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Fragmentation, Underlying Event and Jet Shapes at the Tevatron (CDF)

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Abstract. Experimental tests of QCD processes, in particular fragmentation, underlying event and jet shape studies, are not only essential in their own right to allow an improved understanding of the theoretical models and their limitations but they are also important in searches for new physics. Recent results of such tests are presented here. All the results show good agreement between the latest theoretical models or Monte Carlo predictions.

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1 Introduction

In a hadron-hadron collision there is much more going on than simply the hard scattering processes between the partons. Soft QCD processes give rise to initial- and final-state radiation, beam - beam remnant interactions as well as possible multiple parton interactions. These are all processes which are not yet thoroughly understood.

There are many models which describe the hadronisation process and these need to be thoroughly tested in order to understand better the mechanism linking what we see in our detector, the hadrons, to what we can calculate from a theoretical point of view, the partons.

The study of fragmentation effects deals with final-state radiation along with hadronisation processes. Some recent studies will be shown in the next section. Initial- and final-state radiation along with beam - beam remnants and multiple parton interactions are what are collectively referred to as the underlying event. Some CDF Run II results will be presented in section 3. Finally, in section 4, the fractional transverse momentum distribution inside jets, known as the jet shape, is investigated in inclusive jet production.

2 Fragmentation

The reasons for studying fragmentation are numerous. Fragmentation processes are driven by soft QCD ($k_T < 1$ GeV) which are a theoretical challenge to describe as it pushes the limits of perturbative QCD theory down to $k_T \sim \Lambda_{\mathrm{QCD}}$. Moreover the hadronisation stage is not well understood from a theoretical point of view although several phenomenological models exist which can be tuned to describe the data reasonably well.

The Tevatron in particular and hadron-hadron colliders in general are particularly difficult environments in which to study fragmentation because there are many underlying processes which occur that are not directly related to the primary hard interactions. It is nevertheless interesting to study hadronisation processes at the Tevatron because the energy scale probed is higher than any previous studies and more processes become available than at lepton colliders.

The results shown in this section are for CDF Run I data. These analyses as well as some additional measurements are currently being carried out using Run II data.

One measurement of interest is the study of the particle momentum spectra of charged particles. The analysis in performed in the dijet centre of mass frame and looks at charged particles inside angular cones around the jet axis of $\sim 0.3 - 0.5$ radians. Central dijet events with a dijet mass in the range $M_{\mathrm{jj}} \sim 80 - 600$ GeV are considered.

The results for different dijet mass bins as a function of the momentum transfer are shown in figure 1. A fit to the data using both the shape and the normalisation is performed and also shown on these plots [1]. The agreement between the data and the fit is very good. The shape of the distributions is driven by a single parameter, the Next to Next to Leading Log Approximation (NNLA) effective cutoff scale, Q_{eff}. The fit for all distributions consistently

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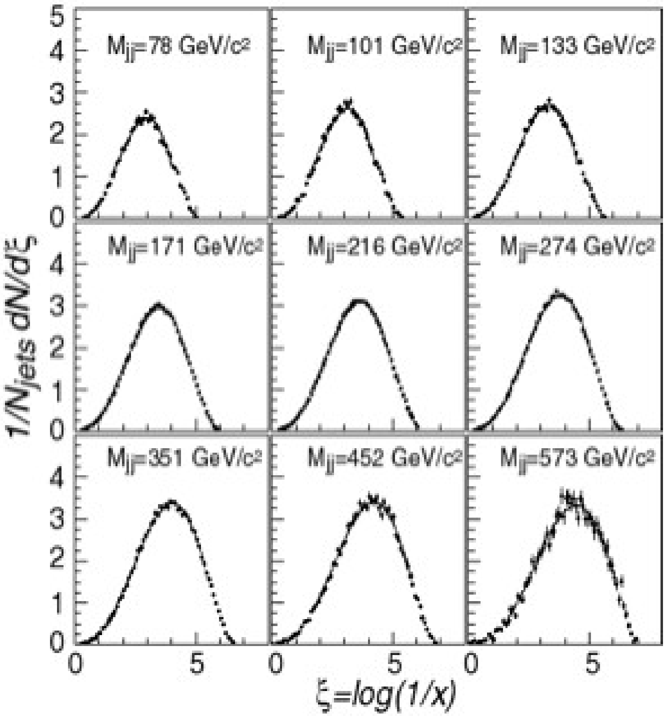

Fig. 1. Average distribution of charged particles as a function of the momentum transfer for different dijet mass bins using CDF Run I data (points). A fit to the data is also shown (smooth curve).

gives $Q_{\mathrm{eff}} = 240 \pm 40$ MeV which tells us that the k_T cut-off can be set as low as Λ_{QCD}. The normalisation constant of the distribution is related to the ratio between the number of charged hadrons and partons, which is found to be 0.56 ± 0.10.

An interesting ratio to look at when studying fragmentation is the ratio of the average number of charged particles in gluon-jets to that in quark-jets. From basic considerations, as well as when using Next to Leading Log Approximation (NLLA), one expects this ratio to be $\frac{9}{4}$. Extensions of this approximation show that this ratio should be slightly lower. This measurement is difficult to carry out without biasing the result and historically the measurements have not been in very good agreement with the different theoretical models.

The CDF analysis looks at two distinct data samples; the first is a dijet sample with dijet mass, M_{jj} , around 100 GeV and the second is a photon + jet sample with dijet mass, $M_{\gamma\mathrm{j}}$, also around 100 GeV. From Monte Carlo studies, the fraction of gluon and quark jets can be extracted for each sample. The gluon fraction is found to be $\sim 60\%$ for the first sample and $\sim 20\%$ in the latter. The number of charged particles inside a cone of $\sim 0.3 - 0.5$ radians around the jet axis is computed for both samples and from this the average number of charged particles for gluon and quark jets as well as their ratio is extracted. The results for this analysis are shown in figure 2 for two different jet energies (41 and 53 GeV) and are compared to the latest results from other experiments and different theoretical predictions. The CDF Run I results are found to be in good agreement with the latest NNLA extensions. The final result, combining the two jet energies, is found to be 1.6 ± 0.2.

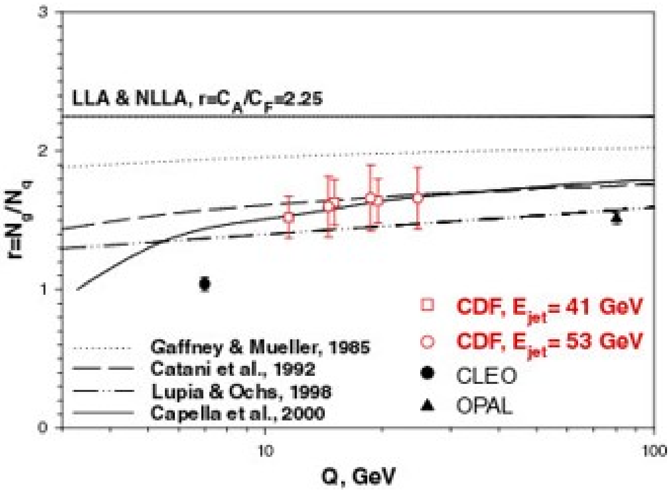

Fig. 2. Ratio of the charged particle multiplicity between gluon and quark jets for different values of jet energies at CDF, along with other recent measurements and theoretical predictions.

3 Underlying event

Charged particle correlations are important quantities to study when looking at the underlying event. There are many variables which can be studied but the charged particle density per unit (η,ϕ), $dN_{\mathrm{chg}}/d\eta d\phi$, where η is the pseudo-rapidity, as a function of the leading jet transverse energy, E_T, or the angle away from the leading jet, $\Delta\phi$, is representative of what is observed. This study uses CDF Run II data [2]. Jets are reconstructed using the JetClu cone algorithm with a cone size of 0.7. The results shown here are detector level quantities.

Event topologies are defined as follows. Leading jet events are events where the highest transverse energy, E_T, jet in the event is central ($|\eta| \leq 0.7$). A subset of these events, called back to back events, have the second highest E_T jet almost opposite in ϕ to the leading jet ($\Delta\phi \geq 5\pi/6$), they must also have a similar transverse energy ($\frac{E_{T,2}}{E_{T,1}} \geq 0.8$) and any potential third jet must have a low transverse energy ($E_{T,3} \leq 15$ GeV).

Having defined these two event topologies one can plot, as done in figure 3, the charged particle density as a function of the angle ϕ away from the leading jet. Figure 3 shows this distribution in a polar plot, where the charged particle multiplicity is shown in the radial direction, for a particular range of E_T of the leading jet ($30 \leq E_T \leq 70$ GeV). The distance between each concentric circle repre-

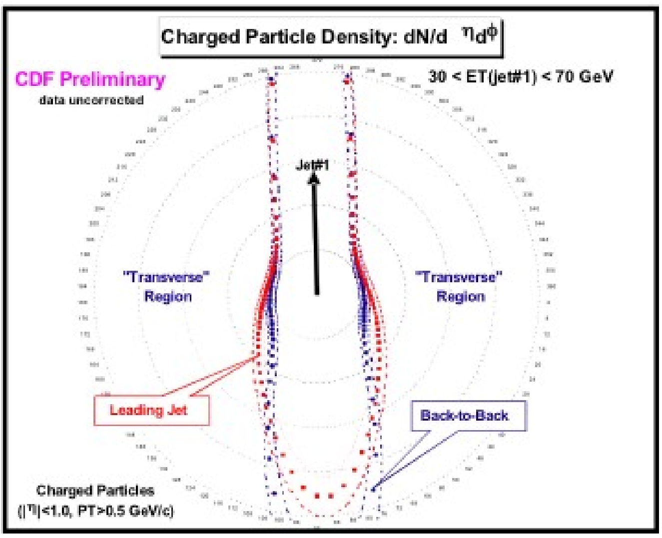

Fig. 3. Polar plot of the charged particle density for leading jet and back to back events. The concentric markers are $\frac{dN_{\mathrm{chg}}}{d\eta d\phi} = 0.5$ apart.

sents a charged particle density interval of 0.5.

One can see that for back to back events the charged particles are strongly aligned with the leading jet direction with a more or less constant charged particle density of about 0.5 in the rest of the ϕ-space. For leading jet events this distribution is slightly less one-dimensional, with a larger spread of charged particles. This is probably due to the formation of three or more jet events.

One can define two spatial regions which are transverse to the leading jet direction ($\frac{1}{3}\pi \leq |\Delta\phi| \leq \frac{2}{3}\pi$) and look at correlations in the charged particle densities in these regions (called here transverse charged particle densities). Figure 4 shows the difference between the transverse charged particle densities in these two regions for both the leading jet and the back to back samples as a function of the transverse energy of the leading jet. This quantity is sensitive to the initial- and final-state radiation components for the underlying event. The data obtained is compared to Pythia Tune A and Herwig. Pythia Tune A was tuned to the underlying event using CDF Run I data and it is interesting to see that this tune still seems to describe Run II data very well. The agreement is not as good with the Herwig Monte Carlo; Herwig does not have multiple parton interactions and has not been tuned to CDF data. This shows how important the underlying event and other soft QCD processes are in the description of the data.

Other similar quantities have also been studied such as the distribution of the smallest of the two transverse charged particle densities, which is very sensitive to the beam-beam remnant component of the underlying event, or the average value of the transverse charged particle densities. In all cases the agreement between the data and Pythia Tune A is very good.

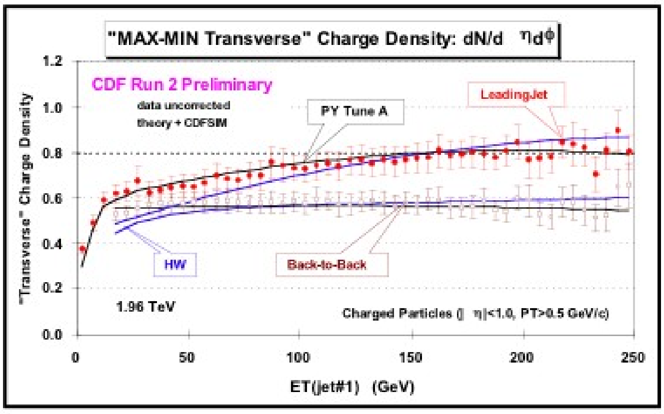

Fig. 4. Difference in the transverse charged particle multiplicity between the two transverse regions as a function of E_T of the leading jet.

4 Jet Shapes

The fractional transverse momentum distribution inside jets as a function of the distance from the jet axis is known as the jet shape. This distance is measured in (ϕ, Y)-space where Y, the rapidity, is defined as $Y = 0.5\ln(\frac{E+p_T}{E-p_T})$. The integrated jet shape is defined as:

$$\Psi(r) = \frac{\int_0^r p_T(r')dr'}{\int_0^R p_T(r')dr'}$$

where by definition $\Psi(r = R) = 1$.

In this analysis, the shapes are computed at calorimeter level and corrected back to hadron level [3]. The MidPoint cone algorithm with a cone size of 0.7 is used to reconstruct the jets. The jets are central, with $0.1 \leq Y \leq 0.7$ The results shown in figure 5 use $170\,\mathrm{pb}^{-1}$ of CDF Run II data and are binned in jet p_T regions which span the whole spectrum from 37 to 380 GeV.

As expected, it is found that the shapes get narrower as the jet's transverse momentum increases. This is due to perturbative QCD effects related to the running of the strong coupling as well as the fact that the mixture of quark- and gluon-jets in the final state changes with p_T. This second effect can be seen when comparing the shapes with those obtained using Pythia Tune A for gluon- and quark-jets separately. Figure 5 (top) shows the fractional p_T outside a cone of $0.3/R$ as a function of p_T of the jet. It shows that jets originate mainly from gluons (dashed line) at low p_T and from quarks (dotted line) at high p_T.

The same evolution of the shape with jet p_T is compared to different Monte Carlo models in figure 5 (bottom). The best agreement is found with Pythia Tune A. It is very encouraging to see that the tune which describes

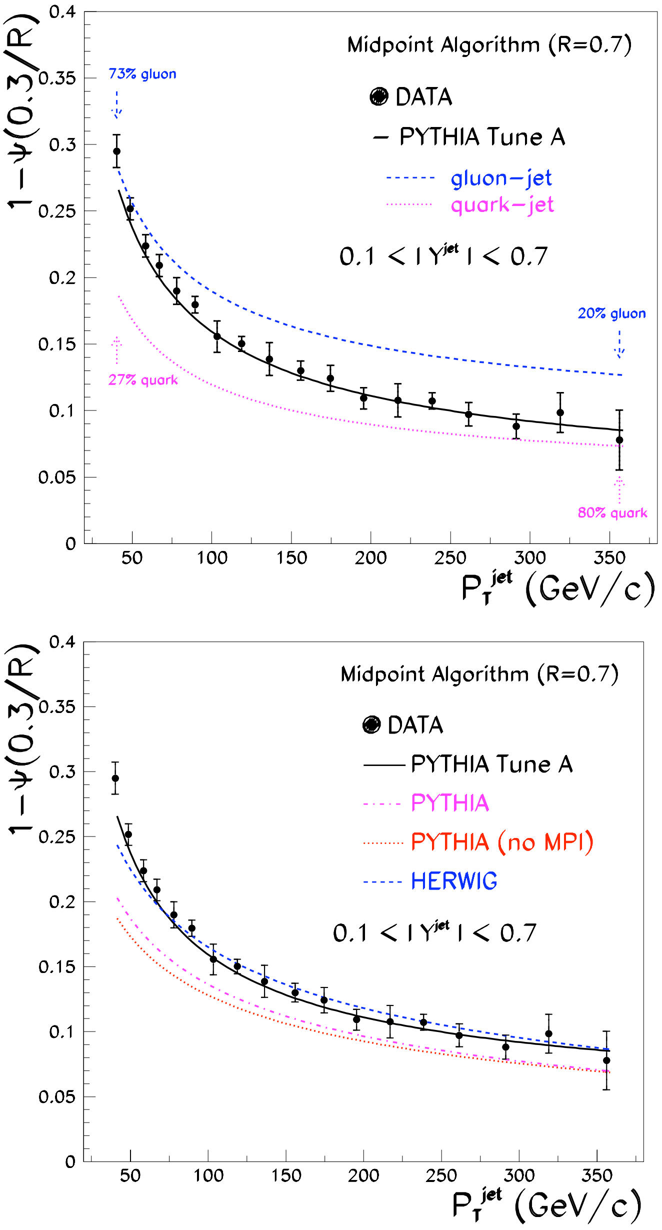

Fig. 5. Fractional p_T outside a cone of $0.3/R$ as a function of the jet p_T. The data is compared to Pythia Tune A Monte Carlo as well as the shapes expected for quark and gluon jets (top) and the shapes obtained from different theoretical models (bottom)

so well the underlying event also describes well other quantities described by QCD, such as the jet shapes. Herwig, despite not having multiple parton interactions, still describes the data reasonably well (dashed line). The importance of the tuning of Pythia can be seen by comparing the data to the default Pythia (dotted-dashed line). Moreover, the inclusion of multiple parton interactions in the models is also important, as shown by the difference between the default Pythia with no multiple parton interactions (dotted line) and the data.

5 Conclusions

A number of different measurements of QCD processes at the Tevatron have been presented here. All have shown that the theory and models behind processes such as soft radiation, hadronisation, fragmentation, to name but a few, describe the data very well. In particular the use of the Pythia Tune A Monte Carlo was found to be very important in the understanding of some processes such as the jet shapes and the underlying event.

6 Acknowledgements

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