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Hadron Production in Quark and Antiquark Jets*

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Representing The SLD Collaboration**

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Abstract

We present a number of jet fragmentation measurements in $e^+e^- \to$ hadrons. The ALEPH collaboration measures inclusive $\rho^0(770)$, $f_0(980)$ and $f_2(1270)$ production rates, improving the world averages. The SLD collaboration measures $\pi^\pm$, $K^\pm$ and p/p̄ production in light-, c- and b-flavor Z^0 decays, as well as leading hadrons in light-quark jets, precisely. The DELPHI collaboration measures the average charged multiplicity in light- and b-flavor events at 183 and 189 GeV, verifying a precise prediction of QCD and excluding flavor-independent fragmentation.

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1. Introduction

The process of fragmentation, by which a high-energy quark or gluon from a hard collision forms a jet of observable hadrons, remains an active frontier in elementary particle physics. It is not understood quantitatively due to the difficulty of calculations in this soft regime, although several phenomenological models have been developed. 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 the origin of a given jet, i.e. whether initiated by a quark, antiquark or gluon, and by what flavor of $q/\bar{q}$.

Identified particles are particularly useful for probing fundamental features of hadronization and constraining models. Hadrons containing a heavy (b or c) quark are produced only as leading particles or by gluon splitting. Strange particles are produced copiously in jets, but less than nonstrange particles, and we would like to understand the mechanism of flavor suppression. Baryons probe diquark production, and the relative production of pseudoscalar, vector, scalar and tensor mesons, and of excited baryons, probes the spin dynamics of hadronization. In section 2 we present contributed results on charged $\pi^{\pm}$, $K^{\pm}$ and p/$\bar{\text{p}}$ [1] and neutral ρ^0, f_0 and f_2 [2] production in hadronic Z^0 decays.

Three recent trends in hadronization studies provide deeper probes. One is the separation of $e^+e^- \to q\bar{q}$ events into different primary flavors: a large quark mass is expected by QCD to affect the particle flow near the jet axis; identified particles in light- and heavy-flavor events provide cleaner tests of models and information on heavy hadron decays, respectively. In section 3 we present results on charged multiplicities in b- and light-flavor events at the highest LEP energies [3], and on flavor-dependent $\pi^{\pm}$, $K^{\pm}$ and p/$\bar{\text{p}}$ production [1].

Another trend, comparing gluon jets with light quark jets, is covered in another talk [4]. The third is the study of leading particles that carry the q or $\bar{q}$ that initiated the jet. In section 4 we present a precise measurement of π^+, π^-, K^+, K^-, p and $\bar{\text{p}}$ production in light quark (u+d+s) jets [1]. Two other contributions, in which u, d, and s jets are separable, are covered in [5].

2. Inclusive Identified Hadron Production

SLD have updated [1] a study of $\pi^{\pm}$, $K^{\pm}$ and p/$\bar{\text{p}}$ production in hadronic jets. Their Cherenkov Ring Imaging Detector measures charged hadron fractions precisely over a wide momentum range, shown in fig. 1. Systematic errors on such measurements are correlated point-to-point, but combined with other, complementary measurements, $\leq$1% precision is available over most of the range, providing tight constraints on hadronization models.

The predictions of three such models are shown in fig. 1; all describe the data qualitatively, but fail in detail. Since the relative production of hadron species is built into

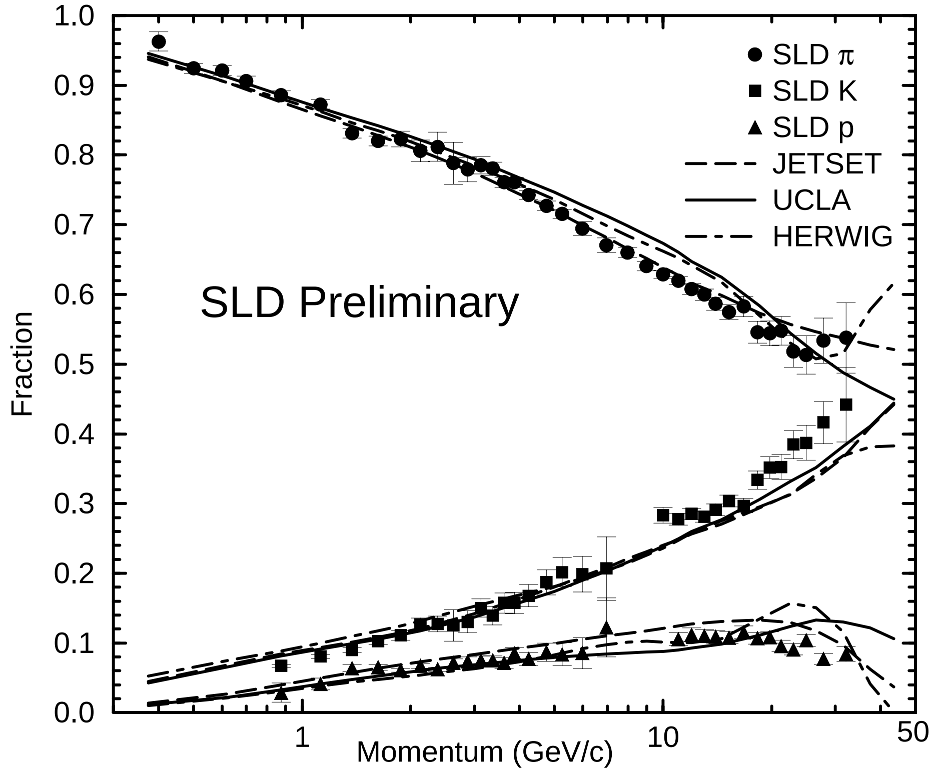

Figure 1: Charged hadron fractions in Z^0 decays; c.f. the predictions of three hadronization models.

the UCLA [6] and HERWIG [7] models via their masses, this suggests that no additional suppression mechanism is needed. The deviations of the JETSET [8] model from the data can be reduced by adjusting its free parameters.

ALEPH have updated their production measurement of the vector meson $\rho^0(770)$, and included the scalar $f_0(980)$ and tensor $f_2(1270)$ mesons in a study [2] of $\pi^+\pi^-$ pairs. The invariant mass spectrum is different from that predicted by JETSET, in both background and signal peak positions. The latter problem is known, and due at least partly to the absence of Bose-Einstein correlations in the model. An analytical approach to fitting the spectrum including these effects yields the production cross sections vs. $x_p = p/p_{beam}$ shown in figs. 2-3.

There are changes in the ρ^0 cross section from their previous result, and the JETSET prediction is consistent with the data. The f_2 and f_0 cross sections are similar in shape to that of the ρ^0 but smaller by factors of seven and nine, respectively. JETSET, with the rate set by previous measurements, predicts a harder f_2 spectrum than is observed. The prediction for f_0, with the f_0:f_2 production ratio set by spin counting, is also too hard and is low by a factor of two.

These results improve our knowledge of ρ^0, f_0 and f_2 production, confirming that tensors and scalars are produced copiously in jets. Over two-thirds of the stable particles in Z^0 decays can now be attributed to decays of resonances; it is therefore important to search for more excited states.

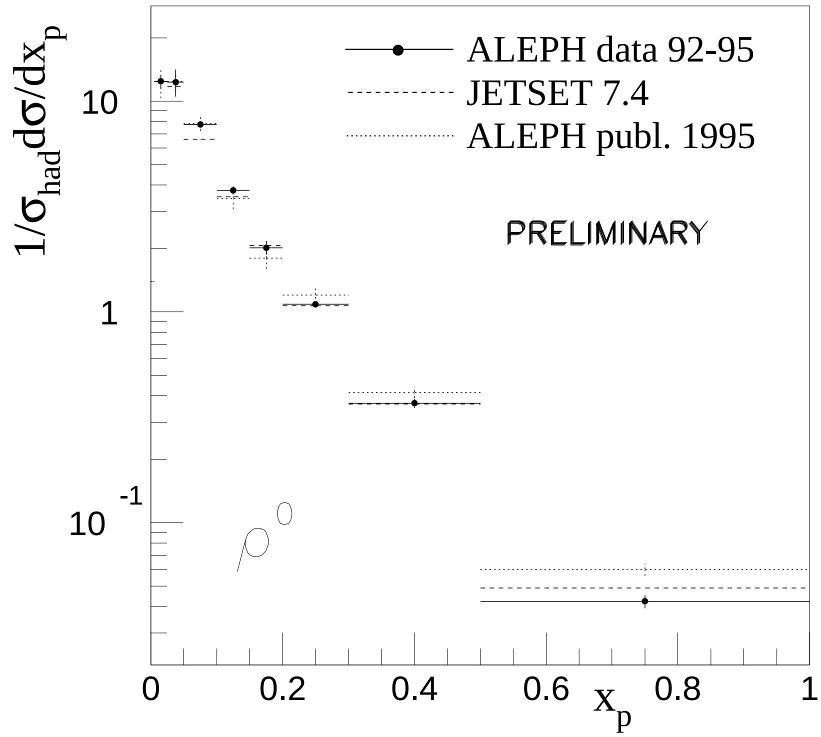

Figure 2: Differential production cross section for ρ^0 mesons in Z^0 decays; the previous ALEPH measurement and the prediction of the JETSET model.

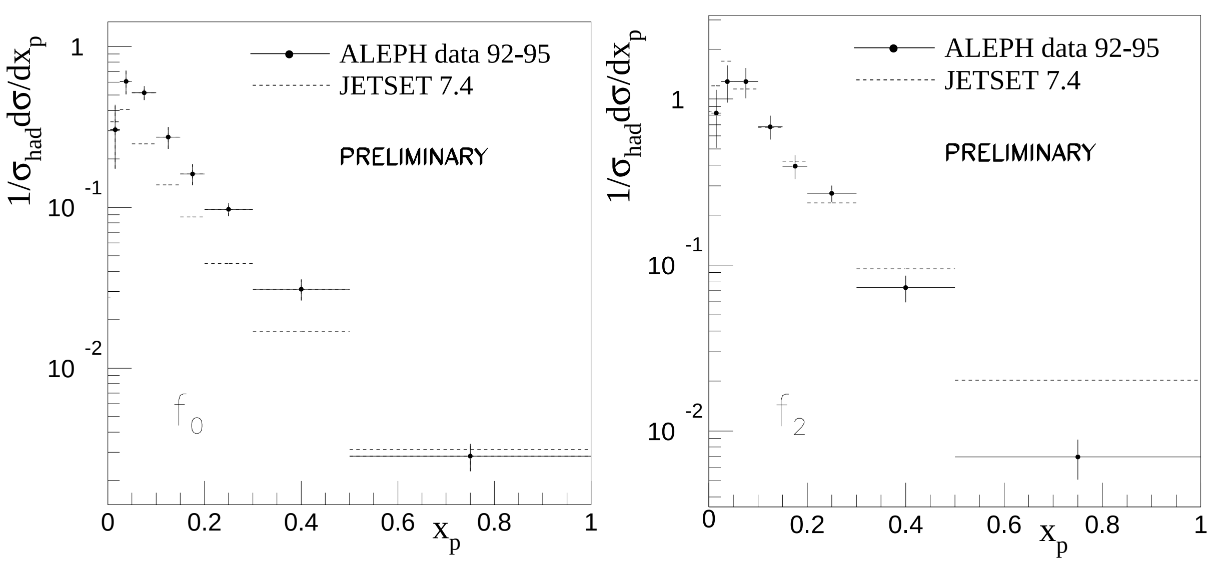

Figure 3: Differential cross section for f_2 (left) and f_0 (right) mesons in Z^0 decays; the JETSET predictions.

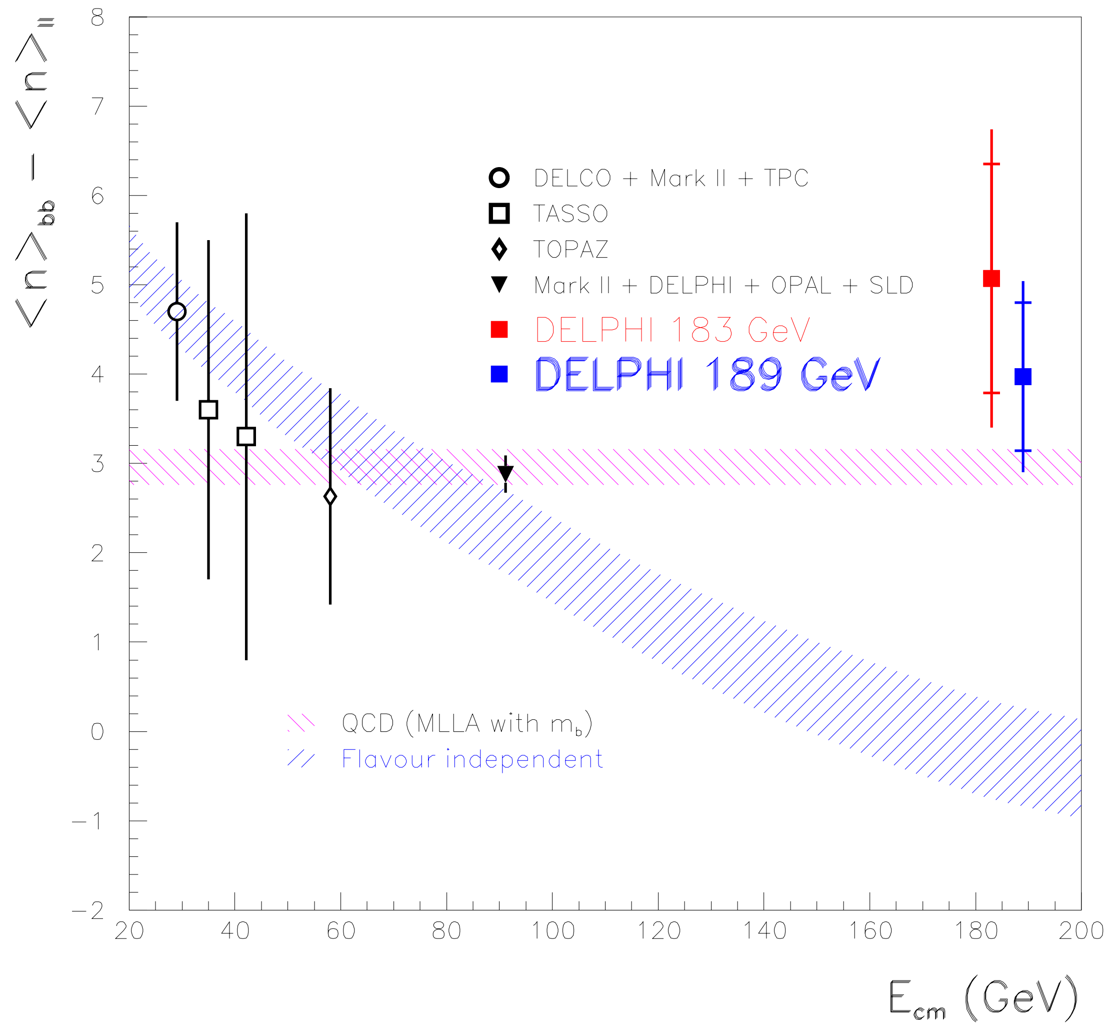

Figure 4: The difference between the average charged multiplicity in b- and light-flavor events as a function of E_{CM}. The horizontal (curved) band represents the prediction of QCD (flavor-independent fragmentation).

3. Flavor Dependent Fragmentation

DELPHI have measured $\langle n \rangle$, the average charged multiplicity, in b-, c- and light-flavor events at center-of-mass energies E_{CM}=183,189 GeV. Secondary vertex, event shape and track information is combined to tag b-, c-, and light-flavor samples of 91%, 26% and 78% purity, respectively, and a careful unfolding for the effects of backgrounds, tagging efficiencies and biases is performed. The differences $\delta\langle n \rangle_{bl} = \langle n \rangle_b - \langle n \rangle_{light}$ are shown in fig. 4, along with similar results from lower E_{CM}.

QCD predicts that $\delta\langle n \rangle_{bl}$ is precisely independent of E_{CM}, due to the suppression of gluon radiation collinear with the massive quark. The world's data are consistent with this, and with the less precise prediction for the value of $\delta\langle n \rangle_{bl}$. The two new points provide enough reach in E_{CM} to rule out an alternative hypothesis, that the nonleading

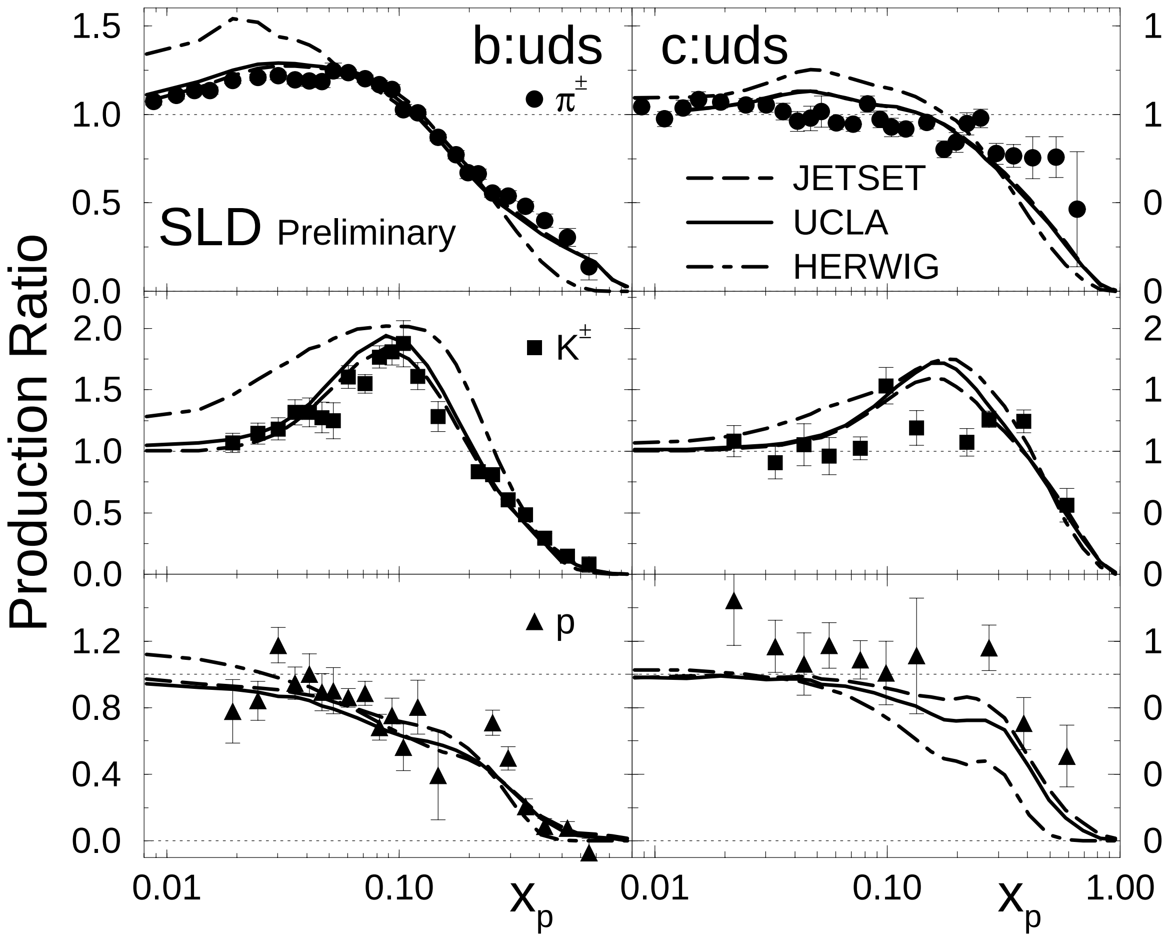

Figure 5: Production ratios in b-:light- (left) and c-: light-flavor (right) events; predictions of three models.

multiplicity in a b jet should equal that of a light-flavor jet with energy $E_{CM}/2 - E_{Bhadron}$ (see fig. 4).

SLD have used similar tagging methods to study $\pi^{\pm}$, $K^{\pm}$ and p/$\bar{\text{p}}$ production in light-, c- and b-flavor events. Results for light flavors (not shown) have coverage and precision comparable to the flavor-inclusive measurement (fig. 1). The same general features and problems with model predictions are observed, indicating that the latter are in the fragmentation modelling itself and not artefacts of the modelling of B and D hadron decays. The relative production in b- and c-flavor events is shown in fig. 5 and displays the features expected from the known fragmentation and decay properties of B and D hadrons. Problems with the detailed modelling of these decays are seen, especially in HERWIG.

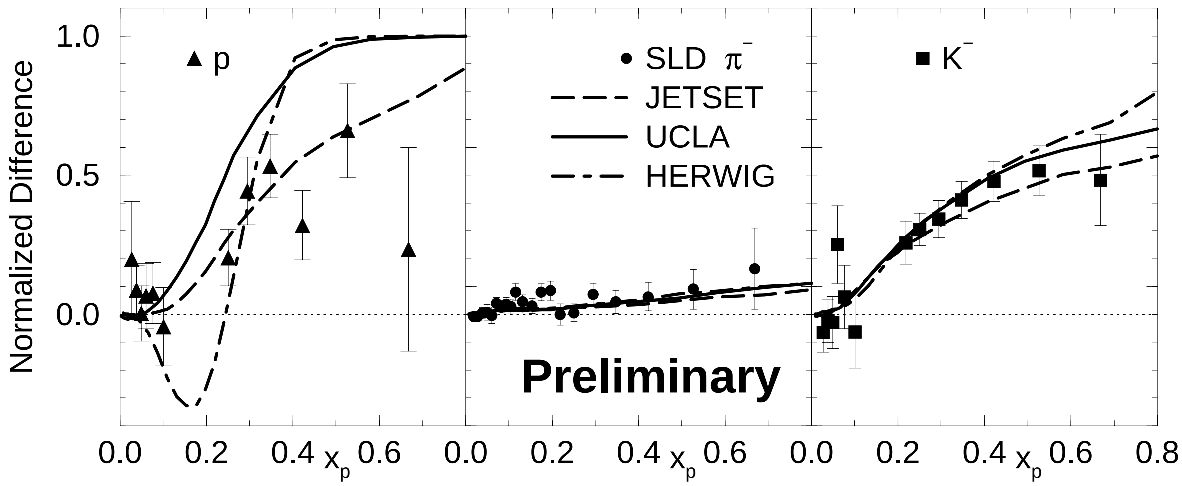

Figure 6: Normalized production differences between a hadron and its respective antihadron in light quark jets; the predictions of three hadronization models.

4. Leading Particle Production

SLD have updated their measurements of π^+, π^-, K^+, K^-, p and $\bar{\mathrm{p}}$ in u,d,s quark jets, using light-tagged events in which the e^- beam polarization is used to tag the quark (vs. antiquark) jet with 73% purity. The fully corrected production differences D_h between hadron h and antihadron $\bar{h}$, normalized by their sums, are shown in fig. 6. They are consistent with zero (equal h and $\bar{h}$ production) at low x_p, but show significant deviations at high x_p.

The positive D_{p} is unambiguous evidence for leading baryon production, as the proton contains valence quarks and not antiquarks; u, d and s jets are expected to contribute with the same sign. Leading π^+ and π^- are expected from u and d quarks, respectively, and the small positive D_{π^-} reflects the 22:17 ratio of Z^0 decays into $d\bar{d}$:$u\bar{u}$. The much larger D_{K^-} indicates that leading K^- are produced predominantly in s rather than $\bar{u}$ jets.

These data provide unique and powerful tests of hadronization models, under the assumption of Standard Model Zqq couplings, $q = u, d, s$. All three predictions for D_{π^-} and D_{K^-} are consistent with the data, as is the JETSET D_{p}; HERWIG and UCLA predict too large a D_{p} at high x_p.

5. Conclusion

Tremendous experimental progress continues to be made in the study of the hadronization process, expanding our knowledge and suggesting further studies on this frontier of particle physics. New ALEPH measurements of ρ^0, f_2 and f_0 production in hadronic Z^0 decays firmly establish the presence of many higher resonances in jets. Detailed SLD measurements of $\pi^\pm$,$K^\pm$ and p/$\bar{\mathrm{p}}$ production provide additional sensitivity, as the majority can be attributed to resonance decays. This motivates continued study in this area, especially searches for additional resonances. If each event comprises only a handful of primary resonances, then this process might be calculable.

Deeper studies have been made by selecting the primary event flavor and/or the quark vs. antiquark jet. New DELPHI measurements of average charged multiplicities in b- and light-flavor events at high E_{CM} confirm the QCD prediction of depleted particle flow around the heavy quark, and exclude flavor-independent fragmentation. Precise SLD studies of flavor-dependent $\pi^{\pm}$, $K^{\pm}$ and p/$\bar{\text{p}}$ production help isolate problems with hadronization models that cannot be explained by heavy flavors, such as the unequal production of $K^{\pm}$ and $K^0/\bar{K}^0$. Precise SLD measurements of leading particle production in light quark jets can be used to develop methods for tagging u, $\bar{u}$, d, $\bar{d}$, s and $\bar{s}$ jets, which could be applied to a wide range of future physics.

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