Higgs-boson pair production in the D=6 extension of the Standard Model

ERC workshop
"Effective Field Theories for Collider Physics, Flavor Phenomena and Electroweak Symmetry Breaking"

Mainz, 10.11.2014

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CERN

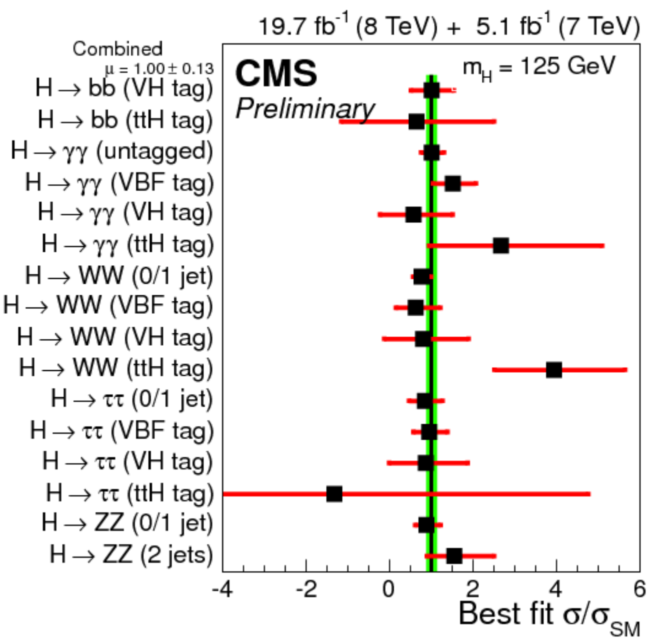
arXiv: 1410.3471
FG, Papaefstathiou, Yang, Zurita

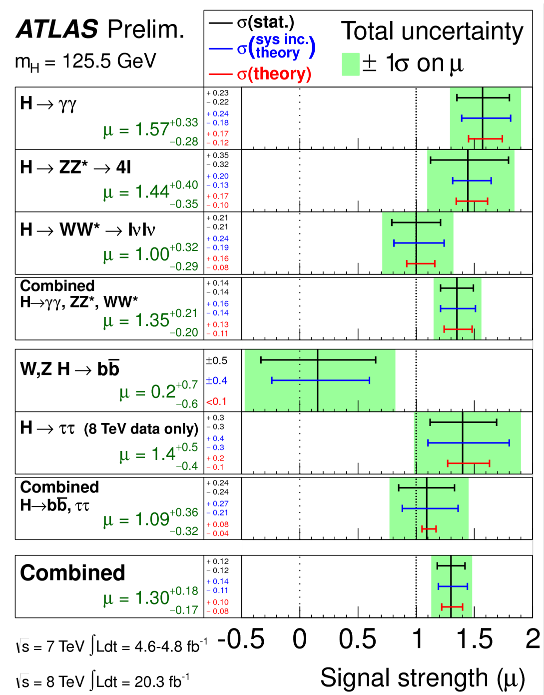
Introduction

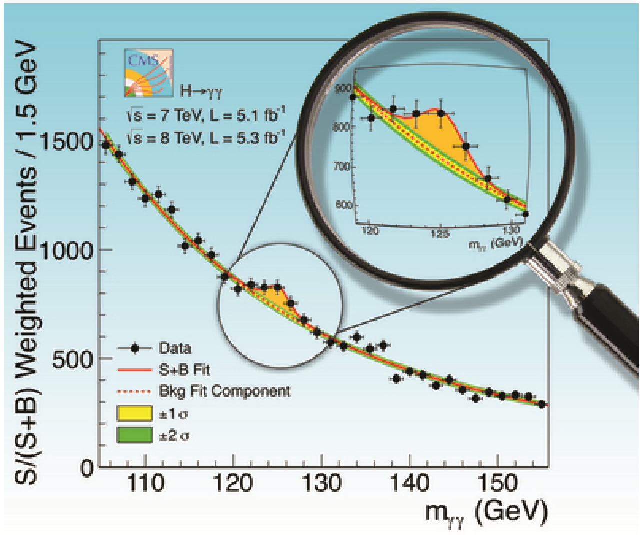
Introduction

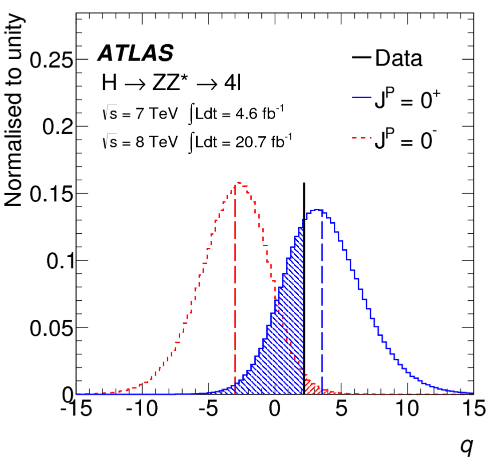
Is it the SM-Higgs Boson?

Scale of New Physics?









Introduction

Very important test:

Higgs potential

↓

self couplings

$$V(h) = \frac{1}{2} m_h^2 \, h^2 + \lambda_{hhh} v \, h^3 + \frac{1}{4} \lambda_{hhhh} \, h^4$$

$(D \leq 4)$

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- In the SM: $\lambda_{hhh}^{SM} = \lambda_{hhhh}^{SM} = \frac{m_h^2}{2v^2} \approx 0.13$

Introduction

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$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_{hhh} v\, h^3 + \frac{1}{4} \lambda_{hhhh}\, h^4$$

$\mathrm{m}_h \simeq 125\,\mathrm{GeV}$ established @LHC

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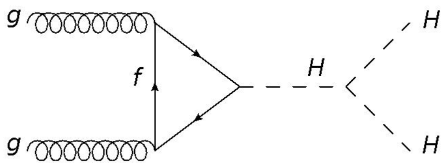
$$V(h) = \frac{1}{2} m_h^2 \, h^2 + \lambda_{hhh} v \, h^3 + \frac{1}{4} \lambda_{hhhh} \, h^4$$

λ_{hhh} can be measured in

Higgs-pair production



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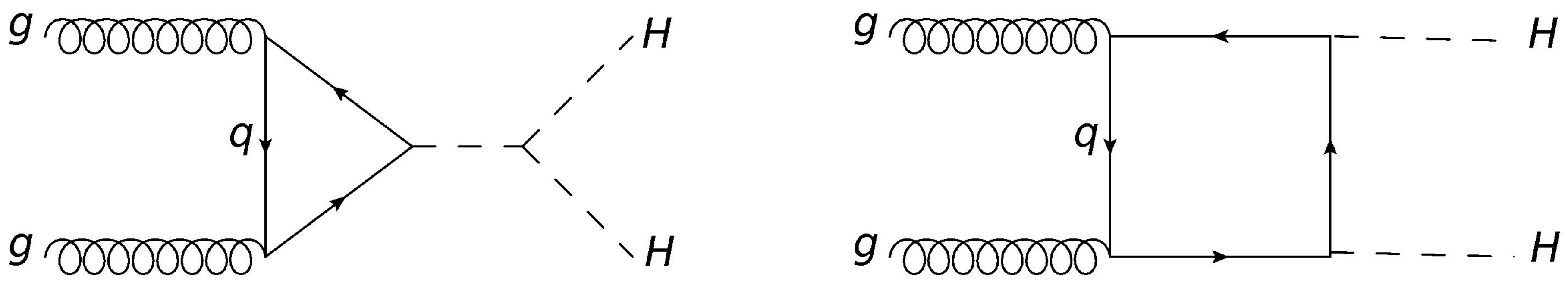
Triple Higgs production: extremely challenging @(V)LHC

0.06 fb @ LHC14; 9.45 fb @ VLHC (200 TeV)

Plehn, Rauch, ph/0507321

HH Production @ LHC

- Most important mechanism: $gg \to hh$



Eboli, Marques, Novaes, Natale, PLB 197(1987)269
Glover, van der Bij, NPB 309(1988)282
Dawson, Dittmaier, Spira, PRD 58(1998)115012
Grigo, Hoff, Melnikov, Steinhauser, 1305.7340
de Florian, Mazzitelli, 1305.5206, 1309.6594
see also Maltoni, Vryonidou, Zaro, 1408.6542

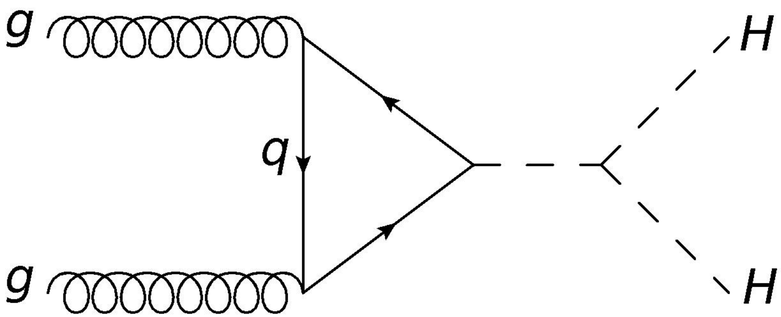
$$\sigma(gg \to hh)_{\mathrm{LO}} \sim 17\,\mathrm{fb}$$
$$\sigma(gg \to hh)_{\mathrm{NLO}} \sim 33\,\mathrm{fb}$$
$$\sigma(gg \to hh)_{\mathrm{NNLO}} \sim 40\,\mathrm{fb}$$

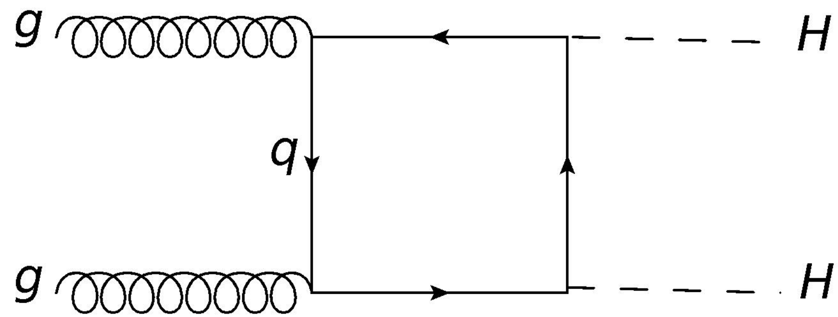
Theoretical error (NNLO): $f_{th} \sim$ 10% (scale) + 10% (pdf+α_s) + 10% (m_t^{-1})

LHC@14TeV
$m_h \sim 125$ GeV

HH Production @ LHC

- Most important mechanism: $gg \to hh$





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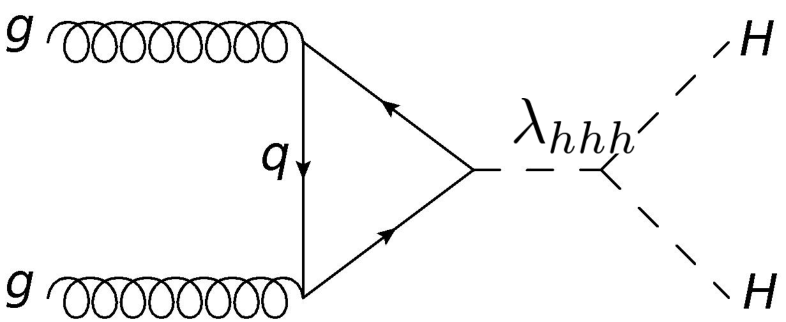
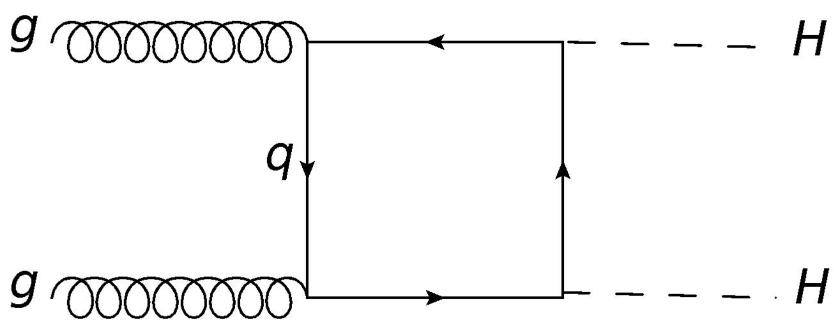
Conservative assumption for analysis: f_{th} = 30%

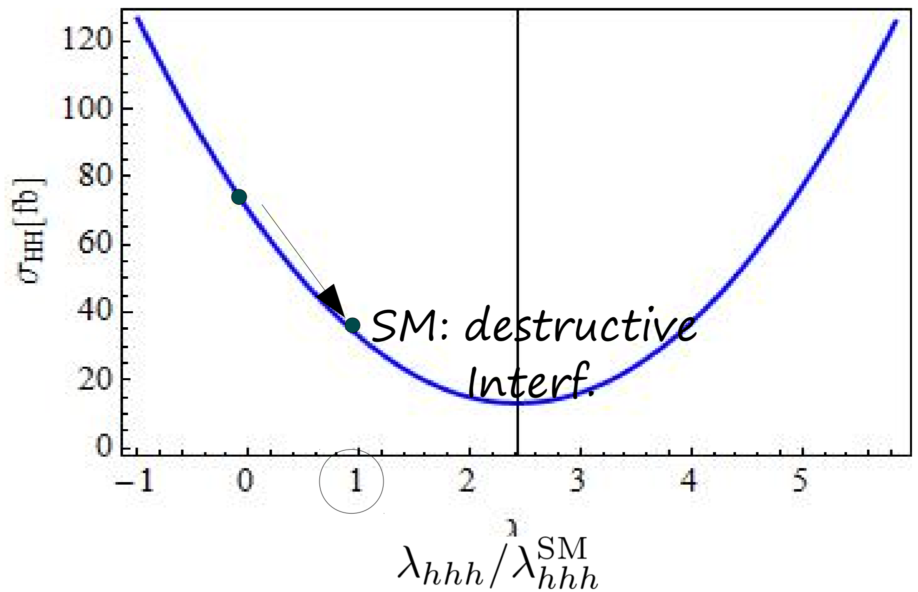
LHC@14TeV
m_h ~125 GeV

HH Production @ LHC

- Most important mechanism: $gg \to hh$



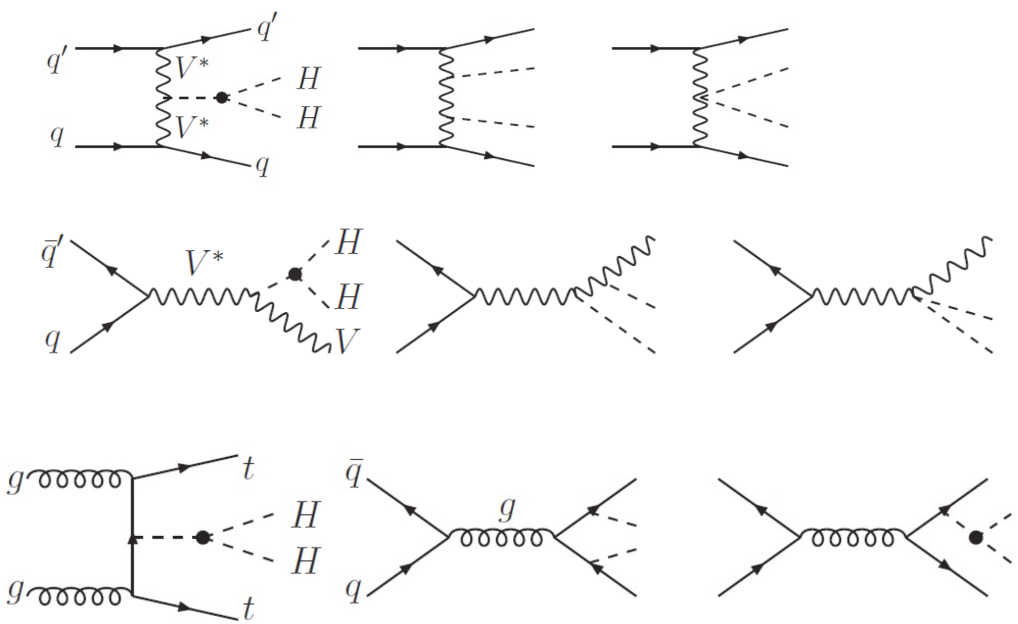


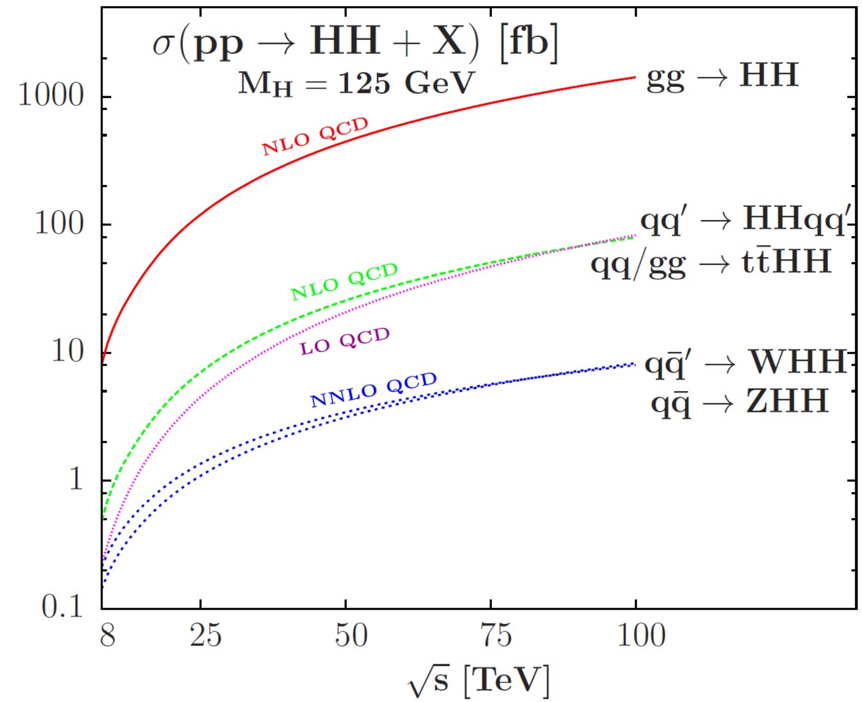


HH Production @ LHC

- Other production channels $qq' \to hhqq', Vhh, t\bar{t}hh$

  ~10-30 times smaller (neglect in the following)

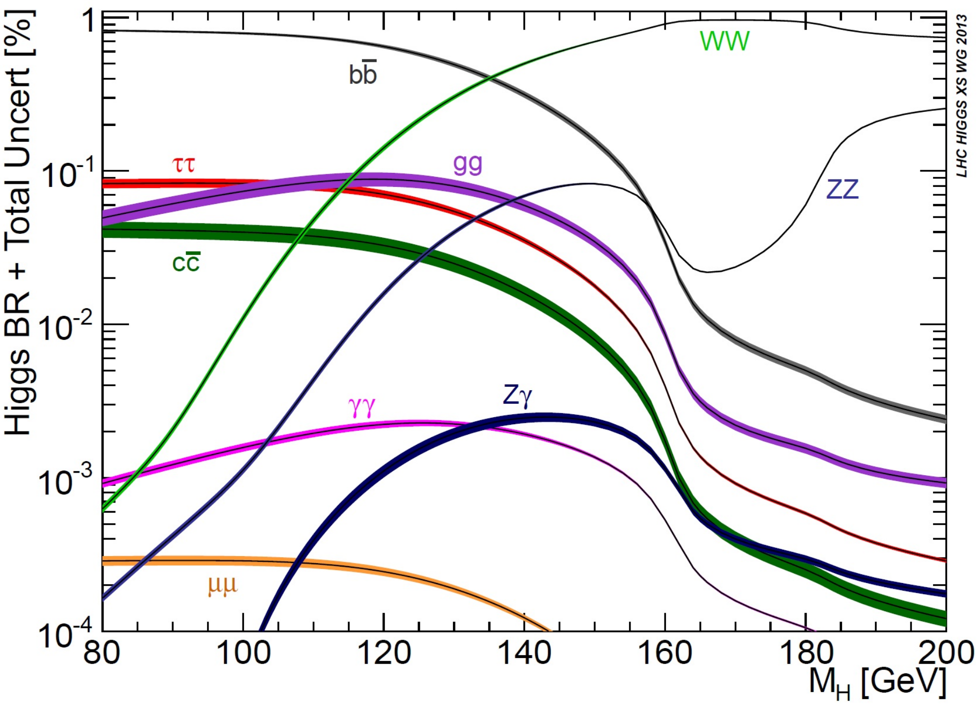




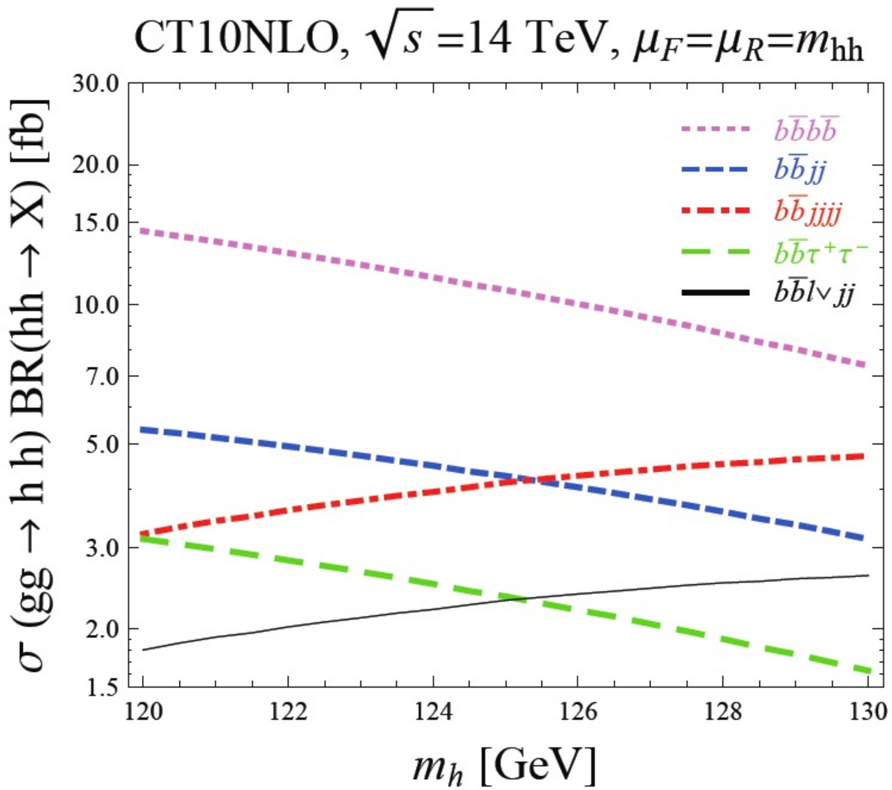
See [e.g.] Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581, and refs. therein

Decay Channels

- Discovery potential at LHC studied in different channels



Baur, Plehn, Rainwater, hep-ph/0310056



Papaefstathiou, Yang, Zurita, 1209.1489

hadronic modes dominate

Decay Channels

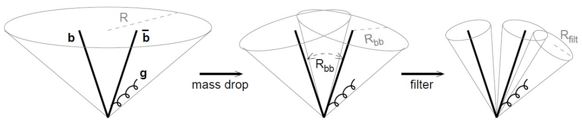
Significance @ 600 fb^{-1}

$hh \to b\bar{b}\gamma\gamma$ $\lesssim 2\sigma$ (S/B=6/12)

Baur, Plehn, Rainwater, hep-ph/0310056

$hh \to b\bar{b}\tau^+\tau^-$ $\sim 4.5\sigma$ (S/B=57/119)

Dolan, Englert, Spannowsky, 1206.5001



Butterworth, Davison, Rubin, Salam, 0802.2470

$hh \to b\bar{b}W^+W^-$ $\sim 3\sigma$ (S/B=12/8)

Papaefstathiou, Yang, Zurita, 1209.1489

Theorists' analyses!

Decay Channels

$$hh \to b\bar{b}\gamma\gamma$$

Baur, Plehn, Rainwater, hep-ph/0310056

$$hh \to b\bar{b}\tau^+\tau^-$$

Dolan, Englert, Spannowsky, 1206.5001

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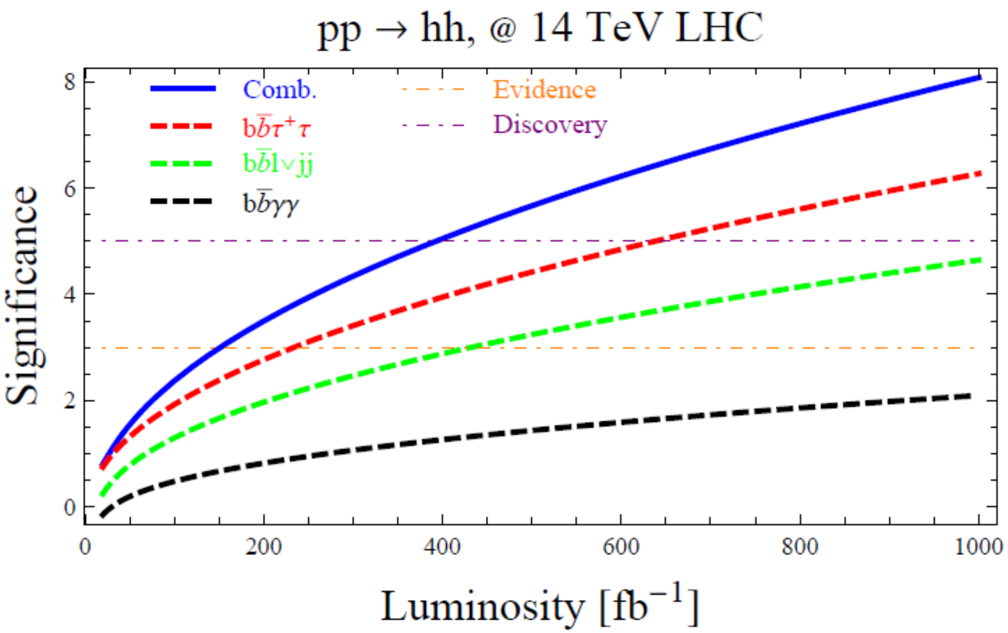
Papaefstathiou, Yang, Zurita, 1209.1489



FG, Papaefstathiou, Yang, Zurita, 1309.3805

Measuring λ_{hhh}

- Expected constraints on $\lambda \equiv \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$ @LHC

from FG, Papaefstathiou, Yang, Zurita, 1301.3492

Process	600 fb^{-1} (2σ)	600 fb^{-1} (1σ)	3000 fb^{-1} (2σ)	3000 fb^{-1} (1σ)
$b\bar{b}\tau^+\tau^-$	(0.22, 4.70)	(0.57, 1.64)	(0.42, 2.13)	(0.69, 1.40)
$b\bar{b}W^+W^-$	(0.04, 4.88)	(0.46, 1.95)	(0.36, 4.56)	(0.65, 1.46)
$b\bar{b}\gamma\gamma$	(-0.56, 5.48)	(0.09, 4.83)	(0.08, 4.84)	(0.48, 1.87)

- Add single D=6 coefficient / consistency test of SM
- Assumed $\lambda_{\rm true} = 1$
- Reduce error by employing ratio $C_{hh} = \frac{\sigma(gg\to hh)}{\sigma(gg\to h)} \equiv \frac{\sigma_{hh}}{\sigma_h}$

  → reduction of scale uncertainty + cancellation of common systematics (to some extend)

Combination yields ~ 30% accuracy with 3000 fb^{-1}

Full Analysis of SM + D=6

Higgs Boson EFT

- Assume (unspecified) New Physics at a scale Λ>>v

→ leading effects: D=6 operators built of SM content

Buchmuller, Wyler, NPB 268(1986)621-653

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

Here:

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} &+ \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6 \\ &- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.}\right) \\ &+ \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' c_\gamma}{4\pi\Lambda^2}|H|^2 B_{\mu\nu} B^{\mu\nu} \\ &+ \frac{ig\, c_{HW}}{16\pi^2\Lambda^2}(D^\mu H)^\dagger \sigma_k (D^\nu H) W^k_{\mu\nu} + \frac{ig'\, c_{HB}}{16\pi^2\Lambda^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ &+ \frac{ig\, c_W}{2\Lambda^2}(H^\dagger \sigma_k \overleftrightarrow{D}^\mu H) D^\nu W^k_{\mu\nu} + \frac{ig'\, c_B}{2\Lambda^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu} \quad (+\mathcal{L}_{\rm CP} + \mathcal{L}_{\rm 4f})\end{aligned}$$

Higgs Boson EFT

- Assume (unspecified) New Physics at a scale $\Lambda >> v$

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Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\rm SM} &+ \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6 \\
&- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.}\right) \\
&+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu} \\
&+ \frac{ig\, c_{HW}}{16\pi^2\Lambda^2} (D^\mu H)^\dagger \sigma_k (D^\nu H) W^k_{\mu\nu} + \frac{ig'\, c_{HB}}{16\pi^2\Lambda^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
&+ \frac{ig\, c_W}{2\Lambda^2} (H^\dagger \sigma_k \overleftrightarrow{D}^\mu H) D^\nu W^k_{\mu\nu} + \frac{ig'\, c_B}{2\Lambda^2} (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu} \quad (+\mathcal{L}_{\rm CP} + \mathcal{L}_{\rm 4f})
\end{aligned}
$$

Loop induced ◄ (the c_g, c_γ, c_{HW}, c_{HB} terms)

see e.g. Einhorn, Wudka, 1307.0478

For non-linear realization, see e.g. Grinstein, Trott 0704.1505; Contino, Grojean, Moretti, Piccinini, Rattazzi 1002.1011

Higgs Boson EFT

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6$$
$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.}\right)$$
$$+ \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' \, c_\gamma}{4\pi\Lambda^2}|H|^2 B_{\mu\nu} B^{\mu\nu}$$
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- Neglected operators that are strongly constrained from precision tests

See e.g.: Elias-Miro, Espinosa, Masso, Pomarol, 1308.1879; Pomarol, Riva, 1308.2803;
Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia 1207.1344, 1211.4580, 1304.1151;
Falkowski, Riva, Urbano, 1303.1812; Contino, Ghezzi, Grojean, Muhlleitner, Spira, 1303.3876;
Dumont, Fichet, von Gersdorff 1304.3369; Falkowski, Riva, 1411.0669

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$$+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' \, c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu}$$
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- Precision tests also lead to the approximate relation (EOM consistent)

$$c_W = -c_B = -\frac{c_{HW}}{16\pi^2} = \frac{c_{HB}}{16\pi^2}$$

Elias-Miro, Espinosa, Masso, Pomarol, 1308.1879
Trott 1409.7605

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Pure Higgs

Yukawa type

$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.} \right)$$

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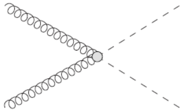

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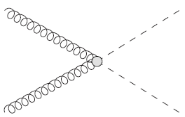

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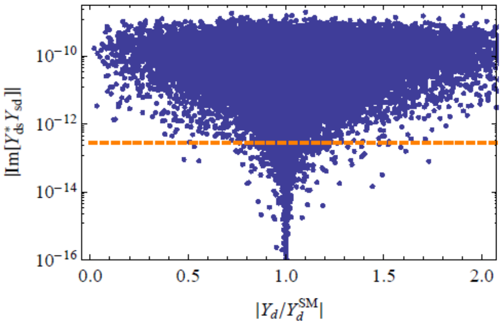
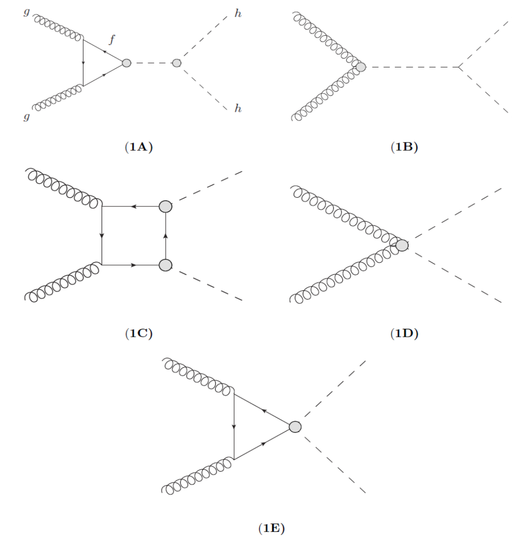
- What about light-quark Yukawas
  → can assume MFV, but even should be negligible on more general grounds: FCNCs



FG, 1406.0102

$gg \to hh$

Relevant Terms:



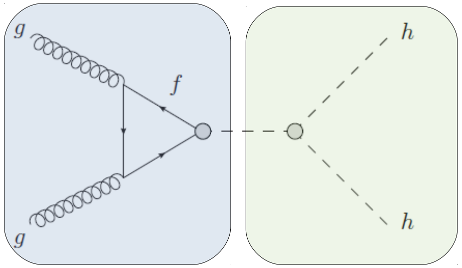
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a - \left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1-\frac{c_H}{2}+c_b\right)\bar{b}_L b_R h + \text{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2}-\frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right]$$

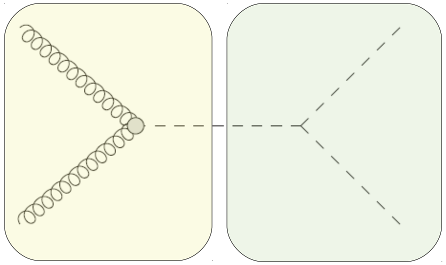
$$c_i \to c_i\,\Lambda^2/v^2,\ \ H = \exp\left(-i\frac{T\cdot\xi}{v}\right)\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix},\quad h \to \left(1-\frac{c_H v^2}{2\Lambda^2}\right)h - \frac{c_H v}{2\Lambda^2}h^2 - \frac{c_H}{6\Lambda^2}h^3$$

non-linear redefinition:
removes momentum-dependent interactions

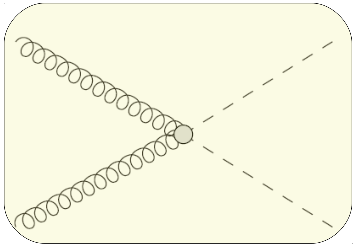
$gg \to hh$

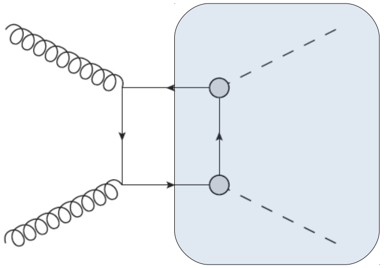
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3$$





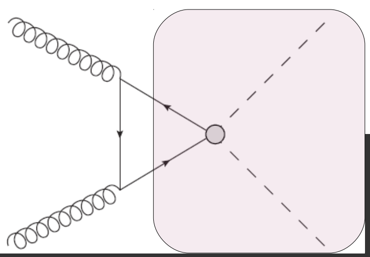
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G_a^{\mu\nu}$$





$$-\left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1-\frac{c_H}{2}+c_b\right)\bar{b}_L b_R h + \text{h.c.}\right]$$

$$-\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2}-\frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right]$$



λ_{hhh} vs λ_{hhhh}

$$\mathcal{L} \supset -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1 - \frac{25}{3}c_H + 6c_6\right)h^4$$

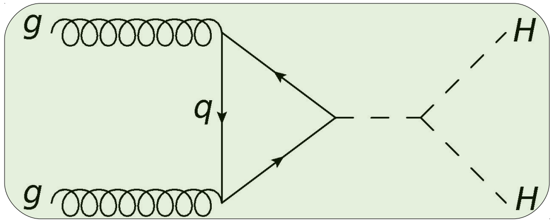
$$\lambda_{hhh} = \frac{m_h^2}{2v^2}(1+\Delta) \;\neq\; \lambda_{hhhh} = \frac{m_h^2}{2v^2}\left(1 + 6\Delta + \frac{2}{3}c_H\right)$$

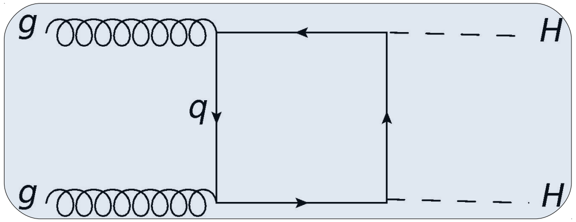
$$\Delta = c_6 - 3c_H/2$$

Cross Section in SM (LO)

spin-0 spin-2

$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \left[|C_\triangle F_\triangle + C_\Box F_\Box|^2 + |C_\Box G_\Box|^2 \right]$$





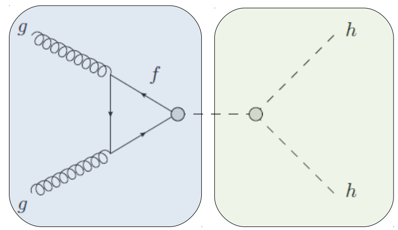
$$C_\triangle = \frac{3m_h^2}{\hat{s} - m_h^2}, \qquad C_\Box = 1$$

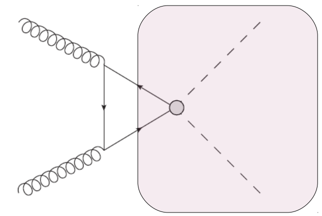
$$F_\triangle = \frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2), \quad F_\Box = -\frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2),$$

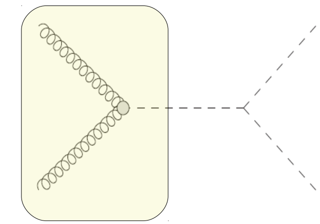
$$G_\Box = \mathcal{O}(\hat{s}/m_Q^2)$$

See Plehn, Spira, Zerwas ph/9603205

Cross Section in D=6 EFT

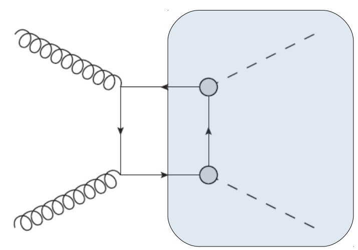


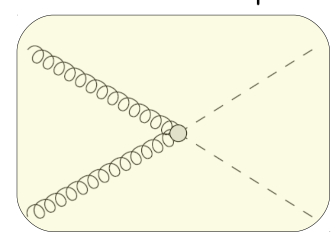




$$\left.\frac{\mathrm{d}\hat{\sigma}(gg\to hh)}{\mathrm{d}\hat{t}}\right|_{\rm EFT}=\frac{G_F^2\alpha_s^2}{256(2\pi)^3}\left\{\left|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)\ +2c_gC_\triangle\right.\right.$$

$$\left.\left.+C_\Box F_\Box(1-c_H+2c_t)+2c_gC_\Box\right|^2+\left|C_\Box G_\Box\right|^2\right\}$$





$$C_\triangle=\frac{3m_h^2}{\hat{s}-m_h^2},\qquad C_\Box=1$$

$$F_\triangle=\frac{2}{3}+\mathcal{O}(\hat{s}/m_Q^2),\ \ F_\Box=-\frac{2}{3}+\mathcal{O}(\hat{s}/m_Q^2),$$

$$G_\Box=\mathcal{O}(\hat{s}/m_Q^2)$$

See Plehn, Spira, Zerwas ph/9603205

Implemented in MC generator Herwig++

Normalize to NNLO: de Florian, Mazzitelli, 1309.6594

Higgs Decays in D=6 EFT

Mode	tree	1 loop QCD	1 loop
$h \to bb$	$\boldsymbol{c_H}, \boldsymbol{c_b}$	$\boldsymbol{c_H}, \boldsymbol{c_b}$	c_H, c_b, c_t, c_6, c_W
$h \to \tau\tau$	$\boldsymbol{c_H}, \boldsymbol{c_\tau}$	-	c_H, c_τ, c_6, c_W
$h \to \gamma\gamma$	$\boldsymbol{c_\gamma}$	-	$c_H, c_b, c_t, c_\tau, c_W$
$h \to WW$	$\boldsymbol{c_H}, \boldsymbol{c_{HW}}, \boldsymbol{c_W}$	-	$c_H, c_W, c_b, c_t, c_\tau, c_6$
$gg \to hh$	$\boldsymbol{c_g}$	$\boldsymbol{c_t}, \boldsymbol{c_b}$	$\boldsymbol{c_t}, \boldsymbol{c_b}, \boldsymbol{c_H}, \boldsymbol{c_6}$
$gg \to h$	$\boldsymbol{c_g}$	$\boldsymbol{c_t}, \boldsymbol{c_b}, \boldsymbol{c_H}$	$\boldsymbol{c_t}, \boldsymbol{c_b}, \boldsymbol{c_H}$

Table 1: Operators that modify the various decays of the Higgs boson at the tree level (second column), at the one-loop level, considering only QCD corrections (third column), as well as at the full one-loop level (fourth column). For completeness, we also include the operators entering $gg \to h$ and $gg \to hh$. The operators that are highlighted in bold text are included in the treatment of the present paper in the corresponding topology.

Higgs Decays in D=6 EFT

Mode	tree	1 loop QCD	1 loop
$h \to bb$	$c_H,\, c_b$	~~$c_H,\, c_b$~~	c_H, c_b, c_t, c_6, c_W
$h \to \tau\tau$	$c_H,\, c_\tau$	-	c_H, c_τ, c_6, c_W
$h \to \gamma\gamma$	c_γ	-	$c_H, c_b, c_t, c_\tau, c_W$
$h \to WW$	$c_H,$ ~~$c_{HW},\, c_W$~~	-	$c_H, c_W, c_b, c_t, c_\tau, c_6$
$gg \to hh$	c_g	$c_t,\, c_b$	$c_t,\, c_b,\, c_H,\, c_6$
$gg \to h$	c_g	$c_t,\, c_b,\, c_H$	$c_t,\, c_b\, ,c_H$

Loop + Λ^2 suppressed wrt SM

Included via eHDECAY:
Contino, Ghezzi, Grojean, Muhlleitner, Spira, 1403.3381

$$c_W = -c_B = -\frac{c_{HW}}{16\pi^2} = \frac{c_{HB}}{16\pi^2}$$

6 Parameters: $\{c_6, c_H, c_t, c_b = c_\tau, c_g, c_\gamma\}$

Unique accessibility in hh production!

HH in D=6 EFT

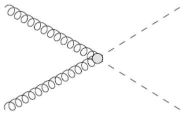
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6$$

Pure Higgs

Yukawa type

$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.} \right)$$

$$+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu}$$



6 Parameters: $\{c_6, c_H, c_t, c_b = c_\tau, c_g, c_\gamma\}$

Unique accessibility in hh production!

Analysis

- Focus on $hh \to b\bar{b}\tau^+\tau^-$ @LHC14

Dolan, Englert, Spannowsky, 1206.5001
Baglio, Djouadi, Grober, Muhlleitner, Quevillon; 1212.5581
Barr, Dolan, Englert, Spannowsky,, 1309.6318
Maierhoefer, Papaefstathiou, 1401.0007

- Main backgrounds:
  - $pp \to t\bar{t} \to b\bar{b}\tau^+\tau^-\ (+E_{\rm mis})$
  - $pp \to ZZ \to b\bar{b}\tau^+\tau^-$
  - $pp \to hZ \to b\bar{b}\tau^+\tau^-$

Generated with aMC@NLO (+ HERWIG++)

Frixione et. al.,, 1010.0568
Frederix et. al., 1104.5613
Alwall et. al., 1405.0301

Analysis: $hh \to b\bar{b}\tau^+\tau^-$

- Main backgrounds:
  - $pp \to t\bar{t} \to b\bar{b}\tau^+\tau^- \; (+E_{\rm mis})$
  - $pp \to ZZ \to b\bar{b}\tau^+\tau^-$
  - $pp \to hZ \to b\bar{b}\tau^+\tau^-$

Generated with aMC@NLO (+ HERWIG++)

Frixione et. al.,, 1010.0568
Frederix et. al., 1104.5613
Alwall et. al., 1405.0301

↳ Cuts:

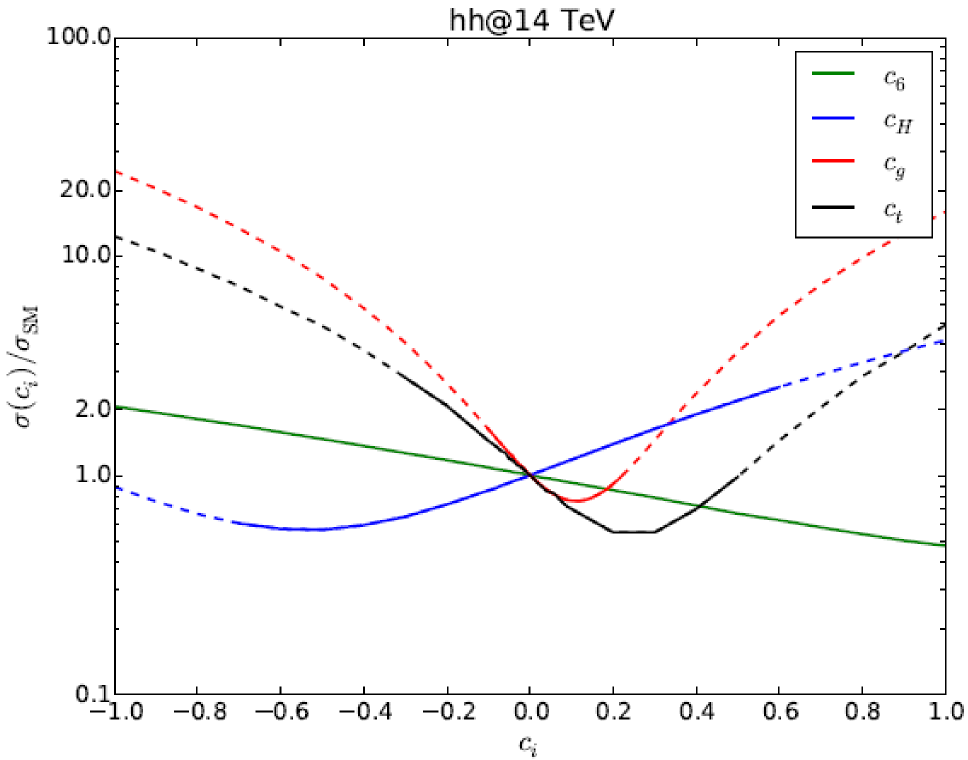
- Two τ-tagged jets with $p_\perp > 20\,\text{GeV}$
- one fat jet with $R = 1.4$ (CA), two hardest sub-jets b-tagged ($|\eta| < 2.5$)
  Butterworth, Davison, Rubin, Salam, 0802.2470
- $m_{\tau^+\tau^-}, m_{\rm fat} \in [m_h - 25\,\text{GeV}, m_h + 25\,\text{GeV}]$
- $p_\perp^{\rm fat}, p_\perp^{\tau\tau} > 100\ \text{GeV},\ \ \Delta R(h,h) > 2.8,\ p_\perp^{hh} < 80\ \text{GeV}$

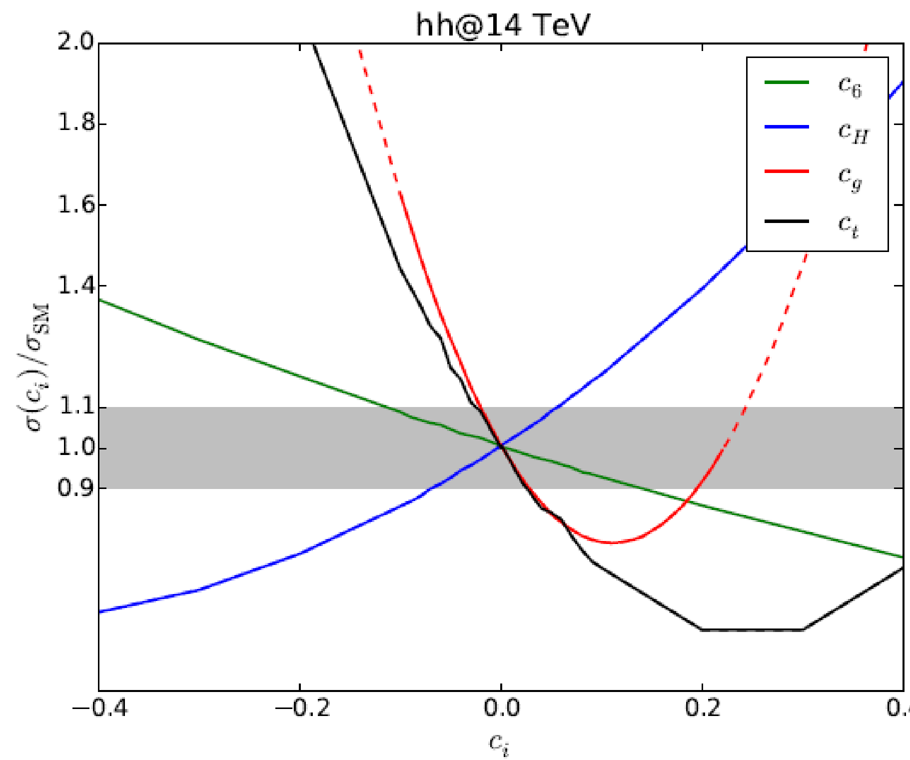
b,τ–tagging efficiencies: 70 %

see: Dolan, Englert, Spannowsky, 1206.5001;
Maierhoefer, Papaefstathiou, 1401.0007

Results

$gg \to hh$ Cross Section





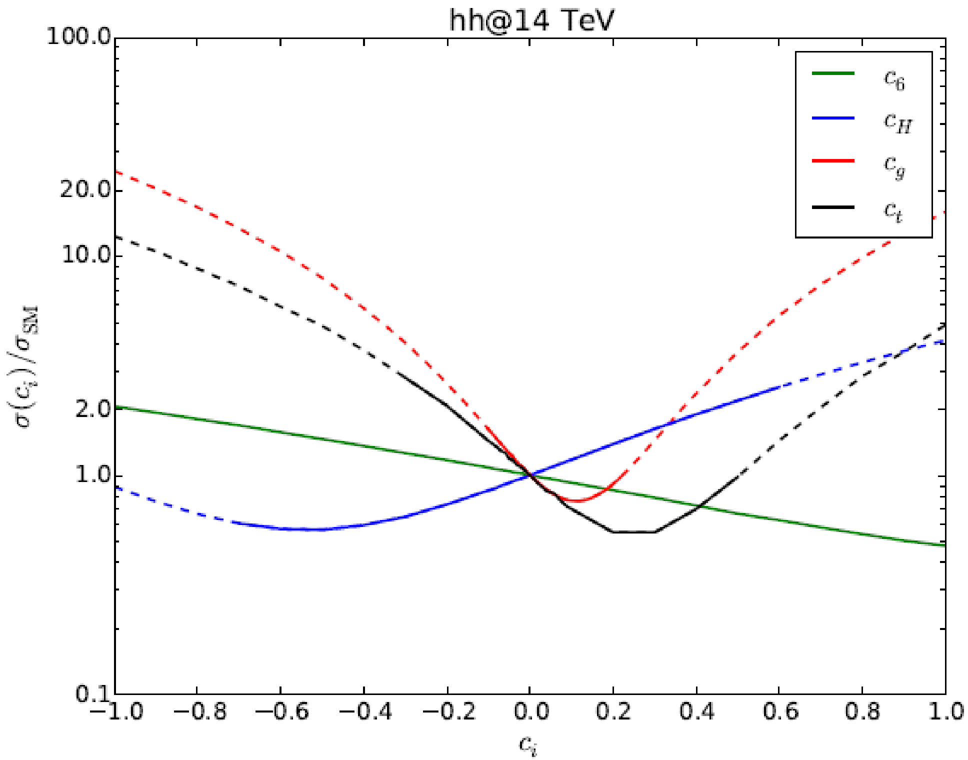
MSTW2008nlo_nf4 PDF

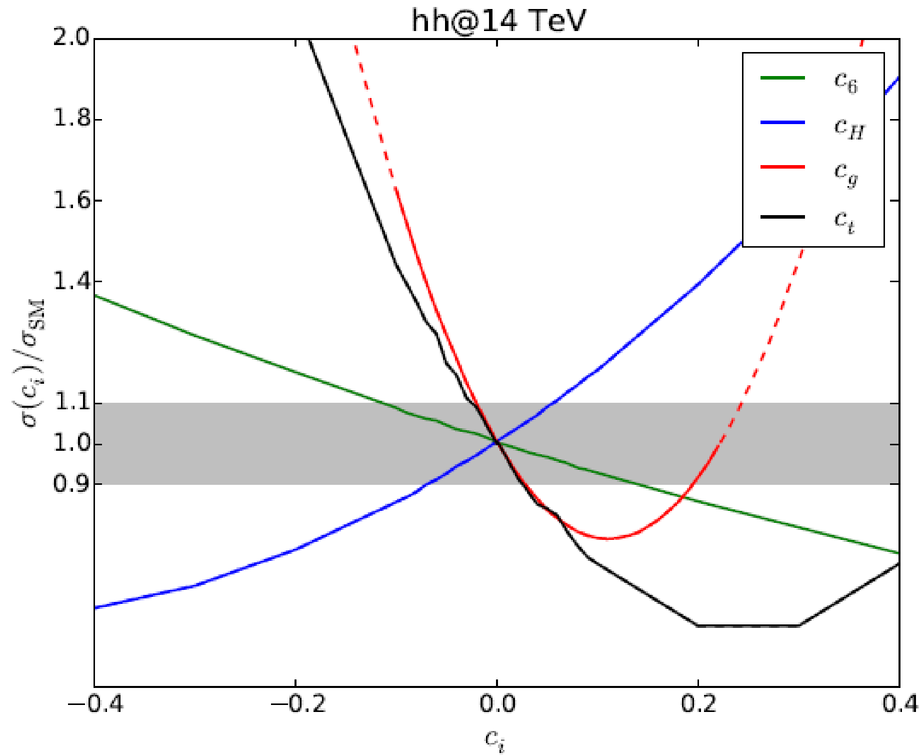
- Effect of varying individual Wilson coefficients
- Dashed: parameter-range excluded from h data at the LHC

  → used HiggsBounds, HiggsSignals on cross sections calculated via eHDECAY

Bechtle et.al., 1311.0055, 1305.1933

$gg \to hh$ Cross Section



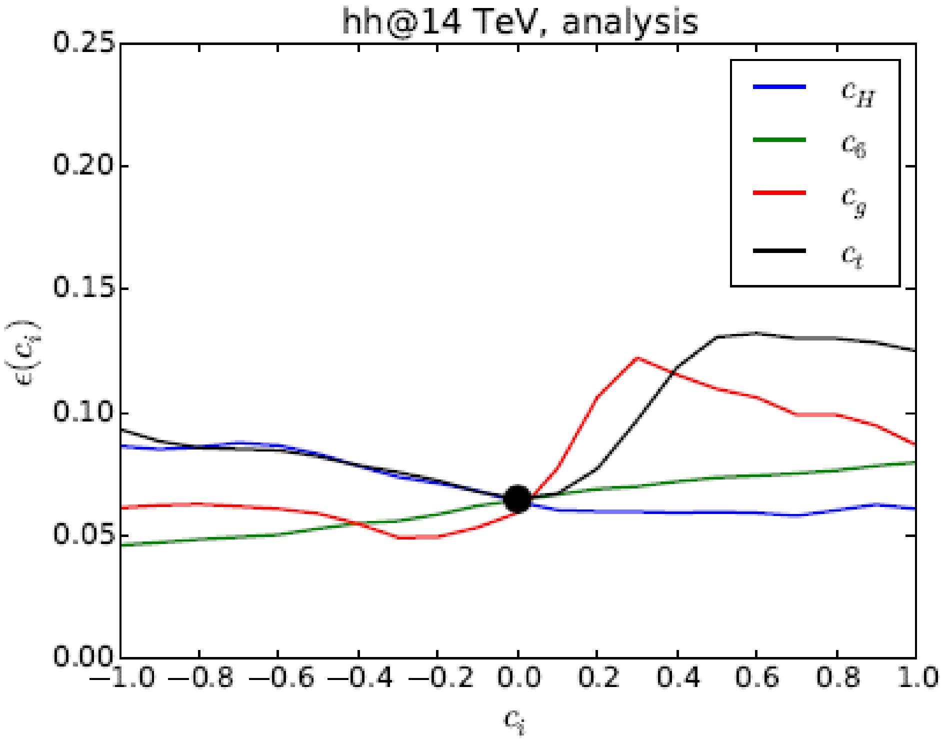


MSTW2008nlo_nf4 PDF

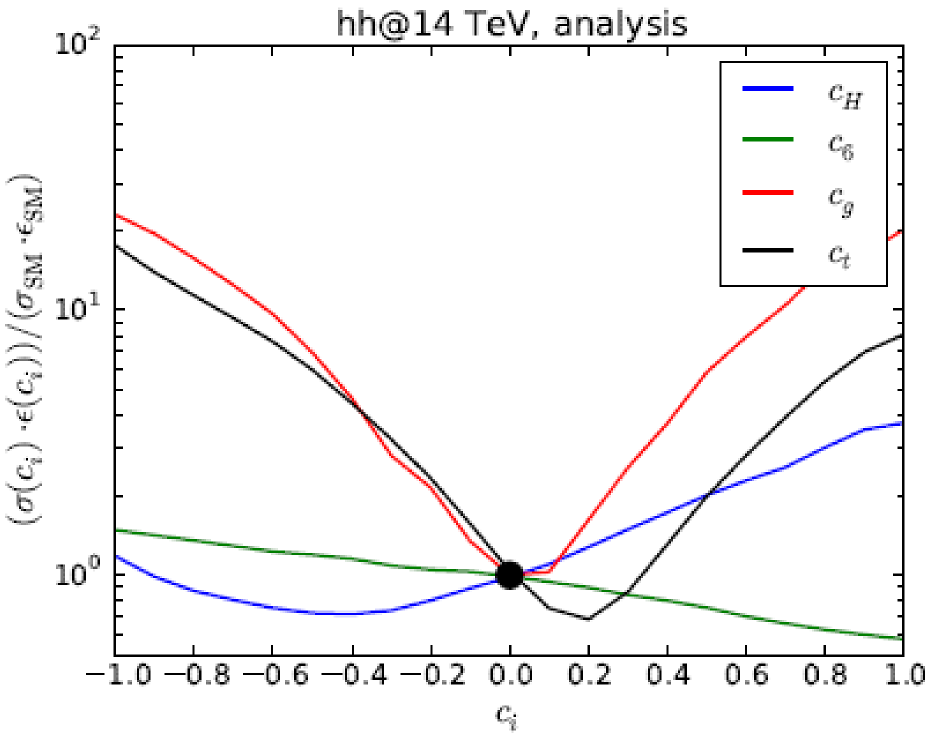
$$\left.\frac{\mathrm{d}\hat{\sigma}(gg\to hh)}{\mathrm{d}\hat{t}}\right|_{\rm EFT} = \frac{G_F^2\alpha_s^2}{256(2\pi)^3}\Bigg\{\Big|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)\ \ +2c_g C_\triangle$$
$$+C_\Box F_\Box(1-c_H+2c_t)+2c_g C_\Box\Big|^2+\Big|C_\Box G_\Box\Big|^2\Bigg\}$$

$gg \to hh$ after cuts

Efficiency



Cross Section



MC generator important for analysis

→ describe distributions, which determine efficiencies $\epsilon(c_i)$

Full Analysis

- Start with model where only $c_6 \neq 0$ (unconstrained from single h)

  ↳ Vary only λ as done in previous studies (→ BRs unchanged)

  - $S(c_6)$ signal + B background events @ given L_{int}
  - $N(c_6) = S(c_6) + B\,,\ \delta N^2 = \delta S^2 + \delta B^2$

Full Analysis

- Start with model where only $c_6 \neq 0$ (unconstrained from single h)

  ↳ Vary only λ as done in previous studies (→ BRs unchanged)

- $S(c_6)$ signal + B background events @ given $L_{\rm int}$
- $N(c_6) = S(c_6) + B\,,\ \delta N^2 = \delta S^2 + \delta B^2 + S^2 f_{\rm th}^2$

$$\delta N^2 = N + S^2 f_{\rm th}^2$$

Full Analysis

- Start with model where only $c_6 \neq 0$ (unconstrained from single h)

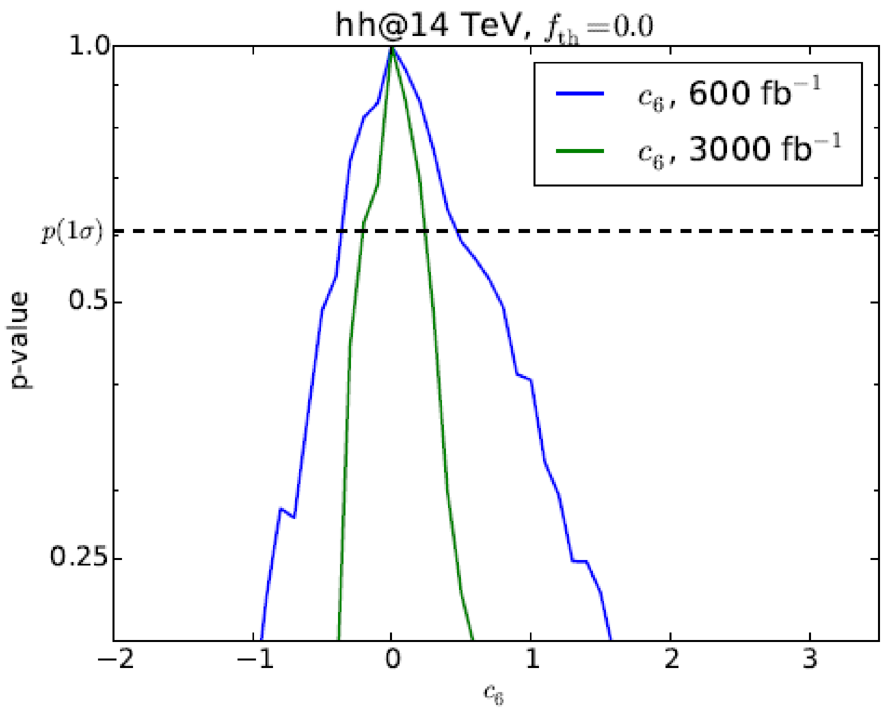
↳ Vary only λ as done in previous studies (→ BRs unchanged)

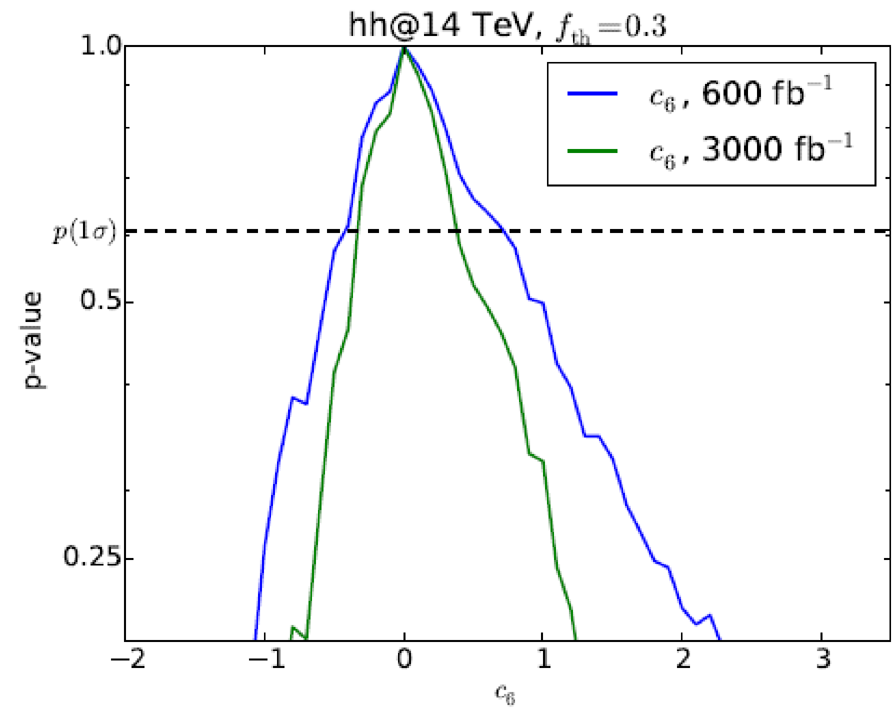
$$\delta N^2 = N + S^2 f_{\rm th}^2$$

- Expected constraint on c_6, assuming the SM to be true (c_6=0):

Compute how many standard deviations $\delta N(c_6)$ away a given $N(c_6)$, as predicted from theory, is from $N(c_6 = 0)$.

Full Analysis





$$c_6^{1\sigma}(600\ \mathrm{fb}^{-1}) \in (-0.4, 0.5),\ \ c_6^{1\sigma}(3000\ \mathrm{fb}^{-1}) \in (-0.3, 0.3),\ \ f_{\rm th}=0$$

$$c_6^{1\sigma}(600\ \mathrm{fb}^{-1}) \in (-0.5, 0.8),\ \ c_6^{1\sigma}(3000\ \mathrm{fb}^{-1}) \in (-0.4, 0.4),\ \ f_{\rm th}=0.3$$

$(c_6 > 0)-$region more challenging as cross section reduced → larger uncertainty

Full D=6 Theory

- Similar as before, assume SM (c_i=0) to be true and calculate distance of predicted $N(c_6,\ldots,c_b)$ from $N(c_6=0,\ldots,c_b=0)$ in units of $\delta N(c_6,\ldots,c_b)$.

- Show results in 2D grids (c_6, c_i), i=H,g,γ,t,b

- Marginalize over other directions, varying the coefficients in the 95% CL allowed regions, obtained from HiggsBounds/Signals (with a Gaussian weight)

Scan of the Parameter Space

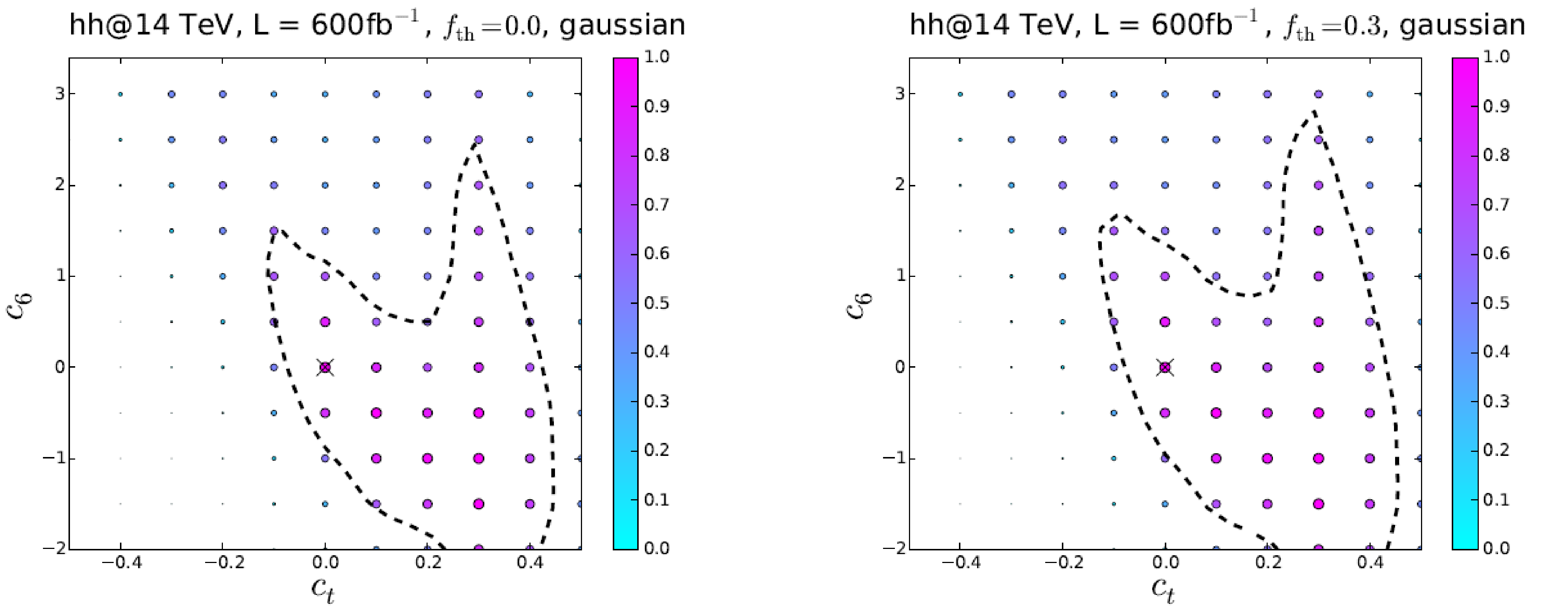
- Show results in 2D grids (c_6, c_i), i=H,g,γ,t,b
- Marginalize over other directions, varying the coefficients in the 95% CL allowed regions, obtained from HiggsBounds/Signals (with a Gaussian weight)

$$p(c_i, c_6) = \frac{\bar{p}(c_i, c_6)}{\max(\bar{p}(c_i, c_6))}, \quad \bar{p}(c_i, c_6) = \sum_{\{c_f\}} p(c_6, c_i, \{c_f\}) \times p_{\text{Gauss.}}(\{c_f\})$$

$$p_{\text{Gauss.}}(\{c_f\}) = \prod_f \frac{1}{\sigma_f \sqrt{2\pi}} \exp\left\{-\frac{(x_f - \mu_f)^2}{2\sigma_f^2}\right\}$$

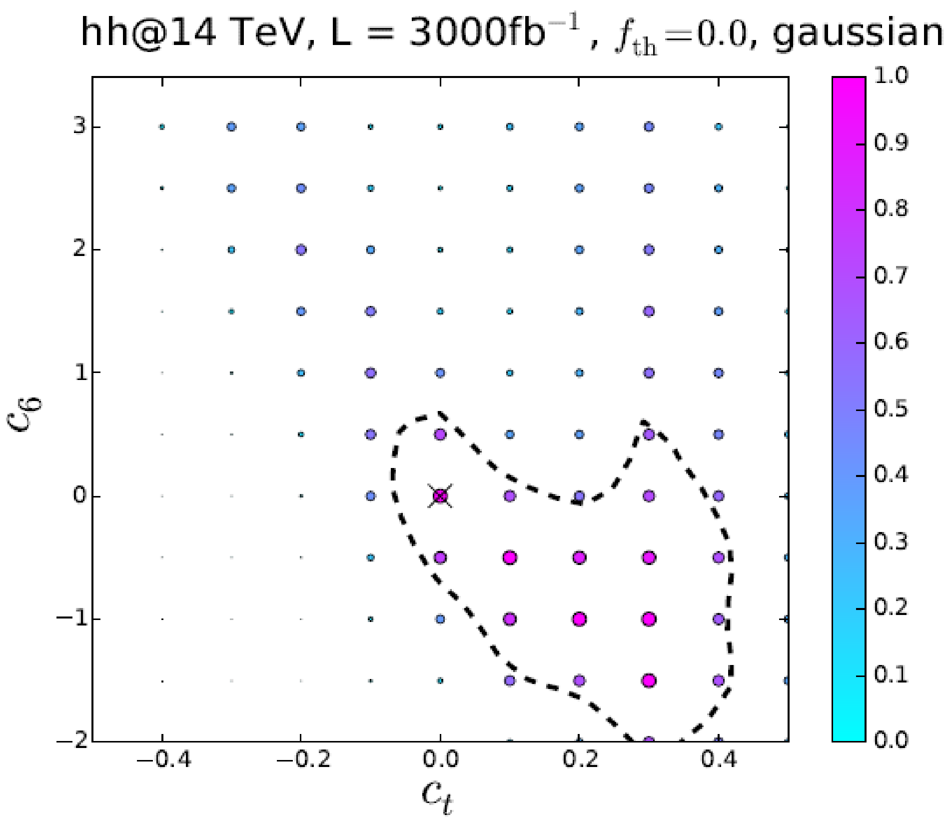
- Draw iso-contours corresponding to probability-drop of 1σ

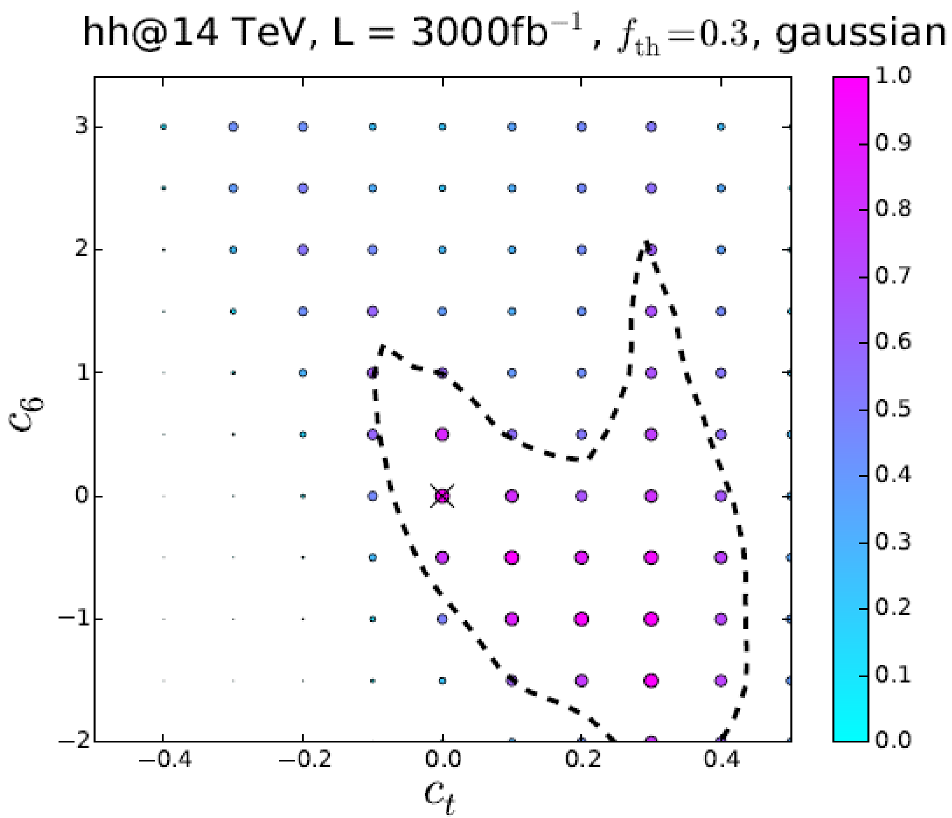
Results: c_t-c_6



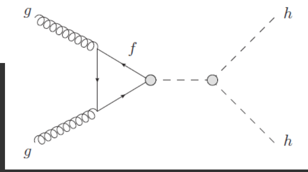
- Clear correlation visible: Enhanced hh cross section due to negative c_t can be compensated by reduction due to positive c_6

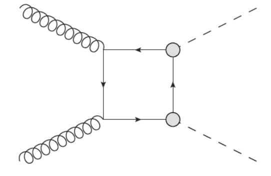
c_t-c_6

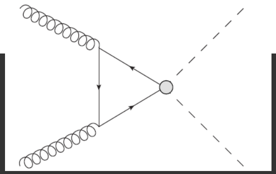




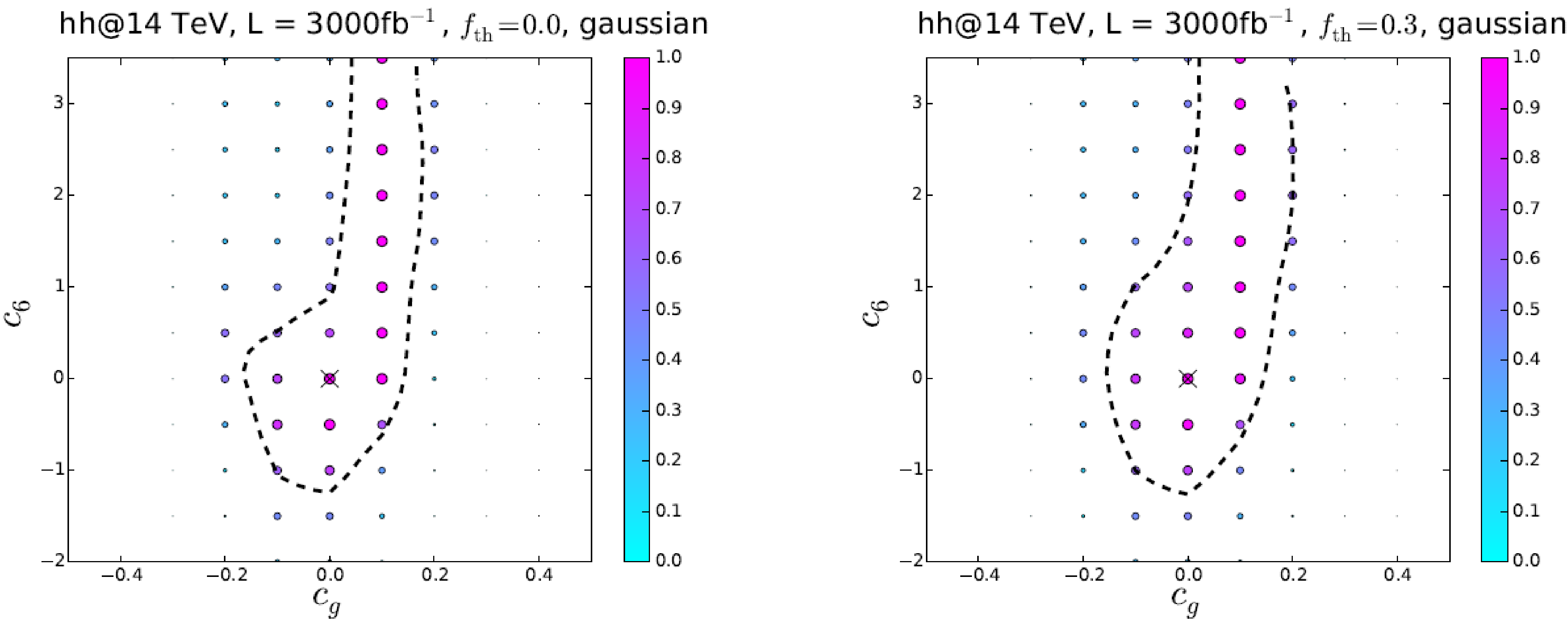
- Better knowledge on 'top Yukawa' c_t helpful to improve the range for c_6
- On the other hand, could also obtain meaningful information on c_t in hh





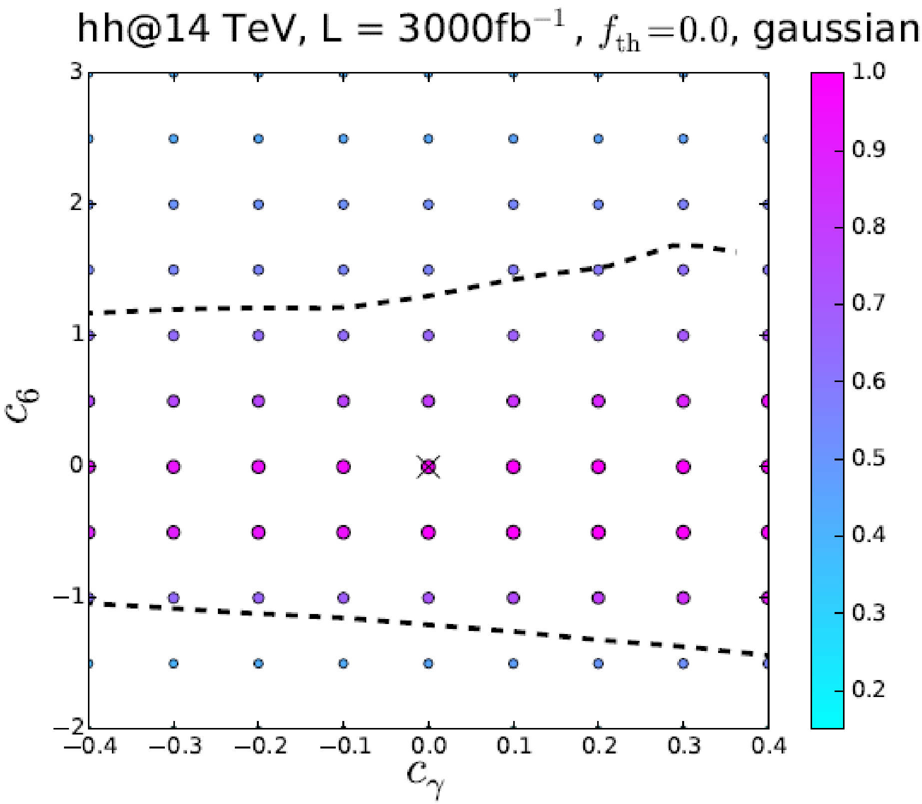


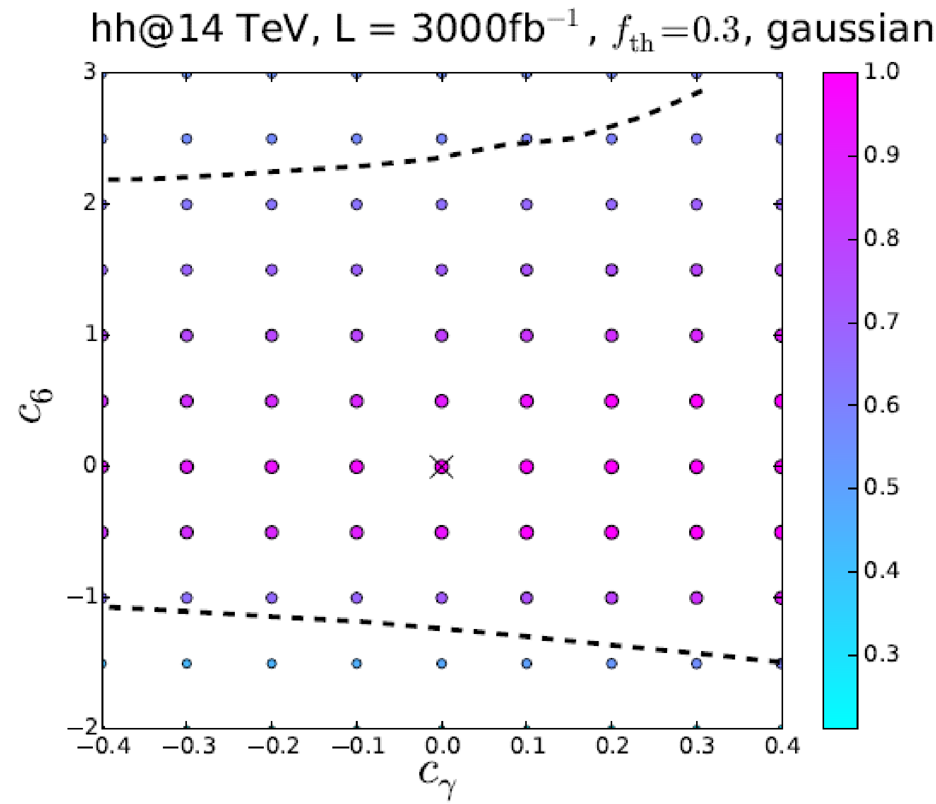
c_g-c_6



- Again compensation of effects from different operators possible
  → range for c_6 depends significantly on other coefficients

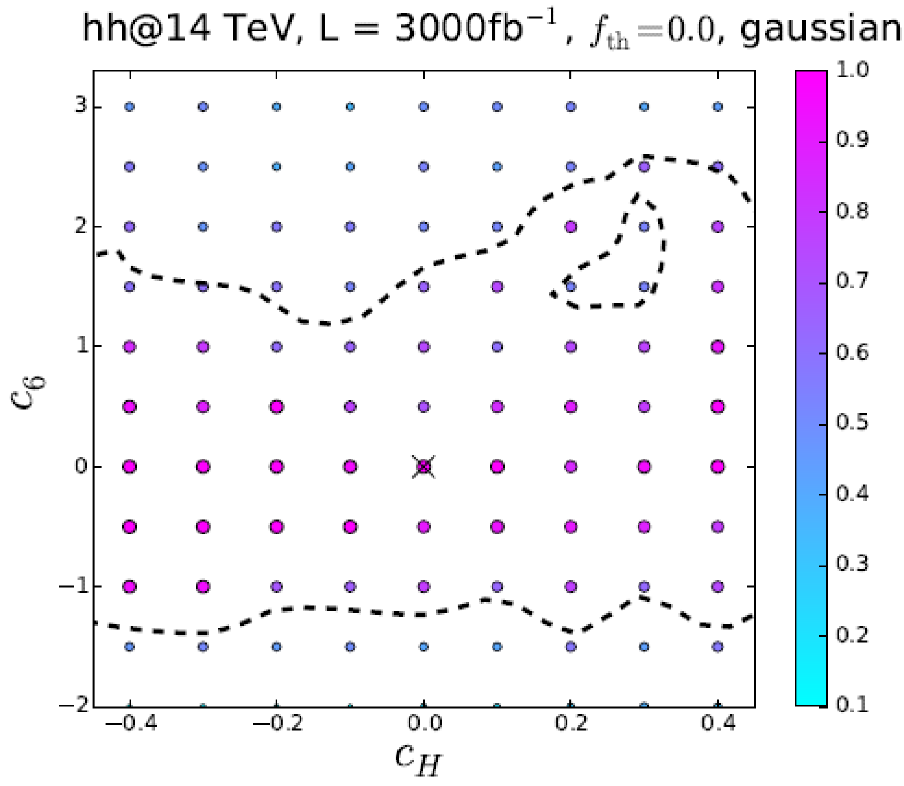
$c_\gamma - c_6$



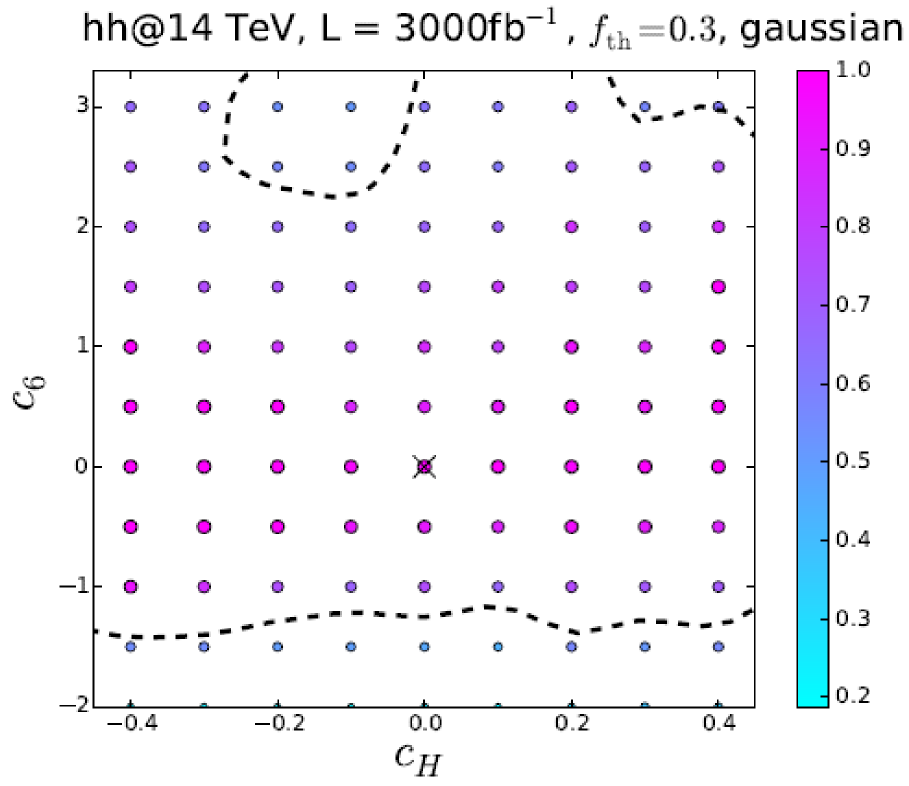


- As expected very weak correlation: only indirectly through dependence of allowed range in c_g on value of c_γ

c_H-c_6

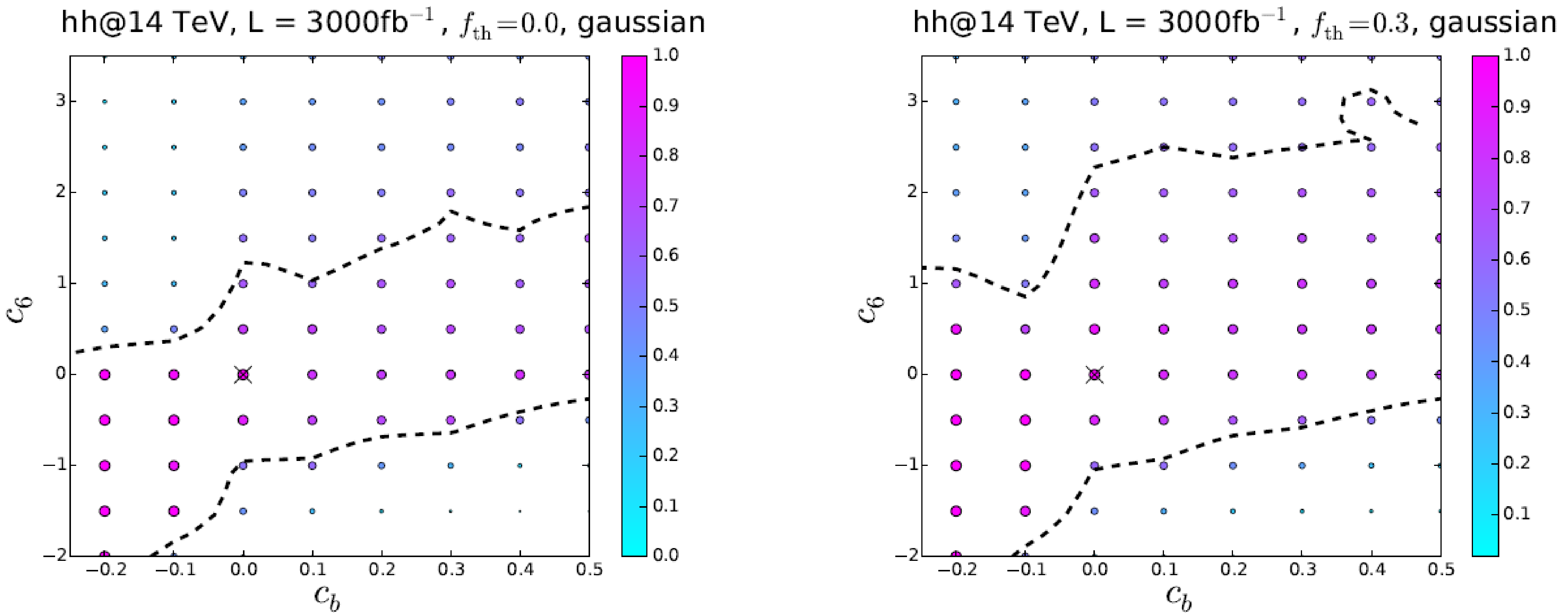


hh@14 TeV, L = 3000fb^{-1} , $f_{\rm th}=0.0$, gaussian
c_6
c_H



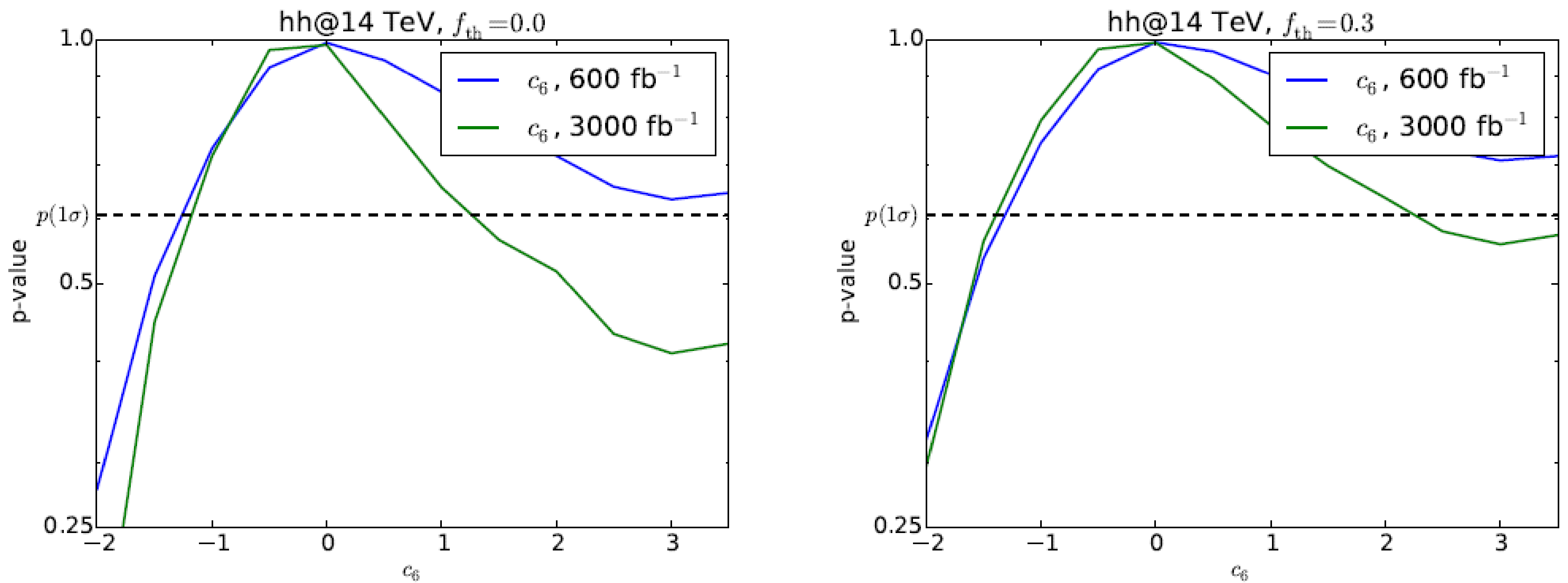
hh@14 TeV, L = 3000fb^{-1} , $f_{\rm th}=0.3$, gaussian
c_6
c_H

$(c_b = c_\tau) - c_6$



- Reduced BR due $(c_b=c_\tau)<0$ to can be compensated by enhanced production cross section due to negative c_6 and vice versa

Full Marginalization → c_6



Final Results

Expected 1σ constraints at the 14 TeV LHC, assuming f_{th} = 30%

model	$L = 600\ \mathrm{fb}^{-1}$	$L = 3000\ \mathrm{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \in (-1.2, 2.4)$

Conclusions and Outlook

Analysis of hh productions can offer viable additional information on the D=6 extension of the SM

Some Future Directions:

- Optimize analysis for different regions of parameter space
- Break degeneracy c_b=c_τ/consider different projections
- Include other decay channels
- Consider distributions to improve bounds

Backup: Hbounds/Signals Ranges

coefficient	μ_f	σ_f
c_H	-0.035	0.225
c_t	-0.04	0.17
c_b	0.0	0.18
c_g	-0.01	0.06
c_γ	-0.25	0.62