Jet Response via $E_T^{\text{miss}}$ Projection

Robert Kehoe (Southern Methodist U.), Hong Ma (Brookhaven National Lab), Azzedine Kasmi (Southern Methodist U.)

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Abstract

We employ the $E_T^{\text{miss}}$ in $Z \rightarrow \text{ee} + \text{jets}$ events to extract a measurement of the response of ATLAS calorimetry to jets. Rome and DC2 data samples with full detector simulation have been analyzed. Calculations are carried out with cells calibrated to the EM scale. We measure the detector response to central jets to increase logarithmically with jet energy and to plateau near 0.8 at high energy. For a fixed jet $p_T$, the relative detector response is measured to decrease by 5% at $|\eta| = 0.8, 1.5$ and by 12% at $|\eta| = 3.2$. These results are within 1-2% of independent results of a comparison of reconstructed jet $p_T$ with the $p_T$ calculated at the final state particle level. Comparison of the response measurement with one based on balancing reconstructed jet and electron $p_T$'s provides agreement on the calibration's energy dependence in the central region and the $|\eta|$ dependence near detector cracks. Differences in the energy dependence on $|\eta|$ may indicate a way to constrain the measurement of out-of-cone losses.

Motivation for \textit{in situ} Jet Calibration

Much work has been done at ATLAS on the fundamental calibration of the calorimeters for electrons and hadrons. This effort has produced cell-level calibrations based on GEANT and test beam studies of single particles and jets. One calibration, termed ‘EM scale’, establishes a linear response for electrons with good energy resolution by use of sampling weight corrections for each cell. Another calibration, termed ‘Hadronic scale’, employs a more sophisticated calibration of the cell-level energies by weighting each cell according to the neighboring occupancy in the calorimeter, as was done for the H1 experiment\textsuperscript{1}. The first calibration method produces a non-linear dependence on jet energy, and significant scale inhomogeneities near detector cracks. The second method removes most of these dependences in most simulated samples. However, systematic effects occurring in test beam or in the simulated samples might not be a realistic representation of what occurs in collider running. Unanticipated hardware effects might also play a role in the final performance of the running detector. Uncertainties of the underlying
physics, such as fragmentation or gluon radiation, and its interplay with jet algorithms can also reduce the effectiveness of the cell-level calibration. For these reasons, we will require a way to provide a measurement of the energy scale of jets in the running experiment.

This note describes an initial study of the utility of $E_T^{\text{miss}}$ in ATLAS $Z \rightarrow ee + \text{jets}$ events to provide a unique, in situ measurement of the detector response to jets. Such a measurement has been performed successfully at the Tevatron$^2$. Our current goal is to establish the fundamental sensitivity of our approach to miscalibrations that effect the response of the detector to jets. Therefore, we employ the EM scale cell calibration which leaves well-known miscalibrations for jets$^3$.

**Jets and the Jet Energy Scale**

The scale of energies of jets is the product of many effects. The calorimeter may exhibit nonlinearities in its response to particles of various energies, and detector cracks may cause energy scale variations in different regions. Fragmentation products shower in the calorimeter, and some of their energy can be deposited far from the parent parton’s direction. Final state gluons (FSR) can also carry energy far from an outgoing parent parton. Initial state radiation (ISR) gluons can deposit unrelated energy that gets incorrectly included in the reconstructed jet energy. Underlying event, noise and pileup are deposited in the vicinity of jets and the rest of the an event in a way uncorrelated with the leading partons in an event.

![Figure 1: Sketch of a wide jet (left) and a narrow jet (right). Cones are drawn to illustrate that a different size of the cone will result in different reconstructed jet axes, and therefore $p_T$’s and multiplicities. For the narrower jet, the jet multiplicity does not change but the $p_T$’s do.](image)
Coupled with these effects, a jet algorithm imposes some constraints on what energy actually is included or excluded in the momentum calculated for a jet. In the example of the fixed-cone algorithm, sketched in Figure 1, substantial differences in jet multiplicities and kinematics arise from different cone-size choices. FSR and fragmentation losses outside of the cone will be lost from a jet, while overlapping underlying event and ISR energy deposition will be added to a jet’s kinematics. It will be important to understand each of these effects if we are to achieve the goal of a 0.5% detector calibration for jets.

$E_T^{\text{miss}}$ Projection and Detector Response

We seek readily available samples from collider running that will permit a useful check of the detector calibration. $Z + $ jets events, where $Z \rightarrow ee$ or $\mu\mu$, and photon + jets events provide a convenient comparison to the jets they recoil against because the $Z$ or photon $p_T$ can be well-measured and calibrated.

To study response separately from other effects, we consider the fact that fragmentation and FSR produce energetic particles that, while not part of their parent reconstructed jet, are nevertheless seen in the calorimeter. As such they are lost from the final jet $p_T$, but are included in the overall event $E_T^{\text{miss}}$. Also, underlying event and noise are expected to be uncorrelated with the azimuth of electrons, photons or jets in a given event. Again, these contribute to the final jet $p_T$, but not the $E_T^{\text{miss}}$. Since $E_T^{\text{miss}}$ is only sensitive to response, we construct a parameter, $R$, by projecting the $E_T^{\text{miss}}$ into the $Z$ direction:

$$R = 1 + \frac{\vec{E}_T^{\text{miss}} \cdot \hat{n}_T^Z}{p_T^Z}$$

When $R \neq 1$, there is some $E_T^{\text{miss}}$ along the $Z$ transverse direction. We attribute this $E_T^{\text{miss}}$ to miscalibration. The calculation of $R$ based on the $E_T^{\text{miss}}$ has two important, related properties. First, it integrates over the whole calorimeter, and over the response of all radiated gluon and other jets in an event. Therefore, it is strictly speaking a property of the full event minus the $Z$ decay products. We will discuss this issue more below when we attempt to use this measurement for individual jets. Second, no jet algorithms are applied to any of the parameters used in the calculation. This minimizes the effects of the jet reconstruction algorithm, such as out-of-cone showering losses, on this parameter.
Because there are other effects besides response which influence a reconstructed jet $p_T$, it is also useful to calculate a balance parameter calculated directly from object $p_T$'s:

$$B = \frac{p_T^{jet} - p_T^Z}{p_T^Z},$$

We will compare $R$ and $B$ later to extract more information about the jet energy scale.

**Event Samples**

Table 1: Data samples used in this study. The number of events reflects events passing final selection of two reconstructed electrons with $75 \text{ GeV} < M_{ee} < 105 \text{ GeV}$.

<table>
<thead>
<tr>
<th>Reconstruction Version</th>
<th>Generation</th>
<th>#events</th>
</tr>
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<tbody>
<tr>
<td>9.0.3</td>
<td>DC2</td>
<td>77k</td>
</tr>
<tr>
<td>10.0.1</td>
<td>DC2</td>
<td>165k</td>
</tr>
<tr>
<td>10.0.1</td>
<td>Rome</td>
<td>53k</td>
</tr>
</tbody>
</table>

The event samples used in this analysis are indicated in Table 1. These samples are fully simulated GEANT samples of $Z \rightarrow ee$ events. Most of the results presented in this note come from the Rome sample, but a number of cross-checks were performed with the DC2 samples. When these revealed differences, they are noted. The analysis was performed on AODs of these samples. We used a modified version of the AnalysisExamples package to perform our analysis. Event selection begins with requiring two electrons with $p_T > 15 \text{ GeV}$ each. Cuts on EM shower profile and hadronic isolation are applied in five $|\eta|$ bins$^5$.

![Figure 2: Dielectron invariant mass (left) and $E_T^{\text{miss}}$ (Base) (right).](image-url)
The dielectron invariant mass, $M_{ee}$, for the Rome sample is shown in Figure 2a. The $E_T^{\text{miss}}$ calculated from cells calibrated to the EM-scale, $E_T^{\text{miss}}$ (Base), is shown in Figure 2b. Figure 3 illustrates the $p_T$ of the Z calculated from the two highest $p_T$ (i.e. ‘leading’) electrons. We observe the steeply falling spectrum expected from the convolution of the physical Z $p_T$ distribution and the transverse momentum resolution from the electron momentum measurements.

Figure 3: Z $p_T$ calculated from two leading electrons.

Approximately 5% of events have more than two electrons that pass our quality selection. The $M_{ee}$ and Z $p_T$ distributions for these events are shown in Figures 4a and 4b. These distributions look similar in all samples listed in Table 1, regardless of reconstruction version. Comparison with Figures 2a and 3, indicates that these events are misreconstructed. One of the three identified electrons does not correspond to an isolated electron from the Z. To avoid a bias, no cut on the maximum number of identified electrons is applied. Instead, we remove problematic events by requiring that $75 \text{ GeV} < M_{ee} < 105 \text{ GeV}$.

Figure 4: Dielectron invariant mass (left) and Z pt (right) for events with more than 2 electrons.
Response of the Recoil of the Z

Since the Z is an outgoing particle in the event, its $p_T$ is an indication of the net $p_T$ of the part of the event that balances the Z in the transverse plane. This balancing part of the event we term the ‘recoil’ of the Z and it includes all of the particles in the event minus the Z decay products. The Z $p_T$ is a well-measured quantity allowing us to probe the non-linearity of calorimeter response. For the selected events, we can provide a measurement of $R$ as a function of the $p_T$ of the reconstructed Z boson (see Figure 5). This response is the net response of the total recoil balancing the Z.

![Figure 5: Measured response vs Z $p_T$.](image)

η-Dependence of Jet Response

Although Figure 5 is an indication of the nonlinearity of the detector response it does not directly reflect the calibration for a specific jet in terms of its properties (eg. $E$, $\eta$). For instance, there are three primary regions in the ATLAS calorimetry where cracks arise from transitions between adjacent subdetector components. Around $|\eta| = 0.8$ there is a boundary between the Tile barrel and extended barrels. At $|\eta| = 1.5$, the Tile and LAr barrels transition to the LAr EM and hadronic endcaps (EMEC and HEC). At $|\eta| = 3.2$, the endcaps transition to the forward calorimeter (FCAL) system. Significant changes in the profile of material occur at these cracks, and this affects the calibration at EM scale.

We employ jets reconstructed with a cone algorithm using a cone size of

$$R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.7.$$  

Jet momenta are calculated from cells calibrated at the EM scale. We remove real electrons from the list of reconstructed jets by requiring the distance in the $\eta \times \phi$ plane to be $\Delta R(e, \text{jet}) > 0.7$. We note that an excess of jets in the 9.0.3 DC2 sample was observed compared to both 10.0.1 samples. Comparison of the two DC2 samples revealed the extra jets to occur preferentially in the forward region. The jet multiplicity distribution for the
Rome sample is shown in Figure 6a. We plot the measured $R$ vs. number of jets in Figure 6b for this sample when $|\eta|_{(\text{leading jet})} < 1.0$. $R$ does not depend strongly on the jet multiplicity.

![Figure 6: Jet multiplicity (left) and measured response vs. jet multiplicity (right).](image)

Lowest order $Z + \text{jet}$ production will produce a $Z$ and jet which are back-to-back in azimuth. Figure 7a indicates the distribution of the difference in azimuth between leading jet and $Z$, $\Delta \phi(Z, \text{jet})$. Most events exhibit the expected back-to-back topology. Figure 7b shows the measured response as a function of $\Delta \phi(Z, \text{jet})$. The dependence of the measured response on $\Delta \phi(Z, \text{jet})$ is flat unless the leading jet and $Z$ are $\pi/2$ or less apart. The $Z$ is not a leading particle in these events. We require $\Delta \phi(Z, \text{jet}) > 2.8$, but the insensitivity of the measured $R$ above $\Delta \phi(Z, \text{jet}) = 2.0$ in Figure 6b indicates that this cut could be significantly loosened.

![Figure 7: Azimuthal distance (left) between leading jet and $Z$, and measured response vs. this distance (right).](image)

Given the known locations of cracks in the detector, an important test is to identify the known scale variations at these places. We require at least one jet in our events and make no cuts on $|\eta|$. The $p_T$ of the $Z$ is required to be greater than 20 GeV to avoid low $p_T$ jets where the reconstruction is inefficient. This leaves us with a roughly constant $\langle p_T \rangle$ across multiple $|\eta|$ bins. Figure 8
shows the result for the Rome data. We observe 4% declines in response in measured response for jets at $|\eta| = 0.8$ and 1.5, and a 12% drop in response when $|\eta| = 3.2$. The DC2 samples exhibit similar relative behavior. This structure is fully consistent with measurements made at the particle level\(^3\). The two samples are in good agreement with each other.

Figure 8: Measured response vs. leading jet abs(eta).

**Energy Dependence of Jet Response**

The detector response to hadrons is expected to have a strongly non-linear dependence on particle energy when using cell energies calibrated at the EM scale. Since these particles comprise a jet and typical constituent particle energies increase as the jet energy increases, the response of the detector to jets is also expected to increase with jet energy. We could plot directly the measured response vs reconstructed jet energy. However, the sampling term for jet energy resolution of approximately $0.5/\sqrt{E}$ is sufficiently poor to produce a moderate bias in the measured response for each jet energy bin. This is because Z and photon + jets events have a steeply falling parton $p_T$ distribution. Within a measured jet $p_T$ bin, jets will tend to have fluctuated
upward (i.e. higher than normal response) and the measured \( \langle R \rangle \) in each bin of energy will be too high. We attempt to overcome this problem by using the quantity \( E' = E_T^2 \cosh(\eta_{jet}) \). The measured correspondence of jet energy and \( E' \) is given in Figure 9a, while in Figure 9b we see the measured response vs. \( E' \). These two plots can be used to generate a plot of response vs. jet energy\(^2\). Above the inefficient region, the response rises as expected from the particle level comparisons.

**Comparisons to \( p_T \)-balance**

As mentioned, \( R \) should be primarily sensitive to response while \( p_T \) balance, \( B \), should be sensitive to all of the effects which influence the reconstructed jet energy. Figure 10a and 10b provide the energy and \( |\eta| \) dependence, respectively, of the balance for the sample that produced Figures 8 and 9b for response, respectively. There are several similarities between these two measurements. First, both register approximately 30\% of an energy scale deficit for central jets which rises slowly with energy. Both exhibit a rise in measured scale for low energy jets. Both indicate approximately 4\% dips in scale, relative to the scale in neighboring bins, at \( |\eta| = 0.8, 1.5 \). Both indicate a larger decrease of 10\%-15\% at \( |\eta| = 3.2 \).

![Figure 10: Measured balance vs. E' (left) and vs. psuedorapidity (right).](image)

**Table 2**: Values of response and balance in three pseudorapidity bins. Characteristic statistical errors are 1\% for response and 1.5\% for balance.

| \( |\eta| < 0.5 \) | 2.0\(<|\eta| < 2.5 \) | 3.5\(<|\eta| < 4.2 \) |
|-----------------|-----------------|-----------------|
| R(response)     | 0.69            | 0.73            | 0.75            |
| B(balance)      | 0.75            | 0.76            | 0.72            |
| Ratio (B/R)     | 1.09            | 1.04            | 0.96            |

There are some interesting differences, however. The ratio of the measured balance for jets to the measured response goes from 1.09 to 0.96
over bins of $|\eta| < 0.5$, $2.0 < |\eta| < 2.5$, and $3.5 < |\eta| < 4.2$, as shown in Table 2. These regions are well away from cracks so response variations should only reflect the fundamental non-linearities inherent in the calorimetry in these regions. For these three regions, the jet energy increases as we move forward. The showers of pions within jets also increase in $\eta \times \phi$ width as we move forward, which means more leakage of energy away from a jet axis. The measurement of $R$ is only sensitive to the increase in energy and therefore the improved response as energy increases. The balance measurement is additionally sensitive to the fact that out-of-cone leakage will increase with forward pseudorapidity. This decreases the energy scale and counteracts the increase in response. These trends are qualitatively consistent with the observed ratios.

Conclusions

We have investigated the ability of the $E_T^{miss}$ projection technique to extract useful information about the energy scale of jets in the ATLAS calorimetry. The study was primarily performed with Rome Z$\rightarrow$ee simulated samples reconstructed with release 10.0.1. The behavior of the energy dependence of the measured response, and the dependence on pseudorapidity matches the expectations from previous particle-level studies of energy scale. The response in crack regions relative to neighboring calorimeter regions agrees to within 1-2% of the particle-level comparisons. For jets which have $p_T$'s above the inefficient low $p_T$ region, a similar level of agreement of the response vs. jet energy is observed. Comparison with $p_T$ balancing reveals similarities where expected and differences which suggest a way to extract more information about the specifics affecting jet calibration. As a result, we believe the $E_T^{miss}$ projection method will be a valuable way to perform systematic checks of the underlying detector calibration. If deviations from perfect calibration are observed in collider data samples, a correction to jets for the miscalibration can be derived from this method. The studies described here can be performed for jets calibrated at the hadronic (‘H1’) scale once the $E_T^{miss}$ properly incorporates the crack corrections for energy deposited in jets.

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1 H1 calibration paper
3 Paige/Padhi particle level comparison, crack calibration in EM scale
4 TDR, 0.5% calibration reference
5 electron ID shower and isolation cuts