New Physics in Higgs Pair Production

Ramona Gröber in collaboration with M. Mühlleitner and M. Spira, arXiv: 1602.05851
and A. Agostini, G. Degrassi and P. Slavich, arXiv: 1601.03671

10.05.16

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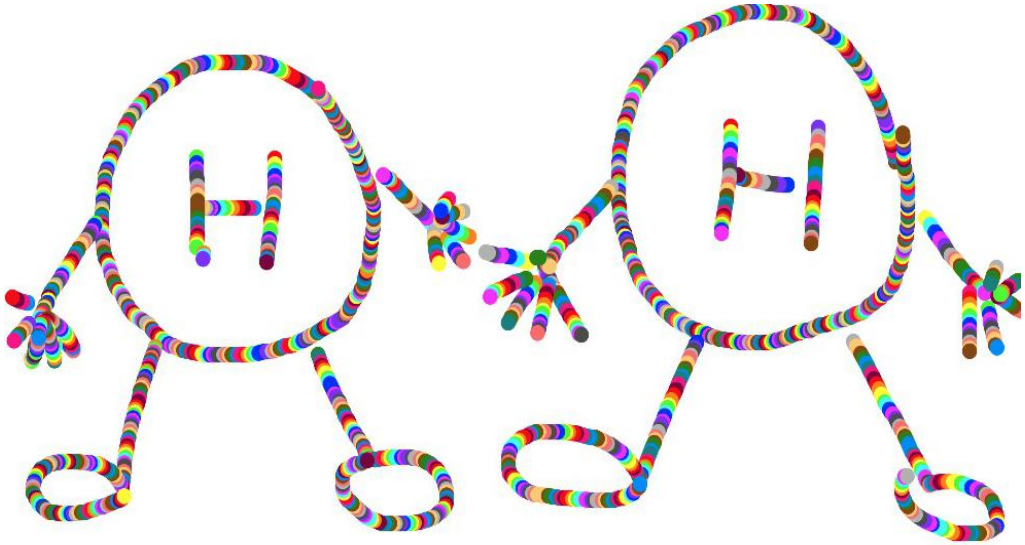


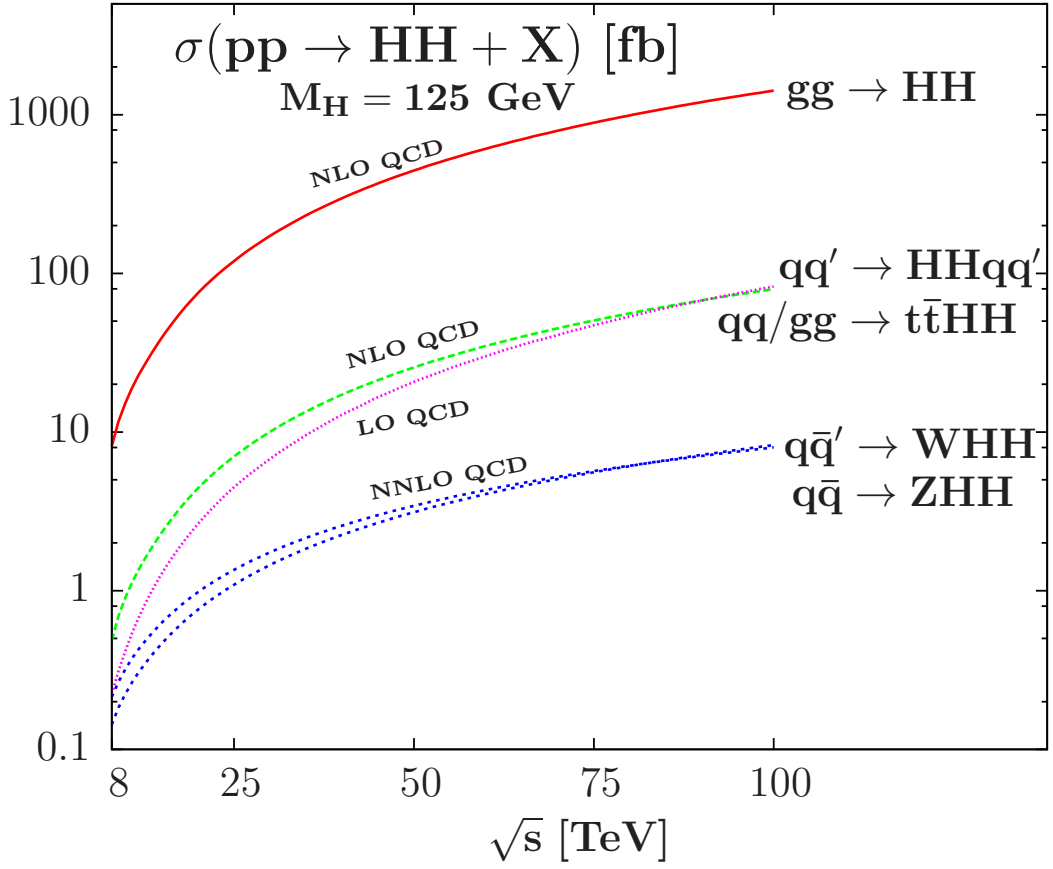
Outline

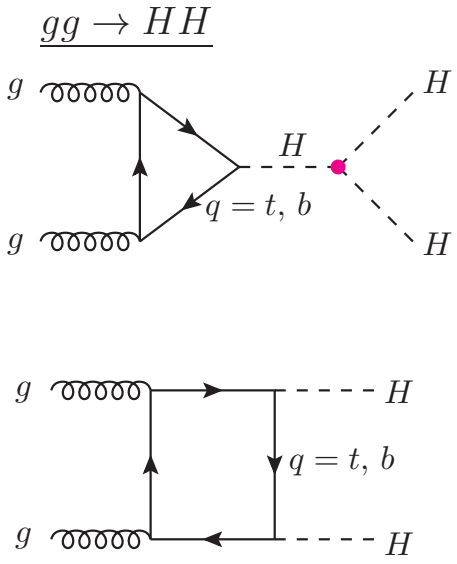
1. Can we see New Physics for the first time in *HH* production?

2. Higher order corrections to MSSM *HH* production

Higgs pair production

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





- Higgs pair production gives access to trilinear Higgs self-coupling
- Small cross sections, hence high luminosities are required
- Gluon fusion is dominant process → in the rest of my talk I will only refer to it

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; ...]
  or non-minimal Composite Higgs Models
- Additional particles in the loop.
  E.g. in SUSY or Composite Higgs Models [Dawson, Ismail, Low '15; MSSM: Batell, McCullough, Stolarski, Verhaaren '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: If new resonance predominantly decaying to Higgs bosons
  $\rightarrow$ large increase of cross section
  $\rightarrow$ distinction from SM possible
- Here other case: No *s* channel resonance, just coupling modifications and new couplings
  $\rightarrow$ Composite Higgs Models.

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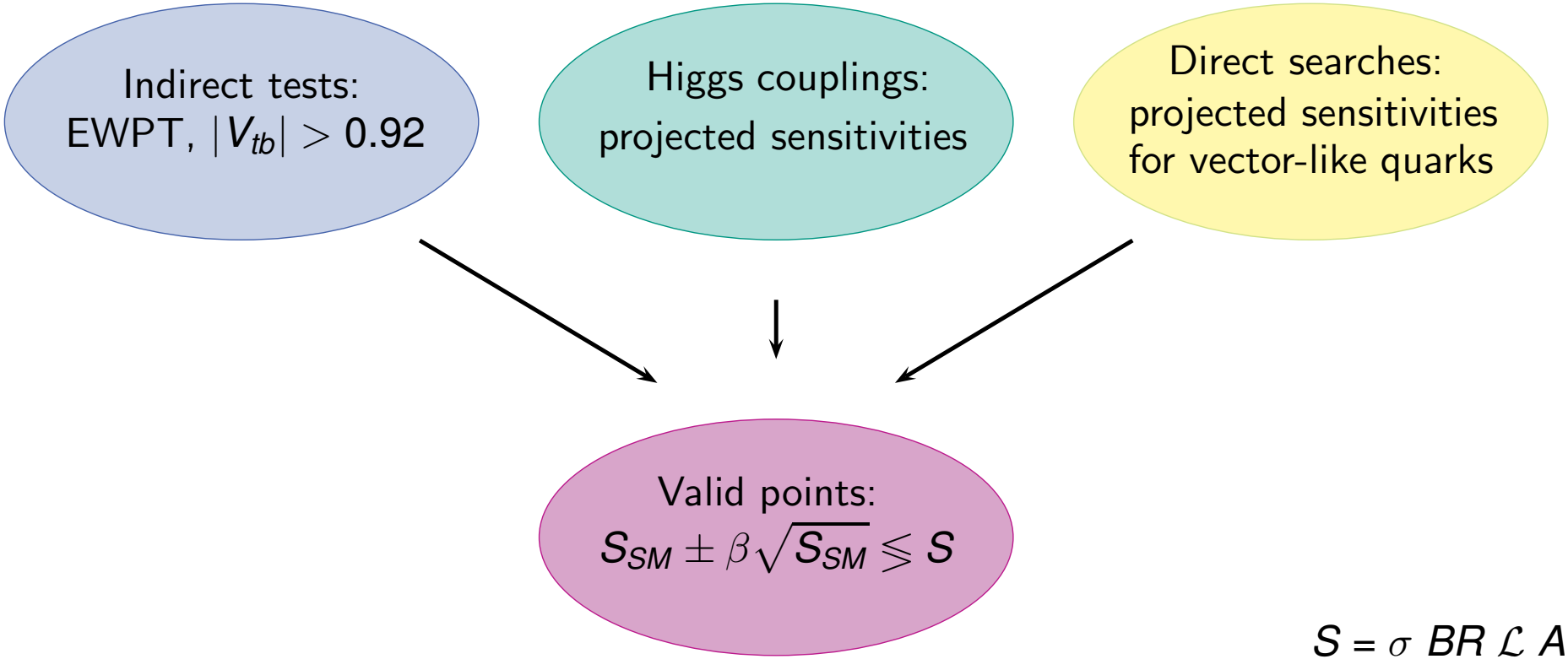
Model:

- Higgs boson as pseudo-Goldstone boson of $SO(5)/SO(4)$
- MCHM10 with vector-like top and bottom partners transforming in one (10) representation
- Parameter $\xi \in [0, 1]$ ($\xi = v^2/f^2$ with global symmetry breaking scale f) describes departure from SM

Philosophy



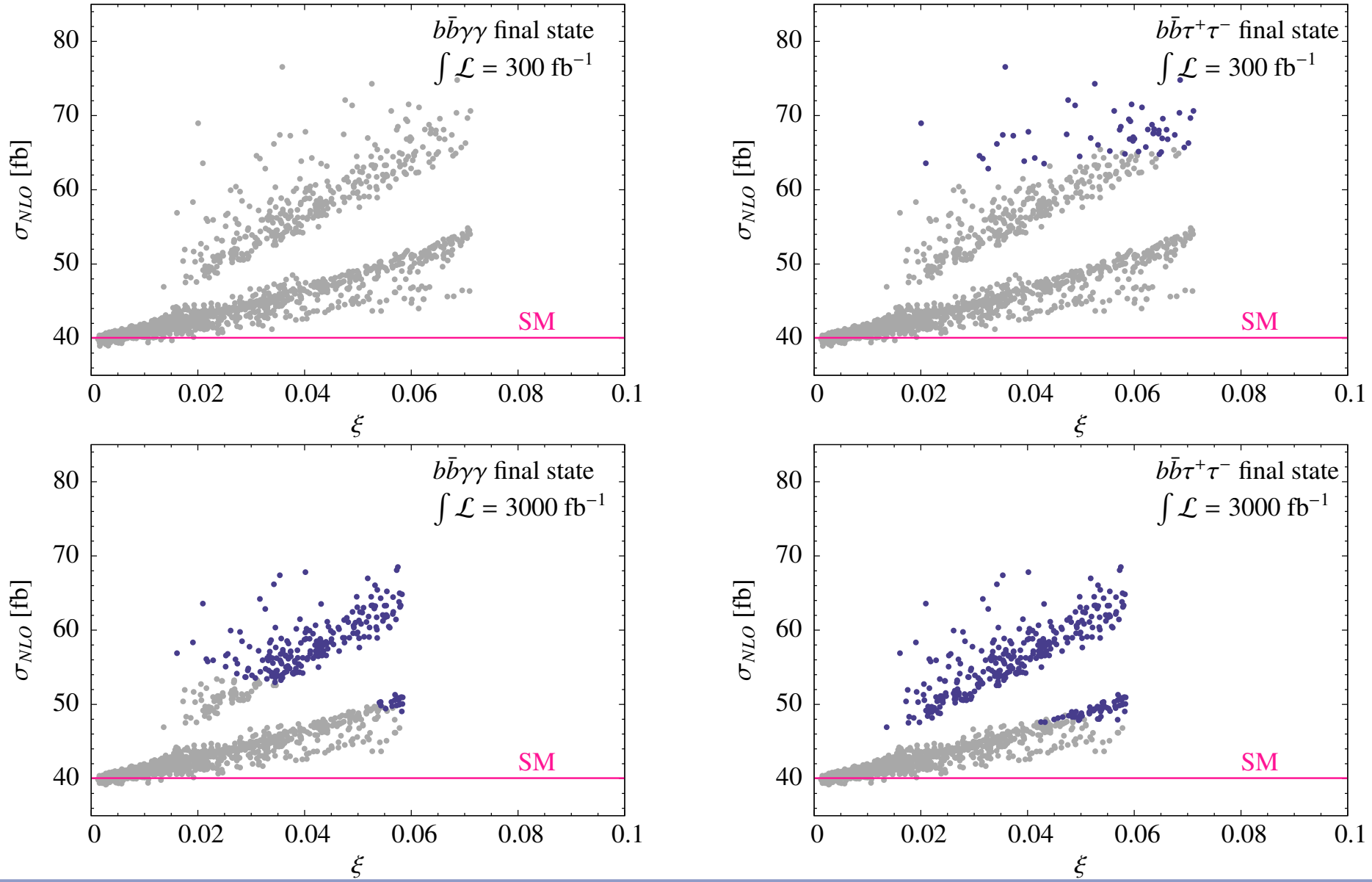
$S = \sigma\ BR\ \mathcal{L}\ A$

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

Results

[RG, Mühlleitner, Spira '16]



Higher Order Corrections to BSM Higgs Pair Production

Higher Order Corrections to Higgs Pair Production

SM:

- NLO QCD corrections to gluon fusion process are large $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$ [Dawson, Dittmaier, Spira '98]
- Many new developments in the recent years → Pier Paolo's talk

BSM:

NLO QCD corrections available in

- Higgs singlet model [Dawson, Lewis '15] → Ian's talk
- 2-Higgs doublet model [Hespel, Lopez-Val, Vryonidou '14]
- SM with dim-6 operators [RG, Mühlleitner, Spira, Streicher '15]
- Composite Higgs Models [RG, Mühlleitner, Spira '16]
- MSSM: top loops [Dawson, Dittmaier, Spira '98]
- MSSM and NMSSM: top, stop and sbottom loops [Agostini, Degrassi, RG, Slavich '16]

Plots for NLO QCD corrections of Composite Higgs Model and SM with dim-6 operators in backup

MSSM SQCD CORRECTIONS

LET approximation:
Useful tool for higher order corrections $\rightarrow$ Loop-induced gluon fusion process can be replaced by effective coupling.
Corresponds to zeroth order coefficient in expansion in small external momenta.

Meaning: 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!

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 box form factors computed from derivatives of the field-dependent contributions of top and stops in the gluon self-energy at 2-loop

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

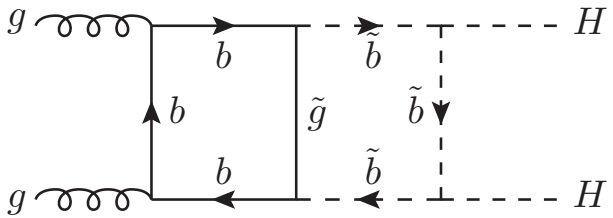
with e.g.

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

$$\sin\theta_{\tilde{t}} = \frac{2y_t(A_t H_u + \mu H_d)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ .$$

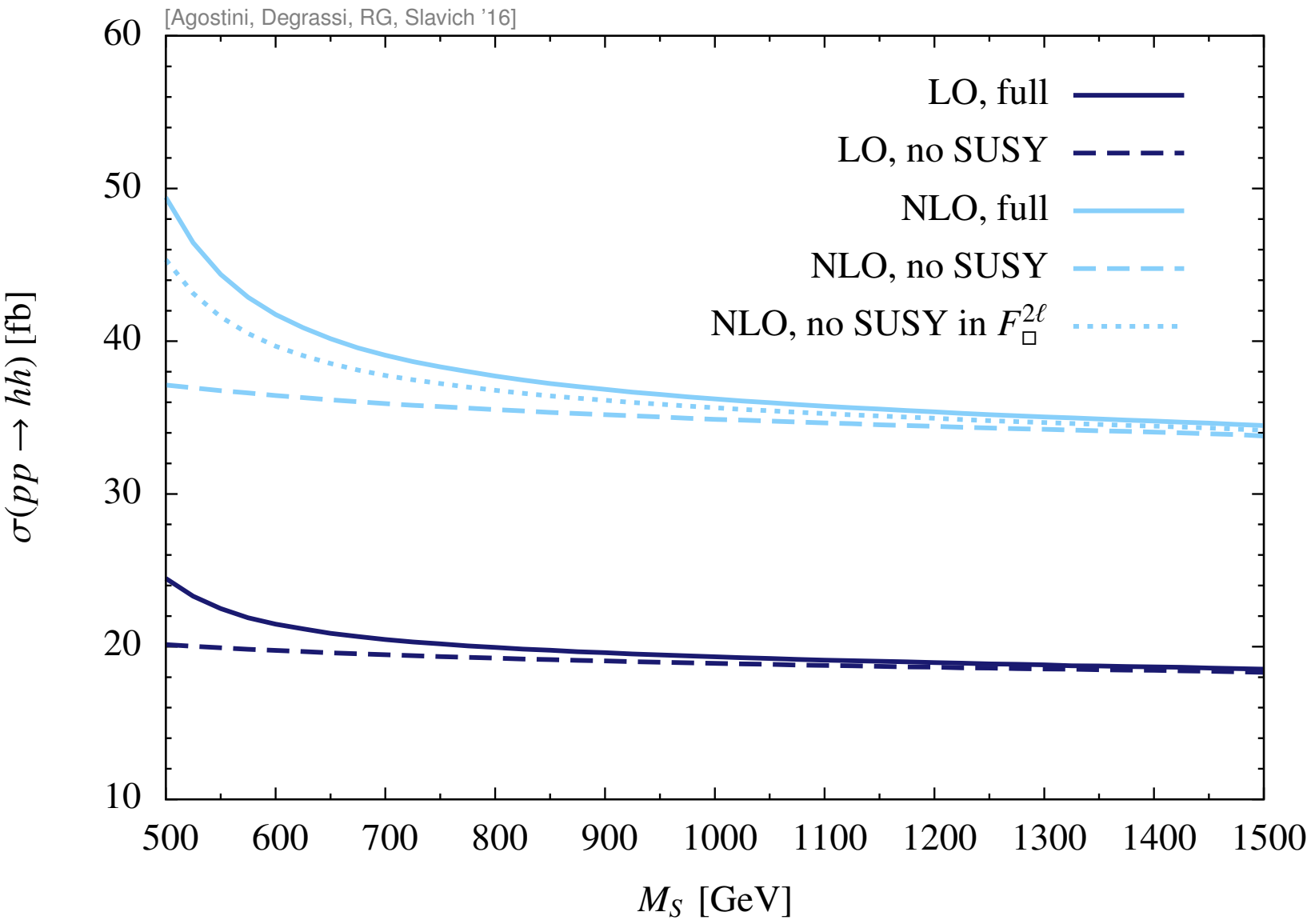
SBOTTOM CONTRIBUTIONS

- 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 $F_{\square}^{2\ell}$
$\sigma(pp \to hh)$ [fb]
60
50
40
30
20
10
500
600
700
800
900
1000
1100
1200
1300
1400
1500
M_S [GeV]

Conclusion

- Higgs pair production not only intersting 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: Non-negligible effect for stop masses below TeV scale

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Thanks for your attention!

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
$W^\pm, Z$

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

- Vector boson couplings to Higgs boson modified by $\xi = \frac{v^2}{f^2}$

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

- Fermion couplings and Higgs self-couplings depend on embedding of fermions.

Consider three models here:

- Pure Higgs non-linearities

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

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

- Fermionic resonances
  Explicit breaking of global symmetry by linear couplings of SM fermions to strong sector

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

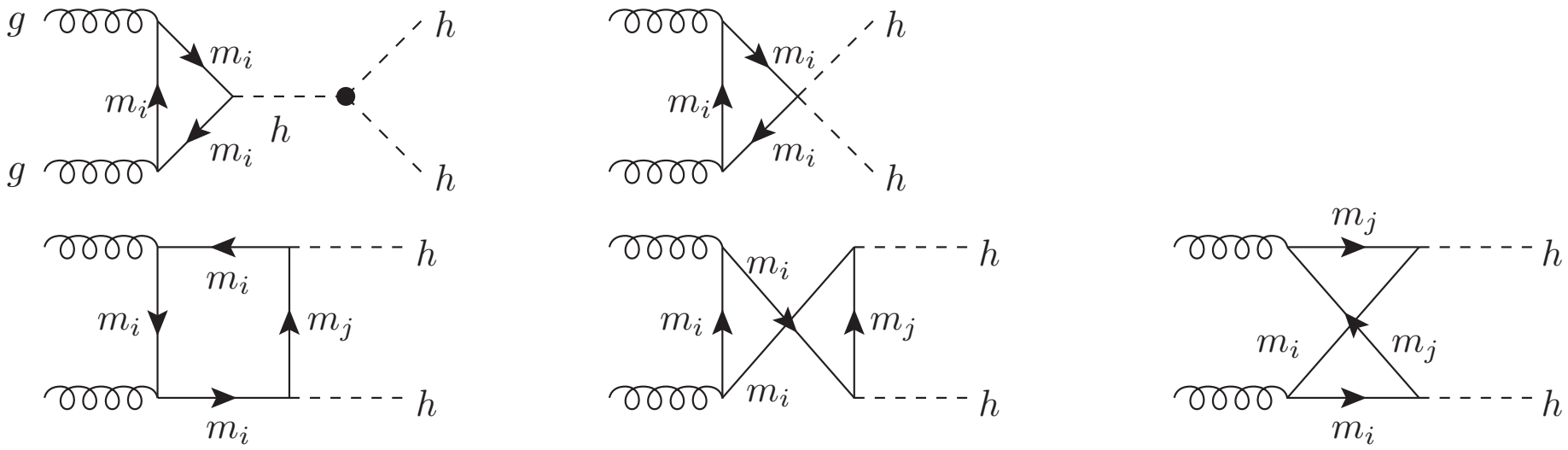
  Leads to mixing of elementary quark with strong sector, mass generation for the top quark.
- Fermions of strong sector in full multiplet ψ of $SO(5)$, e.g. 4, 5, 10, 14 -plets
  MCHM10: Antisymmetric representation (10) contains both bottom and top partner.

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

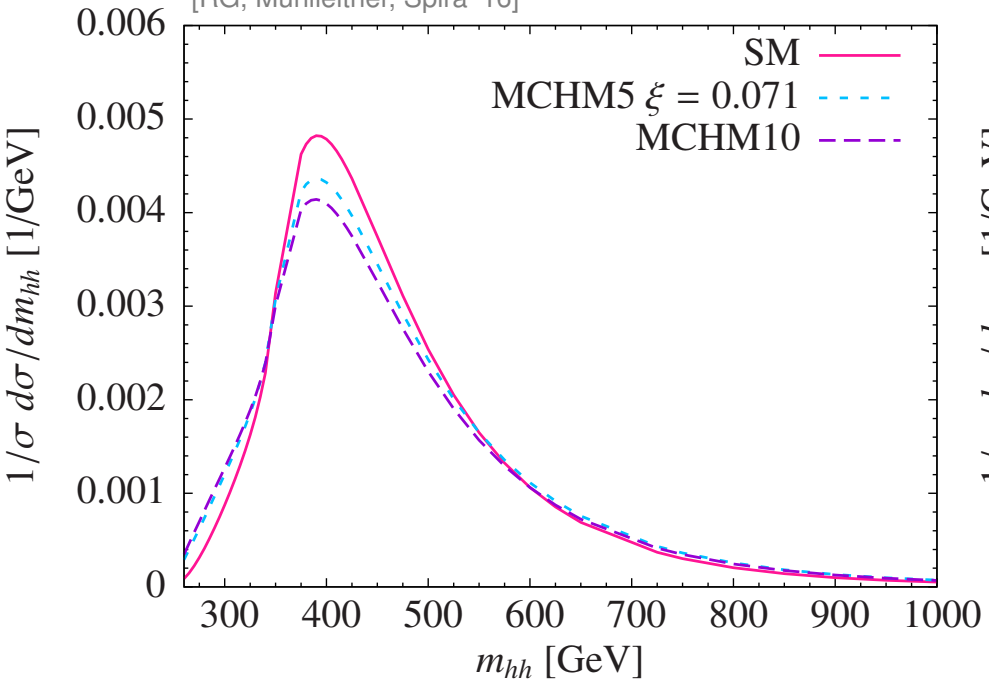
$\longrightarrow$ MCHM4:
we cannot expect to see any significant deviation in *HH* production
$\longrightarrow$ MCHM5:
we will first see new physics in form of deivations in Higgs coupling measurements

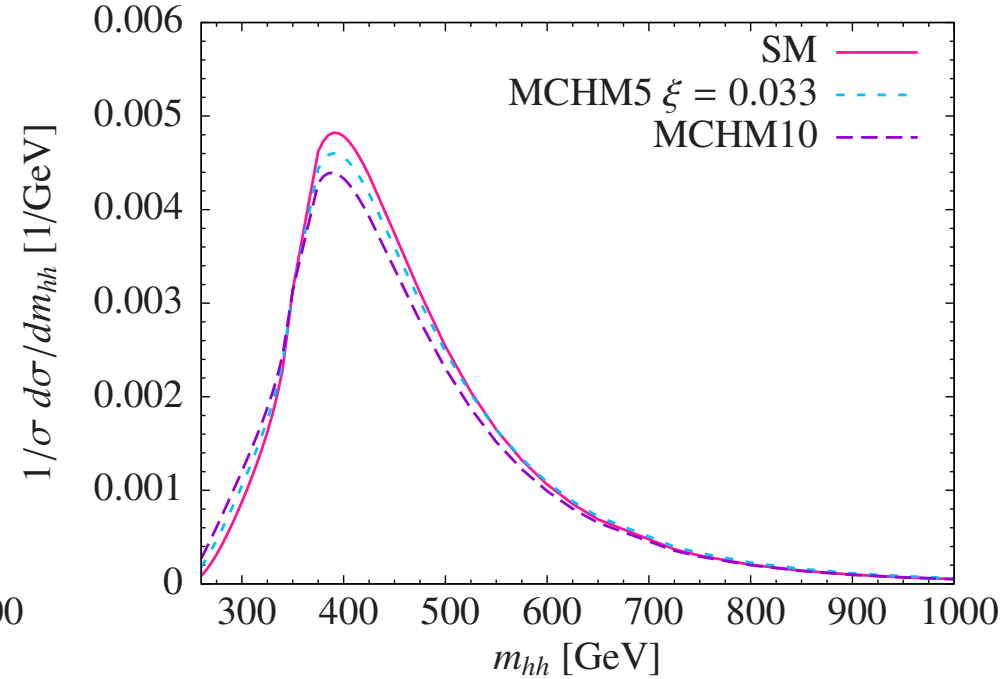
Feynman diagrams for Higgs pair production in Composite Higgs M



INVARIANT MASS DISTRIBUTIONS

[RG, Mühlleitner, Spira '16]





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

Higher order corrections

Gluon fusion:

- LO cross section known exactly in full mass dependence [Glover, van der Bij '88; Plehn, Spira, Zerwas '95]
- NLO QCD corrections known in the LET approximation ($\sqrt{\hat{s}} \ll m_t$): $K = \sigma_{NLO}/\sigma_{LO} \sim 1.7$ [Dawson, Dittmaier, Spira '98]
- Estimation of finite mass effects: $\mathcal{O}(10\%)$ [Grigo, Hoff, Melnikov, Steinhauser '13; Degrassi, Giardino, RG '16]
- Real contributions in full top mass dependence [Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro '14]
- Full NLO computation $\rightarrow$ top mass effects are -14% [Bobrowka, *et al.*'16]
- Threshold resummation at NNLL point to $M_{HH}/2$ as optimal scale [de Florian, Mazzitelli '15]
- NNLO QCD corrections in LET: increase of $\mathcal{O}(20\%)$ [de Florian, Mazzitelli '13; Grigo, Melnikov, Steinhauser '14]
- Top mass effects of NNLO QCD corrections are $\mathcal{O}(5\%)$ [Grigo, Hoff, Steinhauser '15]

BSM extensions:

Singlet-extended SM [Dawson, Lewis '15], 2-Higgs Doublet Model [Hespel, Lopez-Val, Vryonidou '14], SM with dimension six operators [RG, Mühlleitner, Spira, Streicher '15], MSSM [Dawson, Dittmaier, Spira '98;Agostini, Degrassi, RG, Slavich'16] and NMSSM [Agostini, Degrassi, RG, Slavich'16], Composite Higgs Model (with vector-like quarks) [RG, Mühlleitner, Spira'16]

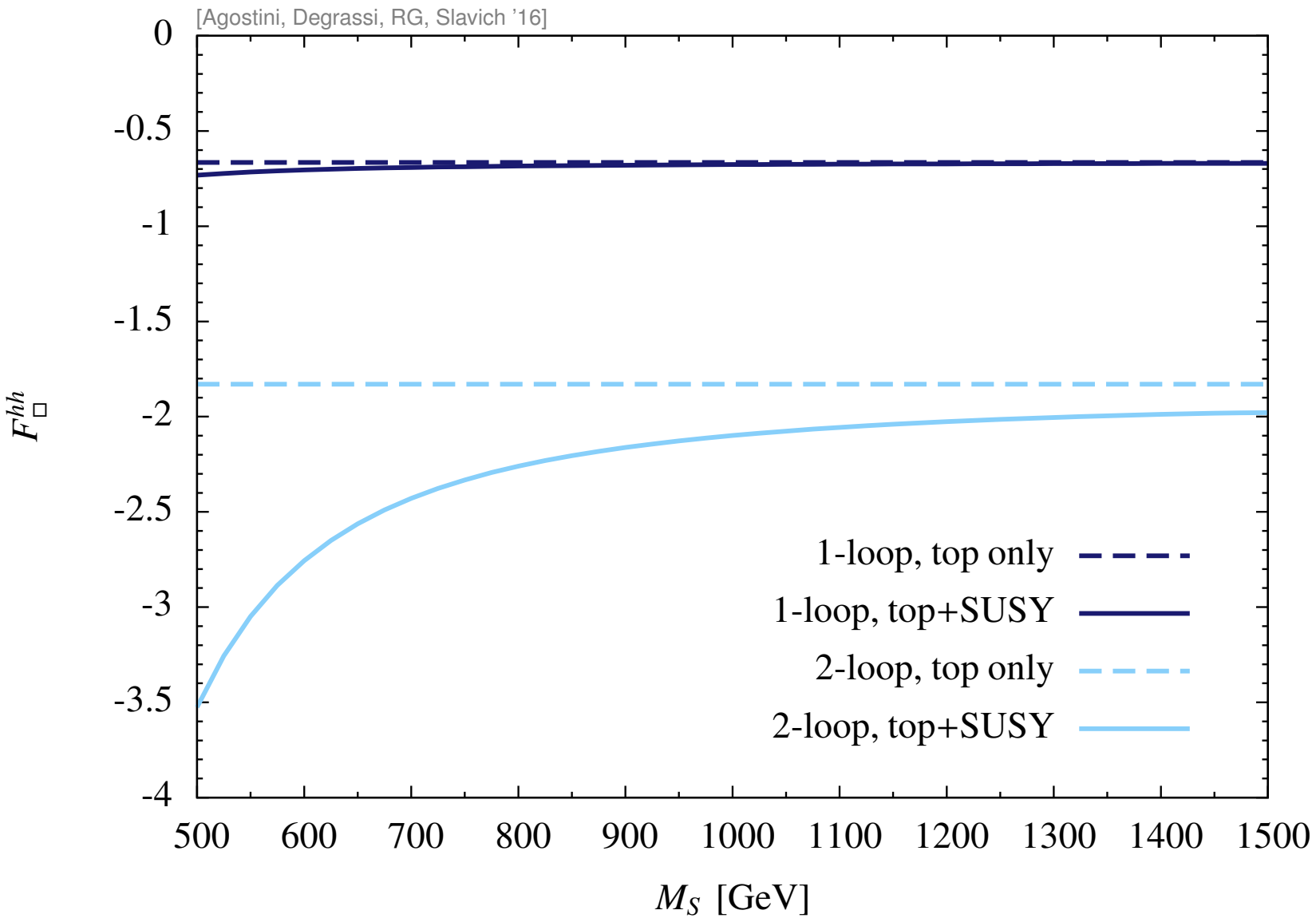
all at NLO QCD in the LET approximation (2-Higgs doublet model with exact real emission)

SUSY parameters of Plot

Parameters defined as on-shell parameters.

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

SQCD corrections: Box form factor



SM WITH DIM-6 OPERATORS

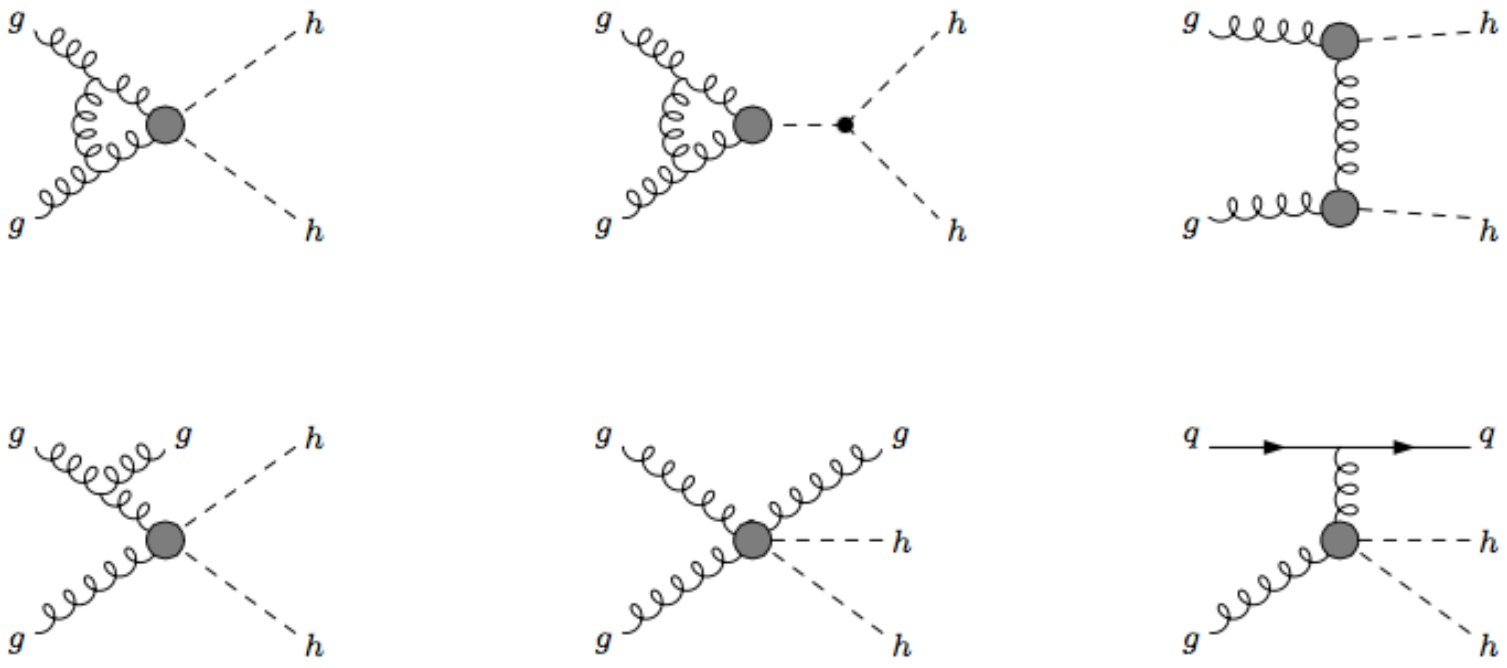
Non-linear effective Lagragian

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

- 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

QCD CORRECTIONS FOR SM WITH DIM-6 OPERATORS

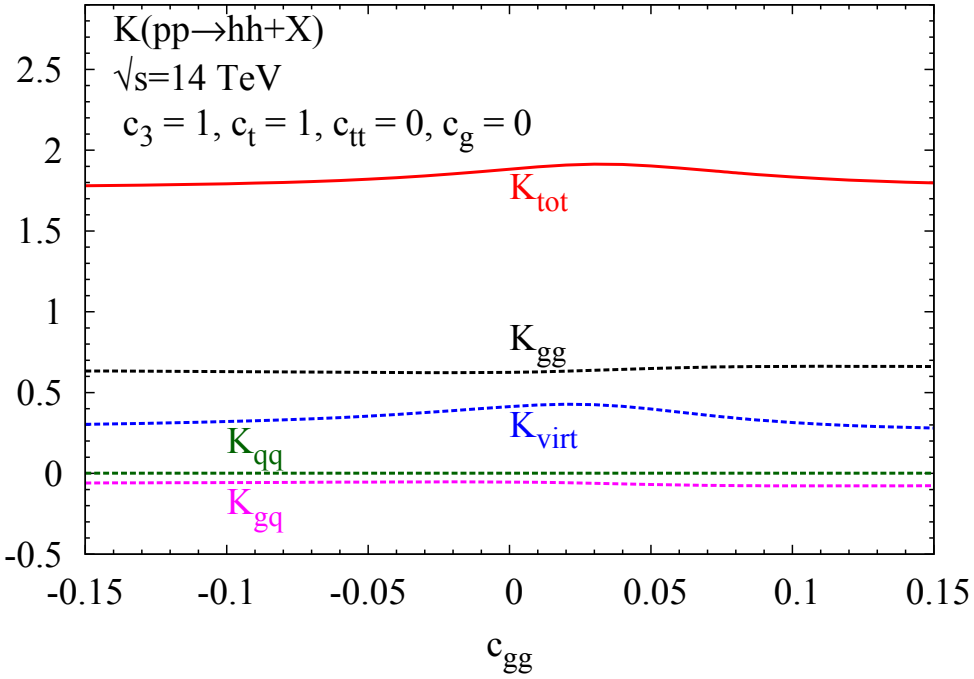
Computed in LET approximation.

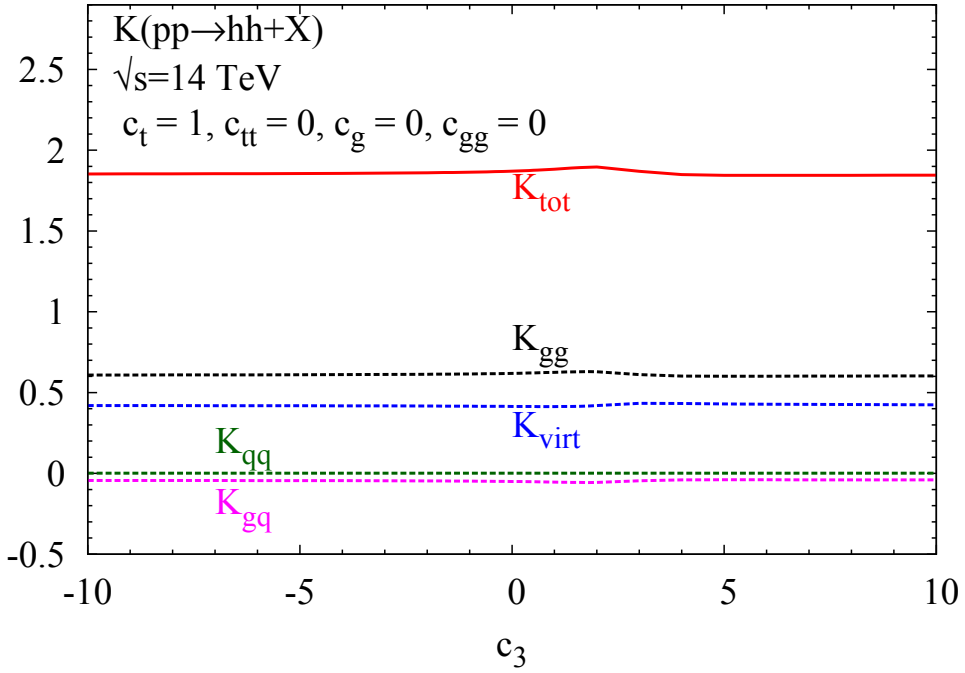


- Real corrections: LO cross section factors out. Can be taken over from SM.
- Virtual corrections: Third diagram needs to be re-evaluated. At NLO in the matching condition no factorization of LO cross section for non-zero c_g and c_{gg}.
- Results implemented in HPAIR [M. Spira's website], also for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

QCD CORRECTIONS FOR SM WITH DIM-6 OPERATORS

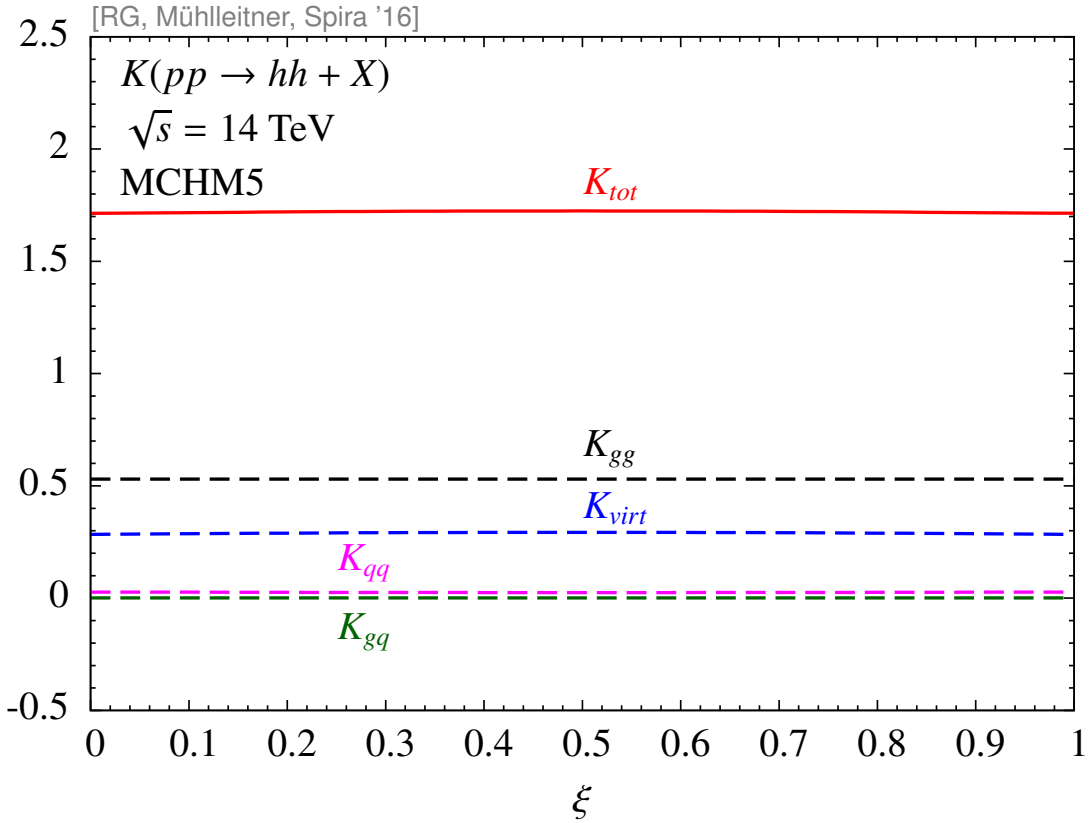
[RG, Mühlleitner, Spira, Streicher '15]





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

QCD corrections in Composite Higgs Models



Plot for MCHM5 (pure Higgs non-linearities)