High-Precision Higgs Masses in the Complex MSSM

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in collaboration with

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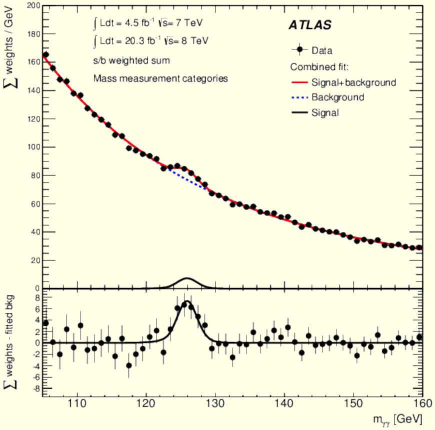
SUSY 2016,

Melbourne, Australia,
5th of July 2016

Experimental discovery and mass measurement

Higgs-like particle discovered, [ATLAS, arXiv:1207.7214 [hep-ex]], [CMS, arXiv:1207.7235 [hep-ex]],

e. g. signal in $H \to \gamma\gamma$, [ATLAS, arXiv:1406.3827 [hep-ex]],



- very good agreement with SM Higgs boson,
- but: SM has many deficiencies,
- test models beyond the Standard Model,

  e. g. Supersymmetry, here: MSSM,
- experimental value:

  $125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV

  [ATLAS, CMS, arXiv:1503.07589].

MSSM Higgs sector

two complex $SU(2)$-Higgs doublets (eight degrees of freedom):

$$\mathcal{H}_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}\left(\phi_1^0 - i\,\chi_1^0\right) \\ -\phi_1^- \end{pmatrix}, \qquad \mathcal{H}_2 = e^{i\,\zeta} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}\left(\phi_2^0 + i\,\chi_2^0\right) \end{pmatrix},$$

positive real vacuum expectation values $v_1\,,\ v_2\,,\ \tan\beta \equiv v_2/v_1\,,$
relative phase $\zeta\,,$

with superpotential

$$\mathcal{W}_{\text{MSSM}} = \mu\, H_1 \cdot H_2 - h_{u,\,ij}\, Q_i \cdot H_2\, U_j^C - h_{e,\,ij}\, H_1 \cdot L_i\, E_j^C - h_{d,\,ij}\, H_1 \cdot Q_i\, D_j^C\ .$$

tree-level mass eigenstates:
CP even h, H; CP odd A; charged $H^\pm$
MSSM CP conserving at tree level

Higgs masses at k loop order given by poles of propagator matrix

$$\mathbf{\Delta}^{(k)}_{hHAG}\left(p^2\right) = i\,\left[p^2\mathbf{1} - \mathbf{M}^{(k)}_{hHAG}\left(p^2\right)\right]^{-1},$$

matrix of renormalized two-point vertex functions:

$$\hat{\mathbf{\Gamma}}^{(k)}_{hHAG}\left(p^2\right) = -\left[\mathbf{\Delta}^{(k)}_{hHAG}\left(p^2\right)\right]^{-1},$$

masses determined by

$$\det\left[\hat{\mathbf{\Gamma}}^{(k)}_{hHAG}\left(p^2\right)\right]_{p^2\,=\,x_i^2} = 0\,, \quad m^2_{h_i} = \mathfrak{Re}\left[x_i^2\right]\,, \quad i \in \{1,\,2,\,3\}\,,$$

(fourth solution belongs to Goldstone boson, equal to zero).

Mass matrix at higher orders

- lowest order: $\mathbf{M}^{(k)}_{hHAG}(p^2)\Big|_{k\,=\,0} = \mathbf{M}^{(0)}_{hHAG}$, diagonal,

- higher order: $\mathbf{M}^{(k)}_{hHAG}(p^2)\Big|_{k\,\geq\,1} = \mathbf{M}^{(0)}_{hHAG} - \sum_{j\,=\,1}^{k} \widehat{\mathbf{\Sigma}}^{(j)}_{hHAG}(p^2)$,

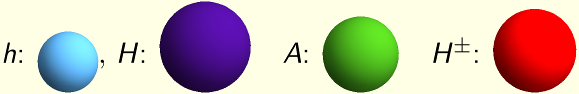
  shift by renormalized self-energies

$$\widehat{\mathbf{\Sigma}}^{(j)}_{hHAG}(p^2) = \begin{pmatrix} \hat{\Sigma}^{(j)}_{h}(p^2) & \hat{\Sigma}^{(j)}_{hH}(p^2) & \hat{\Sigma}^{(j)}_{hA}(p^2) & \hat{\Sigma}^{(j)}_{hG}(p^2) \\ \hat{\Sigma}^{(j)}_{hH}(p^2) & \hat{\Sigma}^{(j)}_{H}(p^2) & \hat{\Sigma}^{(j)}_{HA}(p^2) & \hat{\Sigma}^{(j)}_{HG}(p^2) \\ \hat{\Sigma}^{(j)}_{hA}(p^2) & \hat{\Sigma}^{(j)}_{HA}(p^2) & \hat{\Sigma}^{(j)}_{A}(p^2) & \hat{\Sigma}^{(j)}_{AG}(p^2) \\ \hat{\Sigma}^{(j)}_{hG}(p^2) & \hat{\Sigma}^{(j)}_{HG}(p^2) & \hat{\Sigma}^{(j)}_{AG}(p^2) & \hat{\Sigma}^{(j)}_{G}(p^2) \end{pmatrix},$$

$\hat{\Sigma}^{(j)}_{hA}(p^2)$, $\hat{\Sigma}^{(j)}_{HA}(p^2) \neq 0 \Rightarrow$ complex parameters (e. g. μ, A_t, A_b, M_3, $\ldots$).

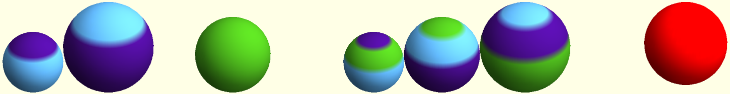
- lowest order mass eigenstates:

CP even	*CP* odd	charged

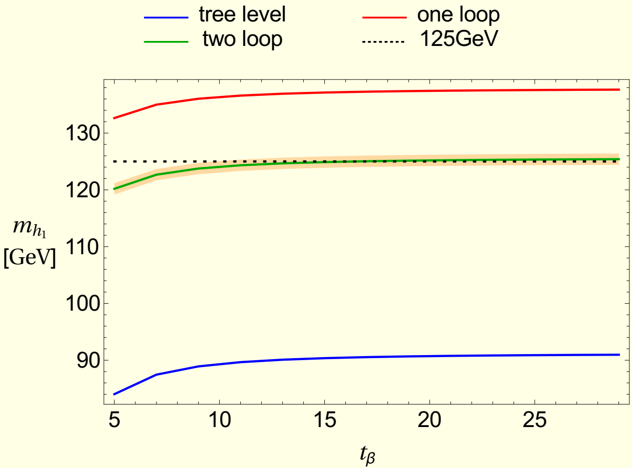


- higher orders: off-diagonal entries in $\hat{\mathbf{\Sigma}}^{(j)}_{hHAG}(p^2)$ induce mixing,

real MSSM		complex MSSM	both
CP even	*CP* odd	*CP* mixed	charged

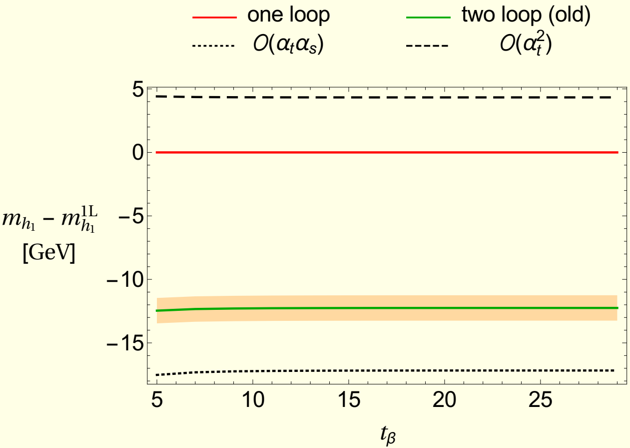


input parameter: m_A or $m_{H^{\pm}}$	input parameter: $m_{H^{\pm}}$	



- upper bound at tree level: M_Z
- huge one-loop corrections: $+50\%$
- two-loop in complex MSSM:
  leading $\mathcal{O}(\alpha_t \alpha_s)$
  [Heinemeyer, Hollik, Rzehak, Weiglein, arXiv:0705.0746]
  leading $\mathcal{O}(\alpha_t^2)$
  [Hollik, SP, arXiv:1401.8275, 1409.1687]
- orange band: $\pm 1\text{GeV}$

m_h^{mod} scenario: $M_{H^\pm} = 0.6\text{TeV}$, $\mu = 0.2\text{TeV}$,
$M_{\text{SUSY}} = 1.0\text{TeV}$, $A_f = 1.5\text{TeV}$, $M_{\tilde{g}} = 1.5\text{TeV}$



- huge effect by $\mathcal{O}(\alpha_t\alpha_s)$: $\approx -17\text{GeV}$
- also big effect by $\mathcal{O}(\alpha_t^2)$: $\approx +5\text{GeV}$

m_h^{mod} scenario: $M_{H^\pm} = 0.6\text{TeV}$, $\mu = 0.2\text{TeV}$, $M_{\text{SUSY}} = 1.0\text{TeV}$, $A_f = 1.5\text{TeV}$, $M_{\tilde{g}} = 1.5\text{TeV}$

new contributions

- extension for leading $\mathcal{O}(\alpha_t \alpha_s)$:
  full lowest order QCD, i. e. $\mathcal{O}(\alpha_{\text{any}} \alpha_s)$, $\alpha_{\text{any}} = \alpha, \alpha_t, \alpha_b, \ldots$

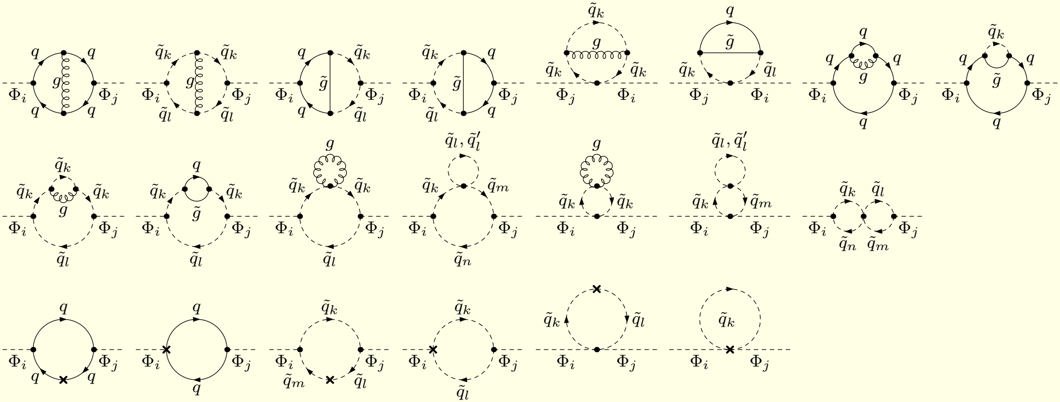
  no approximations applied,
  all subleading terms included,
  momentum dependence taken into account

- extension for leading $\mathcal{O}(\alpha_t^2)$:
  Yukawa^4 terms, i. e. $\mathcal{O}(\alpha_t^2 + \alpha_t \alpha_b + \alpha_b^2)$

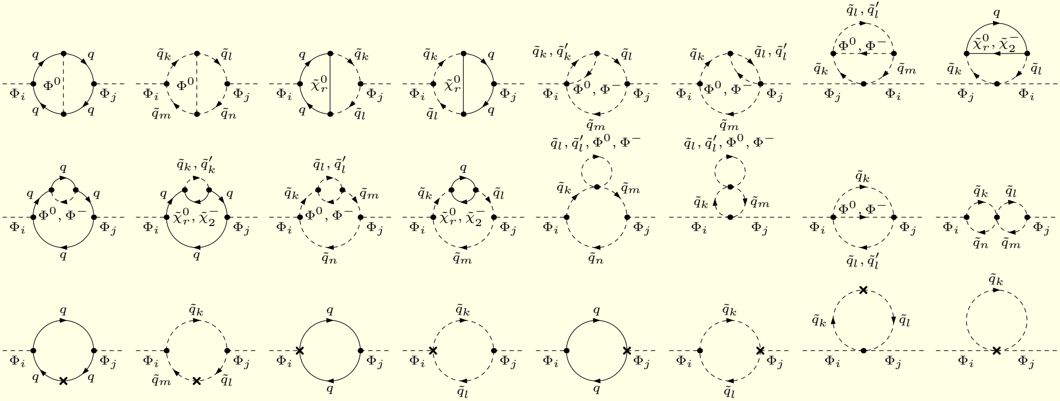
  gauge-less approximation applied,
  subleading Yukawa terms included,
  no momentum dependence

results generated with help of `FeynArts`, `FormCalc`, `TwoCalc`
following previously developed scripts [Hahn, SP, arXiv:1508.00562]

$\mathcal{O}(\alpha_{\text{any}}\alpha_s)$, Feynman diagrams



$\mathcal{O}(\alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$, Feynman diagrams



renormalization schemes

- $\mathcal{O}(\alpha_{\mathrm{any}}\alpha_s)$

  subrenormalization, only $\mathcal{O}(\alpha_s)$:
  $\delta m_{\tilde{t}_{1,2}}, \delta m_{\tilde{t}_{12}}, \delta m_t, \delta m_{\tilde{b}_2}$ on-shell

  $\delta m_b, \delta A_b$ $\overline{\mathrm{DR}}$

  genuine two loop:
  $\delta m_{H^\pm}, \delta T_{h,H,A}, \delta m_W, \delta m_Z$ on-shell

  $\delta Z_{\mathcal{H}_1}, \delta Z_{\mathcal{H}_2}, \delta t_\beta$ $\overline{\mathrm{DR}}$

- $\mathcal{O}(\alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$

  subrenormalization, $\mathcal{O}(\alpha_t + \alpha_b)$:
  $\delta m_{\tilde{t}_{1,2}}, \delta m_{\tilde{t}_{12}}, \delta m_t, \delta m_{\tilde{b}_2}, \delta\mu$ on-shell

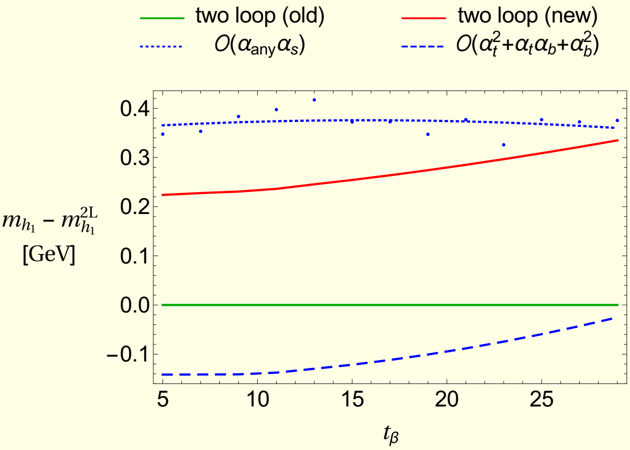
  $\delta m_b, \delta A_b$ $\overline{\mathrm{DR}}$

  $\frac{\delta M_Z}{M_Z}, \frac{\delta M_W}{M_W}$ on-shell

  $\delta m_{H^\pm}, \delta T_{h,H,A}$ on-shell

  $\delta Z_{\mathcal{H}_1}, \delta Z_{\mathcal{H}_2}, \delta t_\beta$ $\overline{\mathrm{DR}}$

  genuine two loop:
  $\delta m_{H^\pm}, \delta T_{h,H,A}$ on-shell

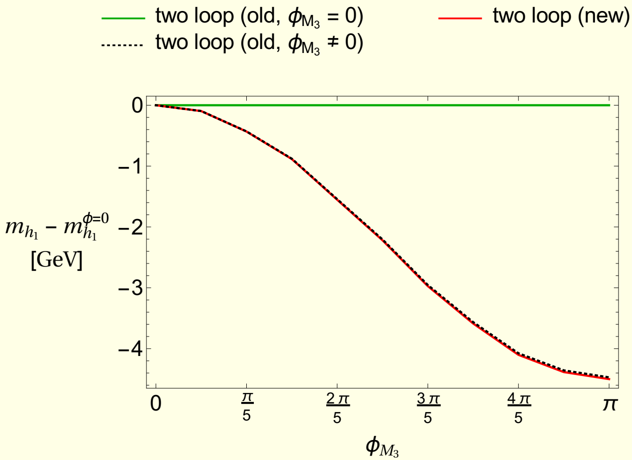


- opposite sign of new contributions
- momentum-dependent integrals evaluated with help of SecDec

  [Borowka, Carter, Heinrich, arXiv:1011.5493, 1204.4152, 1303.1157]

m_h^{mod} scenario: $M_{H^\pm} = 0.6\text{TeV}$, $\mu = 0.2\text{TeV}$, $M_{\text{SUSY}} = 1.0\text{TeV}$, $A_f = 1.5\text{TeV}$, $M_{\tilde{g}} = 1.5\text{TeV}$

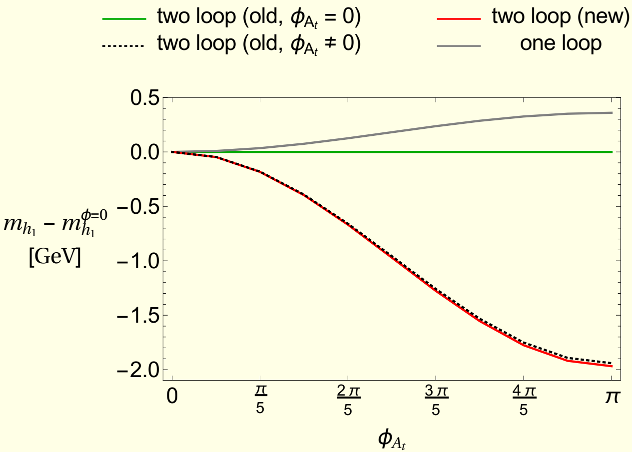
phase dependence: ϕ_{M_3}



- in general: large shift by phase
- new terms of $\mathcal{O}(\alpha_{\text{any}}\alpha_s)$ depend only slightly on ϕ_{M_3}: shift by $\approx -20\text{MeV}$

m_h^{mod} scenario: $M_{H^\pm} = 0.6\text{TeV}$, $\mu = 0.2\text{TeV}$, $t_\beta = 15$, $M_{\text{SUSY}} = 1.0\text{TeV}$, $A_f = 1.5\text{TeV}$, $M_{\tilde{g}} = 1.5\text{TeV}$

phase dependence: ϕ_{A_t}



- in general: large shift by phase
- new terms of $\mathcal{O}(\alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$ depend only slightly on ϕ_{A_t}: shift by ≈ -30MeV

m_h^{mod} scenario: $M_{H^\pm} = 0.6$TeV, $\mu = 0.2$TeV, $t_\beta = 15$, $M_{\text{SUSY}} = 1.0$TeV, $A_f = 1.5$TeV, $M_{\tilde{g}} = 1.5$TeV

outlook

- analyze separately the contributions to $\mathcal{O}(\alpha_{\text{any}}\alpha_s)$ by momentum-dependent terms, gauge terms, m_b terms
- compare $\mathcal{O}(\alpha_{\text{any}}\alpha_s)$ in limit $m_b \to 0$ and real parameters with previous result
- compare $\mathcal{O}(\alpha_q\alpha_{q'})$ in limit of real parameters with previous result
- implement in `FeynHiggs`
- implement running m_t consistently
- make results available in on-shell scheme and $\overline{\text{DR}}$ scheme
- investigate effect on charged Higgs mass in real MSSM