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Absolute determination of D_s branching ratios and f_{D_s} extraction at a neutrino factory

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Abstract

A novel method for a direct measurement of the exclusive D_s branching ratios and of the decay constant f_{D_s} with a systematical error better than 5% is presented. The approach is based on the peculiar vertex topology of the anti-neutrino induced diffractive charm events. The statistical accuracy achievable with a neutrino factory is estimated.

1   Introduction

The experimental knowledge on leptonic D_s decays is rather poor. Currently, the branching ratios for $D_s \to l\nu$ decays are estimated by the Particle Data Group [1] to be $BR(D_s \to \mu\nu) = (4.6 \pm 1.9) \times 10^{-3}$ and $BR(D_s \to \tau\nu) = (7 \pm 4) \times 10^{-2}$. These large uncertainties translate into a large uncertainty on the extraction of the decay constant f_{D_s}.

In this paper we propose a method to build an almost pure sample of D_s^- from diffractive events which allows the extraction of most of the D_s branching ratios and in particular of purely leptonic decays from which f_{D_s} can be extracted with a systematic error better than 5%. A statistics capable of exploiting this systematic error can be accumulated at neutrino factories. Once f_{D_s} is measured with such an accuracy, one would feel more confident about extrapolating to the decay constants in the B system, f_B and f_{B_s}, which are crucial quantities for a quantitative understanding of $B^0_{(s)} - \bar{B}^0_{(s)}$ oscillations and the possible extraction of the CKM matrix elements V_{td} or V_{ts} [2].

This paper is organised as follows: in Section 2 we discuss the available data on neutrino and anti-neutrino induced diffractive $D_s^{(*)}$ [1] production. In Section 3 the leptonic D_s decay mechanism is discussed and the available experimental determinations of f_{D_s} are reviewed. A method for a direct evaluation of D_s branching ratios and f_{D_s} measurement is discussed in Section 4, together with the evaluation of the accuracy achievable at a neutrino factory. In the last section we give our conclusions.

2   (Anti-)Neutrino induced diffractive $D_s^{(*)}$ production

In charged-current (CC) interactions, the W boson can *fluctuate* into a charmed meson. The on-shell meson is produced by scattering off a nucleon or a nucleus without breaking up the recoiling partner. The diffractive production mechanism ($\nu_\mu N \to \mu^- D_s^{*+} N$) is shown schematically in Fig. 1. The same mechanism applies to $D^{(*)}$ production, but the $D_s^{(*)}$ one is Cabibbo favoured by a factor $\left| \frac{V_{cs}}{V_{cd}} \right|^2 \sim 20$.

This process has been observed in previous experiments [3, 4, 5]. In particular, one of these experiments [5] has shown the evidence of a D_s diffractive production through the direct observation in nuclear emulsion of the decay chain $D_s^{*+} \to D_s^+ \gamma$, $D_s^+ \to \tau^+ \nu_\tau$, $\tau^+ \to \mu^+ \bar{\nu}_\tau \nu_\mu$.

Unlike deep-inelastic cross-sections, the diffractive cross-sections are predicted to be the same for ν and $\bar{\nu}$ and for proton and neutron targets. The observed neutrino and anti-neutrino induced diffractive D_s rates relative to CC interactions on an isoscalar target have been measured to be $(1.5 \pm 0.5) \times 10^{-4}$ and $(2.6 \pm 0.9) \times 10^{-4}$, respectively. This is compatible with a 1 : 2

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[1]In the following $D_s^{(*)}$ stands for either D_s or D_s^*. The same notation is also used for $D^{(*)}$.

ratio, as implied by the equality of diffractive cross-sections and the ratio of inclusive cross-sections [3]. It is worth stressing that these numbers have been obtained searching for particular D_s decay channels in $D_s^{(*)}$ diffractive production: therefore the corresponding branching ratio has to be known to get the absolute production rates [3].

The energy dependence of the diffractive cross-section has also been investigated. In the neutrino energy intervals $10 \div 30$, $30 \div 50$ and $50 \div 200$ GeV the observed rate per CC is $(1.8\pm0.7)\times10^{-4}$, $(1.3\pm0.6)\times10^{-4}$ and $(1.6\pm0.7)\times10^{-4}$, respectively, so that no variation is detected at the available statistical level [3]. Theoretically, no steep variation of this relative rate in the $10\div200$ GeV neutrino energy interval is expected.

Taking into account the corresponding branching ratio, the neutrino diffractive $D_s^{(*)}$ production rate has been evaluated to be $(2.8 \pm 1.1) \times 10^{-3}$/CC [3]. An independent evaluation of the same production rate has given $(3.2 \pm 0.6) \times 10^{-3}$/CC [4]. The weighted average of the two evaluations gives a neutrino induced diffractive production rate of $(3.1 \pm 0.5) \times 10^{-3}$/CC. Since the neutrino to anti-neutrino CC production rate is $2 : 1$, the average anti-neutrino induced $D_s^{(*)}$ diffractive production rate is $(6.2 \pm 1.0) \times 10^{-3}$/CC. Therefore, the combined analysis gives an accuracy of about 15% for the diffractive production rate.

For a detailed theoretical review of lepton induced diffractive production we refer to Refs. [6, 7, 8, 9, 10].
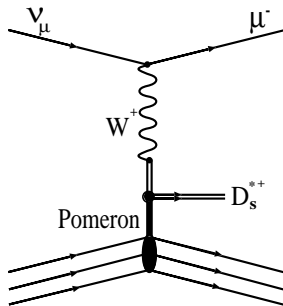

Figure 1: Diagram for neutrino induced diffractive D_s^{*+} meson production.

3   Leptonic D_s^+ decays

From a theoretical point of view, purely leptonic decays of charged mesons are the simplest ones to describe. The effect of the strong interaction can be parameterised in terms of just one factor, called the decay constant. Unlike semi-leptonic decays, where q^2 (and hence the form factors) varies event by

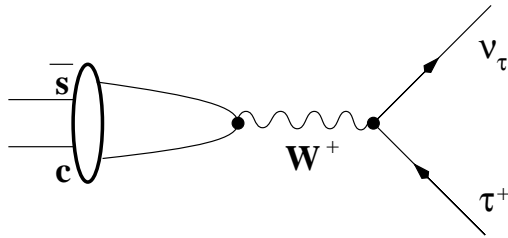event, leptonic decays have a fixed q^2 value ($q^2 = M^2$, where M is the mass of the initial meson).

Figure 2: Feynman diagram of the $D_s^+ \to \tau^+ \nu_\tau$ decay.

By neglecting radiative corrections, the decay rate of a charged pseudo-scalar meson $M_{Q\bar{q}}$ to $l\nu_l$ is

$$\Gamma(M_{Q\bar{q}} \to l\nu_l) = \frac{G_F^2}{8\pi} \times \mid V_{Qq} \mid^2 \times f_M^2 \times M \times m_l^2 \times \left(1 - \frac{m_l^2}{M^2}\right)^2$$

where f_M is the decay constant, V_{Qq} is the CKM matrix element, and m_l and M are the masses of the lepton and charged meson $M_{Q\bar{q}}$, respectively. The decay constant f_M is a measurement of the probability amplitude for the quarks to have zero separation, which is necessary for them to annihilate.

By using the previous notation, the D_s leptonic branching ratio can be written as

$$BR(D_s \to l^- \bar{\nu}_l) = \frac{G_F^2}{8\pi} \times \mid V_{Qq} \mid^2 \times f_{D_s}^2 \times \tau_{D_s} \times M_{D_s} \times m_l^2 \times \left(1 - \frac{m_l^2}{M_{D_s}^2}\right)^2$$

where τ_{D_s} is the D_s life-time.

Decay constants for pseudo-scalar mesons containing a heavy quark have been predicted with lattice QCD, QCD sum rules and potential models, but due to the non-perturbative character of the calculations they vary significantly in the predictions. The predicted value for f_{D_s} lies in the $190 \div 360$ MeV range [11].

A method for extracting f_{D_s} is to measure the leptonic decay modes of D_s. Due to helicity suppression, only the muonic and tauonic decay modes have an appreciable branching ratio. Unfortunately, the measurements of the leptonic D_s decays are rather scarce. A summary of the available measurements together with the determinations of f_{D_s} is shown in Table 1. The errors on f_{D_s} are larger than 30% and, despite the scanty statistics available, the systematic error dominates. This is mainly due to the uncertainty on the normalisation used for the determination of the leptonic decay branching ratios.

Once the absolute value of f_{D_s} is measured with an accuracy of 10% or better, one would feel more confident about the predictions of the decay constants

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Experiment	Channel	f_{D_s} (MeV)
WA75[12]	$D_s \to \mu$	$232 \pm 45 \pm 52$
CLEO I [13]	$D_s \to \mu$	$344 \pm 37 \pm 52 \pm 42$
CLEO II[14]	$D_s \to \mu$	$280 \pm 19 \pm 28 \pm 34$
E653[15]	$D_s \to \mu$	$194 \pm 35 \pm 20 \pm 14$
BEATRICE[16]	$D_s \to \mu$	$323 \pm 44 \pm 12 \pm 34$
BES[17]	$D_s \to l$	$430^{+150}_{-130} \pm 40$
L3[18]	$D_s \to \tau$	$309 \pm 58 \pm 33 \pm 38$

Table 1: Summary of the available experimental determinations of the decay constant f_{D_s}.

in the B system, f_B and f_{B_s}, which are crucial quantities for a quantitative understanding of $\bar{B}^0_{(s)} - B^0_{(s)}$ oscillations and the extraction of $V_{td}(V_{ts})$ from them.

In the following we describe a method for the extraction of the D_s leptonic branching ratios which minimises the systematical error due to the normalisation of the sample. It is based on the direct observation of $D_s^{(*)}$ produced in anti-neutrino induced diffractive interactions and a topological selection of the events which improves the purity of the sample used for the normalisation.

4 Direct evaluation of D_s branching ratios and f_{D_s} measurement

In the following we consider a detector with a capability to exploit vertex and decay topologies with micron precision. We assume to use an emulsion target (see for instance [19]), although the method we are proposing would work with a CCD target [2] as well. This allows the detection of short lived particles with path length larger than 10 μm.

4.1 Kinematical selection: deep-inelastic versus diffractive events

Deep-inelastic charmed events are kinematically quite different with respect to diffractive ones. In particular, the kinematical variable t, defined in Fig. 3, allows a very high rejection power against the background with a good efficiency of the signal. The t determination relies on the momentum determination of the charmed particle. In the E531 emulsion experiment [20, 21], a resolution in measuring the charmed hadron momentum better than 15% was achieved by using a likelihood technique. In the following we make the conservative assumption of momentum resolution in measuring the charmed hadron momentum of 30%, 50% and 100%. The reconstructed t distributions for diffractive and deep-inelastic events are shown in Fig. 4.
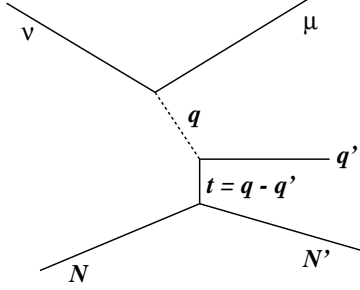
Figure 3: The 4-momentum transfer t in a neutrino CC interaction with charm production. q' is the charmed hadron 4-momentum.
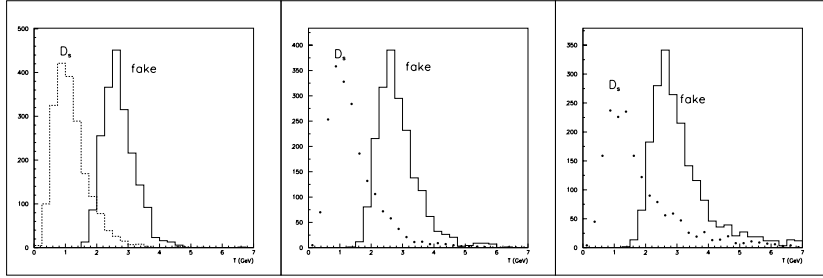

Figure 4: t distributions for both diffractive (D_s) and deep-inelastic (*fake*) interactions with a diffractive topology. A resolution of 30% (left plot), 50% (middle one) and 100% (right one) on the charmed hadron momentum measurement is assumed.

In order to select diffractive events we apply the cut $t < 1.7$ GeV. Cuts on the flight length ($> 10 \ \mu$m) and on the kink angle ($\theta_{kink} > 15$ mrad) are also applied. The efficiency for the signal and the correspondent background are reported in Table 2. From this table we can see that, independently of the momentum resolution, the fraction of deep-inelastic charm events with diffractive topology surviving the kinematical cut is $\varepsilon_{dis} \sim 0.4\%$, while the signal efficiency ranges from about 50 to 80%. In the following we assume a momentum resolution of 50%.

4.2 Topology of neutrino induced diffractive charm events and background

In the $D_s^{(*)}$ or $D^{(*)}$ diffractive production only a muon is produced at the interaction point (primary vertex), besides the charmed meson. Therefore, these events are characterised by a peculiar topology: two charged tracks at the primary vertex, one of them being a short lived particle.

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$\Delta p/p$	$\varepsilon_{dis}(\%)$	$\varepsilon_{D_s}(\%)$
30%	0.3 ± 0.1	83.3±0.8
50%	0.4 ± 0.2	72.5±1.0
100%	0.4 ± 0.2	51.8±1.1

Table 2: Efficiency for the signal, ε_{D_s}, and for the background, ε_{dis}, assuming three different momentum resolutions.

Note that the excited states produced undergo the following decays without leaving an observable track:

$$D_s^{*-} \rightarrow D_s^- \gamma \quad BR = (94.2 \pm 2.5)\% \text{ [1]}$$
$$D_s^{*-} \rightarrow D_s^- \pi^0 \quad BR = (5.8 \pm 2.5)\% \text{ [1]}$$
$$D^{*-} \rightarrow D^0 \pi^- \quad BR = (67.7 \pm 0.5)\% \text{ [1]}$$
$$D^{*-} \rightarrow D^- \pi^0 \quad BR = (30.7 \pm 0.5)\% \text{ [1]}$$
$$D^{*-} \rightarrow D^- \gamma \quad BR = (1.6 \pm 0.4)\% \text{ [1]}.$$

A source of irreducible background is the diffractive production of $D^{(*)-}$. Its contamination relatively to the signal is given by

$$\varepsilon_{D^{(*)}} = \left|\frac{V_{cd}}{V_{cs}}\right|^2 \times [\eta_{D^-} + \eta_{D^{*-}} \times BR(D^{*-} \rightarrow D^-)]$$

where $BR(D^{*-} \rightarrow D^-) = 0.323 \pm 0.006$ [1], η_{D^-} and $\eta_{D^{*-}}$ are the fractions of diffractively produced D^- and D^{*-} respectively. We assume that these fractions are the same for D^- as for D_s^- ($\eta_{D^-} = \eta_{D^{*-}} = 0.5$). The latter can be extracted by the NuTeV results: $\sigma(\nu_\mu N \rightarrow \mu^- D_s N) = (1.4\pm0.3)$fb/nucleon and $\sigma(\nu_\mu N \rightarrow \mu^- D_s^* N) = (1.6 \pm 0.4)$fb/nucleon [4]. Finally we get $\varepsilon_{D^*} = (3.3 \pm 0.8)\%$.
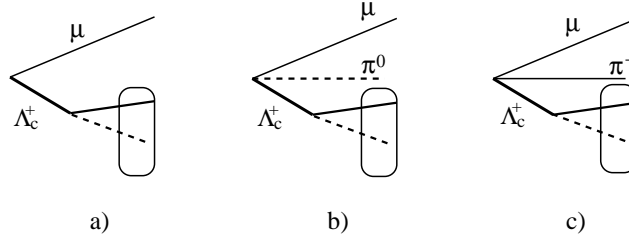

Figure 5: Topology of the quasi-elastic charm neutrino induced events in the case of the reaction a) $\nu_\mu n \rightarrow \mu^- \Lambda_c^+$, b) $\nu_\mu n \rightarrow \mu^- \Sigma_c^+(\Sigma_c^{*+})$ and c) $\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}(\Sigma_c^{*++})$. The particles inside the box represent the Λ_c^+ decay products.

Neutrino induced quasi-elastic charm events are characterised by the topologies shown in Fig. 5 (see Ref. [22]). Therefore, they are similar to the diffractive

ones, but with a cross-section twice as large. Since anti-neutrinos cannot induce quasi-elastic charm production while diffractive production is the same for both ν and $\bar{\nu}$, our interest is focused on $\bar{\nu}$ induced events. Therefore we make the assumption that all the events with the above topology are due to $D_s^{(*)}$ diffractive production.

The charm production in $\bar{\nu}$ deep-inelastic interactions and the event topology have been studied by using the HERWIG event generator [23], an event generator based on JETSET [24] and LEPTO [25] and the energy dependence of the charmed fractions reported in Ref. [26][2]. The average charmed fractions, convoluted with the anti-neutrino spectrum [2], are $F_{\bar{D}^0} = 61\%$, $F_{D^-} = 26\%$, $F_{D_s^-} = 7.3\%$ and $F_{\Lambda_c^-} = 5.7\%$. The kinematics signal has been modeled according to Refs. [6, 7, 8, 9, 10] by using an event generator developed within the CHORUS Collaboration [5].

The contamination of the diffractive sample from deep-inelastic events can be written as

$$\varepsilon_{fake} = \frac{\sigma(\bar{\nu}_\mu N \to \mu^+ C X)}{\sigma(\bar{\nu}_\mu N \to \mu^+ X)} \times \frac{1}{\bar{\mathcal{R}}} \times (F_{D^-} + F_{\Lambda_c^-}) \times f_{fake} \times \varepsilon_{dis} \qquad (1)$$

where

$$\bar{\mathcal{R}} \equiv \frac{\sigma(\bar{\nu}_\mu N \to \mu^+ D_s^{(*)-} N)}{\sigma(\bar{\nu}_\mu N \to \mu^+ X)} \; .$$

We take the charm production in $\bar{\nu}$ interaction to be 3% [27]. By using the charmed fractions given above, $(F_{D^-} + F_{\Lambda_c^-}) = 31.7\%$. The factor $f_{fake} = (6.0 \pm 0.1)\%$ denotes the fraction of deep-inelastic charmed events faking a diffractive topology. ε_{dis} gives the efficiency of kinematical cuts as explained in Section 4.1.

As discussed in Section 2, the experimental determination of $\bar{\mathcal{R}}$ has an accuracy of about 15% which gives $\varepsilon_{fake} = (0.037 \pm 0.009)\%$. The ε_{fake} value and its error are reported in the third column of Table 3 as a function of the error on $\bar{\mathcal{R}}$.

From the numbers given above it turns out that the little knowledge we have about the diffractive charm production cross-section plays a role only in the evaluation of the deep-inelastic contamination, namely a term of the systematic error. Even if the ratio $\bar{\mathcal{R}}$ had an uncertainty of 100%, at 3σ the relative systematic error on the branching ratios would be $\lesssim 0.16\%$ (see Table 3), so that the $\varepsilon_{D^{(*)}}$ contribution is dominant. Therefore, the overall systematic uncertainty does not depend at all on the $\bar{\mathcal{R}}$ accuracy ($\varepsilon_{sys} = (3.3 \pm 0.8)\%$).

4.3 Description of the method

An almost pure sample of D_s^- from diffractive events, with a small contamination of D^- and Λ_c^- produced in deep-inelastic events and in diffractive $D^{(*)-}$ production, can be built by using diffractive $D_s^{(*)}$ production from anti-neutrinos. The normalisation to determine the D_s absolute branching ratios is

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[2]We assume that the charmed fractions are equal for both ν and $\bar{\nu}$ as implemented in the event generators.

$\Delta\mathcal{R}/\mathcal{R}$	$\sigma_{fake}/\varepsilon_{fake}$	$\varepsilon_{fake}(\%)$
15%	22%	0.037±0.009
30%	34%	0.04±0.01
50%	53%	0.04±0.02
100%	101%	0.04±0.04

Table 3: The relative and absolute error on ε_{fake} as a function of the relative error on $\bar{\mathcal{R}}$.

given by the number of events with a vertex topology consistent with one μ plus a short lived particle. No model dependent information is used to define the normalisation.

It is also worth noting that, in particular, the contamination of D^- and Λ_c^- events does not affect the $D_s \to \tau$ channel. Indeed, such events would present a unique topology with two subsequent kinks. An event with a double kink has been recently observed in CHORUS (see Ref. [5]).

4.4   Measurement accuracy at a neutrino factory

At present there are no experiments with both an adequate spatial resolution to fully exploit the diffractive topology and a sufficient anti-neutrino induced CC event statistics. Therefore, the method proposed in this paper could only be exploited with the above-mentioned detector exposed at a neutrino factory.

Let us assume to collect 10^7 $\bar{\nu}$CC events into an emulsion target and to have a detection efficiency of about 73% for the D_s decays (see Table 2). By assuming a vertex location efficiency of about 50%[3] and assuming a $\bar{\nu}$ diffractive production rate of 6.2×10^{-3}/CC, we expect to detect a number of D_s equal to $N_{D_s} = 10^7 \times 6.2 \times 10^{-3} \times 0.73 \times 0.5 \simeq 2.3 \times 10^4$.

The expected accuracy on the determination of the D_s branching ratios is shown in Table 4 for a few channels, together with the current status. To compute the expected number of events in each decay channel we have used the central values (shown in Table 4 together with their errors) given by the Particle Data Group [1].

By using the relation given in Section 3 and the measured branching ratios given in Table 4, the decay constant f_{D_s} can be extracted. If we collect 10^7 $\bar{\nu}_\mu$ CC interactions we get $f_{D_s} = 288 \pm 4\,|_{stat} \pm 5\,|_{sys}$ MeV where the central value is taken from Ref. [1].

5   Conclusions

D_s branching ratios are affected by large uncertainties, mainly due to the difficulty of defining a pure D_s starting sample. These uncertainties translate into

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[3]This efficiency accounts for the electronic detector reconstruction and the automatic location of the event vertex inside the emulsions.

Channel	PDG BR [1]	New method
$D_s \to \mu\nu$	$(4.6 \pm 1.9) \times 10^{-3}$	$(\pm 0.55 \pm 0.15) \times 10^{-3}$
$D_s \to \tau\nu$	$(7 \pm 4)\%$	$(\pm 0.17 \pm 0.23)\%$
$D_s \to \phi l\nu$	$(2.0 \pm 0.5)\%$	$(\pm 0.08 \pm 0.07)\%$

Table 4: Statistical and systematic accuracy achievable in the determination of the D_s absolute branching ratios, assuming a collected statistics of 10^7 $\bar{\nu}_\mu$ CC events. The central values are taken from Ref. [1].

the f_{D_s} determination which is in turn affected by large errors. A new method for the evaluation of the D_s branching ratios and of the f_{D_s} decay constant with a systematic accuracy better than 5% has been presented.

The idea is to build an almost pure sample of D_s's by means of the anti-neutrino induced diffractive $D_s^{(*)}$ production. The vertex topology of these events is extremely simple: there is only a muon and a short lived charmed hadron, the D_s. This peculiarity makes the contamination of D^- and Λ_c^- from anti-neutrino deep-inelastic interactions negligible. The diffractive $D^{(*)}$ production yields a contamination of about 3% which is the dominant systematic uncertainty.

In order to make the statistical error at the same level as the systematic one, a copious ($\mathcal{O}(10^7)$) number of anti-neutrino interactions is needed.

At present there are no experiments with both an adequate spatial resolution to fully exploit the diffractive topology and a sufficient anti-neutrino induced CC event statistics. Therefore, the measurement could only be performed at a neutrino factory.

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