Higgs Sector of the Minimal Supersymmetric Standard Model with Complex Parameters

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HiggsTools First Annual Meeting, Freiburg

April 17, 2015

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- The MSSM with complex parameters
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Supersymmetry: Introduction

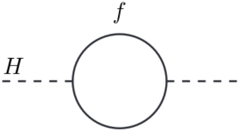
- Supersymmetry is a symmetry between fermions and bosons
- A group generator Q transforms fermions to bosons and vice versa

$$Q|fermion\rangle = |boson\rangle$$
$$Q|boson\rangle = |fermion\rangle$$

- SM particles have superpartners whose spin differs by half a unit
  - Scalar partners of SM fermions $\rightarrow$ *sfermions*
  - Fermionic partners of SM bosons $\rightarrow$ *gauginos, Higgsinos*
- No SUSY partners ever been detected
  $\Rightarrow$ Supersymmetry is a broken symmetry

Supersymmetry: Motivation

- **The Hierarchy Problem**



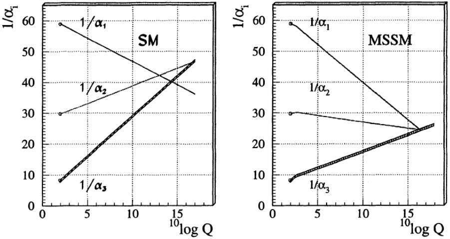
$$\Delta m_H^2 = -\frac{|Y_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ...] \qquad \Delta m_H^2 = 2\frac{Y_s}{16\pi^2}[\Lambda_{UV}^2 + ...]$$

with $Y_s = |Y_f|^2$

Supersymmetry: Motivation

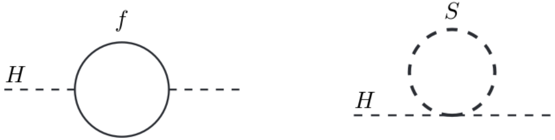
- **The Hierarchy Problem**

- **Unification of Gauge Couplings at GUT scale**
  All gauge couplings α_1, α_2 and α_3 converge at the GUT scale



Supersymmetry: Motivation

- **The Hierarchy Problem**



- **Unification of Gauge Couplings at GUT Scale**
  All gauge couplings α_1, α_2 and α_3 converge at the GUT-scale
- **Dark Matter Candidate**
  The MSSM can provide a Weakly Interacting Massive Particle (WIMP)

The Minimal Supersymmetric Standard Model

- Simplest possible Supersymmetric theory (N=1)
- The fermion superpartners are *squarks* and *sleptons*
- The Higgs superpartners are the *Higgsinos*

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

- The gauge bosons have corresponding *winos*, *binos* and *gluinos*

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \;\; \widetilde{W}^0$	$W^\pm \;\; W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

[Martin, arXiv:hep-ph/9709356]

The Minimal Supersymmetric Standard Model

- Two Higgs doublets H_u and H_d induce lepton, up- and down- type quark masses
- Particles mix with each other after EWSB
  - Two Charginos:

    $\{\tilde{W}^{\pm}, \tilde{H}^{\pm}_{u,d}\} \rightarrow \{\tilde{\chi}^{\pm}_{1,2}, \tilde{\chi}^{\pm}_{1,2}\}$
  - Four Neutralinos:

    $\{\tilde{B}, \tilde{W}^0_3, \tilde{H}^0_d, \tilde{H}^0_u\} \rightarrow \{\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4\}$
  - (Pseudo)scalar fields mix to give h, H, A, $H^{\pm}$
- No particular SUSY breaking mechanism assumed:

  $\mathcal{L}_{soft} \rightarrow$ most general parametrization that keeps relations between dimensionless couplings unchanged

The MSSM with complex parameters

- 105 new parameters + 19 from the SM
- These appear as masses, mixing angles and CP-violating phases
- Minimal flavour violation $\Rightarrow$ 41 independent parameters
- The MSSM allows 14 of 41 parameters to take complex values
- This is not forbidden by a symmetry:

  CP-symmetry is not a fundamental symmetry of nature
- Complex parameters:
  - Trilinear couplings A_f, $f = u, d, c, s, t, b \rightarrow A_f = |A_f| e^{i\phi_{A_f}}$
  - Higgsino mass parameter $\mu \rightarrow \mu = |\mu| e^{i\phi_\mu}$
  - Gluino mass parameter M_3
  - Soft SUSY breaking parameters from chargino and neutralino sectors, M_1, M_2

Soft SUSY Breaking

- Where do the complex parameters enter the theory?
- $\mathcal{L}_{soft}$ contains all possible gauge invariant and renormalizable couplings between SUSY particles

$$\mathcal{L}_{soft} = -M^2_{\tilde{u}_L}|\tilde{u}_L|^2 - M^2_{\tilde{u}_R}|\tilde{u}_R|^2 - M^2_{\tilde{u}_L}|\tilde{d}_L|^2 + ... \qquad \text{sfermion mass terms}$$

$$-[Y_u A_u(\tilde{q}_L.H_2)\tilde{u}^*_R + h.c.] \qquad \text{trilinear coupling breaking terms}$$

$$-\frac{1}{2}(M_V \tilde{V}\tilde{V} + h.c.) \qquad \text{gaugino mass terms}$$

$$-m_1^2|H_1|^2 - m_2^2|H_2|^2 - (m_{12}^2 H_1 H_2 + h.c.) \qquad \text{Higgs mass terms}$$

Higgs Sector at tree level

- The Higgs potential (including soft SUSY breaking terms) is:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} - \epsilon^{ij}(m_{12}^2 H_{1i} H_{2j} + m_{12}^2 H_{1i}^* H_{2j}^*) + \frac{1}{8}(g^2 + g'^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g'^2 |H_{1i}^* H_{2i}|^2$$

— $m_i^2 = \tilde{m}_i^2 + |\mu|^2$: $\tilde{m}_i{}^2$ soft breaking parameters

- The Higgs doublets

$$H_1 \equiv H_d = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}$$

$$H_2 \equiv H_u = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

$\Rightarrow$ The doublets can differ by a phase ξ

Higgs Sector at tree level

- 3 of the 8 d.o.f. give longitudinal component to gauge bosons
  $\Rightarrow$ 5 physical Higgs bosons
- Mass terms: Bilinear terms in the Higgs potential

$$V_{H|bil} = \frac{1}{2} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix}^{\dagger} \mathcal{M}_{\phi\phi\chi\chi} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix}^{\dagger} \mathcal{M}_{\phi^\pm\phi^\pm} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} + \ldots$$

- CPX contained in 2x2 component of $\mathcal{M}_{\phi\phi\chi\chi}$:

$$\mathcal{M}_{\phi,\chi} = \begin{pmatrix} 0 & m_{12}^2 \sin\xi \\ -m_{12}^2 \sin\xi & 0 \end{pmatrix}$$

- CP-even: ϕ_1, ϕ_2
  CP-odd: χ_1, χ_2
- V_H Minimization condition $\rightarrow \xi = 0 \Rightarrow$ **No** CP mixing at tree level

CPX in the Higgs Sector

- The physical mass eigenstates are related to tree level neutral fields as

$$\begin{pmatrix} h \\ H \\ A \\ G \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 & 0 \\ \cos\alpha & \sin\alpha & 0 & 0 \\ 0 & 0 & -\sin\beta & \cos\beta \\ 0 & 0 & \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix}$$

$$\begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = \begin{pmatrix} -\sin\beta & \cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

- CP-even: $(\phi_1, \phi_2) \rightarrow$ (h, H)
  CP-odd: $(\chi_1, \chi_2) \rightarrow$ (A)
- No mixing at tree level
  $\Rightarrow$ Input parameters of the Higgs sector: $\tan\beta = \frac{v_2}{v_1}$, M_A

CPX in the Higgs sector

- CP phases in sfermion, gaugino, Higgsino sectors induce h, H, A mixing at loop level $\Rightarrow$ Input parameters: $\tan\beta$, $M_{H^\pm}$
- Large contributions from $m_f X_f$ term in the sfermion loops in Higgs sector $X_f\{u,d\} = A_f - \mu^*\{\cot\beta, \tan\beta\}$
- Tools for Higgs physics at higher orders
  - **Effective Potential Approach**, CPsuperH
    [Lee,Carena,Ellis et al, arXiv:1208.2212]
    – up to leading log contributions at two loop level
    – Effects of imaginary parts at one loop
  - **Feynman Diagrammatic Approach**, FeynHiggs
    [Heinemeyer, Hollik, Rzehak, Weiglein]
    – Full 1-loop contributions + $\mathcal{O}(\alpha_t\alpha_s)$ corrections + additional contributions (phase dependence treated approximately)

Phenomenology of CPX Benchmark scenario

- CPX Benchmark Scenario
  $\rightarrow$ parameters chosen to maximize effect of complex phases
- In the MSSM Higgs sector CPX effects parametrized by ϕ_μ and ϕ_{A_f}
- ϕ_μ strongly constrained by measurements of electron and neutron EDMs
- For example values ($\tan\beta = 11$ and $M_{H^\pm} = 140$ GeV), neutral higgs masses show large variation with ϕ_{A_t}
  [Williams, Rzehak, Weiglein, arXiv:1103.1335]:

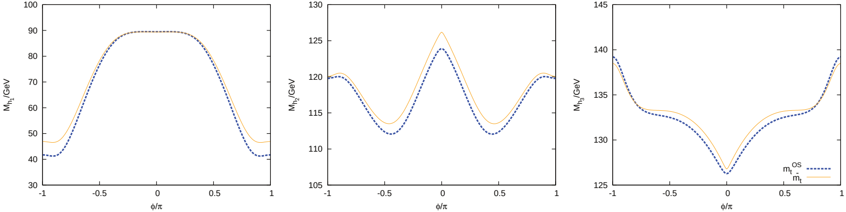
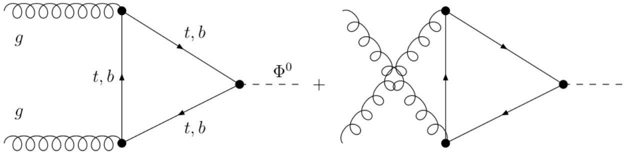


Figure: $M_{A,h,H}$ vs ϕ_{A_t}

Higgs Production in Complex MSSM

- Most important contribution to Higgs production: gg$\rightarrow \Phi^0$ ($\Phi^0 = h, H, A$)
  $\Rightarrow$ Study of effects on gg$\rightarrow \Phi^0$ cross-section in the CPX scenario
- Complex phases alter the strength of the couplings of the Higgs to quarks (loop induced) and squarks
- These effects are manifest in the vertex strength of the ggΦ^0 production channels [Dedes, Moretti, hep-ph/9909418]:



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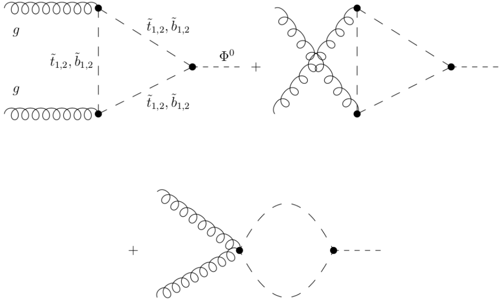

Higgs Production in Complex MSSM

- Starting point:
  Recalculation of squared ME for gg$\to \Phi^0$ in the leading order for real and complex MSSM
- Automation tools: FeynArts $\to$ FormCalc [MSSM.mod; MSSMCT.mod] $\to$ FeynCalc
- Expressions from literature [Dedes, Moretti, hep-ph/9909418]

$$|\bar{\mathcal{M}}|^2_{gg\to h^0} = \frac{\alpha_s^2 M_{h_0}^4}{256\pi^2}\left|\sum_q \frac{\lambda_{h^0 q\bar{q}}}{m_q}\tau_q[1+(1-\tau_q)f(\tau_q)] - \frac{1}{4}\sum_{\tilde{q}} \frac{\lambda_{h^0 \tilde{q}\tilde{q}^*}}{m_{\tilde{q}}^2}\tau_{\tilde{q}}[1-\tau_{\tilde{q}}f(\tau_{\tilde{q}})]\right|^2$$

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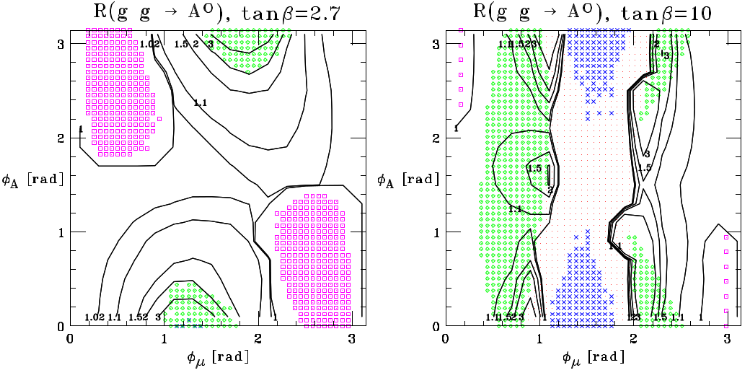
$$|\bar{\mathcal{M}}|^2_{gg\to A^0} = \frac{\alpha_s^2 M_{A_0}^4}{256\pi^2}\left|\sum_q \frac{\lambda_{A^0 q\bar{q}}}{m_q}[\tau_q f(\tau_q)]^2 - \frac{1}{16}\sum_{\tilde{q}} \frac{\lambda_{A^0 \tilde{q}\tilde{q}^*}}{m_{\tilde{q}}^2}\tau_{\tilde{q}}[1-\tau_{\tilde{q}}f(\tau_{\tilde{q}})]\right|^2$$

where
$\tau_{q,\tilde{q}} = \frac{4m_{q,\tilde{q}}^2}{M_{\Phi^0}^2}$, $q = t, b$ and $\tilde{q} = \tilde{t_1}, \tilde{t_2}, \tilde{b_1}, \tilde{b_2}$
$f(\tau)$ is the triangle integral C_0

Higgs Production in Complex MSSM

- Effect of complex phases ϕ_A ($A_u = A_d = A$) and ϕ_μ on $R = \frac{\sigma_{LO}^{MSSM*}(gg \to A)}{\sigma_{LO}^{MSSM}(gg \to A)}$ [Dedes, Moretti, hep-ph/9909418]



The coloured points are the exclusions from negativity of squark masses squared, the constraints by EDMs and Higgs boson and squark direct searches

Supersymmetric Higgs: SusHi

[Harlander, Liebler, Mantler arXiv:1212.3249]

- Fortran code for calculating
  - gluon fusion Higgs production
  - bottom-squark annihilation

  in the 5FS
- Models included: SM, 2HDM, MSSM, NMSSM
- Used for LHC Higgs XSWG predictions
- For gg$\rightarrow$ Φ^0 SusHi contains
  – NLO QCD contributions from 3rd family of quarks
  – NNLO corrections due to top quark etc.
- Higgs masses and mixing matrices obtained from the link to FeynHiggs

Summary + Tasks

- Complex phases in the MSSM manifest in higher order corrections in the Higgs sector
- Effects on gluon fusion Higgs production cross-section
- Study of the gluon fusion Higgs production with external Higgs mixing
- Implementation of Complex MSSM in SusHi
  [Harlander, Liebler, Mantler arXiv:1212.3249]

Backup

Gauge Anomalies: Why we need two Higgs doublets

- In the presence of just one Higgs chiral supermultiplet, EW Gauge symmetry suffers a gauge anomaly
- Condition for cancellation of gauge anomaly: $Tr[T_3^2 Y] = Tr[Y^3] = 0$, $Q_{EM} = T_3 + Y$
- These are satisfied in the SM by the known quarks and leptons
- A fermionic partner of a Higgs chiral supermultiplet must be a weak isodoublet with weak hypercharge $Y = \frac{1}{2}$ or $-\frac{1}{2}$
- In either case, such a fermion will make a non-zero contribution to the trace and result in an anomaly
- If there are two Higgs supermultiplets, one with each of $Y = \pm\frac{1}{2}$, the total contribution to the anomaly trace from the two fermionic members of the Higgs chiral supermultiplets vanishes by cancellation
- Further, only a $Y = \frac{1}{2}$ Higgs chiral supermultiplet has the Yukawa couplings to give masses to up-type quarks
- Only a $Y = -\frac{1}{2}$ Higgs chiral supermultiplet has the Yukawa couplings to give masses to down-type quarks and charged leptons

Sfermion sector at tree level

- The physical squark and charged leptons states $\tilde{f}_1$, $\tilde{f}_2$ are mass eigenstates of a 2x2 complex mass matrix:

$$M_{\tilde{f}} = \begin{pmatrix} M_L^2 + m_f^2 + M_Z^2 \cos 2\beta(I_3^f - Q_f s_W^2) & m_f X_f^* \\ m_f X_f & M_{\tilde{f}_R}^2 + m_f^2 + M_Z^2 \cos 2\beta Q_f s_W^2 \end{pmatrix}$$

–cot β applies to up-type massive fermions $f = u, c, t$
–tan β applies to down-type fermions $f = d, s, b, e, \mu, \tau$

- M_L^2 and $M_{\tilde{f}_R}^2$ are soft symmetry breaking parameters
- $M_{\tilde{f}}$ diagonalized by a 2x2 complex, unitary matrix $U_{\tilde{f}}$
- Bilinear part of the lagranian in the sfermion sector reads

$$\mathcal{L}_{\tilde{f}} = -(\tilde{f}_1^\dagger, \tilde{f}_2^\dagger) U_{\tilde{f}} M_{\tilde{f}} U_{\tilde{f}}^\dagger \begin{pmatrix} \tilde{f}_1^\dagger \\ \tilde{f}_2^\dagger \end{pmatrix}$$

Gluino sector at tree level

- Born lagrangian of the gluino is

$$\mathcal{L}_{\tilde{g}} = -\frac{1}{2}\bar{\tilde{g}} M_3 \tilde{g}$$

- M_3 is the gluino mass parameter

$$M_3 = |M_3| e^{i\phi_{M_3}}$$

- Gluinos only couple to coloured particles, so only enter Higgs sectors at two-loop level

CP-Phases

- 2 of the 14 complex phases can be rotated away
- Theoretically, the phases can be arbitrarily large, giving new sources of CPX for Sakharaov's conditions for baryon asymmetry in the universe
- Experimental limits on EDMs of atoms and neutrins places stringent constrains on the complex phases
- The constraints on third generation trilinear couplings are much weaker
- Higgsino phase ϕ_μ tightly constrained in conventions where ϕ_{M_2} =0

CPX Benchmark Scenario [Williams, Rzehak, Weiglein; arXiv:1103.1335]

- $m_t = 173.1$ GeV
- $M_{SUSY} = 500$ GeV ($=M_L^{onshell}$)
- $\mu = 2000$ GeV
- $|M_3| = 1000$ GeV
- $M_2 = 200$ GeV
- $|A_t^{onshell}| = |A_b| = 900$ GeV
- $\phi_{A_t^{onshell}} = \phi_{A_b} = Q_{M_3} = \frac{\pi}{2}$
- $M_{H^\pm} < 1000$ GeV