HH studies at 100 TeV

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IFAE

'Higgs & BSM at 100 TeV'

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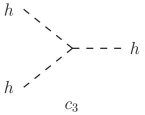
Based on A. Azatov, R. Contino, GP, M. Son arXiv:1502.00539

Introduction

Why $gg \to HH$ production?

Obvious answer:

- measure the **Higgs trilinear coupling!**



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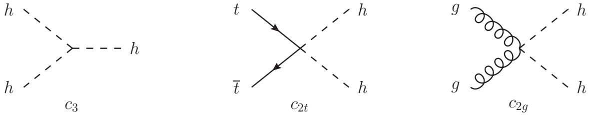

Less obvious answers:

- extract **non-linear couplings** not accessible in single-Higgs measurements (eg. $hh\bar{t}t$ and $h^2 G_{\mu\nu} G^{\mu\nu}$)

- improve **single-Higgs measurements** (in particular $\bar{t}th$)

- probe the **strength of EWSB dynamics** at scales $E \gg m_h$

Interpretation strategy

Several new-physics effects can affect double Higgs production

- modifications of Higgs trilinear coupling
- modification of single Higgs couplings
- new non-linear interactions

❖ Corrections to **all** these couplings can arise **simultaneously**

❖ Assuming that only h^3 is modified limits the validity of the fit

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❖ Proper **interpretation strategy** needed

➢ identify a parametrization of NP effects

➢ perform a global analysis

Note: strategy similar to single Higgs measurements, where distortions of all couplings are taken into account in the fits

The effective parametrization for a Higgs doublet

Assumptions:

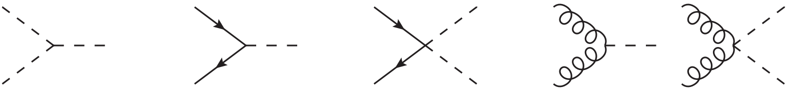
- Higgs is an $\mathrm{SU}(2)_L$ doublet
- derivative expansion
- expansion in Higgs powers

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_6 + \Delta\mathcal{L}_8 + \cdots$$

[Buchmuller and Wyler; ... Giudice at al.; Grzadkowski et al.]

$$\Delta\mathcal{L}_6 \supset \frac{\overline{c}_H}{2v^2}[\partial_\mu(H^\dagger H)]^2 + \frac{\overline{c}_u}{v^2} y_u H^\dagger H \overline{q}_L H^c u_R - \frac{\overline{c}_6}{v^2}\frac{m_h^2}{2v^2}(H^\dagger H)^3 + \frac{\overline{c}_g}{m_w^2} g_s^2 H^\dagger H G_{\mu\nu} G^{\mu\nu}$$

Relevant vertices:



$c_3 \simeq 1 - \frac{3}{2}\overline{c}_H + \overline{c}_6$ $\quad$ $c_t \simeq 1 - \frac{\overline{c}_H}{2} - \overline{c}_u$ $\quad$ $c_{2t} \simeq -\frac{1}{2}(\overline{c}_H + 3\overline{c}_u)$ $\quad$ $c_g = c_{2g} = \overline{c}_g \left(\frac{4\pi}{\alpha_2}\right)$

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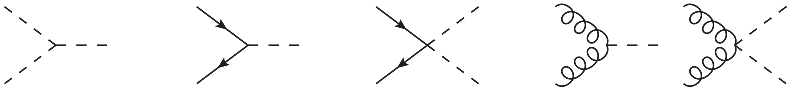

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The same operator modifies the top Yukawa and generates an anomalous $\bar{t}thh$ vertex

The effective parametrization

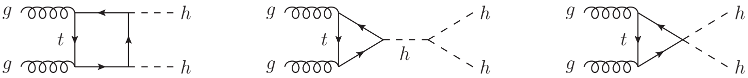
The effective vertices correspond to the interactions in the unitary gauge

$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$

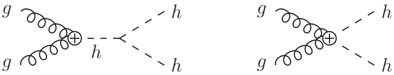
This parametrization is more general than the previous one

- valid for a generic Higgs (even not part of a doublet)
- resums the expansion in Higgs powers (if Higgs is a doublet)

Double Higgs production via gluon fusion



$\sim c_t^2 \times const.$ $\qquad$ $\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$ $\qquad$ $\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



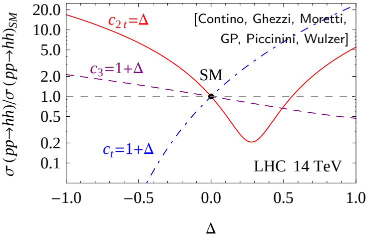
$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$ $\qquad$ $\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

- Different behaviour at high energy $\sqrt{\hat{s}} = m_{hh}$
- Dependence on Higgs trilinear suppressed at high energy
  - Events at threshold more sensitive to Higgs trilinear, events at large m_{hh} more important to determine the other operators

Sensitivity to the Higgs trilinear

Dependence on Higgs trilinear c_3 **much smaller** than on c_t and c_{2t}

[Dib, Rosenfeld, Zerwekh; Grober and Muhlleitner]



➢ Shape analysis is essential to disentangle the different new physics effects and maximize sensitivity

The total cross section

Small total production cross section

- at LO for the SM

$$\begin{aligned}\sigma(pp \to hh)_{SM} &= 16.2 \text{ fb} \qquad (14 \text{ TeV}) \\ &= 874 \text{ fb} \qquad (100 \text{ TeV})\end{aligned}$$

- beyond LO computed mainly in the $m_t \to \infty$ approximation

NNLO k-factors: $k_{14 \text{ TeV}} = 2.27$ [De Florian and Mazzitelli]

$k_{100 \text{ TeV}} = 1.75$

$$\begin{aligned}\sigma(pp \to hh + X)_{SM} &= 36.8 \text{ fb} \qquad (14 \text{ TeV}) \\ &= 1.53 \text{ pb} \qquad (100 \text{ TeV})\end{aligned}$$

- The $m_t \to \infty$ limit severely distorts the m_{hh} distribution. Conservative estimate of error $\sim 10\%$, can limit ultimate precision.

  (complete m_t dependence at NLO known only for real emission)

Final states

Final states studies so far in the literature:

- $hh \to b\bar{b}\gamma\gamma$: cleanest channel but small cross section

  Baur, Plehn, Rainwater PRD 69 (2004) 053004
  Baglio et al. JHEP 1304 (2013) 151
  Yao arXiv:1308.6302
  Barger et al. PLB 728 (2014) 433
  ATLAS, ATL-PHYS-PUB-2014-019
  Barr et al. arXiv:1412.7154

- $hh \to b\bar{b}\tau\tau$: sizable cross section, promising in the boosted regime

  Baur, Plehn, Rainwater PRD 68 (2003) 033001
  Dolan, Englert, Spannowsky JHEP 1210 (2012) 112
  Baglio et al. JHEP 1304 (2013) 151
  Barr, Dolan, Englert, Spannowsky PLB 728 (2014) 308
  Goertz, Papaefstathiou, Yang, Zurita arXiv:1410.3471

- $hh \to b\bar{b}WW$: large $t\bar{t}$ background, maybe observable in the boosted regime

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  Baglio et al. JHEP 1304 (2013) 151
  Papaefstathiou, Yang, Zurita PRD 87 (2013) 011301

- $hh \to b\bar{b}b\bar{b}$: very difficult, maybe observables in the boosted regime

  de Lima, Papaefstathiou, Spannowsky arXiv:1404.7139

The $b\bar{b}\gamma\gamma$ channel

Highlights of the analysis

Simulations: Parton level + Showering + Hadronization

- Signal at LO rescaled by NNLO k-factor
- Background with MadGraph5

Backgrounds included: $b\bar{b}\gamma\gamma$, $jj\gamma\gamma$ (non resonant)

$b\bar{b}h$, Zh , $t\bar{t}h$ (resonant)

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$b\bar{b}h$, Zh , $t\bar{t}h$ (resonant)

$b\bar{b}\gamma\gamma$ has a large NLO k-factor: $k \sim 2$
Mainly due to real emissions

Backgrounds

Number of events with $L = 3\ \mathrm{ab}^{-1}$

	hh	$b\bar{b}\gamma\gamma$	$t\bar{t}h$	$\gamma\gamma jj$	$b\bar{b}h$	Zh
14 TeV	12.8	24.2	9.9	2.21	0.40	0.41
100 TeV	303	137	303	18.2	6.2	3.2

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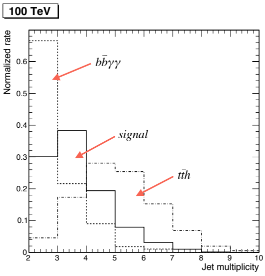
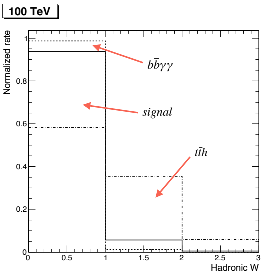
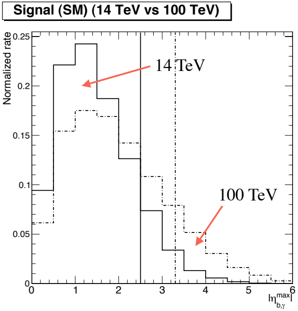
Jet-veto or W-veto can be useful to reduce the $t\bar{t}h$ background at FCC_{100}





η distribution

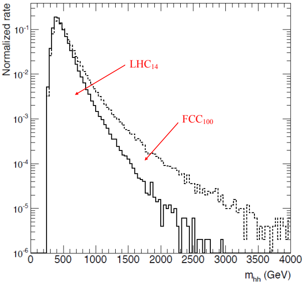
The η distribution is shifted towards higher values at FCC$_{100}$

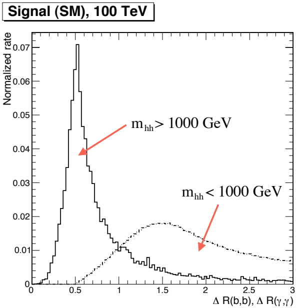


- $\sim 30\%$ of the signal above $\eta = 2.5$ (only $\sim 13\%$ at the LHC)
- need to extend to $\eta = 3.3$ to keep the same fraction as at the LHC

Boosted events

Events with $m_{hh} > 1000$ GeV are significantly boosted



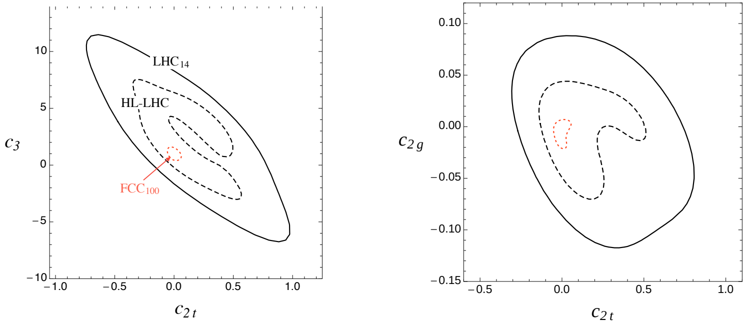


- ➢ jet substructure techniques are important at FCC_{100}

Note: not relevant at LHC due to limited number of events at high m_{hh}

Precision on c_3, c_{2t} and c_{2g}

The non-linear Higgs couplings c_3, c_{2t}, c_{2g} can only be directly accessed in double Higgs production



- Higgs trilinear c_3 can only be extracted at FCC (at LHC only $O(1)$ determination)
- good precision on c_{2t} and c_{2g}

Precision on c_3, c_{2t} and c_{2g}

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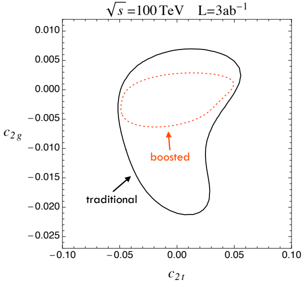
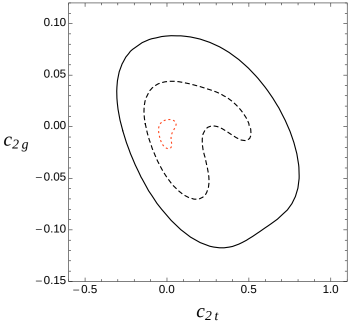
Boosted techniques help with c_{2g}!





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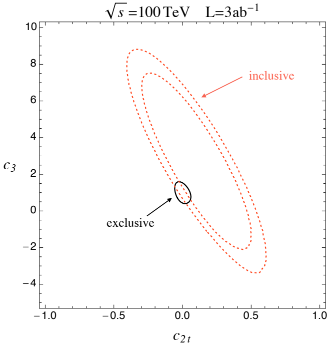
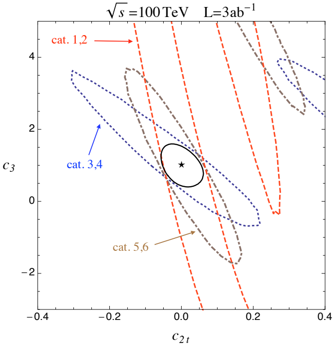
Exclusive vs inclusive analysis

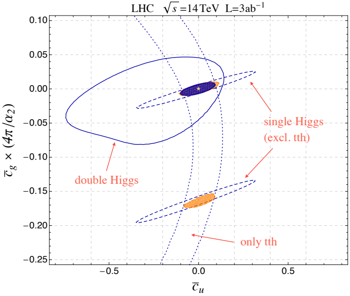
❖ **Exclusive analysis** is crucial at FCC_{100}!

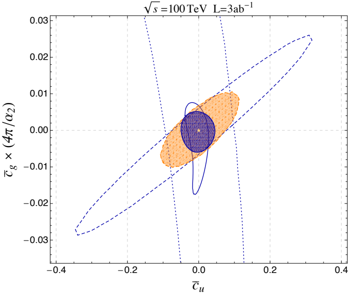




category	1	2	3	4	5	6
m_{hh} [GeV]	$250-400$	$400-550$	$550-700$	$700-850$	$850-1000$	$1000-$

Constraining the dim.-6 operators: $\bar{c}_u$ and $\bar{c}_g$



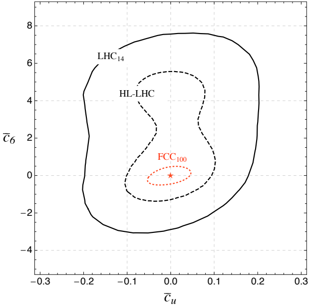


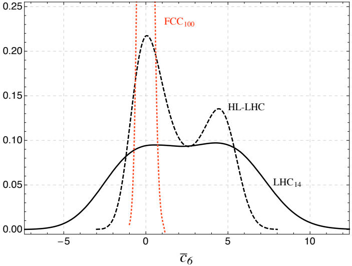
- ➢ double Higgs can resolve the degeneracy in c_g
- ➢ at FCC$_{100}$ it can be competitive with $t\bar{t}h$ for the determination of the top Yukawa $\bar{c}_u$ (if precision from single Higgs similar to the LHC one)

Orange region: single Higgs incl. $t\bar{t}h$

Blue region: single + double Higgs

Constraining the dim.-6 operators: $\bar{c}_u$ and $\bar{c}_6$

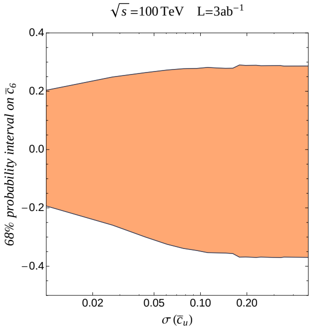




68% probability intervals on $\bar{c}_6$

LHC_{14}	HL-LHC	FCC_{100}
$[-1.2, 6.1]$	$[-1.0, 1.8] \cup [3.5, 5.1]$	$[-0.33, 0.29]$

Constraining the dim.-6 operators: $\overline{c}_u$ and $\overline{c}_6$



Precision on Higgs trilinear $\overline{c}_6$ is influenced by precision on top Yukawa $\overline{c}_u$

- poor precision on $\overline{c}_u$ can nearly double the uncertainty on $\overline{c}_6$
- if $\overline{c}_u$ is poorly determined from single Higgs, double Higgs can fix it with a $\sim 10\%$ precision

Comparison with previous analyses of $hh \to b\bar{b}\gamma\gamma$

We find more pessimistic results than previously claimed in the literature.

This is mainly due to:

- More accurate simulation of the irreducible $b\bar{b}\gamma\gamma$ background, including NLO k-factor
- Larger mass window $m_{\gamma\gamma}^{reco} = m_h \pm 5\ \mathrm{GeV}$ (to be optimized in a fully realistic analysis)
- Precision on c_3 depends on the statistical treatment. For example: uncertainty on top Yukawa coupling reflects into an unknown contribution to the cross section

Summary

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Double Higgs production is essential to extract information on the Higgs non-linear couplings

- several new physics effects modify the $gg \to hh$ process
- global analysis needed to get a model-independent fit

The $hh \to b\bar{b}\gamma\gamma$ final state allows a precision $\sim 30\%$ on the Higgs trilinear at FCC$_{100}$

- useful to combine other channels to improve the accuracy