CMS Physics Analysis Summary

CMS MET Performance in Events Containing Electroweak Bosons from pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

During the spring of 2010, the LHC delivered proton-proton collisions with a centre-of-mass energy of 7 TeV. In this note, we present results of studies of missing transverse energy ($E_T$), as measured by the CMS detector, in events containing W bosons or isolated, high transverse momentum photons. The performance of several different $E_T$ reconstruction algorithms is compared.
1 Introduction

Neutral weakly interacting particles such as neutrinos normally escape from a detector without producing any direct response in the detector elements. Many scenarios of physics beyond the Standard Model predict the existence of new particles which similarly have only weak interactions and will escape ordinary detection. The presence of such particles in collider experiments must be inferred from the imbalance of total momentum. The vector momentum imbalance in the plane perpendicular to the beam direction is particularly useful in \( pp \) and \( p\bar{p} \) colliders, and is known as missing transverse momentum, here denoted \( \vec{E}_T \). Its magnitude is missing transverse energy, and will be denoted \( E_T \).

A good understanding of \( E_T \) is important as it is present not only in signatures of new physics, but is also required for the reconstruction of well known processes, such as leptonically decaying \( W \) bosons. Missing transverse energy is one of the most important quantities for discriminating \( W \) bosons in \( W \rightarrow \ell\nu \) from \( E_T \)-free backgrounds such as QCD, and the degree of signal and background separation that one can achieve depends on the \( E_T \) resolution. \( E_T \) is also a key player in any search for new physics involving weakly interacting particles, and the issue of resolution is correspondingly important.

In this note, we study the performance of three \( E_T \) algorithms using events where an identified vector boson, \( W \) or \( \gamma \), is present. The vector boson in these studies plays the role of a simple and well-understood probe which is deployed to assess the detailed performance of a more complicated object, \( E_T \). Pile-up, namely multiple interactions of protons in the same bunch crossing, is expected because of high LHC bunch currents and can play an important role in \( E_T \) performance. In this study, however, we concentrate primarily on events without pile-up and examine the effects of pile-up only in a few key measurements, while deferring to a future note the more extensive study explicitly including the effects of pile-up. The future note will also include studies with \( Z \) bosons.

Events with vector boson production may be produced in hard parton-parton collisions such as \( qg \rightarrow q\gamma, qg \rightarrow q'W, \) and \( q\bar{q}' \rightarrow gW \). While the lowest order underlying processes may be simple, many physics and experimental issues complicate the assessment of such events. Effects due to jet energy scale corrections and fluctuating jet composition directly impact the measurement of the hadronic products of the hard collision and are closely correlated with the properties of the collision, such as the jet \( p_T \), jet parton flavour, and jet composition. Underlying event activity, pile-up, detector noise, and finite detector acceptance, on the other hand, all result in direct or indirect contributions to the measured detector response which are not dependent on the specifics of the hard collision under study, and are generically present in all events. By selecting events in which a hadronic system recoils against an electroweak vector boson, we can probe the detector response using objects that are both precisely calibrated and able to separate effects correlated and uncorrelated with the hard jet characteristics.

We use data collected by the CMS detector at LHC in \( pp \) collisions at \( \sqrt{s} = 7 \text{ TeV} \).

2 Missing Transverse Energy Algorithms

In general, \( E_T \) is calculated as the negative of the vector sum of the components of momentum transverse to the beam axis of all final-state particles reconstructed in the detector. CMS has developed three distinct algorithms to reconstruct \( E_T \): (a) \( E_T \) based on calorimeter energies and calorimeter tower geometry [1]; (b) \( E_T \) calculated by replacing the calorimeter tower energies matched to charged hadrons with their corresponding charged-track momenta [2]; and (c) \( E_T \)
calculated using a complete particle-flow technique [3]. We will label these Calo $E_T$, TC $E_T$, and PF $E_T$, respectively.

2.1 Calorimetric $E_T$

The first algorithm for reconstructing $E_T$ is described in [1]. Calo $E_T$ uses calorimeter towers up to $|\eta| < 5$, and sums only energy deposits above noise threshold. Since a muon deposits only about 2 GeV in the calorimeter, independent of its momentum, the muon $p_T$ measured by the inner and outer spectrometer must be added into the Calo $E_T$ while simultaneously removing the small calorimetric energy deposit associated to the muon track. No correction is needed for the electron, whose energy is reconstructed without bias by the electromagnetic calorimeter.

Further corrections are generally made to account for the nonlinearity and noncompensating response of the calorimeter to hadronic particles, by applying a correction to the jet energy scale (Type-I correction), as described in [4]. In addition, towers not associated to any jet can be corrected for calorimeter nonlinearity (Type-II correction) as described in [5]. All Calo $E_T$ results presented here will be fully corrected with both Type-I and Type-II corrections applied.

2.2 Track-corrected $E_T$

The second algorithm for $E_T$ reconstruction (TC $E_T$) is described in [2]. It starts from the Calo $E_T$ algorithm described above, and adds in the $p_T$ of the remaining tracks which have been reconstructed in the inner tracker, while subtracting the expected calorimetric energy deposit of each track. All tracks are treated as pions in this process. The calorimetric energy deposit has been estimated from a single-pion Monte Carlo sample, in bins of $p_T$ and $\eta$ and taking into account the track extrapolation in the CMS magnetic field to determine the expected position of the calorimetric energy deposit. No correction is applied for very high-$p_T$ tracks ($p_T > 100$ GeV/c), whose energy is already well measured by the calorimeters. Low-$p_T$ tracks ($p_T < 2$ GeV/c), are fully compensated for, assuming no response from the calorimeter.

2.3 Particle-flow $E_T$

The third algorithm for $E_T$ reconstruction is based on particle-flow (PF) methods. The particle-flow technique [3] aims to reconstruct a complete, unique list of particles in each event using an optimal combination of information across all CMS subdetector systems. Particles which are reconstructed and identified include muons, electrons (with associated bremsstrahlung photons), photons (unconverted and converted), and charged and neutral hadrons. The PF $E_T$ is then simply the negative vector sum of all such reconstructed particles in the event. The performance of PF $E_T$ is studied in detail in [6].

2.4 Notation

In this paper, the following notation will be used: the electroweak boson momentum in the transverse plane is $\vec{q}_T$, and the hadronic recoil, defined as the transverse momentum sum of all particles except the vector boson, is $\vec{u}_T$. Momentum conservation in the transverse plane is then succinctly summarized by $\vec{q}_T + \vec{u}_T + \vec{E}_T = 0$, and the vector $\vec{E}_T$ is defined by the negative sum of all other transverse momentum vectors in the event, $\vec{E}_T \equiv -\vec{q}_T - \vec{u}_T$. We will use the term “recoil” to refer to the magnitude of the measured hadronic momentum vector, $u_T \equiv |\vec{u}_T|$. Figure 1 summarizes these kinematic definitions.

In the case of photons, the presence of a well-measured photon provides both a momentum scale, $q_T \equiv |\vec{q}_T|$, and a unique event axis, $\hat{q}_T$. The hadronic recoil can be projected onto this
axis, yielding two signed components, parallel ($u_{\parallel}$) and perpendicular ($u_{\perp}$) to the event axis. Since $u_{\parallel} \equiv \vec{u}_T \cdot \vec{q}_T$ and the observed hadronic system is usually in the opposite hemisphere from the photon, $u_{\parallel}$ is typically negative. The mean value of the scalar quantity $|\langle u_{\parallel} \rangle|/q_T$ measures the scale factor correction required for $E_T$ measurements in the classes of events considered here, and is closely related to jet energy scale corrections and jet parton flavour. We will refer to $|\langle u_{\parallel} \rangle|/q_T$ as the “response” and will denote plots of this quantity versus $q_T$ as “response curves”. Since $|\langle u_{\parallel} \rangle|/q_T = 1 + \langle E_{\parallel} \rangle/q_T$, deviations of the response curve from unity probe $E_T$ response as a function of $q_T$, and we may interchangeably speak of “hadronic response” or “$E_T$ response”. $E_T$ resolution is assessed by measuring the RMS spread of $u_{\parallel}$ and $u_{\perp}$ about their mean values, which will be denoted $RMS(u_{\parallel})$ and $RMS(u_{\perp})$. As with the response, we will examine the resolutions as functions of $q_T$.

![Figure 1: Kinematics: (a) Photon-Jet events; (b) W events.](image)

Finally, the angle in the transverse plane between the recoil and the photon is defined by $\Delta \phi \equiv \cos^{-1}(\vec{u}_T \cdot \vec{q}_T)$, so that $\Delta \phi = \pi$ when the recoil is back-to-back to the photon.

In the case of $W$ events, the direction of the charged lepton takes the place of the vector boson momentum, which is not measured directly. Thus the components $u_{\parallel}$ and $u_{\perp}$ and the angle $\Delta \phi$ are defined with respect to the direction of the transverse momentum vector of the charged lepton, $p_T^\ell$.

## 3 Data Sample Definition and Selection

The data sets used for this study were collected by the CMS detector at the LHC at $\sqrt{s} = 7$ TeV, in the spring of 2010, and comprise an integrated luminosity of approximately 200 nb$^{-1}$. Only runs that were taken during a period with stable LHC beams and with all CMS subdetectors operating without problems have been used in the analyses. Known dead or noisy channels in the calorimeters were masked before the event reconstruction process. Events with anomalously large occupancy in the pixel detector have been rejected by requiring that the fraction of high-purity tracks in events with more than 10 tracks is greater than 25%. Such events, first seen in the LHC commissioning phase, are characterized by particle bunches or showers traversing the pixel detector longitudinally and are thought to arise from beam-gas interactions.

Events are required to contain at least one well-identified primary vertex. The number of degrees of freedom of the primary vertex fit should be at least 5, and its $z$ position should be less than 15 cm away from the nominal centre of the detector. High LHC bunch currents in the latter portion of the data-taking period resulted in events with multiple proton interactions, and hence multiple primary vertices. These are identified in off-line analysis by the presence of two or more primary vertices separated by at least 1 cm in $z$ from one another. Over the full dataset, 40% of the the events exhibit such pile-up. In the analyses reported here we focus on the intrinsic detector characteristics and for the time being we set aside the additional issues introduced...
by pile-up by requiring exactly one primary vertex. Since primary vertices lying within $\Delta z \leq 1$ cm of one another are merged in the reconstruction process, multi-vertex events contaminate the one-vertex sample, and we estimate and subtract this contamination. Typically about 7% of events with a single reconstructed primary vertex are in fact due to events with two or more primordial $pp$ collisions.

The collision data were compared to samples of simulated Monte Carlo events that were generated using the PYTHIA6.420 Monte Carlo generator [7] and POWHEG NLO matrix element computation [8]. The response of the detector was simulated using GEANT4 [9]. The detector geometry description included realistic subsystem conditions such as dead channels. The spread of the primary vertex of the simulated events along the beam-line was modeled using the distribution measured in the data.

The selection procedure described above was applied to both the data and the Monte Carlo simulation samples.

4 $E_T$ in Photon + Jet Events

We examine first the events in which a hadronic system recoils against a photon. The photon is detected and measured in the electromagnetic calorimeter (ECAL) with good precision, $\sigma_{E_T}/E_T \sim 1\%$. Since the hadronic system exhibits resolutions that are typically an order of magnitude larger in the $E_T$ ranges studied here, the photon serves effectively as a delta-function probe of the detector’s response to the hadronic system.

The primary results from this study are the extraction of response and resolution curves as defined in Section 2.4.

4.1 Event Selection

Candidate events for this class are selected by requiring that each event contain exactly one reconstructed photon in the barrel portion of the ECAL ($|\eta| < 1.479$) with $q_T > 20$ GeV; and that the photon candidate satisfy the set of criteria listed below:

- **Isolation**: Energy deposited in ECAL within a cone of $\Delta R < 0.4$ around the photon direction, excluding the energy associated to the photon, must be less than $4.2 + 0.004 \times q_T$; energy deposited in HCAL within a cone of $\Delta R < 0.4$ around the photon direction must be less than $2.2 + 0.001 \times q_T$; and there must be fewer than 3 tracks in a cone of $\Delta R < 0.4$ around the photon direction. In addition, the scalar $p_T$ sum of tracks consistent with the primary vertex in a hollow cone around the photon candidate in an annular region of inner radius $R = 0.04$ and outer radius $R = 0.4$, is required to be less then $2.0$ GeV $+ 0.001 \times q_T$.

- **Electromagnetic character**: the ratio of energy deposited in HCAL to that deposited in ECAL within a cone of $\Delta R < 0.15$ around the photon direction must be less than 0.05.

- **Shower localization**: the $3 \times 3$ matrix around the seed crystal in ECAL must contain 90% of the total photon candidate super-cluster energy; the major and minor second moments of the photon cluster must be in the range of $0.20 - 0.35$, and $0.15 - 0.3$, respectively; and the longitudinal size of the photon cluster must satisfy $\eta_{\text{width}} < 0.03$.

- **$W$ suppression**: The ECAL shower is required not to match any track that is found in the pixel detector and is consistent with the primary vertex.
The last requirement above addresses a background that can arise from $W \rightarrow e\nu$ followed by a hard bremsstrahlung. While rare, such events are concentrated in a narrow range of photon phase space ($E_\gamma \sim 40$ GeV) and must be carefully considered. This cut eliminates 98% of the $W^+$ bremsstrahlung events, leaving an estimated contamination of 1.7 events in our final sample.

The integrated luminosity used for this study is 198 nb$^{-1}$. The total number of events passing all requirements is 4,594.

### 4.2 Results

Figure 2 shows the photon $q_T$ spectrum for data and Monte Carlo simulation. About half of the observed rate arises from QCD dijet production where one jet passes all photon identification requirements. Such jets are typically highly enriched in $\pi^0 \rightarrow \gamma\gamma$ and contain little hadronic activity. The calorimeter response to these jets is similar to that of single photons, and Monte Carlo studies indicate that response curves extracted from these QCD “background” events match the response of true photon-jet events to within a percent. We therefore make no further attempt to filter them out.

![Figure 2: $q_T$ distribution of events selected as photon-jet candidates. Monte Carlo predicted rates for signal and backgrounds are as shown.](image)

To study the $E_T$ scale and resolution, we decompose the recoil with respect to the photon direction in the transverse plane. Distributions of the components of recoil parallel and perpendicular to the photon axis, $u_\parallel$ and $u_\perp$, are shown in Figure 3 for the three hadronic reconstruction algorithms, Calorimetric, Track-Corrected, and Particle-Flow. As expected, the parallel component is mainly negative, consistent with the back-to-back nature of the events, while the perpendicular component is symmetric. The agreement between data and Monte Carlo is good, and the trend across reconstruction algorithms, viewing the columns from left to right, suggests that explicit inclusion of tracking information in the hadronic reconstruction sharpens kinematic measurements.

Figure 4 shows the distribution of $\Delta\phi = \cos^{-1}(\hat{u}_T \cdot \hat{q}_T)$, the angle between the photon direction and the hadronic recoil, further confirming that the kinematic configuration is predominantly back-to-back. The residual low-level discrepancy between data and Monte Carlo visible in the angle plots in the region $\Delta\phi \lesssim 2$ is under further study.

The principal results of the photon-jet study are the response and resolution measurements
shown in Figures 5 and 6. These measurements calibrate (Figure 5) and characterize (Figure 6) the performance of $E_T$ determination in CMS:

Figure 5 shows the response curves, $|\langle u||/q_T$ versus $q_T$, extracted from data, for the three hadronic reconstruction algorithms, Calorimetric, Track-Corrected, and Particle-Flow. The agreement between data and Monte Carlo is good, and the results indicate that the three reconstruction algorithms are distinct in their capabilities, performing differently in the recovery of hadronic activity in the detector. The response for Calorimetric $E_T$ is found to be slightly larger than one, as expected, since the corresponding jet energy scale corrections are tuned for a mixture of quark and gluon jets. The former are known to have a higher intrinsic response in the
4.2 Results

Figure 5: Response curves measured in photon-jet events, for (left to right) Calo $E_T$, TC $E_T$, and PF $E_T$. Results are shown for events with exactly one primary vertex (full squares) and more than one (open circles). The upper frame of each figure shows the response in data (points) and Monte Carlo (histogram); the lower frame shows the ratio of data to Monte Carlo, with the brown line and the text at the bottom of the frame indicating the average data/MC ratio. The vertical axis labels at the far left apply to all three subfigures.

calorimeter with respect to the latter, and are more common in the direct $\gamma$ production sample. The Track-Corrected and Particle-Flow responses are underestimated due to the absence of jet energy corrections, which are not applied since the effects of the non-linear response of the calorimeters are largely corrected by the algorithms themselves. The figure also shows the response measured in events with more than one reconstructed primary vertex (pile-up events). The response measured in pile-up events agrees well with that for non-pile-up events, indicating that within the statistical uncertainties the response is not sensitive to pile-up.

Figure 6 shows the resolution curves for $u_\parallel$ (left) and $u_\perp$ (right) for data and Monte Carlo, in all three reconstruction algorithms. The resolution measurements are rescaled, bin by bin, to correct for the slight distortions implied by the corresponding response curves of Figure 5. The data confirm the Monte Carlo prediction that tracking information can significantly enhance the $E_T$ resolution. The lower frames compare, in a bin-by-bin ratio, the resolution measurements obtained in events with two or more primary vertices to those obtained in events with exactly one primary vertex. This comparison indicates that pile-up degrades the resolution of $u_\parallel$ and $u_\perp$.

Taken together, Figures 5 and 6 show that effects of pile-up are largely invisible in the first moment of the hadronic recoil distribution (the response), but are readily apparent in the second moment (the resolution). Such a combination of effects is what one expects from extra proton collisions whose energy flow is uncorrelated with the direction of the photon from the hard collision.
At lowest order, $W^\pm$ production in $pp$ collisions takes place through $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$. Such processes favor $W^+$ production over $W^-$, cast the $W$ in the direction of the original quark, and produce $W$s with left-handed polarization. At lowest order, the dominant processes are $u\bar{d} \rightarrow gW^+$, $ug \rightarrow dW^+$ (and charge conjugated), with the gluon or quark emission imparting a soft transverse momentum ($\vec{q}_T$) to the $W$. Viewed in the transverse plane, the $W$ is slightly polarized left-handed at low $q_T$, and becomes increasingly left-handed at large $q_T$ [10].

We identify the $W$ through its leptonic decay, $W \rightarrow \ell \nu$, signaled by the presence of a high-$p_T$, isolated charged electron or muon, and $E_T$ from the undetected neutrino. Since the $W$ is produced mainly at low $q_T$, the direction of the $E_T$ is approximately back-to-back with respect to the lepton. At low $q_T$ the decay axis is not strongly correlated with the $W$ direction. The transverse mass, $M_T$, can be reconstructed, using the lepton measured transverse momentum, $p_T$, and assigning $E_T$ to the neutrino momentum: $M_T^2 = 2p_T^2 E_T (1 - \cos \Delta\phi_{\ell\nu})$, where $\Delta\phi_{\ell\nu}$ is the azimuthal angle between the lepton and $E_T$. When the $q_T$ is small compared to the $W$ mass, $M_T \approx 2E_T + |\vec{u}_||$, where $u_|| \equiv \vec{u}_T \cdot \vec{p}_T$ is the component of the measured recoil parallel to the lepton direction. For most $W$ events, therefore, $M_T$ is dominated by the lepton, but the resolution on the hadronic recoil momentum remains an important consideration for $M_T$ precision.
The absence of a complete reconstruction of the $W$ momentum forces one to use the charged lepton momentum vector to define the event axis, as in the photon case. It is not optimally suited to the task. The recoil vector $\vec{u}_T$ is roughly back-to-back with the $W$ momentum, but is not well correlated with the charged lepton momentum, especially for the majority of the $W$s in our sample which have low $q_T$. With increasing $q_T$, the (left-handed) polarization of the $W$ will increase and in leptonic $W^-$ decays the $V - A$ interaction will tend to throw the left-handed $\ell^-$ forward. This signature behavior of the charged weak interaction, together with the forward-folding effect of the Lorentz boost, means that the $\ell^-$ direction will exhibit increasing correlation with the hadronic recoil direction, $\vec{u}_T \cdot \hat{p}_\ell^T \to -1$, at high $W$ transverse momentum or, equivalently, at high lepton transverse momentum. In $W^+$ decays, on the other hand, the $\ell^+$ is thrown backward and the Lorentz boost works to soften the correlation. In this analysis, however, we do not distinguish between $W^+$ and $W^-$, and our sample is dominated by low transverse momentum, so we do not anticipate a strong correlation between the lepton and the $W$ directions.

The systematic uncertainties due to our imperfect knowledge of the true $W$ $q_T$ distribution are estimated from the difference between the $q_T$ distributions in PYTHIA and POWHEG Monte Carlo samples. We set the systematic error, bin-by-bin in $q_T$, equal to this difference.

5.1 $W \rightarrow \mu \nu$ selection

In the $W \rightarrow \mu \nu$ decay channel, events passing a single-muon high-level trigger with 9 GeV threshold are selected. Offline, the muon is reconstructed using hits in the tracker and muon detectors, and must both fall within the detector acceptance, $|\eta_\mu| < 2.1$, and satisfy a $p_T$ threshold $p_T > 25$ GeV.

Additional requirements on the muon quality include:

- Tracking: $\chi^2$/ndof < 10, at least 10 hits in the silicon tracker, at least one hit in the pixel detector, hit(s) from at least one station in the muon-detector system and a transverse impact parameter with respect the beam spot satisfying $d_{xy} < 2$ mm.
- Calorimeter: The energy deposited in the ECAL and HCAL must be less than 4 GeV and 6 GeV, respectively.
- Isolation: The sum of the $p_T$ of other tracks reconstructed in the silicon tracker, plus the transverse energy deposited in both ECAL and HCAL measured in a cone of $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.3$ is used: $\Sigma(p_{T\, \text{tracks}} + E_{\text{cal}} + E_{\text{hcal}}) < 0.15 \times p_{T\, \mu}$, where the ECAL and HCAL deposit of the muon itself is not included.

To suppress QCD background, we further require that the $W$ candidate pass a minimum transverse mass threshold, $M_T > 50$ GeV, and a minimum $E_T$ threshold, $E_T > 25$ GeV. As discussed in Section 3, we limit the impact of pile-up in these preliminary studies by requiring exactly one primary vertex.

The data sample used for $W \rightarrow \mu \nu$ events comprises 246 nb$^{-1}$. In total, 514 $W \rightarrow \mu \nu$ candidates have been selected.

5.2 $W \rightarrow e \nu$ selection

In the $W \rightarrow e \nu$ decay channel, events passing a single-electron high-level trigger with 10 GeV threshold are selected. Offline, the electron candidate is formed from the association of a high-$E_T$ supercluster in the ECAL and a high-$p_T$ track reconstructed in the silicon tracker with a Gaussian-Sum Filter algorithm which accomodates the emission of bremsstrahlung photons.
in the tracker [11]. The electron candidate must lie within the ECAL acceptance ($|\eta_e| < 2.5$, excluding the barrel-endcap overlap region $1.44 < |\eta| < 1.56$), and must satisfy $p_T > 25$ GeV. Events with a second electron with $E_T > 20$ GeV are rejected to suppress $Z$ contamination, and rejection against $\gamma$ conversion is applied. The electron identification requirements are as follows:

- **Track Isolation:** The relative sum of the track $p_T$'s around the electron in a $\Delta R < 0.3$ cone must be less than 0.09 GeV for electrons in the barrel and less than 0.04 GeV for those in the endcap.
- **ECAL Isolation:** The relative sum of the ECAL deposits around the electron in a $\Delta R < 0.3$ cone must be less than 0.07 in the barrel and less than 0.05 in the endcaps.
- **HCAL isolation:** The relative sum of the HCAL towers around the electron must be less than 0.1 in the barrel and 0.025 in the endcaps.
- **Track-Cluster Matching:** The $\Delta \phi$ between the supercluster and the track extrapolated to the vertex must be less than 0.06 for barrel electrons and 0.03 for endcap ones. Similarly, the $\Delta \eta$ between the supercluster and the track extrapolated to the vertex must be less than 0.004 for the barrel electrons. Due to misalignment between ECAL endcaps and the tracker system, no $\Delta \eta$ cut is made for endcap electrons.
- **Cluster Shape:** The energy-weighted average of the $\eta$ dispersion of the seed cluster crystals around the most energetic one, $\sigma_{\eta\eta}$, must be less than 0.01 for the barrel and less than 0.03 for the endcap electrons.

As with the $W \to \mu \nu$ mode, we additionally require $M_T > 50$ GeV, $E_T > 25$ GeV, and exactly one primary vertex.

The data sample used for $W \to e\nu$ events comprises $255 \text{ nb}^{-1}$. A total of 461 $W \to e\nu$ events have been selected.

### 5.3 Backgrounds and Normalization

The main sources of background to the $W \to \ell\nu$ signal are QCD events with one high-$p_T$ muon or electron and $Z \to \ell\ell$ events with one lepton escaping detection. The QCD events are most prominent at low $M_T$. Other backgrounds include $W$ and $Z$ decaying into $\tau$, followed by $\tau \to \ell\nu\bar{\nu}$, and $t\bar{t}$ events. The different EWK signal and background Monte Carlo event ensembles containing electroweak processes ($W \to \ell\nu$, $Z \to \ell\ell$, $t\bar{t}$) are normalized according to the theoretical cross section computed at Next-to-Leading-Order. This composite EWK shape and the QCD shape from MC are then normalized by fitting to the $E_T$ distribution in data. This establishes the relative normalization of these components. Since we are not measuring a cross section in this analysis, an absolute overall normalization is not needed here. The procedure is to fit the EWK shape, $S(E_T)$, and the QCD shape, $B(E_T)$, to data, $D(E_T)$, with a one-parameter binned fit that fixes their relative normalization throughout the rest of the analysis:

$$D(E_T) = N_{data} [\alpha S(E_T) + (1 - \alpha)B(E_T)].$$ (1)

### 5.4 Results

The figures below summarize all results, with data and Monte Carlo overlaid. The Monte Carlo histograms include a gray shaded band indicating the estimated uncertainty due to modelling of the $W q_T$ spectrum, and the pile-up correction procedure. In most cases this uncertainty is too small to be visible.
Figure 7 shows the $E_T$ distributions for both $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ candidates. Data and Monte Carlo agree well, and the $W$ shows up prominently as expected.

Figure 8 shows the distributions of the hadronic recoil components, $u_\parallel$ and $u_\perp$, parallel and perpendicular to the charged lepton direction, for both $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$. The $u_\perp$ distributions are symmetric about zero as expected, and are primarily indicative of the $E_T$ resolution. They show a marked narrowing as one views the columns from left to right. This pattern is consistent with the observations made in the photon-jet study and summarized in Figure 6. The $u_\parallel$ distributions show a modest asymmetry, towards the negative side, which can be partly attributed to the biasing effects of the lepton isolation requirements, and partly to the mild boost of the $W$.

Figure 9 shows the $u_T$ distribution. In contrast to the $u_\parallel$ and $u_\perp$ distributions which depend on the relative orientations of the leptonic and hadronic axes, $u_T$ is a rotationally invariant quantity, and probes only the recoil process. While $E_T$ in inclusive $W$ events is dominated by the lepton, the resolution has substantial contributions from the mismeasurement of the many particles in the underlying event. These contributions can be more clearly seen in the $u_T$ distribution, since they are not then obscured by the lepton.

Finally, Figure 10 shows the distribution of the opening angle between the lepton and the
hadronic system. As expected, the distribution shows a weak tendency for the lepton and
the hadronic system to anti-align.

In all cases we find good agreement between Monte Carlo and data.

6 Conclusion

The performance of three $E_T$ algorithms, based on purely-calorimetric, track-corrected calori-
metric, and particle-flow reconstruction techniques, have been examined with early data from
$pp$ collisions at 7 TeV in the LHC. By selecting events with a vector boson, the performance of
the $E_T$ algorithms can be studied in detail, with particular emphasis on the calibration scale of
the $E_T$ response measurement, and the resolution of the $E_T$ response.

Within the statistics and kinematic ranges accessible in the available data sets, good agreement
between data and simulation is observed for each of the three $E_T$ algorithms. We note that the
$E_T$ resolutions achieved by the three methods differ, and the improvement that results from
the inclusion of charged-particle tracking in $E_T$ reconstruction is significant. The difference in
performance is further confirmed in $E_T$ distributions of $W \rightarrow \ell \nu$ event samples which contain
genuine $E_T$.

The presence of pile-up events has been shown to worsen the resolution of the $E_T$ for all al-
gorithms, while the response is unaffected. This will be studied in detail with the larger data
samples collected recently.

The excellent performance of the three different $E_T$ reconstruction algorithms promises a ro-
bust exploitation of $E_T$ signatures in the emerging CMS physics program.
Figure 8: Top two rows: $u_{||}$ and $u_{\perp}$ distribution in $W \to ev$ candidate events. Bottom two rows: $u_{||}$ and $u_{\perp}$ distribution in $W \to \mu\nu$ candidate events. The three columns correspond, left to right, to the three $E_T$ algorithms, Calo $E_T$, TC $E_T$, and PF $E_T$. Both data (points) and Monte Carlo (histograms) are shown, with Monte Carlo uncertainties indicated by shaded regions.
Figure 9: $|\mu_T|$ distribution in $W \rightarrow e\nu$ (above) and $W \rightarrow \mu\nu$ (below) candidate events. The three columns correspond, left to right, to the three $E_T$ algorithms, Calo $E_T$, TC $E_T$, and PF $E_T$. Both data (points) and Monte Carlo (histograms) are shown.
Figure 10: $\Delta \phi \equiv \cos^{-1}(\hat{u}_T \cdot \hat{\beta}_T^\ell)$ distribution in $W \rightarrow e\nu$ (above) and $W \rightarrow \mu\nu$ (below) candidate events. The three columns correspond, left to right, to the three $E_T$ algorithms, Calo $E_T$, TC $E_T$, and PF $E_T$. Both data (points) and Monte Carlo (histograms) are shown.
References


