DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 87-084
July 1987

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by

K. Wachs

Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

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DESY 87-084
July 1987

ISSN 0418-9833

SEMILEPTONIC DECAYS OF B MESONS

Karl Wachs *
Representing the Crystal Ball Collaboration[1]

Deutsches Elektronen-Synchrotron DESY
2000 Hamburg

Abstract

The Crystal Ball collaboration has measured the energy spectrum of electrons from semileptonic B meson decays at the e^+e^- - storage ring DORIS II. Branching ratios and semileptonic widths have been measured using several models for the hadronic matrix elements. The branching ratio for semileptonic B meson decays into a charmed state X_c has been found to be $BR(B \to e\nu X_c) = (11.9 \pm 0.4 \pm 0.7)\%$ independent of the model used. The result for the Kobayashi - Maskawa matrix element $|V_{cb}|$ is $0.054 \pm 0.005 \pm 0.005$. The result obtained with the different models varies by at most 0.004. Upper limits on $|V_{ub}/V_{cb}|$ have been obtained. The weakest upper limit of $|V_{ub}/V_{cb}| < 0.26$ is obtained using the model by Grinstein *et al.* with data of electron energy $E_e > 2.4$ GeV. In addition we identify the decay $B \to e\nu D^*$, $D^* \to \pi^0_{slow} X$ and obtain a lower limit on the ratio of branching ratios

$$\frac{BR(B \to e\nu D^*)}{BR(B \to e\nu D^*) + BR(B \to e\nu D)} > 0.4 \text{ at } 90\% \text{ C.L.}$$

*Extended version of a talk given the 22^{nd} Rencontres de Moriond Les Arcs, France, March 8-15 1987.

Introduction

The $\Upsilon(4S)$ resonance is an ideal system to study weak decays of b quarks, because the $\Upsilon(4S)$ resonance - which lies above the open b quark threshold - decays entirely into $B\overline{B}$ meson pairs [2]. A b quark in the B meson decays into a c or u quark emitting a virtual W boson, which then can disintegrate weakly into a an electron and its neutrino. The differential energy spectrum $d\Gamma/dx$ ($x = 2E_e/m_b$) of the electrons depend on the spin and mass of the individual final states in the charmed channels X_c^i ($i = D, D^*...$) and the u quark channels X_u^j ($j = \pi, \rho...$). It can be written

$$\frac{d\Gamma(B \to e\nu X)}{dx} = |V_{cb}|^2 \sum_i \frac{d\hat{\Gamma}(B \to e\nu X_c^i)}{dx} + |V_{ub}|^2 \sum_j \frac{d\hat{\Gamma}(B \to e\nu X_u^j)}{dx} . \quad (1)$$

Integrating $d\Gamma/dx$ over the normalized electron energy x results in the total semileptonic width Γ. This width should be about the same as that obtained from the free quark ($f.q.$) model. Hence for the channel $b \to c$ [1] holds the equation [3] :

$$\begin{aligned} \Gamma_{cb} &= \hbar \frac{BR(B \to e\nu\ D, D^*, ...)}{\tau_B} \quad (2) \\ &= |V_{cb}|^2 \sum_i \hat{\Gamma}(B \to e\nu X_c^i) \\ &\simeq |V_{cb}|^2 \hat{\Gamma}_{f.q.}(b \to e\nu c) = |V_{cb}|^2 \frac{G_F^2 m_b^5}{192\pi^3} f(\frac{m_c}{m_b}) \end{aligned}$$

with $f(z) = 1 - 8z^2 + 8z^6 - z^8 - 24z^4 \ln z$.

Knowledge of the electron energy spectra $d\Gamma/dx$ for different final states – or the branching ratios BR and the B meson lifetime τ_B – allows the determination of the Kobayashi-Maskawa [4] matrix elements $|V_{cb}|$ and $|V_{ub}|$.

Data analysis

The Crystal Ball [1] detector at the storage ring DORIS II has been used to measure the inclusive electron energy spectrum from B meson decays. The detector has been decribed in detail elsewhere [5]. Briefly, it consists of 672 NaI(Tℓ) shower counters which detect photons and electrons with good spatial and energy resolution. Each shower counter has the shape of a truncated triangular pyramid pointing to the e^+e^- interaction point and is viewed by a phototube. The NaI counters form a sphere of 16 radiation length thickness covering 93% of 4π solid angle. Two holes are left for the beam pipe. An additional 5% of 4π is covered

[1] for $b \to u$ a similar equation holds with c replaced by u and D, D^* by π, ρ

by NaI(Tℓ) end-caps. Charged particles are detected in a set of 800 proportional tube chambers assembled in 4 cylindrical double layers around the bam pipe.

The data analyzed are equivalent to an integrated luminosity of 75.6 pb^{-1} on the $\Upsilon(4S)$ (64590$\pm$ 1300 produced $\Upsilon(4S)$ events) and 18.5 pb^{-1} in the continuum below the resonance.

Hadronic events are selected by removing background due to beam gas interactions, cosmic rays, 2 - photon induced events and QED events. The remaining data sample contains contributions from the $\Upsilon(4S)$ and the continuum production in a ratio of $\simeq 1/3.8$. A *bump* crystal is defined by a local maximum of energy deposition in the crystals. We demand the number of *bumps* to be > 7 and the Fox-Wolfram event shape parameter $H2$ [6]

$$H2 = \frac{\sum_{i,j} E_i E_j (3\cos^2\alpha_{i,j} - 1)}{2(\sum_i E_i)^2} < 0.55 \tag{3}$$

where E_i is the energy deposited in the *bump* crystal i and α is the angle between *bumps*. Only *bumps* in the main ball excluding end-caps are used. These cuts have almost no effect on $\Upsilon(4S)$ events, but cut away almost all $\tau\bar{\tau}$ and remaining QED events. The electron candidate in the hadronic event has to be tagged in the proportional wire chamber. Its pattern in the NaI Crystals has to be consistent with the lateral energy distribution of a single electromagnetically showering particle.

Besides electrons from $b \to c$ (intensity $\mathcal{C}$) and $b \to u$ (intensity $\mathcal{U}$) transitions, those from $c \to s$ (intensity $\mathcal{S}$) are present. In addition the following background sources contribute

- hadrons and photons faking electrons (intensity $\mathcal{B}$): we measure the hadronic contribution by the different energy loss in the wire chamber compared to that of electrons. The contribution from photons are determined by measuring the neutral energy spectrum and scaling it down by the conversion probablity in the beam pipe and chambers. The conversion probability is obtained by analyzing $e^+e^- \to \gamma\gamma$ events.

- contribution fróm the continuum production (intensity $\mathcal{K}$): for this contribution we take a smooth function, which is obtained from a fit to the continuum data. The intensity $\mathcal{K}$ is scaled by the ratio r of $\Upsilon(4S)$ /*continuum* luminosities.

All contributions are shown in figure 1 . The efficiency corrected and background subtracted spectrum normalized to the number of produced B mesons is shown in figure 2.

As we want to measure $b \to c$ and $b \to u$ contributions only, we use the data *above* $E_e = 1.5\ GeV$, where the $c \to s$ and fake electron contributions are small. Using the data below $E_e \simeq 1.5\ GeV$ would require a very accurate knowledge of the background and the $c \to s$ intensities and shapes. In order to extract branching ratios we have to use theoretical predictions on the shape of the spectra. For fitting to the observed electron energy spectrum (figure 1) these predictions are boosted to the $\Upsilon(4S)$ restframe, corrected for detection efficiency and energy resolution. We then perform a maximum likelihood fit simultaneously to the binned $\Upsilon(4S)$ data $N^{obs}(E_e) \equiv N_i$, and to the binned continuum data $M^{obs}(E_e) \equiv M_j$. The likelihood function is defined by:

$$\mathcal{L} = \prod_i \left(\frac{e^{-Y_i} \cdot Y_i^{N_i}}{N_i!}\right) \times \prod_j \left(\frac{e^{-V_j} \cdot V_j^{M_j}}{M_j!}\right) \times \exp\left(-\frac{(\mathcal{B} - \mathcal{B}_m)^2}{2\sigma_{\mathcal{B}}^2}\right) \times \exp\left(-\frac{(\mathcal{K} - r \cdot \mathcal{K}_C)^2}{2\sigma_{\mathcal{K}}^2}\right) \tag{4}$$

Here the first and second term represent the likelihoods for the $\Upsilon(4S)$ and continuum data. The 3. and 4. term form contraints, first to the brackground intensity $\mathcal{B}$ by the measured background intensity $\mathcal{B}_m$. The second constraint restricts the intensity of the continuum contribution $\mathcal{K}$ to the measured product of continuum intensity $\mathcal{K}_C$ times the luminosity ratio r.

$Y(E_e) \equiv Y_i$ is the functional form accounting for the observed electron spectrum from the $\Upsilon(4S)$ data

$$Y(E_e) = \mathcal{C}(b \to c) + \mathcal{U}(b \to u) + \mathcal{S}(c \to s) + \mathcal{B}(\text{backg.}) + \mathcal{K}\ E(\alpha,\beta,\gamma,\delta) \tag{5}$$

and $V(E_e) \equiv V_i$ is the functional form accounting for the observed electron spectrum from the continuum data

$$V(E_e) = \mathcal{K}_C\ E(\alpha,\beta,\gamma,\delta) \tag{6}$$

$$\text{where } E = \exp(\alpha E_e^1 + \beta E_e^2 + \gamma E_e^3 + \delta E_e^4) \tag{7}$$

The intensities $\mathcal{C}, \mathcal{B}, \mathcal{U}, \mathcal{S}, \mathcal{K}, \mathcal{K}_C$ and continuum parameters $\alpha, \beta, \gamma, \delta$ are determined by the fit. As the background ($\mathcal{B}$) and the $c \to s$ ($\mathcal{S}$) contributions above $E_e = 1.5\ GeV$ are small and rather similar in shape the intensity $\mathcal{B}$ is not determined by the fit: a higher intensity $\mathcal{B}$ would be compensated by a smaller $c \to s$ intensity $\mathcal{S}$ and vice versa. Therefore the value of the intensity $\mathcal{B}$ does not influence the $b \to c$ and $b \to u$ intensities $\mathcal{C}$ and $\mathcal{U}$, but only the $c \to s$ intensity $\mathcal{S}$.

The parameters $\alpha, \beta, \gamma, \delta$ are determined by both, the $\Upsilon(4S)$ data and the continuum data. This method is useful, as we have only a small continuum data sample. The continuum contribution in the $\Upsilon(4S)$ fit is constrained in shape and intensity by the data between $E_e = 2.6\ GeV$ and $4\ GeV$ where no other contributions exist. This method gives confidence in the function representing the continuum contribution. The result agrees well with the predicted shape from the fit to the contiuum data alone. For the intensity of the continuum contribution we find, that the fitted value $\mathcal{K}$ is within 0.08% of the expected value $r \times \mathcal{K}_C$ from the luminosity ratio, with $\sigma_K/\mathcal{K} = 1\%$ used in the constraint (4).

To comprare results from different fits we calculate a χ^2 according to [7] from the result of the fit:

$$\chi^2 = 2\sum_i (Y_i - N_i + N_i \ln\frac{N_i}{Y_i}) \tag{8}$$

Models used to determine $BR(b \to c)$ and $BR(b \to u)$

The first model, which we use to calculate branching ratios, is a modified free quark spectator model by ACM *et al.* [8]. In the free quark spectator model the energy spectrum[2] $d\Gamma_{cb}/dx$ is given by:[3]

$$d\Gamma_{cb}/dx = |V_{cb}|^2 d\hat{\Gamma}/dx \equiv$$
$$|V_{cb}|^2 \frac{G_F^2 m_b^5}{96\pi^3} \times \frac{x^2[1 - z^2 - x]\,[(1 - x)(3 - 2x) + (3 - x)z^2]}{(1 - x)^3} \tag{9}$$

where $z \equiv m_{u,c}/m_b$ and $x \equiv 2E_e/m_b$. Boundstate effects of the b quark together with the spectator mass m_{sp} inside the B meson are modeled as follows: the b quark is assumed to be moving with momentum $\vec{p}$ inside the meson, where $\vec{p}$ is distributed Gaussianly in all 3 coordinates:

$$\frac{dN(|\vec{p}|)}{d|\vec{p}|} = \frac{4}{\sqrt{\pi}} \frac{|\vec{p}|^2}{P_F^3} \exp(-\frac{|\vec{p}|^2}{P_F^2}) \tag{10}$$

Together with the spectator quark the b quark forms the B meson of mass M_B. Energy and momentum conservation yields for the b quark mass

$$m_b^2 = M_B^2 + m_{sp}^2 - 2M_B\sqrt{|\vec{p}|^2 + m_{sp}^2}\ . \tag{11}$$

The electron spectrum is obtained by boosting the spectrum (9) with momentum $|\vec{p}|$ of the b quark *and* the momentum of the B meson[4] $= 0.325\ GeV/c$. Obviously the theory has some free parameters, namely m_c, m_u, P_F, m_{sp}. The B meson mass is taken from other measurements [9]. As the term $M_B^2 = (5.280\,GeV/c^2)^2$ is much bigger than the mass of the spectator $m_{sp}^2 \simeq (0.15\,GeV/c^2)^2$, this m_{sp} contribution can be neglected. The spectator mass in the argument of the root can be absorbed in an effective change of the momentum P_F.

As we find only a small $b \to u$ contribution – see next chapter – we cannot determine the u quark mass m_u with our electron spectrum. Therefore we deduce upper limits on $b \to u$ for a fixed u quark mass of $m_u = 150 MeV/c^2$, as used in the paper by ACM. But in addition we give the dependence of the upper limit on $b \to u / b \to c$ as function of the u quark mass.

Hence we treat only 2 parameters, the Fermi momentum P_F and the c quark mass m_c, as unpredicted and free in the fitting procedure.

In addition QCD corrections are applied. The correction $Q(z, x) = 1 - 2\alpha_s G(z, x)/3\pi$ has to be multiplied with formula (9). For non-zero quark masses ($z > 0$) G does not depend on x, and can therefore be factorized. G is tabulated in the litrature [10]. With a strong coupling constant $\alpha_s = 0.24$ we obtain for the $b \to u$ channel $\int Q(0.15/5, x)dx = 0.82$ and for the $b \to c$ channel $\int Q(1.6/5, x)dx = 0.88$. These corrections will be used for ACM's model when calculating V_{cb} and V_{ub} from the measured branching ratios.

The next model is the non-relativistic constituent quark model by GIW [3]. The calculated transition rates $(1S, 1P, 2S)$ saturate the free quark prediction in the case of $b \to c$. For $b \to u$, mass states up to $2.5\ GeV/c^2$ are taken into account, but half of the predicted free quark rate is missing. As higher mass states will contribute only to electron energies below $\simeq 2.2\ GeV$ the predicted inclusive electron energy spectrum is only valid above $\simeq 2.2\ GeV$. Hence we use the $b \to u$ prediction for the calculation of branching ratios above $E_e = 2.2\ GeV$ only. AW [16] have applied corrections to formfactors in GIW's model in the $B \to e\nu D^*$ channel. These corrections result in a significantly smaller predicted semileptonic width $\Gamma_{cb}(AW)/\Gamma_{cb}(GIW) \simeq 0.68$. The predicted spectra $B \to e\nu D$ and $B \to e\nu D^*$ are very similar in shape. The superposition of the single predictions will therefore change only in size but not in shape. Hence the results obtained in this analysis will scale with the change of the width.

The third model by WSB [11] uses relativistic bound state wave functions to calculate the rates. Only transitions to D, D^* and π, ρ ($\equiv 1S$)) respectively have been calculated. Following the arguments discussed above, this implies a lower fit limit of $\simeq 1.7\ GeV$ for the $b \to c$ transitions and $\simeq 2.3\ GeV$ for $b \to u$.

[2] $d\Gamma_{ub}$ is obtained by replacing c by u

[3] integrating (9) over x results in formula (2)

[4] a higher B meson momentum results in a harder electron endpoint spectrum.

Results on the Ratio of Branching Ratios $b \to u/b \to c$ and $|V_{ub}/V_{cb}|$

As we do not find a significant $b \to u$ contribution we calculate 90 % C.L. upper limits on $b \to u/b \to c$. They are shown for the different models in figures 3 and 4 as a function of the lower fit limit.

Using ACM's model with free P_F and m_c we get an upper limit $BR(B \to e\nu X_u)/BR(B \to e\nu X_c) < 4.5\%$ or $|V_{ub}/V_{cb}| < 0.147$ at 90% C.L. The best fit values for those parameters are: $P_F = (388 \pm 52)\ MeV/c$ and $m_c = (1607 \pm 46)\ MeV/c^2$. Using equation (11) we obtain for the b quark mass an average value $< m_b >= (4.85 \pm 0.68) GeV/c^2$ where we used $|\vec{P}| = P_F$.

Figure 5 shows the upper limit obtained by the same procedure but for various values for the u quark mass m_u. For higher masses the upper limit gets weaker, because the predicted spectrum becomes softer and comparable to the spectrum from $b \to c$ decays. A u quark mass $m_u = m_c$ would results in no upper limit as the $b \to c$ and $b \to u$ predictions are identical. For u quark masses below 400 MeV/c^2 the upper limit is independent of m_u.

To get $b \to u/b \to c$ values independent of the measured $b \to c$ contribution we increase the lower fit limit to higher energies, where the $b \to c$ contribution becomes smaller and goes to zero above $E_e = 2.4\ GeV$. We fix all the parameters to the best values previously found (besides the $b \to u$ intensity $\mathcal{U}$). We obtain an U.L. $BR(b \to e\nu u)/BR(b \to e\nu c) < 5.4\%$ or $|V_{ub}/V_{cb}| < 0.16$ at 90% C.L. independent of any measured $b \to c$ contribution (see figures 3 and 4).

As the GIW model has no precise prediction for $b \to u$ with $E_e < 2.2\ GeV$, we proceed in the following way: we determine the intensity $\mathcal{C}$ of the $b \to c$ transition for electron energies $E_e > 1.5\ GeV$ together with a free $b \to u$ intensity $\mathcal{U}$, then fix the $b \to c$ intensity $\mathcal{C}$, background $\mathcal{B}$ and continuum contribution $\mathcal{K}$. and then find the upper limit on

$$\frac{BR(B \to e\nu X(1S,1P,2S)_u)}{BR(B \to e\nu X(1S,1P,2S)_c)} < 4.6\% \text{ or } |\frac{V_{ub}}{V_{cb}}| < 0.216 \text{ at } 90\ \% \text{ C.L.}$$

for the spectrum above $E_e = 2.2\ GeV$ (see figures 3 and 4)

For electron energies $E_e > 2.4\ GeV$, where the $b \to c$ contribution is 0 we find

$$\frac{BR(B \to e\nu X(1S,1P,2S)_u)}{BR(B \to e\nu X(1S,1P,2S)_c)} < 6.5\% \text{ or } |\frac{V_{ub}}{V_{cb}}| < 0.257 \text{ at } 90\ \% \text{ C.L.}$$

Using the WSB model results in an upper limit on

$$\frac{BR(B \to e\nu\pi,\rho)}{BR(B \to e\nu D, D^*)} < 2.5\% \text{ or } |\frac{V_{ub}}{V_{cb}}| < 0.149 \text{ at } 90\ \% \text{ C.L.}$$

using the data above $E_e = 2.3 - 2.4\ GeV$.

Results on the Branching Ratio $B \to e\nu X_c$ and $|V_{cb}|$

If the $b \to u$ contribution would not be small, it would be incorrect to measure the inclusive $b \to c$ intensity with the models by GIW and WSB, which do not fully predict the $b \to u$ spectrum at lower electron energies where the $b \to c$ intensity is determined. Fortunately, the $b \to u$ contribution is small and we can calculate the branching ratio $BR(B \to e\nu X_c)$ and $|V_{cb}|$ using all 3 models. With free $b \to u$ contributions, which are not significant and therefore only quoted for completeness, and a B meson lifetime of $\tau_B = (1.13 \pm 0.14) \times 10^{-12} sec$ [15] we get the result of table 1.

Table 1. Results on $BR(B \to e\nu X_c)$ and $|V_{cb}|$

Model	$BR(B \to e\nu X_c)$ [%]	$\lvert V_{cb}\rvert$ 10^{-2}	$b \to u/b \to c$ 10^{-2}	$\frac{\chi^2}{D.o.F.}$
GIW ; X=(1S,1P,2S)	$11.9 \pm 0.4 \pm 0.7$	$4.3 \pm 0.5 \pm 0.5$	2.0 ± 1.3	39.9/42
GIW + AW		$5.2 \pm 0.5 \pm 0.5$		
WSB : X = (1S)	$10.8 \pm 0.4 \pm 0.7$	$5.6 \pm 0.5 \pm 0.5$	$0.0^{+0.8}_{-0.0}$	39.8/38
ACM P_F and m_c free, best $P_F = (388 \pm 52)\ MeV/c$ $m_c = (1607 \pm 46)\ MeV/c^2$	$12.0 \pm 0.5 \pm 0.7$	$5.4 \pm 0.5 \pm 4.0$	1.6 ± 1.6	39.2/40

The errors quoted are: statistical and systematic for the branching ratio measurement and experimental and theoretical in the case of $|V_{cb}|$.

The experimental error of V_{cb} is calculated by adding the statistical and systematic error and that of the the B meson lifetime in quadrature. It is dominated by the B meson lifetime measurement.

The size of the theoretical error in the determination of V_{cb} with ACM's model is due to the smeared b quark mass.

If we assume that the higher spin states – which have not been calculated – add 10% to WSB's branching ratio we get very similar results for the total branching ratio: $BR(B \to e\nu X_c) = (11.9 \pm 0.4 \pm 0.7)\%$ for all three models.

Figure 9 illustrates the shape of spectra from the different theories used. Only those parts of the calculated spectra are shown, where the predictions are complete. Although the amplitudes of the $b \to c$ predictions differ by a factor of $\simeq 2$ the shapes of the spectra are very similar. The AW correction has not been applied to GIW's model in the plots. Figure 10 shows the $b \to c$ spectra normalized to 1 for ACM and GIW. WSB model has been normalized to 0.9 assuming, that the missing higher spin - and mass - states will contribute $\simeq 10\%$ to the spectrum.

The $b \to u$ spectra show a difference in shape and amplitude. This is the reason for the different upper limits obtained with the 3 models.

Comparison with other Experiments

Comparison with results from ARGUS [12] [13]

ARGUS quotes an upper limit on $\frac{BR(B \to e\nu X(1S,1P,2S)_u)}{BR(B \to e\nu X(1S,1P,2S)_c)} < 6\%$ obtained with GIW's model in the electron energy range $E_e > 1.6\ GeV$. With a modified free quark spectator model and a limited data sample of $12pb^{-1}$ ARGUS gets a branching ratio $BR(B \to e\nu X_c) = (12.0 \pm 0.9 \pm 0.8)\%$.

Comparison with results from CLEO [2]

Beside other models they used ACM's model with a fixed parameter setting of $P_F = 215\ MeV/c$ and $m_c = 1700\ MeV/c^2$. They get an upper limit of

$$\frac{BR(B \to e\nu X_u)}{BR(B \to e\nu X_c)} < 2.7\% \text{ at } 90\ \% \text{ C.L.}$$

A branching ratio $BR(B \to e\nu X_c) = (11.0 \pm 0.2 \pm 1.0)\%$ is measured. Using the same fit parameters the Crystal Ball experiment obtains

$$\frac{BR(B \to e\nu X_u)}{BR(B \to e\nu X_c)} < 2.6\% \text{ at } 90\ \% \text{ C.L.}$$

and $BR(B \to e\nu X_c) = (11.0 \pm 0.4 \pm 0.7)\%$ with a $\chi^2/D.o.F. = 43/42$ - a very similar result.

Comparison with results from CUSB [14]

Using ACM's model with a fixed parameter setting of $P_F = 150\ MeV/c$ and $m_c = 1700\ MeV/c^2$ an upper limit of

$$\frac{BR(B \to e\nu X_u)}{BR(B \to e\nu X_c)} < 5.5\% \text{ at } 90\ \% \text{ C.L.}$$

is obtained. A branching ratio $BR(B \to e\nu X_c) = (9.0 \pm 3.0)\%$ is measured. Doing the same we obtain

$$\frac{BR(B \to e\nu X_u)}{BR(B \to e\nu X_c)} < 1.5\% \text{ at } 90\ \% \text{ C.L.}$$

and $BR(B \to e\nu X_c) = (10.7 \pm 0.4 \pm 0.7)\%$ with a $\chi^2/D.o.F. = 52/42$.

Result on the Ratio of Vector to Axial Coupling

We use the decay chain $B \to e\nu D^* \to e\nu D\pi^0$ to measure a ratio of the axial and vector couplings

$$R = \frac{BR(B \to e\nu D^*)}{BR(B \to e\nu D^*) + BR(B \to e\nu D)}.$$

For this analysis we used $\Upsilon(4S)$ data equivalent to a luminosity of $92pb^{-1}$.

B meson decays are tagged with electrons with $E_e > 1.8\ GeV$. This high cut value on the electron energy implies that first of all no other (charmed) mesons besides D and D^* will contribute. On the other hand E_ν is small and therefore the D^* recoils against the electron, resulting in an approximately 2 body decay signature.

The decay $D^* \to D\pi^0$ is tagged by a slow π^0. Due to the small mass difference ($m_{D^*} - m_D \simeq 140\ MeV/c^2$) the π^0 momentum in the D^* rest frame is small, $p_{\pi^0} \simeq 40 MeV/c$. Boosted by the D^* momentum the π^0 preserves approximately the D^* direction and is therefore expected to be found opposite to the electron direction and with rather small momentum ($p_{\pi^0} < 240$ MeV/c).

Figure 6 shows the two photon mass $M_{\gamma\gamma}$ distribution for events with at least one electron of energy $E_e > 1.8\ GeV$ and with the momentum of the $\gamma\gamma$ system in the range $30\ MeV/c < p_{\gamma\gamma} < 240\ MeV/c$. A clear π^0 signal is visible, but on top of a large combinatorial background. An accepted π^0 has to be in the $\gamma\gamma$ mass range indicated by the dotted window in figure 6.

Figure 7 shows the distribution of the angle between the fast electron and the reconstructed slow π^0. We observe a signal at $\cos(e,\pi^0) < -0.9$ with a statistical significance of [17]

$$\frac{N - N_{Background}}{\sqrt{N_{Background} + (\delta N_{Background})^2}} = \frac{120 - 78}{\sqrt{78 + 6.4^2}} = 3.9\ \sigma.$$

The events from the $M_{\gamma\gamma}$ sidebands in figure 6 are used to measure the background below the signal. We perfom a fit with a quadratic polynominal to the $\cos(e,\pi^0)$ distribution of events from the $M_{\gamma\gamma}$ sidebands. After subtracting the fitted polynominal background from the distribution shown in figure 7 we get the $\cos(e,\pi^0)$ distribution in figure 8. Also shown as a histogram is a prediction based on the model by GIW [3] for the decay chain $B \to e\nu D^* \to e\nu D\pi^0$. The normalization of the Monte Carlo calculation corresponds to $R = 1$, i.e. B decays into D^* exclusively. The decay of the D and the second B meson are modeled with the Lund

Monte Carlo program [18] with updated branching ratios [19]. The efficiency to reconstruct the π^0 in the decay $D^* \to D\pi^0$ comes out to be $\simeq 15\%$.

To calculate the ratio R we measure the branching ratio $BR(B \to e\nu D^*)$ and the inclusive branching ratio $BR(B \to e\nu X)$ above 1.8 GeV assuming that only D and D^* are produced. Extrapolating from $E_e > 1.8$ GeV to the full spectrum we obtain the preliminary result $R = 1.2 \pm 0.5 \pm 0.4$. Note, that our estimate of R is the result of two independent measurement, namely $BR(B \to e\nu D^*)$ and $BR(B \to e\nu X)$. Therefore R may fluctuate above 1 within experimental errors.

The first error arrises from statistics only. The second, systematic error includes the uncertainty in the branching ratios $D^* \to D\pi^0$, in the angular distribution of the expected (e, π^0) signal, as well as the uncertainty in the extrapolation of the measured fraction of the D, D^* branching ratios to the full electron energy range. Also contained in the systematic error are theoretical uncertainties estimated by comparing model predictions from GIW [3], WSB [6] and Chau *et al.* [20].

Our measurement on R is translated into a 90 % C.L. lower limit of $R > 0.4$. This is obtained from an integration of the likelihood function over the physically allowed range $0 \leq R \leq 1$ including the influence of the systematic error.

Conclusions

With the Crystal Ball detector we have measured the inclusive electron spectrum from $\Upsilon(4S)$ decays. Using 3 different predictions a branching ratio $BR(B \to e\nu X_c) = (11.9 \pm 0.4 \pm 0.7)\%$ independent of the model has been obtained.

The result on the Kobayashi - Maskawa matrix element $|V_{cb}|$ varies from 0.043 to 0.056 using the 3 models due to the different predicted total semileptonic widths although the predicted shapes are nearly the same. Applying the AW correction to GIW's model results in a change of V_{cb} 0.043 to 0.05. Taking the corrected value all three models agree within errors. Hence we get $|V_{cb}| = 0.054 \pm 0.005 \pm 0.005$.

For the ratio of $|V_{ub}/V_{cb}|$ we obtain an upper limit dependent on the model used. WSB and ACM give a conservative U.L. of $|V_{ub}/V_{cb}| < 0.15$ at 90% C.L., if one uses the data above $E_e = 2.4$ GeV where the $b \to c$ contribution is zero.

GIW gives a significantly weaker upper limit, due to the softer spectrum in the $b \to u$ channel and due to the bigger semileptonic width predicted for the $b \to c$ channel.

In addition we identify the decay $B \to e\nu D^*$, $D^* \to \pi^0_{slow} X$ and obtain a lower

limit on the ratio of branching ratios

$$\frac{BR(B \to e\nu D^*)}{BR(B \to e\nu D^*) + BR(B \to e\nu D)} > 0.4 \text{ at } 90\% \text{ C.L.}$$

Note added in proof-reading

The Argus collaboration has reported on July 21, 1987 the observation of the decays $B^- \to p\bar{p}\pi^-$ and $B^0 \to p\bar{p}\pi^+\pi^-$ thus having given an evidence for $b \to u$ transitions. They estimate a lower limit on $|V_{ub}/V_{cb}| > 0.07$.

Acklowledgements

It is a pleasure for me to thank the whole Crystal Ball collaboration for the many things I was able to learn in the very inspired working atmosphere.
Many thanks go to Thomas Skwarnicky for explaining me in detail his analysis on $B \to e\nu D^*$ and for a lot of other discussions.
Last but not least I would like to express my thankfulness to Prof. J. K. Bienlein. He never let me loose the sight of physics in the maze of the IBM and supported me in various other ways.

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[1] The Crystal Ball Collaboration consists of groups from the following institutes: California Institute of Technology, Pasadena, USA; Carnegie-Mellon University, Pittsburgh, USA; Cracow Institute of Nuclear Physics, Kraków, Poland; Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany; Universität Erlangen-Nürnberg, Erlangen, Germany; INFN and University at Firenze, Firenze, Italy; Universität Hamburg, I. Institut, Hamburg, Germany; Harvard University, Cambridge, USA; NIKHEF and Universiteit Nijmegen, Nijmegen, The Netherlands; Princeton University, Princeton, USA; Stanford Linear Accelerator Center SLAC and Stanford University, Stanford, USA; Universität Würzburg, Würzburg, Germany.

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Figure Caption

1 The measured electron energy spectrum on the $\Upsilon(4S)$ resonance. The predictions from ACM shown are corrected for detector response.

2 Inclusive electron energy spectrum, corrected for efficiency and background contribution; normalized either to the number of produced B mesons (left hand scale) or to the integrated luminosity (right hand scale). Predictions are from the ACM model.

3 Upper limit on $BR(B \to e\nu X_u)/BR(B \to e\nu X_c)$ for different models and fit ranges. Open circles are for comparison only, as they are outside the valid fit range. For GIW and WSB only some final states have been calculated and therefore $X = (1S, 1P, 2S)$ for GIW and $X = 1S$ for WSB

4 Upper limit on $|V_{ub}/V_{cb}|$ for different models and fit ranges. Open circles are for comparison only, as they are outside the valid fit range.

5 Upper limit on $BR(B \to e\nu X_u)/BR(B \to e\nu X_c)$ using ACM's model for different u quark masses. The curve is a smooth function fitted to the points, to guide the eye.

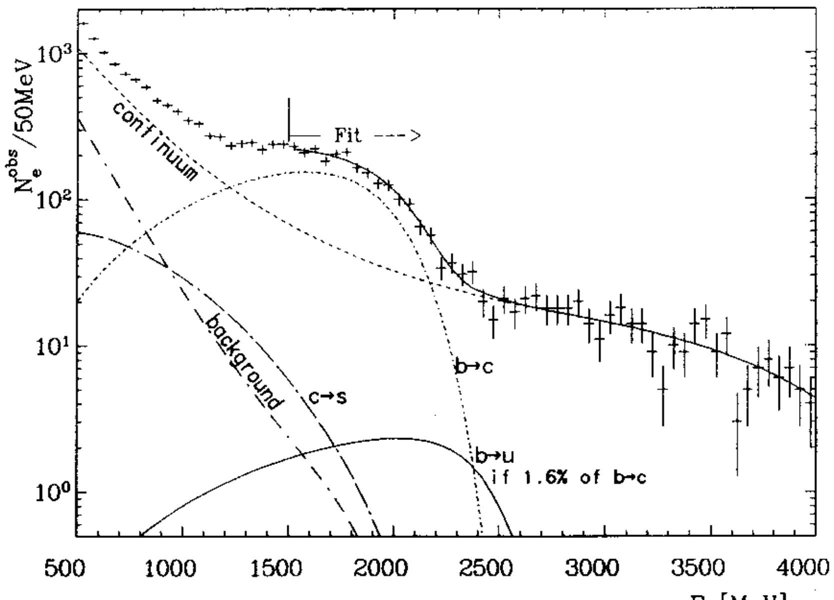
6 $M_{\gamma\gamma}$ for events with a fast electron and a slow π^0. The bins containing the π^0 and the sidebands are indicated.

7 Distribution of the angle between a fast electron a slow π^0.

8 Angle between electron and π^0 after background subtraction. The histogram is a prediction by GIW for the decay $B \to e\nu D^* \to e\nu D\pi^0$. The Monte Carlo calculation assumes $B \to e\nu D^*$ only ($R = 1$).

9 $d\Gamma/dE_e$ as predicted by theory, boosted to the $\Upsilon(4S)$ rest frame, smeared with the detector resolution.
1.solid : ACM; 2.dashed-dotted: GIW; 3.dashed: WSB.
Only those parts are shown where the predictions are complete

10 $d\Gamma_{cb}/dE_e$ as predicted by theory, boosted to the $\Upsilon(4S)$ rest frame, smeared with the detector resolution. 1.solid: ACM normalized to 1.; 2.dotted: GIW normalized to 1.; 3.dashed: WSB normalized to 0.9.
Only those parts are shown where the predictions are complete



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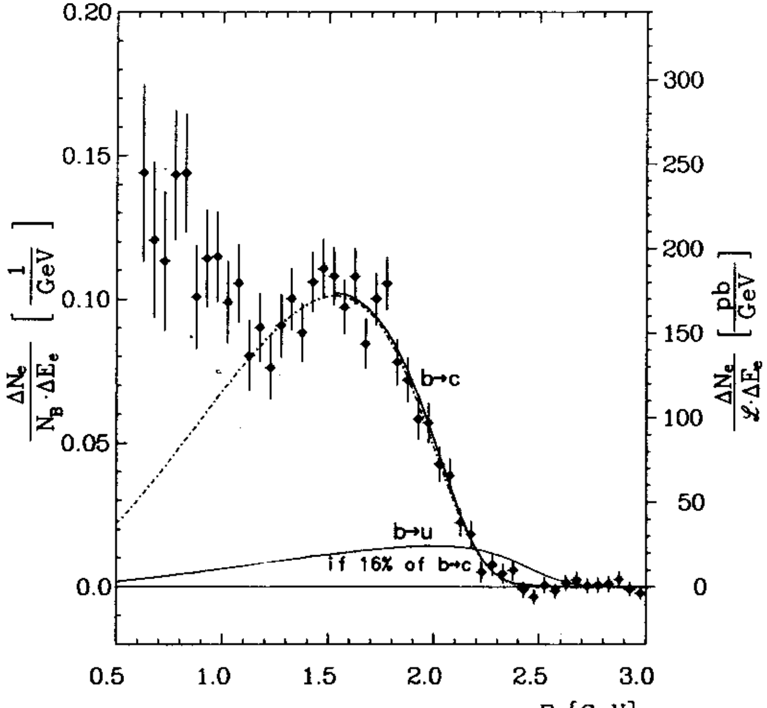

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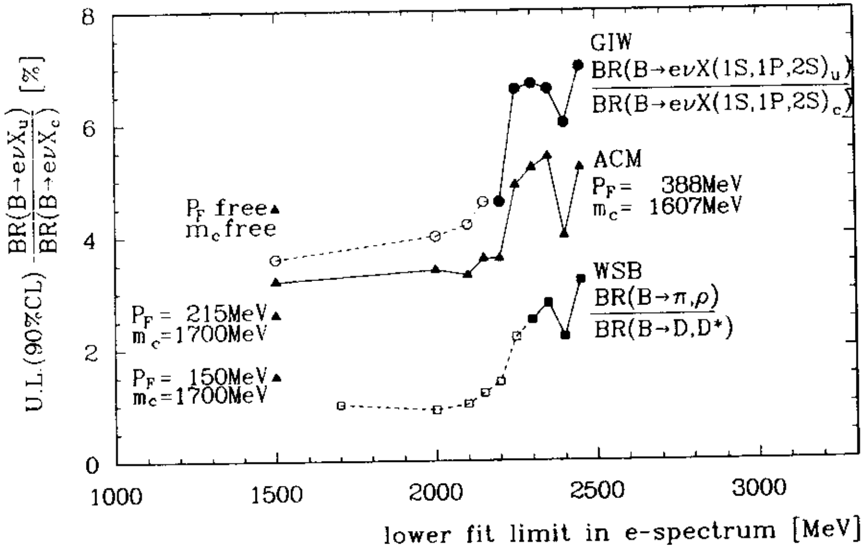

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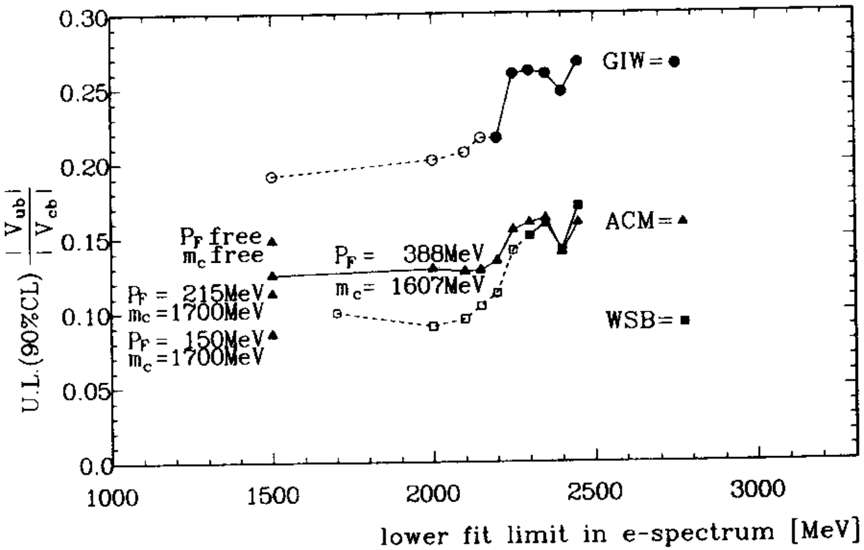

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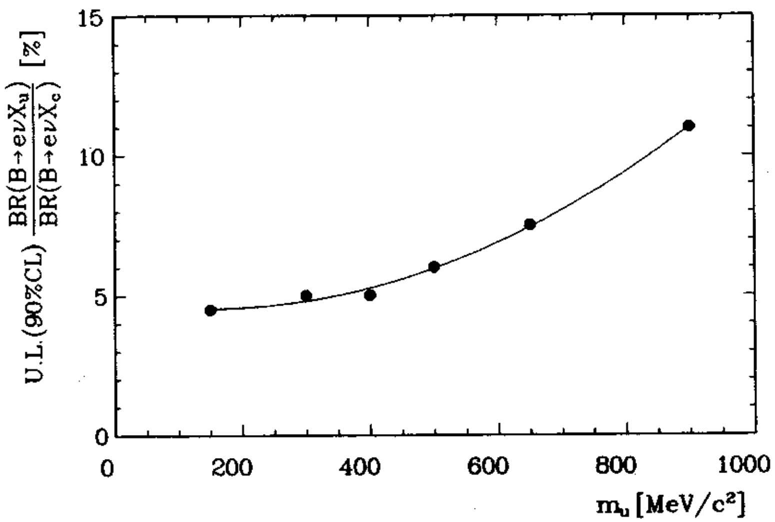

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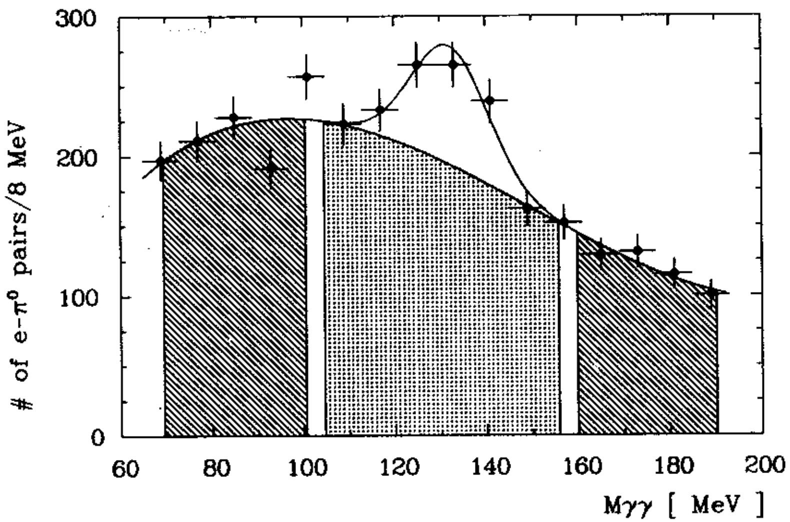

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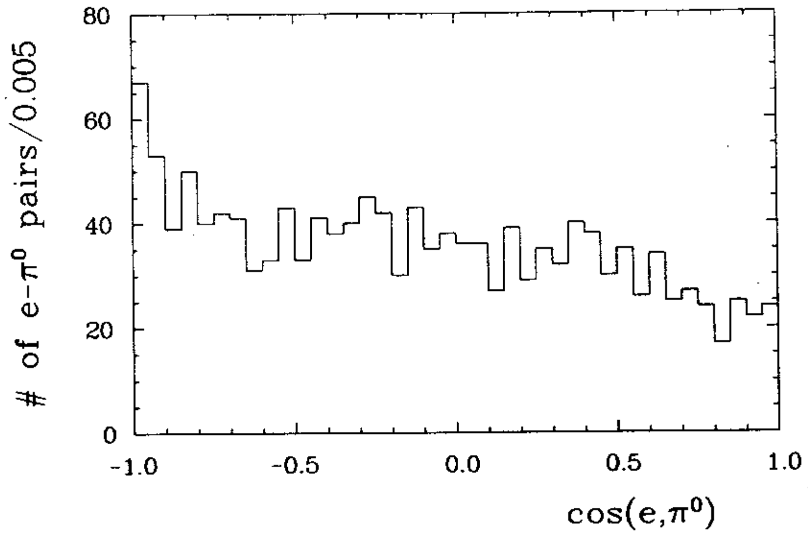

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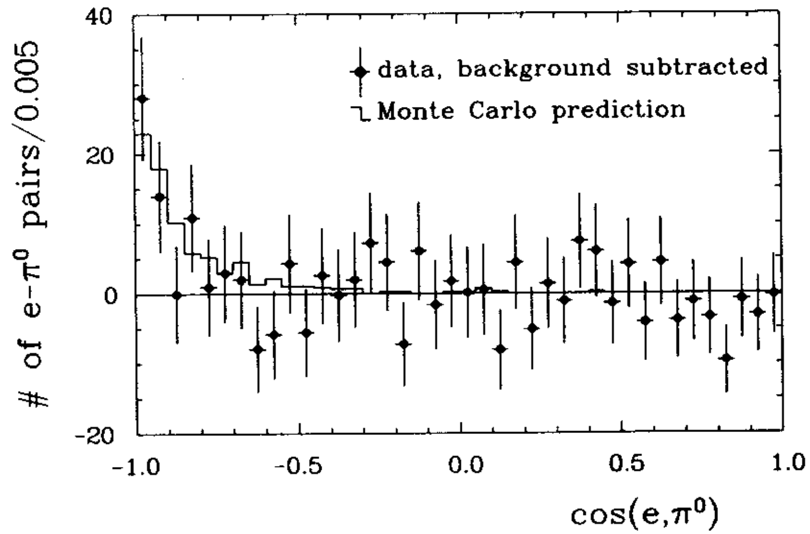

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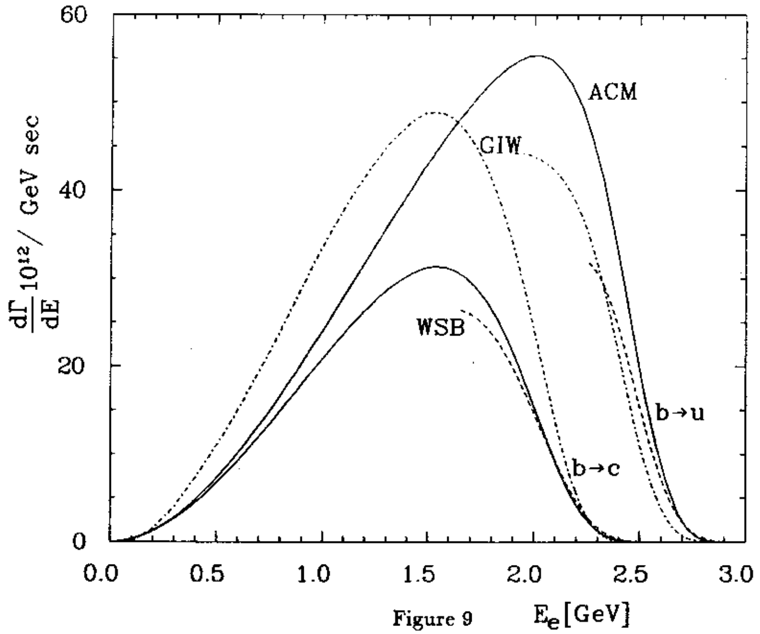

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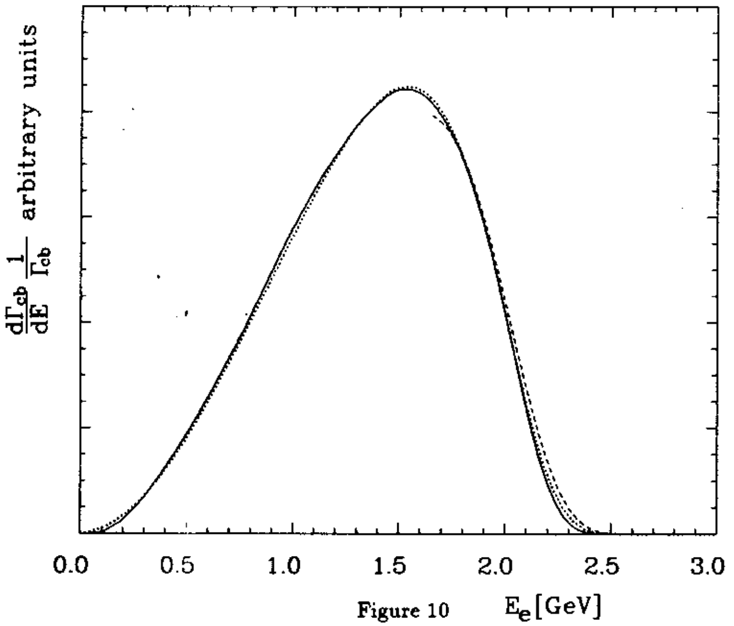

Figure 10