Precision Measurements at The Higgs Resonance: A Probe of Radiative Fermion Masses

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Abstract. The possibility of radiative generation of fermion masses from soft supersymmetry breaking chiral flavor violation is explored. Consistent models are identified and classified. Phenomenological implications for electric dipole moments and magnetic moments, as well as collider probes – in particular those relevant at the Higgs resonance – are discussed. It is shown that partial widths $\Gamma_{h\to ff}$ are enhanced compared with the minimal supersymmetric standard model.

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INTRODUCTION

The main motivations for proposing and building the next generation(s) of hadron and lepton colliders are the discovery of the Higgs boson and the search for signals of physics beyond the Standard Model (SM). Most of the related theoretical work has focused so far on discovery strategies and on the extraction of various parameters within a given theoretical framework. These issues have been and are still extensively addressed in the framework of supersymmetry, in general, and the minimal supersymmetric standard model (MSSM), in particular [1]. Recently, it has been shown that electron colliders could efficiently probe various quantum corrections in supersymmetric models. One-loop corrections to gaugino couplings, that grow logarithmically with the scale of heavy (and kinematically unaccessible) sparticles, modify observables involving light sparticles and may be measured [2]. Hence, if supersymmetry is present at low-energies one may gain a more complete understanding of its realization in a similar manner to the knowledge gained from precision probes of quantum corrections in the electroweak theory.

Complementary measurements (in lepton flavor and energy range) of the corrections discussed above are also possible in a muon collider [3]. Here, however, we would like to consider a unique feature of the muon collider – its beam energy resolution which enables it to explore narrow resonances. In particular, an s-channel Higgs boson [4] could be produced and its properties studied. The resonant Higgs production offers an opportunity to explore quantum effects in the Higgs sector of supersymmetric models. Most studies of the Higgs resonance have focused so far (i) on distinguishing the SM Higgs boson from the light supersymmetric Higgs boson, and (ii) on extracting the properties of the heavier Higgs bosons in supersymmetric and two Higgs doublet models [5]. Here, we propose that precision measurements of a partial width $\Gamma_{H \rightarrow ff}$, along with other low-energy observables discussed below, can reveal whether the respective fermion mass is radiative [6,7] with a corresponding “soft” (rather than tree-level) Yukawa coupling. If the Yukawa couplings are induced by supersymmetry breaking quantum effects, they would enable one to indirectly probe the supersymmetry breaking sector. We note in passing that even if there are tree-level Yukawa couplings, the quantum corrections in supersymmetric models can be possibly measurable.

We will demonstrate how radiative scenarios may arise in supersymmetric frameworks and explore their implications for fermion masses and couplings. We will show that a soft Yukawa coupling arising from supersymmetry breaking chiral flavor violation is always enhanced in comparison with the case of a tree-level coupling. In the case of the muon, however, the enhancement is constrained by the upper bound on the muon anomalous magnetic moment. Before concluding, we will suggest possible avenues for more detailed collider
studies. Here, we will concentrate on the phenomenology of the light supersymmetric Higgs boson, $h^0$, which may be produced in a low-energy machine ($\sqrt{s} \leq 200 - 500$ GeV). Details, as well as applications involving the heavy Higgs bosons and the Higgsinos, can be found in Ref. [7].

I MODEL BUILDING

In the absence of tree-level Yukawa couplings, chiral flavor symmetries can still be broken by trilinear terms in the scalar potential,

$$V = \sum m_i^2 \phi_i^2 + [B_{ij} \phi_i \phi_j + A_{ijk} \phi_i \phi_j \phi_k + A'_{ijk} \phi_i^* \phi_j \phi_k + h.c.] + \lambda_{ij} \phi_i^2 \phi_j^2. \quad (1)$$

In this case, the chiral flavor symmetries in the fermion sector are broken at the quantum level. Gauge loops $\propto A$ or $\propto A'$ which dress the fermion propagator generate the fermion mass and its effective coupling to the Higgs bosons. We will return to the generation of masses and couplings below. First, however, we would like to elaborate on the possible realizations of such a framework.

The flavor symmetries of the high-energy theory can forbid certain fundamental Yukawa couplings but allow for either (i) $ZH_2 \Phi_L \Phi_R/M$ or (ii) $ZZ^\dagger H \Phi_L \Phi_R/M^3$ (superfield) operators in the superpotential or the Kahler potential, respectively. The chiral superfield $Z = z + \theta^2 F_Z$ parameterizes here the supersymmetry breaking sector, and $\langle F_Z \rangle = M_{SUSY}^2$ signals supersymmetry breaking at a scale $M_{SUSY}$. If the scalar component $\langle z \rangle$ vanishes and the auxiliary component $\langle F_Z \rangle$ does not, then no Yukawa couplings arise but only soft supersymmetry breaking trilinear terms $\propto \langle F_Z \rangle^n$ in the scalar potential.

The operators (i) lead to $A$-type terms, $AH \Phi_L \Phi_R$, while the operators (ii) lead to $A'$-type terms, $A'H^* \Phi_L \Phi_R$. The trilinear terms are not proportional to any Yukawa couplings. The symmetries of the models typically allow for only one type of operators for a given flavor, as we will assume. Note that a sufficiently large $A' \sim M_{SUSY}^4/M^3$ requires that the supersymmetry breaking scale, $M_{SUSY}$, and the scale that governs the dynamics in the Kahler potential, $M$, are both relatively low-energy scales. Such a situation could arise, for example, if there is strong dynamics at the scale $M$.

Our results below imply $A/m \sim m_q(M_{weak})/(1.5 - 3$ GeV), $m_l(M_{weak})/(50 - 100$ MeV) for correct quark and lepton mass generation, respectively, assuming a typical sfermion mass scale $m$ (and similarly for $A'/m$). Hence, the maximal magnitude of the trilinear parameters that can be realized consistently determines which fermion masses can be generated radiatively. Their magnitude is constrained most significantly by the requirement of a stable color and charge conserving minimum. One has the sufficient (but not necessary) constraint (for any flavor indices) $|A_{ijk}/m| \lesssim \sqrt{3\lambda}$, where $\lambda = \lambda_{ij} + \lambda_{ik} + \lambda_{jk}$, and similarly for $A'/m$. Models with $A$-type trilinear operators and with minimal (MSSM) matter content have $\lambda = 0$ at tree level and $\lambda < 0$ at one loop. Such models are inconsistent with the stability constraint. On the other hand,
there are other viable possibilities: (a) For minimal matter content but with $A'$-type operators one has $\lambda = g' / 2 \sim 0.06$ (from the $D$-term potential), where $g'$ is the hypercharge coupling. For the $b$-quark one has in addition (from the $F$-term potential) $\lambda = g' / 2 + y_i^2 \sim 1$, but only for a large $t$-quark Yukawa coupling, $y_t$, at tree-level. (b) Mirror matter flavor breaking: An exotic multi-TeV sector with vector-like matter, which is allowed by the symmetries to mix with the SM matter with a typical Yukawa coupling $y$, gives $\lambda \sim y^2[(m_{SB}^2 + m_S^2) / m_{SB}^2] \sim 1$, but only for a large $t$-quark Yukawa coupling, $y_t$, at tree-level.

II THE PHENOMENOLOGY

The one-loop sfermion-gaugino exchange which dresses the fermion propagator generates a finite contribution to the fermion mass. It is given by

$$m_f = -m^2_{LR} \left\{ \frac{\alpha_s}{2\pi} C_f m_s I(m_{j_1}^2, m_{j_2}^2, m_{\tilde{g}}^2) + \frac{\alpha'}{2\pi} m_{\tilde{B}} I(m_{j_1}^2, m_{j_2}^2, m_{\tilde{B}}^2) \right\}, \quad (2)$$

where $C_f = 4/3, 0$ for quarks and leptons, respectively, and $m^2_{LR} = A\langle H \rangle$ or $A'\langle H^* \rangle$. The first and second terms correspond to the QCD (gluino) and hypercharge (bino) contributions, respectively. (Corrections due to possible neutralino mixing are omitted here). The function $I(m_{j_1}^2, m_{j_2}^2, m_{\tilde{g}}^2)$ can be typically approximated $I(m_{j_1}^2, m_{j_2}^2, m_{\tilde{g}}^2) \times \max(m_{j_1}^2, m_{j_2}^2, m_{\tilde{g}}^2) \simeq O(1)$, where $\lambda$ denotes a gaugino (sfermion). This leads to the numerical results given in the previous section. Note that the radiatively generated fermion mass does not vanish for large sparticle masses, provided that $A$ (or $A'$), $m_{\tilde{f}}$, and $m_{\lambda}$, are all of the same order of magnitude. An effective Yukawa coupling $\bar{y}_f H f f$, which is momentum dependent, is generated by the corresponding loop diagrams.\(^2\) When applied to the decay $H \to f f$, it depends only on internal and external masses. Furthermore, it is simplified for a light Higgs boson\(^3\) ($m_h / m_{\tilde{f}}, m_{h^0} / m_\lambda \to 0$) [7],

\(^2\) It differs numerically from the Higgsino-sfermion-fermion coupling [7].

\(^3\) In the case of a massive Higgs boson the vertex is described by a $C$ function. One also finds enhancements in this case [7].
The ratio \( r_f \) of the radiative soft Yukawa coupling to a tree level Yukawa coupling for a given fermion flavor as a function of the mass splitting \( \frac{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2}{m_{\tilde{f}_1}^2 + m_{\tilde{f}_2}^2} \). The different curves correspond to different values of \( \rho_f = \frac{(m_{\tilde{f}_1}^2 + m_{\tilde{f}_2}^2)}{2m_{\lambda}} \).

The ratio \( r_f \equiv \frac{\bar{y}_f}{(m_f/\langle H \rangle)} \) is illustrated in Fig. 1 for sfermion mixing angle \( \sin 2\theta_f = 1 \), which maximizes the effect. One observes that the radiative Yukawa coupling could be enhanced by a significant percentage in comparison to the case of a tree-level fermion mass. The enhancement increases with the mass splitting between the sfermion eigenstates. Most importantly, we would like to stress that the soft coupling is always enhanced. Note that the projecting factors between the physical and interaction Higgs eigenstates were omitted above. In the case of \( A' \)-type operators these factors are different than in the usual case of tree-level couplings. For the light Higgs boson this is irrelevant in the limit in which the heavy Higgs bosons decouple, and which applies to most of the parameter space.

The radiative fermion mass also has strong implications for low-energy phenomena. The mass and one-loop electric dipole moment arise from closely related diagrams, implying that the phases are aligned, \( \text{Arg}(m_e) = \text{Arg}(d^{\text{SUSY}}_e) \).
The one-loop electric dipole moment therefore automatically vanishes. Similarly, if the mass matrix of a whole sector (i.e., lepton, down, or up) is generated radiatively and the soft supersymmetry breaking masses $m_{i}^{2}$ are flavor independent, then the trilinear parameters and the corresponding fermion masses are diagonalized simultaneously, suppressing potential contributions to flavor changing neutral currents. Such a scenario is possible at least in the case of a radiatively generated down-quark sector [7].

The magnetic moment operator is also given by a loop diagram which is similar to the mass diagram. Hence, it is not suppressed by a loop factor compared to the radiatively generated mass as is the case for a tree-level mass, leading to $g_{f} - 2 \sim m_{f}^{2}/m_{\lambda}^{2}$ [7]. If $m_{\mu}$ is radiative one predicts a muon anomalous magnetic moment of the order of current limits ($O(10^{-(9-8)})$) for $m_{\tilde{B}} \lesssim 300$ GeV. Therefore, an observation at the Brookhaven experiment of a deviation from the SM prediction for $g_{\mu} - 2$ could signal a radiative muon mass. An s-channel resonant Higgs production could test the radiative muon mass interpretation of a deviation in $g_{\mu} - 2$, as a radiative $m_{\mu}$ also implies that the Higgs production rate is enhanced. However, because of the constraint $m_{\tilde{B}} \gtrsim 300$ GeV and the smallness of the muon mass, the mixing $\sin 2\theta_{\mu}$ is bounded from above [7]. As a result, the enhancement of $\bar{y}_{\mu}$ cannot be maximal (see eq. (3)) and is typically only a few percent. Nevertheless, efforts to precisely determine $r_{\mu}$ are strongly motivated in such a situation.

III PROSPECTS

It has been shown that soft Yukawa couplings, i.e., radiative generation of fermion masses, is a logical possibility in certain (non-minimal) supersymmetric frameworks. Aside from low-energy implications for $CP$ violation and magnetic moments, such scenarios imply an enhancement of the Higgs - fermion couplings ranging from a few percent up to an order of magnitude in comparison with the MSSM. Hence, the next generation of lepton colliders, and in particular, the muon collider, offer an opportunity to determine experimentally whether fermion masses are generated radiatively.

The production rate on the s-channel Higgs resonance of a fermion whose mass is generated radiatively is enhanced in comparison with the MSSM by $r_{f}^{2}$, or if $m_{\mu}$ is also radiative, by $r_{\mu}^{2}r_{f}^{2}$. The partial width $\Gamma_{h^{0} \rightarrow ff}$ is enhanced by $r_{f}^{2}$. The enhancement can partially cancel out in branching ratios, so partial widths or the ratios $\Gamma_{h^{0} \rightarrow ff}/\Gamma_{h^{0} \rightarrow WW}$ are more sensitive observables. However, an enhancement of the total width can also indicate radiative fermion masses. The projected errors of $\sim 5\%, 10-20\%, 10\%$ in the determination of $\Gamma_{h^{0} \rightarrow \mu\mu}$, $\Gamma_{h^{0} \rightarrow cc, bb}$ and the total width [5], respectively, suggest that such tests are feasible. However, detailed studies are needed. Decay modes of the heavy Higgs bosons, the Higgsinos, and the sfermions offer additional probes of such scenarios in high energy machines [7]. For example, if the $b$ mass is radiative
then one expects enhancement of $\tilde{b}_1 \to H\tilde{b}_2$. Similarly, in the case of, e.g., the $c$-quark, one would also observe mixing (which vanishes in the MSSM) between the scalar charms.

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