Recent Results on Jet Fragmentation from CDF

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RECENT RESULTS ON JET FRAGMENTATION FROM CDF

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In this paper, the most recent results on jet fragmentation obtained at the Collider Detector at Fermilab Tevatron are presented. The multiplicity and momentum distribution of charged particles inside jets in dijet events are compared to the predictions of the Modified Leading Log Approximation complemented with the hypothesis of Local Parton-Hadron Duality. Values for the two parameters of the model are extracted, the cut-off scale \( Q_{\text{eff}} = 230 \pm 40 \text{ MeV} \) and the rate of parton-to-hadron conversions \( K_{\text{LPHD}}^{\text{charged}} = 0.56 \pm 0.10 \). A fit of the data for the ratio of multiplicities in gluon and quark jets \( r \), where \( r \) is treated as a free parameter, results in \( r = 1.9 \pm 0.5 \). Also, we compare the charged particle multiplicities in dijet and \( \gamma \)-jet events. The comparison allows for an extraction of a model-independent ratio of multiplicities in gluon and quark jets. We report \( r = N_g/N_q = 1.61 \pm 0.11(\text{stat}) \pm 0.28(\text{syst}) \) for \( E_{\text{jet}} = 40 \text{ GeV} \).

1 Introduction and Theoretical Background

Perturbative QCD calculations, carried out in the framework of the Modified Leading Log Approximation \(^1\) (MLLA), complemented with the Local Parton-Hadron Duality Hypothesis \(^2\) (LPHD), predict the shape of the momentum distribution, as well as the total inclusive multiplicity, of particles in jets. The MLLA is an asymptotic calculation, which proves to be infrared stable, in the sense that the model cutoff parameter \( Q_{\text{eff}} \) can be safely pushed down to \( \Lambda_{\text{QCD}} \). LPHD is responsible for the hadronization stage and implies that hadronization is local and occurs at the end of the parton shower development. In its simplest interpretation, the model has one parameter \( K_{\text{LPHD}} \), the rate of parton-to-hadron conversion:

\[
N_{\text{hadrons}} = K_{\text{LPHD}} \times N_{\text{partons}}.
\] (1)

In the most favorable scenario, \( K_{\text{LPHD}} \sim 1 \). If only charged particles were observed, one would expect \( K_{\text{LPHD}}^{\text{charged}} \) to be between 1/2 and 2/3. If the MLLA cutoff parameter \( Q_{\text{eff}} \) is indeed low, this would allow the inclusion of hadrons with low transverse momentum, which constitute the majority of all hadrons in jets and could not be controlled in ordinary pQCD with a conventional cutoff scale of the order of 1 GeV.
In MLLA\textsuperscript{3}, momentum distributions and multiplicities in quark and gluon jets in a restricted cone of size $\theta_c$ around the jet axis are functions of $E_{jet} \sin \theta_c/Q_{eff}$ and differ by a simple factor $r$:

$$N^{q-jet}(\xi) = \frac{1}{r} N^{g-jet}(\xi), \text{ where } \xi = \log \frac{1}{x}, x = p_{\text{track}}/E_{jet}$$

(2)

Jets at the Tevatron are a mixture of quark and gluon jets. Therefore,\n
$$N_{k=charge}(\xi) = K_{LPHD}^{charge}(\epsilon_g + (1-\epsilon_g)\frac{1}{r})F_{n_{MLLA}}^{q-jet}(\xi) = KN_{part}^{g-jet}(\xi)$$

(3)

where $\epsilon_g$ is the fraction of gluon jets in the events, the factor of $1/r$ reflects the difference between gluon and quark jets, and, finally, factor $F_{n_{MLLA}}$ accounts for the next-to-MLLA corrections to the gluon spectrum. Theoretical calculations\textsuperscript{4} predict somewhat different values of $F_{n_{MLLA}}$, but all agree that $F_{n_{MLLA}}$ has almost no dependence on the jet energy in the region relevant to this analysis. We choose the average of the results above and use the difference between predictions as a theoretical error: $F_{n_{MLLA}} = 1.3 \pm 0.2$. The same papers predict the value of $r$ to be between 1.5 and 1.8.

2 Analysis of the Dijet Data

We used data collected by the CDF experiment during the 1993-1995 running period. For this analysis, we selected events with two jets well balanced in
For determination of the yield and branching ratio, the CDF calorimeter is used to measure the energy deposited by the charged particles. The CDF calorimeter is a sampling calorimeter with a lead-scintillator sandwich. The energy deposition in each layer is measured and the total energy is calculated.

The energy resolution is determined by the fluctuations in the energy deposition and the fluctuations in the readout electronics. The energy resolution is typically a few percent for hadrons and a few percent for photons.

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From the individual fits of the momentum distributions for 27 combinations of dijet mass and cone-sizes, we extracted values for \( Q_{eff} \) and found that \( Q_{eff} \) is reasonably stable, but there was a slight trend for decreasing \( Q_{eff} \) with larger dijet masses and smaller cone-sizes (see Fig. 2(left)). We conclude that \( Q_{eff} \) is not absolutely universal, which may be an indication of the higher order effects. However, the scale of the deviations was very moderate, suggesting that these effects are not large. We report the value of \( Q_{eff} = 230 \pm 40 \text{ MeV} \).

Eq. (3) suggests that analysis of the fitted parameter K can allow extraction of both \( K_L^{charged} \) and r. Note that if the extracted parameter K for 9 dijet masses for a fixed cone-size is plotted as a function of the fraction of gluon jets in the corresponding dijet mass bin, one should expect a linear dependence. The fractions of gluon jets \( \epsilon_g \) can be extracted using Herwig 5.6 with various parton distribution function sets (PDFs). This procedure is safe as the dijet production at these energies is a well calculable leading order QCD process (the requirement of a strict balance of the jet energies applied to the data eliminates three-jet events). Fig. (3) shows this dependence and
the fit results. We finally report $K_{LP/HD}^{\text{charged}} = 0.56 \pm 0.10$ and $r = 1.9 \pm 0.5$.

In our earlier studies of the inclusive charged particle multiplicities, we used the integral version of Eq. (3), and the result of the fit is shown in Fig. 2(right). It is important that the value of $K_{LP/HD}$ is in good agreement with the expectation of roughly one-to-one conversion rate of partons into hadrons. Fig. 3 shows the fits of the $K$ vs $\epsilon_g$ for three available cone-sizes. It is remarkable that the two results are in such a good agreement even though the result shown in Fig. 2(right) relies only on the integrated multiplicity and is completely independent of the exact shape of the distribution.

3 Model-independent Measurement of $r$

We compared the multiplicity in dijet and $\gamma$-jet events (the data selection was similar in both cases) to extract a model-independent measurement of the ratio of multiplicities in gluon and quark jets, $r = N_g/N_q$. These data samples have very different fraction of gluon jets for the jet energies 40-60 GeV (roughly 60% for dijets and 25% for $\gamma$-jet).

Measurement of the multiplicities of charged particles was performed in exactly the same way for both datasets (see the previous section). The only difference was that we had to subtract the contribution of fake $\gamma$-jet events. Fake $\gamma$-jet events mostly come from rare dijet events when one of the jets fluctuates into low charged multiplicity, e.g. when one or two neutral pions carry most of the jet energy and are misidentified as a photon. Even though
such fluctuations are rare, the large dijet production cross-section makes the rate of such occurrences comparable to the one of real γ-jet events. A special study was performed to understand properties of these fake events in order to properly compensate for presence of fakes.

The multiplicities measured for each of the samples and a knowledge of the gluon jet fractions (using Herwig Monte Carlo and several choices of the PDF sets) allowed us to extract the final ratio \( r \). Fig. 4(left) shows the measured \( r \) as a function of the jet hardness \( (E_{jet} \sin \theta_e) \) along with earlier experimental data and theoretical predictions. We report \( r = 1.61 \pm 0.11 \text{ (stat)} \pm 0.28 \text{ (syst)} \) for \( E_{jet} = 40 \text{ GeV} \) and \( r = 1.65 \pm 0.13 \text{ (stat)} \pm 0.20 \text{ (syst)} \) for \( E_{jet} = 53 \text{ GeV} \), in good agreement with the result obtained in the framework of MLLA (and presented in previous section).

Fig. 4(right) shows the measured ratio of momentum distributions of charged particles in gluon and quark jets. Note the large ratio in the soft (large \( \xi \)) part of the spectrum, where MLLA is applicable. The fall of the ratio towards the hard side of the spectrum is caused by energy conservation as gluon jets have twice more particles in the soft region, which carry a larger fraction of the jet energy as compared to the quark jets.

**Conclusion**

The presented results support the perturbative nature of jet fragmentation. The measured value of \( Q_{eff} = 230 \pm 40 \text{ MeV} \) allows a consistent description of the majority of particles produced in jets. Measurements of \( K_{charged}^{LPHD} = 0.56 \pm 0.10 \) and \( r = 1.9 \pm 0.5 \) are not only self-consistent within the model, but also well agree with the model-independent result \( r = 1.61 \pm 0.11 \pm 0.28 \).

**References**