Several physics analyses could profit from a better knowledge of $\rho$, cross-section measurements have been published up to now, in general poor precision. $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section.

I. The neutrino cross-section measurements


Open access: neutrino cross-section, neutrino beam, neutrino factory

No cross-section has been published at low $Q^2$, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section, $\sigma (F) \approx \sigma (F')$ is not meaningful at all on cross-section.

Abstract

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Neutrino beam from muon decay

Neutrino cross-section measurement with...
- *Atmospheric neutrino analysis.* The present atmospheric neutrino measurements suffer from a poor knowledge of $\sigma_\nu$, which forces the use of double-ratios in order to cancel the systematics (the absolute rates are not reliable). The precision on the measurement of $\Delta m_{23}$ and $\theta_{23}$ is limited by systematics on the flux and on the cross-sections. Also, the study whether the atmospheric neutrino anomaly is due to $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_\tau$ oscillations is limited by cross-sections uncertainties, and $\nu_\tau$ appearance search requires detailed understanding of final state topologies.

- *Proton decay searches.* A good knowledge of the $\nu$ cross-section is required to evaluate in a reliable way the expected backgrounds. An accurate modeling of the background is needed for these channels that require background subtraction.

- *Long Baseline neutrinos.* One of the main goals of the Long Baseline neutrino programs is the precise measurement of the mixing parameters using appearance experiments, for which it is mandatory a careful understanding of the expected backgrounds.

- *Astrophysics.* The neutrino-nucleus cross-sections are also required for calculating certain astrophysical processes involving interactions in the outer shells of stars undergoing supernova explosions, which cause further nucleosynthesis to occur, changing the nuclear composition of the star.

In addition, the nuclear targets vastly complicate the description of the neutrino reactions. Effects like the target motion, the binding energy or the final state interactions (specially important in proton decay searches) can depend on the neutrino helicity and on the target type. Even if there is a number of theoretical models trying to account for nuclear effects in neutrino interactions, only a few comparisons with experimental data are available.

For all these reasons, it is clear that a new and precise measurement of the neutrino cross-sections is needed.

## 2 Measurement of $\sigma_\nu$ : The idea and the assumptions

The idea proposed here is based on the use of a low energy muon beam as source of neutrinos. This has two clear advantages compared to the traditional pion beams: in one hand, it is possible to measure, at the same time, $\nu_\mu$ and $\nu_\tau$ cross-sections and both helicities (selecting the muon sign, $\mu^- \rightarrow \nu_\mu \bar{\nu}_\tau e^-$ or $\mu^+ \rightarrow \bar{\nu}_\mu \nu_\tau e^+$); on the other, the measurement is done in a low contamination environment and one profits from the precise knowledge of the muon flux.

The analysis presented in this paper assumes a low energy ($E_\mu = 2$ GeV) and low intensity $\mu^-$ beam of $10^{15}$ \textsuperscript{2} useful muons/year. The detector is considered to be a cylinder of 1 m radius with a moderate mass of 100 tons (a narrow and

\textsuperscript{2} muons decaying on the direction of the detector
long detector clearly benefits from the beam shape characteristics). Because of the limited geometrical acceptance of the detector, it is clear that placing it as close as possible to the muon storage ring will increase the flux of neutrinos traversing the cylinder: the shorter the baseline, the higher the statistics and the smaller the error. Therefore, the baseline is fixed to 10 meters. The length of the straight section of the muon storage ring is fixed to 30 meters.

As shown in section 3, the above conditions allow a measurement of $\sigma_\nu / E_\nu$ below 2 GeV with $\sim 10\%$ error and a bin size of 100 MeV. Many channels can be studied under this assumptions (and this counts for both, $\nu_\mu$ and $\bar{\nu}_e$):

(1) Charge Current (CC) interactions ($\nu N \rightarrow l X$):
   - Quasi-elastic (QE) interaction ($\nu N \rightarrow l N'$)
   - Single/Multi pion production ($\nu N \rightarrow l N' + n \pi$, $n > 0$)
   - Resonant ($\nu N \rightarrow l N^*$ or $\nu N \rightarrow l N')$
   - Deep-inelastic scattering ($\nu q \rightarrow l q'$ or $\nu q \rightarrow l q$)

(2) Neutral Current (NC) interactions ($\nu N \rightarrow \nu N + \pi^0$, $n \geq 0$)

(3) Elastic electron scattering ($\nu e^- \rightarrow \nu e^-$):

The CC (NC) events are characterized by the presence (absence) of a lepton in the final state. Specially important is the measurement of the QE channels, since the $\nu_\mu$ QE interaction is the dominant atmospheric reaction in a water Čerenkov detectors like SuperK ($\sim 60\%$ of the total CC events). A good particle identification and energy resolutions are desired to separate between the charged ($\sim 27\%$) and the neutral ($\sim 10\%$) single pion production channels. The study of the Resonant interactions is specially relevant since it can be an important source of background for proton decay events. Finally, if the detector energy threshold for electrons is low enough ($< 10$ MeV), the measurement of the elastic electron scattering cross-sections can be extremely useful for solar neutrino studies. No particle miss-identification is assumed in this analysis.

3 Results

As described in section 2, we assume a flux of intensity $10^{15}$ useful muons/year of 2 GeV energy. The detector is considered to be a cylinder of 1 m radius with a total mass of 100 tons. The baseline is 10 meters. Under these conditions, the quoted number of expected $\nu_\mu$ and $\bar{\nu}_e$ events/year from charge-current, quasi-elastic and resonant events can be found in Table 1.

The proposed set-up allows a clean measurement of the different neutrino cross-sections with a small error and a high number of data points, as shown in Figure 1. The four plots on the left part of the figure give the relative errors on $\sigma_\nu / E_\nu$ as a function of the neutrino energy ($\bar{\nu}_e$ and $\nu_\mu$) for charge-current and quasi-elastic interactions. The bin size is 100 MeV. Above 0.5 GeV, the largest part of the points exhibit an error smaller than 10%. Figure 1 (right)
Fig. 1. Left: Survey of the present $\sigma_{\nu}\mu$ published data. Right: Obtained $\sigma_{\nu}/E_{\nu}$ spectra for $\nu_{\mu}$ interactions with the proposed method.

shows the final obtained $\sigma_{\nu}/E_{\nu}$ spectrum for the three $\nu_{\mu}$ interactions. The dotted lines are the theoretical predictions from the NUX model.

One attractive feature of the idea launched on this paper is that with moderate means we can do a relevant measurement. The requirements in terms of intensities and energies are far below the neutrino factory needs, for instance (a factor ~ $10^{-5}$ a 10 less, respectively). Also the required detector sizes (a factor $10^{-2}$ less) and the baseline are much smaller. Specially interesting should be to perform the cross-section measurements using different types of detectors since some nuclear effects (like final state interactions) depend on the nature of the target (water, Iron, Argon, etc.). Moreover, this can allow a test of the full detector (measuring efficiencies, backgrounds, etc.) in real conditions and much before the starting of the neutrino factory program.

<table>
<thead>
<tr>
<th>$\nu_{\mu}$</th>
<th>$\bar{\nu}_{e}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Charge-Current (QE+DIS)</td>
<td>5600</td>
</tr>
<tr>
<td>Quasi-Elastic interactions (QE)</td>
<td>2460</td>
</tr>
<tr>
<td>Resonances</td>
<td>1450</td>
</tr>
</tbody>
</table>

Table 1
Expected number of CC, QE and Resonant events/year from $\nu_{\mu}$ and $\bar{\nu}_{e}$ interactions.

References