Pair production of Beyond the Standard Model Higgs Bosons

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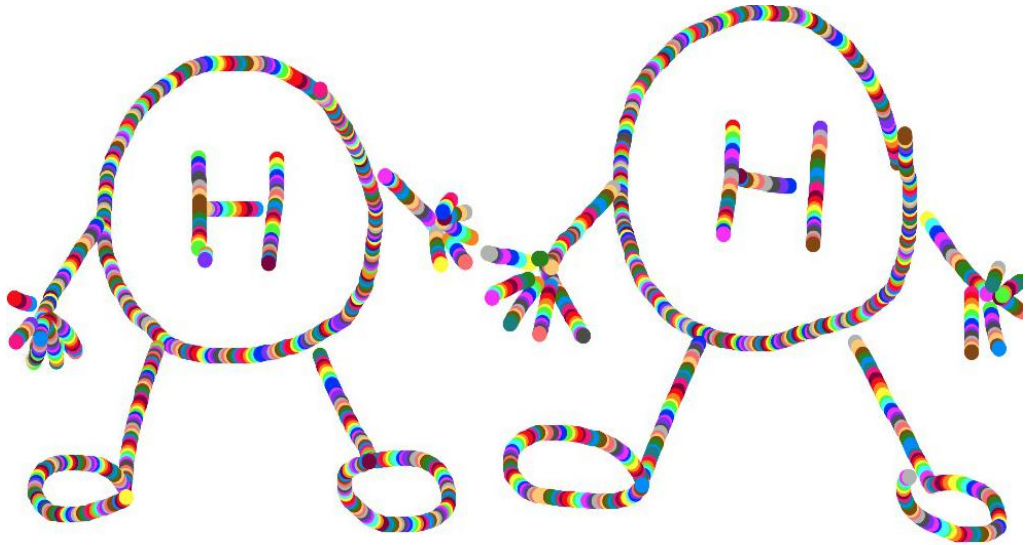
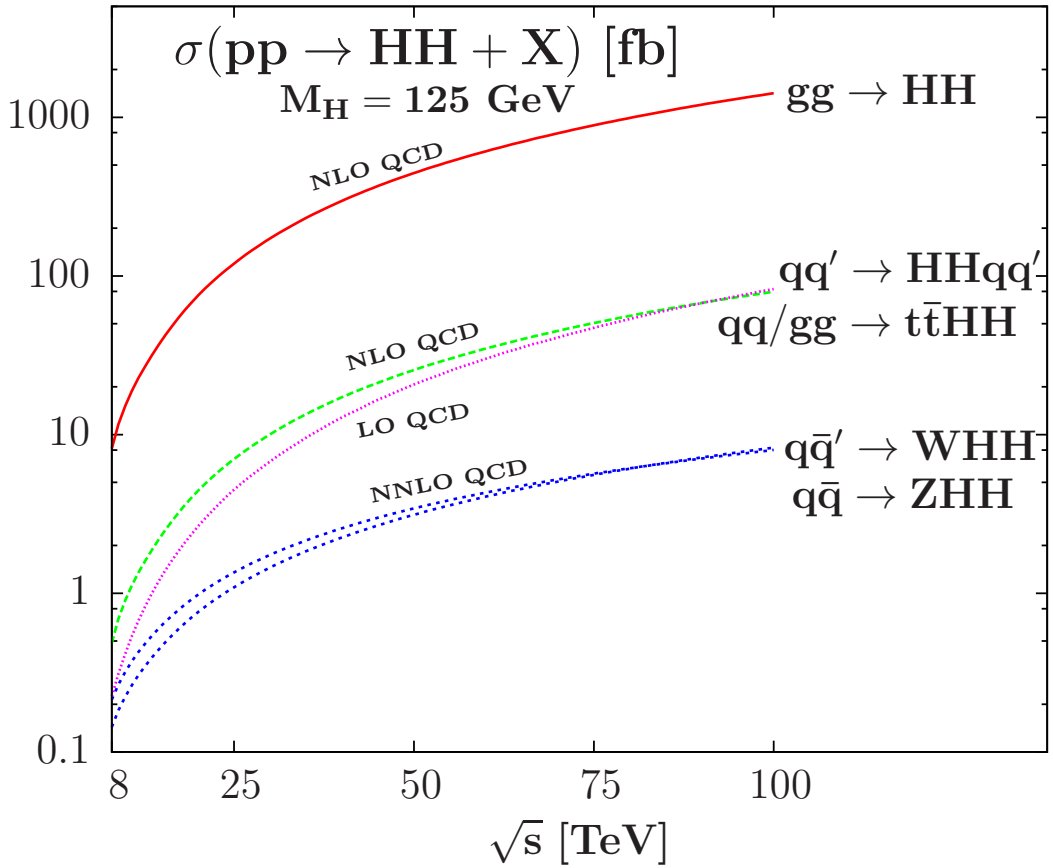


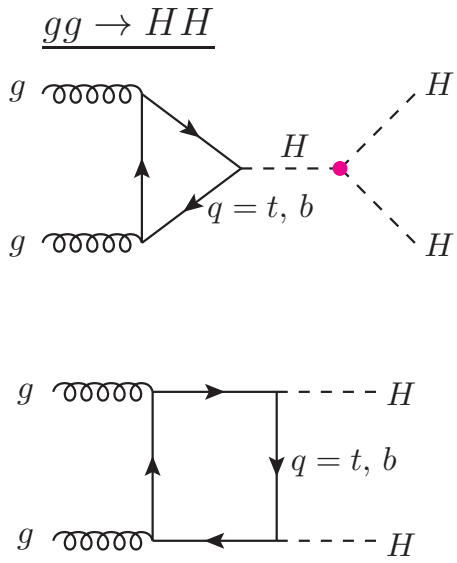
Outline

1. Higgs pair production in the SM
2. New Physics in Higgs pair production
3. Higher order corrections to BSM Higgs pair production

Higgs pair production in the SM

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





- Small cross sections
- Can the process even be measured?

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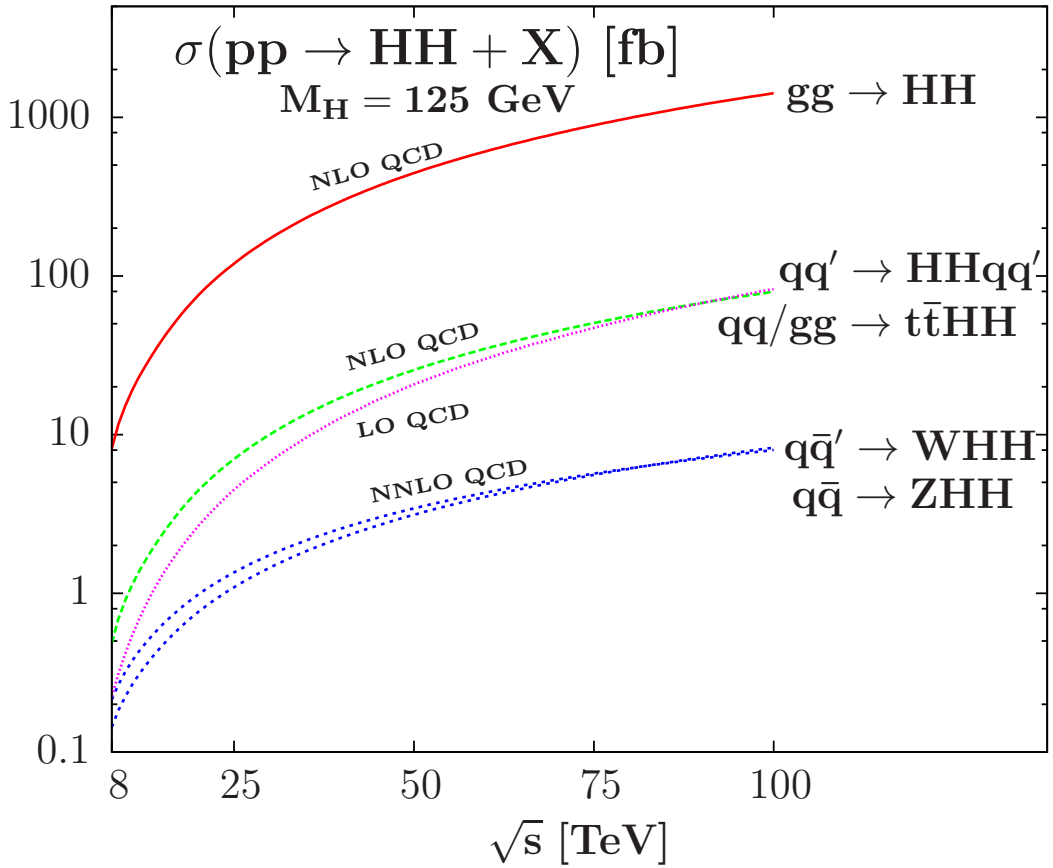

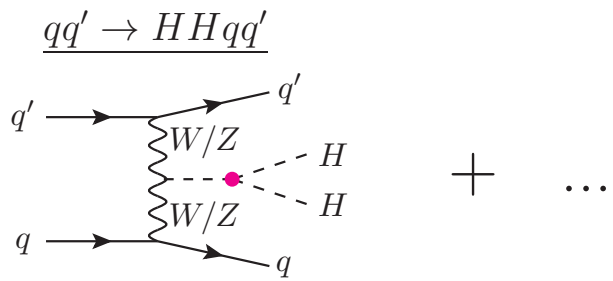

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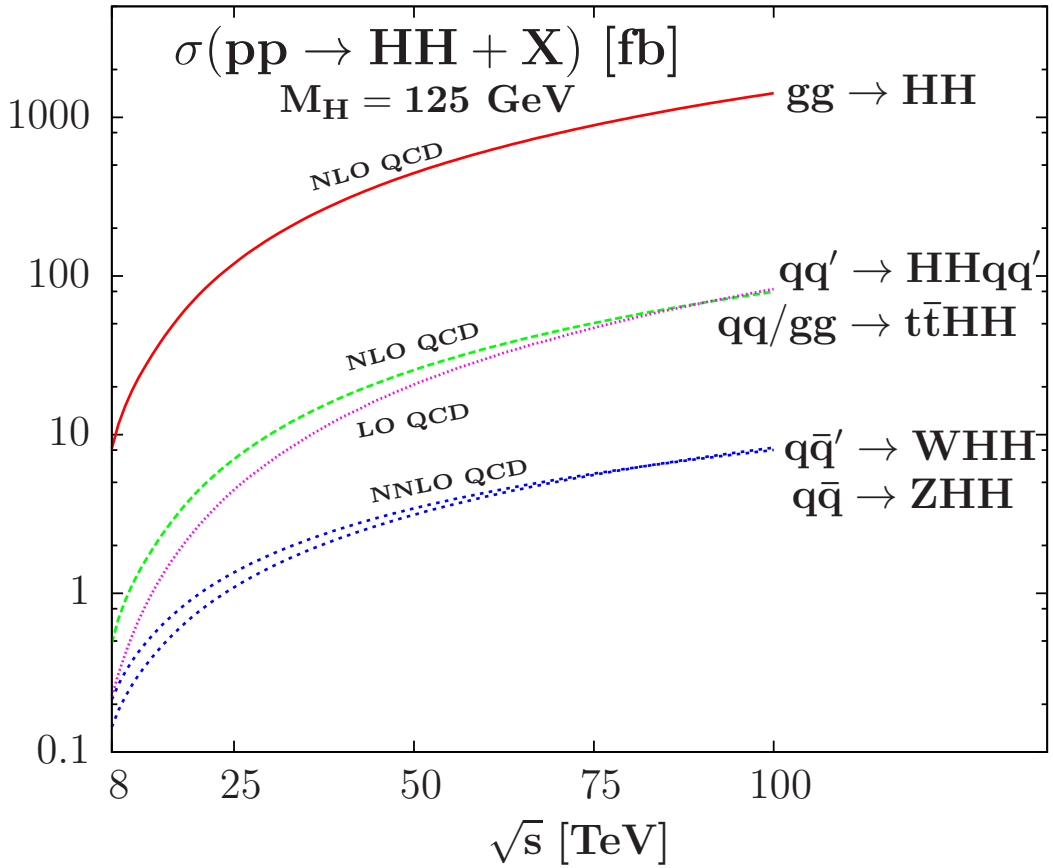
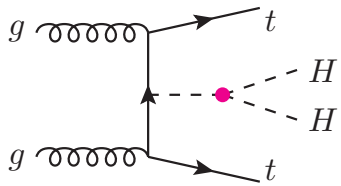


$q\bar{q}/gg \to t\bar{t}HH$



+ ...

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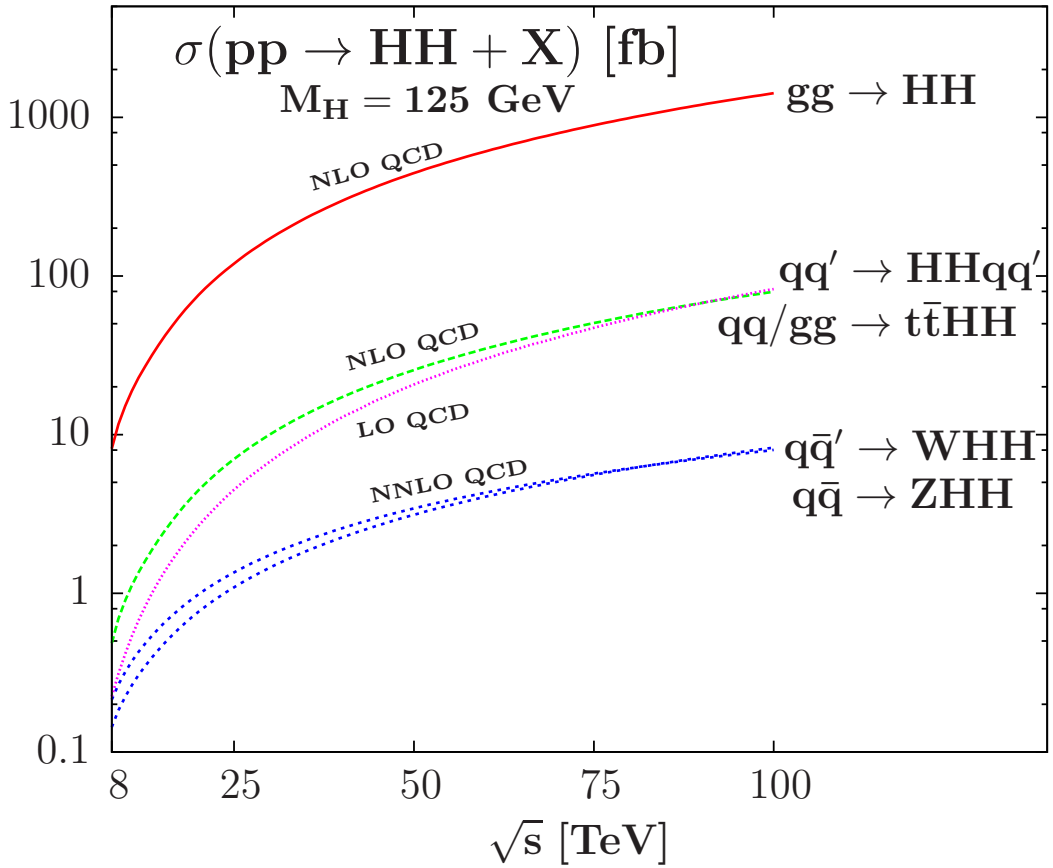
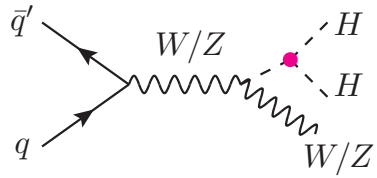


$q\bar{q}' \to ZHH/WHH$



$+ \quad \ldots$

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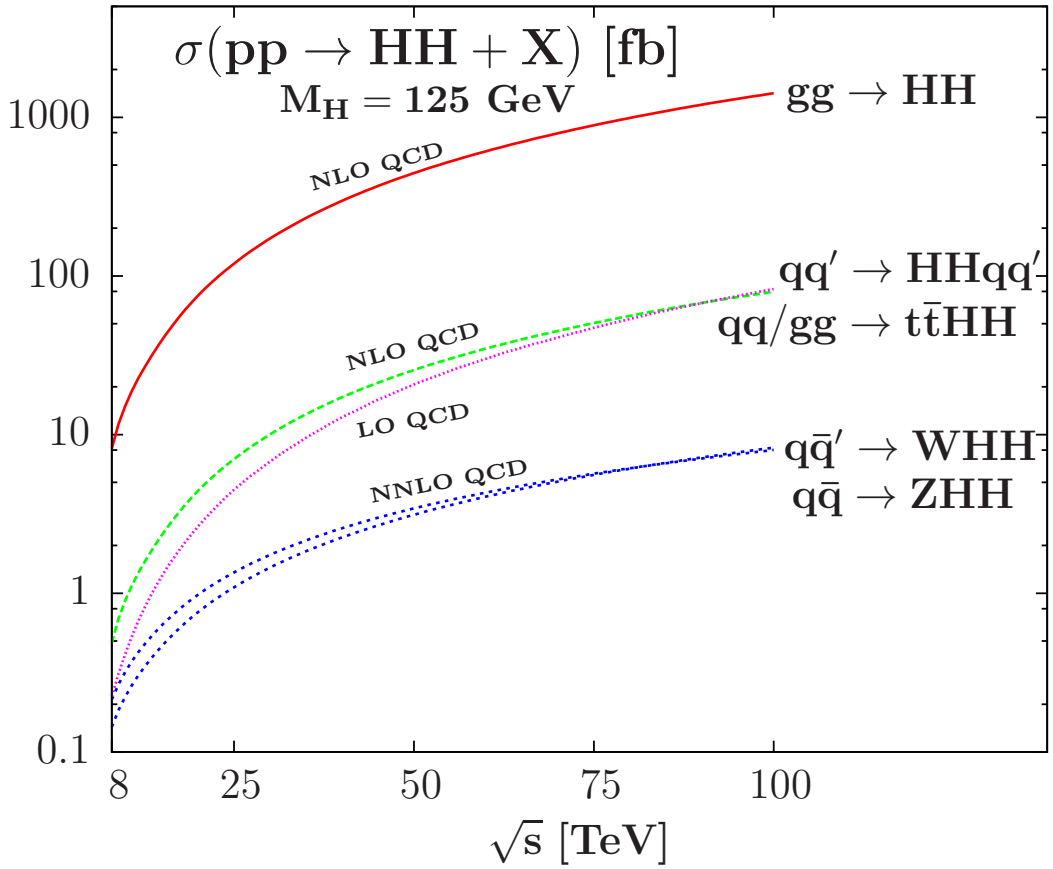


- Small cross sections
- Can the process even be measured? → next speakers. Theorist answer: difficult but yes, with $b\bar{b}\gamma\gamma$ most promising channel

[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]

THEORETICAL CHALLENGES

Gluon fusion:

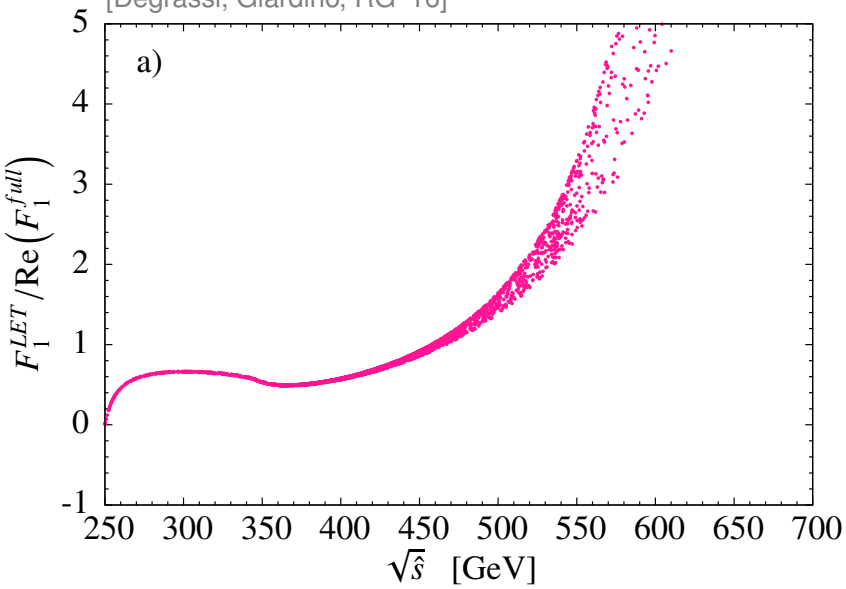
- LO cross section known exactly in full mass dependence [Glover, van der Bij '88; Plehn, Spira, Zerwas '95]
- NLO QCD corrections
  Difficulty: Multi-scale problem m_t^2, $\hat{s}$, $\hat{t}$, $\hat{u}$, m_h^2.
- improved LET: $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$ [Dawson, Dittmaier, Spira '98]

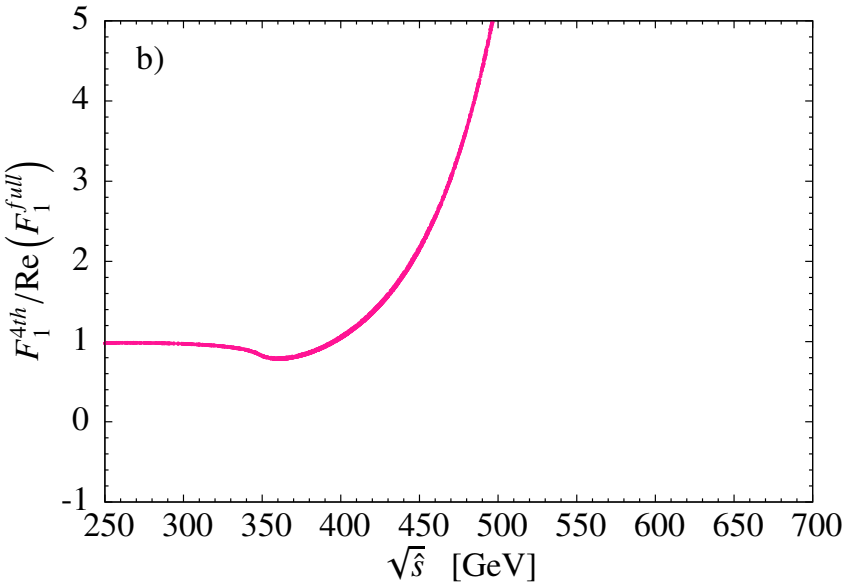
  LET approximation $\rightarrow$ small external momenta $\hat{s}$, $\hat{t}$, $\hat{u}$, $m_h^2 \ll m_t^2$

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

At LO, however,

[Degrassi, Giardino, RG '16]





THEORETICAL CHALLENGES

- 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 are -14%

  [Bobrowka, *et al.*'16]

  Caveat: 4680 hours of GPGPU time!
  Efforts for a fast MC should still be made.

- Lot of recent progress in NNLO QCD corrections (of $\mathcal{O}(20\%)$) but also in 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]

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]
  Two Higgs Doublet Model [Baglio, Eberhardt, Nierste, Wiebusch '14; Arhrib, Benbrik, Chen, Guedes, Santos '09; ...]
  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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But could we see new physics for the first time in Higgs pair production?

NEW PHYSICS FOR THE FIRST TIME IN *HH* PRODUCTION

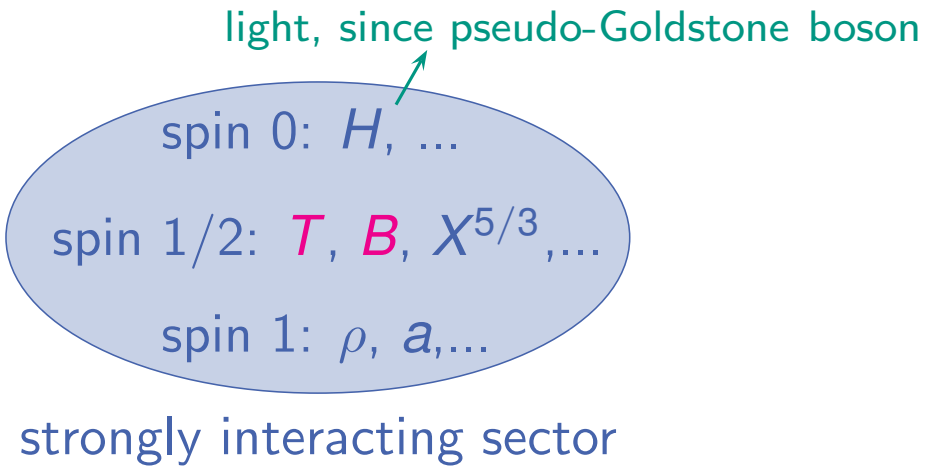
- This question can of course only be answered in concrete models.
- Resonant production in *s* channel, with new resonance predominantly decaying to Higgs bosons
  $\rightarrow$ large increase in cross section
  $\rightarrow$ distinction from SM possible
- Here other case: No *s* channel resonance, just coupling modifications and new couplings
  $\rightarrow$ Composite Higgs Models.

Composite Higgs models (CHM)

u	c	t
d	s	b
e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ

elementary particles

gluon g
photon γ
$W^\pm, Z$



- 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

- Description by non-linear σ-model

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

  $\sin H/f$ and $\cos H/f$ lead to non-linear Higgs couplings to gauge bosons and fermions

- Parameter $\xi = \frac{v^2}{f^2} = \sin \frac{\langle H \rangle}{f}$ describes departure from SM
- Gauge boson-Higgs couplings:

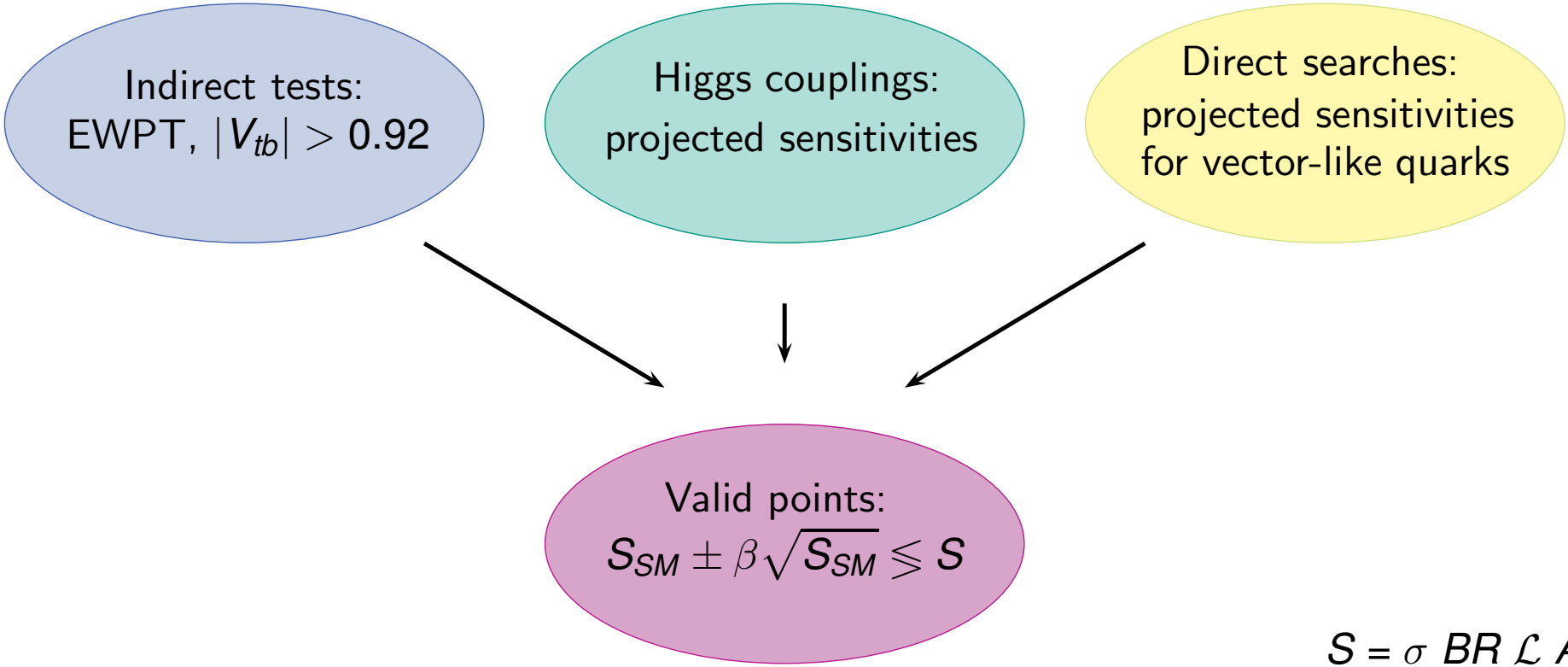
$$g_{hVV} = g^{SM}_{hVV}\sqrt{1-\xi}, \qquad g_{hhVV} = g^{SM}_{hhVV}(1-2\xi)$$

- Higgs fermion and Higgs self-couplings depend on embedding of fermions

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

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

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



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

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

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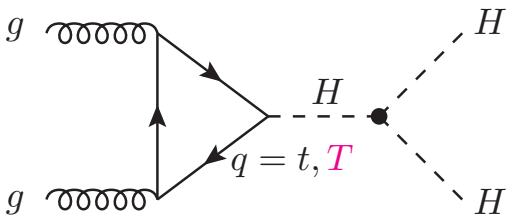
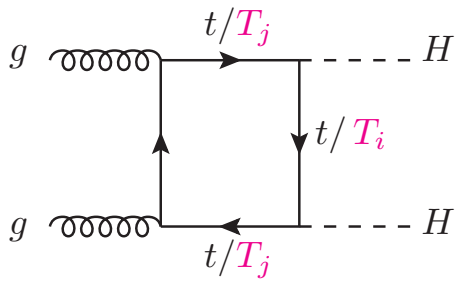
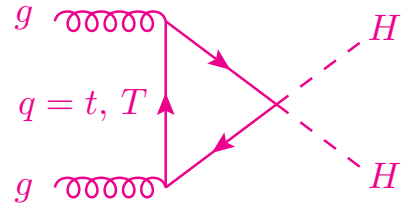
Let's look at yet another model with more freedom...

- Fermionic resonances
  Explicit breaking of global symmetry by 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 mixing of elementary quark with strong sector, mass generation for the top quark.
- MCHM10: Antisymmetric representation (10) contains both bottom and top partner.
- 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.

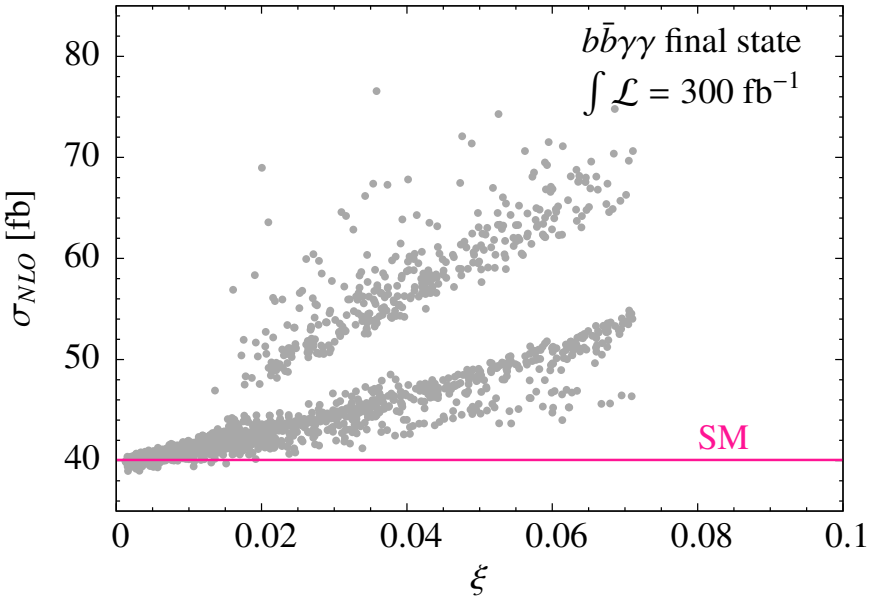


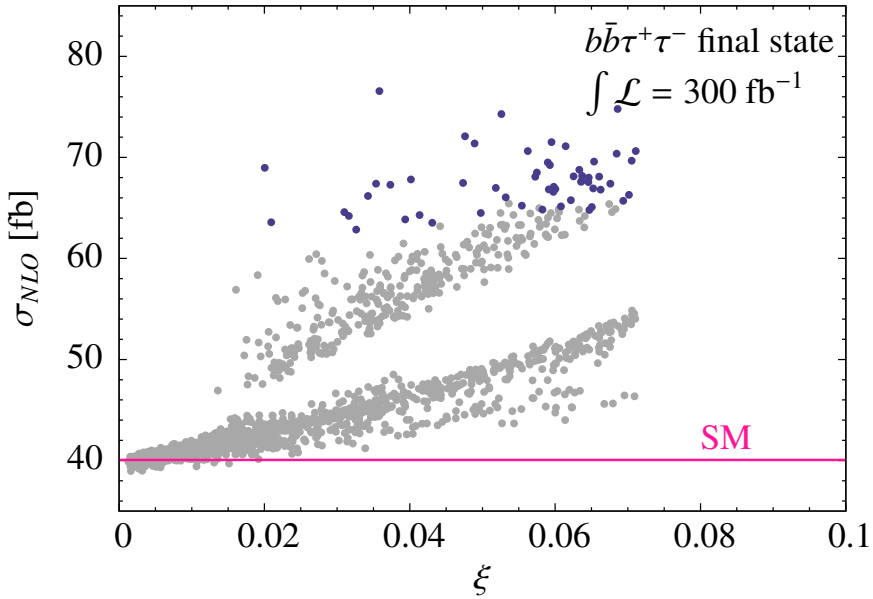


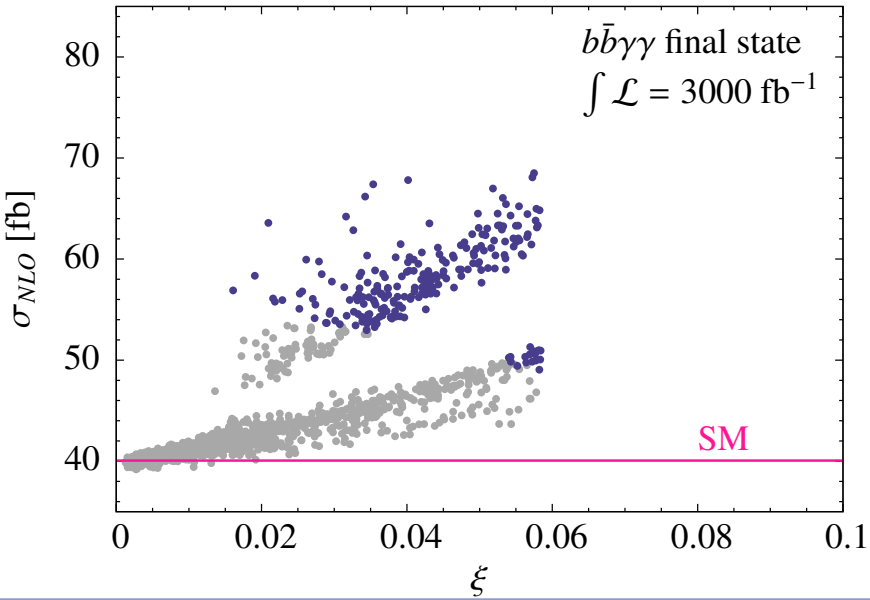


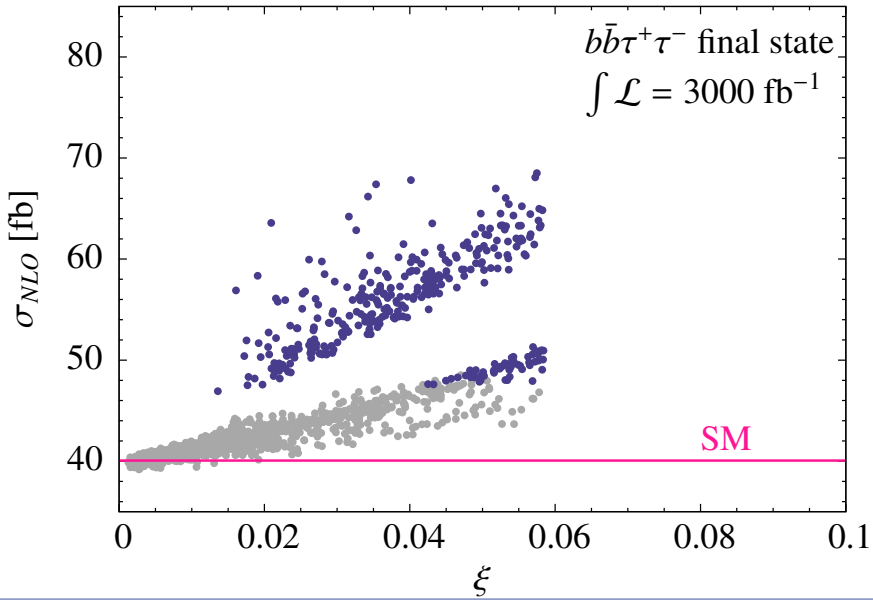
Results

[RG, Mühlleitner, Spira '16]









Higher Order Corrections to BSM Higgs Pair Production

- SM + dimension 6 operators
- MSSM

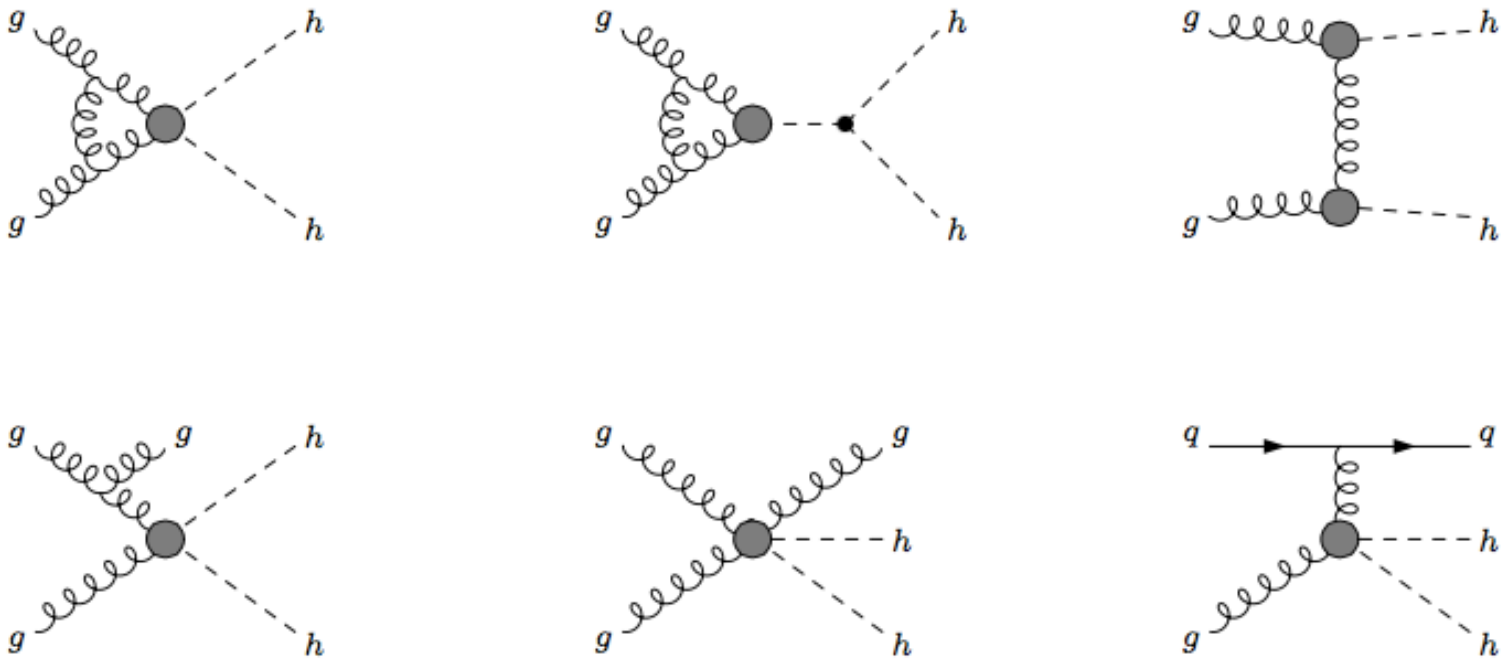
Non-linear effective Lagragian

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

- 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

QCD CORRECTIONS FOR SM WITH DIM-6 OPERATORS

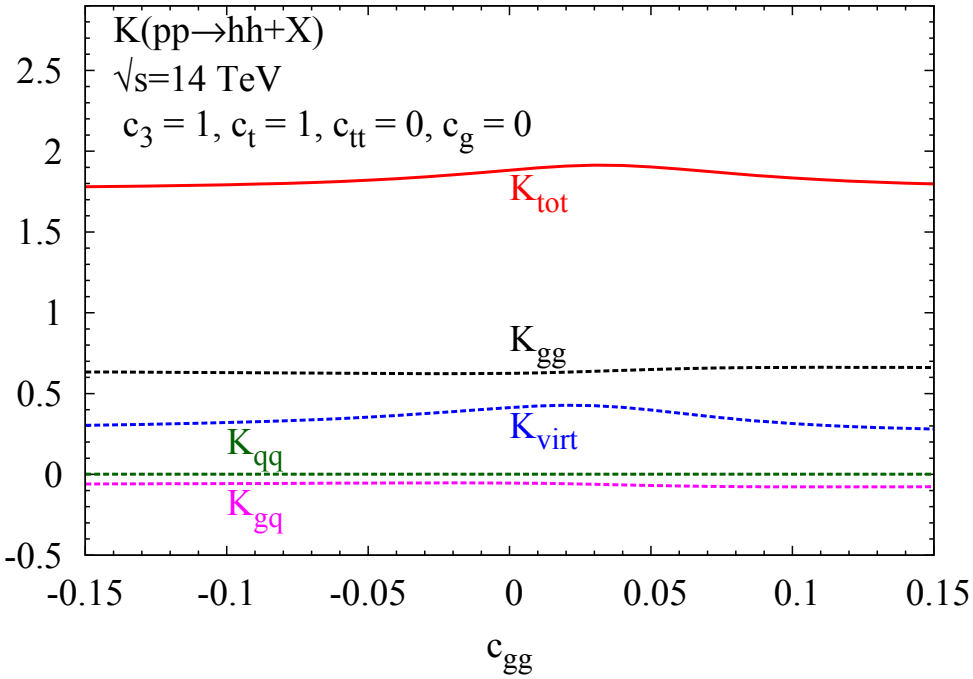
Computed in LET approximation.

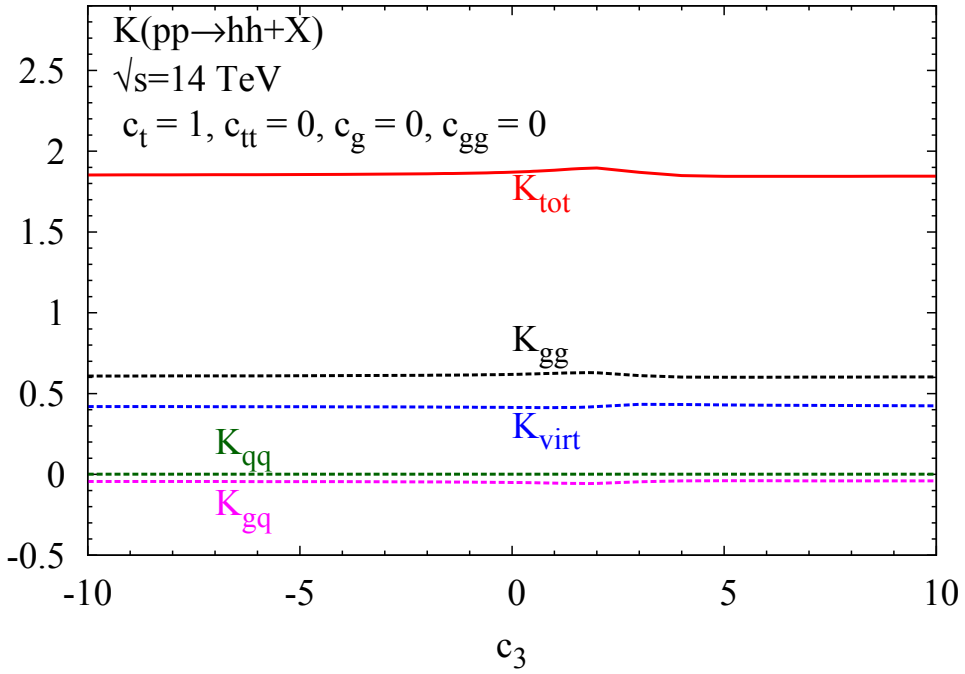


- Real corrections: LO cross section factors out. Can be taken over from SM.
- Virtual corrections: Third diagram needs to be re-evaluated. At NLO in the matching condition no factorization of LO cross section for non-zero c_g and c_{gg}.
- Results implemented in HPAIR [M. Spira's website], also for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

QCD CORRECTIONS FOR SM WITH DIM-6 OPERATORS

[RG, Mühlleitner, Spira, Streicher '15]





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

MSSM SQCD CORRECTIONS

Top-loop contributions to MSSM Higgs pair production computed in [Dawson, Dittmaier, Spira '98]
In [Agostini, Degrassi, RG, Slavich'16] we computed stop and sbottom loop contributions.

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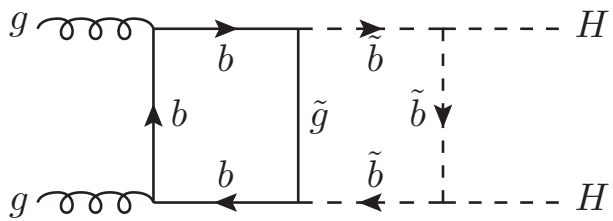
LET approximation:
Triangle form factors can be borrowed from single Higgs production [Anastasiou et al '06, Aglietti et al '06, Mühlleitner, Spira '06, Bonciani, Degrassi, Vicini '07]
NLO form factors computed from derivatives of the field-dependent contributions of top and stops in the gluon self-energy at 2-loop

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

Remember: Valid for $\hat{s}, \hat{t}, \hat{u}, m_H^2 \ll m_{loop}^2$!
$\rightarrow$ Can be applied as long as stop masses are not very light!

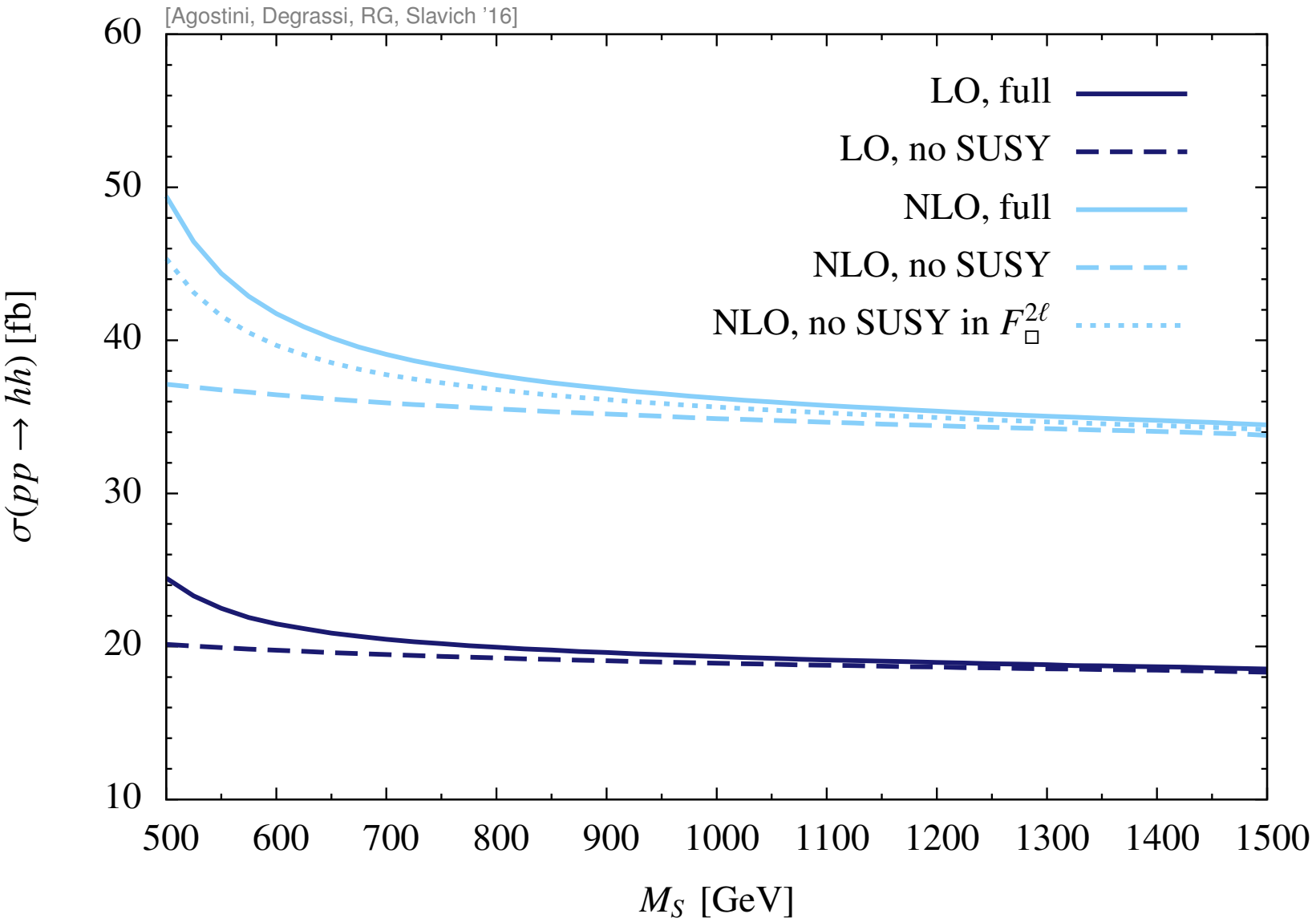
SBOTTOM CONTRIBUTIONS

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

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.
- SM + dim-6 operators: K factor of SM good approximation.
- SQCD corrections in the MSSM: Stops have non-negligible effect for masses below the TeV scale

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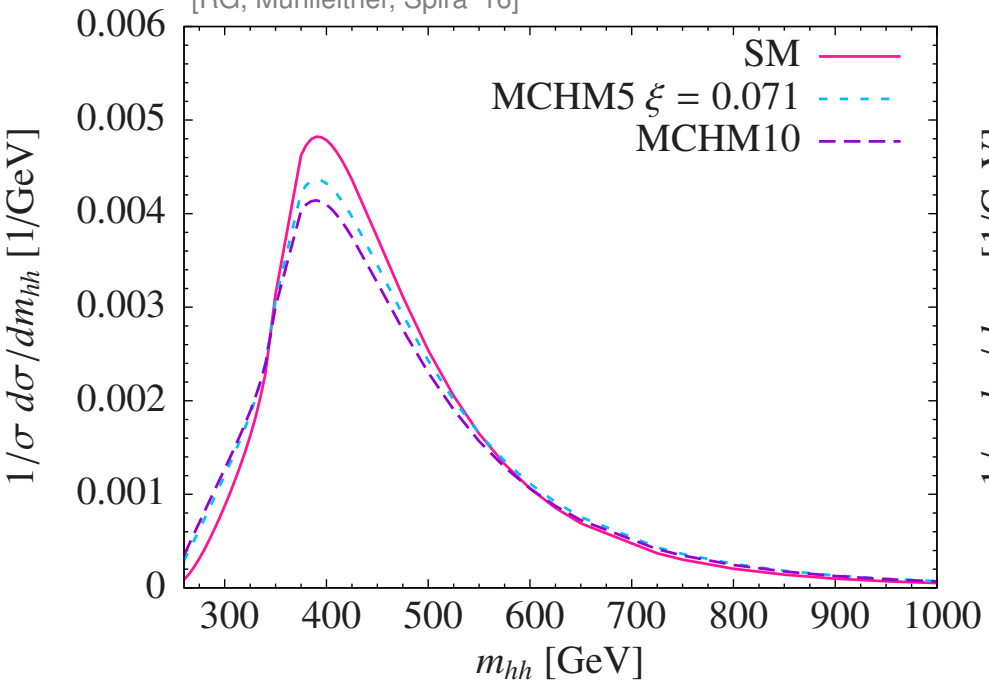
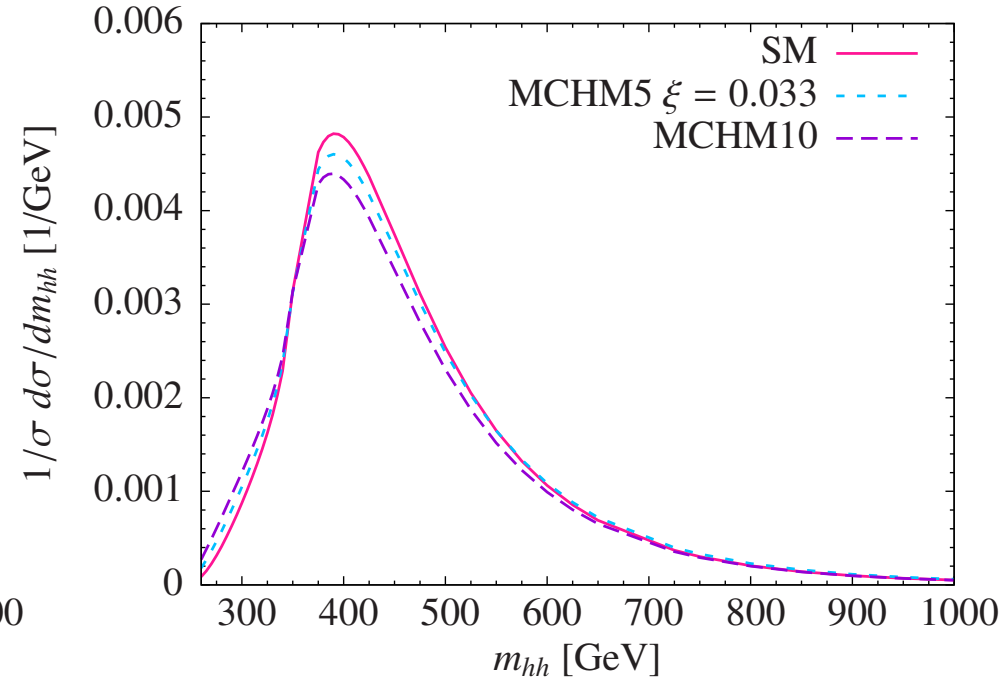
Thanks for your attention!

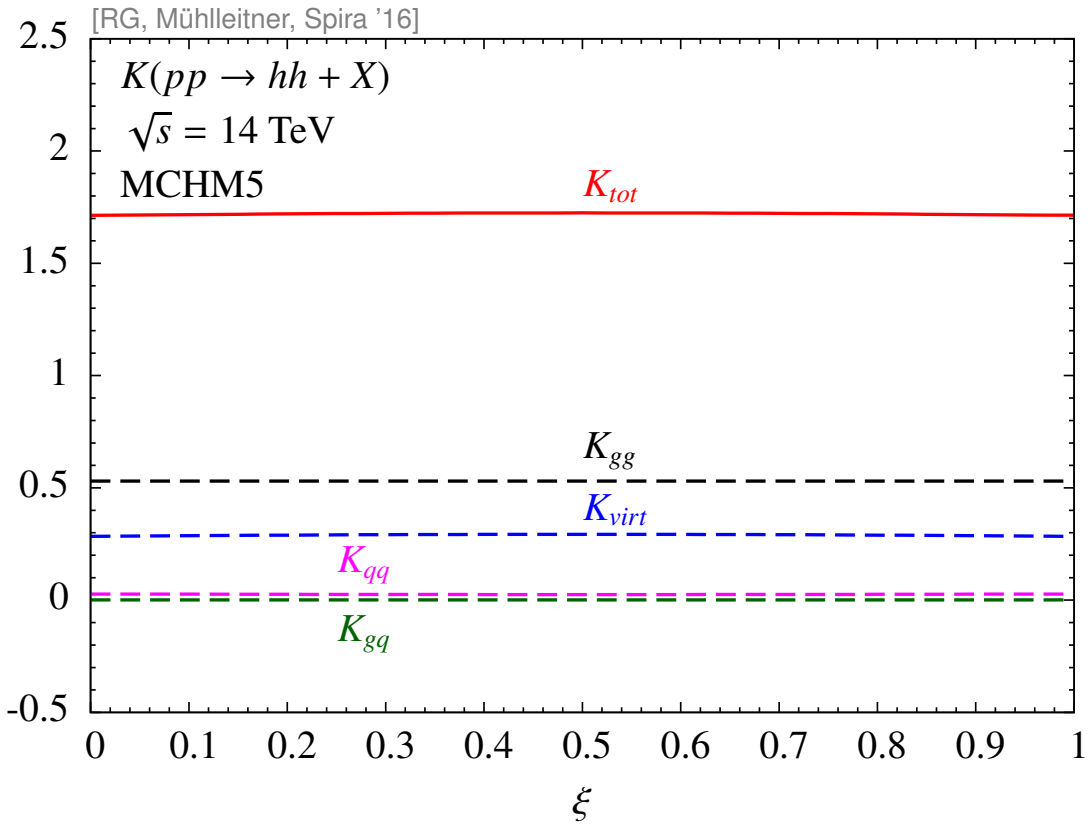
INVARIANT MASS DISTRIBUTIONS

[RG, Mühlleitner, Spira '16]





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



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.

SUSY PARAMETERS OF PLOT

Parameters defined as on-shell parameters.

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

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