A Measurement of the Charm Quark Asymmetry at the Z Pole

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Abstract

From a sample of about 187,000 selected hadronic events taken in 1991 with the DELPHI detector at the Z peak, about 300 $D^{*\pm}$ at large energy fraction X_E are reconstructed. The measured differential $D^{*\pm}$ asymmetry corresponds to a c quark forward-backward asymmetry $A_{FB}^{c\bar{c}} = 0.107 \pm 0.075(stat) \pm 0.013(sys)$, and to an effective weak mixing angle $\sin^2\theta_{eff} = 0.221 \pm 0.017(stat) \pm 0.003(sys)$.

1 Introduction

The measurement of the vector and axial-vector couplings of all fermions to the Z, as derived from the corresponding partial widths and the forward-backward asymmetries, permits a better understanding of the theory of electroweak interactions. On top of the Z resonance and after separation of higher-order QED effects, a non-zero forward-backward asymmetry results from vector/axial-vector interference of the coupling of both the initial-state electrons and the final-state quarks to the Z. The integrated asymmetry on peak in Born approximation is

$$A_{FB}^{q\bar{q}} \simeq \frac{3}{4}\frac{2v_e a_e}{v_e^2 + a_e^2}\frac{2v_q a_q}{v_q^2 + a_q^2}\,.$$

In the Standard Model, the electroweak vector and axial-vector couplings depend on the effective mixing angle $\sin^2\theta_{eff}$ including a flavour dependent weak vertex correction [1] ($\delta_b = 1$ for b quarks, and 0 otherwise)

$$\frac{v_q}{a_q} = 1 - \frac{2e_q}{I_q^{3L}} \cdot \sin^2\theta_{eff} \cdot (1 + \delta_b \frac{2}{3}\Delta\rho_t) \quad (1)$$

with

$$\Delta\rho_t = 3\frac{G_\mu m_{top}^2}{8\pi^2\sqrt{2}}\,.$$

Precise measurements of the partial width of the b and c quark [2] [3] and of the forward-backward asymmetry for the b quark [4] have already been published. In this note a measurement of the forward-backward asymmetry of c quarks from reconstructed D^{*+} [1] is presented. The measured forward-backward asymmetry receives contributions from direct D^{*+} production from c quarks and from D^{*+}'s originating in B decays. For the latter contribution $B-\bar{B}$ mixing must be considered. To enrich the c sample and reduce the influence of B decays and background the measurement is restricted to D^{*+} at large X_E.

D^{*+}'s are identified through the decay $D^{*+} \to D^\circ\pi^+$ using the $D^\circ \to K^-\pi^+$ and the $D^\circ \to K^-\rho^+ \to K^-\pi^+\pi^\circ$ channel for the reconstruction of

[1]Throughout the paper charge-conjugate states are implicitly included

the D°. For the decay mode including the π° the invariant mass of the $K^-\pi^+$ pair was demanded to be around the so called S° peak (1.62 GeV/c^2), which is due to the polarisation of the ρ^+ produced directly from the D° and decaying into the π^+ and the π°.

2 Detector description and event selection

For this analysis only charged particles measured with the tracking system of DELPHI are used. The relevant detectors are the Inner Detector (ID), the Time Projection Chamber (TPC), the Outer Detector (OD) and the Forward Chambers A and B (FCA,FCB).

Particles satisfying the following selection criteria enter the analysis:

- momentum p larger than 0.5 GeV/c
- relative error on p less than 100%
- track length more than 30 cm
- $20^\circ \leq \theta_{track} \leq 160^\circ$

In an iterative procedure the primary vertex is fitted separately for each detector hemisphere using the beam spot constraint. The average beam spot and its errors are determined using the Microvertex Detector (VD) for each LEP fill. The separation into the two hemispheres compensates for misalignments and calibration problems in the beam direction. In each cycle of the vertex fit procedure the track with the largest contributions to the overall χ^2 is removed until the $\chi^2/track$ was acceptable. Afterwards tracks with very large impact parameters to the fitted vertex:

- $\Delta xy \geq 6.0$ cm
- $\Delta z \geq 10.0$ cm

(where Δxy is the distance in the plane perpendicular to the beam) are discarded. All remaining tracks are improved using the above primary vertex constraint.

Events are accepted if:

- the charged energy is larger than 12% of the center of mass energy
- the charged multiplicity ≥ 5

A sample of about 238,000 hadronic events is selected from the 1991 data set, corresponding to a selection efficiency of 95%. Due to the energy dependence of the forward-backward asymmetry only events at the Z resonance are used for the asymmetry measurement. This cut further reduces the data sample to about 187,000 events. Finally the selection used insures good agreement between data and Monte Carlo.

3 Reconstruction of $D^{*+} \rightarrow D^{\circ}\pi^{+}$

For the reconstruction of D^{*+} decays optimal track parameters and minimal combinatorial background are essential. Here this is obtained by performing a secondary vertex fit. The information of the Microvertex Detector (VD) is not used directly because this would limit the angular acceptance and therefore the sensitivity of the asymmetry measurement. However the Microvertex Detector enters in the determination of the primary vertex in the way described above.

The aim of the secondary vertex fit is to reconstruct direct D^{*+} production from c quarks. However as the track impact parameters due to measurement errors dominate the impact parameters due to B decays the applied method reconstructs D^{*+} 's originating from B decays equally well as can be shown from Monte Carlo studies.

The detailed procedure applied is as follows :
Two oppositely charged tracks assigning the K^- and the π^+ mass are combined and the invariant mass $m_{K\pi}$ is calculated. The resulting pseudoparticle is considered as a D° candidate if its mass is in the range $1.5\text{GeV/c}^2 \leq m_{K\pi} \leq 2.5\text{GeV/c}^2$. A D^{*+} candidate is obtained by adding a slow π^+ ($p < 4.5$ GeV/c) to the $K^-\pi^+$ combination and the secondary vertex fit is performed if the mass difference between the $K^-\pi^+\pi^+$ and the $K^-\pi^+$ combination is less than 200 MeV/c^2.

The secondary vertex is demanded to be at the direction of flight of the D° candidate as determined from the $K^-\pi^+$ momentum vector starting at the primary vertex. Then the D^{*+} vertex is asked to be between the D° vertex and the primary vertex. Bad vertices are rejected using the following cuts:

- distance of the D° vertex to the primary vertex between -1.5 cm and 2.0 cm
- distance of the D^{*+} vertex to the primary vertex between -1.0 cm and 1.5 cm
- maximum impact parameter of a track to the vertex position in the plane transverse to the beam direction (Δ_{xy}) less than 6 mm (10 mm for the slow π^+)
- maximum impact parameter of a track to the vertex position in the beam direction (Δ_z) less than 2.5 cm

A further reduction of background is achieved using cuts (see Table 1) on the $K^-\pi^+$ mass and the helicity angle distribution (i.e., the angle of the K^- in the D° center of mass system with respect to the D° direction), which is expected to be isotropic for D°'s whereas the background is strongly peaked at large $|\cos\theta_h|$ values.

$D^{*+} \to D^\circ\pi^+ \to (K^-\pi^+)\pi^+$			$D^{*+} \to D^\circ\pi^+ \to (K^-\pi^+\pi^\circ)\pi^+$		
X_E	$\|\cos\theta_h\|$	$m_{K\pi}$ [GeV/c^2]	X_E	$\|\cos\theta_h\|$	$m_{K\pi}$ [GeV/c^2]
$0.2-0.3$	< 0.8	$1.79-1.94$	$0.3-0.4$	< 0.6	$1.55-1.75$
$0.3-0.4$	< 0.85	"	$0.4-0.5$	< 0.7	"
$0.5-1.0$	< 0.9	"	$0.5-0.6$	< 0.8	"
			$0.6-1.0$	< 0.9	"

Table 1: *Mass and helicity cuts.*

$X_E = \frac{2E_{K\pi\pi}}{\sqrt{s}}$ is calculated from momentum and mass of the K^- and both π^+'s. In total 342 ± 26 D^{*+} with $X_E > 0.2$ from the $D^\circ \to K^-\pi^+$ decay mode and 249 ± 41 D^{*+} with $X_E > 0.3$ from the $D^\circ \to K^-\pi^+\pi^\circ$ decay mode are reconstructed.

The Δm distribution is given in Figure 1a (Figure 2a) for the $D^{*+} \to (K^-\pi^+)\pi^+$ and $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ decay mode respectively and is compared to the DELSIM Monte Carlo results (see Figure 1b,2b). Demanding $\Delta m < 0.15$ the $m_{K\pi}$ spectra shown in Figure 3a,3b are obtained.

Using DELSIM Monte Carlo the efficiency for reconstructing the decay $D^{*+} \to D^\circ\pi^+$ is calculated to be $35 \pm 2\%$ and $31 \pm 3\%$ for the S° peak (i.e., from the $D^\circ \to K^-\pi^+\pi^\circ$ mode). No significant energy dependence of these efficiencies is found.

4 Measurement of A_{FB}^{meas}

The differential asymmetry distribution for the D^{*+} 's is defined by

$$A(\cos\theta) = \frac{N_{+}^{total}(\cos\theta) - N_{-}^{total}(\cos\theta)}{N_{+}^{total}(\cos\theta) + N_{-}^{total}(\cos\theta)} = \frac{8}{3} A_{FB}^{meas} \frac{\cos\theta}{1+\cos^2\theta} \quad (2)$$

with

$$N_{\pm}^{total}(\cos\theta) = N_{D^{*\pm}}(\cos\theta) + N_{D^{*\mp}}(-\cos\theta) \, .$$

$A(\cos\theta)$ is obtained by fitting the $\Delta m = m_{K\pi\pi} - m_{K\pi}$ spectra individually for each $\cos\theta$ bin. Here the shape of the Δm distribution is described by the ansatz :

$$f(\Delta m) = N_{D^*} e^{-\frac{1}{2}\frac{(\Delta m - \overline{\Delta m})^2}{\sigma^2}} + N_{back}(\Delta m - m_{\pi^+})^{\alpha} \, .$$

The peak position $\overline{\Delta m}$ and its width σ are taken from the overall Δm distribution. The total number of D^{*+} 's, the differential asymmetry $A(\cos\theta)$ as well as the shape parameter α and the normalisation N_{back} of the background are fitted for each $\cos\theta$ bin. The normalisation is further splitted in N_{back}^{+} and N_{back}^{-} to account for background fluctuations.

To enrich the c sample and reduce the influence of B decays and background the asymmetry measurement is restricted to $X_E > 0.3$ ($X_E > 0.4$) for the $D^{*+} \to (K^-\pi^+)\pi^+$ and the $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ channel respectively. A sample of 188 ± 18 D^{*+} and 115 ± 39 remained after these cuts for the individual decay modes (a total of 303 ± 43 D^{*+} 's). Due to the energy dependence of the forward-backward asymmetry only events at the Z resonance are used.

The resulting differential asymmetry for the $D^{*+} \to (K^-\pi^+)\pi^+$ and $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ as a function of $\cos\theta$ is shown in Figure 4 and agrees well within errors with the functional dependence given in Eq.(2). The fit of the differential asymmetry distributions to Eq.(2) yields $A_{FB}^{meas} = 0.094 \pm 0.082$ for the $D^{*+} \to (K^-\pi^+)\pi^+$ decay mode and $A_{FB}^{meas} = 0.112 \pm 0.109$ for the $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ decay mode respectively. The overall result for the measured forward-backward asymmetry is

$$A_{FB}^{meas} = 0.100 \pm 0.066(stat) \pm 0.010(sys) \, , \quad (3)$$

with a $\chi^2 = 0.82 \times 7$ Degrees of Freedom.

The asymmetry measurement is insensitive to the acceptance or acceptance differences in both detector hemispheres. Only a charge dependence of the acceptance which furthermore must be different in both detector hemispheres influences the asymmetry result. Such acceptance problems are unlikely to be present. Subdividing the detector into both hemispheres ($\pm z$) no significant differences between the acceptances are found and no charge dependence of the D^{*+} reconstruction is seen in the data. No differences in the shape of the Δm distributions are found which should be expected in the case of such reconstruction problems.

An effect leading to a simular systematic error would be a bias in the fit procedure which can be different for $N_+^{total}(\cos\theta)$ and $N_-^{total}(\cos\theta)$ because of the different statistic due to the asymmetry present. The given systematic error is calculated conservatively assuming the upper limit for this bias estimated from Monte Carlo studies to be $\pm 3\%$ ($\pm 10\%$) of the total number of D^{*+}'s for the $D^{*+} \to (K^-\pi^+)\pi^+$ and the $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ channel respectively.

5 Measurement of $\sin^2\theta_{eff}$

From the differential asymmetry of the D^{*+}'s a flavour independent effective weak mixing angle $\sin^2\theta_{eff}$ is derived. The measured asymmetry including a mixing correction for the b system is given by:

$$A_{FB}^{meas} = R_c \cdot A_{FB}^{c\bar{c}} + (1 - R_c) \cdot A_{FB}^{b\bar{b},mix} ; \quad (4)$$

$$A_{FB}^{b\bar{b},mix} = (1 - 2\chi) \cdot A_{FB}^{b\bar{b}} \quad , \quad R_c = \frac{N_c}{N_c + N_b} .$$

The mixing parameter $\chi_d = 0.167 \pm 0.037$ based on the measurements of ARGUS[5] and CLEO[6] at the $\Upsilon 4(S)$ is used for the B° contributions and the standard model prediction $\chi_s = 0.5_{-0.1}$ is used for the B_s° contributions. The relative contributions from B decays to the D^{*+} sample are taken from the JETSET 7.3 prediction (see Table 2).

$\bar{B}^0 \to D^{*+} + X$	88.6%	$(1-2\chi_d) \cdot A_{FB}^{b\bar{b}}$
$B^- \to D^{*+} + X$	2.7%	$A_{FB}^{b\bar{b}}$
$\bar{B}_s^0 \to D^{*+} + X$	0.8%	$(1-2\chi_s) \cdot A_{FB}^{b\bar{b}}$
$\bar{b} \to W^+ \to c \to D^{*+}$	5.4%	$-A_{FB}^{b\bar{b},mix}$
$others^1$	2.5%	~ 0

Table 2: *Relative contributions to b sample.*

The c quark frequency $R_c = \frac{N_c}{N_c+N_b}$ in the D^{*+} samples for both decay modes is obtained using JETSET 7.3 PS with Peterson fragmentation [7] after fixing the fragmentation coefficients to the LEP average $<X_E>_c = 0.507 \pm 0.013$ [8] [9] [10] and $<X_E>_b = 0.705 \pm 0.011$ [11]. The comparison of the (normalised) JETSET prediction to the energy spectra obtained directly from the $D^{*+} \to D^\circ \pi^+$ reconstruction is shown in Figure 5a,5b for both decay modes. After cuts the c quark frequency is found to be:

$$\begin{aligned} R_c^{D^* \to (K\pi)\pi} &= 54.4\% \\ R_c^{D^* \to (K\pi\pi^\circ)\pi} &= 67.5\% \quad . \end{aligned}$$

Using the program ZFITTER [12] to account for QED and weak corrections a combined fit of the differential asymmetry distributions from both decay modes to Eq.(1) yields :

$$\sin^2\theta_{eff} = 0.221 \pm 0.017(stat) \pm 0.003(sys) \tag{5}$$

with a $\chi^2 = 0.81 \times 7$ Degrees of Freedom.

The main contributions to the quoted systematic error (see Table 3) are due to the systematic uncertainties on A_{FB}^{meas}, on the mixing parameters and on the rate of the process $\bar{b} \to W^+ \to c \to D^{*+}$. The observed asymmetry of this process has the opposite sign of the b asymmetry. The other sources of systematic errors are found to be of minor importance. The variations in the branching ratios for B decays and in the production probability for D^{*+}'s in c quark events are chosen very conservatively. They also account for uncertainties in the fragmentation and possible differences in the D^{*+} reconstruction probabilities for D^{*+}'s in b and c quark events due to the fit method.

[1] fragmentation, B_c , $b - baryon \to D^{*+} + baryon$ ...

Source of errors	Variation	$\Delta \sin^2\theta_{eff}$
ΔA_{FB}^{meas}		± 0.0024
$\sqrt{s} = 91.207\mathrm{GeV/c^2}$	$\pm 0.02\mathrm{GeV/c^2}$	± 0.0002
$\chi_d = 0.167$	± 0.037	± 0.0011
$\chi_s = 0.5$	$0.4 - 0.5$	< 0.0001
$P_{c \to D^{*+}}$	$\pm 20\%$	± 0.0003
$BR(\bar{B}^0 \to D^{*+} + X)$	$\pm 30\%$	± 0.0001
$BR(B^- \to D^{*+} + X)$	$\pm 30\%$	± 0.0001
$BR(\bar{B}_s^0 \to D^{*+} + X)$	$\pm 50\%$	± 0.0001
$P_{\bar{b} \to W^+ \to c \to D^{*+}}$	$\pm 100\%$	± 0.0012
$m_z = 91.175\mathrm{GeV/c^2}$	$\pm 0.03\mathrm{GeV/c^2}$	
$m_{top} = 130\mathrm{GeV/c^2}$	$50 - 200\mathrm{GeV/c^2}$	± 0.0002
$m_{Higgs} = 300\mathrm{GeV/c^2}$	$10 - 1000\mathrm{GeV/c^2}$	
TOTAL		± 0.003

Table 3: *Contributions to the systematic error.*

The forward-backward asymmetry for c quarks at the Z resonanze can be calculated from the $\sin^2\theta_{eff}$. Using ZFITTER this yields to :

$$A_{FB}^{c\bar{c}} = 0.107 \pm 0.075(stat) \pm 0.013(sys)\,.$$

This result together with previous measurements [15][16][17][18][19] using reconstruced D mesons is shown in Figure 6 as a function of centre-of-mass energy. The results are compared to the Standard Model prediction (obtained using ZFITTER) for $m_Z = 91.175GeV/c^2$, $m_{top} = 130GeV/c^2$, $m_{Higgs} = 300GeV/c^2$ and $\sin^2\theta_W = 0.230$. The energy dependence is well described by the Standard Model.

6 Conclusion

From a fit of the differential D^{*+} asymmetry distribution an effective weak mixing angle for c quarks is obtained to be:

$$\sin^2\theta_{eff} = 0.221 \pm 0.017(stat) \pm 0.003(sys)\,.$$

This result agrees well with the $\sin^2\theta_{eff}$ as determined from the DELPHI measurements of the $b\bar{b}$-asymmetry using semileptonic decays into muons [4], the di-lepton asymmetries and the Z lineshape [13] and the charge asymmetry of hadronic events [14]. The value corresponds to a forward-backward asymmetry for c quarks at $\sqrt{s} = m_Z$ of:

$$A_{FB}^{c\bar{c}} = 0.107 \pm 0.075(stat) \pm 0.013(sys)\,.$$

The energy dependence of the charm asymmetry between PEP and LEP energies is well described by the Standard Model.

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Figure Captions

1. $m_{K\pi\pi} - m_{K\pi}$ distribution for the $D^{*+} \to (K^-\pi^+)\pi^+$ channel using a D0 mass cut of $1.79\mathrm{GeV/c^2} < m_{K\pi} < 1.94\mathrm{GeV/c^2}$ and an energy cut of $X_E > 0.3$. (a) fit of the Δm distribution and (b) comparison with the DELSIM prediction.

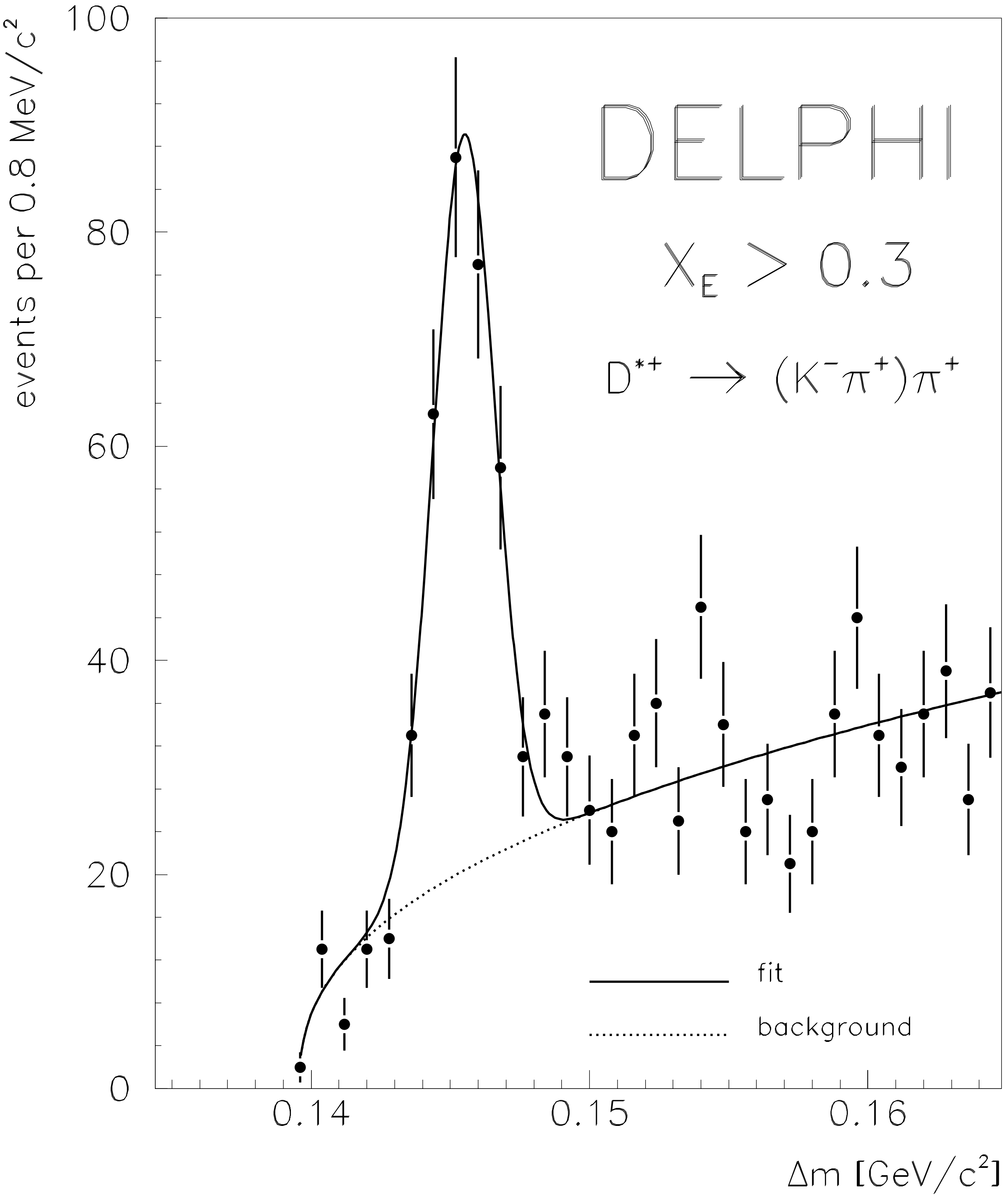
2. $m_{K\pi\pi} - m_{K\pi}$ distribution for the $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ channel using a $\mathrm{S^0}$ mass cut of $1.55\mathrm{GeV/c^2} < m_{K\pi} < 1.75\mathrm{GeV/c^2}$ and an energy cut of $X_E > 0.4$. (a) fit of the Δm distribution and (b) comparison with the DELSIM prediction. Presumably the background in Monte Carlo is slightly overestimated.

3. $m_{K\pi}$ distribution after the cut $0.14\mathrm{GeV/c^2} < m_{K\pi\pi} - m_{K\pi} < 0.15\mathrm{GeV/c^2}$ and an energy cut of $X_E > 0.4$. (a) fit of the $\mathrm{D^0}$ peak and the upper background band. The background function is extrapolated to the $\mathrm{S^0}$ region. (b) Comparison with the DELSIM prediction.

4. The differential asymmetry as a function of $\cos\theta$ obtained from about 300 D^{*+}'s from the $D^{*+} \to (K^-\pi^+)\pi^+$ and $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ decay modes. The plotted function is the result of the fit of the differential asymmetry to Eq.(2).

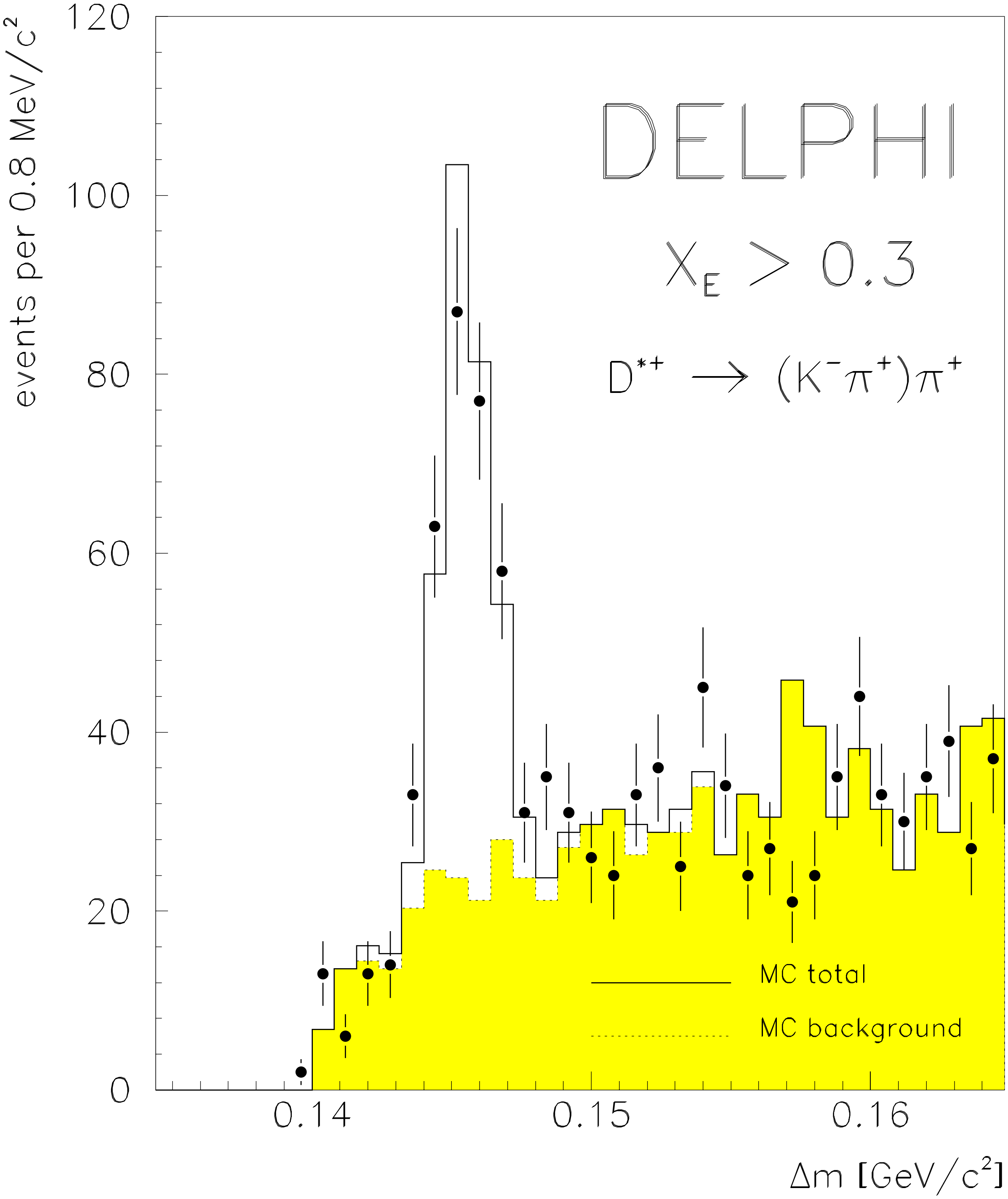
5. The X_E distribution of the $D^{*+} \to (K^-\pi^+)\pi^+$ (a) and the $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ (b) channel compared with the normalized JETSET prediction after fixing the fragmentation parameters. The distribution for the $D^{*+} \to (K^-\pi^+\pi^\circ)\pi^+$ (b) channel is shifted because of the missing energy of the π°.

6. The charm quark forward-backward asymmetry as a function of $\sqrt{s}$. The measurements use reconstructed D mesons and are corrected for B decays. The statistical and systematic errors are added in quadrature. QED and QCD corrections have beeen removed from the measured asymmtries of TASSO and VENUS. The results are compared to the Standard Model expectation for $m_Z = 91.175 GeV/c^2$, $m_{top} = 130 GeV/c^2$, $m_{Higgs} = 300 GeV/c^2$ and $\sin^2\theta_W = 0.230$.



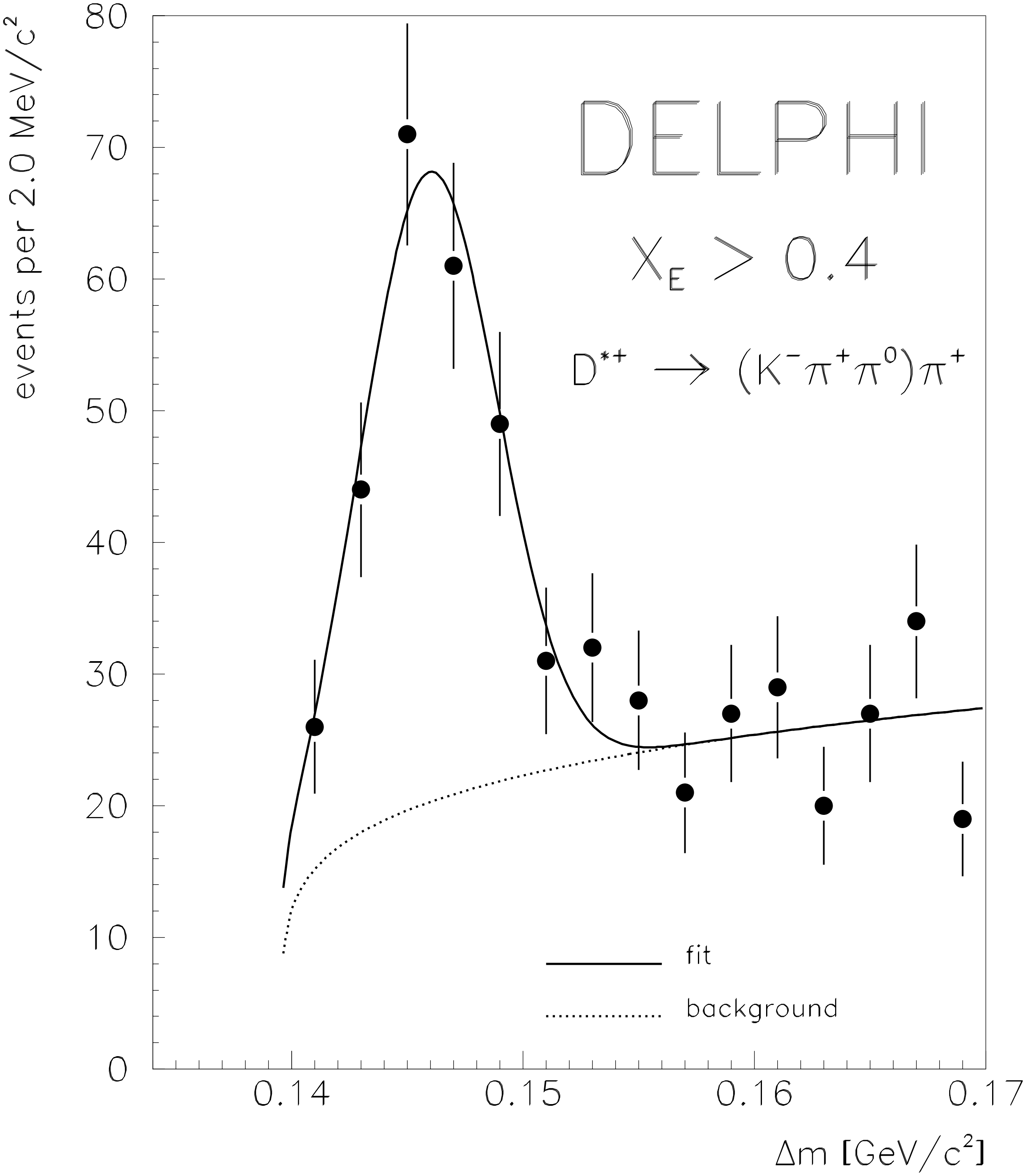
$m_{K\pi\pi} - m_{K\pi}$, data 1991

figure 1a



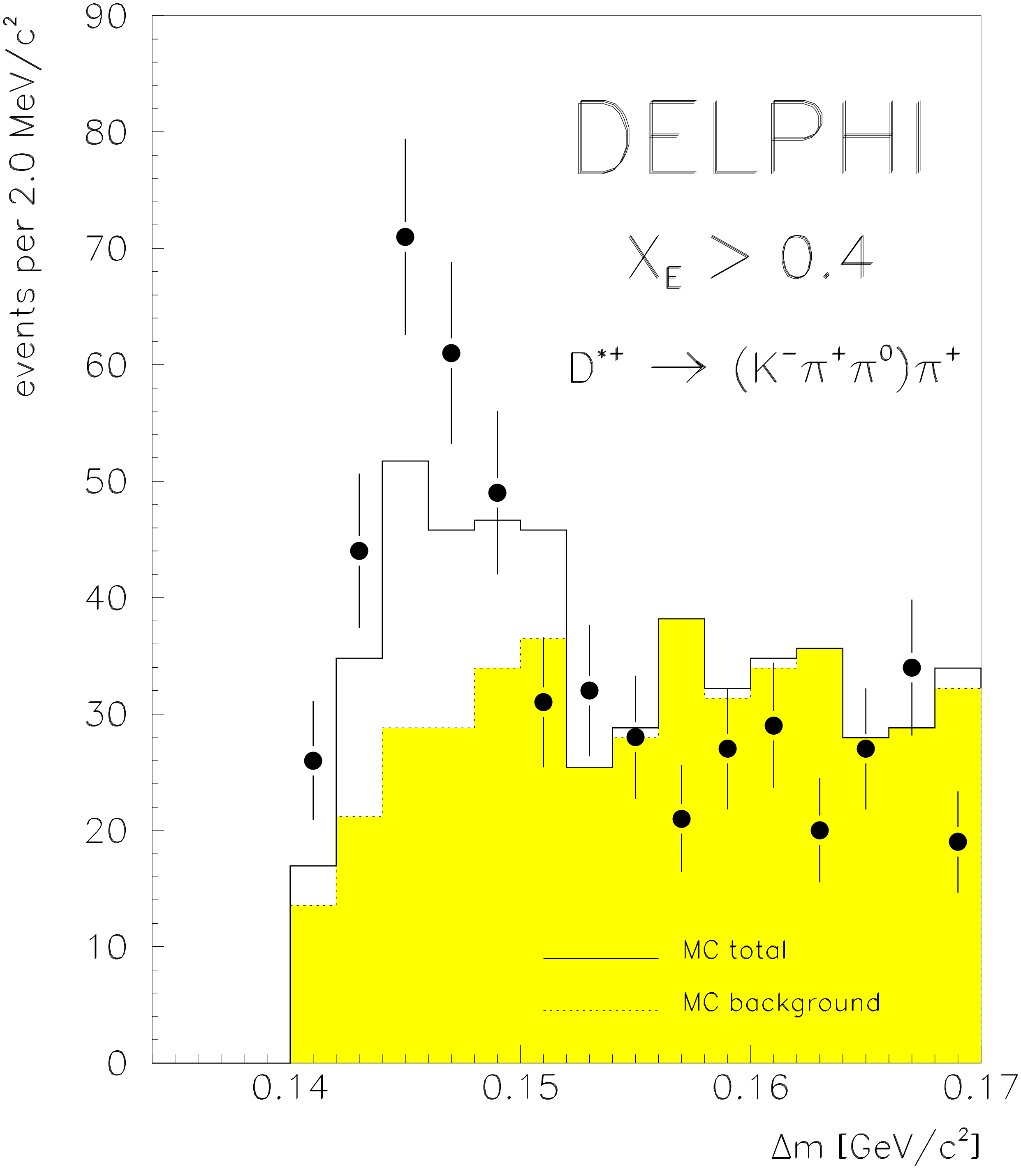
$m_{K\pi\pi} - m_{K\pi}$, data 1991

figure 1b



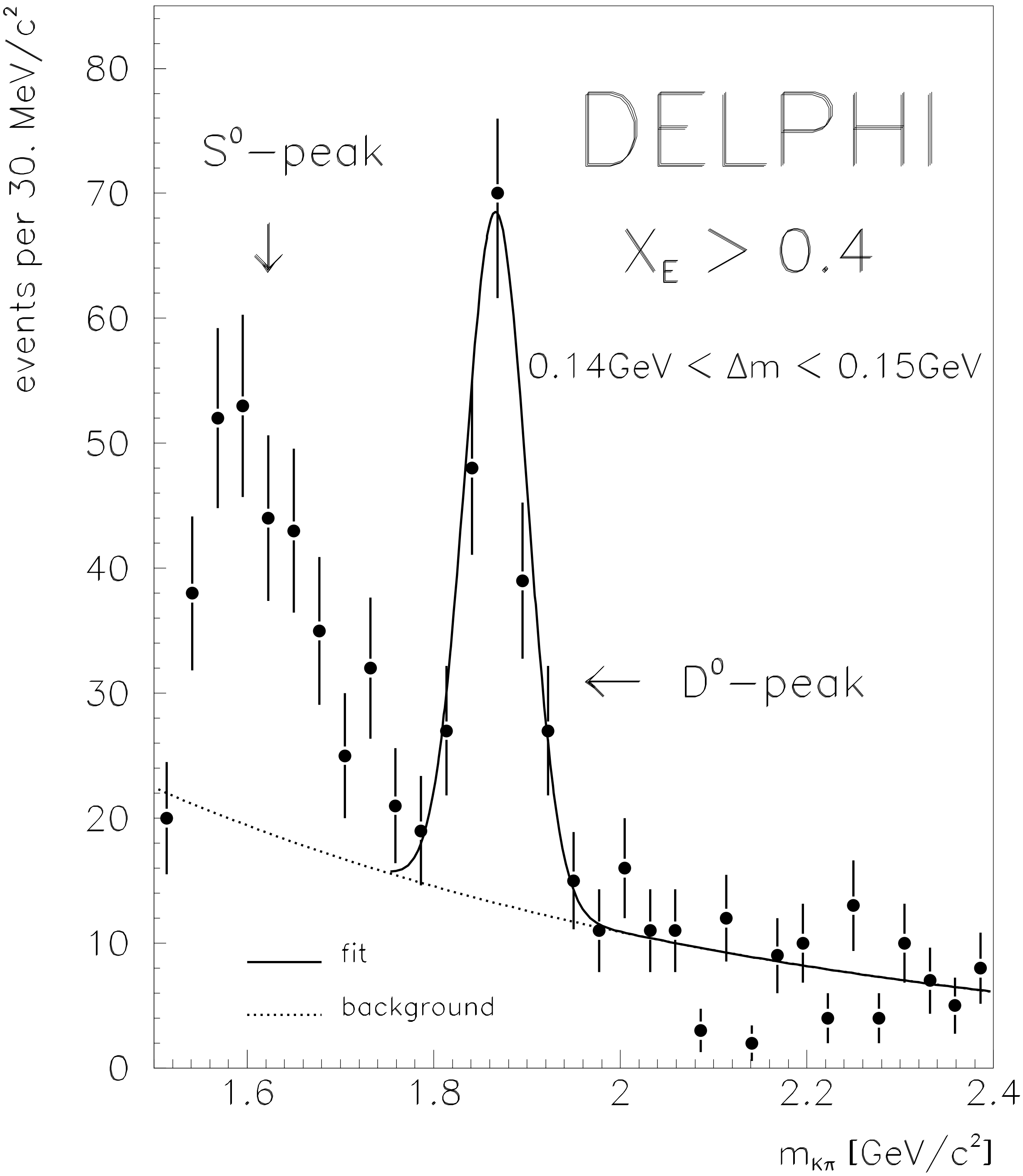
$m_{K\pi\pi} - m_{K\pi}$, data 1991

figure 2a



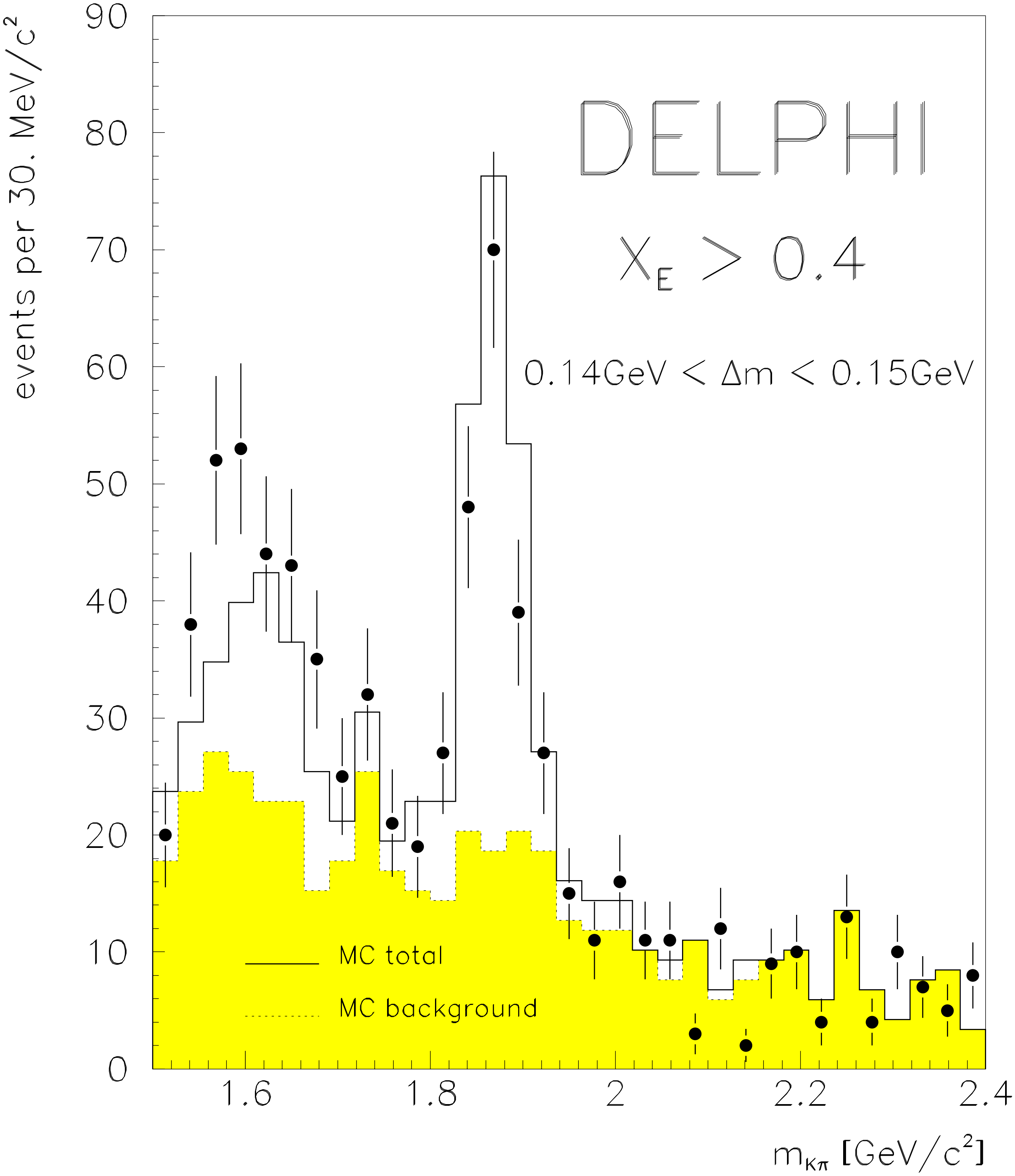
$m_{K\pi\pi} - m_{K\pi}$, data 1991

figure 2b



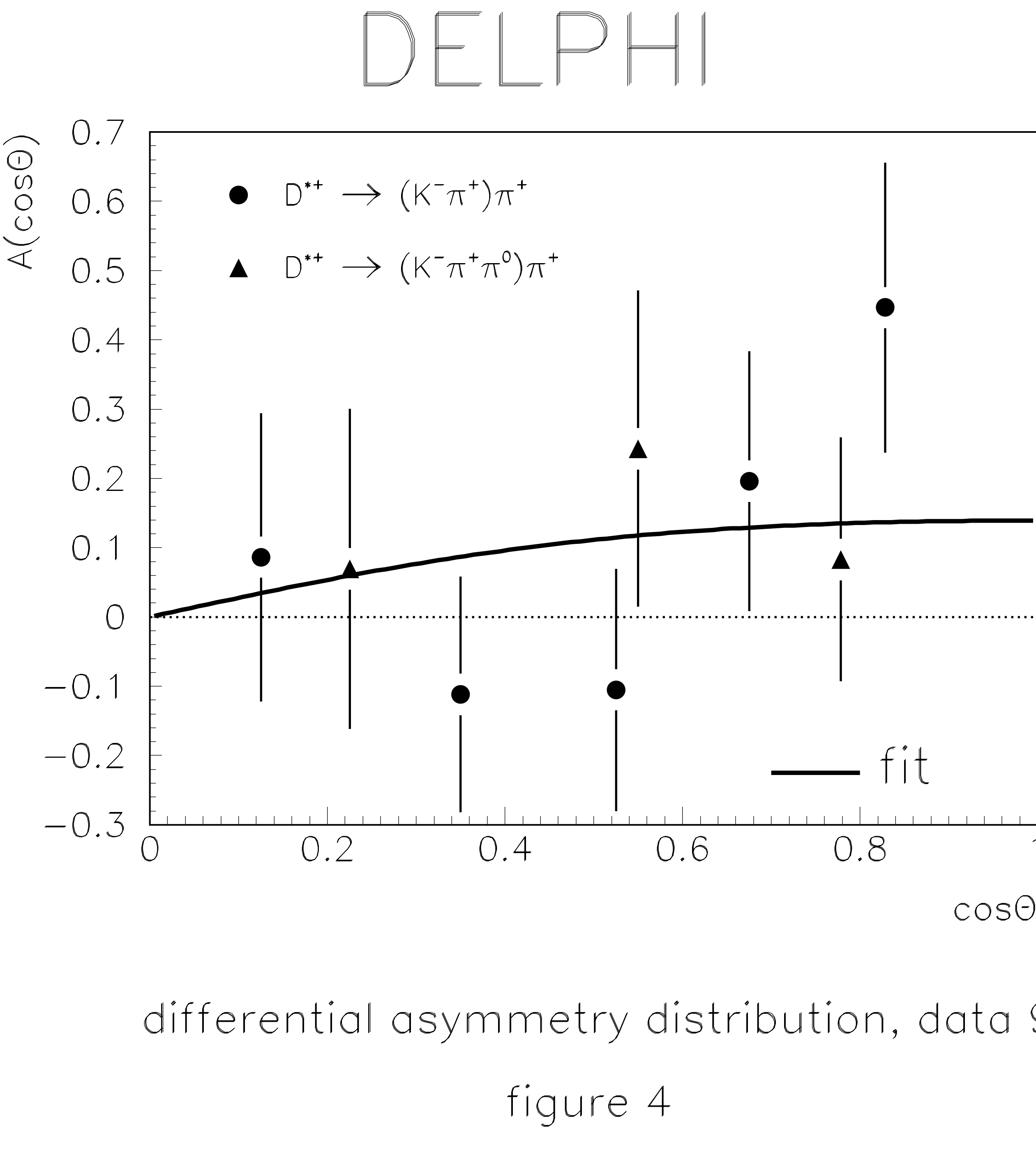
$m_{K\pi}$, data 1991

figure 3a



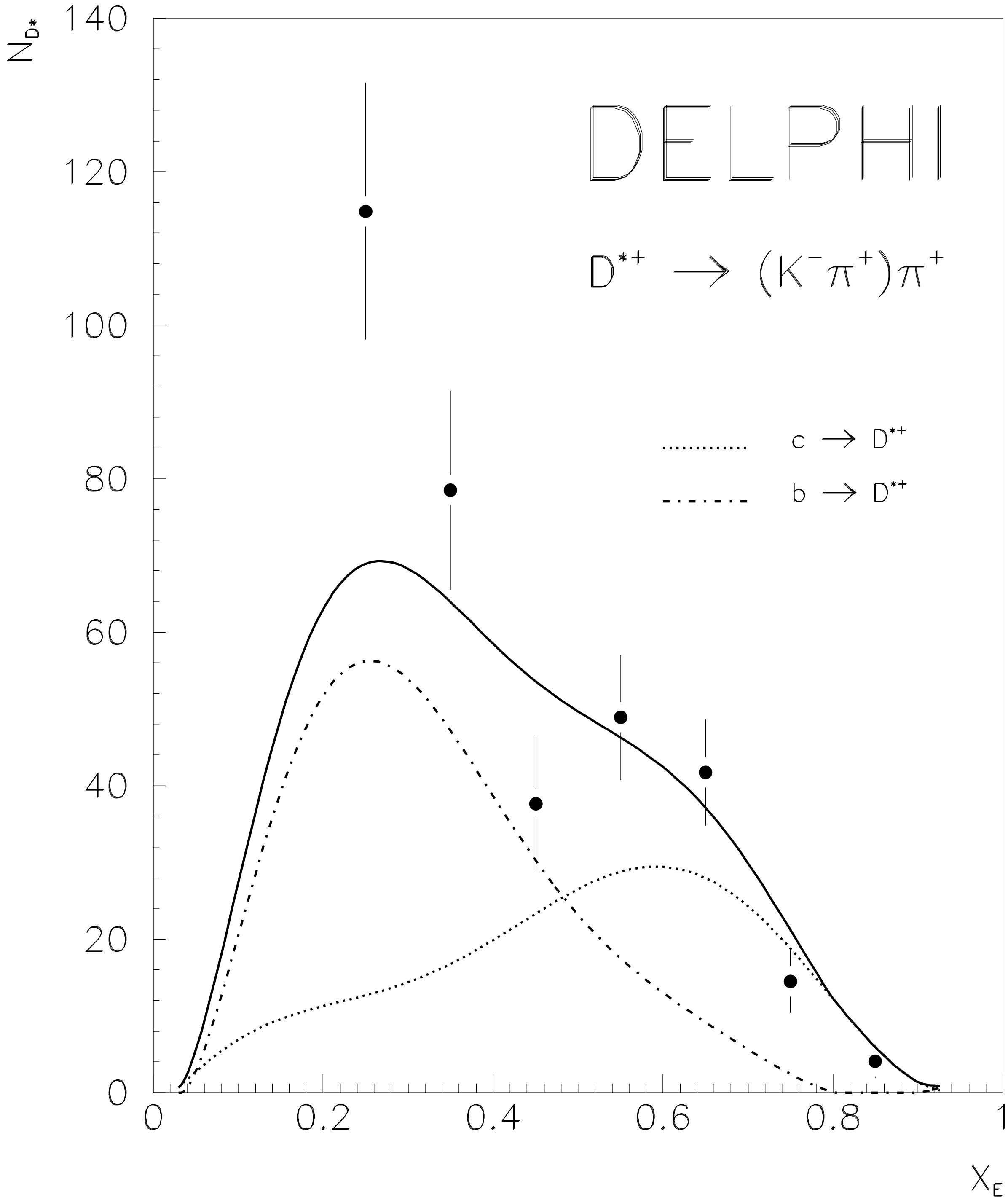
$m_{K\pi}$, data 1991

figure 3b



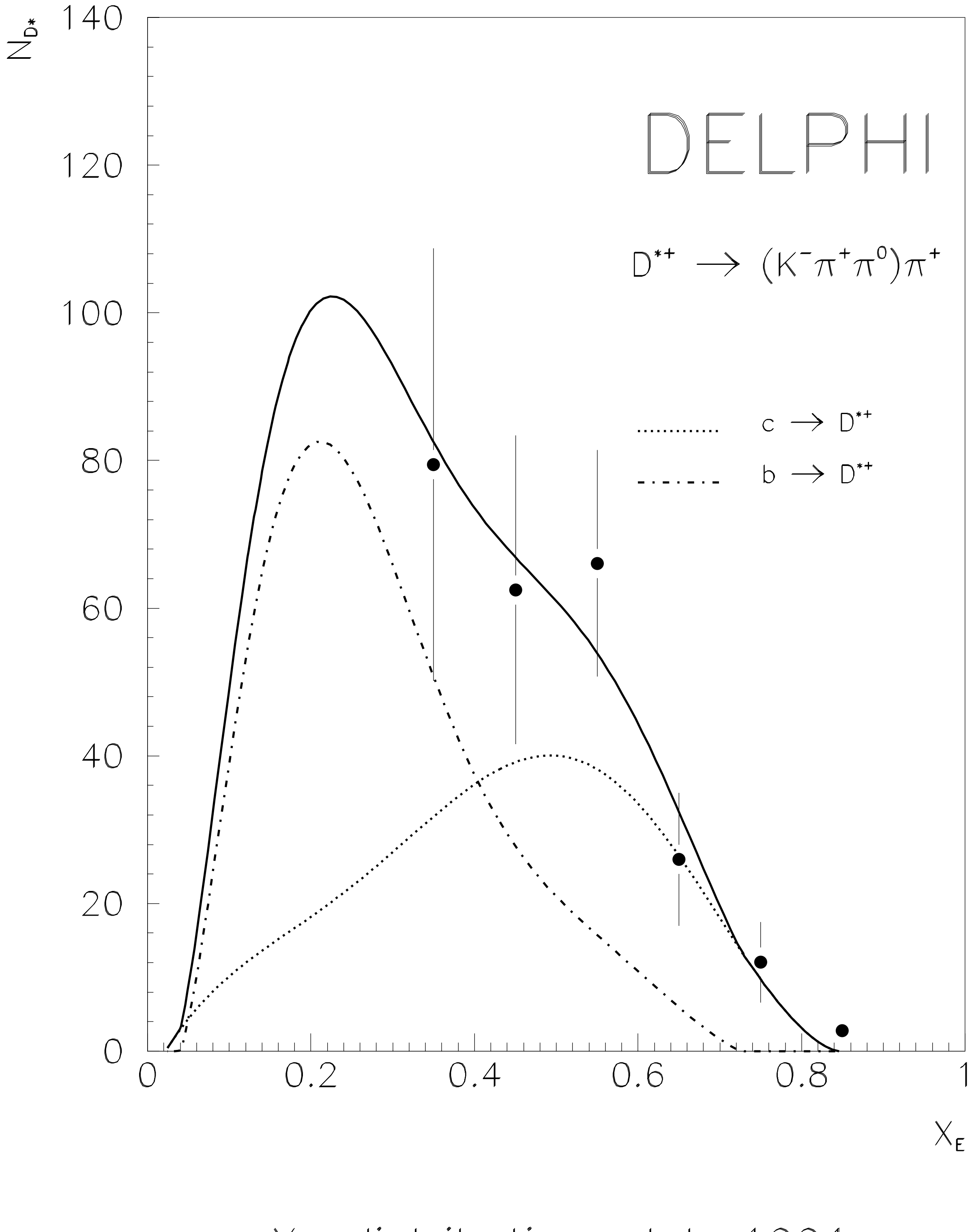
differential asymmetry distribution, data 91

figure 4



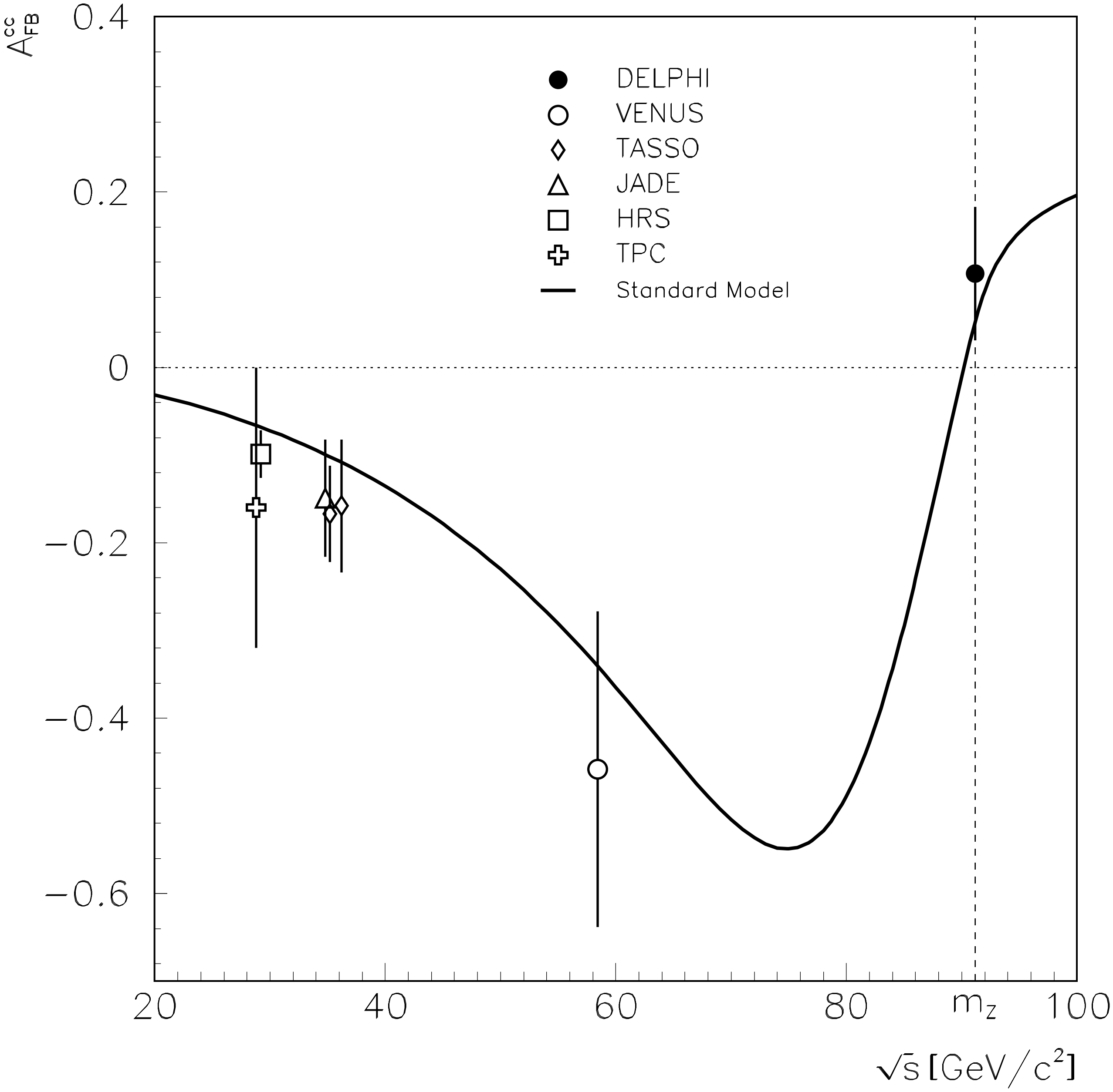
X_E–distribution , data 1991

figure 5a



X_E–distribution , data 1991

figure 5b



charm asymmetry as function of $\sqrt{s}$

figure 6