Jet energy corrections and uncertainties in CMS: reducing their impact on physics measurements

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Abstract. The measurement of any physical quantity at CMS includes the estimation of a systematic error propagated from the uncertainties on the jet energy calibration. For some physical quantities the main systematic error results from this propagation. This talk will present the main uncertainties considered on the jet energy calibration, the effect these have on some particular analyses, and a novel way of handling uncertainties recently deployed at CMS to reduce the dependence on these uncertainties.

1. Introduction
Since the LHC began operations less than 2 years ago the CMS collaboration has shown an excellent understanding of the CMS detector as well as of its corresponding Monte Carlo simulations, it has produced accurate calibration constants that are the among the best in the world and published the first basic analysis rediscovering the known features of the Standard Model. But the current path to discovery requires now more sophisticated analysis techniques, as well as a more accurate set of calibration constants. The jet energy scale is a perfect example of the growing success achieved in the calibration area where the current jet energy scale uncertainties has been reduced to about 2%.

There are currently several studies being developed at CMS with varying degrees of complexity, and as detailed in the main text and despite the excellent accuracy of the jet energy calibrations many of these studies still report the jet energy scale as one of the largest source of uncertainties. This paper describes common methodologies to estimate the effect of these uncertainties on physical observables as well as novel procedures for reducing their overall impact.

Section 2 gives a brief overview of the jet energy corrections and uncertainties used at CMS, section 3 details standard methodologies for their application to most analyses, and section 4 details improvements in the application to reduce the overall impact of the uncertainties. The paper finished with conclusions on section 5.

2. Jet calibration at CMS
The detector response and its efficiency together with the details of the jet algorithm used for jet clustering result in measurement of jet energies that are different than the energy of the jet obtained at particle level. The jet energy is corrected, or calibrated, on average to the particle-level energy of the jet in the generic flavor mixture of the QCD sample. This is achieved by
applying a sequence of corrections that individually deal with different aspects of the calibration.

A brief overview of the correction level follows:

- **Pile up**: this is the first correction applied to jet. It subtracts the average extra energy deposited in the jet that comes from other vertices present in the event and is therefore not part of the hard jet. It is parameterized as a function of the median jet energy in the event as defined in [1], or alternatively on the number of primary vertices ($N_{\text{PV}}$). This function has an excellent linearity up to $N_{\text{PV}} = 30$ and has very little $\eta$ dependence within the tracker coverage. It is derived from zero-bias data and Monte Carlo simulations (MC). A more detailed discussion on pile up mitigation techniques can be found in [1].

- **$\eta$ dependence**: it corrects for the non-uniform response of the detector in eta. The response of each position in eta is related to the detector response averaged over $|\eta| < 1.3$. Derived from Monte Carlo simulations shows an excellent performance correcting back to the 0.5% level for jet $p_T > 30$ GeV. The response of different flavors is within the 1.5% of the QCD flavor mixture.

- **$p_T$ dependence**: it corrects for the non-uniform response of the detector as a function of $p_T$. Obtained from Monte Carlo simulations.

- **$\eta$ and $p_T$ residuals**: applied to data only to correct for $\eta$ and $p_T$ residual differences between data and Monte Carlo. The $\eta$ residual is derived from QCD dijet sample and the $p_T$ residual from $\gamma$+jet and $Z$+jets samples in data.

A more detailed explanation of the correction levels and methodologies to derived them can be found in [2]. More discussion and a set of updated plots can be found in [3].

### 2.1. Jet energy uncertainties at CMS

Each one of these correction levels has uncertainties arising from many different sources. In general these sources can be categorized as being one of the following:

- Physics modeling in MC such as showering, modeling of underlying event, etc.
- MC modeling of true detector response and properties such as noise, zero suppression, etc.
- Potential biases in the methodologies used to estimate the corrections.

At CMS more than 16 sources of uncertainties have been identified from the above origins. Several of these uncertainty sources are related and can be combined into groups we label "Absolute scale", "Relative scale", "Extrapolation in $p_T$", "Pile-up", "Jet flavor", and "Time stability". The figures 1 and 2 show the contribution of the jet energy correction uncertainty from the combined sources as a function of the jet $p_T$ and jet $\eta$. At CMS the total uncertainty on the jet energy correction is computed as the quadrature sum of the uncertainty of each different source and it shown for reference in figures 1 and 2 in a solid grey color.

### 3. Application of jet energy correction uncertainties

The measurement of any physical quantity includes the estimation of an uncertainty on the quantity due to the uncertainty on jet energy calibrations. At CMS the most common practice consists of the evaluation of the change in the measured quantity when the jet energy is fluctuated up and down according to the total jet energy uncertainty. The following examples show the effect of this application on three different analysis.

#### 3.1. WW cross section in the lepton+jets channel

As an example application of let's consider the measurement of the WW cross section in the lepton+jets channel. Figure 3 shows a simultaneous fit to an average pseudodata to the $W$+jets background and the WW diboson event yields on the dijet invariant mass. In this fit the jet
energy uncertainty was not considered and the result of the fit is $322 \pm 98$ diboson events. However if the same fit is performed when the jets are scaled down (up) by their uncertainty the result is $363\pm 98$ ($279\pm 100$) diboson events. This indicates that the error is obtained by simply scaling jets up and down by their uncertainty is about 43 events, or about 13% the diboson signal size.

![Figure 1](image1.png)

**Figure 1:** Jet energy uncertainty as a function of jet $p_T$ for combined uncertainty sources.

![Figure 2](image2.png)

**Figure 2:** Jet energy uncertainty as a function of $\eta$ for combined uncertainty sources.

3.2. *Top mass measurement in the lepton+jets channel*

The measurement of the top mass is in general very sensitive to the jet energy corrections and uncertainties. Figure 4 shows a relative large effect of about 5 GeV on the fitted top mass when varying the jet energy scale about 4% as shown for example from [4]. To reduce this dependance the top mass analysis perform a simultaneous fit to the top mass and the jet energy scale as

![Figure 3](image3.png)

**Figure 3:** Simultaneous fit to an average pseudo-dataset expected of the W+jets background and the WW diboson event yields on the dijet invariant mass. Uncertainties on the jet energy corrections were not considered. The fit resulted in an expectation of $322 \pm 98$ diboson events and $3717 \pm 206$ W+jets events.
determined directly from the dataset. A summary table of the all the systematic errors on the top mass measurement after the jet energy fit is shown in table 1. From this table it can be seen that, even with a reduced jet energy dependance, the residual systematic error on the top mass due to jet energy uncertainties still amounts to about 23% of the total error on the top mass measurement.

| Error Source                          | \( \delta m_t \) (GeV) | \( \delta_{JES} \) (GeV) |
|---------------------------------------|-------------------------|--------------------------|
| Calibration                           | 0.15                    | 0.001                    |
| b-tagging                             | 0.17                    | 0.002                    |
| b-JES                                 | 0.66                    | 0.000                    |
| \( p_T \) and \( \eta \) dependent JES | 0.23                    | 0.003                    |
| Jet energy resolution                 | 0.21                    | 0.003                    |
| Missing transverse energy             | 0.08                    | 0.001                    |
| Factorization scale                   | 0.76                    | 0.007                    |
| ME-PS matching threshold              | 0.25                    | 0.007                    |
| Non-\( t\bar{t} \) background        | 0.09                    | 0.001                    |
| Pile-up                               | 0.38                    | 0.005                    |
| PDF                                   | 0.05                    | 0.001                    |
| Total                                 | 1.18                    | 0.012                    |

Table 1: List of systematic uncertainties extracted from [4].

3.3. Inclusive jet cross section in pp collisions

The results of the measurement of the ratio of the jet differential cross section to the theoretical prediction as a function of \( p_T \) [5] is shown in figure 5. The shaded yellow band represents the total experimental systematic uncertainty which is dominated by jet energy uncertainties followed by a smaller contribution from uncertainty on luminosity estimations. The uncertainties from the proton parton distribution function are included as part of the uncertainty in the theory. Changes in the jet energy uncertainty propagate directly to this measurement.

Figure 4: Fitted top invariant mass as a function of the jet energy scale for Monte Carlo simulations

Figure 5: Ratio of the inclusive jet cross section of data over theoretical prediction as a function of jet \( p_T \) for different jet \( \eta \) regions. The yellow bands indicate the experimental uncertainty and the solid lines the theoretical uncertainty.
4. Reducing the effect of jet energy correction uncertainties

4.1. Better methodologies

The basic way to reduce the effect of jet energy uncertainties on a physical quantity is the utilization of better and smarter methodologies. Many analysis take advantage of other information on the events to produce an measurement of the jet energy corrections from their same dataset and often simultaneously measure the quantity of interest and the jet energy scale. This is most commonly done for top quark mass measurements, where a measurement of the correction scale is obtained from the hadronic decay of the W boson [4]. Furthermore, the measurement is not only done in the same dataset where the measurement is done, but an uncertainty is obtained "in-situ" in an event by event basis.

Another example is the study of dijet invariant mass spectrum in the W+2jet channel where the particular study is in the 125 to 180 GeV region in order to investigate an excess of event reported by the CDF collaboration [6]. This analysis fits the signal region to the excess seen at CDF but also reduces the dependance on jet energy uncertainty by performing a simultaneous fit to it. In addition, this dependance is further reduced by convoluting the fit in the signal region with an independent measurement of the systematic error due to jet energy uncertainties performed on a control region. This also require the consideration of the possible difference in jet-flavor between both regions. This methodology results in a very limited effect of the jet energy uncertainties on the final result.

4.2. Using full-fledged uncertainty correlations

There is another techniques that could help reduce the effect of uncertainties even more. At CMS we have provided not only up and down absolute uncertainties but also the up and down uncertainties as a function of the $p_T$ and $\eta$ of the jet for each different source. Each source represents a ±1σ uncertainty on the jet energy. The plot on figure 6 shows some of the total uncertainty and the breakdown by sources that depend on $p_T$.

![Figure 6: Sources of jet energy scale uncertainty. The yellow band represent the sources that depends on $p_T$. The grey band represent the total uncertainty and contain uncertainties that depend on eta.](image)

![Figure 7: Difference between using absolute uncertainties and the uncertainty sources and their correlations on the dijet invariant mass distribution. Produced with toy Monte Carlo. Standard Up and down approach shifts the peak 1.85 GeV. Using the fully correlated uncertainty sources the shift is 1.18 GeV.](image)
For any given jet these uncertainty sources are mutually uncorrelated, but each source is fully correlated with the same source of another jet, and this true whether the other jet is in the same event or not. When a physical quantity is derived from information that depends on one or more jets the proper uncertainty on this quantity can be obtained by varying each source independently and evaluating the systematic change in the physical quantity. The final error on the quantity can then computed as the sum in quadrature of the systematic error obtained from each source. This methodology is akin to the computation of the uncertainties due to the different eigenvalues of the parton distribution function.

These correlations can reduce the uncertainty in cases where there is a direct data-Monte Carlo comparison of shapes, regardless of the actual "position" of either data or MC in the distribution of interest. For example the Higgs boson production in association of vector boson is described in [7] and the results are obtained from a direct comparison of the dijet invariant mass of a Higgs boson produced with a given mass to data. In this case the correlation of the different uncertainty sources between data and Monte Carlo can play a beneficial role reducing the overall sensitivity to jet energy uncertainties.

In general let's consider the effect on the dijet invariant mass distribution produced with toy Monte Carlo and shown in figure 7. The peaked distribution could represent a quantity such as the background-subtracted distribution where a resonance signal is to be fit. The distribution is narrow just to emphasize the effect but the same results apply to any peaked distribution. When using the absolute energy uncertainty up and down the peak shifts about 1.85 GeV with respect the original peak. However, when using the fully correlated uncertainties the shift is only 1.18 GeV. It should be noted that taking the uncertainty correlation into account is always the right way of propagate the uncertainties in each source. However it is not guaranteed that the net effect on the physical quantity is the reduction of the systematic error when comparing with the error computed using the absolute total uncertainty.

5. Conclusions

The effect of jet energy uncertainties on physical observables can be significant and needs to be dealt with appropriately. Several analyses achieve a reduced sensitivity to these uncertainties with the incorporation of smarter methodologies such as the simultaneous fit of the uncertainties when possible or the further constraint of these uncertainties from control regions of the analysis. The incorporation of the different uncertainty sources into the analysis is preferred against the simple use of total absolute uncertainties because of the proper consideration of uncertainty correlations between jets. Although not necessarily by construction, the usage of uncertainty sources can result in smaller uncertainties as shown in the example case discussed in the previous section.

References

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