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1. INTRODUCTION

Access to open bottom decays offers the possibility of measuring one or more of the fundamental constants of nature. The recent confirmation of the second excited state Υ'' at 10.38 GeV gives one confidence that the potential-model calculations of the Υ-system are reliable.[1] In particular these calculations predict the existence of a third excited state Υ''' at 10.63 GeV, which is expected to lie in the continuum just above the B$\bar{B}$ threshold. This state should prove to be a uniquely intense source of open bottom (B-) mesons - an open bottom factory. Such a source should be capable of producing B's in sufficient number to observe their rare decay modes. This will make it possible to

(1) measure the ratio of the Kobayashi-Maskawa angles θ_2/θ_3 ,

(2) detect B-$\bar{B}$ mixing, and

(3) observe a new source of CP-violation and determine its fundamental parameter δ.

It is the aim of this work to present detailed estimates of the running times needed to carry out the above measurements.

2. THE $^3S_1$ - STATES OF THE Υ-SYSTEM

The Υ-system is known experimentally to have at least three bound states[2]:

Υ : $m_\Upsilon = 9.46 \pm 0.01$ GeV $\Gamma_{ee}^{\Upsilon} = 1.26 \pm 0.09$ keV

Υ': $m_{\Upsilon'} = 10.01 \pm 0.02$ GeV $\Gamma_{ee}^{\Upsilon'} = 0.33 \pm 0.1$ keV

Υ'': $m_{\Upsilon''} = 10.34 \pm 0.04$ GeV $\Gamma_{ee}^{\Upsilon''} = 0.33$ keV (calculated)

Various calculations of the Υ-spectrum indicate the existence of a fourth state [2a]

Υ''': $m_{\Upsilon'''} = 10.63$ GeV $\Gamma_{ee}^{\Upsilon'''} = 0.18$ keV.

It is not known yet whether this state lies above or below the bottom threshold. However, one suggestion that it lies in the continuum is provided by the rule [3)]

$$n \sim 2 \cdot \sqrt{\frac{m_b}{m_c}} \qquad (1)$$

where n is the number of bound $^3S_1$-states. For reasonable quark masses $n < 4$. In the event that Υ does lie above the bottom threshold this state would serve as a uniquely large source of B-mesons. The width of the Υ'' is then given by

$$\Gamma = |M|^2 \rho \qquad (2)$$

where ρ is the phase space for the allowed two body decay

$$\Upsilon''' \rightarrow B\bar{B}$$

and M the matrix element for this process $\langle B\bar{B}|H|\Upsilon'''\rangle$. If we assume this matrix element to be the same as for $\Psi' \rightarrow D\bar{D}$ then Γ is determined by the two-body phase space factor ρ. In the favourable case that Υ''' lies just over the $B\bar{B}$ threshold this gives a width

$$\Gamma_{\Upsilon'''} \sim 20 \text{ MeV}, \qquad (3)$$

which is of the same order as the experimental resolution that can be obtained at DORIS. Thus in this favourable case

$$\Gamma_{\Upsilon'''} \sim \sqrt{2} \cdot 20 \text{ MeV} \sim 30 \text{ MeV} . \qquad (4)$$

If we further assume the same radiative corrections for all $^3S_1$-states we find that

$$\sigma^{\Upsilon'''}_{peak} (e^+e^- \rightarrow \text{hadrons}) = \sigma^{\Upsilon}_{peak} \left(\frac{M_{\Upsilon}}{M_{\Upsilon'''}}\right)^4 \frac{\Gamma^{\Upsilon'''}_{ee}}{\Gamma^{\Upsilon}_{ee}} \sim 1.0 \text{ nb} \qquad (5)$$

Fig. 1 shows the spectrum of the $^3S_1$-states as observed in e^+e^- - annihilations including the Υ''' . The signal to background ratio can be enhanced

by cutting in the sphericity distribution. For the remainder of the discussion we shall assume that the estimate (5) is sound. We shall also assume that the luminosity of DORIS is 100/nb/day [3a)]. Together with (5) this luminosity implies that it should be possible to obtain $\sim$ 100 $B\bar{B}$ pairs/day.

3. THE KOBAYASHI-MASKAWA ANGLES

The success of the charm hypothesis along with the discovery of the Υ suggests that the hadronic part of the weak charged current is constructed from three quark doublets :

$$\begin{pmatrix} u \\ d_1 \end{pmatrix} \qquad \begin{pmatrix} c \\ s_1 \end{pmatrix} \qquad \begin{pmatrix} t \\ b_1 \end{pmatrix}$$

where d_1, s_1, and b_1 are linear combinations of the d, s, and b quarks. In the old 4-quark model the mixing was determined by a single (Cabibbo) angle θ_c, whereas in the 6-quark model four angles are required. In this case the mixing is described by means of the Kobayashi-Maskawa matrix [4)] :

$$\begin{pmatrix} d_1 \\ s_1 \\ b_1 \end{pmatrix} = M \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad (6)$$

where

$$M = \begin{pmatrix} \cos\theta_1 & \sin\theta_1\cos\theta_3 & \sin\theta_1\sin\theta_3 \\ -\sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3\, e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3\, e^{i\delta} \\ \sin\theta_1\sin\theta_2 & -\cos\theta_1\sin\theta_2\cos\theta_3-\cos\theta_2\sin\theta_3\, e^{i\delta} & -\cos\theta_1\sin\theta_2\sin\theta_3+\cos\theta_2\cos\theta_3\, e^{i\delta} \end{pmatrix} \qquad (7)$$

The corresponding couplings $(u,c,t) \rightarrow (d,s,b)$ are conveniently represented on the diagram in Fig. 2. As will be noted presently θ_1 is small, and there exist upper limits on θ_2 and θ_3 which are also small. Consequently, we have put the cosines of these angles equal to unity in Fig. 2 and will take this to be true throughout the remainder of this work.

At present the angles θ_1, θ_2, θ_3, and δ are regarded as fundamental parameters to be taken from experiment. Of these only the angle θ_1 is known with any degree of certainty. From superallowed β-decay [5]

$$\theta_1 = 13.0^0 \pm 0.5^0 \qquad (8)$$

Only upper limits exist for the angles θ_2 and θ_3. From semileptonic hyperon decays ($\propto \sin^2\theta_1 \cos^2\theta_3$) it is known that [6]

$$\theta_3 \lesssim 10^0 \, , \qquad (9)$$

whereas from the K_1-K_2 mass difference and the present lower limit of 15 GeV for the mass of the top quark [7]

$$\theta_2 \lesssim 20^0 \, . \qquad (10)$$

The angle δ gives rise to CP-violation. From $\Gamma(K_L \to 2\pi)$ it is known that

$$\delta \geq 0.4^0 \, . \qquad (11)$$

From Fig. 2 we see that the couplings of the charmed quark are given by

$$\begin{array}{ll} c \to s : & 1 \\ c \to u : & \sin\theta_1 \end{array} \qquad (12)$$

whereas the bottom quark couples to c and u with strengths

$$\begin{array}{ll} b \to c : & \sin\theta_3 + \sin\theta_2 \, e^{i\delta} \\ b \to u : & \sin\theta_1 \sin\theta_3 \end{array} \qquad (13)$$

In terms of physically observable particles this means D-meson decays are insentitive to θ_2 and θ_3. However, we can obtain information about these angles from the decays of the open bottom (B). Experience with the D's indicates that the non-leptonic decays cannot be relied upon for this purpose because of strong interaction effects [8]. So we shall concentrate on the leptonic modes indicated in Fig. 3. From the branching ratio of these decays we can extract a certain combination of the above angles.

The branching ratio of the most important of the Kobayashi-Maskawa suppressed decays is given by [9]

$$R_{\rho/D} = \frac{\Gamma(B \to \rho l \nu)}{\Gamma(B \to D l \nu)} \simeq \frac{0.08 \sin^2\theta_3}{\sin^2\theta_2 + \sin^2\theta_3 + 2\sin\theta_2 \sin\theta_3 \cos\delta} \qquad (14)$$

This branching ratio if difficult to measure. Even in the most favourable case $\theta_2 \ll \theta_3$,

$$R_{\rho/D} \simeq 0.08 \, . \qquad (15)$$

Thus we are looking a 10% effect. Moreover, the single lepton inclusive modes of $B\bar{B}$ decay are subject to a serious background from the $c\bar{c}$ channel. This can be demonstrated by means of a simple Monte-Carlo calculation, the results of which are shown on the graphs in Fig. 4. It is clear that D - decays in flight cannot be kinematically separated from the $\rho l \nu$ decay of the B [10]. On the other hand the like sign dilepton signal from the $B \to D \to K$ cascade is free of this background. Let us compare, for example,

$$\begin{array}{ll} B \to D + X & \bar{B} \to \rho + l^+ + \nu \\ \quad \hookrightarrow K + l^+ + \nu & \end{array} \qquad (16)$$

with

$$D \to K + l^+ + \nu \qquad \bar{D} \to K + l^- + \nu \quad . \qquad (17)$$

In the latter the leptons have opposite signs, so they can clearly be separated from the former. We can also see from Fig. 4 that the suppressed mode $\rho l \nu$ of the B can be separated kinematically from the dominant $D l \nu$ mode above 2.3 GeV. The Monte-Carlo indicates a fraction [11]

$$f \simeq 17 \, \% \qquad (18)$$

of the leptons in the suppressed mode lie above 2.3 GeV.

Assuming no enhancement of the non-leptonic decay modes of the B the branching ratio for each lepton is 1/6. On the other hand for the second lepton from the cascade D we have

$$B \to D + X \quad (\sim 100\ \%) \qquad (19)$$
$$\hookrightarrow K + l + \nu \quad (10\%/\text{lepton}) \ .$$

Electrons are identifiable in the ARGUS detector over their full energy range whereas muons are identifiable only above 700 MeV. The Monte-Carlo indicates that in 30% of the events both like sign leptons are detected. Thus the useful leptonic branching ratio is

$$R_{ll} = \frac{B\bar{B} \to l^+l^+ + B\bar{B} \to l^-l^-}{B\bar{B} \to \text{all}} \qquad (20)$$

$$= 2 \cdot \frac{1}{6} \cdot 3 \cdot 0.1 \cdot 3 \cdot 0.3 = 0.09 \ .$$

The event rate to be expected for the signal from the suppressed mode is given by

$$N = L \cdot \sigma(B\bar{B})\ R_{ee} \cdot f \cdot R_{\rho/D} \qquad (21)$$

$$= 100\ \text{nb}^{-1}/\text{day} \cdot 1.0 \cdot 0.09 \cdot 0.17 \cdot R_{\rho/D}$$

With the $\sim$ 200 useful measuring days/y this amounts to a maximum number of 25 events/year depending on $\sin\theta_2 / \sin\theta_3$ and $\cos\delta$. This number can be improved if there exists a non-negligible probability to tag one B-meson and to look for the $\rho l \nu$ - decay of the other B-meson. On the other hand the number of events might slightly decrease due to the finite energy resolution of the detector.

If $\cos\delta$ is close to unity, we can expect the following accuracy for the ratio $r = \sin\theta_2 / \sin\theta_3$ after one year of running :

$$\sigma_r = 40\ \% \quad \text{if } \theta_2 \simeq \theta_3$$
$$r < 0.25\ (95\%\ \text{C.L.}) \text{ if } \theta_2 \ll \theta_3 \qquad (22)$$
$$\frac{1}{r} < 0.25\ (95\%\ \text{C.L.}) \text{ if } \theta_2 \gg \theta_3$$

4. $B\bar{B}$ MIXING

One can also study B-$\bar{B}$ mixing by means of the like.sign dilepton signal. In this case the reactions are

$$\bar{B}^0 \to B^0 \to \bar{D} + l^+ + \nu \qquad B^0 \to D^- + l^+ + \nu \text{ and h.c.} \qquad (23)$$

These reactions are kinematically distinguishable from the K-M suppressed mode of the previous section because, unlike the latter case, the spectrum does not extend above 2.3 GeV. Moreover, the Monte-Carlo indicates that a lepton energy cut

$$E_l \geq 1.8\ \text{GeV} \qquad (24)$$

will separate the reactions (23) from the principal background,

$$B \to D + X \qquad B \to D + l^+ + \nu \text{ and h.c.} \qquad (25)$$
$$\hookrightarrow K + l^+ + \nu$$

The low-energy peaking of the leptons from the cascade D (see Fig. 4) makes this separation possible.

Since the build-up of the $\bar{B}$ occurs only during the lifetime of the original B, the important parameter that determines the amount of mixing is

$$\Delta m_{B_1B_2}\tau_B = \frac{\Delta m_{B_1B_2}}{\Gamma_B} \qquad (26)$$

where $\Delta m_{B_1B_2}$ is the mass difference of the longer and shorter lived components and $\tau_B = 1/\Gamma_B$ is the average lifetime of the B's. The mass difference in (26) is related to the off-diagonal mass-matrix element

$$\Delta m = 2\ |\langle B^0|H|\bar{B}^0\rangle| \qquad (27)$$

An estimate of this matrix element has been given by Ellis et al. and by Ali and Aydin [12]. Their calculations are based on an earlier analysis of the $K_1 - K_2$ mass difference by Gaillard and Lee [13]. These authors showed that within the framework of the standard model the principal contributions to (27) come from the diagram in Fig. 5 along with a virtual Z^o-contribution of the same order. The leading term is proportional to the square mass of the exchanged quark of greatest mass, and the couplings of the quarks to the W-bosons are weighted by the appropriate K-M matrix element. For the $B\bar{B}$ system the t-exchange dominates so that

$$\langle B^o|H|\bar{B}^o\rangle \propto m_t^2 \sin^2\theta_1 \sin^2\theta_2 \quad . \qquad (28)$$

With the proper factors inserted this gives

$$\left.\frac{\Delta m}{\Gamma}\right|_{B\bar{B}} \simeq \frac{m_t^2}{700\ \mathrm{GeV}^2} \left(\frac{\sin^2\theta_2}{\sin^2\theta_2+\sin^2\theta_3+\sin\theta_2\sin\theta_3\cos\delta}\right) \qquad (29)$$

provided the angular factor in parenthesis is of order unity and $m_t \geq 15$ GeV [14]. Note that this assumption implies $\theta_2 \gg \theta_3$, whereas in obtaining the estimate (22) it was assumed that $\theta_3 \gg \theta_2$. The point is that we obtain a large signal from ($b \to u$) above 2.3 GeV if $\theta_3 \gg \theta_2$ or a large mixing signal ($B \to \bar{B}$) below 2.3 GeV if $\theta_2 \gg \theta_3$. On the other hand if $\theta_2 \simeq \theta_3$ then both estimates are reduced; (22) is reduced by roughly a factor of 4, whereas $B \to \bar{B}$ mixing decreases by a factor of 16. For comparison we observe that if this analysis is correct

$$\left.\frac{\Delta m}{\Gamma}\right|_{B\bar{B}} \leq \left.\frac{\Delta m}{\Gamma}\right|_{K\bar{K}} \gg \left.\frac{\Delta m}{\Gamma}\right|_{D\bar{D}} \qquad (30)$$

Note that in contrast to the $D\bar{D}$ case $B\bar{B}$ mixing can be substantial - almost comparable to $K\bar{K}$ mixing. The reason for this is that the large mass of the t-quark essentially compensates for one of the $\sin^2$ factors in (28), and the decay probability is also Cabbibo-suppressed. On the other hand in the D-case the leading term comes from an exchange of an s-quark [15] :

$$\langle D^o|H|\bar{D}^o\rangle \propto (m_s - m_u)^2 \sin^2\theta_1 \ . \qquad (31)$$

In this case the decay probability is Cabibbo-allowed and the mass factors are not sufficient to compensate for the $\sin^2$ factor. Consequently, the

$D\bar{D}$ splitting is small.

With the same set of assumptions concerning the production of $B\bar{B}$ we can estimate the running time needed to measure the $B\bar{B}$ splitting. The "wrong" sign lepton signal is given by [12]

$$\frac{\Gamma(B \to \bar{B} \to l^+ + \nu + \bar{D})}{\Gamma(B \to l^- + \bar{\nu} + D)} \simeq \frac{1}{2}\left(\frac{m_t^2}{700\ \mathrm{GeV}^2}\right)^2 \cdot \left(\frac{\sin^2\theta_2}{\sin^2\theta_2+\sin^2\theta_3+2\sin\theta_2\sin\theta_3\cos\delta}\right)^2$$

(32)

If the angular factor is of order unity, then this branching ratio $\gtrsim$ 0.05.

Summing over both signs we expect a branching ratio

$$R\left(\frac{(++)+(--)}{(+-)}\right) = \frac{\Gamma(B,\bar{B} \to l^+l^- + l^-l^- + X)}{\Gamma(B,\bar{B} \to l^+l^- + X)} \gtrsim 0.1 \qquad (33)$$

in the entire dilepton signal from direct leptonic decays of the B's ($\bar{B}$'s). The Monte-Carlo indicates that 30% of the leptons from $B \to KL\nu$ (curve 1 in Fig. 4) have $E_l > 1.8$ GeV, whereas only 2% of the background signal from the $B \to D \to KL\nu$ cascade lies in this region. This gives an effective signal/background ratio

$$\frac{B \to \bar{B} \to \bar{D} + l + \nu}{B \to D \to K + l + \nu} \gtrsim \frac{10}{6} \cdot \frac{30}{2} \cdot \frac{0.1}{2} \gtrsim 1.3 \ . \qquad (34)$$

Thus the lepton spectrum ought to be sensitive to mixing in this region.

With the assumptions for $B\bar{B}$ production given previously, the expected event rate if given by [16]

$$R = L\,\sigma(B\bar{B}) \left| \frac{\Gamma(B \to D + l + \nu)}{(B \to \mathrm{all})} \right|^2 \cdot R\,\frac{(++)+(--)}{(+-)}$$

$$\cdot\ f(E_l > 1.8\ \mathrm{GeV})^2$$

$$(R) = 100\ nb^{-1}/day \quad 0.5\ nb \quad (1/3)^2 \quad 0.1 \quad (0.3)^2$$
$$= 0.05\ \text{event/day} \qquad (35)$$

Assuming 200 measuring days/year and θ_2/θ_3 favouring $B \to \bar{B}$ mixing, the following result can be expected :

Measuring time : 1.0 y
Number of events : 10 ± 5 (36)

Note : The number of events is sensitive to the top quark and could be substantially larger if the mass of the top quark is much larger than 15 GeV. The error includes fluctuations in the background.

5. CP - VIOLATION

The dilepton signal can also be used to test CP violation in B decays. The relevant quantity is

$$\varepsilon = \frac{\text{Im} <B^0|H|\bar{B}^0>}{\Delta m_B} \qquad (37)$$

because if CP is conserved the off-diagonal elements of the mass matrix are real [17]. Ellis et al. pointed out that

$$\varepsilon = \tan 2\delta \qquad (38)$$

This means a measurement of the parameter ε constitutes a measurement of the parameter δ. Since nothing is known about δ, CP violation, which is suppressed in the $K\bar{K}$ system by a factor $\sin^2\theta_1$ can be substantial in the $B\bar{B}$ system [18]. Experimentally ε is measured by comparing the l^+l^+ and l^-l^- signals. The connection is [19]

$$\frac{\Gamma(B,\bar{B} \to X + l^- + l^-)}{\Gamma(B,\bar{B} \to X + l^+ + l^+)} = \left|\frac{1-\varepsilon}{1+\varepsilon}\right|^4 \qquad (39)$$

In the event that ε is small compared to unity this gives approximately

$$\varepsilon \approx \frac{1}{4}\,\frac{\Gamma(B,\bar{B} \to X + l^+ + l^+) - \Gamma(B,\bar{B} \to X + l^- + l^-)}{\Gamma(B,\bar{B} \to X + l^+ + l^+) + \Gamma(B,\bar{B} \to X + l^- + l^-)} \qquad (40)$$

We can thus use the same signal to study CP violation as for $B\bar{B}$ mixing.

The single sign signal should be of the order of half the signal predicted by (36). Thus for a measurement of ε the like sign signal should be not larger than $\sim$ 0.03 events/day for the favourable case $\theta_2 >> \theta_3$. However, to look for CP-violation we can actually use a larger portion of the spectrum. Since we look for a difference between l^+l^+ and l^-l^- it is only necessary that the statistical fluctuations of the background leptons from $B \to D \to Kl\nu$ be less than the desired signal. The Monte Carlo indicates that this will be the case if $E_l > 1.4$ GeV, in which case 50% of the lepton signal is useful. This raises the maximum expected event rate to 0.07 events/day. Therefore, we can expect the following [20] :

Measuring time : 1.0 y
Result : 14 ± 5 events => (41)
observation of CP violation (95% C.L.)
if $\delta \geq 3^0$.

A determination of this angle δ would then possibly even set a lower limit on the mass of the top quark should this quantity still be in doubt. Moreover, recent measurement of the lifetime of the D-meson decaying in an emulsion [21] gives one the hope that this can also be accomplished for the B. Roughly,

$$\Gamma_B \lesssim \Gamma_D \times (m_b/m_c)^5\ (\sin^2\theta_2+\sin^2\theta_3+2\sin\theta_2\sin\theta_3\cos\delta)$$
$$\sim 20\Gamma_D \quad \text{for } \sin^2\theta_2+\sin^2\theta_3+2\sin\theta_2\sin\theta_3\cos\delta \sim 0.1 \qquad (42)$$

The point is that the angle factor partically compensates for the increase in phase space. The sensitivity of the D-measurement indicates that if Γ_B is of the order of the upper limit (42) it should be detectable. If so then coupled with the measurement of the dilepton branching ratio and the detection of CP violation it should be possible at least in principle to determine all the Kobayashi-Maskawa angles from B-meson decays.

6. SUMMARY

The rate decay modes of the B-meson harbor fundamental information concerning weak interactions. In particular observation of a like-sign dilepton signal may yield the ratio of the Kobayashi-Maskawa angles θ_2 / θ_3, the amount of B-$\bar{B}$ mixing, and the fundamental strength of CP-violation. At the same time the expected low rates of these decays present a real challenge to the experimentalist. By raising the maximum energy of DORIS a few percent to get above the $B\bar{B}$ threshold it should be possible to meet this challenge with the ARGUS detector.

7. ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1 The $^3S_1$ - states of the Υ-system. The vertical line on the right indicates the probable position of the $B\bar{B}$-threshold.

Figure 2 The weak couplings of the quarks in the 6-quark model of Kobayashi and Maskawa.

Figure 3 The important leptonic decay modes of the B-meson.
a) Cacibbo allowed mode
b) Cabibbo suppressed mode.

Figure 4 Leptonic decay spectra. The B-mesons are at rest whereas the momentum of the D-meson is 5 GeV. For small momenta of the B-mesons ($p_B \sim 200$ MeV/c) the difference in the $B \to Dl\nu$ and $B \to \rho l\nu$ - spectra remains essentially the same. The spectra are only slightly shifted to higher momenta.

Figure 5 Principal diagrams contributing to the off-diagonal elements of the mass matrix of the B.

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9. The constant term 0.08 on the right is $\sin^2\theta_1$ times a phase space factor.

10. There is also a background from $\tau^+\tau^-$. This background can be suppressed by a multiplicity cut.

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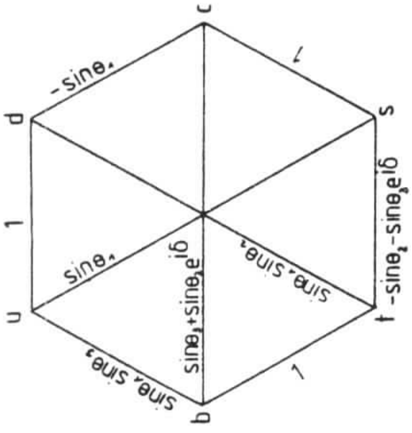


Fig.2

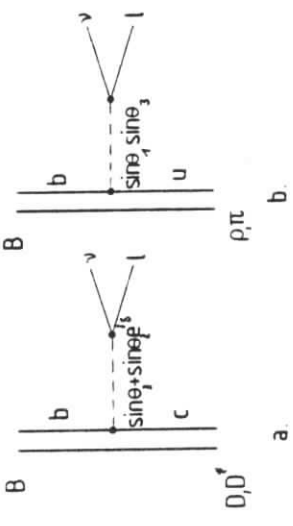


Fig.3

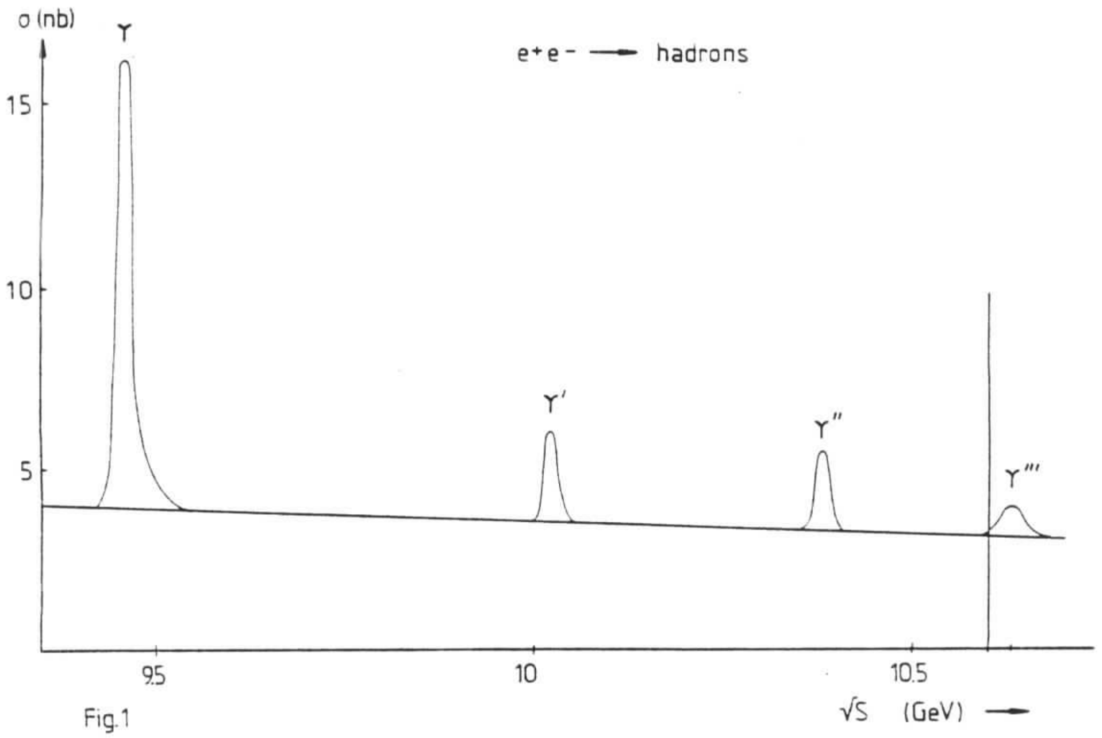
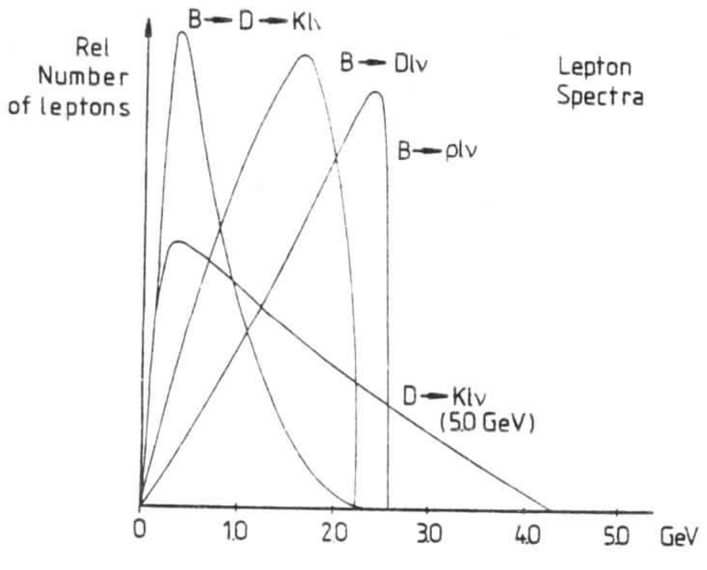
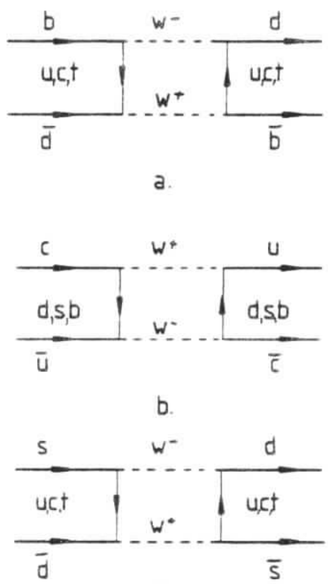


Fig.1



Rel
Number
of leptons
B → D → Klν
B → Dlν
Lepton
Spectra
B → ρlν
D → Klν
(5.0 GeV)
0
1.0
2.0
3.0
4.0
5.0
GeV

Fig.4



b
w⁻
d
u,c,t
w⁺
u,c,t
d̄
b̄
a.
c
w⁺
u
d,s,b
w⁻
d,s,b
ū
c̄
b.
s
w⁻
d
u,c,t
w⁺
u,c,t
d̄
s̄
c.

Fig.5