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JET FRAGMENTATION STUDIES AT TEVATRON

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The particle multiplicity and momenta distributions within a jet, measured by CDF collaboration, are in good agreement with the Modified Leading Logarithms Approximation (MLLA) predictions. The MLLA cut-off scale is found to be $Q_{\text{eff}} = 240 \pm 40$ MeV. In this framework, the measured value of ratio of multiplicities in gluon and quark jets is $r = 1.8 \pm 0.4$. The ratio of charged hadrons multiplicity to the predicted parton multiplicity $K^{charged}_{LPHD} = 0.58 \pm 0.10$. The ratio of the charged particle multiplicity in quark and gluon jets is determined to be $1.74 \pm 0.11 \pm 0.07$ using di-jet and photon-jet data independent of MLLA formalism. The ratio of additional subjet multiplicities in quark and gluon jet $R = 1.91 \pm 0.04\,(\text{stat})\,^{+0.23}_{-0.19}(\text{sys})$. is extracted from 1800 GeV and 630 GeV data by DØ collaboration which is consistent with Herwig Monte Carlo predictions.

1 Charge and Momenta distributions within a jet

Quantum Chromo-dynamics (QCD) is very successful in describing the hadronic process with astonishing accuracy at large momentum transfer (short distance) scales where the QCD coupling constant is small and a first few terms in perturbation theory give sufficiently accurate predictions. However, at very large distances, the coupling constant becomes large and the perturbative calculation can not be performed. The jet fragmentation can be thought as a two stage process. Immediately after hard interaction, the parton develops a shower through cascade emission of partons. This stage can be described well within perturbative QCD framework. At large time/distance scale, when partons hadronize, the process becomes non-perturbative and need phenomenological treatment. The boundary between these two stages is fuzzy and characterized by some cut off scale which may be as low as Λ_{QCD}. At large k_T, transverse momentum of particle with respect to initial parton, pQCD based shower Monte Carlo programs, *e.g.* Herwig, with phenomenological hadronization model describe the data well but in low k_T region, where most of the hadrons are produced, one need to sum the pQCD to all orders to adequately describe the data.

In MLLA, the terms in powers of leading logarithms are summed to all orders while taking care of interference between various emissions (angular ordering). The result is an infra-red stable expression for parton multiplicity and momentum distribution, valid down to a cut off parameter Q_{cutoff}, to be determined from experiment. In this framework, the ratio of hadron multiplicities in quark and gluon jets is given by ratio of their color charges $r = N_g/N_q = C_A/C_F = 9/4$. The next-to-MLLA (nMLLA) corrections[2] increase the multiplicity by a scale factor of 1.2–1.4, depending on the calculation, almost independent of initial parton energy. At nMLLA, the multiplicity ratio, $r = 1.5 - 1.7$ for a 100 GeV jet, with a weak energy dependence. According to local parton hadron duality hypothesis (LPHD), the partons hadronize locally and thus, the hadrons remember parton distributions. The number of hadrons is given by

$$N_{hadron} = K_{LPHD} \times N_{partons}$$

where K_{LPHD} is a parameter of order unity to be determined from the experimental data. For charged hadrons, $K_{LPHD} \sim 2/3$.

Well balanced, central di-jet events with dijet mass $80 < M_{JJ} < 630$ GeV, collected during 1993-95 by CDF collaboration at Fermilab Tevatron, are used to measure

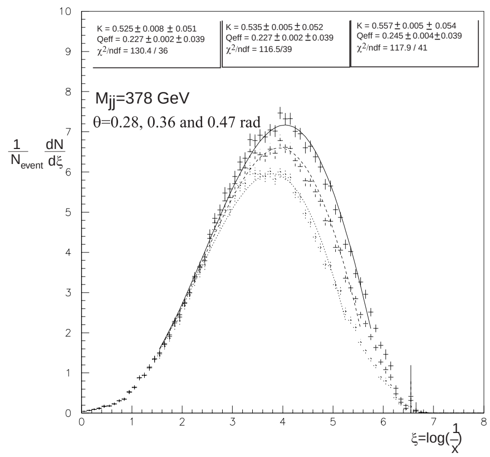

Figure 1. $\xi = \log E_{Jet}/p$ distributions in a jet for cone size θ=0.28,0.36 and 0.47 radians.

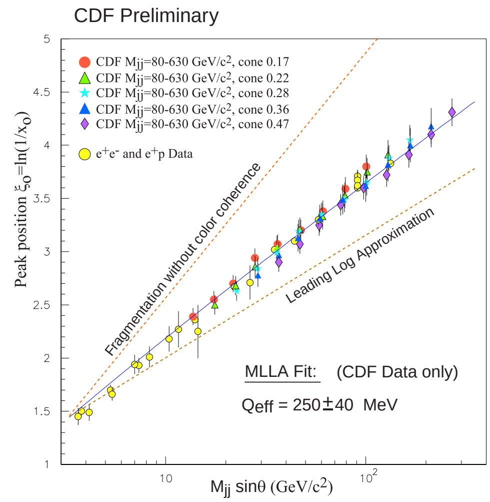

Figure 2. Peak position of the ξ distribution of charge tracks in a jet.

the charged particle multiplicity and momentum distributions. Herwig Monte Carlo predicts that $\sim$ 62% of these jets are gluon jets at M_{JJ} = 80, decreasing to 22% at M_{JJ} = 630 GeV. The jets are reconstructed using cone algorithm with R=0.7. Charged tracks, corrected for track reconstruction inefficiency, underlying event and multiple $p\bar{p}$ interactions, in restricted cones around the jet axis are used in this analysis. Fits to $\xi = \log(E_{jet}/p)$ distribution to MLLA shape function $dN(\xi, Y)d\xi$ where Y=$E_{jet} \sin\theta/Q_{\text{eff}}$ for 27 points (9 mass ranges and 3 cones) yields $Q_{\text{eff}} = 240 \pm 40$ MeV.

The K_{LPHD} can be determined through the variation of momentum distribution with M_{JJ} through $N_h(\xi) = K(M_{jj})N^g(\xi)$ where

$$K(M_{jj}) = K_{LPHD}\,(f_g + (1 - f_g)/r)\,F_{nMLLA},$$

N^g is MLLA-predicted ξ distribution for gluon jets, f_g is the gluon fraction, determined from HERWIG, and we use F_{nMLLA} = 1.30 ± 0.20 for the nMLLA scale factor.

The charged particle momenta distribution for three cone sizes (θ=0.28,0.36 and 0.47 radians) for $M_{JJ} = 378$ as a function of ξ, is shown in Fig. 1. As expected, the $K(M_{JJ})$= $0.53 \pm 0.05, 0.54 \pm 0.05, 0.56 \pm 0.05$ for three cone sizes, is almost constant. From $K(M_{JJ})$ distribution, we determine $r = 1.8 \pm 0.4$ and $K_{LPHD} = 0.58 \pm 0.05 \pm 0.8$. This ratio, r, depends on MLLA-predicted shape of ξ distribution. The variation of multiplicity with M_{JJ} yields $r = 1.7 \pm 0.3$ and K_{LPHD} = 0.55 ± 0.06. The multiplicity variation with M_{JJ} is also well described by Herwig Monte Carlo after scaling by 0.89.

The peak values of the ξ distributions, $\xi_0 = Y/2 + \sqrt{cY} - c$ (c=0.29 for three flavors) are shown in Fig.2 along with the data from e^+e^- and e^+p colliders. The peak position is determined by fitting the distribution locally and is insensitive to the very low/high momentum particles. This is the first evidence of the predicted scaling in $E_{Jet} \sin\theta$. The extracted Q_{eff} = 250 ± 40 in very good agreement with the determination from the shape of momentum distribution.

The di-jet data at low and moderate E_T is dominated by gluon-gluon scattering. The HERWIG Monte Carlo, using CTEQ4M parton distribution functions (PDF) predicts that 62 ± 2% of the jets are gluon-type at E_T = 40 GeV at $\sqrt{s}$ = 1800 GeV, where the uncertainty is derived using different PDF. The true photon-jet sample is predicted to contain 84 ± 2% quark jets. However, $\sim$30% of events tagged as γ-jet events are actually

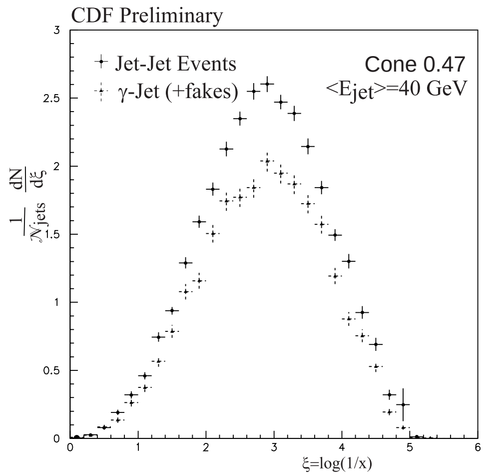

Figure 3. ξ distribution of charged tracks in a jet in di-jet and γ-jet events.

di-jet events with one of the jet fluctuating to fake a photon. The average multiplicity of di-jet sample is 5.77 ± 0.3 tracks/jet compared to 4.83 ± 0.05 tracks/jet in γ-jet sample. Using gluon fraction from Herwig Monte Carlo and measured fake rate, we determine $r = 1.74 \pm 0.11 \pm 0.07$, independent of MLLA formalism. These data show that r may depend on particle momenta, (~ 1.1 for high momentum particles), but errors are to large to be conclusive.

The CDF data are in good agreement with MLLA predictions. The measured $K_{LPHD} = 0.56 \pm 0.10$ is in good agreement with previous measurement of 0.59 ± 0.01 by TASSO. The $\alpha_s = 2\pi/[b\log(k_T/\Lambda_{\rm QCD})]$ evaluated by substituting $\Lambda_{\rm QCD}$ with $Q_{\rm eff} = 240 \pm 40$ MeV is in a good agreement with the world average value.

2 Sub-Jet Multiplicity

Instead of measuring the particle multiplicity which depends on the hadronization effect, one can separate the perturbative QCD effect by looking at clusters of particles, sub-jets, within a jet. The sub-jet multiplicity is both infrared and collinear safe and can be calculated to all orders in perturbative theory for large leading and next-to-leading logarithms. The soft gluon emission or collinear parton pair preserve the jet's net flavor. The effect of $\mathcal{O}(\alpha_s)$ correction on jet flavor is small[4]. QCD predicts that gluons radiate more than quarks. Asymptotically, the ratio of sub-jets multiplicities in gluon and quark jets is expected to be equal to ratio of their color charges $C_A/C_F = 9/4$. Experimentally, the sub-jet multiplicity is less sensitive to cuts and reconstruction efficiencies than particle multiplicity.

At a $\sqrt{s}$ value, the jets are mixture of quarks and gluons. The measured sub-jet multiplicity can be written as

$$M = f_g M_g + (1 - f_g) M_q$$

where f_g the fraction of gluon jets. Using the data at two $\sqrt{s}$ values, the sub-jet multiplicity in quark and gluon jets can be determined. The gluon fraction, f, at $\sqrt{s} = 1800(630)$, determined from LO QCD Monte Carlo HERWIG with CTEQ4M PDFs, is $f_g = 0.59 \pm 0.02(0.33 \pm 0.03)$ where the uncertainty is determined by varying the PDFs.

The jets are identified using k_T algorithm with jet clustering parameter $D = 0.5$[3]. The calorimeter towers/particles are pre-clustered in pseudo-rapidity(η)-azimuthal angle(ϕ) space with minimum distance$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.2$. These pre-clusters are clustered into objects by following prescription. For each object i, the distance $d_{ii} \equiv E_{T,i}^2$ is where E_T is the energy transverse to the beam. For each pairi, j, $d_{ij} \equiv min(E_{T,i}^2, E_{T,j}^2)\Delta R_{i,j}^2/D^2$. The object i and j are replaced by a new object given by their 4-vector sum provided d_{ij} in minimum of all possible combinations i, j, including d_{ii}. If $d_{ii} < d_{ij}$ for all i, j, the object i is promoted to a jet and removed from object list. This process is repeated until object list is empty.

For this study by DØ collaboration, the $p\bar{p}$ data taken at $\sqrt{s} = 630$ and 1800 GeV during 1992-1995 is used. Of the two highest transverse energy (E_T) jet in the event, those with $55 < E_T < 100$ GeV and $|\eta| < 0.5$ are

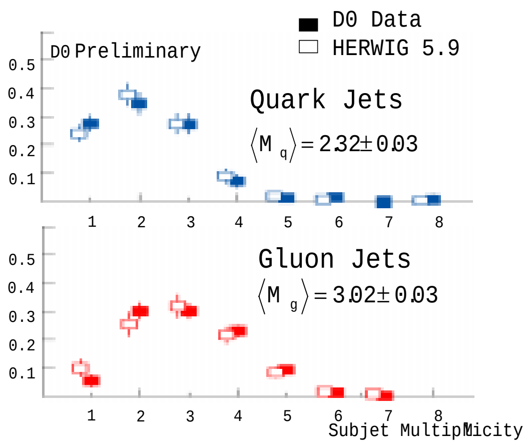

Figure 4. Fully simulated sub-jet multiplicity in quark and gluon jets compared with raw DØ data

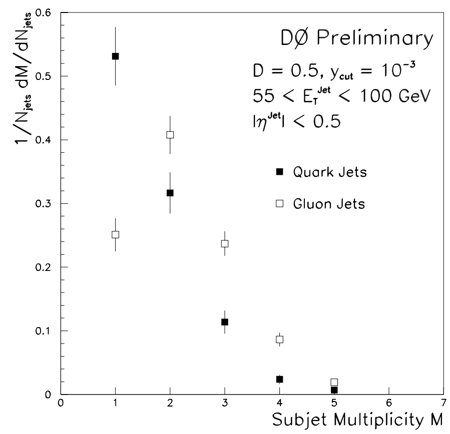

Figure 5. Fully corrected Sub-Jet multiplicity in quark and gluon jets.

used to measure subjet multiplicities.

The sub-jets multiplicity, M, within a jet is determined by running the same k_T algorithm on the pre-cluster list of a jet but with a resolution parameter $y_{cut} = 10^{-3}$. Pairs of objects with the smallest d_{ij} are merged successively until all remaining $d_{ij} > y_{cut} E_T^2$. As shown in Fig.4, the raw subject multiplicity for quark and gluon jets is well described by Herwig Monte Carlo.

The measured sub-jet multiplicity is corrected for detector effects using the corrections derived from Herwig Monte Carlo and detector simulations. The true sub-jet multiplicity (M^{true}) is determined by running the clustering procedure described above on the particle list from HERWIG Monte Carlo and the observed multiplicity (M^{obs}) is determined using the same procedure on the calorimeter towers after detector simulation. The observed jets are matched to true jets in $\eta - \phi$ space. Two dimensional correlations between M^{true} and M^{obs}, determined separately for gluon and quark jets, are used to correct the data. The procedure was tested on simulated data and works well. The corrected sub-jet multiplicities in quark and gluon jets are shown in Fig. 5.

As expected, the gluon jets have higher subjet multiplicity than quark jets. The ratio of additional subjets in gluon to quark jets

$$R = \frac{<M_g>-1}{<M_q>-1} = 1.91 \pm 0.04(\mathrm{stat})^{+0.23}_{-0.19}(\mathrm{sys})$$

where the dominant source of systematic uncertainty is the gluon fraction $(^{+0.18}_{-0.12})$ uncertainty. Other sources include Jet E_T cut($\pm$0.12), detector smearing ($\pm$0.08) and the unsmearing procedure ($\pm$0.04). The measured ratio R is consistent with Herwig Monte Carlo (1.86$\pm$0.04) and is slightly lower than the naive expectation of 9/4. The recent calculation of the sub-jet multiplicity [4], at next-to-leading accuracy in $\log(y_{cut})$, can not be compared because of the preclustering used in the jet finding algorithm.

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