Comparisons of Quark and Gluon Jets

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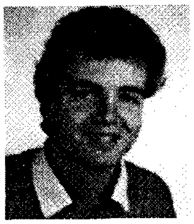

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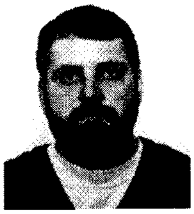

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A summary of the latest results of the DELPHI Collaboration on the properties of identified quark and gluon jets is given. It covers the measurement of the fragmentation functions of gluons and quarks and their scaling violation behaviour as well as an analysis of the scale dependence of the multiplicities in gluon and quark jets. Further, a precision measurement of C_A/C_F from the multiplicities in symmetric three jet events is discussed. The charged hadron multiplicity in a cone perpendicular to the event plane of symmetric three jet events is analysed. A precise measurement of inclusive distributions of π^+, K^+ and p and their antiparticles in gluon and quark jets has been performed. The study of isoscalar resonance production shows no indication for an excess of $\phi(1020)$ production in gluon jets.

1 Introduction

In QCD, the three fundamental splittings of the two types of colour charged fields (quarks (q) and gluons (g)) are $q \to qg$, $g \to gg$, and $g \to q\bar{q}$. The corresponding *splitting kernels*, which describe both the kinematics and the relative strengths of these splittings, are proportional to the *colour factors* $C_F = \frac{4}{3}, C_A = 3$, and $T_R = \frac{1}{2}n_F$, respectively, where n_F is the number of active quark flavours in $g \to q\bar{q}$ decays. As quarks and gluons are not free particles one has to use jets induced by gluons and quarks in three jet events as the best approximation of the tree level graphs.

2 Experimental Access to Gluon and Quark Jets

Gluon jets were originally identified in symmetric three jet events (*Y events*) [1,2,3]. By identifying heavy quark jets using impact parameter techniques, the remaining jet is identified indirectly as a gluon jet. The properties of a comparable *udsc*-quark jet sample can then be obtained from non-*b* events, where the gluon properties are eliminated by subtraction techniques [2,3]. Recently this technique has also been extended to non-symmetric events [3]. This improves the available statistic and gives access to a wider range of energy scales, but requires a criterion for the selection of comparable gluon and quark jets. The DELPHI analysis yields about 24,000 identified gluons in Y events and about 142,000 in the asymmetric events.

3 Jet Scales

The relevant scale for the jet evolution is not just the jet energy. Soft radiation is limited to cones given by the opening angles between the jets. This motivates transverse momentum like scales. The *hardness* $\kappa_H = E \sin\theta_1/2$ is a better choice than the jet energy, as it accounts for the limited phase space available for gluon radiation due to the interference of radiated gluons[a]. In FIG. 1, the fragmentation functions of quark jets as a function of their hardness scale are shown. The *rows* in this figure correspond to data taken in the same x_E intervals. FIG. 1 shows the good agreement of light quark jets in three jet events with jets in e^+e^- annihilations from PETRA energies [5] to the highest LEP energies both in normalization and slopes. Here κ_H is taken as the scale in three jet events and E_{beam} in e^+e^- annihilation. This agreement confirms the interpretation of κ_H as a valid scale for jet evolution in three jet events.

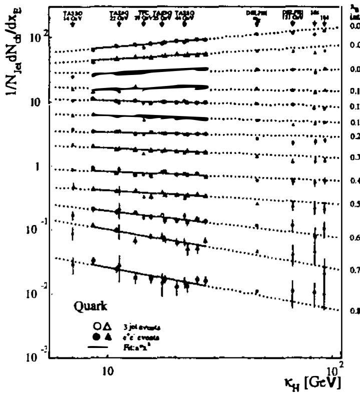

Figure 1: Quark-frag. func. vs. κ_H

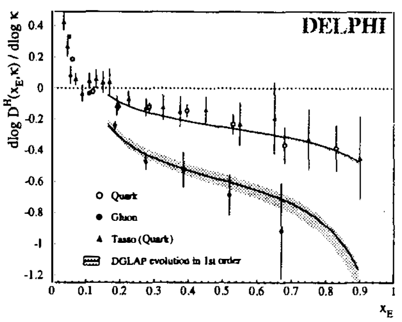

Figure 2: (Logarithmic) slopes of the scale (κ_H) dependence of the quark and gluon fragmentation functions as a function of x_E

4 Results

4.1 Gluon and Quark Fragmentation Functions and their Scaling Violation

The gluon and quark fragmentation functions $D_{g,q}(x_E, \kappa_H)$ are measured in dependence of κ_H at a fixed CMS energy. The softening of the fragmentation functions with increasing κ_H is observed. This effect is more pronounced for gluon jets than for quark jets. The predictions are derived from the numerical solution of the DGLAP evolution equation in first order. The following ansatz has been used to parameterize the fragmentation function at a fixed scale κ_0 to start the evolution: $D_p^{g,q}(x_E) = p_3^{g,q} \cdot x_E^{p_1^{g,q}} \cdot (1-x_E)^{p_2^{g,q}} \cdot \exp\left(-p_4^{g,q} \cdot \ln^2 x_E\right)$. A simultaneous fit with the first order DGLAP equations to both the quark and gluon fragmentation functions has been performed [6]. Beyond the parameters of the analytic ansatz of the fragmentation functions, Λ_{QCD} and C_A have been treated as free parameters. The fit is sensitive to the occurrence of C_A in the $g \to gg$ splitting kernel. The fit describes the data well and yields: $\frac{C_A}{C_F} = 2.19 \pm 0.09_{stat}$(preliminary) for the colour factor ratio.

[a] This definition corresponds to the beam energy of an $e^+e^- \to q\bar{q}$ event. Often also the definition $\kappa = 2E\sin\theta/2 \sim E\theta$ is used.

In FIG. 2 the logarithmic slope of the gluon and quark fragmentation functions are compared in dependence of x_E superimposed by the result of the DGLAP fits. The shaded area indicates the statistical uncertainty of C_A. The data points were obtained from power law fits to each x_E interval individually. As expected from the structure of the DGLAP equation, the scaling violations are ~ 2 times larger for gluons than for quarks. Furthermore, the observed scaling violation in quark jets is in very good agreement with the measurements of the TASSO Collaboration [5] (already visible in FIG. 1).

4.2 Scale Dependence of the Gluon and Quark Jet Multiplicities

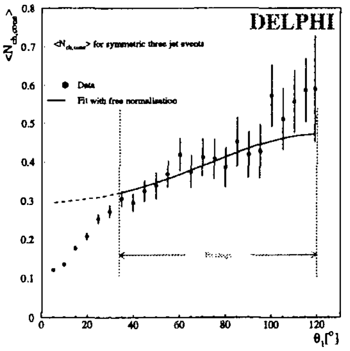

Figure 3: Cone multiplicity

The scale dependence of the gluon and quark jet multiplicities has been discussed in detail in [7]. A precise measurement of the colour factor ratio C_A/C_F has been performed with multiplicities from symmetric three jet events using a MLLA prediction [4]: $\frac{C_A}{C_F} = 2.246 \pm 0.062_{stat} \pm 0.080_{sys} \pm 0.095_{theo}$. As far as we know this result is the most accurate measurement of C_A/C_F so far.

The charged hadron multiplicity in a cone with half-opening angle of 30°perpendicular to the event plane of symmetric three jet events is also determined. The corresponding prediction is given in QCD. The measurement constitutes a test of the colour coherence property of QCD and of LPHD. FIG. 3 shows the fit of the prediction $N_{\perp}^{q\bar{q}g} = a \cdot \frac{N_C}{4C_F}[2 - \cos\Theta_{1+} - \cos\Theta_{1-} - \frac{1}{N_C^2}(1 - \cos\Theta_{+-})]$ with $\Theta_{1+} = \Theta_{qg} = \pi - \Theta_1/2$, $\Theta_{1-} = \Theta_{\bar{q}g} \equiv \Theta_1$, $\Theta_{+-} = 2\pi - \Theta_{1+} - \Theta_{1-}$, and a normalization factor a to the data. Here Θ_1 is the angle between the closest Y jets. The slope is described well by the theory (The $\chi^2/n.d.f.$ of the fit is 0.8).

4.3 Identified Charged Particles and Resonances

For the measurement of π^+ 's, K^+ 's, and protons a combined tagging procedure based on the Cherenkov angle measurement in the RICH detector and on the ionization energy loss (dE/dx) in the TPC was applied which is described in detail in [8]. Its application allows a continuous particle identification in the momentum range of 0.3-45 GeV/c[9]. Different observables have been measured for identified particles in quark and gluon jets: the momentum p, the multiplicity n, ξ_p and the rapidity η. For each observable Z the following quantities are determined: the spectrum for particle X, the ratio $r_X(Z)$ of gluon to quark jets for particle X and the normalized ratio $R_X(Z) = r_X(Z)/r_{ch}(Z)$, with $r_{ch}(Z)$ the ratio gluon/quark for all charged particles [10].

FIG. 4 shows the ratios of the momentum spectra of identified hadrons in gluon and quark jets . More low energy particles are produced in gluon jets than in quark jets for all kind of particles. At high particle momenta this structure is inverted. The normalized ratio stresses particle specific differences between quark and gluon jets (s. FIG. 4). Especially the proton enhancement in gluon jets is bigger than that for all charged particles.

The data of normalized multiplicity ratios, $R' = R/R_{ch}$, with $R = N_q/N_g$ show a significant proton enhancement in gluon jets, $R'_p = 1.205 \pm 0.041_{stat.}$. HERWIG underestimates both the kaon and the proton production in gluon jets. In contrast JETSET and ARIADNE overestimate the proton production in gluon jets.

To measure resonances, the following procedure has been applied. Firstly, single particles are tagged as kaons or pions and the energy of the particles is recalculated assuming the correct mass of the tagged particle. Secondly, any two particles with opposite sign (KK in the case of the $\phi(1020)$ and $K\pi$ for the $K^*(892)^0$) are combined. It is further requested that at least one of the particles is *standard* tagged in the case of $\phi(1020)$ and that both are *standard* tagged for the

$K^*(892)^0$). Then the four momenta of the two particles are added to a "new particle". From this "new particle" the invariant mass is calculated. In the last step this particle is assigned to the jet with the minimal angle in space.

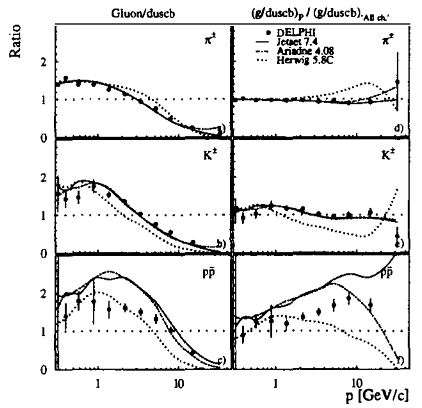

Figure 4: Ratios of the momentum spectra of identified hadrons in gluon and quark jets of Υ events; a)-c) ratios of the spectra of pions, kaons, and protons in gluon jets to those in quark jets; d)-f) corresponding spectra normalized to the ratio gluon/quark for all charged particles; The predictions of the generator models JETSET, ARIADNE und HERWIG are drawn as lines.

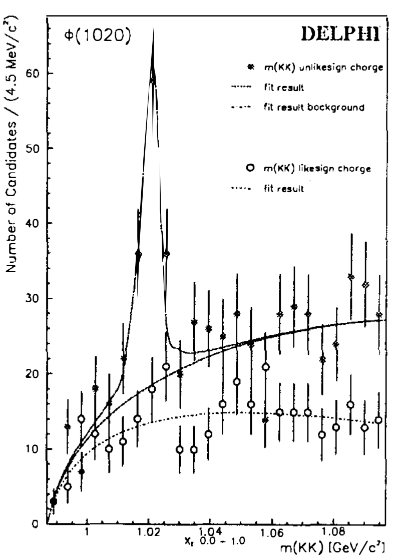

Figure 5: $\phi(1020)$ resonance in gluon jets from Υ events

The fit of the invariant mass spectra has been performed using the Breit-Wigner formula with Γ fixed to the world average plus a smooth background. As our interest is to consider mainly gluon/quark ratios, most of the systematic errors cancel out and are negligible w.r.t. the large statistical errors. Only a correction to pure quarks and gluons is needed. After the purity correction one yields $R = \frac{N_g}{N_q} = 0.7 \pm 0.3$ for the $\phi(1020)$, consistens with unity and $R = \frac{N_g}{N_q} = 1.7 \pm 0.5$ for the $K^*(892)^0$.

Acknowledgments

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