News on NMSSMCALC

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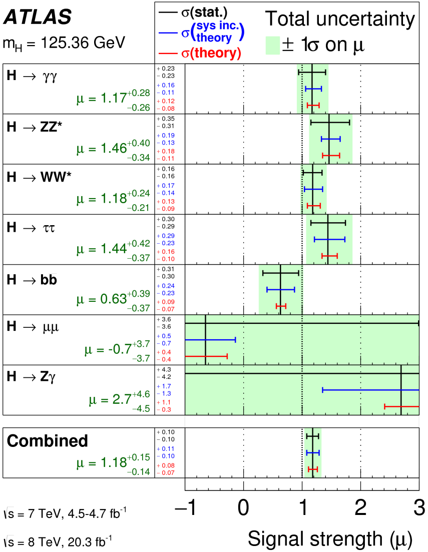
in coll. with J. Baglio, R. Gröber, M. Mühlleitner, H. Rzehak, M. Spira, J. Streicher, K. Walz and Hanna Ziesche

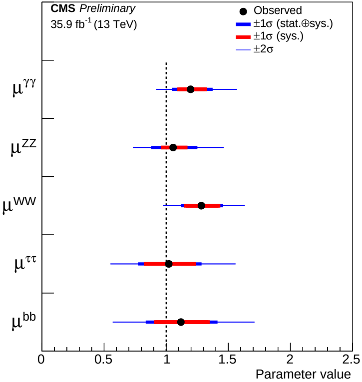
Windows on the Universe, 5-11 August 2018, Quy Nhon

Overview

Facts

We have discovered a SM-like Higgs boson $m_H = 125.09 \pm 0.21(stat.) \pm 0.11(syst.)$GeV





SM cannot be an ultimate theory

Constraints on BSM Higgs sector

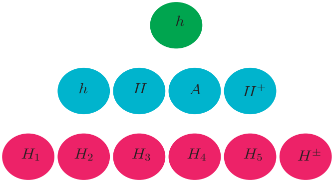
Need dedicated codes → Higgs decays

NMSSMCALC

The Next-to Minimal Supersymmetric Standard Model (NMSSM)

Higgs sector

- SM: H doublet
- MSSM: H_d, H_u doublets
- NMSSM: H_d, H_u doublets and S singlet



Positive points compared to MSSM

- Solve the $\mu-$problem.
  Superpotential

$$W_{NMSSM} = \epsilon_{ij}[y_e \hat{H}_d^i \hat{L}^j \hat{E}^c + y_d \hat{H}_d^i \hat{Q}^j \hat{D}^c - y_u \hat{H}_u^i \hat{Q}^j \hat{U}^c] - \epsilon_{ij} \lambda \hat{S} \hat{H}_d^i \hat{H}_u^j + \frac{1}{3} \kappa \hat{S}^3$$

$$\epsilon_{ij} \lambda \hat{S} \hat{H}_d^i \hat{H}_u^j \overset{\langle S \rangle = v_S/\sqrt{2}}{\Longrightarrow} \mu = \frac{\lambda v_S}{\sqrt{2}}$$

- Less finetuning compared to MSSM

$$(M_h^{\text{tree}})^2 < M_Z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta)$$

thanks to the additional contribution to the tree-level Higgs mass, we do not require large stop masses and mixing to obtain a 125 GeV Higgs boson.

Public tools for NMSSM

- Real NMSSM
  1. NMSSMTools: spectrum generator and decay branching ratios
  2. SOFTSUSY: spectrum generator and decay branching ratios
  3. NMSSMCALC: spectrum generator and decay branching ratios
  4. SARAH-SOFTSUSY-FlexibleSUSY: spectrum generator
  5. SARAH-SPHENO: spectrum generator and decay branching ratios
  6. FEYNHIGGS: spectrum generator and decay branching ratios
- Complex NMSSM
  1. NMSSMCALC
  2. SARAH-SPHENO
  3. FEYNHIGGS

The difference of SM-like Higgs boson masses computed in those codes can be of several GeV.

- running top Yukawa and alphas couplings
- different approximations used
- different choices for renormalization conditions and scales

- Tree-level Higgs boson masses are determined by $\tan\beta, M_{H^\pm}, v_s, \lambda, \kappa, A_\kappa$
- Loop-corrected Higgs mass matrices

$$M^2(p^2) = \begin{pmatrix} m_{h_1}^2 - \hat{\Sigma}_{h_1h_1} & -\hat{\Sigma}_{h_1h_2} & -\hat{\Sigma}_{h_1h_3} & -\hat{\Sigma}_{h_1h_4} & -\hat{\Sigma}_{h_1h_5} \\ -\hat{\Sigma}_{h_2h_1} & m_{h_2}^2 - \hat{\Sigma}_{h_2h_2} & -\hat{\Sigma}_{h_2h_3} & -\hat{\Sigma}_{h_2h_4} & -\hat{\Sigma}_{h_2,h_5} \\ -\hat{\Sigma}_{h_3h_1} & -\hat{\Sigma}_{h_3h_2} & m_{h_3}^2 - \hat{\Sigma}_{h_3h_3} & -\hat{\Sigma}_{h_3h_4} & -\hat{\Sigma}_{h_3h_5} \\ -\hat{\Sigma}_{h_4h_1} & -\hat{\Sigma}_{h_4h_2} & -\hat{\Sigma}_{h_4h_3} & m_{h_4}^2 - \hat{\Sigma}_{h_4h_4} & -\hat{\Sigma}_{h_4h_5} \\ -\hat{\Sigma}_{h_5h_1} & -\hat{\Sigma}_{h_5h_2} & -\hat{\Sigma}_{h_5h_3} & -\hat{\Sigma}_{h_5h_4} & m_{h_5}^2 - \hat{\Sigma}_{h_5h_5} \end{pmatrix},$$

  - $\hat{\Sigma}_{h_ih_j}(p^2)$ is renormalized self-energy of $h_i \to h_j$ transition

$$\hat{\Sigma}_{h_ih_j}(p^2) = \hat{\Sigma}^{(\alpha)}_{h_ih_j}(p^2) + \hat{\Sigma}^{(\alpha_s\alpha_t)}_{h_ih_j}(0) + \hat{\Sigma}^{(\alpha_t^2+\alpha_t\alpha_\lambda)}_{h_ih_j}(0)$$

  - Iterative method is used to evaluate complex poles

- Loop corrected Higgs boson masses : corrections are sizable

$$M_{H_i}^2 = M_{h_i}^2(\text{tree}) + \Delta M_{H_i}^2(\text{loop})$$

- Loop corrected Higgs boson mixing: $H_i = \mathbf{Z}^{\mathbf{S}}_{\mathbf{ik}} h_k$

  $p^2 \neq M_{H_i}^2$, **Z** not unitary, will be used in decay processes.

  $p^2 = 0$, **Z** is an orthogonal matrix and identical to the rotation matrix

- In all computer codes which compute loop-correctd Higgs masses, one uses approximation

$$\hat{\Sigma}^h_{ij}(p^2) = \hat{\Sigma}^h_{ij}(\mathrm{Re}\,p^2) + i\mathrm{Im}\,p^2 \frac{\partial \hat{\Sigma}^h_{ij}(\mathrm{Re}\,p^2)}{\partial \mathrm{Re}\,p^2}.$$

to take into account contribution from imaginary part of complex momentum. New version NMSSMCALC: we implemented one-loop two-point function with complex monentum (real masses).

Avoid threshold singularity
Improve stability, convergence

- We are computing the dominant EW corrections of order $\alpha_t^2 + \alpha_t\alpha_\lambda$ in NMSSM with complex phases. NOT YET FINISHED!

$$\hat{\Sigma}_{h_i h_j}(p^2) = \hat{\Sigma}^{(\alpha)}_{h_i h_j}(p^2) + \hat{\Sigma}^{(\alpha_s\alpha_t)}_{h_i h_j}(0) + \hat{\Sigma}^{(\alpha_t^2+\alpha_t\alpha_\lambda)}_{h_i h_j}(0)$$

The new correction is expected to increase the SM-like Higgs boson mass by about 5 GeV.

Higgs boson decays in NMSSMCALC

Γ in NMSSMCALC-2.0 Γ improvements in new version NMSSMCALC

1. Decay into SM fermionic pairs: $H_i \to t\bar{t}, b\bar{b}, c\bar{c}, s\bar{s}, \tau\bar{\tau}, \mu\bar{\mu}$

$$\Gamma_{tree} + \Gamma_{NLO}^{SMQCD} + \Gamma_{NLO}^{SUSYQCD,EW} + \Gamma_{N^2/N^3LO}^{SMQCD}$$

2. Decay into gluons: loop-induced process

$$\Gamma_{1Loop}^{QCD} + \Gamma_{2loop}^{SMQCD} + \Gamma_{3loop}^{SMQCD} + \Gamma_{4loop}^{SMQCD}$$

3. Decay into a pair of photons: loop-induced process

$$\Gamma_{1Loop} + \Gamma_{2loop}^{SMQCD}$$

4. Decay into ZZ, W^+W^-: $\Gamma_{tree} + \Gamma_{1Loop}^{EW}$
5. Decay into $Z\gamma$, a gauge and a Higgs boson: loop-induced process Γ_{1Loop}
6. Decay into H_iZ: $\Gamma_{tree} + \Gamma_{1Loop}^{EW}$
7. Decay into H_iH_j: $\Gamma_{tree} + \Gamma_{1Loop}^{EW}$
8. Decay into neutralino pairs: $\Gamma_{tree} + \Gamma_{1Loop}^{EW}$
9. Decay into chargino pairs: $\Gamma_{tree} + \Gamma_{1Loop}^{EW}$
10. Decay into a squark pair, slepton pairs: $\Gamma_{tree} + \Gamma_{1Loop}^{EW/QCD}$

Renormalization

Renormalization of Higgs sector

Option I

$$\underbrace{t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}, e, M_W^2, M_Z^2, M_{H^\pm}^2}_{\text{on-shell scheme}}, \underbrace{\tan\beta, v_S, |\lambda|, |\kappa|, \mathrm{Re}\, A_\kappa}_{\overline{\text{DR}}\text{ scheme}}$$

Option II

$$\underbrace{t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}, e, M_W^2, M_Z^2}_{\text{on-shell scheme}}, \underbrace{\tan\beta, v_S, |\lambda|, |\kappa|, \mathrm{Re}\, A_\lambda, \mathrm{Re}\, A_\kappa}_{\overline{\text{DR}}\text{ scheme}}$$

Renormalization of neutralino/chargino sector

five neutralinos $m_{\chi_1}, m_{\chi_2}, m_{\chi_3}, m_{\chi_4}, m_{\chi_5}$, two charginos $m_{\chi_1^\pm}, m_{\chi_2^\pm}$ receive loop corrections NEW!

$$\underbrace{M_W, M_Z, \tan\beta, v_S, |\lambda|, |\kappa|}_{\text{as in Higgs sector}}, \quad \underbrace{|M_1|, |M_2|}_{\overline{\text{DR}}\text{ or OS scheme}}$$

Renormalization of squark sector

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ receive loop corrections NEW!

$$\underbrace{M_W, M_Z, \tan\beta, v_S, |\lambda|}_{\text{as in Higgs sector}}, \underbrace{m_b, m_t, m_{\tilde{Q}_3}^2, m_{\tilde{t}_R}^2, m_{\tilde{b}_R}^2, A_t, A_b}_{\overline{\text{DR}}\text{ or OS scheme}}$$

Complex phases $\phi_u, \phi_s, \phi_\kappa, \phi_\lambda, \phi_{M_1}, \phi_{M_2}$ do not need to be renormalized.

Decay into SM fermion pairs: $H_i \to t\bar{t}, b\bar{b}, c\bar{c}, s\bar{s}, \tau\bar{\tau}, \mu\bar{\mu}$

$-\frac{im_f}{v}\left[\tilde{g}^S_{h_i f\bar{f}} - i\gamma_5 \tilde{g}^P_{h_i f\bar{f}}\right]$

$\Delta^{S/P}_{\text{QCD}} = 1 + \frac{17}{3}\frac{\alpha_s(M^2_{H_i})}{\pi} + \mathcal{O}(\alpha_s^2 + \alpha_s^3 + \alpha_t^2)$

$\Delta^{S/P}_{\text{QED}} = 1 + \frac{\alpha}{\pi} Q_f^2 \left(\frac{9}{4} - 3\log\frac{m_f^2}{M^2_{H_i}}\right)$

$$\Gamma_{H_i \to f\bar{f}} = \frac{3 G_F M_{H_i}}{4\sqrt{2}\pi}\,\overline{m}_f^2(M_{H_i}) \times \Big[(1-4x_b)^{3/2}\,\Delta^S_{\text{QCD}}\Delta^S_{\text{QED}}\Gamma^S_{H_i\to f\bar{f}} + (1-4x_b)^{1/2}\,\Delta^P_{\text{QCD}}\Delta^P_{\text{QED}}\Gamma^P_{H_i\to f\bar{f}}\Big]$$

$$\Gamma^{S/P}_{H_i\to f\bar{f}} = \left(\sum_{j=1}^{5} \mathbf{Z}^H{}_{ij}\tilde{g}^{S/P}_{h_j f\bar{f}}\right)\left(\sum_{k=1}^{5} \mathbf{Z}^H{}_{ik}\tilde{g}^{S/P}_{h_k f\bar{f}}\right)^* + 2\mathrm{Re}\left[\left(\sum_{j=1}^{5} \mathbf{Z}^H{}_{ij}\tilde{g}^{S/P}_{h_j f\bar{f}}\right)\left(\sum_{k=1}^{5} \mathbf{Z}^H_{ik}\,\delta\mathcal{M}^{rem,S/P}(h_k\to f\bar{f})\right)^*\right] + 2\mathrm{Re}\left[\left(\sum_{j=1}^{5} \mathbf{Z}^H{}_{ij}\tilde{g}^{S/P}_{h_j f\bar{f}}\right)\left(\sum_{k=1}^{5} \mathbf{Z}^H{}_{ik}\,\delta^{S/P}_{sub}(h_k\to f\bar{f})\right)^*\right]$$

One-loop SUSY-EW and SUSY-QCD corrections are included in $\delta\mathcal{M}^{rem,S}(h_k\to f\bar{f})$. Large correction proportional to $\tan\beta$ is resummed into $\tilde{g}^S_{h_j f\bar{f}}$. We need to subtract $\delta^S_{sub}(h_k\to f\bar{f})$ in one-loop amplitude the part which are already resummed

Loop correction for Higgs decay into squark pairs

Decay into squark pairs: $H_i \to \tilde{q}_j{}^* q_k$

$$\Gamma(H_i \to \tilde{q}_j \tilde{q}_k^*) = \Gamma^{\rm tree}(H_i \to \tilde{q}_j \tilde{q}_k^*) + \Gamma^{(1)}_{QCD} + \Gamma^{(1)}_{EW}.$$

$$\Gamma^{(1)}_{QCD/EW} = \Gamma^{virt}_{QDC/EW}(H_i \to \tilde{q}_j \tilde{q}_k^*) + \Gamma^{real}_{QDC/EW}(H_i \to \tilde{q}_j \tilde{q}_k^* g\gamma).$$

QCD correction

$$\Gamma^{virt}_{QCD} = N_F R_2 2\mathrm{Re}\left[\mathcal{M}^{0*}_{H_i \tilde{q}_j \tilde{q}_k^*}\left(\sum_{i'=1}^{5} \mathbf{Z}^H{}_{ii'}(\mathcal{M}^{\Delta,QCD}_{h_{i'}\tilde{q}_j\tilde{q}_k^*} + \mathcal{M}^{Cterm,QCD}_{h_{i'}\tilde{q}_j\tilde{q}_k^*})\right)\right].$$

EW correction

$$\Gamma^{virt}_{EW} = N_F R_2 2\mathrm{Re}\left[\mathcal{M}^{0*}_{H_i \tilde{q}_j \tilde{q}_k^*}\sum_{i'=1}^{5} \mathbf{Z}^H{}_{ii'}\left(\mathcal{M}^{\Delta,EW}_{h_{i'}\tilde{q}_j\tilde{q}_k^*} + \mathcal{M}^{Cterm,EW}_{h_{i'}\tilde{q}_j\tilde{q}_k^*} + \mathcal{M}^{GZ,mix}_{h_{i'}\tilde{q}_j\tilde{q}_k^*}\right)\right].$$

Real photon/gluon radiation

I_{ij} are bremstrahlung integrals

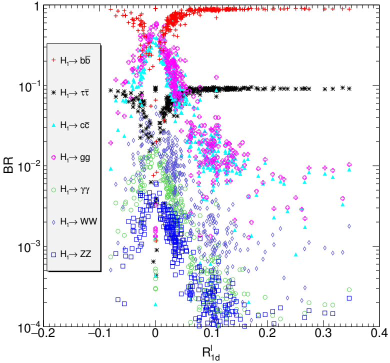
$$\Gamma^{real}_{EW}(H_i \to \tilde{q}_j \tilde{q}_k \gamma) = \frac{N_F}{4\pi^2 M_{H_i}} Q_q^2 \alpha\Big(-I_1 - I_2 - M^2_{\tilde{q}_j} I_{11} - M^2_{\tilde{q}_k} I_{22} + (M^2_{H_i} - M^2_{\tilde{q}_j} - M^2_{\tilde{q}_k}) I_{12}\Big)|\mathcal{M}^0_{H_i\tilde{q}_j\tilde{q}_k^*}|^2.$$

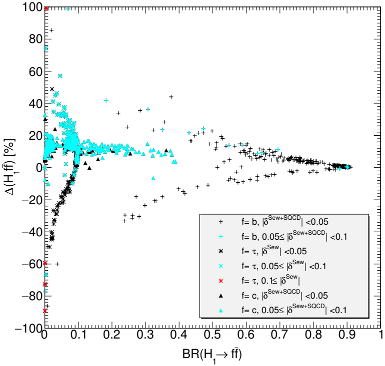
we have implemented both OS and $\overline{\rm DR}$ schemes

Numerical analysis: inputs and constraints

- SM parameters and soft SUSY breaking parameters are given at a given SUSY scale, using SLHA convention. Renormalization scale is chosen to be the SUSY scale, by default
$$\mu_R = M_s = \sqrt{m_{\tilde{Q}_3} m_{\tilde{t}_R}}$$
- Using NMSSMCALC to compute effective couplings of the Higgs bosons, normalized to the corresponding SM values, as well as the masses, the widths and the branching ratios of the Higgs bosons.
- We choose the scenarios which are in accordance with the LHC Higgs data by using the programs HiggsBounds and HiggsSignals
$$124 \text{ GeV} \leq M_{H_{\rm SM}} \leq 127 \text{ GeV}.$$
- The resulting supersymmetric particle spectrum is in accordance with present LHC searches for SUSY particles

The lightest Higgs boson is a singlet-like state (most of cases h_s-like)
[Preliminary]





$$\Delta(H_i q\bar{q}) = \frac{\mathrm{BR}^{SEW+SQCD}_{\mathbf{Z}^H}(H_i \to q\bar{q}) - \mathrm{BR}^{\mathrm{tree}}_{R^l}(H_i \to q\bar{q})}{\max(\mathrm{BR}^{SEW+SQCD}_{\mathbf{Z}^H}(H_i \to q\bar{q}), \mathrm{BR}^{\mathrm{tree}}_{R^l}(H_i \to q\bar{q}))}.$$

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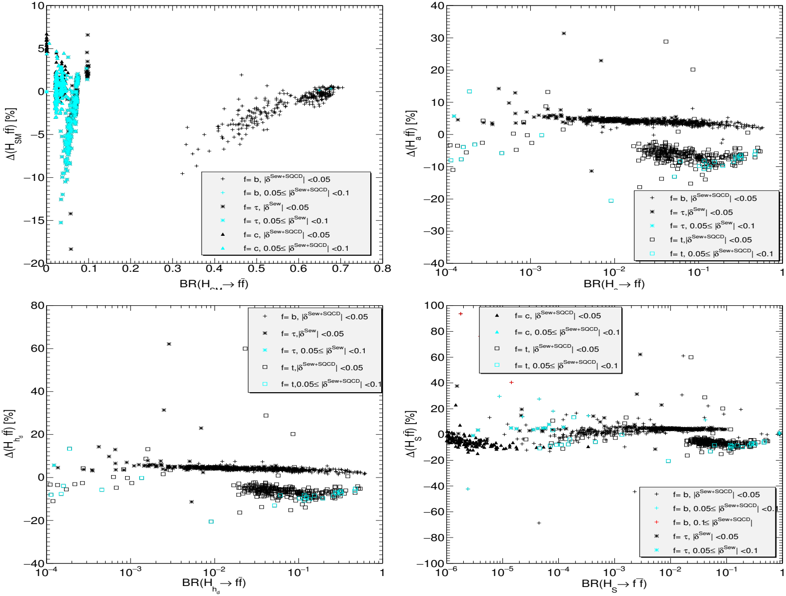


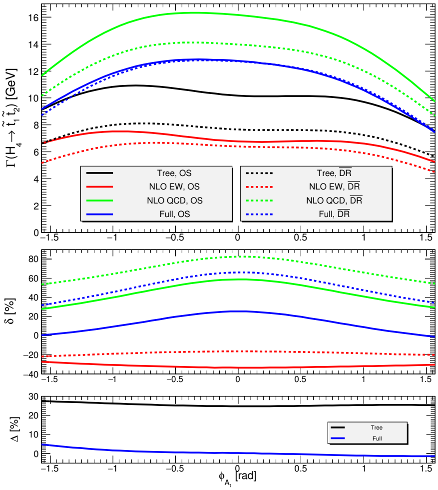
$H_i \to \tilde{q}_j^* q_k$ has been computed in Baglio et. al. JHEP 10, 024 (2015) in real NMSSM. We extended the calculation to the complex case. We investigate both $\overline{\text{DR}}$ and OS schemes.

[Preliminary]

$$\delta = \frac{(X^{\text{NLO EW/NLO QCD}} - X^{\text{Tree}})}{X^{\text{Tree}}}$$

$$\Delta = \frac{(X^{\text{OS}} - X^{\overline{\text{DR}}})}{X^{\text{OS}}}.$$

$M_{H_4} = 1027$ GeV,
$M_{\tilde{t}_1}^{\overline{\text{DR}},tree} = 399$ GeV, $M_{\tilde{t}_1}^{\overline{\text{DR}},1L} = 296$ GeV,
$M_{\tilde{t}_1}^{OS} = 282$ GeV,
$M_{\tilde{t}_2}^{\overline{\text{DR}},tree} = 725$ GeV, $M_{\tilde{t}_2}^{\overline{\text{DR}},1L} = 689$ GeV,
$M_{\tilde{t}_2}^{OS} = 699$ GeV



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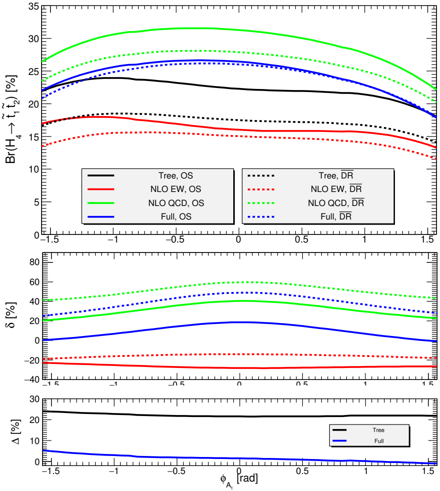

Conclusions

- We have improved the stability, convergence of the Higgs mass evaluation by using one-loop two point functions with complex momentum (real masses)
- We computed EW/QCD corrections for decays of neutral Higgs bosons to $f\bar{f}$, W^+W^-, ZZ, H_iZ, $\chi_i\chi_j$, $\chi_i^+\chi_j^-$ and $\tilde{q}_i\tilde{q}_j$.
- These improvements have been implemented in new version of NMSSMCALC which will be published soon.