Effective field theory for double Higgs production

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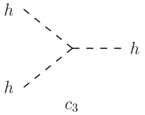
Based on A. Azatov, R. Contino, GP, M. Son arXiv:1502.00539

Introduction

Why $gg \to HH$ production?

Obvious answer:

- measure the **Higgs trilinear coupling!**



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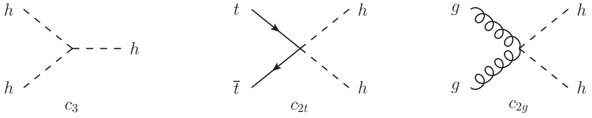

Less obvious answers:

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

❖ 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:

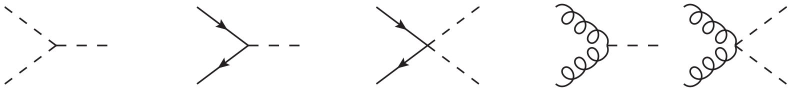
- Higgs is an $\mathrm{SU}(2)_L$ doublet
- derivative expansion
- expansion in Higgs powers

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

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

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

Relevant vertices:



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

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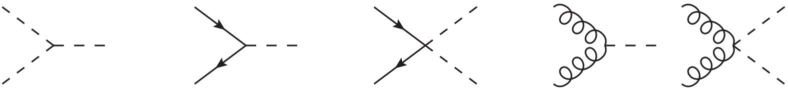

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The same operator modifies the top Yukawa and generates an anomalous $\bar{t}thh$ vertex

The effective parametrization

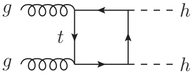
The effective vertices correspond to the interactions in the unitary gauge

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

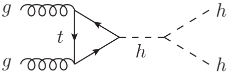
This parametrization is more general than the previous one

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

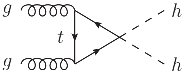
Double Higgs production via gluon fusion



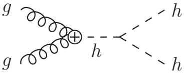
$\sim c_t^2 \times const.$



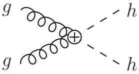
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



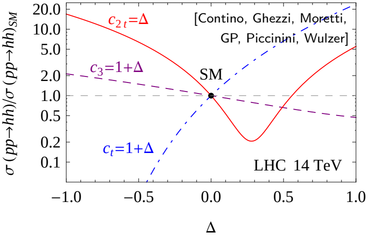
$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

- 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}

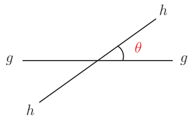
[Dib, Rosenfeld, Zerwekh;
Grober and Muhlleitner]



➢ Using the m_{hh} distribution (shape analysis) is essential to disentangle the different new physics effects and maximize sensitivity

The angular distribution

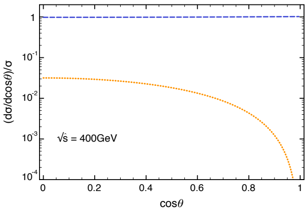
The signal is also characterized by the angle between the Higgs pair and the beam axis in the c.o.m. frame

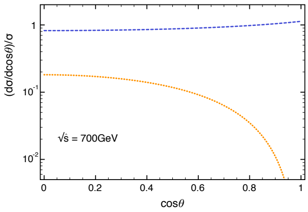


The scattering is mainly due to two partial waves $J_z = 0$ and $J_z = \pm 2$

$$\frac{d\sigma}{d\cos\theta} \sim const. \quad (J_z = 0) \qquad \frac{d\sigma}{d\cos\theta} \sim \sin^2\theta \quad (J_z = \pm 2)$$

- In the SM the $J_z = \pm 2$ amplitude comes only from the box diagram and is extremely suppressed





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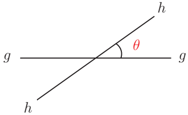

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- The BSM diagrams (from dim.-6 operators) do not generate contributions with $J_z = \pm 2$

➢ the **angular analysis** is **not useful** to disentangle NP effects

[possible exception: effects from dim.-8 operators (only at $100\ \mathrm{TeV}$)]

The total cross section

Small total production cross section

- at LO for the SM

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

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

NNLO k-factors: $k_{14 \text{ TeV}} = 2.27$ [De Florian and Mazzitelli]
$k_{100 \text{ TeV}} = 1.75$

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

- 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

  Dolan, Englert, Spannowsky JHEP 1210 (2012) 112
  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

- Analysis at the 14 TeV LHC

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

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Selection tags: 2 b-tagged jets + 2 photons

efficiencies: $\epsilon_b = 0.7\,, \quad \epsilon_{j\to b} = 0.01\,, \quad \epsilon_\gamma = 0.8$

Kinematic selection for the $14\ \mathrm{TeV}$ LHC

basic objects reco.: $p_T(j,\gamma) > 25\ \mathrm{GeV}, \quad |\eta(j,\gamma)| < 2.5$

veto isolated leptons: $p_T(l) > 20\ \mathrm{GeV}, \quad |\eta(l)| < 2.5$

first selection: $p_{T>}(b,\gamma) > 50\ \mathrm{GeV}$

$p_{T<}(b,\gamma) > 30\ \mathrm{GeV}$

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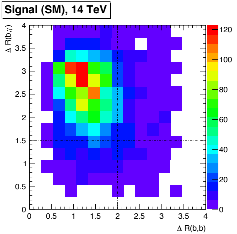
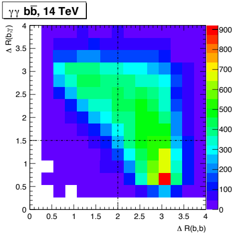
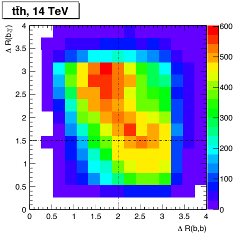
angular cuts: $\Delta R(b,b) < 2$, $\Delta R(\gamma,\gamma) < 2$, $\Delta R(b,\gamma) > 1.5$







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Higgs reconstruction: $105 \text{ GeV} < m_{bb}^{\text{reco}} < 145 \text{ GeV}$

$120 \text{ GeV} < m_{\gamma\gamma}^{\text{reco}} < 130 \text{ GeV}$

Backgrounds and shape analysis

Events in **SM signal** and **backgrounds** with $L = 3\ \mathrm{ab}^{-1}$

	hh	$b\bar{b}\gamma\gamma$	$\gamma\gamma jj$	$t\bar{t}h$	$b\bar{b}h$	Zh
After first selection	28.5	6919	684	130	7.2	24.5
After angular cuts	17.8	1274	104	29	1.2	15.8
After Higgs reco.	12.8	24.2	2.21	9.9	0.40	0.41

➢ dominant background: irreducible $b\bar{b}\gamma\gamma$

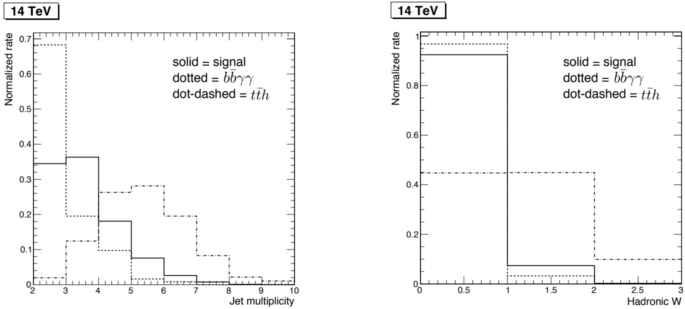
Simple **shape analysis** by binning the m_{hh} distribution (in 6 categories)

m_{hh}^{reco} [GeV]	$250-400$	$400-550$	$550-700$	$700-850$	$850-1000$	$1000-$
hh	2.14	6.34	2.86	0.99	0.33	0.17
$\gamma\gamma b\bar{b}$	7.69	10.1	3.35	1.38	1.18	0.59
$\gamma\gamma jj$	0.66	0.95	0.31	0.16	0.08	0.045
$t\bar{t}h$	3.33	4.53	1.41	0.41	0.16	0.043
$b\bar{b}h$	0.20	0.16	0.03	0.0054	0.0022	0.00054
Zh	0.13	0.19	0.067	0.021	0.009	0.0009

Jet and W veto

Only marginal improvement from veto on extra hadronic activity

- Jet veto: $N(jets) < 4$ removes 80% of $t\bar{t}h$, keeps 70% of signal
- W veto: $N(W_{had}) = 0$ removes 50% of $t\bar{t}h$, keeps 90% of signal



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

- Prospects at a future $100\ \mathrm{TeV}$ collider

Kinematic selection at 100 TeV

- Angular cuts and Higgs reconstruction windows equal to the ones for the 14 TeV LHC

$$\Delta R(b,b) < 2, \quad \Delta R(\gamma,\gamma) < 2, \quad \Delta R(b,\gamma) > 1.5$$

$$105\ \text{GeV} < m_{bb}^{\text{reco}} < 145\ \text{GeV}$$

$$120\ \text{GeV} < m_{\gamma\gamma}^{\text{reco}} < 130\ \text{GeV}$$

- Slightly tighter p_T cuts

$$p_{T>}(b,\gamma) > 60\ \text{GeV}\,, \qquad p_{T<}(b,\gamma) > 40\ \text{GeV}$$

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

- main background at LHC_{14}: $b\bar{b}\gamma\gamma$
- main background at FCC_{100}: $t\bar{t}h$

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
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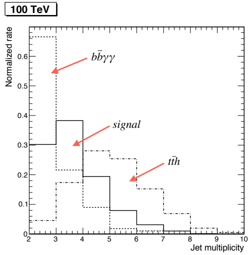
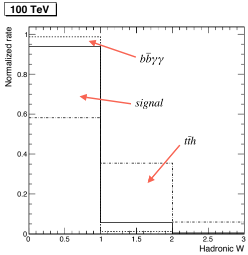
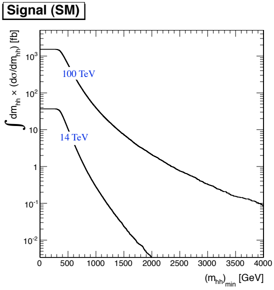
- main background at LHC_{14}: $b\bar{b}\gamma\gamma$
- main background at FCC_{100}: $t\bar{t}h$

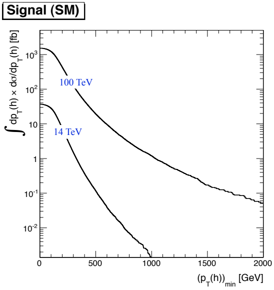
Jet-veto or W-veto can be useful to reduce the $t\bar{t}h$ background at FCC_{100}





Reach in m_{hh} and p_T: Boosted events





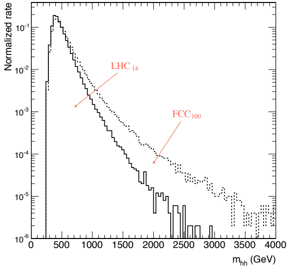
The highest accessible m_{hh} and p_T can be estimated by requiring at least 5 events beyond the threshold
(we use $L = 3\ \mathrm{ab}^{-1}$ and assume 10% efficiency)

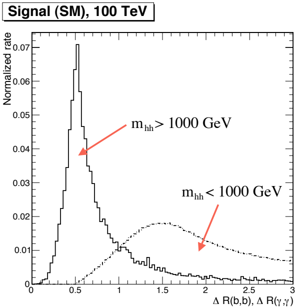
channel	$b\bar{b}WW^*$ (24.9%)	$b\bar{b}\tau^+\tau^-$ (7.35%)	$b\bar{b}\gamma\gamma$ (0.264%)
Cross section	> 0.067 fb	> 0.227 fb	> 6.31 fb
m_{hh} [GeV]	$< 1280\ (4170)$	$< 1039\ (3235)$	$< 558\ (1552)$
p_T [GeV]	$< 575\ (2000)$	$< 550\ (1890)$	$< 210\ (664)$

[numbers in parenthesis are for the 100 TeV collider]

Boosted events

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



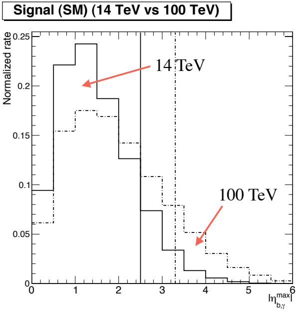


➢ jet substructure techniques are important at FCC_{100}

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

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

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

- Sensitivity on the EFT coefficients

Sensitivity on the EFT coefficients

We consider three benchmark scenarios

	LHC_{14}	HL-LHC	FCC_{100}
$\sqrt{s}$	14 TeV	14 TeV	100 TeV
Luminosity	$L = 300\ \mathrm{fb}^{-1}$	$L = 3\ \mathrm{ab}^{-1}$	$L = 3\ \mathrm{ab}^{-1}$

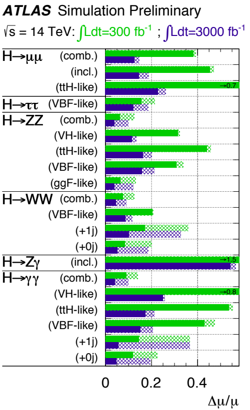
- Bayesian analysis for parameters of interest, marginalizing or fixing the others
- Flat prior for unconstrained EFT coefficients
- Gaussian constraints from single-Higgs data (we use ATLAS projections [ATL-PHYS-PUB-2013-014])
- No theoretical uncertainties or systematic error included

Sensitivity on the EFT coefficients

Precision on single-Higgs observables from ATLAS projection

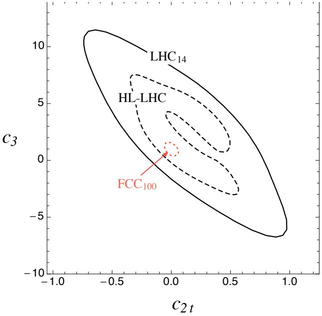
[ATL-PHYS-PUB-2013-014]

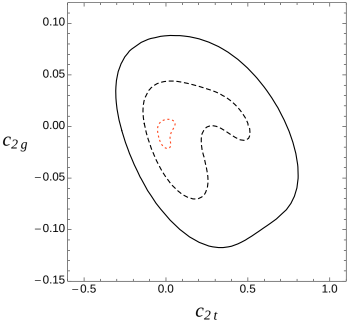
	$300\ \text{fb}^{-1}$	$3\ \text{ab}^{-1}$
$\sigma(\bar{c}_H)$	7.9%	5.4%
$\sigma(\bar{c}_u)$	5.9% $(w/t\bar{t}h)$	5.4% $(w/t\bar{t}h)$
	20% $(t\bar{t}h)$	7.7% $(t\bar{t}h)$
$\sigma(\bar{c}_d)$	6.3%	4.4%



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

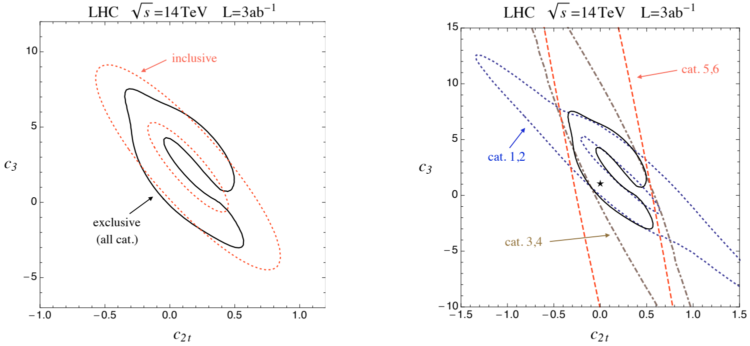




- Higgs trilinear c_3 can only be extracted at FCC (at LHC only $O(1)$ determination)
- good precision on c_{2t} and c_{2g}

Exclusive vs inclusive analysis

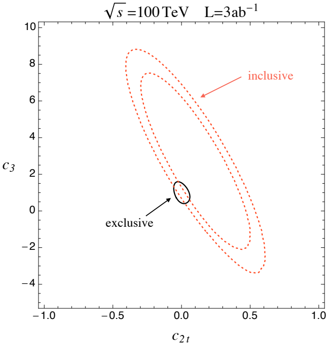
❖ Modest improvement from **exclusive analysis**

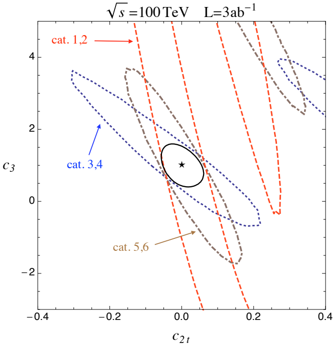


category	1	2	3	4	5	6
m_{hh} [GeV]	$250-400$	$400-550$	$550-700$	$700-850$	$850-1000$	$1000-$

Exclusive vs inclusive analysis

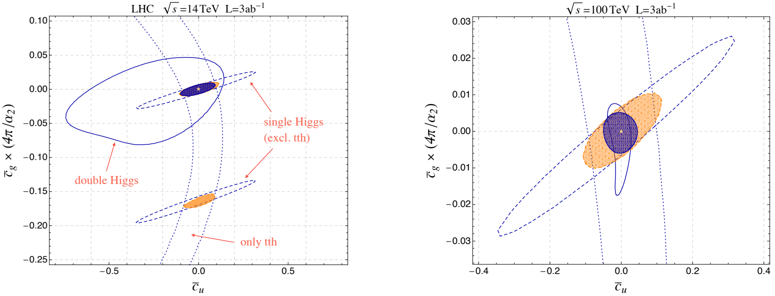
- **Exclusive analysis** is crucial at FCC_{100}!





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: $\overline{c}_u$ and $\overline{c}_g$



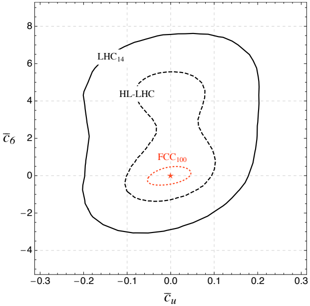
- ➢ double Higgs can resolve the degeneracy in c_g

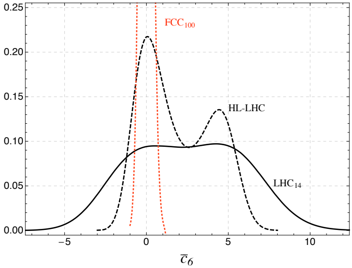
- ➢ at FCC$_{100}$ it can be competitive with $t\bar{t}h$ for the determination of the top Yukawa $\overline{c}_u$ (if precision from single Higgs similar to the LHC one)

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

Blue region: single + double Higgs

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



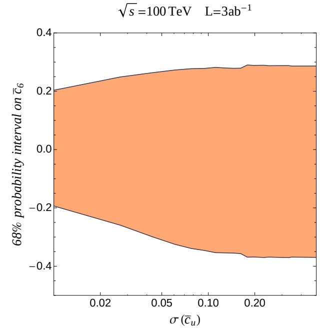


68% probability intervals on $\overline{c}_6$

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

➢ only $\mathcal{O}(1)$ determination possible at LHC

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

Conclusions

Conclusions

Double Higgs production is an essential channel 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 an easy analysis, but has limited statistics

- can be used to measure the Higgs trilinear coupling

$$\delta\lambda \sim \mathcal{O}(1) \quad @\ \mathrm{HL-LHC} \qquad\qquad \delta\lambda \sim 30\% \quad @\ \mathrm{FCC}$$

- important to combine other channels to improve the accuracy