

# Higgs pair production in Strongly Interacting Models

Ramona Gröber | 28.04.2015

INFN SEZIONE DI ROMA TRE



# HIGGS PAIR PRODUCTION BEYOND THE STANDARD MODEL

How can the Higgs pair production cross section be influenced by new physics effects?

- **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, Mühleitner, Zerwas '99; ... NMSSM: Ellwanger '13; Nhung, Mühleitner, Streicher, Walz '13]

Two Higgs Doublet Model [Baglio, Eberhardt, Nierste, Wiebusch '14; ...]  
or non-minimal Composite Higgs Models

- **Additional particles in the loop.**

E.g. in SUSY or Composite Higgs Models [CHM: Gillioz, RG, Grojean, Mühleitner, Salvioni '12; Dolan, Englert, Spannowsky '12]

- **Novel couplings.**

E.g. in Composite Higgs Models and Little Higgs Models [CHM: RG, Mühleitner '10; ... LHM: Dib, Rosenfeld, Zerwekh '05]

# HIGGS PAIR PRODUCTION BEYOND THE STANDARD MODEL

How can the Higgs pair production cross section be influenced by new physics effects?

- **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, Mühleitner, Zerwas '99; ... NMSSM: Ellwanger '13; Nhung, Mühleitner, Streicher, Walz '13]

Two Higgs Doublet Model [Baglio, Eberhardt, Nierste, Wiebusch '14; ...]  
or non-minimal Composite Higgs Models

- **Additional particles in the loop.**

E.g. in SUSY or Composite Higgs Models [CHM: Gillioz, RG, Grojean, Mühleitner, Salvioni '12; Dolan, Englert, Spannowsky '12]

- **Novel couplings.**

E.g. in Composite Higgs Models and Little Higgs Models [CHM: RG, Mühleitner '10; ... LHM: Dib, Rosenfeld, Zerwekh '05]

# HIGGS PAIR PRODUCTION BEYOND THE STANDARD MODEL

How can the Higgs pair production cross section be influenced by new physics effects?

- **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; ...]

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; ... LHM: Dib, Rosenfeld, Zerwekh '05]

# HIGGS PAIR PRODUCTION BEYOND THE STANDARD MODEL

How can the Higgs pair production cross section be influenced by new physics effects?

- **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; ...]

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; ... LHM: Dib, Rosenfeld, Zerwekh '05]

# HIGGS PAIR PRODUCTION BEYOND THE STANDARD MODEL

How can the Higgs pair production cross section be influenced by new physics effects?

- **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; ...]

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; ... LHM: Dib, Rosenfeld, Zerwekh '05]

# HIGGS PAIR PRODUCTION BEYOND THE STANDARD MODEL

How can the Higgs pair production cross section be influenced by new physics effects?

- **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; ...]

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; ... LHM: Dib, Rosenfeld, Zerwekh '05]

**My talk:** Composite Higgs Models, Littlest Higgs Model, Universal Extra dimensions

**Christoph's talk:** Weakly-interacting Models

**Florian's talk:** EFT for HH

## OUTLINE

- 1 Models
- 2 Novel couplings
- 3 New loop particles
- 4 How well are the top partners described by EFT?
- 5 Can the SM  $K$ -factor for QCD corrections be taken over?
- 6 Can BSM scenarios also be accessible in other production modes such as VBF or  $t\bar{t}hh$ ?



# Models

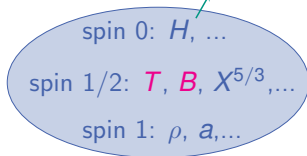
# COMPOSITE HIGGS MODELS (CHM)

$u$	$c$	$t$
$d$	$s$	$b$
$e^-$	$\mu^-$	$\tau^-$
$\nu_e$	$\nu_\mu$	$\nu_\tau$

elementary particles

gluon $g$
photon $\gamma$
$W^\pm, Z$

light, since pseudo-Goldstone boson



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

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

- Description by non-linear  $\sigma$ -model

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

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:

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

- $h\bar{f}f$ ,  $hhh$ , ... couplings depend on fermion embedding

- Fermion embeddings in  $SO(5)$ :  
spinorial (4), fundamental (5), antisymmetric (10), ...
- SM fermion masses introduced by partial compositeness

Lagrangian for an  $SO(5)$  multiplet  $\psi$  transforming in the fundamental representation:

$$\mathcal{L} = \frac{f^2}{2} (D_\mu \Sigma)^T (D^\mu \Sigma) + i \bar{q}_L \not{D} q_L + i \bar{t}_R \not{D} t_R + i \bar{b}_R \not{D} b_R + \bar{\psi} (i \not{D} - M_5) \psi +$$

$$- y f (\bar{\psi} \cdot \Sigma) (\Sigma^T \cdot \psi) - (\lambda_L \bar{q}_L Q_R + \lambda_R \bar{T}_L t_R)$$

- Mixing of all 2/3 charged top-partners with top quark
- Term with coupling  $y$  introduces  $t_i \bar{t}_j h$ ,  $t_i \bar{t}_j h h$ , ... couplings

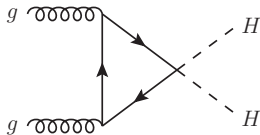
### Littlest Higgs Models with $T$ parity:

- Coset  $SU(5)/SO(5)$  with  $[SU(2) \times U(1)]^2$  gauged.
- New scalars, but  $T$  parity forbids  $hh\phi$  couplings  $\Rightarrow$  no resonant  $hh$  production.
- Top partners  $T$  to cancel quadratic top mass dependence in Higgs mass.
- $hh\bar{t}t$  coupling.

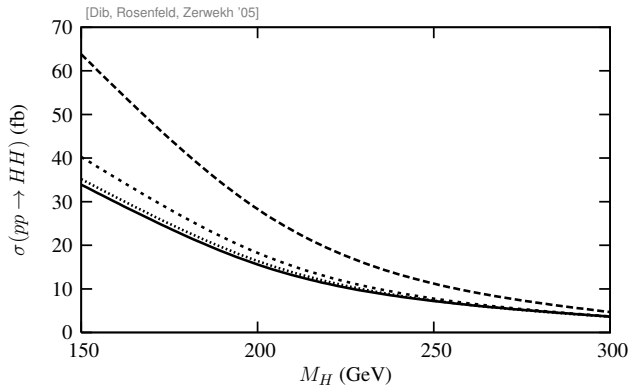
### Universal extra dimensions

- 5D Lagrangian compactified on circle with radius  $R$
- 4D description: Kaluza Klein tower of states, SM particles correspond to zero component
- All fields propagate in extra dimension  $\rightarrow$  approximate KK number conservation  $\rightarrow$  KK excitations are pair-produced
- two degenerate top partners per level with  $m_{T_n} = \sqrt{m_t^2 + n^2/R^2}$

# Novel couplings

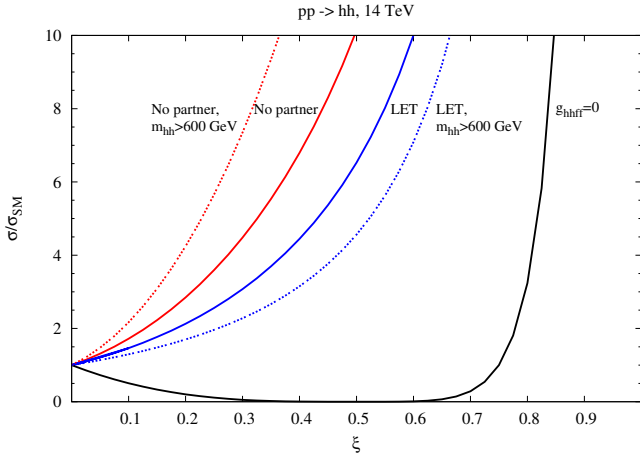


- Strong increase of cross section compared to SM due to  $t\bar{t}hh$  coupling



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

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



MCHM5:

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

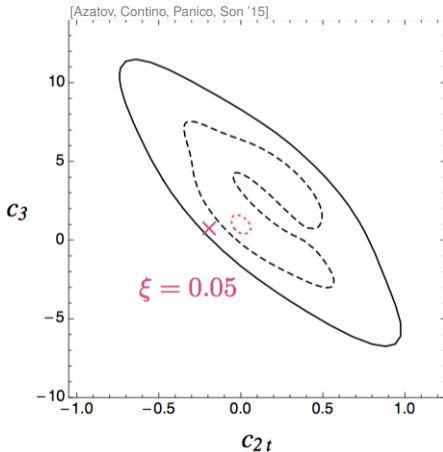
$$g_{h\bar{t}t} = \frac{1-2\xi}{\sqrt{1-\xi}} g_{h\bar{t}t}^{SM}$$

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



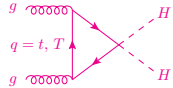
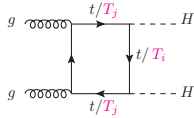
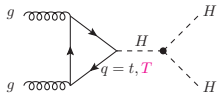
# ACCESSABILITY OF $t\bar{t}hh$ COUPLING

- Study focused on CHMs [Contino, Ghezzi, Moretti, Panico, Piccini, Wulzer '12]  
⇒  $t\bar{t}hh$  coupling can be constrained with higher precision than  $hhh$  coupling
- Newer study in context of EFT [Azatov, Contino, Panico, Son '15]

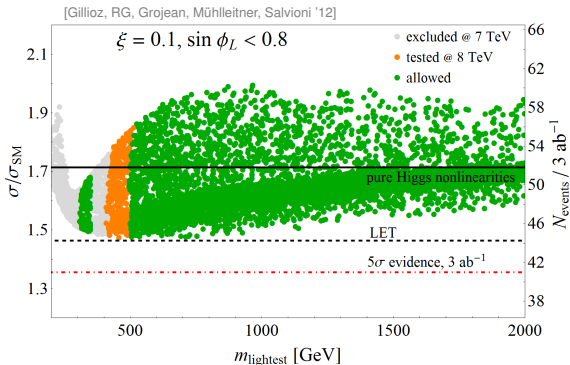
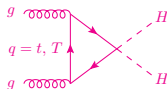
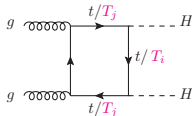
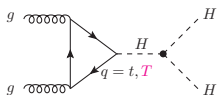


# New fermions in the loop

# HIGGS PAIR PRODUCTION IN COMPOSITE HIGGS MODELS

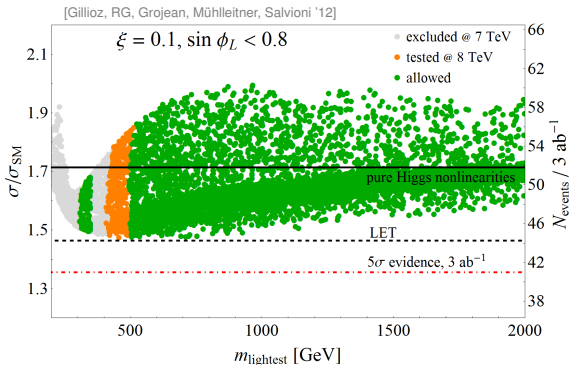
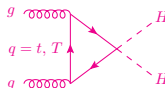
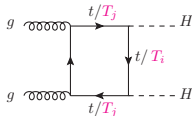
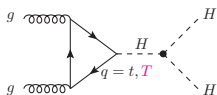


# HIGGS PAIR PRODUCTION IN COMPOSITE HIGGS MODELS



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]

# HIGGS PAIR PRODUCTION IN COMPOSITE HIGGS MODELS



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]

Can  $hh$  give us any information on the spectrum of the loop particles?

## CAN $hh$ GIVE US ANY INFORMATION ON THE LOOP PARTICLES?

What can we get from single Higgs?

## What can we get from single Higgs?

In many CHMs/LHMs: Top partners simultaneously shift  $t\bar{t}h$  coupling and lead to  $hgg$  contact interaction [Falkowski '07; Low, Vichi '10; Azatov, Galloway '11; Gillioz, RG, Grojean, Mühlleitner, Salvioni '12] **Need measurement to lift degeneracy:**

- $t\bar{t}h$  production
- $hj$  [Azatov, Paul '13; Banfi, Martin, Sanz '13; Grojean, Salvioni, Schlaffer, Weiler '13]
- Off-shell measurements  $gg \rightarrow ZZ$  [Azatov, Grojean, Paul, Salvioni '14]

# CAN $hh$ GIVE US ANY INFORMATION ON THE LOOP PARTICLES?

## What can we get from single Higgs?

In many CHMs/LHMs: Top partners simultaneously shift  $t\bar{t}h$  coupling and lead to  $hgg$  contact interaction [Falkowski '07; Low, Vichi '10; Azatov, Galloway '11; Gillioz, RG, Grojean, Mühlleitner, Salvioni '12] Need measurement to lift degeneracy:

- $t\bar{t}h$  production
- $hj$  [Azatov, Paul '13; Banfi, Martin, Sanz '13; Grojean, Salvioni, Schlaffer, Weiler '13]
- Off-shell measurements  $gg \rightarrow ZZ$  [Azatov, Grojean, Paul, Salvioni '14]

## What can we get from double Higgs?



## What can we get from single Higgs?

In many CHMs/LHMs: Top partners simultaneously shift  $t\bar{t}h$  coupling and lead to  $hgg$  contact interaction [Falkowski '07; Low, Vichi '10; Azatov, Galloway '11; Gillioz, RG, Grojean, Mühlleitner, Salvioni '12] **Need measurement to lift degeneracy:**

- $t\bar{t}h$  production
- $hj$  [Azatov, Paul '13; Banfi, Martin, Sanz '13; Grojean, Salvioni, Schlaffer, Weiler '13]
- Off-shell measurements  $gg \rightarrow ZZ$  [Azatov, Grojean, Paul, Salvioni '14]

## What can we get from double Higgs?

- $c_g$  (in EFT approach) can be further constrained by  $hh$  [Azatov, Contino, Panico, Son '15]
- For chiral fermions and scalars,  $M_{HH}$  distributions change.
  - For vector-like fermions as in CHM and LHM, they do not. [Dawson, Ismail, Low '15]

# CAN $hh$ GIVE US ANY INFORMATION ON THE LOOP PARTICLES?

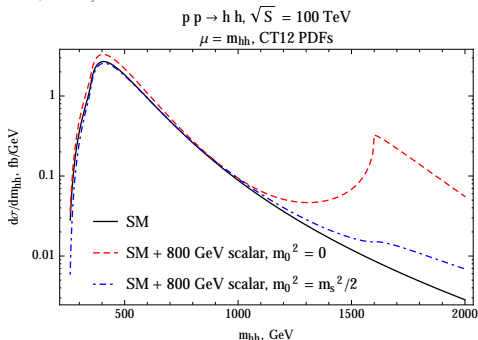
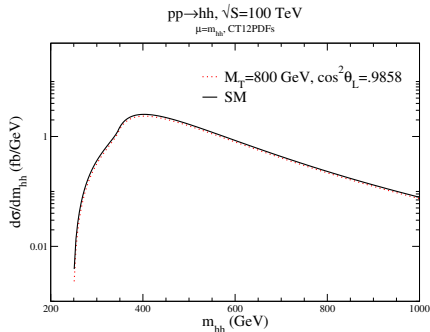
## What can we get from double Higgs?

- $c_g$  (in EFT approach) can be further constrained by  $hh$
- For chiral fermions and scalars,  $M_{HH}$  distributions change.
- For vector-like fermions as in CHM and LHM, they do not.

[Azatov, Contino, Panico, Son '15]

[Dawson, Ismail, Low '15]

[Dawson, Ismail, Low '15]



# CAN $hh$ GIVE US ANY INFORMATION ON THE LOOP PARTICLES?

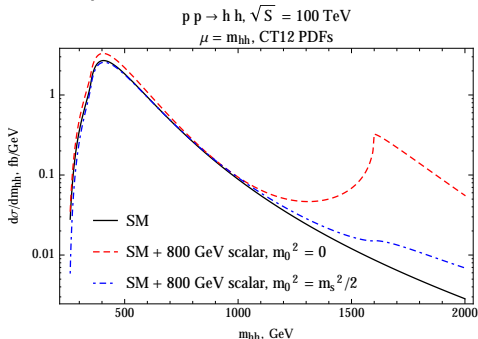
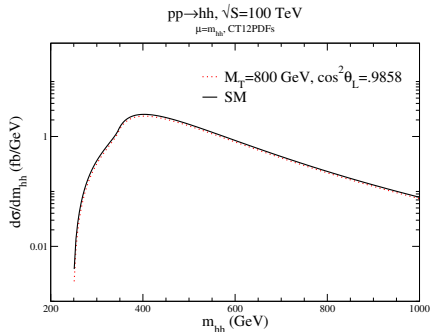
## What can we get from double Higgs?

- $c_g$  (in EFT approach) can be further constrained by  $hh$
- For chiral fermions and scalars,  $M_{HH}$  distributions change.
- For vector-like fermions as in CHM and LHM, they do not.

[Azatov, Contino, Panico, Son '15]

[Dawson, Ismail, Low '15]

[Dawson, Ismail, Low '15]



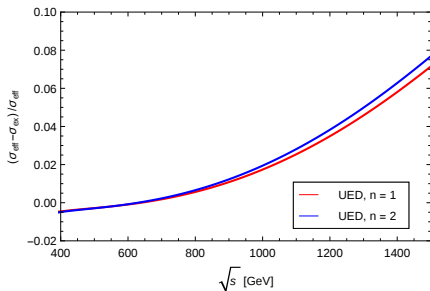
However the measurement of distributions is difficult.

# HOW WELL ARE THE TOP PARTNERS DESCRIBED BY EFT?

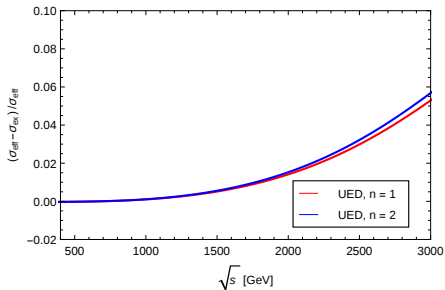
## Universal extra dimensions

[Edelhäuser, Knochel, Steeger '15]

$1/R = 1000$  GeV



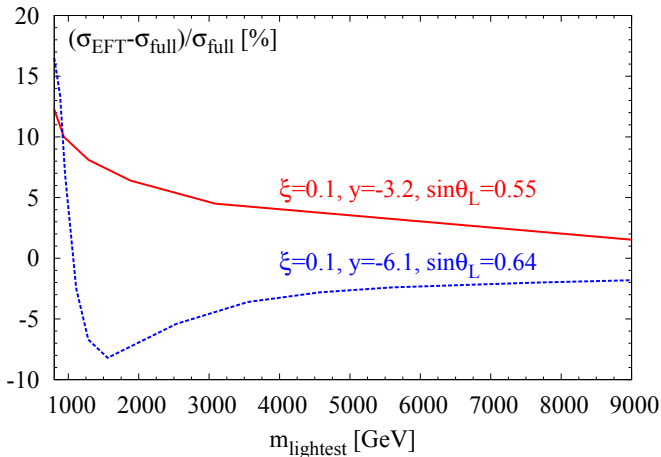
$1/R = 2000$  GeV



And for CHMs and LHM?

There are diagrams with both top quark and heavy top partner.

## HOW WELL ARE THE TOP PARTNERS DESCRIBED BY EFT?



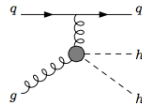
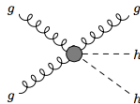
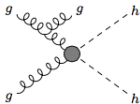
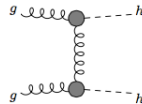
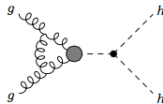
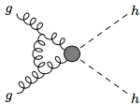
This very preliminary analysis shows: If we do not find top partners before we measure  $hh$  the deviations between EFT/full are small.

Can SM  $K$ -factor for QCD corrections  
be taken over?

# QCD CORRECTIONS

Computed in LET approximation.

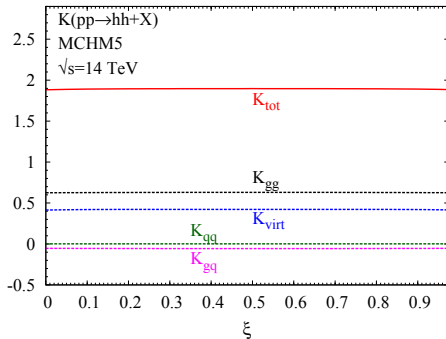
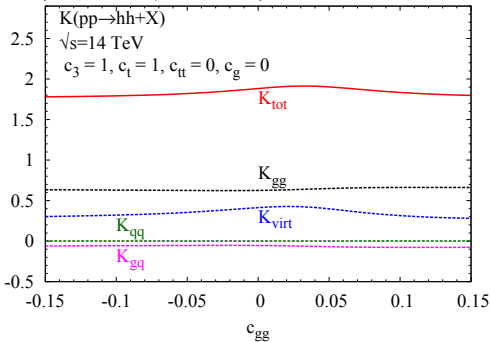
$$\mathcal{L} = -m_t \bar{t}t \left( c_t \frac{h}{v} + c_{tt} \frac{h}{2v^2} \right) - c_3 \frac{1}{6} \frac{3M_h^2}{v} h^3 + \frac{\alpha_s}{\pi} G^{a\mu\nu} G_{\mu\nu}^a \left( c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$



- **Real corrections:** LO cross section factors out. Can be taken over from SM.
- **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  $c_{gg}$ .

# QCD CORRECTIONS

[RG, Mühlleitner, Spira, Streicher '15]



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



Can BSM scenarios also be accessible  
in other production modes such as VBF  
or  $t\bar{t}hh$ ?

## hh production via vector boson fusion:

- In CHMs: Increase of cross section with partonic c.m. energy [Contino, Grojean, Moretti, Piccini, Rattazzi '10]  
Coupling modifications in CHMs weaken the destructive interference between the different contributions [Gröber, Mühlleitner '10]
- Process gives access to  $hhVV$  coupling
- Ongoing studies, seems difficult but can give bounds on anomalous  $hhVV$  coupling [Bondu, Contino, Gouzevitch, Massironi, Oliveira, Rojo '14]
- Study of resonant production of KK graviton in warped extra-dimensional models finds low significances [Belyaev, Bondu, Massironi, Oliveira, Rosenfeld, Sanz '14]

## $t\bar{t}hh$ :

- For  $\lambda > \lambda_{SM}$   $t\bar{t}hh$  can even be the leading channel
- First study in [Englert, Krauss, Spannowsky, Thompson '14]
- Studies in context of BSM models? Also  $t\bar{t}hh$  coupling accessible?

- Interesting  $hh$  phenomenology of strongly-interacting models including novel couplings and new fermions in the loops.
- Gluon fusion cross section enhanced in Composite Higgs Model and Littlest Higgs Model; reduced in Universal Extra Dimension.

Thanks for your attention!