Measurement of the Jet Energy Scale at DØ

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Abstract. Jets of hadrons are the most commonly produced objects at high-energy hadronic colliders. It is therefore important to identify and quantify jet energies in events. However, collisions involving interesting physical processes can overlap in time with additional collisions. This is especially troublesome at high luminosities, as such additional energy depositions in detectors can compromise the reconstruction of jets. The DØ detector at Fermilab relies mainly on the energy information obtained using its uranium/liquid-argon (LAr) sampling calorimetry. The experiment has developed a set of corrections, collectively known as the jet energy scale (JES), that translate jet energies measured in the detector to the energies carried by the produced particles. This correction is extracted from two-body events, separately for those observed in the detector and for the ones from Monte-Carlo simulation. The corrections include effects from the jet reconstruction algorithm, the response of the calorimeter and the impact of simultaneous interactions. We describe the JES correction used at DØ, focusing on the main contributions and discuss the precision achieved in the measurement of jet energy.

1. Instrumentation

The Tevatron at Fermi National Accelerator Laboratory accelerates protons and antiprotons that collide at a centre of mass energy of 1.96 TeV. Before the shutdown planned for October 2011, the accelerator is expected to deliver to the experiments about 12 fb⁻¹, which will provide CDF and DØ experiments about 10 fb⁻¹ of good data. This achievement is a result of the outstanding performance of the accelerator, including an instantaneous luminosity (L) that has greatly exceeded original design specifications. In fact, the initial L of each store is often ≈ 3 · 10³² cm⁻²s⁻¹. DØ data has been taken with an average of the order of 10³² cm⁻²s⁻¹. This, together with a frequency of almost 1.7 million bunch crossings per second at a cross section of 60 mb, causes on average 4 interactions for each bunch crossing.

The DØ detector [1] is a multi-purpose detector made of an inner tracking section; a calorimetry section; and outer tracking detectors for identifying muons and measuring their momenta. Most of the detector is used in the reconstruction of jets: the reconstruction of the primary interaction vertex, based on tracks, provides a reference point to reconstruct the jet, any associated muon is used to improve the estimation of jet energy, but the main information is extracted from the calorimeter.

The core of DØ calorimetry is a sampling calorimeter (Fig. 1) that uses liquid argon as active material and depleted uranium (or copper and steel in some forward regions) as absorber [2]. To keep the argon in liquid state, the whole calorimeter is contained in cryogenic tanks. The detector is split into one central calorimeter (CC) and two end-cap calorimeters (EC), each in separate cryostats. The region between the cryostats, called intercryostat region (ICR), is instrumented with scintillators to improve the coverage of the calorimeter. The calorimeter is fully sensitive in azimuthal angle (ϕ_d) and up to 4.1 units in pseudorapidity (|η_d|). The effect of the gap in the ICR is most evident for jets with axis on 0.9 < |η_d| < 1.6. Central and forward preshower scintillator elements complete the calorimeter.
The overall thickness of the electromagnetic layers of the detector can be measured in 20 radiation lengths ($X_0$) and the entire calorimeter varies from 7.2 to 8.0 strong interaction lengths ($\lambda_I$), while the material in front of the calorimeter is about 4 $X_0$ thick.

The calorimeter is segmented longitudinally, and split into 17 layers grouped into electromagnetic parts, three fine hadronic parts layers and a coarse-hadronic part. Cells are aligned across layers in a roughly pointing-geometry to form “calorimeter towers”. The cells have a size of $\eta_d \times \varphi_d = 0.1 \times 0.1$.

2. Algorithms

2.1. Zero suppression

There are about 50000 cells in the calorimeter, each read out independently. To reduce the bandwidth needed to store this amount of data at a 1.7 MHz event rate, a filter is applied, commonly known as “zero suppression” (ZS).

The ZS algorithm discards the readings from the cells that have no relevant energy deposition. Each cell has a noise level ($\sigma$) and a pedestal setting, which correspond respectively to the RMS and average of the cell readings without collisions. The readout electronics discards the readings below $1.5\sigma$ (Fig. 2.) The others are analysed by an algorithm (called “T42”) which, using the geometry of the detector, discards all cells with readings below $2.5\sigma$, and the ones with reading below $4\sigma$ that do not have any neighbouring cell with reading above $4\sigma$ (Fig. 3.)

This procedure causes an underestimation of the measured energy, which is corrected though the jet energy scale.

2.2. Jet reconstruction

DØ uses a fixed-cone algorithm with midpoints [3] to reconstruct jets from energy depositions in calorimeter cells.

The algorithm starts from seeds consisting of highly energetic calorimeter towers; a calorimeter tower is a group of cells aligned on a given direction from the centre of the detector, spanning all the longitudinal...
Figure 2. Hardware zero suppression: cutoff on the noise, with the curve representing a typical distribution in units of RMS cell noise $\sigma$, with the origin set to the cell mean pedestal value (grey areas are always suppressed).

Figure 3. Software zero suppression (T42 algorithm): in this example each cell from the same layer contains its readout in $\sigma$ units and the only not suppressed cells are the four cells highlighted (note that the DØ algorithm considers all the layers in the decision).

layers of the calorimeter. For the reconstruction to be stable and less sensitive to gluon radiation (“infrared safety”), additional artificial seeds, mid points, are added between the existing seeds.

Proto-jets are formed by drawing cones of fixed opening $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. The procedure is iterative, and on the first iteration the direction of the seed is used to define the axis of the cone; the jet axis is then recomputed at each iteration, and the new value is used as the axis of the cone for the next iteration, until the axis stabilises.

The “$E$-scheme” [3] is used to compute the jet energy and axis. The cells are treated as independent, massless objects, and the jet four-momentum is computed from $(E_{\text{jet}}, \vec{p}_{\text{jet}}) = \sum_{c \in \text{cells}} (E_c; \hat{u}_c)$, where $E_c$ and $\hat{u}_c$ are, respectively, the calibrated energy and the direction of the cell relative to the primary vertex.

If any proto-jets overlap, they are merged into one jet in case the shared energy is large, or they are split and each cell is assigned to the closest jet in $\Delta R$.

DØ uses $\Delta R = 0.5$ for most of the analyses, while $\Delta R = 0.7$ is used most often for dijet and trijet analyses, which have lower final-state multiplicity and can thereby collect more of the energy of each jet. Jet Energy Scale corrections are extracted independently for each cone size.

3. Jet Energy Scale
The evolution of the gluons and quarks (“partons”) produced in the hard-scattering QCD process to jets of particles is usually described in three phases or “levels”:

- **parton level** reflects the hard scattering of two partons, which produces quarks and gluons, the seeds for jets
- **particle level** reflects the strong potential between quarks and gluons that increases as they separate in space, creating thereby more partons that eventually bind into hadrons, with their direction clustered around their original partons. The details of the development during this phase is model dependent, but at the end of the development, short-lived hadrons decay and only relatively long-lived particles remain; these final particles (including e.g. photons, pions, nucleons, $\Lambda^0$, $K$, electrons, muons) enter the detector
- **reconstruction level** reflects the interaction of the particles in the detectors as they deposit their energy through electromagnetic or strong interactions in the detector material. Some energy is “lost” as
neutrinos escape detection and nucleons are stopped in the material.

We measure the energy of all objects at the reconstruction level. While our physics analyses are most concerned with the parton energies, the goal of the Jet Energy Scale correction is to convert the reconstructed energy back to energies of particles, which are observable and directly measurable. The next corrective step to the parton level includes other refinements such as unfolding detector and hadronization effects, which are strongly model-dependent: these are not included in the JES.

### 3.1. Overview of the JES correction

The Jet Energy Scale correction is summarized by this formula:

$$E_{\text{ptcl}\text{jet}} = \frac{E_{\text{meas}\text{jet}} - \hat{E}_O}{R_{\text{jet}} S_{\text{jet}}} \cdot \frac{k_O}{k_R}$$  \hspace{1cm} (1)

The jet energy at the particle level ($E_{\text{ptcl}\text{jet}}$), is computed from the detected energy ($E_{\text{meas}\text{jet}}$) (sum of energies from calorimeter cells), and:

- Subtracting the “offset” energy ($E_O$) from activity not associated with the main hard $p\bar{p}$ collision
- Correcting for calorimeter response ($R_{\text{jet}}$) to the jet of particles
- Accounting for the fact that only a fraction ($S_{\text{jet}}$) of the jet energy is captured in the jet cone

An estimator is used for each term, which can be biased, and therefore requires additional correction factors for e.g. energy response and offset ($k_O$ and $k_R$ respectively, accounting for zero-suppression effects, selection biases and contamination of the residual $\gamma+\text{jet}$ events sample).

The following sections describe each one of the three main components of the correction factors.

### 3.2. Energy offset

The energy-offset correction accounts for energy deposited in the calorimeter which does not come from the main $p\bar{p}$ hard scattering. It includes (i) noise in the detector, both from the electronics and uranium (which, although depleted, has substantial residual activity), (ii) effects from the slow response of the calorimeter electronics relative to the bunch-crossing time ("pile up"), where the charge collected from a cell in the current crossing overlaps the remnant charge distribution from the previous collisions, (iii) additional energy from other $p\bar{p}$ interactions ("multiple interactions,” MI), usually elastic, diffractive, or soft inelastic collisions. The offset correction does not account for the energy from the remnants of the proton and antiproton spectator partons that do not participate in the high-$Q^2$ hard scattering (the "underlying event").

The correction is defined in two steps. In the first step, the energy contained in a ring of the detector, i.e. all the cells at a fixed rapidity (all azimuthal angles and all layers), are defined as:
The energy is contributed from two sources: (i) the noise and pile-up energy ($\hat{E}_{\text{ring}}^{\text{NP}}$) depends on the rapidity of the ring, as the background activity increases in the large $|\eta_d|$ regions, and (ii) the instantaneous luminosity ($L$). $\hat{E}_{\text{ring}}^{\text{NP}}$ is extracted from data collected using a “zero bias” (ZB) trigger, which reads out an event at random times, when a bunch crossing is expected, requiring in addition zero reconstructed interaction vertices. This ensures that the measured activity is not from in-time physical events.

The energy from multiple interactions ($\hat{E}_{\text{ring}}^{\text{MI}}$) also depends on the number of reconstructed interaction vertices ($n_{PV}$), which describes precisely how many interactions take place during each event. This information is extracted from data taken with a “minimum bias” (MB) trigger, which detects in-time activity in both forward ends of the detector, ensuring the presence of some kind of activity in the detector.

Each jet is assigned a correction depending on the area of the detector it spans, getting a contribution from each ring $\hat{E}_{\text{ring}}^{\text{O}}$ proportional to its area within that ring. Since we do not wish to subtract the energy of the main hard scatter, for each jet in an event with $n_{PV}$ primary vertices, we use the correction for $n_{PV} - 1$ vertices (jets in events with just one primary vertex get offset contributions only from the noise and pile-up term).

The measured offset energy can become huge in extreme conditions (many primary vertices, high luminosity, very large $|\eta_d|$ regions), but it is usually below 25 GeV for most of the jets used in the physics analyses ($\Delta R = 0.5$ jets within $|\eta_d| \leq 2.5$), and only a few GeV for jets at most central $\eta_d$ values. The systematic uncertainties on this correction are very small and dominated by the uncertainty on the bias correction.

3.3. Energy response

The energy response is defined as the fraction of the jet energy that we measure, relative to the true energy of the particles within the jet cone. It includes: (i) effects from the difference in energy response for different particles, e.g. hadrons vs. electrons (since the calorimeter is not entirely compensating), (ii) energy not detected because converted in nucleon mass, (iii) energy loss due to inactive material (cracks) or uninstrumented regions (inter-cryostat gaps), (iv) non-uniformity of response in different regions of the calorimeter, (v) energy leaking beyond the calorimeter (“punch through”) and (vi) non-linearity due to zero-suppression. In principle, it also includes undetected energy from neutrinos and reduced response from muons; a more precise evaluation of energy from muons is added as an additional correction including information from the muon detectors.

To evaluate the calorimeter response, a “tag and probe” method is used in studies of two-body events of simplest topology:

$\gamma + \text{jet}$ is the most important process, defining a relation between jet energy and the energy of an electromagnetic object, the photon, assumed to be well measured;

$d\text{ijet}$ events are used to enhance statistics for the estimation of the uniformity of response, once the absolute energy scale for some jets is set through $\gamma + \text{jet}$ sample. In a second step, these jets can be used as tag objects for dijet events;

$Z(\rightarrow e^+e^-) + \text{jet}$ events, although excellent candidates for such studies, have not been used because of low statistics of the data samples.

The above events are required to have a low number of reconstructed primary vertices, and the two objects are required to be back to back ($\Delta \varphi \geq 3$ rad), to ensure the cleanliness of the events. Also, the requirements on the tag objects are kept stringent: photon-identification criteria for the $\gamma + \text{jet}$ events are very tight, and tag jets in the dijet sample are required to have a relevant fraction of their energy from charged particles pointing back to the main primary vertex.
Figure 5. The Projected Missing $E_T$ Fraction (MPF) method, used for the estimation of the response to the hadronic recoil to a photon ($R_{\text{had}}$), also approximated to the response to the jet ($R_{\text{jet}}$).

All our corrections are not parametrized as function of the jet energy, which is subject to greater uncertainties and resolution effects, and we use instead the quantity:

$$E' \equiv p_T^{\text{tag}} \cosh \eta^{\text{probe}}$$

where the transverse momentum $p_T^{\text{tag}}$ of the tag is fully corrected, and we assume the direction (and the pseudorapidity $\eta$) of the probe jet from the interaction vertex to be well measured and its transverse momentum well approximated by the $p_T$ of the tag object.

The determination of the response is based on the Projected Missing $E_T$ Fraction (MPF) (Fig. 5), which can be described as follows. Relying on the two objects being back-to-back ($\vec{p}_{T\gamma} + \vec{p}_{T\text{had}} = 0$), the imbalance in transverse momentum $\vec{E}_T$ is assumed to reflect the deficiency in the measured jet energy, and we obtain the response as

$$R_{\text{had}} = 1 + \frac{\vec{E}_T \cdot \vec{p}_{T\gamma}}{|\vec{p}_{T\gamma}|^2}$$

The missing energy is computed directly from the calorimeter cells. In fact in this formula we do not consider the jet at all; instead we are measuring the response $R_{\text{had}}$ of the calorimeter to the whole event recoiling against the tag object. A next approximation considers the response to the full recoil to be the same as the response to the jet, $R_{\text{jet}} \approx R_{\text{had}}$. This approximation is no better than $\approx 1\%$, and a bias correction is included for that. The MPF response is independent of the algorithm or cone size used to reconstruct the jet.

The first step in obtaining the response correction is the measurement of absolute response, which uses very clean $\gamma$+jet events to measure the response of very central jets ($|\eta| \leq 0.4$) relative to the well measured photon energy. The residual dijet contamination is corrected by measuring the purity of the sample, and the response from the contaminating dijet events. This is the largest contribution to the JES correction.

The response is found to increase with energy, mainly because of the higher response of the calorimeter to photons and electrons relative to hadrons, together with the fact that the fraction of neutral pions in jets increases with jet energy.

The main uncertainties on the corrections are from the energy of the $\gamma$ and the estimation of dijet contamination of the $\gamma$+jet sample. The DØ $\gamma$+jet data have enough events to provide a measurement for the response up to about $E' = 300$ GeV. For a cone $\Delta R = 0.7$ jets, which is used for two and three-body analyses, where the few objects present have high energy, this response is extrapolated to higher energies using simulation.

The second step in the response correction is the measurement of the relative jet response. This uses dijet events with at least one jet in the very central region of the calorimeter ($|\eta| \leq 0.4$), while the probe jet can be anywhere in the calorimeter up to $|\eta| = 3.6$. This response is called relative as it relates the response in any part of the calorimeter to the central one; the product of the relative response by the absolute response yields the jet response $\hat{R}_{\text{jet}}$. 
The response is strongly reduced in the inter-cryostat region, where the scintillator detectors can’t provide as good a response as the LAr calorimetry.

The response for $\gamma +\text{jet}$ and dijet events is found to be very different due to the different jet composition. At low energy, dijet events have a larger component of gluons relative to $\gamma +\text{jet}$ events, while at high energies this is reversed. The main uncertainty to this part of the response comes from the two-dimensional parametrization of the response in terms of $E'$ and $\eta_d$.

### 3.4. Out-of-cone energy

The last of the three main corrections takes into account the geometric size of the jet, correcting for (i) the energy of particles from the jet that fall outside the jet cone, (ii) vice versa for the energy of other particles from the main $p\bar{p}$ interaction that accidentally falls inside the jet cone, and (iii) the energy of particles from the jet with very low energy that don’t reach the calorimeter due to the magnetic field. The correction does not account for energy lost because of gluon radiation (at parton level) at large angles.

The correction for a jet of cone $\Delta R$ (either 0.5 or 0.7), for a given energy and pseudorapidity is:

$$
\hat{S}_{\text{jet}}(E', \eta) = \frac{E_{\text{MC from-jet}}(\delta R < \Delta R)}{E_{\text{MC from-jet}}} + \frac{\alpha}{\beta} \frac{E_{\text{MC non-jet}}(\delta R < \Delta R)}{E_{\text{MC from-jet}}}
$$

(5)

The first and second ratios describe the fraction of measured energy of particles, respectively from the jet and outside the jet, that fall inside the cone $\Delta R$. As the superscripts suggest, the estimate of the energy in and out of the cone is extracted from Monte Carlo (MC) simulation, using $\gamma +\text{jet}$ events. In fact, this is the only of the main corrections that relies on MC.

The global parameters $\alpha$ and $\beta$ are simulation-to-data energy scale factors for the two categories of particles ($\beta$ factor cancels out in the first ratio), that are needed when applying these energy ratios on data. To evaluate the factors, energy profiles of data and MC are compared, and the factors are defined by the energy of particles within an annulus of given radius $R$ from the jet axis: $E(R) = \sum_{R \leq \delta R < R + 0.1} E_{\text{particles}}$. For each $E'$ and $\eta$ region, a profile is extracted from measured $\gamma +\text{jet}$ data events is extracted. Three profiles are also extracted from MC for the energy from the jet, the energy from outside the jet and the offset energy. The coefficients are then computed from best fit to the relation $E_{\text{data}} = \alpha E_{\text{from-jet}} + \beta E_{\text{non-jet}} + E_{\text{offset}}$, where the offset energy scale can be assumed consistent with data, up to $R \leq 2.0$.

The most relevant uncertainties for this correction are from the simulation of the gluon radiation, the statistical uncertainty on the energy profiles used to estimate $\alpha$ and $\beta$, and the purity of the $\gamma +\text{jet}$ sample in data.

### 4. Uncertainties

Beside the three main components of the JES correction, other minor corrections are also performed, with each of these relying on a variety of assumptions, with many sources of uncertainty identified. Most of these are very small. The largest uncertainty is from the largest correction, namely the energy response (Fig. 6). While most of these uncertainties can be reduced with additional data, the conditions and performances of the detector and the accelerator also change, so that it is more effective to split the correction into different running periods, which reduces the data available for each period.

### 5. Validation of the corrections

Many analyses strongly rely on the consistency of jet energy scale between data and simulation: in fact, we often measure quantities calibrated with simulation.

We verify the consistency of JES applied on data and simulation (Fig. 7) analysing $\gamma +\text{jet}$ events, integrated in the simulation with additional multijet events that reflect the contamination in the data.
Figure 6. Relative uncertainty on Jet Energy Scale correction, split into the three different main sources, for three measured jet energies ($E_T^{\text{meas}}$). These uncertainties are extracted from $\approx 1.3 \text{ fb}^{-1}$ DØ $\gamma+$jet data.

Figure 7. Validation of corrections: ratio between the corrected energy of jets in data and simulation, in two detector regions, as function of the jet energy $E'$. The difference is statistically consistent within the uncertainty band shown shaded.

6. Summary
At high energy hadron colliders, the Jet Energy Scale is of paramount importance for most analyses, since jets are very common objects in signals and omnipresent in backgrounds. A comprehensive derivation of the Jet Energy Scale corresponds to a separate major analysis, made very complex by the demand of precision of the other analyses that rely on it. There are many corrections that have been ignored in this brief report. The Jet Energy Scale is measured with a precision of the order of 2% in most regions of the calorimeter, with the best precision achieved in the central part of the detector, especially for low-to-medium jet energies, which are the most employed in most physics analyses. The main corrections are extracted directly from data, limiting the propagation of uncertainties from simulation to the measurement.

For this quality to be maintained, corrections must be updated periodically to reflect the changing operating conditions, and to include the newly collected data.

References
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