Performance of missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector

The CMS Collaboration

Abstract

The performance of algorithms for the reconstruction of missing transverse momentum for data from proton-proton collisions with a center-of-mass energy of 13 TeV collected with the CMS detector at the LHC is presented. The data sample corresponds to an integrated luminosity of 35.9 fb$^{-1}$. The results include detailed studies of the identification of events with anomalous missing transverse momentum and measurements of its scale and resolution. The performance of a missing transverse momentum reconstruction algorithm that mitigates the effects of multiple proton-proton interactions, using the Puppi method, is also presented. Lastly, the performance of an algorithm used to estimate the compatibility of the reconstructed missing transverse momentum with the null hypothesis is shown.
1 Introduction

Weakly interacting neutral particles produced in the proton-proton collisions at the LHC pass through the collider’s detectors unobserved. However, if such particles are produced along with other visible particles, their presence can be inferred through the visible momentum imbalance in the plane perpendicular to the beam direction. The visible momentum imbalance vector is known as missing transverse momentum ($p_T^{\text{miss}}$), and its magnitude is denoted as $p_T^{\text{miss}}$.

The precise measurement of $p_T^{\text{miss}}$ is critical for standard model (SM) measurements in final states with neutrinos, such as leptonic decays of the W boson. In addition, $p_T^{\text{miss}}$ is one of the most important observables in searches for physics beyond the standard model targeting new weakly interacting particles. However, $p_T^{\text{miss}}$ reconstruction is sensitive to the resolutions and mis-measurements of the reconstructed particles, and to detector artifacts. In addition, the performance of $p_T^{\text{miss}}$ is affected by additional proton-proton interactions in the same or nearby bunch crossings (pileup). A detailed understanding of all these effects, both in data and in simulation, is important to achieve the optimal $p_T^{\text{miss}}$ performance.

In this document, we present studies of $p_T^{\text{miss}}$ reconstruction algorithms used on data collected by the CMS detector [1] at the CERN LHC [2], corresponding to an integrated luminosity of 35.9 fb$^{-1}$ during 2016 (LHC Run 2). A brief overview of the CMS detector is given in Section 2. Information about the event reconstruction is discussed in Section 3, and a description of the different $p_T^{\text{miss}}$ reconstruction algorithms is provided in Section 4. Information about the event simulation and selection is provided in Section 6. In Section 7, sources of anomalous $p_T^{\text{miss}}$ measurements from known detector and reconstruction effects, and methods for identifying them, are described. The performance of the $p_T^{\text{miss}}$ reconstruction at the trigger level is discussed in Section 8. Section 9 details the performance the $p_T^{\text{miss}}$ algorithms in events without and with genuine $p_T^{\text{miss}}$. The algorithm that provides an estimate of the $p_T^{\text{miss}}$ significance is described in Section 10. Lastly, a summary is given in Section 11.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungsten crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity [3] coverage provided by the barrel and endcap detectors.

In the ECAL and HCAL barrel region ($|\eta| < 1.74$), the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth ($\phi$). In the $\eta$-$\phi$ plane, and for $|\eta| < 1.48$, the HCAL cells map on to $5 \times 5$ ECAL crystals arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. In the ECAL and HCAL endcap regions, the size of the towers increases and the matching ECAL arrays contain fewer crystals. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15148 silicon strip detector modules. Isolated particles of $p_T = 100$ GeV emitted at $|\eta| < 1.4$ have track resolutions of 2.8% in $p_T$ and 10 (30) $\mu$m in the transverse (longitudinal) impact parameter [4].
Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers, embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [5]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 $\mu$s. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [3].

3 Event reconstruction

The CMS particle-flow (PF) event algorithm [6] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the detector. Particles are identified as charged hadrons, neutral hadrons, photons, electrons, or muons, and constitute the mutually exclusive list of PF candidates in the event. The PF candidates are then used to build higher level objects such as jets and $p_T^{\text{miss}}$.

Events are required to have at least one reconstructed vertex. When multiple vertices are reconstructed due to pileup, the vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary proton-proton interaction vertex (PV). The physics objects are those returned by a jet finding algorithm [7, 8] applied to the tracks associated with the vertex, and the associated $p_T^{\text{miss}}$.

Photon candidates are reconstructed from energy deposits in the ECAL using algorithms that constrain the clusters to the size and shape expected from a photon [9]. The identification of the candidates is based on shower-shape and isolation variables [10]. For a photon to be considered isolated, the scalar $p_T$ sum of PF candidates originating from the primary vertex, excluding muons and electrons, within a cone of $\Delta R < 0.3$ around the photon candidate, is required to be small. Only the PF candidates that do not overlap with the electromagnetic shower of the candidate photon are included in the isolation sums. The analyses described in this document use two sets of photon identification criteria: loose and tight. The loose photon candidates are required to be reconstructed within $|\eta| < 2.5$, whereas tight photon candidates used are required to be reconstructed in the ECAL barrel ($|\eta| < 1.44$). The tight photon candidates are also required to pass identification and isolation criteria that ensure an efficiency of 80% for the selection of prompt photons, and a sample purity of 95% for performance measurements. In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [9].

Electrons within the geometrical acceptance of $|\eta| < 2.5$ are reconstructed by associating tracks reconstructed in the silicon detector with clusters of energy in the ECAL. Electron candidates are required to satisfy identification criteria [10] based on the shower shape of the energy deposit in the ECAL and the consistency of the electron track with the primary vertex [4]. Electron candidates that are identified as coming from photon conversions in the detector material are
removed. The isolation requirement is based on the sum of the energies of the PF candidates originating from the primary vertex within a cone of $\Delta R < 0.3$ around the electron direction, excluding PF candidates identified as electrons or muons. The exclusion of electron and muon PF candidates, also known as “footprint removal”, was significantly refined for the LHC Run 2. The mean energy deposited in the isolation cone of the electron from pileup is estimated following the method described in Ref. [10] and is subtracted from the isolation sum. Two types of electron identification selection requirements are used: loose and tight. The loose electrons are selected with an average efficiency of 95%. The loose identification requirements are used in some of the analyses presented in this document as part of selection requirements designed to remove backgrounds containing electrons e.g. $Z \rightarrow e^+e^-$ events. The tight electrons are selected with an average efficiency of 70%, and are used to select events used in the performance measurements.

Muons within the geometrical acceptance of $|\eta| < 2.4$ are reconstructed by combining information from the silicon tracker and the muon system [11]. The muons are required to pass a set of quality criteria based on the number of spatial points measured in the tracker and in the muon system, the fit quality of the muon track, and its consistency with the primary vertex of the event. The isolation requirements for muons are based on the sum of the energies of the PF candidates originating from the primary vertex within a cone of $\Delta R < 0.3$ around the muon direction, excluding PF candidates identified as electrons or muons from the sum. The muon isolation variable is corrected for pileup effects by subtracting half of the $p_T$ sum of the charged particles that are inside the isolation cone and not associated with the primary vertex. Two types of muon identification selection requirements are used: loose and tight. The loose muons are selected with an average efficiency of 98% and are used when appropriate to veto some kinds of background events (e.g. $Z \rightarrow \mu^+\mu^-$), whereas tight muons are selected with an average efficiency of 95% and are used to select the events used in the performance measurements. The relative transverse momentum resolution for muons with $20 < p_T < 100$ GeV is $1.3-2.0\%$ in the barrel and better than $6\%$ in the endcaps, The $p_T$ resolution in the barrel is better than $10\%$ for muons with $p_T$ up to 1 TeV [11].

Hadronically decaying $\tau$ lepton candidates detected within $|\eta| < 2.3$ are required to pass identification criteria using the hadron-plus-strips algorithm [12]. The algorithm identifies a jet as a hadronically decaying $\tau$ lepton candidate if a subset of the particles assigned to the jet is consistent with the decay products of a $\tau$ candidate. In addition, $\tau$ candidates are required to be isolated from other activity in the event. The isolation requirement is computed by summing the $p_T$ of the PF charged and PF photon candidates within an isolation cone of $\Delta R = 0.5$ and 0.3, respectively, around the $\tau$ candidate direction. A more detailed description of the isolation requirement can be found in Ref. [12].

Jets are reconstructed by clustering PF candidates using the infrared and collinear safe anti-$k_T$ algorithm [7] with a distance parameter of 0.4. To reduce the effect of pileup collisions, charged PF candidates identified as originating from pileup vertices are removed [13] before the jet clustering. Jet momentum is determined as the vector sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the full $p_T$ spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from pileup. Jet energy corrections are derived from simulation to bring measured response of jets to that of particle level jets on average. Measurements done in situ of the momentum balance in dijet, multijet, $\gamma +$jet, and leptonic $Z +$jet events are used to account for any residual differences in jet energy scale in data and simulation [13].

Jets originating from the hadronization of bottom (b) quarks are identified through the com-
bined secondary vertex (CSVv2) algorithm [14]. The working point used provides an efficiency of \( \sim 80\% \) to identify jets originating from b quarks whereas the misidentification rate for light quarks or gluons is \( \sim 10\% \), and \( \sim 40\% \) for charm quarks.

4 Reconstruction and calibration of \( p_{\text{T}}^{\text{miss}} \)

The \( p_{\text{T}}^{\text{miss}} \) reconstruction in hadron colliders relies on the conservation of momentum in the plane transverse to the beam direction. Therefore, the total \( p_T \) of weakly interacting, undetected final-state particles can be inferred from the negative vector \( p_T \) sum of all visible final-state particles. The CMS Collaboration has developed two distinct \( p_{\text{T}}^{\text{miss}} \) reconstruction algorithms, both based on PF candidates.

4.1 The \( p_{\text{T}}^{\text{miss}} \) reconstruction algorithms

The first \( p_{\text{T}}^{\text{miss}} \) reconstruction algorithm, referred to as PF \( p_{\text{T}}^{\text{miss}} \) in this document, is defined as the negative vector sum of the \( p_T \) of all the PF candidates in an event [15, 16]. The PF \( p_{\text{T}}^{\text{miss}} \) is used in the majority of the CMS analyses, since it provides a simple, robust, yet very performant \( p_{\text{T}}^{\text{miss}} \) reconstruction.

A second algorithm has been developed to reduce the dependence on pileup of \( p_{\text{T}}^{\text{miss}} \). This algorithm relies on the “pileup per particle identification” (Puppi) method [17] and attempts to use local shape information around each particle in the event, event pileup properties, and tracking information to reduce the pileup dependence of jet and \( p_{\text{T}}^{\text{miss}} \) observables. This \( p_{\text{T}}^{\text{miss}} \) algorithm will be referred to as Puppi \( p_{\text{T}}^{\text{miss}} \) in what follows.

The Puppi \( p_{\text{T}}^{\text{miss}} \) method employs a local shape variable, \( \alpha \), which contrasts the collinear structure of quantum chromodynamics (QCD) with the soft diffuse radiation coming from pileup. The \( \alpha \) variable is computed on an event-by-event basis, for each particle, and is used as a weight. These weights, which serve as a metric of the probability that the particle originates from pileup, are used to rescale the 4-momenta of the particles.

The Puppi method is applied in CMS using the list of PF candidates as particles. A different \( \alpha \) definition is adopted for PF candidates in the central (within tracker acceptance) and forward (outside tracker acceptance) regions. In the central region, the shape variable for a given PF candidate \( i \) is defined as:

\[
\alpha_i = \log \sum_{j \in \text{Ch}_{PV}, j \neq i} \left( \frac{p_{\text{T}j}}{\Delta R_{ij}} \right)^2 \Theta(R_0 - \Delta R_{ij})
\]

where \( \Theta \) is the step function, \( i \) refers to the PF candidate and \( j \) to neighboring charged particles from the primary vertex within a cone of radius \( R_0 \) in the \( \eta - \phi \) space around PF candidate \( i \). In addition, charged PF candidates not associated with the PV are used in the calculation if they satisfy \( d_z < 0, 3 \text{ cm} \), where \( d_z \) is the distance along the \( z \) axis with respect to the leading vertex. In the absence of tracking coverage, the summation index \( j \) in Eq. 1 extends to all PF candidates within a cone of radius \( R_0 \).

A \( \chi^2 \) approximation

\[
\chi_i^2 = \frac{(\alpha_i - \overline{\alpha}_{\text{PU}})^2}{\text{RMS}_{\text{PU}}^2},
\]

where \( \overline{\alpha}_{\text{PU}} \) is the median value of the \( \alpha_i \) distribution for all charged PF candidates associated to the pileup vertices (pileup PF candidates) in the event and \( \text{RMS}_{\text{PU}} \) is the corresponding
4. Reconstruction and calibration of $p_T^{\text{miss}}$

RMS is used to determine the likelihood that a PF candidate came from pileup. In the tracker region, $\alpha_{\text{PU}}$ and $\text{RMS}_{\text{PU}}$ are calculated using all charged pileup PF candidates, while in the forward region they are calculated using all the particles in the event. In order to assign a measure of the likelihood of each PF candidate to stem from pileup, the $\chi^2$ distribution in Eq. 2 is transformed to a weight based on:

$$w_i = F_{\chi^2,\text{NDF}=1}(\chi^2_i),$$

where $F_{\chi^2,\text{NDF}=1}$ is the cumulative distribution function of the $\chi^2$ distribution with one degree of freedom. The weights range from zero to one, with zero indicating PF candidates originating from a pileup vertex, whereas PF candidates originating from the primary vertex have values close to one.

The PF candidate weights ($w_i$) are required to be larger than 0.01 and the minimum scaled $p_T$ of neutral PF candidates is required to be $w_i \cdot p_T > (A + B \cdot n_{\text{PV}})$. In this equation, A and B are adjustable parameters that depend on $\eta$ and $n_{\text{PV}}$ is the reconstructed vertex multiplicity. An optimization of the tunable parameters is performed to achieve the best jet $p_T$ and $p_T^{\text{miss}}$ resolutions in pseudorapidity regions $|\eta| < 2.5$, $2.5 < |\eta| < 3$, and $|\eta| > 3$. The chosen algorithm parameters are similar to the recommendation from Ref. [17], where the cone radius is set to 0.4. The Puppi-weighted PF candidates are used as inputs for the jet clustering algorithm. No additional pileup corrections are applied to jets clustered from these weighted inputs.

Once a weight per PF candidate is determined, the $p_T^{\text{miss}}$ can be computed using the sum of 4-vectors weighted by the Puppi weight.

4.2 Calibration of $p_T^{\text{miss}}$

Several sources, such as the nonlinearity of the response of calorimeters to hadronic particles, minimum energy thresholds in the calorimeters, and $p_T$ thresholds and inefficiency in the tracker, can lead to an inaccurate estimation of $p_T^{\text{miss}}$. The estimation of $p_T^{\text{miss}}$ is improved by correcting the $p_T$ of the jets to the particle level using the jet energy corrections as described in [13], and propagating these corrections to $p_T^{\text{miss}}$ in the following way:

$$\text{Type-I } p_T^{\text{miss}} = p_T^{\text{miss}} - \sum_{\text{jets}} (\vec{p}^{\text{corr}}_T,_{\text{jet}} - \vec{p}_T,_{\text{jet}}).$$

where the sum is over jets passing with $p_T$ above a threshold. The $p_T$ thresholds are optimized to achieve a satisfactory $p_T^{\text{miss}}$ scale while minimizing the contributions of jets coming from pileup. To achieve this balance, all jets with corrected $p_T$ above 15 GeV are considered in the $p_T^{\text{miss}}$ calibration. The corresponding threshold in LHC Run 1 was 10 GeV. In order to remove the overlap of jets with electrons and photons, jets with more than 90% of their energy deposited in ECAL are also not included in the sum. In addition, if a muon reconstructed using both the inner and outer tracking system, or only the outer tracking system, overlaps with a jet, its 4-momentum is subtracted from the 4-momentum of the jet and the jet energy scale correction appropriate for the modified jet momentum is used in the $p_T^{\text{miss}}$ calculation.

The results presented in this document exclusively use the corrected $p_T^{\text{miss}}$, and therefore the prefix Type-I is omitted to improve clarity.

The $p_T^{\text{miss}}$ relies on the accurate measurement of the reconstructed physics objects, namely muons, electrons, photons, taus, jets and unclustered energy, defined as the contribution from the PF candidates not clustered into any of the previous physics objects. Therefore, uncertainties related to the $p_T^{\text{miss}}$ measurement depend strongly on the event topology. In order to
estimate the uncertainty on $p_T^{\text{miss}}$, we factorize the object to the aforementioned physics objects and vary each object within its scale and resolution uncertainties. The uncertainty in $p_T^{\text{miss}}$ is evaluated by comparing the recalculated $p_T^{\text{miss}}$ to the nominal $p_T^{\text{miss}}$.

The jet energy scale uncertainties are less than 3% for jets within the tracker acceptance and 1-12% outside. The jet energy resolution uncertainties typically range between 5-20%. The muon energy scale uncertainty is 0.2%, whereas the electron and photon energy scale uncertainties are 0.6% in the barrel and 1.5% in the endcap. For taus the energy scale uncertainty is 1.2%. The uncertainties related to the leptons are small compared to those from jet energy scale and resolution and will not be considered in the results presented in this document.

The uncertainty on the unclustered energy during the LHC Run 1 was set arbitrary to 10%, to account for the differences observed between the data and the simulation [16]. The method is improved for the LHC Run 2. The unclustered energy uncertainty is evaluated based on the resolution of the momentum measurement of each PF candidate, which depends on the flavor of the candidate. A detailed description of the PF candidate calibration can be found in [4, 9, 18]. Table 1 lists the functional forms of the resolution in the measurement of the PF candidate classes contributing to the unclustered energy.

5 Simulated events

To model the SM backgrounds, simulated Monte Carlo (MC) events are produced for $\gamma +$jets and the QCD multijet processes at leading order (LO) using the MadGraph [19] generator with up to four additional partons in the matrix element calculations. The samples for the $\gamma +$ jets and $W+$ jets processes are produced at next-to-leading order (NLO) using the MadGraph5_aMC@NLO generator with up to two additional partons in the matrix element calculations. The $t\bar{t}$ and single top quark background processes are simulated at NLO using POWHEG 2.0 and 1.0, respectively [20, 21]. The diboson samples, $WW$, $WZ$ and $ZZ$, are produced at NLO using MadGraph5_aMC@NLO and POWHEG, respectively. A set of triboson samples ($WWW$, $WWZ$, $WZ Z$, $Z Z Z$) samples is produced at NLO with MadGraph5_aMC@NLO. Lastly, the $Z \gamma$ and $W \gamma$ processes, collectively referred to as $V \gamma$ in what follows, are simulated at LO with MadGraph5_aMC@NLO.

The MC samples produced using MadGraph5_aMC@NLO and POWHEG generators are interfaced with Pythia [22] using the CUETP8M1 tune [23] for the fragmentation, hadronization, and underlying event description. In the case of the MadGraph5_aMC@NLO samples, jets from the matrix element calculations are matched to the parton shower description follow-
6. Event selection

In this document, several data samples are utilized to evaluated the performance of $p_T^{\text{miss}}$ in data. The monojet and dijet samples are primarily used to study the performance of the cleaning algorithms developed to reject spurious events with anomalous $p_T^{\text{miss}}$ and will be discussed in Section 7. The dilepton and single-photon samples are used to study the $p_T^{\text{miss}}$ scale and resolution. A single-lepton sample is utilized to study the $p_T^{\text{miss}}$ performance in events with genuine $p_T^{\text{miss}}$. Finally, the single-lepton and di-lepton samples are also used to study the performance of $p_T^{\text{miss}}$ significance. The event selection of each sample is discussed below.

6.1 The monojet and dijet samples

The events for the monojet sample are selected using triggers with requirements on both $p_T^{\text{miss,}\text{trig}}$ and $H_T^{\text{miss,}\text{trig}}$, where $p_T^{\text{miss,}\text{trig}}$ is the magnitude of the vector $\vec{p}_T$ sum of all the PF candidates reconstructed at the trigger level, and the $H_T^{\text{miss,}\text{trig}}$ is the magnitude of the vector $\vec{p}_T$ sum of jets with $p_T > 20\text{ GeV}$ and $|\eta| < 5.0$ reconstructed at the trigger level. Candidate events are required to have $p_T^{\text{miss}} > 250\text{ GeV}$ and the highest $p_T$ (leading) AK4 jet in the event is required to have $p_T > 100\text{ GeV}$ and $|\eta| < 2.4$. The background from processes with W bosons is suppressed by imposing a veto on events containing one or more loose muons or electrons with $p_T > 10\text{ GeV}$, or $\tau$ leptons with $p_T > 18\text{ GeV}$. Events that contain a loose, isolated photon with $p_T > 15\text{ GeV}$ and $|\eta| < 2.5$ are also vetoed. This helps suppress electroweak (EW) backgrounds in which a photon is radiated from the initial state. To reduce the contamination from top quark backgrounds, events are rejected if they contain a b-tagged jet with $p_T > 20\text{ GeV}$ and $|\eta| < 2.4$.

Lastly, QCD multijet background with $p_T^{\text{miss}}$ arising from mismeasurements of the jet momenta is suppressed by requiring the minimum azimuthal angle between the $p_T^{\text{miss}}$ direction and each of the first four leading jets with $p_T$ greater than 30 GeV to be larger than 0.5 radians. This selection enables the study of detector malfunctioning based sources that could lead to artificially large $p_T^{\text{miss}}$, and are presented in Section 7.

The events for the dijet sample are selected using the $p_T^{\text{miss,}\text{trig}}$ and $H_T^{\text{miss,}\text{trig}}$ triggers as well. Candidate events are required to have $p_T^{\text{miss}}$ greater than 250 GeV and the leading (trailing) AK4 jet in the event is required to have $p_T > 500\text{ (200)}\text{ GeV}$. Similar to the monojet sample, events with an identified loose lepton, photon or a b-tagged jet are rejected.

6.2 The di-lepton samples

The di-lepton samples are subdivided into two categories based on the flavor of the lepton, namely $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ samples. The events for the $Z \rightarrow \mu^+\mu^-$ sample are recorded using dimuon triggers that select on the $p_T$ of the two leading muons. Candidate events are required to have both the leading and subleading muon $p_T$ greater than 20 GeV and an invariant mass in the range of 80 to 100 GeV, compatible with a Z boson decay. Events are vetoed if
there is an additional muon or electron with $p_T > 20$ GeV. The events for the $Z \rightarrow e^+e^-$ samples are recorded using dielectron triggers that select on the $p_T$ of the two leading electrons. Candidate events are required to have the leading (subleading) electron $p_T$ greater than 25 (20) GeV. Similarly to the dimuon case, the invariant mass of the dielectron system is required to be in the range of 80 to 100 GeV. Events are vetoed if there is an additional muon or electron with $p_T > 20$ GeV. The spectrum of the Z boson transverse momentum $q_T$ is shown in Fig. 1.

Figure 1: Upper panel: Distributions of Z boson $q_T$ in $Z \rightarrow \mu^+\mu^-$ (left) and $Z \rightarrow e^+e^-$ (right) samples. The last bin contains the overflow content. Lower panel: Data to simulation ratio. The gray band corresponds to the statistical uncertainty of the simulated samples.

6.3 The single-photon sample

The events in the single-photon sample are selected using a set of isolated single-photon triggers with varying thresholds. The $p_T$ thresholds of the triggers are 30, 50, 75, 90, 120 and 165 GeV, and the first five triggers had differing prescales during the data taking period. Candidate events are weighted based on the prescales of the triggers.

Candidate events are required to have a tight photon with $p_T$ greater than 50 GeV. To match the trigger conditions, the leading photon is further required to have the ratio of the energy deposited in a 3x3 crystal region centered around the crystal containing an energy deposit greater than all of its immediate neighbors to the energy of the entire deposit of the photon greater than 0.9.

The single-photon sample events are also required to have at least one jet with $p_T$ greater than 40 GeV, and events with additional leptons with $p_T$ greater than 20 GeV are vetoed. The photon $q_T$ spectrum is shown in Fig. 2.

6.4 The single-lepton samples

The single-lepton samples are subdivided into two categories based on the flavor of the lepton. The events for the single-muon (electron) sample are selected using triggers that impose selection on the $p_T$ and the isolation of the muon (electron). Candidate events are required to have a tight muon (electron) with $p_T$ greater than 25(26) GeV. Events with an additional lepton with $p_T$ greater than 10 GeV, or with a b-tagged jet, are rejected.

The single-lepton samples consist mainly of W+jets events. A source of background stems from QCD multijet events containing a jet misidentified as a lepton. The simulation indicates that
7. Anomalous $p_T^{\text{miss}}$ events

Anomalous high-$p_T^{\text{miss}}$ events can be due to a variety of reconstruction failures or detector malfunctions. In the ECAL, spurious deposits may appear due to particles striking sensors in the
ECAL photodetectors, dead cells, or from real showers with non-collision origins such as those caused by beam halo particles. In the HCAL, spurious energy can arise due to noise in the hybrid photodiode (HPD) and readout box (RBX) electronics, as well as from direct particle interactions with the light guides and photomultiplier tubes of the forward calorimeter. These sources have been studied extensively in the data collected in LHC Run 1 [16, 29]. The set of algorithms (filters) developed during LHC Run 1 to identify and suppress events with anomalous high $p_T^{\text{miss}}$ was also used for LHC Run 2 with the necessary modifications to account for the upgraded detector and the different data-taking conditions. An additional set of filters was also developed during Run 2 to identify new sources of artificial $p_T^{\text{miss}}$. Details of the various filters are given below.

- **HCAL filters**
  The geometrical patterns of HPD or RBX channels as well as the pulse shape and timing information are utilized by various HCAL barrel and endcap (HBHE) algorithms to identify and eliminate the noise signals originating from HCAL. These noise algorithms operate both in noise-cleaning and noise-rejecting modes. In noise cleaning mode, the anomalous energy deposits are removed from the event reconstruction; in the rejection mode, the event is removed from the dataset. In addition, there is an isolation-based noise filter that utilizes a topological algorithm where energy deposits in HCAL and ECAL are combined and compared with measurements from the tracker to identify isolated anomalous activity in HBHE. An additional filter, the negative energy filter, is a pulse-shape filter that acts at the cluster reconstruction level, targeting uncharacteristic noise signals in HBHE HPDs and is used in the noise-cleaning mode. It relies on the known pulse-shapes of HPDs (similar to the RBX pulse-shape filters) [30] but explicitly allows for the presence of in-time and out-of-time pileup when testing for anomalous pulse-shapes.

- **ECAL filters**
  For the ECAL, much of the electronics noise and spurious signals from particle interactions with the photodetectors is removed during reconstruction using solely ECAL information (local reconstruction) with topological and timing selections. The remaining effects that lead to high-$p_T^{\text{miss}}$ signatures, such as anomalously high energy supercrystals and the lack of information for channels that have non-functional readout electronics are removed through dedicated event filters.
  During LHC Run 2, five ECAL endcap supercrystals produced large, anomalous pulses, leading to spurious $p_T^{\text{miss}}$. These crystals were removed from the readout, and their energies were not used. Furthermore, in about 0.7% of ECAL towers, the crystal by crystal level information is not available. The trigger primitive (TP) [5] information, however, is still available, and is used to estimate the energy. The TP information saturates above 127.5 GeV. Events with a TP close to saturation in one of these towers are removed.

- **Beam halo filter**
  Machine-induced backgrounds, especially the production of muons when beam protons undergo collisions upstream of the detector (beam halo), can cause anomalous large $p_T^{\text{miss}}$. Beam halo particles travel nearly parallel to the collision axis and can sometimes interact in the calorimeters, leaving energy deposits along a line at constant $\phi$ in the calorimeter. In addition, interactions in the cathode strip chambers (CSCs), a subdetector with good reconstruction performance for both collision and non-collision muons, will often line up with the deposits. The beam halo filter was
redesigned for LHC Run 2. In LHC Run 1 the filter was based solely on information from the CSCs. However, the LHC Run 2 filter exploits information from both the CSCs and the calorimeters, resulting in a significant improvement in performance. An example event display for a beam halo event is shown in Fig. 4 where collinear hits in the CSCs are visible.

Figure 4: Event display for a beam halo event with collinear hits in the CSC (black), $p_T^{\text{miss}}$ of 250 GeV and a jet of 232 GeV. The hadronic deposit is spread in $\eta$ but it is narrow in $\phi$.

- **Reconstruction filters**
  An additional new source of anomalous high-$p_T^{\text{miss}}$ during LHC Run 2 was due to mis-reconstruction of muons during the muon-tracking iteration step [31]. If a high-$p_T$ track is reconstructed with low-quality it could contribute to the $p_T^{\text{miss}}$ computation either as a misreconstructed PF muon, or as a misreconstructed PF charged hadron. The misreconstructed muons and charged hadrons are identified based on the ratio of the relative $p_T$ error of the best track $p_T$ that is determined by the Tune-P algorithm [11], or the inner track $p_T$. Once a misreconstructed muon or a charged hadron is identified, the entire event is removed from the physics datasets.

Figure 5 shows a comparison of the $p_T^{\text{miss}}$ (left) and jet $\phi$ (right) distribution before and after the application of the event cleaning algorithms in the dijet and monojet samples, respectively. The anomalous events with large $p_T^{\text{miss}}$ in the dijet sample are found to be mostly due to electronic noise in the calorimeters. In the monojet sample, the excess of events with jet $\phi \approx 0$ or jet $\phi \approx \pi$ are removed by the beam halo filter. In both samples, the simulated $p_T^{\text{miss}}$ and jet $\phi$ distributions are found to be in good agreement with data after the application of all the cleaning algorithms. The event filters are designed to identify more than 85-90% of the spurious high-$p_T^{\text{miss}}$ events with a mistagging rate less than 0.1%. In addition to the event cleaning algorithms, a jet identification selection is imposed, which requires the neutral hadron energy fraction of a jet to be less than 0.9. This selection rejects more than 99% of the noise jets, independent of jet $p_T$, with a negligible mistagging rate.
8 Performance of $p_{T}^{\text{miss}}$ reconstruction at the trigger level

Triggers based on $p_{T}^{\text{miss}}$ play a critical role in the online selection of events used for SM measurements involving the $W$, $Z$ and Higgs bosons and also for searches for physics beyond the standard model with weakly interacting neutral particles. At L1, $p_{T}^{\text{miss}}$ is computed in Layer 2 of the global calorimeter trigger as the vector sum of the transverse energies of trigger towers it receives from Layer 1, which forms the towers using the sum of ECAL and HCAL trigger primitive transverse energies and quality flags. The $p_{T}^{\text{miss}}$ is calculated by first summing separately the $x$ and $y$ components of tower transverse energies for rings in phi at fixed eta, then summing the phi rings for all eta for each half of the detector. The $x$ and $y$ components for each half are then added, and then used in a cordic function to calculate the magnitude and direction of the $p_{T}^{\text{miss}}$ vector. A more detailed description can be found in [5]. Although the regional calorimeter coverage could be extended to $|\eta| = 5.0$, the $p_{T}^{\text{miss}}$ algorithm at L1 only uses information from trigger towers within $|\eta| = 3.0$, due to bandwidth restrictions of the data acquisition system. The HLT has two $p_{T}^{\text{miss}}$ reconstruction algorithms. A $p_{T}^{\text{miss}}$ variable using only information from the calorimeter ("Calo") is used as a prefilter to a more complex, PF-based $p_{T}^{\text{miss}}$ reconstruction. The calorimeter-based $p_{T}^{\text{miss}}$ is computed by taking the negative vector sum of the transverse energy of all calorimeter towers where as PF $p_{T}^{\text{miss}}$ is based on the negative vector $p_{T}^{\text{miss}}$ sum of all reconstructed PF jets without a $p_{T}$ requirement, similar to the case of the offline reconstruction algorithms.

In order to maintain lowest possible thresholds for the $p_{T}^{\text{miss}}$ triggers, event cleaning algorithms are applied at the trigger level. In contrast to the offline case, at the trigger level, the calorimeter energy deposits associated with either a HB/HE noise or a beam halo deposit, are removed from the energy sum, and cleaned calorimeter based $p_{T}^{\text{miss}}$ is recomputed. Additional $p_{T}$ selection is then imposed on the cleaned quantity. The noise cleaning algorithms at the HLT were found to be fully efficient with respect to the offline cleaning algorithms and had reduced the rate of $p_{T}^{\text{miss}}$ triggers by a factor of 2.5.

As with the offline reconstruction, HLT PF $p_{T}^{\text{miss}}$ is calibrated by correcting the $p_{T}$ of the jets using the JEC. In contrast to the offline calibration, the corrections for the jets are only propagated to $p_{T}^{\text{miss}}$ if the jet $p_{T}$ is above 35 GeV. The performance of the $p_{T}^{\text{miss}}$ triggers is measured
in single-electron samples, and the efficiency of each $p_T^{\text{miss}}$ object type used at trigger level is shown in Fig. 6. The calibrated $p_T^{\text{miss}}$ at the HLT level yields an improved efficiency. As a result, online trigger thresholds are set to higher values yielding the same performance offline, for a 10% rate reduction.

Figure 6: The $p_T^{\text{miss}}$ trigger efficiency measured in the single-electron sample. The efficiency of each reconstruction algorithm, namely the L1, the calorimeter and the PF based $p_T^{\text{miss}}$ algorithms, is shown separately. The numbers in parenthesis correspond to the online $p_T^{\text{miss}}$ thresholds.

9 The performance of $p_T^{\text{miss}}$ algorithms

The scale and resolution of $p_T^{\text{miss}}$ is studied in samples with an identified Z boson or an isolated photon. Such events have no genuine $p_T^{\text{miss}}$, and the performance is measured through comparing the momenta of the vector boson to that of the hadronic recoil system. The hadronic recoil system is defined as the vector sum $p_T$ of all PF candidates except the vector boson (or its decay products in the case of Z). In Fig. 7 the kinematic representation of the vector boson momentum in the transverse plane ($\vec{q}_T$) and the transverse momentum of the hadronic recoil ($\vec{u}_T$) is depicted. Momentum conservation in the transverse plane yields $\vec{q}_T + \vec{u}_T + \vec{p}_T^{\text{miss}} = 0$.

Figure 7: Illustration of Z (left) and photon (right) event kinematics in the transverse plane. The vector $\vec{u}_T$ denotes the vectorial sum of all particles reconstructed in the event except for the two leptons from the Z decay (left) or the photon (right).
A well-measured $Z/\gamma$ boson provides a unique event axis and a precise momentum scale. The components of the hadronic recoil parallel and perpendicular to the boson axis are denoted $u_{||}$ ($u_{\perp}$), respectively. The $u_{||}$ and $u_{\perp}$ are used to study the $p_T^{\text{miss}}$ scale and resolution. Specifically, the mean of the $u_{||} + q_T$ distribution is used to estimate the $p_T^{\text{miss}}$ scale, whereas the root-mean-square (RMS) of the $u_{||} + q_T$ and $u_{\perp}$ distributions are used to estimate the resolution of $u_{||}$ and $u_{\perp}$, denoted by $\sigma(u_{||})$ and $\sigma(u_{\perp})$, respectively. The absolute scale of $p_T^{\text{miss}}$ is defined as $-\langle u_{||} \rangle / \langle q_T \rangle$. This method can be sensitive to any non-Gaussian tails in the $p_T^{\text{miss}}$ distribution.

An alternative method, in which the $u_{||} + q_T$ and $u_{\perp}$ distributions are parametrized using a Voigtian function, defined as the convolution of a Breit-Wigner distribution with a Gaussian distribution, was also exploited. The results obtained with the alternative method agree within $\sim 2\sigma$ with the ones obtained using the primary method (i.e. mean/RMS), indicating that the effect of the non-Gaussian tails in the $p_T^{\text{miss}}$ performance is small. In the following sections, the performance of the PF and Puppi $p_T^{\text{miss}}$ algorithms are shown using the primary method.

### 9.1 Performance of the PF $p_T^{\text{miss}}$ algorithm

The PF $p_T^{\text{miss}}$ distributions in dilepton and photon samples are shown in Fig. 8. The data distributions are modeled well by the simulation. The $p_T^{\text{miss}}$ resolution in these events is dominated by the resolution of the hadronic activity, since the momentum resolution for leptons (photons) is $\sigma_p / p_T$ of 1–4% (1–3%), compared to 10–15% for the jet momentum resolution. The uncertainty shown in the figures include uncertainties in the jet energy scale, jet energy resolution, and detector noise and underlying event. Good agreement is observed between the data and simulation for all the distributions.

Distributions of $u_{||} + q_T$ and $u_{\perp}$ in $Z \to \mu^+\mu^-$, $Z \to e^+e^-$, and photon events are shown in Fig. 9. The kinematic definition of $u_{||}$ dictates that for processes with no genuine $p_T^{\text{miss}}$, $u_{||}$ is balanced with the boson $q_T$. Therefore, the vectorial sum of $u_{||}$ and $q_T$ results to a symmetric distribution, centered at zero; any deviations from this behavior imply imperfect calibration of $p_T^{\text{miss}}$. In events with genuine $p_T^{\text{miss}}$, due to the presence of the neutrinos, $u_{||}$ and $q_T$ are not balanced, leading to an asymmetric distribution. The $u_{\perp}$ distribution is symmetric with a mean value of zero. This symmetry is due to the isotropic nature of the energy fluctuations of the detector noise and underlying event. Good agreement is observed between the data and simulation for all the distributions.

Figure 10 shows the $p_T^{\text{miss}}$ response as a function of $q_T$ in data and simulation in $Z \to \mu^+\mu^-$, $Z \to e^+e^-$, and photon events. The response reaches unity for boson $p_T$ greater than 100 GeV. Deviations from unity indicate imperfect calibration of the hadronic energy scale. The underestimation of the hadronic response observed at smaller $q_T$ ($q_T \lesssim 10$ GeV) is due to the significant contribution of the uncalibrated component of $p_T^{\text{miss}}$, which mainly consists of jets with $p_T < 15$ GeV and unclustered particles. Currently there is no dedicated response correction for the unclustered energy. The response of $p_T^{\text{miss}}$ is found to agree between the different samples (i.e. $Z \to \mu^+\mu^-$, $Z \to e^+e^-$, and $\gamma$) within 2%; a significant improvement with respect to the results from the LHC Run 1 [16]. The refined “footprint removal” discussed in Section 3 played an important role in this improvement. The residual response difference between the samples stems from the different mechanism used to disambiguate muons, electrons, and photons from jets, as discussed in Section 4.2. In the case of the electrons and photons, a small fraction ($\lesssim 10\%$) of jets survive the disambiguation criteria and yet overlap with prompt electrons and photons. As a result, these jets wrongly contribute to the $p_T^{\text{miss}}$ calibration, leading
9. The performance of $p_T^{\text{miss}}$ algorithms

Figure 8: Upper panel: Distributions of $p_T^{\text{miss}}$ in $Z \rightarrow \mu^+\mu^-$ (top left), $Z \rightarrow e^+e^-$ (top right), and photon events (lower middle) in data and simulation. The last bin includes the overflow content. Lower panel: Data to simulation ratio. The systematic uncertainty due to the jet energy scale, jet energy resolution, and variations on the unclustered energy is displayed with a gray band.
Figure 9: Distribution of $u_{\parallel}+q_T$ and $u_{\perp}$ components of the hadronic recoil, in data (filled markers) and simulation (solid histograms) in the $Z \rightarrow \mu^+\mu^-$ (upper), $Z \rightarrow e^+e^-$ (middle) and $\gamma$ (lower) samples. The first and the last bins include the underflow and overflow content, respectively. The points in the lower panel of each plot show the data to simulation ratio. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.

...to an 1-2% lower response in the electron and photon channels. Future studies aim to further...
The performance of $p_T^{\text{miss}}$ algorithms

9. The performance of $p_T^{\text{miss}}$ algorithms

improve the electron/photon and jet disambiguation mechanism. Overall, we observe good agreement between data and simulation.

![Graph](image)

Figure 10: Upper panel: Response of $p_T^{\text{miss}}$ in data in $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow e^+e^-$ and $\gamma$ events. Lower panel: Ratio of the $p_T^{\text{miss}}$ response in data and simulation. The gray band corresponds to the systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy, estimated from the $Z \rightarrow e^+e^-$ sample.

The resolution of $p_T^{\text{miss}}$ for the $u_\parallel$ and $u_\perp$ components of the hadronic recoil as a function of $q_T$ is shown in Fig. 11 (top row). In order to compare the resolution of $p_T^{\text{miss}}$ consistently across the samples, the resolution in each sample is corrected for the differences observed in the response. Nevertheless, the effect of the correction has a negligible impact on the results. The resolution measured in the different samples is found to be in good agreement. The relative resolution both in $u_\parallel$ and $u_\perp$ is found to improve as a function of $q_T$ because of the improved energy resolution in the calorimeter. Furthermore, due to the isotropic nature of energy fluctuations in detector noise and underlying event, the dependence of the resolution of $u_\perp$ on $q_T$ is smaller than for $u_\parallel$. For $q_T > 200$ GeV, the $p_T^{\text{miss}}$ resolution is $\approx 13\%$ and $\approx 9\%$, for the $u_\parallel$ and $u_\perp$, respectively.

The resolution of the $u_\parallel$ and $u_\perp$ components of the hadronic recoil is also studied as a function of number of reconstructed vertices and is shown in Fig. 11 (middle row). The resolution measured in different samples and between data and simulation are found to be in good agreement. However, the resolution shows strong dependence on the number of pileup vertices, since no pileup mitigation technique is employed in the PF $p_T^{\text{miss}}$ algorithm.

The resolution in the different samples is parametrized as:

$$f(N_{\text{vtx}}) = \sqrt{\sigma_c^2 + \frac{N_{\text{vtx}}}{0.70} \sigma_{\text{PU}}^2},$$  \hspace{1cm} (5)$$

where $\sigma_c$ is the resolution term induced by the hard-scattering interaction and $\sigma_{\text{PU}}$ is the reso-
lution term induced on average by one additional pileup interaction. The factor 0.70 accounts for the vertex reconstruction efficiency [31]. Results of the parametrization for the \( u_\parallel \) and \( u_\perp \) components are given in Table 2. Each additional pileup is found to degrade the resolution of both components by 3.9–4.2 GeV.

Lastly, the resolution of \( u_\parallel \) and \( u_\perp \) is also studied as a function of the scalar \( p_T \) sum of all PF candidates (\( \sum E_T \)) in the event and is shown in Fig. 11 (bottom row). The resolution measured in different samples and between data and simulation is found to be in good agreement.

The relative \( p_{T\text{miss}} \) resolution improves with \( \sum E_T \), driven by the amount of the activity in the calorimeters. The resolution in different samples is parametrized as:

\[
\sigma_{u_\perp,u_\parallel} = \sigma_0 + \sigma_s \sqrt{\sum E_T},
\]

where \( \sigma_0 \) is the resolution term induced by intrinsic detector noise and \( \sigma_s \) is the stochastic resolution term. Results of the parametrization for the \( u_\parallel \) and \( u_\perp \) components are given in Table 3.

Table 2: Parametrization results of the resolution curves for \( u_\parallel \) and \( u_\perp \) components as a function of number of reconstructed vertices. The parameter values for \( \sigma_c \) are obtained from data and simulation, and the values for \( \sigma_{PU} \) are obtained from data, along with a ratio \( R_{PU} \) of data and simulation. The uncertainties displayed for both the quantities are obtained from the fit, and for simulation the jet energy scale, jet energy resolution and unclustered energy uncertainties are propagated.

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma_c ) (data) [GeV]</th>
<th>( \sigma_c ) (MC) [GeV]</th>
<th>( \sigma_{PU} ) (data) [GeV]</th>
<th>( R_r = \sigma_{PU} ) (data) / ( \sigma_{PU} ) (MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z \rightarrow \mu^+\mu^- )</td>
<td>13.9 ± 0.07</td>
<td>11.9 ± 1.53</td>
<td>3.82 ± 0.01</td>
<td>0.95 ± 0.04</td>
</tr>
<tr>
<td>( Z \rightarrow e^+e^- )</td>
<td>14.6 ± 0.09</td>
<td>12.0 ± 1.09</td>
<td>3.80 ± 0.02</td>
<td>0.95 ± 0.03</td>
</tr>
<tr>
<td>( \gamma + \text{jets} )</td>
<td>12.2 ± 0.10</td>
<td>10.2 ± 1.98</td>
<td>3.97 ± 0.02</td>
<td>0.97 ± 0.05</td>
</tr>
</tbody>
</table>

\( u_\parallel \) component

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma_c ) (data) [GeV]</th>
<th>( \sigma_c ) (MC) [GeV]</th>
<th>( \sigma_{PU} ) (data) [GeV]</th>
<th>( R_r = \sigma_{PU} ) (data) / ( \sigma_{PU} ) (MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z \rightarrow \mu^+\mu^- )</td>
<td>10.3 ± 0.08</td>
<td>8.58 ± 2.20</td>
<td>3.87 ± 0.01</td>
<td>0.97 ± 0.04</td>
</tr>
<tr>
<td>( Z \rightarrow e^+e^- )</td>
<td>10.7 ± 0.10</td>
<td>8.71 ± 1.76</td>
<td>3.89 ± 0.01</td>
<td>0.96 ± 0.03</td>
</tr>
<tr>
<td>( \gamma + \text{jets} )</td>
<td>9.04 ± 0.11</td>
<td>6.93 ± 2.70</td>
<td>3.94 ± 0.01</td>
<td>0.97 ± 0.04</td>
</tr>
</tbody>
</table>

9.2 Performance of the Puppi \( p_T^{\text{miss}} \) algorithm

The Puppi \( p_T^{\text{miss}} \) distributions in the dilepton samples are shown in Fig. 12. The data distributions are modeled well by the simulation, in both the muon and the electron channels. Similar to the case of PF \( p_T^{\text{miss}} \), the \( p_T^{\text{miss}} \) resolution in these events is dominated by the resolution of the hadronic activity, but the Puppi-weighted PF candidates yield a much improved resolution for jets compared to the PF case. This is also reflected in the uncertainty shown in the figures, which includes the uncertainties due to jet energy scale and resolution, and the energy scale of the unclustered particles.

The distributions in \( Z \rightarrow \mu^+\mu^- \) and \( Z \rightarrow e^+e^- \) events of the vectorial sum \( u_\parallel + q_T \) and of \( u_\perp \), using Puppi \( p_T^{\text{miss}} \) are shown in Fig. 13. Following the same arguments as in the PF \( p_T^{\text{miss}} \) case, in events with no genuine \( p_T^{\text{miss}} \), the vectorial sum of \( u_\parallel \) and \( q_T \) is symmetric around zero, whereas for processes with genuine \( p_T^{\text{miss}} \) an asymmetric behavior is observed. The distribution of \( u_\perp \) is symmetric around zero. Simulation describes data well for all the distributions.
Figure 11: Resolution of the $u_T$ and $u_\perp$ components of the hadronic recoil as a function of $q_T$ (top row), the reconstructed primary vertices (middle row), and the scalar $p_T$ sum of all PF candidates (bottom row), in $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow e^+e^-$ and $\gamma$ events. In each plot, the upper panel shows the resolution in data, whereas the lower panel shows the ratio of data to simulation. The gray band corresponds to the systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy, estimated from the $Z \rightarrow e^+e^-$ sample.
The resolution of Puppi $p_T^\text{miss}$ in $Z \to \mu^+\mu^-$ (left) and $Z \to e^+e^-$ (right). The last bin shown, includes the overflow content. Lower panel: Data to simulation ratio. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.

Figure 14 shows the Puppi $p_T^\text{miss}$ response as a function of $q_T$, extracted from data and simulation in $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ events. The response reaches unity for $Z \to \mu^+\mu^-$ events at a boson $p_T$ of 150 GeV; while for PF $p_T^\text{miss}$ the response is close to unity at 100 GeV. The slower rise of the response to unity is due to the removal of PF candidates that are wrongly associated to pileup interactions by the Puppi algorithm. Similarly to PF $p_T^\text{miss}$, there is no response correction for the unclustered energy for Puppi $p_T^\text{miss}$, which results in an underestimated response for low $q_T$. The response of $p_T^\text{miss}$ is found to agree between the different samples within 2%.

The resolution of Puppi $p_T^\text{miss}$ for the $u_\parallel$ and $u_\perp$ components of the hadronic recoil as a function of number of reconstructed vertices is shown in Fig. 15. In order to compare the resolution of $p_T^\text{miss}$ consistently across the samples, the resolution in each sample is corrected for the differences observed in the scale. The resolution measured in different samples is found to be in good agreement. In Fig. 16, the results obtained for the case of Puppi $p_T^\text{miss}$ are overlayed with

Table 3: Parametrization results of the resolution curves for $u_\parallel$ and $u_\perp$ components as a function of the scalar $p_T$ sum of all PF candidates. The parameter values for $c_0$ are obtained from data and simulation, whereas the $\sigma_s$ are obtained from data along with a ratio $R_s$, the ratio of data and simulation. The uncertainties displayed for both the quantities are obtained from the fit, and for simulation the jet energy scale, jet energy resolution and unclustered energy uncertainties are propagated.

<table>
<thead>
<tr>
<th>Process</th>
<th>$c_0$(data)/GeV</th>
<th>$c_0$(MC)/GeV</th>
<th>$\sigma_s$(GeV$^{1/2}$)</th>
<th>$R_s = \sigma_s$(data)/$\sigma_s$(MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \mu^+\mu^-$</td>
<td>1.98 ± 0.07</td>
<td>0.85 ± 2.45</td>
<td>0.64 ± 0.01</td>
<td>0.95 ± 0.11</td>
</tr>
<tr>
<td>$Z \to e^+e^-$</td>
<td>2.18 ± 0.09</td>
<td>0.19 ± 2.90</td>
<td>0.64 ± 0.01</td>
<td>0.92 ± 0.11</td>
</tr>
<tr>
<td>$\gamma$ +jets</td>
<td>1.85 ± 0.09</td>
<td>0.94 ± 2.52</td>
<td>0.64 ± 0.01</td>
<td>0.96 ± 0.11</td>
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<tr>
<td>$u_\parallel$ component</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z \to \mu^+\mu^-$</td>
<td>-1.63 ± 0.06</td>
<td>-1.72 ± 2.53</td>
<td>0.68 ± 0.01</td>
<td>0.99 ± 0.11</td>
</tr>
<tr>
<td>$Z \to e^+e^-$</td>
<td>-1.42 ± 0.08</td>
<td>-1.98 ± 2.95</td>
<td>0.69 ± 0.01</td>
<td>0.96 ± 0.12</td>
</tr>
<tr>
<td>$\gamma$ +jets</td>
<td>-1.16 ± 0.08</td>
<td>-1.31 ± 2.53</td>
<td>0.68 ± 0.01</td>
<td>0.98 ± 0.11</td>
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<tr>
<td>$u_\perp$ component</td>
<td></td>
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...
Figure 13: Upper panel: Distributions of the $u_\parallel + q_T$ and $u_\perp$ components of the hadronic recoil, in data (filled markers) and simulation (solid histograms) for the $Z \rightarrow \mu^+ \mu^-$ (upper) and $Z \rightarrow e^+ e^-$ (lower) samples. The first and the last bins include the underflow and overflow content, respectively. Lower panel: Data to simulation ratio. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.
Figure 14: Upper panel: Response of Puppi $p_T^{\text{miss}}$ in data in $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ events. Lower panel: ratio of the Puppi $p_T^{\text{miss}}$ response in data and simulation. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.

The ones obtained using PF $p_T^{\text{miss}}$. Compared to the case of PF $p_T^{\text{miss}}$, the resolutions show a much reduced dependence on the number of pileup interactions.

Figure 15: Puppi $p_T^{\text{miss}}$ resolution of the $u_\parallel$ (left) and $u_\perp$ (right) components of the hadronic recoil as a function of reconstructed primary vertices in $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ events. In each plot, the upper panel shows the resolution in data, whereas the lower panel shows the ratio of data to simulation. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.

The resolution in different samples is parametrized using Eq. 5, and the results of the parametrization are given in Table 4. Each additional pileup is found to degrade the resolution of both components up to 2 GeV per additional interaction vertex. This resolution degradation corresponds to half of what is observed in the case of PF $p_T^{\text{miss}}$. 
Table 4: Parametrization results of the resolution curves for Puppi $u_{\parallel}$ and $u_{\perp}$ components as a function of number of reconstructed vertices. The parameter values for $\sigma_c$ are obtained from data and simulation, and the values for $\sigma_{PU}$ are obtained from data, along with a ratio $R_{PU}$ of data and simulation. The uncertainties displayed for both the quantities are obtained from the fit, and for simulation the jet energy scale, jet energy resolution and unclustered energy uncertainties are propagated.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_c$(data) [GeV]</th>
<th>$\sigma_c$(MC) [GeV]</th>
<th>$\sigma_{PU}$(data) [GeV]</th>
<th>$\sigma_{PU}$(MC) [GeV]</th>
<th>$R_{PU} = \sigma_{PU}$(data) / $\sigma_{PU}$(MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu^+\mu^-$</td>
<td>18.9 ± 0.05</td>
<td>17.5 ± 0.74</td>
<td>1.93 ± 0.02</td>
<td>0.97 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>18.9 ± 0.06</td>
<td>17.4 ± 0.80</td>
<td>1.94 ± 0.03</td>
<td>0.98 ± 0.12</td>
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</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_c$(data) [GeV]</th>
<th>$\sigma_c$(MC) [GeV]</th>
<th>$\sigma_{PU}$(data) [GeV]</th>
<th>$\sigma_{PU}$(MC) [GeV]</th>
<th>$R_{PU} = \sigma_{PU}$(data) / $\sigma_{PU}$(MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu^+\mu^-$</td>
<td>14.2 ± 0.04</td>
<td>13.6 ± 0.59</td>
<td>1.78 ± 0.01</td>
<td>0.97 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>14.3 ± 0.05</td>
<td>13.6 ± 0.59</td>
<td>1.80 ± 0.02</td>
<td>0.96 ± 0.09</td>
<td></td>
</tr>
</tbody>
</table>

Figure 16: Upper panel: Resolution of $u_{\parallel}$ (left) and $u_{\perp}$ (right) components of the hadronic recoil as function of the reconstructed vertices. The blue (yellow) markers correspond to the PF $p_T^{\text{miss}}$ reconstruction algorithm for the nominal (high pileup) data, whereas the green (magenta) markers correspond to the Puppi $p_T^{\text{miss}}$ reconstruction algorithm for the nominal (high pileup) data. The results are obtained after correcting for the difference in the response seen between the two algorithms. Lower panel: Data to simulation ratio. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.
9.3 Performance of $p_T^{\text{miss}}$ in single-lepton samples

Single-lepton events which contain genuine $p_T^{\text{miss}}$ are also utilized to study the performance of the $p_T^{\text{miss}}$ algorithms. In events with a W boson, the magnitude of the $p_T^{\text{miss}}$ is approximately equal to the $p_T$ of the lepton, and its resolution is dominated by the hadronic recoil.

In Fig. 17, the PF and Puppi $p_T^{\text{miss}}$ distributions are compared in single-muon and single-electron samples, where the QCD multijet background is corrected based on the method discussed in Section 6.4. A larger discrimination between events with and without intrinsic $p_T^{\text{miss}}$, is observed for the Puppi $p_T^{\text{miss}}$ algorithm.

Figure 17: PF (left) and Puppi (right) $p_T^{\text{miss}}$ distribution is shown for single-muon (top) and single-electron (bottom) events. In all the distributions, the lower panel shows the ratio of data to simulation. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.

The transverse mass ($M_T$) of the lepton-$p_T^{\text{miss}}$ system is compared between the algorithms and shown in Fig. 18. The $M_T$ of the system is computed as:

$$M_T = \sqrt{2 p_T^{\text{miss}} \ p_T^{\text{lepton}} (1 - \cos \Delta \phi)},$$

(7)

where $p_T^{\text{lepton}}$ is the $p_T$ of the lepton, and $\Delta \phi$ is the angle between $p_T^{\text{lepton}}$ and $p_T^{\text{miss}}$. Similar to the $p_T^{\text{miss}}$ case, Puppi algorithm is found to have better discrimination between events with and
10. The $p_T^{\text{miss}}$ significance

The ability to distinguish between events with intrinsic $p_T^{\text{miss}}$ and those with spurious $p_T^{\text{miss}}$ is very important for analyses targeting signatures with weakly-interacting particles. The $p_T^{\text{miss}}$ significance variable, denoted $S$, quantifies the degree of compatibility of the $p_T^{\text{miss}}$ with zero on an event-by-event basis and it is computed using all clustered objects and the unclustered energy in each event. The factorized approach followed allows for the construction of a significance variable that is applicable to a variety of event topologies. The variable is described in detail in Refs. [16, 29]. Here we give an overview of updates and performance studies conducted using the CMS 13 TeV data set.

without intrinsic $p_T^{\text{miss}}$. In addition, the spread of the Jacobian mass peak is found to be smaller when $M_T$ is computed using Puppi $p_T^{\text{miss}}$. The summary of the mean and the spread of the Jacobian mass peak, calculated in simulated $W$+jets events, is provided in Table 5. Utilizing Puppi $p_T^{\text{miss}}$ for the $M_T$ calculation results to a $\sim 10 - 15\%$ relative improvement on the resolution of the Jacobian mass peak with respect to PF $p_T^{\text{miss}}$.

Figure 18: PF (left) and Puppi (right) $M_T$ distribution is shown for single-muon (top) and single-electron (bottom) events. In all the distributions, the lower panel shows the ratio of data to simulation. The systematic uncertainty due to the jet energy scale, jet energy resolution and variations on the unclustered energy is displayed with a gray band.
Table 5: The summary of the mean and the spread of the Jacobian mass peak on the $M_T$ distribution in single lepton events for PF and Puppi $p_T^{\text{miss}}$ algorithms. The results are obtained using simulated W+jets events.

<table>
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<tbody>
<tr>
<td></td>
<td>PF algorithm</td>
<td>Puppi algorithm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>$76.26 \pm 0.01$</td>
<td>$15.01 \pm 0.01$</td>
<td>$73.44 \pm 0.01$</td>
<td>$13.01 \pm 0.01$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$77.46 \pm 0.01$</td>
<td>$15.37 \pm 0.01$</td>
<td>$74.61 \pm 0.01$</td>
<td>$13.18 \pm 0.01$</td>
</tr>
<tr>
<td>$20 &lt; \text{Number of vertices} \leq 30$</td>
<td>$78.58 \pm 0.01$</td>
<td>$16.45 \pm 0.01$</td>
<td>$74.21 \pm 0.01$</td>
<td>$13.65 \pm 0.01$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>$79.96 \pm 0.01$</td>
<td>$16.74 \pm 0.01$</td>
<td>$75.45 \pm 0.01$</td>
<td>$13.87 \pm 0.01$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$82.26 \pm 0.03$</td>
<td>$17.73 \pm 0.02$</td>
<td>$76.68 \pm 0.02$</td>
<td>$14.70 \pm 0.02$</td>
</tr>
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</table>

The significance is defined as the log-likelihood ratio

$$S \equiv 2 \ln \left( \frac{L(\vec{\epsilon} = \sum \vec{\epsilon}_i)}{L(\vec{\epsilon} = 0)} \right),$$

where the $\vec{\epsilon}$ is the true $p_T^{\text{miss}}$ and $\sum \vec{\epsilon}_i$ is the observed $p_T^{\text{miss}}$. In the numerator, we evaluate the likelihood that the true value of $p_T^{\text{miss}}$ equals the observed value, while the denominator corresponds to the null hypothesis (that the true $p_T^{\text{miss}}$ is zero). To a very good approximation the likelihood $L(\vec{\epsilon})$ has the form of a Gaussian distribution. Therefore, the significance can be written as:

$$S = (\sum \vec{\epsilon}_i)^T V^{-1} (\sum \vec{\epsilon}_i),$$

where $V$ is the $2 \times 2$ $p_T^{\text{miss}}$ covariance matrix. In this formulation, $S$ is conveniently a $\chi^2$ variable with two degrees of freedom (one degree of freedom for the x- and y-axis component of $p_T^{\text{miss}}$) for events with zero true $p_T^{\text{miss}}$.

The covariance matrix $V$ in Eq. 9 models the $p_T^{\text{miss}}$ resolution resolution in each event. It is constructed by propagating the individual resolutions of the objects entering the $p_T^{\text{miss}}$ sum. In most cases, the $p_T^{\text{miss}}$ resolution captured in covariance $V$ is primarily determined by the hadronic components of the event, which includes jets with $p_T > 15$ GeV and the unclustered energy. Jets enter into the total covariance $V$ with an individual covariance of the form:

$$U = \begin{pmatrix} \sigma_{p_T}^2 & 0 \\ 0 & \sigma_{\phi}^2 \end{pmatrix},$$

where the quantities $\sigma_{p_T}$ and $\sigma_{\phi}$ are measured and then re-tuned with a combination of simulation and data driven techniques as explained in Ref. [16]. On the other hand, momenta of all the PF candidates that are not included in to a jet are summed vectorially, and the resulting momentum is assigned into a single pseudo-object with $p_T = \sum_i p_T i$. The resolution of this pseudo-object is parametrized by the scalar $p_T$ sum of its constituents:

$$\sigma_{uc}^2 = \sigma_0^2 + \sigma_s^2 \sum_{i=1}^{n} |\vec{p}_T i|,$$
where the values of $\sigma^2_0$ and $\sigma^2_s$ are determined using a data driven technique as explained in Ref. [16]. The resolution of this object is assumed to be isotropic in the transverse plane of the detector. Lastly, electrons and muons are assumed to have perfect resolutions when compared to the hadronic component of the event, and make no contribution to the covariance $V$.

10.1 Unclustered energy studies

The unclustered PF candidates are combined into a pseudo-object. Its resolution should be isotropic in the transverse plane, with a size proportional to its magnitude. This approach, called the “standard” method of $S$ in what follows, is motivated by its simplicity, and shows good agreement between data and simulation. The diagonal elements of the contribution of the unclustered energy to the covariance matrix are given in Eq. 11.

During LHC Run 2, alternative methods to obtain the covariance matrix were explored, such as the so-called “jackknife technique” [32, 33]. The jackknife method allows the estimation of a covariance matrix that is not necessarily isotropic, and also includes off-diagonal elements. The covariance matrix is calculated using the “delete-1 method”, in which a single candidate is removed. This approach leads to “$N-1$” samples per event, with $N$ the total numbers of constituents contributing to the unclustered energy. The covariance matrix takes the form:

$$\hat{V}_{ij} = \frac{N-1}{N} \sum_{k=1}^{N} (p^k_i - \bar{p}_i)(p^k_j - \bar{p}_j)$$

(12)

where $k$ is the removed candidate, $p^k_i$ and $p^k_j$ are the x and y components of the unclustered energy calculated after removing the $k$-th candidate, and $\bar{p}_i$ and $\bar{p}_j$ are mean values of the x and y components of the unclustered energy over all samples, defined as:

$$\bar{p}_{ij} = \frac{1}{N} \sum_{k=1}^{N} p^k_{ij}$$

(13)

Again, the resolution is scaled by parameters tuned in data and simulated samples, here referred to as $a_x$ and $a_y$. The parameters are determined following a similar approach as in the standard method of $S$ discussed above. The resolutions of the components of the unclustered energy are then defined as

$$\sigma^2_x = a_x^2 \times \hat{V}_{xx}$$
$$\sigma^2_{xy} = a_x a_y \times \hat{V}_{xy}$$
$$\sigma^2_y = a_y^2 \times \hat{V}_{yy}$$

(14)

10.2 Performance evaluation

The performance of the two versions of $S$, the standard and the jackknife, and $p_T^{\text{miss}}$, is compared in terms of receiver-operating-characteristic (ROC) curves. We consider as signal processes with intrinsic $p_T^{\text{miss}}$. Processes without intrinsic $p_T^{\text{miss}}$ are considered backgrounds. The results are shown in Fig. 19 using simulated dimuon events (i.e. events with no intrinsic $p_T^{\text{miss}}$) and single-electron events (i.e. events with intrinsic $p_T^{\text{miss}}$). No significant difference between the two $S$ versions is observed. Both versions of $S$ offer better signal to background separation compared to $p_T^{\text{miss}}$. For example, choosing a working point with 1% background efficiency the $S$ variables offer 5% higher signal efficiency than $p_T^{\text{miss}}$. For the remainder of the section, we focus only on the standard version of $S$. Further developments in the jackknife version of $S$ (e.g. algorithm tuning and PF candidate selection) will be investigated in a future publication.
The performance of $S$ is evaluated in data using di-lepton and single-lepton events. The results are displayed in Fig. 20 and Fig. 21 for different jet multiplicities. In Fig. 20, where events with no genuine $p_T^{\text{miss}}$ dominate, the core of the $S$ spectrum follows an ideal $\chi^2$ distribution. For large values of $S$ the spectrum begins to deviate from a perfect $\chi^2$ distribution as the processes with intrinsic $p_T^{\text{miss}}$ become important. This deviation also has contributions from the non-Gaussian tails of the jet $p_T$ resolution function, which are not considered in Eq. 9. A detailed discussion of the treatment of non-Gaussian resolutions in CMS can be found in [16].

The stability of $S$ against pileup is studied using dimuon and single-electron events. Figure 22 displays the average $S$ as a function of the number of reconstructed vertices. In the dimuon sample, dominated by events with no intrinsic $p_T^{\text{miss}}$, the value of $S$ is robust against pileup, with an average value of $\sim 2$, as expected for a $\chi^2$ variable with two degrees of freedom. This behavior can be explained qualitatively with the following arguments. In the case of events with no genuine $p_T^{\text{miss}}$, the contribution of pileup affects in a similar manner both $p_T^{\text{miss}}$ and the variance of $p_T^{\text{miss}}$, since both are dominated by the hadronic resolution. This results in an essentially constant value of $S$ which does not depend on the number of pileup interactions.

However, in events with genuine $p_T^{\text{miss}}$, as in the single-electron sample, pileup has a small impact on $p_T^{\text{miss}}$, whereas the impact on the resolution on $p_T^{\text{miss}}$ is similar to the case of no genuine $p_T^{\text{miss}}$, leading to a decrease of $S$ as pileup increases. This results to a degradation in the performance of $S$ in events with large number of reconstructed vertices.

11 Summary

The performance of missing transverse momentum ($p_T^{\text{miss}}$) reconstruction algorithms is presented using events with and without intrinsic missing transverse momentum in proton-proton collisions recorded at $\sqrt{s} = 13$ TeV, using a sample of data corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The performance of algorithms used to identify and remove events with anomalous missing transverse momentum have been also studied using events with one or more jets. The scale
Figure 20: Distributions of $S$ in data and simulation in dimuon (top) and dielectron (bottom) for events with 0 (left) and $\geq 1$ jet (left). The red straight line corresponds to a $\chi^2$ distribution of 2 degrees of freedom. The bands in the bottom panel display the effect of various sources of systematic uncertainties in simulation. Good agreement between data and simulation is observed.
Figure 21: Distributions of $S$ in data and simulation in single-muon (top) and single-electron (bottom) for events with 0 (left) and $\geq 1$ jet (left). The red straight line corresponds to a $\chi^2$ distribution of 2 degrees of freedom. The bands in the bottom panel display the effect of various sources of systematic uncertainties in simulation. Good agreement between data and simulation is observed.
Figure 22: Dependence of the average $S$ on pileup, for dimuon events (left) and single-electron events (right). Small dependence is observed for processes with no genuine $p_T^{\text{miss}}$, whereas in events with intrinsic $p_T^{\text{miss}}$ the behavior of $S$ depends strongly on vertex multiplicity.

and resolution of the missing transverse momentum determination has been measured using events with an identified Z boson or isolated photon. The measured scale and resolution in data are found to be in agreement with the expectations from the simulation. The performance of an advanced $p_T^{\text{miss}}$ reconstruction algorithm, the Puppi $p_T^{\text{miss}}$, specifically developed to cope with a large number of pileup interactions has also been presented. This algorithm shows a significantly reduced dependence of the $p_T^{\text{miss}}$ resolution on pileup interactions.

The studies presented in this note provide a solid foundation for all CMS measurements with $p_T^{\text{miss}}$ in the final state, including standard model measurements of the Higgs boson, W boson and top quark and searches for new neutral weakly interacting particles beyond the standard model.

References


