A direct evaluation of the $\Lambda_c^+$ absolute branching ratios: a new approach

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Abstract

A novel method for a direct measurement of the exclusive $\Lambda_c^+$ branching ratios is here described. The approach is based on the peculiar topology of the quasi-elastic charm neutrino-induced events on nucleons. The intrinsic potentiality of the method is thoroughly discussed using a perfect detector. As an application, the statistical accuracy reachable with existing data sample has been estimated. From a theoretical point of view, such measurement provides a better understanding of the baryonic $b$-decays.

Submitted to Physics Letters B

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1 Introduction

There exists no direct measurement of \( BR(\Lambda_c^+ \rightarrow p K^- \pi^+) \). However, using different assumptions and experimental data, two indirect determinations of the above branching ratio have been given \([1, 2]\). These two values are quite different, and thus it is likely that one of the procedures is incorrect.

Note that, since the channel \( \Lambda_c^+ \rightarrow p K^- \pi^+ \) is used for normalisation, a change in its branching ratio will affect most of the \( \Lambda_c^+ \)-exclusive decay widths.

Here we propose a method, based on neutrino quasi-elastic charm production process, to directly measure the \( \Lambda_c^+ \)-branching ratios. This measurement, solving the above puzzle, will provide new insight on the underlying hadronic physics.

This letter has the following structure: in Section 2 we discuss the two different determinations of \( BR(\Lambda_c^+ \rightarrow p K^- \pi^+) \) and the physics impact of a direct measurement. In Section 3, the charm production in neutrino scattering is analysed by studying topology, kinematics and cross-sections of quasi-elastic processes and deep inelastic reactions, which are the main source of background. The evaluation of the accuracy achievable for these \( \Lambda_c^+ \)-exclusive decay widths in neutrino scattering is performed in Section 4. In the last section, we give our conclusions.

2 Model dependent extraction of \( BR(\Lambda_c^+ \rightarrow p K^- \pi^+) \)

As stated above, two different methods to extract \( BR(\Lambda_c^+ \rightarrow p K^- \pi^+) \) from the experimental data have been proposed in literature \([1, 2]\).

**Method A**

The ARGUS \([3]\) and CLEO \([4]\) experiments have measured the quantity \( BR(\bar{B} \rightarrow \Lambda_c^+ X) \times BR(\Lambda_c^+ \rightarrow p K^- \pi^+) \). Moreover, under the assumptions that \( \Gamma(\bar{B} \rightarrow \text{baryon } X) \) is dominated by \( \bar{B} \rightarrow \Lambda_c^+ X \), CLEO \([4]\) and ARGUS \([5]\) have been able to determine the branching ratio \( BR(\bar{B} \rightarrow \Lambda_c^+ X) \). Thus, combining these above measurements one obtains \([1]\)

\[
BR(\Lambda_c^+ \rightarrow p K^- \pi^+) = (4.14 \pm 0.91)\%.
\]

It is worth pointing out, as emphasised in \([2]\), that in order to derive \( BR(\bar{B} \rightarrow \Lambda_c^+ X) \)

i) \( \Xi_c \) and \( \Omega_c \) production in \( \bar{B} \)-decays,

ii) \( \bar{B} \rightarrow D^* \bar{N}NX \) like decay channels

have been neglected.

**Method B**

A different determination of \( BR(\Lambda_c^+ \rightarrow p K^- \pi^+) \) is based on the independent measurements of \([6, 7]\)

\[
\sigma(e^+e^- \rightarrow \Lambda_c^+ X) \times BR(\Lambda_c^+ \rightarrow p K^- \pi^+),
\]

2
and \[\sigma(e^+ e^- \rightarrow \Lambda^+_c X) \times \text{BR}(\Lambda^+_c \rightarrow \Lambda l^- \nu_l). \quad (3)\]

Averaging over the results of the two experiments one obtains \[\]

\[
R = \frac{\text{BR}(\Lambda^+_c \rightarrow pK^- \pi^+) \times \sigma(e^+ e^- \rightarrow \Lambda^+_c X) \times \text{BR}(\Lambda^+_c \rightarrow \Lambda l^- \nu_l)}{\text{BR}(\Lambda^+_c \rightarrow \Lambda l^- \nu_l) \times \sigma(e^+ e^- \rightarrow \Lambda^+_c X) \times \text{BR}(\Lambda^+_c \rightarrow \Lambda l^- \nu_l)} = 2.40 \pm 0.43. \quad (4)
\]

Then the branching ratio for \(\Lambda^+_c \rightarrow pK^- \pi^+\) can be obtained from the following relation

\[
\text{BR}(\Lambda^+_c \rightarrow pK^- \pi^+) = \frac{R f F}{1 + |V_{cd}/V_{cs}|^2} \times \Gamma(D^0 \rightarrow X l^+ \nu_l) \times \tau(\Lambda^+_c), \quad (5)
\]

where

\[
f = \frac{\text{BR}(\Lambda^+_c \rightarrow \Lambda l^- \nu_l)}{\text{BR}(\Lambda^+_c \rightarrow X_s l^+ \nu_l)}, \quad (6)
\]

\[
F = \frac{\Gamma(\Lambda^+_c \rightarrow X_s l^+ \nu_l)}{\Gamma(D^0 \rightarrow X_s l^+ \nu_l)}. \quad (7)
\]

The ratio \(f\) is obviously < 1 since there are non-vanishing contributions to the leading \(X_s = \Lambda\) from \(\Sigma^\pm \pi^\mp\), and \(nK^0, pK^-,\) which however are phase space suppressed. The analogous fraction for the meson \(D\) has been measured by CLEO [10]

\[
\frac{\Gamma(D \rightarrow (K + K^*) l^+ \nu_l)}{\Gamma(D \rightarrow X_s l^+ \nu_l)} = 0.89 \pm 0.12. \quad (8)
\]

Thus one can reasonably expect \(f \simeq 0.9 \pm 0.1\). In any case, experiments might measure \(f\) directly.

Theoretical estimates of \(F\) are based on Operator Product Expansion in the framework of the heavy quark effective theory [11], where the amplitudes for \(\Lambda^+_c \rightarrow X_s l^+ \nu_l\) and \(D^0 \rightarrow X_s l^+ \nu_l\) are predicted to have the same leading terms, while the \(O(1/m_c^2)\) corrections are found to be larger for \(\Lambda^+_c\). As a result \(F = 1.3 \pm 0.2\) [11]. Thus, if one uses for \(R\) the value of Eq. (4) and [4] for

\[
1 + |V_{cd}/V_{cs}|^2 = 1.05, \quad (9)
\]

\[
\Gamma(D^0 \rightarrow X l^+ \nu_l) = (0.163 \pm 0.006) \times 10^{12} \, s^{-1}, \quad (10)
\]

\[
\tau(\Lambda^+_c) = (0.206 \pm 0.012) \times 10^{-12} \, s, \quad (11)
\]

we obtain from Eq. (5)

\[
\text{BR}(\Lambda^+_c \rightarrow pK^- \pi^+) = (7.7 \pm 1.5 \pm 2.3)\%. \quad (12)
\]

Ref. [3] gives the weighted value of the two measurements \(\text{BR}(\Lambda^+_c \rightarrow pK^- \pi^+) = (5.0 \pm 1.3)\%\), where also the theoretical uncertainty is included. However, it is also stressed that this number is rather arbitrary. Indeed Ref. [3] advocates method \(B\) suggesting that one should reanalyse the existing \(B \rightarrow \text{baryon}\) sample to look for \(\bar{B} \rightarrow D^* \bar{N} N X\) decay channels. As a result, if this interpretation is correct, then:
Table 1: Predicted quasi-elastic charm production cross-section assuming a neutrino energy of 10 GeV.

| Model | F.R. [12] | S.L. [13] | A.K.K. [14] | A.G.Y.O. [17] | K. [18] |
|-------|-----------|-----------|-----------|---------------|--------|
| \(\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}\) | 0.02 | 0.9 | 0.8 | 0.1 | 0.3 |
| \(\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}\) | 0.06 | 1.6 | 1.0 | 0.06 | - |
| \(\nu_\mu n \rightarrow \mu^- \Lambda_c^+\) | 0.1 | 2.3 | 4.1 | 0.3 | 0.5 |
| \(\nu_\mu n \rightarrow \mu^- \Sigma_c^+\) | 0.01 | 0.5 | - | 0.06 | 0.15 |
| \(\nu_\mu n \rightarrow \mu^- \Sigma_c^{*+}\) | 0.03 | 0.8 | - | 0.03 | - |

3 Neutrino charm production

3.1 Neutrino quasi-elastic charm processes

The simplest exclusive charm-production reaction is the quasi-elastic process where a \(d\)-valence quark is changed into a \(c\)-quark, thus transforming the target nucleon into a charmed baryon. Explicitly the quasi-elastic reactions are

\[
\nu_\mu n \rightarrow \mu^- \Lambda_c^+(2285),
\]

\[
\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}(2455),
\]

\[
\nu_\mu n \rightarrow \mu^- \Sigma_c^+(2455),
\]

\[
\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}(2520),
\]

\[
\nu_\mu n \rightarrow \mu^- \Sigma_c^{*+}(2520).
\]

In literature there are two classes of models which try to describe the processes [13]–[17]. The first class [12]–[17] is based on the \(SU(4)\) flavour symmetry, but since \(SU(4)\) is badly broken, the parameters (axial and vectorial mass) entering the cross-section formula cannot be reliably predicted.

A different approach [18] is based on the Bloom-Gilman [19] local duality in \(\nu N\) scattering modified on the basis of QCD [20, 21].

The cross-sections predicted by the different models, assuming a neutrino energy of 10 GeV, are shown in Table 1. As we can see, these predictions can even differ by one order of magnitude. From Fig. 3 in Refs. [13] and [18] we note that the total cross-section in both models is almost flat for a neutrino energy larger than 8 GeV.

Only one measurement of the neutrino quasi-elastic charm production cross-section exists. The E531 experiment [22], based on a sample of 3 events and
\begin{table}
\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
  Reaction          & \(\sigma(10^{-39} \text{ cm}^2)\) & \(\mathcal{R}\) & Expected events \\
\hline
  \(\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}\) & 0.14 & 0.14 & 1400 \\
  \(\nu_\mu p \rightarrow \mu^- \Sigma_c^{++}\) & 0.06 & 0.06 & 600 \\
  \(\nu_\mu p \rightarrow \mu^- \Lambda_c^+\) & 0.3 & 0.3 & 3000 \\
  \(\nu_\mu n \rightarrow \mu^- \Sigma_c^+\) & 0.07 & 0.07 & 700 \\
  \(\nu_\mu n \rightarrow \mu^- \Sigma_c^{++}\) & 0.03 & 0.03 & 300 \\
  All & 0.6 & 0.6 & 6000 \\
\hline
\end{tabular}
\end{center}
\end{table}

Table 2: Quasi-elastic charm production cross-section and its contribution to the total charged-current neutrino cross-section. In the last column the expected number of events, assuming a starting sample of 1 million charge-current neutrino-induced events, is shown.

Using a neutrino beam with an average energy of \(\sim 22 \text{ GeV}\), measured the \(\Lambda_c^+\) quasi-elastic production cross-section to be:

\[
\sigma(\nu_\mu n \rightarrow \mu^- \Lambda_c^+) = 0.37^{+0.37}_{-0.23} \times 10^{-39} \text{ cm}^2
\]

\[
\mathcal{R} \equiv \frac{\sigma(\nu_\mu n \rightarrow \mu^- \Lambda_c^+)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = 0.3^{+0.3}_{-0.2}\%
\]

Despite the large statistical error, this measurement is clearly inconsistent with the predictions of Refs. [13]-[16], while the agreement is fair for [12, 17, 18]. An average value of the cross-sections predicted by Refs. [12, 17, 18] has been used to have a rough estimate of the expected number of events, see Table 2.

### 3.2 Topology of the quasi-elastic events

In the quasi-elastic processes (13)-(17), besides the charmed baryon, only a muon is produced at the interaction point (primary vertex). For reaction (13) we expect the topology shown in Fig. 1a), namely, a muon track plus the \(\Lambda_c^+\) immediately decaying. For reactions (14) and (16), since the produced \(\Sigma_c^{++}\) strongly decays into a \(\Lambda_c^+\) and a \(\pi\), we expect three charged particles at the primary vertex as shown in Fig. 1c). For reactions (15) and (17) we expect a number of charged particles produced at the primary vertex equal to the one of reaction (13), plus a neutral pion produced in the \(\Sigma_c^{++}\) decay (see Fig. 1c)).

Indeed, these events are characterised by a peculiar topology: two charged tracks produced at the primary vertex, with \(\Sigma_c\), if present, decaying strongly. In any case, the final charmed baryon can only be a \(\Lambda_c^+\). This feature is very important and will be exploited heavily in the following.
3.3 Kinematics of the quasi-elastic reaction

Let us assume, for simplicity, the initial nucleon at rest. In this frame, given the transferred 4-momentum squared \( q^2 \), the energy of the charmed baryon is

\[
E_C = \frac{q^2 + m_C^2 + m_N^2}{2m_N},
\]

where \( m_C \) is its mass and \( m_N \) is the mass of the struck nucleon. The \( q^2 \)-distribution, at a fixed neutrino energy, \((1/\sigma) d\sigma/dq^2\) is in general model dependent \([12]-[18]\). Nevertheless, despite the large disagreement in the theoretical total cross-sections, the predicted \( q^2 \)-distributions are very similar and lie mostly in the range \( 0 < q^2 < 2 \text{ GeV}^2 \). We study the kinematics of the quasi-elastic process at different values of \( q^2 \) integrating over the neutrino energy spectrum\(^2\).

As reference values of \( q^2 \) we use \((0.1, 0.5, 1, 2) \text{ GeV}^2 \). The flight length and the decay kinematics of the \( \Lambda_c^+ \) have been evaluated using the package PYTHIA5.7/JETSET7.4 \([24]\). The flight length distributions for four different \( q^2 \) values are shown in Fig. 2. From this figure we can see that, because of the small \( \gamma \) factor, almost all the \( \Lambda_c^+ \) decay within 500 \( \mu m \) from the production point. This parameter is crucial when we start thinking of a detector able to see the topologies shown in Fig. 1.

3.4 Deep inelastic charm processes

Charmed hadrons can be produced in deep inelastic neutrino interactions through the reaction \( \nu_\mu N \rightarrow \mu^- CX \), where \( C = D^0, D^+, D_s^+, \Lambda_c^+ \) and \( X \) is purely hadronic. Using the CERN-SPS WANF neutrino beam \([23]\), \((57\pm5)\%\) of the charmed particles produced in deep inelastic interactions is neutral. The rest can be split as follows: \((19\pm4)\%\ D^+, (12\pm4)\%\ D_s^+\) and \((12\pm3)\%\ \Lambda_c^+\). For details about the charm production fractions in neutrino interactions we refer

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\(^2\)As an example of neutrino beam we considered the CERN-SPS WANF neutrino beam \([23]\), which has an average energy of about of 27 GeV.
Figure 2: Flight length distribution for different $q^2$ values: a) $q^2 = 0.1$ GeV$^2$, b) $q^2 = 0.5$ GeV$^2$, c) $q^2 = 1$ GeV$^2$, d) $q^2 = 2$ GeV$^2$.

to [23].

Through a Monte Carlo simulation, we also checked that (15.48±0.09)% of the deep inelastic events with a charmed hadron in the final state has a topology similar to those shown in Fig. 1a) and Fig. 1b) and (8.43±0.04)% to the one in Fig. 1c).

### 3.5 Quasi-elastic versus deep inelastic charm events

A suitable variable to discriminate quasi-elastic from deep inelastic events is the visible hadronic energy, see Fig. 3. According to Eq. (18), a large fraction of the visible energy in quasi-elastic events is expected to lie in the range (3±5) GeV. It is, indeed, possible to achieve a high rejection power against deep inelastic events keeping high efficiency for quasi-elastic ones. For example, the cut $E_{\text{vis}} \leq 5$ GeV rejects (97.1±0.1)% of the deep inelastic processes keeping more than 90% of quasi-elastic events.

It is important to have high rejection power against deep inelastic charm production due to its large cross-section [22] ($\sigma(\nu_\mu N \to \mu^- CX)/\sigma(\nu_\mu N \to \mu^- X) \sim 5\%$, $R = 0.6\%$) and to the fact that not only $\Lambda^+_c$, but also $D^+$ and $D^+_s$ are produced. In fact, $D^+$ or $D^+_s$ hadrons, wrongly identified, could bias the determination of the $\Lambda^+_c$ branching ratios. The quasi-elastic sample contamination, which comes from deep inelastic events, can be written using Table 1 as

$$\varepsilon_{\text{fake}} = \frac{\sigma(\nu_\mu N \to \mu^- CX)}{\sigma(\nu_\mu N \to \mu^- X)} \times \frac{1}{R} \times f_{\text{fake}} \times f_{E<5\text{GeV}} \times f_{(D^+orD^+_s)}.$$  \hspace{1cm} (19)

\textsuperscript{3}This result includes also the production of neutral charmed particles.
Table 3: The relative and absolute errors on $\varepsilon_{\text{fake}}$ are shown as a function of the relative error on $R$.

The factor $f_{\text{fake}} (= (23.9 \pm 0.1)\%)$ denotes the fraction of deep inelastic events which fakes a quasi-elastic topology, $f_{E<5\text{GeV}} (= (2.9 \pm 0.1)\%)$ is the fraction of the deep inelastic events which survives to the energy cut, and $f_{(D^+\text{or } D_s^+)} (= (8.2 \pm 0.4)\%)$ is the fraction, among fake quasi-elastics, with a charmed meson in the final state. Hence, the contamination is $\varepsilon_{\text{fake}} \simeq 0.5\%$. The relative error on $\varepsilon_{\text{fake}}$ as a function of the relative error on $R$ is shown in Table 3.

4 Description of the method

Due to the peculiar topology and kinematics of the quasi-elastic events an almost pure sample of $\Lambda_c^+$, with a small contamination of $D^+$ and $D_s^+$ produced in deep
inelastic events, can be selected. No model dependent information is used to
determine the number of $\Lambda_+^{c}$. The contamination of $D^{+}$ and $D_0^{+}$ from deep
inelastic events can be taken into account assigning it as relative systematic
error on the branching ratios. We assumed the relative systematic error to be
$\varepsilon_{\text{fake}} + 3\sigma_{\text{fake}}$. The normalisation to determine the $\Lambda_+^{c}$ absolute branching
ratios is simply given by the number of events with a vertex topology consistent
with Fig. 1. We want to stress, here, that no model dependent information is
used to determine the normalisation. The little knowledge we have about the
quasi-elastic charm production cross-section, which is model dependent unless
measured, plays a role only in the evaluation of the deep inelastic contamination,
namely the systematic error. It is worth noticing that, even if the ratio $R$
is known with an uncertainty of 500%\(^4\), the relative systematic error on the
branching ratios is $\sim 7.2\%$ (see Table 3).

4.1 Measurement accuracy in a perfect detector

The perfect detector by definition has the following features:

- vertex topology measurement with 100% efficiency resolution for charmed
  baryon decays;
- infinite energy resolution;
- particle identification capability with infinite resolution.

In Table 4 the expected accuracy on the determination of the $\Lambda_+^{c}$ branching
ratios as a function of the relative error on $R$ is shown. To compute the expected
number of events in each decay channel we used the central values (shown in
Table 4 together with their errors) given by the Particle Data Group \(^1\). From
this Table we can see that, even assuming very large (unrealistic) systematic
error, it is still possible to discriminate among methods $A$ and $B$ discussed in
Section 2. In Table 5 the achievable accuracy on the absolute $BR$ determination
as a function of the collected charged-current statistics is shown.

4.2 Measurement accuracy with statistics of present and
future experiments

Among the neutrino experiments which are currently taking data or analysing
data, CHORUS \(^2\), which uses nuclear emulsions as a target, has an adequate
spatial resolution to fully exploit the topologies shown in Fig. 1. Starting from a
sample of about of 500000 charged-current events, it is estimated that $\sim 350000$
events will be analysed in the emulsions \(^2\). Assuming a 50% efficiency to
detect the $\Lambda_+^{c}$ decay and taking into account that $R = 0.6\%$, a statistics of $\sim$
1000 quasi-elastic events can be expected. Due to the good muon identification
of the electronic detector and the emulsion capability in identifying electrons,

\(^4\)Nevertheless, this is not the case. We recall that E531 \(^2\), with only 3 events observed,
measured $R$ with an accuracy of 100%.
| Channel             | PDG BR | $\Delta BR$ ($\frac{N}{N} = 10\%$) | $\Delta BR$ ($\frac{N}{N} = 100\%$) | $\Delta BR$ ($\frac{N}{N} = 500\%$) |
|---------------------|--------|-----------------------------------|------------------------------------|--------------------------------------|
| $\Lambda^+_c \rightarrow pK^\circ$ | $(2.5\pm0.7)\%$ | $(\pm0.2\pm0.02)\%$ | $(\pm0.2\pm0.05)\%$ | $(\pm0.2\pm0.2)\%$ |
| $\Lambda^+_c \rightarrow pK^\pi^+\pi^-$ | $(5.0\pm1.3)\%$ | $(\pm0.3\pm0.04)\%$ | $(\pm0.3\pm0.09)\%$ | $(\pm0.3\pm0.4)\%$ |
| $\Lambda^+_c \rightarrow pK^\Lambda^0\eta$ | $(1.3\pm0.4)\%$ | $(\pm0.1\pm0.01)\%$ | $(\pm0.1\pm0.02)\%$ | $(\pm0.1\pm0.09)\%$ |
| $\Lambda^+_c \rightarrow pK^\pi^+\pi^-$ | $(2.4\pm1.1)\%$ | $(\pm0.2\pm0.02)\%$ | $(\pm0.2\pm0.04)\%$ | $(\pm0.2\pm0.2)\%$ |
| $\Lambda^+_c \rightarrow pK^\pi^+\pi^-$ | $(4.7\pm1.3)\%$ | $(\pm0.3\pm0.04)\%$ | $(\pm0.3\pm0.08)\%$ | $(\pm0.3\pm0.3)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\pi^+\pi^0$ | $(3.6\pm1.3)\%$ | $(\pm0.2\pm0.03)\%$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.2\pm0.3)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\pi^+\pi^0$ | $(3.3\pm1.0)\%$ | $(\pm0.2\pm0.02)\%$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.2\pm0.2)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\pi^+\pi^0$ | $(1.7\pm0.6)\%$ | $(\pm0.2\pm0.01)\%$ | $(\pm0.2\pm0.03)\%$ | $(\pm0.2\pm0.1)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^+\pi^0$ | $(1.0\pm0.3)\%$ | $(\pm0.1\pm0.01)\%$ | $(\pm0.1\pm0.02)\%$ | $(\pm0.1\pm0.07)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^+\pi^+\pi^-$ | $(3.4\pm1.0)\%$ | $(\pm0.2\pm0.02)\%$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.2\pm0.2)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^-$ | $(1.8\pm0.8)\%$ | $(\pm0.2\pm0.01)\%$ | $(\pm0.2\pm0.03)\%$ | $(\pm0.2\pm0.1)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^-$ | $(1.8\pm0.8)\%$ | $(\pm0.2\pm0.01)\%$ | $(\pm0.2\pm0.03)\%$ | $(\pm0.2\pm0.1)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^-$ | $(1.1\pm0.4)\%$ | $(\pm0.1\pm0.01)\%$ | $(\pm0.1\pm0.02)\%$ | $(\pm0.1\pm0.08)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^-$ | $(2.7\pm1.0)\%$ | $(\pm0.2\pm0.02)\%$ | $(\pm0.2\pm0.05)\%$ | $(\pm0.2\pm0.2)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\mu^+\nu\mu$ | $(2.0\pm0.7)\%$ | $(\pm0.2\pm0.01)\%$ | $(\pm0.2\pm0.04)\%$ | $(\pm0.2\pm0.1)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\nu^+\nu\mu$ | $(2.1\pm0.7)\%$ | $(\pm0.2\pm0.01)\%$ | $(\pm0.2\pm0.04)\%$ | $(\pm0.2\pm0.2)\%$ |

Table 4: Statistical and systematic accuracy achievable in the determination of the $\Lambda^+_c$ absolute branching ratios, assuming a collected statistics of $10^6\ \nu\mu$ charged-current events, as a function of the relative error on $\mathcal{R}$. The central values are taken from ref. $[1]$. 

| Channel             | $N_\mu = 10^6$ | $N_\mu = 10^6$ | $N_\mu = 10^6$ |
|---------------------|----------------|----------------|----------------|
| $\Lambda^+_c \rightarrow pK^\circ$ | $(\pm0.2\pm0.05)\%$ | $(\pm0.6\pm0.05)\%$ | $(\pm1.8\pm0.05)\%$ |
| $\Lambda^+_c \rightarrow pK^\pi^+\pi^-$ | $(\pm0.3\pm0.09)\%$ | $(\pm0.9\pm0.09)\%$ | $(\pm2.8\pm0.09)\%$ |
| $\Lambda^+_c \rightarrow pK^\pi^+\eta$ | $(\pm0.1\pm0.02)\%$ | $(\pm0.5\pm0.02)\%$ | $(\pm1.7\pm0.02)\%$ |
| $\Lambda^+_c \rightarrow pK^\pi^+\Lambda^0$ | $(\pm0.2\pm0.04)\%$ | $(\pm0.6\pm0.04)\%$ | $(\pm1.0\pm0.04)\%$ |
| $\Lambda^+_c \rightarrow pK^+\pi^+\pi^0$ | $(\pm0.3\pm0.08)\%$ | $(\pm0.9\pm0.08)\%$ | $(\pm2.8\pm0.08)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\pi^+\pi^0$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.8\pm0.06)\%$ | $(\pm2.3\pm0.06)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\pi^+\pi^0$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.7\pm0.06)\%$ | $(\pm2.3\pm0.06)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\pi^+\eta$ | $(\pm0.2\pm0.03)\%$ | $(\pm0.5\pm0.03)\%$ | $(\pm1.7\pm0.03)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^+\pi^+$ | $(\pm0.1\pm0.02)\%$ | $(\pm0.4\pm0.02)\%$ | $(\pm1.0\pm0.02)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^0$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.7\pm0.06)\%$ | $(\pm2.3\pm0.06)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^+\pi^+\pi^0$ | $(\pm0.2\pm0.06)\%$ | $(\pm0.5\pm0.03)\%$ | $(\pm1.7\pm0.03)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^0$ | $(\pm0.1\pm0.02)\%$ | $(\pm0.4\pm0.02)\%$ | $(\pm1.0\pm0.02)\%$ |
| $\Lambda^+_c \rightarrow \Sigma^0\pi^+\pi^0$ | $(\pm0.2\pm0.05)\%$ | $(\pm0.7\pm0.05)\%$ | $(\pm2.2\pm0.05)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\mu^+\nu\mu$ | $(\pm0.2\pm0.04)\%$ | $(\pm0.6\pm0.04)\%$ | $(\pm1.8\pm0.04)\%$ |
| $\Lambda^+_c \rightarrow \Lambda\nu^+\nu\mu$ | $(\pm0.2\pm0.04)\%$ | $(\pm0.6\pm0.04)\%$ | $(\pm1.8\pm0.04)\%$ |

Table 5: Accuracy achievable ($\Delta BR$), assuming a 100% error on $\mathcal{R}$, as a function of the collected charged-current statistics.
CHORUS is well suited to study $\Lambda_c^+$ semi-leptonic decays. Assuming 100% error on $\mathcal{R}$ and the PDG central value [1], the following accuracy could be achieved:

$$
\Delta BR(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (\pm 0.44 |_{\text{stat}} \pm 0.01 |_{\text{sys}})\% \quad (20)
$$

$$
\Delta BR(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (\pm 0.45 |_{\text{stat}} \pm 0.01 |_{\text{sys}})\% \quad (21)
$$

A measurement with higher sensitivity could be performed exposing a dedicated detector, whose feasibility study has not yet been worked out, at the future neutrino beams from muon storage rings [28]. Such beams could provide $\mathcal{O}(10^6)$ $\nu_\mu - CC$ events/year in a 10 kg fiducial mass detector, 1 km away from the neutrino source, allowing for a strong reduction of the statistical uncertainty on the $\Lambda_c$ branching ratios, see Table [3].

Conclusions

We have presented a new method for a direct evaluation of the $\Lambda_c^+$ branching ratios. We have also stressed that this has very interesting consequences for our understanding of baryon production in charm decays. Even just a good determination of the $\Lambda_c^+$ semi-leptonic exclusive decay widths would be sufficient: indeed from Eq. (4) we would determine $BR(\Lambda_c^+ \to pK^-\pi^+)$, very important phenomenologically as pointed out particularly in Section [2]. We have also shown that, already with existing data, it should be possible to perform a direct measurement of $\Lambda_c^+$ exclusive decay widths, which is lacking to date.

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