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# Modelling Calorimeter Energy Flow from the Underlying Event in $t\bar{t}$ Events

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**Abstract**

We present a study of the modelling of calorimeter energy flow from the "underlying event" in $t\bar{t}$ events. We compare Monte Carlo samples created using different parton density functions, including PYTHIA Tune A, and compare the results with a data sample consisting of W plus three or more jets, chosen due to its similarity to $t\bar{t}$ events. We find that while PYTHIA Tune A exhibits a more energetic "underlying event" than our other Monte Carlo samples, all of the Monte Carlo samples substantially underestimate the energy of the "underlying event" in the W+ $\geq 3$ jet data.

## 1 Introduction

In the study of high $p_T$ $p\bar{p}$ interactions, we rely heavily on Monte Carlo calculations to model real data and form methods to study it. It is thus pertinent that this modelling is reasonable and that we understand its accuracy. It is also important that we understand the dependence of the models on parameters of the Monte Carlo generators, such as the Parton Density Function used by the generator.

The "underlying event" in $t\bar{t}$ events consists of all particles produced in the event except the outgoing high $p_T$ leptons and jets produced by the top and anti-top quarks' decay products. In general, understanding the "underlying event" in hard $p\bar{p}$ interactions should allow for improved jet energy calibration. The underlying event contributions are convolved with out-of-cone jet energy and final state radiation effects, so it is important to find an independent measure and constraint on the underlying event contributions. In particular, better measurements of these different effects in $t\bar{t}$ events are necessary for improvements in the top mass measurement.

The "underlying event" in hard scattering interactions has already been studied by comparing dijet events modelled with PYTHIA Tune A to Min Bias and jet trigger data by isolating regions that are perpendicular to the plane of the hard scattering [1]. Additionally, the energy deposition in jet-sized cones in Min Bias events has been examined [2]. The latter study found an average $E_T$ of 0.32 GeV in cones of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ in events with one vertex. Here, we restrict our study to Monte Carlo $t\bar{t}$ events and W+ $\geq 3$ jet data (which we use as a proxy for $t\bar{t}$ events).

By examining the sensitivity of the "underlying event" to the use of different parton density functions (PDFs), we can enhance our understanding of the uncertainty that should be attached to the underlying event energy in Monto Carlo top quark pair production. Our primary intention in this note is to study calorimeter energy flow in regions that are dominated by the underlying event and to provide a preliminary evaluation of the modelling of this energy flow. We look at $t\bar{t}$ events created using different PDFs and at W+ $\geq 3$ jet samples, which should be comparable to $t\bar{t}$ events. In Section II, we describe the Monte Carlo and data samples used and briefly outline our approach to study and measure the energy flow. We present our results in Section III and provide conclusions in Section IV.

## 2 Method

According to the standard model, top quarks decay almost always into a b quark and a W boson. The W in turn decays either leptonically, into a lepton and a neutrino, or hadronically, into a quark and an antiquark. In a $t\bar{t}$ event, then, we will have two W bosons and thus two decay mechanisms. Here we focus on events where one W decays leptonically and the other hadronically.

Using the PYTHIA Monte Carlo generator, we generated, simulated and reconstructed 50 000 $t\bar{t}$, lepton + jet events for each of the PDFs CTEQ5L, MRS G, and BM Set A and for PYTHIA Tune A (which is based on CTEQ5L). We also select a W+ $\geq 3$ jet sample from the 4.8.4 REMAKE version of the official top group data sample for summer 2003 [3]. Jets were defined using the JetCluModule with $R = 0.4$ and an $E_T$ threshold cut of 5 GeV (uncorrected). We keep events that have one tight lepton [4], at least three tight jets (jets within $|\eta| < 2$ with $E_T > 15$ GeV) and missing $E_T > 20$ GeV. To minimize energy flow from additional multiple interactions (which are not modelled in the Monte Carlo samples), we require that data events have either zero or one z vertex in ZVertexColl with at least 10 tracks associated to the vertex.

We use several methods to measure the energy associated with the underlying event. One approach is to isolate $\eta - \phi$ regions that are not significantly influenced by jet activity. We searched for cones of $R = 0.4$ in $\eta - \phi$ space whose centroids are seperated from the centroids of all jets in the event by an $\eta - \phi$ distance of at least 1.4. For each event in which such a cone can be found, we define the best cone as the one which is farthest from the nearest jet. We first find the best cone whose centroid is within $|\eta| < 2.8$. Additionally, we divide $\eta - \phi$ space into "strips", each with a $|\Delta\eta| = 0.5$, and identify the cones farthest from all jets in these regions. The average transverse energy deposition in these cones is one measure of the underlying energy in an event.

As a second technique, We measured the energy density in $|\eta|$ strips that are 2 calorimeter towers wide as a function of $|\eta|$ to understand the rapidity dependence of the underlying energy. To avoid the flow of energy from jets, we require all towers in this measurement to be at least $R = 1.0$ from all jets (with what ET cut??). Essentially, this method measure the same property as the preceeding one; however the first method is biased towards those regions that are farthest from the jets, so we expect to see more energy flow on average in the second measurement.

It is also desirable to have a more complete measure of the underlying event energy, and so we also examine the total tranverse energy density ($E_T$ per unit $\eta - \phi$) outside of all jets.

To minimize the effects of out-of cone energy, we require such energy deposition to be at least $R = 1.0$ from the centroid of every jet in the event. We also obtained a measure of the out of cone energy by looking at the $E_T$ density in regions that are between a distance of $R = 0.4$ and 0.6 from a jet's centroid, as well as between 0.6 and 0.8 and between 0.8 and 1.0, on an event by event basis.

## 3 Results

The transverse energy density in the best cone comparison is shown in Fig. 1. The $E_T$ density in the best cone in PYTHIA tune A is on average at least 50% larger than what is predicted by other Monte Carlo samples, however still lower than what is seen in data by about 30%. The transverse energy density in cones of $R = 0.4$ in the $|\eta|$ regions described in the last section is compared in Fig. 2. The decrease in energy due to increasing $|\eta|$ may be attributed to the higher jet concentration in the central region (note as well that there is a dip in $0.5 < |\eta| < 1.5$, which may be attributed to the cracks in that region). Fig. 3 and Fig. 4 demonstrate the $|\eta|$ dependence of the $\eta - \phi$ distance from the cone to the nearest jet and the depedence of the $E_T$ in that cone on this distance, respectively. For all entries, the Monte Carlo samples demonstrate an underlying event that is less energetic than that seen in the data.

Fig. 5 shows the $\eta$ dependence of the $E_T$ density, measured in bins of two $\eta$ towers. As this measurement is taken in an entire strip of $\eta - \phi$ space, rather than only the area that is farthest from the jets, we expect it to be more representative of energy flow than the measurements made in the cones. In both cases, the largest difference among the Monte Carlo samples is seen between PYTHIA Tune A and the other samples. Among the different PDFs, the discrepencies are on average about 15 percent, which is somewhat significant, though small compared to the difference between these samples and the Tune A sample. Again, the data gives results that are far higher than the Monte Carlo.

Figure 6 shows the $E_T$ density of the region that is at least $R = 1.0$ from all the jets. As this measurement includes regions that are closer to the jets than previous calculations, it is more sensitive to out of cone energy. We thus expect it to be higher than the others. Note the broader distribution of PYTHIA Tune A compared to the other Monte Carlo samples. The average $E_T$ densities calculated by the methods explained above are compared for data and MC with different PDFs and tuning in Table 1.

Figure 7 shows the $E_T$ density within various annuli from a jet's centroid. Note the steeper drop in the data in comparison to the Monte Carlo. The larger difference between the 0.4-0.6 and 0.6-0.8 bins in Monte Carlo may be an indication that the Monte Carlo over estimates jet fragmentation, or that the jets are too narrow (though we haven't controlled for possible differences in average jet energies in this comparison). Also note that at a displacement of close to $R = 1.0$ from the centroid the $E_T$ density is comparable to that found with the other measurements. We conclude that out-of-cone corrections do not significanty influence our underlying event measurements made in towers by requiring at least $R = 1.0$ separation from the nearest jet. Table 2 compares the average $E_T$ densities within various annuli from a jet's centroid.

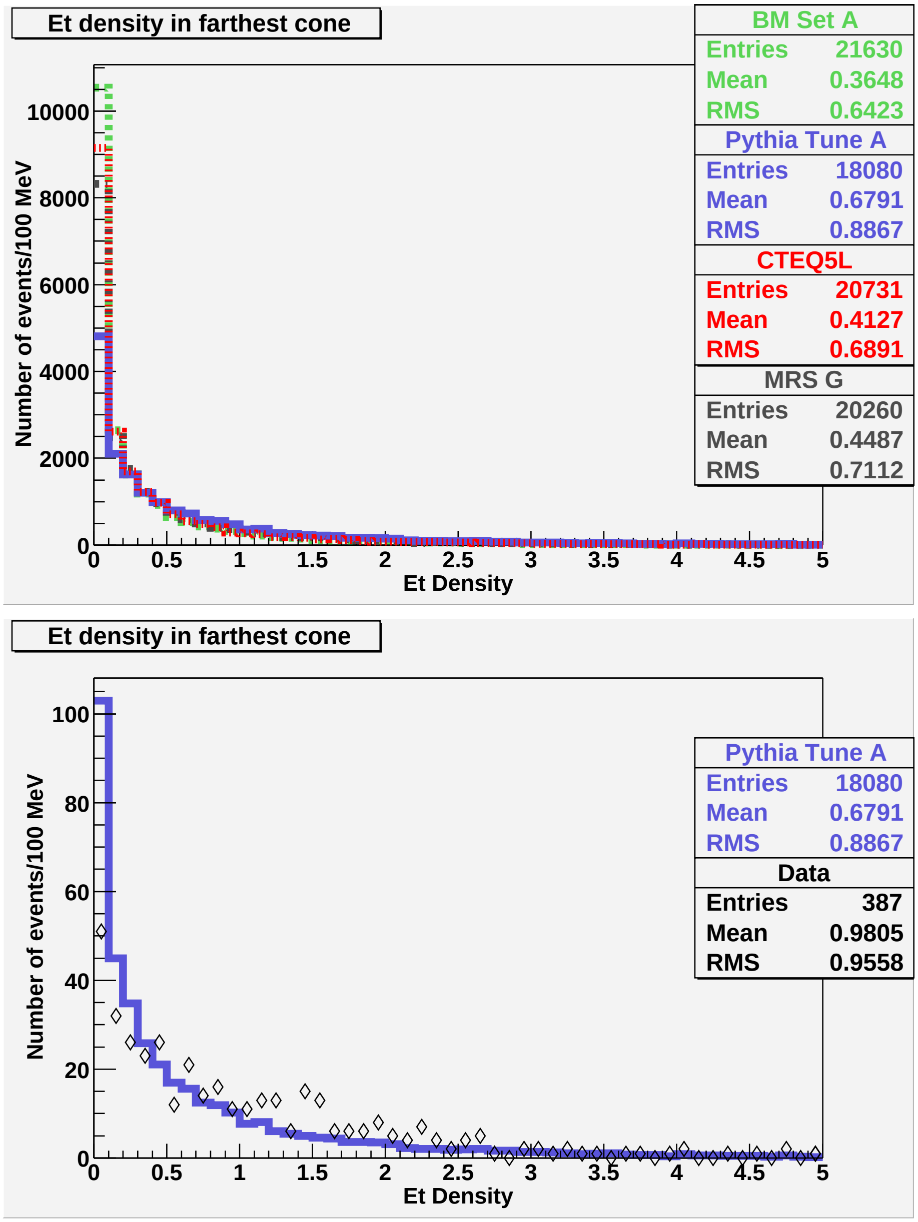

Figure 1: $E_T$ density [GeV/(unit $\eta - \phi$)] in the cone farthest from all jets in an event. Monte Carlo samples are compared on the top and data is compared with PYTHIA Tune A on the bottom. The PYTHIA Tune A entries on the latter curve are scaled by a factor of 0.0214 to facilitate comparison with the data. On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

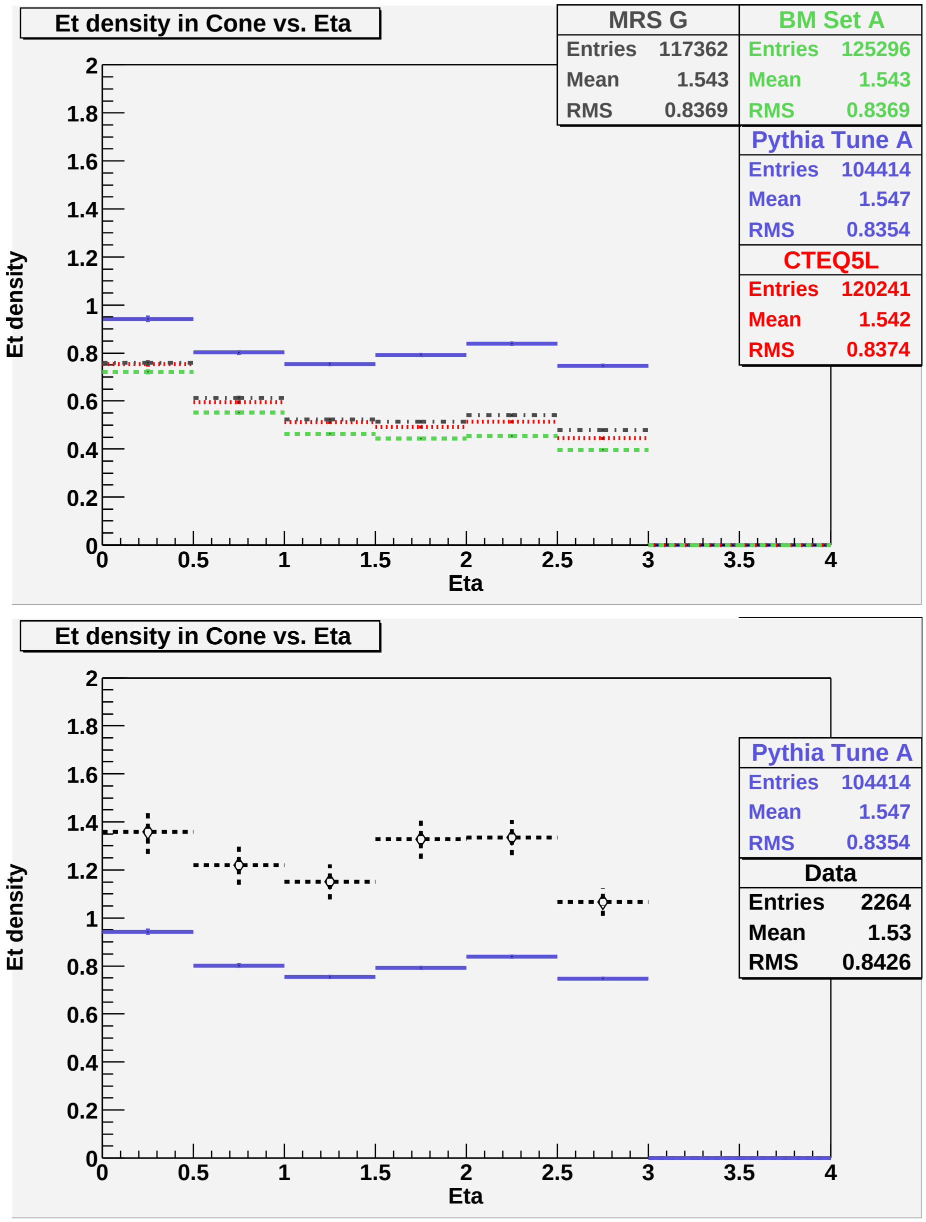

Figure 2: $E_T$ density [GeV/(unit $\eta - \phi$)]in cones of $R = 0.4$ vs $\eta$ . Monte Carlo samples are shown on the top and data on the bottom. PYTHIA Tune A is also included on the data plot to facilitate comparison. On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

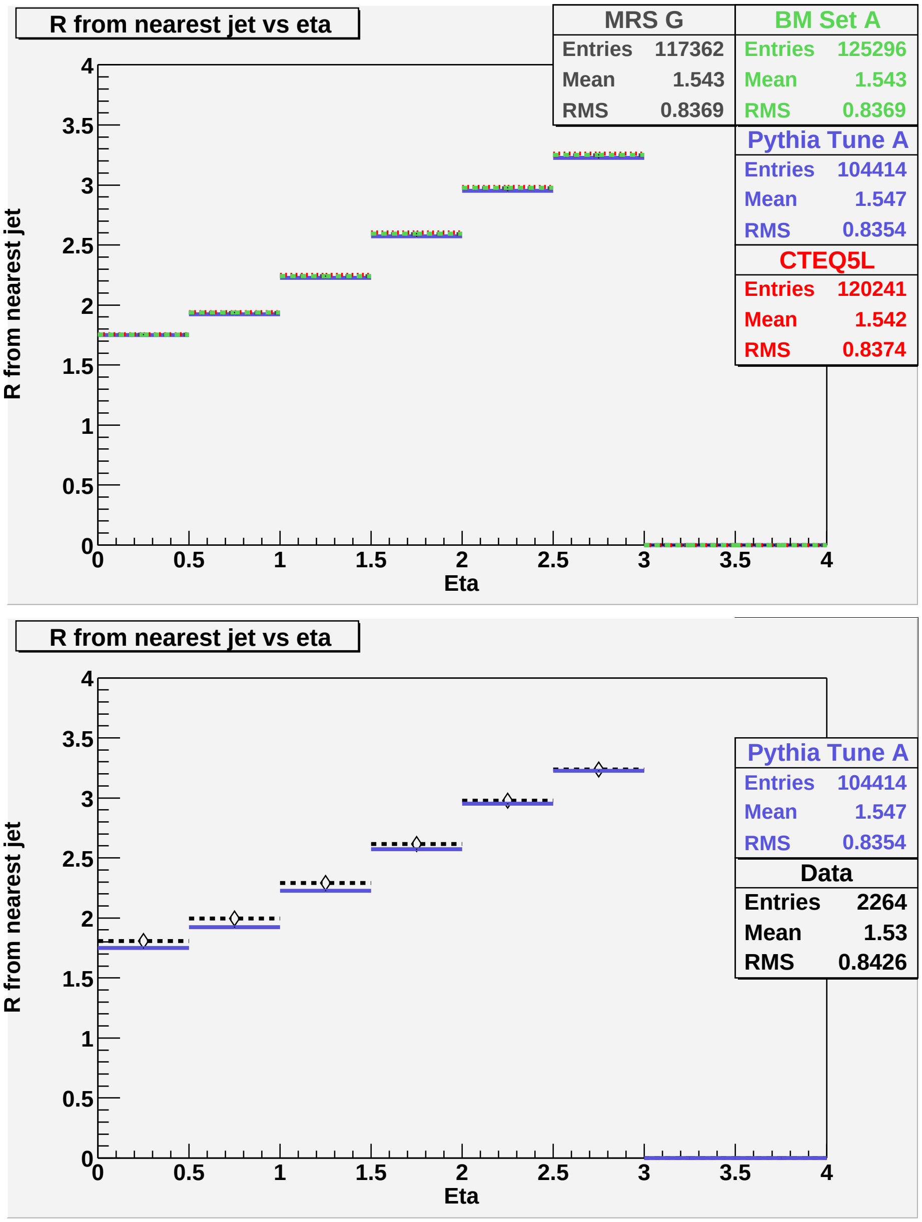

Figure 3: Average $\eta$ dependence of the distance from the cone to the nearest jet in the Monte Carlo (top) and data (bottom). On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

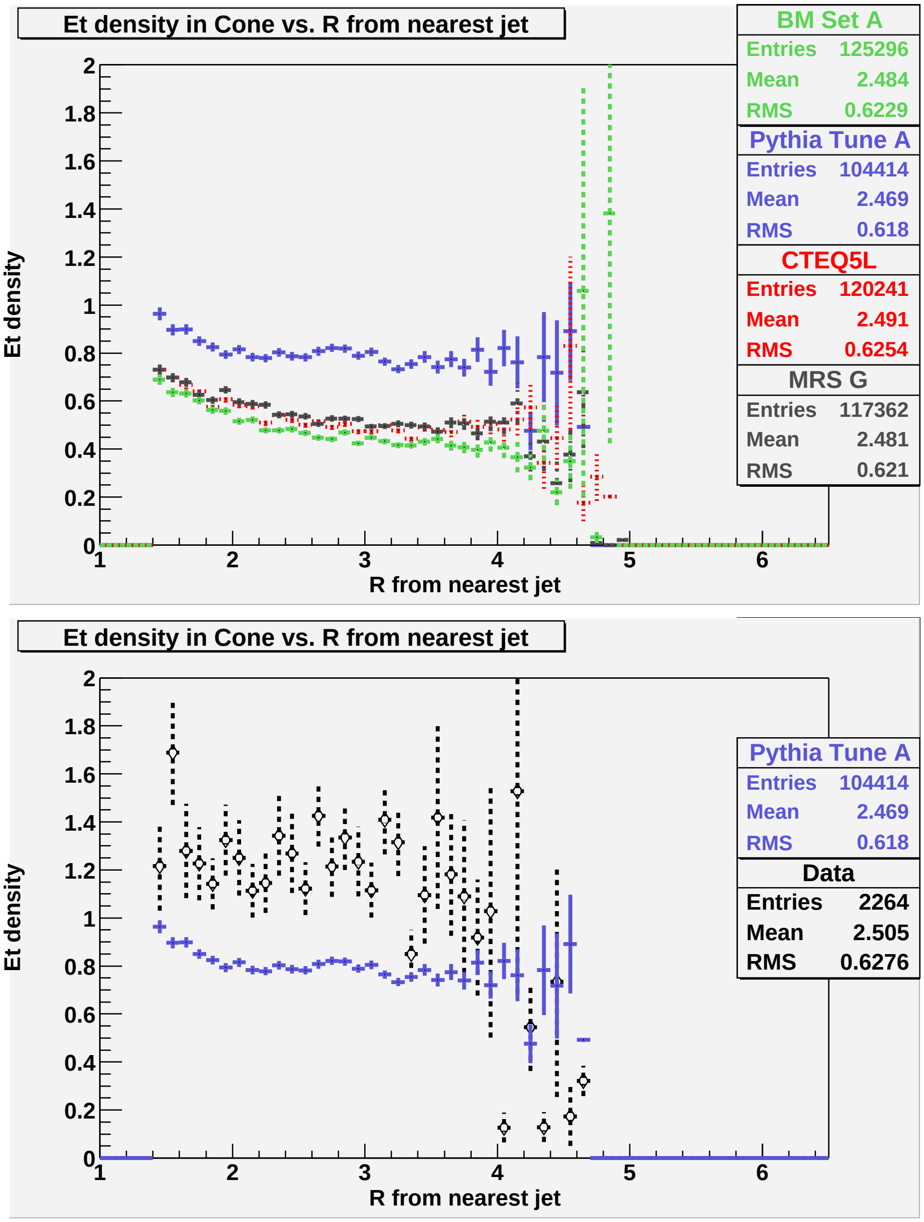

Figure 4: Dependence of the $E_T$ density [GeV/(unit $\eta - \phi$)]in a cone of $R = 0.4$ on the displacement from the nearest jet in the Monte Carlo (top) and data (bottom). PYTHIA Tune A is also included on the data plot to facilitate comparison. On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

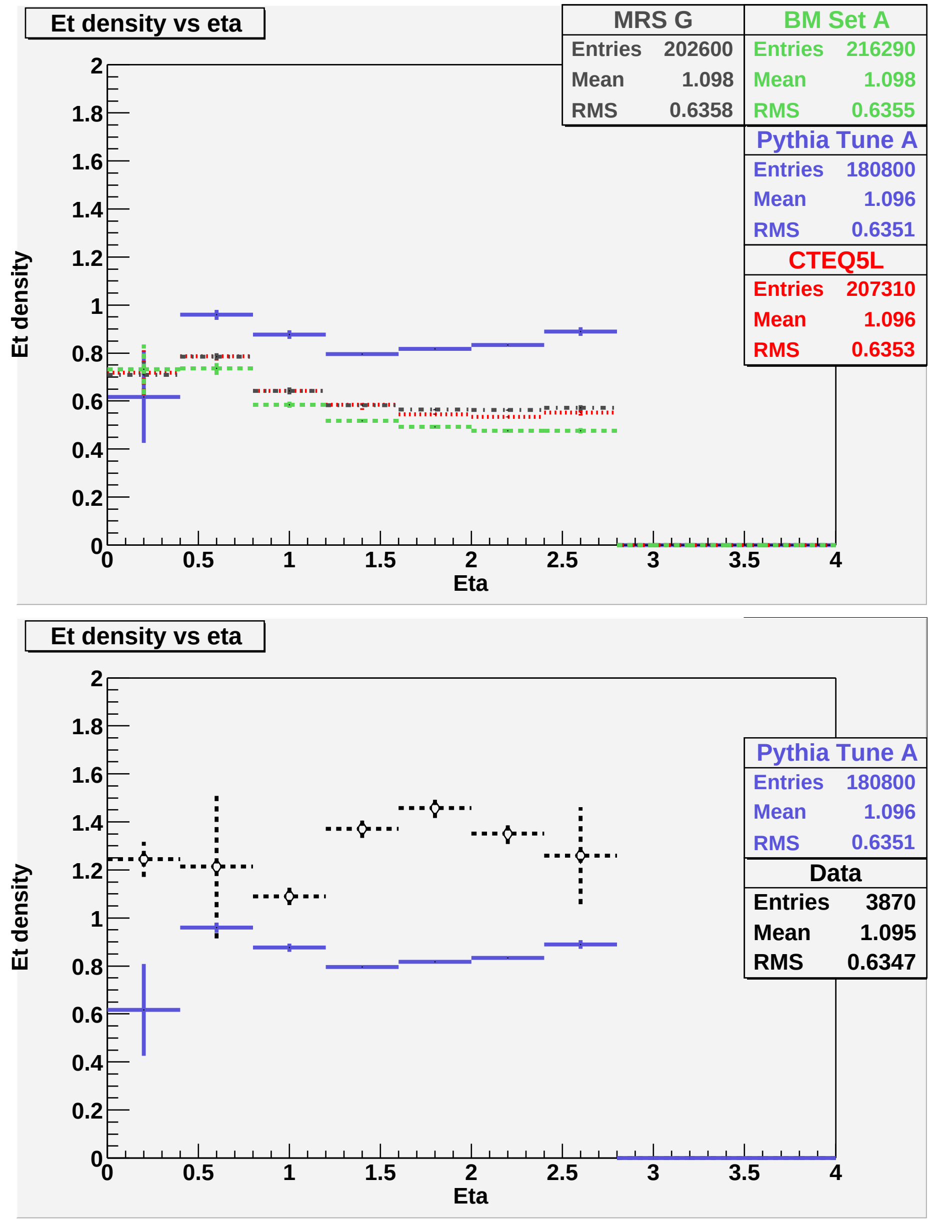

Figure 5: $E_T$ density [GeV/(unit $\eta - \phi$)] vs $\eta$ . Measurements are made in slices with width of two $\eta$ towers and the density is measured outside $R = 1.0$ from all jets. Monte Carlo samples are shown on the top and data on the bottom. PYTHIA Tune A is also included on the data plot to facilitate comparison. On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

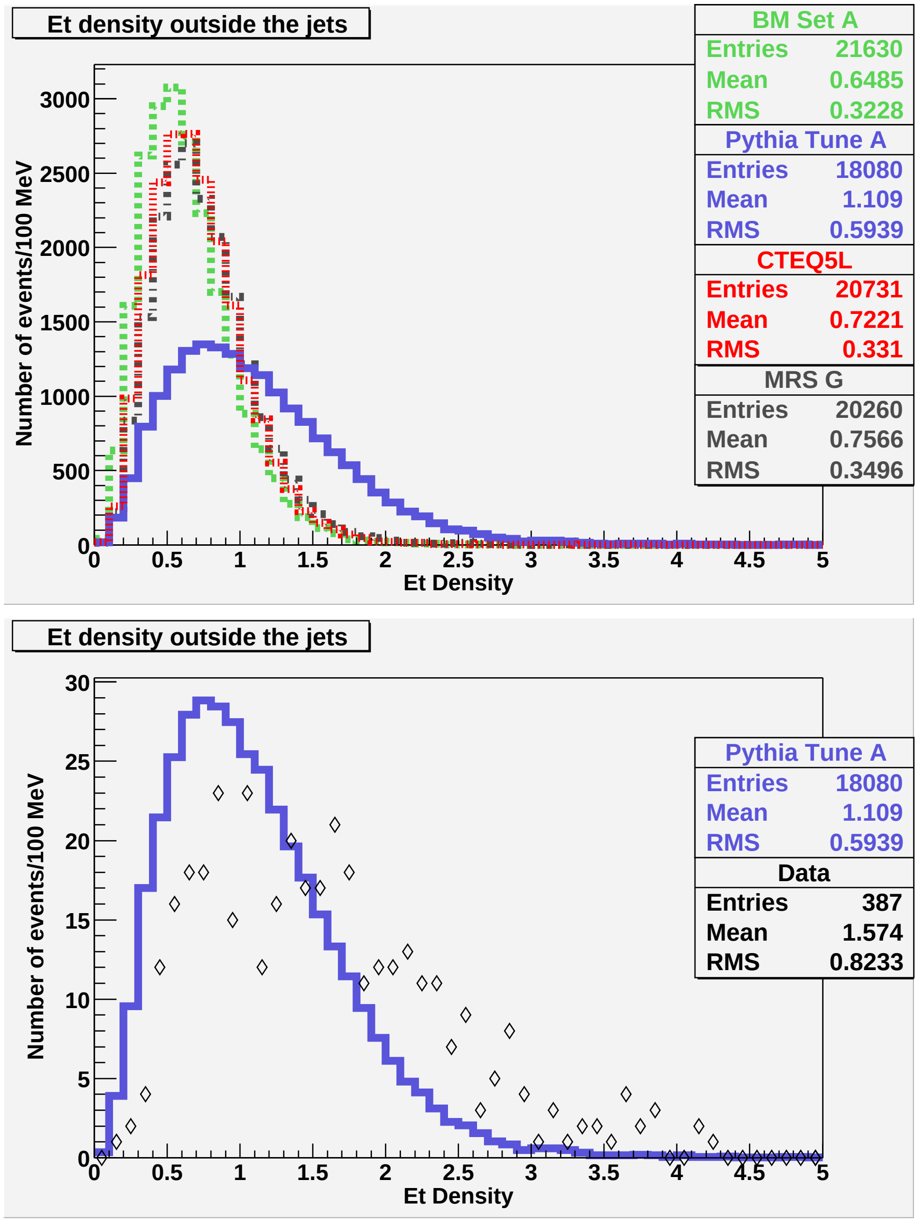

Figure 6: $E_T$ density [GeV/(unit $\eta - \phi$)] in entire $\eta - \phi$ space excluding the region that is within R=1.0 from any jet's centroid in the Monte Carlo samples (top) and data (bottom). PYTHIA Tune A is also included on the data plot to facilitate comparison. The PYTHIA Tune A entries on the latter curve are scaled by a factor of 0.0214 to facilitate comparison with the data. On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

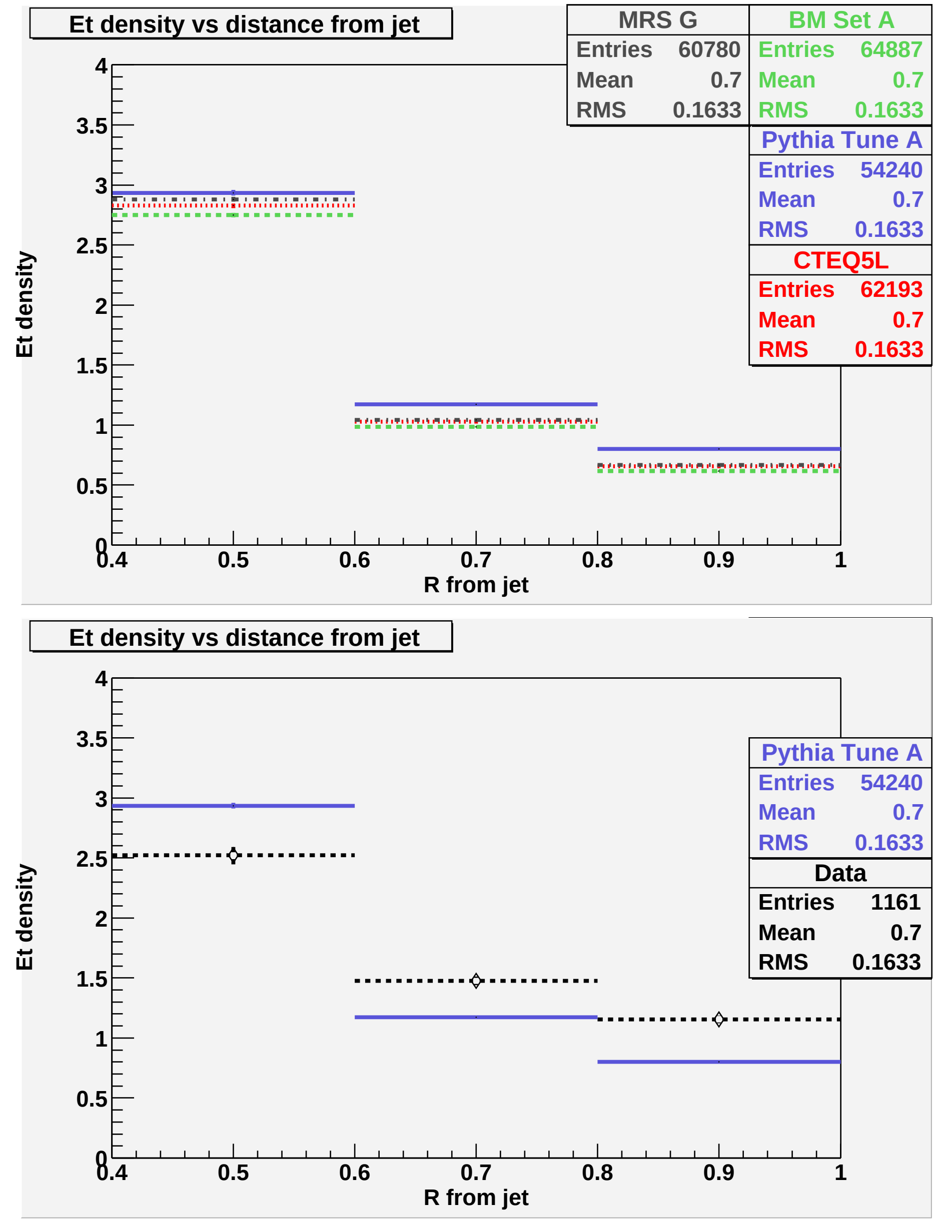

Figure 7: $E_T$ density [GeV/(unit $\eta - \phi$)] as a function of distance from the jets in the Monte Carlo samples (top) and data (bottom). PYTHIA Tune A is also included on the data plot to facilitate comparison. On the Monte Carlo plot, the red (dotted) curve corresponds to CTEQ5L, the green (dashed) to BM Set A, the grey (dot-dash) to MRS G and the purple (solid) to PYTHIA Tune A.

|  | cone in $\|\eta\| \leq 1$ | cone in $\|\eta\| > 1$ | towers in $\|\eta\| \leq 1$ | towers in $\|\eta\| > 1$ | away from jets | farthest cone |
|---|---|---|---|---|---|---|
| Data | 1.228 ± 0.056 | 1.171 ± 0.032 | 1.302 ± 0.030 | 1.245 ± 0.021 | 1.574 ± 0.042 | 0.980 ± 0.049 |
| Tune A | 0.811 ± 0.007 | 0.757 ± 0.004 | 0.956 ± 0.004 | 0.781 ± 0.002 | 1.109 ± 0.004 | 0.679 ± 0.007 |
| CTEQ5L | 0.627 ± 0.006 | 0.477 ± 0.003 | 0.778 ± 0.004 | 0.530 ± 0.002 | 0.722 ± 0.002 | 0.413 ± 0.005 |
| MRS G | 0.645 ± 0.006 | 0.498 ± 0.003 | 0.788 ± 0.004 | 0.553 ± 0.002 | 0.757 ± 0.002 | 0.449 ± 0.005 |
| BM Set A | 0.583 ± 0.006 | 0.426 ± 0.003 | 0.721 ± 0.003 | 0.479 ± 0.001 | 0.648 ± 0.002 | 0.365 ± 0.004 |

Table 1: The average $E_T$ density in GeV calculated in different methods for data and different PDFs and tunings.

|  | 0.4 - 0.6 annulus | 0.6 - 0.8 annulus | 0.8 - 1.0 annulus |
|---|---|---|---|
| Data | 2.522 ± 0.075 | 1.467 ± 0.038 | 1.155 ± 0.032 |
| Tune A | 2.786 ± 0.014 | 1.169 ± 0.005 | 0.800 ± 0.003 |
| CTEQ5L | 2.671 ± 0.013 | 1.026 ± 0.004 | 0.657 ± 0.003 |
| MRS G | 2.718 ± 0.014 | 1.039 ± 0.004 | 0.667 ± 0.003 |
| BM Set A | 2.640 ± 0.013 | 0.983 ± 0.004 | 0.616 ± 0.003 |

Table 2: The average $E_T$ density in GeV compared for data and different PDFs and tunings within various annuli of a jet's centroid.

## 4 Conclusion

Understanding the underlying event and ensuring that the Monte Carlo models it well is an important factor in understanding jet energy corrections. Here we have started looking at the underlying event in $t\bar{t}$ events, with the ultimate intention being to help improve the top mass measurement. We compared calorimeter energy flow in regions that are sensitive to the underlying event in Monte Carlo samples created with different PDFs, as well as one with PYTHIA Tune A, and a data sample.

By all measures, PYTHIA Tune A exhibits a more energetic underlying event than the other samples. All of the Monte Carlo samples considerably underestimate the underlying event energy that we see in the data. The underlying event $E_T$ density seen in PYTHIA Tune A is between 0.8 and 1.0 GeV, while the other Monte Carlo samples show a density of between 0.5 and 0.7 GeV and discrepencies of up to about 15 percent between themselves. The data shows an underlying event $E_T$ density of between 1.0 and 1.4 GeV. Additionally, there is possibly an indication that energy flow near jets is modelled incorrectly compared with the W+ $\geq 3$ jet data, though we note that more detailed studies are necessary to understand this observation.

## References

[1] R. Field, CDFNote 6548 (April 2003).

[2] J.-F. Arguin and B. Heinemann, CDFNote 6239 (February 2003).

[3] Evelyn J. Thomson, CDFNote 6403 (July 2003).

[4] We make the following selection cuts on the leptons: For electrons candidates, we require electromagetic $E_T$ greater than 20 GeV, track $p_T$ greater than 10 GeV/c, isolation fraction less than 0.1 and $|\eta| < 2$. For muons candidates, we require electromagnetic energy less than 2 GeV, hadronic energy less than 6 GeV, isolation fraction less than 0.1, track $p_T$ greater than 20 GeV and $|\eta| < 2$.