Charged Higgs boson contribution to $\nu_{\tau}N \rightarrow \tau^- X$ for very large $\tan \beta$ in the two Higgs doublet model with UHE-neutrinos

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Abstract

We study the deep inelastic process $\nu_{\tau} + N \rightarrow \tau^- + X$ (with $N \equiv (n + p)/2$ an isoscalar nucleon), in the context of the two Higgs doublet model type two (2HDM(II)). In particular, we discuss the contribution to the total cross section of diagrams, in which a charged Higgs boson is exchanged. We show that for large values of $\tan \beta$ such contribution for an inclusive dispersion generated through the collision of an ultrahigh energy tau-neutrino on a target nucleon can reach up to 57% of the value of the contribution of the $W^+$ exchange diagrams (i.e. can reach up to 57% of the standard model (SM) prediction) and could permit to distinguish between the SM and the 2HDM(II) predictions at the Pierre Auger Observatory.

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I. INTRODUCTION.

Although the Standard Model (SM) \[1\], of the strong and electroweak interactions describes correctly Particle Physics at present energies, one of its basic ingredients, the scalar Higgs sector, still remains untested. In the SM, the Higgs sector consists of a single $SU(2)$ doublet, and after spontaneous symmetry breaking (SSB) it remains a physical state, the Higgs boson ($h_{_{SM}}^0$), whose mass is not predicted in the theory. On the other hand, the SM is not expected to be the ultimate theoretical structure responsible for electroweak symmetry breaking (EWSB) \[2, 3\]. One of the most simple extensions of the SM is the so called two Higgs doublet model (2HDM). There are four classes of 2HDM which naturally avoid tree-level flavor-changing neutral currents that can be induced by Higgs boson exchange \[4\]. These models include a Higgs sector with two scalar doublets, which give masses to the up and down-type fermions as well as the gauge bosons. Particularly interesting is the model II, in this model one of the Higgs scalar doublet couples to the up-components of isodoublets while the second one to the down-components. Model II is that one which is present in SUSY theories. The 2HDM(II) has a rich structure and predicts interesting phenomenology \[2\]. The physical spectrum consists of two neutral CP-even states ($h^0, H^0$) and one CP-odd ($A^0$), as well as a pair of charged scalar particles ($H^{\pm}$). The charged Higgs boson in this model has the following lower mass limits \[5\] and \[6\]:

\[
M_{H^\pm} > 79.3 \text{ GeV}
\]  \(1\)

and

\[
M_{H^\pm} \gtrsim 1.71 \tan \beta \text{ GeV}
\]  \(2\)

Large-scale neutrino telescopes \[4\] have as a main goal the detection of ultrahigh-energy (UHE) cosmic neutrinos ($E_\nu \geq 10^{12} \text{ eV}$) produced outside the atmosphere (neutrinos produced by galactic cosmic rays interacting with interstellar gas, and extragalactic neutrinos) \[8, 9\]. UHE neutrinos can be detected by observing long-range muons and tau-leptons decays produced in charged-current neutrino-nucleon interactions. UHE tau-neutrinos are generated through neutrino oscillations \[10, 11\]. The detection of UHE neutrinos will provide us with the possibility to observe $\nu N$-collisions with a neutrino energy in the range $10^{12} \text{ eV} \leq E_\nu \leq 10^{21} \text{ eV}$ and a target nucleon at rest. An enlightening discussion on UHE neutrino interactions is given by R. Gandhi et al. \[9\].
We discuss in this paper the cross section of the deep inelastic process $\nu_\tau + \mathcal{N} \rightarrow \tau^- + X$ ($\mathcal{N} \equiv (n + p)/2$ an isoscalar nucleon), in the context of the SM and the 2HDM(II) by using the parton model \cite{12} with the parton distribution functions reported by J. Pumplin et al. \cite{13}. We use the CTEQ PDFs provided in a $n_f = 5$ active flavors scheme. Our aim is to calculate how large can be the contribution of diagrams, in which a charged Higgs boson is exchanged, to the total cross section of the mentioned inclusive process in the frame of the 2HDM(II). In the 2HDM(II) the couplings of the down-type quarks and charged leptons are proportional to $m_f \times \tan \beta$. Hence, for large $\tan \beta$ the contribution of $H^\pm$-exchange diagrams will be maximal in this model.

II. THE CROSS SECTION FOR THE INCLUSIVE PROCESS $\nu_\tau + \mathcal{N} \rightarrow \tau^- + X$

A. The differential cross section for the process $\nu_\tau + \mathcal{N} \rightarrow \tau^- + X$ in the SM

The differential cross section for the inclusive reaction

$$\nu_\tau(p) + \mathcal{N}(P_\mathcal{N}) \rightarrow \tau^-(p') + X,$$

where $\mathcal{N} \equiv (n + p)/2$ is an isoscalar nucleon, at the lowest order in $\alpha$ in the frame of the SM (see Fig. 1) is given as follows \cite{14}:

$$d^2\sigma_{\text{sm}} = \frac{2G_F^2 M_{\nu}}{\pi} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \left[ x q_{\text{W}}(x, Q^2) + x \bar{q}_{\text{W}}(x, Q^2)(1 - y)^2 \right],$$

where $M$ stands for the nucleon mass, $Q^2$, $x$ and $y$ are defined as usual

$$s = (p + P_\mathcal{N})^2, \quad Q^2 = -(p - p')^2, \quad \nu = P_\mathcal{N}(p - p'),$$

and

$$x = \frac{Q^2}{2\nu}, \quad y = \frac{2\nu}{s}.$$

The quantities $q_{\text{W}}(x, Q^2)$ and $\bar{q}_{\text{W}}(x, Q^2)$ are given as

$$q_{\text{W}}(x, Q^2) = \frac{u_v(x, Q^2) + d_v(x, Q^2)}{2} + \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} + s_s(x, Q^2) + b_s(x, Q^2),$$

$$\bar{q}_{\text{W}}(x, Q^2) = \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} + c_s(x, Q^2),$$

(7)
FIG. 1: Diagrams which contribute at the quark level to the process $\nu_\tau + N \rightarrow \tau^- + X$ at the lowest order in $\alpha$ in the SM ($d$ stands for $d$, $s$, and $b$-quark; and $u$ stands for $u$- and $c$-quark).

where the valence and sea parton distribution functions (PDFs), $q_v(x, Q^2)$ and $q_s(x, Q^2)$, can be expressed as

$$u_v(x, Q^2) = u(x, Q^2) - \bar{u}(x, Q^2),$$
$$d_v(x, Q^2) = d(x, Q^2) - \bar{d}(x, Q^2),$$
$$u_s(x, Q^2) = \bar{u}(x, Q^2),$$
$$d_s(x, Q^2) = \bar{d}(x, Q^2),$$
$$c_s(x, Q^2) = c(x, Q^2) = \bar{c}(x, Q^2),$$
$$s_s(x, Q^2) = s(x, Q^2) = \bar{s}(x, Q^2),$$
$$b_s(x, Q^2) = b(x, Q^2) = \bar{b}(x, Q^2),$$

where the PDFs $q(x, Q^2)$ describe the quark $q$ content of the proton.

In the case of the standard model the couplings of the fermions to the $W^\pm$ boson are given by the lagrangian

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \sum_{(f_u, f_d)} \left\{ \left( \bar{f}_u \gamma^\mu \frac{1 - \gamma^5}{2} f_d \right) W_{\mu}^+ + \left( \bar{f}_d \gamma^\mu \frac{1 - \gamma^5}{2} f_u \right) W_{\mu}^- \right\},$$

where $f_u$ and $f_d$ stand for the up- and down-components of the fermion doublet.

**B. The differential cross section for the process $\nu_\tau + N \rightarrow \tau^- + X$ in the 2HDM(II)**

The differential cross section for the inclusive reaction (3), at the lowest order in $\alpha$ in the frame of the 2HDM(II) (see Fig. 2), can be written as follows:

$$\frac{d^2\sigma_{2hdm}}{dx dy} = \frac{d^2\sigma_{sm}}{dx dy} + \frac{d^2\sigma_{H^+}}{dx dy},$$

where $f_u$ and $f_d$ stand for the up- and down-components of the fermion doublet.
\[ \begin{align*} 
\nu &\rightarrow W^+ d, \bar{u} \\
\bar{\nu} &\rightarrow W^- u, \bar{d} \\
\end{align*} \]

\[ \begin{align*} 
\nu &\rightarrow H^+ d, \bar{u} \\
\bar{\nu} &\rightarrow H^- u, \bar{d} \\
\end{align*} \]

(a) 
(b)

FIG. 2: Diagrams which contribute at the quark level to the process \( \nu_\tau + N \rightarrow \tau^- + X \) at the lowest order in \( \alpha \) in the 2HDM (\( d \) stands for \( d^- \), \( s^- \) and \( b^- \)-quark; and \( u \) stands for \( u^- \) and \( c^- \)-quark).

where for large \( \tan \beta \)

\[ \frac{d^2 \sigma_{H^+}}{dxdy} = \frac{G_F^2 M E_\nu m_\nu^2 M_W^2 \tan^4 \beta}{(Q^2 + M_{H^\pm}^2)^2} y^2 \left[ xq_H(x, Q^2) + x\overline{q}_H(x, Q^2) \right], \]

where \( Q^2, x \) and \( y \) are defined in (5) and (6) and \( M \) stands for the nucleon mass. The quantities \( q_H(x, Q^2) \) and \( \overline{q}_H(x, Q^2) \) are given as follows

\[ q_H(x, Q^2) = \frac{m_\nu^2}{M_W^2} \left( \frac{u_\nu(x, Q^2) + d_\nu(x, Q^2)}{2} + \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} \right) + \frac{m_s^2}{M_W^2} s_s(x, Q^2) + \frac{m_b^2}{M_W^2} b_s(x, Q^2) \]

\[ \overline{q}_H(x, Q^2) = \frac{m_\nu^2}{M_W^2} \left( \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} \right) + \frac{m_s^2}{M_W^2} c_s(x, Q^2). \]

In the case of the 2HDM(II) the couplings of the fermions to the \( W^\pm \) boson are given, in a similar way as in the SM [2], by the lagrangian in Eq.(9). On the other side, taking the elements of the CKM-matrix \( V_{ij} = \delta_{ij} \), the couplings of the fermions to the \( H^\pm \) boson are given by the lagrangian [2]

\[ \mathcal{L} = \frac{g}{M_W} \left\{ m_\tau \tan \beta \left( \frac{1 + \gamma_5}{2} \tau \right) + m_u \cot \beta \left( \frac{1 - \gamma_5}{2} u \right) + m_d \tan \beta \left( \frac{1 + \gamma_5}{2} d \right) \right\} H^\pm + h.c. \]

III. RESULTS FOR DEEP INELASTIC \( \nu_\tau N \) IN THE SM AND THE 2HDM(II)

We present results for the case of unpolarized deep inelastic process \( \nu_\tau + N \rightarrow \tau^- + X \) with a neutrino energy in the range \( 10^{14} \text{ eV} \leq E_\nu \leq 10^{20} \text{ eV} \) and the nucleon at rest, \( i.e. \) a target nucleon. We take \( 10^{14} \text{ eV} \leq E_\nu \) to make possible to neglect all fermion masses
with respect to the total energy \( s = 2m_NE_\nu \), even the top quark mass. We take cuts of \( \sim 2 \text{ GeV}^2 \) and 10 GeV\(^2\) for \( Q^2 \) and the invariant mass \( W \), respectively. We have checked numerically that the total cross section rates do not depend on the choice of the cuts on the momentum transfer square \( Q^2 \), when they take on values of a few GeV\(^2\). The reason of this fact is that the propagators involved in the cross section calculation go as \( 1/(M_{H^\pm} + Q^2) \) and \( 1/(M_{H^\pm} + Q^2) \).

We perform our numerical calculations taking for the quark masses: \( m_u = 4 \text{ MeV}, \) \( m_d = 8 \text{ MeV}, \) \( m_c = 1.5 \text{ GeV}, \) \( m_s = 150 \text{ MeV}, \) \( m_b = 4.9 \text{ GeV} \) and \( m_t = 174 \text{ GeV} \) \[15\]. For the evaluation of the \( H^+\tau^-\nu_\tau \) coupling we take \( m_{\nu_\tau} = 0 \) and \( m_\tau = 1,777 \text{ MeV} \).

We take \( M_{W^+} = 80.4 \text{ GeV} \) for the mass of the charged boson \( W^+ \) \[15\] and show in Fig. 3 our numerical results for the total cross section as a function of \( E_\nu \). We compare the results for the \( \sigma_{sm}^{tot} \) with those obtained for the \( \sigma_{2hdm}^{tot} \) by taking: (a) \( M_{H^\pm} = 100 \text{ GeV} \) and \( \tan \beta = 50; \) (b) \( M_{H^\pm} = 200 \text{ GeV} \) and \( \tan \beta = 100; \) (c) \( M_{H^\pm} = 300 \text{ GeV} \) and \( \tan \beta = 150; \) (d) \( M_{H^\pm} = 400 \text{ GeV} \) and \( \tan \beta = 200. \) Since in all cases \( M_{H^\pm} = 2 \tan \beta \text{ GeV}, \) then the conditions (1) and (2) are fulfilled. Further, based on the discussions on \( \tan \beta \) given in Refs. \[16\] and \[17\] we restrict ourselves to take \( \tan \beta \leq 200. \)

Further, we present in Fig. 4 our results for the ratio \( \sigma_{H^+}^{tot}(\nu_\tau + N \rightarrow \tau^- + X)/\sigma_{sm}^{tot}(\nu_\tau + N \rightarrow \tau^- + X) \) as a function of \( E_\nu \) for the cases: (a) \( M_{H^\pm} = 100 \text{ GeV} \) and \( \tan \beta = 50; \) (b) \( M_{H^\pm} = 200 \text{ GeV} \) and \( \tan \beta = 100; \) (c) \( M_{H^\pm} = 300 \text{ GeV} \) and \( \tan \beta = 150; \) (d) \( M_{H^\pm} = 400 \text{ GeV} \) and \( \tan \beta = 200. \) In particular, we have gotten \( \sigma_{H^+}^{tot}/\sigma_{sm}^{tot} = 0.57 \) for \( E_\nu = 10^{20} \text{ eV}, \) \( M_{H^\pm} = 400 \text{ GeV} \) and \( \tan \beta = 200. \)

Finally, in Fig. 5 we compare the contribution to \( \sigma_{2hdm}^{tot}(H^+) \) from the different allowed initial quarks (see Fig. 2(b)). We observe in this plot that the contribution from the bottom quark dominates by far.

**IV. CONCLUSIONS**

We have calculated the total cross section rates for the deep inelastic process \( \nu_\tau + N \rightarrow \tau^- + X \), where \( N \equiv (n + p)/2 \) is an isoscalar nucleon, in the frame of the SM and the 2HDM(II). In the case of the 2HDM(II) we have taken into account the contribution of the diagrams in which a charged Higgs boson is exchanged \( \sigma_{H^+}^{tot} \). We have shown that the most important contribution to \( \sigma_{H^+}^{tot} \) comes from the \( H^\pm\)-exchange diagram with an initial
b-quark (and hence an outgoing t-quark). This fact implies that the contribution of the $H^\pm$ exchange diagrams to the total cross section of the $\nu_\tau N$ scattering in the frame of the 2HDM is independent whether the nucleon is a proton, a neutron or an isoscalar nucleon, because these particles have the same content of b-quark.

We showed that the contribution of the charged Higgs boson exchange diagrams could imply an enhancement with respect to the SM cross section rates for the charged current $\nu_\tau N$ deep inelastic scattering. We have obtained that for the case of an ultrahigh energy tau-neutrino ($10^{14}$ eV $\leq E_\nu \leq 10^{20}$ eV) colliding on a target nucleon such enhancement can reach up to 57% and could help to discriminate between the SM and the 2HDM predictions at the Pierre Auger Observatory.

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FIG. 4: $\sigma_{H^±}^{tot}(\nu_τ + N → τ^- + X)/\sigma_{sm}^{tot}(\nu_τ + N → τ^- + X)$ as a function of $E_\nu$ in the range $10^{14}$ eV $\leq E_\nu \leq 10^{20}$ eV, with $E_N = m_N$ for the cases: (a) $M_{H^±} = 100$ GeV and $\tan \beta = 50$; (b) $M_{H^±} = 200$ GeV and $\tan \beta = 100$; (c) $M_{H^±} = 300$ GeV and $\tan \beta = 150$; (d) $M_{H^±} = 400$ GeV and $\tan \beta = 200$.

[1] S. L. Glashow, Nucl. Phys. 22, 579 (1961); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, Proc. 8th NOBEL Symposium, ed. N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

[2] J. Gunion, H. Haber, G. Kane and S. Dawson, The Higgs Hunter’s Guide, Addison-Wesley Publishing Company, Reading, MA, 1990.

[3] H. E. Haber, in Testing the Standard Model, Proceedings of the 1990 Theoretical Advanced Study Institute in Elementary Particle Physics, edited by M. Cvetic and P. Langacker (World Scientific, Singapore, 1991) p. 340-475.

[4] V. D. Barger, J. L. Hewett and R. J. N. Phillips, Phys. Rev. D 41, 3421 (1990).

[5] A. Heister et al. [ALEPH Collaboration], Phys. Lett. B 543, 1 (2002) arXiv:hep-ex/0207054.
FIG. 5: Contribution to $\sigma_{H^+}^{tot}$ from the different allowed initial quarks.

[6] M. Krawczyk and D. Temes, Eur. Phys. J. C 44, 435 (2005) [arXiv:hep-ph/0410248].

[7] AMANDA Collaboration, E. Andres et al., Nature 410, 441 (2001); ANTARES Collaboration, Y. Becherini et al., e-Print Archive: hep-ph/0211173; AUGER Collaboration, D. Zavrtanik et al., Nucl. Phys. Proc. Suppl. 85, 324 (2002); NESTOR Collaboration, P. K. F. Grieder et al., Nuovo Cim. 24C, 771 (2001); RICE Collaboration, I. Kravchenko et al., Astropart. Phys. 19, 15 (2003).

[8] V. S. Beresinsky and G. T. Zatsepin, Phys. Lett. B 28, 423 (1969); V. S. Berezinsky and V. I. Dokuchaev, Nucl. Phys. Proc. Suppl. 110, 522 (2002); V. S. Berezinsky, Nucl. Phys. Proc. Suppl. 38, 363 (1995); and Nucl. Phys. Proc. Suppl. 31, 413 (1993); T. Stanev, Nucl. Phys. Proc. Suppl. 14A, 17 (1990); K. Greisen, Phys. Rev. Lett. 16, 748 (1966); C. T. Hill and D. N. Schramm, Phys. Lett. B 131, 247 (1983); and Phys. Rev. D 31, 564 (1985).

[9] R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Phys. Rev. D 58, 093009 (1998) [arXiv:hep-ph/9807264].

[10] O. Blanch and P. Billoir, "Acceptance and Flux Limit for $\nu_\tau$ with the Pierre Auger Observatory Surface Detector", Preprint LPNHE, Paris (France), September 26, 2005.

[11] X. Bertou, P. Billoir, O. Deligny, C. Lachaud and A. Letessier-Selvon, Astropart. Phys. 17,
183 (2002) [arXiv:astro-ph/0104452].

[12] R. P. Feynman: Photon-hadron interactions. Reading: Benjamin 1972; V.D. Barger and R.J.N. Phillips, Collider Physics (Updated Edition), Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1997.

[13] J. Pumplin et al., JHEP 207, 12 (2002); D. Stump et al., e-Print Archive: [hep-ph/0303013]

[14] M. H. Reno and C. Quigg, Phys. Rev. D 37, 657 (1988); C. Quigg, M. H. Reno and T. P. Walker, Phys. Rev. Lett. 57, 774 (1986).

[15] S. Eidelman et al. [Particle Data Group], Phys. Lett. B 592, 1 (2004).

[16] D. P. Roy, AIP Conf. Proc. 805, 110 (2006) [arXiv:hep-ph/0510070].

[17] H. Baer, J. Ferrandis and X. Tata, Phys. Lett. B 561, 145 (2003) [arXiv:hep-ph/0211418].