Anomalous Couplings in Double Higgs Production

arXiv:1205.5444

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Outline

General parametrization of the Higgs couplings

Contino, Grojean, Moretti, Piccinini, Rattazzi, JHEP **1005** (2010) 089

- Custodial symmetry
- NG boson in the coset $SU(2)_L \times SU(2)_R / SU(2)_V \sim SO(4)/SO(3)$

$$\Sigma = \exp\left(\imath \sigma_a \chi^a(x)/v\right), \quad a = 1,2,3, \quad v = 246 \text{ GeV}$$

- Effective Lagrangian at energies much below new physics states:

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2a\frac{h}{v} + \ldots\right] + \frac{1}{2}\left(\partial_\mu h\right)^2 - \frac{1}{2} m_h^2 h^2 - d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + \ldots$$
$$- m_t \bar{q}_L^i \Sigma_{i1} t_R \left(1 + c_t \frac{h}{v} + c_2 \frac{h^2}{v^2} + \ldots\right) - m_b \bar{q}_L^i \Sigma_{i2} b_R \left(1 + c_b \frac{h}{v} + \ldots\right) + \text{h.c.}$$

SM: $a = d_3 = c_t = c_b = 1; \quad c_2 = 0$

For simplicity we set: $c_t = c_b = c$.

Minimal Composite Higgs Models

- Symmetry pattern: $SO(5)/SO(4)$
- $\xi = \frac{v^2}{f^2}$ free parameter

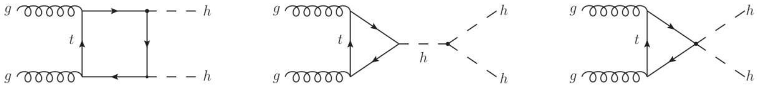
- MCHM4: spinorial representation

$$a = c = d_3 = \sqrt{1-\xi}, \qquad c_2 = -\frac{\xi}{2}$$

- MCHM5: fundamental representation

$$a = \sqrt{1-\xi}, \quad c = d_3 = \frac{1-2\xi}{\sqrt{1-\xi}}, \quad c_2 = -2\xi$$

Double Higgs Production via Gluon Fusion



High invariant mass limit

$\hat{s} = m_{hh}^2 \gg m_t^2, m_h^2$

$$\mathcal{A}_{\Box} \sim c^2 \alpha_s \frac{m_t^2}{v^2}$$

$$\mathcal{A}_{\triangle} \sim c d_3 \alpha_s \frac{m_h^2 m_t^2}{v^2 \hat{s}} \left[\ln \frac{m_t^2}{\hat{s}} + \imath\pi \right]^2$$

$$\mathcal{A}_{\triangle \mathrm{nl}} \sim c_2 \alpha_s \frac{m_t^2}{v^2} \left[\ln \frac{m_t^2}{\hat{s}} + \imath\pi \right]^2$$

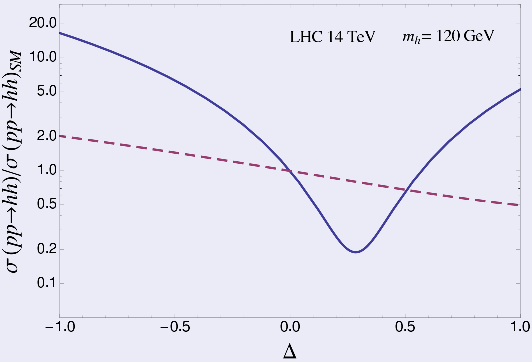
$pp \rightarrow hh$ total cross section

Numerical simulation

- ALPGEN event generator
- arbitrary choice of the Higgs couplings $c,\ d_3,\ c_2$
- automatic computation of matrix element, total cross section, differential distributions and event generation
- CTEQ6l parton distribution functions
- renormalization and factorization scale: $Q = m(hh)$
- QCD K-factor $= 2$ (Dawson, Dittmaier and Spira, 1998)

$pp \to hh$ total cross section

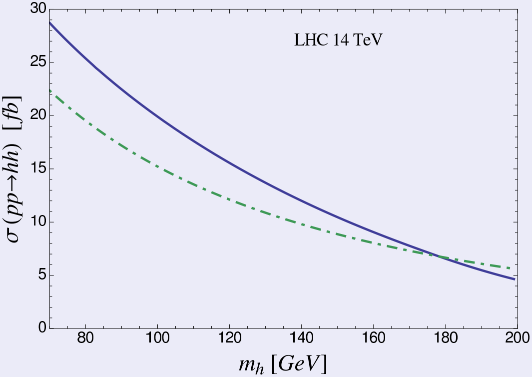
...modifying Higgs couplings:



- solid blue: $c_2 = \Delta$
- dashed purple: $d_3 = 1 + \Delta$

$pp \to hh$ total cross section

...as a function of m_h:



- solid blue: full (1 loop)
- dot-dashed green: $m_t \to \infty$

$pp \to hh$ total cross section

Fit — SM: $\sigma = 15.2$ fb

- Quadratic polynomial in the variables c_2, c^2 and cd_3
- @LHC 14 TeV, $m_h = 120$ GeV

$$\sigma = (151.3\ \text{fb}) \times \Big[c_2^2 + \left(0.453c^2\right)^2 + (0.164cd_3)^2 - 1.86c_2 \times \left(0.453c^2\right) -1.77\left(0.453c^2\right) \times (0.164cd_3) + 1.66c_2 \times (0.164cd_3)\Big]$$

What if $m_h = 125$ GeV? — SM: $\sigma = 14.3$ fb

- Less than 7% of decrease of the overall factor
- @LHC 14 TeV

$$\sigma = (144.6\ \text{fb}) \times \Big[c_2^2 + \left(0.457c^2\right)^2 + (0.169cd_3)^2 - 1.85c_2 \times \left(0.457c^2\right) -1.79\left(0.457c^2\right) \times (0.169cd_3) + 1.68c_2 \times (0.169cd_3)\Big]$$

$pp \to hh$ total cross section

Fit @ LHC 8 TeV

- $m_h = 120$ GeV

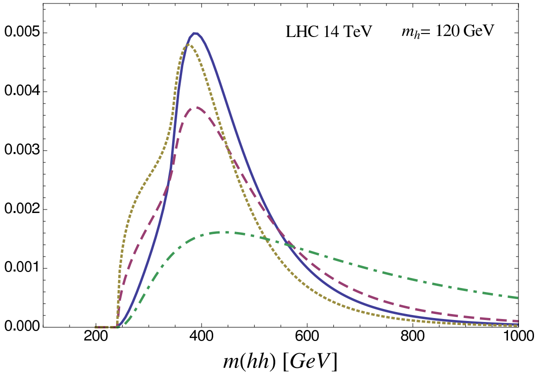
$$\sigma = (32.6\ \text{fb}) \times \Big[c_2^2 + \left(0.474c^2\right)^2 + (0.178cd_3)^2 - 1.89c_2 \times \left(0.474c^2\right) - 1.78\left(0.474c^2\right) \times (0.178cd_3) + 1.68c_2 \times (0.178cd_3)\Big]$$

- $m_h = 125$ GeV

$$\sigma = (30.5\ \text{fb}) \times \Big[c_2^2 + \left(0.475c^2\right)^2 + (0.185cd_3)^2 - 1.89c_2 \times \left(0.475c^2\right) - 1.79\left(0.475c^2\right) \times (0.185cd_3) + 1.70c_2 \times (0.185cd_3)\Big]$$

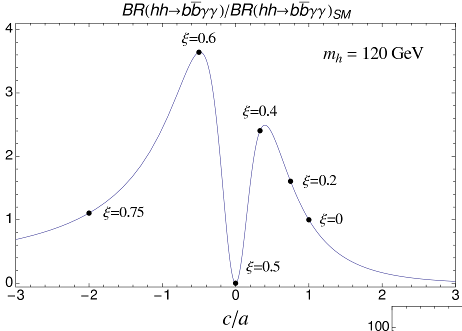
- factor ~ 5.2 lower than cross section @14TeV

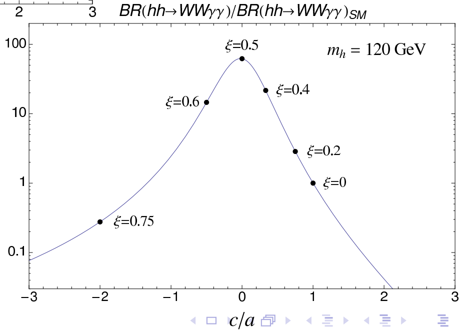
Invariant mass distribution



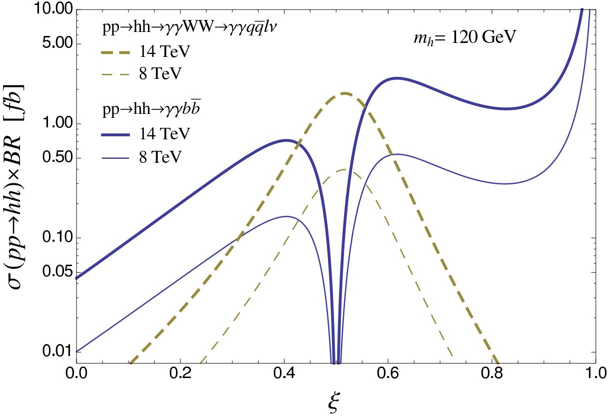
solid blue	Standard Model	15.2 fb
dashed purple	$c = d_3 = 1,\ c_2 = -1$	253 fb
dotted yellow	$c = 1,\ d_3 = c_2 = 0$	31.6 fb
dot-dashed green	SM, $m_t \to \infty$ approximation	12.2 fb

Higgs Decay channels





Cross sections in MCHM5



- $pp \to hh \to \gamma\gamma WW \to \gamma\gamma q\bar{q} l \nu$
- $pp \to hh \to \gamma\gamma b\bar{b}$

The $WW\gamma\gamma$ and $4W$ channels

Fermiophobic Higgs

- The point $(a = 1,\ c = 0)$ has already been excluded at 95% CL in the range $m_h = 110 - 192$ GeV by CMS searches
- The point $\xi = 0.5$ in MCHM5 $(a = 1/\sqrt{2},\ c = 0)$ is still allowed for $m_h \sim 125$ GeV
- The $hh \to WW\gamma\gamma \to l\nu q\bar{q}\gamma\gamma$, $hh \to 4W \to l^{\pm}l^{\pm}\nu\nu 4q$, $hh \to 4W \to 3l3\nu q\bar{q}$ channels are largely enhanced in MCHM5 $(\xi = 0.5)$ and can be observed at 8 TeV LHC
- $m_h = 120$ GeV, $\mathcal{L} = 20$ fb^{-1}:
  - $hh \to WW\gamma\gamma \to l\nu q\bar{q}\gamma\gamma$: ~ 15 events
  - $hh \to 4W \to l^{\pm}l^{\pm}\nu\nu 4q$: ~ 42 events
  - $hh \to 4W \to 3l3\nu q\bar{q}$: ~ 27 events

$b\bar{b}\gamma\gamma$ channel: Standard Model analysis

Baur, Plehn and Rainwater, Phys. Rev. D **69** (2004) 053004

Acceptance cuts

$$p_T(b) > 45 \text{ GeV}, \qquad |\eta(b)| < 2.5, \qquad \Delta R(b,b) > 0.4,$$
$$m_h - 20 \text{ GeV} < m_{b\bar{b}} < m_h + 20 \text{ GeV},$$
$$p_T(\gamma) > 20 \text{ GeV}, \qquad |\eta(\gamma)| < 2.5, \qquad \Delta R(\gamma,\gamma) > 0.4,$$
$$m_h - 2.3 \text{ GeV} < m_{\gamma\gamma} < m_h + 2.3 \text{ GeV},$$
$$\Delta R(\gamma, b) > 0.4.$$

Efficiencies and fake rates

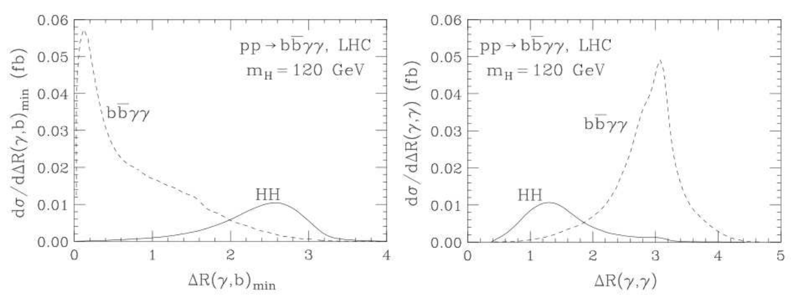
$$\epsilon_\gamma = 0.8, \qquad \epsilon_b = 0.5, \qquad r_{c\to b} = 13, \qquad r_{j\to b} = 140,$$
$$r_\gamma = 1600 \text{ (high) or } 2500 \text{ (low)}.$$

Detector effects: 79% efficiencies of reconstructing the Higgs invariant masses.

$b\bar{b}\gamma\gamma$ channel: Standard Model analysis

Baur, Plehn and Rainwater, Phys. Rev. D **69** (2004) 053004

QCD Background

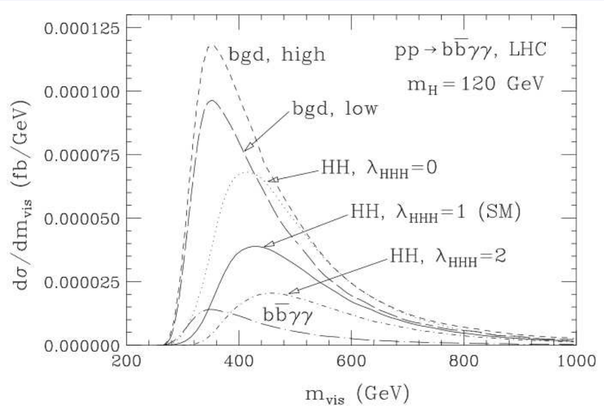


Cuts: $\Delta R(\gamma, b) > 1.0$, $\Delta R(\gamma, \gamma) < 2.0$.

$b\bar{b}\gamma\gamma$ channel: Standard Model analysis

Baur, Plehn and Rainwater, Phys. Rev. D **69** (2004) 053004

Visible invariant mass distribution



$b\bar{b}\gamma\gamma$ channel: Standard Model analysis

Baur, Plehn and Rainwater, Phys. Rev. D **69** (2004) 053004

Results

- Small sensitivity on the trilinear coupling
- 1 b-tag to preserve the signal
- Higgs trilinear coupling is substantially unconstrained
- Define $\lambda_{HHH} \equiv \frac{\lambda}{\lambda_{SM}} - 1$
- with $\mathcal{L} = 600$ fb^{-1} @ LHC 14 TeV:
  - “High“: $-1.1 < \lambda_{HHH} < 1.9$
  - ”Low“: $-1.1 < \lambda_{HHH} < 1.6$

MonteCarlo simulation

with ALPGEN MonteCarlo generator

Updated efficiencies and fake rates — Total bkg: $r_b = 5.5$ ab

$$\epsilon_\gamma = 0.8\,, \qquad r_\gamma = 2500\,, \qquad \epsilon_b = 0.7\,, \qquad r_{c\to b} = 5\,, \qquad r_{j\to b} = 25\,.$$

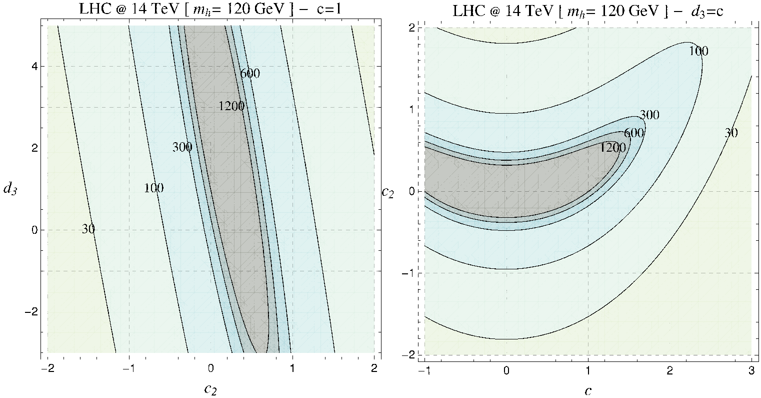
- Detector effects: 79% efficiencies of reconstructing the Higgs invariant masses
- 2 b-tags required

	$b\bar{b}\gamma\gamma$	$c\bar{c}\gamma\gamma$	$b\bar{b}\gamma j$	$c\bar{c}\gamma j$	$jj\gamma\gamma$	$b\bar{b}jj$	$c\bar{c}jj$	γjjj	$jjjj$
acc. cuts	0.056	0.42	65	250	11	2.5×10^4	2.5×10^4	7700	5×10^6
bkg. cuts	0.0060	0.0215	8.28	17.0	0.84	4520	4520	364	4×10^5
tags	0.0019	5×10^{-4}	0.0013	2×10^{-4}	9×10^{-4}	4×10^{-4}	3.0×10^{-5}	2×10^{-4}	1×10^{-4}

Fit of the cross section after cuts — SM signal: $r_s = 4.9$ ab

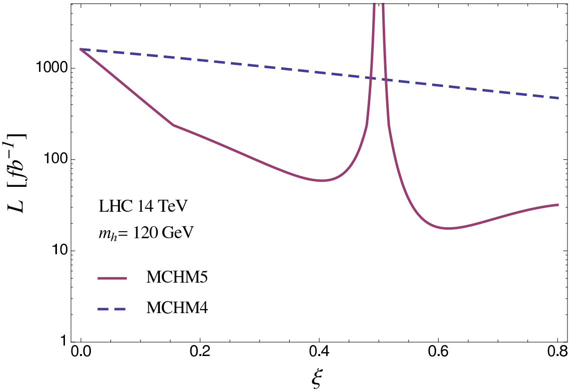
$$r_s = \frac{BR\left(hh\to\gamma\gamma b\bar{b}\right)}{BR\left(hh\to\gamma\gamma b\bar{b}\right)_{SM}} \times (49.3\text{ ab})\Big[c_2^2 + \left(0.407c^2\right)^2 + \left(0.101cd_3\right)^2 - 1.76c_2\left(0.407c^2\right) - 1.82\left(0.407c^2\right)\left(0.101cd_3\right) + 1.72c_2\left(0.101cd_3\right)\Big]$$

Results: discovery regions



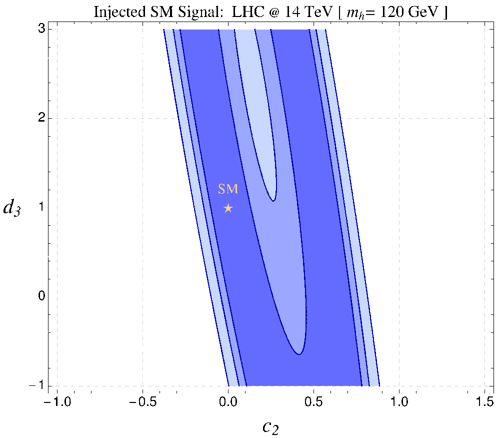
- We define a point in the parameter space to be discoverable at a certain luminosity $\mathcal{L}$ if the probability of having a total number of events smaller than $r_b\mathcal{L}$ is below 1%, and if the number of observed events $(r_s + r_b)\mathcal{L}$ is 5 or larger.

Results: discovery luminosity



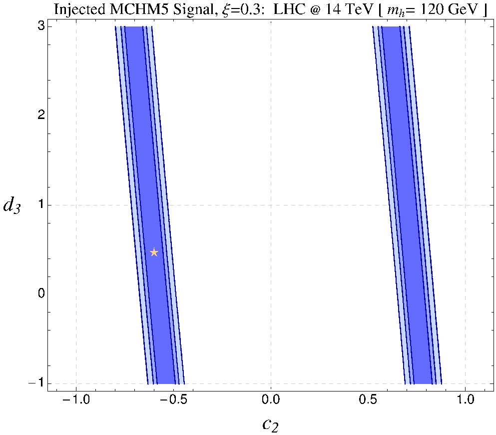
- dashed blue: MCHM4
- continuous purple: MCHM5

Results: regions of 68% probability



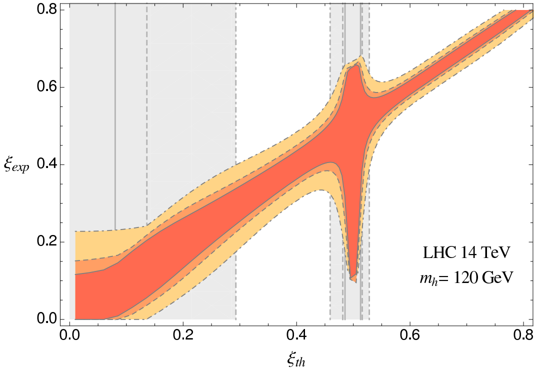
- Injected signal: Standard Model ($c = d_3 = 1,\ c_2 = 0$)
- Integrated luminosities: 300, 600 and 1200 fb^{-1}
- The coupling c and the BRs are fixed to their theoretical value

Results: regions of 68% probability



- Injected signal: MCHM5 with $\xi = 0.3$ ($c = d_3 = 0.48$, $c_2 = -0.6$)
- Integrated luminosities: 300, 600 and 1200 fb^{-1}
- The coupling c and the BRs are fixed to their theoretical value

Results: precision on the extraction of the parameter ξ



- MCHM5; injected value: ξ_{th}
- 68% probability intervals
- Integrated luminosities: 600, 300 and 100 fb^{-1} (red, orange, yellow)
- Gray regions: too small signal rate to make a discovery
- The BRs are fixed to their theoretical value

Conclusions

- Precise knowledge of the Higgs couplings is important to understand if the new dynamics at the EW scale is weakly or strongly interacting.
- A strong dynamics shows modified linear interactions with SM fields and new non-linear couplings.
- We have performed a model-independent study of $gg \to hh$, where the new interaction $t\bar{t}hh$ greatly enhances the cross section.
- In the fermiophobic Higgs limit, the $hh \to 4W$ and $hh \to WW\gamma\gamma$ final states seem to be very promising.
- In a SM-like case, the most powerful decay channel is $hh \to b\bar{b}\gamma\gamma$. We have performed a MC study of this final state.
- As a result of the enhancement due to the $t\bar{t}hh$ vertex, the strength of the $t\bar{t}hh$ interaction can be extracted with good accuracy, while the one of Higgs trilinear interaction remains substantially unconstrained.
- The code used for this analysis will be made public in the next ALPGEN official release as one of the available processes in the event generator.