36. HEAVY-QUARK FRAGMENTATION IN e^+e^- ANNIHILATION

Written January 1998 by D. Besson (University of Kansas).

Measurement of the fragmentation functions of heavy quarks provides information about non-perturbative particle production in a variety of experimental environments. The CDF observation of high p_T $J/\psi(1S)$ production rates far in excess of the extant theoretical predictions prompted the development of the color octet model (*e.g.*, $p\overline{p} \to gg \to \chi_c \to \psi + \mathrm{X}$) and highlighted the role of gluon fragmentation in charmonium production. Recent results from both LEP and HERA have also helped elucidate the gluonic contribution to charmed meson production. Current estimates from LEP are that gluon fragmentation accounts for approximately half of the D^* production in the lowest momentum region (the lowest quarter of the allowed kinematic region).

Many functional forms have been suggested to describe these momentum spectra for heavy quarks produced in e^+e^- annihilations. The functional form given by Peterson *et al.* [1] in terms of just one free parameter ϵ_P has found widespread use; other parameterizations are also given in the literature [2]. The earliest Peterson form was a function of one variable z, defined for a heavy-quark Q, light-quark $\overline{q}$ system as the ratio of the energy plus the longitudinal momentum of the hadron $Q\overline{q}$ to the sum of the energy and momentum of the heavy quark after accounting for initial state radiation, gluon bremsstrahlung, and final state radiation: $z = (E + p_{||})_{Q\overline{q}}/(E + p_Q)$. The main advantage of this variable is that it is relativistically invariant with respect to boosts in the direction of the primary quark. Unfortunately, as this quantity is not directly accessible, experiments typically use other scaling variables which are close approximations to z—either $x^+ = (p_{||} + E)_{\mathrm{hadron}}/(p_{||} + E)_{\mathrm{max}}$, $x_p = p/p_{\mathrm{max}}$, or $x_E = E_{\mathrm{hadron}}/E_{\mathrm{beam}}$.

The Peterson functional form is:

$$\frac{dN}{dz} = \frac{1}{z[1 - (1/z) - \epsilon_P/(1 - z)]^2} \qquad (36.1)$$

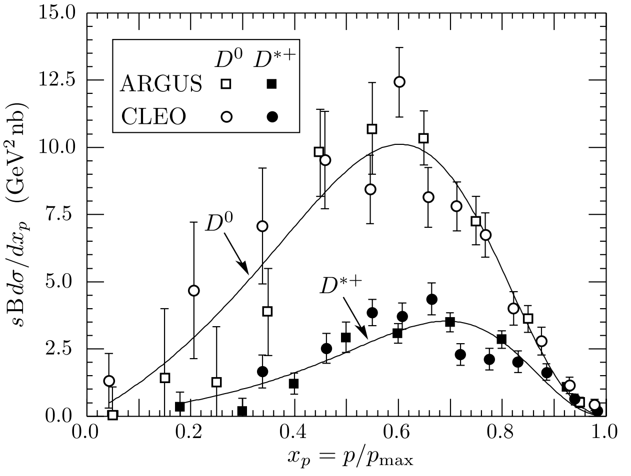

Figure 36.1: Efficiency-corrected inclusive cross section measurements for the production of D^0 and D^{*+} in e^+e^- measurements at $\sqrt{s} \approx 10$ GeV. The variable x_p is related to the Peterson variable z, but is not identical to it.

The bulk of the available fragmentation function data on charmed mesons (excluding $J/\psi(1S)$) is from measurements at $\sqrt{s} = 10$ GeV. Shown in Fig. 36.1 are the efficiency-corrected (but not branching ratio corrected) CLEO [3] and ARGUS [4] inclusive cross sections ($s \cdot \mathcal{B}d\sigma/dx_p$ in units of GeV^2-nb, with $x_p = p/p_{\mathrm{max}}$) for the production of pseudoscalar D^0 and vector D^{*+} in e^+e^- annihilations at $\sqrt{s} \approx 10$ GeV. For the D^0, $\mathcal{B}$ represents the branching fraction for $D^0 \to K^-\pi^+$; for the D^{*+}, $\mathcal{B}$ represents the product branching fraction: $D^{*+} \to D^0\pi^+; D^0 \to K^-\pi^+$. These inclusive spectra have not been corrected for cascades from higher states, nor for radiative effects. Note that since the momentum spectra are sensitive to radiative corrections, comparison of charm spectra at $\sqrt{s} = 10$ GeV cannot be compared directly with spectra at higher center-of-mass energies, and must be appropriately evolved.

Fits to the combined CLEO and ARGUS D^0 and D^{*+} data give $\epsilon_P(D^0) = 0.135 \pm 0.01$ and $\epsilon_P(D^*) = 0.078 \pm 0.008$; these are indicated in the solid curves. Measurement of the fragmentation functions for a variety of particles has allowed comparisons between mesons and baryons, and particles of different spin structure, as shown in Table 36.1

Table 36.1: The Peterson momentum hardness parameter ϵ_P as obtained from $e^+e^- \to$ (particle) + X measurements.

Particle	L	$\sqrt{s}$	ϵ_P	Reference
D^0	0	10 GeV	0.135 ± 0.01	[3]
D^{*+}	0	10 GeV	0.078 ± 0.008	[3]
D_s^*	0	10 GeV	$0.04^{+0.03}_{-0.01}$	[5]
$D_1^0(2420)$	1	10 GeV	$0.034^{+0.018}_{-0.012}$	[6]
$D_2^0(2460)$	1	10 GeV	0.015 ± 0.004	[6]
$D_1^+(2420)$	1	10 GeV	$0.020^{+0.011}_{-0.006}$	[7]
$D_2^+(2460)$	1	10 GeV	0.013 ± 0.007	[7]
$D_{s1}(2536)$	1	10 GeV	$0.06^{+0.035}_{-0.03}$	[8]
$D_{s2}(2573)$	1	10 GeV	$0.027^{+0.043}_{-0.016}$	[9]
$\varLambda_c$	0	10 GeV	0.25 ± 0.03	[10,11]
$\varXi_c$	0	10 GeV	0.23 ± 0.05	[12,13]
$\varSigma_c$	0	10 GeV	0.29 ± 0.06	[14,15]
$\varSigma_c^*$	0	10 GeV	$0.30^{+0.10}_{-0.07}$	[16]
$\varXi_c^{*+}$	0	10 GeV	$0.24^{+0.22}_{-0.10}$	[17]
$\varXi_c^{*0}$	0	10 GeV	$0.22^{+0.15}_{-0.08}$	[18]
$\varLambda_{c,1}$	1	10 GeV	0.059 ± 0.028	[19,20]
$\varLambda_{c,2}$	1	10 GeV	0.053 ± 0.012	[19,21]
$\varXi_{c,2}$	1	10 GeV	$0.058^{+0.037}_{-0.021}$	[22]
b hadrons	—	90 GeV	$0.0047^{+0.0010}_{-0.0008}$	[23]

We note from Table 36.1 that the mass dependence of ϵ_P is less marked than the dependence on the orbital angular momentum structure of the charmed hadron being measured. Orbitally excited $L = 1$ charmed hadrons (D_J, $D_{s,J}$, and $\varLambda_{c,J}$) show consistently harder spectra (*i.e.*, smaller values of ϵ_P) than the $L = 0$ ground states, whereas the data for the ground state charmed baryons $\varLambda_c$ and $\varXi_c$ show agreement with the lighter (by ≈ 400–600 MeV) ground-state D and D_s charmed mesons. To some extent, the harder spectra of $L = 1$ hadrons can be attributed to the fact that all the $L = 1$ charmed hadrons will eventually decay into $L = 0$ hadrons.

Bottom-flavored hadrons at LEP have been measured to have an even harder momentum spectrum than charmed hadrons at lower energies [23–25]. Qualitatively, whereas charm spectra peak at $x_p \approx 0.6$, the spectra of bottom hadrons peak at $x_p \approx 0.8$. This is as expected in the Peterson model, where the value ϵ_P is expected to vary as the ratio of the effective light quark mass to the heavy quark mass in a heavy quark + light (di)quark hadron. In the case of charm, the Peterson functional form provides an acceptable description of the shape of the x_p distribution, provided the appropriate ϵ_P value is independently determined for each separate species of charmed particle. However, unlike charm, the numbers of fully reconstructed b-flavored hadrons is too small to allow a statistically compelling measure of ϵ_P for each separate bottom hadron. Consequently, a b-enriched sample is isolated kinematically, using, *e.g.*, a high p_T lepton and/or a displaced vertex to tag a primary b quark. The x_p distribution therefore includes all b-flavored hadrons in the sample, and does not yet allow a straightforward species-by-species ϵ_P extraction. Additional uncertainties in the case of bottom arise from the sensitivity of ϵ_P to the fragmentation model used to non-perturbatively evolve the initial $q\overline{q}$ system into final state hadrons.

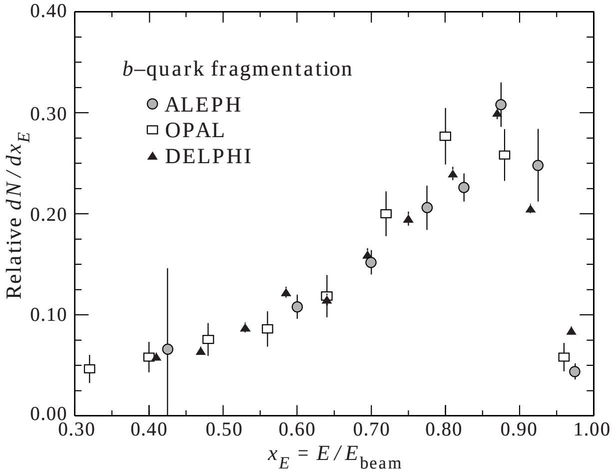

Figure 36.2: Fractional energy distribution for b-quark fragmentation for inclusive b production at LEP.

In general, the b-quark fragmentation function distribution is found to be somewhat narrower than the shape of the Peterson function; this may be due to a systematic underestimate of soft gluon emission in event generators, and/or uncertainties in the appropriate mix of b-flavored hadrons. The match of a single Peterson function to data is therefore much more difficult for bottom than charm at this time, although there is relatively good agreement from experiment to experiment, as seen in Fig. 36.2, which displays the fragmentation function data from OPAL [23], ALEPH [24], and DELPHI [25].

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