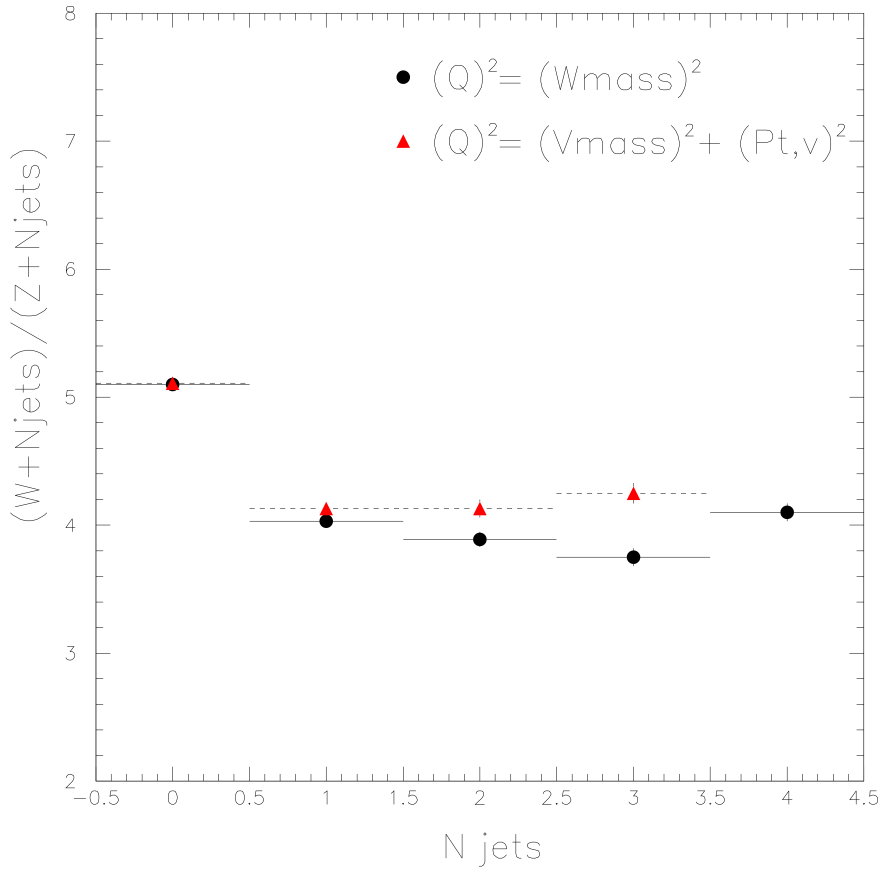

Figure 17: Ratios (W+Njets) / (Z+Njets) using different Q^2 scales in MadGraph.

11 Conclusions and To Do List

From our work thus far, we make several preliminary conclusions regarding the ratios of (W+Njets) to (Z+Njets), as well as the importance of knowing exactly how the generators work, and further studies necessary.

- The very basic processes $W \to e^+\bar{\nu}_e$ and $Z^0 \to e^+e^-$ are a very good starting point for these studies. Discrepancies in the cross sections for these processes (for identical selection criteria) among different matrix element generators indicate subtle differences in ways the generators are making calculations.
- It is crucial to understand the basic assumptions and inputs the different generators are using before relying on the cross sections for comparison to data. For example, we found that some generators include the b quark in the pdf for the proton while others do not; these two approaches result in slightly different predictions for cross sections.
- A first look at the ratios of (W+Njets) to (Z+Njets) does not yet refute the idea of using the ratio to make precision measurements.
- We need to investigate further the dependence of the ratios on the Q^2 scale and on the pdf used by the generator.
- We need to generate cross sections for top processes in order to look at the ratios where top is included.
- Currently, our MadGraph calculations have been limited to processes with up to 5 jets. The 5 jet calculations take a great deal of computer time; we are looking into running these calculations in parallel to reduce the time needed for 5 jet calculations and to possibly make calculations for 6 or more jets.

12 Summary

The ratio of W to Z production as a function of the number of observed jets, including as a subset the number of b-jets, is a broad test for new physics across a wide variety of signatures. We have new Monte Carlo tools developed since Run I to predict the ratios expected in the SM, and are in the process of determining these. The analysis will be driven out of the high-$\mathrm{p_T}$ inclusive lepton data sets; standard lepton, jet, tag, and $\not{E}_t$ criteria will allow comparisons to other top and EWK analyses and will maintain a certain simplicity.

13 Acknowledgments

It is a pleasure to acknowledge helpful conversations with Edward Boos, John Campbell, Lev Dudko, Keith Ellis, Michelangelo Mangano, Stephen Mrenna, Jon Rosner, and Tim Stelzer. Special thanks to Tim Stelzer, who provided us with a test version of MadGraph and much patient advice and help with it.

14 Appendix A

This appendix contains cross sections and ratios for processes involving charm quarks using selection criteria from 8.2. Tables 24 and 25 contain the cross sections for W+Njets and Z+Njets where some of the jets are required to be charm quarks.

W+Jets Cross Sections (pb)					
N jet	# b	(QCD, QED)	QCD W+Jets	W$c\bar{c}$	W$\bar{c}$
0 j	0 b	(0,2)	341.5 ± 0.5	-	-
1 j	0 b	(1,2)	42.1 ± 0.3	-	1.489 ± 0.003
2 j	0 b	(2,2)	8.28 ± 0.05	0.0988 ± 0.0006	0.536 ± 0.009
2 j	2 b	(4,2)	0.0917 ± 0.0008	-	-
3 j	0 b	(4,2)	1.68 ± 0.02	0.0350 ± 0.0003	0.132 ± 0.002
3 j	2 b	(4,2)	0.0307 ± 0.0003	-	(4.25 ± 0.04)E-4
4 j	0 b	(4,2)	0.357 ± 0.005	0.0097 ± 0.0002	0.0282 ± 0.0003
4 j	2 b	(4,2)	0.0095 ± 0.0003	(8.9 ± 0.1)E-5	(3.03 ± 0.04)E-4
4 j	4 b	(4,2)	(4.1 ± 0.1)E-5	-	-
5 j	0 b	(6,2)		0.00300 ± 0.00007	
5 j	2 b	(6,2)	0.00261 ± 0.00004	(4.6 ± 0.2)E-5	
5 j	4 b	(6,2)	(2.12 ± 0.05)E-5	-	

Table 24: A tabulation of LO SM predicted W+jet cross-sections and uncertainties, giving the cross sections for processes with one W^+ including cases where charm quarks are required.

Z+Jets Cross Sections (pb)					
N jet	# b	(QCD QED)	QCD Z^0+Jets	$Z^0 c\bar{c}$	$Z^0 c$
0 j	0 b	(0,2)	67.0 ± 0.2	-	-
1 j	0 b	(1,2)	10.45 ± 0.01	-	0.0767 ± 0.0005
2 j	0 b	(2,2)	2.13 ± 0.03	0.0355 ± 0.0002	0.0575 ± 0.0003
2 j	2 b	(2,2)	0.0362 ± 0.0002	-	-
3 j	0 b	(4,2)	0.448 ± 0.006	0.0133 ± 0.0002	0.0173 ± 0.0002
3 j	2 b	(4,2)	0.0132 ± 0.0002	-	(3.12 ± 0.07)E-5
4 j	0 b	(4,2)	0.087 ± 0.001	(3.87 ± 0.07)E-3	(4.58 ± 0.07)E-3
4 j	2 b	(4,2)	(3.81 ± 0.05)E-3	(3.84 ± 0.06)E-5	(5.05 ± 0.09)E-5
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 25: A tabulation of LO SM predicted Z+jet cross-sections and uncertainties, giving the cross sections for processes with one Z including cases where charm quarks are required.

14.1 The Cost of Adding a c-quark Pair to a Boson+jet Event:Ratios of (V+n jets)/($Vc\bar{c}$+n-2 jets)

(N jets)/($c\bar{c}$+(N-2) jets) for W *or* Z			
W+jets		Z+jets	
W+2j/W$c\bar{c}$+0j	83.81 ± .72	Z+2j/Z$c\bar{c}$+0j	60.00 ± .91
W+3j/W$c\bar{c}$+1j	48.00 ± .70	Z+3j/Z$c\bar{c}$+1j	33.68 ± .68
W+4j/W$c\bar{c}$+2j	36.80 ± .92	Z+4j/Z$c\bar{c}$+2j	22.48 ± .48
W+5j/W$c\bar{c}$+3j		Z+5j/Z$c\bar{c}$+3j	

Table 26: Ratios for (W+Njets)/(W$c\bar{c}$+(N-2)jets) and for (Z+Njets)/(Z$c\bar{c}$+(N-2)jets)

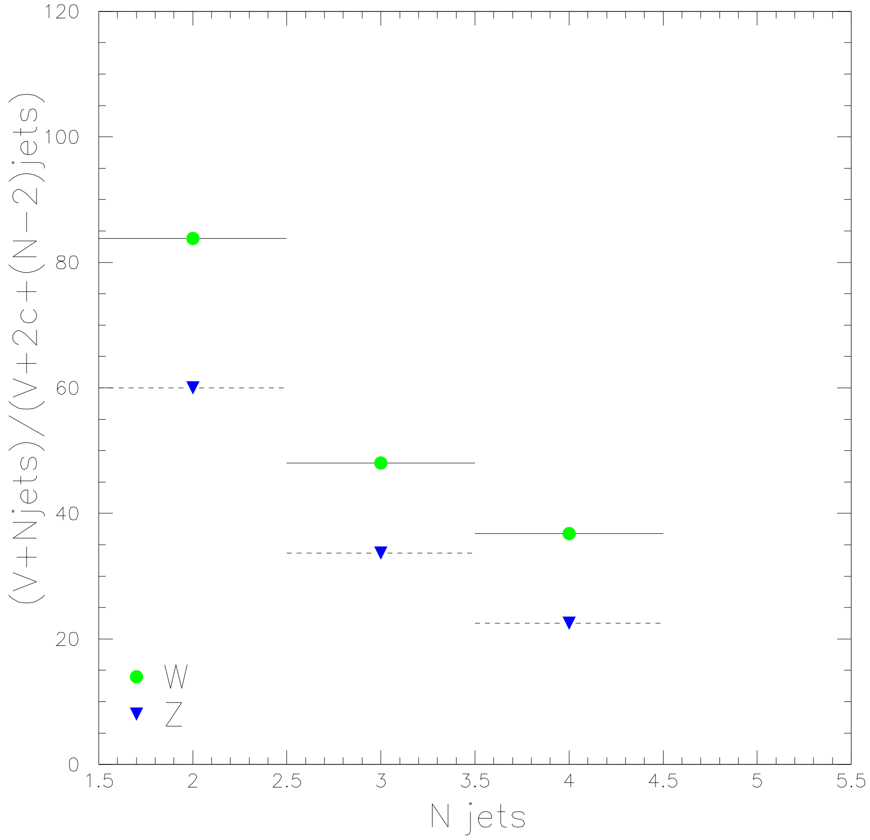

Figure 18: The ratios of cross sections for N jets to 2c+(N-2)jets for W and Z production.

14.2 The Cost of Adding a Jet to a Boson Event with a c-quark Pair: Ratios of (V$c\bar{c}$+n jets)/(V$c\bar{c}$+n+1 jets)

($c\bar{c}$+Njets)/($c\bar{c}$+(N+1)jets) for W *or* Z			
W+jets		**Z+jets**	
W$c\bar{c}$+0j/W$c\bar{c}$+1j	2.82 ± .03	Z$c\bar{c}$+0j/Z$c\bar{c}$+1j	2.67 ± .04
W$c\bar{c}$+1j/W$c\bar{c}$+2j	3.61 ± .08	Z$c\bar{c}$+1j/Z$c\bar{c}$+2j	3.44 ± .08
W$c\bar{c}$+2j/W$c\bar{c}$+3j		Z$c\bar{c}$+2j/Z$c\bar{c}$+3j	

Table 27: Ratios for (W+2c+Njets)/(W+2c+N+1jets) and (Z+2c+Njets)/(Z+2c+N+1jets)

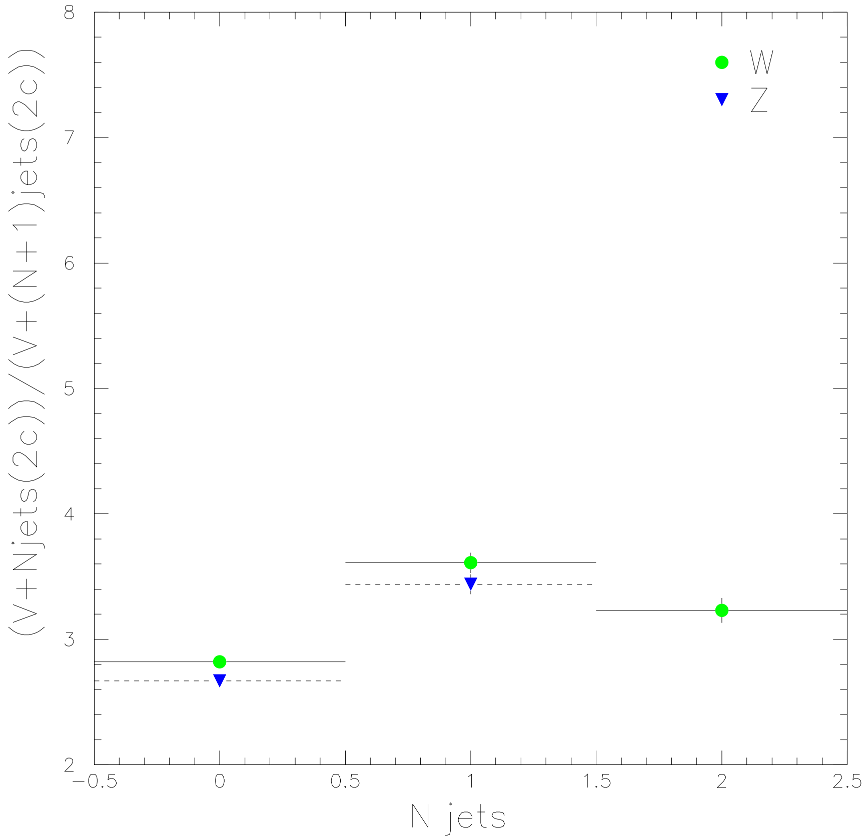

Figure 19: The ratios of cross sections for N jets (including 2 c jets) to N+1 jets (including 2 c jets) for W and Z production.

14.3 The Cost of Adding a b-quark Pair to a Boson+$c\bar{c}$ Event:Ratios of (V$c\bar{c}$+ n jets)/($Vc\bar{c}$+$b\bar{b}$+n-2 jets)

($c\bar{c}$+Njets)/($c\bar{c}+b\bar{b}$+(N-2)jets) for W *or* Z			
W+jets		**Z+jets**	
W$c\bar{c}$+2j/W$c\bar{c}b\bar{b}$	108.99 ± 2.56	Z$c\bar{c}$+2j/Z$c\bar{c}b\bar{b}$	100.78 ± 2.41
W$c\bar{c}$+3j/W$c\bar{c}b\bar{b}$+1j	65.22 ± 3.22	Z$c\bar{c}$+3j/Z$c\bar{c}b\bar{b}$+1j	

Table 28: Ratios for (W$c\bar{c}$ + Njets)/(W$c\bar{c}$ + $b\bar{b}$ + (N-2)jets) and for (Z$c\bar{c}$ + Njets)/(Z$c\bar{c}$ + $b\bar{b}$ + (N-2)jets)

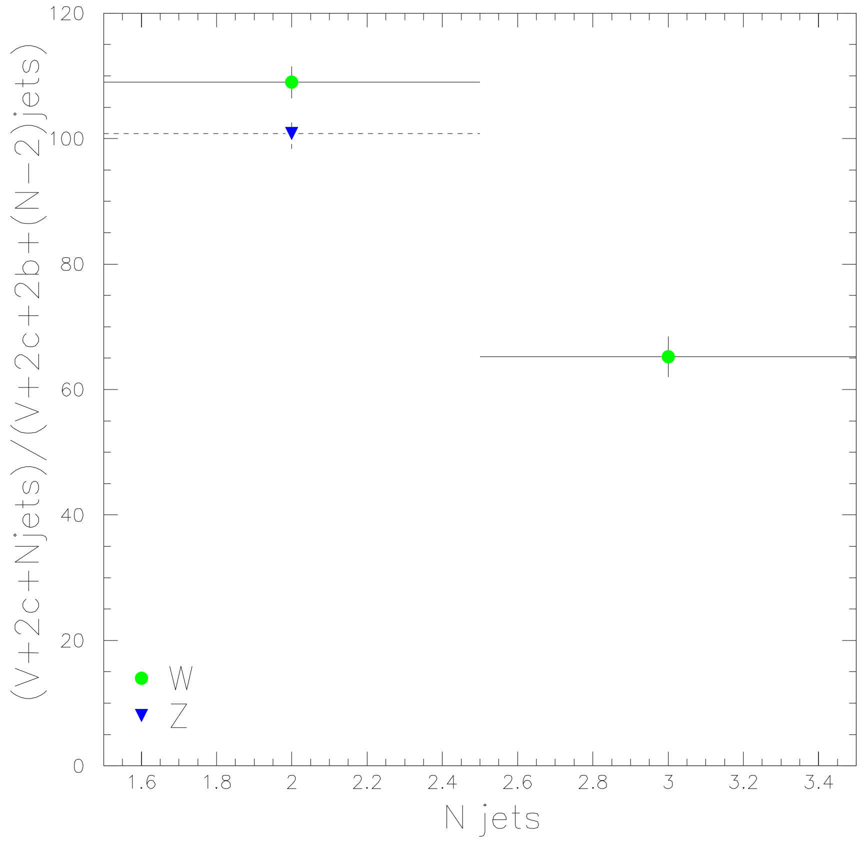

Figure 20: The ratios of cross sections for $c\bar{c}$ + Njets to $c\bar{c}$ + $b\bar{b}$ + (N-2)jets for W or Z production.

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[58] N. Cabibbo, II Topical Conference on Proton-Antiproton Collider Physics, Rome, Jan. 1983.

[59] *measurement of sigma(W→ENU) and SIGMA(Z→EE) in pbarp collisions at..*, C. Campagnari, P. Derwent, H. Frisch, C. Grosso-Pilcher, M. Miller; CDF/ANAL/ELECTROWEAK/CDFR/1107, 1/4/90

[60] *Measurement of ratio sigma(W-ENU)/SIGMA(Z-EE) at 1.8 tev*, S. Kopp, G. Sullivan; CDF/DOC/ELECTROWEAK/CDFR/2183, 7/29/93

[61] *A Measurement of R using the CDF Detector in* $\bar{p}p$ *Collisions at* $\sqrt{s} = 1800\ GeV$, John Wahl; CDF/ANAL/ELECTROWEAK/CDFR/4864, 1/26/99

[62] *measurement of sigma*B(W→mu nu), sigma*B(Z→mu mu) 18.8 PB-1 (UPDATE)*,W. Badgett; CDF/ANAL/ELECTROWEAK/CDFR/2667, 6/27/94

[63] This was intended to be a subject of John Wahl's thesis at the start (1997 or so), but didn't happen.

[64] See http://hep.uchicago.edu/cdf/datasets.html

[65] . Sacha Kopp, Ph.D Thesis, University of Chicago 1994.

[66] John Wahl, Ph.D Thesis, University of Chicago, 1999.

[67] See, for example: *QCD MATRIX ELEMENTS + PARTON SHOWERS* S. Catani, F. Krauss, R. Kuhn, B.R. Webber, JHEP 0111:063,2001; e-Print Archive: hep-ph/0109231. For the definite CDF study, see: *Tests of Enhanced Leading Order QCD in W Boson plus Jets Events from 1.8 TeV pbar p Collisions*, T. Affolder et al., The CDF Collaboration; CDF/PUB/JET/PUBLIC/5140; Phys. Rev. D63, 072003 (2001).

[68] For a beginning point, see CDF5054, *Jet Flavor Tagging Using Tracking Variables*, David Wolinski Dante Amidei Regina Demina; CDF/ANAL/EXOTIC/CDFR/5054; 7/15/99

[69] *SEPARATING TOP AND Z'S IN DILEPTON EVENTS INSIDE THE Z MASS WINDOW*, H. J. FRISCH CDF/ANAL/TOP/CDFR/3387; 10/22/95

[70] CDF5821: *Top Dilepton Monte Carlo Datasets and Disk Needs*, Top Dilepton Group

[71] Many thanks to E. Boos.

[72] T. Stelzer, private communication.

[73] See CDF5938 for a brief description and web links to the Monte Carlo Data Base (MCDB).

[74] Because we are measuring ratios of W to Z production the analysis is less sensitive to the selection criteria for the first leg. These selections will most likely become more sophisticated; we will use whatever is the standard electron and muon inclusive selection. The tables are intended to show the current defaults.

[75] See Figure 2.4 of Ref. [65] for distributions in these variables for inclusive electrons and electrons from W's.

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[77] See, for an example of the theoretical considerations for the choice of threshold: *QCD MATRIX ELEMENTS + PARTON SHOWERS*, S. Catani, F. Krauss, R. Kuhn, B.R. Webber; JHEP 0111:063,2001; hep-ph/0109231

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[79] T. Stelzer, W. F. Long; Comput.Phys.Commun. 81 (1994) 357-371. We thank T. Stelzer for allowing us to use a very powerful new version of his program.

[80] *ALPGEN, A Generator For Hard Multiparton Processes in Hadronic Collisions*, M. Mangano et al., CERN-TH/2002-129.