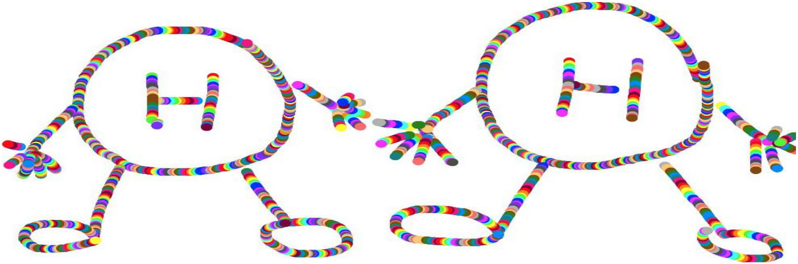
Higgs pair production and the trilinear Higgs self-coupling

Ramona Gröber | 20/09/2017

IPPP, Durham University

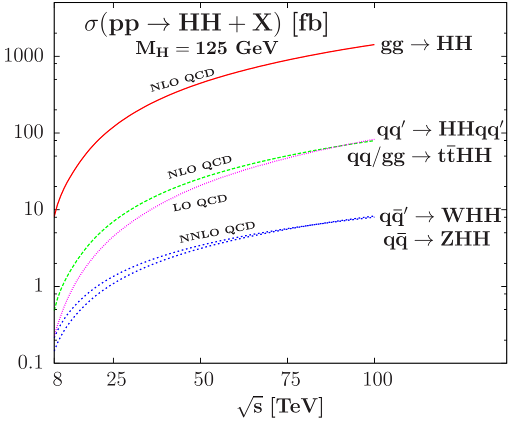


Outline

1. Why?
2. Experimental status
3. Standard Model
4. Beyond the Standard Model
5. trilinear Higgs self-coupling

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

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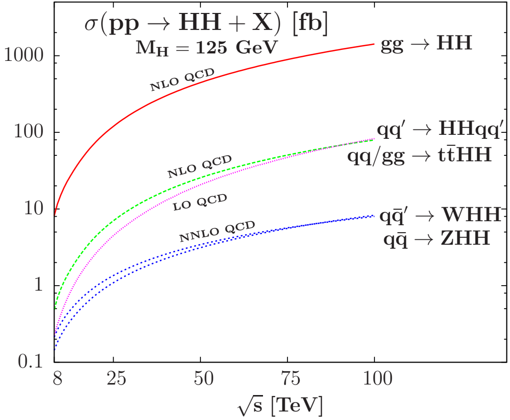

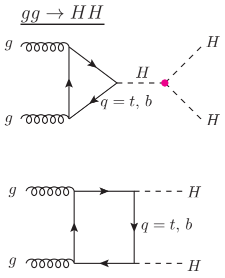

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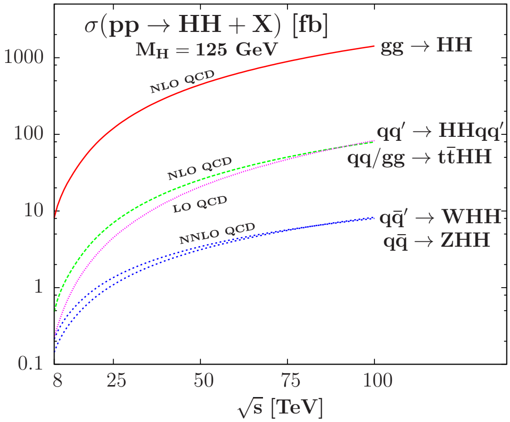

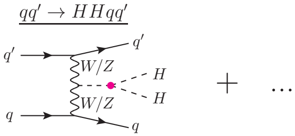

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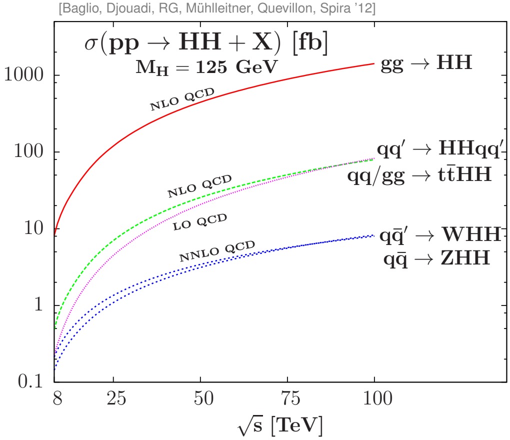

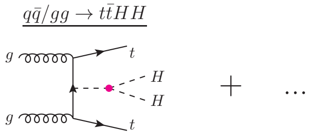

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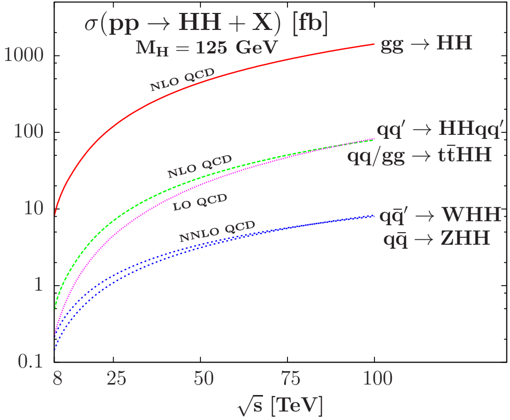
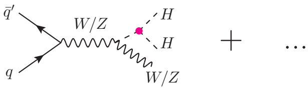


$q\bar{q}' \to ZHH/WHH$



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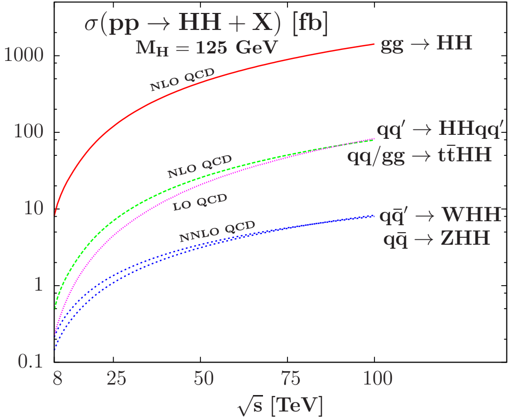

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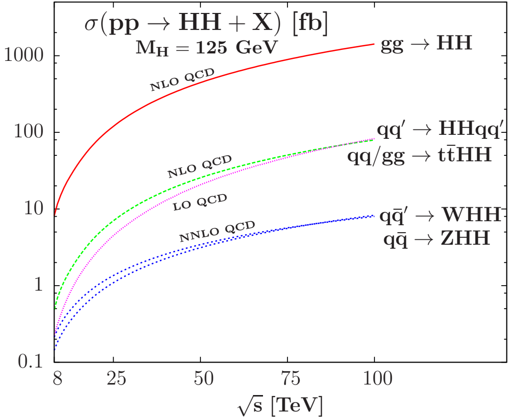

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WHY?

- Measurement of trilinear Higgs coupling.
- Constraining the effective Lagrangian.
  - Higgs couplings to gluons, top Yukawa
  - Resolve degeneracy? I.e. probe additional particles in the loop
- Test if EWSB is linear or nonlinear.
  - $3/2\,(c_t - 1) \neq c_{tt}$?
  - $c_g \neq c_{gg}$?
- Probe resonant production of additional Higgs bosons.

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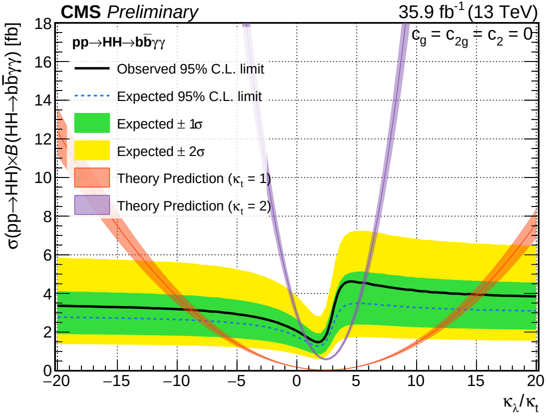
Experimental status

see yesterday's talks by Arnaud and Abdollah

EXPERIMENTAL STATUS

[CMS-PAS-HIG-17-008]



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

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

[ATL-PHYS-PUB-2017-001]

Standard Model

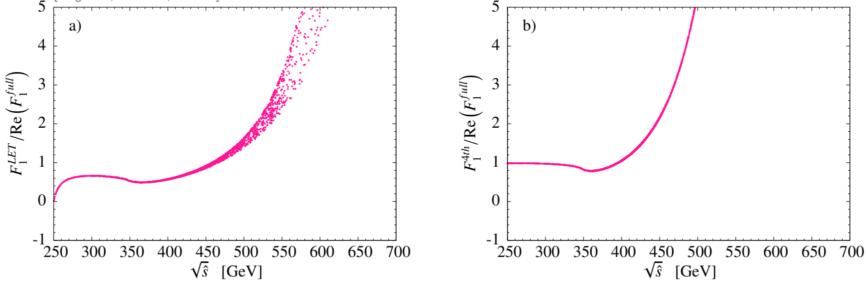
Gluon fusion:

- LO cross section known exactly in full mass dependence [Glover, van der Bij '88; Plehn, Spira, Zerwas '95]
- NLO QCD corrections
  Difficulty: Multi-scale problem m_t^2, $\hat{s}$, $\hat{t}$, $\hat{u}$, m_h^2.
- improved LET: $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$ [Dawson, Dittmaier, Spira '98]
  LET approximation $\rightarrow$ small external momenta $\hat{s}$, $\hat{t}$, $\hat{u}$, $m_h^2 \ll m_t^2$

$$\frac{1}{(p+q_i)^2 - m_t^2} \approx \frac{1}{p^2 - m_t^2}\left(1 + \frac{2p\cdot q_i + q_i^2}{p^2 - m_t^2}\right)$$

At LO, however,

[Degrassi, Giardino, RG '16]



GLUON FUSION: STATUS

- Estimation of finite mass effects: Inclusion of higher orders in large top mass expansion $\mathcal{O}(\pm 10\%)$ [Grigo, Hoff, Melnikov, Steinhauser '13; Grigo, Hoff, Steinhauser '15; Degrassi, Giardino, RG '16]
- Real contributions in full top mass dependence $\rightarrow$ top mass effects $\mathcal{O}(-10\%)$ [Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro '14]
- Full NLO computation $\rightarrow$ top mass effects -14% [Bobrowka, *et al.*'16]

  Caveat: 4680 hours of GPU time!

  Grid of numerical values with interpolation function implemented in `POWHEG` [Heinrich, Jones, Kerner, Luisoni, Vryonidou '17]
- NNLO QCD corrections are of $\mathcal{O}(20\%)$ available only in in expansion in small external momenta [de Florian, Mazzitelli '13; Grigo, Melnikov, Steinhauser '14; Grigo, Hoff, Steinhauser '15; de Florian, Mazzitelli '15; de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16]
- Threshold resummation further increases the result
  - NNLO+ NNLL in large top mass limit [De Florian, Mazzitelli '15]
  - NLL with top quark mass effects [Ferrera, Pires '16]
- Theoretical uncertainty:

  Scale 6%, PDF 2%, α_s 2% [LHC Higgs cross section working group]

- Top quark mass effects are important
- What about NNLO?
- What about similar processes
  - Higgs + jet
  - $gg \to HZ$ (contributes at NNLO to associated production with Z)
  - $gg \to ZZ$ (top loop, contributes at NNLO to ZZ production)

MASS EFFECTS IN GLUON FUSION

- Top quark mass effects are important
- What about NNLO?
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$\to$ Given the full computation of HH we can test new methods

PADÉ APPROXIMATION

Approach:

- Conformal mapping: with $z = \frac{\hat{s}}{4\, m_t^2}$ [Fleischer, Tarasov '94]

$$z = \frac{4\omega}{(1+\omega)^2}$$

- Padé approximant

$$P_{[n/m]}(\omega) = \frac{\sum_{i=0}^{n} a_i \omega^i}{1 + \sum_{j=0}^{m} b_j \omega^j}$$

  $n + m + 1$ conditions needed to fix coefficients a_i, b_j
- Input for Padé:
  5 conditions from large top mass expansion [Degrassi, Giardino, RG '16],
  3 (2) conditions from threshold expansion [RG, Maier, Rauh to appear]
- Padé approximant for rescaled form factor with

$$(1 + a_R z)F$$

  to fix correct high energy behavior
- error estimate by varying a_R and for different n, m

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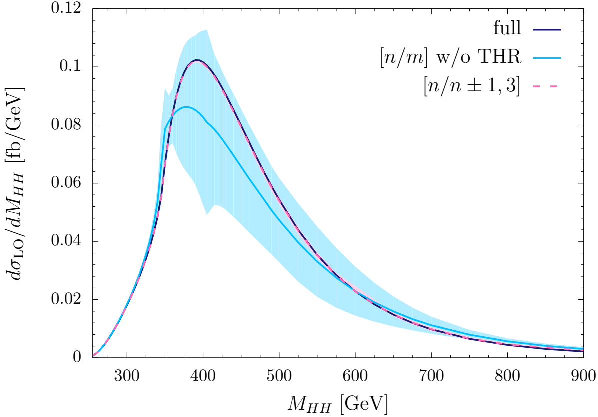
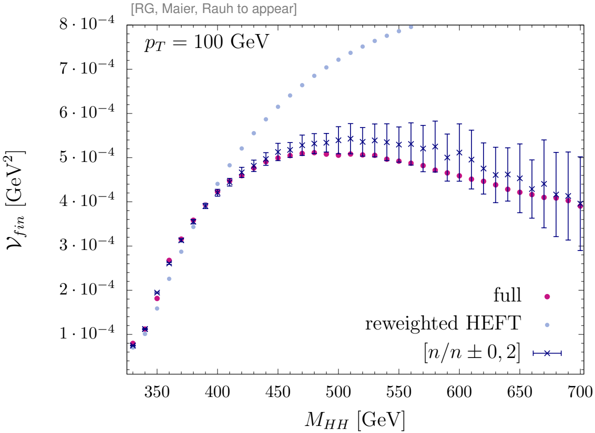


→ with input from threshold expansion: approximation very good

Padé approximation at NLO

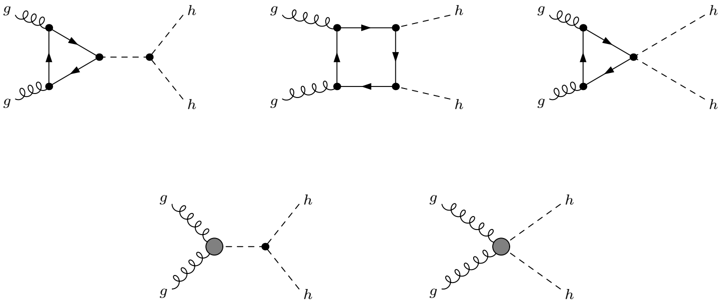


$\rightarrow$ reliable approximation with correct scaling behaviour, full result within error estimate

full virtual corrections from [Heinrich, Jones, Kerner, Luisoni, Vryonidou '17]

Beyond the Standard Model

HH PRODUCTION BEYOND THE STANDARD MODEL



- Resonant production, i.e. in extended Higgs sectors
- modified couplings: λ_{hhh}, top Yukawa
- novel couplings, i.e. in Composite Higgs Models [RG, Mühlleitner '11]
- new particles in the loop, i.e. stops, fermionic top partners

Can we see New Physics for the first time in *HH* production?

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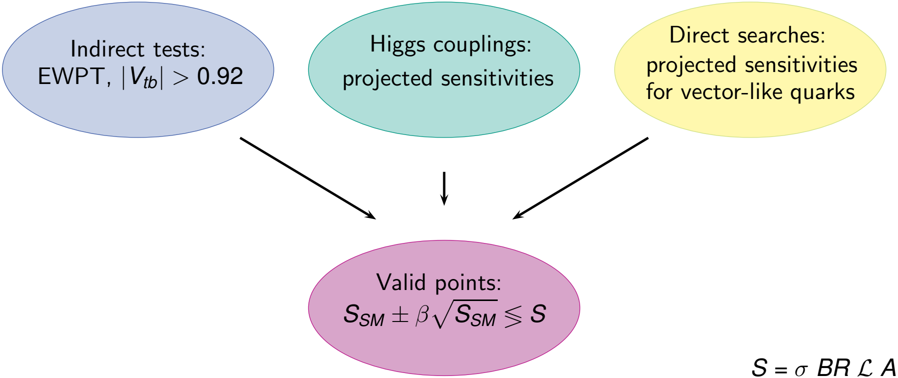
- This question has to be answered in concrete models.
- Obviously for resonant production in *s* channel, with new resonance predominantly decaying to Higgs bosons this will be the case.
- Here other case:
  No *s* channel resonance, just coupling modifications and new couplings
  $\rightarrow$ Composite Higgs Models.



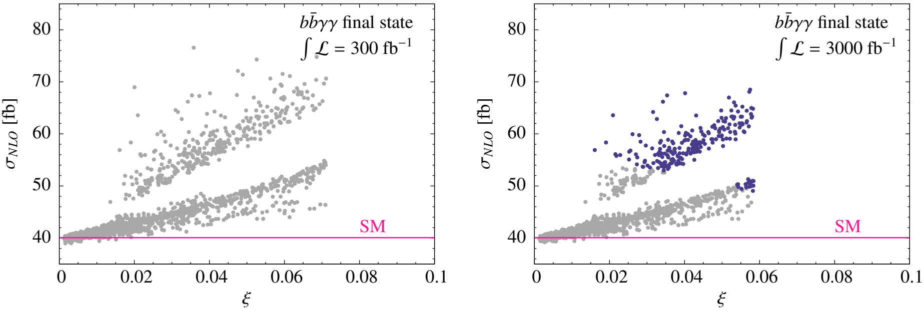
$S = \sigma \, BR \, \mathcal{L} \, A$

Consider two final states: $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$

EWPTs from [Gillioz, RG, Kapuvari, Mühlleitner '14]
Higgs coupling sensitivity from [Englert, Freitas, Mühlleitner et. al'14]
Vector-like quarks, projected sensitivities $m \lesssim 1.5$ TeV

Can New Physics be seen for the first time in *HH* production?

[RG, Mühlleitner, Spira '16]



- Most sensitive final state $b\bar{b}\gamma\gamma$
- For $\mathcal{L} = 3000$ fb^{-1} distinction on 3σ level from SM possible even if we do not see New physics elsewhere first

Grey points: Cannot be distinguished at LHC from SM

Blue points: Can be distinguished only in *HH* from SM

Higher order corrections in BSM in LET available

- singlet extension [Dawson, Lewis '15]
- SUSY-QCD corrections in MSSM and NMSSM [Agostini, Degrassi, RG, Slavich '16] $\rightarrow$ appendix
- dim-6 operators [RG, Mühlleitner, Spira, Streicher '15, NNLO: de Florian, Mazzitelli '17, CP-violation: RG, Mühlleitner, Spira '17]
- Composite Higgs Model [RG, Mühlleitner, Spira '16]
- 2HDM [Hespel, Lopez-Val, Vryonidou '14; RG, Mühlleitner, Spira '17] $\rightarrow$ appendix

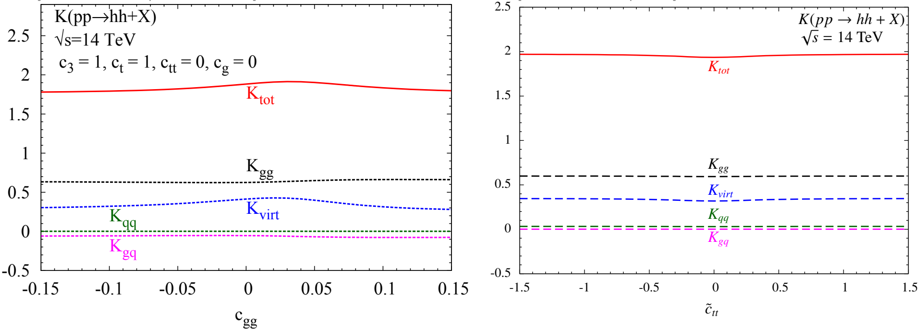
Higher order corrections in BSM

Non-linear effective Lagrangian:

$$\mathcal{L} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \frac{3M_h^2}{v} h^3 + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} G^a_{\mu\nu} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$

$$-i m_t \bar{t} \gamma_5 t \left(\tilde{c}_t \frac{h}{v} + \tilde{c}_{tt} \frac{h^2}{2v^2} \right) + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} \tilde{G}^a_{\mu\nu} \left(\tilde{c}_g \frac{h}{v} + \tilde{c}_{gg} \frac{h^2}{2v^2} \right)$$

[RG, Mühlleitner, Spira, Streicher '15] [RG, Mühlleitner, Spira '17]



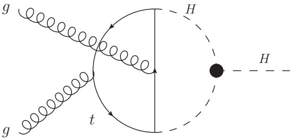
$\Rightarrow$ Effect of dim-6 operatoren on $K = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$ is $\mathcal{O}$(few %)

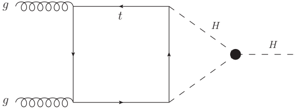
The trilinear Higgs self-coupling

Reminder:

LHC projection: [ATL-PHYS-PUB-2017-001] $-0.8 < \kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} < 7.7$

- **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 [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?

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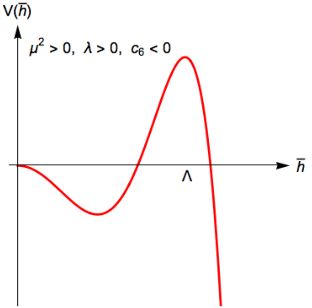
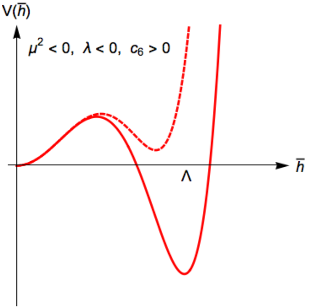
How large can the trilinear Higgs self-coupling be in concrete models?

VACUUM STABILITY

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

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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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

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

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

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

h^6 operator makes potential seem unstable!

LARGE FIELD INSTABILITY

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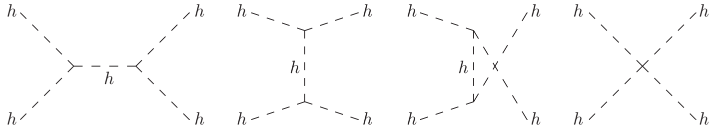
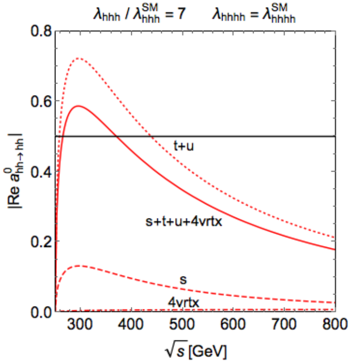
h^6 operator makes potential seem unstable!

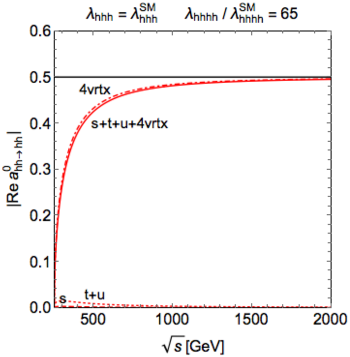
$\longrightarrow$ for a vacuum stability analysis full tower of EFT operators necessary!



Partial wave analysis

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





PERTURBATIVITY

- 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
- $\left|\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}\right| \lesssim 6.5$ and $\left|\lambda_{hhhh}/\lambda_{hhhh}^{\mathrm{SM}}\right| \lesssim 65$.

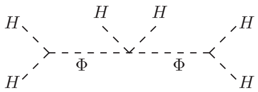
- another criterium: [Di Luzio, Kamenik, Nardecchia '16]
  requirement that loop-corrected vertex < tree-level vertex
- we find $\left|\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}\right| \lesssim 6$

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 $\mathcal{L}_6 = \frac{c_6}{\Lambda^2} |H|^6$.

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



All such scalar extensions can be classified.

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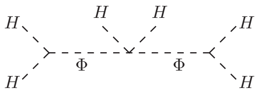

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Φ	$\mathcal{O}$
$(1,1,0)$	$\Phi HH^\dagger$
$(1,3,0)$	$\Phi HH^\dagger$
$(1,3,1)$	$\Phi H^\dagger H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi HH^\dagger H^\dagger$
$(1,4,\frac{1}{2})$	$\Phi HH^\dagger H^\dagger$
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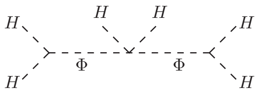

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$$V(H,\Phi) = \mu_1^2|H|^2 + \lambda_1|H|^4 + \frac{1}{2}\mu_2^2\Phi^2 + \mu_4|H|^2\Phi + \frac{1}{2}\lambda_3|H|^2\Phi^2 + \frac{1}{3}\mu_3\Phi^3 + \frac{1}{4}\lambda_2\Phi^4$$

In scan treat parameters for masses, VEVs and mixing angle

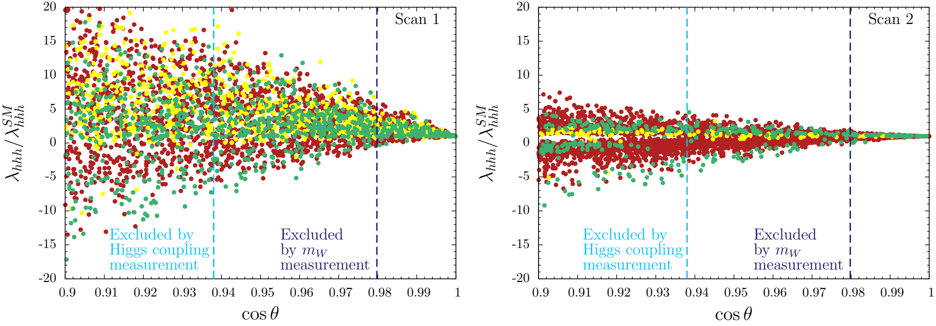
$$m_1 = 125 \text{ GeV}, \qquad 800 \text{ GeV} < m_2 < 2000 \text{ GeV},$$
$$v_H = 246.2 \text{ GeV}, \qquad |v_S| < m_2, \qquad 0.9 < \cos\theta < 1\,.$$

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

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

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

TRILINEAR HIGGS SELF-COUPLING IN SINGLET EXTENSION



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]

- From a measurement of Higgs pair production we can potentially learn a lot about the Higgs boson.
- Experimental and theoretical efforts ongoing.
- Recent results on NLO QCD corrections in full top mass dependence allow to test approximation methods $\rightarrow$ they can be applied to other processes.
- Perturbative range for $|\lambda_{hhh}/\lambda_{hhh}^{\rm SM}|$ not yet tested by *HH* results and indirect methods.

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Thanks for your attention!

MSSM SQCD CORRECTIONS

- Top-loop contributions given in [Dawson, Dittmaier, Spira '98]
- Triangle form factor can be borrowed from single Higgs [Anastasiou et al '06, Aglietti et al '06, Mühlleitner, Spira '06, Bonciani, Degrassi, Vicini '07]
- box form factors for stop contributions need to be computed
  LET approximation:
  NLO form factors (for CP-even Higgs bosons) computed from derivatives of the field-dependent contributions of top and stops in the gluon self-energy at 2-loop

$$\mathcal{M}_{ij} \propto \frac{\partial \Pi_t^g(0)}{\partial H_i \partial H_j}$$

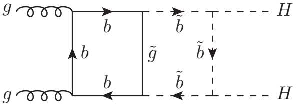
  with

$$m_t = y_t H_u \;, \qquad \sin\theta_{\tilde{t}} = \frac{2y_t(A_t H_u + \mu H_d)}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}} \;,$$

$$m^2_{\tilde{t}_{1/2}} = \frac{1}{2}\left(m^2_{\tilde{Q}_L} + m^2_{\tilde{t}_R} + 2y_t^2 H_u^2 \pm \sqrt{(m^2_{\tilde{Q}_L} - m^2_{\tilde{t}_R})^2 + 4y_t^2(A_t H_u + \mu H_d)^2}\right)$$

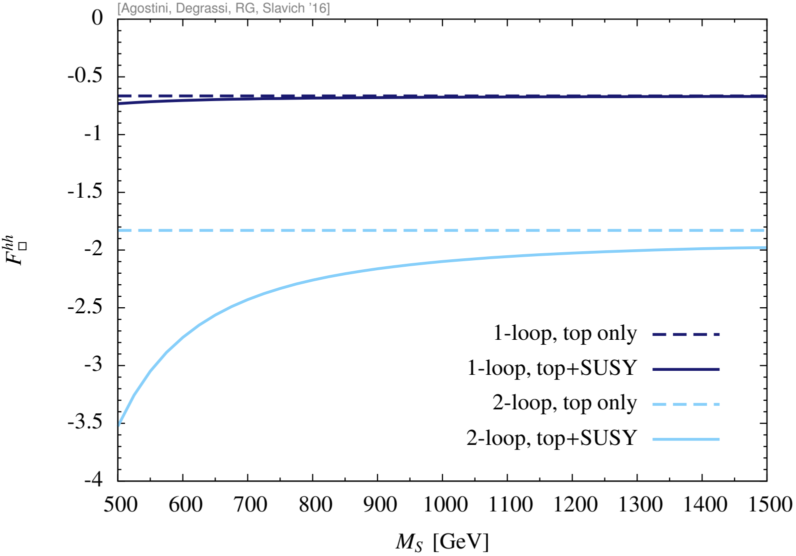
- Validity: $\hat{s}, \hat{t}, \hat{u}, m_H^2 \ll m^2_{loop}$

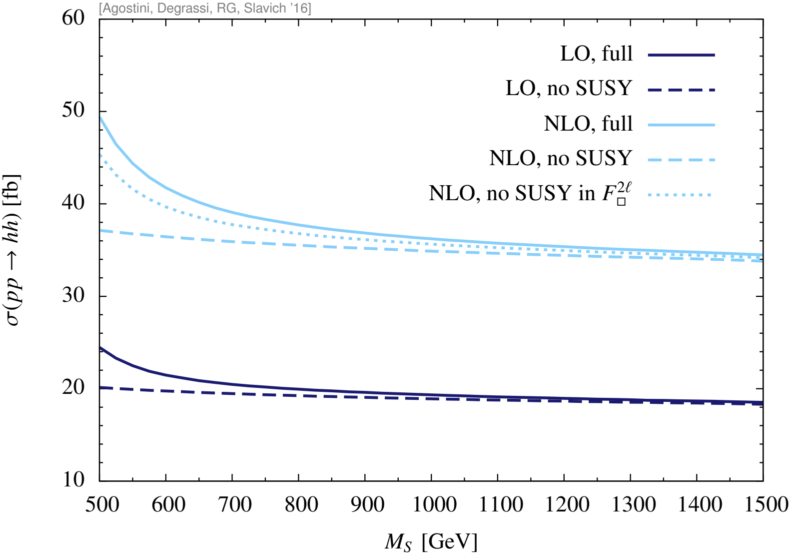
- For $m_b = 0$, contribute only via D-terms.
- Cannot be computed via LET since there are diagrams containing sbottom, gluinos and bottoms. [Degrassi, Slavich '10]



$\rightarrow$ Computed as zeroth order cofficient of an asymptotic expansion for $m_b = 0$

MSSM SQCD CORRECTIONS: RESULTS

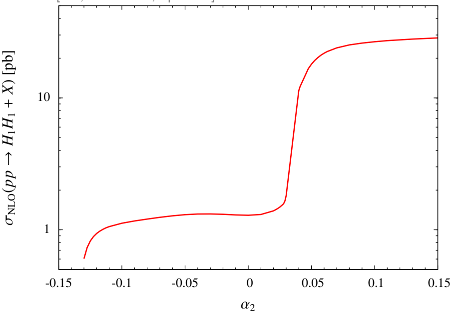


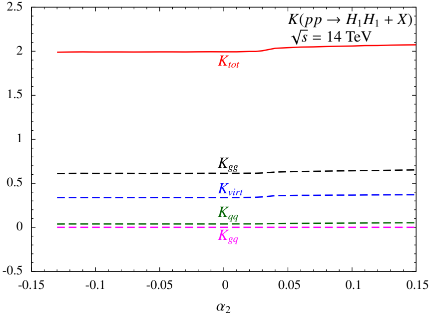

[Agostini, Degrassi, RG, Slavich '16]
LO, full
LO, no SUSY
NLO, full
NLO, no SUSY
NLO, no SUSY in $F_{\Box}^{2\ell}$
$\sigma(pp \to hh)$ [fb]
M_S [GeV]
10
20
30
40
50
60
500
600
700
800
900
1000
1100
1200
1300
1400
1500

Scenario: [Mühlleitner, Sampaio, Santos, Wittenbrodt '17]

$$\alpha_1 = 0.853\,,\ \alpha_3 = 0.0072\,,\ \tan\beta = 0.969\,,\ \mathrm{Re}(m_{12}^2) = 70957\ \mathrm{GeV}^2\,,$$
$$m_{H_1} = 125\ \mathrm{GeV}\,,\ m_{H_2} = 377.6\ \mathrm{GeV}\,,\ m_{H^\pm} = 709.7\ \mathrm{GeV}\,.$$

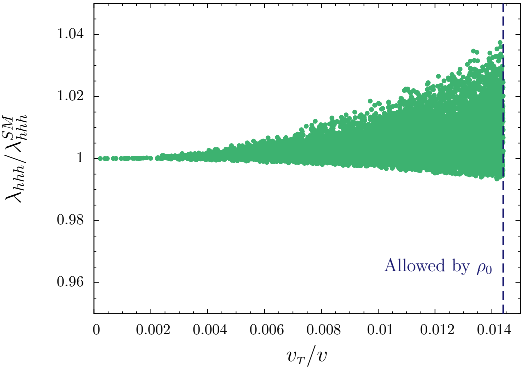
[RG, Mühlleitner, Spira '17]





CUSTODIAL VIOLATING: TRIPLET

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

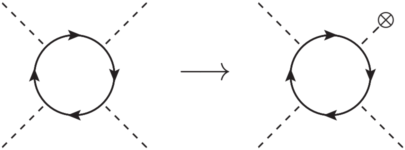


Strongest bound on model from ρ parameter

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

Loop-induced corrections to the trilinear Higgs self-coupling

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



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 $\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} < 0.1\%$.