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The Forward-Backward Asymmetry for Charm Quarks at the Z Pole

Abstract

High momentum $D^{*\pm}$'s are used to define a purified sample of $Z \rightarrow c\bar{c}$ events, from which is measured the charm forward-backward asymmetry. This analysis is based on 1.4 million Z decays recorded with the ALEPH detector at LEP, more than three times the sample used for the previously published value. The charm quark forward-backward asymmetry at the Z pole is measured to be $A_{FB}^{0,c} = (8.1 \pm 2.3)\%$ corresponding to an effective electroweak mixing angle of $sin^2\theta_W^{eff} = 0.2300 \pm 0.0052$.

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1 Introduction

The forward-backward asymmetry in the $Z \rightarrow \mathrm{f\bar{f}}$ decay is related to couplings in the Standard Model. At the Z pole, this asymmetry is expressed as :

$$A^f_{FB} \simeq \frac{3}{4} \frac{2\mathrm{v_e a_e}}{(\mathrm{v_e}^2 + \mathrm{a_e}^2)} \frac{2\mathrm{v_f a_f}}{(\mathrm{v_f}^2 + \mathrm{a_f}^2)}$$

Therefore, the measurement of the F-B asymmetry for each produced fermion type constitutes an important test of the Standard Model. In this contribution is described a measurement of the charm quark asymmetry, experimentally defined as :

$$A^c_{FB} = \frac{\sigma^F_{charm} - \sigma^B_{charm}}{\sigma^F_{charm} + \sigma^B_{charm}}$$

This paper is an update of Ref. [1], with statistics increased to 1.4 million hadronic Z's collected at a center-of-mass energy of 91.25 GeV. $\mathrm{D}^{*\pm}$ produced in the $Z \rightarrow \mathrm{q\bar{q}}$ process are used to tag charm and beauty quarks. Indeed, in hadronic Z decays, charmed mesons are expected to be produced either directly from the hadronization of charm quarks in the process $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ or from the decay of b hadrons produced in $Z \rightarrow \mathrm{b\bar{b}}$ events, with an approximately equal rate. A selection of high momentum $\mathrm{D}^{*\pm}$'s, removing a large amount of background events and enriching the sample to 79% in charmed mesons originating from the $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ process, allows a precise measurement of the charm asymmetry.

D^{*+}'s are searched for in the decay channel $\mathrm{D}^{*+} \rightarrow \mathrm{D}^0\pi^+$, and three D^0 decay channels have been considered (charge-conjugate modes are implied throughout):

$$\begin{array}{ll} (i) & \mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+ ; \\ (ii) & \mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+\pi^+\pi^- ; \\ (iii) & \mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+\pi^0 . \end{array}$$

The channel (iii) is studied in a different way from Ref. [1]. The π^0, previously reconstructed with the electromagnetic calorimeter for energy above 0.5 GeV, is not used here in the D^0 reconstruction. D^0's containing a soft π^0 and originating mainly from a ρ^+ are considered through the so-called S^0 peak. This new selection increases the number of selected $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+\pi^0$ by a factor of 2.

2 Selection of the D^{*+} Decays

The channels $\mathrm{D}^{*+} \rightarrow \pi^+_s K^-\pi^+$ and $\mathrm{D}^{*+} \rightarrow \pi^+_s \mathrm{K}^-\pi^+\pi^+\pi^-$ are selected as described in detail in Ref. [1]. Namely, the invariant mass of a system combining 2 tracks ($\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$) or 4 tracks ($\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+\pi^+\pi^-$) with relevant mass assignments is required to be within 30 MeV of the D^0 mass. A low momentum pion ($P_{\pi_s^+} < 4.2\ GeV$) is added to the system and a D^{*+} candidate is kept if it satisfies :

$143.5\ MeV < \Delta M = M_{\pi_s^+ D^0} - M_{D^0} < 147.5\ MeV$ and $X_E = E_{D^{*+}}/E_{beam} > 0.5$.

The scalar nature of the D^0 is exploited to remove a large fraction of the remaining background, requiring $|\cos\theta^*| \leq 0.8$, where θ^* is the angle between the K track ($D^0 \to K^-\pi^+$ case) or the sphericity axis of the four decay products ($D^0 \to K^-\pi^+\pi^+\pi^-$ case) and the D^0 direction, in the D^0 rest frame.

The background behaviour is reproduced by selecting D^0 candidates in a mass range above the D^0 mass from 1.96 GeV to 2.26 GeV, and passing the other selection criteria. The background mass-difference spectrum is normalized to the data upper side spectrum ($\Delta M > 160$ MeV), giving an estimate of the number of background events under the selected ΔM region (fig. 1 and 2). A fraction of D^0 from $D^{*+} \to \pi_s^+ K^-\pi^+\pi^+\pi^-$ are only partially reconstructed, but the charm-quark signed angular distribution is well estimated in such case because the π_s carries the D^* charge. Thus, their contribution is taken into account and tagged as signal when estimating the background. In addition, a D^0 decaying into $K^-\pi^+\pi^+\pi^-$ is counted twice in about 18% of the cases due to extra-candidates with a K^-/π^- inversion in the D^0 or with one of the four D^0 tracks taken from the combinatorial background. Therefore, for each $Z \to q\bar{q}$ event, only the candidate with the mass closest to the D^0 mass is kept. The selection leads to samples containing 1022 ± 33 $D^{*+} \to \pi_s^+ K^-\pi^+$ and 1860 ± 72 $D^{*+} \to \pi_s^+ K^-\pi^+\pi^+\pi^-$.

The D^0's from $D^{*+} \to \pi_s^+ K^-\pi^+\pi^0$ are not fully reconstructed. Leaving out the π^0, the D^0 is selected by requiring a $K\pi$ invariant mass in the range from 1.5 GeV to 1.7 GeV, populated mainly by the $D^0 \to K^-\rho^+$ contribution to the $D^0 \to K^-\pi^+\pi^0$ channel. The selection is done along the same lines as for previous channels, but the X_E cut is lowered to 0.42 and the range for ΔM is enlarged from 141 MeV to 152 MeV, to take into account the 4-momentum carried by the π^0. The mass-difference distribution is shown in fig. 3. This selection leads to a sample of 2439 ± 73 $D^{*+} \to \pi_s^+ K^-\pi^+\pi^0$.

3 Forward-Backward Asymmetry Measurement

The thrust axis oriented to the reconstructed D^* direction is used to define the production angle θ_{thrust} of the $q\bar{q}$ pair with respect to the e^- beam axis. The charge sign of the D^* labeling the c quark, the cosine of the c quark production angle is well estimated by $cos\theta = Q_{\pi_s} \times cos\theta_{thrust}$. The distribution of the 3 samples are considered simultaneously. The charm-quark asymmetry is extracted from the observed angular distributions by means of an unbinned maximum likelihood fit. The likelihood function is defined as :

$$l = \sum_{modes} {}_{i=1}^{i=3} \sum_{j=1}^{n_i} log(\mathcal{L}_{ij})$$

$$\text{where } \mathcal{L}_{ij} = f_{ij}^{charm} + f_{ij}^{beauty} + f_{ij}^{back}$$

with the probability density for observing an event of kind q being:

$$f_{ij}^q = F_i^q \times (1 + cos\theta_j^2 + \frac{8}{3} * A_{FB}{}_i^q * cos\theta_j)$$

The function is calculated for each D^{*+} candidate j and l is maximized to get the best estimate of the single unknown parameter A_{FB}^c.

The fraction of D^{*+}'s in each sample has been deduced from the mass difference spectrum (see §2), and the relative abundance of charm and beauty in the D^* signal is taken from the ALEPH Monte Carlo together with previously fitted values of ε_c and $\frac{P_{b \to D^{*\pm}}}{P_{c \to D^{*\pm}}}$[1]. This abundance, depending mostly on the X_E cut, is found to be the same in each of the 3 samples and equal to $(79 \pm 3)\%$. The proportion F_i^q of each kind of event in the samples are deduced from these fraction numbers.

Background asymmetries $A_{FB}{}_i^{back}$ are computed from D^0 side band samples, and an average value $A_{FB}^{back} = (1.45 \pm 0.91)\%$ is used in the fit. The ALEPH measurement : $A_{FB}^b = (8.46 \pm 0.72)\%$ [3] was used to fix the b quark asymmetry in the analysis. This asymmetry is diluted, on one hand by the $B^0 - \bar{B}^0$ mixing, and by b decays producing a D^{*-} through the W on the other hand. The effective b asymmetry can be expressed as the true b asymmetry corrected by two dilution factors depending on parameters χ_{mix} and $\chi_{D^{*-}}$:

$$A_{FB}^{b,eff} = A_{FB}^b \times (1 - 2\chi_{mix}) \times (1 - 2\chi_{D^{*-}}).$$

A value $\chi_{mix} = 0.152 \pm 0.036$ is deduced in the same way as in Ref. [1], with updated values of χ_d from CLEO and ARGUS[4], and ALEPH b mixing value [3].

The decay $b \to cW, W \to \bar{c}s$ has a rate of about 14%, and produces three types of final states :

$$\begin{array}{ll} (i) & b \to (c\bar{c})X\,; \\ (ii) & b \to D_s^{(*)}X\,; \\ (iii) & b \to D^{(*)}X\,; \end{array}$$

where the X states do not contain the $\bar{c}$ from the decay $W \to \bar{c}s$. Decay of type (iii) only produces D^* states of wrong charge sign. Assuming a proportion of 50% in charged

Background normalization	0.0020
Background asymmetry	0.0065
b,c relative contribution	0.0010
b asymmetry	0.0010
χ_{mix}	0.0020
$\chi_{D^{*-}}$	0.0010
$\sum_{syst}$	0.0073

Table 1: Sources of systematic errors on the measured asymmetry.

states and 75% of in vector states, charged D*'s are produced in a fraction of 37.5% in the decay (*iii*). Using recent CLEO and ARGUS measurements for decays (*i*) and (*ii*) [5], an estimate of $\chi_{D^{*-}} = 0.035$ is obtained and assumed with a relative uncertainty of 100%.

The simultaneous fit yields:

$$A^c_{FB} = (7.12 \pm 2.11(\text{stat.}) \pm 0.73(\text{syst.}))\%$$

The contributions to systematics are listed in table 1.

Figure 4 shows the combined angular distribution after background subtraction and acceptance correction, with the result of the fit.

The MIZA program [2] is used to calculate all the corrections needed to extract the pole asymmetry and the effective electroweak mixing angle $\sin^2\theta_W^{\text{eff}}$ from this measurement. Table 2 summarizes the various corrections derived using MIZA, giving:

$$A^{0,c}_{FB} = (8.1 \pm 2.3)\%$$

and

$$sin^2\theta_W^{eff} = 0.2300 \pm 0.0052.$$

	correction
$\sqrt{(s)} \neq M_Z$	- 0.0028
QED initial state	+ 0.0090
QED final state	+ 0.0001
QCD final state	+ 0.0020
γ exchange and interference	- 0.0007

Table 2: Corrections to the measured c-quark asymmetry.

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[3] ALEPH Collab., '$B^0 - \bar{B}^0$ mixing and $b\bar{b}$ asymmetry from high $p_\perp$ leptons. Update with 1990-1993 data', Contributed paper to the 1994 La Thuile and Moriond Winter Conferences.

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[5] H. Albrecht *et al.* (ARGUS Collab.), Z. Phys. C 54 (1992) 1.
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Figure Captions

Fig. 1. Mass-difference distribution, for $X_E(\mathrm{K}\pi\pi_s) > 0.5$. The K$\pi$ mass is required to be between 1.8345 and 1.8945 GeV/c^2. The background, estimated from the side-band, is shown. The arrows indicate the selection cuts.

Fig. 2. Mass-difference distribution, for $X_E(\mathrm{K}\pi\pi\pi\pi_s) > 0.5$. The K$\pi\pi\pi$ mass is required to be between 1.8345 and 1.8945 GeV/c^2 and all D^0 candidates are kept. The background, estimated from the side-band, is shown, in addition to the contribution from partially reconstructed $\mathrm{D}^{*+} \rightarrow \pi_s^+\mathrm{K}^-\pi^+\pi^+\pi^-$ estimated by Monte-Carlo. The arrows indicate the selection cuts.

Fig. 3. Mass-difference distribution, for $X_E(\mathrm{K}\pi(\pi^0)\pi_s) > 0.5$. The K$\pi$ mass is required to be between 1.5 and 1.7 GeV/c^2. The background, estimated from the side-band, is shown. The signal shape predicted by Monte-Carlo is added demonstrating that the background size is correctly estimated by the upper side-band normalization. The arrows indicate the selection cuts.

Fig. 4. Distribution of the signed cosine angle of the thrust axis. The distribution is corrected for acceptance, background and beauty contribution subtracted. A function (solid line) corresponding to the measured charm asymmetry is superimposed.

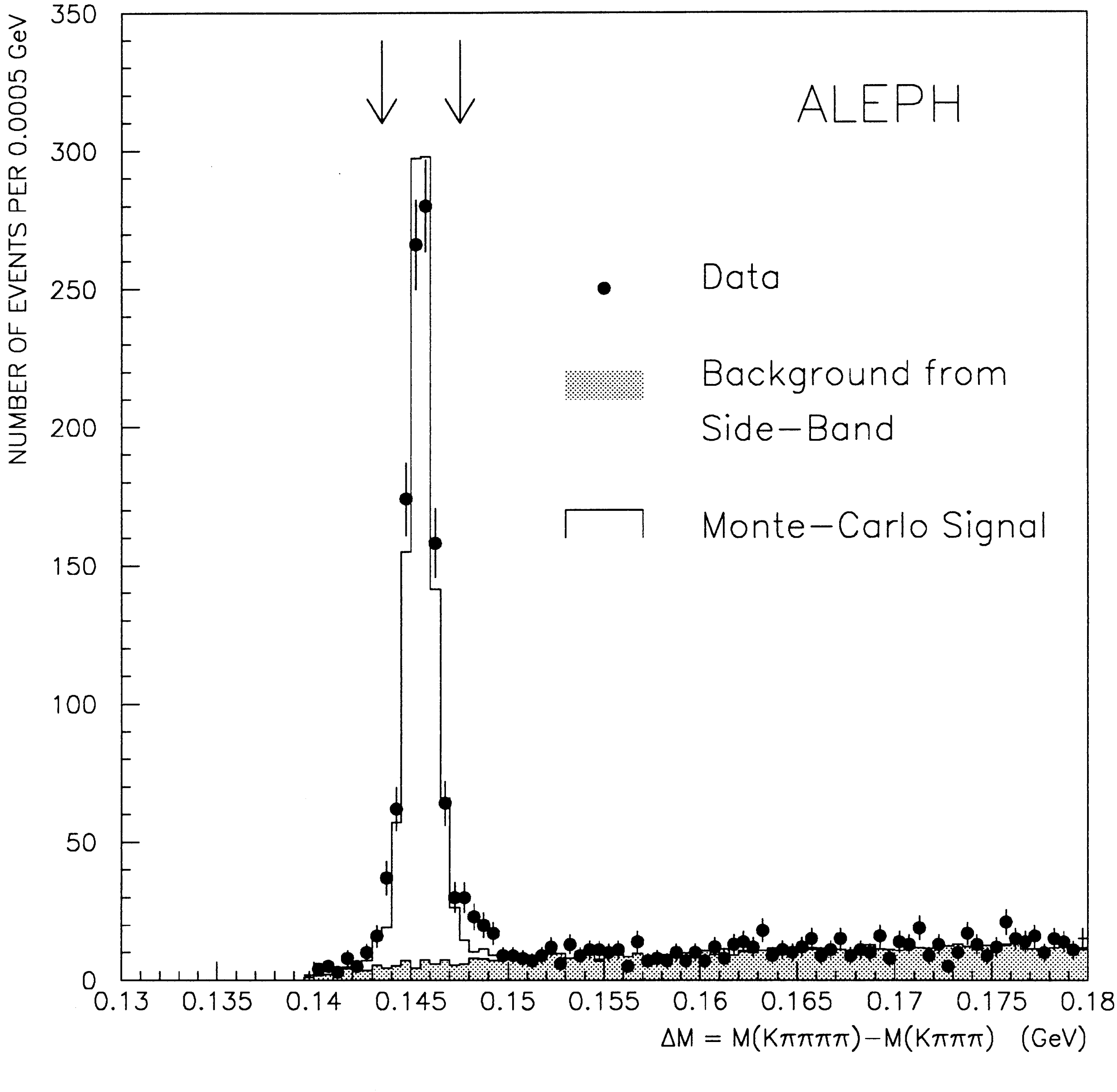
ALEPH
Data
Background from Side-Band
Monte-Carlo Signal
NUMBER OF EVENTS PER 0.0005 GeV
350
300
250
200
150
100
50
0
0.13
0.135
0.14
0.145
0.15
0.155
0.16
0.165
0.17
0.175
0.18
ΔM = M(Kππππ)−M(Kπππ) (GeV)

Fig. 1

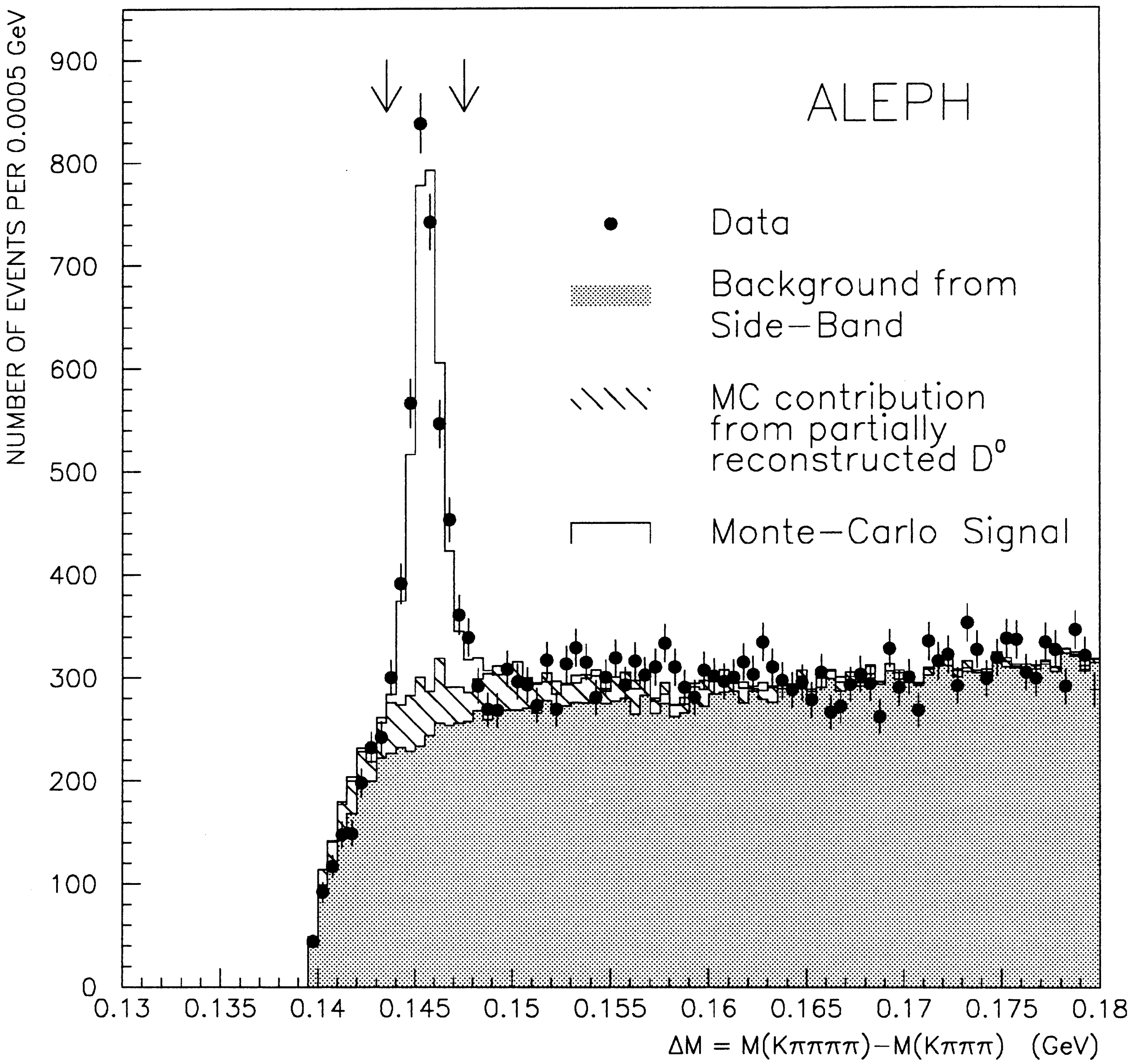
ALEPH
Data
Background from Side–Band
MC contribution from partially reconstructed D^0
Monte–Carlo Signal
NUMBER OF EVENTS PER 0.0005 GeV
900
800
700
600
500
400
300
200
100
0
0.13
0.135
0.14
0.145
0.15
0.155
0.16
0.165
0.17
0.175
0.18
ΔM = M(Kππππ)–M(Kπππ) (GeV)

Fig. 2

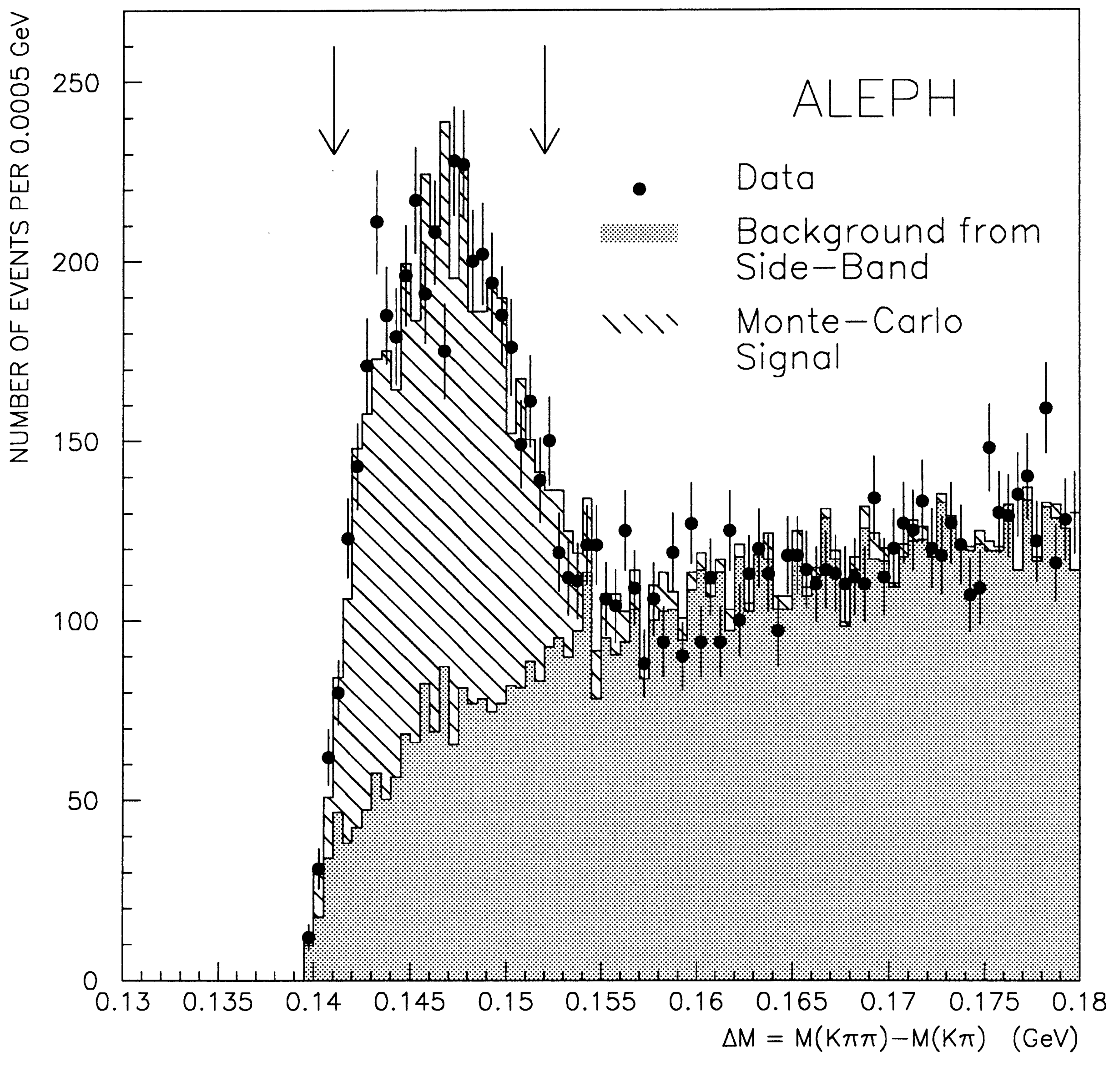
NUMBER OF EVENTS PER 0.0005 GeV
ALEPH
Data
Background from
Side–Band
Monte–Carlo
Signal
0
50
100
150
200
250
0.13
0.135
0.14
0.145
0.15
0.155
0.16
0.165
0.17
0.175
0.18
ΔM = M(Kππ)−M(Kπ) (GeV)

Fig. 3

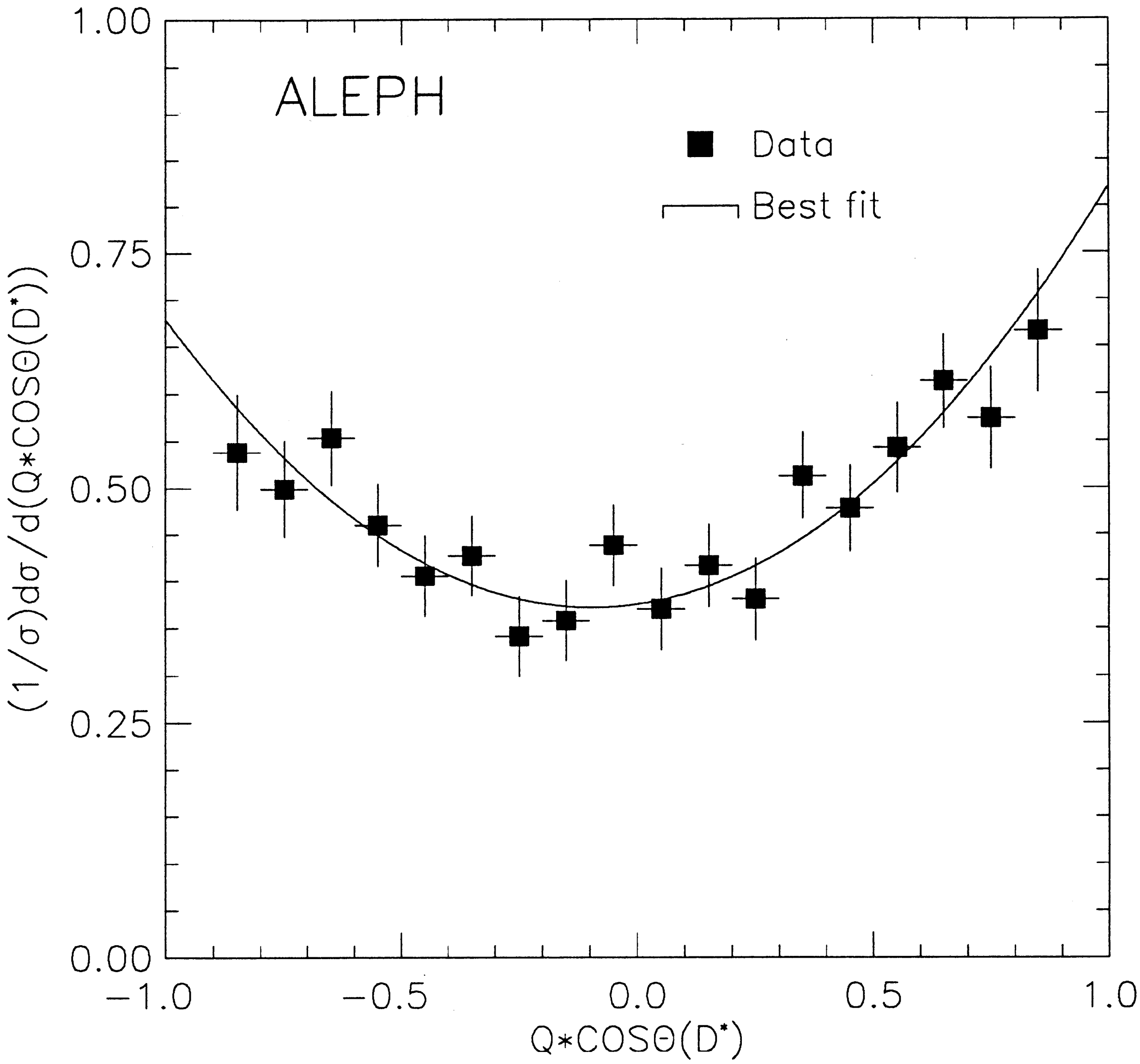
ALEPH
Data
Best fit
1.00
0.75
0.50
0.25
0.00
−1.0
−0.5
0.0
0.5
1.0
(1/σ)dσ/d(Q*COSΘ(D*))
Q*COSΘ(D*)

Fig. 4