Trilinear Higgs self-coupling in supersymmetric models

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Outline

One of the potential discoveries at the HL-LHC could be the discovery of Higgs pair production. This process depends on Higgs self-interactions. Today I will discuss

- when will the Higgs self-coupling in SUSY look like that of the SM
- when and how can the Higgs self-coupling deviate from its SM value
- what are the implications for Higgs pair production

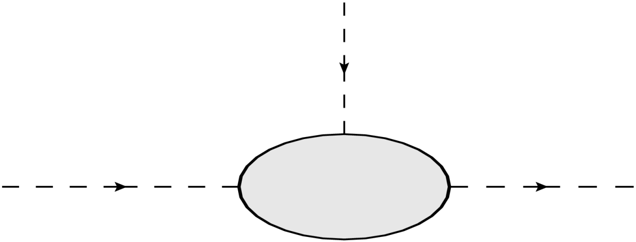
This talk is based on work in progress together with Stefano Moretti, Luca Panizzi and Jörgen Sjölin.

Assumptions

I'll be considering only SUSY models — we are in a SUSY conference after all — but some of the ideas can obviously be generalized. In the following I shall assume

- The doublet components of the Higgs are at the exact alignment limit, mixing with other Higgs states is possible
  - the deviations from alignment are small anyways
- The 125 GeV Higgs is the lightest doublet state
  - lighter singlet-dominated states are allowed, though

The Higgs self-coupling is related to its mass



- In the SM the Higgs self-coupling is known, once the mass and VEV are measured: $\lambda = m_h^2/2v^2$, where $v = 246$ GeV
- Even in BSM theories the Higgs self-couplings are related to its mass as the diagrams are corrections to the mass (at zero incoming momentum) if the additional legs are replaced with the VEV
- A lot of the possibilities to deviate from the SM self-coupling are related to how the Higgs mass is generated

In the the MSSM self-coupling is SM-like

- At tree-level the MSSM Higgs self-coupling is a combination of gauge couplings and is always too small to give a 125 GeV Higgs
- Hence positive loop corrections are necessary and the most economical way is to use the largest coupling available, the top Yukawa
- To maximize the Higgs mass one needs to make sure that the SM-like state is mostly H_u^0, that the cancellation between top and stop loops is incomplete and to find the part of parameter space that maximizes the effect of loops
- This leads to a large value of $\tan\beta$, large stop masses and large stop mixing, respectively, the well-known recipe for a 125 GeV Higgs
- In this limit the only relevant term for Higgs mass generation is $\lambda_{eff}|H_u^0|^4$, like in the SM and hence $\lambda_{eff} \simeq \lambda_{SM}$ [Osland, Pandita, hep-ph/9806351, Djouadi et al. hep-ph/9903229, Hollik, Penaranda hep-ph/0108245. . .]

Interlude: the structure of the MSSM Higgs mass matrix

The CP-even Higgs mass matrix in the MSSM is of the form

$$m_H^2 = \begin{pmatrix} m_{uu}^2 & m_{ud}^2 \\ m_{ud}^2 & m_{dd}^2 \end{pmatrix}$$

- The contributions from the bilinear $H_u H_d$ term always have a structure that leads to a zero determinant and do not affect the smaller eigenvalue
- Terms of the form H_u^2 and H_d^2 do not give a contribution to m_{uu}^2 or m_{dd}^2 as they get eliminated by the tadpole equations
- Only quartic (or cubic, but they are not relevant for doublet fields) terms lead to a contribution that survives in m_{uu}^2 or m_{dd}^2 and contributes to the smaller eigenvalue
- The relevant terms in m_{ud}^2 arise from $|H_u|^2|H_d|^2$, which has a negative coefficient in the MSSM; in general off-diagonal terms push the smaller eigenvalue down

Deviations from the SM: NMSSM with singlet decoupled

- In the NMSSM at low $\tan\beta$ the extra term $\lambda S H_u H_d$ can give a tree-level contribution to the lightest Higgs mass
- This is because $|\lambda|^2 |H_u|^2 |H_d|^2$ comes with an opposite sign compared to the MSSM and the off-diagonal term becomes smaller, hence allowing a larger smallest eigenvalue
- The contribution from quartic terms to the mass gets a factor 4×3, while terms of the type $|S_1|^2 |S_2|^2$ gets a factor 2×2 — the contribution to the trilinear self-interactions is equal, as long as there is a significant overlap between both scalars and the SM-like Higgs
- Hence the term $|\lambda|^2 |H_u|^2 |H_d|^2$ can cause a deviation in the trilinear Higgs coupling, if $\tan\beta$ is at most moderate
- In order to achieve a 125 GeV Higgs with low or moderate values of $\tan\beta$, λ needs to be large and hence the trilinear self-coupling is larger than in the SM — has been seen in numerical scans, *e.g.* [Wu et al., 1504.06392]

Deviations from the SM: NMSSM when singlet not decoupled

When the singlet is not decoupled, it can mix with the doublets and this results in two additional contributions:

- Superpotential terms of the form $|\lambda|^2(|H_u|^2 + |H_d|^2)|S|^2$ lead to new off-diagonal contributions to the mass matrix and to the self coupling
- The soft trilinear interaction $A_\lambda S H_u H_d$ can contribute to the trilinear self coupling

These contributions can lead to both larger and smaller trilinear couplings, but all contributions are proportional to singlet-doublet mixing, which leads to an universal suppression of Higgs signal strengths $\Rightarrow$ only limited deviations possible any more

Deviations from the SM: hyperchargeless triplet

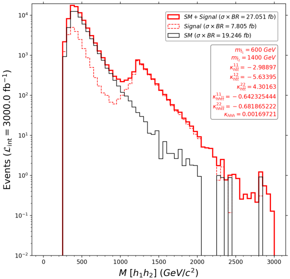
The superpotential is $W = W_{MSSM} + \lambda H_u T H_d + \mu_T \mathrm{Tr}(T^2)$.
Four sources for deviations:

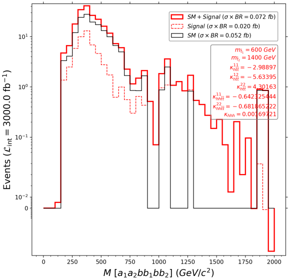
1. Like in the NMSSM the $|\lambda|^2|H_u|^2|H_d|^2$ in the scalar potential with similar effects
2. Trilinear scalar couplings from the μ-term, of the form $\mu\lambda(H_u^2 + H_d^2)T$
3. Trilinear scalar couplings from $\mu_T \lambda H_u H_d T$, these also lead to mixing between doublets and triplet $\Rightarrow$ decoupling only with small λ ($\Rightarrow$ SM-like couplings)
4. Soft SUSY breaking trilinear coupling $A_\lambda H_u T H_d$

- Overall (if $\tan\beta$ not very close to 1) largest effect from μ-term, because of $\mu\lambda H_u^2 T$ structure, *sign*(μ) determines the sign of $\Delta\lambda_{hhh}$
- Almost always large deviations of λ_{hhh} lead to a too large $h \to \gamma\gamma$ rate

Implications for Higgs pair production

Higgs pair production in SUSY is not only about the change in λ_{hhh}!





1. Changes in λ_{hhh} are most clearly seen in low m_{hh}, $bb\gamma\gamma$ most sensitive
2. Light stops can change the overall cross section by $\sim 40\%$, seen throughout the m_{hh}
3. Around $2m(\tilde{t})$ resonant features possible

Remarks on di-Higgs production

- A simple κ_λ interpretation of Higgs pair production in SUSY may lead to incorrect conclusions, deviations from stop loops can be more important
- Stop effects visible even with arbitrarily small mass splittings, though maybe not the ideal way to search for stops
- Stops beyond 1 TeV lead to too small deviations to be detected with current energies

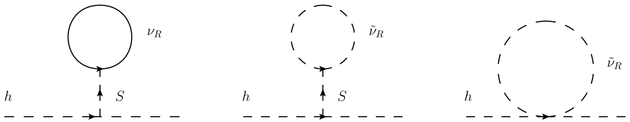
Summary

- Trilinear Higgs coupling in the MSSM always SM-like, in all SUSY models there is a SM-like limit
- Higgs extensions can lead to deviations in λ_{hhh} even if extra states are decoupled
- Smaller λ_{hhh} needs other states to mix with the SM-like Higgs, deviations in Higgs properties should reveal this
- Higgs pair production in SUSY can deviate through λ_{hhh}, but stop effects usually larger

What about other models?

Haven't tested any of these numerically yet.

- Type-II seesaw has terms $\lambda_1 H_u \Delta H_u + \lambda_2 H_d \overline{\Delta} H_d$, if triplets decouple, no large deviations to λ_{hhh}, because contributions to mass matrix are quartic
- However $\mu \lambda_1 H_u H_d \Delta$ can lead to some deviations, though smaller than in the model with $Y = 0$ triplets
- In NMSSM with RH neutrinos it is possible to have loop corrections to Higgs mass, where you cannot attach a Higgs leg, but these corrections are too small to be observed



What about other models?

- In gauge extensions haven't yet figured any model that could lead to deviations based on D-terms, of course Higgs content may lead to deviations
- The B-L model was studied recently and as expected no deviations from the SM were found as Higgs isn't charged under B-L [He et al., 2206.04450], some deviations from extra states to *hh* production, though

Would two stops give a larger signal?

In the NMSSM you can have two light stops in the λSUSY region, but the excess does not get amplified, it almost vanishes.