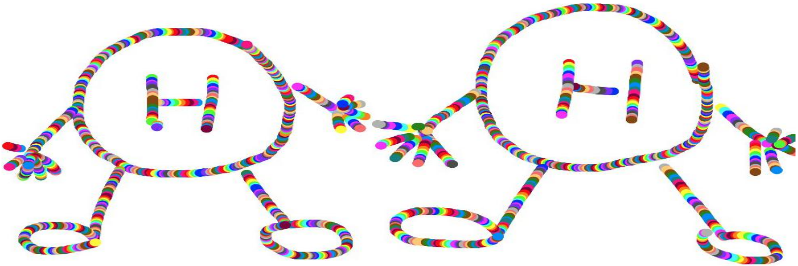
On the Higgs self-coupling modifications

Ramona Gröber, in collaboration with L. Di Luzio and M. Spannowsky [arXiv:1704.02311] | 18/04/2017

IPPP, Durham University

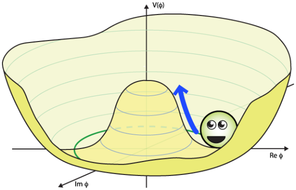


Higgs potential:

$$V(\phi) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

unitary gauge: $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$

$$\Longrightarrow V(H) = \underbrace{\frac{1}{2} m_h^2}_{\mu^2} h^2 + \frac{1}{3!} \lambda_{hhh} h^3 + \frac{1}{4!} \lambda_{hhhh} h^4$$



[quantumdiaries.org]

SM: $\lambda_{hhh}^{\mathrm{SM}} = \frac{3 m_h^2}{v}$ $\lambda_{hhhh}^{\mathrm{SM}} = \frac{3 m_h^2}{v^2}$

- In SM Higgs self-couplings fixed by Higgs mass.
- Trilinear coupling accessible in Higgs pair production.
- Quartic Higgs self-coupling can be neither measured at the LHC nor at ILC/CLIC.

[CLIC Physics working group; Plehn, Rauch '05; Djouadi, Kilian, Mühlleitner, Zerwas '99; Binoth, Karg, Kauer, Rückl '06]

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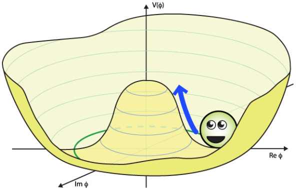

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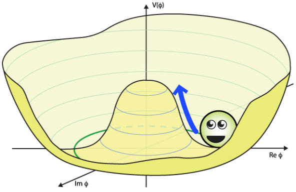

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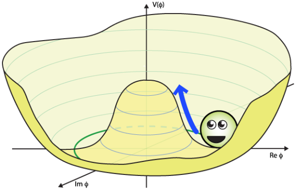

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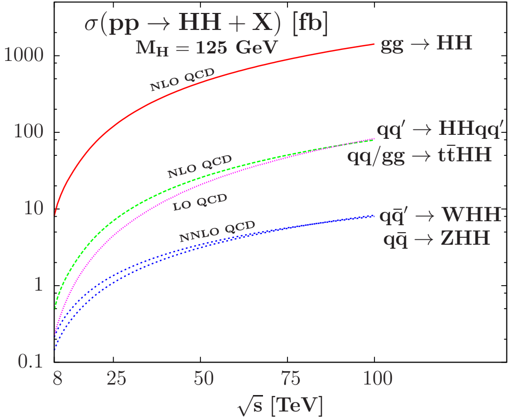
Higgs pair production in the SM

[Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]



- Small cross sections
- Difficult measurement, $b\bar{b}\gamma\gamma$ most promising channel

[Baur, Plehn, Rainwater '03; Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12; Yao '13; Barger, Everett, Jackson, Shaughnessy '13; Azatov, Contino, Panico, Son '15; Lu, Chang, Cheung, Lee '15; Kling, Plehn, Schichtel '16]

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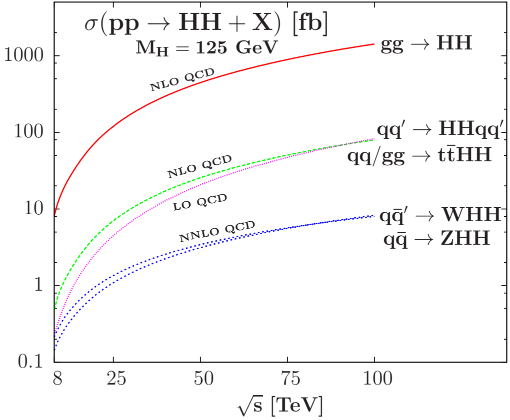

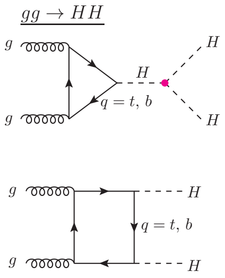

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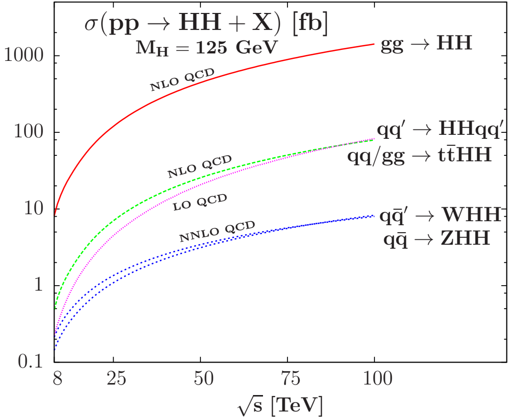

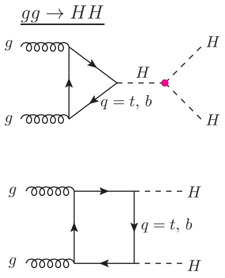

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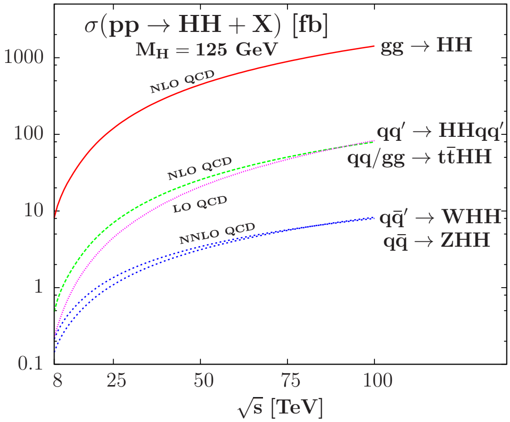

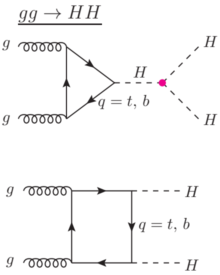

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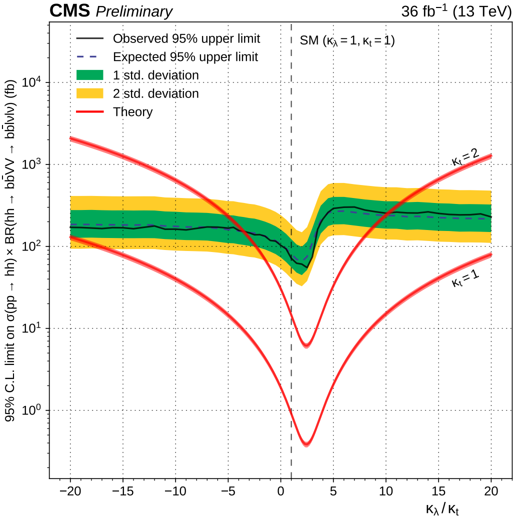
EXPERIMENTAL STATUS

[CMS-PAS-HIG-17-006]

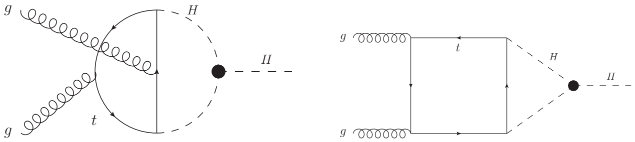


- Experimental measurement difficult, requires high luminosities
- Efforts ongoing, searches in many final states
- Current constraints of $\mathcal{O}(\pm(15-20)\lambda_{hhh}^{\text{SM}})$
  [arXiv:1509.0467; arXiv:1506.0028; arXiv:1603.0689; ATLAS-CONF-2016-049]
- Prospects in $b\bar{b}\gamma\gamma$ final state:

$$-0.8 < \lambda_{hhh}/\lambda_{hhh}^{\text{SM}} < 7.7$$

[ATL-PHYS-PUB-2017-001]

- Single Higgs production
  λ_{hhh} enters in NLO corrections to single Higgs production



Under the assumption of purely a trilinear Higgs self-coupling modification

$$-9.4 < \kappa_\lambda^{2\sigma} < 17$$

[McCullough '14, Gorbahn, Haisch '16, Degrassi, Giardino, Maltoni, Pagani '16, Bizon, Gorbahn, Haisch, Zanderighi '16]
Global analysis, prospects at HL-LHC → see Christophe's talk tomorrow [Di Vita, Grojean, Panico, Rimbau, Vantalon '17]

$$0.1 < \kappa_\lambda^{1\sigma} < 2.3$$

- Electroweak precision tests
  λ_{hhh} enters at 2-loop order

$$-14.0 < \kappa_\lambda^{2\sigma} < 17.4$$

[Degrassi, Fedele, Giardino '17, Kribs, Maier, Rzehak, Spannowsky, Waite '17]

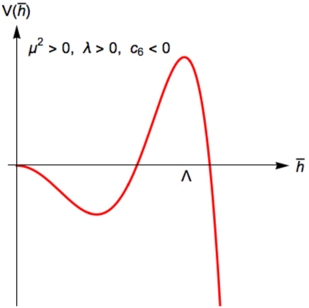
Can the trilinear Higgs self-coupling be bounded by theoretical arguments?

Can the trilinear Higgs self-coupling be bounded by theoretical arguments?

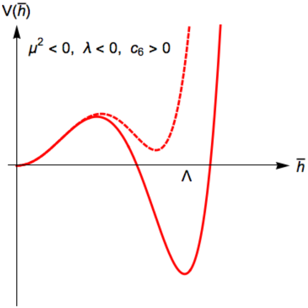
How large can the trilinear Higgs self-coupling be in concrete models?

$$V^{(6)}(H) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{c_6}{v^2} |H|^6 \ ,$$

large field instability



small field instability



$\longrightarrow$ it turns out that we cannot connect the possible instabilities of such a deformed potential to a bound on the trilinear Higgs self-coupling

LARGE FIELD INSTABILITY

Toy model: for a similar argument, see [Burgess, Di Clemente, Espinosa '02]

$$V(h,\phi) = -\frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}M^2\phi^2 + \xi h^3\phi + \kappa h^2\phi^2 + \frac{1}{4}\lambda'\phi^4 \,.$$

Electroweak vacuum absolutely stable if

$$\kappa > 0\,, \quad \wedge \quad \lambda > \frac{\xi^2}{\kappa}\,, \quad \wedge \quad \lambda' > 0\,.$$

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Integrating ϕ out and expanding instead in $M^2 \gg 2\kappa h^2$ leads to

$$V_{\rm EFT}(h) \simeq -\frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 - \frac{1}{2}\frac{\xi^2}{M^2}h^6 + \frac{\xi^2\kappa}{M^4}h^8 + \dots\,.$$

h^6 operator makes potential seem unstable!

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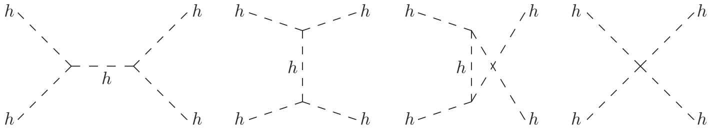
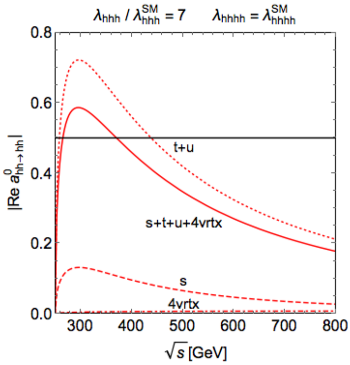
$\longrightarrow$ for a vacuum stability analysis full tower of EFT operators necessary!

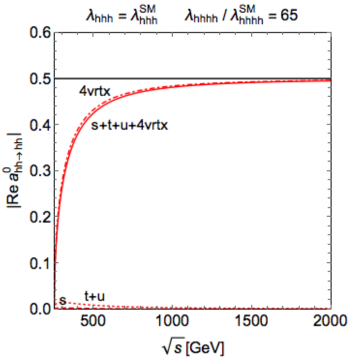
PERTURBATIVITY



Partial wave analysis

$$|\text{Re}\, a^0_{hh\to hh}| < \frac{1}{2}\,,$$





- 4-vertex contribution and $s+t+u$ channel dominate in different kinematical regimes
  $\longrightarrow$ a bound on λ_{hhh} and λ_{hhhh} can be set seperately
- $\left|\lambda_{hhh}/\lambda_{hhh}^{\rm SM}\right| \lesssim 6.5$ and $\left|\lambda_{hhhh}/\lambda_{hhhh}^{\rm SM}\right| \lesssim 65\,.$

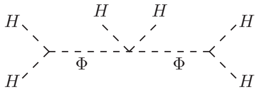
- another criterium: [Di Luzio, Kamenik, Nardecchia '16]
  requirement that loop-corrected vertex < tree-level vertex
- we find $\left|\lambda_{hhh}/\lambda_{hhh}^{\rm SM}\right| \lesssim 6$

Full models

Which models?

In which model we expect the largest shifts in the trilinear Higgs self-couplings?
If there is a tree-level contribution to $\mathcal{L}_6 = \frac{c_6}{\Lambda^2}|H|^6$.

$$\mathcal{L} = HH\Phi \quad \text{or} \quad \mathcal{L} = HHH\Phi$$



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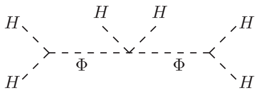

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Φ	$\mathcal{O}$
$(1,1,0)$	$\Phi H H^\dagger$
$(1,3,0)$	$\Phi H H^\dagger$
$(1,3,1)$	$\Phi H^\dagger H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,4,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
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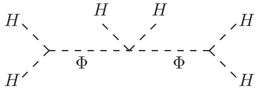

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$$V(H,\Phi) = \mu_1^2|H|^2 + \lambda_1|H|^4 + \frac{1}{2}\mu_2^2\Phi^2 + \mu_4|H|^2\Phi + \frac{1}{2}\lambda_3|H|^2\Phi^2 + \frac{1}{3}\mu_3\Phi^3 + \frac{1}{4}\lambda_2\Phi^4$$

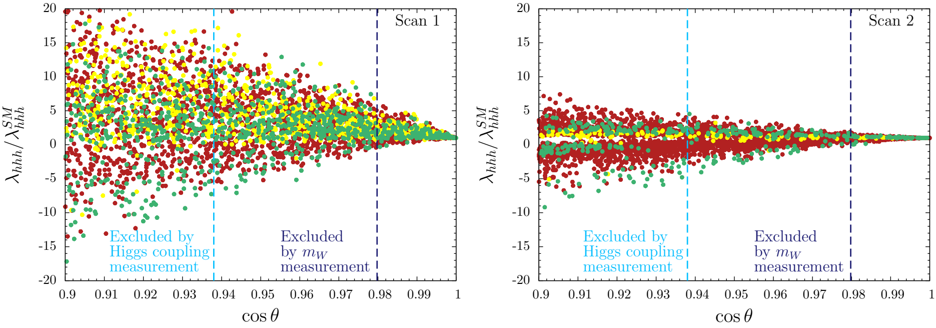
In scan treat parameters for masses, VEVs and mixing angle

$$m_1 = 125\ \text{GeV}, \qquad 800\ \text{GeV} < m_2 < 2000\ \text{GeV},$$
$$v_H = 246.2\ \text{GeV}, \qquad |v_S| < m_2, \qquad 0.9 < \cos\theta < 1\,.$$

$$\text{Scan 1:} \qquad 0 < \lambda_2 < \frac{8}{3}\pi, \qquad |\lambda_3| < 16\pi,$$

$$\text{Scan 2:} \qquad 0 < \lambda_2 < 1/6, \qquad |\lambda_3| < 1,$$

We impose perturbativity, check for vacuum stability with `Vevacious` [Carmargo-Molina, O'Leary, Porod, Staub '13]



Singlet Model allows for deviations in the trilinear Higgs self-coupling of

$$\text{Scan 1:} \quad -1.5 < \lambda_{hhh}/\lambda_{hhh}^{\text{SM}} < 8.7$$

$$\text{Scan 2:} \quad -0.3 < \lambda_{hhh}/\lambda_{hhh}^{\text{SM}} < 2.0$$

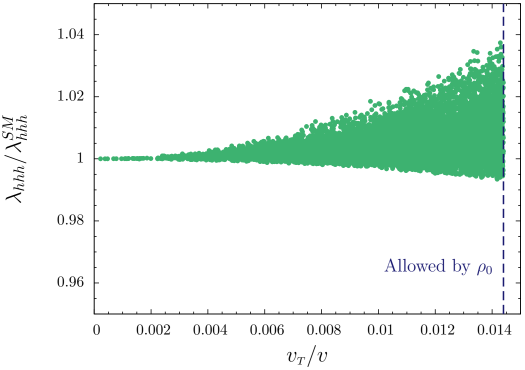
Color code: ew vacuum is stable, metastable, unstable

Exclusion from m_W (Δr) from [Lopez-Val, Robens '14]

Higgs coupling measurement, see [ATLAS, arXiv:1509.00672]

CUSTODIAL VIOLATING: TRIPLET

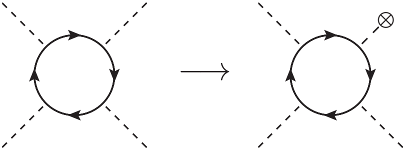
$$V(H,\Phi) = \mu_1^2|H|^2 + \frac{1}{2}\mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \frac{1}{4}\lambda_2\,|\Phi|^4 + \frac{1}{2}\lambda_3|H|^2|\Phi|^2 + \mu_4 H^\dagger\sigma^\alpha H\Phi^\alpha$$



Strongest bound on model from ρ parameter

$$\rho_0^{\text{tree}} = 1 + 4\frac{v_T^2}{v_H^2}$$

If a shift in the trilinear Higgs self-coupling is induced by fermion loops a connection to vacuum stability is re-established



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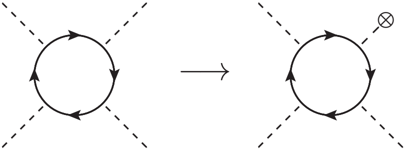
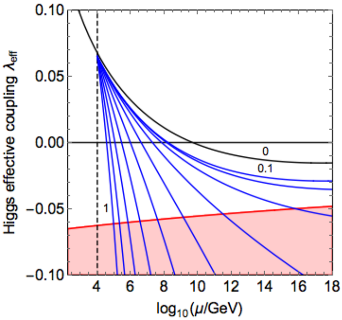


Example:
RH neutrinos inverse seesaw, with common mass scale $M = 10$ TeV and $Y_\nu = |y_\nu| I_3$ trilinear Higgs self-coupling computed in: [Baglio, Weiland '16]
$|y_\nu| = 0.8$ requires already UV completion within a 2 orders of magnitude restricts $\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} < 0.1\%$.



Conclusion

- We investigated theoretical arguments to bound the trilinear Higgs self-coupling
- in EFT and in scalar extensions, no direct connection between trilinear Higgs self-coupling and vacuum stability
- perturbativity arguments $|\lambda_{hhh}/\lambda_{hhh}^{\rm SM}| \lesssim 6$
- a factor of a few modifications of λ_{hhh} in singlet extension still possible (close to the perturbativity limit)
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Thanks for your attention!