

Measurement of the  $e^+e^- \rightarrow b\bar{b}$  cross section and forward-backward charge asymmetry at a center-of-mass energy of 57.2 GeV

The AMY Collaboration

ABSTRACT

Measurements of the  $e^+e^- \rightarrow b\bar{b}$  forward-backward charge asymmetry,  $A_b$ , and the ratio of the cross-section for  $e^+e^- \rightarrow b\bar{b}$  to the theoretical QED cross-section for  $e^+e^- \rightarrow \mu^+\mu^-$ ,  $R_b$ , at an average center-of-mass energy of 57.2 GeV are reported. We use 196 multihadronic inclusive muon events corresponding to an integrated luminosity of  $33.3 \text{ pb}^{-1}$  accumulated by the AMY detector at TRISTAN. The results,  $A_b = -0.82 \pm 0.25(\text{stat}) \pm 0.14(\text{syst})$  and  $R_b = 0.47 \pm 0.12 \pm 0.10$  are consistent with the standard model predictions of  $-0.58$  and  $0.56$ , respectively. The results for the charge asymmetry are used to set a 90% confidence level limit on  $\chi$ , the  $B^0 - \bar{B}^0$  mixing parameter, of  $\chi < 0.20$ .

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## 1. Introduction

In the standard model [1], the process  $e^+e^- \rightarrow b\bar{b}$  can proceed through one-photon and one- $Z^0$  annihilation. The coupling of the b-quark to the photon involves only a vector current, while that to the  $Z^0$  is a weak coupling with both vector and axial-vector components. A forward-backward charge asymmetry is induced by the interference between the axial-vector coupling to the  $Z^0$  and the vector coupling to both the photon and the  $Z^0$ . The standard electroweak model gives an absolute prediction for this asymmetry; the measurement reported here is a direct test of the model.

The angular distribution for the reaction  $e^+e^- \rightarrow b\bar{b}$  is described by the relation

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} R_b \left( 1 + \cos^2\theta + \frac{8}{3} A_b \cos\theta \right), \quad (1)$$

where  $\alpha$  is the fine structure constant,  $s$  is the square of the c.m. energy, and  $\theta$  is the angle of the outgoing  $b(\bar{b})$  with respect to the incoming  $e^-(e^+)$  direction. Ignoring QCD corrections, which amount to about 5% in our energy region,  $R_b$  and  $A_b$  are expressed as

$$R_b = 3[Q_b^2 - 8Q_b g_V^e g_V^b \text{Re}(\chi) + 16(g_V^e{}^2 + g_A^e{}^2)(g_V^b{}^2 + g_A^b{}^2)|\chi|^2] \quad (2)$$

$$A_b = 3[-6Q_b g_A^e g_A^b \text{Re}(\chi) + 48g_V^e g_V^b g_A^e g_A^b |\chi|^2]/R_b, \quad (3)$$

where  $Q_b$  is the charge of the b-quark,  $\chi$  is the contribution from the  $Z^0$  given by

$$\chi = \frac{1}{16\sin^2\theta_W \cos^2\theta_W} \frac{s}{(s - M_Z^2 + i\Gamma_Z M_Z)}, \quad (4)$$

and  $g_V^b$  and  $g_A^b$  are the vector and axial-vector couplings to the b-quark, respectively.

As can be seen in Eq. 3, the asymmetry  $A_b$  strongly depends on  $g_A^b$ , which in the

standard model is simply  $-\frac{1}{2}$ . The asymmetry is expected to reach its maximum (negative) value at TRISTAN energies.

Previously, the AMY experiment at the KEK  $e^+e^-$  storage ring TRISTAN reported results [2] for  $A_b$  and  $R_b$  using an  $18.6 \text{ pb}^{-1}$  data sample accumulated at center-of-mass energies from 52 to 57 GeV. This report is an update to that measurement, including new data.

## 2. The AMY detector

The AMY detector [3] is a compact detector based on a 3 Tesla solenoid superconducting magnet and is optimized for lepton identification. Charged particles are detected by a tube-type inner tracking chamber (ITC) and a cylindrical drift chamber (CDC). Between the CDC and the magnet coil is a finely segmented electromagnetic shower counter (SHC). Outside the SHC is the superconducting magnet and the muon identification system (MUO). The MUO consists of a 1.6 m iron equivalent hadron filter (which is also the return flux for the superconducting magnet), two double-layer orthogonal drift chambers, and scintillation counters, covering the region  $|\cos\theta| \leq 0.74$ . The 3 Tesla magnetic field allows AMY to be compact and still provide good momentum resolution for charged tracks. The compactness of AMY reduces background from the decay of pions and kaons to muons. The end-cap region is covered by a two-layer lead/scintillator tagging counter system covering the region  $26.5^\circ \leq \theta \leq 39.5^\circ$ , and a lead/scintillator calorimeter with a proportional tube array covering  $15^\circ \leq \theta \leq 26.5^\circ$ . The end-cap detection system

is used for detecting Bhabha events to measure luminosity.

### 3. Selecting b quark events

Muons in  $e^+e^-$  annihilations to hadron final states are produced primarily from semileptonic decays of heavy quarks in the processes  $e^+e^- \rightarrow b\bar{b}$  ( $b \rightarrow c\mu^-\bar{\nu}_\mu$ ) and  $e^+e^- \rightarrow c\bar{c}$  ( $c \rightarrow s\mu^+\nu_\mu$ ). Events that originate from u-, d- and s-quark pair productions do not produce prompt muons. Non-prompt backgrounds to the muon signal arise principally from hadron showers in the hadron filter, where the debris reaches the muon chamber (punchthroughs), or from the decay-in-flight of  $\pi^\pm$  and  $K^\pm$  mesons to a muon that reaches the muon chamber (decays).

The inclusive muon event sample was selected from the sample of events that passed the standard AMY hadronic event criteria [4] with the additional requirement of the presence of at least one muon track. A muon track is defined as: 1) hits in the muon drift chamber in at least three out of a total of four planes and with at least one set of adjacent wires having hits in either of the two double-layer drift chambers, 2) a transit time measured by the muon scintillation counters that is consistent with the beam crossing, and 3) a hit position in the muon chamber that matches the extrapolated position of one of the CDC tracks within a momentum dependent matching distance cut. The matching distance, defined as the distance between the muon track and the charged track extrapolation at the muon chamber, was studied using a sample of  $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$  events. Matching distance cuts that depend on the extrapolated track momentum at the muon chamber (final mo-

mentum) were determined such that 96% of the muons from the  $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$  data sample were accepted. This final-momentum dependent matching distance cut varied smoothly from 32.6 cm for muons with final momentum of 1.0 GeV to a constant value of 14 cm for muons with final momenta above 5 GeV/c. This momentum dependence reflects the fact that high momentum muons tend to suffer less multiple coulomb scattering in the material of the hadron filter. The CDC reconstruction efficiency for charged particles in a hadron jet is about 95%. The reconstruction efficiency of the muon detection system was determined to be 98% from a study of cosmic rays. A minimum momentum of 1.9 GeV/c is required for the muons to penetrate the hadron absorber. About 88% of the Monte Carlo prompt muons (in a jet) that were reconstructed by the CDC and the muon chamber system satisfy the matching distance cut. The overall detection efficiency for muons above 3 GeV/c in the angular region of  $|\cos\theta| \leq 0.74$  is 82%.

A sample of 196 multihadronic inclusive muon events was found in a  $33.3\text{pb}^{-1}$  data sample accumulated at center-of-mass energies between  $\sqrt{s} = 52$  and 61.4 GeV. (The luminosity-weighted center-of-mass energy is 57.2 GeV.) In addition to events of interest, namely  $e^+e^- \rightarrow b\bar{b}$  with subsequent semileptonic decay either directly,  $b \rightarrow \mu^-(\bar{b} \rightarrow \mu^+)$ , or in the cascade decay,  $b \rightarrow c \rightarrow \mu^+(\bar{b} \rightarrow \bar{c} \rightarrow \mu^-)$  [5], this event sample also contains additional prompt muons coming from  $e^+e^- \rightarrow c\bar{c}$ , followed by  $c \rightarrow \mu^+(\bar{c} \rightarrow \mu^-)$ , hadron punchthroughs, and decays-in-flight of  $\pi^\pm$  and  $K^\pm$  mesons. For the determination of the forward-backward charge asymmetry for  $e^+e^- \rightarrow b\bar{b}$ , it was assumed that the yield and asymmetry of  $e^+e^- \rightarrow c\bar{c}$  was correctly

described by the standard model. The estimated contributions from  $c\bar{c}$  production, punchthroughs, and decays were determined from a Monte Carlo simulation, where five quark flavors were generated according to the standard model using the LUND 6.3 event generator [6]. These contributions were subtracted from the inclusive muon data in order to extract the  $e^+e^- \rightarrow b\bar{b}$  signal. The level of punchthrough and decay background *coming from b-flavored hadrons* requires a knowledge of the  $e^+e^- \rightarrow b\bar{b}$  cross-section and asymmetry, which is measured by this analysis. However, this corresponds to only  $\sim 1/10$  of the backgrounds that originate from u,d,s, and c flavor hadrons and does not introduce a large uncertainty. About 35% of the inclusive muon data sample are from non-prompt backgrounds: 20% punchthrough and 15% decays. The Monte Carlo was also used to estimate the ratio of muons from  $b\bar{b}$  cascade decays to those from direct decays; this ratio depends only on the decay kinematics of the b quark and not on the dynamics of the  $b\bar{b}$  pair production. Cascade decays produce muons with charge opposite to those produced by direct decay and hence have the opposite asymmetry. This effect was corrected during the unfolding of the data described in the next section.

Distributions for  $P_T$ , the transverse momentum of the muon relative to the thrust axis of the event, and  $\cos\theta$ , where  $\theta$  is defined as the direction of the thrust axis associated with the  $\mu^-(\mu^+)$  with respect to the the incoming  $e^-(e^+)$  direction, are shown in Figs. 1 and 2, together with the estimated contributions of  $c\bar{c}$ , non-prompt background, and the  $b\bar{b}$  contribution obtained in this analysis. Semileptonic decays of heavy quarks ( $b \rightarrow c\mu^-\bar{\nu}_\mu$ ,  $c \rightarrow s\mu^+\nu_\mu$ ) lead to a prompt muon with large

$P_T$ . The average  $P_T$  of prompt muons from b-quark decays is generally higher than that from a c-quark, reflecting the heavier mass of b-flavored mesons. A b-quark enriched event-sample is obtained by selecting multihadronic events with high  $P_T$  muons. As expected, the angular distribution for the non-prompt background does not show any asymmetry, while the  $c\bar{c}$  contribution has a positive asymmetry. (The  $e^+e^- \rightarrow c\bar{c}$  has a negative asymmetry; the positive observed asymmetry is due to the convention of tagging the b-quark with a  $\mu^-$ .)

#### 4. Unfolding $A_b$ and $R_b$

Figure 1 shows that background from  $c \rightarrow \mu$  and non-prompt backgrounds are rejected at a faster rate (relative to prompt  $\mu$ 's from b-quark decay) as one selects events with increasingly higher muon  $P_T$ . However, above  $P_T \sim 1.0 \text{ GeV}/c$ , the number of  $b \rightarrow \mu$  events are rejected faster than the background. Thus the data sample can be enriched with b-quark events without losing too many  $b \rightarrow \mu$  events by the application of a suitable  $P_T$  cut. A study using Monte Carlo simulated events indicated that the statistical and systematic errors for  $A_b$  were minimized by a cut of  $P_T \geq 0.7 \text{ GeV}/c$ . After subtracting  $c\bar{c}$  and non-prompt backgrounds from the data sample, the resulting distribution was unfolded to give the correct  $e^+e^- \rightarrow b\bar{b}$  differential cross-section. Monte Carlo simulation studies show that about 19% of  $e^+e^- \rightarrow b\bar{b}$  events produce prompt muons with  $P_T \geq 0.7 \text{ GeV}/c$  that are detected by AMY within  $|\cos\theta| \leq 0.6$ . This 19% includes the average efficiency for detecting b-quarks from its semileptonic muon decay and the muon detection

efficiency of 82%. An unfolding factor was obtained by comparing Monte Carlo simulated results for the  $e^+e^- \rightarrow b\bar{b}$  angular distribution with the original angular distribution of the event generator. The unfolding procedure takes into account both 1) the effect of different  $\theta$  definition; the theoretical (generated)  $e^+e^- \rightarrow b\bar{b}$  angle  $\theta$  was defined by the  $b$  quark axis while the detected event angle  $\theta$  was defined by the thrust axis, and 2) the effect of the cascade decay  $b \rightarrow c \rightarrow \mu$ .

The resulting  $e^+e^- \rightarrow b\bar{b}$  differential cross section was fit to Eq. 1 over the angular range of  $|\cos\theta| \leq 0.6$ , allowing  $A_b$  and  $R_b$  to vary.

## 5. Systematic Errors

The main systematic uncertainty was the effect of the non-prompt background. Pion punchthroughs are well understood since there are data that can be compared to the results of the Monte Carlo simulation[7]. However, there are no data for kaon punchthrough in the TRISTAN energy range. This was estimated from Monte Carlo studies to cause approximately half of the punchthroughs (corresponding to about 30% of the non-prompt events), mainly because of the smaller absorption cross section for kaons in the iron. The Monte Carlo event generator is in good agreement with measured results for the pion:kaon:proton ratio [8], so estimates of the decay background are reliable. Since the largest uncertainty is that from kaon punchthrough, systematic errors were estimated by repeating the analysis with the non-prompt contribution varied by  $\pm 30\%$ , corresponding to doubling and eliminating  $K^\pm$  induced punchthroughs. The larger of the resulting shifts in  $A_b$  and  $R_b$  are

used as estimates for the systematic errors.

## 6. Results

The final results, measured at an average center-of-mass energy of  $\sqrt{s}=57.2$  GeV, are  $A_b = -0.82 \pm 0.25 \pm 0.14$  and  $R_b = 0.47 \pm 0.12 \pm 0.10$ , where the errors are statistical and systematic, respectively. The results of the fit are shown in Fig. 3. No corrections were made for  $B^0 - \bar{B}^0$  mixing. These observed results are consistent with the standard model predictions of  $A_b = -0.58$  and  $R_b = 0.56$ . Figure 4 compares our result for  $A_b$  with those from previous measurements [9], which were also not corrected for the  $B^0 - \bar{B}^0$  mixing. Figure 5 shows the results for  $R_b$  compared with the standard electroweak prediction including QCD effects and QED prediction. The measurements are consistent with the standard model prediction throughout the energy region explored so far.

## 7. Limit on $B^0 - \bar{B}^0$ mixing

In the presence of  $B^0 - \bar{B}^0$  mixing a  $\mu^-$  is sometimes produced from an initial  $\bar{b}$ -quark, thereby confusing the quark identification. Consequently the observed numbers of forward and backward events become

$$N_F^{\text{obs}} = N_F - \chi N_F + \chi N_B, \quad (5)$$

$$N_B^{\text{obs}} = N_B - \chi N_B + \chi N_F, \quad (6)$$

where the  $B^0 - \bar{B}^0$  mixing parameter  $\chi$  is defined by

$$\chi = \frac{\Gamma(B^0 \rightarrow \bar{B}^0 \rightarrow \bar{X})}{\Gamma(B^0 \rightarrow X \text{ or } \bar{X})}. \quad (7)$$

The asymmetry is reduced from the value given by the standard model and is given by

$$A_b^{\text{obs}} = \frac{N_F^{\text{obs}} - N_B^{\text{obs}}}{N_F^{\text{obs}} + N_B^{\text{obs}}} = (1 - 2\chi)A_b. \quad (8)$$

Since our measurement is done in the continuum, we must use an effective mixing parameter that takes into account all B mesons. The ratio of production of  $B_u^+ : B_d^0 : B_s^0$  is expected to be about 3:3:1 in  $e^+e^-$  annihilation. This is deduced from the 3:3:1 ratio for the quark pairs ( $u\bar{u} : d\bar{d} : s\bar{s}$ ) production from color fields and assuming that they are independent of the primary quark. Charge conservation demands that mixing can only happen in the neutral meson system and hence  $\chi_u$  must be zero. Assuming equal semi-leptonic branching ratio for all B mesons, the effective  $\chi$  is then

$$\chi = 3/7\chi_d + 1/7\chi_s. \quad (9)$$

The range of possible values of  $\chi_d$  and  $\chi_s$  is from 0 to 0.5. The  $\chi_d$  is measured by CLEO [10] ( $\chi = 0.123 \pm 0.048$ ) and ARGUS [11] ( $\chi = 0.167 \pm 0.055 \pm 0.046$ ). There is a good theoretical reason to believe that the  $B_s$  mixing is maximal [12] ( $\chi_s = 0.5$ ). We therefore expect  $\chi = 0.13 \pm 0.02$ . Any experimental observation that significantly deviates from this value will indicate that the above assumptions are incorrect.

Using the measured asymmetry of  $A_b^{\text{obs}} = -0.82 \pm 0.29$  and standard model prediction of  $A_b = -0.58$ , we can set a 90% confidence level limit of  $\chi < 0.20$ . This

is consistent with the above expectation. Also this agrees with the 90% CL limits found by MARK II [13] ( $\chi < 0.12$ ) and by JADE [14] ( $\chi < 0.13$ ) but is in poor agreement with the 95% CL limit reported by MAC [15] ( $\chi > 0.21$ ).

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### Figure Captions

**Figure 1** The transverse momentum distribution of the muons with respect to the thrust axis for all multihadronic events including muons. Estimated contributions from  $c\bar{c}$  and non-prompt background were determined from a Monte Carlo simulation. The  $b\bar{b}$  was obtained from the analysis described in the text. The solid line is a sum of these three processes.

**Figure 2** The angular distribution  $dN/d\cos\theta$  for the multihadronic events including muons. The data are divided into two separate regions,  $p_T$  above (a) and below (b) 0.7 GeV. Estimated contributions from  $c\bar{c}$ , non-prompt background,

$b\bar{b}$ , and their sum are also shown as in Figure 1.

Figure 3  $d\sigma/d\Omega$  for  $e^+e^- \rightarrow b\bar{b}$  with the results of the fit. The Standard Model prediction is also shown.

Figure 4 The forward-backward charge asymmetry for  $e^+e^- \rightarrow b\bar{b}$  as a function of center-of-mass energy. The result of this experiment at a mean  $\sqrt{s} = 57.2$  GeV is compared with previous measurements. The solid curve is the standard model prediction using  $M_Z = 91$  GeV,  $\Gamma_Z = 2.5$  GeV and  $\sin^2\theta_W = 0.230$ .

Figure 5  $R_b$  as a function of center-of-mass energy compared with the standard electroweak theory prediction and the QED expectation (i.e. without the  $Z^0$  contribution).

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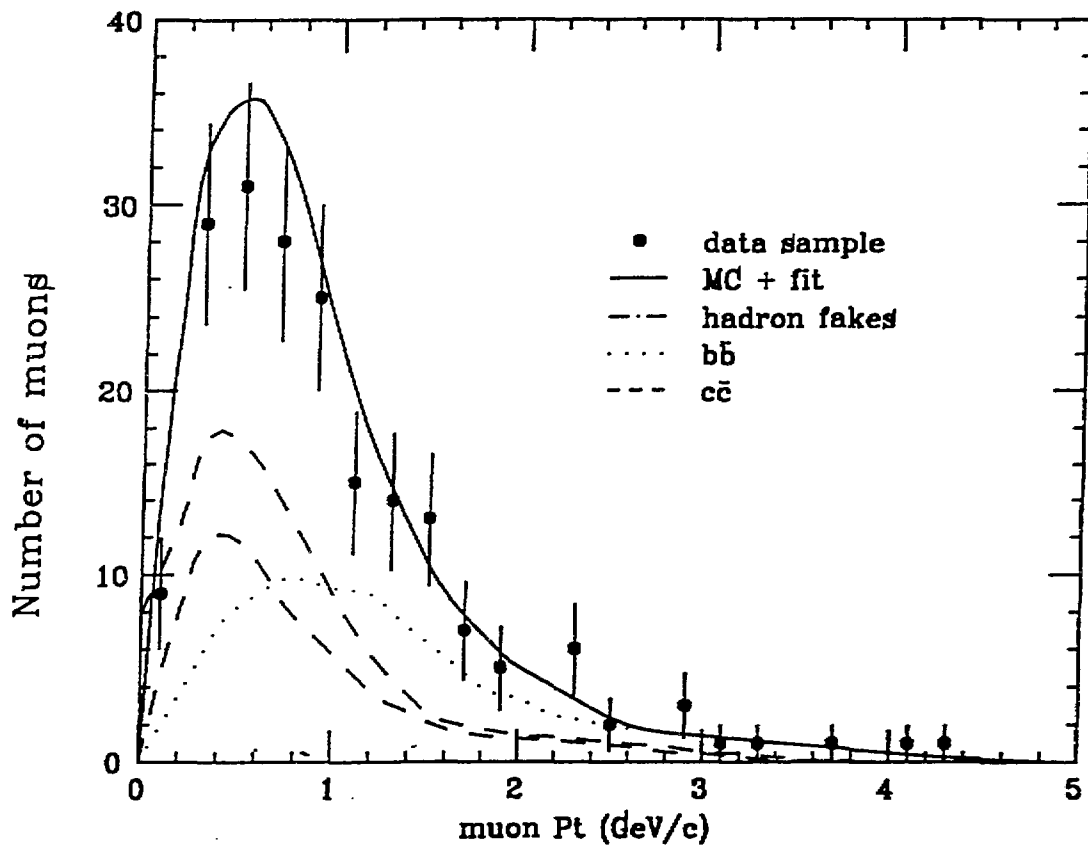


Figure 1

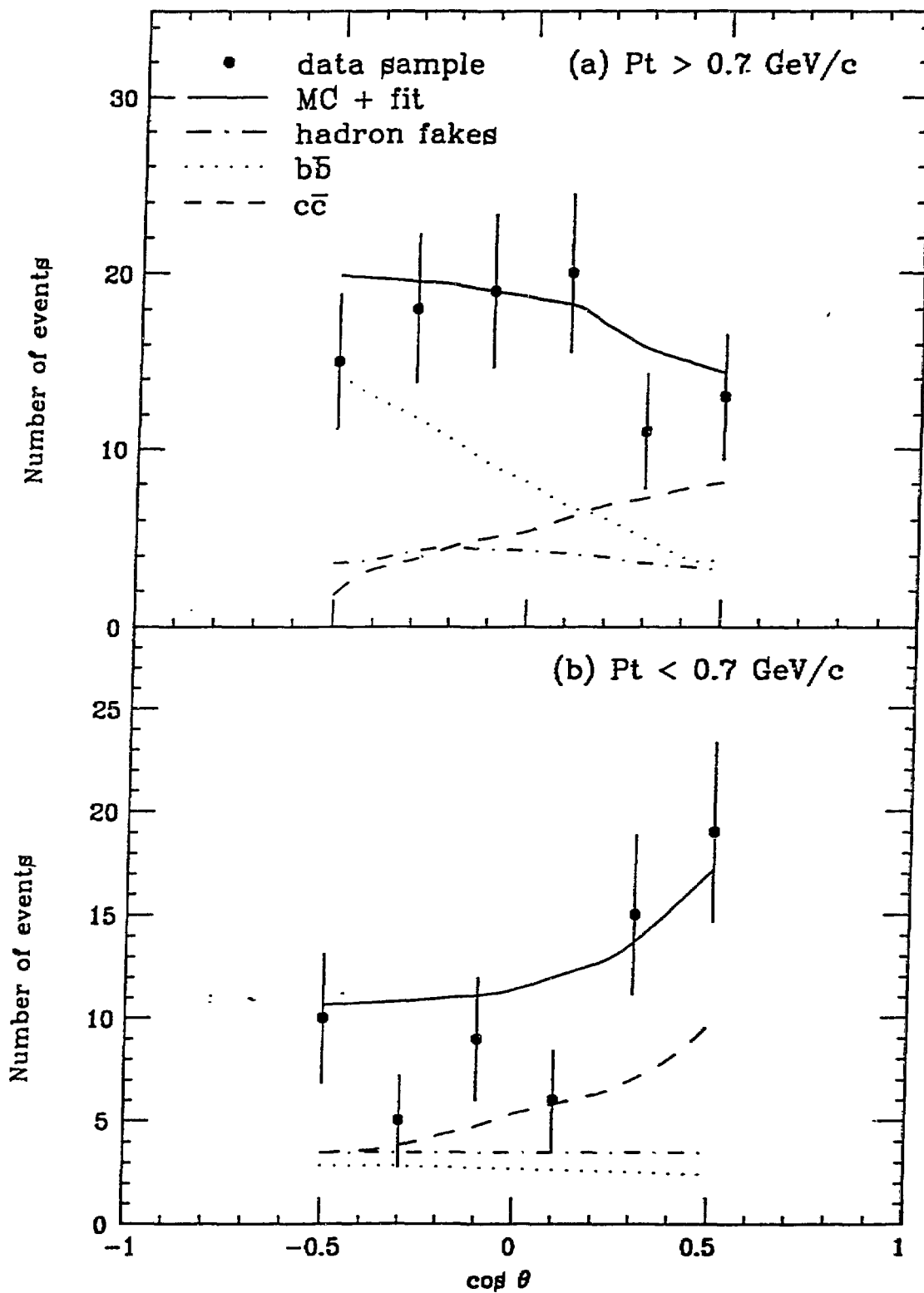


Figure 2

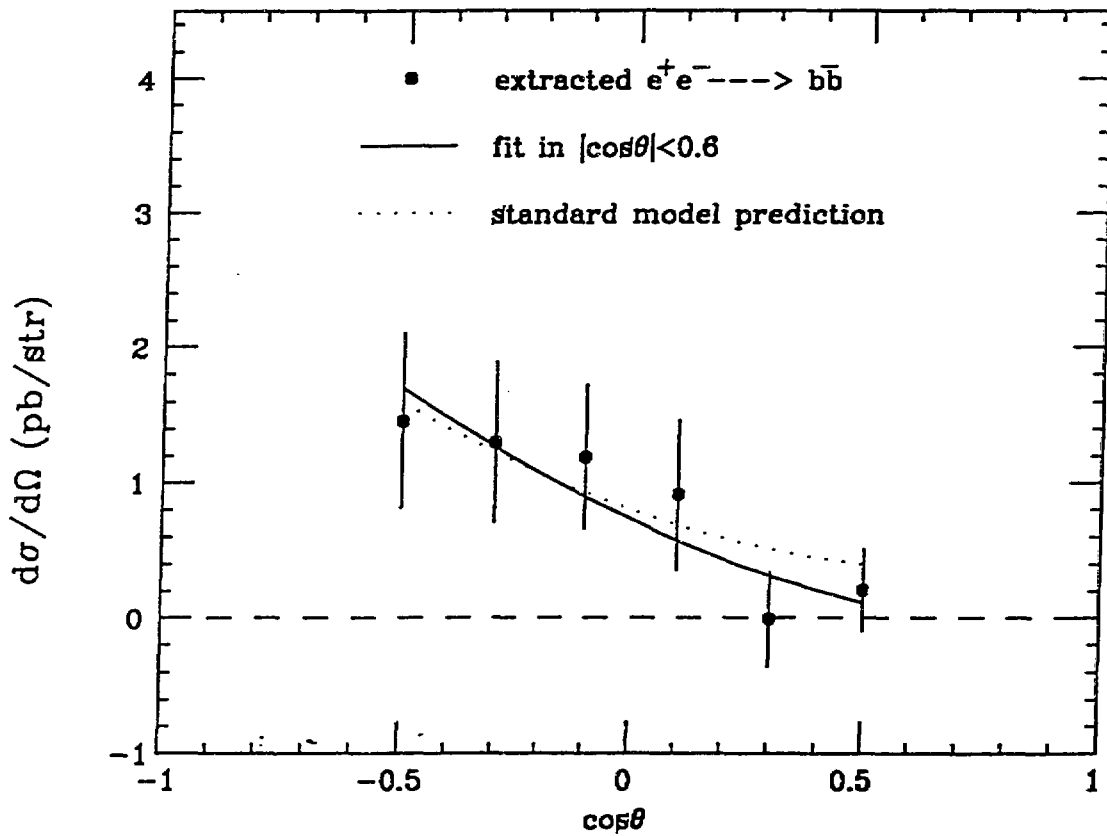


Figure 3

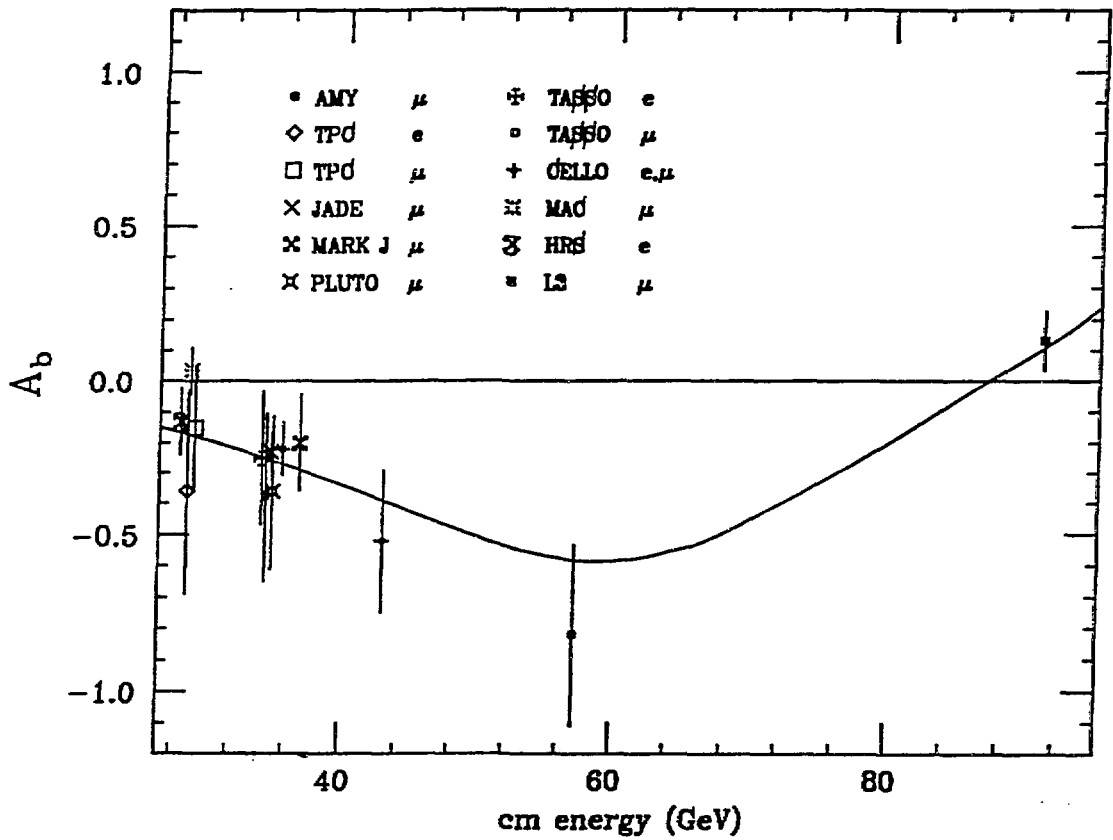


Figure 4

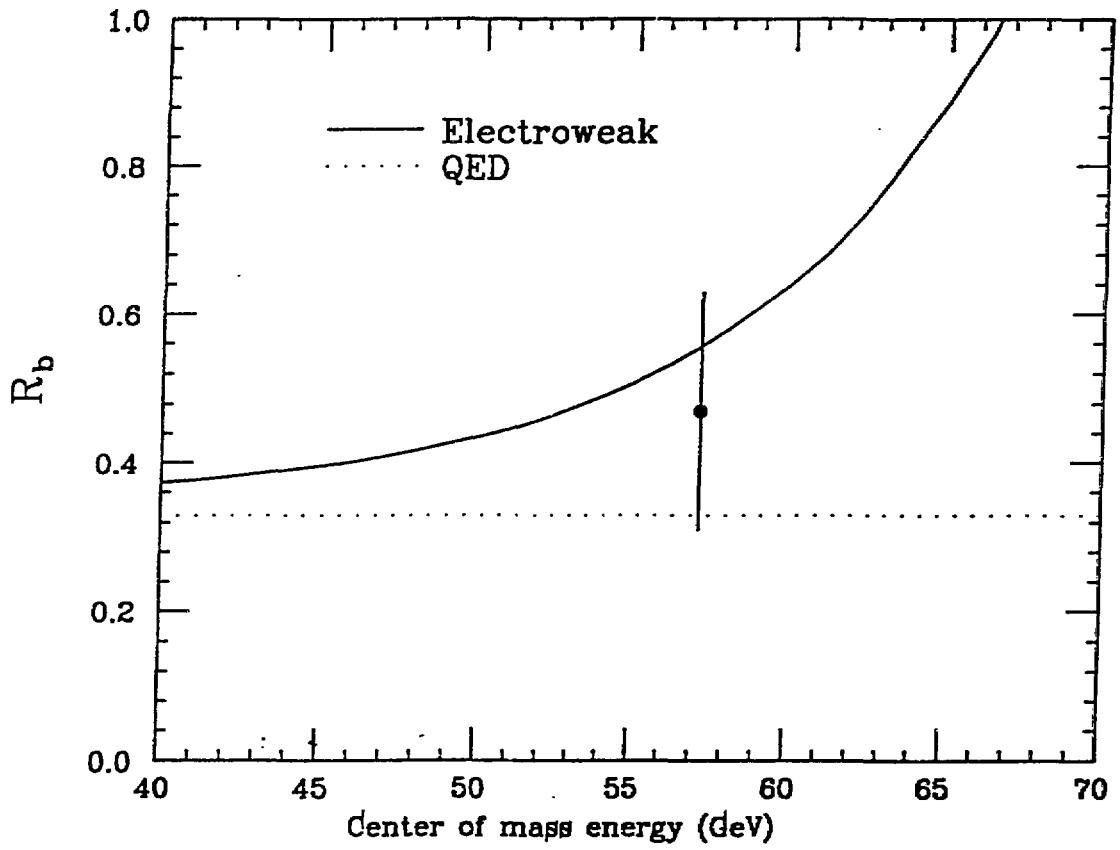


Figure 5