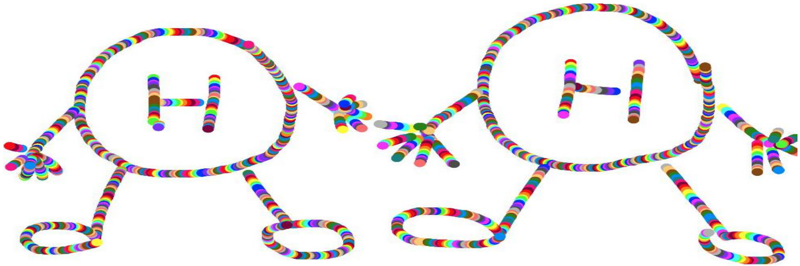
Pair production of beyond the Standard Model Higgs bosons

Ramona Gröber | 11.11.2016

IPPP, Durham University



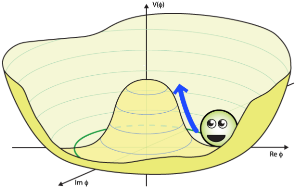
- Motivation
- Higgs pair production in the SM
  Can it be measured?
- New Physics in Higgs pair production
  Can we observe new physics in Higgs pair production?
- Higher order corrections to Higgs pair production
  MSSM and SM + dim 6 operators

Higgs potential:

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

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

$$\Longrightarrow V(H) = \underbrace{\frac{1}{2} M_H^2}_{\mu^2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$



[quantumdiaries.org]

- 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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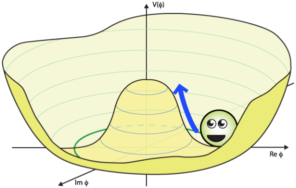

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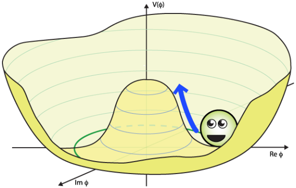

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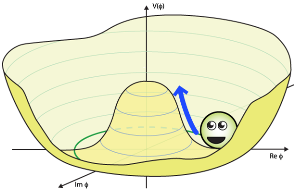

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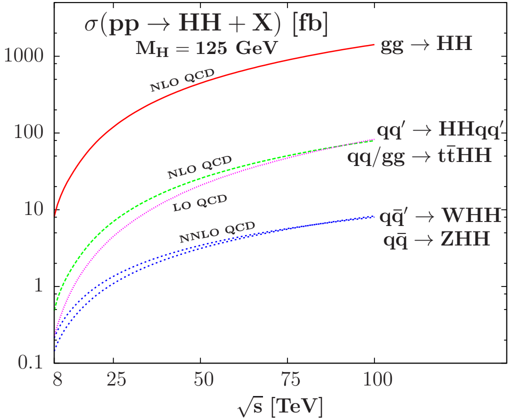

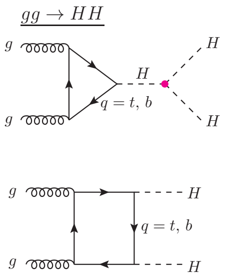

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- Can the process even be measured?

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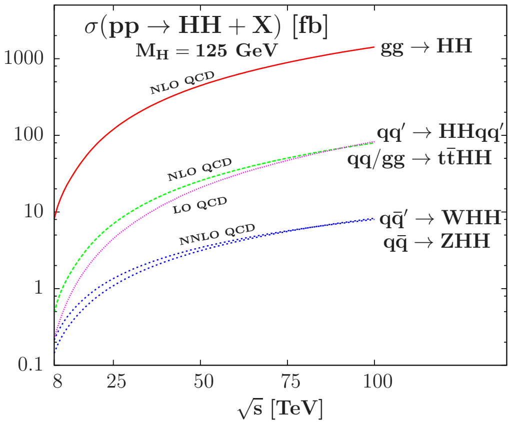

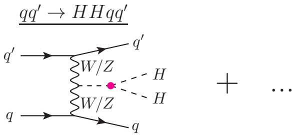

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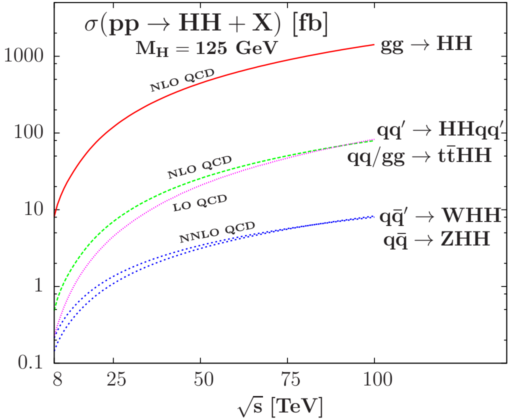

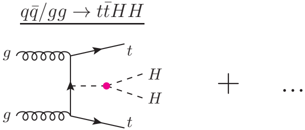

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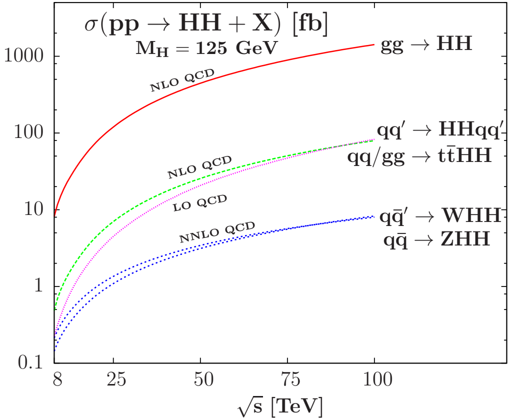

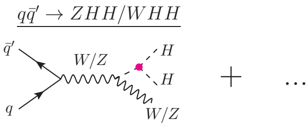

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- Consider only largest production process: Gluon fusion (at $\sqrt{s} = 14$ TeV)
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- $HH \rightarrow b\bar{b}b\bar{b}$: Overwhelmed by large QCD background [Baur, Plehn, Rainwater '03]
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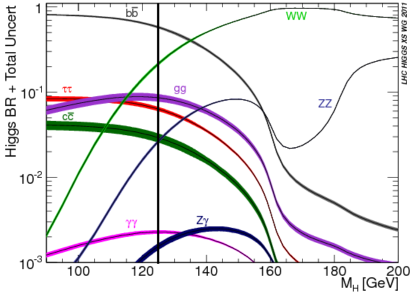

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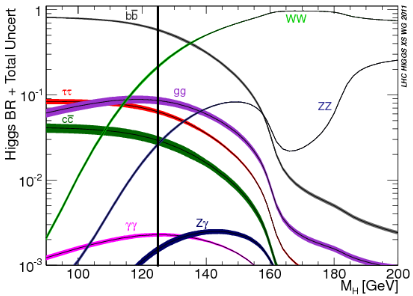

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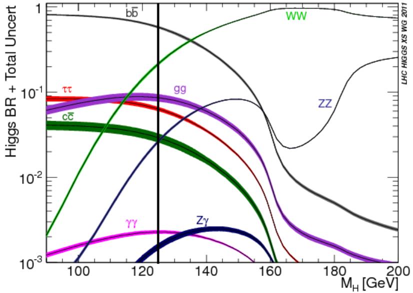

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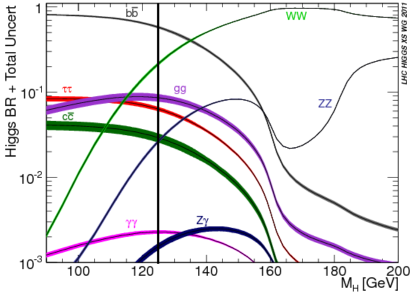

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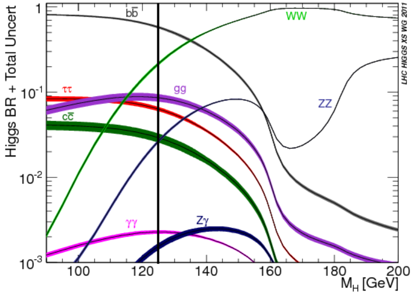

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Feasability studies for $\sqrt{s} = 14$ TeV and $\int \mathcal{L} = 3000$ fb^{-1}:

ATLAS: 1.3σ signal significance for $b\bar{b}\gamma\gamma$ final state. [ATLAS-PHYS-PUB-2014-019]

CMS: 1.9σ combination of $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$. [CMS PAS FTR-15-002]

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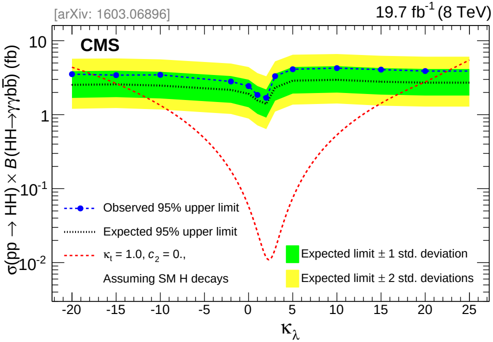
However, limits are and will be set on non-resonant and resonant BSM *HH* pair production

- Non-resonant production: $\mathcal{O}(50 - 100\,\sigma_{SM})$ excluded [ATLAS 1509.04670, CMS 1603.06896, ATLAS-CONF-2016-017, CMS PAS HIG-15-013, ATLAS 1606.04782]
- Limits on resonant production $\sigma(pp \to X)BR(X \to hh)$ are $\mathcal{O}(10\text{ fb} - 10\text{ pb})$ [ATLAS 1509.04670, CMS 1603.06896, CMS 1510.01181]



New Physics in Higgs Pair Production

How can new physics modify *HH* production?

- Shift in the trilinear Higgs coupling.
  In most models: also shift in the other couplings.
  Exception e.g. singlet with zero VEV [ew baryogenesis scenario, see e.g. Curtin, Meade, Yu '14]
- Shift in the other Higgs boson couplings.
- Additional Higgs bosons.
  E.g. in SUSY, [MSSM: Djouadi, Kilian, Mühlleitner, Zerwas '99; ... NMSSM: Ellwanger '13; Nhung, Mühlleitner, Streicher, Walz '13]
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  Singlet extended SM [Dawson, Lewis '15; ...]
  or non-minimal Composite Higgs Models
- Additional particles in the loop.
  E.g. in SUSY or Composite Higgs Models [Dawson, Ismail, Low '15; CHM: Gillioz, RG, Grojean, Mühlleitner, Salvioni '12; Dolan, Englert, Spannowsky '12]
- Novel couplings.
  E.g. in Composite Higgs Models and Little Higgs Models [CHM: RG, Mühlleitner '10; Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer '12; LHM: Dib, Rosenfeld, Zerwekh '05]
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  Singlet extended SM [Dawson, Lewis '15; ...]
  or non-minimal Composite Higgs Models
- Additional particles in the loop.
  E.g. in SUSY or Composite Higgs Models [Dawson, Ismail, Low '15; CHM: Gillioz, RG, Grojean, Mühlleitner, Salvioni '12; Dolan, Englert, Spannowsky '12]
- Novel couplings.
  E.g. in Composite Higgs Models and Little Higgs Models [CHM: RG, Mühlleitner '10; Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer '12; LHM: Dib, Rosenfeld, Zerwekh '05]
- Exotic decays of the Higgs bosons
  E.g. invisible decays [Banerjee, Batell, Spannowsky '16]

HOW CAN NEW PHYSICS MODIFY *HH* PRODUCTION?

- Shift in the trilinear Higgs coupling.
  In most models: also shift in the other couplings.
  Exception e.g. singlet with zero VEV [ew baryogenesis scenario, see e.g. Curtin, Meade, Yu '14]
- Shift in the other Higgs boson couplings.
- Additional Higgs bosons.
  E.g. in SUSY, [MSSM: Djouadi, Kilian, Mühlleitner, Zerwas '99; ... NMSSM: Ellwanger '13; Nhung, Mühlleitner, Streicher, Walz '13]
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But could we see new physics for the first time in Higgs pair production?

- 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.

u	c	t
d	s	b
e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ

elementary particles

gluon g
photon γ
$W^\pm, Z$

light, since pseudo-Goldstone boson

spin 0: H, ...

spin 1/2: T, B, $X^{5/3}$,...

spin 1: ρ, a,...

strongly interacting sector

- Top quark t can mix with fermionic resonances of the strongly-interacting sector ("top partner" T)
- Higgs boson is pseudo-Goldstone boson of spontaneous symmetry breaking of global symmetry at scale f
  Here: $SO(5) \times U(1)/SO(4) \times U(1)$
- global symmetry explicitly broken $\rightarrow$ Higgs potential generated by quantum corrections

Composite Higgs Models

- Parametrization of 4 Goldstone bosons

$$\Sigma(x) = \Sigma_0 e^{-iT^{\hat{a}}h^{\hat{a}}\sqrt{2}/f}, \qquad \Sigma_0 = (0,0,0,0,1)$$

- Description by non-linear σ-model

$$\mathcal{L} = \frac{f^2}{2}(D_\mu\Sigma)^T(D^\mu\Sigma), \qquad \text{in unitary gauge:} \quad \Sigma = (0,0,0,\sin H/f, \cos H/f)$$

Leads to

$$\mathcal{L} = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{f^2}{4}\sin^2\left(\frac{H}{f}\right)\left[g^2 W^\mu W_\mu + \frac{g^2}{\cos\theta_W} Z^\mu Z_\mu\right] + \dots$$

$$\downarrow$$

$$\xi = \frac{v^2}{f^2} = \sin^2\frac{\langle H\rangle}{f}$$

- Gauge boson-Higgs couplings:

$$g_{hVV} = g_{hVV}^{SM}\sqrt{1-\xi}, \qquad g_{hhVV} = g_{hhVV}^{SM}(1-2\xi)$$

- *hff*, *hhh*, ... couplings depend on fermion embedding

Consider three models here:

- Pure Higgs non-linearities

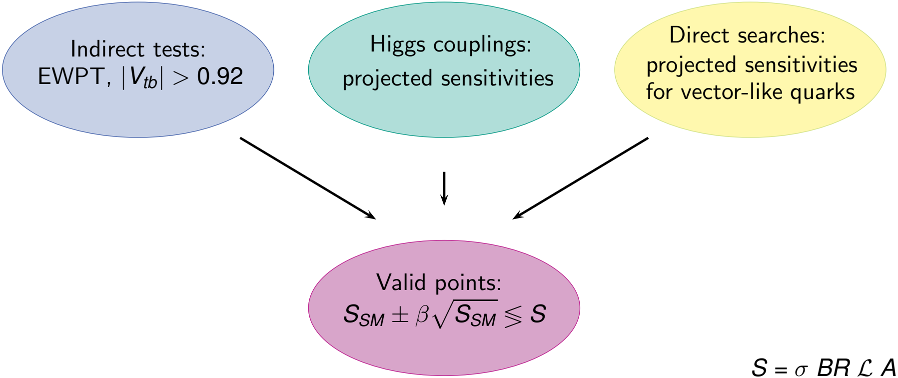
$$\text{MCHM4: } g_{hf\bar{f}/hhh} = g^{SM}_{hf\bar{f}/hhh}\sqrt{1-\xi}, \qquad g_{hhf\bar{f}} = -\xi\frac{m_f}{v^2}$$

$$\text{MCHM5: } g_{hf\bar{f}/hhh} = g^{SM}_{hf\bar{f}/hhh}\frac{(1-2\xi)}{\sqrt{1-\xi}}, \qquad g_{hhf\bar{f}} = -4\xi\frac{m_f}{v^2}$$

- Fermionic resonances
  Linear couplings of SM fermions to strong sector

$$\mathcal{L} = -\left(\lambda_L \overline{q}_L Q_R + \lambda_R \overline{\tilde{T}}_L t_R\right)$$

  Leads to
  - explicit breaking of global symmetry
  - mixing of elementary quark with strong sector
  - mass generation for the top quark.
- Fermions of strong sector in full multiplet ψ of $SO(5)$, e.g. 4, 5, 10, 14 -plets
  MCHM10: Antisymmetric representation (10) contains both bottom and top partner.



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

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

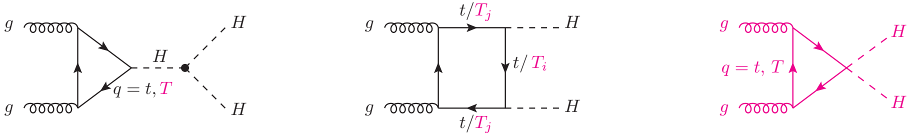
Model with pure Higgs non-linearities: Results

		$\sigma_{b\bar{b}\gamma\gamma}$ [fb]	$\Delta_{3\sigma}$	$\sigma_{b\bar{b}\tau^+\tau^-}$ [fb]	$\Delta_{3\sigma}$
MCHM4	$\xi = 0.12$ (LHC20.3)	0.119	no	3.26	no
	$\xi = 0.076$ (LHC300)	0.114	no	3.13	no
	$\xi = 0.051$ (LHC3000)	0.112	no	3.07	no
MCHM5	$\xi = 0.15$ (LHC20.3)	0.315	yes	5.35	yes
	$\xi = 0.068$ (LHC300)	0.175	no	3.96	no
	$\xi = 0.015$ (LHC3000)	0.119	no	3.14	no

$\longrightarrow$ MCHM4:
we cannot expect to see any significant deviation in *HH* production
$\longrightarrow$ MCHM5:
we will first see new physics in form of deviations in Higgs coupling measurements

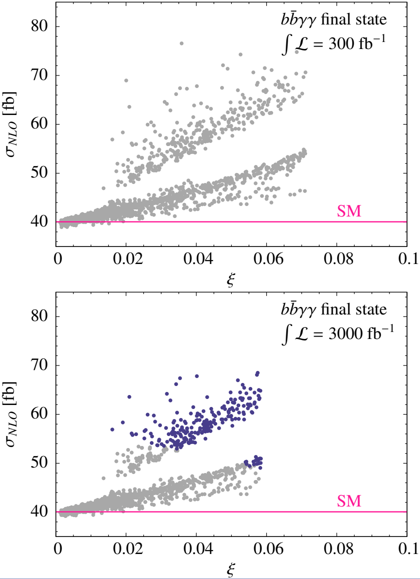
Let's look at yet another model with more freedom...

MCHM10 :
Both top- and bottom-partners in only one 10-plet.
Model has more freedom, since bottom partners introduce parameter dependence in $h \to b\bar{b}$, $h \to \gamma\gamma$ and $gg \to h$ rates.

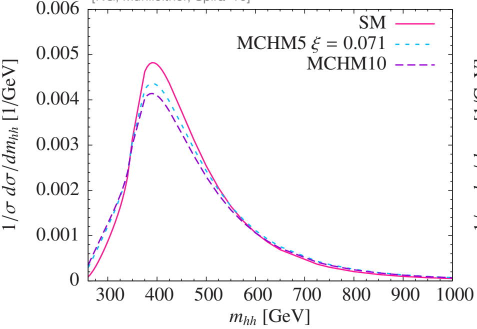


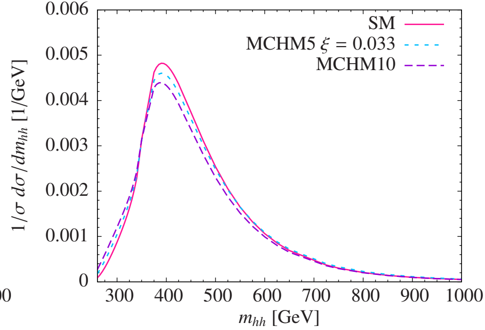
Results

[RG, Mühlleitner, Spira '16]



[RG, Mühlleitner, Spira '16]





$\rightarrow$ Details of top-partner spectrum only show small effect on invariant Higgs mass distribution.

Higher Order Corrections to BSM Higgs Pair Production

Higher order corrections to the SM cross section

- 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.
- LET: $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$ [Dawson, Dittmaier, Spira '98]
  LET approximation $\rightarrow$ small external momenta $\hat{s}$, $\hat{t}$, $\hat{u}$, $m_h^2 \ll m_t^2$

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

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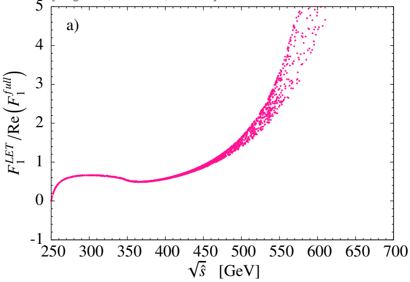
At LO, however, $$\frac{1}{(p+q_i)^2 - m_t^2} \approx \frac{1}{p^2 - m_t^2}\left(1 + \frac{2p\cdot q_i + q_i^2}{p^2 - m_t^2} + \ldots\right)$$

[Degrassi, Giardino, RG '16]



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Born-improved HEFT:
LO cross section in exact top-mass dependence is factored out
$\rightarrow$ Used for BSM NLO calculations.

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- Full NLO computation $\rightarrow$ top mass effects are -14% [Bobrowka, *et al.*'16; Johannes talk in Dec]
- Lot of recent progress in NNLO QCD corrections (of $\mathcal{O}(20\%)$) based on expansion in small external momentum [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]

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BSM NLO corrections:
2HDM [Hespel, Lopez-Val, Vryonidou '14], SM + dimension 6 operators [RG, Mühlleitner, Spira, Streicher '15], scalar singlet [Dawson, Lewis '15], composite Higgs models with and without fermionic resonances [RG, Mühlleitner, Spira '16], MSSM [QCD: Dawson, Dittmaier, Spira '98, SQCD: Agostini, Degrassi, RG, Slavich '16] and NMSSM [Agostini, Degrassi, RG, Slavich '16]

- 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

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

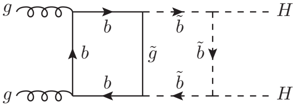
with

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

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

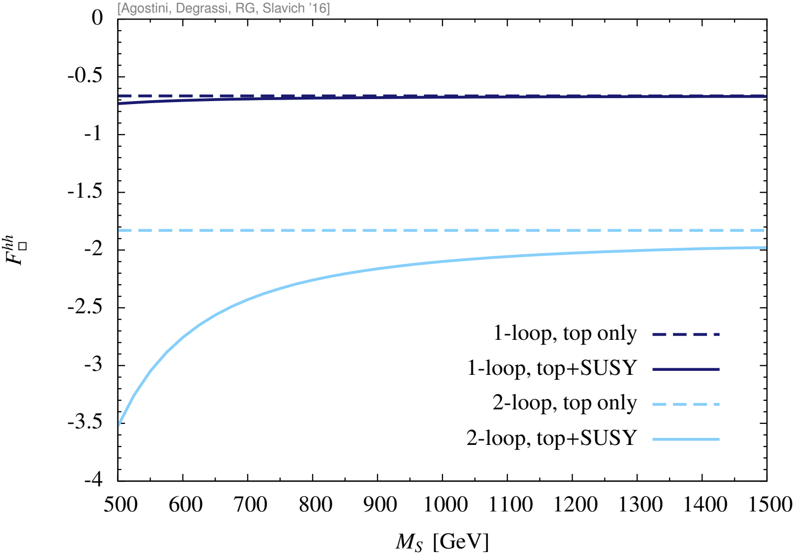
- Validity: $\hat{s}, \hat{t}, \hat{u}, m_H^2 \ll m^2_{loop}$

- 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]

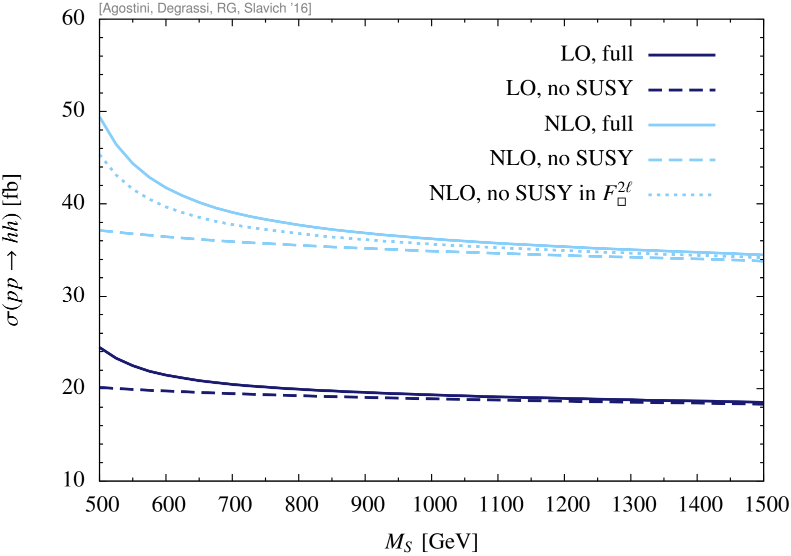


$\rightarrow$ Computed as zeroth order cofficient of an asymptotic expansion for $m_b = 0$

RESULTS


[Agostini, Degrassi, RG, Slavich '16]
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
$F_{\Box}^{hh}$
1-loop, top only
1-loop, top+SUSY
2-loop, top only
2-loop, top+SUSY
500
600
700
800
900
1000
1100
1200
1300
1400
1500
M_S [GeV]

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]
60
50
40
30
20
10
500
600
700
800
900
1000
1100
1200
1300
1400
1500
M_S [GeV]

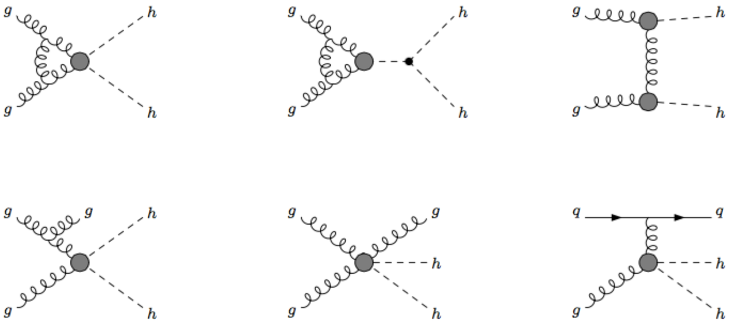
SM WITH DIM-6 OPERATORS

Non-linear effective Lagragian

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

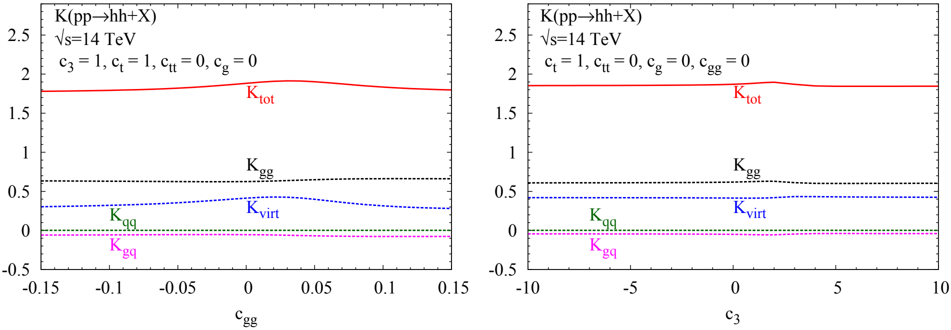
- c_t: Parameterizes deviations in the top-Yukawa coupling
- c_{tt}: Effective coupling of two top quarks to two Higgs bosons
- c_3: Shift in Higgs self-coupling
- c_g: Higgs gluon gluon coupling
- c_{gg}: Higgs Higgs gluon gluon coupling

Computed in LET approximation.



- Real corrections: LO cross section factors out. Can be taken over from SM.
- Virtual corrections: Third diagram needs to be re-evaluated. At NLO in the matching condition no factorization of LO cross section for non-zero c_g and c_{gg}.
- Results implemented in HPAIR [M. Spira's website], also for SILH Lagrangian (linearized)

[RG, Mühlleitner, Spira, Streicher '15]



⇒ Effect of dim-6 contributions on K-factor is $\mathcal{O}$(few %)

Conclusion

- Higgs pair production not only interesting for a measurement of trilinear Higgs self-coupling but New Physics can modify it in many different ways
- In certain models New Physics might even be seen for the first time in Higgs pair production.
- SQCD corrections in the MSSM: Stops have non-negligible effect for masses below the TeV scale
- SM + dim-6 operators: K factor of SM good approximation.

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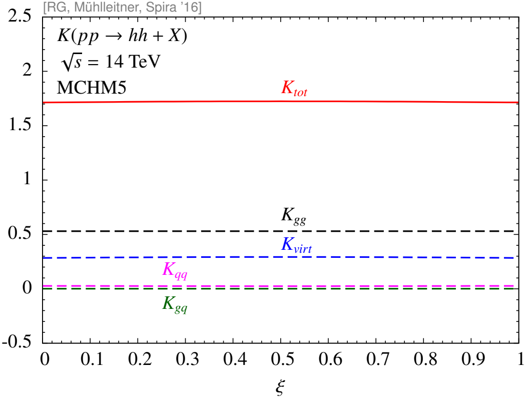
Thanks for your attention!

SUSY PARAMETERS OF PLOT

Parameters defined as on-shell parameters.

$$\tan\beta = 10, \;\; m_A = 500 \text{ GeV}, \;\; \mu = -400 \text{ GeV}, \;\; M_3 = 1500 \text{ GeV},$$
$$X_t = 2\, M_S \;, \;\; m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} = M_S,$$

Leads to 324 GeV $< m_{\tilde{t}_1} <$ 1326 GeV



Plot for MCHM5 (pure Higgs non-linearities)

- Vector-like quarks contribute to the gluon self-energy at 2-loop.
- They couple however in the same way to gluons than the top quark.
- Modification only in the reducible double-triangle contribution.