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Excelente Myriam y Liliana!!

Higgs mass in the MSSM with flavor mixing soft terms

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Motivation

The *breaking of the EW symmetry* still requires to be proven experimentally:

the Higgs mechanism h^0 $\rightsquigarrow$ intrinsically related to flavor physics current experimental results on Higgs can set bound to FV parameters

Accomplish for non-experimentally excluded but non-vanishing ~~*flavor*~~ processes

In *Supersymmetric* models:

- EW scale is stabilized,
- couplings are unified,
- generates candidates for DM,
- **could accomplish for FV couplings through** *SUSY 1- loop*

Outline

- *"gender"* **overview of the fermion-sfermion MSSM sector**

- **flavor structure Ansatz on MSSM soft-SUSY breaking terms**

- **Non-universal sfermion masses and mixing angles**

- **Possible effects on phenomenology**
  - sfermion sector
  - leptonic sector
  - quark sector
  - Higgs sector

Supersymmetry

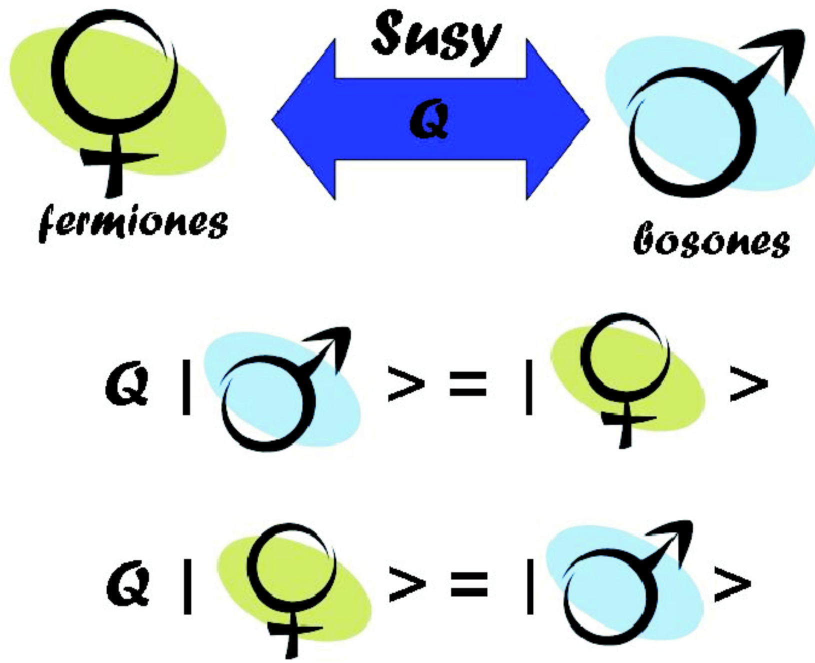


Figure 1: *Symmetry which relates fermions with bosons*

Supersymmetry field structure for fermions

Supermultiplets:
Each of the fermion is accompanied by a complex scalar $\longrightarrow$ *chiral superfield.*

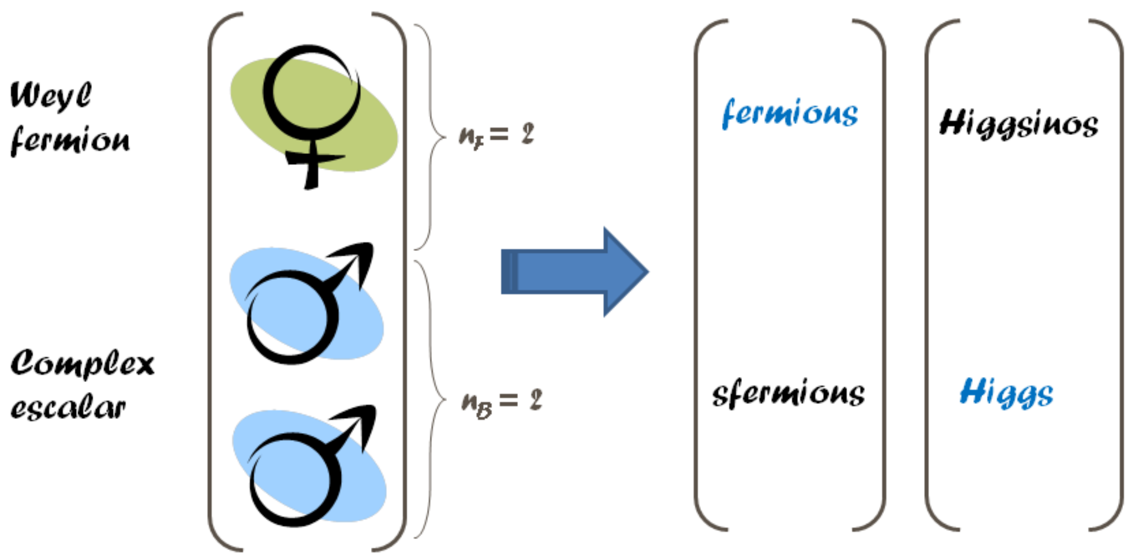


Figure 2: *Quiral supermultipletes: equal fermionic and bosonic d.o.f.*

Super potential of the MSSM

All the fields have the canonical kinetic Lagrangian with the usual D_μ and field strengths $F_{\mu\nu}$.

Interactions $\rightsquigarrow$ SUSY and Gauge invariance

The only *freedom* that one has is the choice of the *superpotential* **W** which gives the form of the scalar potential and theYukawa interactions between fermion and scalar fields.

[A .DJOUADI, The Anatomy of ElectroWeak Symmetry Breaking Tome II: The Higgs bosons in the Minimal Supersymmetric Model]

$$W_{MSSM} = \frac{1}{2} M^{ij} \phi_i \phi_j + \frac{1}{6} y^{ijk} \phi_i \phi_j \phi_k \quad (1)$$

By renormalization only bilinear and trilinear terms are permited

[see for instance S.P. Martin 07]

~~SUSY~~ $\rightarrow$ Soft-terms of MSSM

Soft SUSY Lagrangian

$$\mathcal{L}_{soft}^{MSSM} = \mathcal{L}_{gauginogluino}^{mass} - \mathcal{L}_{sfermion}^{mass} - \mathcal{L}_{Higgs} - \mathcal{L}_{trilinear} \tag{2}$$

with

$$-\mathcal{L}_{gauginogluino}^{mass} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a + h.c.\right] \tag{3}$$

$$-\mathcal{L}_{sfermion}^{mass} = \sum_{i=gen} m_{\tilde{Q}_i}^2 \tilde{Q}_i^\dagger \tilde{Q}_i + m_{\tilde{L}_i}^2 \tilde{L}_i^\dagger \tilde{L}_i + m_{\tilde{u}i}^2 |\tilde{u}_{Ri}| + m_{\tilde{d}i}^2 |\tilde{d}_{Ri}|^2 + m_{\tilde{l}i}^2 |\tilde{l}_{Ri}|^2 \tag{4}$$

$$-\mathcal{L}_{Higgs} = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \mu B (H_2.H_1 + h.c.) \tag{5}$$

$$-\mathcal{L}_{trilinear} = \sum_{i,j=gen} \left[A_{ij}^u \tilde{Q}_i H_2 \tilde{u}_{Rj}^* + A_{ij}^u \tilde{Q}_i H_1 \tilde{d}_{Rj}^* + A_{ij}^l \tilde{L}_i H_1 \tilde{l}_{Rj}^*\right] \tag{6}$$

Reducing MSSM parameters

phenomenological, pMSSM

Making 3 assumptions:

① CP-conserving (no extra source)

② no FCNC

③ $m_{\tilde{f}1} \approx m_{\tilde{f}2}$ to accomplish $K^0 - \bar{K}^0$ mixing

22 input parameters:

$\tan\beta$;
m_1^2, m_2^2;
M_1, M_2, M_3;
$\tilde{m}_q,\ \tilde{m}_{uR}, \tilde{m}_{dR}, \tilde{m}_l, \tilde{m}_{eR}$;
$\tilde{m}_{Qt},\ \tilde{m}_{tR}, \tilde{m}_{bR}, \tilde{m}_{L\tau}, \tilde{m}_{\tau R}$;
$A_{u,c}, A_{d,s}, A_{e,\mu}; \quad A_t, A_b, A_\tau$;

... or constraining the MSSM parameters

- mSUGRA → cMSSM (most common) → *gravitational SUSY breaking* in a hidden sector.
  ⇝ *soft SUSY breaking* parameters obey a set of universal boundary conditions at the GUT scale.

- AMSB → *Anomaly Mediated SUSY breaking* in a hidden sector, trasmited by the super-Weyl anomaly
  ⇝ *soft SUSY breaking* parameters related to the scale dependance of gauge and matter kinetic functions.

- GMSB → *SUSY breaking is mediated by SM gauge interactions* .
  ⇝ *soft SUSY breaking* parameters arise from one-loop or two-loops diagrams

Higgs sector of the MSSM

Two complex SU(2) Higgs doublets:

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

$H_1 \to d - type$ quarks

$H_2 \to u - type$ quarks

Physical Higgs particle spectrum :

ϕ_i , $CP = 1 \to$ two scalar fields: h^0, H^0,

χ_i , $CP = -1 \to$ one pseudoscalar fields: A^0.

and

$\phi^{\pm}$, $\to$ two charged fields: $H^{\pm}$

SSB: Assuming the scalar fields to develop nonzero vacuum expectation values that break $SU(2)_L$

MSSM sfermion mass matrix

$$\mathbf{M}_{\tilde{q}} = \begin{pmatrix} m_{sqL}^2 + m_q^2 + M_Z^2 \cos 2\beta (I_3^q - Q_q s_{\mathrm{w}}^2) & m_q \; X_q \\ m_q \; X_q & m_{sqR}^2 + m_q^2 + M_Z^2 \cos 2\beta Q_q s_{\mathrm{w}}^2 \end{pmatrix}, \quad (7)$$

with

$$X_q = A_q - \mu \{\cot \beta, \tan \beta\}, \quad (8)$$

where $\{\cot \beta, \tan \beta\}$ applies for up- and down-type squarks, respectively.

$$m_{sqR}^2 \simeq m_{sqL}^2 \simeq \tilde{m}_0^2 \mathbf{I}_{3x3}$$

Flavor Ansatz for the trilinear terms

$$A_l^{ij} = A_l^{\prime ij} + \delta A_l^{ij} \tag{9}$$

$$A_{LO} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & w & z \\ 0 & y & 1 \end{pmatrix} A_0 \tag{10}$$

sfermion mass matrix

$$\tilde{M}_{\tilde{l}}^2 = \left(\begin{array}{cc|cccc} \tilde{m}_L^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \tilde{m}_R^2 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & \tilde{m}_L^2 & X_2 & 0 & A_z \\ 0 & 0 & X_2 & \tilde{m}_R^2 & A_y & 0 \\ 0 & 0 & 0 & A_y & \tilde{m}_L^2 & X_t \\ 0 & 0 & A_z & 0 & X_t & \tilde{m}_R^2 \end{array}\right), \tag{11}$$

con $X_2 = A_w - \mu m_{f2} \tan\beta \, \{\cot\beta\}$
$X_t = A_0 - \mu m_{f3} \tan\beta \, \{\cot\beta\}$

New general physical masses for sfermions

Sfermion physical masses:

$$
\begin{aligned}
m^2_{f\tilde{2}_1} &= \frac{1}{2}(2\tilde{m}_0^2 + X_2 + X_t - R) \\
m^2_{f\tilde{2}_2} &= \frac{1}{2}(2\tilde{m}_0^2 - X_2 - X_t + R) \\
m^2_{f\tilde{3}_1} &= \frac{1}{2}(2\tilde{m}_0^2 - X_2 - X_t - R) \\
m^2_{f\tilde{3}_2} &= \frac{1}{2}(2\tilde{m}_0^2 + X_2 + X_t + R)
\end{aligned} \tag{12}
$$

where $R = \sqrt{4A_y^2 + (X_2 - X_t)^2}$

$$A_y = yA_0, \tag{13}$$

$$X_2 = wA_0 - \mu m_{d2} \tan\beta \,\{m_{u2} \cot\beta\}\,, \tag{14}$$

$$X_t = A_0 - \mu m_{d3} \tan\beta \,\{m_{u3} \cot\beta\}\,, \tag{15}$$

Rotation matrix for sfermions

$$\mathcal{O}_{\tilde{f}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Theta & \sigma^1 \Theta \\ -\Theta & \sigma^1 \Theta \end{pmatrix} \tag{16}$$

where

$$\Theta = \begin{pmatrix} -\sin\frac{\psi}{2} & \cos\frac{\psi}{2} \\ -\cos\frac{\psi}{2} & -\sin\frac{\psi}{2} \end{pmatrix} \tag{17}$$

$$sin\psi \to \frac{2A_y}{\sqrt{4A_y^2 + (X_2 - X_t)^2}}, \tag{18}$$

$$cos\psi \to \frac{(X_2 - X_t)}{\sqrt{4A_y^2 + (X_2 - X_t)^2}} \tag{19}$$

Limit to MSSM non-flavor mixing

$$\begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\sin\frac{\varphi}{2} & -\cos\frac{\varphi}{2} & 0 & \sin\frac{\varphi}{2} & \cos\frac{\varphi}{2} \\ 0 & \cos\frac{\varphi}{2} & -\sin\frac{\varphi}{2} & 0 & -\cos\frac{\varphi}{2} & \sin\frac{\varphi}{2} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -\sin\frac{\varphi}{2} & \cos\frac{\varphi}{2} & 0 & -\sin\frac{\varphi}{2} & \cos\frac{\varphi}{2} \\ 0 & \cos\frac{\varphi}{2} & \sin\frac{\varphi}{2} & 0 & \cos\frac{\varphi}{2} & \sin\frac{\varphi}{2} \end{pmatrix} \begin{pmatrix} \tilde{e}_1 \\ \tilde{\mu}_1 \\ \tilde{\tau}_1 \\ \tilde{e}_2 \\ \tilde{\mu}_2 \\ \tilde{\tau}_2 \end{pmatrix} \tag{20}$$

no-mixing limit $y \to 0 \to A_y \to 0$

$$\begin{aligned} \sin\psi &\to 0 \to \psi \to \pi, \\ \cos\psi &\to -1 \to \psi \to \pi \end{aligned} \tag{21}$$

1 Sfermion masses

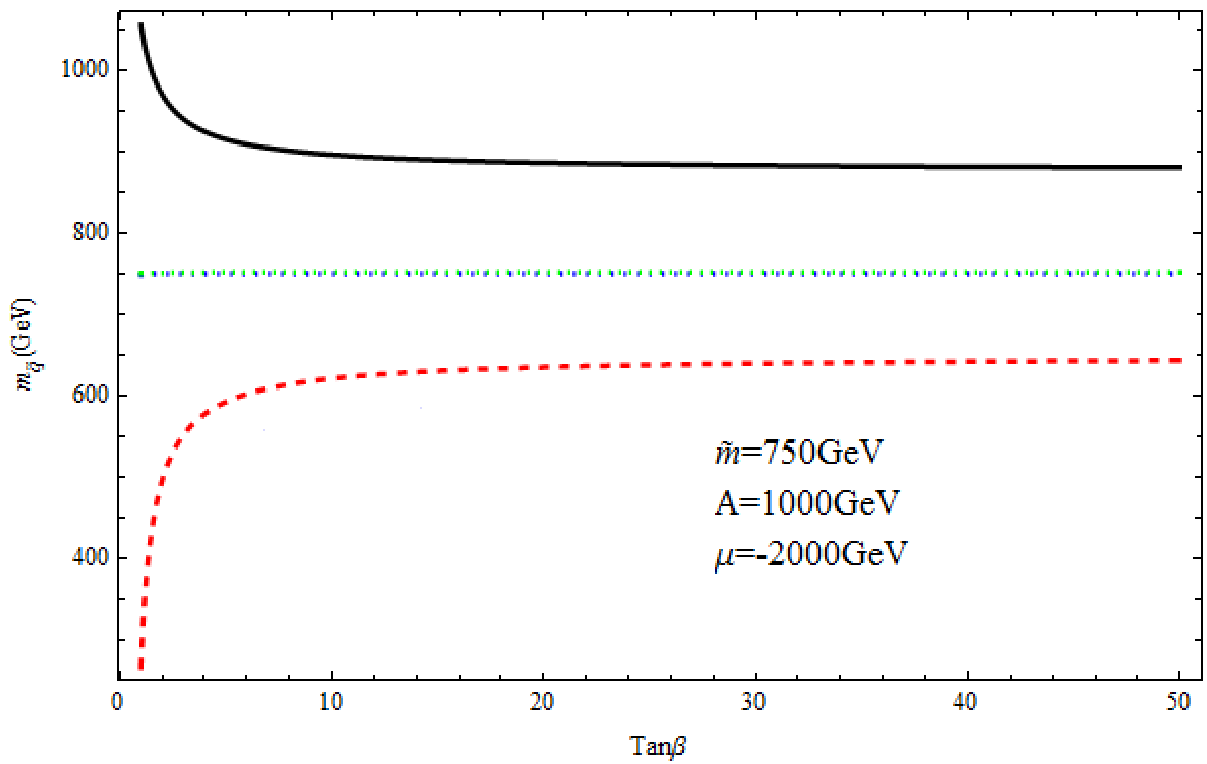


Figure 3: *2nd and 3rd family u-type quarks masses*

2. leptonic sector

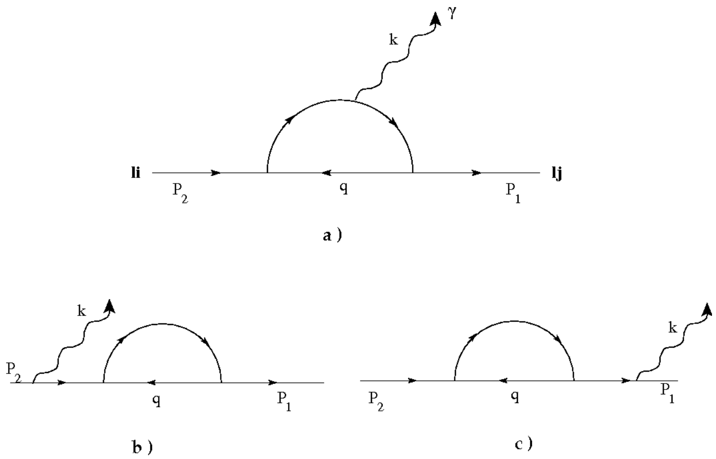


Figure 4: $\tau \to \mu\gamma$

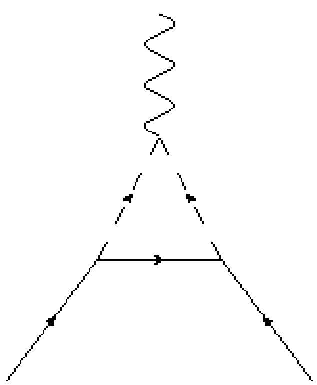


Figure 5: *muon magnetic dipole moment contribution*

3. quark sector

- $BR(B \to X_s \gamma)$
- $BR(t \to c\gamma)$
- possible non-negligible correction to the production of Higgs via gluon gluon fusion
- possible non-negligible correction to the $\gamma\gamma$ decay of the Higgs via stop-scharm loop

Tree level Higgs mass MSSM

At leading order we have the CP-even neutral Higgs masses releted using m_{A^0} as free parameter:

$$
\begin{aligned}
m^2_{h,H} &= \frac{1}{2}(m^2_A + m^2_Z) \\
&\mp \frac{1}{2}\sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z \cos^2 2\beta} \\
m^{\pm}_H &= m^2_A + \cos^2\theta_w m^2_Z
\end{aligned} \tag{22}
$$

☆ The relations within MSSM parameters impose, at tree level, a strong hierarchical structure on mass spectrum:

$m_h < m_Z$, $m_A < m_H$ and $m_W < m_{H\pm}$, $\rightarrow$ which is broken by radiative corrections.

The elements of the mass matrix M^2_h is constructed explicitly from self-energies contributions diagrams: Σ_h. And the renormalized self-energies are given by

[Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein 06]

$$\hat{\Sigma}_{h_{ij}} = \Sigma_{h_{ij}} + \delta \mathcal{Z}_{h_{ij}}(p^2 - m_h^2) - \delta m^2_{h_{ij}}$$

$\Sigma_{h_{ij}}$ $\rightarrow$ **self-energy diagrams**

$\delta \mathcal{Z}_{h_{ij}}(p^2 - m_h^2)$ $\rightarrow$ **filed renormalization kinetic term**

$\delta m^2_{h_{ij}}$ $\rightarrow$ **Higgs mass counterterms**

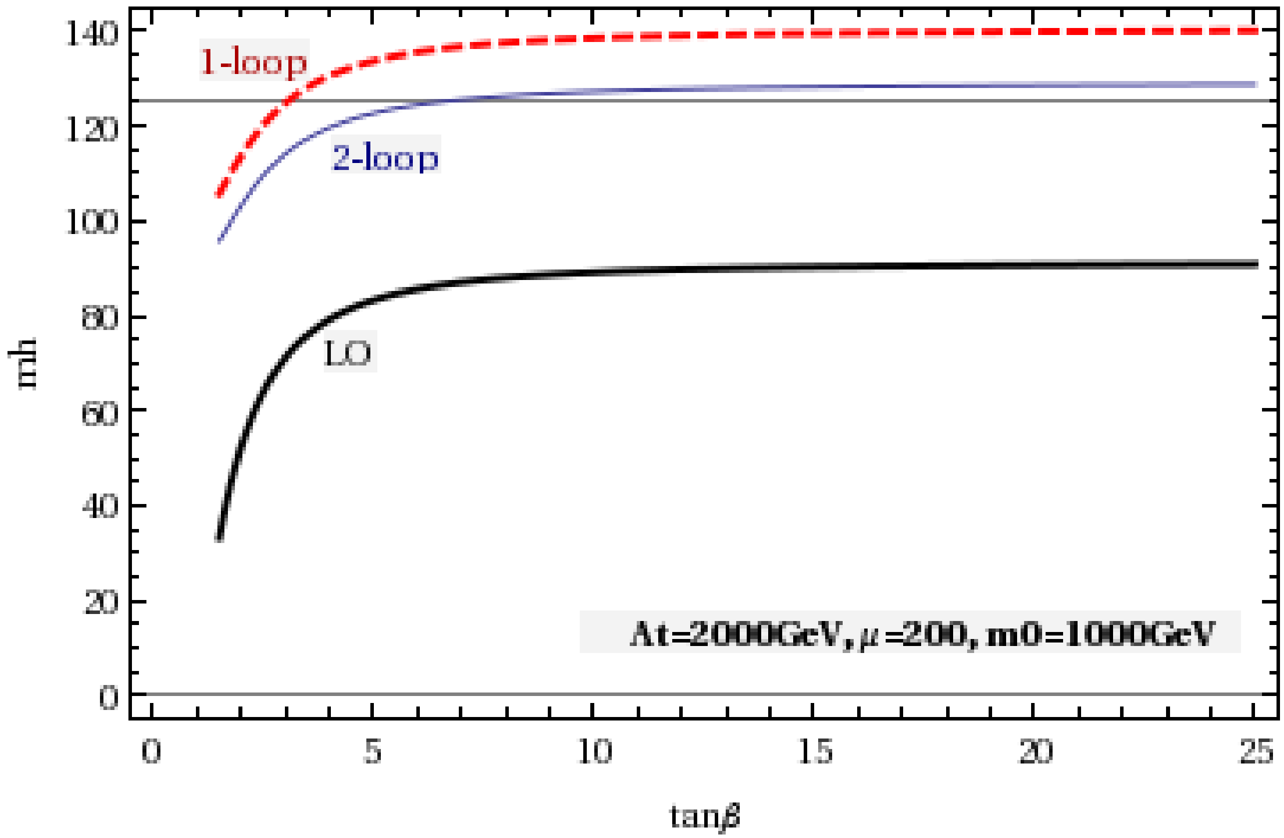
The Higgs mass is defined as the poles of the propagator, and the propagator is given as

$$\hat{\Delta}^{-1}_{h_{ij}}(s) = s - \mathcal{M}^2_{h_{ij}}(s)$$

with the mass matrix elements

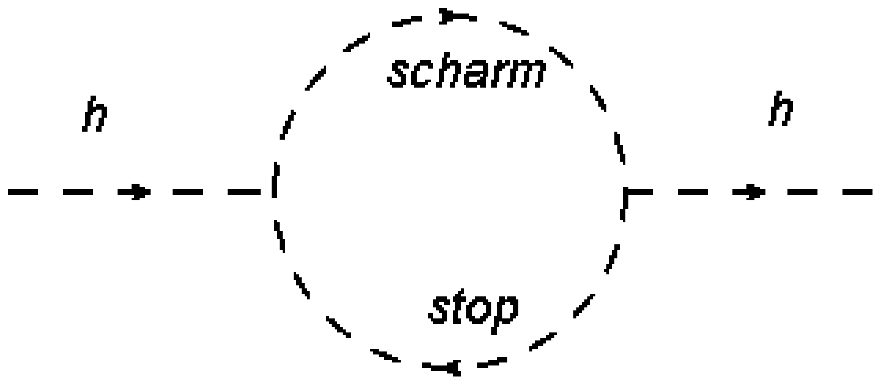
$$\mathcal{M}^2_{h_{ij}}(s) = m^2_{h_{ii}} - \hat{\Sigma}_{h_{ij}}(s)$$

Radiative corrections to h^0 mass up to 2-loops



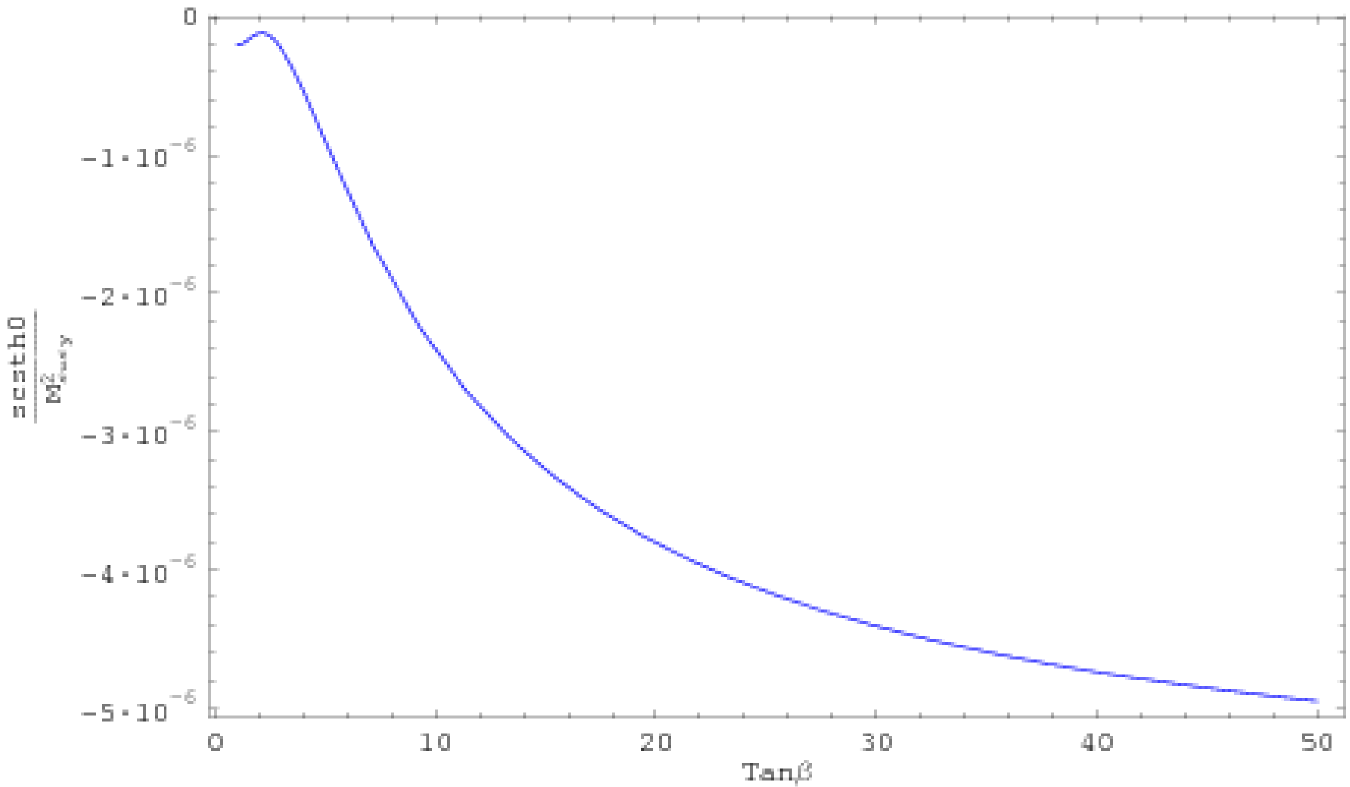
FeynHiggs code used

FV *squarks radiative corrections to* h^0 *mass*



$$\Sigma_{h0}^{scst} = \frac{\cos^2\frac{\psi}{2} e^2 \cos^2\frac{\psi}{2} \csc^2(\beta)}{8\pi^2 M_W^2 s_W^2} \times$$
$$\left\{ B_0\left[0, \tilde{m}_{c1}^2, \tilde{m}_{t2}^2\right] \left(\cos(\alpha)(m_c + m_t)(\mathsf{A0} + 2m_c - 2m_t) + \mu\sin(\alpha)(m_c - m_t)\right)^2\right.$$
$$\left.+ B_0\left[0, \tilde{m}_{c2}^2, \tilde{m}_{t1}^2\right] \left(\cos(\alpha)(m_c + m_t)(A_0 - 2m_c + 2m_t) + \mu\sin(\alpha)(m_c - m_t)\right)^2\right\} \quad (23)$$

FV squarks radiative corrections to h^0 mass



Conclusions

- We obtain analytical mixing angles for a possible mixing within 2nd and 3rd families, which gives a comprehensive easy manipulating of the parameters
- We obtain FV couplings which avoids complicated methods as MI to accomplish for FV processes as:
  $BR(t \to c\gamma)$, $BR(b \to s\gamma)$, $BR(\tau \to \mu\gamma)$ or muon dipole moment contribution.
- The additional contribution to the Higgs mass could be used to bound the parameters of the mixing.

thank you