Jet Energy Scale Determination at the DØ

Jiří Kvita

Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic

Abstract. Many physics measurements at a hadron collider critically depend on an accurate knowledge of the energy of jets resulting from the fragmentation of quarks and gluons generated in the hard scatter. The precise determination of the jet energy scale is a challenging project, involving corrections for physics, instrumental and jet algorithm-related effects. We present the most recent determination of the jet energy scale at the DZero experiment during Run II of the Tevatron proton-antiproton collider. We review the procedure followed, the estimated systematic uncertainties, as well as the validation studies performed. The experience gained by the Tevatron experiments in achieving percent-level determination of the jet energy scale should be of great value for the LHC.

Keywords: Jets, energy calibration, Dzero experiment.
PACS: 07.20.Fw, 13.87.-a

INTRODUCTION

With the 1fb^{-1} Run IIa dataset delivered by the Tevatron accelerator, we can explore a wealth of unique data with the DØ detector. As most physics analyses use jets as final hadron states, precision jet energy calibration is an essential input to already systematics limited measurements. The increased luminosity yields high statistics and potential to reach high accuracy. Here we present the preliminary JES determination on 150 pb^{-1}, the full ≈ 1 fb^{-1} in progress. DØ has performed a full Calorimeter Calibration (ϕ-intercalibration as well as absolute calibration) and new and more advanced JES procedure and tools have been developed.

The DØ Detector

The DØ detector is in detail described in following Run I [1] and Run II [2] references. Here we shall mention only the essential parts. The main subdetectors relevant for the Jet Energy Scale determination are DØ Calorimeters (see Figure 1). These are Central and two End Cap Uranium-Liquid Argon Calorimeters providing uniform hermetic coverage up to $|\eta| \leq 4.2$ ($\eta \equiv -\ln\tan(\theta/2)$) and with fine segmentation up to $|\eta| < 3.2$: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. With the DØ Calorimeter at the Tevatron Run II, we are challenged by the shorter bunch crossing (396 ns) and shorter charge integration time.

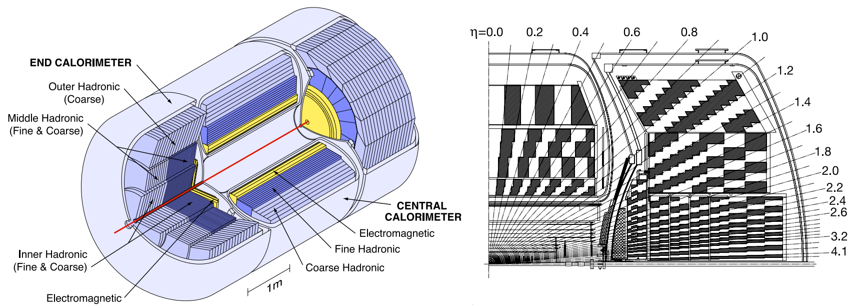

FIGURE 1. DØ Calorimeters in perspective and beam-parallel plane views.

Jet Algorithms

The same Run II cone jet algorithm is applied at three different levels on corresponding objects: at the parton level, Monte Carlo stable particles level and the detector level, where calorimeter clusters are used as seeds. The algorithm combines 4-vectors within a cone of radius R_{cone} (0.5 or 0.7) in $y \times \phi$ space. The jet axis is calculated and the procedure is iterated until a stable solution is found. The algorithm uses midpoints between jets to improve the infrared safety. At the end, identical solutions are removed and overlapping jets properly treated.

JET ENERGY SCALE DETERMINATION

The aim of the Jet Energy Scale (JES) procedure is to calibrate calorimeter jet energies to the particle level jets. There are various physics, instrumental and jet algorithm effects to be corrected for. As the agreement between simulation and Data is not precise enough to use only Monte Carlo samples, we need to employ in-situ calibration and derive JES separately for Data and Monte Carlo.

The basic idea is to assume calibrated EM calorimeter (using Z events) and use events with a well-measured EM object balanced by jet to determine the jet response.

The JES determination procedure involves the measurement of several subtle corrections, for each we also perform systematics cross checks and detailed error analysis. As a last point, we perform Closure tests where we compare the JES performance in Data and Monte Carlo to particle level jets. We calibrate separately Run II Algorithm Jets of Cone 0.5 and 0.7. The master JES formula is the following decomposition

$$E_{\text{new}} \equiv \frac{E_{\text{raw}} - \mathscr{O}}{\mathscr{F}_\eta \cdot \mathscr{R} \cdot \mathscr{S}},$$

where $\mathscr{O}$, $\mathscr{F}_\eta$, $\mathscr{R}$ and $\mathscr{S}$ stand for energy Offset, η-dependent correction, jet Response and Showering correction respectively.

In more detail, the corrections are derived sequentially, so the decomposition actually reads

$$E_{\text{new}} \equiv \frac{E_{\text{raw}} - \mathscr{O}(R_{\text{cone}}; \eta, \mathscr{L}, n_{\text{PV}})}{\mathscr{F}_\eta \cdot \mathscr{R}\left(R_{\text{cone}}; \frac{E_{\text{raw}} - \mathscr{O}}{\mathscr{F}_\eta}\right) \cdot \mathscr{S}\left(R_{\text{cone}}; E_{\text{raw}}\right)}.$$

First the energy Offset is measured as a function of η, inst. luminosity and number of Primary Vertices (multiple interactions dependence). Then the η-dependent correction is derived in several energy bins. Such η+Offset corrected energy serves as in input to Response measurement. As the last step, the Showering correction is derived.

The main data and Monte Carlo samples are γ+jets, dijet events and Z+jets.

Energy Offset

Offset ($\mathscr{O}$) is the energy not associated with the hard scatter process and can be decomposed as

$$\mathscr{O} = \text{Underlying Event} + \text{Noise} + \text{Multiple Interactions} + \text{Signal Pile-up}.$$

In essence, we measure the energy density profile in detector projective towers, for which we use Minimum Bias events (luminosity monitor trigger) and bin Offset in number of primary vertices. Then, for each jet, the Offset energy is computed using the density for towers contained within the cone. The Offset energy in Central Calorimeter is typically 1 GeV $\times$ n_{PV}.

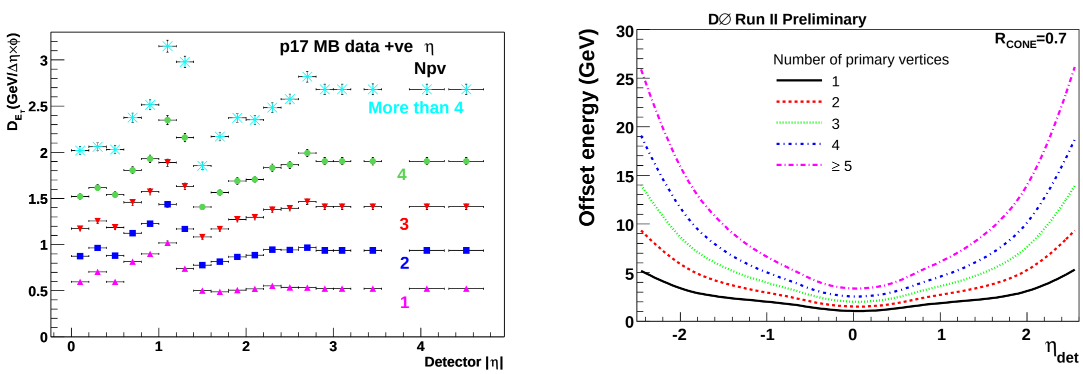

FIGURE 2. Energy density (left) and Offset energy for 0.7 Cone jets as functions of number of primary interactions vertices.

The MPF Method

The Missing E_{T} ($\not{E}_{\mathrm{T}}$) projection fraction method (MPF, see Figure 3) for the Response measurement uses back-to-back γ+jets events. Assuming a calibrated EM calorimeter ($Z \to e^+e^-$), we measure only the photon and missing transverse energy, so the method is jet algorithm independent. From the assumed p_{T} balance one can derive the MPF Response as

$$R_{\mathrm{MPF}} \equiv 1 + \frac{\not{E}_{\mathrm{T}} \cdot \vec{p}_{\mathrm{T}}^{\,\mathrm{EM}}}{(p_{\mathrm{T}}^{\mathrm{EM}})^2}.$$

Assuming back-to-back Tag object and the leading jet, the MPF response is expected to be the Jet Response. The same method is used for dijet events to derive the η correction.

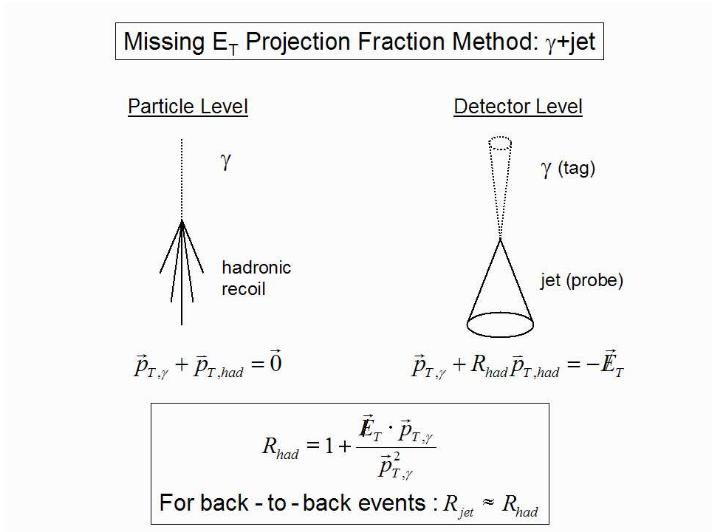

FIGURE 3. Illustration of the MPF method.

η-dependent Corrections

The purpose of the η correction is to make detector response uniform in η, which is especially important in the Inter Cryostat Region between Central and End Cap Calorimeters. We need to separate different instrumentation effects found over large η range. We measure jet Response relatively to Central Calorimeter Response using a Tag central object (jet or γ) and Probe jet anywhere.

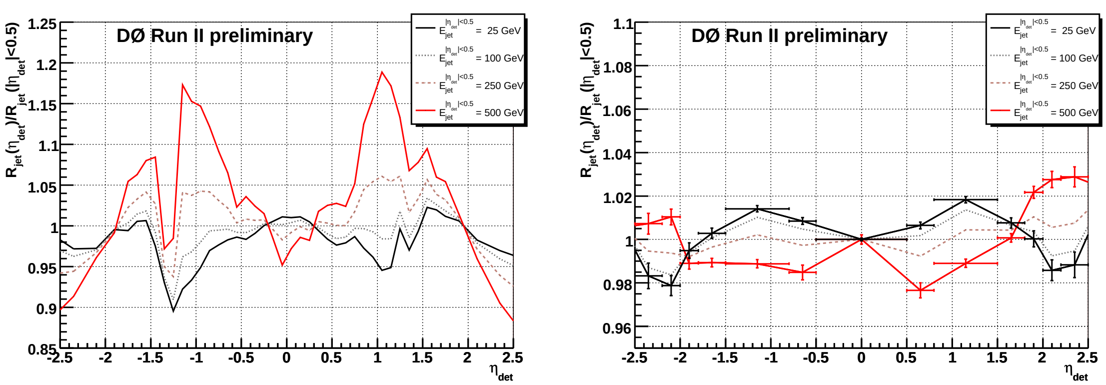

FIGURE 4. η-correction (left) and residuals in closure tests.

Response

As mentioned above, the Response measurement uses the MPF method. This particular correction is the largest correction (about 30%). An energy estimator combining well-measured photon energy and jet η is used to bin Response in terms of:

$$E' \equiv p_T^\gamma \cosh \eta_{\rm jet} \,.$$

Measuring simultaneously Response and corrected jet energy as function of E', we finally remap $\mathscr{R}(E')$ to $\mathscr{R}(E_{\rm jet})$. As can be seen in Figure 5, all η regions are on the same curve indicating the η correction work as desired.

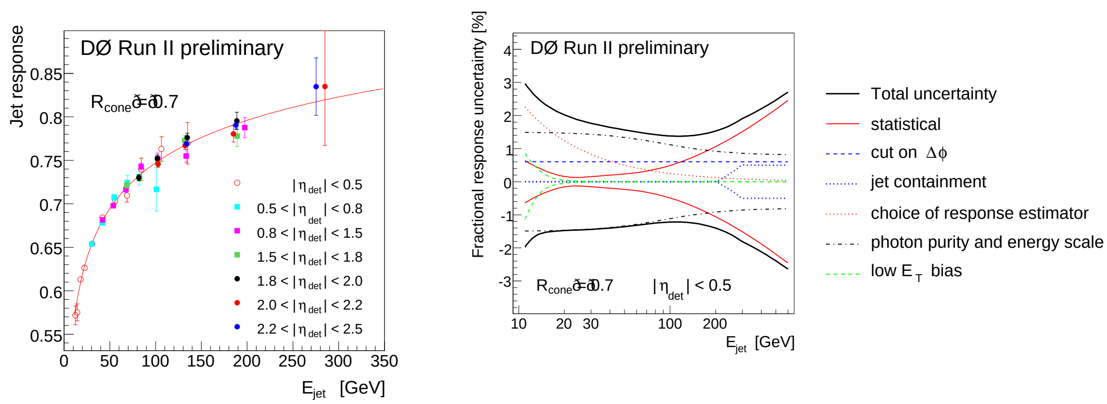

FIGURE 5. Response (left) as a function of (response corrected) energy in various calorimeter regions, and Response systematical error for Central Calorimeter jets (right).

Due to the preliminary dataset used in the report, large uncertainties appear at high energies. Another source of systematical error is the photon purity, since almost half of low p_T photons are actually background (jet faking an electromagnetic object), their energy undercorrected. It turns out that there is also an opposite effects, as we simultaneously overcorrect γ scale using the electron scale. Both effects partially cancel, while in the future we will specifically correct for both. Another error source are non-Gaussian tails in Response, especially in the ICR region and in Data.

Showering

The purpose of the Showering correction is to determine and correct for the fraction of jet energy inside the cone due to detector showering, being a result of multiple scattering, bending in the magnetic field etc.

Measuring the effect at detector level we observe effects of both detector+physics showering. Performing the same algorithm on MC particle jets we are sensitive only to physics showering effects. Thus, the ratio of these factors is the desired detector effect only.

In essence, we measure the energy density profile as a function of the distance from the jet center, subtract the fitted baseline due to Offset energy and determine the energy fraction inside and outside of the jet cone.

We have to treat properly not only particles leaking outside the jet, which would nominally be part of it, but also particles leaking inside the jet. Showering is a 1-2% correction, but a large uncentainty of the order of the correction itself is assigned due to the method.

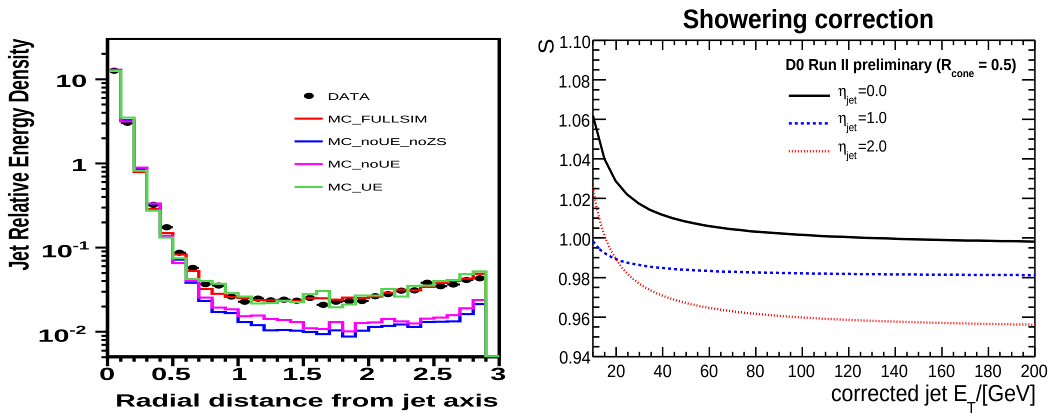

FIGURE 6. Jet profile, i.e. the energy density as a function of distance to jet center (left) and 0.5 Cone Showering correction itself (right).

JES Uncertainties

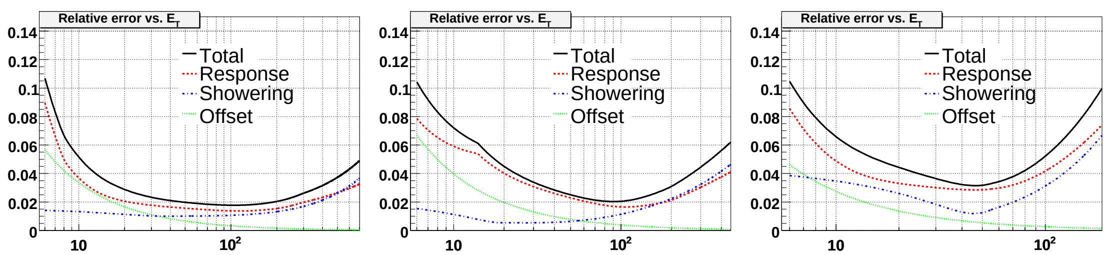

FIGURE 7. Fractional jet energy scale uncertainty for $R_{\text{cone}} = 0.7$ jets in data at $\eta = 0., 1., 2.$, as a function of uncorrected jet transverse energy.

Leading JES systematics is the Response. Offset uncertainties contribute mainly at low energies. η-dependent correction systematics comes from observed residuals after repeating the flattening procedure, being about 2% in the Inter Cryostat Region. Showering becomes important in forward region, i.e. at high energies, the uncertainty coming from statistics and instrumentation effects (detector edge), but mainly the method itself, which is now being significantly improved.

Closure Tests

It is important to test all corrections performance together, on broader range of samples and different event topologies. The goal is to validate JES within quoted uncertainties while we need to disentangle many effects from the possible JES failure itself. For many physics analyses, the relative Data-MC scale is most important, so it is useful to subtract Data and Monte Carlo, expecting points around 0.

The Hemisphere Method

In the so-called Hemisphere imbalance method (see Figure 8), we use a Tag object (EM-like: γ/Z, or a jet) and the highest p_T jet as our JES Probe, but we in fact combine information from all jets in the event. We project p_T's of all objects onto the Tag axis in the $x-y$ and compute separate scalar sums of projections lying in the EM Tag and Jet Probe hemispheres. We then define the Hemisphere imbalance as

$$\mathscr{H} \equiv \frac{\sum\limits_{\text{Probe hemi}} |\vec{p}_T \cdot \vec{n}_{EM}|}{\sum\limits_{\text{Tag hemi}} |\vec{p}_T \cdot \vec{n}_{EM}|} \approx 1.$$

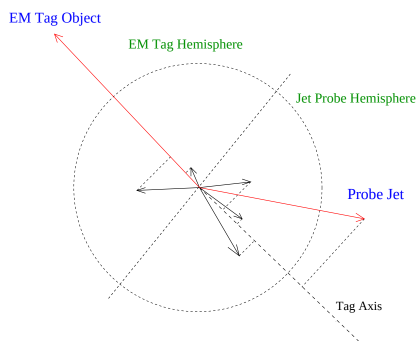

FIGURE 8. Hemisphere method illustration.

There are in fact many reasons why Hemi is not expected to be around 1. due to resolution, selection, kinematics and other biases. Therefore, we subtract Data and Simulation points, expecting to observe (in the case of the same biases present at both levels) points centered around zero.

Resulting Closure plots (see Figure 9) prove we correct jet energies in Data and Monte Carlo consistently to the same level and that all biases are present at both levels withing quoted uncertainties.

SUMMARY

Detailed understanding of JES at DØ has been achieved at the 2% level in Central Calorimeter at jet p_T in the 30-200 GeV range. This has only been possible due to the precision calorimeter calibration and new techniques to extract separate corrections and cross check their performance. There are ongoing efforts to further improvements in the areas of b-jets energy scale and semileptonic correction to correct semi-muonic b decays, as well as in improving standard corections themselves. Many algorithms of this in-situ JES technique can be of great importance for LHC experimets.

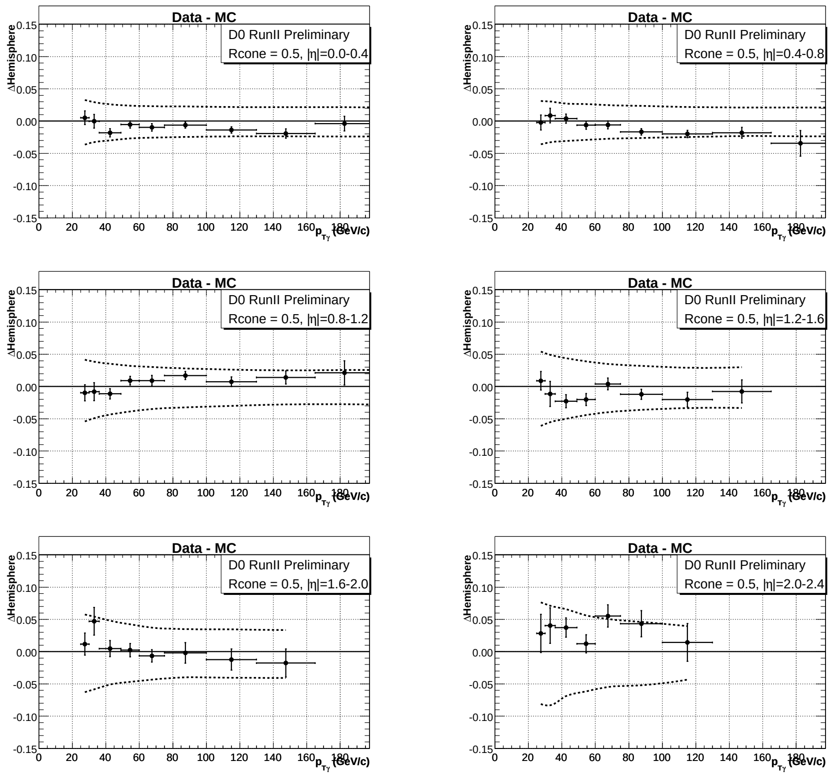

FIGURE 9. Hemisphere Method Closure, Data-MC, Cone 0.5

ACKNOWLEDGMENTS

This report is a result of long term efforts within the Jet energy Scale Group at the DØ experiment and would not be possible without the support of the whole DØ collaboration. The author would also like to thank the INGO grant 1P05LA257 of Ministry of Education of the Czech Republic, as well as the kind CALOR06 support of students.

REFERENCES

1. S. Abachi *et al.* [D0 Collaboration], "The D0 Detector," Nucl. Instrum. Meth. A **338**, 185 (1994).
2. V. M. Abazov *et al.* [D0 Collaboration], "The upgraded D0 detector," arXiv:physics/0507191, FERMILAB-PUB-05-341-E.
3. B. Abbott *et. al.* [D0 Collaboration], "Determination of the Absolute Jet Energy Scale in the DZERO Calorimeters", NUCL.INSTRUM.METH.A, **424**, 352 (1999).