

# Production of $W^\mp$ with an anomalous magnetic moment via the collision of an ultrahigh-energy (anti)neutrino on a target nucleon

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We discuss the production of  $W^\mp$  bosons in deep inelastic processes  $(\bar{\nu}_l)\nu_l + \mathcal{N} \rightarrow l^\pm + W^\mp + X$  ( $\mathcal{N}$ :  $P$  proton,  $N$  neutron), in the context of an electroweak model, in which the vector boson self interactions may be different from those prescribed by the electroweak standard model. We present results which show the strong dependence of the cross section on the anomalous magnetic dipole moment  $\kappa$  of the  $W^\pm$ . We show that even small deviations from the standard model value of  $\kappa$  ( $\kappa = 1$ ) could imply large deviations in the cross section rates of  $W^\mp$  production through the collision of an ultrahigh energy (anti)neutrino on a target nucleon. However, the enhancement of the cross section rates is not large enough to be detectable.

*Keywords:* Heavy boson production; ultra-energy neutrinos; neutrino nucleon scattering.

Se discute la producción de bosones  $W^\mp$  en procesos de dispersión muy inelásticos  $(\bar{\nu}_l)\nu_l + \mathcal{N} \rightarrow l^\pm + W^\mp + X$  ( $\mathcal{N}$ :  $P$  protón,  $N$  neutrón), en el contexto de un modelos electrodebil, en el cual las autointeracciones bosónicas pueden ser diferentes de las prescritas por el modelo estándar de la interacción electrodebil. Se presentan resultados que muestran la fuerte dependencia de la sección transeversaql en el momento dipolar magnético anómalo  $\kappa$  del  $W^\pm$ . Se muestra que inclusive pequeñas desviaciones del valor del modelo estándar  $\kappa$  ( $\kappa = 1$ ) podrían implicar grandes desviaciones en el valor de la sección transversal de la producción de bosones  $W^\mp$  a través de la colisión de un (anti) neutrino ultraenergético sobre un nucleón blanco. Sin embargo, el incremento de los valores de la sección trnasversal no es suficientemente grande para ser detectable.

*Descripciones:* Producción de bosones pesados; neutrinos ultraenergéticos dispersión neutrino nucleón.

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## 1. Introduction

One of the most important features of the standard model of electroweak interactions [1] is the non-Abelian gauge nature of the vector bosons. In the present paper, we discuss this point, namely the structure of the self couplings of the electroweak vector bosons. In order to do it, we analyze  $W^\mp$  production in deep inelastic (anti)neutrino-nucleon scattering by using the parton model [2], in the context of an electroweak model with non-standard vector boson self interactions. Such a model was proposed by M. Kuroda *et al.* (KMSS model) [3]. In this model the trilinear vector boson coupling constants depend on only one free parameter,  $\kappa$ , the anomalous magnetic dipole moment of the  $W^\mp$  [4]. The diagrams which contribute to the  $W^\mp$  boson production cross section, at quark level in the lowest order in  $\alpha$ , contain only three vector boson self interactions, hence the boson production rates depend only on  $\kappa$ . At the present time the best limits on  $\kappa$  are  $0.76 < \kappa < 1.36$  from a recent analysis of the L3 Collaboration at LEP [5].

In a previous work [6], we have discussed the heavy boson production via the deep inelastic  $\nu_l\mathcal{N}$  in the context of the standard model. We pointed out there that the process  $\nu_l + \mathcal{N} \rightarrow l^- + W^+ + X$  ( $\mathcal{N}$ :  $P$  proton,  $N$  neutron) is the only one which gets contribution from photon-exchange diagrams, and that its total cross section reaches significant values for ultrahigh-energy (UHE) neutrinos [7] colliding on a target nucleon. Therefore, we restrict ourselves our study to the mentioned process in this paper\*.

In this work, we calculate separately, in the context of the standard model, the contribution to the process  $\nu_l + \mathcal{N} \rightarrow l^- + W^+ + X$  from two different mechanisms which cooperate at the lowest order in  $\alpha$ , keeping only photon exchange diagrams: production at the leptonic vertex, and through the boson self interaction. We show explicitly the compensation via destructive interference inherent to the standard model as a non-Abelian gauge theory. We find that this compensation reaches up to four orders of magnitude, for ultrahigh-energy neutrinos with energy  $E_{\nu_l} \approx 10^{21}$  eV colliding on a target nucleon. Hence, one could expect that even small deviations from the coupling structure of the standard model, like an anomalous dipole magnetic moment different from 1, would lead to observable effects in the predictions for charged boson production in  $\nu_l\mathcal{N}$  collisions.

This paper is organized as follows. In Sec. 2, we take the formulae given in Ref. 6 for heavy boson production in  $\nu_l\mathcal{N}$ -scattering, and extended them for the case of  $W^+$  boson production via the process  $\nu_l + \mathcal{N} \rightarrow l^- + W^+ + X$ , in the frame of an electroweak model, in which the trilinear vector boson coupling constants may deviate through an anomalous magnetic dipole moment term from those given by the standard model. In Sec. 3, we describe briefly the non-standard electroweak model, which we will take for our study. In Sec. 4, we present and discuss our results for the total cross section of deep inelastic process  $\nu_l + \mathcal{N} \rightarrow l^- + W^+ + X$ , which is the only one that gets contribution from  $\gamma$ -exchange diagrams. Finally, in Sec. 5, we summarize our conclusions.

## 2. The differential cross section for non-standard $W^+$ production in $\nu\mathcal{N}$ scattering

We have discussed in Ref. 6 the heavy boson production via deep inelastic  $\nu_l\mathcal{N}$  collisions in the context of the standard model. We showed there that the process

$$\nu_l + \mathcal{N} \rightarrow l^- + W^+ + X \quad (1)$$

is the only one which gets contribution from photon-exchange diagrams, and that its total cross section reaches significant values for UHE neutrinos colliding on a target nucleon. Therefore, we restrict our study to the mentioned reaction in this paper. The diagrams which contribute at the

lowest order in  $\alpha$  at the quark parton level to the cross section of process (1) are depicted in Fig. 1.

We have presented in detail the kinematics of heavy boson production in deep inelastic  $\nu_l\mathcal{N}$  scattering in Ref. 6, and have pointed out there how to take care of the different ways in which the bosons are arranged in the non-Abelian couplings diagrams. Now, we will extend the formulae given there for process (1) for the case in which the  $W^+$  boson may have an anomalous magnetic moment  $k$  different from that predicted by the standard model. We will assume for the trilinear coupling constants of the vector bosons, the following general form:

$$\begin{aligned} \gamma_\mu(p^0)W_\nu^+(p^+)W_\rho^-(p^-) &\Rightarrow ig_{\gamma W^+W^-} \{g_{\mu\nu}(\kappa p^0 - p^+)_\rho + g_{\nu\rho}(p^+ - p^-)_\mu + g_{\mu\rho}(p^- - \kappa p^0)_\nu\}, \\ Z_\mu(p^0)W_\nu^+(p^+)W_\rho^-(p^-) &\Rightarrow ig_{ZW^+W^-} \{g_{\mu\nu}(\kappa_Z p^0 - p^+)_\rho + g_{\nu\rho}(p^+ - p^-)_\mu + g_{\mu\rho}(p^- - \kappa_Z p^0)_\nu\}. \end{aligned} \quad (2)$$

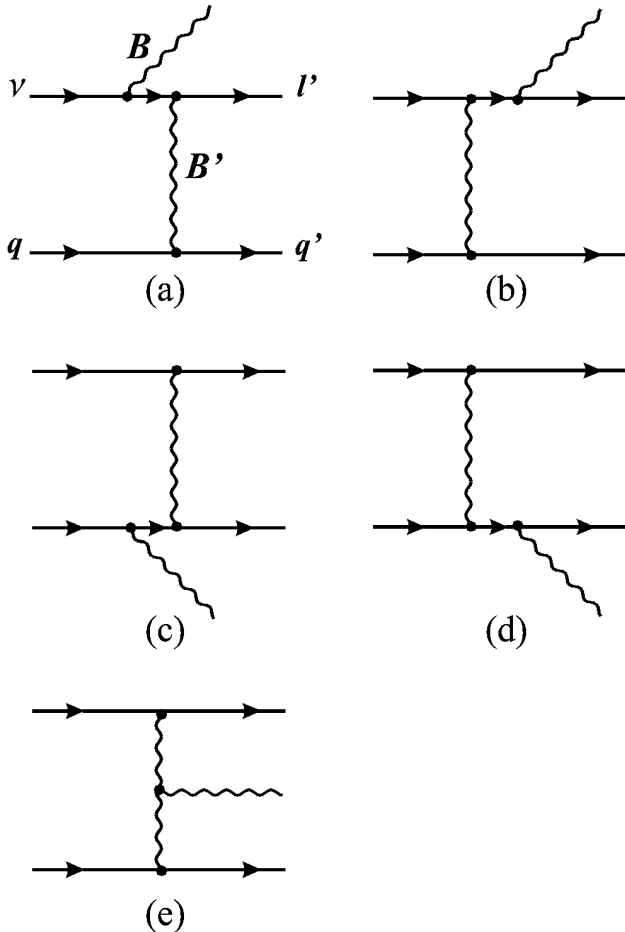


FIGURE 1. Feynman diagrams which contribute to process (1): (a) boson production from the incoming neutrino, (b) the outgoing lepton, (c) the initial (d) and final quark, and (e) through the non-Abelian couplings ( $u$  stands for  $u, c, \bar{d}, \bar{s}, \bar{b}$ ;  $d$  for  $d, s, b, \bar{u}, \bar{c}$ ).

The standard model self interactions are obtained by taking  $\kappa = 1, \kappa_Z = 1, g_{\gamma W^+W^-} = e$  and  $g_{ZW^+W^-} = e(\cos\theta_W/\sin\theta_W)$  ( $\theta_W$  being the electroweak mixing angle).

In order to calculate  $W^+$  boson production through process (1), with the non-standard non-Abelian couplings given in (2), we may take the formulae given in Sec. 3 of Ref. 6, provided the following changes and extensions are performed

- 1) The index  $r$  runs now from 1 to 4.
- 2)  $\mathcal{F}_i^{\mu\nu}, f_{P_q, P_l}^{i,l}, f_{P_q, P_l}^{i,h}$  for  $i = \{1, 2, 3\}$ , and  $C_{P_q, P_l}^{l,i}, C_{P_q, P_l}^{l,f}, C_{P_q, P_l}^{h,i}, C_{P_q, P_l}^{h,f}$  remain as they are defined in Ref. 6.
- 3)  $\mathcal{F}_4^{\mu\nu} = \varepsilon^\mu k^\nu + k^\mu \varepsilon^\nu$
- 4)  $f_{P_q, P_l}^{4,l} = 0, f_{P_q, P_l}^{4,h} = 0.$
- 5)  $f_{P_q, P_l}^{1,n} = 2\varepsilon(p - p')C_{P_q, P_l}^{n,a}, f_{P_q, P_l}^{2,n} = 2C_{P_q, P_l}^{n,b}, f_{P_q, P_l}^{3,n} = 0, f_{P_q, P_l}^{4,n} = 2C_{P_q, P_l}^{n,c}$

where

$$C_{L,L}^{n,x} = \frac{\sum_{B'=\gamma,Z} L_{\nu_l l'}^W L_{q'q}^{B'} C_x^{B'} g_{B'WW}}{(Q^2 + M_W^2)(Q'^2 + M_{B'}^2)}, \quad (3)$$

with  $x = a, b, c$ . For other polarizations,  $L$  has to be replaced by  $R$  in an appropriate way. The values for  $C_x^\gamma$  and  $C_x^Z$  are given in Table I. In the Appendix we present the explicit expressions for the quantities  $T^{r,r'}$ , and we also perform there the summation over the polarizations of the produced boson.

TABLE I. Expressions for  $C_x^\gamma$  ( $x = a, b, c$ ) as a function of  $\kappa$  for the process (1). The expressions for  $C_x^Z$  are obtained changing  $\kappa \rightarrow \kappa_Z$  from those given for  $C_x^\gamma$ .

Process	$C_a^\gamma$	$C_b^\gamma$	$C_c^\gamma$
$\nu_l \mathcal{N} \rightarrow l^- W^+ X$	$1 + \kappa$	$2 + (\kappa - 1)/2$	$(\kappa - 1)/2$

TABLE II. Leptonic, non-Abelian, and total contribution to the cross section as a function of  $E_\nu$  ( $E_P = m_P$ ).

$E_\nu$ in eV	$\sigma(\nu_l P \rightarrow l^- W^+ X)$ in $\text{cm}^2$		
	$\sigma_{\text{leptonic}}$	$\sigma_{\text{non-Abelian}}$	$\sigma_{\text{total}}$
$10^{14}$	$2.45 \times 10^{-37}$	$2.26 \times 10^{-37}$	$4.01 \times 10^{-38}$
$10^{15}$	$2.23 \times 10^{-35}$	$2.25 \times 10^{-35}$	$9.04 \times 10^{-37}$
$10^{16}$	$3.55 \times 10^{-34}$	$3.56 \times 10^{-34}$	$5.02 \times 10^{-36}$
$10^{17}$	$3.76 \times 10^{-33}$	$3.77 \times 10^{-33}$	$2.29 \times 10^{-35}$
$10^{18}$	$3.80 \times 10^{-32}$	$3.81 \times 10^{-32}$	$1.28 \times 10^{-34}$
$10^{19}$	$3.81 \times 10^{-31}$	$3.81 \times 10^{-31}$	$5.27 \times 10^{-34}$
$10^{20}$	$3.81 \times 10^{-30}$	$3.81 \times 10^{-30}$	$1.23 \times 10^{-33}$
$10^{21}$	$3.81 \times 10^{-29}$	$3.81 \times 10^{-29}$	$2.03 \times 10^{-33}$

To end this section, we want to mention the following. We have already pointed out in Ref. 6 that, in contrast to deep inelastic lepton nucleon scattering, the choice of the scale parameter  $\hat{Q}^2$  is not unambiguous in the case of heavy boson production. In this work, however, we are going to use the same prescription which we have used in Ref. 6.

### 3. The KMSS model

The KMSS model is an electroweak model proposed by M. Kuroda *et al.* (KMSS model) [3], in which the bosons may have different self interactions from those prescribed by the standard model [1]. The Lagrangian of the KMSS model contains only dimension-four terms. P or C violations of the electromagnetic vector boson interactions are not allowed. In this model, the trilinear vector boson coupling constants can be written in the form given in (2) with

$$\kappa_Z = \frac{e(\kappa \tan \theta_W - \frac{\hat{g}}{\cos \theta_W})}{(e \tan \theta_W - \frac{\hat{g}}{\cos \theta_W})},$$

$$g_{WW\gamma} = e,$$

$$g_{WWZ} = -e \tan \theta_W + \frac{\hat{g}}{\cos \theta_W}, \tag{4}$$

where  $\theta_W$  stands for the electroweak mixing angle.  $\hat{g}$  and  $\kappa$  are free parameters, and  $\kappa$  being the anomalous magnetic dipole moment of  $W^\pm$ . H. Neufeld, J.D. Strouhair and D. Schildknecht [4] have considered the vector boson loop corrections to the  $\rho$  parameter in the context of the KMSS model, and concluded that in order to get an agreement with the experimental measurements:  $\rho = 1 \pm 0.05$  [9] the relation

$$\hat{g} \sin \theta_W = e\kappa, \tag{5}$$

has to be fulfilled in very good approximation, in order to avoid a large deviation from  $\rho = 1$ . Hence, we can reduce the set of relations given in (4) depending on two free parameters to a set of relations depending on only one parameter, namely  $\kappa$ , the  $W^\pm$  anomalous magnetic moment:

$$\kappa_Z = \frac{\kappa \cos^2 \theta_W}{\kappa - \sin^2 \theta_W},$$

$$g_{WW\gamma} = e,$$

$$g_{WWZ} = e \frac{\kappa - \sin^2 \theta_W}{\sin \theta_W \cos \theta_W}. \tag{6}$$

### 4. Dependence on $\kappa$ of the non-standard $W^+$ production rates

The numerical results given in this section are obtained taking  $M_W=80.4$  GeV and  $M_Z=91.2$  GeV for the masses of the neutral and charged bosons (hence  $\sin^2 \theta_W=0.223$ ) [10]. We leave out the contribution from heavy boson exchange diagrams in our computations of the total cross section. We give results for the case of unpolarized deep inelastic  $\nu_l \mathcal{N}$  collisions with an neutrino energy in the range  $10^{14} \text{ eV} \leq E_{\nu_l} \leq 10^{21} \text{ eV}$ , and the nucleon at rest ( $E_{\mathcal{N}}=m_{\mathcal{N}}$ ). We take cuts of  $4 \text{ GeV}^2$ ,  $4 \text{ GeV}^2$  and  $10 \text{ GeV}^2$  for  $Q^2$ ,  $Q'^2$ , and the invariant hadronic mass square  $W$ , respectively. These cuts are suited for the parton distribution functions reported by J. Pumplin *et al.* [8], which we use in our performances.

First, we calculate separately, in the context of the standard model the contribution to the process  $\nu_l + P \rightarrow l^- + W^+ + X$  from two different mechanisms which contribute at the lowest order in  $\alpha$  (keeping only photon exchange diagrams): production at the leptonic vertex and through the boson self interaction. We show in Table II, from the first to the third column, our results for these two mechanisms (leptonic, non-Abelian) and for the total contribution. We see in this Table the compensation via destructive interference inherent to the standard model as a non-Abelian gauge theory. We can observe that this compensation reaches up to four orders of magnitude. Therefore, one could expect that even small deviations from the coupling structure of the standard model, like an anomalous dipole magnetic moment different from 1, would lead to observable effects in the predictions for charged boson production in  $\nu_l \mathcal{N}$  collisions.

Now, in order to investigate the dependence of  $W^+$  production, via deep inelastic  $\nu_l \mathcal{N}$ -scattering, on the  $W^+$  anomalous magnetic dipole moment. We give results for the cross section rates of the process  $\nu_l + \mathcal{N} \rightarrow l^- + W^+ + X$ , making use of the electroweak model proposed by M. Kuroda *et al.* (KMSS model) [3]. We have seen in the previous section, that in this model the trilinear vector boson coupling constants depend on only one free parameter,  $\kappa$ , the anomalous magnetic dipole moment of the  $W^\pm$ . Further, the diagrams which contribute to the  $W^+$  boson production cross

TABLE III. Contribution to the total cross section as a function of  $\kappa$  and  $E_\nu$  ( $E_P = m_P$ ).

$E_\nu$ in eV	$\sigma(\nu_l P \rightarrow l^- W^+ X)$ in $\text{cm}^2$				
	$\kappa = 0.76$	$\kappa = 0.88$	$\kappa = 1(\text{S.M.})$	$\kappa = 1.18$	$\kappa = 1.36$
$10^{14}$	$3.82 \times 10^{-38}$	$3.91 \times 10^{-38}$	$4.01 \times 10^{-38}$	$4.16 \times 10^{-38}$	$4.32 \times 10^{-38}$
$10^{15}$	$8.22 \times 10^{-37}$	$8.62 \times 10^{-37}$	$9.04 \times 10^{-37}$	$9.73 \times 10^{-37}$	$1.05 \times 10^{-36}$
$10^{16}$	$4.24 \times 10^{-36}$	$4.61 \times 10^{-36}$	$5.02 \times 10^{-36}$	$5.71 \times 10^{-36}$	$6.48 \times 10^{-36}$
$10^{17}$	$1.70 \times 10^{-35}$	$1.98 \times 10^{-35}$	$2.29 \times 10^{-35}$	$2.83 \times 10^{-35}$	$3.44 \times 10^{-35}$
$10^{18}$	$8.26 \times 10^{-35}$	$1.04 \times 10^{-34}$	$1.28 \times 10^{-34}$	$1.70 \times 10^{-34}$	$2.20 \times 10^{-34}$
$10^{19}$	$3.16 \times 10^{-34}$	$4.14 \times 10^{-34}$	$5.27 \times 10^{-34}$	$7.23 \times 10^{-34}$	$9.51 \times 10^{-34}$
$10^{20}$	$7.27 \times 10^{-34}$	$9.62 \times 10^{-34}$	$1.23 \times 10^{-33}$	$1.70 \times 10^{-33}$	$2.25 \times 10^{-33}$
$10^{21}$	$1.19 \times 10^{-33}$	$1.59 \times 10^{-33}$	$2.03 \times 10^{-33}$	$2.82 \times 10^{-33}$	$3.73 \times 10^{-33}$

TABLE IV. Contribution to the total cross section as a function of  $\kappa$  and  $E_\nu$  ( $E_N = m_N$ ).

$E_\nu$ in eV	$\sigma(\nu_l N \rightarrow l^- W^+ X)$ in $\text{cm}^2$				
	$\kappa = 0.76$	$\kappa = 0.88$	$\kappa = 1(\text{S.M.})$	$\kappa = 1.18$	$\kappa = 1.36$
$10^{14}$	$2.87 \times 10^{-38}$	$2.92 \times 10^{-38}$	$3.01 \times 10^{-38}$	$3.12 \times 10^{-38}$	$3.25 \times 10^{-38}$
$10^{15}$	$6.66 \times 10^{-37}$	$6.97 \times 10^{-37}$	$7.31 \times 10^{-37}$	$7.87 \times 10^{-37}$	$8.45 \times 10^{-37}$
$10^{16}$	$3.44 \times 10^{-36}$	$3.75 \times 10^{-36}$	$4.07 \times 10^{-36}$	$4.63 \times 10^{-36}$	$5.23 \times 10^{-36}$
$10^{17}$	$1.34 \times 10^{-35}$	$1.56 \times 10^{-35}$	$1.81 \times 10^{-35}$	$2.24 \times 10^{-35}$	$2.71 \times 10^{-35}$
$10^{18}$	$6.32 \times 10^{-35}$	$7.95 \times 10^{-35}$	$9.77 \times 10^{-35}$	$1.30 \times 10^{-34}$	$1.68 \times 10^{-34}$
$10^{19}$	$2.38 \times 10^{-34}$	$3.12 \times 10^{-34}$	$3.95 \times 10^{-34}$	$5.42 \times 10^{-34}$	$7.12 \times 10^{-34}$
$10^{20}$	$5.46 \times 10^{-34}$	$7.21 \times 10^{-34}$	$9.23 \times 10^{-34}$	$1.27 \times 10^{-33}$	$1.69 \times 10^{-33}$
$10^{21}$	$8.97 \times 10^{-34}$	$1.19 \times 10^{-33}$	$1.52 \times 10^{-33}$	$2.11 \times 10^{-33}$	$2.79 \times 10^{-33}$

TABLE V.  $\sigma(\nu_l \mathcal{N} \rightarrow l^- W^+ X) / \sigma_{SM}(\nu_l \mathcal{N} \rightarrow l^- W^+ X)$  as a function of  $\kappa$  and  $E_\nu$  ( $E_{\mathcal{N}} = m_{\mathcal{N}}$ ).

$E_\nu$ in eV	$\sigma(\nu_l \mathcal{N} \rightarrow l^- W^+ X) / \sigma_{SM}(\nu_l \mathcal{N} \rightarrow l^- W^+ X)$			
	$\kappa = 0.76$	$\kappa = 0.88$	$\kappa = 1.18$	$\kappa = 1.36$
$10^{14}$	0.95	0.97	1.04	1.08
$10^{15}$	0.91	0.95	1.08	1.16
$10^{16}$	0.84	0.92	1.14	1.29
$10^{17}$	0.74	0.86	1.24	1.50
$10^{18}$	0.65	0.81	1.33	1.72
$10^{19}$	0.60	0.79	1.37	1.80
$10^{20}$	0.59	0.78	1.38	1.83
$10^{21}$	0.59	0.78	1.39	1.84

section, at the quark level in the lowest order in  $\alpha$ , contain only three vector boson self interactions, therefore the boson production rates depend only on  $\kappa$ . Table III contains from the first to the fifth column our results for the total cross section at the lowest order in  $\alpha$  of the total cross section of process  $\nu_l + P \rightarrow l^- + W^+ + X$ , taking different values for  $\kappa$ . We take the values of  $\kappa = 0.76, 0.88, 1, 1.18, 1.36$  which do not deviate too much from the SM value of  $\kappa = 1$ , and which are allowed according to the experimental range

$0.76 < \kappa < 1.36$ , reported by the L3 Collaboration [5]. We present in Table IV, the same as in Table III, but for the process  $\nu_l + N \rightarrow l^- + W^+ + X$ . Finally, we display in Table V, from the first to the fourth column our results for the ratio  $\sigma(\nu_l \mathcal{N} \rightarrow l^- W^+ X) / \sigma_{SM}(\nu_l \mathcal{N} \rightarrow l^- W^+ X)$ . From the results given in Tables III, IV and V, one can see that the standard model prediction for the cross section is enhanced in a 84% when we take  $\kappa = 1.36$  for  $E_{\nu_l} = 10^{21}$  eV. However, this enhanced cross section rate remains unobservable at the neutrino telescopes [11].

### 5. Conclusions

We have analyzed the effects of a non-standard anomalous magnetic dipole moment  $\kappa$  of the  $W^\pm$  in the charged boson production in unpolarized deep inelastic  $\nu_l \mathcal{N}(\bar{\nu}_l \mathcal{N})$ -scattering for UHE neutrinos colliding on a target nucleon, using the electroweak model proposed by M. Kuroda *et al.* (KMSS model), in which  $\kappa$  may be different from 1, the value predicted by the electroweak standard model. We found, that even small deviations of  $\kappa$  from its standard model value (at the present time the best limits on  $\kappa$  are  $0.76 < \kappa < 1.36$ , from a recent analysis of the L3 Collaboration at LEP) could lead to large enhancement in the predicted cross section rates for  $W^+(W^-)$  production via  $\nu_l \mathcal{N}(\bar{\nu}_l \mathcal{N})$  collisions. How-

ever, such enhanced rates remain too small to be detectable experimentally at the UHE neutrino telescopes.

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## A Appendix

We give in this Appendix, taking all fermion massless, the expressions for the quantities  $T^{r,r'}$ , which are defined as follows:

$$T_{P_q, P_l}^{r,r'} = \mathcal{H}_{\mu\nu}^{P_q} \mathcal{F}_r^{\mu\nu} (\mathcal{F}_{r'}^{\mu'\nu'})^* \mathcal{L}_{\nu\nu'}^{P_l}, \quad (r, r' = 1, 2, 3, 4), \quad (\text{A.1})$$

with

$$\mathcal{L}_{\mu\nu}^{L,R} = 2\{p_\mu p'_\nu + p'_\mu p_\nu - g_{\mu\nu} p p' \mp i\varepsilon_{\mu\nu\rho\sigma} p^\rho p'^\sigma\}$$

$$\mathcal{H}_{\mu\nu}^{L,R} = 2\{q_\mu q'_\nu + q'_\mu q_\nu - g_{\mu\nu} q q' \mp i\varepsilon_{\mu\nu\rho\sigma} q^\rho q'^\sigma\}$$

$$\mathcal{F}_1^{\mu\nu} = g^{\mu\nu}$$

$$\mathcal{F}_2^{\mu\nu} = \varepsilon^\mu k^\nu - \varepsilon^\nu k^\mu$$

$$\mathcal{F}_3^{\mu\nu} = i\varepsilon^{\mu\nu\rho\sigma} \varepsilon_\rho k_\sigma$$

$$\mathcal{F}_4^{\mu\nu} = \varepsilon^\mu k^\nu + \varepsilon^\nu k^\mu,$$

and  $P_q, P_l$  being the polarization of the initial quark and incoming neutrino, respectively. In general, these quantities are functions of scalar products of the momenta  $p, q, p', q', k$ , and the polarization vector  $\varepsilon$  of the produced boson.

Using the polarization sum for the massive vector boson

$$\sum_\lambda \varepsilon_\mu(k, \lambda) \varepsilon_\nu(k, \lambda) = -g_{\mu\nu} + \frac{k_\mu k_\nu}{M_B^2}, \quad (\text{A.2})$$

and the definitions given in (A.1) for the  $T_{s,s'}^{r,r'}$  we get

$$\sum_\lambda \mathcal{F}_2^{\mu\nu} (\mathcal{F}_4^{\rho\sigma})^* = -(g^{\mu\rho} k^\nu k^\sigma + g^{\mu\sigma} k^\nu k^\rho)$$

$$+ g^{\nu\rho} k^\mu k^\sigma + g^{\nu\sigma} k^\mu k^\rho$$

$$\sum_\lambda \mathcal{F}_3^{\mu\nu} (\mathcal{F}_4^{\rho\sigma})^* = -i(\varepsilon^{\mu\nu\rho\beta} k^\sigma k_\beta + \varepsilon^{\mu\nu\sigma\beta} k^\rho k_\beta)$$

$$\sum_\lambda \mathcal{F}_4^{\mu\nu} (\mathcal{F}_4^{\rho\sigma})^* = -(g^{\mu\rho} k^\nu k^\sigma + g^{\mu\sigma} k^\nu k^\rho + g^{\nu\rho} k^\mu k^\sigma$$

$$+ g^{\nu\sigma} k^\mu k^\rho) + 4k^\mu k^\nu k^\rho k^\sigma / M_B^2.$$

With help of these expressions we obtain ( $P_q P_l = LL, RR, LR, RL$ )

$$\sum_\lambda T_{P_q, P_l}^{24} = 16(qq' \cdot kp \cdot kp' - pp' \cdot kq \cdot kq'),$$

$$\sum_\lambda \text{Re } T_{LL}^{34} = -\sum_\lambda \text{Re } T_{LR}^{23},$$

$$\sum_\lambda \text{Re } T_{RR}^{34} = -\sum_\lambda \text{Re } T_{RL}^{23},$$

$$\sum_\lambda \text{Re } T_{LR}^{34} = -\sum_\lambda \text{Re } T_{LL}^{23},$$

$$\sum_\lambda \text{Re } T_{RL}^{34} = -\sum_\lambda \text{Re } T_{RR}^{23},$$

$$\sum_\lambda T_{P_q, P_l}^{44} = -\sum_\lambda T_{P_q, P_l}^{22} - 16(M_B^2 pp' \cdot qq'$$

$$- 4pk \cdot p'k \cdot qk \cdot q'k / M_B^2).$$

We can express  $\sum_\lambda \text{Re } T_{P_q, P_l}^{14}$  as follows

$$\text{Re } T_{P_q, P_l}^{14} = \begin{cases} 8[\varepsilon p \cdot p'q \cdot q'k + \varepsilon p' \cdot pq' \cdot qk & LL, RR \\ + \varepsilon q \cdot pq' \cdot p'k + \varepsilon q' \cdot p'q \cdot pk \\ - qq'(\varepsilon p \cdot p'k + \varepsilon p' \cdot pk) \\ - pp'(\varepsilon q \cdot q'k + \varepsilon q' \cdot qk)] & \\ 8[\varepsilon p \cdot p'q' \cdot qk + \varepsilon p' \cdot pq \cdot q'k & LR, RL \\ + \varepsilon q \cdot p'q' \cdot pk + \varepsilon q' \cdot pq \cdot p'k \\ - qq'(\varepsilon p \cdot p'k + \varepsilon p' \cdot pk) \\ - pp'(\varepsilon q \cdot q'k + \varepsilon q' \cdot qk)] & \end{cases}$$

Using (A.2) and the definitions given above in (A.1) for the  $T_{s,s'}^{r,r'}$  we get

$$\sum_\lambda \varepsilon P \cdot \mathcal{F}_4^{\mu\nu} = \mathcal{F}_4^{\mu\nu} \left( \varepsilon \rightarrow -P + \frac{kP}{M_B^2} k \right)$$

for  $P = p, q, p', q'$ . Hence

$$\sum_\lambda \varepsilon P \cdot \text{Re } T_{P_q, P_l}^{14} = \text{Re } T_{P_q, P_l}^{14} \left( \varepsilon \rightarrow -P + \frac{kP}{M_B^2} k \right).$$

The expressions for the remaining  $T^{r,r'}$  can be found in the Appendix of Ref. 6.

\*. The results for  $\bar{\nu}_l \mathcal{N}$ -scattering can be obtained from those of  $\nu_l \mathcal{N}$ -scattering by the replacement  $W^+ \rightarrow W^-, l^- \rightarrow l^+$  and  $u$ -type quarks  $\leftrightarrow d$ -type quarks.

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