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Semileptonic Decays of Bottom Baryons at LEP

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1 Introduction

Heavy quarks provide a useful tool to look into the standard model and beyond. In particular, the determination of the CKM matrix elements V_{cb} and V_{ub} from b quark decays[1] and the observation of mixing in the neutral B meson system[2] have been important benchmarks in establishing the standard model.

From the theoretical point of view heavy quark systems may be described systematically within QCD by means of the Heavy Quark Effective Theory (HQET) [3,4]. It exploits the fact that the masses of the heavy quarks m are large compared to the scale parameter Λ_{QCD} associated with the light QCD degrees of freedom. In the limit $\Lambda_{QCD}/m \rightarrow 0$ new symmetries arise above those already present in QCD. These lead to considerable simplifications in the description of heavy quark systems. Corrections to the heavy quark limit are of the order Λ_{QCD}/m and $\alpha_s(m)/\pi$. Thus one expects that corrections are at the percent level for systems with bottom quarks and are at the ten percent level for the ones involving charm quarks.

There have been many beautiful and important results on the spectroscopy of charmed mesons and baryons and their hadronic and semileptonic decays[5]. In the bottom sector most data so far are on b mesons: In e^+e^- continuum production and in hadroproduction b baryons are very difficult to observe. On the other hand, fixed target experiments as well as e^+e^- resonance production on the $\Upsilon(4s)$ are below the b baryon threshold. Yet, we expect important advances in b baryon physics from LEP and HERA. In fact, first evidences for these baryons were already reported by ALEPH [6]. Theoretically, the lowest lying b baryon, Λ_b , is particularly challenging since it is here where HQET has its largest predictive power. The light degrees of freedom are in a spin zero state for a Λ_b . Thus the spin of the baryon is the spin of the heavy quark due to the decoupling of the heavy quark spin in HQET.

We shall focus on the exclusive semileptonic decays $\Lambda_b \rightarrow \Lambda_c \ell \nu$ and discuss its differential decay distributions. We shall exploit the fact that there are three widely separated mass scales in the problem: $s \gg m \gg \Lambda_{QCD}$ where \sqrt{s} is the cms energy of the collider, $s = M_Z^2$ for LEP. Note that we have to calculate the decay distributions in the LEP lab frame rather than in the rest frame of the heavy bottom hadron as it is needed for resonance production of B mesons at the $\Upsilon(4s)$. The heavy hadron is in general highly relativistic at a collider and the present paper is the first application of HQET in such a context.

In the following we shall argue that the energy distribution of the charged decay lepton depends on the polarization of the b quark and can thus be used to extract the vector and axial vector couplings g_V and g_A for the b quark from such a measurement. The dependence of the decay lepton energy distribution on the b quark polarization is analogous to the τ polarization case $\tau \rightarrow \nu_\tau + \ell + \bar{\nu}_\ell$. Vice versa, assuming the couplings to be known, the lepton energy distribution can be used to discriminate between different bottom hadrons. This point will be pursued in a forthcoming paper.

The process which creates the heavy quark is in the present case governed by the large scale s and is usually treated in a perturbative way. The subsequent fragmentation of the heavy quark into a heavy hadron involves the light QCD degrees of freedom. Thus it is governed by the small scale Λ and the symmetries of the heavy quark limit are present already in the hadronization process with corrections being of the order of Λ/m . This means in particular that the spin of the heavy quark decouples from the hadronization process and has the interesting consequence that for the heavy ground state baryons (Λ_c and Λ_b) the spin of the baryon is given by the spin direction of the heavy quark. Thus in systems with

Abstract

We study semileptonic Λ_b decays where the Λ_b originates from Z_0 decays into b quarks. The differential decay distributions are calculated using the heavy quark effective theory. We investigate the energy distribution of the decay leptons. In Λ_b decays the lepton energy distribution is sensitive to the standard model parameters via the nontrivial Λ_b polarization. We also discuss a possibility to study b quark fragmentation into baryons using the semileptonic decays.

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heavy baryons there is the unique chance to measure the polarization of the quarks created for instance in Z_0 decays at LEP.

There are two reasons to focus on the semileptonic decays $\Lambda_b \rightarrow \Lambda_c \ell \nu$ and $\Lambda_b \rightarrow X_c \ell \nu$ with $\ell = e, \mu$. The first reason is that we expect them to constitute a substantial fraction of the total decay rate of the bottom baryons, namely to be close to the one given by the free b quark decay which yields branching fractions of about 12%. Furthermore, we shall argue that the exclusive decay $\Lambda_b \rightarrow \Lambda_c e \nu$ should saturate the inclusive semileptonic width to a large extent, i.e. to about 90%. With these estimates one can obtain some information on the fragmentation process of b quarks in particular on the number of baryons created per number of fragmenting b quarks.

The second reason is that the semileptonic decays are relatively easy to reconstruct, in particular the energy distribution of the charged lepton is accessible. As it is well known from the polarization analysis of $Z_0 \rightarrow \tau^+ \tau^- \rightarrow \nu_e \bar{\nu}_e e^+ X$ the polarization of the τ lepton may be inferred from the energy spectrum of the electron in the lab frame. In the present paper we give the corresponding formulae for a polarization analysis of Λ_b baryons created from a Z_0 decay. Similarly to the τ case the lepton energy spectrum in the lab frame contains the information on the baryon polarization, although matters become more complicated, since care has to be taken of the hadronic matrix element for which we shall apply HQET.

2 Exclusive Semileptonic Decay: $\Lambda_b \rightarrow \Lambda_c e \nu$

We first discuss the exclusive decay $\Lambda_b \rightarrow \Lambda_c \ell \nu$ where the decaying Λ_b is assumed to be polarized. We give the energy distribution in the laboratory frame in which the Λ_b has a momentum large compared to its mass. We shall use the typical parameters encountered at LEP where $|\vec{p}_{\Lambda_b}| \approx M_Z/2$. The dependence of the energy distribution on the polarization of the Λ_b is studied and the possibility to extract g_A and g_V for the b quark from this polarization measurement is discussed.

We employ the heavy quark limit [3] to write down the current for the weak transition from Λ_b to Λ_c . This current is in general given in terms of six independent form factors:

$$\begin{aligned} & \langle \Lambda_c(v_e, s_c) | \bar{c} \gamma_\mu (1 - \gamma_5) b | \Lambda_b(v_b, s_b) \rangle = \\ & \bar{u}_{\Lambda_c}(v_e, s_c) (F_1(v_b \cdot v_e) \gamma_\mu + F_2(v_b \cdot v_e) v_{b\mu} + F_3(v_b \cdot v_e) v_{e\mu}) u_{\Lambda_b}(v_b, s_b) \\ & - \bar{u}_{\Lambda_c}(v_e, s_c) (G_1(v_b \cdot v_e) \gamma_\mu + G_2(v_b \cdot v_e) v_{b\mu} + G_3(v_b \cdot v_e) v_{e\mu}) \gamma_5 u_{\Lambda_b}(v_b, s_b) \end{aligned} \quad (1)$$

where v_e, v_b are the velocities of the heavy baryons which are related to the momenta p_e, p_b by $p_e = m_e v_e, p_b = m_b v_b$ and s_b, s_c denote the spin vectors of the two baryons.

In leading order of HQET these six form factors reduce to only one independent form factor F

$$F(v_b \cdot v_e) = F_1(v_b \cdot v_e) = G_1(v_b \cdot v_e) \quad (2)$$

$$F_2(v_b \cdot v_e) = F_3(v_b \cdot v_e) = G_2(v_b \cdot v_e) = G_3(v_b \cdot v_e) = 0 \quad (3)$$

In addition, due to heavy quark symmetries this single form factor is normalized at maximum momentum transfer, i.e. at $v_b \cdot v_e = 1$, to

$$F(v_b \cdot v_e = 1) = 1 \quad (4)$$

The $v_b \cdot v_e$ dependence of the form factor contains nonperturbative informations on the matrix element and may not be calculated from first principles. For the numerical estimates we shall use a simple form motivated by a pole ansatz

$$F(w) = \frac{w_0^2}{w_0^2 - 2 + 2w} \quad (5)$$

We shall take the value $w_0 = 0.89$ which was obtained from fitting the lepton spectrum of exclusive semileptonic B decays [7]. The parametrization (5) yields a good description of the inclusive semileptonic B decays into D and D^* mesons and we expect the same for the decays considered here.

From this form of the hadronic current we obtain the rate for the exclusive semileptonic decay

$$\Lambda_b(p_b = m_b v_b, s_b) \rightarrow \Lambda_c(p_c = m_c v_c, s_c) + \ell(p_\ell, s_\ell) + \bar{\nu}_\ell(p_\nu, s_\nu) \quad (6)$$

summed over the spins of the final state particles

$$d\Gamma = 64 G_F^2 \frac{1}{2} \frac{\vec{d}p_\nu \cdot \vec{d}p_\ell \vec{d}p_c}{E_b} (2\pi)^4 \delta(p_b - p_c - p_\ell - p_\nu) |F(v_b \cdot v_e)|^2 (p_c \cdot p_\ell) [(p_\nu \cdot p_b) - m_b (s_b \cdot p_\nu)] \quad (7)$$

Here $E_b = p_{b0}$ is the energy of the decaying Λ_b and $\vec{d}p = d^3\vec{p}/(2E(2\pi)^3)$. We shall express the rate doubly differential in the momentum transfer to the leptonic system $q^2 = (p_\ell + p_\nu)^2 = 2(p_\ell \cdot p_\nu)$ and the energy of the lepton $E_\ell = p_{\ell 0}$ in the laboratory frame. Note that $v_b \cdot v_e = (m_b^2 + m_c^2 - q^2)/(2m_b m_c)$.

The phase space integration may be performed by standard methods to yield the doubly differential rate $d^2\Gamma/(dq^2 dx)$, where $x = E_\ell/E_b$ is the scaled lepton energy. We first give the result for the unpolarized piece Γ_u . It may be expressed in terms of the function

$$f(s) = (\Delta + q^2)s - \frac{1}{2}s^2 - q^2 \Delta \ln s \quad (8)$$

where we have defined $\Delta = m_b^2 - m_c^2 + q^2$. The unpolarized doubly differential rate is then given by

$$\frac{d^2\Gamma_u}{dq^2 dx} = \frac{G_F^2}{16\pi^3} \frac{1}{E_b \beta} |F(v_b \cdot v_e)|^2 (f(s_{\max}) - f(s_{\min})) \quad (9)$$

where the integration limits s_{\max} and s_{\min} are functions of q^2 and x

$$s_{\max} = \text{Min} \left(\frac{1}{2} (\Delta + \sqrt{\Delta - 4m_b^2 q^2}), \frac{2zm_b^2}{1 - \beta} \right) \quad (10)$$

$$s_{\min} = \text{Max} \left(\frac{1}{2} (\Delta - \sqrt{\Delta - 4m_b^2 q^2}), \frac{2zm_b^2}{1 + \beta} \right) \quad (11)$$

and $\beta = |\vec{p}_b|/E_b$.

The polarized piece Γ_p , i.e. the piece containing the polarization vector s_b , is given in terms of the function g

$$\begin{aligned} g(s) = & -\frac{1}{4}s^2 + \frac{s}{2} [2m_b^2 x + \Delta + q^2] \\ & - \ln s \left[m_b^2 x (\Delta + q^2) + \frac{1}{2} q^2 (2m_b^2 + \Delta) \right] \\ & - \frac{1}{3} [m_b^2 x q^2 (2m_b^2 + \Delta) + (m_b q^2)^2] + \frac{1}{3} x (m_b^2 q^2)^2. \end{aligned} \quad (12)$$

We obtain

$$\frac{d^2\Gamma_p}{dq^2 dx} = \frac{G_F^2}{8\pi^3} \frac{1}{E_b \beta^2} |F(v_b, v_c)|^2 (g(s_{max}) - g(s_{min})) \quad (13)$$

Finally, the rate Γ for the decay of polarized Λ_b baryons with a degree of polarization

$$P \equiv \frac{d\Gamma(+s) - d\Gamma(-s)}{d\Gamma(+s) + d\Gamma(-s)} \quad (14)$$

is given by

$$\frac{d^2\Gamma}{dq^2 dx} = \frac{d^2\Gamma_u}{dq^2 dx} + P \frac{d^2\Gamma_p}{dq^2 dx} \quad (15)$$

We note that the Λ_b decay rate depends on $\beta = |\vec{p}_b|/E_b$. Taking carefully the limits $\beta = 0$ in (9) and (13) and a constant form factor $F(w) = 1$ we recover the well known formula for the semileptonic decay width of a free b quark [8]. At LEP the energy of the b quark is of the order of half of the Z_0 mass, since the fragmentation function for $b \rightarrow \Lambda_b$ is expected to be similarly hard as the one for $b \rightarrow B$. For our numerical results we take $E_b = M_Z/2 = 45$ GeV yielding $\beta - 1 = 1.2\%$. We have explicitly checked that the lepton energy distribution is very insensitive to the precise value of E_b as long as $E_b \gg m_b$.

We now concentrate on the lepton energy distribution which is arrived at by integrating over q^2 . We show in figure 1 the resulting x shapes for three different cases. (5). The two pieces Γ_u and Γ_p of the rate are plotted separately for $m_b = 5.2$ GeV. The solid line is the case of constant form factor $F(w) = 1$ and $m_c = 0$. In this limit the q^2 integration may be performed analytically. It yields

$$\frac{1}{\Gamma} \frac{d\Gamma}{dx} = \frac{1}{3} (5 - 9x^2 + 4x^3) - \mathcal{P} \frac{1}{3} (1 - 9x^2 + 8x^3). \quad (16)$$

the well known result for the lepton energy spectrum obtained for the process $Z_0 \rightarrow \tau^+ \tau^- \rightarrow \ell\nu X$ [9]

The dashed curve is the lepton energy spectrum for finite charm quark mass but still $F(w) = 1$. We have taken the value $m_c = 1.8$ GeV. Including the finite charm quark mass has the effect that the variable x has the upper limit $x \leq (\beta + 1)(1 - m_c^2/m_b^2)/2 \approx 0.88$. Furthermore, small values of x are enhanced and large values become suppressed in the unpolarized rate. Similarly the polarized piece depends stronger on x than in the case $m_c = 0$.

Finally, the dashed dotted curve includes the form factor as given in (5). For the unpolarized piece this reduces the x dependence compared to the case with constant form factor, while the x dependence of the polarized piece gets strongly enhanced. In particular for small lepton energies the polarized contribution gets enlarged by about a factor of two.

As remarked already before the heavy quark spin decouples in the heavy quark limit and the spin of the heavy baryon is the spin of the bound b quark. The hadronization process is soft and thus HQET predicts that the polarization of the heavy baryon is the polarization of the heavy quark as it was produced in the Z_0 decay. The polarization of the b quark is given by the vector and axial vector couplings g_V and g_A of the b quark to the Z_0 . Thus a measurement of the polarization of the Λ_b gives a possibility to measure g_A and g_V for the b quark. The standard model prediction for the polarization \mathcal{P} of a Λ_b or, equivalently, of a b quark from a Z_0 decay is quite large

$$P = \frac{2g_A g_V}{g_A^2 + g_V^2} = 0.94. \quad (17)$$

In order to investigate the sensitivity of the lepton spectrum to the polarization \mathcal{P} we plot in figure 2 the x distribution $d\Gamma/dx = d\Gamma_u/dx + \mathcal{P}d\Gamma_p/dx$ for the case of an unpolarized Λ_b (dashed curve) and for a polarized Λ_b (solid curve) with a polarization as given in (17). The shapes of the two curves are quite different. In particular for small values of x the sensitivity to the polarization (and thus to g_A and g_V) is very large, since in the region $0 \leq x \leq 0.3$ the spectrum is a monotonically increasing function of x while the unpolarized one decreases.

3 Inclusive Decay: $\Lambda_b \rightarrow X_c \ell \nu$

Heavy quark methods are not directly applicable to inclusive processes. On the other hand it is known from the semileptonic B meson decays that the major contribution to the total semileptonic branching fraction comes from the two lowest lying D meson states; the D and the D^* meson saturate about 90% of the inclusive semileptonic rate. This saturation is expected in the heavy quark picture where one argues that the light QCD degrees of freedom do not change due to the weak decay of the heavy quark. Thus the lowest spin symmetry doublet, namely the D and D^* , should saturate the inclusive semileptonic rate.

We expect a similar behaviour for the Λ_b . Since the two polarization directions of the Λ_b are the lowest baryonic spin symmetry doublet with a charm quark the decay $\Lambda_b \rightarrow \Lambda_c \ell \nu$ alone should saturate the inclusive rate $\Lambda_B \rightarrow X_c \ell \nu$ to the same extent like $B \rightarrow D \ell \nu$ and $B \rightarrow D^* \ell \nu$ saturate $B \rightarrow X_c \ell \nu$, namely to about 90%.

In addition, $\Lambda_b \rightarrow \Sigma_c \ell \nu$ transitions are suppressed by at least one power of Λ_{QCD}/m_c [4] and thus we expect that the above lepton spectrum should also be a reasonable approximation to the inclusive lepton spectrum. This is of some importance since at the present stage the semileptonic Λ_b decays are not fully reconstructed and thus only the inclusive rate is accessible.

4 Fragmentation of a b Quark into Baryons

Baryon production at colliders is usually described as a two step process, the production of a heavy quark occurring at a short time scale $\sim 1/Q$ where Q is of the order of the heavy quark mass, and a subsequent fragmentation occurring at much smaller scale, of the order of Λ_{QCD} . While heavy quark production can reliably be calculated in perturbation theory, quark fragmentation into mesons and baryons can so far only be modelled and is thus subjected to rather large uncertainties. In the LUND string model [10], for example, it is assumed that antidiquark diquark (colour triplet antitriplet) pairs are produced in the chromo-electric field in a way similar to the production of quark antiquark pairs. The production can be treated as a tunneling phenomenon and its probability is therefore proportional to $\exp(-\pi m^2/\kappa)$ where $\kappa \approx 0.2 \text{ GeV}^2$. Thus the relative probability for diquark to quark production is about $q : q = 0.09 : 1$ which corresponds to a nonstrange diquark mass of about 420 MeV. This assumption also implies that strange diquarks will be much suppressed compared to non-strange diquarks. Furthermore, spin 1 diquarks will have about the same probability since the relative heavier mass compared to the spin 0 diquarks is (roughly) compensated by an extra factor of 3 from counting the different spin states. Since also the spin $3/2$ b baryons and the Σ_b^0 decay strongly or electromagnetically into the low lying states the following fragmentation processes of a b

quark into baryons decaying weakly are expected:

$$\begin{aligned}
 b &\rightarrow \Lambda_b^0 = (b(ud)_0) & (18) \\
 &\Sigma_b^+ = (b(uu)_1) \\
 &\Sigma_b^- = (b(dd)_1)
 \end{aligned}$$

From our above discussion of semileptonic decays we propose a measurement of $b \rightarrow \Lambda_b$ in e^+e^- annihilation at LEP. The method is based on the decay chain

$$\Lambda_b \rightarrow \Lambda_c + l^- + \bar{\nu}_l + X \rightarrow \Lambda + l^- + X \quad (19)$$

and the experimental ability to distinguish between Λ and $\bar{\Lambda}$ [6]. Consider first the inclusive semileptonic decay $\Lambda_b \rightarrow X_c + l^- + \bar{\nu}_l$. Since the free quark decay formula works reasonably well in the B and the D system we shall take this branching ratio equal to the one for a free b quark decay. The same argument holds for the B mesons and we expect that the inclusive semileptonic branching fraction of Λ_b should be very close to the one for the inclusive semileptonic B meson decays. Thus we expect

$$\text{Br}(\Lambda_b \rightarrow X_c l \bar{\nu}) = 10 - 13\% \quad (20)$$

Consider now $X_c \rightarrow \Lambda + X$. Since $V_{cb} \gg V_{ub}$ we may neglect possible $b \rightarrow u$ transitions. Furthermore, as argued in the last section we expect the exclusive decay $\Lambda_b \rightarrow \Lambda_c e \bar{\nu}$ to saturate the inclusive semileptonic rate to about 90%.

Thus we have $\text{Br}(\Lambda_b \rightarrow \Lambda_c X l \bar{\nu}) \geq 90\% \cdot \text{Br}(\Lambda_b \rightarrow X_c l \bar{\nu})$, where X may be empty and we may take this branching fraction to be one for the estimates presented here. The decay $\Lambda_c \rightarrow \Lambda X$ is known to have a branching fraction of $27 \pm 9\%$ and may be used to identify the Λ through the Λl^- combination.

The other two Σ -like ground state bottom baryons are both charged and may be distinguished from Λ_b baryons by a measurement of the charge of the decay products. In addition they may be distinguished from Λ_b decays by the different shape of their lepton energy spectrum. We shall elaborate on this point in a forthcoming article.

5 Conclusions

Heavy flavor physics at colliders is an interesting way to obtain information on those heavy hadrons which may not be investigated at e^+e^- machines running on the $\Upsilon(4s)$ resonance. In particular bottom baryons may be accessible only in this way in the near future. Theoretically heavy hadrons may be consistently described by HQET, which is a systematic expansion of QCD in powers of Λ_{QCD}/m . This framework has been successfully used to describe heavy flavor decays in an environment of an e^+e^- machine running on the $\Upsilon(4s)$ resonance.

The present note is the first time where HQET is applied to heavy hadrons created at colliders, where the heavy hadrons are light compared to the cms energy of the collider. They are thus highly relativistic and the various limits have to be treated with care.

We have presented a detailed analysis of how to extract information on standard model parameters from the semileptonic Λ_b decays at an e^+e^- collider. Our results may be easily transferred to other types of colliders, since only the spectrum of the b quarks enters the

analysis. We pointed out that one can do polarization measurements of the heavy quarks created in Z_0 decays, since the heavy quark spin decouples from the soft hadronization process and the polarization of the Λ_b baryons is the same as for the bottom quarks. The polarization of the Λ_b baryon may be measured from the energy distribution of the lepton in the laboratory frame and yields direct access to the vector and axial vector couplings of the bottom quark. Since the exclusive decay $\Lambda_b \rightarrow \Lambda_c e \bar{\nu}$ is expected to saturate about 90% of the inclusive semileptonic rate of the Λ_b , it will be possible to obtain some information from the inclusive lepton spectra.

Finally we discussed a way to obtain some information on the fragmentation process of a b quark into bottom baryons. From the analysis we have presented it should be possible to measure the number of Λ_b baryons created per fragmenting b quark in the near future.

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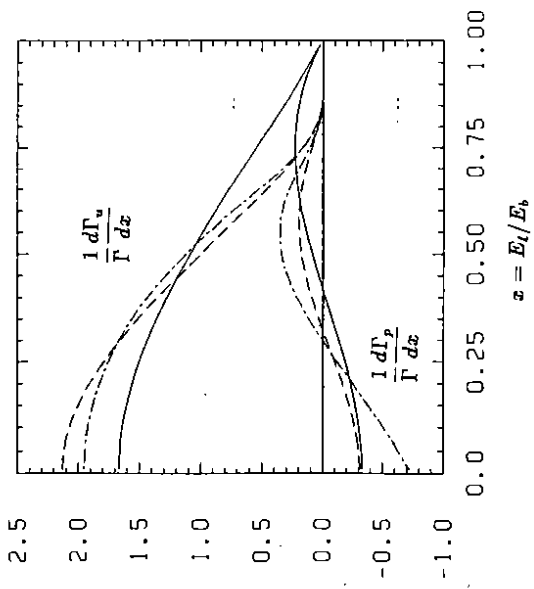
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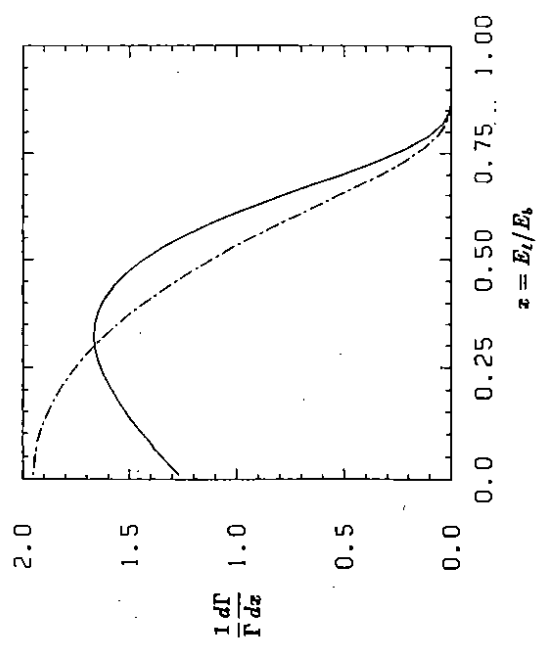
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Figure Captions

- Fig.1: The energy distribution of the lepton in the laboratory frame split into the polarized and unpolarized piece. solid curves: constant form factor and $m_c = 0$, dashed curves: constant form factor and $m_c = 1.8$ GeV, dashed dotted curves: form factor as in (5) and $m_c = 1.8$ GeV.
- Fig.2: The energy distribution of the lepton in the laboratory frame for unpolarized Λ_b decay (dashed curve) and the standard model prediction (solid curve).



• Fig.1



• Fig.2