$W^{\pm}$-production in $e^{-}p$-collisions at CERN LEP/LHC energies with a non-standard $W^{\pm}$ anomalous magnetic moment

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We discuss the production of charged bosons in deep inelastic $e^{-}p$-scattering, 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 κ of the $W^{\pm}$. We show that even small deviations from the standard model value of κ ($\kappa = 1$) implies an observable deviation in the $W^{\pm}$-production rates at CERN LEP/LHC energies. We also show that for the analysis of the charged boson production via $e^{-}p$ collisions at LEP/LHC energies will be very important to include the contribution from heavy boson exchange diagrams to the cross section rates.

Keywords: Heavy boson production; *ep* collisions

Discutimos la producción de bosones cargados en la dispersión muy inelástica $e^{-}p$, en el contexto de un modelo electrdébil, en el cual la interacción del bosón vectorial puede ser diferente de aquella prescrita por el modelo estándar electrodébil. Se presentan resultados los cuales muestran la fuerte dependencia del momento dipolar magnético anómalo κ en la sección transversal de los $W^{\pm}$. Mostramos que pequeñas desviaciones del valor del modelo estándar ($\kappa = 1$) de κ implican una desviación observable en la razón de producción de $W^{\pm}$ a energías de LEP/LHC de CERN. también se muestra que para el análisis de la producción de bosones cargados vía colisiones $e^{-}p$ a energías de LEP/LHC puede ser muy importante incluir la contribución de diagramas con intercambio de bosón pesado para la razón de la sección transversal.

Descriptores: Producción de bosones; colisiones *ep*

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1. Introduction

At the present time, all available experimental data for electroweak processes can be well understood in the context of the standard model of the electroweak interactions [1]. However, in spite of this succes, there are important features of the standard model that have not yet been tested, such as 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 calculate charged boson production in deep inelastic $e^{-}p$-scattering 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) [2]. In this model the trilinear vector boson coupling constants depend on only one free parameter, κ, the anomalous magnetic dipole moment of the $W^{\pm}$ [3]. The diagrams which contribute to the boson production cross section, at the quark level in the lowest order in α, contain only three vector boson self interactions, hence the boson production rates depend only on κ.

In a previous work [4], we have calculated in the context of the standard model separately the contributions to $W^{\pm}$ production from the different mechanisms: production at the leptonic vertex, at the hadronic vertex and through the boson self interaction. We have shown explicitly the compensation via destructive interference inherent to the standard model as a non-Abelian gauge theory. We found that this compensation reaches at LEP/LHC energies up to two orders of magnitude, hence one can expect that even small deviations from the coupling structure of the standard model, like an anomalous dipole magnetic moment different from 1, will lead to observable effects in the predictions for charged boson production in $e^{-}p$ collisions. This is precisely our aim in this work. We investigate in detail the dependence of the $W^{\pm}$-production, via deep inelastic $e^{-}p$- scattering, on the $W^{\pm}$ anomalous magnetic dipole moment, κ. We are going to work in the context of the KMSS model and perform our calculations using the parton distribution functions CTEQ4 reported by Lai *et al.* [5] for energies availables at LEP/LHC in the near future. In our computations for the cross section, we include besides the γ-exchange also the heavy boson exchange diagrams. We have already pointed out the importance of the contributions from heavy boson diagrams to the differential cross section of the charged boson production via $e^{-}p$ collisions in a previous paper [4].

There are already in the literature calculations of the effects of a deviation of κ from its standard model value ($\kappa = 1$) on the rates of $W^{\pm}$-production via $e^{-}p$ collisions [6,7]. But these authors take into account only the γ-exchange contribution to the cross sections, leaving out heavy boson exchange. Unfortunately, we cannot compare directly all our results with those reported by Neufeld [6] and Gabrielli [7] because they performed their computation applying different cutoffs for the squares of the momentum transfers and the invariant hadronic mass square W (Gabrielli has performed his calculations using the Weizsäcker-Williams approximation) or using different parton distributions. However, for comparison we have calculated, including only γ-exchange contribution, the total cross section for the process $e^-p \to \nu_e W^- X$ with a cutoff of O(1) GeV^2 for an energy in the center of mass of 1,296 GeV and we found a reasonable agreement with the corresponding results given by Gabrielli [7]. More recently, other authors have reported more detailed calculations [8–19]. It is not possible to compare directly all our results with those of former papers because different cutoffs or different parton distributions where aplied.

Kim *et al.* [19] calculated the total cross section for the reactions $e^-p \to e^-W^{\pm}X$, $e^-p \to \nu_e W^- X$ taking into account all the important production mechanisms and study the dependence of the total $W^{\pm}$ cross sections on the anomalous $WW\gamma$ couplings, κ and λ. In the SM at tree level, $\lambda = 0$ and $\kappa = 1$. At the present time, the best experimental limits are $-3.6 < \lambda < 3.5$ [20] and $-1.3 < \kappa < 3.2$ from a recent analysis of the CDF Collaboration [21]. Our results are in good agreement with those obtained by Kim *et al.* provided that $\lambda = 0$.

Besides the total cross sections we present also results for differential cross sections as a function of the dimensionless variable y. Our plots for the y-distributions for different values of κ show that this quantity can be very useful to detect a deviation of κ from its standard value.

This paper is organized as follows. In Sec. 2 we discuss the $W^{\pm}$ boson production in deep inelastic electron proton scattering, in the case when the charged bosons may have a non-standard anomalous magnetic moment. We consider 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 present and discuss our results for the total cross section and y distributions for the different deep inelastic unpolarized e^-p processes in which a charged vector boson is produced. Finally, in Sec. 4, we summarize our conclusions.

2. The differential cross section for inclusive charged non-standard boson production in electron proton-scattering

Our aim in this paper is to analize the effects of a non-standard self-interactions of the weak vector bosons in the boson production via deep inelastic e^-p collisions[(a)] at the lowest order in α. In other words we look for the changes induced by a deviation from the standard trilinear vector boson coupling constants, in the boson production rates. Consequently we consider the following processes:

$$e^- + p \longrightarrow e^- W^- X, \tag{1}$$

$$e^- + p \longrightarrow e^- W^+ X, \tag{2}$$

$$e^- + p \longrightarrow \nu_e W^- X, \tag{3}$$

$$e^- + p \longrightarrow \nu_e Z^0 X. \tag{4}$$

The reaction (4) gets only contributions from heavy boson exchange diagrams and hence its cross section is very small [4] and we are not going to discuss it in this work. In Fig. 1, are shown the diagrams which contribute at the lowest order in α at the quark parton level to the processes (1)–(3).

We have discussed in detail Z^0-production and also the kinematics of heavy boson production in deep inelastic e^-p scattering [22]. In a later work [23] is extended the analysis to $W^{\pm}$-production and pointed out how to take care for the different ways in which the bosons are arranged in the non-Abelian couplings diagrams. In Ref. 24, it was extended the formulae for $W^{\pm}$ boson production for the case in which the $W^{\pm}$ bosons 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:

$$\begin{aligned}
&A_\mu(p^0)W^+_\nu(p^+)W^-_\rho(p^-) \Rightarrow \\
&\quad ig_{WW\gamma}\{g_{\mu\nu}(\kappa p^0 - p^+)_\rho \\
&\qquad + g_{\nu\rho}(p^+ - p^-)_\mu + g_{\mu\rho}(p^- - \kappa p^0)_\nu\}, \\
&Z_\mu(p^0)W^+_\nu(p^+)W^-_\rho(p^-) \Rightarrow \\
&\quad ig_{WWZ}\{g_{\mu\nu}(\kappa_Z p^0 - p^+)_\rho \\
&\qquad + g_{\nu\rho}(p^+ - p^-)_\mu + g_{\mu\rho}(p^- - \kappa_Z p^0)_\nu\}.
\end{aligned} \tag{5}$$

The self interactions of the standard model are obtained taking $\kappa = 1$, $\kappa_z=1$, $g_{WW\gamma}=e$ and $g_{WWZ}=-e(\cos\theta_W/\sin\theta_W)$ (θ_W being the electroweak mixing angle).

It has been already pointed in previous works [22,23] that, in contrast to deep inelastic lepton nucleon scattering, the choice of the scale parameter $\tilde{Q}^2$ is not unambiguos in the case of heavy boson production. For our calculations here, we are going to use the prescriptions, given in Ref. 23.

3. Results for the dependence on κ of the deep inelastic charged boson production at CERN LEP/LHC Energies

As mentioned in the introduction, there exist already calculations for the dependence on the anomalous magnetic dipole moment κ of the $W^{\pm}$ of the charged boson production via e^-p-scattering. These calculations were performed taking into account only the contribution from photon exchange di-

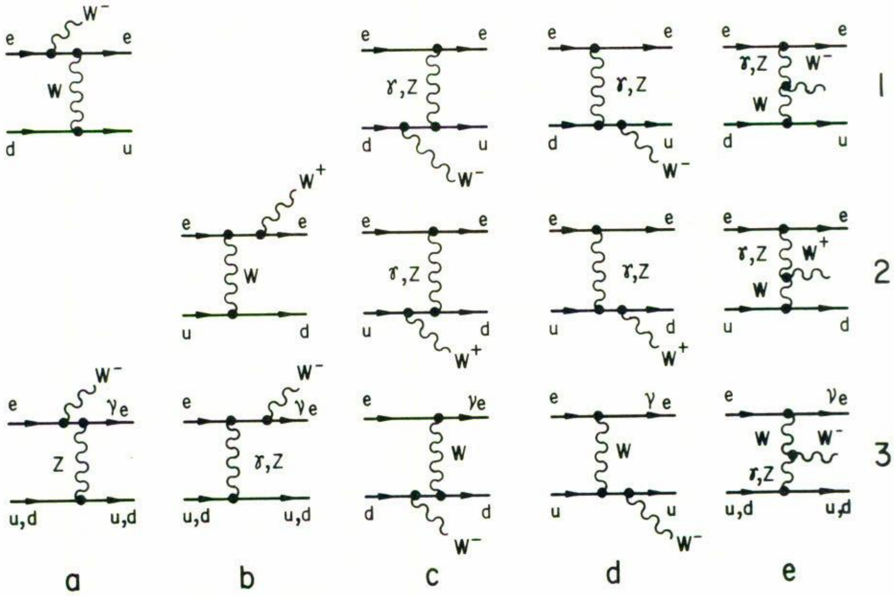

FIGURE 1. Feynman diagrams which contribute to the amplitude of processes (1), (2), and (3). (upper panel, middle panel, and lower panel, respectively); boson production from the initial (a) and final (b) lepton (leptonic vertex), the initial (c) and final (d) quark (hadronic vertex) and through the non-Abelian couplings (e). u stands for u, c, t, $\bar{d}$, $\bar{s}$, $\bar{b}$; d for d, s, b $\bar{u}$, $\bar{c}$, $\bar{t}$; p, (p'), q, (q') and k for the four momentum of the incoming (outgoing) electron, incoming (outgoing) quark and produced boson.

agrams to the cross sections. However, we have shown in a previous work [4] that the contribution from heavy boson exchange diagrams to the e^-p boson production cannot be neglected, particularly for the process $e^-p \to \nu_e W^- X$. Hence we will perform complete computations including besides γ-exchange diagrams also the contributions of Z^0- and $W^\pm$-exchange. For comparison with Gabrielli and Kim *et al.* calculations and to show explicitly the importance of heavy boson exchange contributions we give also results for the cross section rates of the process $e^-p \to \nu_e W^- X$, leaving out heavy boson exchange contributions.

In order to get numerical results, we make use of an electroweak model proposed by M. Kuroda *et al.* (KMSS model) [2], in which the bosons may have self interactions different from those prescribed by the standard model [1]. The Lagrangian of the KMSS model contains only dimension-four terms. P or C violation 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 Eq.(5) with

$$\begin{aligned}\kappa_Z &= \frac{e\left(\kappa \tan\theta_W - \dfrac{\hat{g}}{\cos\theta_W}\right)}{\left(e\tan\theta_W - \dfrac{\hat{g}}{cos\theta_W}\right)},\\ g_{WW\gamma} &= e,\\ g_{WWZ} &= e\tan\theta_W - \frac{\hat{g}}{\cos\theta_W},\end{aligned} \tag{6}$$

where θ_W stands for the electroweak mixing angle. $\hat{g}$ and κ are free parameters, κ being the anomalous magnetic dipole moment of the $W^\pm$. Neufeld, Stroughair and Schildknecht [3] have considered the vector boson loop corrections to the ρ parameter in the context of the KMSS model and concluded that in order to get good agreement with the experimental measurements: $\rho = 1 \pm 0.05$ [25] the relation

$$\hat{g}\sin\theta_W = e\kappa, \tag{7}$$

has to be fulfilled in very good approximation, in order to avoid large deviation from $\rho = 1$. Hence we can reduce the set of relations given in Eq. (6) depending on two free parameters to a set of relations depending on only one parameter, namely κ, the $W^\pm$ anomalous magnetic moment:

$$\begin{aligned}\kappa_Z &= \frac{\kappa\ \cos^2\theta_W}{\kappa - \sin^2\theta_W},\\ g_{WW\gamma} &= e,\\ g_{WWZ} &= e\frac{\sin^2\theta_W - \kappa}{\sin\theta_W\cos\theta_W}.\end{aligned} \tag{8}$$

In this section we present results for unpolarized e^-p-scattering with an electron energy $E_e = 60$ GeV and a proton energy $E_P = 7$ TeV, taking $M_Z = 91.2$ GeV and $M_W = 80.3$ GeV for the masses of the neutral and charged bosons. We take cuts of 4 GeV^2, 4 GeV^2 and 10 GeV^2 for Q^2, Q'^2 and the invariant hadronic mass square W, respectively. These cuts are suited for the parton distribution functions of Lai *et al.* [5], which we use in our performances. Besides γ-exchange also heavy boson exchange contributions are included in our computations.

TABLE I. Contribution to the total cross sections as a function of κ at LEP/LHC energies $E_e = 60$ GeV, $E_P = 7$ TeV.

	$\sigma(\text{cm}^2)$				
Processes	$\kappa = 0$	$\kappa = 0.5$	$\kappa = 1$(S.M.)	$\kappa = 1.5$	$\kappa = 2$
$e^- p \to e^- W^- X$	6.1×10^{-36}	7.3×10^{-36}	9.8×10^{-36}	1.6×10^{-35}	2.2×10^{-35}
$e^- p \to e^- W^+ X$	5.3×10^{-36}	6.8×10^{-36}	9.2×10^{-35}	$1..2 \times 10^{-35}$	1.8×10^{-35}
$e^- p \to \nu_e W^- X$	5.8×10^{-37}	4.8×10^{-37}	6.6×10^{-37}	9.7×10^{-37}	1.4×10^{-36}
$e^- p \to \nu_e W^- X$ (only γ-exchange)	3.1×10^{-37}	3.9×10^{-37}	5.3×10^{-37}	6.8×10^{-37}	8.8×10^{-37}

3.1. Total cross sections

We present in Table I, from the first to the third line our results for the complete calculations at the lowest order in α of the total cross section of processes (1)–(3), taking different values for κ. We take the values of $\kappa = 0, 0.5, 1, 1.5, 2$ which do not deviate too much from the SM value of $\kappa = 1$ according to the experimental range $-1.3 < \kappa < 3.2$, reported by the CDF collaboration [21]. From these results it is clear that it will be possible to detect the effects of an small deviation from the standard model value of κ at LEP/LHC experiments. In the last line of this Table, we give the results for the total cross section of proces (3), taking into account only the contribution from photon exchange diagrams. These results make apparent the big importance of including the Z^0- and $W^{\pm}$-exchange diagram contributions. Our results of the last line and the corresponding results reported by Gabrielli [7] are in reasonable agreement.

3.2. The y-distribution

In Figs. 2a, 2b and 2c we compare $d\sigma_T/dy$, for different values of κ. These plots show that the y-distribution will be an important tool to look for small deviation from $\kappa = 1$, specially for $0.1 \lesssim y < 0.3$. In Fig. 2d we show the same calculations as in Fig. 2c, but leaving out the contribution from Z^0 and $W^{\pm}$ boson exchange diagrams to the differential cross section. The comparison of the results plotted in Figs. 2c and 2d demonstrate that the heavy boson exchange diagrams contribution can grow very much the results $d\sigma/dy$ obtained by taking only the γ-exchange contribution, in particular in the region $0.1 <\lesssim y < 0.4$.

4. Conclusions

We have analyzed the effects of a non-standard anomalous magnetic dipole moment κ of the $W^{\pm}$ in the charged boson production in unpolarized deep inelastic e^-p-scattering at LEP/LHC energies, using the electroweak model proposed by Kuroda *et al.* [2] (KMSS model), in which κ may be different from 1, the value predicted by the standard model of the electroweak interactions [1]. We found, that even small

TABLE II. Total production of $W^{\pm}$ bosons according to our calculations, for an integrated luminosity of 500 pb^{-1}, at LEP/LHC energies.

Total Production of Bosons	$\kappa = 0$	$\kappa = 0.5$	$\kappa = 1$ (S.M.)	$\kappa = 1.5$	$\kappa = 2$
W^+	2650	3400	4600	6000	9000
W^-	3340	3890	5230	8485	11700

deviations of κ from its standard model value lead to observable effects in the predictions for e^-p charged boson production at LEP/LHC experiments.

Taking $M_W = 80.3$ GeV, $\sin^2\theta_W = 0.223$, $E_e = 60$ GeV, and $E_P = 7$ TeV (energy of the incoming electron and proton, respectively), and using the parton distributions of Lai *et al.*, we present in Table II the total production of W^+ and W^- bosons for differents values of κ. From these results we can see that it will be easier to detect effects due to $\kappa > 1$ than to $\kappa < 1$.

We have presented also plots for the y distribution of the differential cross section. We found that this distribution permits a very clear discrimination between the predictions of differents values of κ, specially for $0.1 \lesssim y < 0.3$.

Besides the contribution of γ-exchange diagrams we have also included that of Z- and $W^{\pm}$-exchange diagrams in our performances. However, in order to make clear the importance of the incorporation of the heavy boson exchange contribution, we computed also the cross sections and y distributions for the process $e^-p \to \nu_e W^- X$ leaving out them. We found that these contribution can grow from around 24.5% ($\kappa = 1$) up to around 87.1% ($\kappa = 0$) the total cross section rates, being in general particularly important for $0.1 \lesssim y \lesssim 0.4$.

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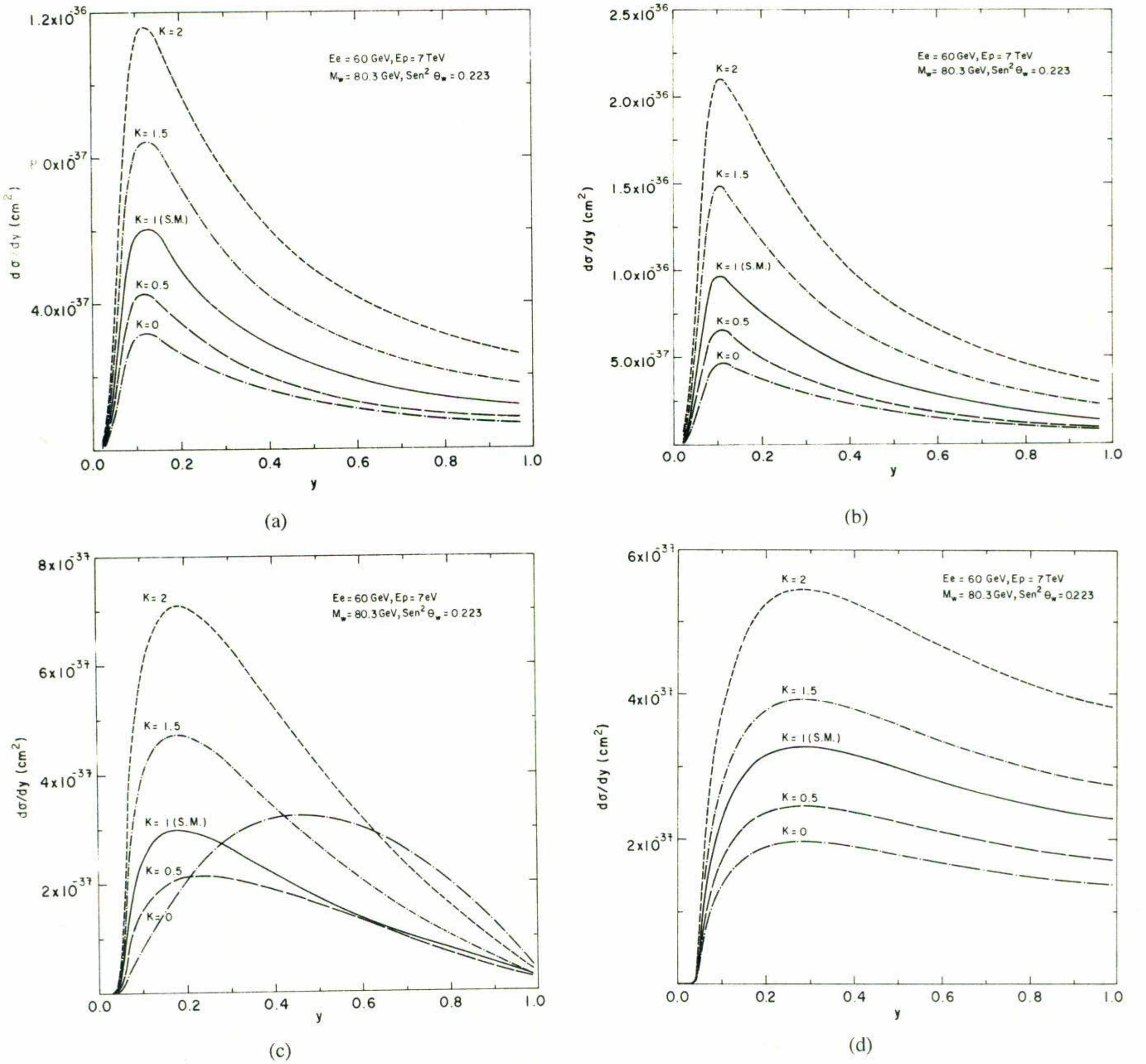

FIGURE 2. Comparison of the complete calculation of $d\sigma/dy$ of (a) process (2) at the lowest order in α, for different values of the anomalous magnetic moment κ of the $W^{\pm}$ ($\sqrt{s} = 1,296$ GeV); (b) process (3); (c) process (4); (d) leaving out the contribution from the Z^0- and $W^{\pm}$-exchange diagrams.

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[a] The results for e^+p-scattering can be obtained from those of e^-p-scattering by the replacement $W^{\pm} \longrightarrow W^{\mp}$ and u-type quarks $\leftrightarrow$ d-type quarks.

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