

Instrumental Backgrounds to $t\bar{t}$ and Single Top Production at Hadron Colliders

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Abstract. A number of backgrounds to top-quark production at the LHC and Tevatron experiments are characterized as instrumental: beam related-backgrounds, cosmic ray backgrounds, and backgrounds from non-prompt (or *fake*) leptons. A number of strategies have been deployed in the experiments to minimize these backgrounds and to estimate their rates. The strategies are applied at the level of the accelerator, the detector apparatus, the first few cuts which are common to many physics analyses, and more refined kinematic cuts. Remaining fake lepton background is estimated using sophisticated data-driven techniques. We present here a survey of the state-of-the-art in the reduction of instrumental backgrounds and also their estimation.

1. Introduction

Instrumental backgrounds are those coming from beam-related effects, detector noise, cosmic rays, and misidentified leptons. In this paper, we survey the effects leading to instrumental backgrounds, explain how they are minimized, and discuss how the remaining irreducible background of fake leptons is estimated.

Events with top quarks in the final state require the use of the entire detector system, since all types of physics objects are present in $t\bar{t}$ and single top signatures. Tracking systems and electromagnetic calorimetry are both important for electron identification, tracking and muon chambers for muon identification, calorimetry for jet-finding and energy estimation, tracking for their classification as b - or light-jets, and the whole detector for the estimate of the missing transverse energy ($\cancel{E}_T$). This makes the analysis of $t\bar{t}$ and single top events susceptible to many effects, such as fake leptons from the accelerator beam, cosmic rays, pion and kaon decay-in-flight and punch-through.

2. Beam-related backgrounds

The first type of instrumental background we discuss is commonly called *beam halo*. Protons in the LHC (or Tevatron, as the case may be) strike limiting apertures, or beam gas, producing neutrons, γ -rays, pions and kaons which decay in flight along the beam direction to muons. These particles, having energies up to the beam energy, impinge on the detector from the side facing the LHC tunnel[1]. Events of this type reconstructed in the ATLAS and CMS detectors are shown in Fig. 1. Backgrounds not originating from the collision region include calorimeter noise bursts and cosmic rays, the latter overlapping approximately 1 event in 10^4 .



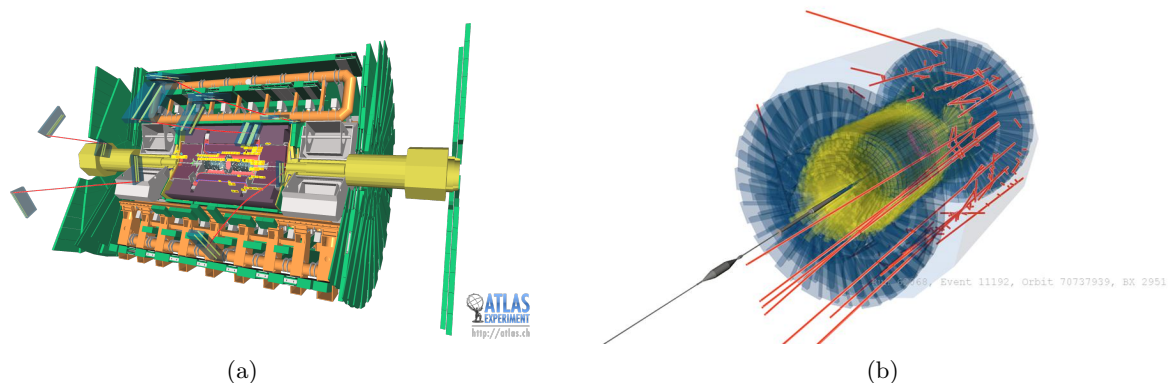


Figure 1. Beam halo events from ATLAS (a) and CMS (b) showing muons tracks traversing the detectors quasi-parallel to the beam line and originating from a location outside the respective detector volumes.

These backgrounds were carefully considered during the construction of the LHC[2] and the CMS[3] and ATLAS[4] detectors. A beam cleansing system consisting of scrapers developed first at the Tevatron was incorporated into the design of the LHC. In addition, large steel shielding elements plug the opening of the LHC tunnel at the entrance to the caverns in both ATLAS and CMS. This suppresses hadrons and γ -rays, leaving muons as the dominant component of beam halo reaching the LHC detectors. The first few cuts applied to top-physics analysis remove the remaining beam-halo and cosmic ray background. CMS generally requires that the primary vertex be found within a cylinder of radius 2 cm and length 24 cm centered around the nominal interaction point[5]. ATLAS[6] requires a primary vertex with at least five tracks, and in order to reject cosmic rays, further discards events containing muon pairs with $\Delta\phi > 3.1$ and $|d_0| > 0.5$ mm where d_0 is the signed distance of closest approach to the primary vertex. In dilepton analyses, the d_0 of the two leptons are required to have opposite sign. Timing information from calorimeters and scintillators is no longer required to reject beam background, since the overlap rate is presently at the level of about 1 in 10^8 .

3. Multijet production background

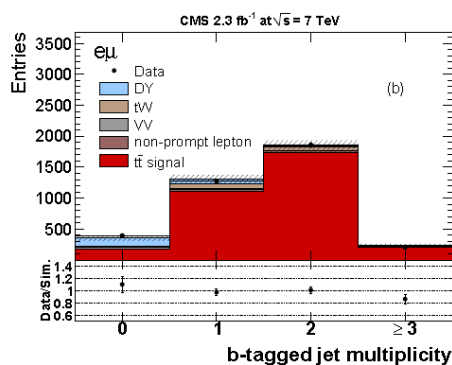
Multijet events with u , d , c , s or b quarks becomes a background to $t\bar{t}$ when they contain a reconstructed lepton from the weak decay of a hadron, a misidentified hadron, or a misidentified jet. We refer to all of these objects as *fake leptons*. Fake electrons can come from photon conversions in the detector material, tracks overlapping with photons, and jets with fluctuations to a larger neutral component (i.e. π^0 's), implying low numbers of charged tracks and early showering in the calorimeter, and semileptonic decays of b - and c -quarks. Fake muons can arise from *sail-through* hadrons that pass through the calorimeter material without showering, *punch-through* hadrons which emerge from hadronic showers, semileptonic decays of b - and c -quarks, and the decay of pions and kaons within the tracking volume. This happens rarely, however the enormous multijet cross section, four orders of magnitude greater than that of $t\bar{t}$ production, makes them an important source of background. Their simulation is impractical because of the large sample sizes, and unreliable because the processes that lead to fake leptons are difficult to model precisely. Instead, data-driven techniques are used to estimate the multijet background to $t\bar{t}$ and single top production. Typically, these data-driven methods are variants of what is known as the *Matrix method*, the *Jet-electron method*, or the *Anti-electron method*.

3.1. The Matrix Method

The matrix method was developed and first applied by the D0 collaboration[7] to determine the number of fake leptons from multijet production (muons or electrons) in a selected event sample. Consider the case of a $t\bar{t}$ with one top-quark decaying semileptonically and the other hadronically (the lepton+jets channel). The standard selection is relaxed (e.g. by loosening an isolation cut) in order to obtain a loose selection. A simple model is now constructed to account for the observed number of events in each category, N^{loose} and N^{std} . In the loose sample, one has $N_{\text{real}}^{\text{loose}}$ events with real leptons and $N_{\text{fake}}^{\text{loose}}$ events with fake leptons. The probability for these events to survive the final selection is r for events with real leptons and f for events with fake leptons. The population of observed events is then predicted to be:

$$\begin{pmatrix} N^{\text{loose}} \\ N^{\text{std}} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ r & f \end{pmatrix} \cdot \begin{pmatrix} N_{\text{real}}^{\text{loose}} \\ N_{\text{fake}}^{\text{loose}} \end{pmatrix} \quad (1)$$

If the efficiencies r and f are known, the equation can be inverted to determine the composition of the loose sample; then the selection efficiencies can be used again to determine the composition of the final sample. In practice, r and f are commonly determined from pure or background-subtracted samples of real and fake leptons. This idea can be extended to more complicated situations. In events with two leptons (e.g. the top dilepton channel, or the single top Wt channel), more categories are required (std/std, loose/std, std/loose, loose/loose) and the data model is more complicated, but the basic idea is the same. Distributions in any kinematic variable for multijet background can also be determined, by assigning to each event in the loose sample a probability for being real or fake, according to whether the event passes the standard selection or only the loose selection. To obtain samples of real leptons, leptons from $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$ are often used, and sometimes Monte Carlo. Fake leptons are taken from samples enriched in multijet events, with systematic uncertainties evaluated by varying the choice of the sample. Typically, the background estimation is conducted in bins of transverse momentum p_T or pseudorapidity η , after correcting the real and fake samples for contamination. Results from a CMS analysis of the dilepton channel [8] are shown in Fig. 2. In this example, where two leptons are involved, the level of fake lepton background from multijet production is relatively low. This is also a feature of the single top Wt channel.



Fake leptons (CMS dilepton)

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\pm$
N_W	1.8 ± 4.8	9.8 ± 5.6	42.4 ± 14.6
N_{MJ}	0.6 ± 0.5	0.2 ± 0.1	7.5 ± 3.9

Figure 2. CMS dilepton analysis from Ref. [8]. Estimated backgrounds are shown in the table, where W (W -like) indicates one fake lepton and MJ (*Multijet-like*) indicates two fake leptons.

3.2. The Jet-electron Method

In the *Jet-electron* method, a sample of jets (the *jet-electron* sample) is selected whose properties resemble those of jets likely to fake electrons, i.e. those with few tracks which have showered early

in the calorimeter. In an ATLAS analysis of single top t -channel production[9], for example, 80-95% of the energy must have been deposited in the electromagnetic section of the calorimeter; p_T and η selections are identical to those used for an electron selection, at least four tracks must be found in the jet, and no other electron or muon candidate may be present in the event. The shape of the multijet background is taken from the jet-electron sample, while the overall normalization is determined from a fit to the $\cancel{E}_T$ distribution before any cuts on $\cancel{E}_T$ are applied. While there is no *a priori* reason to believe that the jet-electron model should also describe the multijet background with fake muons, in practice the model adequately describes this background. The analysis from ATLAS[9] is illustrated in Fig. 3. A variant of the jet-electron method is the anti-electron method, which uses a sample of lepton candidates for which some but not all of the electron identification cuts have been satisfied. This method was used frequently in the CDF collaboration. Systematic uncertainties are estimated by varying the template shape. In CDF this was done by obtaining alternate templates from two-track (rather than one-track) lepton candidates. CMS has applied anti-lepton background estimates for muons, where non-isolated muons are used to derive muon template shapes, and for electrons, for which *marginal failures* (candidates failing two out of six electron identification cuts) were used. In the case of CMS, the normalization was determined from a sideband region $\cancel{E}_T < 20$ GeV and from a fit to the reconstructed vertex mass.

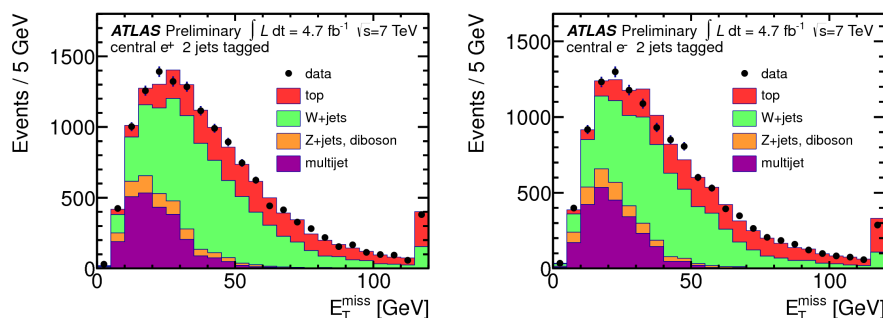


Figure 3. Results from ATLAS single top t -channel analysis from Ref. [9], which require a single lepton in addition to jets and $\cancel{E}_T$. The multijet background is relatively high. Here it has been estimated with the jet-electron method.

3.3. Other methods

Every analysis is unique, and occasionally one encounters background-estimate techniques which don't fall into any of the above categories. One can observe from the plots of Fig. 2 and Fig. 3 that the probability of fake leptons from multijet production is much lower when two leptons are required than when one lepton is required. The background to a dilepton analysis usually contains one real lepton from a W boson decay and one fake lepton. In Ref. [10], a CDF dilepton analysis, tracks with $p_T > 20$ GeV which point to electron-like or muon-like signatures in the calorimeters are called *fakeable objects*. Events in a high- p_T lepton sample accompanied by a fakeable object is called a *fakeable event*. Finally, the rate of fake dilepton events is computed by weighting each fakeable event by the fake rate for the fakeable objects in the event, the latter being measured in data in a sample of generic jets satisfying a trigger requirement of $E_T^{\text{trig}} > 20, 50, 70$, and 100 GeV. The selection criteria are varied to obtain an estimate of the systematic uncertainty on the fake-lepton background, which is quoted to be 30%. This makes an important contribution to the overall uncertainty in the top dilepton cross section.

Table 1. Methods used in CMS, ATLAS, CDF, and D0 for a few example analyses. MM=Matrix Method. JE=Jet-electron Method. AE=Anti-electron method.

Exp.	Channel	Observable	$\int \mathcal{L} dt$ [fb ⁻¹]	Ref.	Method
ATLAS	lepton+jets	$\sigma(t\bar{t})$	0.035	[11]	MM(μ), AE(e)
ATLAS	dilepton	$\sigma(t\bar{t})$	0.7	[12]	MM
ATLAS	single top lepton+jets	$\sigma(t)$, t -channel	1.04	[13]	JE
CMS	lepton+jets	$\sigma(t\bar{t})$	0.036	[14]	AE
CMS	dilepton	$\sigma(t\bar{t})$	2.3	[8]	MM
CMS	single top leptons+jets	$\sigma(t)$, t -channel	0.036	[15]	AE
CDF	lepton+jets	$\sigma(t\bar{t})$	2.7	[16]	AE
CDF	dilepton	$\sigma(t\bar{t})$	2.8	[10]	other
CDF	single top lepton+jets	$\sigma(t)$, s , Wt , t -channel	3.2	[17]	JE/AE hybrid
D0	lepton+jets	$\sigma(t\bar{t})$	0.9	[18]	MM
D0	dilepton	$\sigma(t\bar{t})$, m_t	1.0	[19]	AE
D0	single top	$\sigma(t)$, t -channel	2.3	[20]	MM

4. Conclusions

We have discussed a number of approaches to minimizing instrumental backgrounds and the methodology of estimating irreducible fake-lepton backgrounds. Good design of detector and accelerator systems have kept the former sources of background under control, while remaining fake-lepton backgrounds have been estimated in a variety of ways at CDF, D0, ATLAS, and CMS. Usually the methodology consists of either the matrix method, the jet-electron method, or the anti-electron method, but a creative physics community and different challenges leads to some variation in these techniques which occasionally defies the above classification. Table 1 gives a few examples analyses where one can find these techniques applied.

References

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