Physics Beyond Standard Model

(mostly supersymmetry)

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Outline

1) Recap of Superfields and SUSY Lagrangian
2) SUSY QED example
3) MSSM recap
4) Electroweak symmetry breaking
5) Mass Spectrum of SUSY particles
6) Higgs spectrum
7) 1-loop corrections to the Higgs mass.

Recap: Superfields and Superspace (x^μ, θ)

scalar field (x^μ)

fermion field

$$\Phi = \phi + \sqrt{2}\theta\psi + \theta\theta F,$$

auxiliary scalar field

Grassman variable (fermionic)

$$V = -\theta\sigma^\mu\bar{\theta}A_\mu + i\theta\theta\bar{\theta}\bar{\lambda} - i\bar{\theta}\bar{\theta}\theta\lambda + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D$$

Vector Field

fermion field

Recap: Supersymmetric Invariant Lagrangians.

Lagrangian derived from Kahler, Superpotential functions of superfields is automatically supersymmetric invariant

For a supersymmetric gauge theory, the lagrangian is given by

$$\mathcal{L} = \int \left(d\theta^2 \; W(\Phi) + H.c\right) + \int d\theta^2 \; d\bar{\theta}^2 \; \Phi_i^\dagger \; e^{gV} \; \Phi_i + \int \left(d\theta^2 \; \mathcal{W}^\alpha \mathcal{W}_\alpha + H.c\right)$$

superpotential

Kahler potential

Field strength superfield (derived from V)

Recap: Functions of Superfields

Superpotential : is analytic function of superfields (zzz or $z^\star z^\star z^\star$)

expand the superfields and do the grassman integration :

(coefficient of $\theta\theta$ is supersymmetric invariant)

$$\Phi_i\Phi_j\Phi_k|_{\theta\theta} = -\psi_i\psi_j\phi_k - \psi_j\psi_k\phi_i - \psi_k\psi_i\phi_j$$
$$+F_i\phi_j\phi_k + F_j\phi_k\phi_i + F_k\phi_i\phi_j,$$

$$\Phi_i\Phi_j|_{\theta\theta} = -\psi_i\psi_j + F_i\phi_j + F_j\phi_i + F_k$$

$$\Phi_i|_{\theta\theta} = F_i$$

(all possible yukawa interactions)

Recap:
Kahler Potential

real function of superfields. $(zz^\star)$

Take the product of the fields as before, the exponential is simply :

$$\exp V_{WZ} = 1 - \theta\sigma^\mu\bar{\theta}A_\mu + i\theta\theta\bar{\theta}\bar{\lambda} - i\bar{\theta}\bar{\theta}\theta\lambda + \frac{1}{2}\,\theta\theta\bar{\theta}\bar{\theta}\,\left(D - \frac{1}{2}A^\mu A_\mu\right),$$

$$\Phi^\dagger = \phi^\star + \sqrt{2}\bar{\theta}\bar{\psi} + \bar{\theta}\bar{\theta}F^\star$$

(WZ = Wess- Zumino Gauge)

Grassman integration leaves just the coefficient of $\theta\theta\bar{\theta}\bar{\theta}$

supersymmetric invariant (and power expand, chiral superfields around $x^\mu \to y^\mu + i\theta\bar{\sigma}\bar{\theta}$)

$$\phi^\dagger e^{gV}\phi|_{\theta\theta\bar{\theta}\bar{\theta}} = FF^\star + \phi\Box\phi^\star + i\bar{\psi}\partial_\mu\bar{\sigma}_\mu\psi + gA_\mu\left(\frac{1}{2}\bar{\psi}\bar{\sigma}\psi + \frac{i}{2}\phi^\star\partial_\mu\phi - \frac{i}{2}\phi\partial_\mu\phi^\star\right) + \frac{i}{\sqrt{2}}g(\phi\bar{\lambda}\bar{\psi} - \phi^\star\lambda\psi) + \frac{1}{2}\left(gD - \frac{1}{2}g^2A_\mu A^\mu\right)\phi^\star\phi$$

kinetic terms for matter particles, gauge interactions of matter particles and gaugino-fermion-scalar interactions

Recap: Field Strength Superfield is derived from the Vector Superfield

$$\mathcal{W}_\alpha = -\frac{1}{4}\bar{\mathcal{D}}\bar{\mathcal{D}}\mathcal{D}_\alpha V_{WZ}$$

differential operators in superspace:

$$\mathcal{D}_\alpha = \frac{\partial}{\partial\theta^\alpha} + 2i\sigma^\mu_{\alpha\dot{\alpha}}\frac{\partial}{\partial x^\mu} \qquad \bar{\mathcal{D}}_{\dot{\alpha}} = -\frac{\partial}{\partial\bar{\theta}^{\dot{\alpha}}}$$

And it leads to the lagrangian

$$\mathcal{L} \supset \frac{1}{4}\left(\mathcal{W}^\alpha\mathcal{W}_\alpha|_{\theta\theta} + \mathcal{W}^{\dot{\alpha}}\mathcal{W}_{\dot{\alpha}}|_{\bar{\theta}\bar{\theta}}\right) = \frac{1}{2}D^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - i\lambda\sigma^\mu\partial_\mu\bar{\lambda}$$

kinetic terms for gauge bosons and gauginos

What about the auxiliary fields : Using equations of motion, we find:

$$F_i = \frac{\partial W}{\partial\phi_i} \quad ; \quad D_A = -g_A \ \phi_i^\star \ T^A_{ij} \ \phi_j,$$

The total supersymmetric invariant lagrangian
is the sum of all the three parts we have seen so far.
Notice that there is a part which is completely scalar:

$$V = \sum_i |F_i|^2 + \frac{1}{2} D^A D_A$$

Supersymmetric QED

$$\mathcal{L}_{\mathrm{QED}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\Psi}\left(i\partial^{\mu}\gamma_{\mu} - m_e\right)\Psi + ie\bar{\Psi}\gamma_{\mu}\Psi A^{\mu}$$

$$\Psi \longrightarrow \begin{cases} \Phi_L & (\tilde{e}_L, e_L) \quad Q = +1 \\ \Phi_R & (\tilde{e}_R, e_R) \quad Q = -1 \end{cases}$$

$$A_{\mu} \longrightarrow V(A_{\mu}, \lambda)$$

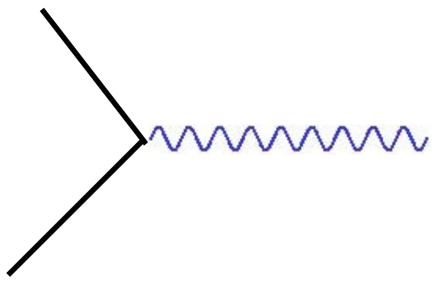
$$W_{\mathrm{SQED}} = m_e \Phi_L \Phi_R \qquad K_{SQED} = \Phi_L^{\dagger} e^{eV}\Phi_L + \Phi_R^{\dagger} e^{eV}\Phi_R$$

$$\begin{aligned}\mathcal{L}_{\mathrm{SQED}} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\lambda}\bar{\sigma}^{\mu}\partial_{\mu}\lambda + (D_{\mu}\tilde{e}_L)^{\dagger}D^{\mu}\tilde{e}_L \, + \\ (D_{\mu}\tilde{e}_R)^{\dagger}D^{\mu}\tilde{e}_R + i\bar{e}_L\bar{\sigma}^{\mu}D^{\mu}e_L + \bar{e}_R i\bar{\sigma}^{\mu}D^{\mu}e_R \\ + \left(\sqrt{2}e\ e_L\lambda\tilde{e}_L^{\dagger} + H.c\right) - \left(\sqrt{2}e\ e_R\lambda\tilde{e}_R^{\dagger} + H.c\right) \\ -m_e\left(e_L e_R + \bar{e}_R\bar{e}_L\right) - m_e^2(|\tilde{e}_L|^2 + |\tilde{e}_R|^2) - \frac{e^2}{2}(\tilde{e}_L^2 - \tilde{e}_R^2)^2\end{aligned}$$

$$\boxed{D_{\mu} = \partial_{\mu} - i\ eA_{\mu}}$$

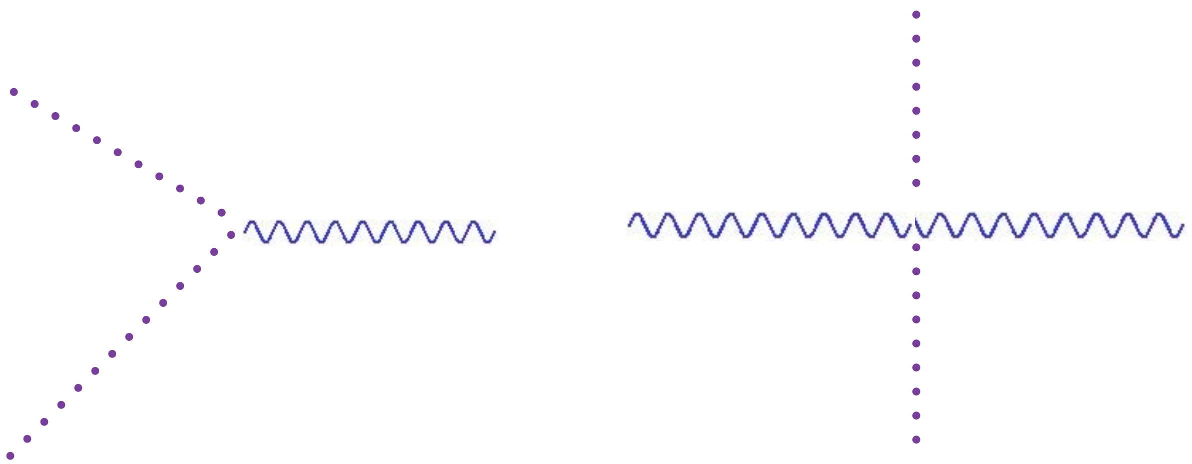
no covariant derivative

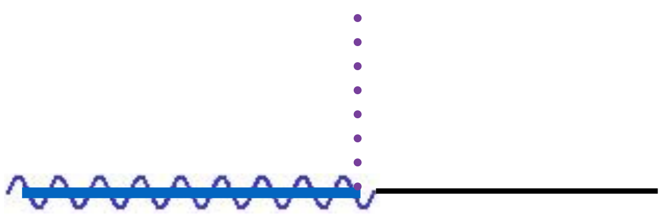
Feynman Rules in Supersymmetric QED



Only one vertex in QED

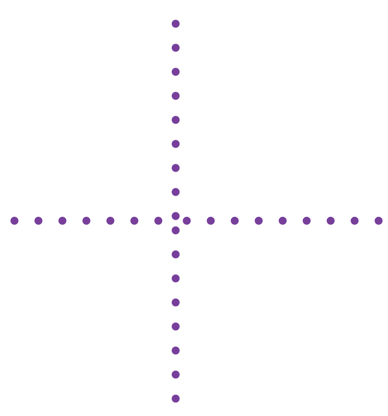
QED





scalar QED

photino-selectron-electron



quartic coupling of the scalar particles of the

same strength as gauge coupling

the selectron mass is protected in this theory
from large radiative corrections

The MSSM is generalisation of the Supersymmetric QED to the Standard Model gauge group

$$G_{SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y,$$

The lagrangian is derived in a similar way using the three parts from kahler potential, superpotential and the field strength superpotential.

However with one difference : supersymmetry is broken

in terms of auxiliary fields, supersymmetry is spontaneously broken if either of the F or D fields gets a VEV

however we cannot incorporate spontaneous susy breaking in MSSM as they predict sum rules like $m^2_{\tilde{e}_L} + m^2_{\tilde{e}_R} = 2m^2_e$

these are violated phenomenologically

so instead of looking for a detailed model of supersymmetry breaking, we parameterise all the breaking effects in terms of soft supersymmetry breaking terms.

So the total lagrangian of the MSSM is given by

$$\mathcal{L}_{\mathrm{MSSM}} = \mathcal{L}_{\mathrm{gauge/kinetic}}\left(K(\Phi, V)\right) + \mathcal{L}_{\mathrm{field\ strength}}\left(V\right) + \mathcal{L}_{\mathrm{yukawa}}\left(W(\Phi)\right) + \mathcal{L}_{\mathrm{Soft}}$$

the kahler potential for SM gauge group over all matter fields and Vector fields

$$\mathcal{L}_{kin} = \int d\theta^2 d\bar{\theta}^2 \sum_{\mathrm{SU(3),SU(2),U(1)}} \Phi_\beta^\dagger \, e^{gV} \Phi_\beta$$

Similarly for each Vector superfield, field strength superfields give kinetic terms for gauge bosons and gauginos

Recap: particle spectrum of the MSSM

$$Q_i \equiv \begin{pmatrix} u_{L_i} & \tilde{u}_{L_i} \\ d_{L_i} & \tilde{d}_{L_i} \end{pmatrix} \sim \left(3,\ 2,\ \frac{1}{6}\right) \qquad U_i^c \equiv \left(u_i^c \ \ \tilde{u}_i^c \right) \sim \left(\bar{3},\ 1,\ -\frac{2}{3}\right)$$

$$D_i^c \equiv \left(d_i^c \ \ \tilde{d}_i^c \right) \sim \left(\bar{3},\ 1,\ \frac{1}{3}\right)$$

$$L_i \equiv \begin{pmatrix} \nu_{L_i} & \tilde{\nu}_{L_i} \\ e_{L_i} & \tilde{e}_{L_i} \end{pmatrix} \sim \left(1,\ 2,\ -\frac{1}{2}\right) \qquad E_i^c \equiv \left(e_i^c \ \ \tilde{e}_i^c \right) \sim (1,\ 1,\ 1)$$

(1

matter particles

$$H_1 \ \equiv \ \begin{pmatrix} H_1^0 & \tilde{H}_1^0 \\ H_1^- & \tilde{H}_1^- \end{pmatrix} \sim \left(1,\ 2,\ -\frac{1}{2}\right)$$

$$H_2 \ \equiv \ \begin{pmatrix} H_2^+ & \tilde{H}_2^+ \\ H_2^0 & \tilde{H}_2^0 \end{pmatrix} \sim \left(1,\ 2,\ \frac{1}{2}\right)$$

$$V_s^A \ : \ \left(G^{\mu A} \ \ \tilde{G}^A \right) \ \sim \ (8,1,0)$$

$$V_W^I \ : \ \left(W^{\mu I} \ \ \tilde{W}^I \right) \ \sim \ (1,3,0)$$

$$V_Y \ : \ \left(B^\mu \ \ \tilde{B} \right) \ \sim \ (1,1,0)$$

Higgs particles

gauge bosons

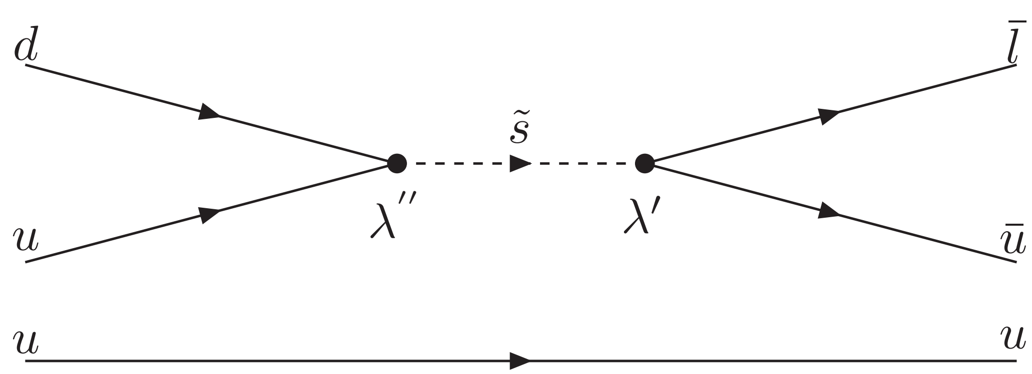
The superpotential is a gauge invariant analytic function of the superfields

$$W_0 = h^u_{ij} Q_i U^c_j H_2 + h^d_{ij} Q_i D^c_j H_1 + h^e_{ij} L_i E^c_j H_1 + \mu H_1 H_2$$

$$\boxed{W_1 = \epsilon_i L_i H_2 + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k.}$$

Unlike SM, lepton and baryon number are no longer conserved symmetries

Impose R parity



Avoid diagrams of this type which reduce the proton life time to 10^(-13) secs for O(1) couplings and TeV SUSY partners

R-parity assures that every vertex has atleast two superpartners

$$R_p = (-1)^{(3B+L+2S)}$$

vertices from superpotential:

$$
\begin{aligned}
\mathcal{L}_{yuk} \supset & \quad h^u_{ij} \; Q_i u^c_j H_2 \;|_{\theta\theta} \\
\supset & \quad h^u_{ij} \; (\; u_i u^c_j H^0_2 - d_i u^c_j H^+_2 \;) \;|_{\theta\theta} \\
\supset & \quad h^u_{ij} (\psi_{u_i} \psi_{u^c_j} \phi_{H^0_2} + \phi_{\tilde{u}_i} \psi_{u^c_j} \psi_{\tilde{H}^0_2} + \psi_{u_i} \phi_{\tilde{u}^c_j} \psi_{\tilde{H}^0_2} \\
- & \quad \psi_{d_i} \psi_{u^c_j} \phi_{H^+_2} - \phi_{\tilde{d}_i} \psi_{u^c_j} \psi_{\tilde{H}^+_2} - \psi_{d_i} \phi_{\tilde{u}^c_j} \psi_{\tilde{H}^+_2}) \\
\equiv & \quad h^u_{ij} \; (\; u_i u^c_j H^0_2 + \; \tilde{u}_i u^c_j \tilde{H}^0_2 + u_i \tilde{u}^c_j \tilde{H}^0_2 - d_i u^c_j H^+_2 \\
- & \quad \tilde{d}_i u^c_j \tilde{H}^+_2 \; - d_i \tilde{u}^c_j \tilde{H}^+_2 \;),
\end{aligned}
$$

SM (2HDM)
Yukawa coupling

squark-quark-Higgsino

charged Higgs
interaction

Finally, $\mathcal{L}_{soft}$ is given by the terms discussed yesterday

mass terms for super partners and dimensional couplings.

gaugino masses $M_1 \tilde{B}\tilde{B}, M_2 \tilde{W}_I \tilde{W}_I, M_3 \tilde{G}_A \tilde{G}_A,$

scalar mass terms $m^2_{Q_{ij}} \tilde{Q}_i^\dagger \tilde{Q}_j, m^2_{u_{ij}} \tilde{u^c}_i^\star \tilde{u^c}_j, m^2_{d_{ij}} \tilde{d^c}_i^\star \tilde{d^c}_j, m^2_{L_{ij}} \tilde{L}_i^\dagger \tilde{L}_j, m^2_{e_{ij}} \tilde{e^c}_i^\star \tilde{e^c}_j, m^2_{H_1} H_1^\dagger H_1, m^2_{H_2} H_2^\dagger H_2.$

trilinear couplings $A^u_{ij} \tilde{Q}_i \tilde{u}^c_j H_2, A^d_{ij} \tilde{Q}_i \tilde{d}^c_j H_1, A^e_{ij} \tilde{L}_i \tilde{e}^c_j H_1$

bilinear couplings $B H_1 H_2$

A total of about 105 parameters

Electroweak Symmetry breaking and minimisation conditions

so far we have built the MSSM lagrangian keeping the SM gauge symmetry in tact.

We would like to incorporate the Higgs mechanism in the MSSM to break the electroweak symmetry and give masses to fermions and SM gauge bosons.

For that we will concentrate on the Higgs potential in the scalar potential of the MSSM. The scalar potential of the MSSM is given by :

$$V = |F|^2 + |D|^2 + V_{soft}$$

Electroweak Symmetry breaking and minimisation conditions

a kind of two higgs doublet model

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

$$Y_{H_u} = +1 \qquad Y_{H_d} = -1$$

$$V_H = (|\mu|^2 + m_{H_d}^2)|H_d|^2 + (|\mu|^2 + m_{H_u}^2)|H_u|^2 - B_\mu \epsilon_{ij}(H_u^i H_d^j + \text{c.c.}) + \frac{g_2^2 + g_1^2}{8}(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2} g_2^2 |H_d^\dagger H_u|^2$$

$$V_H = (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) + (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) - [B_\mu(H_d^- H_u^+ - H_d^0 H_u^0) + \text{c.c.}] + \frac{g_2^2 + g_1^2}{8}(|H_d^0|^2 + |H_d^-|^2 - |H_u^0|^2 - |H_u^+|^2)^2 + \frac{g_2^2}{2}|H_d^{-*} H_u^0 + H_d^{0*} H_u^+|^2$$

$2B_\mu < 2|\mu|^2 + m_{H_2}^2 + m_{H_1}^2$ potential should be bounded from below

$B_\mu^2 > (|\mu|^2 + m_{H_2}^2)(|\mu|^2 + m_{H_1}^2)$ at least one of the higgs mass squared should be negative

Electroweak Symmetry breaking and minimisation conditions

Concentrating on the neutral part :

$$\langle H_u^0 \rangle = \frac{v_2}{\sqrt{2}} \qquad \langle H_d^0 \rangle = \frac{v_1}{\sqrt{2}} \qquad \frac{\partial V_H}{\partial H_u^0} = \frac{\partial V_H}{\partial H_d^0} = 0$$

$$\boxed{\begin{aligned} |\mu|^2 &= \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{M_Z^2}{2} \\ B_\mu &= \frac{1}{2}\left[\left(m_{H_d}^2 - m_{H_u}^2\right)\tan 2\beta + M_Z^2 \sin 2\beta\right] \end{aligned}}$$

where $\tan\beta = \frac{v_2}{v_1}$ and $v_1^2 + v_2^2 = v^2 = (246\ \mathrm{GeV})^2$

If these conditions are satisfied,
electroweak symmetry is broken in MSSM

Mass spectrum of MSSM partners

Neutral parts of gauginos and Higgsinos mix to form Neutralinos

$$\Psi_N = \{\tilde{B},\ \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0\} \qquad \mathcal{L} \supset \frac{1}{2}\,\Psi_N \mathcal{M}_N \Psi_N^T \ + H.c$$

$$\mathcal{M}_N \ = \ \left(\begin{array}{cccc} M_1 & 0 & -M_Z c\beta\ s\theta_W & M_Z s\beta\ s\theta_W \\ 0 & M_2 & M_Z c\beta\ c\theta_W & M_Z s\beta\ c\theta_W \\ -M_Z c\beta\ s\theta_W & M_Z c\beta\ c\theta_W & 0 & -\mu \\ M_Z s\beta\ s\theta_W & -M_Z s\beta\ c\theta_W & -\mu & 0 \end{array} \right),$$

$$c\beta = \cos\beta$$

$$s\theta_W = \sin\theta_W$$

these are majorana particles

The chargino mass matrix :

$$\mathcal{L} \supset -\frac{1}{2} \left(\begin{array}{cc} \tilde{W}^- & \tilde{H}_1^- \end{array} \right) \left(\begin{array}{cc} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{array} \right) \left(\begin{array}{c} \tilde{W}^+ \\ \tilde{H}_2^+ \end{array} \right),$$

charginos are Dirac Particles.

The sfermion sector : 6X6 mass matrices

$$\xi^\dagger \; M_{\tilde{f}}^2 \xi \quad ; \quad \xi = \{\tilde{f}_{L_i}, \tilde{f}_{R_i}\} \qquad m_{ij}^2 = \left(\begin{array}{cc} \frac{\partial^2 V}{\partial \phi_i \partial \phi_j^\star} & \frac{\partial^2 V}{\partial \phi_i \partial \phi_j} \\ \frac{\partial^2 V}{\partial \phi_i^\star \partial \phi_j^\star} & \frac{\partial^2 V}{\partial \phi_i^\star \partial \phi_j} \end{array} \right)$$

$$M_{\tilde{f}}^2 = \begin{pmatrix} m_{\tilde{f}_{\rm LL}}^2 & m_{\tilde{f}_{\rm LR}}^2 \\ m_{\tilde{f}_{\rm LR}}^{2\,\dagger} & m_{\tilde{f}_{\rm RR}}^2 \end{pmatrix},$$

$$\begin{aligned} m_{\tilde{f}_{L_i L_j}}^2 &= M_{\tilde{f}_{L_i L_j}}^2 + m_f^2 \delta_{ij} + M_Z^2 \cos 2\beta (T_3 + \sin^2\theta_W Q_{\rm em}) \delta_{ij} \\ m_{\tilde{f}_{L_i R_j}}^2 &= \left((Y_f^A \cdot {}^{v_2}_{v_1} - m_f \mu^{\tan\beta}_{\cot\beta}) \text{ for } f =^{e,d}_{u} \right) \delta_{ij} \\ m_{\tilde{f}_{\rm RR}}^2 &= M_{\tilde{f}_{R_{ij}}}^2 + \left(m_f^2 + M_Z^2 \cos 2\beta \sin^2\theta_W Q_{\rm em} \right) \delta_{ij} \end{aligned}$$

Higgs Spectrum

two Higgs doublets -> eight degrees of freedom

three goldstone bosons -> five physical Higges.

three higgs mass matrices: charged,
CP odd (imaginary neutral) and CP even (real neutral)

set $m_1^2 = m_{H_1}^2 + \mu^2, \quad m_2^2 = m_{H_2}^2 + \mu^2, \quad m_3^2 = B_\mu \mu.$

$$\begin{pmatrix} H_1^+ & H_2^+ \end{pmatrix} \begin{pmatrix} m_1^2 + \frac{1}{8}(g_1^2+g_2^2)(v_1^2-v_2^2) + \frac{1}{4}g_2^2 v_2^2 & m_3^2 + \frac{1}{4}g_2^2 v_1 v_2 \\ m_3^2 + \frac{1}{4}g_2^2 v_1 v_2 & m_2^2 - \frac{1}{8}(g_1^2+g_2^2)(v_1^2-v_2^2) + \frac{1}{4}g_2^2 v_2^2 \end{pmatrix} \begin{pmatrix} H_1^- \\ H_2^- \end{pmatrix}$$

using the minimisation conditions

$$\begin{pmatrix} H_1^+ & H_2^+ \end{pmatrix} \left(\frac{m_3^2}{v_1 v_2} + \frac{1}{4}g_2^2\right) \begin{pmatrix} v_2^2 & v_1 v_2 \\ v_1 v_2 & v_1^2 \end{pmatrix} \begin{pmatrix} H_1^- \\ H_2^- \end{pmatrix}$$

$$\begin{aligned} m_{G^\pm}^2 &= 0 \\ m_{H^\pm}^2 &= \left(\frac{m_3^2}{v_1 v_2} + \frac{1}{4}g_2^2\right)(v_1^2 + v_2^2), \\ &= \frac{2m_3^2}{sin2\beta} + M_W^2 \end{aligned}$$

Summary of Higgs mass spectrum at tree level

$$M_A^2 = \frac{2B_\mu}{\sin 2\beta} \qquad M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

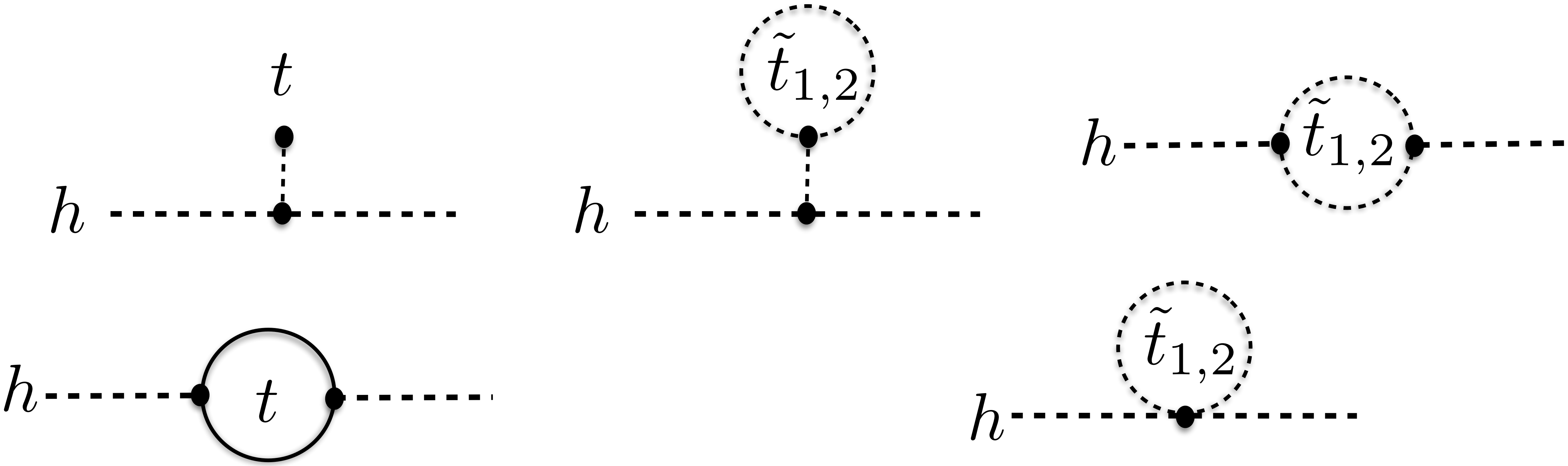
$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\tan 2\beta \qquad -\frac{\pi}{2} < \alpha < 0$$

at tree level the lightest Higgs mass upper limit is

$$\boxed{M_h \le M_Z |\cos 2\beta| \le M_Z}$$

tree level catastrophe !!

Lightest Higgs mass @ 1-loop (top-stop enhanced)



in the limit of no-mixing

$$\Delta m_h^2 = \frac{3g_2^2}{8\pi^2 M_W^2} m_t^4 \log\left(\frac{M_S^2}{m_t^2}\right)$$

Ellis, Ridolfi, Zwirner, Haber-Hempfling, Yanagida et. al

$$M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

in the case of non-zero mixing the correction is

$$\Delta m_h^2 \simeq \frac{3g_2^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$$

where $X_t = A_t - \mu \cot\beta$

$$M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Haber, Hempfling and Hoang,9609331

1-loop correction adds ~20 GeV to the tree-level, assuming the sparticles are < 1 TeV (in no-mixing scenario).

Effective potential methods are more useful

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

diagonalizing

$$\begin{pmatrix} m_{H,tree}^2 & 0 \\ 0 & m_{h,tree}^2 \end{pmatrix}$$

$$M_{\text{Higgs}}^{2,\text{corr}} = M_{\text{Higgs}}^{2,\text{tree}} - \begin{pmatrix} \Pi_{\phi_1} & \Pi_{\phi_1\phi_2} \\ \Pi_{\phi_1\phi_2} & \Pi_{\phi_2} \end{pmatrix} \qquad \Pi_{\phi_i} = \text{self energy of } \phi_\text{i}$$

One loop terms +

dominant 2-loop contribution due to top-stop loops

$$\Pi_{\phi_1}^{(2-\text{loop})}(0) = 0 \qquad \Pi_{\phi_1\phi_2}^{(2-\text{loop})}(0) = 0$$

$$\Pi_{\phi_2}^{(2-\text{loop})}(0) = \frac{G_F\sqrt{2}}{\pi^2}\frac{\alpha_s}{\pi}\frac{\bar{m}_t^4}{\sin^2\beta}\left[4 + 3\log^2\left(\frac{\bar{m}_t^4}{M_S^4}\right) + 2\log\left(\frac{\bar{m}_t^4}{M_S^4}\right) - 6\frac{X_t}{M_S} - \frac{X_t^2}{M_S^2}\left\{3\log\left(\frac{\bar{m}_t^2}{M_S^2}\right) + 8\right\} + \frac{17}{12}\frac{X_t^4}{M_S^4}\right]$$

$$\bar{m}_t = \bar{m}_t(m_t) \approx \frac{m_t^{\text{pole}}}{1 + \frac{4}{3\pi}\alpha_s(m_t)} \qquad +\mathcal{O}(G_F^2 m_t^6)$$

Heinemeyer et.al, 9812472

dominant 2-loop correction increases the lightest Higgs mass <10 GeV to the tree-level, assuming the sparticles are < 1 TeV (in no-mixing scenario).

3-loop correction

calculated up to $\mathcal{O}(\alpha_t \alpha_s^2)$

keeping only the leading terms $\sim m_t^4$

no mixing in the stop sector $\Rightarrow X_t = 0$

Harlander et al. ‘08
Martin ‘07

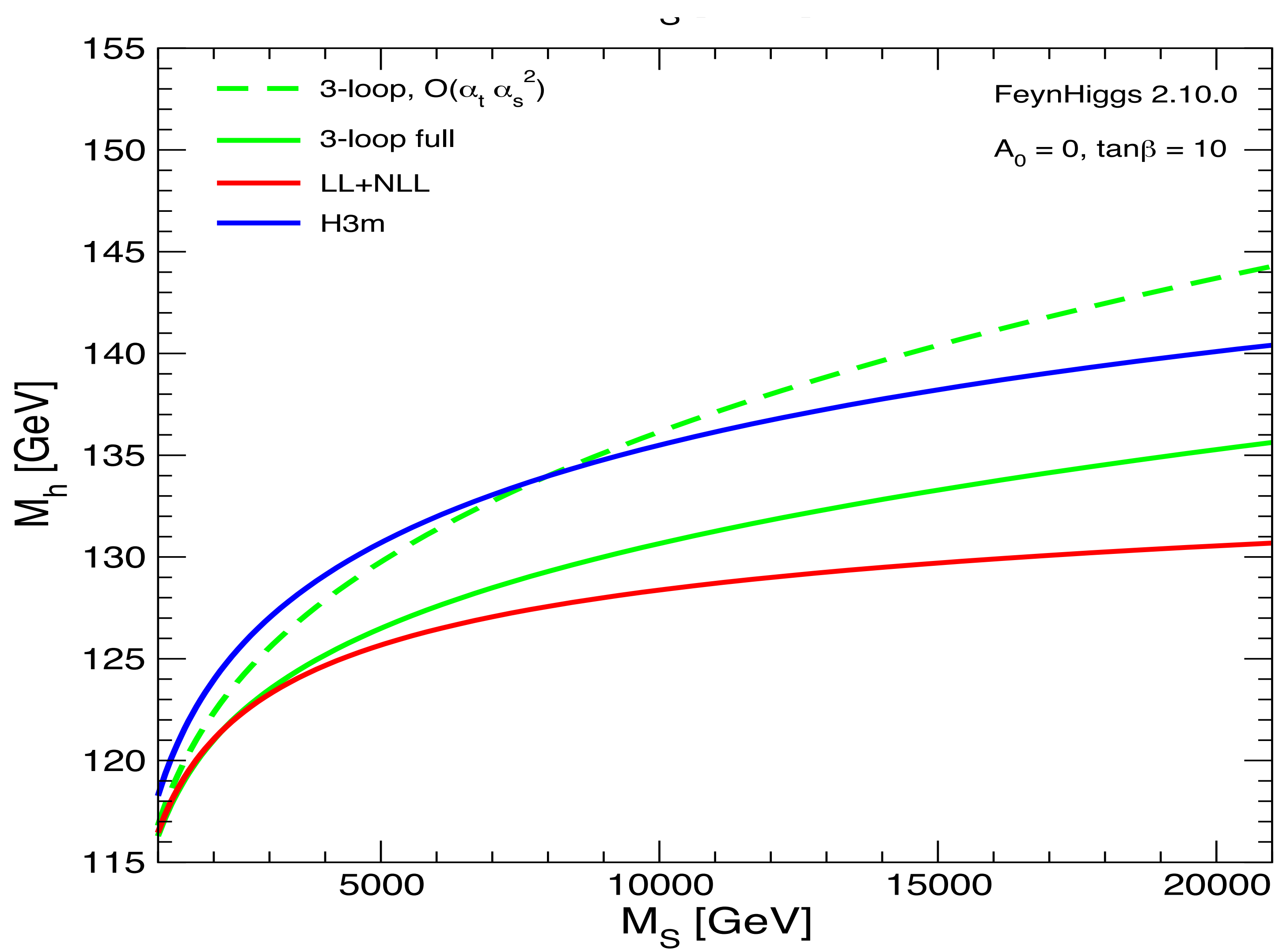
Susy HD

$$\Delta m_h^{3-\mathrm{loop}} \approx 500 \ \mathrm{MeV}$$

Most Publicly available spectrum generators calculate the CP-even Higgs spectrum at the 2-loop order.

Theoretical Status of the Higgs mass computation

T.Hahn et. al,
arXiv: 1312.4937.
Buchmueller et. al,
arXiv:1312.5233
Draper et. al
1312.5743



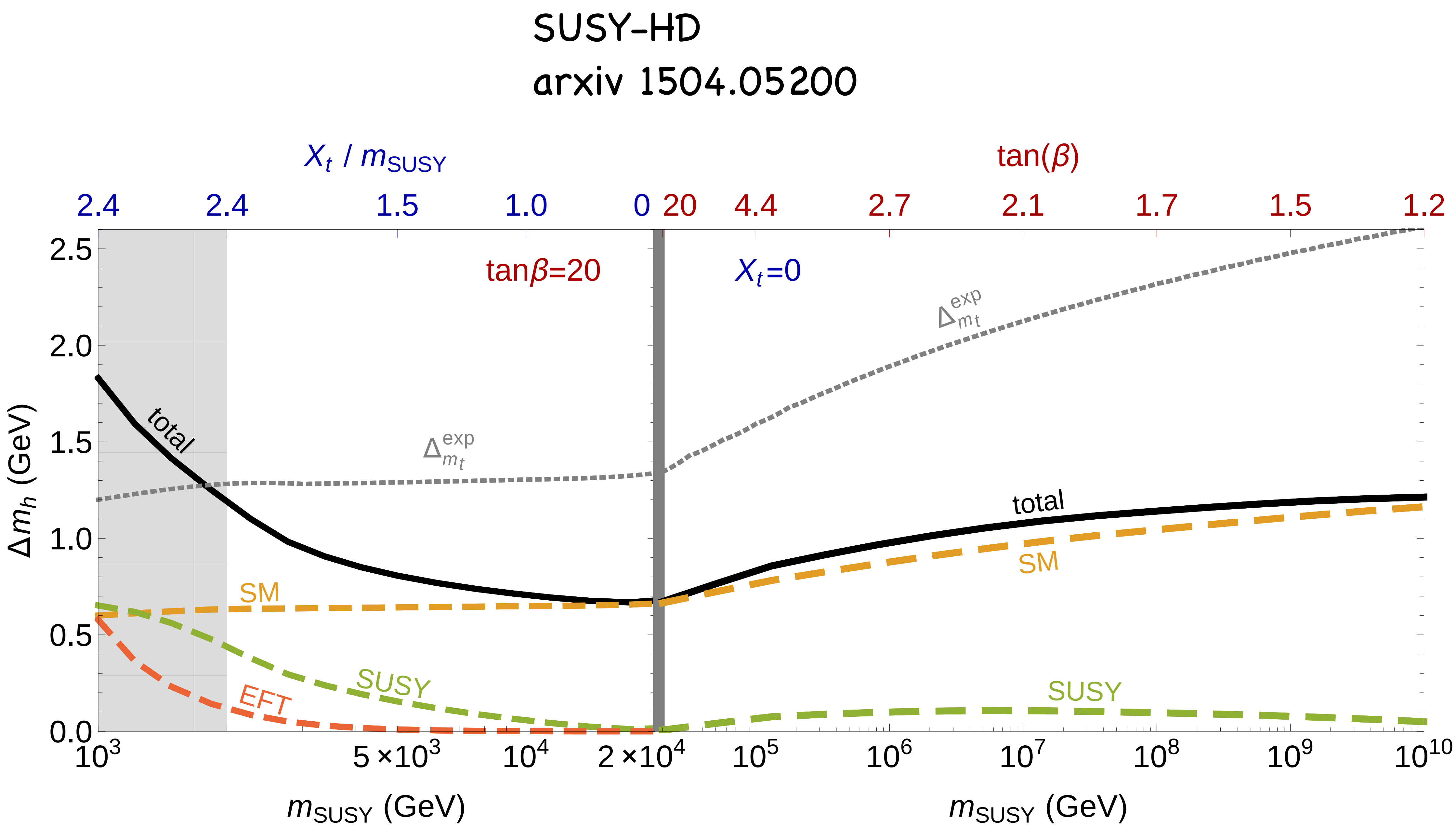


Figure 1: *Breakdown of the uncertainties for a 125 GeV Higgs mass as a function of the (degenerate) superparticle masses $m_{\rm SUSY}$. The Higgs mass has been kept fixed at 125 GeV by varying either the stop mixing (with fixed* $\tan\beta = 20$ *for* $m_{\rm SUSY} < 20$ *TeV, left panel of the plot) or* $\tan\beta$ *(with vanishing stop mixing for* $m_{\rm SUSY} > 20$ *TeV, right panel of the plot. Note that for* $m_{\rm SUSY} < 2$ *TeV (the gray region) the 125 GeV value for the Higgs mass cannot be reproduced anymore but is within the theoretical uncertainties. The black "total" line is the linear sum of the theoretical uncertainties from SM, SUSY and EFT corrections (in dashed lines). The dotted line* $\Delta^{\rm exp}_{m_t}$ *corresponds to the* 2σ *experimental uncertainty on the top mass.*

SUSY-HD

arxiv 1504.05200

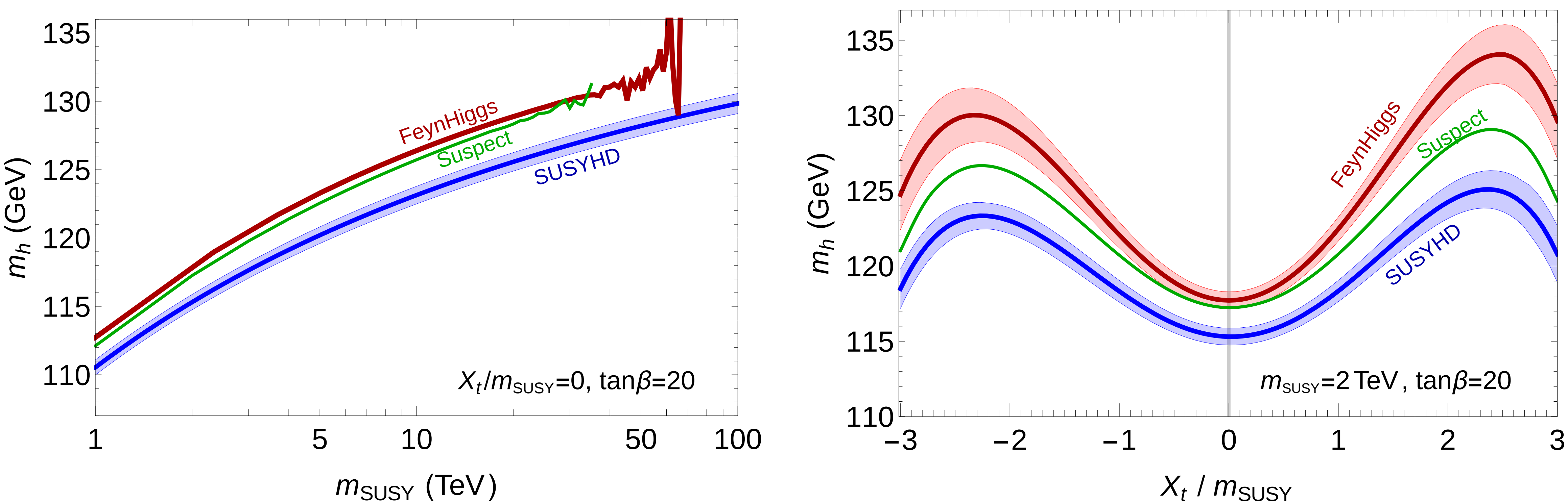


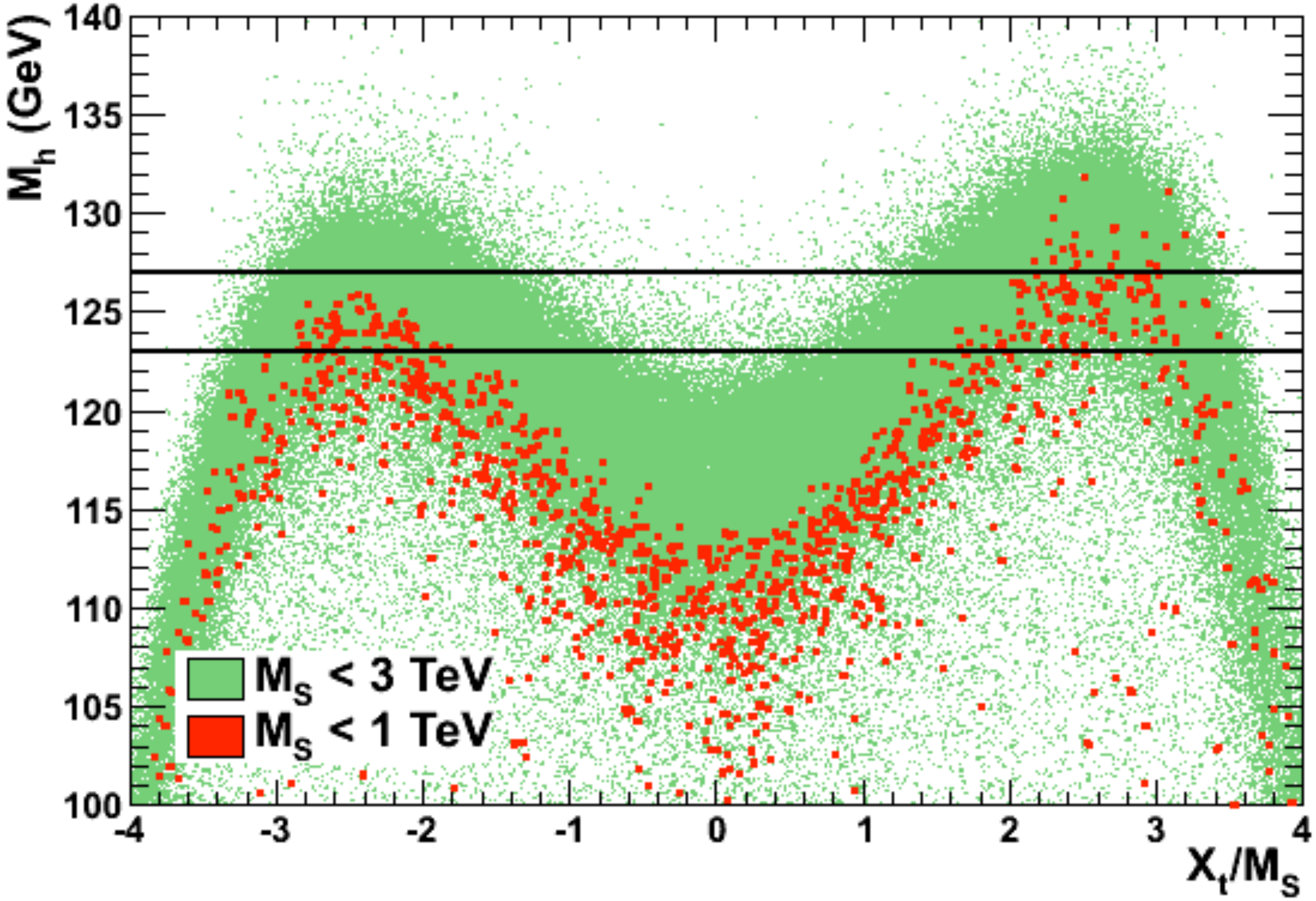
Figure 3: *Comparison between the EFT computation (lower blue band) and two existing codes: FeynHiggs [41] and Suspect [39]. We used a degenerate SUSY spectrum with mass $m_{\rm SUSY}$ in the $\overline{\rm DR}$-scheme with* $\tan\beta = 20$. *The plot on the left is m_h vs $m_{\rm SUSY}$ for vanishing stop mixing. The plot on the right is m_h vs $X_t/m_{\rm SUSY}$ for $m_{\rm SUSY} = 2$ TeV. On the left plot the instability of the non-EFT codes at large $m_{\rm SUSY}$ is visible.*

Slavich, SUSY 2015

- If the EFT valid at the weak scale is the SM, part of the corrections can be borrowed from the SM calculation, reducing the uncertainty to less than 1%

phenomenological models

Abrey et al.
1112.3028;
2012 updates

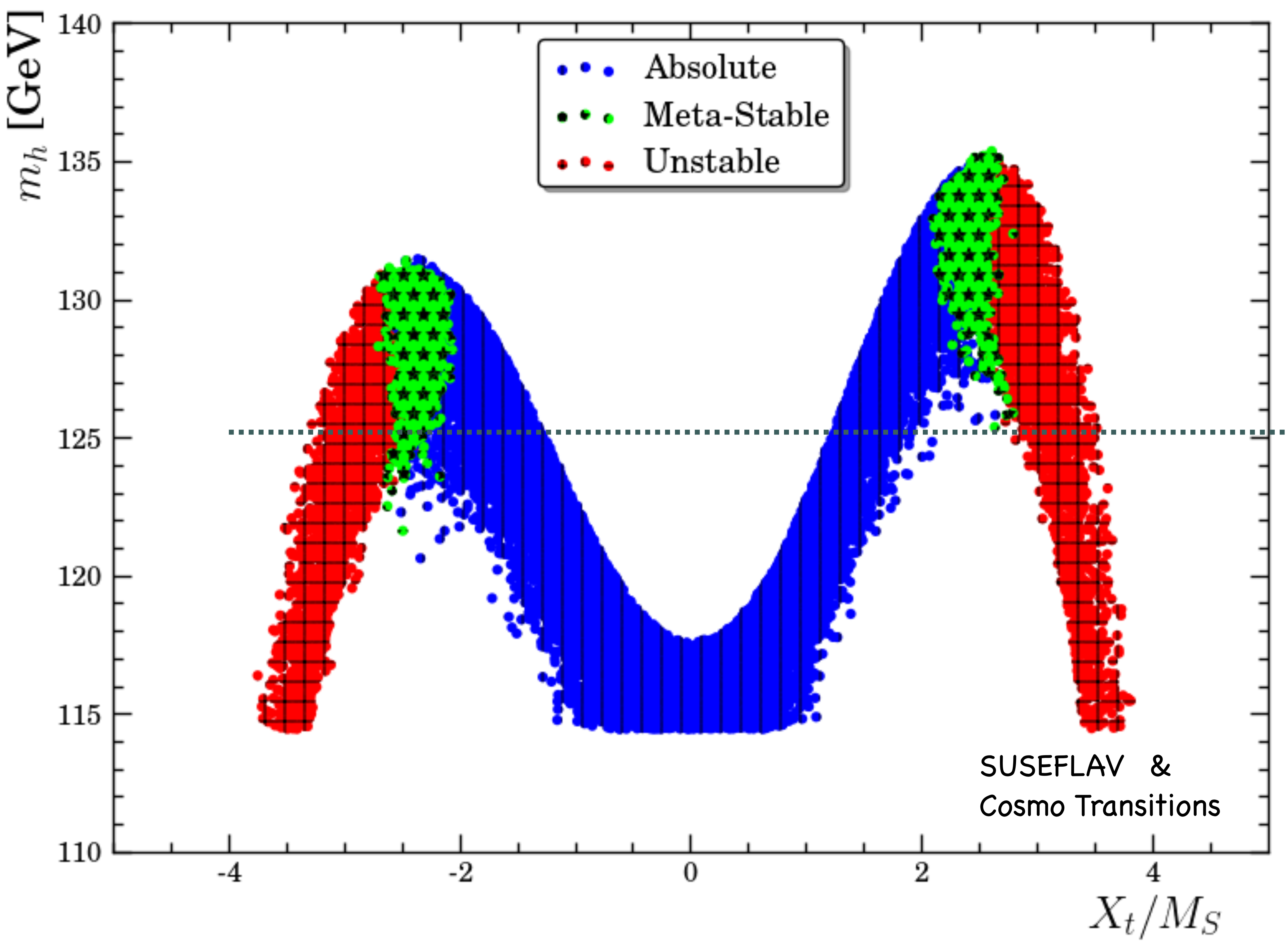


For zero mixing, we need multi TeV Stops !!!

Other option is to have maximal mixing : $|X_t| \sim \sqrt{6} M_S$

Is the universe in a *critical* parameter SUSY parameter space ?

Stability of MSSM vacuum analysis with four fields, the two Higgs fields and the stop fields (considering they are light)



Chowdhury, Godbole, Mohan, Vempati, arXiv: 1310.1932 JHEP

and other groups

associated with criticality

~ Giudice & Rattazzi hep-ph/0606105

Charge and Colour breaking Minima

Chowdhury, Godbole, Mohan, Vempati,
arXiv: 1310.1932
JHEP

$$\mathcal{V}_3 = \left(m_{H_u}^2 + \mu^2\right)|H_u|^2 + m_{\tilde{t}_L}^2 |\tilde{t}_L|^2 + m_{\tilde{t}_R}^2 |\tilde{t}_R|^2 + \left(y_t A_t\, H_u^* \tilde{t}_L \tilde{t}_R + \text{c.c.}\right)$$
$$+ y_t^2 \left(|\tilde{t}_L \tilde{t}_R|^2 + |H_u \tilde{t}_L|^2 + |H_u \tilde{t}_R|^2\right) + \frac{g_1^2}{8}\left(|H_u|^2 + \frac{1}{3}|\tilde{t}_L|^2 - \frac{4}{3}|\tilde{t}_R|^2\right)^2$$
$$+ \frac{g_2^2}{8}\left(|H_u|^2 - |\tilde{t}_L|^2\right)^2 + \frac{g_3^2}{6}\left(|\tilde{t}_L|^2 - |\tilde{t}_R|^2\right)^2 .$$

Full Four Field Numerical Analysis