Measurement of b Quark Fragmentation Fractions in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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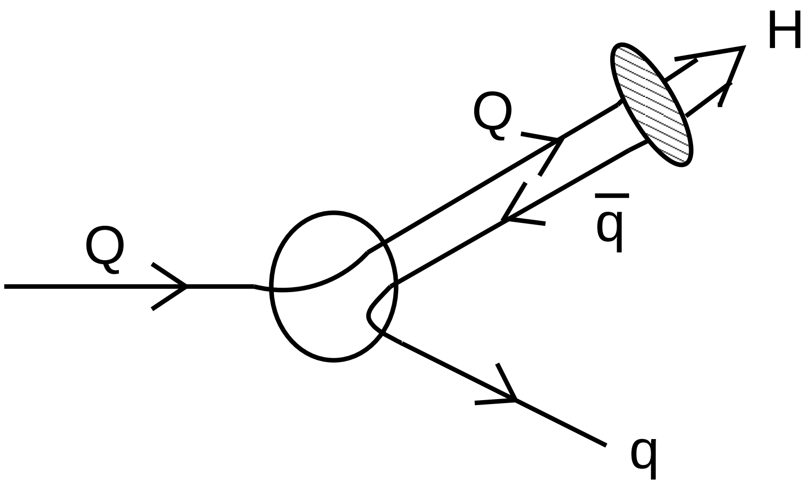
Fragmentation



The fragmentation of a heavy quark Q into a hadron H is

- a long-distance process
- governed by nonperturbative QCD
- described by phenomenological models, e.g.,
  1. Lund colour string model
  2. Feynman-Field independent jet model

Fragmentation Fractions

Bottom quark fragmentation fractions are defined as the relative fraction of weakly-decaying B hadrons, i.e.,

$$f_{u,d,s,baryon} = \frac{N(B_{u,d,s}, \overline{\Lambda}_b)}{N(\text{all } b \text{ hadrons})}.$$

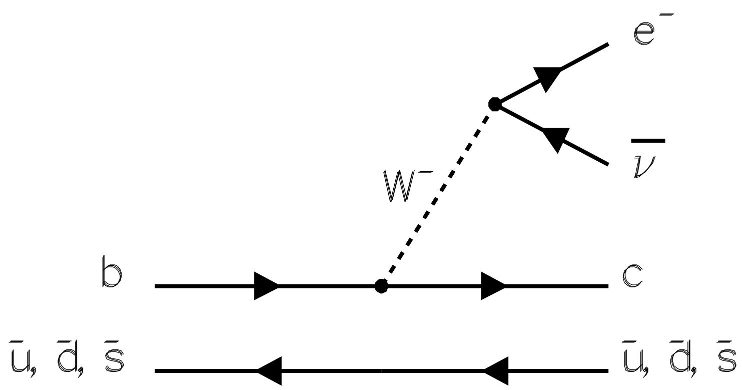
Studies of these fractions are important for precision studies of

1. CKM matrix elements V_{cb} and V_{ub}
2. $B\overline{B}$ mixing parameters Δm_d and Δm_s
3. B hadron lifetime measurements
4. B hadron decay branching fraction measurements

Reconstruct Semileptonic Decays

$$
\begin{array}{llll}
B_u^+ & \to e^+\nu X & \overline{D}^0 & \\
 & & \hookrightarrow & K^+\pi^- \\
B_d^0 & \to e^+\nu X & D^- & \\
 & & \hookrightarrow & K^+\pi^-\pi^- \\
B_s^0 & \to e^+\nu X & D_s^- & \\
 & & \hookrightarrow & \phi\pi^- \\
 & & & \hookrightarrow K^+K^-
\end{array}
$$

- Spectator model can be used to estimate unknown branching fractions



$\boxed{\text{Ratios of Fragmentation Fractions}}$

$$\frac{f_s}{f_u+f_d} = \frac{N(e^+D_s^-)}{\mathcal{B}(B_s^0 \to D_s^- e^+\nu)\cdot\mathcal{B}(D_s^- \to \phi\pi^-)\cdot\mathcal{B}(\phi \to K^+K^-)\cdot\varepsilon(D_s^-)}$$

$$\cdot\left[\frac{N(e^+\overline{D}^0)}{\mathcal{B}(B^+ \to \overline{D}^0 e^+\nu)\cdot\mathcal{B}(\overline{D}^0 \to K^+\pi^-)\cdot\varepsilon(\overline{D}^0)} + \frac{N(e^+D^-)}{\mathcal{B}(B^0 \to D^- e^+\nu)\cdot\mathcal{B}(D^- \to K^+\pi^-\pi^-)\cdot\varepsilon(D^-)}\right]^{-1}$$

$$f_{baryon}/(f_u + f_d)$$

$$f_d/f_u$$

Using $f_u + f_d + f_s + f_{baryon} \equiv 1$, we obtain

$$f_d$$
$$f_u$$
$$f_s$$
$$f_{baryon}$$

Event Selection

$$B_u^+ \rightarrow e^+ \nu X \quad \overline{D}^0$$

$$\hookrightarrow \quad K^+ \pi^-$$

$$B_d^0 \rightarrow e^+ \nu X \quad D^{*-}$$

$$\hookrightarrow \quad \overline{D}^0 \pi^-$$

$$\hookrightarrow K^+ \pi^-$$

$$B_d^0 \rightarrow e^+ \nu X \quad D^-$$

$$\hookrightarrow \quad K^+ \pi^- \pi^-$$

$$B_s^0 \rightarrow e^+ \nu X \quad D_s^-$$

$$\hookrightarrow \quad \phi \pi^-$$

$$\hookrightarrow K^+ K^-$$

$$\overline{\Lambda}_b^0 \rightarrow e^+ \nu X \quad \Lambda_c^-$$

$$\hookrightarrow \quad \overline{p} K^+ \pi^-$$

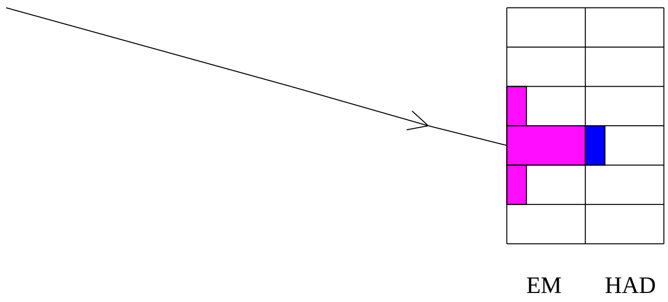
Kinematically similar decays for B_u^+, B_d^0 and B_s^0 mesons and $\overline{\Lambda}_b^0$ baryons are selected so that certain efficiencies cancel.

Electron Identification

- EM energy cluster in central detector with $E_T > 8$ GeV

- Single charged track matched to cluster

- Lateral and longitudinal energy leakage is small

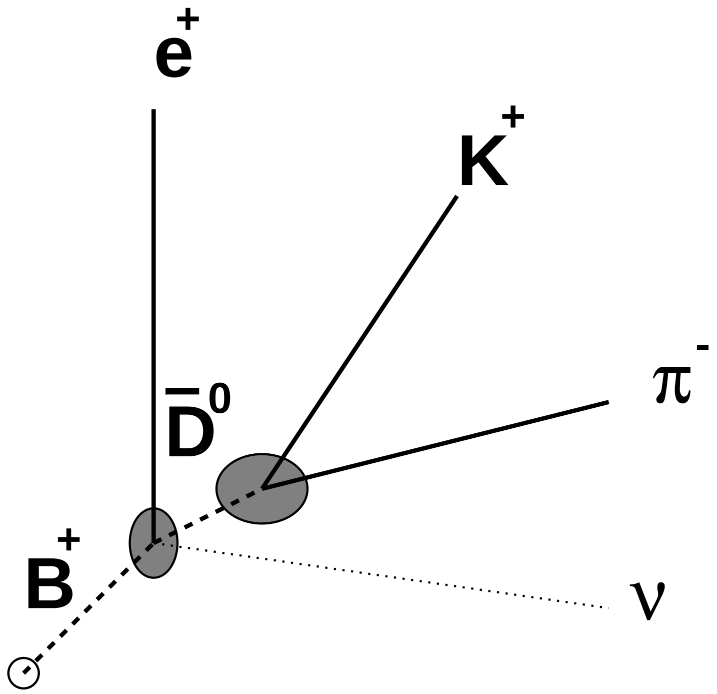


- Photon conversions removed

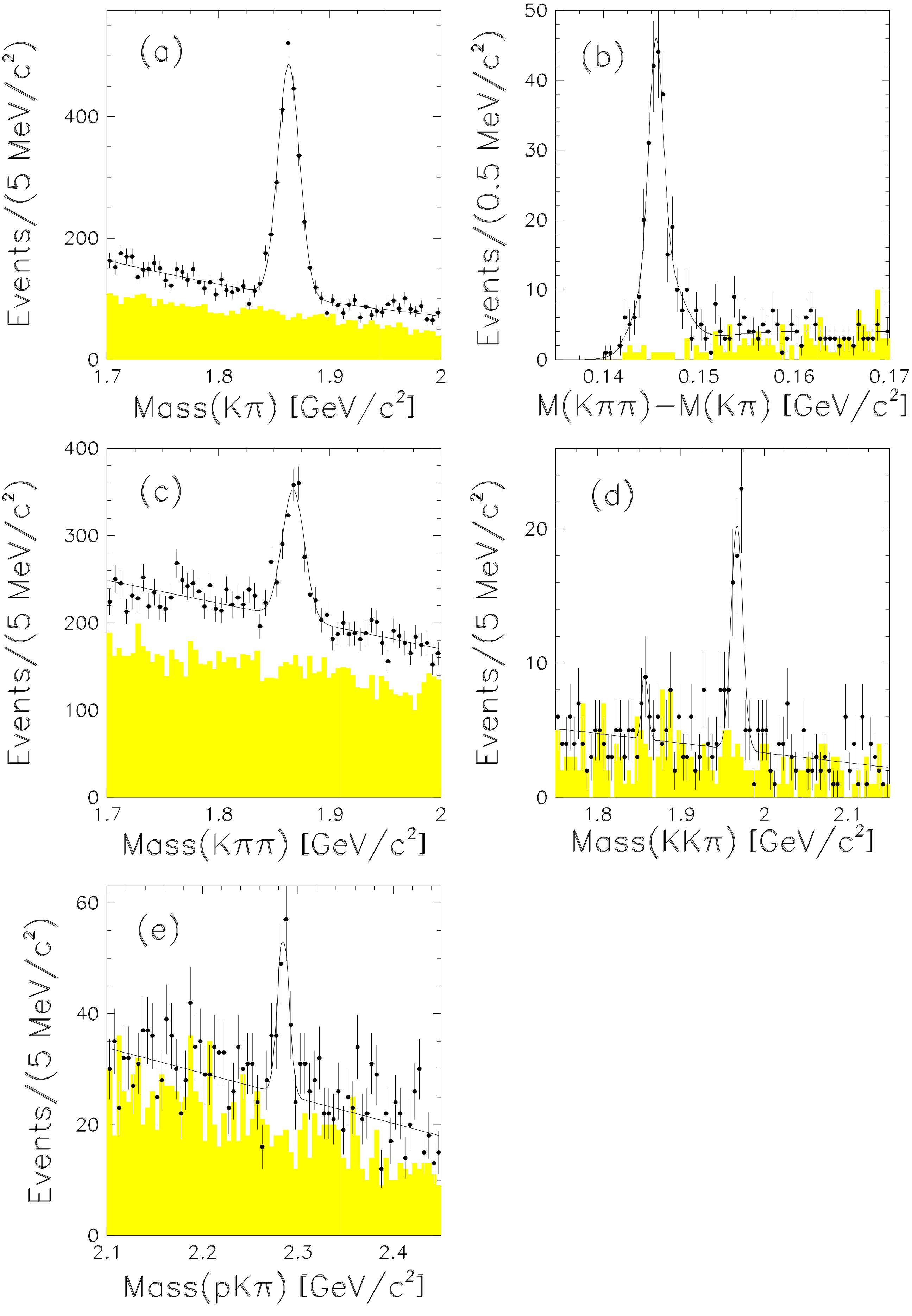
- Electrons from $W^{\pm}$ and Z^0 bosons removed

$\boxed{\text{110 pb}^{-1} \text{ of Run 1 data} \Rightarrow \text{3 million electrons}}$

$B^+ \to \overline{D}^0 e^+ \nu$ Decay Identification



- Daughter tracks near electron
- Significant impact parameter
- Displaced decay vertex
- Mass($eK\pi$) $<$ mass(B^+)


(a)
(b)
(c)
(d)
(e)
Events/(5 MeV/c^2)
Events/(0.5 MeV/c^2)
Mass(Kπ) [GeV/c^2]
M(Kππ)−M(Kπ) [GeV/c^2]
Mass(Kππ) [GeV/c^2]
Mass(KKπ) [GeV/c^2]
Mass(pKπ) [GeV/c^2]

Event Yields Summary

$$B^+ \to e^+\nu X \quad \overline{D}^0$$
$$\hookrightarrow K^+\pi^- \qquad 1848 \pm 58$$

$$B^0 \to e^+\nu X \quad D^{*-}$$
$$\hookrightarrow \overline{D}^0\pi^-$$
$$\hookrightarrow K^+\pi^- \qquad 249 \pm 19$$

$$B^0 \to e^+\nu X \quad D^-$$
$$\hookrightarrow K^+\pi^-\pi^- \qquad 736 \pm 62$$

$$B_s^0 \to e^+\nu X \quad D_s^-$$
$$\hookrightarrow \phi\pi^-$$
$$\hookrightarrow K^+K^- \qquad 59 \pm 10$$

$$\overline{\Lambda}_b^0 \to e^+\nu X \quad \Lambda_c^-$$
$$\hookrightarrow \overline{p}K^+\pi^- \qquad 79 \pm 17$$

Cross Contamination

- $D_s^- e^+$ and $\Lambda_c^- e^+$ final states are pure samples of B_s^0 and $\overline{\Lambda}_b^0$ decays, respectively

- However, not all semileptonic decays of B_s^0 mesons result in $D_s^- e^+$ final state

- For example, D^- mesons result from B^0, B^+ and B_s^0 decays:

$$B^0 \to e^+\nu \quad D^-$$

$$B^+ \to e^+\nu \quad \overline{D}^{**0}$$
$$\hookrightarrow \quad D^-\pi^+$$

$$B_s^0 \to e^+\nu \quad D_s^{**-}$$
$$\hookrightarrow \quad D^-K^0$$

Branching Fractions

Three semileptonic decay modes

$$
\begin{aligned}
g = & \; \mathcal{B}(B \;\rightarrow De^{+}\nu_e) \\
g^{*} = & \; \mathcal{B}(B \;\rightarrow D^{*}e^{+}\nu_e) \\
g^{**} = & \; \mathcal{B}(B \;\rightarrow D^{**}e^{+}\nu_e)
\end{aligned}
$$

PDG 98 values exist for

- g_0, g_0^{*}, g_0^{tot} for B^0 mesons
- g_+, g_+^{*}, g_+^{tot} for B^+ mesons

$$g^{tot} = g + g^{*} + g^{**} = \mathcal{B}(B \rightarrow l\nu X)$$

Use spectator model calculations for

- g_s, g_s^{*}, g_s^{tot} for B_s^0 mesons
- g_{baryon}^{tot} for $\overline{\Lambda}_b^0$ baryons

$\boxed{\text{Spectator Model}}$

Since full widths are equal

$\Gamma(B_s^0 \to e^+\nu_e X) = \Gamma(B \to e^+\nu_e X)$

and partial widths are equal

$\Gamma(B^+ \to \overline{D}^0 e^+\nu_e) = \Gamma(B^0 \to D^- e^+\nu_e) = \Gamma(B_s^0 \to D_s^- e^+\nu_e)$

can calculate B_s^0 branching fractions:

e.g., $\mathcal{B}(B_s^0 \to e^+\nu_e X) = \frac{\tau(B_s^0)}{\langle\tau(B)\rangle}\mathcal{B}(B \to e^+\nu_e X)$.

Reconstruction Efficiencies

Several efficiencies cancel in the ratio:

- the plateau electron trigger efficiency,
- the electron identification efficiency, and
- the conversion removal efficiency.

Non-cancelling efficiencies include

- Trigger and tracking efficiencies $\Rightarrow$ data.
- Other efficiencies $\Rightarrow$ Monte Carlo calculation.
  1. Geometric and kinematic acceptances
  2. Charmed hadron reconstruction

Monte Carlo calculation:

1. B hadron generator
2. CLEOMC (QQ) for B hadron decays (ISGW)
3. CDF simulation

Determination of the Fragmentation Fractions

Calculate the 5 predicted event yields, e.g.,

$$\begin{aligned} N(e^+\overline{D}^0) = \; & [N(B^+) \cdot \mathcal{B}(B^+ \to \overline{D}^0 e^+ \nu) \cdot \varepsilon_1(e^+\overline{D}^0)... \\ & + f_d/f_u \cdot N(B^+) \cdot \mathcal{B}(B^0 \to D^{*-} e^+ \nu) \\ & \cdot \mathcal{B}(D^{*-} \to \overline{D}^0 \pi^-) \cdot \varepsilon_2(e^+\overline{D}^0)... \\ & + f_s/f_u \cdot N(B^+) \cdot \mathcal{B}(B_s^0 \to D_s^{**-} e^+ \nu) \\ & \cdot \mathcal{B}(D_s^{**-} \to \overline{D}^0 K^-) \cdot \varepsilon_3(e^+\overline{D}^0)...] \\ & \cdot \mathcal{B}(\overline{D}^0 \to K^+ \pi^-) \end{aligned}$$

where

$$\begin{aligned} \mathcal{B}(B^+ \to \overline{D}^0 e^+ \nu_e) &= g_+ \\ \mathcal{B}(B^0 \to D^{*-} e^+ \nu_e) &= g_0^* \\ \mathcal{B}(B_s^0 \to D_s^{**-} e^+ \nu_e) &= g_s^{**} \end{aligned}$$

From the relationship $f_d + f_u + f_s + f_{baryon} \equiv 1$, calculate the absolute values.

Systematic Uncertainties

- $\mathcal{B}(B \to e^+\nu_e X) \Rightarrow \sigma = 2.0\%$

- Lifetimes $\Rightarrow 2.4 < \sigma < 4.5\%$

- Daughter branching fractions
  1. $\mathcal{B}(\overline{D}^0 \to K^+\pi^-) \Rightarrow \sigma = 2.3\%$
  2. $\mathcal{B}(D^- \to K^+\pi^-\pi^-) \Rightarrow \sigma = 6.7\%$
  3. $\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-) \Rightarrow \sigma = 2.0\%$
  4. $\mathcal{B}(\phi \to K^+K^-) \Rightarrow \sigma = 1.6\%$

- Efficiencies $\Rightarrow 2.1 < \sigma < 9.3\%$
  1. Tracking efficiency
  2. Trigger efficiency
  3. Peterson parameter ϵ_b
  4. $\overline{\Lambda}_b^0$ production polarization

- χ^2 terms in the fit explicitly constrain g, g^* and Σg to their measured/calculated values

Summary of Results

$\frac{f_d}{f_u}$	0.84 ± 0.16	1.0000
$\frac{f_s}{f_u+f_d}$	0.211 ± 0.067	0.213 ± 0.068
$\frac{f_{baryon}}{f_u+f_d}$	0.118 ± 0.042	0.118 ± 0.042
f_u	0.408 ± 0.048	0.375 ± 0.023
f_d	0.344 ± 0.040	0.375 ± 0.023
f_s	0.159 ± 0.043	0.160 ± 0.044
f_{baryon}	0.089 ± 0.029	0.090 ± 0.029

Comparison to Other b-quark Fragmentation Fraction Measurements

- This result: $f_s/(f_u + f_d) = 0.213 \pm 0.068$.

- CDF: Used sequential semimuonic decays to determine

$$f_s/(f_u + f_d) = 0.210 \pm 0.036^{+0.038}_{-0.030}.$$

$$\begin{array}{llll}
B_s^0 & \rightarrow \mu^+ \nu X \;\; D_s^- & & \\
 & \quad\quad\quad\;\; \hookrightarrow & \phi \mu^- \nu & \\
 & & \;\hookrightarrow & K^+ K^-
\end{array}$$

1998 Particle Data Group values

$$\begin{aligned}
f_u = f_d &= 0.397^{+0.018}_{-0.022} \\
f_s &= 0.105^{+0.018}_{-0.017} \\
f_{baryon} &= 0.101^{+0.039}_{-0.031}
\end{aligned}$$

Combined $\overline{p}p$ Results

$\frac{f_d}{f_u}$	0.84 ± 0.16	1.0000
$\frac{f_s}{f_u+f_d}$	0.212 ± 0.041	0.213 ± 0.038
$\frac{f_{baryon}}{f_u+f_d}$	0.118 ± 0.042	0.118 ± 0.041
f_u	0.408 ± 0.046	0.375 ± 0.015
f_d	0.344 ± 0.039	0.375 ± 0.015
f_s	0.159 ± 0.026	0.160 ± 0.025
f_{baryon}	0.089 ± 0.029	0.090 ± 0.028

Conclusions

- First time all four b fragmentation fractions have been measured in a single experiment

  1. $f_u = f_d = 0.375 \pm 0.023$
  2. $f_s = 0.160 \pm 0.044 \rightarrow 0.160 \pm 0.025$
  3. $f_{baryon} = 0.090 \pm 0.029$

- Most accurate direct measurement of the b fragmentation fractions to date

- $f_d/f_u = 0.84 \pm 0.16$ consistent with CLEO result and with isospin

- f_s consistent with CDF sequential semimuon-ic result but 2σ above LEP results

- f_{baryon} agrees well with other measurements

$\boxed{\text{Comments}}$

- Fragmentation phenomenology

  1. lacks precise predictions for fragmentation fractions.

  2. does not address possible hadronization differences associated with b production mechanism, i.e., Tevatron, LEP, $\Upsilon(4S)$.

  3. is unclear about light flavor dependence of Peterson fragmentation parameter.

- Would be nice to have more precise measurements for

  1. semileptonic and daughter branching fractions,

  2. B hadron lifetimes.