

# Monte Carlo for top background at the Tevatron

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## Abstract

We review the use of Monte Carlo (MC) simulation to model backgrounds to top signal at the Tevatron experiments, CDF and D0, as well as the relevant measurements done by the experiments. We'll concentrate on the modeling of  $W$  and  $Z$  boson production in association with jets, in particular heavy flavor jets (HF), and also comment on the Tevatron experience using matched MC.

## 1 Introduction

The Fermilab Tevatron Collider has provided over  $4\text{fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96\text{ GeV}$ , allowing the CDF and D0 experiments to make precise measurements using  $t\bar{t}$  production, and to find evidence for the rare single top production process. Both endeavors require a solid understanding of the background processes, and MC simulation is a crucial ingredient of the background models used.

## 2 The background processes

Precision measurements of top quark properties are performed by studying  $t\bar{t}$  production in either:

- the dilepton decay channel, where the  $t \rightarrow bW$  decays are followed with  $W \rightarrow l\nu(X)$  and  $l$  is an electron or muon. Or in
- the semileptonic (“lepton plus jets”) decay channel, where one of the  $W$  bosons decays as  $W \rightarrow l\nu(X)$  and the other decays hadronically.

Fig 1 shows typical sample compositions in these channels.

The dominate background in the dilepton channels is Drell-Yan plus jets production,  $Z \rightarrow e^+e^-$  in the  $e^+e^-$  channel,  $Z \rightarrow \mu^+\mu^-$  in the  $\mu^+\mu^-$  channel, and  $Z \rightarrow \tau^+\tau^-$  with subsequent leptonic  $\tau$  decays in the  $e\mu$  channel. In these proceedings we'll follow the common practice of referring to this background as “ $Z$ +jets”. This background dominates the early stages of the event selection,

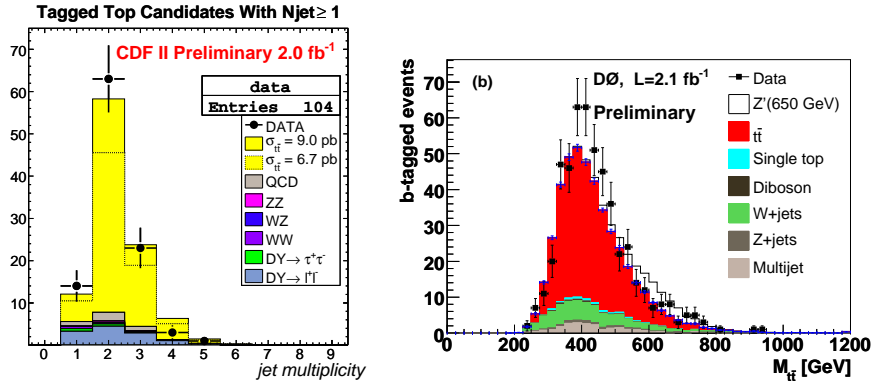


Figure 1: Examples of sample composition in top pair analyses for the dilepton channel [1] (left) and the lepton plus jets channel [2] (right). The “DY” label refers Drell-Yan production, as does the “Z+jets” label. The right plot is taken from a search for resonant  $t\bar{t}$  production, and shows (in white) a conceivable new physics component.

when the experimental understanding of the samples is verified, e.g., by examining many distributions for control samples with fewer jets than the signal. But after the final selection, its contribution is small. Dilepton samples are quite pure, hence most analyses do not rely on  $b$  tagging and the precise flavor composition of the  $Z$ +jets background is not important.

The second largest background is multijet production, often referred to as “QCD” background. Multijet events are selected when jets are misreconstructed as leptons. It is quite difficult to simulate these mistaken reconstructions both at the MC generator level and at the detector simulation level. Therefore data driven models are used for these backgrounds (see also sec 7). The next background component is from diboson plus jets production. These background are quite small, so even a rough simulation suffices for top physics, and they are estimated purely from MC.

In the lepton plus jet channel, the dominate background is  $W$ +jets production, which is important both in the control samples and in the signal samples. This channel provides the most precise measurements, and most measurements use  $b$  tagging to suppress background [3]. As a result, the flavor composition of the jets produced in association with a  $W$  boson is relevant in this channel.

The search for single top production is characterized by high level of background, as the experimental signature of this process contains fewer jets. Thus the single top analyses use  $b$  tagging to suppress background. A typical sample composition is shown in fig 2. These samples are dominated by  $W$ +jets production, and knowledge of the flavor composition of the jets produced in association with a  $W$  boson is required to identify the small single-top signal.

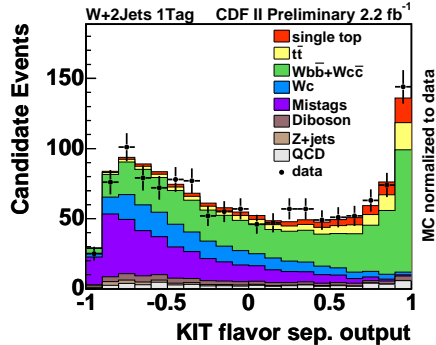


Figure 2: Sample composition in CDF’s single top search. The “mistag” label refers to  $W$  plus light-flavored jets production.

### 3 Matched MC in $V$ +jets

The calculation of the differential cross sections for  $W$ +jets and  $Z$ +jets processes ( $V$ +jets), and in particular  $W$  plus heavy flavor ( $W + \text{HF}$ ) production, is far from trivial. It was the motivation for the development of the ALPGEN event generator [4], and recent calculations show that sizable NLO corrections exist for some final states [5].

Production of hard additional partons is well simulated by matrix element (ME) generators that calculate  $2 \rightarrow n$  processes at tree level, such as ALPGEN. But parton shower (PS) MC, such as PYTHIA [6], are better at simulating softer radiation, as the PS approximates the sum of soft contributions from all orders in perturbation theory. Hence these tools are used together, the hard  $2 \rightarrow n$  interactions being modeled by the ME generator, and the showering by the PS generator. Care must be taken to avoid double counting final states, for example, those where the 3rd hardest parton can be generated either by the ME or by the PS. This is done using a matching prescription, discussed elsewhere [7].

The CDF and D0 collaborations both generate  $V$ +jets MC with ALPGEN using the MLM matching prescription [8], with some small differences in the matching technology. Since  $W + \text{HF}$  production is important for top physics, both collaborations produce such samples separately. But these samples overlap with the  $W$ +jets samples, which include heavy flavor jets in the PSs, and this overlap must be removed. The CDF collaboration does so by classifying  $b\bar{b}$  and  $c\bar{c}$  pairs into those that are in the same parton jet and those that are not. The former are taken only from the PS MC (HERWIG [9]), and the latter only from the ME MC (ALPGEN). This has the advantage of playing to each MC’s strength. The D0 collaboration uses the more straight-forward solution of discarding any events that were generated as  $W$ +jets by the ME MC (ALPGEN) and contain heavy-flavor jets added by the PS MC (PYTHIA).

Other differences are in the  $p_T$  cut used for the matching within each sample (15 GeV in CDF, 8 GeV in D0), which has little effect, in the light-parton jet

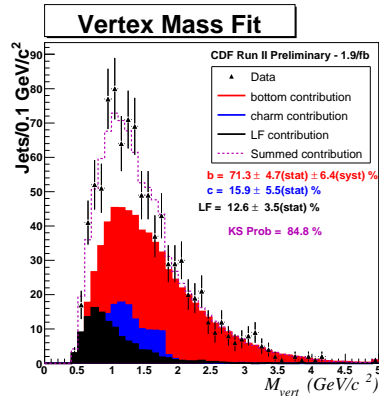


Figure 3: Vertex mass fit for tagged jets in selected sample of ref [11].

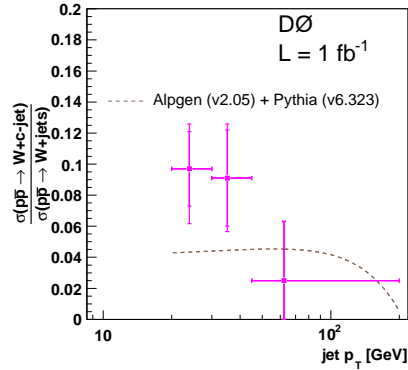


Figure 4: Measured ratio  $[\sigma(W + c\text{-jet})/W + \text{jets}]$  from ref [13].

multiplicities produced for each sample (up to 4 in CDF, up to 5 in D0), and in the treatment of  $W+c$  production (separate in CDF, included in  $W + \text{LF}$  in D0).

## 4 Measurements of $V+\text{jets}$ processes

Given the difficulties in calculating and simulation  $V+\text{jets}$  processes, it is instructive to compare them to data. In this section we review measurements of  $V+\text{jets}$  production from CDF and D0. The leptonic  $W$  and  $Z$  decay channels provide clear experimental signatures and are used throughout. Since the additional jets are produced by the strong interaction, which favors soft and collinear radiation, selection cuts on energies and angles have a large effect on the cross sections. Relevant selection cuts will be stressed in this section.

Both collaborations have preliminary results from measurements of  $W + b\text{-jet}$  production. The D0 collaboration set a limit of  $\sigma(p\bar{p} \rightarrow Wb\bar{b}) < 4.6$  pb at 95% C.L. using  $382 \text{ pb}^{-1}$  of data [10]. The jets'  $p_T$  was required to be above 20 GeV and their direction to satisfy  $|\eta^{\text{jet}}| < 2.0$ , and only events with one or two jets were used. On the first day of the conference, the CDF collaboration released preliminary results from a measurement of the  $b\text{-jet}$  production cross section in association with a  $W$  boson:  $\sigma_{b\text{-jets}}(p\bar{p} \rightarrow W + b\text{-jets}) \cdot B(W \rightarrow l\nu) = 2.74 \pm 0.27$  (stat.)  $\pm 0.42$  (syst.) pb. The dataset used in this measurement had an integrated luminosity of  $1.9 \text{ pb}^{-1}$  [11] (see fig 3). Jets were reconstructed with  $R_{\text{cone}} = 0.4$ , and counted as  $b$  jets if  $\Delta R_{bj} < 0.4$ ,  $E_T^{\text{jet}} > 20$  GeV, and  $|\eta^{\text{jet}}| < 2$ . The measured cross section is significantly higher than the ALPGEN prediction of 0.78 pb.

Both collaborations studied the rate of  $W + c\text{-jet}$  production. The CDF col-

laboration measured  $\sigma(p\bar{p} \rightarrow W + c\text{-jet}) \cdot B(W \rightarrow l\nu) = 9.8 \pm 2.8$  (stat.) $_{-1.6}^{+1.4}$  (syst.)  $\pm 0.6$  (lumi.) pb using  $1.8 \text{ fb}^{-1}$  of data [12]. The  $c$ -jet  $p_T$  was required to be above 8 GeV and their direction to satisfy  $|\eta| < 3.0$ . A recent preliminary result from the D0 collaboration was shown at the conference, they measure the ratio

$$R = \frac{\sigma(p\bar{p} \rightarrow W + c\text{-jet})}{\sigma(p\bar{p} \rightarrow W + \text{jets})}, \quad (1)$$

and find  $R = (7.4 \pm 1.9$  (stat.) $_{-1.4}^{+1.2}$  (syst.)) % using  $1 \text{ fb}^{-1}$  of data [13] (see also fig 4). The jets'  $p_T$  was required to be above 20 GeV and their direction to satisfy  $|\eta^{\text{jet}}| < 2.5$ . The measured fraction is higher than the ALPGEN prediction of  $(4.4 \pm 0.3$  (PDF)) %.

Finally, the CDF collaboration measured the differential  $W$ +jets production cross section as a function of the number of jets and the jet transverse energy using  $320 \text{ pb}^{-1}$  of data [14]. Jets are required to have  $|\eta| < 2.0$ . The measured cross sections are compared to next-to-leading order predictions and to predictions from two matched MC generators.

## 5 Modeling $Z$ +jets production as a background

$Z$ +jets production appears at a lower rate than  $W$ +jets production, but has much less background, making it a good process for tuning the simulations. Usually it suffices to normalize simulated cross sections according to cross sections calculated at next-to-leading order (NLO) by the MCFM program [15], though next-to-next-to-leading order calculations are also used sometimes. As noted above, the strong dependence of the cross sections on the kinematic cuts must be taken into account. Some analyses normalize the total rate to data, for example, ref [16] where the apparent data vs. MC discrepancy for  $W$  plus a few jets production can be resolved either by jet energy calibration effects or by the appropriate choice of the hadronization and factorization scales.

The kinematics of  $Z$ +jets production can also be tuned to data. Recently the D0 collaboration noted that RESBOS [17] calculations match their observed  $d\sigma/dp_T^Z$  distributions well [18] (see fig 5), and are starting to use RESBOS as a surrogate to the data, reweighting ALPGEN+PYTHIA MC so it agrees with the  $p_T$  spectrum predicted by RESBOS. This reweighting is also carried over to  $W$ +jets production. During the conference, ALPGEN authors commented that this may be due to the tuning of ALPGEN parameters used at D0, as ALPGEN with the default parameters agrees with RESBOS [19].

The D0 collaboration also compared differential  $Z$ +jets cross sections between data and the predictions of the SHERPA [20] and PYTHIA event generators [21]. As expected, since PYTHIA is a parton shower generator it does not generate sufficient additional radiation, while SHERPA simulates these aspects adequately. Some inaccuracies are also evident in the PYTHIA simulation of the unsigned rapidity difference between the two leading jets. It is interesting to note that again, SHERPA simulates the distribution adequately.

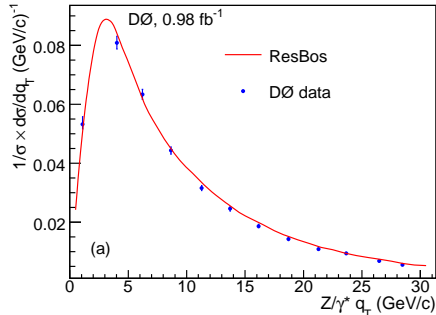


Figure 5: Normalized differential cross section as a function of transverse momentum for the inclusive sample in ref [18].

The differential  $Z$ +jets cross sections were also measured by the CDF collaboration, which compared the data both to NLO calculations (performed using MCFM) and to different matched MCs [22]. They found excellent agreement between the data and the NLO calculations of the cross sections as a function of  $N_{\text{jets}}$  and  $|y^{\text{jet}}|$ .

## 6 Modeling $W$ +jets production as background

Top quark measurements by the CDF and D0 collaborations model  $W$ +jets production on the basis of the differential distributions predicted by matched ALPGEN MC. There are some indications that small corrections to the differential distributions may be required, and these are treated as systematic uncertainties in some analysis (e.g. ref [23]). On the other hand, there is a clear need for correcting the predicted integrated  $W$ +jets and  $W$  + HF cross sections, and these are normalized to data, after other backgrounds (multijets, dibosons, etc.) are subtracted. Typically,  $W$ +jets production is normalized to data before  $b$  tagging, and the fraction of  $W$  + HF in the total  $W$ +jets production is then fitted to data after  $b$  tagging.

In D0 analyses the  $W$ +jets normalization differs from analysis to analysis. It is determined either by counting events with one or two jets, or by fitting a discriminant in  $t\bar{t}$  signal samples (with  $\geq 3$  jets). The fraction of heavy flavor in the  $W$ +jets was normalized to data using the number of events with no  $b$  tagged jets [24]. This yielded a correction of  $K_{\text{HF}} = 1.5 \pm 0.45$  (see fig 6) to be applied to the heavy flavor fraction simulated by ALPGEN. Later analyses used tighter selection cuts and normalized the fraction of events with no  $b$  tags (rather than their absolute number). Tests for systematic effects revealed that this factor is sensitive to the other background in these samples, and to the jet selection. The resulting normalization was  $K_{\text{HF}} = 1.17 \pm 0.18$ . Oddly, switching from ALPGEN version 2.05 to version 2.12 changed the  $W$  + HF cross section by a factor of  $\approx 2$ , which together with more minor improvements to the analyses

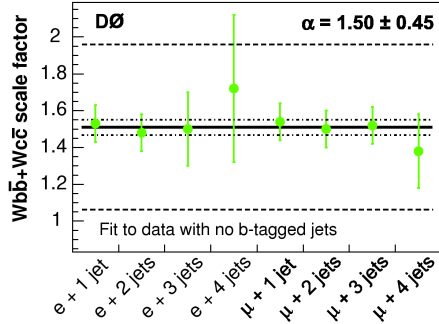


Figure 6: Measurements of  $K_{\text{HF}}$  from ref [24]. The points are the measured correction factor in each dataset. The solid line is the average of these values. The dot-dash inner band shows the uncertainty from the the fit to the eight data points. The dashed outer line shows the uncertainty used in the analysis.

yielded a new value of  $K_{\text{HF}} = 1.9 \pm 0.3$

In CDF analyses, distributions of jet-flavor discriminating variable such as the output of neural network  $b$  tagger or the mass of reconstructed secondary vertex in  $W + 1\text{jet}$  data are fit to the sum of light, charm, and bottom jet templates. This yields  $K_{\text{HF}} = 1.4 \pm 0.4$ . The  $W + \text{LF}$  component of the  $b$ -tagged samples is then determined by applying  $b$ -tagging rates either to the data before  $b$  tagging or to  $W + \text{LF}$  MC samples. To date,  $K_{b\bar{b}} = K_{c\bar{c}} = 1$  and  $K_c = 1$  are used in all Tevatron top quark measurements as they are consistent with the data.

In searches for physics beyond the SM in top samples, the data often allows for significant non-standard production. When the  $V + \text{jets}$  background is normalized to data in the signal samples (e.g.  $\geq 3$  jets for  $t\bar{t}$ ), the possible non-standard production can affect the measured normalization. For example, in the searches for resonant top-pair production this is explicitly accounted for [25].

## 7 MC use in the modeling of multijet background

Background from multijet production with a fake lepton is modeled using various data-driven techniques with little use of MC inputs. Still, there is a place for MC in the modeling of multijet background. The data samples on which these estimations are based are typically dominated by three jet events that are reconstructed as a lepton and two jets. As three jet production can be easily generated by MC techniques, such samples can be used to verify that the data driven techniques work as intended.

## 8 D0 experience in using matched MC

Most of Tevatron experience with using matched MC is with ALPGEN, as at the time it was the only matched MC that could be run, integrated with the experiments' software, and be mass produced. Both experiments produced a wide range of physics results using ALPGEN. But this success did not come without some difficulties, and a few lessons may be learned from D0's experience.

The D0 collaboration overlays data collected with no trigger bias over the simulated hard scatters, to simulate additional interactions, pileup effects, noise, etc. As the Tevatron luminosity increases, it is desirable to overlay both older data and the very latest data. But data quality issues can arise at the late stages of data analysis, and data that was overlaid over the MC may later be classified as bad. Thus D0 removes events from the MC samples if their overlaid data was of bad quality. The HF removal described in sec 3 is also performed in this post-processing step.

This contributes to the problem of long turnaround times. Once a new feature is put into the MC, it waits for the MC authors to make a software release, then the experiment needs to build and verify its software using the new MC version, the samples need to be produced (lots of events needed with one or no extra jets, generating events with many extra jets is slow), the post-production described above is done, and finally the new samples must be propagated through the physics analyses. Overall, six to twelve months pass before a change in the MC is evaluated. The long turnaround times have made even small mistakes, such as in setting random seeds, very costly. This limits our ability to generate sufficient samples to study systematics.

When using matched MC, the different parton-jet bins must be matched with the correct weights. These weights have a wide range, which complicates the statistical analysis of the simulated background. This wide range is unavoidable when simulating extra jet production, as more detailed simulation of the rare processes with many extra jets is needed. The weights are also sample dependent, and so depend also on the post-processing described above. Therefore the simulated samples must be frozen, resulting in difficult book keeping which is further complicated by the need for generating  $Z$ +jets MC in different mass bins. A possible lesson is that MC production should be designed to avoid any post processing that changes the matching weights. E.g. in order to avoid changes due to data quality, it may be possible to overlay the same set of data events on top of all MC samples to be matched together.

## 9 Conclusions

Modeling  $W$ +jets and  $Z$ +jets backgrounds purely from the simulation is insufficient, and additional inputs from data are required. Though a generic solution can work for most analyses, some analyses can make due without the most sophisticated treatments, and some (especially new physics searches) have their own unique requirements. Several approaches are used to estimate the heavy



flavor contributions, and the overall  $W$ +jets contributions. The data indicates that  $W$ +jets and in particular  $W + \text{HF}$  production is more copious than predicted by ALPGEN.

Matched ALPGEN MC has been used extensively for the last couple of years and was able to meet all our physics needs. Some possible inaccuracies have been identified, in particular in jet angular variables, and some technical lessons can be learned. Other generators seem promising, but have received much less scrutiny at the Tevatron.

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