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# DETERMINATION OF THE ABSOLUTE JET ENERGY SCALE IN THE DØ CALORIMETERS

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The DØ detector is used to study $p\overline{p}$ collisions at the 1800 GeV and 630 GeV center of mass energies available at the Fermilab Tevatron. To measure jets, the detector uses a sampling calorimeter composed of uranium and liquid argon as the passive and active mediums respectively. The understanding of the jet energy calibration is not only critical for precision tests of QCD, but also in the measurement of particle masses and the determination of physics backgrounds associated with new phenomena. This paper describes the 1996-1997 re-evaluation of the jet energy calibration for the DØ detector, which resulted in a significant reduction of the systematic uncertainty.

## 1 Introduction

Jet production is the dominant process in $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV. Because almost every physics measurement at the Tevatron involves events with jets, an accurate energy calibration is essential. Currently, the jet energy scale is still the major source of systematic uncertainty in both the DØ inclusive jet cross section and top quark mass measurements. This paper describes the determination and verification of the jet energy calibration at DØ.

## 2 DØ Calorimeters

The DØ Uranium-Liquid Argon Sampling Calorimeters [1] are shown in Figure 1. They constitute the primary system used to identify $e$, $\gamma$, jets and missing transverse energy ($\not\!\!E_T$ ). $\not\!\!E_T$ is defined as the negative of the vector sum of the calorimeter cell transverse energies ($E_T$'s). The Central (CC) and End (EC) Calorimeters contain approximately 7 and 9 interaction lengths of material respectively, ensuring containment of nearly all particles except high $p_T$ muons and neutrinos. The intercryostat region (IC), between the CC and the EC calorimeters, is covered by an intercryostat detector (ICD) and massless gaps (MG) [1]. DØ defines a coordinate system with the origin in the

[a] representing the DØ Collaboration.

geometric center of the detector and the $z$ axis along the direction of the proton beam. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. Segmentation is $\Delta\phi \times \Delta\eta$ =0.1×0.1 in $\eta$-$\phi$ space.

Energy resolution was measured from test beam $e$ and $\pi$ data [2]. For electrons, the sampling term is 14.8 (15.7)% in the CC (EC), and the constant term 0.3% in both the CC and EC. For pions, the sampling term is 47.0 (44.6)%, and the constant term 4.5 (3.9)% in the CC (EC). The DØ calorimeters are nearly compensating, with an $\frac{e}{\pi}$ ratio less than 1.05 above 30 GeV [2,3]. Due to the hermeticity and linearity of the DØ calorimeters [2], the asymmetry variable $(E_{T1} - E_{T2})/(E_{T1} + E_{T2})$ for dijet events is well described by a gaussian function, as shown in Figure 1. These characteristics make the DØ calorimeter system well suited for jet and $\not\!\!E_T$ measurements. They are the basis of the *in-situ* calibration method described later.

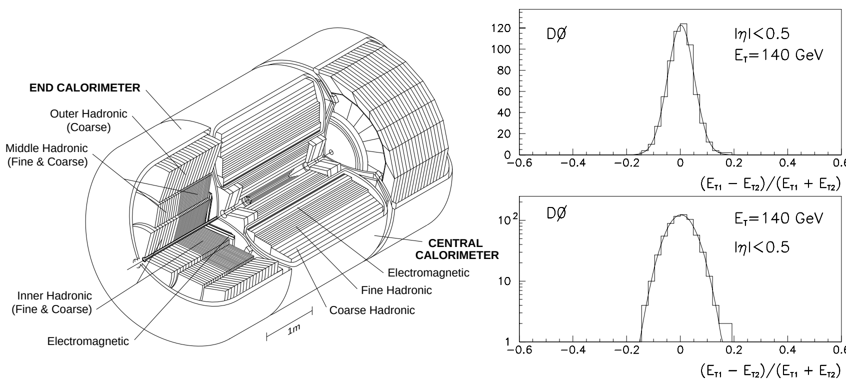


Figure 1: General view of the DØ calorimeters (left). Asymmetry distributions from dijet events observed with the DØ central calorimeter (right).

## 3 Jet Energy Scale

The *in-situ* calibration described in the following sections uses mostly reconstructed collider data and it is based on previous work [3]. The measured energy of a jet $E_{jet}^{meas}$ depends strongly on the jet definition. Here, a fixed cone algorithm is used to reconstruct jets from cell energy depositions in the calorimeter [4]. The *particle* level jet energy $E_{jet}^{ptcl}$ is defined as the energy of a jet found from final state particles using a similar algorithm to that used at the *calorimeter* level.

The jet energy scale corrects the measured jet energy, on average, back to the energy of the final state particle level jet. $E_{jet}^{ptcl}$ is determined as:

$$E_{jet}^{ptcl} = \frac{E_{jet}^{meas} - E_O}{R_{jet} \cdot S}.$$

- $E_O$ is an offset term, including both detector noise and energy from underlying event.
- $R_{jet}$ is the calorimeter energy response to jets, due to e/$\pi$ and energy lost in readout cracks [2].
- **S** is the fraction of the jet energy showered inside the algorithm cone in the calorimeter.

The calibration is performed for several jet cone sizes ($\mathcal{R}$ =1.0, 0.7, 0.5, 0.3), from data taken in $p\overline{p}$ collisions at $\sqrt{s}$ =1800 GeV and 630 GeV. Only representative plots are shown here, typically for central 0.7 cone jets. For detailed information see Ref. [5,6].

## 4 Offset Correction

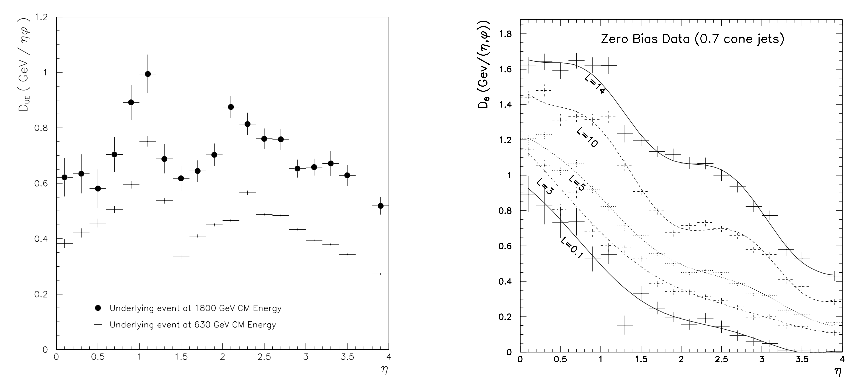


Figure 2: Physics underlying event density $D_{ue}$ versus $\eta$ for events with $\sqrt{s}$ = 1800 GeV and $\sqrt{s} = 630$ GeV (left). $D_\Theta$ versus $\eta$ for different luminosities in units of $10^{30}$ cm$^{-2}$sec$^{-1}$ (right).

The total offset correction is measured as a transverse energy density in $\eta$-$\phi$ space and factorized as $D_O = D_{ue} + D_\Theta$. The first term is the contribution of the underlying event, or energy associated with the spectator partons in a high $p_T$ event. The second term accounts for uranium noise, pile-up and energy from additional $p\overline{p}$ interactions. Pile-up is the residual energy from previous $p\overline{p}$ crossings as a result of the long shaping times associated with the preamplification stage in calorimeter readout cells.

$D_{ue}$ is measured as the average transverse energy density in minimum bias events (a hard interaction has occurred). $D_{\Theta}$ is determined from a zero bias sample ( a crossing has occurred). The $\eta$ dependence of both quantities and the luminosity dependence of $D_{\Theta}$ is shown in Figure 2. The statistical and systematic error of the offset correction is 8% and 0.25 GeV respectively.

## 5 Response Correction

DØ makes a direct measurement of the jet energy response using conservation of $p_T$ in photon-jet ($\gamma$-jet) events [3]. Previously, the photon energy scale is determined from the DØ $Z \rightarrow e^+e^-$, $J/\psi$ and $\pi^\circ$ data samples, using the masses of these known resonances [2]. In the case of a $\gamma$-jet two body process, the jet response can be measured as:

$$R_{jet} = 1 + \frac{\not{E}_T \cdot \hat{n}_{T\gamma}}{E_{T\gamma}} \,,$$

where $E_{T\gamma}$ and $\hat{n}$ are the transverse energy and direction of the photon. To avoid response and trigger biases, $R_{jet}$ is binned in terms of $E' = E^{meas}_{T\gamma} \cdot \cosh(\eta_{jet})$ and then mapped onto $E^{meas}_{jet}$. $E'$ depends only on photon variables and jet pseudorapidity, which are quantities measured with very good resolution.

### *5.1 $\eta$ dependent Corrections*

Most of the physics measurements need a high level of accuracy in the jet energy scale at all rapidities. An $\eta$ dependent correction becomes necessary to make the calorimeters uniform.

The cryostat factor $F_{cry}$ is defined as the ratio $R^{EC}_{jet}/R^{CC}_{jet}$. The measured factor $0.977 \pm 0.005$ is a constant function of $E'$. This was expected because the CC and the EC calorimeters are based upon the same technology.

The intercryostat region, which covers the pseudorapidity range $0.8< |\eta| <1.6$, is the most poorly instrumented region of the calorimeter system. A substantial amount of energy is lost in the cryostat walls, module endplates and support structures. This IC correction is performed after the $F^{cry}$ correction and before the energy dependent response correction. Because the energy dependence of $R_{jet}$ is folded into $R_{jet}$ versus $\eta$, this function is not a constant; but it must be smooth for a uniform calorimeter. The IC correction is obtained by means of a smooth interpolation through the IC of a fit $R_{jet} = a + b \cdot \ln[\cosh(\eta)]$ to the measured $R_{jet}$ versus $\eta$ in the CC and the EC, as shown in Figure 3.

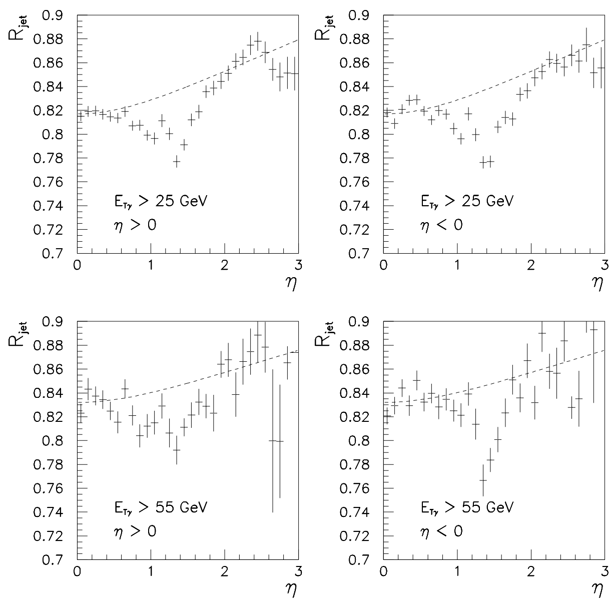


Figure 3: Response versus $\eta$ for $\gamma$-jet data. The dashed line is the fit to the expected IC correction.

### *5.2 Energy Dependent Correction*

The offset and $\eta$ dependent corrections are applied to the jet energy and $\not{E}_T$ to remove the energy not associated with the parton scattering and make the calorimeters uniform in pseudorapidity (see Figure 4). The energy dependence of $R_{jet}$ is then determined as described in Sec. 5.

Uniformity allows to use data from both the CC and the EC to measure $R_{jet}$ versus jet energy. The rapidly falling photon cross section limit the use of CC data to energies $\lesssim$120 GeV. EC data is used to extend the energy reach to $\sim$300 GeV, exploiting the fact that jet energy is larger than in the CC for the same $E_T$. Monte Carlo information is also included at high energy to constrain the jet response extrapolated from the available data. A set of $\gamma$-jet events is generated using HERWIG[7], processed through the DØGEANT[8] detector simulation and reconstructed with the standard photon and jet algorithms.

The Monte Carlo simulation is improved by incorporating the single particle response of the calorimeter as measured in the DØ test beam [2].

The response versus energy for the 0.7 cone algorithm is shown in Figure 4. The data is fit with the functional form $R_{jet}(E) = a + b \cdot \ln(E) + c \cdot \ln(E)^2$. This function is motivated by the hadronic shower becoming increasingly, but slowly, more "electromagnetic" with increasing energy [9]. If $e$ and $h$ are the responses of the calorimeter to the EM and non-EM components of a hadron shower, and $\pi$ is the response to charged pions, then $e/\pi = 1/[\frac{h}{e} - \langle f_{em}\rangle(\frac{h}{e} - 1)]$. The functional form for $\langle F_{em}\rangle$ is $\sim \alpha \cdot \ln(E)$, giving the expected logarithmic dependence for charged pions and, therefore, jets.

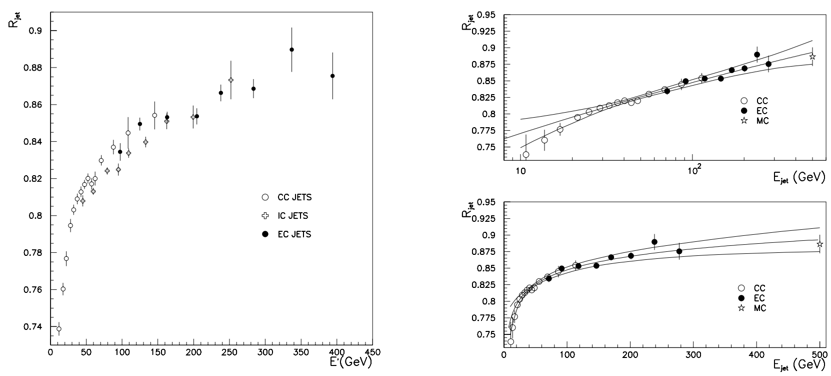


Figure 4: $R_{jet}$ versus $E'$ measured in the CC, IC and EC calorimeter regions after $\eta$ dependent corrections (left). $R_{jet}$ versus energy for the 0.7 cone jet algorithm. The solid lines are the fit and the associated error band (right).

### *5.3 Systematic Errors en $R_{jet}$*

In addition to the error of the fit, 1.5-0.5-1.6% for 20-100-450 GeV jets, there is also a ~0.5% error from the $W$ background in the photon sample. Most of the events in the $\gamma$-jet sample are not two body processes. This topology bias in the $R_{jet}$ measurement is compensated by another bias due to contamination from highly electromagnetic jets faking photons. In the IC region, the $\eta$ dependent corrections contribute an additional ~1% error, which is larger above $\eta$ =2.5.

### *5.4 Showering Correction*

As the collimated beam of particles strikes the detector, it interacts with the calorimeter material producing a wide shower of more particles. Some particles produced inside the cone deposit a fraction of their energy outside the cone as the shower develops inside the calorimeter, and vice versa.

The correction is determined using jet energy density profiles from data and particle level HERWIG[7] Monte Carlo. The data contains the contributions of both gluon radiation and showering effects outside the cone. The former contribution is subtracted using the particle level Monte Carlo profiles. $S$ is defined as the inverse of the measured correction factor; that means $S$ is the fraction of the jet energy showered inside the algorithm cone in the calorimeter.

The showering correction is negligible for 0.7 cone jets above $\sim$100 GeV and the error is $\sim$1%. Both the correction and uncertainty increase for lower energies, higher $\eta$ and smaller cone sizes.

## 6 Summary and Verification Studies

Figure 5 shows the magnitude of the correction and uncertainty for 0.7 cone jets with $\eta$ =0. Point-to-point correlations in energy are very high between 200 GeV and 450 GeV jets.

The accuracy of the jet energy scale correction is verified using a HERWIG $\gamma$-jet sample and the DØGEANT detector simulation. A Monte Carlo jet energy scale is derived and the corrected jet energy compared directly to the energy of the associated particle jet. Figure 5 shows the ratio of calorimeter and particle jet energy before (open circles) and after (full circles) the jet scale correction, in the CC. Within errors, the ratio versus $E_{jet}^{ptcl}$ is consistent with unity to within $\sim$0.5%.

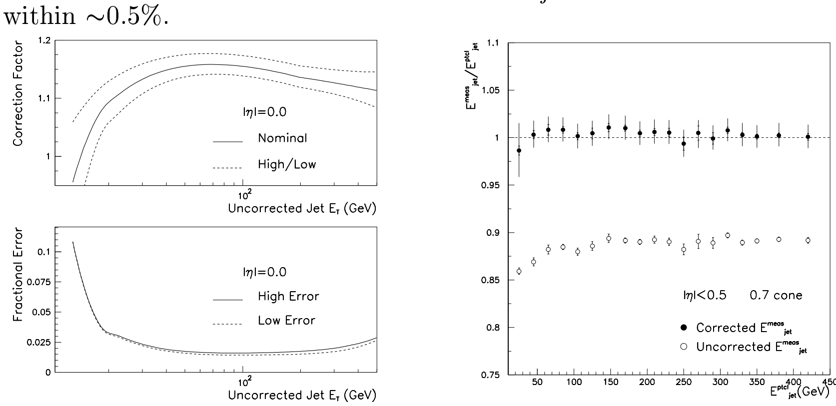


Figure 5: Corrections and Errors for $\eta_{jet}$ =0.0, $\mathcal{R}$ =0.7 (left). Monte Carlo verification test (right). Corrected $E_{jet}^{meas}/E_{jet}^{ptcl}$ ratio is consistent with 1.0 within errors.

## 7 conclusions

The DØ jet energy scale correction was re-evaluated during 1996-1997. The calibration is primarily based on data taken by the DØ detector during the 1992-1996 collider run at the Fermilab Tevatron. Jets in the DØ detector were calibrated to compensate for spectator interactions, uranium noise, response and showering loss. The method is verified with a Monte Carlo simulation which shows that jet energy is corrected to the particle level to within the quoted errors. The overall correction factor to jet energy in the central calorimeter is $1.160 \pm 0.018$ and $1.120 \pm 0.025$ at 70 and 400 GeV, respectively. The errors were reduced by up to 50% with respect to previously published numbers[3].


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