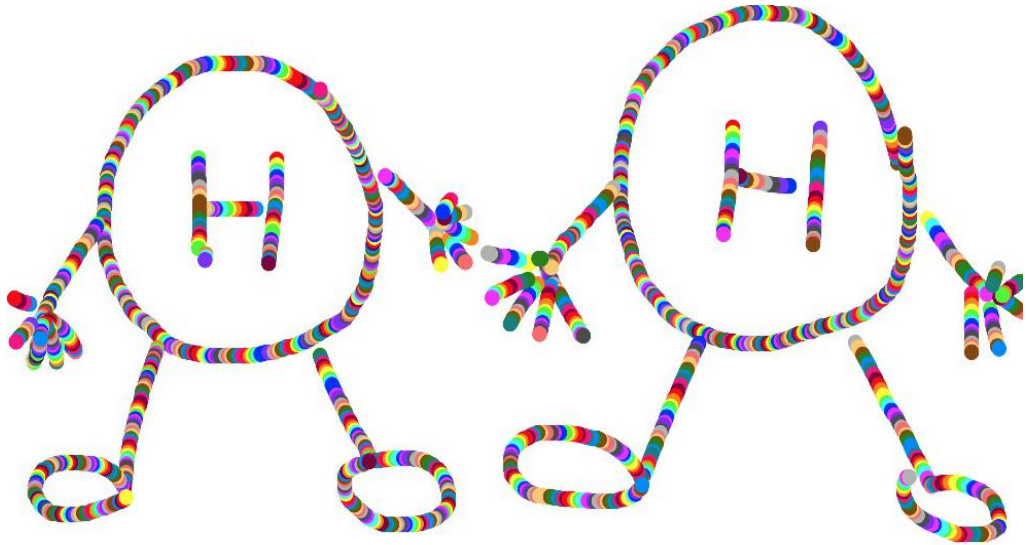
Higgs pair production beyond the Standard Model

Ramona Gröber

05.09.2015

INFN Sezione di Roma Tre



Outline

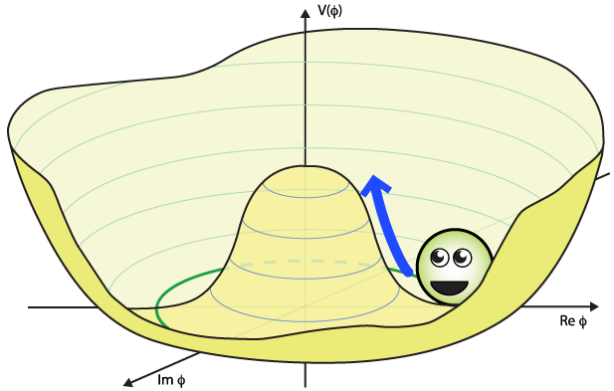
1. Two motivations
2. Higgs pair production in the SM
3. Higgs pair production in Composite Higgs Models
4. NLO QCD corrections to HH production with dim-6 operators

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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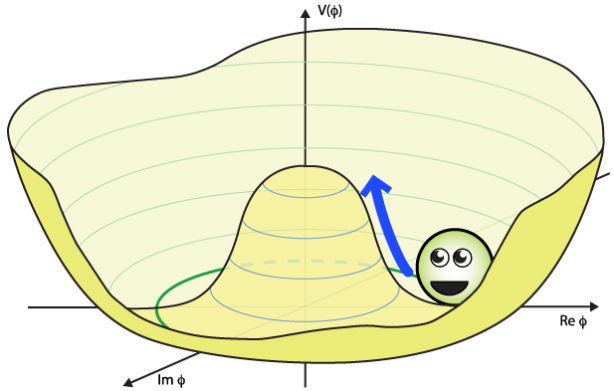

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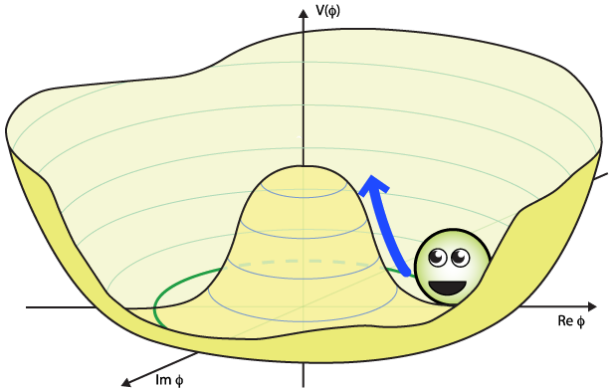

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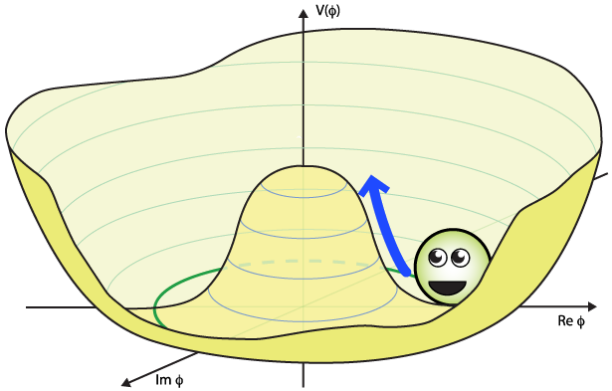

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Second Motivation

- 13% of Maggie's papers are on *HH* production or the trilinear Higgs coupling.
- Most probably more than 90 % of Maggie's papers are on BSM physics.
- Maggie's first paper is on *HH* production (in the SM and the MSSM).
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$\Longrightarrow$ Enough motivation to give this talk here.

Higgs pair production in the SM

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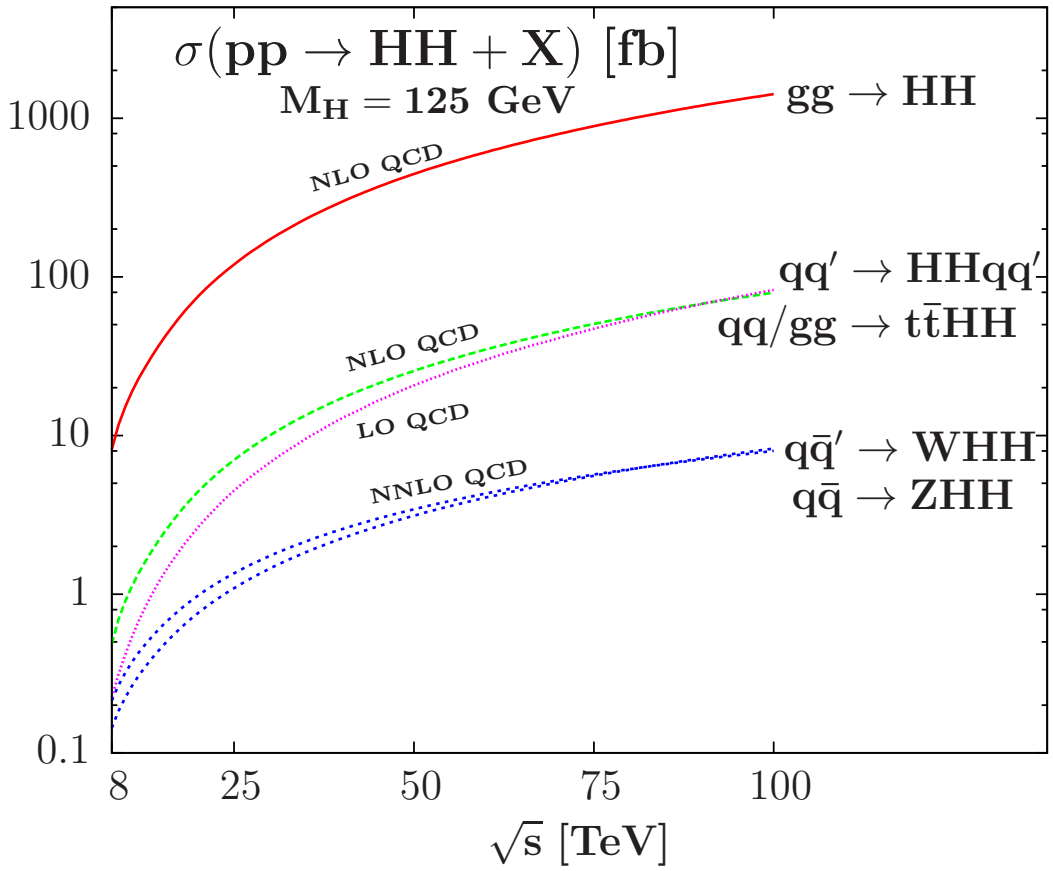

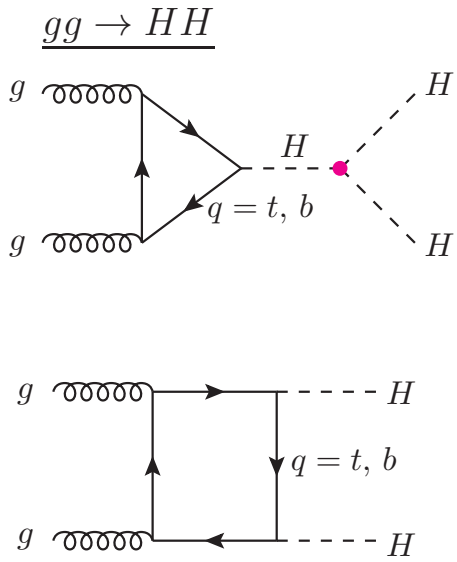

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- Can the process even be measured?

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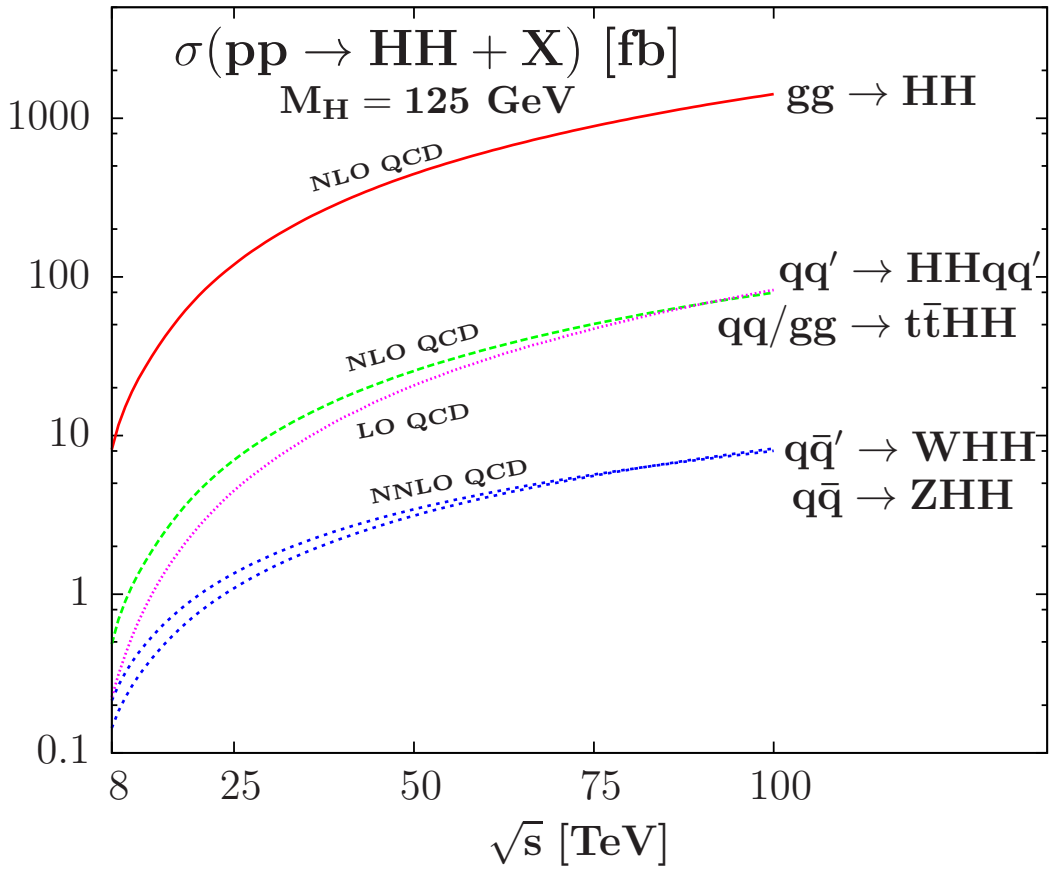

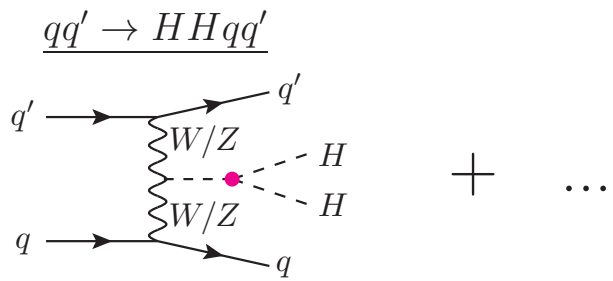

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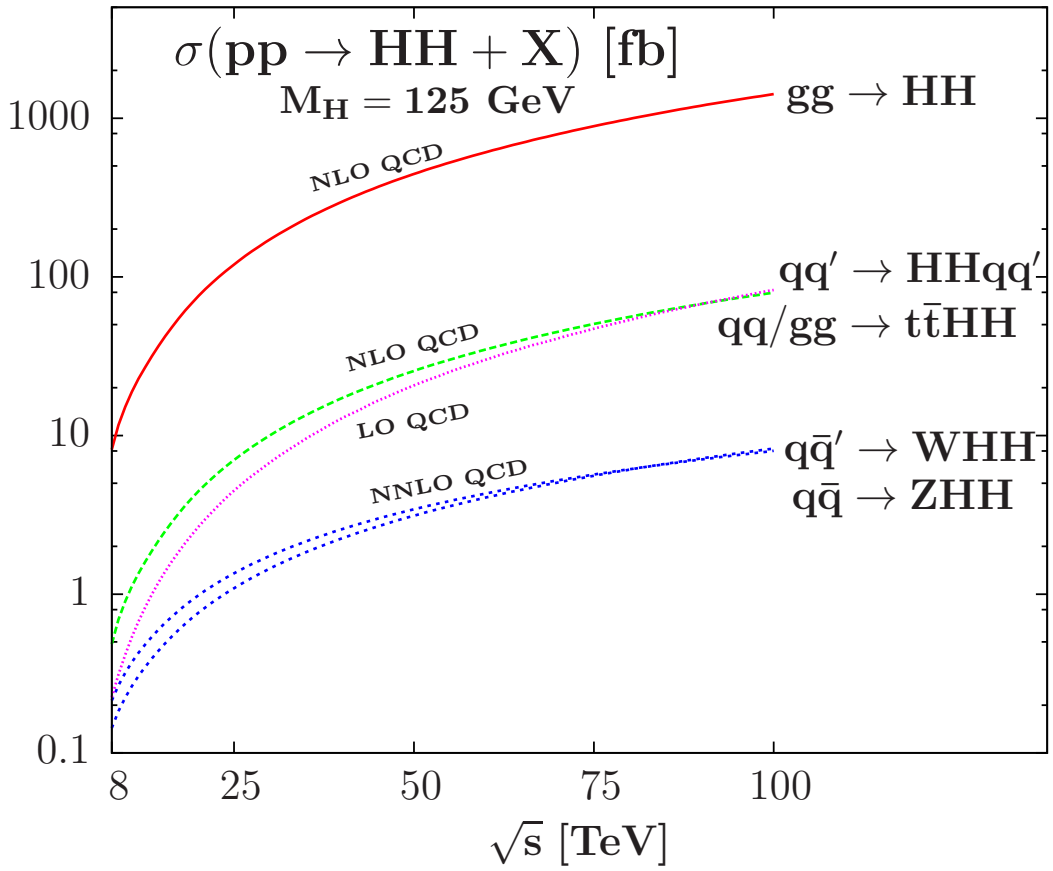
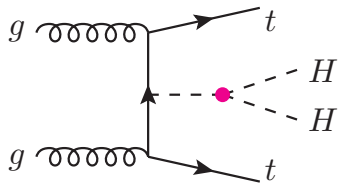


$q\bar{q}/gg \to t\bar{t}HH$



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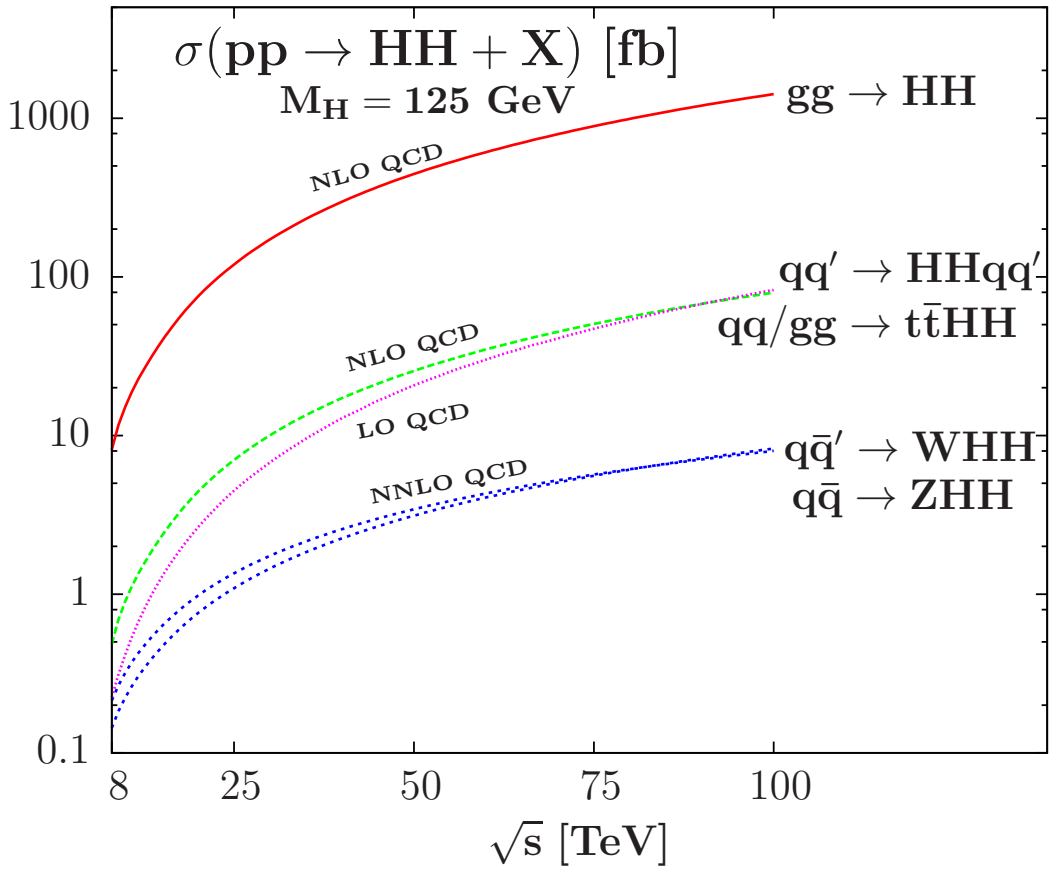
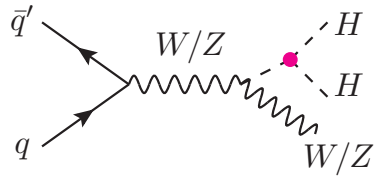


$q\bar{q}' \to ZHH/WHH$



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CAN WE MEASURE HH PAIR PRODUCTION?

- Consider only largest production process: Gluon fusion (at $\sqrt{s} = 14$ TeV)
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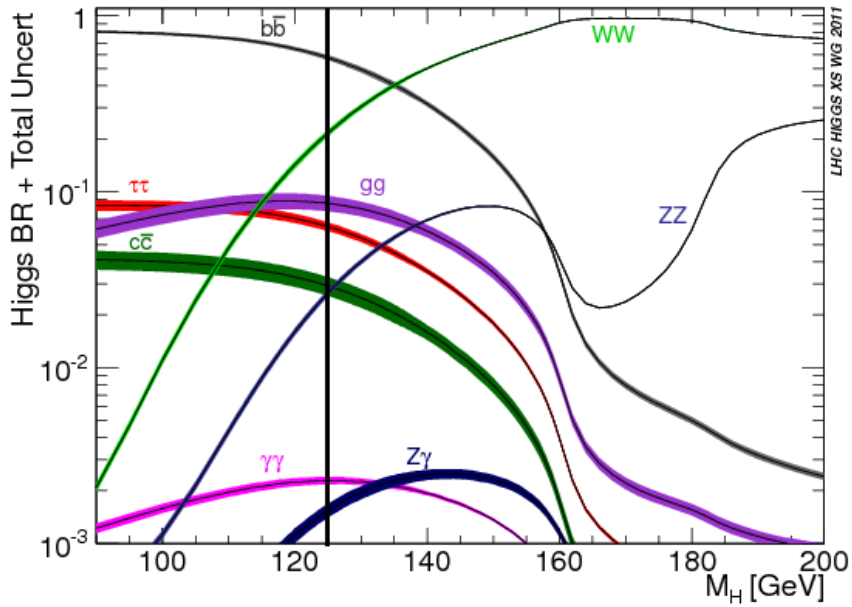

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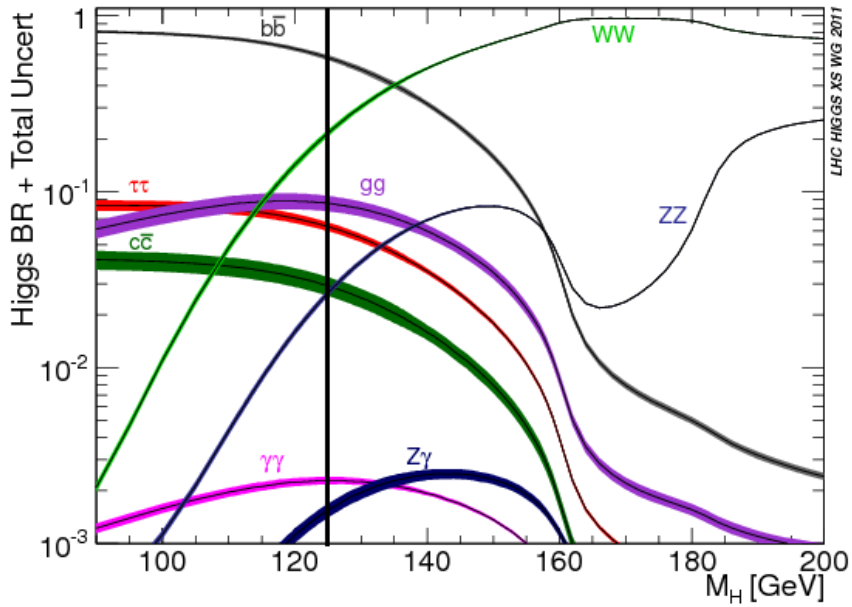

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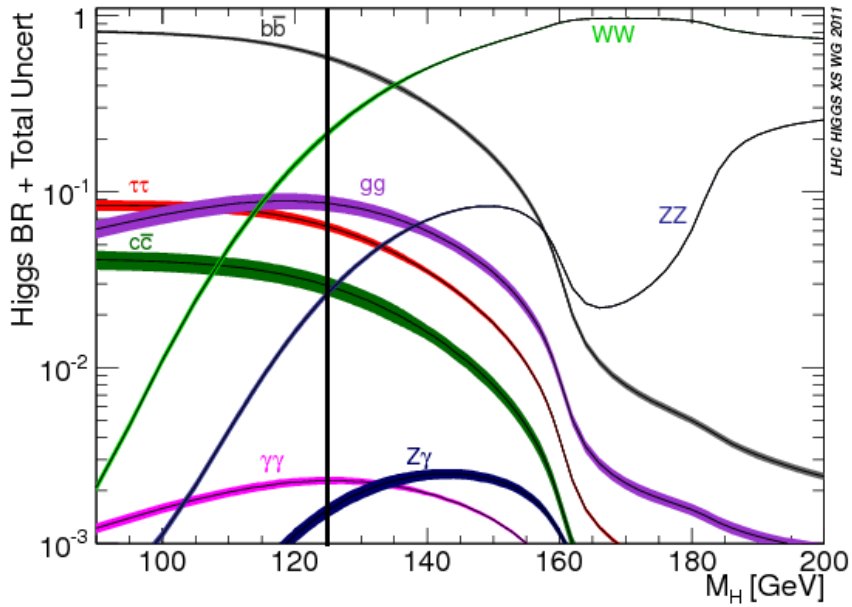

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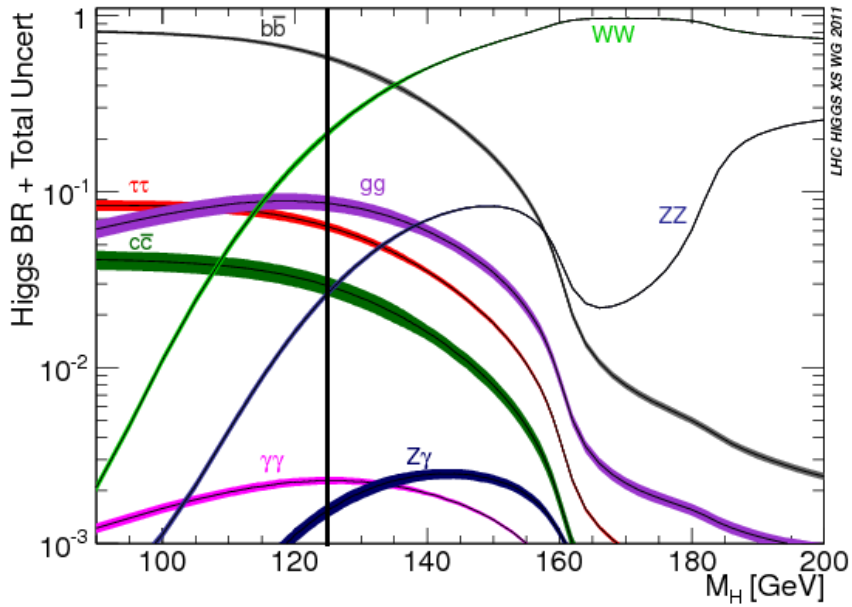

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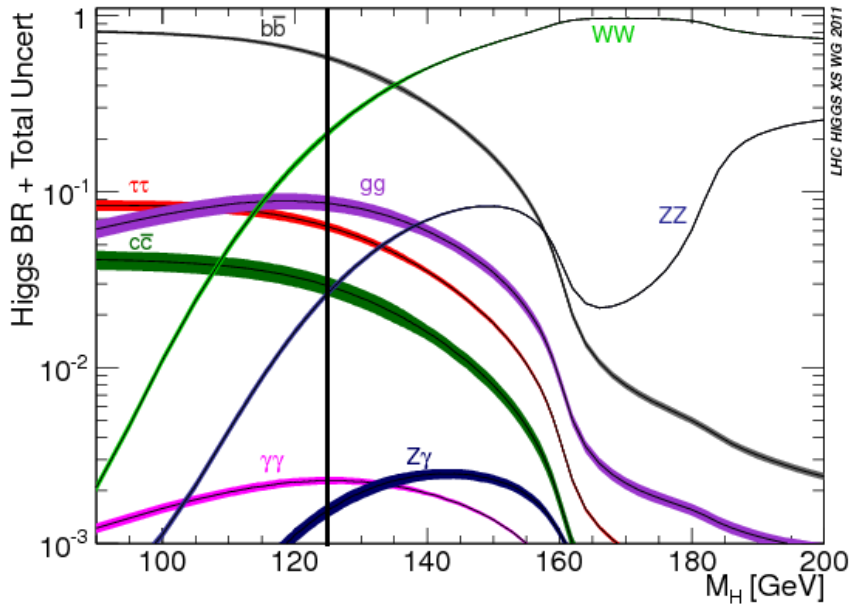

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Feasability studies:

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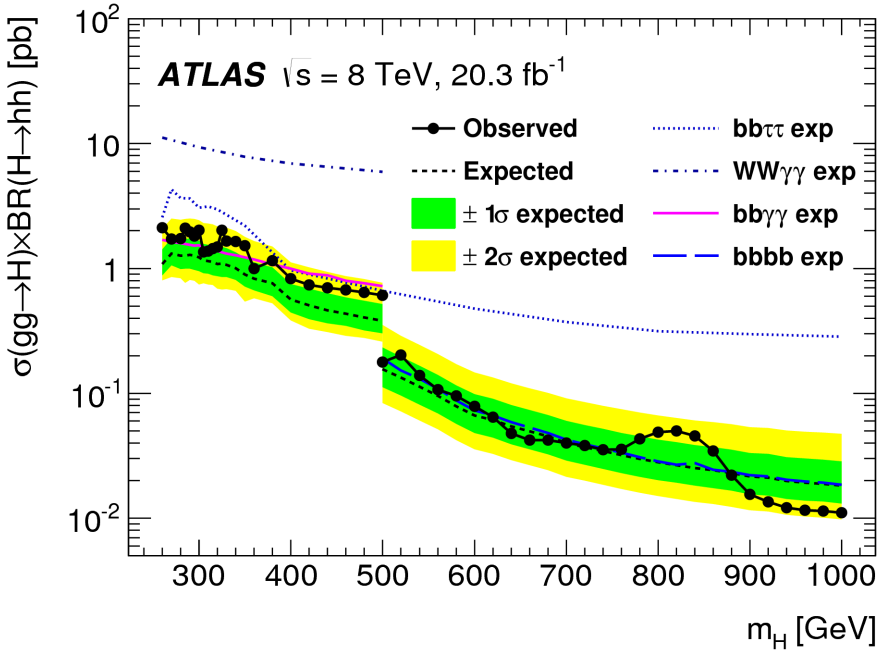
However, limits are and will be set on non-resonant and resonant BSM HH pair production [CMS 1503.04114, CMS-PAS-HIG-13-032; ATLAS 1406.5053, 1506.00285, 1509.04670]

- Non-resonant production: 70 σ_{SM} excluded [ATLAS 1509.04670]
- Limits on resonant 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; ...]
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  E.g. in SUSY or Composite Higgs Models [CHM: Gillioz, RG, Grojean, Mühlleitner, Salvioni '12; Dolan, Englert, Spannowsky '12]
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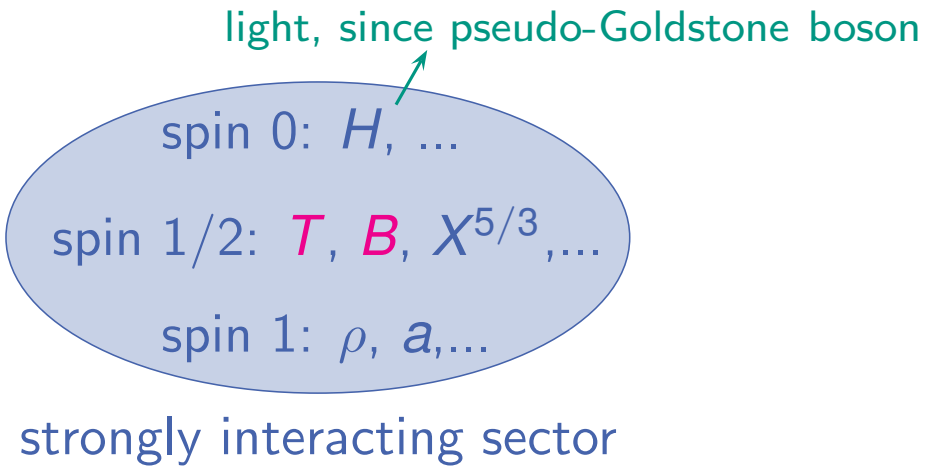
  E.g. in SUSY, [MSSM: Djouadi, Kilian, Mühlleitner, Zerwas '99; ... NMSSM: Ellwanger '13; Nhung, Mühlleitner, Streicher, Walz '13]
  Two Higgs Doublet Model [Baglio, Eberhardt, Nierste, Wiebusch '14; Arhrib, Benbrik, Chen, Guedes, Santos '09; ...]
  or non-minimal Composite Higgs Models
- Additional particles in the loop.
  E.g. in SUSY or Composite Higgs Models [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]

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

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

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

- Partial compositeness
  Explicit breaking of global symmetry by linear couplings of SM fermions to strong sector

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

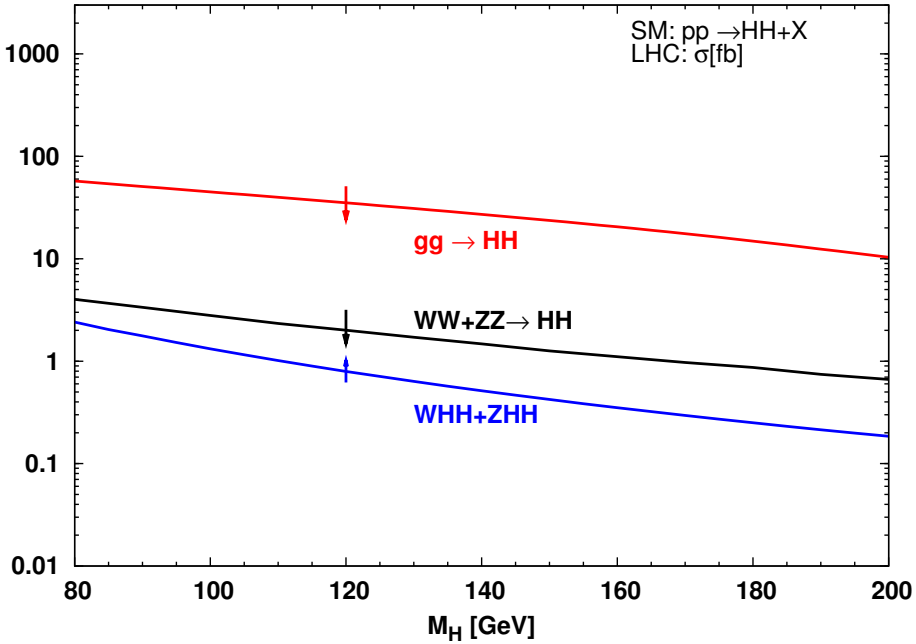
  Leads to mixing of elementary quark with strong sector, mass generation for the top quark.
- Fermions of strong sector in full multiplet ψ of $SO(5)$
- Couplings to Goldstone field Σ

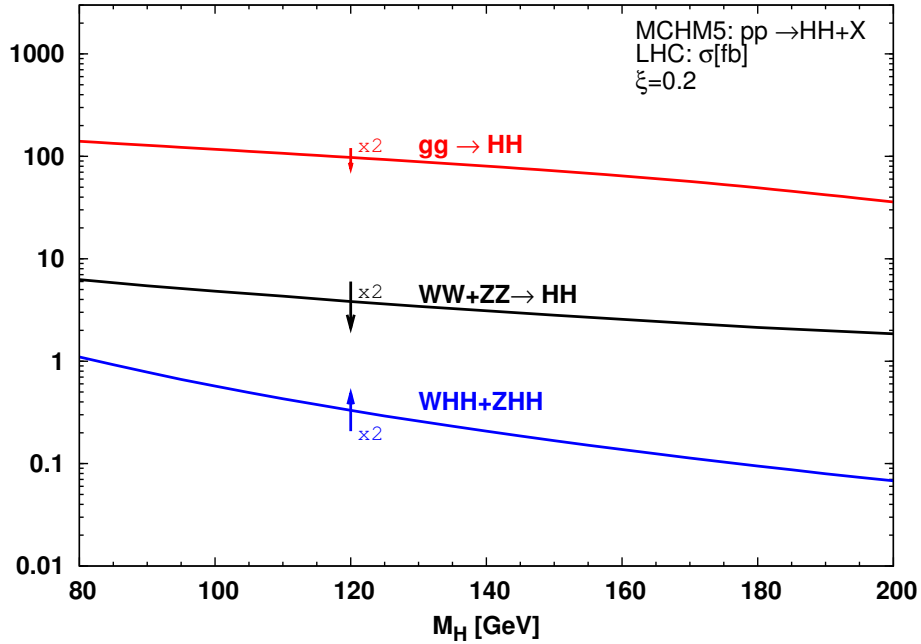
$$\mathcal{L} = -y\, f \left(\overline{\psi}\cdot\Sigma\right)\left(\Sigma^T\cdot\psi\right)$$

  introduces couplings $ht_i\bar{t}_j$, $hht_i\bar{t}_j$.

Composite Higgs Pair Production Cross Sections

[RG, Mühlleitner, '11]





SM

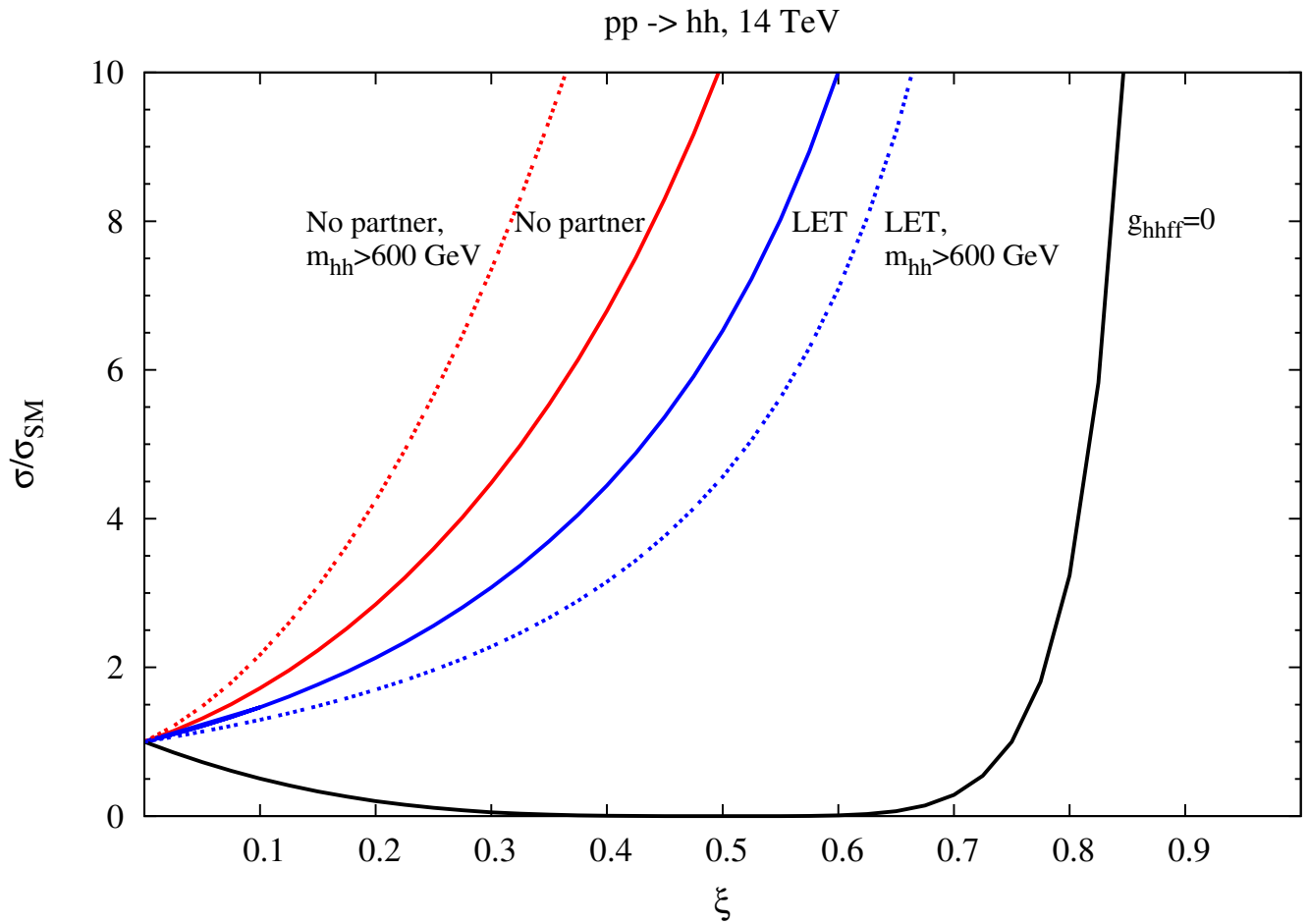
MCHM5, $\xi = 0.2$

gghh and *VBF* increased compared to SM

$hht\bar{t}$ COUPLING

- Strong increase of cross section compared to SM due to $t\bar{t}hh$ coupling

[Gillioz, RG, Grojean, Mühlleitner, Salvioni '12]



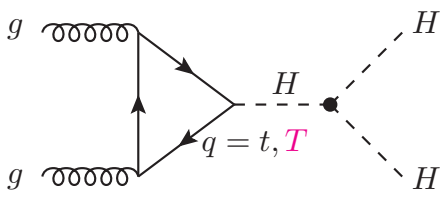
MCHM5:

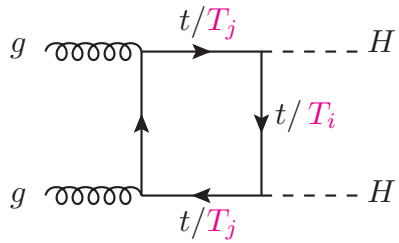
$$g_{hh\bar{t}t} = -4\xi \frac{g^{SM}_{ht\bar{t}}}{v}$$

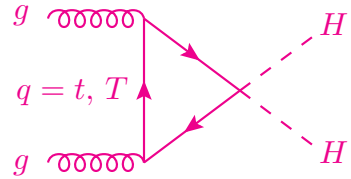
$$g_{h\bar{t}t} = \frac{1-2\xi}{\sqrt{1-\xi}} g^{SM}_{ht\bar{t}}$$

$$g_{hhh} = \frac{1-2\xi}{\sqrt{1-\xi}} g^{SM}_{hhh}$$

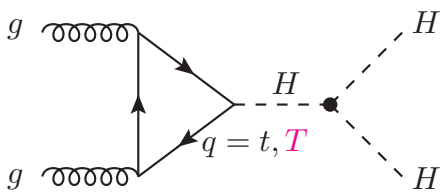
Higgs pair production in Composite Higgs Models

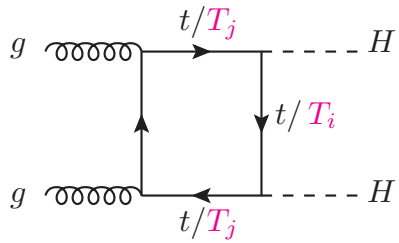


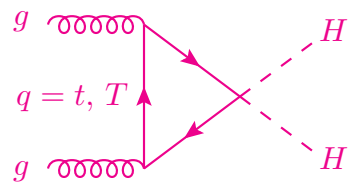




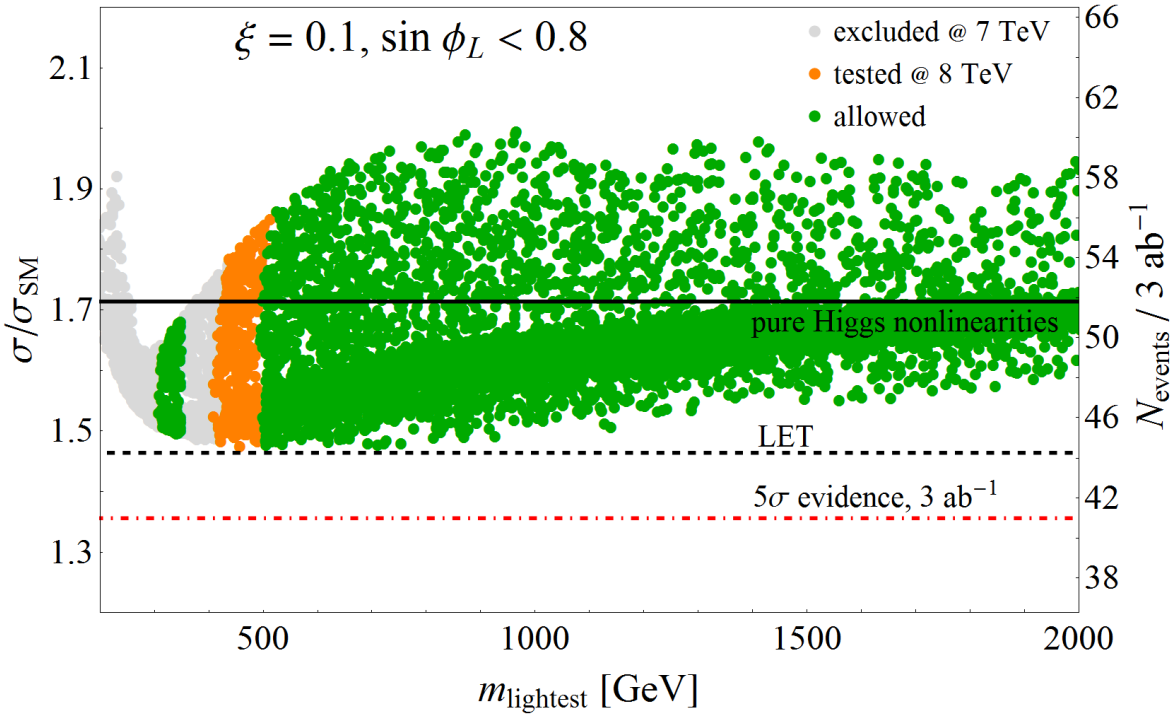
Higgs pair production in Composite Higgs Models







[Gillioz, RG, Grojean, Mühlleitner, Salvioni '12]

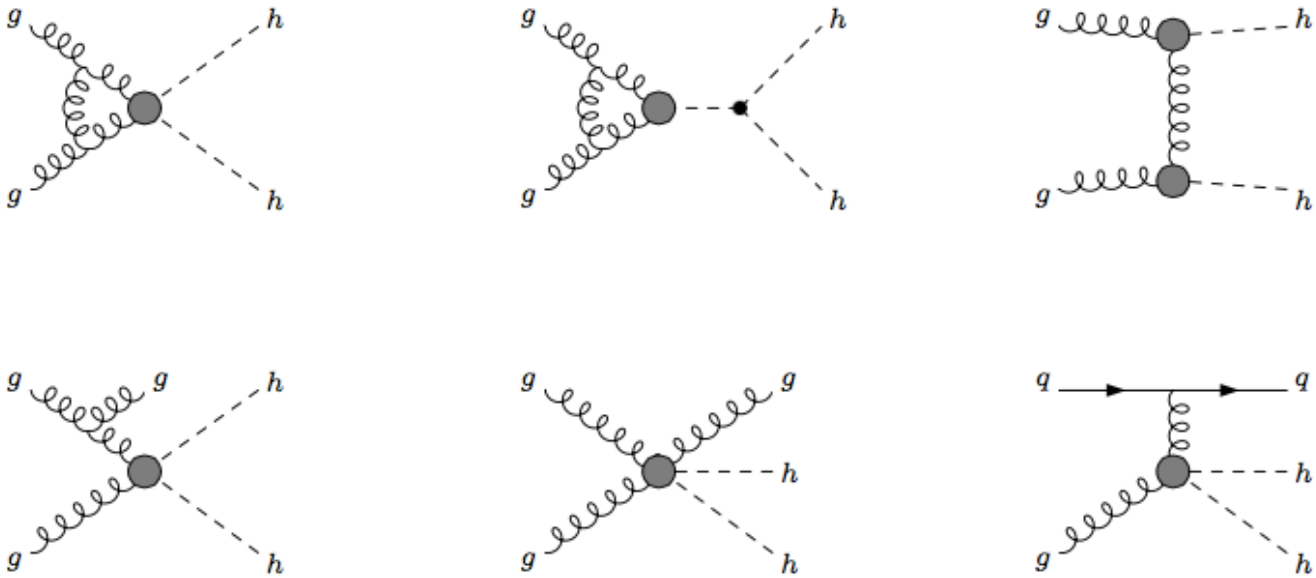


Fermions with masses below cut-off $\rightarrow$ cross section depends explicitly on the masses of new resonances. [Gillioz, RG, Grojean, Mühlleitner, Salvioni '12; Dolan, Englert, Spannowsky '12]

QCD CORRECTIONS TO *HH* PRODUCTION

In SM (for $gg \to HH$ at $\sqrt{s} = 14$ TeV) : [see Matthias talk]

- NLO in LET approximation ($\hat{s}, \hat{t}, \hat{u}, m_h^2 \ll m_t^2$): $K_{NLO} = 1.89$ [Dawson, Dittmaier, Spira '98]
- Top mass effects $\mathcal{O}(10\%)$ [Grigo, Hoff, Melnikov, Steinhauser '13; Frederix et al. '14]
- NNLO in LET approximation $K_{NNLO} = 2.27$ [de Florian, Mazzitelli '13; Grigo, Melnikov, Steinhauser '14]



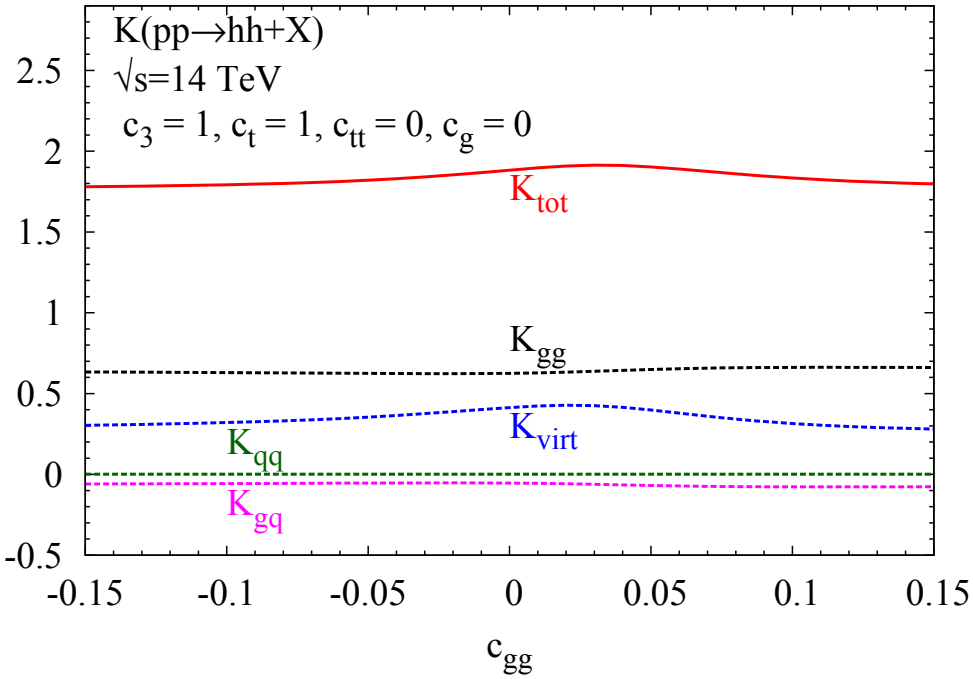
Here: [RG, Mühlleitner, Spira, Streicher '15]
NLO QCD corrections in LET approximation to *HH* production with dim-6 operators

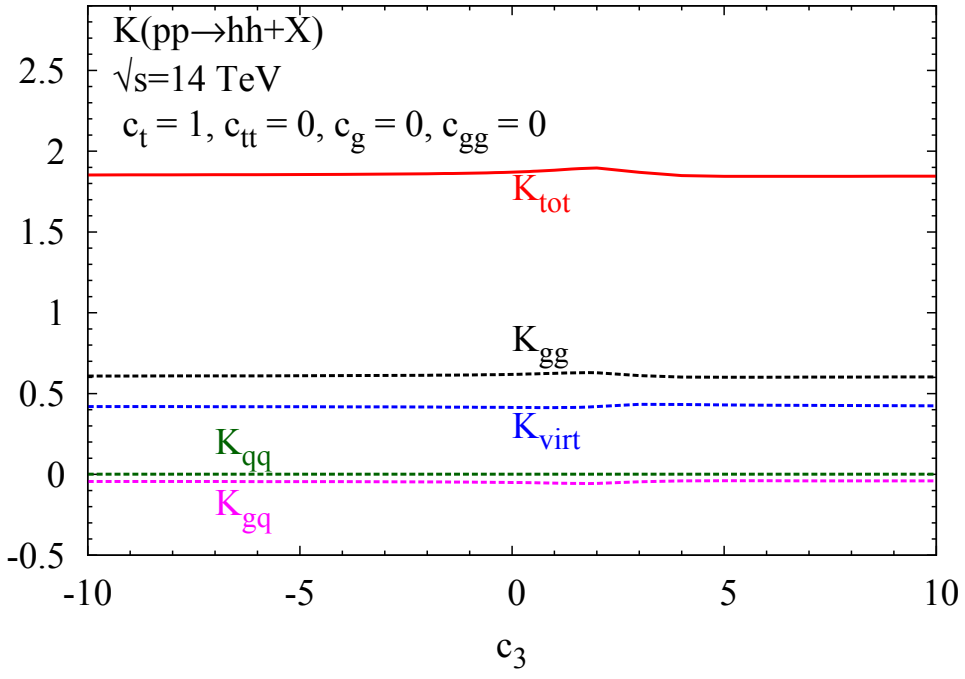
$$\mathcal{L} = -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \frac{3M_h^2}{v} h^3 + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} G^a_{\mu\nu} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$

- Real corrections: LO cross section factors out. Can be taken over from SM [Dawson, Dittmaier, Spira '98].
- Virtual corrections: Third diagram needs to be re-evaluated. c_g and c_{gg} do not contribute to matching of full to effective theory at NLO.
- Now available in `HPAIR` [Spira]

NLO QCD CORRECTIONS TO *HH* PRODUCTION WITH DIM-6 OPERATORS

[RG, Mühlleitner, Spira, Streicher '15]





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

Conclusion

- Measurement of Higgs pair production is not only interesting (yet difficult) to measure λ_{HHH} coupling, but can also constrain or even lead to a discovery of new physics.
- New physics can affect HH production in several ways
  Here:
  - Novel coupling $hht\bar{t}$ can lead to strong increase of σ
  - σ can be affected by new fermions in loop

Conclusion

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Thanks for your attention and ...

... let's stay tuned for the discovery of new physics (maybe in *HH* production)!