EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PPE 93-27
18 February 1993

Measurement of relative branching fractions for $D^+ \to K^-K^+K^+$ and $D_S^+ \to \pi^-\pi^+\pi^+$ decays

WA82 Collaboration

M. Adamovich[5], Y. Alexandrov[5], F. Antinori[2], D. Barberis[3], W. Beusch[2], A. Buys[4], V. Casanova[3], M. Dameri[3], M. Davenport[2], J.P. Dufey[2], A. Forino[1], B.R. French[2], R. Gessaroli[1], F. Grard[4], K. Harrison[2], R. Hurst[3], A. Jacholkowski[2], A. Kirk[2], E. Lamanna[2], J.C. Lassalle[2], P. Legros[4], P. Mazzanti[1], F. Muller[2†], P. Netchaeva[5], B. Osculati[3], A. Quareni[1], N. Redaelli[2], C. Roda[2], L. Rossi[3], G. Tomasini[3], M. Weymann[2] and M. Zavertyaev[5]

1 Dipartimento di Fisica and INFN, Bologna, Italy.
2 CERN, European Organization for Nuclear Research, Geneva, Switzerland.
3 Dipartimento di Fisica and INFN, Genova, Italy.
4 Université de Mons-Hainaut and IISN, Mons, Belgium.
5 Lebedev Physical Institute, Moscow, Russia.
† Deceased.

Submitted to Physics Letters B

Abstract

The decay modes $D_S^+ \to \pi^-\pi^+\pi^+$ and $D^+ \to K^-K^+K^+$ have been studied in the hadroproduction experiment WA82. The following ratios of branching fractions have been measured:

$$B(D_S^+ \to \pi^-\pi^+\pi^+)/B(D_S^+ \to \phi\pi^+) = 0.33 \pm 0.10 \pm 0.04$$
$$B(D^+ \to K^-K^+K^+)/B(D^+ \to K^-\pi^+\pi^+) = 0.057 \pm 0.020 \pm 0.007$$
$$B(D^+ \to K^-K^+K^+)/B(D^+ \to \phi\pi^+) = 0.49 \pm 0.23 \pm 0.06$$

Much theoretical work has been carried out in trying to understand the so-called charm-decay puzzle [1] and, in particular, the difference between the lifetime of the D^+ meson and the lifetimes of the D^0 and D_S^+ mesons. Effects of possible relevance include non-leptonic decays occurring via processes not described by spectator diagrams, final-state interactions and the destructive interference that may arise in the Cabibbo-favoured decays of the D^+ but not in the decays of the D^0. It is noted that doubly Cabibbo-suppressed D^+ decays are not subject to destructive interference, therefore their relative branching fractions might be enhanced [2].

In a previous paper [3] we reported on the WA82 measurements of the relative branching fractions of D^0 Cabibbo-suppressed decays. Here we present results based on an analysis of the three-body decays $D_S^+ \to \pi^- \pi^+ \pi^+$ and $D^+ \to K^- K^+ K^+$ (the charge conjugate states will be implicitly included throughout this paper). These decays cannot be described by simple spectator diagrams, but must involve annihilation subprocesses or final-state rescattering. Furthermore, the $D^+ \to K^- K^+ K^+$ mode is doubly Cabibbo-suppressed. The E691 collaboration has observed the decay $D_S^+ \to \pi^- \pi^+ \pi^+$ [4] in addition to the decay $D^+ \to \pi^- \pi^+ \pi^+$ previously reported by Mark III [5]. The decay $D^+ \to K^- K^+ K^+$ has been studied by E691 [6] in the ϕ-resonant mode only.

In the WA82 experiment the CERN Omega Spectrometer, supplemented with a silicon microstrip detector, was used to study charmed hadrons produced by interactions of 340 GeV/c π^- mesons on a 2 mm thick target. On-line enrichment for charmed particles was achieved by triggering on events in which at least one track was found to miss the primary interaction vertex by more than 100 μm . Some 5×10^7 events were recorded and are used in the present analysis. For 60 % of the data, particle identification was provided by a Ring Imaging CHerenkov detector (RICH). The experimental set-up, the trigger requirements and the data processing have been fully described in previous publications [7].

Identification of charmed particles was made possible by the high precision in secondary vertex reconstruction (30 μm transversally, 500 μm longitudinally) provided by the silicon microstrip telescope. The present analysis of three-body decays is similar to our previous analysis of decays of the D^0 [3]. Invariant mass distributions were obtained for events where a secondary vertex was found outside the thin target and where the longitudinal separation between the secondary vertex and the primary interaction vertex was greater than 6 standard deviations. When extrapolated backwards the reconstructed momentum vector of a decay candidate was required to pass within 30 μm of the primary vertex.

Particle identification with the RICH was performed using the following procedure: first chi-squared probabilities, derived from expected and observed numbers of photoelectrons and ring radii, were obtained for the different mass hypotheses; next conditional probabilities were calculated using *a priori* probabilities determined from the data through an iterative method [8]; then the results were expressed in terms of ratio between the conditional and the *a priori* probability for each mass hypothesis (x_P denotes this ratio for particle hypothesis $P = \pi, K, p$ in the following discussion); finally, particles were identified by cutting on x_P. The RICH identification efficiency for kaons has been determined experimentally as a function of momentum by considering the signals for D^0 and D^+ Cabibbo-favoured decays.

Fig. 1 shows our signals for ϕ-resonant $D_S^+ \to K^- K^+ \pi^+$ and $D^+ \to K^- K^+ \pi^+$, without and with RICH identification, the latter obtained by requiring that x_K, the ratio of the kaon probability to the kaon *a priori* probability, be greater than 0.5 for both kaon candidates. Fig. 2 (a) shows the $D^+ \to K^- \pi^+ \pi^+$ signal without RICH identification. The signal over noise ratio can be further improved by cutting on the proper lifetime of the decay candidate, as shown in fig. 2 (b).

Fig. 3 shows the $\pi^-\pi^+\pi^+$ invariant mass distribution for the full data sample, where the large peak appearing to the left of the D^+ and D_S^+ signals is due to the reflection of $D^+ \to K^- \pi^+ \pi^+$ in which the kaon is wrongly assumed to be a pion. The RICH identification is not used for this mode since the background under the signals is mostly made of pions. Instead we have asked that the calculated proper lifetime, τ, of a decay candidate should be greater than some specified value. Results are shown in fig. 3 (a) for $\tau > 0.5$ ps and in fig. 3 (b) for $\tau > 0.8$ ps. The cut $\tau > 0.8$ ps eliminates a substantial part of the D_S^+ signal, while the D^+ signal is little affected, as is to be expected from the D^+ and D_S^+ lifetimes. For the calculation of relative branching fractions we obtain a reduced background, with no significant loss of statistics, by requiring $\tau > 0.8$ ps when considering D^+ and $\tau > 0.5$ ps when considering D_S^+.

Fig. 4 (a) shows the $K^-K^+K^+$ invariant mass distribution for the data sample for which RICH information was available. In order to optimise background reduction, while keeping evidence of a signal, we request $x_K > 0.5$ for both K^+ candidates. In this analysis we do not consider secondary vertices that are compatible within 15 MeV/c^2 with $D^+ \to K^- \pi^+ \pi^+$, with $D^+/D_S^+ \to \phi\, \pi^+$, with $\Lambda_C^+ \to p\, K^- \pi^+$ or within 10 MeV/c^2 with $K_S^0 \to \pi^- \pi^+$ to which a third track was associated. The RICH cut approximately halves, to 13.1 ± 4.5, the number of events in the peak at the D^+ mass. This is consistent with the RICH efficiency for the mode considered (0.40 ± 0.03). By contrast, the background is reduced by more than a factor of 5. To further reduce the background and check the compatibility of the observed peak with a D^+ signal, we have also applied cuts on proper lifetime, obtaining the invariant mass distribution shown in fig. 4 (b) for $\tau > 1.3$ ps. There is then a peak of 5.7 ± 2.8 events at the D^+ mass, in agreement with the expected number of 4.1 ± 1.5 according to fig. 2 (b).

The number of events in the various decay modes was determined by maximum likelihood fits to the invariant mass distributions, as in [3]. Signal peaks are fitted with gaussians. Linear functions are used to describe the structureless backgrounds except in the case of the $K^-K^+K^+$ mode, where a quadratic function is adopted. The tail of the reflection peak in the $\pi^-\pi^+\pi^+$ distribution is modelled as a Breit-Wigner curve, as given by simulated data for $D^+ \to K^- \pi^+ \pi^+$. When considering signals other than $D^+ \to K^- \pi^+ \pi^+$, the D^+ and D_S^+ masses are fixed to the PDG values [9] and peak widths are those determined from simulated events: $\sigma = 8.3$ MeV/c^2 for $D_S^+ \to \pi^- \pi^+ \pi^+$, 7.1 MeV/$c^2$ for $D^+ \to \pi^- \pi^+ \pi^+$ and 5.3 MeV/c^2 for $D^+ \to K^- K^+ K^+$. The simulated events, generated using PYTHIA [10] and passed through a detector simulation program, have been subjected to the same selection criteria and analysis procedures as the experimental data. The numbers of events obtained in the different modes are given in table 1.

Relative detection efficiencies for the decay modes considered have been determined from the simulated data [11]. The effect on the $\pi^-\pi^+\pi^+$ and $K^-K^+K^+$ invariant mass distributions of the proper lifetime cuts used in our analysis is compatible with the expectations both from simulation and from the observed reduction of the $D^+ \to K^- \pi^+ \pi^+$ signal. Our results are summarized in table 2 and are compared with the current PDG data [9]. For each of our measurements the first error quoted is statistical and the second is systematic, taking into account uncertainties in the calculated detection efficiencies and different parameterisations of the background. Our results for previously established modes are in agreement with the PDG values. Of particular interest, we find:

$$B(D_S^+ \to \pi^-\pi^+\pi^+)/B(D_S^+ \to \phi\pi^+) = 0.33 \pm 0.10 \pm 0.04 .$$

For $D^+ \to K^- K^+ K^+$, without cut on proper lifetime, we obtain:

$$B(D^+ \to K^-K^+K^+)/B(D^+ \to K^-\pi^+\pi^+) = 0.057 \pm 0.020 \pm 0.007$$

$$B(D^+ \to K^-K^+K^+)/B(D^+ \to \phi\pi^+) = 0.49 \pm 0.23 \pm 0.06 .$$

With the cut $\tau > 1.3$ ps, we measure $B(D^+ \to K^-K^+K^+)/B(D^+ \to K^-\pi^+\pi^+) = 0.069 \pm 0.034 \pm 0.009$, consistent with the result given above. We find no evidence for $D_S^+ \to K^- K^+ K^+$ or for a significant $D^+ \to \phi K^+$ resonant contribution in $D^+ \to K^- K^+ K^+$. This latter observation is not incompatible with the E691 result [6] of $B(D^+ \to \phi K^+)/B(D^+ \to \phi\pi^+) = (5.8^{+3.2}_{-2.6} \pm 0.7) \times 10^{-2}$, which in our data would give a signal of 1.3 events (with no cut on proper lifetime).

In conclusion, we have measured relative branching fractions for some D^+ and D_S^+ decays. This analysis includes the study of a new doubly Cabibbo-suppressed decay $D^+ \to K^- K^+ K^+$ in the non-resonant mode, the identification of which was possible using RICH information.

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Table 1. Number of events in the three-body D^+ and D_S^+ decay modes for the different selection criteria.

Decay mode	x_K	τ(ps)	Number of events
$D^+ \to K^- \pi^+ \pi^+$	–	–	939 ± 45
	> 0.5	–	425 ± 34
$D^+ \to \phi \pi^+$	–	–	32.7 ± 9.0
	> 0.5	–	19.3 ± 6.0
$D_S^+ \to \phi \pi^+$	–	–	45.8 ± 8.3
	> 0.5	–	19.4 ± 6.0
$D^+ \to \pi^- \pi^+ \pi^+$	–	> 0.5	19.5 ± 7.1
	–	> 0.8	19.7 ± 7.0
$D_S^+ \to \pi^- \pi^+ \pi^+$	–	> 0.5	28.6 ± 8.4
	–	> 0.8	11.7 ± 5.1
$D^+ \to K^- K^+ K^+$	> 0.5	–	13.1 ± 4.5
	> 0.5	> 1.3	5.7 ± 2.8

Table 2. Comparison of WA82 results with PDG values.

	WA82	PDG
$\Gamma(D^+ \to \pi^-\pi^+\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$	$0.032 \pm 0.011 \pm 0.003$	0.035 ± 0.007
$\Gamma(D^+ \to \phi\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$	$0.062 \pm 0.017 \pm 0.006$	0.075 ± 0.007
$\Gamma(D^+ \to \pi^-\pi^+\pi^+)/\Gamma(D^+ \to \phi\pi^+)$	$0.52 \pm 0.23 \pm 0.05$	–
$\Gamma(D_S^+ \to \pi^-\pi^+\pi^+)/\Gamma(D_S^+ \to \phi\pi^+)$	$0.33 \pm 0.10 \pm 0.04$	$0.44 \pm 0.10 \pm 0.04$
$\Gamma(D^+ \to K^-K^+K^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$	$0.057 \pm 0.020 \pm 0.007$	–
$\Gamma(D^+ \to K^-K^+K^+)/\Gamma(D^+ \to \phi\pi^+)$	$0.49 \pm 0.23 \pm 0.06$	–

Figure captions

Figure 1.

(a) $K^-K^+\pi^+$ invariant mass distribution for full data sample, m(K^-K^+) within 10 MeV/c^2 of the ϕ mass, no RICH identification.

(b) $K^-K^+\pi^+$ invariant mass distribution for the 60 % of the data for which RICH information is available, m(K^-K^+) within 10 MeV/c^2 of the ϕ mass, $x_K > 0.5$ for both kaon candidates.

Figure 2.

(a) $K^-\pi^+\pi^+$ invariant mass distribution for the full data sample, no RICH identification.

(b) Relative values of signal-to-background ratio (S/B) and signal (S) as a function of the cut on proper lifetime $\tau > \tau_{min}$. Values are normalised to 1 for no explicit proper lifetime cut (i.e. when there are only the requirements of trigger and filter and the requested vertex separation).

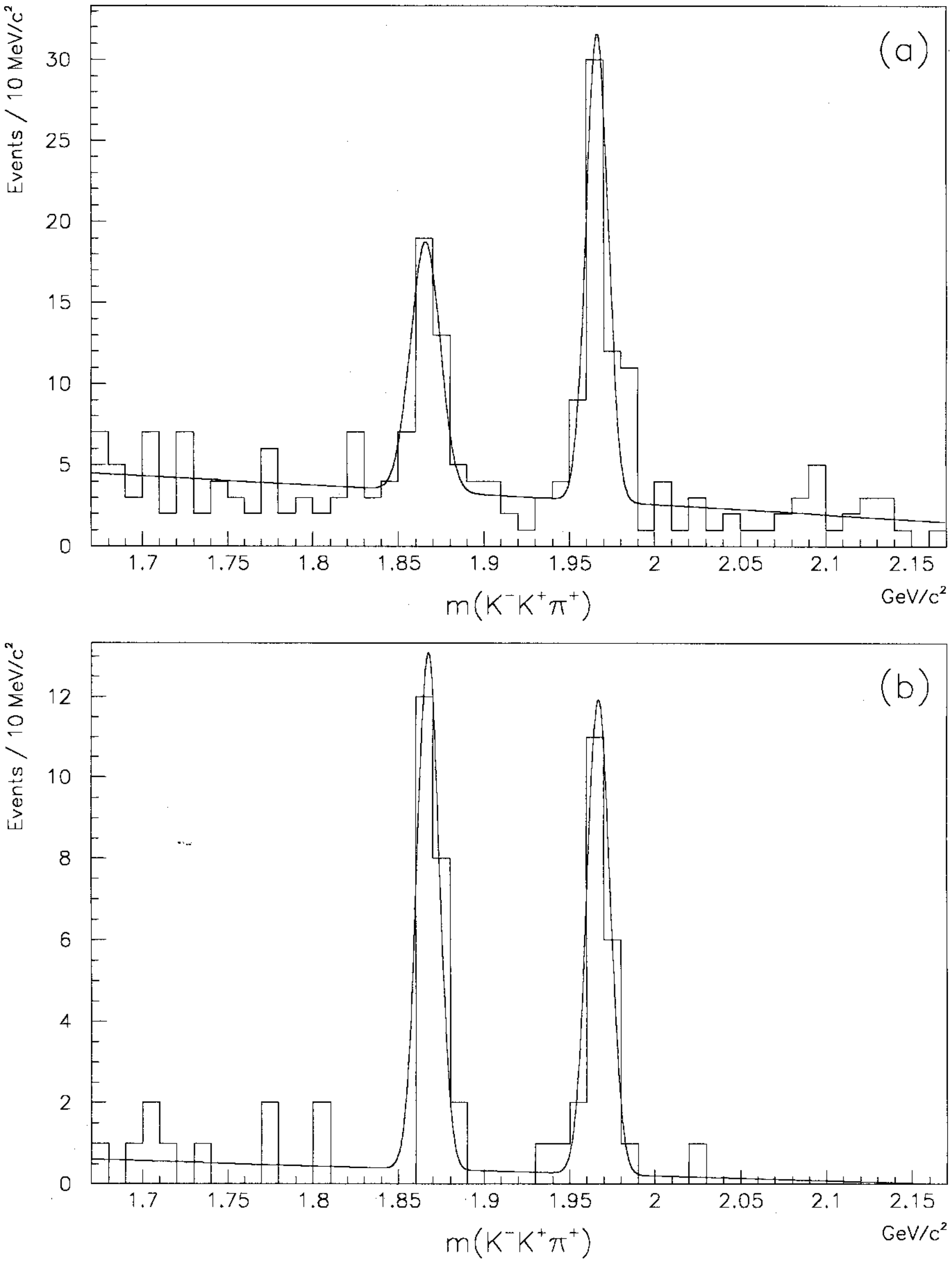
Figure 3.

$\pi^-\pi^+\pi^+$ invariant mass distribution for full data sample, no RICH identification, cuts on proper lifetime as indicated.

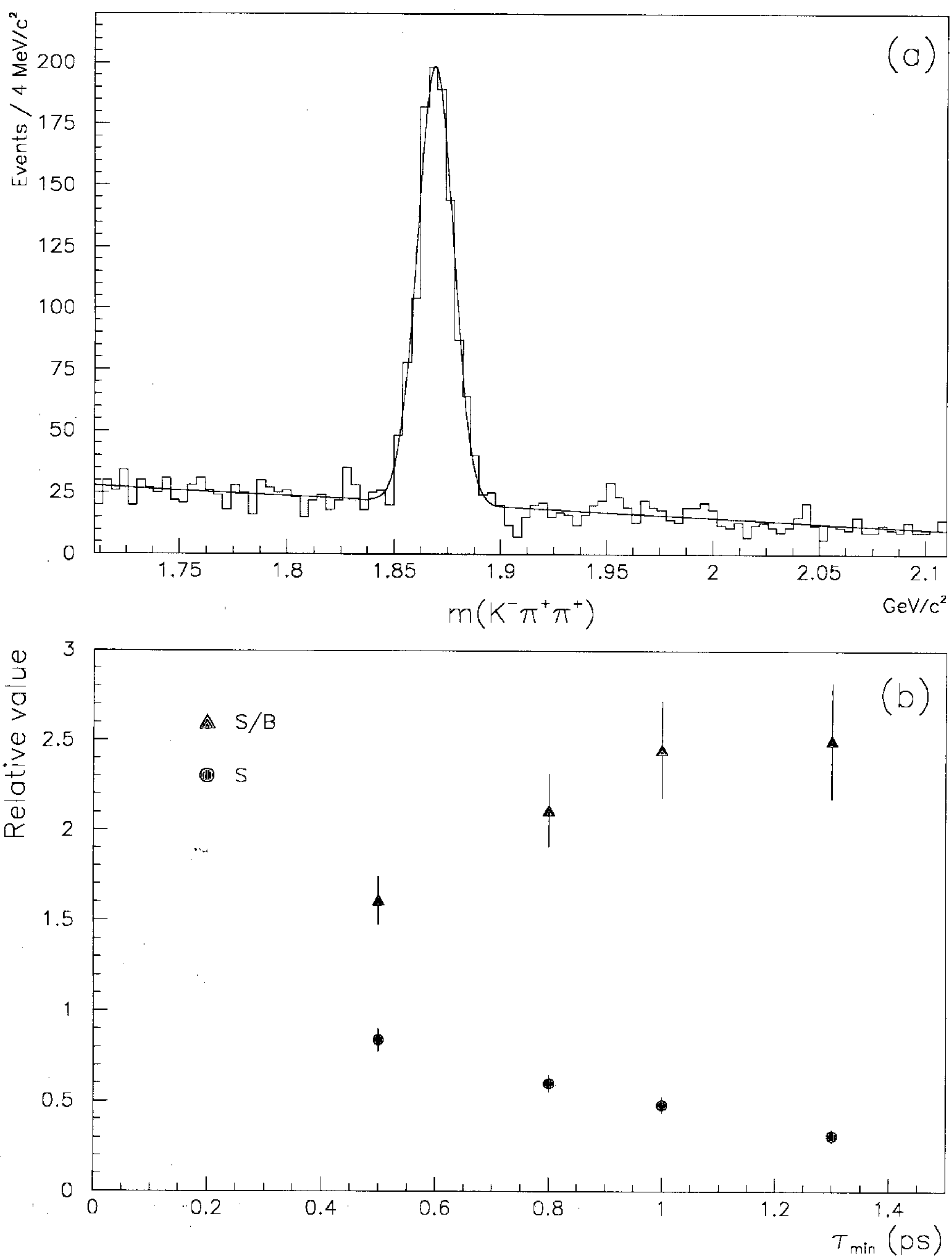
Figure 4.

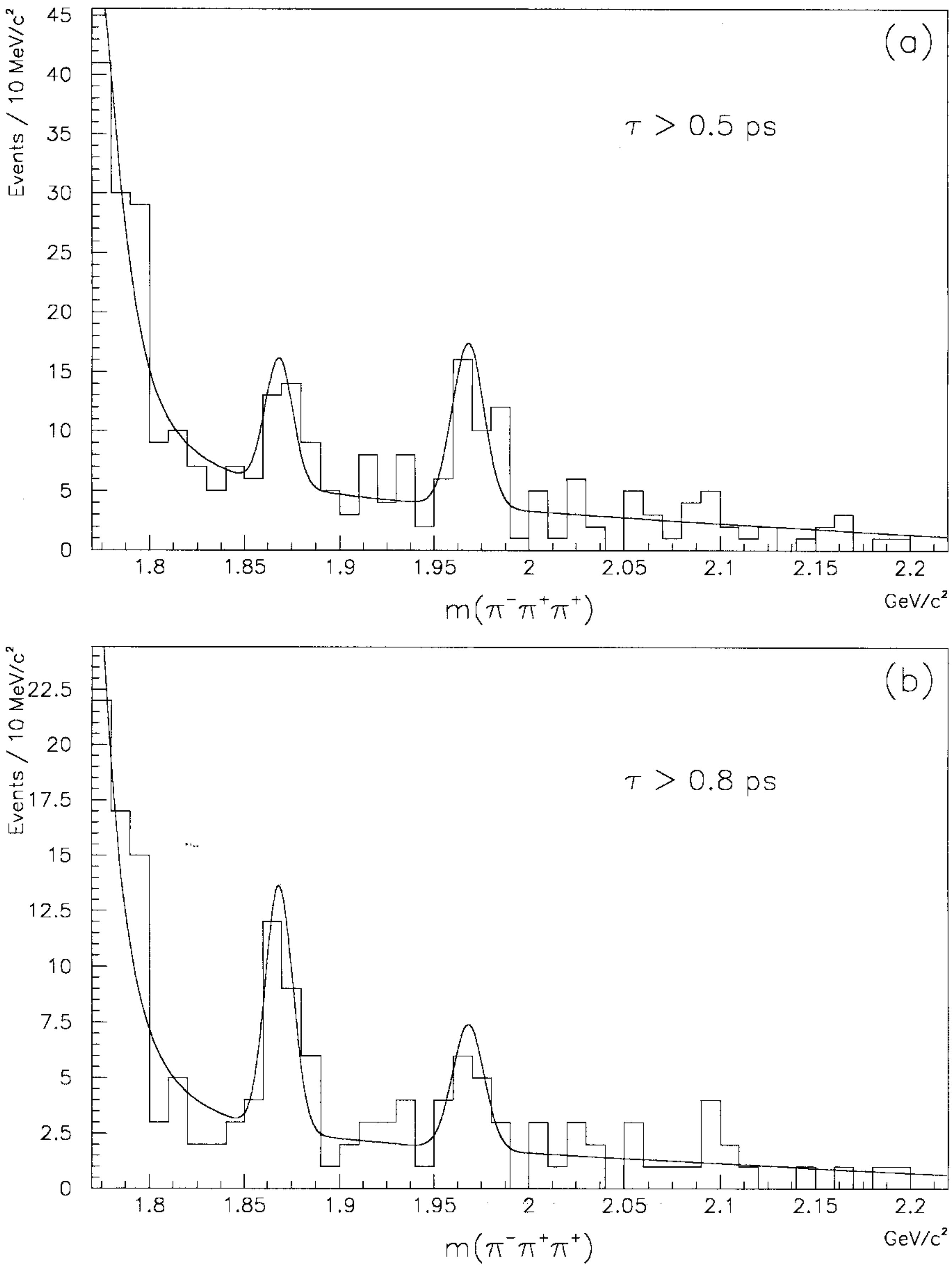
(a) $K^-K^+K^+$ invariant mass distribution for the 60 % of data for which RICH information is available, with no RICH identification (dotted line) and with $x_K > 0.5$ for both K^+ candidates (solid line).

(b) Upper curve as solid line of (a); shaded area with additional requirement $\tau > 1.3$ ps.

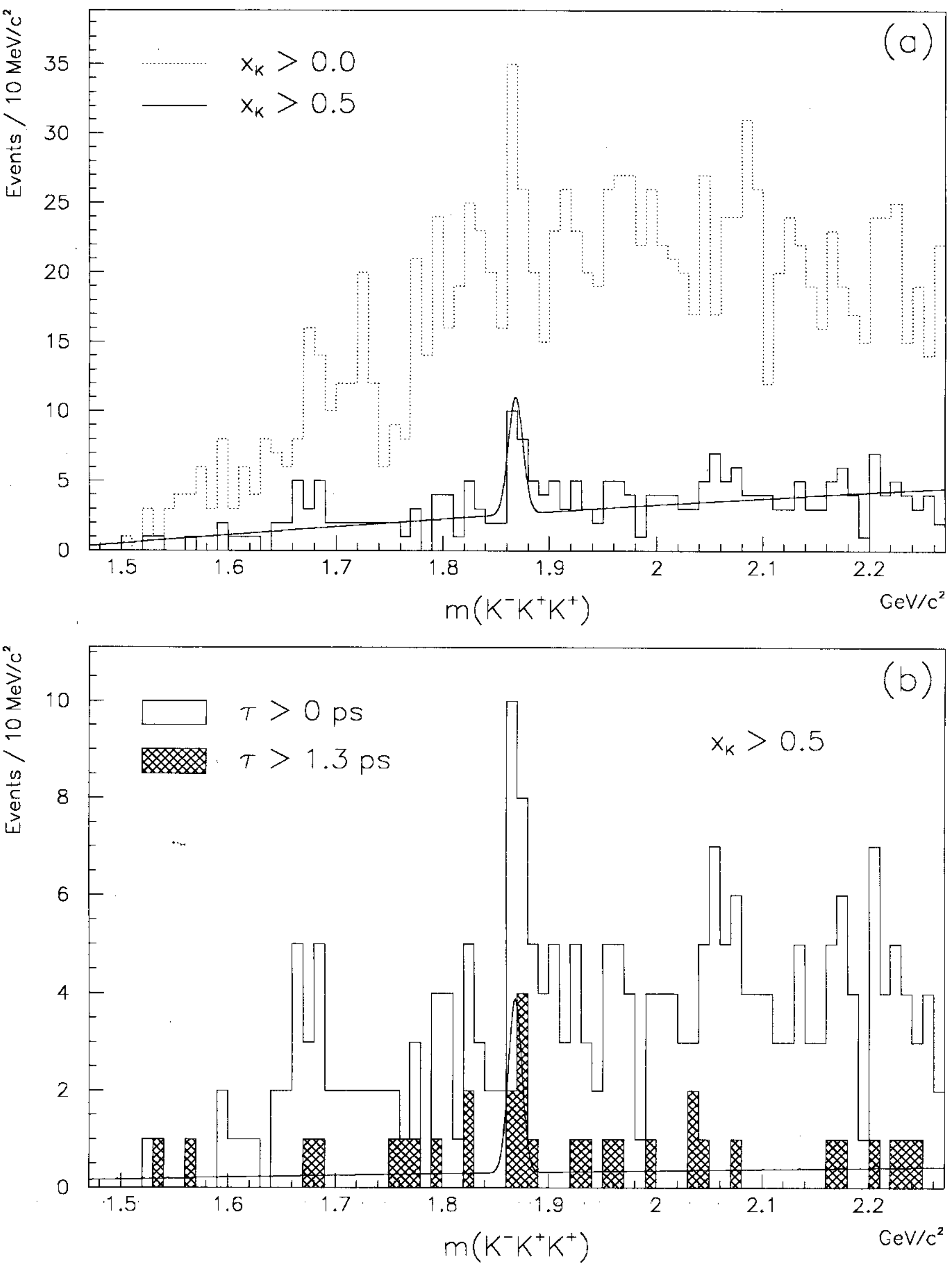


(a)
Events / 10 MeV/c²
m(K⁻K⁺π⁺)
GeV/c²
(b)
Events / 10 MeV/c²
m(K⁻K⁺π⁺)
GeV/c²


(a)
Events / 4 MeV/c²
m(K⁻π⁺π⁺)
GeV/c²
(b)
Relative value
S/B
S
τ_min (ps)



Events / 10 MeV/c²
(a)
τ > 0.5 ps
m(π⁻π⁺π⁺)
GeV/c²
(b)
τ > 0.8 ps



Events / 10 MeV/c²
(a)
$x_K > 0.0$
$x_K > 0.5$
$m(K^-K^+K^+)$
GeV/c²
Events / 10 MeV/c²
(b)
$\tau > 0$ ps
$\tau > 1.3$ ps
$x_K > 0.5$
$m(K^-K^+K^+)$
GeV/c²