Spin asymmetry in single pion production induced by weak interactions of neutrinos with the polarized nucleons

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The single pion production (SPP) in the charged-current neutrino (antineutrino) scattering off the polarized nucleon is discussed. The spin asymmetry is predicted within two approaches. The longitudinal and perpendicular, to the neutrino momentum, spin polarizations of the target nucleon are considered. It is shown, in several examples, that the spin asymmetry contains complementary to spin averaged cross section measurements information about the SPP dynamics. Indeed, the spin asymmetry is sensitive to the nonresonance background description of the SPP model. For the normal polarization of the target the spin asymmetry is given by the interference between the resonance and the nonresonance contributions.

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1. INTRODUCTION

The neutrino oscillation phenomenon has been investigated for several decades. The oscillation parameters are relatively well established [1], however, still two parameters, δ – CP-violation phase and θ_{23} – mixing angle, are poorly known [2].

In the simplest two-flavor scenario the probability for the oscillation \( \nu_\alpha \rightarrow \nu_\beta \) reads

\[
P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2(2\theta) \sin^2(\Delta m^2 L/4E),
\]

where \( \Delta m \) is neutrino mass differences, \( \theta \) is a mixing angle, \( E \) is the neutrino energy, while \( L \) is a distance between the source of the neutrinos and the detector.

In the long baseline experiments, such as T2K [1] or Nova [3], the distance \( L \) is known. The neutrino beam, produced at accelerator, consists of mainly muon neutrinos of the energy of the order of 1 GeV. However, the beam is not monochromatic and its energy profile is obtained from the analysis of the interaction of the neutrinos with the target. Therefore the determination of the oscillation parameters depends on the accuracy in estimation of the neutrino energy.

Usually the neutrino energy is reconstructed from the analysis of the quasielastic (QE) neutrino-nucleus scattering. The reconstruction bases on the knowledge of the neutrino-nucleon and the neutrino-nucleus cross sections [4,5]. However, in the 1 GeV energy range a sizable fraction of the detected interactions is inelastic. In particular, the so-called single pion production (SPP) processes are distinguished. The SPP events contribute to the background for the measurement of the QE scattering. Moreover, the neutral current \( \pi^0 \) production events can be mislead with the signal for \( \nu_\mu \rightarrow \nu_e \) oscillation.

Intense studies of the fundamental neutrino properties caused a new interest in the investigation of the neutrino-nucleon and the neutrino-nucleus scattering. In this work we focus on the problem of the single pion production in the neutrino-nucleon scattering in the energy range characteristic for the long baseline neutrino oscillation experiments. This topic has been studied theoretically [6-26] and experimentally [27-32] for last fifty years.

The SPP scattering amplitude is dominated by the resonance (RES) contribution given by a weak nucleon-resonance transition. However, a complete SPP model should include also the diagrams describing the so-called nonresonance background (NB) terms. The way the RES and NB contributions are treated gives rise to the differences between various theoretical approaches.

In order to test the SPP models their predictions must be confronted with the experimental measurements of the neutrino-nucleon and the neutrino-nucleus cross sections. As it is explained in our previous paper [33], the spin averaged cross sections contain only a part of the information about the dynamical structure of the SPP amplitudes. The complementary information can be obtained from the analysis of the polarization transfer (PT) observables.

The investigation of the PT in the neutrino-nucleon and the neutrino-nucleus scattering have been discussed since sixties [33-46]. Recently in [33,47] we reported the results of the discussion of the impact of the NB contribution on the PT observables. It was shown that the components of the polarizations of the charged lepton and the final nucleon contain a unique information about the relative phase between the RES and NB amplitudes which can be used to constrain theoretical models, in particular, the description of the nonresonant background.

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FIG. 1: The longitudinal target polarization. The full balls denote the target, the direction of the polarization is indicated by the dashed arrow.

FIG. 2: The perpendicular target polarization. The full balls denote the target, the direction of the polarization is indicated by the dashed arrow.

In this report, instead of analyzing the polarizations of the final particles, the neutrino scattering off the polarized target is considered. We propose to investigate properties of a spin asymmetry observable. Similar quantity was discussed for the elastic electron-nucleon and the electron-nucleus scattering [48, 49]. Indeed, the measurement of the asymmetry in the electron-nucleon scattering was proposed as an alternative technique, to the Rosenbluth method, for getting the electric and magnetic form factors of the nucleon \(^1\). In this work we calculate and analyze the spin asymmetry in the SPP induced by interactions of the neutrinos with the nucleons. We show that this observable is sensitive to the NB contribution. Hence, the spin asymmetry contain unique information about the SPP dynamics not accessible in the spin averaged cross section measurements.

Similarly as in [33], two different SPP approaches are consider [8, 51]. Our studies are restricted to the neutrinos of the energy of the order of 1 GeV. Therefore to model the RES contribution we consider only the weak \(N \to \Delta(1232)\) transition. The predictions are made for full models (RES and NB contributions) and the version of the models with resonance contribution only.

The paper is organized as it follows: in Sec. [2] the necessary formalism is introduced, Sec. [3] presents the numerical results and their discussion, a summary is given in Sec. [4].

### 2. SPIN ASYMMETRY

Let us consider the SPP processes induced by the charged current muon neutrino/antineutrino interactions with the polarized nucleon target, namely

\[
\begin{align*}
\nu_\mu (k) + \vec{N}(p, s) &\rightarrow \mu^- (k') + N'(p') + \pi(k_\pi), \\
\bar{\nu}_\mu (k) + \vec{N}(p, s) &\rightarrow \mu^+ (k') + N'(p') + \pi(k_\pi),
\end{align*}
\]

where \(k^\alpha = (E, k)\) and \(k'^\alpha = (E', k')\) are the four-momenta of the initial and the final leptons respectively, while \(p^\alpha = (E_p, p)\), \(p'^\alpha = (E'_p, p')\) and \(k_\pi^\alpha = (E_\pi, k_\pi)\) denote the four-momenta of the incoming nucleon (N), the outgoing nucleon (\(N'\)) and the pion respectively. The calculations are made in the laboratory frame, hence the spin four-vector of the target reads

\[
s^\mu = (0, s),
\]

where \(s^2 = 1\).

The four-momentum transfer is given by:

\[
q^\alpha \equiv k^\alpha - k'^\alpha = (\omega, q),
\]

where \(\omega\) and \(q\) denote the transfer of the energy and the momentum respectively.

Let us introduce the hadronic invariant mass

\[
W \equiv (p + q)^2
\]

and

\[
Q^2 \equiv -q^2.
\]

Eventually let \(\Omega(\theta, \phi)\) denotes a solid angle depending on \(\theta \equiv \angle(k, k')\) and \(\phi\) is a corresponding azimuth angle.

We define a spin asymmetry by the ratio:

\[
A(s, d\sigma) = \frac{d\sigma(s) - d\sigma(-s)}{d\sigma(s) + d\sigma(-s)},
\]

where \(d\sigma\) is the differential cross section. The asymmetry is linear in \(s\), namely \(A = s \cdot a\).
FIG. 3: Diagrams contributing to the SPP induced by $\nu N$ interaction in the HNV (blue solid frame) and the FN (red dashed frame) models. The resonance contribution is framed by the densely dotted line. The non-resonance contribution is framed by the loosely dotted line. NP – nucleon pole, CNP – conjugate nucleon pole, CT – contact term, PP – pion pole, PF – pion in flight, $\Delta P$ – $\Delta$ pole, $C\Delta P$ – conjugate $\Delta$ pole.

Two variants of the nucleon polarization are studied, namely:

(i) longitudinal polarization – nucleon polarized along the momentum of the incoming neutrino, see Fig. 1, in this case $s = s^{||}$ and

$$A(s^{||}, d\sigma) \equiv A^{||}(d\sigma);$$

(ii) perpendicular polarization – nucleon polarized along an $x$ axis which is perpendicular to the neutrino momentum, see Fig. 2, in this case $s = s^{\perp}$ and

$$A(s^{\perp}, d\sigma) \equiv A^{\perp}(d\sigma).$$

Notice that in the last variant the $\phi$-dependence of $d\sigma/d\Omega$ can not be trivially integrated out. Indeed the rotational symmetry (along $k$) is broken by the choice of the direction of the target’s spin. In order to perform calculations we choose the coordinates so that

$$\phi = \angle(s^{\perp}, \hat{n}),$$

where $\hat{n}$ is the normal vector of the scattering plane spanned by $k$ and $k'$.

3. RESULTS AND DISCUSSION

3.1. Numerical implementation

Our main objective is to study the properties of the spin asymmetry, in particularly, its sensitivity to the NB contribution. To achieve this goal, similarly as in our previous work [33], in order to perform the calculations, two SPP approaches are considered: the model by Hernandez, Nieves, and Valverde (HNV), as described in [51], and the model by Fogli and Nardulli (FN), as given in [8]. In both descriptions the scattering amplitude is calculated in tree level approximation.

The predictions of the spin asymmetry for neutrino (antineutrino) scattering off longitudinally [8] and perpendicularly [9] polarized target are made for six charged-current SPP processes:

$$\nu_\mu + \vec{p} \rightarrow \mu^- + p + \pi^+$$
$$\nu_\mu + \vec{n} \rightarrow \mu^- + n + \pi^+$$
$$\nu_\mu + \vec{n} \rightarrow \mu^- + p + \pi^0$$
$$\bar{\nu}_\mu + \vec{n} \rightarrow \mu^+ + n + \pi^-$$
$$\bar{\nu}_\mu + \vec{p} \rightarrow \mu^+ + p + \pi^-$$
$$\bar{\nu}_\mu + \vec{p} \rightarrow \mu^+ + n + \pi^0.$$
FIG. 4: Dependence of the asymmetry $A_\parallel(E, \sigma)$ on the energy. The solid/dashed line denotes the full/RES model contributions of the HNV model while dotted-dashed/dotted denotes the full/RES model contributions the FN model. The resonance contribution is given by $|M_{\Delta P} + M_{C\Delta P}|^2$ and $|M_{\Delta P}|^2$ in the HNV and the FN models respectively.

The full amplitude of the HNV model consists of contributions from seven diagrams. The NB amplitudes are obtained from the nonlinear sigma model. The SPP contribution in the FN approach is given by five diagrams, where the NB contribution is motivated by the linear sigma model. All diagrams are plotted in Fig. 3. Our discussion is restricted to the first resonance region, hence, all calculations are performed for $W < 1.4$ GeV.

In the HNV model the NB contribution is given by the following diagrams: nucleon-pole (NP), conjugate nucleon-pole (CNP), contact term (CT), pion in flight (PF) and pion-pole (PP). The $\Delta(1232)$ resonance contribution is described by two diagrams: $\Delta P$ – delta pole, and $C\Delta P$ – conjugate delta pole.

The NB contribution in the FN model consists of three diagrams: pion in flight ($PF$) and two nucleon pole diagrams: $NP$, and $CNP$. But in the latter two diagrams the pseudoscalar pion-nucleon coupling is implemented, in contrast to HNV model, where the pseudovector coupling is considered. The weak $N \to \Delta(1232)$ transition is oversimplified. Indeed, there is only one resonance diagram and the $NW^-\Delta$ vertex is described by only two form factors.

More details about the implementation of both models, the choice of the transition form factors etc. can be found in our previous paper [33].

3.2. Spin asymmetry for longitudinal polarized target

The Fig. 4 presents the plots of the longitudinal spin asymmetry $A_\parallel(\sigma, E)$ calculated for the neutrino and the antineutrino scattering off the polarized target. The asymmetry varies from $-0.5$ to $0.5$. Above $E = 1$ GeV $A_\parallel(\sigma, E)$ weakly depends on the neutrino energy.

For the channels (11) and (14) (related by the isospin symmetry), the NB contribution to $A_\parallel(\sigma, E)$ is negligible. Indeed in this case the resonance contribution, from $\Delta P$, is dominant. Therefore the predictions of $A_\parallel(\sigma, E)$ within the HNV and the FN models are very similar. However, for the other channels the asymmetry is quite model-dependent. Indeed for the processes (12) and (15) (also related by the isospin symmetry) the asymmetry predicted within the HNV and FN models have com-
FIG. 5: Decomposition of the longitudinal asymmetry $A_\parallel(E, \sigma)$, for process (12), into contributions from interference between diagrams. On the diagonal the contribution from $|M_d|^2$ ($M_d$ – matrix element for $d$-diagram) are given, while below diagonal the interference terms $2\Re(M_iM_j^*)$ ($j$ – column, $i$ – row) are plotted. The solid/dotted (black/red) line represents the HNV/FN model predictions.

### 3.3. Spin asymmetry for perpendicularly polarized target

The spin asymmetry is given by the scalar product $s \cdot a$. In the case of the perpendicularly polarized target the components of $s_\perp$ are proportional to either $\sin(\phi)$ or $\cos(\phi)$. As the result the spin asymmetry can be written in the form:

$$A_\perp(\phi) = a_1 \cos(\phi) + a_2 \sin(\phi).$$  \hspace{1cm} (18)

The $A_\perp(\phi)$ is dominated by the sinusoidal part. It is shown in Fig. 7 where the asymmetry $A_\perp(d\sigma/d\phi)$ is plotted. The sinusoidal character is maintained also when the asymmetry is calculated for the flux averaged cross sections, as it is illustrated in Fig. 8 where the
The spin asymmetry $A_{\perp}(\phi)$ has contributions from $a_2 \sin(\phi)$ and $a_1 \cos(\phi)$, however, plots of Figs. 7 and 8 suggest that the $a_2$ is dominant. It is interesting to remark that the $a_1$ component, connected with cosine, is given by the interference between resonance and nonresonance amplitudes. Hence, any deviation of $A_{\perp}(\phi)$ from the sinusoidal dependence is induced by the NB contribution. If the spin vector $s_\perp$ is parallel to normal vector $\mathbf{n}$ then only $a_1$ component contributes to the spin asymmetry. In this case

$$A_{\perp}(\phi = 0^\circ) \sim M_{\text{RES}} M_{NB}^*.$$  

The above property is illustrated in Fig. 10 where we plot the decomposition of $A_{\perp}(\phi = 0^\circ)$ into contributions from various interferences between diagrams.

In Fig. 11 (top panel) we plot $A_{\perp}(\phi = 0^\circ)$ as a function of energy. It is seen that the asymmetry is small but non-vanishing function of the energy. The asymmetry takes the largest values when $s_\perp$ is perpendicular ($\phi = 90^\circ$) to the normal vector $\mathbf{n}$, see Fig. 11 (bottom panel).

4. SUMMARY

The single pion production in the neutrino/antineutrino scattering off the polarized target has been discussed. Two polarization of the target have been considered, namely, longitudinal and perpendicular to the neutrino beam. In both cases the spin asymmetry has been calculated within two different models for the SPP. It is demonstrated, in several examples, that the
spin asymmetry is sensitive to the nonresonant background. Moreover, it is shown that when polarization of the target is parallel to the normal of the scattering plane, the asymmetry is given by the interference between the resonance and the nonresonance diagrams.

Summarizing: the spin symmetry contains additional, with respect to spin averaged cross sections measurements, information about the SPP dynamics, which can be used to constrain significantly the single pion production models.

The scattering amplitudes, cross sections have been calculated using symbolic programming language FORM [53].

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FIG. 8: The dependence of the asymmetry $A_\perp (\theta = 10^\circ, d^2\sigma/d\Omega)$, see Eq. 19, on $\phi$ angle calculated for T2K energy distribution. The solid/dashed line denotes the full/RES model contributions of the HNV model while dotted-dashed/dotted denotes the full/RES model contributions the FN model. The RES contribution is given by $|M_{\Delta P} + M_{C\Delta P}|^2$ and $|M_{\Delta P}|^2$ in the HNV and the FN models respectively.
FIG. 9: Decomposition of $A_{\perp}(E = 1 \text{ GeV}, \frac{d\sigma}{d\phi})$, for the process (12), into contributions from interference between diagrams. On the diagonal the contribution from $|M_d|^2$ ($M_d$—scattering matrix element for $d$-diagram) are given, while below diagonal the interference terms $2\Re(M_i M_j^*)$ ($j$—column, $i$—row) are plotted. The solid/dotted (black/red) line represents the HNV/FN model predictions.
FIG. 10: Decomposition of the perpendicular asymmetry $A_\perp(\phi = 0^\circ, d\sigma/d\phi)$, for the process (11), into contributions from interference between diagrams. On the diagonal the contribution from $|M_d|^2$ ($M_d$–scattering matrix element for $d$-diagram) are given, while below diagonal the interference terms $2\Re(M_iM_j^*)$ ($j$ – column, $i$ – row) are plotted. The solid/dotted (black/red) line represents the HNV/FN model predictions.
FIG. 11: Dependence of the asymmetry $A_{\perp}(d\sigma/d\phi)$ on energy calculated: for $\phi = 0^\circ$ (top panel) and $\phi = 90^\circ$ (bottom panel). The solid/dashed line denotes the full/RES model contributions of the HNV model while dotted-dashed/dotted denotes the full/RES model contributions the FN model. The RES contribution is given by $|M_{\Delta P} + M_{C\Delta P}|^2$ and $|M_{\Delta P}|^2$ in the HNV and the FN models respectively.