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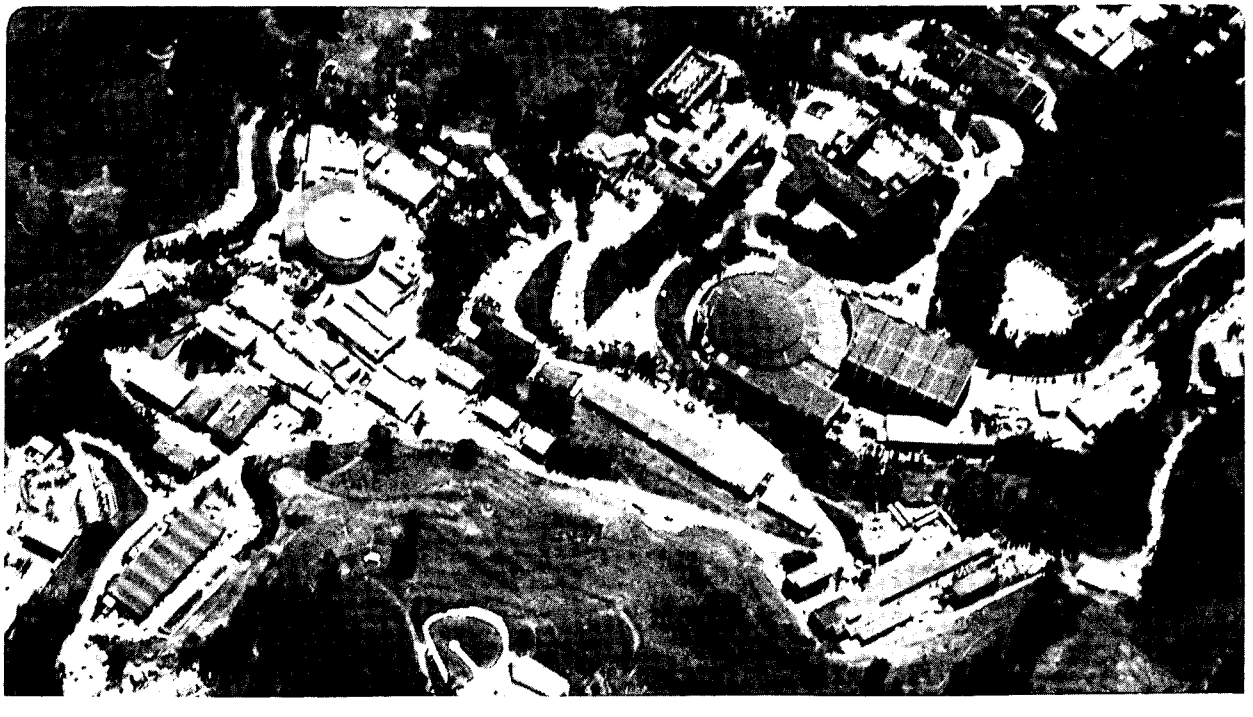
S. Dawson, G. Kane, C.P. Yuan,
and S.S.D. Willenbrock

September 1986



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Heavy Lepton Production in the Effective W Approximation *†

S. Dawson
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

G. Kane and C. P. Yuan
Randall Laboratory of Physics
University of Michigan
Ann Arbor, Michigan 48109

Scott S. D. Willenbrock
Center for Particle Theory
University of Texas
Austin, Texas 78712

Abstract

We examine production of fourth generation heavy leptons and neutrinos in the effective W approximation. At high energy *pp* colliders, gauge boson fusion is larger than the Drell–Yan mechanism for heavy lepton production for a range of heavy lepton and neutrino masses.

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S. Dawson
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

G. Kane and C.P. Yuan
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109

S.S.D. Willenbrock
Center for Particle Theory, University of Texas, Austin, Texas 78712

Summary

We examine production of fourth generation heavy leptons and neutrinos in the effective W approximation. At high energy pp colliders, gauge boson fusion is larger than the Drell-Yan mechanism for heavy lepton production for a range of heavy lepton and neutrino masses.

Introduction

The parton picture of the proton has been extremely successful in describing hadronic interactions at high energies. As higher energies are reached experimentally, it is necessary to include the effects of more components in the parton sea in theoretical calculations. At the energy of the proposed Superconducting Super Collider, $\sqrt{s} = 40$ TeV, the W and Z gauge bosons of the Weinberg-Salam model make important contributions to the parton sea.

The picture of the W and Z bosons as partons has received much attention in recent years, primarily as a mechanism for heavy Higgs production.[1] The distribution of W's in a proton can be calculated in a manner similar to the effective photon approximation for the distribution of photons in an electron. In this note, we consider heavy lepton production in the effective W approximation. We present rates for $pp \to W^+W^- + ZZ \to L^+L^-$ and $pp \to W^\pm Z \to L^\pm N$ (where $L(N)$ is a fourth generation charged lepton (neutrino)) and compare them with the relevant contributions from Drell-Yan production.[2]

The Effective W Approximation

Proton-proton colliders can be considered as a source of polarized beams of gauge bosons. The boson-boson luminosity is

$$\frac{d\mathcal{L}}{d\tau}\Big|_{pp/VV} = \sum_{i,j} \int \frac{d\tau'}{\tau'} \int \frac{dx}{x} f_i(x) f_j\left(\frac{\tau'}{x}\right) \frac{d\mathcal{L}}{d\xi}\Big|_{q_iq_j/VV} \tag{1}$$

where $\xi = \tau/\tau'$ and f_i are the appropriate quark structure functions. For heavy lepton production, only the contribution from longitudinally polarized gauge bosons is relevant and we have,

$$\begin{aligned} \frac{d\mathcal{L}}{d\tau}\Big|_{q_iq_j/V_LV_L} &= \frac{(C_V^2 + C_A^2)_{q_i}(C_V^2 + C_A^2)_{q_j}}{16\pi^4\tau} \\ &\quad [(1+\tau)ln\,(1/\tau) + 2(\tau - 1)] \end{aligned} \tag{2}$$

where

$$C_V = -C_A = \frac{g}{2\sqrt{2}} \tag{3}$$

for a W boson and

$$\begin{aligned} C_V &= \frac{g}{\cos\theta_W}\left(\frac{1}{2}T_{3_L} - Q\sin^2\theta_W\right) \\ C_A &= \frac{-g}{2\cos\theta_W}T_{3_L} \end{aligned} \tag{4}$$

for a Z boson, where $g = e/\sin\theta_W$, $T_{3_L} = \pm 1/2$ is the third component of weak isospin of q, and Q is the electric charge of q. Using the gauge boson luminosities, hadronic cross-sections involving vector boson fusion can be calculated in a straightforward manner,

$$\sigma_{pp\to VV\to X}(s) = \int d\tau \frac{d\mathcal{L}}{d\tau}\Big|_{pp/VV} \sigma_{VV\to X}(\tau s)\,. \tag{5}$$

Heavy Lepton Production

We calculate cross sections for heavy lepton production to leading order in M_W^2/s_{VV} and M_W/m_{lepton}, where s_{VV} is the total center-of-mass energy of the boson-boson system.[3] The interactions involving longitudinal gauge bosons are enhanced by factors of m_{lepton}/M_W relative to those with transverse gauge bosons, which we neglect. Yuan[3] and Eboli et al.[2] have examined the contribution of transversely polarized gauge bosons to heavy lepton production. They found that the longitudinal contribution is always dominant.

The cross section for producing a heavy lepton L and its associated neutrino N from gauge boson fusion is,

$$\begin{aligned} \sigma(W_L^\pm Z_L \to L^\pm N) &= \frac{\alpha^2\pi}{8\sin^4\theta_W M_W^4}\frac{1}{s_{WZ}} \\ &\quad \cdot \Big\{ -(m_L^2 - m_N^2)^2\beta - (m_L^2 \\ &\quad + m_N^2)(m_N^2\Lambda_1 + m_L^2\Lambda_2)\Big\} \\ &\quad + O(m_W^2/s_{WZ}) \end{aligned} \tag{6}$$

where

$$\begin{aligned} \beta &= \sqrt{1 - (m_L + m_N)^2/s_{WZ}}\ \sqrt{1 - (m_L - m_N)^2/s_{WZ}} \\ \Lambda_1 &= ln\left|\frac{(m_L^2 - m_N^2)/s_{WZ} - 1 + \beta}{(m_L^2 - m_N^2)/s_{WZ} - 1 - \beta}\right| \\ \Lambda_2 &= ln\left|\frac{(m_N^2 - m_L^2)/s_{WZ} - 1 + \beta}{(m_N^2 - m_L^2)/s_{WZ} - 1 - \beta}\right|. \end{aligned} \tag{7}$$

In Fig. 1, we compare the Drell-Yan mechanism, $q\bar{q} \to L^{\pm}N$, with the rate from gauge boson fusion for $m_N = 0$ and for $m_L = m_N$. For massless fourth generation neutrinos, production by WZ fusion is always smaller than by the Drell-Yan mechanism if $m_L \lesssim 1$ TeV. As the neutrino mass is increased, the $L^{\pm}N$ production rate from WZ fusion increases. For $m_L = m_N$, WZ fusion is the major production mechanism for $m_L \gtrsim 500$ GeV. For all values of the neutrino mass, our results lie between, or slightly above, the curves of Fig. 1.

The experimentally measured values of the W and Z boson masses limit the allowed mass splitting in an $SU(2)$ lepton doublet,[4]

$$|m_L^2 - m_N^2| \lesssim (600 \text{ GeV})^2. \tag{8}$$

Note that for $m_L = m_N$, there is no limit. Hence for lepton doublets where both m_L and m_N are equally massive, there is no experimental restriction from Eq.(8) and vector boson scattering becomes an important source of $L^{\pm}N$ production.

Heavy leptons can be pair produced from both W^+W^- and ZZ fusion. The rate for W^+W^- fusion is,

$$\begin{aligned}
\sigma\,(W_L^+W_L^- \to L^+L^-) &= \frac{\alpha^2\pi}{4\sin^4\theta_W M_W^4}\frac{1}{s_{WW}} \\
&\cdot \Big\{ -2\beta(m_N^4 + m_L^4 - m_N^2 m_L^2) \\
&- [m_N^4 + m_L^4 + \frac{2m_N^2}{s_{WW}}(m_L^2 - m_N^2)^2]\Lambda_3 \\
&+ \frac{1}{2}\frac{m_H^4 m_L^2 s_{WW}\beta^3}{(s_{WW} - m_H^2)^2 + \Gamma_H^2 m_H^2} \\
&- \frac{2m_L^2 m_H^2 (s_{WW} - m_H^2)}{(s_{WW} - m_H^2)^2 + \Gamma_H^2 m_H^2} \\
&\cdot \Big[(m_L^2 + m_N^2)\beta + \Big(\frac{m_L^2 - m_N^2)^2}{s_{WW}} + m_N^2\Big)\Lambda_3\Big]\Big\}
\end{aligned} \tag{9}$$

where

$$\begin{aligned}
\beta &= \sqrt{1 - 4m_L^2/s_{WW}} \\
\Lambda_3 &= \ln\left|\frac{2(m_L^2 - m_N^2)/s_{WW} + \beta - 1}{2(m_L^2 - m_N^2)/s_{WW} - \beta - 1}\right|.
\end{aligned} \tag{10}$$

The rate from ZZ fusion is always an order of magnitude smaller than that from W^+W^- fusion and so we do not give the cross section explicitely here. (It can be found in Ref. (3)).

In Fig. 2, we compare Drell-Yan production with that from gauge boson fusion for $m_N = 0$. We have added together the contributions for W^+W^- and ZZ scattering. Almost identical results are obtained for massive fourth generation neutrinos. (The Drell-Yan contribution is independent of the neutrino mass.) We see that for $m_L \gtrsim 500$ GeV, vector boson fusion dominates over $q\bar{q}$ annihilation.

In the case of heavy lepton pair production, there is another production mechanism which is important if there are fourth generation heavy quarks as well as leptons. The process $gg \to L^+L^-$ which proceeds by a triangle diagram with Higgs or Z s–channel exchange has been examined by Willenbrock and Dicus[5] and found to be large. The upper lines in Fig. 2 are the contribution from gluon fusion to lepton pair production, where we have assumed $m_U = m_D = m_L$. Increasing m_U increases the cross section. Our conclusion is that if there is a complete fourth generation, the dominant lepton pair production mechanism is gluon fusion.

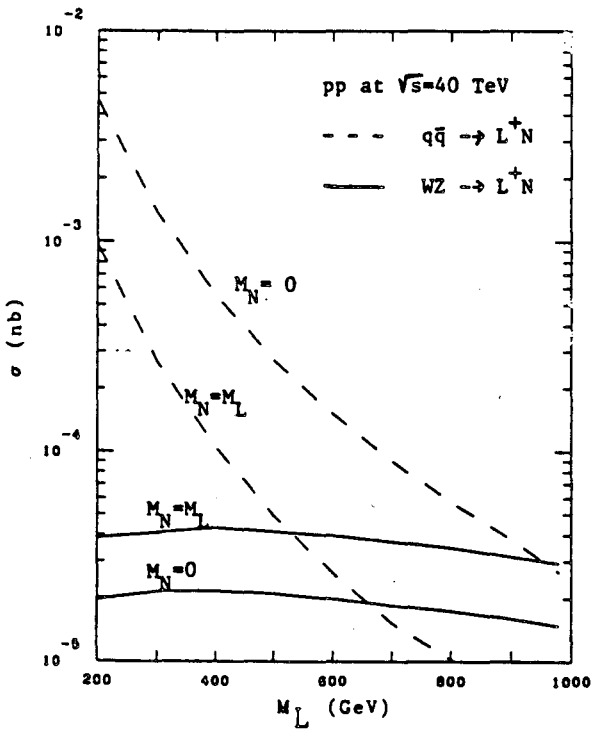

Fig.1. Cross section for $pp \to L^{\pm}NX$ at $\sqrt{s} = 40$ GeV in the effective W approximation versus the charged lepton mass (solid lines). The upper (lower) solid line hs $m_N = m_L (m_N = 0)$. The contribution from Drell–Yan production ($q\bar{q} \to L^{\pm}N$) is shown by the dashed lines. The upper (lower) dashed line has $m_N = 0 (m_N = m_L)$.

Conclusion

For the process $pp \to L^{\pm}N$ at $\sqrt{s}$ =40 TeV, the Drell-Yan contribution is dominant over vector boson fusion if $m_N = 0$ and $m_L \lesssim 1$ TeV. If the fourth generation neutrino is massive and $m_N = m_L$, then WZ fusion becomes the dominant mechanism when m_L is 500 GeV. Lepton pair production is dominated by gauge boson fusion for $m_L \gtrsim 500$ GeV unless there is a complete fourth generation of heavy fermions. In that case, the largest production mechanism for heavy lepton pairs is gluon fusion.

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2. Similar calculations have been performed by O. Éboli et al., Phys. Rev. D34 (1986) 771. We disagree with their results.

3. A detailed description of our results is contained in S. Dawson and S. Willenbrock, LBL-22087 (1986) and C. P. Yuan, University of Michigan preprint.

4. Particle Data Group, Phys. Lett. 170B (1986) 1.

5. Willenbrock and Dicus, Phys. Lett. 156B (1985) 429.

Acknowledgements

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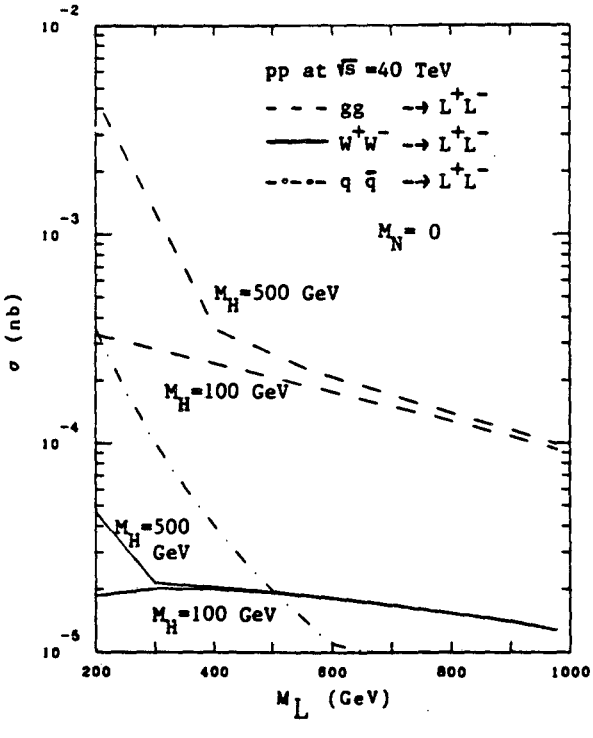

Fig. 2 Cross section for $pp \to L^+L^-X$ at $\sqrt{s} = 40$ TeV. The solid lines are the result for $W_L^+W_L^- + Z_LZ_L \to L^+L^-$ with $m_H = 100$ GeV and $m_H = 500$ GeV, for $m_N = 0$. The dot-dash line is the contribution from $q\bar{q} \to L^\pm L^-$. The dashed lines are the contribution from gluon fusion with fourth-generation quarks where we have assumed $m_L = m_U = m_D$.

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