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Fragmentation and Hadronization in e^+e^- Collisions*

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Abstract

We present a number of jet fragmentation and hadronization measurements in $e^+e^- \rightarrow Z^0 \rightarrow$ hadrons. The L3 collaboration has searched for pointlike color singlet radiation in multi-jet events, limiting any such contribution to rapidity gap events at the few percent level. ALEPH and SLD have measured production rates of a number of identified hadrons, including precise, full-coverage spectra of B hadrons. L3 and SLD have studied charged track and identified hadron production in heavy- and light-flavor events. OPAL has made a pioneering comparison of charged multiplicities between events of the three light flavors, $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$.

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1. Introduction

The fields of fragmentation, by which an energetic quark or gluon from a hard collision radiates a cascade of softer partons, and hadronization, by which these partons form a jet of hadrons, remain active frontiers in elementary particle physics. Quantitative QCD calculations are challenging, however several inclusive properties of jets have been calculated in (next-to-)leading logarithm approximations ((N)LA) and numerical models for the parton cascase have been developed, as have phenomenological models of hadronization. Measurements of the properties of jets test these models and encourage theoretical development. Since jets are used in precision tests of electroweak and strong physics and will constitute the largest signal for, and background to, any heavy particles to be discovered, our understanding must be as complete as possible. It would be especially useful to identify whether a given jet was initiated by a quark, antiquark or gluon, and the flavor of the $q/\bar{q}$.

Measurements of particle flow in hadronic events at the Z^0 are becoming extremely precise, as are measurements of the inclusive properties of charged tracks and many types of identified particles. Not only do these measurements provide stringent tests of theoretical and model predictions, but some have become sensitive to new physics. In section 2 we present contributed results on charged track multiplicity and event structure from L3 [1], $\pi^{\pm}$, $K^{\pm}$ and p/$\bar{\text{p}}$ production from SLD [2], and ω and η production from ALEPH [3].

Great strides have been made in the study of gluon jets and jets of different initial quark flavor, especially their leading particles. The B hadron spectrum is now among the best measured; results from ALEPH [3] and SLD [2] are presented in section 3, along with new studies of the properties of heavy- and light-flavor events from L3 [1] and SLD [2], gluon jets from SLD [2], and a first comparison of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ jets from OPAL [4].

2. Precision Inclusive Measurements

High statistics and years of hard work in understanding the Z^0 detectors have resulted in excellent precision on a number of basic measurements. For example, the charged multiplicity distribution in fig. 1 from L3 [1] covers 5 orders of magnitude. The JETSET [5] and HERWIG [6] hadronization models are able to describe the data at the percent level, but not in detail. From this distribution one can extract sensitive probes of the underlying dynamics, such as the ratios of cumulant to factorial moments shown as a function of the moment rank q in fig. 1. The minimum at $q = 5$ and subsequent oscillatory behaviour were predicted by a NNLLA calculation and have been observed in various types of collisions, apparently confirming the theory. However a careful study sees the effect in events of all flavors and topologies, and in simulations that do not explicitly include NNLL effects,

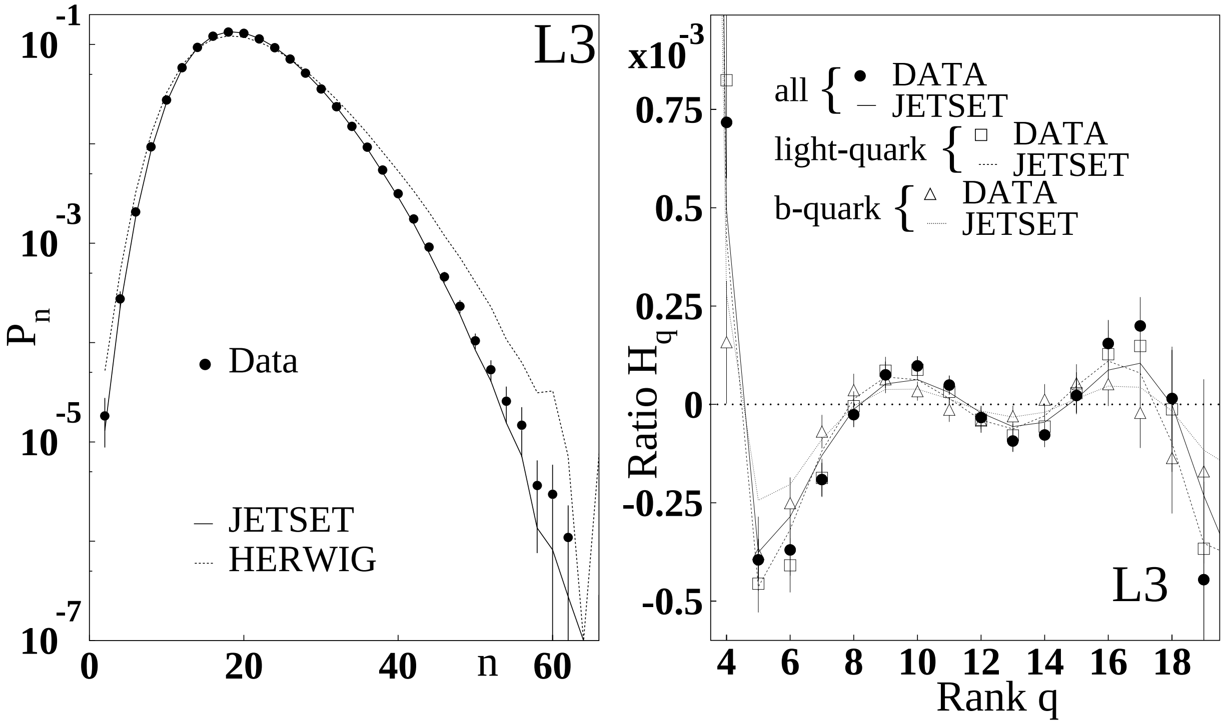

Figure 1: Charged multiplicity distribution (left) in hadronic Z^0 decays; predictions of the JETSET and HERWIG hadronization models. Ratio (right) of cumulant to factorial moments of the n_{chg} distribution.

rendering previous observations inconclusive.

Events with large gaps in their rapidity structure have been a hot topic in ep and p$\bar{\text{p}}$ collisions and interpreted in terms of the exchange of a color singlet object. If a pointlike color singlet is responsible, then it should give rise to 3- and 4-jet events in e^+e^- with a characteristic structure. In another detailed study [1], L3 has searched for such events using several optimized observables. No evidence was found, limiting the contribution of a pointlike color singlet to gap processes elsewhere to 6-8%.

SLD has updated [2] measurements of identified $\pi^\pm$, $K^\pm$ and p/$\bar{\text{p}}$ production that, together with previous measurements, provide coverage and precision comparable to that on inclusive charged tracks. The JETSET, HERWIG and UCLA [7] models all describe the data at the percent level, but not in detail. ALEPH have updated their measurements for the ω and η mesons [3], fig. 2a. A wide range of momentum is covered precisely,

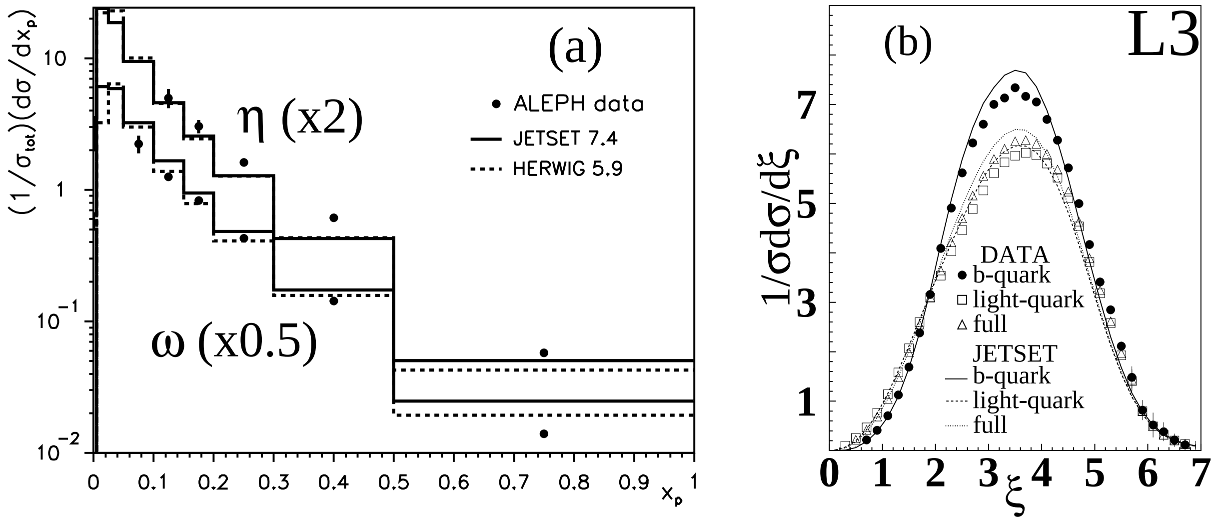

Figure 2: (a) Differential cross sections vs. $x_p = 2p/E_{CM}$ for ω and η mesons in hadronic Z^0 decays. (b) Distribuitons of $\xi = \ln(1/x_p)$ for charged tracks in all, $b\bar{b}$ and light flavor events.

and the model predictions are inconsistent with the data. Unfortunately, combinatoric background is very high at low momenta, preventing measurements over the full range.

3. Flavor Dependence and Leading Particles

In $Z^0 \to b\bar{b}$, $c\bar{c}$ events it is known that the initial heavy $q(\bar{q})$ appears in a leading $B(\bar{B})$ or $D(\bar{D})$ hadron, respectively, with large average energy and flight distance. These properties can be used to (anti)tag $b\bar{b}$ and $c\bar{c}$ ($u\bar{u}+d\bar{d}+s\bar{s}$) events for a variety of electroweak and strong interaction physics. Superb precision has been reached on e.g. $\xi = \ln(1/x_p)$, $x_p = 2p/E_{CM}$, for charged tracks in $b\bar{b}$ and light flavor events from L3 [1], fig. 2b, and ratios of charged hadrons in $b\bar{b}$:light and $c\bar{c}$:light flavors from SLD [2], fig. 3. Comparison of light-flavor events with the above models reveals the same differences from the data, a useful verification that the problems are in the simulation of hadronization and not just of production and decay of heavy hadrons. Additional problems with these models are seen in the heavy-flavor events.

The energy spectrum of leading B hadrons has been studied in detail by ALEPH [3] and SLD [2]. ALEPH uses the energies of a lepton and a reconstructed D meson in the same jet, along with its missing energy, ascribed to a neutrino, to measure individual energies of B hadrons that decay semi-leptonically. SLD uses a missing mass technique

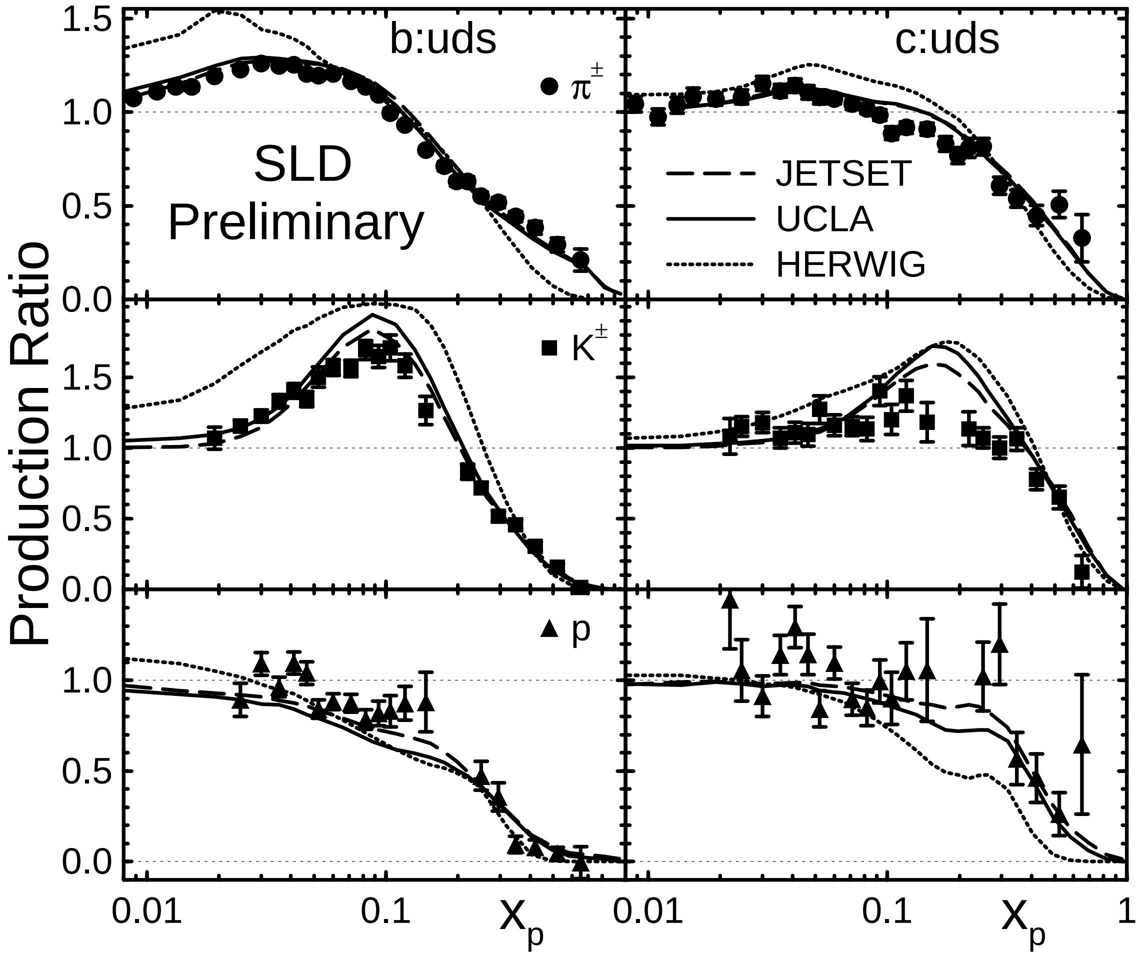

Figure 3: Ratios of hadron production in b:light (left) and c:light flavor (right) events.

that relies only on the set of charged tracks associated with a secondary vertex to measure energies of any weakly decaying B hadrons. Both measured spectra cover the full kinematic range, from the B mass to the beam energy, and exclude a number of proposed models. The two corrected spectra, fig. 4, appear to be inconsistent; however they agree on the set of models that are able to describe the shape of the distribution, and have consistent mean values.

The three light flavors, $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ are more difficult to separate from each other, as their lighter and softer leading particles are swamped at low momentum by hadronization particles of the same type, and the origin of an identified leading particle is ambigous, i.e. a K^- could be from an s or $\bar{u}$ jet, a Λ^0 could be from u, d or s, etc. Measurements from

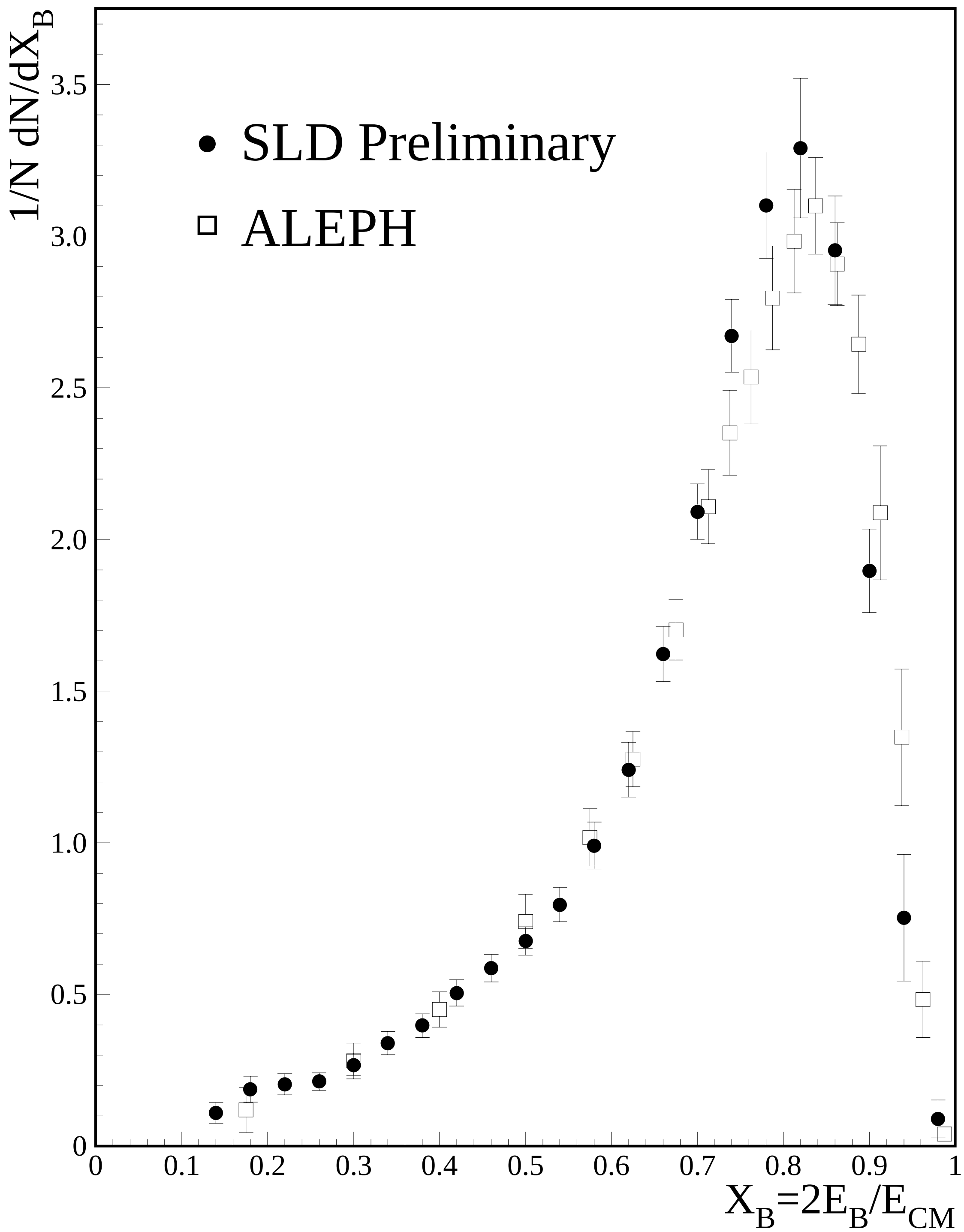

Figure 4: Scaled energy distribution of weakly decaying B hadrons.

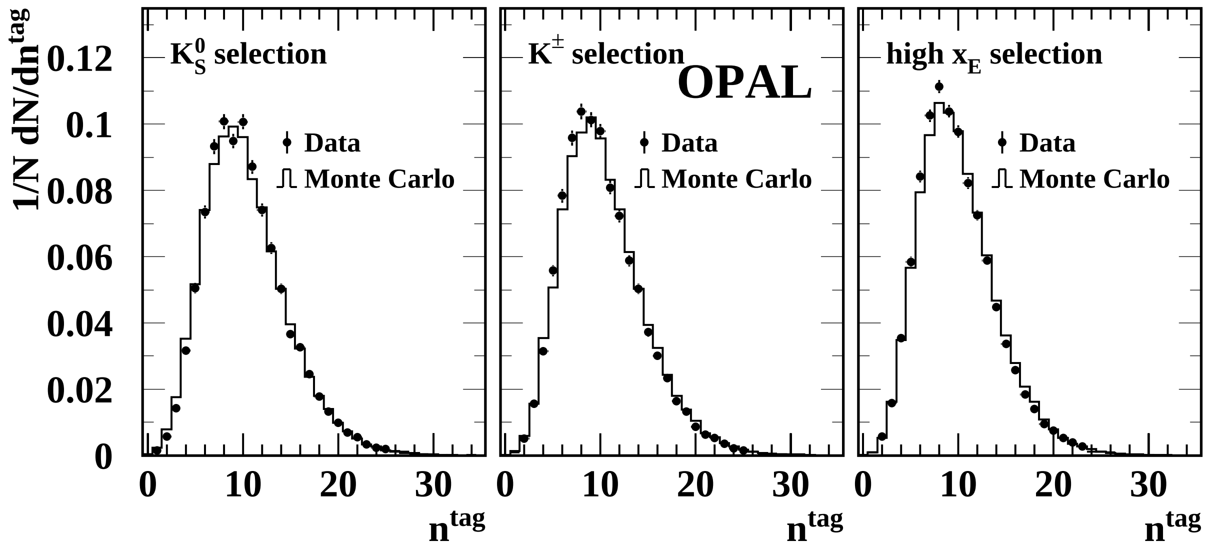

Figure 5: Meausured charged multiplicity distributions in three light-tagged samples.

SLD [2] and OPAL [8] have become sensitive to leading particles, but are statistics limited in their quantitative results. Still a very nice first measurement of charged multiplicities in $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ has been made by OPAL [4] using high momentum K^0_s, $K^{\pm}$ and charged tracks to tag samples enhanced in $s\bar{s}$+$d\bar{d}$, $s\bar{s}$+$u\bar{u}$ and $u\bar{u}$+$d\bar{d}$+$s\bar{s}$ events, respectively. The n_{chg} distributions in the tagged samples, fig. 5, show excellent coverage and precision. The data are consistent with equal averages, $\bar{n}_u \approx \bar{n}_d \approx \bar{n}_s$, but precision is limited by knowledge of the tag purities and a strong anticorrelation between $\bar{n}_u$ and $\bar{n}_d$:

$$\begin{aligned}
\bar{n}_u &= 17.77 \pm 0.51 \quad (\text{stat.}) \quad {}^{+0.86}_{-1.20}(\text{syst.}) \\
\bar{n}_d &= 21.44 \pm 0.63 \qquad\qquad\quad {}^{+1.46}_{-1.17} \\
\bar{n}_s &= 20.02 \pm 0.13 \qquad\qquad\quad {}^{+0.39}_{-0.37}.
\end{aligned}$$

Gluons are expected to fragment differently from quarks due to their higher color charge. Higher multiplicities of softer particles have been seen in several g jet studies, implying both that the fragmentation is understood and that the hadronization stage is quite similar on average. Identified particles may be sensitive to small differences in hadronization, but studies so far are statistics limited. SLD have compared charged hadron production in g and uds jets [2], where the former are identified cleanly as the non-heavy-quark jet in 3-jet $b\bar{b}g$ or $c\bar{c}g$ events. Uncorrected ratios of hadron fractions, fig. 6, show deviations from unity; however similar differences in the simulation indicate

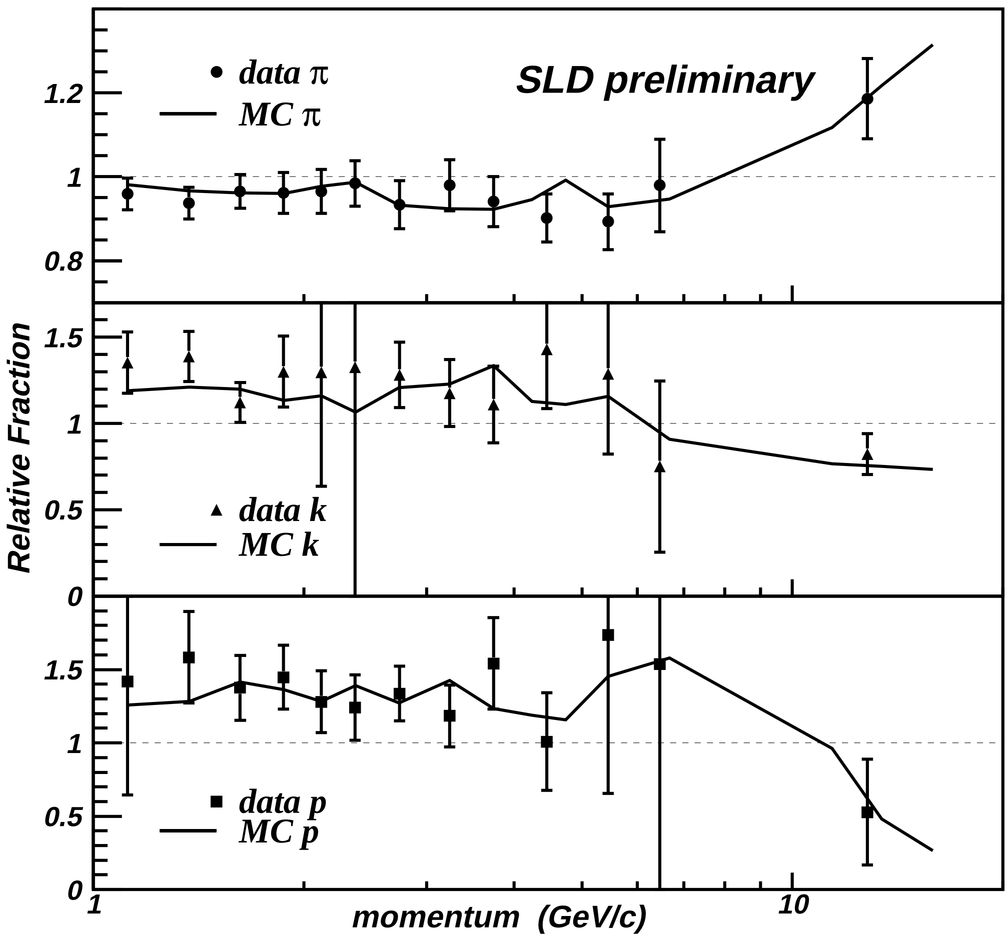

Figure 6: Ratios of charged hadron fractions in g-tagged jets to those in uds-tagged jets.

large biases in the tagging procedure. Improvements might limit differences to the few percent level.

4. Conclusions

Tremendous experimental progress has been made at LEP and SLC in understanding the processes of fragmentation and hadronization. Many predictions of calculations in leading logarithm approximations have been verified, including differences between quark and gluon jets. The fragmentation process is now understood sufficiently that some observables are sensitive to new physics. A new measurement from L3 limits the contribution of the radiation of pointlike color singlet partons to multi-jet events to the few percent level.

Calculations and phenomenological models are able to describe many properties of hadronization. However experiments continue to find new and better tests, e.g. flavor dependences, leading particles, etc., that reveal further limitations. Progress in theory and modelling is desirable. The precise B energy distribution and nice start on other leading particles bode well for future studies requiring tags of all flavors of quark and gluon jets.

Future studies will benefit most from higher statistics, especially in understanding jet flavors with doubly tagged events. Running a future lepton collider at the Z^0 would calibrate the detector *and* the physics of flavor tagging, enabling a full study of the decays of the Higgs or any other massive particle. Combinatoric background is reduced at *lower* energies. B factories have very high statistics and excellent detectors, providing opportunities to study e.g. *primary* particles/resonances in detail, and charm cleanly.

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