Productions of heavy charged leptons via gluon fusion at LHC: A revisit Postprint

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Date: 2017-09-17T00:00:00+00:00

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Full Text

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Abstract

Heavy charged lepton production via gluon fusion at the LHC is revisited. Full loop calculations are performed with updated parton distribution functions and electroweak data. Including contributions from new generation quarks in the loop, pair production of sequential heavy leptons via gluon fusion at the LHC dominates over the Drell-Yan mechanism in certain heavy lepton mass ranges. Exotic lepton single production in vectorlike lepton extended models is also calculated. In the latter case, the gluon fusion mechanism via Higgs exchange is emphasized.

Our numerical results for both pair and single production of heavy leptons are smaller than previous studies, especially for large heavy lepton masses, as a result of our full loop calculation and the inclusion of mixing angles.

PACS numbers: 14.60.Hi, 12.60.-i, 13.85.Qk

Introduction

The CERN Large Hadron Collider (LHC) is the highest energy physics experiment of our time. In addition to the Higgs particle, which is the final missing piece of the Standard Model (SM), its main goal is searching for physics beyond the SM. Imaginable new physics discoveries at the LHC include new fermions, new gauge bosons, extra Higgs bosons, and so on.

Among these possibilities, we study new charged leptons. Although new lepton observation may be challenging at the LHC, once they are produced, their decay signals are relatively easy to identify.

New charged leptons are introduced in many new physics models such as grand unification theories, mirror fermions, supersymmetry, and little Higgs models. In some models, new fermions play an important role in electroweak symmetry breaking or CP violation, and their properties may differ from those of presently known fermions. Discovery of such new fermions would revolutionize our understanding of electroweak symmetry breaking and other fundamental problems.

At hadron colliders, the Drell-Yan process [1] and the gluon fusion process [2] are expected to be the main mechanisms for heavy charged lepton production. In the extreme case where new leptons are vectorlike and have no Yukawa interactions, the Drell-Yan mechanism dominantly accounts for new lepton production. On the other hand, if the new leptons are chiral with large Yukawa couplings, their production through Higgs-mediated processes can be significant, with the virtual Higgs produced via gluon fusion. Due to the large gluon flux at the LHC, as well as new contributions from new quarks, the gluon fusion production can dominate over the Drell-Yan mechanism for new chiral charged leptons in some parameter regions, as studied in refs. [3-8]. In an effort to understand the Higgs, an extra vectorlike generation of matter has been introduced within the framework of supersymmetry [9]. What is new in the lepton sector of that model after supersymmetry breaking is a vectorlike SU(2)L singlet lepton with a mass of O(400) GeV. We are interested in examining its production at the LHC. There are other vectorlike extensions to the minimal supersymmetric SM [10]. Generally, heavy leptons—even if they are vectorlike—have Yukawa interactions that may enhance their production rates. The gluon fusion mechanism is the focus of this study.

In view of current knowledge about parton distribution functions, relevant electroweak data, and the top quark mass, previous results on heavy lepton production via gluon fusion should be updated. Furthermore, previous studies of the gluon fusion mechanism for lepton production used tree-level approximations. We update previous studies of heavy charged lepton production via the gluon fusion mechanism with complete loop calculations. We find that the tree-level approximation should be used carefully in heavy lepton production from the gluon fusion mechanism and is only valid in certain limits.

This paper is organized as follows. In Sec. II, simple heavy fermion scenarios and their phenomenological constraints are described. In Sec. III, pair production of sequential charged fermions is calculated. Sec. IV discusses vectorlike fermion extensions of the SM and single production of exotic fermions in this scenario. Finally, we present discussion and conclusions in Sec. V.

II. The New Leptons

New fermions appear in various new physics models. They can be classified as chiral or vectorlike. In this section, we begin with a description of these two scenarios of new fermions and then discuss the phenomenological bounds.

One can make a replica of an SM family to obtain the simplest fourth generation, the so-called sequential fermions [11]. The sequential new leptons L4, Ec4 fall into the representations (2, -1) and (1, -2) under SU(2)L U(1)Y, respectively.

The new leptons can also be vectorlike, where the left- and right-handed components transform identically under SU(2)L U(1)Y. Both vectorlike doublet leptons and vectorlike singlet leptons are simple examples [8]. The quantum numbers for the vectorlike singlet lepton pair e4, ec4 are (1, -2), while those for the vectorlike doublet leptons L4, Lc4 are (2, -1).

Now let us consider phenomenological constraints on these scenarios. Direct experimental searches for new leptons at LEP II require that new charged leptons be heavier than 102 GeV and the fourth neutrino heavier than 101 GeV [12]. The results for pure Dirac neutrinos and for neutrinos with Majorana masses are slightly different. As for new quarks, the strongest bound on u4 is mu4 > 256 GeV [13], which comes from CDF searches for u4ū4 with u4(ū4) decaying to W+(W−) bosons and ordinary quarks. Assuming the branching ratio BR(d4 → bZ) = 1, CDF obtains the bound md4 > 268 GeV [14]. Additionally, constraints from the Z width require new fermion masses larger than MZ/2, which are weaker than those from direct searches.

For sequential fermions, the most stringent constraints come from the "oblique parameters" S, T, and U [15]. These constraints can be relaxed by allowing T to vary or by having non-degenerate fourth-generation masses [16, 17]. Recently, ref. [17] identified a region for new sequential fermions that agrees with all experimental constraints and has minimal contributions to oblique parameters.

In this paper, we assume similar parameters to those in [17]. Flavor physics also gives constraints on the fourth generation. Mixing parameters between the extra fermions and the ordinary three generations are subject to processes such as D0–D̄0 mixing. These constraints [15] are strong on mixing between the first or second generation and the fourth generation, suggesting that mixings need to be smaller than 0.01. For mixing between the third generation and the fourth generation, the flavor constraints are not very strong.

As for vectorlike extensions, the most important consequence is flavor-changing neutral currents (FCNC). Because vectorlike fermions are introduced, there is no GIM mechanism to suppress FCNCs related to these fermions. Furthermore, there is a resultant effect on flavor-diagonal neutral currents [18]. The decay width of the Z boson forces this effect to be small, which strongly constrains the mixing angles. Vectorlike fermions do not contribute to "oblique parameters" at leading order, and thus these parameters do not constrain their masses.

III. Pair Production of Charged Sequential Heavy Leptons

Within the framework of the fourth chiral generation, pair production is the main focus for heavy charged leptons. In addition to production via the Drell-Yan process, heavy leptons can also be produced via the gluon fusion mechanism induced by fermion loops, as shown in Fig. 1 [Figure 1: see original paper]. This mechanism could dominate over the Drell-Yan mechanism in some parameter space due to the large gluon flux at the LHC [2, 3]. There are no photon exchange diagrams, and only the Higgs and Z boson with axial-vector coupling contribute to this gluon fusion process due to Furry's theorem. As the ggH vertex in the Higgs exchange diagram is a symmetric tensor while the ggZ vertex in the Z exchange diagram is antisymmetric, there is no interference between these two contributions. In this section, we study the pair production of sequential leptons via the Higgs exchange diagram and the Z exchange diagram separately.

The Higgs exchange diagram for heavy lepton production in Fig. 1 is related to Higgs production via the gluon-gluon fusion mechanism. The ggH effective Lagrangian can be presented as G G HIH, where IH is the following loop function [19]:

$$I_Q = \frac{3xy}{(m_Q^2/\hat{s})}$$

Replacing the center-of-mass energy of the subprocess $\sqrt{\hat{s}}$ by mH, one obtains the loop function for Higgs production. In general, the loop function IH is complex, and evaluation of the integral gives IQ in terms of $Q = mQ^2/\hat{s}$, where:

$$I_Q = \frac{[2\lambda_Q + \lambda_Q(4\lambda_Q - 1)f(\lambda_Q)]}{2}$$

with

$$f(\lambda) = \begin{cases} \sin^{-1}\left(\frac{1}{\sqrt{\lambda}}\right)^2 & \text{for } \lambda > 1 \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-\lambda}}{1-\sqrt{1-\lambda}}\right) - i\pi\right]^2 & \text{for } \lambda < 1 \end{cases}$$

For convenience in discussion, we show the curve of I^2 as a function of Q in Fig. 2 [Figure 2: see original paper]. When mQ is much heavier than $\sqrt{\hat{s}}$, i.e., Q   1, IQ → 2/3, which is just the so-called heavy top quark limit for light Higgs production via gluon fusion. In the small mQ limit Q   1, IQ → 0. There is also a peak for Q being 0.17. For the process of gluon-gluon fusion to a light Higgs where $\sqrt{\hat{s}}$ = mH, it is correct to take the limit Q = mt^2/mH^2 1 for the top quark and Q = mb^2/mH^2 0 for light quarks. However, when it turns to heavy lepton pair production, the subprocess center-of-mass energy $\sqrt{\hat{s}}$ varies from $4mL^2$ to several TeV, and thus Q is not fixed. In ref. [2], it was assumed that IQ receives a value of unity from every quark with mQ > mL, which is a rough approximation. However, in some later studies IQ was taken to be unity irrespective of the relation between mQ and mL and the variation of $\sqrt{\hat{s}}$. That is unreasonable and would overestimate the cross section for large mL.

In fact, the effective function IH should be carefully used for different Q, and it is better to calculate the cross section in full loops for dilepton production from gluon fusion. We deduce the interaction vertices of ggH and ggZ and express them in terms of Passarino-Veltman scalar loop functions [21]. The cross sections are calculated in complete loop calculations with LoopTools [22]. Detailed representations are shown in the appendix. We have used the CTEQ6L [23] parton distribution function with factorization scale f = 2mL. The input parameters relevant to our computation are mt = 172.7 GeV [24], mb(mb) = 4.2 GeV, mZ = 91.1876 GeV, $\sin^2$ W = 0.2315, e(mZ) = 1/128.8, and the two-loop running coupling constant s(mZ) = 0.1176 [15].

Figure 3 [Figure 3: see original paper] plots the cross section for new sequential lepton pair production at the LHC with $\sqrt{s}$ = 14 TeV versus the mass parameter mL of the new charged lepton for several choices of the Higgs mass mH. Here only contributions from the top quark and bottom quark are included. Actually, the bottom quark's contribution is tiny in heavy lepton pair production as mb/$\sqrt{\hat{s}}$ → 0 for most of $\sqrt{\hat{s}}$, which differs from the case of Higgs production. We find that the cross section is sensitive to the square of the mass of the new lepton and can be enhanced by a heavy Higgs mass, especially for a light new lepton. For a typical new lepton mass mL = 200 GeV and Higgs mass mH = 300 GeV (mH = 120 GeV), the cross section is 7.8 fb (4.2 fb).

We also take into account the contributions from new generation sequential quarks in the loop for mH = 120 GeV, which significantly enhances the cross section across the entire parameter space, as shown in Fig. 4 [Figure 4: see original paper]. Several typical heavy quark mass parameter values mu4 = 300 GeV, 400 GeV, 600 GeV and the relation md4 = mu4 - 50 GeV, which agrees well with current data [17], are used. The loop function of the ggH interaction does not depend monotonically on $\sqrt{\hat{s}}$, so the effects due to new quarks are complicated, as can be seen in Fig. 4. For fixed mL with mL < 0.17, the value of u4 = mu4^2/4mL^2 is smaller than 0.17 for all $\hat{s}$, and the loop function IQ is in the monotonous region. The heavy quark effect in this region is more important than in other regions. We find that the contributions from new generation quarks are significant. For mu4 = 400 GeV and mL = 200 GeV, the cross section is 32 fb. Even for a larger mass mL = 500 GeV, the cross section is still as large as 3.85 fb. Unlike the case of light Higgs production via gluon fusion where a generation of quarks increases the cross section by roughly a factor of 9 [17, 25], in lepton pair production the increase is smaller than 9 times in the low mL region but much larger than 9 times in the high mL region.

Now we consider the Z exchange diagram. The ggZ interaction vertex can be expressed as [26]:

$$F^{\alpha\mu\nu} = \frac{g_s^2}{4\pi^2}\mathrm{Tr}[T^aT^b]\,\big[\epsilon^{\mu\nu\omega\phi}p_\omega q_\phi k^\alpha F_1(k^2) + (\epsilon^{\alpha\mu\omega\phi}q^\nu - \epsilon^{\alpha\nu\omega\phi}q^\mu)p_\omega q_\phi F_2(k^2) + (\epsilon^{\alpha\mu\omega\phi}p^\nu - \epsilon^{\alpha\nu\omega\phi}p^\mu)p_\omega q_\phi F_3(k^2$$

where ga is the coupling of the axial-vector current and Fi(k^2) (i = 1-4) are scalar functions:

$$\begin{aligned}
F_1 &= \int_0^1 dx \int_0^{1-x} dy \frac{1}{[m_Q^2 - k^2xy]} \\
F_2 = F_3 &= \int_0^1 dx \int_0^{1-x} dy \frac{(x+y)(1-y)+4xy}{[m_Q^2 - k^2xy]} \\
F_4 &= 1 + \int_0^1 dx \int_0^{1-x} dy \frac{(x+y)(1-y)-2xy}{[m_Q^2 - k^2xy]}
\end{aligned}$$

where the unity in F4 is the anomaly term.

Because of the different signs of the axial-vector coupling for up-type and down-type quarks, the contributions from up-type and down-type quarks are destructive. For the first two generations, the mass splitting between up-type and down-type quarks ΔmQ ~ 0, so the total contribution from the first two generations is vanishing. The cross section with only top quark and bottom quark contributions is shown as the solid line in Fig. 5 [Figure 5: see original paper]. The cross section with only top and bottom quark contributions is larger than that of the corresponding Higgs exchange diagrams. For heavy leptons with masses from 150 GeV to 250 GeV, the cross section can reach 8.1–38 fb. We have also considered contributions from new quarks with mu4 = 300 GeV or 400 GeV and md4 = mu4 - 50 GeV. The role of the new quarks is significant for larger mL. Generally, a larger splitting between new generation quarks will result in a higher production rate in Z exchange diagrams, which was used in previous studies, but a very large splitting conflicts with phenomenological constraints.

The total cross section for heavy lepton pair production via gluon fusion gg is the sum of contributions from the Z exchange diagram and the Higgs exchange diagram. In Fig. 6 [Figure 6: see original paper], this cross section is compared with that via the $\bar{q}q \to LL$ Drell-Yan mechanism DY. If only third-generation quarks are considered, gg < DY. By taking into account new generation quarks, gg dominates over DY in the large mass region. For instance, assuming mu4 = 400 GeV and md4 = mu4 - 50 GeV, gg > DY for heavy lepton masses ranging from 350 GeV to 1000 GeV. Our numerical results for gluon fusion are smaller than previous studies [2, 3], especially for large heavy lepton masses. This is mainly because we have used full loop calculations and included axial couplings.

The total cross section of heavy lepton pair production is enhanced significantly, which increases the possibility of detecting the heavy lepton signal. With an integrated luminosity of 100 fb ^{1}, including contributions from new generation quarks, we predict that for a sequential lepton mass mL = 250 GeV, 8100 heavy charged lepton pair events can be produced at the LHC with $\sqrt{s} = 14$ TeV. If the heavy charged lepton mass mL is larger than the heavy neutrino mass m L, the main decay modes of the heavy charged lepton are $L \to$ $LW^* \to$ $L\bar{q}q$. In the other case where mL < mN [27], L will only decay via Cabibbo-suppressed $L \to$ W^* with leptonic and hadronic decays of W^*. Assuming mL > m L and the fourth-generation neutrino is massive, early work [28] argued that the heavy lepton signal would be buried by Standard Model backgrounds, which are mainly single and pair production of weak bosons at the SSC with $\sqrt{s} = 40$ TeV. However, as discussed in Sec. II, current constraints require that the fourth-generation neutrino have a large mass, which results in different kinematic distributions of the signal compared to those in ref. [28]. If we consider the large contributions from new quarks and use some kinematic techniques, it may be possible to detect the heavy lepton signal in some lower mL region at the LHC. Further detailed studies are needed.

IV. Single Production of Exotic Leptons in Vectorlike Extended Models

For vectorlike fermions, both single production [5] and pair production [3, 4, 6] are possible via the gluon fusion mechanism. Because single production has a larger rate than pair production, we consider heavy lepton single production in this work. Both Drell-Yan processes [3, 5] and gluon fusion processes [5] contribute to single production. While ref. [5] considered the Z boson-mediated gluon fusion process, we also include the Higgs boson-mediated gluon fusion, which can be important due to potentially large Yukawa couplings. In addition, third-generation quarks in the loop are considered. Our calculation also uses full loop calculations together with updated parton distribution functions and electroweak data.

Single heavy lepton production via gluon fusion processes is distinguishable from that via W boson-mediated Drell-Yan processes because, besides the charged heavy lepton, the gluon fusion process also produces an ordinary charged lepton that can be identified experimentally in principle. Nevertheless, we will compare the gluon fusion results with the Z boson-mediated Drell-Yan results.

For the vectorlike singlet extension, a lepton pair e4 and ec4 with quantum numbers (1, -2) and (1, 2) under SU(2)L U(1)Y are introduced. For convenience, we only consider mixing relevant to the third generation and the new vectorlike fermion. The Lagrangian for lepton masses is:

$$\mathcal{L} \supset y_{33} L_3 \tau_2 \Phi^* e_3^c + f e_4 e_4^c + y_{34} L_3 \tau_2 \Phi^* e_4^c + \text{h.c.}$$

where y33 and y34 denote Yukawa couplings, Φ is the Higgs doublet, L3 = (3, l3) and e3^c are the third-generation lepton doublet and singlet, respectively. Note that there is no y43 term in the formula. After electroweak symmetry breaking, the charged lepton mass matrix is given by:

$$\mathcal{M}_l = \begin{pmatrix} m_{33} & m_{34} \\ 0 & f \end{pmatrix}$$

This matrix is diagonalized by two orthogonal matrices, where m33 = y33v/√2 and m34 = y34v/√2. The physical lepton and the new heavy lepton L are:

$$\tau = \cos\theta_L l_3 - \sin\theta_L e_4, \quad L = \sin\theta_L l_3 + \cos\theta_L e_4$$
$$\tau^c = \cos\theta_R e_3^c - \sin\theta_R e_4^c, \quad L^c = \sin\theta_R e_3^c + \cos\theta_R e_4^c$$

The corresponding masses and mixing parameters are:

$$m_\tau \approx \frac{f m_{33}}{\sqrt{f^2 + m_{33}^2}}, \quad m_L \approx \sqrt{f^2 + m_{33}^2}$$
$$\sin\theta_L \approx \frac{m_{34}}{\sqrt{f^2 + m_{33}^2}}, \quad \sin\theta_R \approx \frac{m_{33} m_{34}}{f\sqrt{f^2 + m_{33}^2}}$$

where we have made an expansion to order v/f and kept only leading non-vanishing results, assuming f > m34, m33.

Now let us turn to the vectorlike doublet fermions. The vectorlike doublet extension introduces a doublet lepton pair L4 and L4^c with quantum numbers (2, -1) and (2, 1) under SU(2)L U(1)Y. The Lagrangian relevant to the mass is:

$$\mathcal{L} \supset y_{33} L_3 \tau_2 \Phi^* e_3^c + f L_4 L_4^c + y_{43} L_4 \tau_2 \Phi^* e_3^c + \text{h.c.}$$

As in the vectorlike singlet model, the masses and mixing parameters are obtained:

$$m_\tau \approx \frac{f m_{33}}{\sqrt{f^2 + m_{33}^2}}, \quad m_L \approx \sqrt{f^2 + m_{33}^2}$$
$$\sin\theta_L \approx \frac{m_{43} m_{33}}{f\sqrt{f^2 + m_{33}^2}}, \quad \sin\theta_R \approx \frac{m_{43}}{\sqrt{f^2 + m_{33}^2}}$$

The interaction vertices are obtained after replacing the weak eigenstates by the physical states. Higgs-fermion-fermion and Z-fermion-fermion interactions for physical and L are listed in Table I. The Feynman rules for ZLL and ZL agree with those given in ref. [29]. L-related tree-level FCNC is explicitly seen.

TABLE I: Higgs-fermion-fermion and Z-fermion-fermion interactions in the vectorlike singlet model and the vectorlike doublet model. PL,R = (1   5)/2, s = sin , c = cos .

Interaction	Vectorlike Singlet Model	Vectorlike Doublet Model
H	m cLcR	m cLcR
HLL	mLsLsR	mL(1 + s^2)cLcR
HL	m sLcR + mLsLcR	(1 + s^2)m sLcR
Z	(2sin^2 W - 1)PLcL^2	(2sin^2 W - 1)PRcR^2
ZLL	(2sin^2 W - 1)PLsL^2	(2sin^2 W - 1)PRsR^2
ZL	(PLcLsL)	(PRcRsR)

The main phenomenological constraints come from the branching ratio of Z → . Non-vanishing sin L results in Z →   deviating from SM predictions. The current experimental data and SM prediction are [15]:

$$\Gamma_{\text{exp}}(Z \to \tau\tau) = (84.09 \pm 0.2)\ \text{MeV}, \quad \Gamma_{\text{SM}}(Z \to \tau\tau) = (83.82 \pm 0.1)\ \text{MeV}$$

Considering the central value difference and 3 uncertainties of both experimental and theoretical results, the Z →   decay width still allows at most one percent to come from new physics (which corresponds to 0.3% of the branching ratio). Requiring the uncertainty of the Z →   width to be smaller than 1%, we obtain sin L < 0.0686 in the vectorlike singlet case.

New interactions ZL and HL provide the mechanism for single production of exotic leptons via gluon fusion. We perform calculations with LoopTools [22]. The results for the cross section are shown in Fig. 7 [Figure 7: see original paper] for sin L = 0.05. They include both $^{-}$L and $\bar{L}$ production. The figure also shows the Z boson-mediated Drell-Yan process for comparison. We see that Drell-Yan always dominates over gluon fusion. For mL = 150 GeV, the cross section via gluon fusion is about 0.3 fb while that via Drell-Yan is several fb, which is marginally within detectability at the LHC. For mL > 250 GeV, even the Drell-Yan cross section is smaller than 1 fb, which is too small for detection of such heavy leptons.

One way to enhance the gluon fusion mechanism is to consider an additional generation of sequential fermions with large Yukawa couplings. Namely, the physics is the SM plus a fourth chiral generation and the vectorlike singlet charged lepton. New sequential quark loops with mU = 400 GeV and mD = mU - 40 GeV, for example, increase the gluon fusion contribution in single production processes. Then the cross sections of Higgs-mediated gluon fusion are larger than those of Z boson-mediated gluon fusion, and the gluon fusion mechanism can dominate over the Drell-Yan mechanism, as shown in Fig. 7 for mL > 350 GeV. In this case the cross section can be as large as 0.3 fb. This is still challengingly small for detection at the LHC.

Let us make a few remarks: (1) Compared to heavy sequential lepton pair production studied in the last section, the vectorlike lepton single production rate is small, despite the phase space enhancement. This is mainly due to our use of full loop calculations. The smallness is also due to suppression from sin L, which is strongly constrained by the branching ratio of Z → . Note that we have used sin L = 0.05, which is just half of that adopted in previous studies [5]. (2) For vectorlike lepton pair production, because the HLL interaction and axial-vector current ZLL interaction are proportional to sin L and $\sin^2$ L, respectively, in this model, the cross sections of the Higgs exchange diagram and Z exchange diagram are significantly suppressed by powers of sin L. (3) The phenomenological analysis for vectorlike doublet lepton models is similar to the singlet case. The production results are similar to the above singlet scenario, so we will not discuss the doublet lepton scenario further.

V. Conclusion

In this paper we have revisited heavy lepton production at the LHC. Our focus is the gluon fusion mechanism, which can be important due to the large gluon flux at the LHC. If contributions from new generation quarks are considered, the cross sections via the gluon fusion mechanism can be enhanced significantly. The pair production of new sequential heavy leptons from gluon fusion at the LHC dominates over the Drell-Yan mechanism in the large lepton mass region. With an integrated luminosity of 100 fb ^{1}, we predict that for a sequential lepton mass mL = 250 GeV, 8100 heavy charged lepton pair events can be produced at the LHC with $\sqrt{s}$ = 14 TeV.

We have also calculated exotic lepton single production in vectorlike lepton extended models. In the gluon fusion mechanism, we have included Higgs exchange. However, the production rate for exotic leptons is small due to suppression from mixing parameters.

Our numerical results for both pair and single production of heavy leptons are smaller than previous studies, especially for heavy leptons in the large mass region. The main reason is that we have not used tree-level approximations. In our loop computations, we have also adopted updated parton distribution functions and new electroweak physics data.

Acknowledgments

The authors would like to thank Tao Han, Zong-guo Si, Wen-Long Sang, and Lei Wang for helpful discussions. This work was supported in part by the National Science Foundation of China under Grant Nos. 90503002 and 10821504, and by the National Basic Research Program of China under Grant No. 2010CB833000.

Appendix

The cross section for a 2→2 process at hadron colliders is:

$$\sigma(P_A P_B \to F_3 F_4) = \sum_{a,b} \int dx_1 dx_2 f_{a/A}(x_1, Q^2) f_{b/B}(x_2, Q^2) \frac{|\mathcal{M}|^2}{32\pi^2 \hat{s}^{3/2}} \sqrt{P_{\text{out}}^2}$$

where

$$P_{\text{out}} = \sqrt{(\hat{s} - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}$$

and m3 and m4 are the masses of final states F3 and F4, respectively.

For the Higgs and Z exchange diagrams of pair production and single production of heavy leptons, the Feynman amplitudes are represented as follows:

$$\mathcal{M}_H = \frac{g_s^2}{4\pi^2} I_H(g_{\mu\nu}) \epsilon^\mu(p_1) \epsilon^\nu(p_2) \frac{i}{k^2 - m_H^2 + i m_H \Gamma_H} \bar{u}(p_3) v(p_4)$$

$$\mathcal{M}_Z = \frac{g_s^2}{4\pi^2} F^{\alpha\mu\nu} \epsilon_\mu(p_1) \epsilon_\nu(p_2) \frac{-i(g_{\alpha\beta} - k_\alpha k_\beta / m_Z^2)}{k^2 - m_Z^2 + i m_Z \Gamma_Z} \bar{u}(p_3) i\gamma^\beta (g_V + g_A \gamma_5) v(p_4)$$

In formula (A.3), F µ is the ggZ interaction vertex as represented in formula (5). The IH represented in Passarino-Veltman form is:

$$I_H = \frac{1}{2}\left(1 + \frac{2m_Q^2}{\hat{s}}\right) C_0[0, 0, \hat{s}, m_Q^2, m_Q^2, m_Q^2]$$

and the F' i in F µ represented in scalar loop functions are:

$$F_1 = \frac{1}{2}\left(B_0[0, m_Q^2, m_Q^2] - B_0[\hat{s}, m_Q^2, m_Q^2] + \frac{1}{\hat{s}} + 2C_0[0, 0, \hat{s}, m_Q^2, m_Q^2, m_Q^2]\right)$$

$$F_2 = F_3 = \frac{1}{2}\left(B_0[0, m_Q^2, m_Q^2] - B_0[\hat{s}, m_Q^2, m_Q^2] + \frac{1}{\hat{s}} + 2C_0[0, 0, \hat{s}, m_Q^2, m_Q^2, m_Q^2]\right)$$

$$F_4 = \frac{1}{2}\left(B_0[0, m_Q^2, m_Q^2] - B_0[\hat{s}, m_Q^2, m_Q^2] + \frac{1}{\hat{s}} + 2C_0[0, 0, \hat{s}, m_Q^2, m_Q^2, m_Q^2]\right) + 1$$

and LoopTools [22] is used for the numerical calculation of the scalar loop functions.

The general representations of Passarino-Veltman scalar loop functions B0 and C0 are [21]:

$$B_0[p_1^2, m_1^2, m_2^2] = \int \frac{d^n q}{i\pi^2} \frac{1}{[q^2 - m_1^2][(q + p_1)^2 - m_2^2]}$$

$$C_0[p_1^2, p_2^2, (p_1{+}p_2)^2, m_1^2, m_2^2, m_3^2] = \int \frac{d^n q}{i\pi^2} \frac{1}{[q^2 - m_1^2][(q + p_1)^2 - m_2^2][(q + p_1 + p_2)^2 - m_3^2]}$$

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