

Track-based improvement in the jet transverse momentum resolution for ATLAS

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Abstract

We present a track-based method for improving the jet momentum resolution in ATLAS. Information is added to the reconstructed jet after the standard jet energy scale corrections have been applied. Track-based corrections are implemented, and a 10 – 15% improvement in the jet transverse momentum resolution at low p_T is achieved. The method is explained, and some validation and physics results are presented. Additional variables are described and analyzed for their resolution improvement potential.

1 Introduction

ATLAS, one of the general-purpose detectors at the LHC [1], began taking data in 2008. Many of the proposed physics studies include energetic jets, collimated collections of particles often initiated by a single quark or gluon in a hard scatter collision. The calorimeter's response to hadronic jets will be a significant source of systematic uncertainties for both searches for new phenomena, particularly in hadronic decay channels, and Standard Model studies. Understanding the jet energy response is of vital importance. By improving the jet energy resolution, it is possible to improve mass resolution and decrease combinatorial backgrounds as well.

Jet reconstruction in ATLAS has traditionally relied on calorimeter information alone. During event reconstruction, corrections are applied to raw cell energies due to the non-compensating nature of the calorimeter [2]. These jet energy scale (JES) corrections set the energy scale of jets such that -on average- jets have a uniform response in transverse momentum, $R = p_T^{reco} / p_T^{true} = 1$. However, on a jet-by-jet basis, jets may be over-corrected or under-corrected depending on their topology, particle content, etc.

We describe a technique that uses tracks found within jets to extract information about the jet topology and fragmentation in order to improve the jet transverse momentum resolution [2]. The approach is conceptually different from more traditional energy flow methods [3], where precise track momentum measurements replace calorimeter clusters. Rather, tracks are used to correct the response of jets as a function of the jets' particle composition, using the fraction of jet p_T carried by tracks pointing to the jet, $f_{trk} = \frac{p_T^{tracks}}{p_T^{calorimeter}}$. Here $p_T^{calorimeter}$ refers to the jet p_T



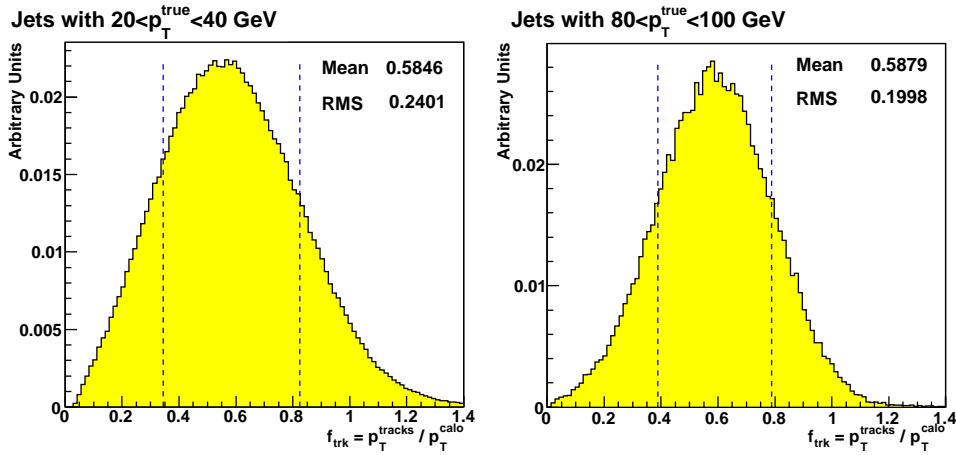


Figure 1: Sample distributions of f_{trk} for jets in two bins of p_T^{true} . Dotted lines are placed at 1 standard deviation above and below the mean of each distribution.

reconstructed using the standard (calorimeter-only) ATLAS reconstruction, and p_T^{tracks} refers to the p_T carried by all the tracks found within the jet.

In general, jets are composed primarily of neutral and charged pions. Charged particles leave tracks in the inner detectors, and so one might naively expect that between half and two-thirds of the jet p_T will be carried by tracks associated with that jet. As shown in Figure 1, Monte Carlo QCD di-jet samples have roughly Gaussian f_{trk} distributions centered near 0.6, with tails extending above one. The tails are more prominent at low energies and include, for example, jets with a true f_{trk} near one and one or more tracks with incorrectly measured momenta. In this all-pion approximation of jet composition, the number of tracks corresponds to the hadronic fraction of the jet, and f_{trk} provides a method for adjusting the jet energy for the non-compensating calorimeter of ATLAS. Additionally, an extreme f_{trk} can point to a very poorly calibrated jet, since a fluctuation reconstructed jet p_T will cause a fluctuation in f_{trk} .

The transverse jet momentum resolution, $\frac{\sigma(p_T^{reco} - p_T^{true})}{p_T^{true}}$, where σ is the standard deviation of the distribution, is proportional to the width of the jet momentum response in bins of transverse momentum, normalized to the average true jet momentum in a bin. If the response of these jets varies significantly with f_{trk} , the transverse jet momentum resolution will be artificially broadened, as shown in Figure 2. One sees that the total measured transverse jet momentum response distribution is considerably wider than either of the constituent distributions corresponding to jets with different charged particle fractions. By correcting the jet response as a function of jet p_T and f_{trk} we reduce the overall width of the momentum distribution and, hence, improve the jet momentum resolution.

Although the variable f_{trk} demonstrates the method clearly, this principle holds for other track or calorimeter variables as well. Many variables can hold information about jet topology, including the number of tracks associated to a jet, the spread of the tracks within the jet, and the fraction of track p_T carried by the leading track. By using a combination of these variables, one could considerably improve the transverse jet momentum resolution.

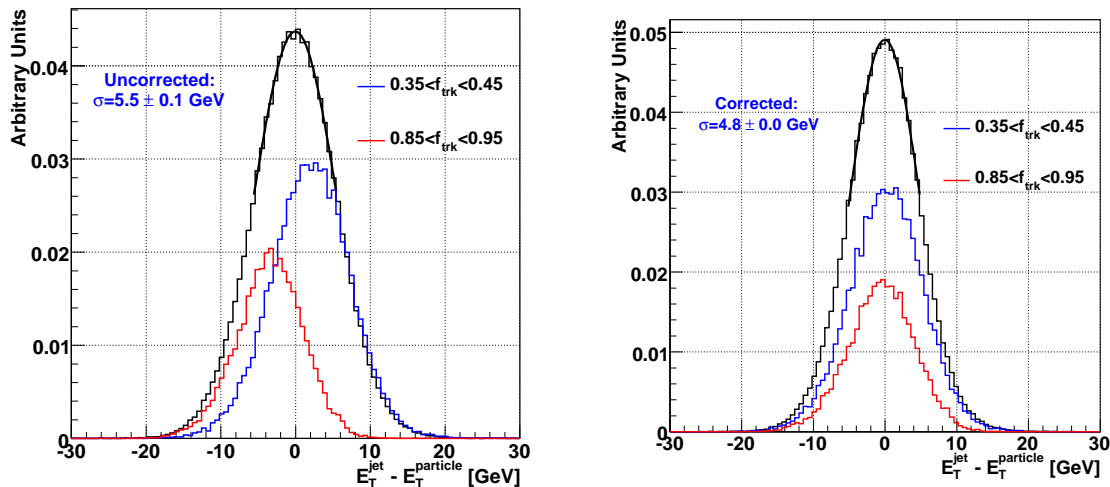


Figure 2: Black: difference between reconstructed and true jet p_T for jets with $|\eta| < 0.7$ and $40 \text{ GeV} < p_T < 60 \text{ GeV}$ before (left) and after (right) a correction based on f_{trk} is applied. The mean (width) of this distribution is proportional to the jet momentum response (resolution). Since jets with different f_{trk} have different responses, the transverse momentum resolution is artificially broadened because of the offset of the distributions for each f_{trk} bin. The f_{trk} bins are centered at ± 1 standard deviation in the f_{trk} distribution. The normalization is arbitrary.

2 Monte Carlo Samples and Event Selection

Track-based jet corrections were determined using QCD di-jet events. A list of the samples used, including cross sections and leading parton p_T ranges, is included in Table 1. Samples were not normalized.

Table 1: Properties of the QCD di-jet samples used in this analysis. The samples are divided into slices according to the transverse momentum of the leading parton from the hard scatter.

Sample	Leading Parton p_T Range	Cross Section	Number of Events
J1	17-35 GeV	1.4 mb	302,000
J2	35-70 GeV	93 μb	1,161,750
J3	70-140 GeV	5.9 μb	254,750
J4	140-280 GeV	0.31 μb	336,000
J5	280-560 GeV	12 nb	321,550
J6	560-1120 GeV	0.4 nb	371,800

Reconstructed tower-seeded, 0.4 cone jets selected from the events ranged in p_T from 7 GeV to 1120 GeV. Only jets with energies between 20 and 600 GeV were considered to derive the corrections. Fits were formed only for central jets with pseudorapidity $|\eta| < 0.7$, however the technique can be extended to other regions of η . Because the ATLAS tracker acceptance ends at $|\eta| = 2.5$, jets beyond $|\eta| = 2.0$ must be examined more carefully and may not be suitable

for this technique. We begin from jets with uniform response, $R = p_T^{reco} / p_T^{true} = 1$ on average.

Jets were also required to have a “truth” jet (i.e. a jet made from particles immediately after the hard scatter, prior to any interactions with the detector) matched within 0.1 in $\eta - \phi$ space and were required not to be matched to a truth c - or b -quark. Such heavy-flavor jets could have different momentum responses compared to light-quark jets and were excluded from the fits (see Section 4.2). About 3% of the jets in these di-jet samples were c - or b -jets.

Tracks within a cone of radius 0.4 in $\eta - \phi$ around a jet’s axis were included in the calculation of f_{trk} . In order to remove jets with a single poorly measured track, jets were required to be associated with at least two tracks to derive the corrections, and each track was required to have $p_T > 0.5$ GeV and $\chi^2/DoF < 3.0$, both of which are standard ATLAS track quality cuts. No other requirements were placed on the tracks. To determine the track-based momentum corrections, jets were also required to be isolated in a cone of 0.8 in $\eta - \phi$ space, to avoid jet-jet contamination which may skew f_{trk} considerably for low momentum jets. The removal of this isolation criterion will be explored in future studies.

3 Determination of the Track-Based Jet Momentum Response Correction

Jet momentum response is non-Gaussian when plotted in bins of reconstructed transverse momentum but is roughly Gaussian when plotted in bins of true transverse momentum. The momentum response is therefore calculated in bins of true jet momentum. Then, using the definition of jet response, $R \equiv p_T^{reco} / p_T^{true}$, pairs are formed of jet momentum response and reconstructed jet transverse momentum ($R(p_T^{true}), p_T^{reco}(p_T^{true})$). These pairs are then used to derive corrections for response. A grid was constructed with 20 bins in p_T between 20 and 600 GeV, with finer binning at low p_T , and 12 bins in f_{trk} between 0 and 1.04. Grid points were constructed so that each bin had roughly an equal number of jets. Fits to the jet momentum response are made as functions of f_{trk} and p_T . A two-dimensional fit was then used to fit the data. Slices of the fit surfaces are shown in Figure 3.

4 Algorithm Performance

The track-jet response correction $R(p_T, f_{trk})$ described previously was applied to jets selected for determining the parameterization. The jet momentum response was checked as a function of f_{trk} . Figure 3 shows the dependence of the response on f_{trk} before and after applying the track-based correction. Track-based corrections flatten the response, $R(p_T, f_{trk}) = p_T^{jet} / p_T^{true}$, to a mean value of unity for all $f_{trk} < 1$. Above $f_{trk} = 1$, the fits do not completely correct the jet momentum response. As the f_{trk} distribution in Figure 1 demonstrates, very few jets lie in this region, and so the mean transverse momentum resolution is not significantly affected. When correcting jets, a cut was applied at $f_{trk} = 1.4$, above which jets were not corrected owing to inconsistent variation in response.

As described earlier and shown in Figure 2, the jet resolution before the $R(p_T, f_{trk})$ correction can be thought of as re-centering several offset Gaussians with different f_{trk} . By re-centering the underlying distributions we improve the jet transverse momentum resolution.

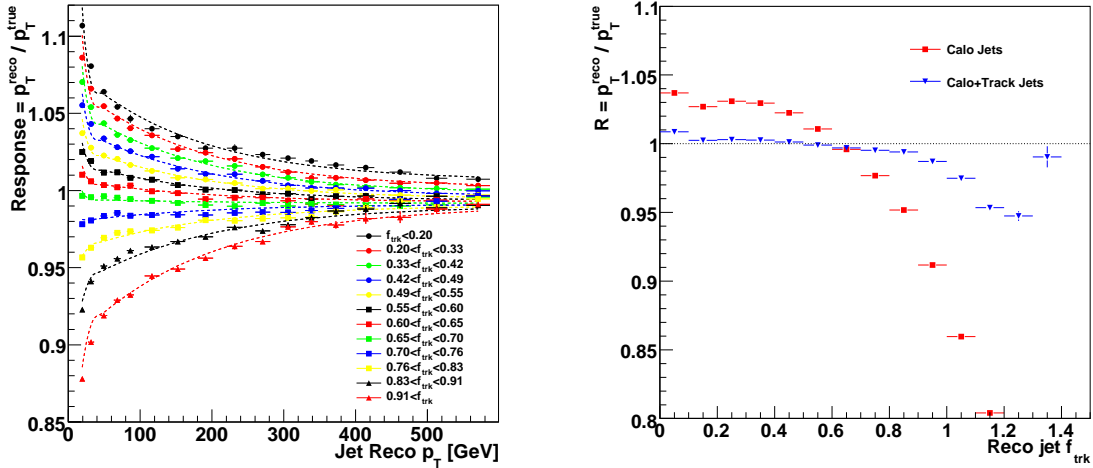


Figure 3: Left, slices of the data and the fit surface. Fits are shown as dotted lines over the data points. Right, jet response as a function of f_{trk} , before (Calo Jets) and after (Calo+Track Jets) applying the track-based response correction. The distribution of f_{trk} , as shown in Figure 1, drops off before one, so few jets are in the poorly corrected high f_{trk} region.

Figure 2 shows the overlapping distributions after corrections. The tails of the distribution have been improved without affecting the mean.

4.1 Jet Transverse Momentum Resolution

The jet transverse momentum resolution is considerably improved at low jet p_T , as demonstrated in Figure 4. Fits are shown both before and after the corrections are applied. A 10 – 15% transverse momentum resolution improvement is achieved at low p_T . The transverse momentum resolution is fit with a function:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{a^2}{p_T} + \frac{b^2}{p_T^2} + c^2} \quad (1)$$

where a^2/p_T is a stochastic term, b^2/p_T^2 is a noise term, and c^2 is a constant term.

4.2 Heavy Quark Jets

Because of presumed differences between the fragmentation of a heavy-quark jet and that of a light-quark jet, there was some concern that their properties would be sufficiently different that the same corrections could not be applied. In fact, this is not the case: b -quark tower jet transverse momentum resolution is indeed improved by the same corrections derived from and applied to the light-quark tower jets, and the response is corrected properly. The transverse momentum resolution improvement at 40 GeV is approximately 8%.

A great deal of the concern over heavy-quark jets was caused by the assumption that their distributions for f_{trk} would be significantly different from those of light-quark jets. The mean

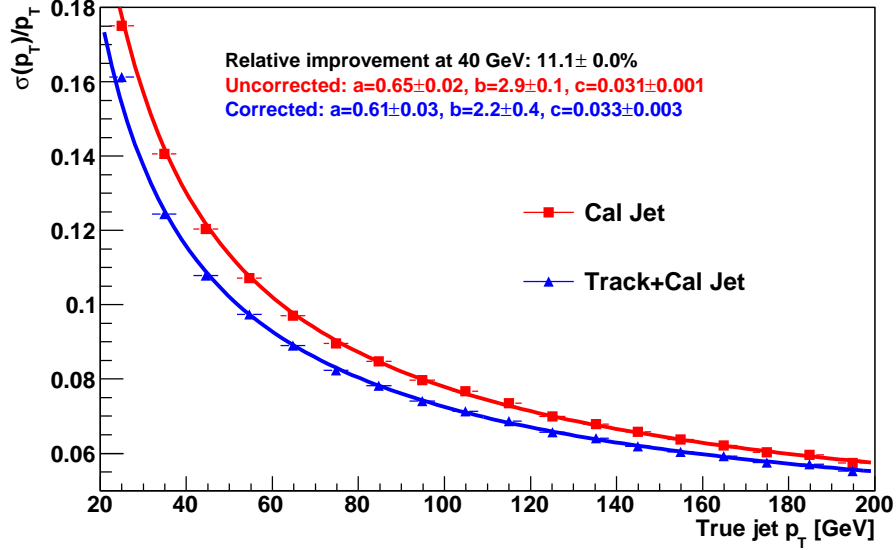


Figure 4: Jet transverse momentum resolution as a function of true jet p_T before (Cal Jet) and after (Track+Cal Jet) correcting for f_{trk} .

and standard deviation of each the f_{trk} and track multiplicity distributions for light- and heavy-quark jets can be found in Figure 5. The different types of jets show few significant differences at low p_T , where this technique is most useful.

4.3 Missing Transverse Energy Bias

Track-based jet corrections can also be used to improve the scale of the missing transverse energy, \cancel{E}_T . The track-corrected \cancel{E}_T is computed as

$$\cancel{E}_{T,x,y}^{corr} = \cancel{E}_{T,x,y} - \sum_{jets} (p_T^{corr} - p_T^{reco}) \quad (2)$$

where $p_T^{corr} = p_T^{reco} / R(p_T^{reco}, f_{trk})$ and the sum is over all jets in the event.

Figure 6(a) shows the mean value of the $\cancel{E}_T^{reco} - \cancel{E}_T^{true}$ for the J4 sample alone (see Table 1) as a function of the f_{trk} difference between the two leading jets in a di-jet sample. \cancel{E}_T^{true} is simply the sum of neutrino p_T . Both leading jets were required to have $|\eta| < 2.0$ and $p_T > 20$ GeV for this study. Events were required to have no more than three reconstructed jets, and the two leading jets were required to have $\Delta\phi > 2.9$.

Figure 6(a) shows a large imbalance of transverse energy when the two jets have large differences in f_{trk} . Here f_{trk}^1 (f_{trk}^2) refers to the f_{trk} of the first (second) leading jet, and the similarly p_T^1 (p_T^2) refers to the p_T^{reco} of the first (second) leading jet. When $\Delta f_{trk} < 0$, $f_{trk}^2 > f_{trk}^1$ and p_T^2 is underestimated resulting in a positive bias on \cancel{E}_T . A similar argument explains a negative \cancel{E}_T bias for $\Delta f_{trk} > 0$.

Figure 6(b) shows that the \cancel{E}_T scale is properly corrected after applying the track-based response correction to the leading two jets, and the \cancel{E}_T bias has been removed.

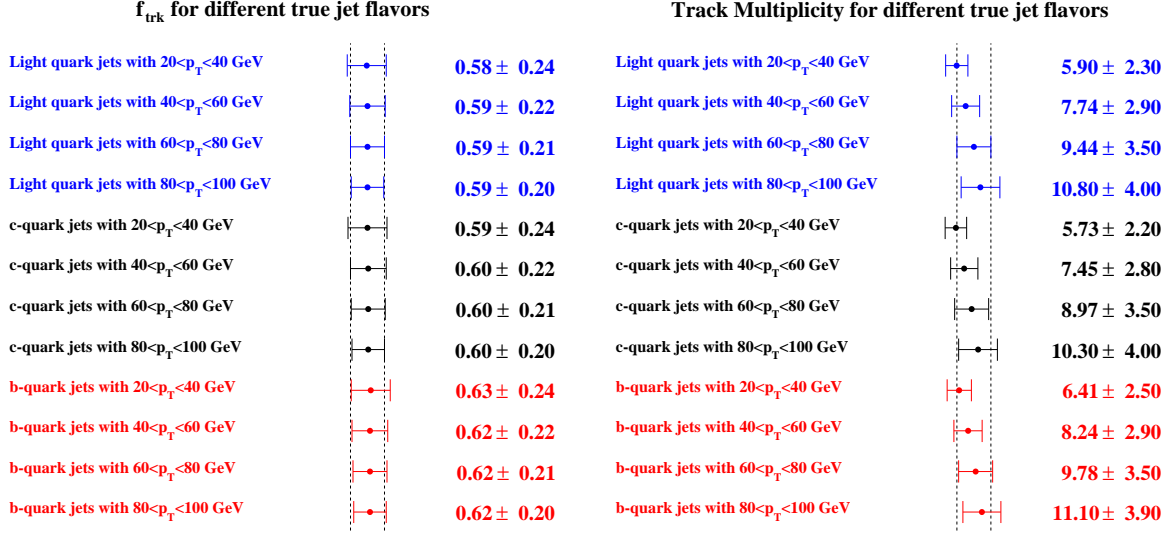


Figure 5: Mean f_{trk} (left) and track multiplicity (right) in light-quark jets, c -quark jets, and b -jets. Widths represent the standard deviation of the distribution. Dotted lines are placed at one standard deviation above and below the mean of the $60 < p_T < 80$ GeV light-quark distribution.

5 Evaluation of Additional Variables

Additional variables must be considered to maximally improve jet transverse momentum resolution. The variables should be uncorrelated in order to not introduce correction ordering problems and should be the minimal set that provides maximum information about jet topology.

The improvement provided by a single variable can be evaluated based on the difference in response between those jets at one standard deviation above and below the mean of the variable distribution. The difference should be related to the improvement in jet transverse momentum resolution that will be seen after a correction has been applied. We evaluate the variables both before and after corrections based on f_{trk} in order to understand which variable contains the most useful additional information about jet topology.

If f_{trk} is a measure of the hadronic energy in a jet, the number of tracks pointing to a jet gives some measure of the division of that hadronic energy. A high number of tracks means that hadrons in the jet are each lower energy and may not travel as far into the calorimeter. The softer particles may also result in an increase in non-linearity effects. The variable is highly correlated to jet p_T as well. Distributions of track multiplicity are shown in Figure 7, and the variation in response can be seen in Figure 8. Response shows a 3% variation with track multiplicity. Simply considering the number of tracks pointing to a jet may introduce problems with track reconstruction efficiency, ambiguity between low- and high- p_T tracks, and the radius used to associate tracks to jets. Corrections could be explored as a function of a ratio involving track multiplicity in order to resolve some of these issues.

The p_T carried by the leading track may also provide a handle on improving the jet transverse momentum resolution. We have examined the ratio of p_T of the leading track to the p_T carried by all tracks, p_T^1 , and the response variation. By using this ratio rather than, for example,

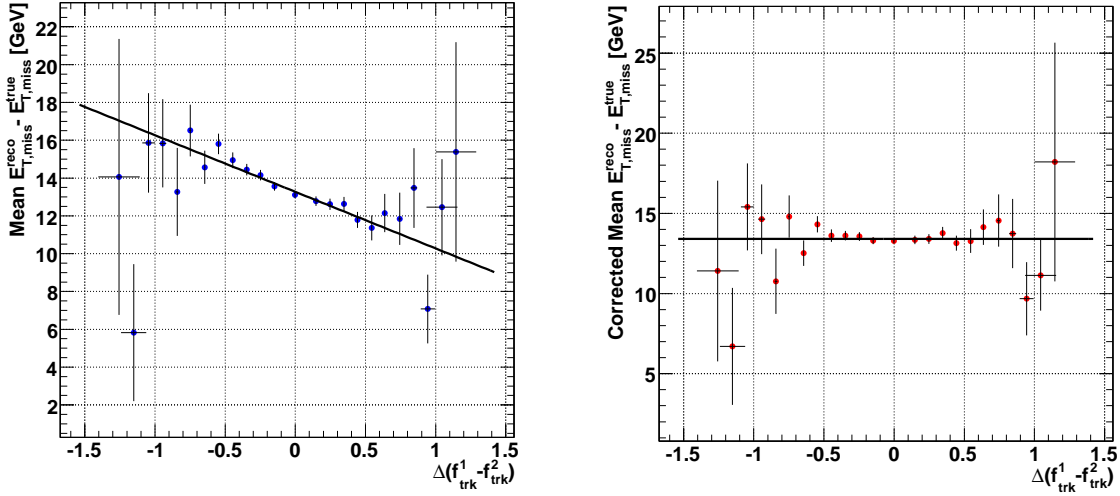


Figure 6: Mean missing transverse energy in a J4 sample as a function of the f_{trk} difference between the two leading jets in a di-jet sample before (left) and after (right) track-based jet momentum corrections.

the ratio of p_T of the leading track to the p_T of the jet, the variable may be less correlated to f_{trk} and thus independent of corrections based on f_{trk} .

Some measure of track width may also provide useful information about jet topology. A very narrow set of tracks may be included in a single hadronic cluster, whereas several widely spaced tracks may produce several different hadronic clusters. One measure of shower width is the maximum distance in $\eta - \phi$ between any two tracks associated to the jet. One can also construct a measurement of track width using the average distance in $\eta - \phi$ between all tracks, with or without a p_T weighting. This variable is somewhat less sensitive to single low- p_T tracks on the edges of jets when there is a clear group of high- p_T tracks at the core of the jet, a feature that can be particularly important for high- p_T jets which typically contain many tracks. Different weighting schemes may also be explored.

Although these variables are each worth exploring, clearly the optimal set will not include all possibilities. The various ways of describing jet width are likely highly correlated, and correction for one may prove sufficient. There are certainly other variables worth exploring that could provide additional information about jet topology either from track information or from some subset of calorimeter information. Initial corrections can be achieved by applying a second fit on top of the f_{trk} fits already applied. In order to maximize the improvement in response and correctly take into account correlations, full multi-dimensional fits will have to be produced.

6 Conclusions and Future Studies

We have introduced a track-based method for correcting the response of jets in ATLAS that provides a 10-15% improvement in jet transverse momentum resolution at low p_T over the

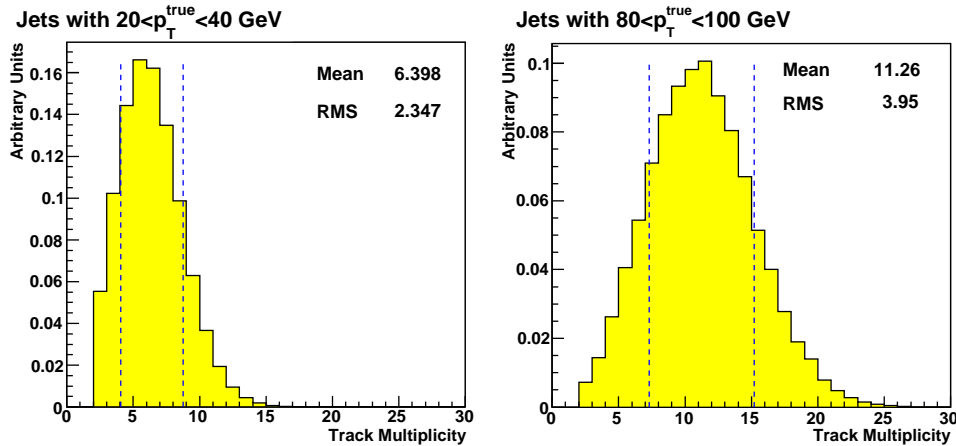


Figure 7: Distributions of track multiplicity for several bins of jet p_T^{true} . Dotted lines are placed at one standard deviation above and below the mean of each distribution.

standard ATLAS calorimeter jet reconstruction alone. The corrections derived based on light-quark tower-seeded jets are also effective on c - and b -quark jets. The corrections also improve missing energy distributions and biases. These corrections do not require new jet energy scale corrections and can be applied after the standard reconstruction. By systematically adding information from the tracker to jets already reconstructed based on calorimeter information, considerable progress can be made. A tool has been developed in the ATLAS software framework that provides f_{trk} and a correction based on f_{trk} as jet moments for all reconstructed jets.

Additional variables have been examined for their ability to improve jet transverse energy resolution. Several variables are promising and will be explored further. Ultimately, some combination of variables will be used to gain the maximum improvement.

These track-based corrections may be sufficiently sensitive to differences in fragmentation between quark- and gluon-initiated jets, for example, that they may be able to account for differences in jet energy scale between the two. By removing the sample-dependence of the jet energy scale corrections, the jet transverse momentum resolution can be improved.

There are several modifications to the technique being explored to further improve the jet transverse momentum resolution using this and other similar track-based variable methods. The radius used for track-jet association may be adjusted to improve performance, and extrapolated track position may be used rather than track direction at the interaction point. Since pile-up will be a significant issue at the LHC even from early on, these corrections will be tested in combination with a jet-vertex association technique already in progress [2].

References

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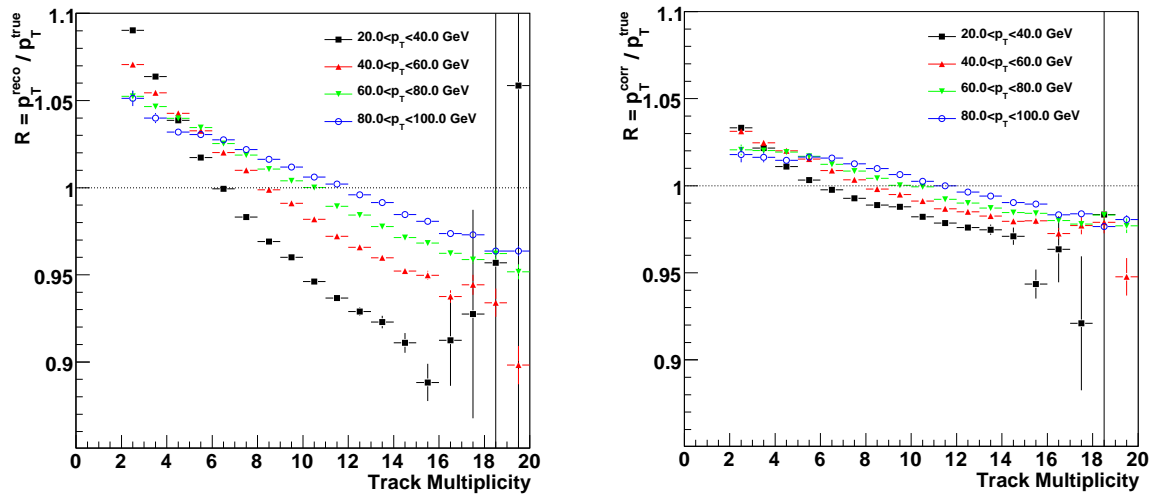


Figure 8: Jet response as a function of track multiplicity, before (left) and after (right) corrections for f_{irk} . A cut required each jet to have at least two tracks associated to it.