NEUTRAL HIGGS PRODUCTION
in the MSSM with Complex Parameters

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Deutsches-Elektronen Synchrotron

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Outline

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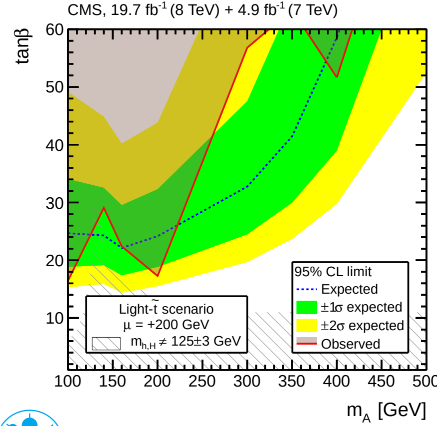
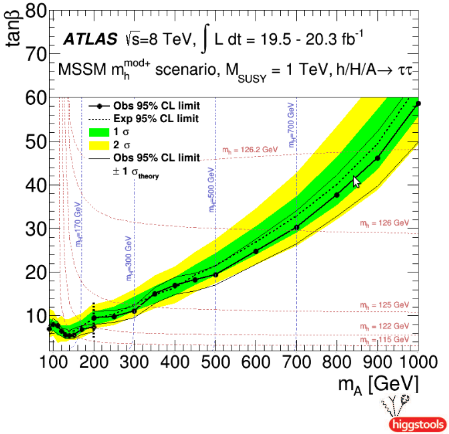
2. The MSSM: An Overview
3. Complex Parameters in the MSSM
4. Effects of CP-violation (CPX) in the MSSM Higgs Sector
5. Gluon Fusion Higgs Production in the MSSM
6. `SusHi` & `FeynHiggs`
7. Phenomenology of Benchmark Scenarios
8. Conclusions + Outlook

Experimental searches for heavy Higgs bosons $\phi = H, A$:
Production $gg \to \phi, b\bar{b} \to \phi$ × Decay $\phi \to \tau\tau, b\bar{b}, \mu\mu$...





- Two Higgs doublets H_u and H_d induce lepton, up- and down- type quark masses
- Five physical Higgs fields:
  - CP even: h, H
  - CP odd: A
  - Charged: $H^{\pm}$
- MSSM Higgs sector is CP-conserving at tree-level
- Gauginos and Higgsinos mix after EWSB
  - Two Charginos: $\{\tilde{W}^{\pm}, \tilde{H}^{\pm}_{u,d}\} \to \{\tilde{\chi}^{\pm}_{1,2}, \tilde{\chi}^{\pm}_{1,2}\}$
  - Four Neutralinos: $\{\tilde{B}, \tilde{W}^0_3, \tilde{H}^0_d, \tilde{H}^0_u\} \to \{\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4\}$
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Complex Parameters in the MSSM

- 105 new parameters + 19 from the SM
  - appear as masses, mixing angles and CP-violating phases
  - Minimal flavour violation $\Rightarrow$ 41 independent parameters
- 14 of 41 parameters can take complex values
- Complex parameters:
  - Trilinear couplings A_f, $f = u, d, c, s, t, b, e, \mu, \tau \rightarrow A_f = |A_f| e^{i\phi_{A_f}}$
  - Higgsino mass parameter $\mu \rightarrow \mu = |\mu| e^{i\phi_\mu}$
  - Gluino mass parameter $M_3 \rightarrow M_3 = |M_3| e^{i\phi_{M_3}}$
  - Gaugino mass parameters M_1, M_2 (Only ϕ_{M_1} physical)
- Higgs sector primarily parametrized by $M_{H^\pm}$ and $\tan\beta$
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- Complex parameters enter the Higgs sector through higher order corrections
- Self-energy terms appear in the propagator matrix at higher orders
- Higher order masses determined by complex poles of the propagator matrix Δ_{hHA}

$$\Delta^{-1}_{hHA}(p^2) = \hat{\Gamma}_{hHA}(p^2) = i[p^2\mathbb{1} - \mathbf{M}(p^2)]$$

$$\mathbf{M}(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{Hh}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{Ah}(p^2) & -\hat{\Sigma}_{AH}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

- Loop-corrected masses obtained from the real parts of the complex pole: $\mathcal{M}^2 = M^2 - iM\Gamma$

$\mathcal{CP}$X Effects in the MSSM Higgs Sector

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- h, H, A mix into new mass eigenstates $H_{1,2,3}$ $(m_{H_1} \leq m_{H_2} \leq m_{H_3})$
- Diagonal propagator: $\Delta_{ii}(p^2) = \frac{i}{p^2 - m_i^2 - \hat{\Sigma}_{ii}^{\text{eff}}(p^2)}$
- On-shell properties of external Higgses established by wave-function normalization factors $\hat{Z}_{ij}$ [Williams et al. '11]:

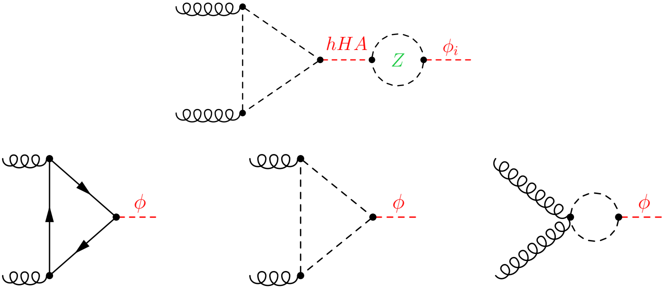
$$\hat{Z}_{ii} = \frac{1}{p^2 - m_i^2 - \hat{\Sigma}_{ii}^{\text{eff}\prime}} \qquad \hat{Z}_{ij} = \frac{\Delta_{ij}(p^2)}{\Delta_{ii}(p^2)}$$

- Wave function normalisation factors expressed as non-unitary $\hat{\mathbf{Z}}$ matrix:

$$\begin{pmatrix} \hat{\Gamma}_{H_1} \\ \hat{\Gamma}_{H_2} \\ \hat{\Gamma}_{H_3} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix}$$

Gluon Fusion in the MSSM: LO Cross section

- Complex phases enter the XS through **Z** factors or squark loops



Early Work: [Dedes, Moretti '00]

- Gluon fusion at LO using $\tau_\phi = m_\phi^2/s$:
  - $\sigma(pp \to \phi + X) = \sigma_0 \tau_\phi \mathcal{L}^{gg} \longleftarrow \mathcal{L}^{gg} = \int_\tau^1 \frac{dx}{x} g(x) g\left(\frac{\tau}{x}\right)$
  - LO partonic XS:

$$\sigma_0 \propto |Z_h A_h^{t,b,\tilde{t},\tilde{b}} + Z_H A_H^{t,b,\tilde{t},\tilde{b}} + Z_A A_A^{\tilde{t},\tilde{b}}|^2 + |Z_A A_A^{t,b}|^2$$

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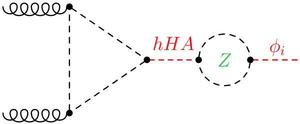

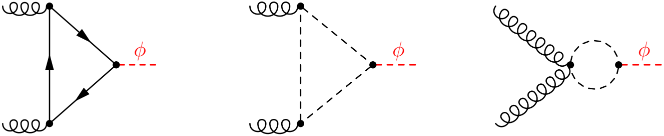

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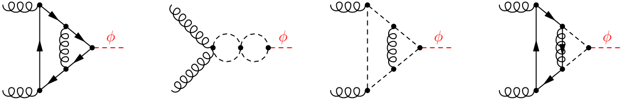
Gluon Fusion in the MSSM: NLO and NNLO

- Gluon fusion at NLO: $\sigma(pp \to \phi + X) \propto \sigma_0 \tau_\phi \mathcal{L}^{gg} \left[1 + C^\phi \frac{\alpha_s}{\pi}\right]$
- NLO contributions from gluon-quark, gluon-squark and gluino-squark-quark amplitudes enter C^ϕ



  - $a_q^{\phi,(1)}$: known analytically (higher orders) [Spira et al '95; Harlander Kant '05]
  - $a_{\tilde{q}}^{\phi,(1)}$: known analytically/numerically [Anastasiou et al '06; Aglietti et al '06; Muehlleitner Spira '06; Bonciani et al '07]
  - $a_{\tilde{q}\tilde{g}}^{\phi,(1)}$: analytically known in various expansions; implemented in `SusHi` [Harlander Liebler Mantler '12]
- Inclusion of NLO EW corrections from SM
- Top quark induced gluon-Higgs coupling taken into account at NNLO using program `ggh@nnlo` [Harlander: robert-harlander.de/software/ggh@nnlo]

SusHi & FeynHiggs

SusHi calculates neutral Higgs boson production XS through gluon fusion and bottom-quark annihilation (5FS) in the SM, the 2HDM, MSSM and the NMSSM. [Harlander Liebler Mantler '12; Liebler '15: sushi.hepforge.org]

FeynHiggs calculates the masses, couplings and Z factors of the Higgs sector in the MSSM. [Heinemeyer, Hollik, Rzehak, Weiglein: feynhiggs.de]

- New development: extension of SusHi to the CP-violating case of the MSSM
- CP-violating MSSM in SusHi produces XS predictions for neutral Higgs production via gluon fusion
- Scope of current implementation

$$\sigma = \sigma^{t,b}_{\text{NNLO}} + \sigma^{t,b,\tilde{t},\tilde{b}}_{\text{LO}} - \sigma^{t,b}_{\text{LO}}$$

- Admixture of h, H, and A described through Z factors obtained from FeynHiggs

The effect of ϕ_{A_t} studied in two benchmark scenarios:

$\mathbf{M_h^{mod+}}$:

- $M_{\text{SUSY}} = 1000$ GeV
- $X_t^{\text{OS}} = 1.5\ M_{\text{SUSY}}$
- $|A_t| = |A_b| = |A_\tau|$
- $\mu = 1000$ GeV
- $\tan\beta = 10$
- $M_3 = 1500$ GeV
- $M_{H\pm} = 600$ GeV
- $M_2 = 500$ GeV
- $M_{\tilde{l}_3} = 1000$ GeV

lightstop:

- $M_{\text{SUSY}} = 500$ GeV
- $X_t^{\text{OS}} = 2\ M_{\text{SUSY}}$
- $|A_t| = |A_b| = |A_\tau|$
- $\mu = 400$ GeV
- $\tan\beta = 5$
- $M_3 = 1500$ GeV
- $M_{H\pm} = 500$ GeV
- $M_2 = 400$ GeV
- $M_{\tilde{l}_3} = 1000$ GeV

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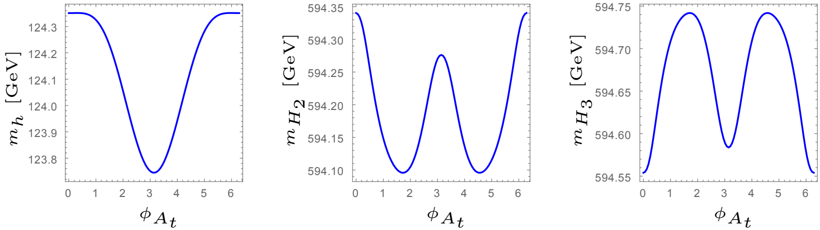
Benchmark Scenario: M_h^{mod+}

Higgs mass variation with ϕ_{A_t} for $H_1 \sim h, H_2, H_3$



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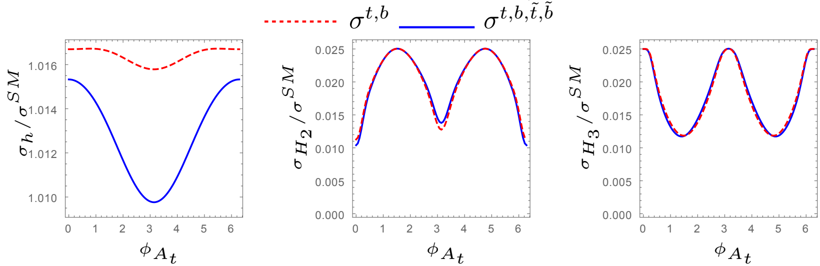
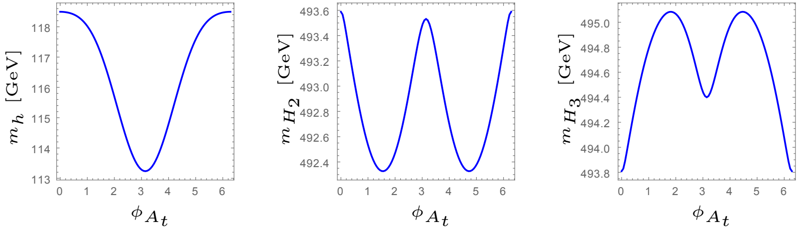


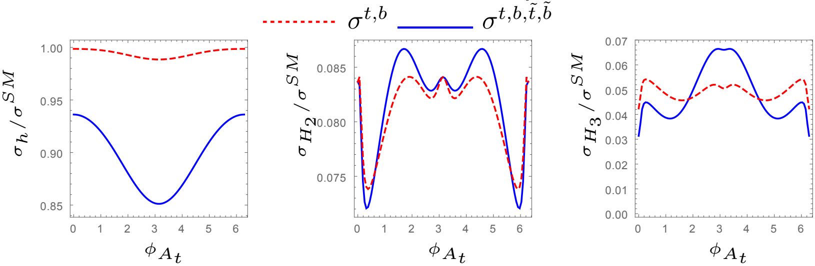
Changes in normalized heavy Higgs XS $(\Delta\sigma^{\text{rel}}_{H_2,H_3}) \sim 100\%$

Benchmark Scenario: **lightstop**

Higgs mass variation with ϕ_{A_t} for $H_1 \sim h, H_2, H_3$



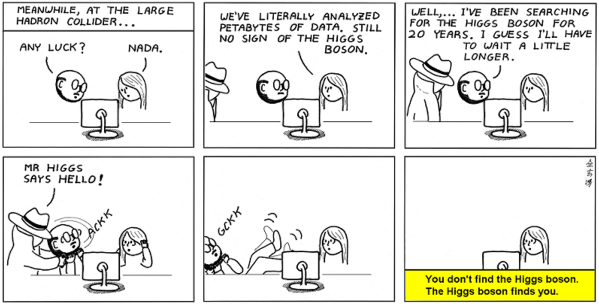
Higgs XS variation with ϕ_{A_t}:



$$\Delta\sigma_h^{\text{rel}} \sim 15\%,\ \Delta\sigma_{H_2}^{\text{rel}} \sim 20\%\ ,\ \Delta\sigma_{H_3}^{\text{rel}} \sim 100\%$$

Summary + Outlook

- Conclusions:
  - Complex parameters produce significant effects on neutral Higgs productions XS
  - Z factors, which are propagator-type, and genuine vertex corrections induce mixing between the heavy Higgses which can lead to interference effects
- Outlook:
  - Investigation of the influence of Δ_b corrections
  - Study of interference effects including final states in Higgs production and decay $\rightarrow$ talk by Elina Fuchs



BACKUP

Gluon Fusion in the MSSM: LO Cross section

The ingredients of the LO Amplitude are:

- Quark contributions
  - $A^q_{h,H} \propto g^q_{h,H}\tau^q_{h,H}[1+(1-\tau^q_{h,H})f(\tau^q_{h,H})]$
  - $A^q_A \propto g^q_A\tau^q_A f(\tau^q_A)$
- Squark contributions
  - $A^{\tilde{q}}_{h,H} \propto \tau^q_{h,H}\sum_{i=1}^{2} g^{\tilde{q},ii}_{h,H}[1-\tau^{\tilde{q}i}_{h,H} f(\tau^{\tilde{q}i}_{h,H})]$
  - $A^{\tilde{q}}_A \propto \tau^q_A\sum_{i=1}^{2} g^{\tilde{q},ii}_{A}[1+\tau^{\tilde{q}i}_{A}(1-\tau^{\tilde{q}i}_{A} f(\tau^{\tilde{q}i}_{A}))]$

For $\phi = h, H, A$:

$$\tau^q_\phi = \frac{4m_q^2}{m_\phi^2}, \tau^{\tilde{q}i}_\phi = \frac{4m_{\tilde{q}i}^2}{m_\phi^2}, f(\tau) = \begin{cases} \arcsin^2\frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left(\log\frac{1+\sqrt{1-\tau}}{1+\sqrt{1+\tau}} - i\pi\right)^2 & \tau < 1 \end{cases}$$

- Expressions from literature [Dedes, Moretti, hep-ph/9909418]

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

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

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

where

$\tau_{q,\tilde{q}} = \frac{4m_{q,\tilde{q}}^2}{M_\Phi^2}, q = t, b$ and $\tilde{q} = \tilde{t_1}, \tilde{t_2}, \tilde{b_1}, \tilde{b_2}$

$f(\tau)$ is the triangle integral C_0

Tensor structure of loop-amplitudes at LO

Non-existence of the interference terms between quark and squark loops for A:

$$i\epsilon_\mu(P_1)\epsilon_\nu(P_2)\mathcal{M}^{\mu\nu}_{ab}(gg \to A) = -\frac{\alpha_s(Q)}{2\pi}\delta_{ab}\epsilon_\mu(P_1)\epsilon_\nu(P_2)\times$$
$$i\epsilon^{\mu\nu\rho\sigma}P_{1\rho}P_{2\sigma}\sum_q \frac{\lambda_{Aq\bar{q}}}{m_q}[\tau_q f(\tau_q)] + \frac{1}{4}\sum_{\tilde{q}} \frac{\lambda_{A\tilde{q}\tilde{q}*}}{m^2_{\tilde{q}}}(g^{\mu\nu}P_1\cdot P_2 - P_1^\nu P_2^\nu)\tau_{\tilde{q}}[1 -$$
$$\tau\tilde{q}f(\tilde{q})]$$

with P_1, P_2 the gluon four momenta, a, b their colours.

Anti-symmetric part associated with the quark contributions and symmetric part associated with squark loops

- The off-diagonal entries of the propagator matrix are

$$\Delta_{ij}(p^2) = \frac{\tilde{\Gamma}_{ij}\tilde{\Gamma}_{kk} - \tilde{\Gamma}_{jk}\tilde{\Gamma}_{ki}}{\tilde{\Gamma}_{ii}\tilde{\Gamma}_{jj}\tilde{\Gamma}_{kk} + 2\tilde{\Gamma}_{ij}\tilde{\Gamma}_{jk}\tilde{\Gamma}_{ki} - \tilde{\Gamma}_{ii}\tilde{\Gamma}^2_{jk} - \tilde{\Gamma}_{jj}\tilde{\Gamma}^2_{ki} - \tilde{\Gamma}_{kk}\tilde{\Gamma}^2_{ij}}$$

- The diagonal entries are:

$$\begin{aligned}\Delta_{ii}(p^2) &= \frac{\tilde{\Gamma}_{jj}\tilde{\Gamma}_{kk} - \tilde{\Gamma}^2_{jk}}{-\tilde{\Gamma}_{ii}\tilde{\Gamma}_{jj}\tilde{\Gamma}_{kk} + \tilde{\Gamma}_{ii}\tilde{\Gamma}^2_{jk} - 2\tilde{\Gamma}_{ij}\tilde{\Gamma}_{jk}\tilde{\Gamma}_{ki} + \tilde{\Gamma}_{jj}\tilde{\Gamma}^2_{ki} + \tilde{\Gamma}_{kk}\tilde{\Gamma}^2_{ij}} \\ &= \frac{i[\tilde{\Gamma}_{jj}\tilde{\Gamma}_{kk} - \tilde{\Gamma}^2_{jk}]}{-i(\tilde{\Gamma}_{ii}[\tilde{\Gamma}_{jj}\tilde{\Gamma}_{kk} - \tilde{\Gamma}^2_{jk}] + [2\tilde{\Gamma}_{ij}\tilde{\Gamma}_{jk}\tilde{\Gamma}_{ki} - \tilde{\Gamma}_{jj}\tilde{\Gamma}^2_{ki} - \tilde{\Gamma}_{kk}\tilde{\Gamma}^2_{ij}])} \\ &= \frac{i}{p^2 - m_i^2 + \tilde{\Sigma}_{ii} - i\frac{2\tilde{\Gamma}_{ij}\tilde{\Gamma}_{jk}\tilde{\Gamma}_{ki} - \tilde{\Gamma}_{jj}\tilde{\Gamma}^2_{ki} - \tilde{\Gamma}_{kk}\tilde{\Gamma}^2_{ij}}{\tilde{\Gamma}_{jj}\tilde{\Gamma}_{kk} - \tilde{\Gamma}^2_{jk}}}\end{aligned}$$

- Effective self energy. separates the diagonal self energy, which exists already at 1-loop from the mixing 2-point functions that only contribute at 2-loop

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:

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

  with $X_f\{u,d\} = A_f - \mu^*\{\cot\beta, \tan\beta\}$
  –$\cot\beta$ applies to up-type massive fermions $f = u, c, t$
  –$\tan\beta$ 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

Complex Parameters

- 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 neutrinos 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 $\phi_{M_2} = 0$