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Performance and calibration of the DØ uranium liquid-argon calorimeter * †

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The performance of the DØ uranium liquid-argon calorimeter is discussed, as well as the electromagnetic energy calibration. Results from test beam studies and collider data are incorporated to estimate the energy scale. The phi symmetry of the events is used to improve the understanding of the electromagnetic part of the calorimeter, and the EM energy scale is determined from $Z \rightarrow e^+e^-$ events. The calorimeter's response to other resonances is also investigated.

The DØ detector is a general purpose, 4π detector with no central magnetic field, located at the FNAL Tevatron collider and is described in detail elsewhere.[1] It was designed for studying the properties of electrons, jets, muons, and missing transverse energies. As such, the calorimeter is an important part of this detector. Its performance is discussed below. In particular, the energy measured by the calorimeter is important. The overall calibration can be obtained in many ways. One method of doing this is to use actual collider data to set the scale. This is done, for the electromagnetic scale, using $Z \rightarrow e^+e^-$ events and checked by looking at $J/\psi \rightarrow e^+e^-$ and $\pi^0 \rightarrow \gamma\gamma$ decays. The results are discussed below.

1. The Calorimeter

The DØ calorimeter is a uranium liquid-argon sampling calorimeter. The calorimeter is hermetic with coverage down to η of approximately 4, where η is the pseudo-rapidity variable, $\eta \equiv -\ln(\tan\frac{\theta}{2})$ and θ is the polar angle. There are actually three separate calorimeters located in three independent cryostats. Surrounding the barrel region is located the central calorimeter

with $|\eta| < 1.2$. The end calorimeters are located on either end of the central calorimeter.

The electromagnetic calorimeter consists of 3 mm or 4 mm uranium absorber plates for the central and end regions, respectively. Interleaved between the uranium plates are signal boards, and on either side of these boards is located a 2.3 mm gap for the liquid argon. Contained inside these boards are the copper readout pads, the size of which are nominally 0.1 units in η by 0.1 radians in ϕ (azimuth). For $|\eta| > 3.2$, near the beam pipe, the pad size increases to approximately 0.2 by 0.2. Besides the transverse segmentation, there is also segmentation in the radial direction. First, radially, there is an electromagnetic calorimeter section followed by an outer hadronic section. The electromagnetic section consists of four layers of 2, 2, 7, and 10 radiation lengths thick in the central region and 1, 3, 8, and 9 radiation lengths thick in the end regions. The third electromagnetic layer, where most of the energy of an electromagnetic shower occurs, has a finer segmentation in $\Delta\eta \times \Delta\phi$ of 0.05×0.05 . In the central portion of the electromagnetic calorimeter, the above structure is contained in 32 modules forming a ring around the beam pipe at a radius of approximately 84 cm. The first layer of the electromagnetic part of the end calorimeter is located 170 cm, in z , from the center of the detector; the uranium plates are

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orientated vertically.

The hadronic calorimeter has a structure very similar to the electromagnetic calorimeter. The uranium plates are 6 mm thick. The eta-phi segmentation is the same as for the electromagnetic section. The longitudinal readout segmentation is 1.4, 1.0, and 0.8 interaction lengths thick in the central region and 1.3, 1.2, 1.2, and 1.2 in the end regions. The central region consists of 16 separate modules forming a ring 100 cm from the beam pipe. Behind the uranium portion of the hadronic calorimeter is located the leakage or coarse section of the hadronic calorimeter. This consists of one or three layers, 3.0 interaction lengths thick, of copper in the central region and stainless steel in the end regions. These plates are 46.5 mm thick.

2. Performance

The DØ detector has been in operation for over two years; thus, its performance can now be evaluated. The stability of the electronics is very good. As can be seen from Figure 1, the pedestals and gains are very stable. The means of the pedestals vary by less than 0.1 ADC count/year, which is less than 1 MeV/year. While, the means of the gains vary by less than 0.2%/year. The reliability of the electronics for the DØ calorimeter has also been very good. Other than from initial installation problems, where 37 channels were damaged, there are typically less than 10 in-operative channels at any given time. This corresponds to approximately 0.1% of the total 47800 channels.

Another important factor in the performance of the calorimeter is the purity of the liquid argon. If the argon becomes contaminated then the amount of charge collected for each cell is reduced. This can happen if electro-negative contaminants, i.e. oxygen or nitrogen, present in the argon combine with the electrons traversing the gap. Thus the measured energy is very dependent upon knowing the change in any contamination level.

The DØ calorimeter has three test cells in each of the three cryostats.[2] Each test cell independently measures the response of the liquid. Each

Calorimeter Electronics Stability (all channels)

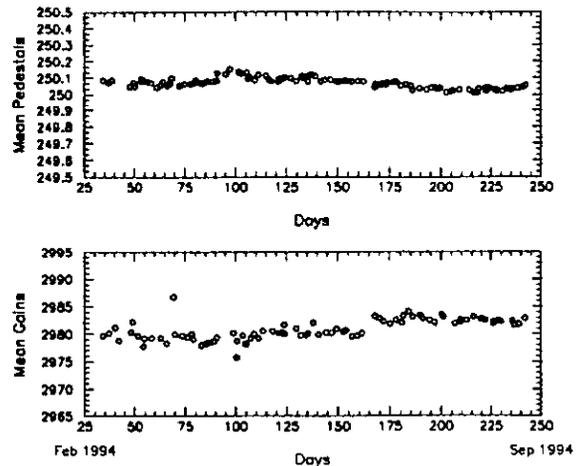


Figure 1. Pedestal and Gains stability over an 8 month period.

test cell consist of two radioactive sources, one α and one β , along with high voltage and ground planes separated by a 2.3 mm gap. The results from the alpha cells show that the response has been constant in time to within approximately 0.5% over the last year, for all three cryostats. The beta cells also show that the contamination level is not changing. The response from the beta cells have been constant to within 1% during the last year. There is no measurable degradation in the signal due to contamination of the argon.

3. Calibrating the Calorimeter

In a liquid-argon calorimeter, the energy response from high energy particles is dependent upon the sampling fraction of the detector, the purity and temperature of the argon, and the response of the electronics. The sampling fraction (SF) is defined as the fraction of energy deposited by dE/dx in the active medium (liquid argon) to the amount of energy deposited in the

entire calorimeter for minimum ionizing particles:

$$SF = \frac{dE/dx * \Delta x_{active}}{dE/dx * \Delta x_{active} + dE/dx * \Delta x_{absorber}}$$

This number can be studied in a test beam, where the initial energies of the particles are known. The energy of the electron, which is deposited in the calorimeter, is determined by summing the response from the four electromagnetic sections and the first hadronic section. $E_{tot} = \alpha \sum_{i=1}^5 \beta_i E_i + \delta$, where E_i is the response of the i^{th} layer in ADC counts, α is an overall scale factor in MeV/count, β_i is the weight for each layer, normalized to the third EM layer, and δ is an offset due partially to energy lost before the calorimeter. These weights, β_i , are inversely proportional to the sampling fractions. It is possible to improve these weighting factors by extracting them from the data. This is done with a χ^2 fit by minimizing the deviation of the reconstructed energy from the measured momentum. This was done independently for the central and end calorimeters.[3]

Applying these sampling fractions to test-beam data of various energy electron beams, the energy resolution and the linearity of the calorimeter response can be determined. The calorimeter response is determined from the mean of a Gaussian fit. The energy resolution[3] is found to have a sampling term of $13\%/\sqrt{E(GeV)}$ and $16\%/\sqrt{E(GeV)}$ for the central and end regions, respectively. The deviations from linearity[3] are less than 1% from 10 to 150 GeV. The largest relative deviations occur for the energy region below 10 GeV.

After determining some of the basic characteristics of a few modules in the test beam and before applying this information to the entire DØ calorimeter, it must be shown whether all modules in the calorimeter are similar in their response. In the central calorimeter, there are 32 separate electromagnetic modules in ϕ . Since the p and \bar{p} beams are not polarized, the particle distribution should be independent of ϕ . Any observed ϕ dependence should be only instrumental and can thus be corrected. By looking at the ϕ distribution of electromagnetic objects found during collider running, one can determine cali-

bration constants for all the modules.[4]

From ϕ symmetry, the number of particles with energy greater than threshold for each ϕ region is constant. Equating the number of electromagnetic clusters in each ϕ region (or module), determines a calibration constant for each region. After making fiducial cuts, to be away from the edges of modules, the results from the central region are shown in Figure 2. In the central region, the calorimeter is uniform in ϕ with an r.m.s. spread of 1.4%. In the end regions, the uniformity is estimated from test beam studies to be approximately 0.5%. Once the constants have been determined, these corrections can be applied to the data.

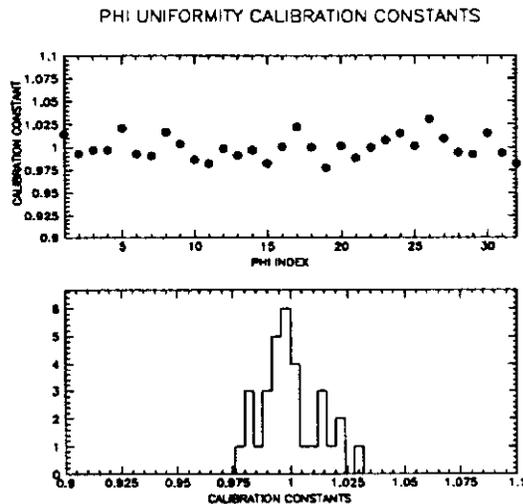


Figure 2. ϕ uniformity distribution of the central calorimeter modules.

4. Electromagnetic Energy Scale

To determine the absolute energy scale for the DØ calorimeter, one can use the known mass of the Z[5], and then scale the DØ measured Z mass as described below. This assumption of a scale factor can be checked by looking at lower mass

resonances, i.e., π^0 and J/ψ , and even by looking at the Z , itself. The energy of the electrons from the Z can be used to determine the scale factor and the offset. This is done, since assuming

$$E_{true} = \alpha E_{meas} + \delta,$$

$$\text{then } M_{true} = \alpha M_{meas} + f\delta, \quad (1)$$

$$\text{where } f = [(E_1 + E_2)/\sqrt{2E_1E_2}]\sqrt{1 - \cos\theta}.$$

θ is the opening angle between the two electrons, and E_1 and E_2 are the measured energies of the two electrons. Note that f is solely determined from the kinematics of the decay.

The dielectron invariant mass spectrum near the Z mass is shown in Figure 3, for electrons only in the central calorimeter region. The fitted Z mass is given in Table 1, where the absolute energy scale is determined solely from test beam measurements. The scale factors for all three $D\phi$ calorimeters are shown in Table 2. The errors are statistical only. By fitting the measured Z mass as a function of f , from Equation 1, one can determine α and δ . [6] The results are shown in Table 1.

Table 1
Fitted Parameters from the central calorimeter only.

	mass(GeV/c ²)	α	δ (MeV)
Z	87.11 ± 0.18	1.050 ± 0.015	-320 ± 780
π^0	0.135 ± 0.010	1.051 ± 0.008	-245 ± 314
J/ψ	3.032 ± 0.193	1.049 ± 0.009	-140 ± 410

Two lower energy resonances have also been studied for the central calorimeter. The diphoton invariant mass spectrum in the π^0 [7] region is shown in Figure 4, while the dielectron invariant mass spectrum for the J/ψ [8] region is shown in Figure 5. For the π^0 spectrum, only events are selected where both photons convert before the central tracking chambers. Then at least one electron or positron from the conversion of each photon must be found in the inner tracking chambers.

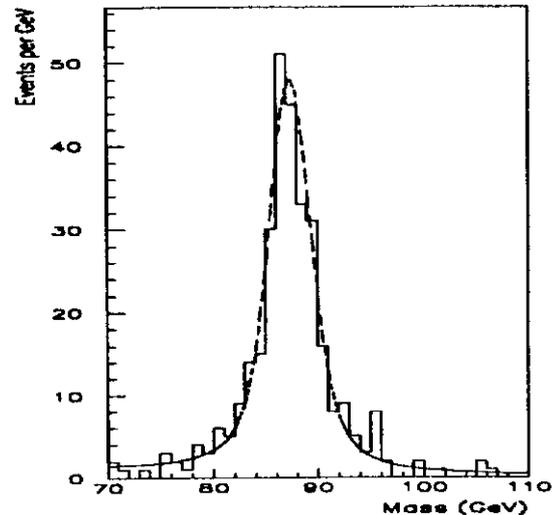


Figure 3. Dielectron invariant mass distribution in the Z mass region.

The two photons overlap in the central calorimeter and thus are assumed to have the equal energies; therefore, a symmetric mass was formed, $M_{sym} = \sqrt{E_{\pi^0}^2(1 - \cos\theta)}/2$. The background was determined from data, using electron candidates which fail cuts related to the e^+e^- conversions. The fitted π^0 mass is shown in Table 1.

Table 2
Scale Factors for the Three Cryostats.

central	north end	south end
1.046 ± 0.002	1.035 ± 0.011	1.005 ± 0.011

Using both the measured π^0 and Z masses, along with the measured distribution for f , Equation 1 yields a value for the energy scale factor and offset as seen in Table 1. Similarly, the scale factor and offset can be determined from the measured mass of the J/ψ instead of the π^0 . This result is also shown in Table 1.

The scale factors determined from the Z , π^0 , and J/ψ resonances are all consistent with each

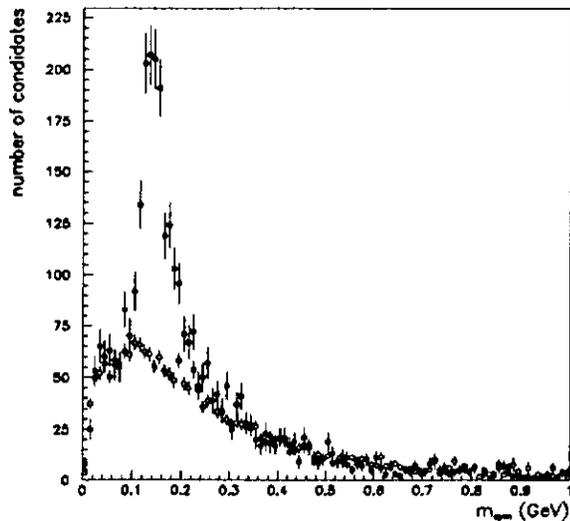


Figure 4. Diphoton invariant mass distribution in the π^0 mass region (Preliminary).

other. The offset is consistent for the three methods and is also consistent with zero.

5. Conclusions

The DØ calorimeter has performed very well during the first two years of operation. The electronics have been very stable in time, with little variation of the pedestals or the gains. There is no evidence that the purity of the liquid argon has changed at all since it was first introduced over two years ago. The electromagnetic energy scale is understood and can be determined *in situ* using the many e^+e^- or $\gamma\gamma$ resonances that exist. This study will continue, and with more data the errors will decrease, thereby giving a better calibration of the DØ calorimeter.

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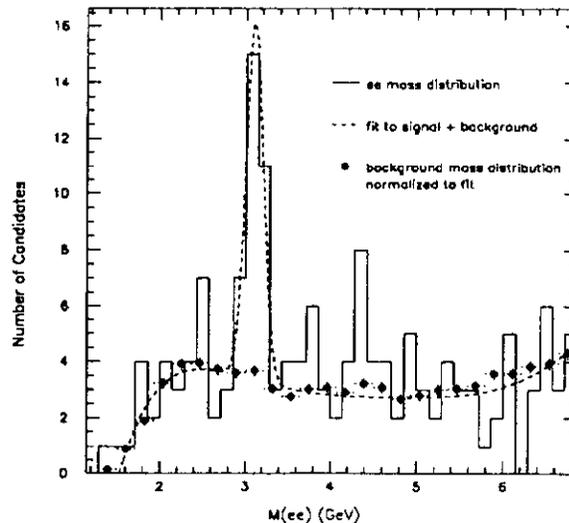


Figure 5. Dielectron invariant mass distribution in the J/ψ mass region (Preliminary).

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