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IFT.P-09/86
IFUSP/P-592

PRODUCTION OF A NEW GENERATION OF LEPTONS IN HADRONIC COLLISIONS

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ABSTRACT

We study the contribution of vector boson fusion processes to the production of a heavy charged lepton accompanied by its neutral partner at multi-TeV hadronic colliders. We show that vector boson fusion dominates over the usual quark-antiquark fusion mechanism, for a very heavy lepton and high energies.

Our present theoretical understanding of elementary particle physics does not enable us to predict the number of fermion generations. Therefore, one has to rely on phenomenological data in order to get some insight on this, up to know, unknown parameter. From the analysis of primordial abundance of light elements, it follows that the number of families should not exceed five[1]. The number of light neutrinos can also be inferred from the Z^0 decay[2], and it is comparable with the cosmological bound. Furthermore, it has been argued that superstring theories lead to an even number of fermion families[3]. Thus it becomes a very relevant task to investigate the production of possible new generations, beyond the stablished ones.

In this letter we shall be concerned with the production of leptons belonging to an extra generation in proton-proton and proton-antiproton collisions. We work within the framework of the standard model of electroweak interactions. The charged lepton is assumed to be very heavy ($M_L^2 > M_{W,Z}^2$) and its neutral partner massless.

According to the current parton model ideas, a hadron is viewed as a collection of quasi-free partons. For very high energies one expects that the role played by heavy partons, such as W and Z , will be important. This makes the analysis of the contribution of these partons in high energy processes worthwhile.

The usual mechanism for a lepton-neutrino pair production is through the quark-antiquark fusion (Drell-Yan mechanism)[4,5], i.e. $q\bar{q}' \to W^{\pm} \to \ell^{\pm} \overset{(-)}{\nu}_{\ell}$. Nevertheless, as will be shown, vector boson fusion becomes competitive and even more important than the Drell-Yan mechanism for charged heavy leptons and high energies. Actually, recent studies have shown that vector boson fusion plays an important role in the production of heavy Higgs boson[6], vector boson pairs[7] and heavy charged leptons (L^+L^-)[8]. Therefore, such a kind of mechanism will be of great interest in particle production at the future generation of pp and $p\bar{p}$ colliders.

We shall consider the production of a heavy charged lepton accompanied by its neutrino as a result of the following subprocesses:

(a) $W^{\pm} Z^0 \to L^{\pm} \overset{(-)}{\nu}_L$,

(b) $W^{\pm} \gamma \to L^{\pm} \overset{(-)}{\nu}_L$.

We shall compute the rapidity distribution at $y = 0$ for the above subprocesses, which are shown in Fig. 1. In terms of the distribution functions associated to the vector bosons in a hadron, (V_h), this quantity is

$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{h_1 h_2 \to L\nu} = \int_{M_L^2/s}^{1} d\tau \left[V_{h_1}^{i}(\sqrt{\tau})\, V_{h_2}^{j}(\sqrt{\tau}) + (i \leftrightarrow j) \right] \hat{\sigma}_{V_i V_j \to L\nu}(\tau s) \quad , \qquad (1)$$

where $\hat{\sigma}_{V_i V_j \to L\nu}$ is the cross section for the subprocesses (a) and (b).

The determination of the distribution functions

associated to the different vector partons can be carried out by using the effective vector boson approximation[9], which treats separately the contributions due to transverse and longitudinal polarizations. In the processes under study the contribution of the longitudinal modes dominates over the transverse ones. For this reason we shall consider only the longitudinal contributions.

The probability distribution of longitudinal bosons in a quark (V_q^L), when the quark subenergy E is much larger than the vector boson mass (M_V), is

$$V_q^L(x) = \frac{(C_V^2 + C_A^2)}{4\pi^2} \frac{(1-x)}{x} \qquad (2)$$

where, for $V = Z^0$

$$C_V = \frac{g}{\cos\vartheta_W} \left(\frac{1}{2} T_{3L} - Q \sin^2 \vartheta_W \right) \quad ,$$

$$C_A = - \frac{g}{\cos\vartheta_W} \left(\frac{1}{2} T_{3L} \right) \quad , \qquad (3a)$$

whereas for $V = W^{\pm}$

$$C_V = - C_A = \frac{g}{2\sqrt{2}} \quad . \qquad (3b)$$

T_{3L} in the above expressions is the third component of the weak isospin and Q is the quark electric charge. As was pointed out by Lindfors[9] this leading approximation (Eq. (2))

for the longitudinal structure function, is excellent when compared to the exact result.

The longitudinal vector boson distribution in a hadron is obtained by the convolution of (2) with the quark distribution function (q_h), that is

$$V_h^L(x) = \sum_i \int_{x_{min}}^{1} \frac{dy}{y} q_h^i(y) V_{q^i}^L(x/y) \quad , \qquad (4)$$

where the sum is carried out over the relevant quark and anti-quark flavors.

Finally, we consider the elementary cross sections for the subprocesses shown in Fig. (1) in the limit $M_L^2 \gg M_V^2$. The cross section for longitudinally polarized W and Z bosons, for the subprocess (a) is

$$\hat{\sigma}_{W_L Z_L \to L\nu} = \sum_{i,j} \hat{\sigma}_{ij} \qquad (i,j = W,L,\nu) \quad , \qquad (5)$$

where,

$$\hat{\sigma}_{WW} = \frac{\pi \alpha^2 \cos^2 \vartheta_W}{24 \sin^4 \vartheta_W} \cdot \frac{s}{M_W^2 M_Z^2} (2+\eta)(1-\eta)^2 \quad , \qquad (6a)$$

$$\hat{\sigma}_{LL} = \frac{\pi\alpha^2}{48 \sin^4 \vartheta_W \cos^2 \vartheta_W} \cdot \frac{s}{M_W^2 M_Z^2} \Big\{ 4 \sin^4 \vartheta_W (1+2\eta)(1-\eta)^2 +$$

$$+ (1 - 4 \sin^2 \vartheta_W) \left[(1-\eta)^3 - 3\eta(1-\eta^2) + 6\eta^2 L \right] \Big\} \quad , \qquad (6b)$$

$$\hat{\sigma}_{\nu\nu} = \frac{\pi \alpha^2}{48 \sin^4 \vartheta_W \cos^2 \vartheta_W} \frac{s}{M_W^2 M_Z^2} (1+2\eta)(1-\eta)^2 \quad , \qquad (6c)$$

$$\hat{\sigma}_{WL} = - \frac{\pi \alpha^2}{24 \sin^4 \vartheta_W} \cdot \frac{s}{M_W^2 M_Z^2} \Big\{ (2+\eta)(1-\eta)^2 - 3\eta(1-\eta) L$$

$$+ 2 \sin^2 \vartheta_W \left[6\eta(1-\eta) - (2+\eta)(1-\eta)^2 + 3\eta(1-3\eta) L \right] \Big\} \quad , \qquad (6d)$$

$$\hat{\sigma}_{W\nu} = - \frac{\pi \alpha^2}{24 \sin^4 \vartheta_W} \cdot \frac{s}{M_W^2 M_Z^2} (2+\eta)(1-\eta)^2 \quad , \qquad (6e)$$

$$\hat{\sigma}_{L\nu} = \frac{\pi \alpha^2}{24 \sin^4 \vartheta_W \cos^2 \vartheta_W} \cdot \frac{s}{M_W^2 M_Z^2} \Big\{ (1-\eta)^3 - 3\eta(1-\eta^2) + 6\eta^2 L$$

$$- 2 \sin^2 \vartheta_W \left[(1-\eta)^3 - 3\eta(3+\eta)(1-\eta) + 12\eta^2 L \right] \Big\} \quad . \qquad (6f)$$

whereas the cross section for the subprocess (b), for the longitudinally polarized W boson is

$$\hat{\sigma}_{W_L \gamma \to L\nu} = \frac{\pi \alpha^2}{2 \sin^2 \vartheta_W} \frac{M_L^2}{M_W^2} \cdot \frac{1}{s} \left\{ -1 + \eta + \left[1 + 2\eta(1-\eta) \right] L \right\} \quad , \qquad (7)$$

where we have defined:

$$\eta \equiv \frac{M_L^2}{s} \quad , \qquad (8)$$

$$L \equiv \ln \left(\frac{1 + \beta}{1 - \beta} \right) \quad , \qquad (9)$$

and $\beta = \frac{(1-\eta)}{(1+\eta)}$ is the massive lepton velocity in CM frame.

Note that there are terms in (6) violating unitarity bounds. However, when we take the sum in (5) these terms cancel among themselves in the high energy limit.

In the numerical evaluation of (1) we assumed $\sin^2\vartheta_W = 0.226$, $M_W = 82.5$ GeV and $M_Z = 93.8$ GeV. We have used, for the photon distribution in a quark, the well known Weizsäcker-Williams approximation[10], and, for the Q^2-dependent quark distribution functions, we have taken the set 2 of Ref. 5.

Figures 2 and 3 show the rapidity distribution at $y = 0$ against the lepton mass for the subprocess (a) in pp and $p\bar{p}$ collisions respectively. For the sake of completeness, we also plot the contribution of the Drell-Yan mechanism. We have evaluated the contribution due to the subprocess (b) for both polarizations. However, we do not exhibit the results for $W_T Z_T$ and $W_{L(T)}\gamma$ fusions since they lie at least one order of magnitude below either the $W_L Z_L$ fusion or the Drell-Yan mechanism.

The essential feature of our results is that, for high enough energies, the vector boson fusion process (a) dominates over the usual Drell-Yan mechanism, when the vector bosons are longitudinally polarized. As can be seen in Fig. 2, this dominance holds for large lepton masses, e.g., $M_L \gtrsim 700$ GeV for $\sqrt{s} = 40$ TeV or $M_L \gtrsim 600$ GeV for $\sqrt{s} = 70$ TeV in pp collisions.

The search for a new generation of leptons can also be implemented via the production of a pair of charged leptons

(L^+L^-). This channel has already been analyzed in Refs. 5, 8 and 11. It seems that the process studied here would be less relevant for detecting this extra generation, since the cross section due to gluon fusion producing L^+L^- [11] is a factor of ~ 7 larger, for $200 \text{ GeV} < M_L < 1$ TeV and $\sqrt{s} = 40$ TeV. However, if we take into account the efficiency for detecting a charged lepton, we are led to a different conclusion.

The decay of the heavy lepton ($M_L > M_W$) occurs via $L^\pm \to W^\pm \overset{(-)}{\nu}_L$. Therefore the ability for detecting $L^\pm$ depends on the efficiency for identifying the $W^\pm$ boson. This efficiency, with $W^\pm$ decaying into electronic and muonic channels, does not exceed 15% and this modifies the effective luminosity[5]. So that, the effective luminosity for L^+L^- is 0.15 times smaller than the effective luminosity for $L\nu_L$ identification. Thus, the number of identified events coming from the gluon fusion mechanism is expected to be of the same order as the one obtained via the process studied here. Furthermore, the channel L^+L^- has a more severe background from conventional electroweak process than the $L\nu_L$ channel[5].

The conclusion to be drawn from our analysis is that the production of a heavy charged lepton accompanied by its neutrino is a very promising mechanism for detecting new lepton generations at very high energies. Consequently, the vector boson fusion subprocess can no longer be ignored.

ACKNOWLEDGMENTS

We are grateful to C.O. Escobar for enlightening discussions. We are indebted to FAPESP (S.F.N.), CNPq and FINEP (G.C.M. and A.A.N.) for their financial support. We thank the Instituto de Física Teórica (S.F.N.) and Depto. de Física Matemática - USP (O.J.P.E) for their kind hospitality. This work was partially supported by the UNESP-IFT contract.

REFERENCES

1. D. Sciama, in the Proceedings of the International Europhysics Conference on High-Energy Physics, Bari, Italy, July 1985; edited by L. Nitti and G. Preparata, p. 707.
2. G. Arnison et al., Phys. Lett. 166B (1986) 484.
   L. Dilella, preprint CERN-EP/85-184.
3. P. Candelas, G.T. Horowitz, A. Strominger and E. Witten, Nucl. Phys. B258 (1985) 46.
4. S.D. Drell and T.M. Yan, Phys. Rev. Lett. 25 (1970) 316, Ann. Phys. (N.Y.) 66 (1971) 578.
5. E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579.
6. R.N. Cahn and S. Dawson, Phys. Lett. 136B (1984) 196.
   S. Dawson and J.L. Rosner, Phys. Lett. 148B (1984) 497.
   H. Georgi and M. Machacek, Nucl. Phys. B262 (1985) 463.
7. M.J. Duncan, G.L. Kane and W.W. Repko, University of Michigan preprint UM-TH-85-18.
8. O.J.P. Éboli, G.C. Marques, S.F. Novaes and A.A. Natale, preprint IFUSP/P-584 (to appear in Phys. Rev. D).
9. G.L. Kane, W.W. Repko and W.B. Rolnick, Phys. Lett. 148B (1984) 367.
   S. Dawson, Nucl. Phys. B249 (1985) 42.
   J. Lindfors, Z. Phys. C28 (1985) 427.
10. S.J. Brodsky, T. Kinoshita, H. Terazawa, Phys. Rev. D4 (1971) 1532.
11. S.S.D. Willenbrock and D.A. Dicus, Phys. Lett. 156B (1985) 429.

FIGURE CAPTIONS

Figure 1 - Vector bosons fusions contributing to lepton-neutrino production.

Figure 2 - Rapidity distribution at $y=0$ for the processes $pp \to W_L Z_L \to L\nu+X$ (solid lines) and $pp \to q\bar{q}' \to L\nu+X$ (dashed lines) at $\sqrt{s}$ = 20, 40 and 70 TeV.

Figure 3 - Rapidity distribution at $y=0$ for the processes $p\bar{p} \to W_L Z_L \to L\nu+X$ (solid lines) and $p\bar{p} \to q\bar{q}' \to L\nu+X$ (dashed lines) at $\sqrt{s}$ = 20, 40 and 70 TeV.

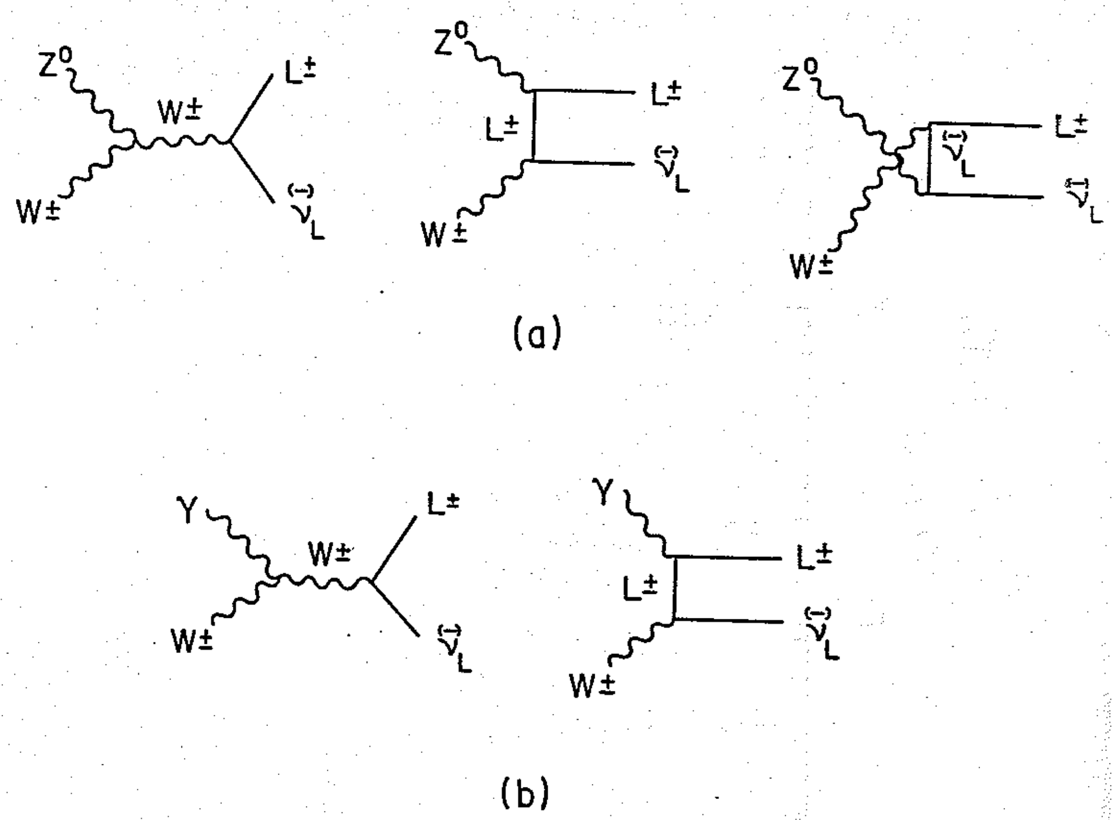
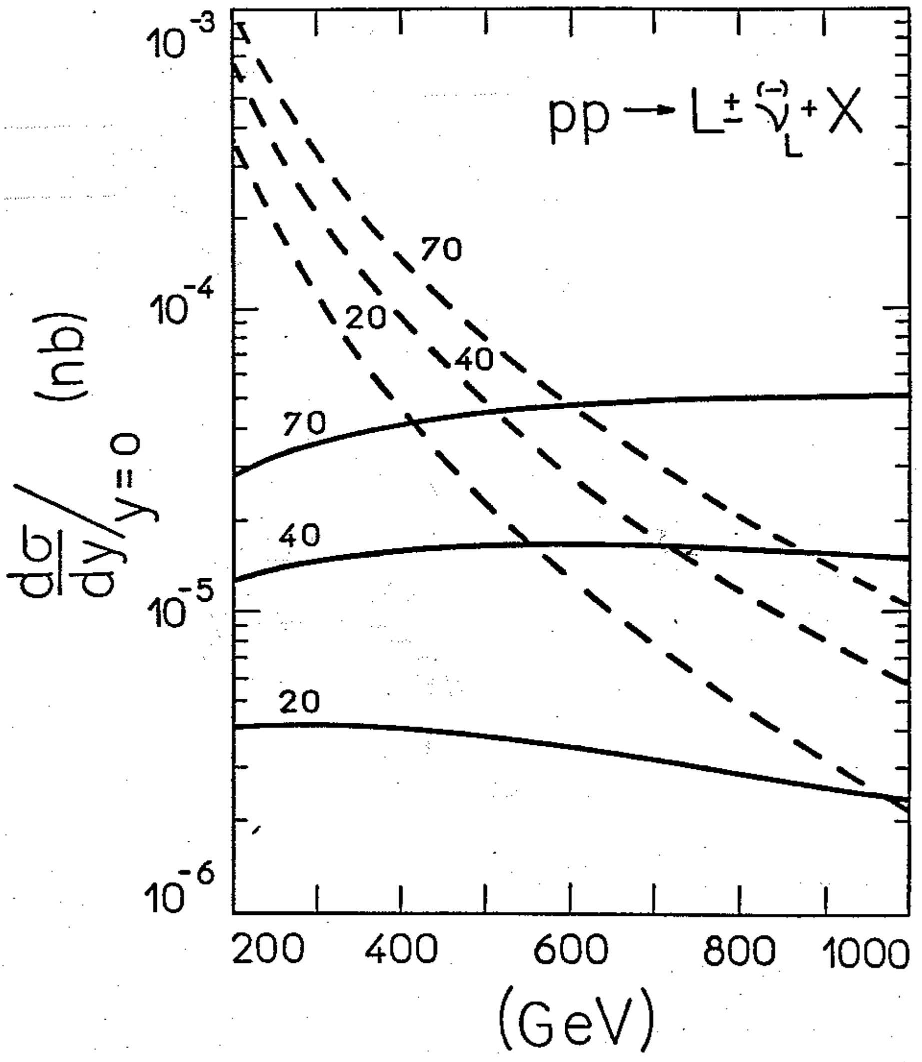
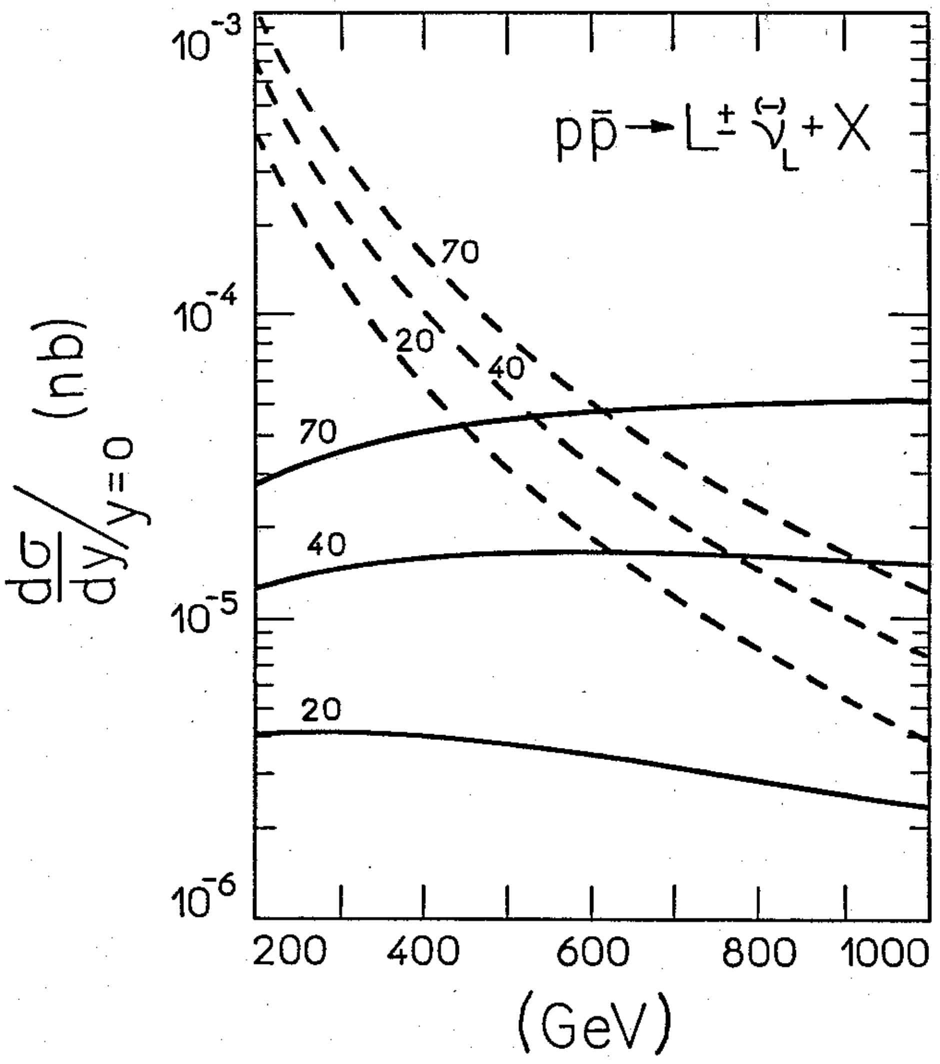


FIG. 1



$pp \to L^{\pm} \overset{(-)}{\nu}_L + X$
$\frac{d\sigma}{dy}\Big/_{y=0}$ (nb)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
70
20
40
70
40
20
200
400
600
800
1000
(GeV)

FIG. 2



$p\bar{p} \to L^{\pm} \overset{(-)}{\nu}_L + X$
$\frac{d\sigma}{dy}\Big/_{y=0}$ (nb)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
70
20
40
70
40
20
200
400
600
800
1000
(GeV)

FIG. 3