Tests of the Uplifted Higgs region

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Electroweak symmetry breaking

We know that $SU(2)_W \times U(1)_Y \to U(1)_Q$

$\Rightarrow$ $W^\pm$ **and** Z **have not only transverse polarizations,**

but also longitudinal ones: three spin-0 states have been eaten.

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What is the origin of electroweak symmetry breaking?

We do not know:

- **why is there a VEV that breaks** $SU(2) \times U(1)$ **?**
- **what are the properties of the field that has a VEV?**
- **what unitarizes** $W_L^+ W_L^-$ **scattering?**

Minimal Supersymmetric Standard Model

Superpotential: $W = y_u \, \hat{u}^c \hat{H}_u \hat{Q} - y_d \, \hat{d}^c \hat{H}_d \hat{Q} - y_\ell \, \hat{e}^c \hat{H}_d \hat{L} + \mu \, \hat{H}_u \hat{H}_d$

We assign R-charges such that the soft susy-breaking term $B\mu H_u H_d$ is forbidden, *e.g.*, $R[\hat{H}_d, \hat{Q}, \hat{u}^c, \hat{e}^c] = 0$ **and** $R[\hat{H}_u, \hat{d}^c, \hat{L}] = 2$**.**

Higgs potential:

$$\left(|\mu|^2 + m_{H_u}^2\right) |H_u|^2 + \left(|\mu|^2 + m_{H_d}^2\right) |H_d|^2 + \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u|^2 - |H_d|^2\right)^2$$

$m_{H_u}^2$ **and** $m_{H_d}^2$ **are susy-breaking parameters.**

We impose that

$$|\mu|^2 + m_{H_u}^2 < 0$$
$$|\mu|^2 + m_{H_d}^2 > 0$$

and, in order for the potential to be bounded from below, that

$$2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 > 0 \ .$$

$\Rightarrow$ only H_u acquires a VEV.

H_d has no VEV $\Rightarrow$ down-type quarks and leptons do not acquire masses from the Yukawa couplings given in the superpotential.

Should one dismiss this region of parameter space?

No: the Yukawa couplings explicitly break the chiral symmetries from $U(3)^5$ to $U(1)_B \times U(1)_L$

$\Rightarrow$ *loops will generate masses for the down-type quarks and leptons.*

Holomorphy dictates that the supersymmetric Higgs sector is a Two-Higgs-Doublet model of type-II
(only up-type quarks get masses from H_u).

However, once supersymmetry (and the R-symmetry) is broken, all gauge invariant operators may be present in the low-energy effective Lagrangian. These include:

$$-y'_d\, d^c H_u^\dagger Q - y'_\ell\, e^c H_u^\dagger L$$

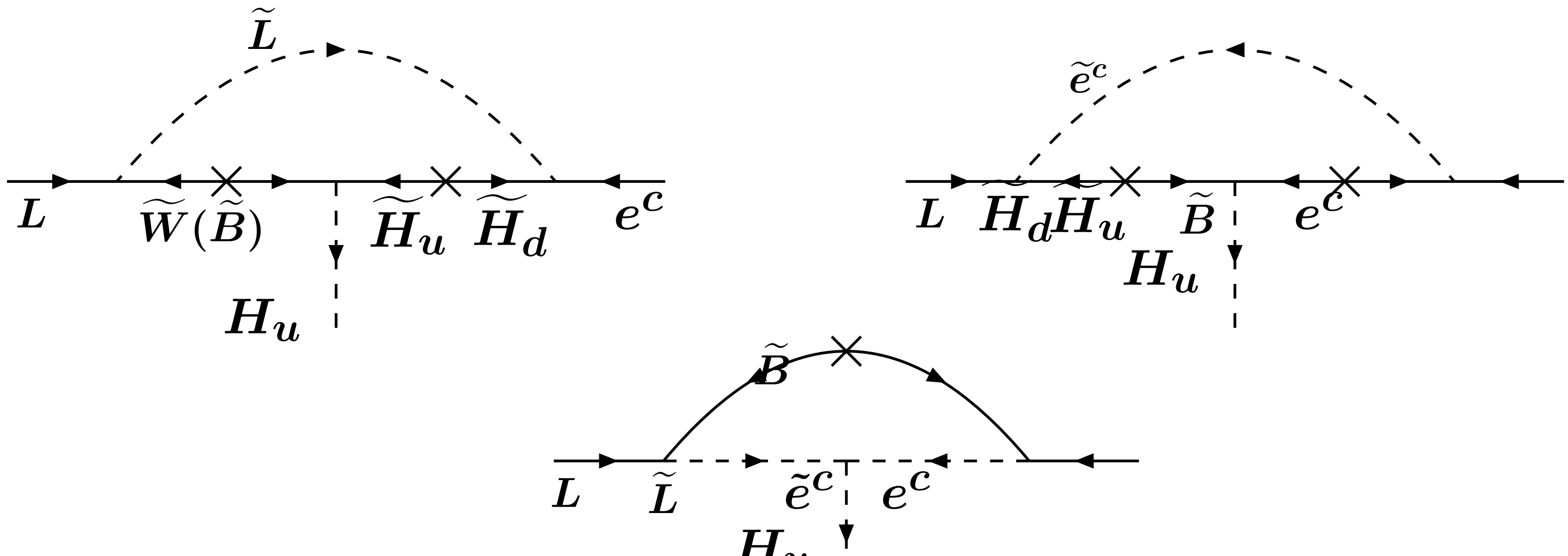
The F term for H_d which follows from the superpotential is

$$F_{H_d}^\dagger = y_d\, \tilde{d}^c \widetilde{Q} + y_\ell\, \tilde{e}^c \widetilde{L} - \mu H_u \quad .$$

This F term generates the following trilinear scalar interactions in the Lagrangian:

$$\mu^* H_u^\dagger \left(y_d \tilde{d}^c \widetilde{Q} + y_\ell \tilde{e}^c \widetilde{L} \right) + \text{H.c.}$$

Loop-induced lepton masses



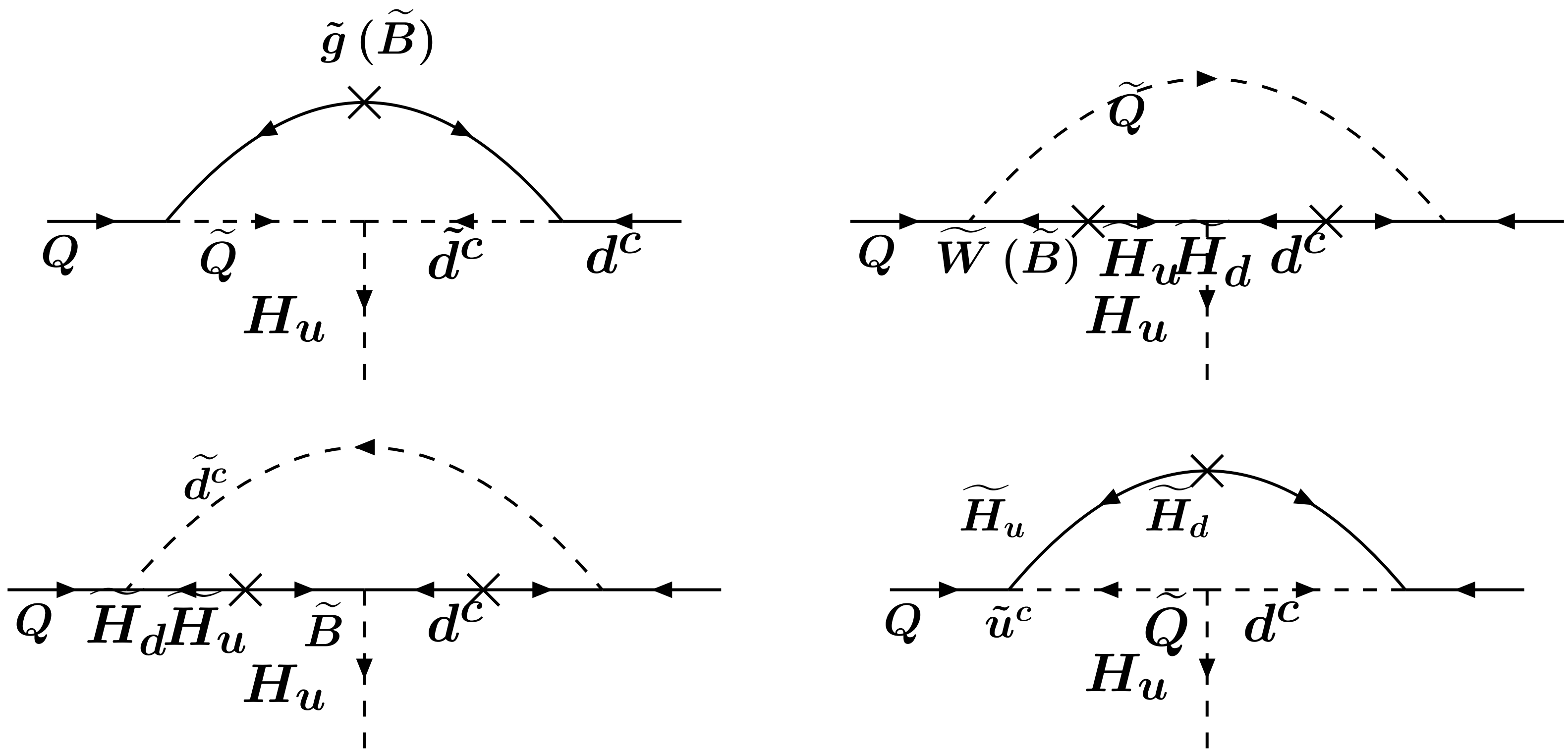
These 1-loop diagrams are finite, and give rise to an uplifted-Higgs lepton coupling:

$$y'_\ell = \frac{y_\ell\,\alpha}{8\pi} e^{i(\theta_W-\theta_\mu)} \Bigg\{ \frac{3}{s_W^2} F\left(\frac{M_{\tilde{W}}}{M_{\tilde{L}}}, \frac{|\mu|}{M_{\tilde{L}}}\right) + \frac{e^{i(\theta_B-\theta_W)}}{c_W^2}\Bigg[-F\left(\frac{M_{\tilde{B}}}{M_{\tilde{L}}}, \frac{|\mu|}{M_{\tilde{L}}}\right)$$

$$+\,2F\left(\frac{M_{\tilde{B}}}{M_{\tilde{e}}}, \frac{|\mu|}{M_{\tilde{e}}}\right) - \frac{2|\mu|}{M_{\tilde{e}}} F\left(\frac{M_{\tilde{B}}}{M_{\tilde{L}}}, \frac{M_{\tilde{e}}}{M_{\tilde{L}}}\right)\Bigg]\Bigg\}$$

$$F(x,y) = \frac{2xy}{x^2-y^2}\left(\frac{y^2\ln y}{1-y^2} - \frac{x^2\ln x}{1-x^2}\right)$$

Contributions to the y'_d Yukawa coupling of the down-type quarks:



The F-term interaction for quarks given in appears in a loop that involves either a bino (as in the case of leptons) or a gluino.

$$(y'_d)_F = \frac{y_d}{3\pi} e^{i(\theta_g-\theta_\mu)} \frac{2|\mu|}{M_{\tilde{d}}} \left[\alpha_s F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}} \right) + \frac{\alpha e^{i(\theta_B-\theta_g)}}{24 c_W^2} F\left(\frac{M_{\tilde{B}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}} \right) \right]$$

The Higgs boson h^0 that couples to WW is at tree level entirely part of the H_u doublet

The other physical states, H^0, A^0 and $H^\pm$, are all part of the H_d doublet and have the same tree-level mass:

$$M_{H^0}^2 = M_{A^0}^2 = M_{H^\pm}^2 = |\mu|^2 + m_{H_d}^2$$

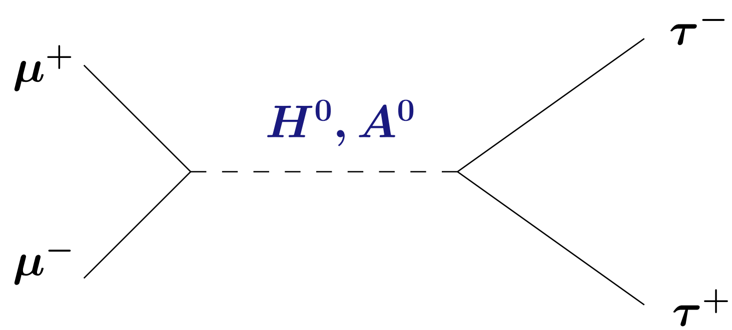
This may range between several hundred GeV to a few TeV.

The heavy "Higgs" bosons $(H^0, A^0, H^\pm)$ have a large Yukawa coupling to the τ, such that the branching fractions for $H^0, A^0 \rightarrow \tau^+\tau^-$ and $H^\pm \rightarrow \tau^\pm\nu$ may be as large as 90%.

The Yukawa coupling of H^0 and A^0 to $\mu^+\mu^-$ is

$$y_\mu \approx y_\tau \frac{m_\mu}{m_\tau} \gtrsim 0.07$$

s-channel production of H^0 and A^0 at a muon collider would allow detailed studies of the heavy Higgs bosons.



Relatively broad resonances, because $y_\tau \gtrsim 1.5$:

$$\Gamma(H^0) \approx \Gamma(H^0) \approx \frac{y_\tau^2 + 3y_b^2}{16\pi} M_{H^0}$$

Natural spread in the muon collider beam energy is smaller than $\Gamma(H^0)$.

$$\sigma(\mu^+\mu^- \to H^0, A^0 \to \tau^+\tau^-) \approx \frac{8\pi}{M_{H^0}^2} B(H^0 \to \mu^+\mu^-) B(H^0 \to \tau^+\tau^-)$$

$$B(H^0 \to \tau^+\tau^-) \approx \frac{y_\tau^2}{y_\tau^2 + 3y_b^2} \approx 30 - 90\%$$

$$B(H^0 \to \mu^+\mu^-) \approx \frac{m_\mu^2}{m_\tau^2} B(H^0 \to \tau^+\tau^-)$$

Resonably large cross section:

$$\sigma(\mu^+\mu^- \to H^0, A^0 \to \tau^+\tau^-) \approx 17 \text{ pb} \left(\frac{1 \text{ TeV}}{M_{H^0}} \times \frac{B(H^0 \to \tau^+\tau^-)}{0.7} \right)^2$$

Conclusions

Explorations of the energy frontier require a muon collider. In particular, a muon collider would be crucial for understanding the origin of electroweak symmetry breaking.

The Minimal Supersymmetric Standard Model has been hiding (for over 30 years) a large region of parameter space with surprising phenomenological implications.

In this "Uplifted region" of the MSSM Higgs sector all fermion masses are generated predominantly by their couplings to H_u. $\tan\beta \approx 300$ is a confusing parameter.

The Yukawa coupling of H^0 and A^0 to $\mu^+\mu^-$ is 0.1 or larger. s-channel production of H^0 and A^0 at a muon collider would be the best way of studying this supersymmetric Higgs sector.