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A measurement of the branching ratios for the decays $D_s^\pm \to K^0 K^\pm$ and $D_s^\pm \to K^{*\pm} K^0$

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Abstract

The D_s decay channels $D_s^\pm \to K^\pm K^0$ and $D_s^\pm \to K^{*\pm} K^0$ have been searched for in the data from 1991 to 1994, recorded by the ALEPH-detector. In 3076670 hadronic Z^0-decays, a signal of 408±40 events has been found for $D_s^\pm \to K^\pm K^0$ and of 67±25 events has been found for $D_s^\pm \to K^{*\pm} K^0$.
With these numbers, the branching ratio for $D_s^\pm \to K^\pm K^0$ was determined to be $BR(D_s^\pm \to K^\pm K^0) = (2.1 \pm 0.3 \pm 0.3)\%$. For $D_s^\pm \to K^{*\pm} K^0$ it was found to be $BR(D_s^\pm \to K^{*\pm} K^0) = (4.4 \pm 1.7^{+0.8}_{-0.7})\%$.
Furthermore, the branching ratios relative to the D_s decay channel $D_s^\pm \to \phi\pi^\pm$ were calculated as $\frac{BR(D_s^\pm \to K^\pm K^0)}{BR(D_s^\pm \to \phi\pi^\pm)} = 0.71 \pm 0.09^{+0.09}_{-0.02}$ and $\frac{BR(D_s^\pm \to K^{*\pm} K^0)}{BR(D_s^\pm \to \phi\pi^\pm)} = 1.52 \pm 0.59^{+0.26}_{-0.09}$ respectively.
In addition, the production rates $BR(b\bar{b} \to D_s)$ and $BR(c\bar{c} \to D_s)$ were determined to be $BR(b\bar{b} \to D_s) = (46.22 \pm 3.00^{+9.05}_{-4.90})\%$ and $BR(c\bar{c} \to D_s) = (21.82^{+3.42}_{-2.66}{}^{+3.20}_{-4.62})\%$.

1 Reconstruction of D_s mesons

The complete data sample from 1991 to 1994 contains about $3.5 \cdot 10^6$ Z^0 decays. With the class 16 selection, the data sample is reduced to purely hadronic events, so that after the preselection, there are 3076670 hadronic Z^0 decays left.

1.1 The channel $D_s \to KK^0$

In this channel, the D_s-mesons are reconstructed via the decay $D_s \to KK^0_S \to K\pi^+\pi^-$. To evaluate the efficiency of the reconstruction algorithm, a $q\bar{q}$ Monte Carlo was generated with 10000 events under the condition, that each event at least contains one D_s, decaying in $D_s \to KK^0_S$. To find a D_s, at first neutral kaons are selected from the sample of V^0 objects. These neutral kaons then are combined to a D_s by adding a charged kaon.

K^0 selection cuts

The K^0 are selected by looping over the V^0 objects and applying cuts to their daughter particles. These cuts are

- the cosine of the decay angle of one K^0 daughter particle with respect to the direction of flight of the K^0 in the lab frame has to be greater than 0.95,
- the transverse distance of the K^0 daughter tracks to the primary vertex at the point of closest approach has to be greater than 0.4 cm,
- the value $c \cdot \tau$ for the K^0_S has to be in the interval $0.52 \text{ cm} < c \cdot \tau < 13 \text{ cm}$,
- the invariant mass of the $\pi^+\pi^-$ system has to be within 22 MeV/c^2 of the K^0_S mass
- the momentum of the K^0 has to be greater than 2 GeV/c,
- the transverse momentum has to be greater than 0.35 GeV/c and
- the χ^2 of the K^0 vertex refit has to be less than 12.

Selection cuts for the charged K

The charged kaons are separated from the charged pions by calculating the estimators

$$\chi^2_K = \left(\frac{x_{meas} - x_{theo}{}^K}{\sigma_{x_{theo}{}^K}}\right)^2$$

and

$$\chi^2_\pi = \left(\frac{x_{meas} - x_{theo}{}^\pi}{\sigma_{x_{theo}{}^\pi}}\right)^2$$

x denotes the specific ionization in the TPC. The values are provided by the QDEDX routine of the ALPHA software. A particle is accepted as a charged kaon if the relation

$$\chi^2_K < \chi^2_\pi$$

is fulfilled.
These kaons have to have a momentum greater than 2 GeV and a transverse momentum greater than 0.4 GeV.

Selection cuts for the D_s candidates

The D_s vertex that is fitted from the tracks of the neutral and the charged kaon has to pass the following cuts :

- χ^2 of the vertex fit less than 13,
- cosine of the decay angle of the D_s daughters with respect to the direction of flight of the D_s in the lab frame greater than 0.8,
- momentum in the interval 7 GeV/c $< p(D_s) <$36 GeV/c,
- transverse momentum greater than 0.35 GeV and
- decay length greater than 0, *i.e.* the D_s has to decay in the same hemisphere in which the two kaons were found.

The resulting mass distribution is shown in figure 1, the signal is 408 ± 40 events.

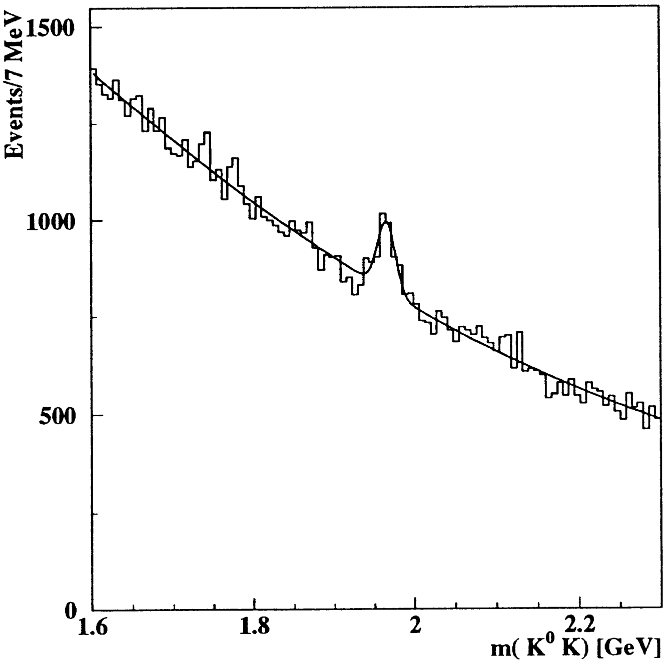

Figure 1: *Distribution of the mass of the D_s-mesons in the channel $D_s \rightarrow KK^0$*

The curve in this distribution is the result of an unbinned log likelihood fit with a second order polynomial for background and a Gaussian for the signal. The results are shown in table 1:

Parameter	Value
$N_{rec}(D_s)$	408 ± 40
$m(D_s)$	(1.9655 ± 0.0014) GeV/c^2
$\sigma(D_s)$	10.4 MeV/c^2 (taken from MC, fixed)

Table 1: *Fit results for* $D_s \rightarrow KK^0$

1.2 The channel $D_s \rightarrow K^* K^0$

For the reconstruction of this channel, the K^* has to decay into a neutral kaon and a charged pion $K^{*\pm} \rightarrow K^0 \pi^\pm$. The neutral kaons again have to decay into two charged pions.
The selection cuts for the search for two neutral kaons are nearly the same as in the previous channel. Differences are :

- the momentum of the K^0 has to be greater than 2.5 GeV/c and
- no cut on the transverse momentum.

With one of the K_S^0 and a charged pion a vertex for the K^* is fitted. The momentum of the pion has to be greater than 0.6 GeV/c.

Cuts for the K^*

- χ^2 of the K^* vertex fit has to be less than 15,
- all K^* candidates must have a mass within ± 42 MeV of the K^* mass.

The K^* and the remaining neutral kaon are taken to fit a vertex for the D_s.

Cuts for the D_s

- χ^2 of the D_s vertex fit has to be less than 15,
- the cosine of the D_s daughters decay angle with respect to the direction of flight of the D_s in the lab frame must be less than 0.8,
- the momentum of the D_s is required to be in the interval 11 GeV /c $< p(D_s) <$ 36 GeV/c and
- the transverse momentum of the D_s has to be greater than 0.1 GeV/c.

Figure 2 shows the mass spectrum of the D_s. Again, the unbinned log-likelihood fit was performed with a second order polynomial for background and a Gaussian for the signal.

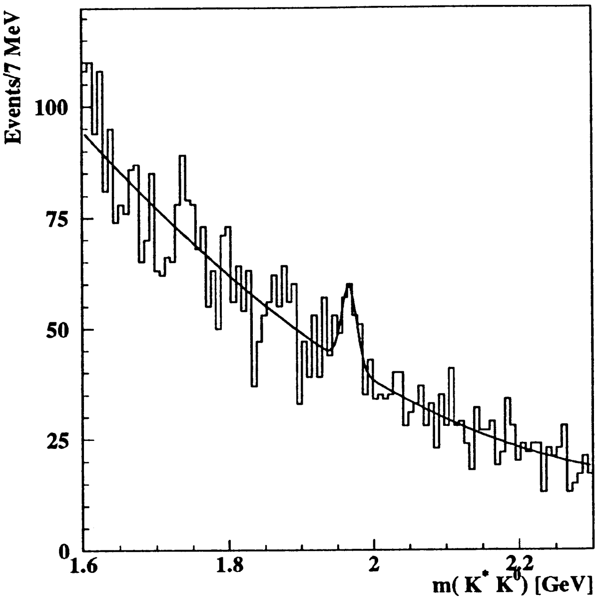

Figure 2: *mass distribution of the D_s mesons*

Table 2 shows the results.

Parameter	Value
$N_{rec}(D_s)$	67 ± 25
$m(D_s)$	$(1.9667 \pm 0.0047)\ GeV/c^2$
$\sigma(D_s)$	$(10 \pm 5) MeV/c^2$

Table 2: *Fit results for $D_s \to K^* K^0$*

2 Determination of branching ratios

The absolute branching ratio is defined as

$$BR(D_s \to X) = \frac{N(D_s \to X)}{N_{tot}(D_s)}$$

Therefore one needs the total number of D_s mesons in data $N_{tot}(D_s)$. This number is given for purely hadronic Z^0 decays by

$$N_{tot}(D_s) = N(Z^0) \cdot R_b \cdot BR(b\bar{b} \to D_s) + N(Z^0) \cdot R_c \cdot BR(c\bar{c} \to D_s)$$

The production rates $BR(c\bar{c} \to D_s)$ and $BR(b\bar{b} \to D_s)$ have been determined directly out of the data.

2.1 Determining the production rates $BR(c\bar{c} \to D_s)$ and $BR(b\bar{b} \to D_s)$

The procedure to determine these production rates consists of two steps:

1. creating three data samples in which $b\bar{b}$, $c\bar{c}$ and (uds) events are enriched,
2. counting the number of D_s mesons in these data samples.

The enrichment of the samples is done with the routine QVSRCH [1]. It produces for each hemisphere a value called Btag that denotes the 'probability' to find a secondary vertex. The sum of Btag for the two hemispheres here called Σ is used to perform a cut to classify events by existence of secondary vertices. Figure 3 shows the regions defined for a general $q\bar{q}$ Monte Carlo, generated with HVFL03.

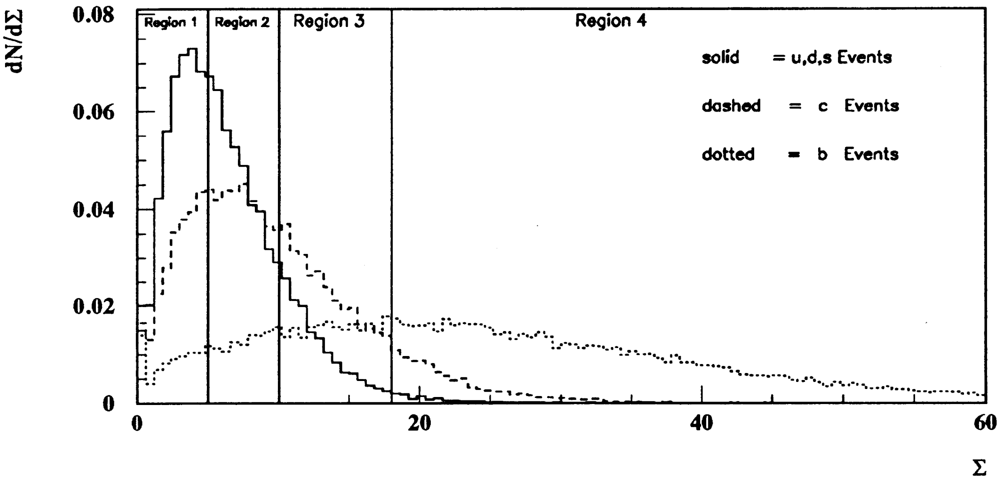

Figure 3: *Distribution of* Σ *for different quark flavours*

1. enrichment with (uds) : $\Sigma < 5$
2. enrichment with $c\bar{c}$: $5 < \Sigma < 10$
3. control region : $10 < \Sigma < 18$
4. enrichment with $b\bar{b}$: $\Sigma > 18$

In these regions, the number of D_s mesons now has to be counted. This is done by reconstructing the D_s in the channel $D_s \to \phi\pi$, since this channel has a small background and therefore a small statistical error.
Finally, there are four equations of the form

$$N^i(D_s \to \phi\pi) = N(Z^0) \cdot BR(D_s \to \phi\pi) \cdot BR(\phi \to K^+K^-) \cdot \Big(f^i_{b\bar{b}} \cdot \varepsilon^i_{b\bar{b}} \cdot BR(b\bar{b} \to D_s) + f^i_{c\bar{c}} \cdot \varepsilon^i_{c\bar{c}} \cdot BR(c\bar{c} \to D_s) + f^i_{(uds)} \cdot \varepsilon^i_{(uds)} \cdot BR((uds) \to D_s)\Big) \qquad (1)$$

and three variables $BR(q\bar{q} \to D_s)$. The parameters in these equations are :

- $f^i_{q\bar{q}}$ denoting the eventfractions of flavour q in the region i,
- $\varepsilon^i_{q\bar{q}}$ denoting the efficiency with which D_s mesons, produced in $q\bar{q}$ events in region i, are reconstructed,
- the branching ratios of $D_s \to \phi\pi$ and of $\phi \to K^+K^-$, needed because the D_s mesons are reconstructed in this channel. These values are taken from [4]

A MINUIT fit was set up in order to find a result for these equations. The χ^2 defined is

$$\chi^2 = \sum_{i=1}^{27} \left(\frac{p_i - \overline{p_i}}{\sigma_{\overline{p_i}}} \right)^2 + \sum_{i=1}^{4} \left(\frac{N^i_{calc} - N^i_{meas}}{\sigma_{N^i_{meas}}} \right)^2$$

Here, the constraint parameters p_i are the event fractions, the efficiencies etc. The value N^i_{meas} is the number of D_s mesons found in the region i in the channel $D_s \to \phi\pi$ and N^i_{calc} is, what is calculated with equation 1 for a chosen set of fit parameters $BR(q\bar{q} \to D_s)$.

Region	$\varepsilon_{b\bar{b}}$ in %	$\varepsilon_{c\bar{c}}$ in %	$\varepsilon_{(uds)}$ in %	$f_{b\bar{b}}$ in %	$f_{c\bar{c}}$ in %	$f_{(uds)}$ in %	N_{meas}
$\Sigma < 5$	1.14 ± 0.21	5.41 ± 0.36	3.71 ± 1.01	1.9 ± 0.2	4.7 ± 0.2	27.9 ± 0.4	25 ± 10
$5 < \Sigma < 10$	2.77 ±0.77	10.00 ± 0.42	2.88 ± 0.81	3.3 ± 0.2	6.4 ± 0.3	22.7 ± 0.4	97 ± 15
$10 < \Sigma < 18$	7.42 ± 0.33	12.95 ± 0.51	7.31 ± 1.74	5.4 ± 0.2	4.9 ± 0.2	8.3 ± 0.4	159 ± 16
$\Sigma > 18$	13.56 ± 0.28	16.66 ± 1.05	4.17 ± 2.45	12.2 ± 0.2	1.7 ± 0.2	0.6 ± 0.4	413 ± 24

Table 3: *Parameters used in the fit*

With the numbers in table 3, the fit produces as result

$$\boxed{BR(b\bar{b} \to D_s) = (46.22 \pm 3.00(\text{stat})^{+9.05}_{-4.90}(\text{syst}))\%}$$

$$\boxed{BR(c\bar{c} \to D_s) = (21.82^{+3.42}_{-2.66}(\text{stat})^{+3.20}_{-4.62}(\text{syst}))\%}$$

$$\boxed{BR((uds) \to D_s) = (0\ ^{+1.34}_{-0.00}(\text{ stat}))\%}$$

The value for $BR((uds) \to D_s)$ is compatible with zero. In the further considerations it has no longer been taken into account.
In section 3, there will be given a complete overview over the sources for systematic uncertainties and their contributions to the errors. The systematic uncertainties for the production rates mainly arise from the uncertainty in $BR(D_s \to \phi\pi)$ and differences between Monte Carlo and data in the variable Σ used to create the enriched data samples.
The result for $BR(c\bar{c} \to D_s)$ is compatible with the earlier ALEPH measurement [2], where the D_s production rate for a single c-quark was found to be $BR(c \to D_s) = (12.8 \pm 1.9(\text{stat}) \pm 1.9(\text{syst}))\%$.
With the obtained numbers, the value $N_{tot}(D_s)$ is

$$N_{tot}(D_s) = 428530 \pm 27520$$

2.2 The branching ratio for $D_s \to KK^0$

As the D_s mesons in this channel are reconstructed in the decay chain $D_s \to KK^0_S \to K\pi^+\pi^-$, the branching ratio $BR(D_s \to KK^0)$ is given by

$$BR(D_s \to K^0K) = \frac{N_{rec}(D_s)}{N_{tot}(D_s) \cdot f_{K^0_S} \cdot BR(K^0_S \to \pi^+\pi^-) \cdot \varepsilon}.$$

Here, $N_{rec}(D_s)$ denotes the number of D_s mesons found (408 ± 40), $f_{K^0_S}$ is the fraction of K^0_S in the K^0 sample (50%), $BR(K^0_S \to \pi^+\pi^-)$ is the branching ratio of K^0_S into two charged pions ((68.61 ± 0.28)%) and ε denotes the efficiency of the reconstruction ((13.36 ± 0.48)%). The efficiency is calculated from Monte Carlo.
The result for the branching ratio is:

$$\boxed{BR(D_s \to KK^0) = (2.1 \pm 0.3(\text{stat}) \pm 0.3(\text{syst}))\%}$$

The systematic error arises from differences between Monte Carlo and data in the distributions of the cut variables for the D_s selection, different background parametrisations and the uncertainties in $BR(b\bar{b} \to D_s)$ and $BR(c\bar{c} \to D_s)$.

2.3 The branching ratio for $D_s \to K^*K^0$

This channel can be described with a similar formula as the previous one. It is

$$BR(D_s \to K^*K^0) = \frac{N_{rec}(D_s)}{N_{tot}(D_s) \cdot BR(K^* \to K^0\pi) \cdot f^2_{K^0_S} \cdot BR^2(K^0_S \to \pi^+\pi^-) \cdot \varepsilon}$$

Here, the values are

$$\begin{aligned} N_{rec}(D_s) &= 67 \pm 25 \\ BR(K^* \to K^0\pi) &= \frac{2}{3} \quad \text{from Isospin analysis} \\ \varepsilon &= (4.49 \pm 0.35)\% \end{aligned}$$

This efficiency is calculated from a general $q\bar{q}$ Monte Carlo sample of 10000 events which have to contain at least one D_s decaying into $D_s \to K^*K^0_S$. The result is

$$\boxed{BR(D_s \to K^*K^0) = (4.4 \pm 1.7(\text{stat})^{+0.8}_{-0.7}(\text{syst}))\%}$$

The systematic errors have the same origins as in the previous channel. They include the uncertainties in the $D_s \to \phi\pi$ branching ratio.

2.4 The $D_s \to KK^0$ branching ratio relative to $D_s \to \phi\pi$

In order to calculate relative branching ratios, the channel $D_s \to \phi\pi$ is chosen for normalization. With a routine already available [3], the number of $D_s \to \phi\pi$ has been determined to be $N(D_s \to \phi\pi) = 669 \pm 33$ for the data sample from 1991 to 1994 (figure 4).

The reconstruction is in the channel $D_s \to \phi\pi \to KK\pi$, so that the relative branching ratio is given by

$$\frac{BR(D_s \to K^0 K)}{BR(D_s \to \phi\pi)} = \frac{N_{rec}^{K^0 K}(D_s)}{N_{rec}^{\phi\pi}(D_s)} \cdot \frac{\varepsilon_{\phi\pi}}{\varepsilon_{K^0 K}} \cdot \frac{BR(\phi \to K^+ K^-)}{f_{K_S^0} \cdot BR(K_S^0 \to \pi^+\pi^-)}$$

Here, $N_{rec}^{X}(D_s)$ denotes the number of D_s mesons having been reconstructed in the channel $D_s \to X$ and ε_X denotes the efficiency in this channel to reconstruct the mesons.
With $\varepsilon_{\phi\pi} = (10.9 \pm 0.4)\%$ and the numbers stated before, the result is

$$\boxed{\frac{BR(D_s \to K^0 K)}{BR(D_s \to \phi\pi)} = 0.71 \pm 0.09(\mathrm{stat})\,^{+0.09}_{-0.02}(\mathrm{syst})}$$

The systematic uncertainties are due to different possibilities in the parametrisation of the background in the mass distributions and to differences between Monte Carlo and data in the distributions of the cut variables.

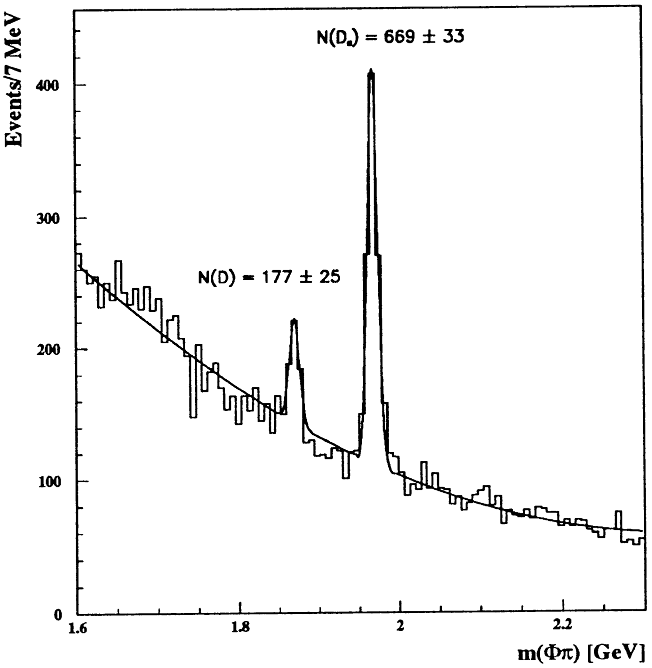

Figure 4: *The decay $D_s \to \phi\pi$ (Peak on the right). The signal on the left arises from the decay $D \to \phi\pi$*

2.5 The $D_s \to K^* K^0$ branching ratio relative to $D_s \to \phi\pi$

In the same way as in the previous section, the relative branching ratio of the channel $D_s \to K^* K^0$ is given by

$$\frac{BR(D_s \to K^* K^0)}{BR(D_s \to \phi\pi)} = \frac{N_{rec}^{K^* K^0}(D_s)}{N_{rec}^{\phi\pi}(D_s)} \cdot \frac{\varepsilon_{\phi\pi}}{\varepsilon_{K^* K^0}} \cdot \frac{BR(\phi \to K^+ K^-)}{{f_{K_S^0}}^2 \cdot BR(K_S^0 \to \pi^+\pi^-)^2 \cdot BR(K^* \to K^0\pi)}$$

This gives the result

$$\boxed{\frac{BR(D_s \to K^* K^0)}{BR(D_s \to \phi\pi)} = 1.52 \pm 0.59(\mathrm{stat})\,^{+0.26}_{-0.09}(\mathrm{syst})}$$

The systematic errors are due to the same sources as in the previous channel.

3 Systematics

In the following tables, this section gives an overview over the contributions of the systematic error sources. All values given are absolute errors.
For $BR(b\bar{b} \to D_s)$ they are :

Source	upper variation	lower variation
uncertainties in the parameters of the χ^2 fit	+6.30 %	−4.90 %
differences in QVSRCH between MC and data	+6.50 %	−

Table 4: *Systematic uncertainties in* $BR(b\bar{b} \to D_s)$

For the production rate $BR(c\bar{c} \to D_s)$ the values are :

Source	upper variation	lower variation
uncertainties in the parameters of the χ^2 fit	+3.20 %	−2.10 %
differences in QVSRCH between MC and data	−	−4.12%

Table 5: *Systematic uncertainties in* $BR(c\bar{c} \to D_s)$

Uncertainties for the branching ratio of $D_s \to KK^0$ are :

Source	upper variation	lower variation
uncertainties in the parameters of the χ^2 fit	+0.2 %	−0.2 %
differences in QVSRCH between MC and data	−	−0.2 %
background parametrisation by a third order polynomial	+0.2 %	−
variation of the cuts	+0.1 %	−0.1 %

Table 6: *Systematic uncertainties for* $BR(D_s \to KK^0)$

The branching ratio of $D_s \to K^*K^0$ has uncertainties as follows :

Source	upper variation	lower variation
uncertainties in the parameters of the χ^2 fit	+0.4 %	−0.5 %
differences in QVSRCH between MC and data	−	−0.2 %
background parametrisation by a third order polynomial	+0.6 %	−
variation of the cuts	+0.4 %	−0.4 %

Table 7: *Systematic uncertainties for* $BR(D_s \to K^*K^0)$

For the relative branching ratio of $D_s \to KK^0$ the contributions are :

Source	upper variation	lower variation
background parametrisation by a third order polynomial	+0.08	−
variation of the cuts	+0.04	−0.02

Table 8: *Systematic uncertainties for* $\frac{BR(D_s \to KK^0)}{BR(D_s \to \phi\pi)}$

Uncertainties for the relative branching ratio of $D_s \to K^*K^0$ are :

Source	upper variation	lower variation
background parametrisation by a third order polynomial	+0.2	−
variation of the cuts	+0.17	−0.09

Table 9: *Systematic uncertainties for* $\frac{BR(D_s \to K^*K^0)}{BR(D_s \to \phi\pi)}$

4 Conclusion

In 3×10^6 hadronic Z^0 decays, a signal of 408 events for the $D_s \to KK^0$ channel and of 67 events for the $D_s \to K^*K^0$ channel could be extracted. The production rates $BR(b\bar{b} \to D_s)$ and $BR(c\bar{c} \to D_s)$ from data, were determined to be

$$BR(b\bar{b} \to D_s) = (46,22 \pm 3,00(\text{stat.}) \begin{array}{l}+9,05\\-4,90\end{array}(\text{syst.}))\%$$

$$BR(c\bar{c} \to D_s) = (21,82 \begin{array}{l}+3,42\\-2,66\end{array}(\text{ stat. }) \begin{array}{l}+3,20\\-4,62\end{array}(\text{syst.}))\%$$

With these numbers, the absolute branching ratios for these decay channels have been found to be

$$BR(D_s \to K^0K) = (2,1 \pm 0,3(\text{stat.}) \pm 0,3(\text{syst.}))\%$$

$$BR(D_s \to K^*K^0) = (4,4 \pm 1,7(\text{stat.}) \begin{array}{l}+0,8\\-0,7\end{array}(\text{syst. }))\%$$

Furthermore, the branching ratios relative to the channel $D_s \to \phi\pi$ were calculated to be

$$\frac{BR(D_s \to K^0K)}{BR(D_s \to \phi\pi)} = 0,71 \pm 0,09(\mathrm{stat.}) \begin{array}{l} +0,09 \\ -0,02 \end{array} (\mathrm{syst.})$$

$$\frac{BR(D_s \to K^*K^0)}{BR(D_s \to \phi\pi)} = 1,52 \pm 0,59(\mathrm{stat.}) \begin{array}{l} +0,26 \\ -0,09 \end{array} (\mathrm{syst.})$$

These results for the branching ratios are compatible to those of A. Cordier and F. Courault in [5] and [6].

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