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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 the two parameters of the model are extracted, the cut–off scale $Q_{eff} = 230 \pm 40$ MeV and the rate of parton–to–hadron conversions $K_{LPHD}^{charged} = 0.56 \pm 0.10$. 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 γ-jet events. The comparison allows for an extraction of a model–independent ratio of multiplicities in gluon and quark jets. We report $r = N_g/N_q = 1.61 \pm 0.11(stat) \pm 0.28(syst)$ for $E_{jet} = 40$ 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_{eff} can be safely pushed down to Λ_{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_{LPHD}, the rate of parton-to-hadron conversion:

$$N_{hadrons} = K_{LPHD} \times N_{partons}. \quad (1)$$

In the most favorable scenario, $K_{LPHD} \sim 1$. If only charged particles were observed, one would expect $K_{LPHD}^{charged}$ to be between 1/2 and 2/3. If the MLLA cutoff parameter Q_{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.

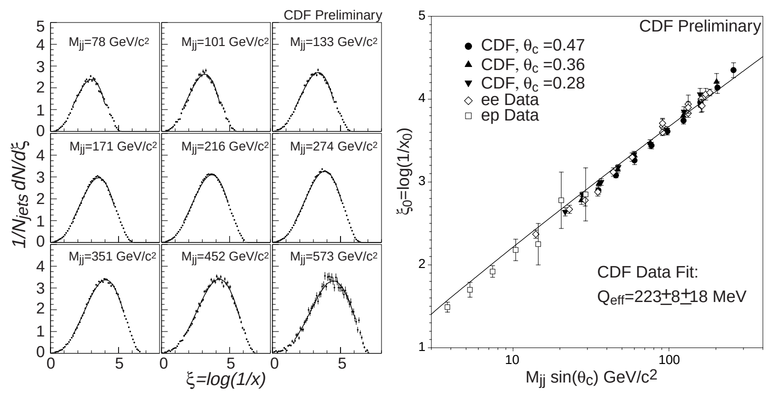

Figure 1. Left: Momentum distribution of charged particles in jets within cone of $\theta_c = 0.47$ rad around the dijet axis. Data was fitted with the MLLA spectrum for Q_{eff} and K. Right: Peak position of the momentum distribution vs $M_{jj} \sin\theta_c$ verifies the scaling predicted by MLLA.

In MLLA [3], momentum distributions and multiplicities in quark and gluon jets in a restricted cone of size θ_c around the jet axis are functions of $E_{jet} \sin\theta_c / Q_{eff}$ and differ by a simple factor r:

$$N^{q-jet}(\xi) = \frac{1}{r} N^{g-jet}(\xi), \text{ where } \xi = \log\frac{1}{x}, x = p_{track}/E_{jet} \quad (2)$$

Jets at the Tevatron are a mixture of quark and gluon jets. Therefore,

$$N^{charged}_{hadrons}(\xi) = K^{charged}_{LPHD}(\epsilon_g + (1-\epsilon_g)\frac{1}{r}) F^{nMLLA} N^{g-jet}_{part}(\xi) = K N^{g-jet}_{part}(\xi) \quad (3)$$

where ϵ_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^{nMLLA} accounts for the next-to MLLA corrections to the gluon spectrum. Theoretical calculations [4] predict somewhat different values of F^{nMLLA}, but all agree that F^{nMLLA} 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^{nMLLA}=1.3±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

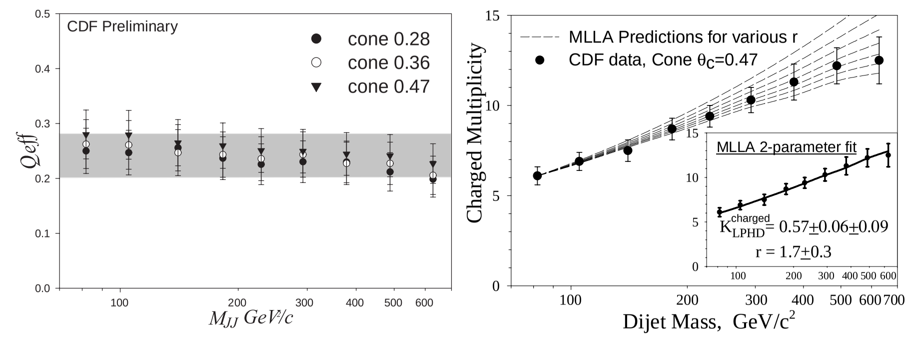

Figure 2. Left: Result of the fits of the momentum distributions for the MLLA cut–off parameter Q_{eff}. The data points correspond to the available combinations of the dijet mass and cone–sizes. Right: Measured multiplicity of charged particles in jets for cone–size θ_c=0.47. The result is fitted for LPHD parameter K_{LPHD} and the ratio of charged particle multiplicities in gluon and quark jets (insert).

transverse energy. Both jets were required to be in the central region of the detector to ensure reliable tracking reconstruction. To avoid biases, third and fourth jets were allowed if soft ($|\vec{E}_{T_{jet3}} + \vec{E}_{T_{jet4}}| \leq 5\% \times |\vec{E}_{T_{jet1}} + \vec{E}_{T_{jet2}}|$). The data are subdivided into 9 dijet mass bins (corrected mean values of the dijet masses are ranging from 80 to 560 GeV).

Tracks are counted in restricted cones of sizes 0.28, 0.36 and 0.47 around the jet axis. Corrections are applied to compensate for detector inefficiencies and physics effects. First, track vertex cuts are applied to eliminate γ–conversions, K_S and Λ decays. Then we correct for tracking inefficiencies and the underlying event contribution is subtracted. Finally, a few small corrections were applied to remove the remaining conversions and compensate for calorimeter resolution in measuring the jet energy.

Fig. 1(left) shows the inclusive mometum distribution of charged particles in jets for the 9 dijet mass bins for the largest cone-size of 0.47. The data was fitted with Eq.(3) for the parameters Q_{eff} and K (see Eq.(3)). The visual agreement is good; however, the χ^2 is generally large indicating the importance of the higher order and hadronization effects. We separately fitted the position of the peak of the momentum distribution for 27 combinations (9 dijet mass bins × 3 cone sizes). In MLLA, the peak position depends on Q_{eff} and is predicted to obey the $E_{jet} \sin\theta_c / Q_{eff}$ scaling. Fig. 1(right) shows the dependence of the peak position on $M_{jj} \sin\theta$ (e^+e^- and ep data is shown as well). Clearly, the predicted scaling is present in data.

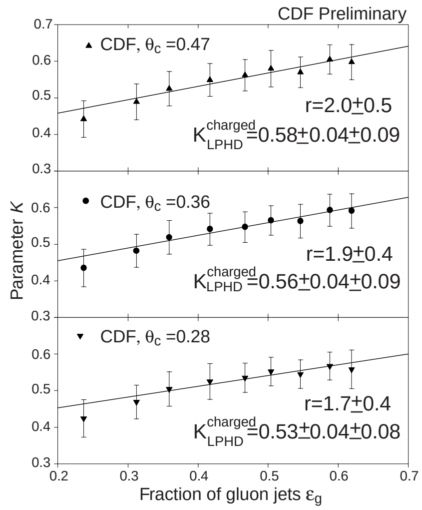

Figure 3. Parameter K extracted from the fits of momentum distributions for each dijet mass bin as a function of the fraction of gluon jets in the bin. Parton–to–hadron conversion ratio K_{LPHD} and the ratio of multiplicities in gluon and quark jets is extracted from a linear fit. Three plots correspond to three cone-sizes θ_c.

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 $Q_{eff} = 230 \pm 40$ MeV.

Eq.(3) suggests that analysis of the fitted parameter K can allow extraction of both $K_{LPHD}^{charged}$ 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 ϵ_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

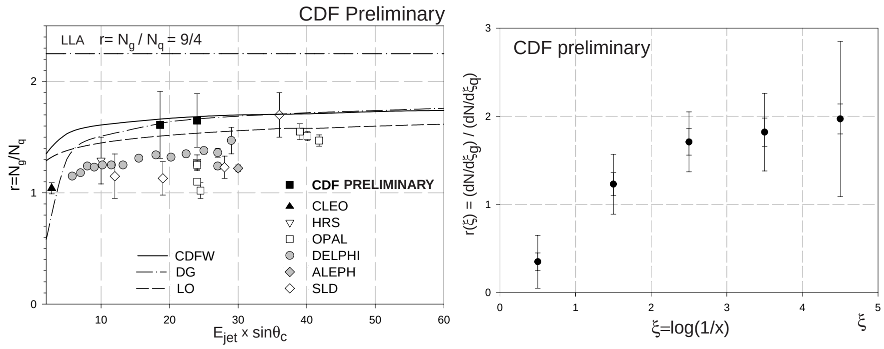

Figure 4. Left: Model–independent ratio r of multiplicities of charged particles in gluon and quark jets as a function of jet hardness. Also shown are earlier experimental results and theoretical predictions. Right: The ratio of momentum distributions of charged particles in gluon and quark jets for the bin with mean jet energy of 40 GeV.

the fit results. We finally report $K_{LPHD}^{charged} = 0.56 \pm 0.10$ and $r = 1.9 \pm 0.5$.

In our earlier studies of the inclusive charged particle multiplicities [5], 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_{LPHD} 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 ϵ_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 γ-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 γ-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 γ-jet events. Fake γ–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 occurances 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 ($E_{jet} \sin\theta_c$) along with earlier experimental data and theoretical predictions. We report r=1.61±0.11($stat$) $\pm$ 0.28($syst$) for $E_{jet} = 40$ GeV and $r = 1.65 \pm 0.13(stat) \pm 0.20(syst)$ for $E_{jet} = 53$ 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 ξ) 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 $Q_{eff} = 230 \pm 40$ 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 $r = 1.61 \pm 0.11 \pm 0.28$.

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