DiHiggs Production and New Physics

Higgs Hunting 2015
Orsay

31.7.2015

Higgs Hunting
July 30-August 01, 2015, Orsay, France
Bruno Mazoyer - LAL Orsay 2015

Florian Goertz
CERN

New Physics (in DiHiggs)

Probe our current understanding of the fundamental laws of nature...

Many hints and evidences for NP!

- Gravity
- Hierarchy Problem
- Neutrino Masses (See Saw)
- Grand Unification of Forces
- Flavor Structure
- Baryogenesis
- Dark Matter
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- Hints in Flavor/Precision Measurements?
- ...

How to get access to NP?

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- Many links to Higgs Sector

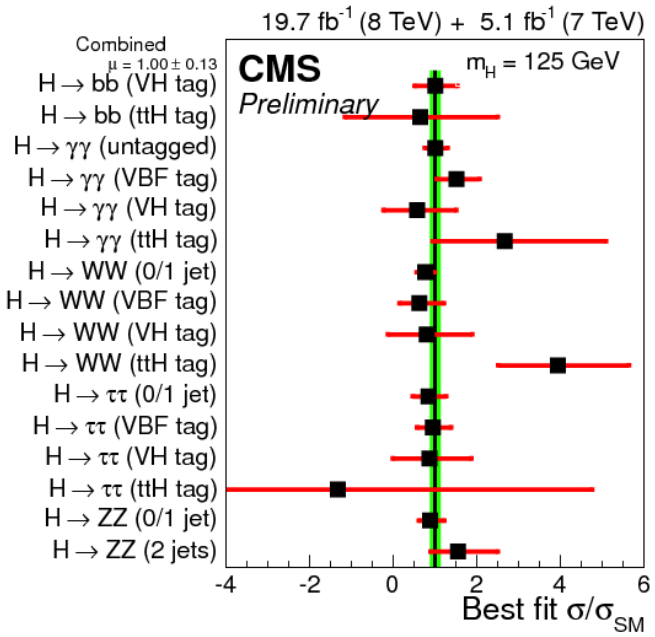
The Higgs Sector...

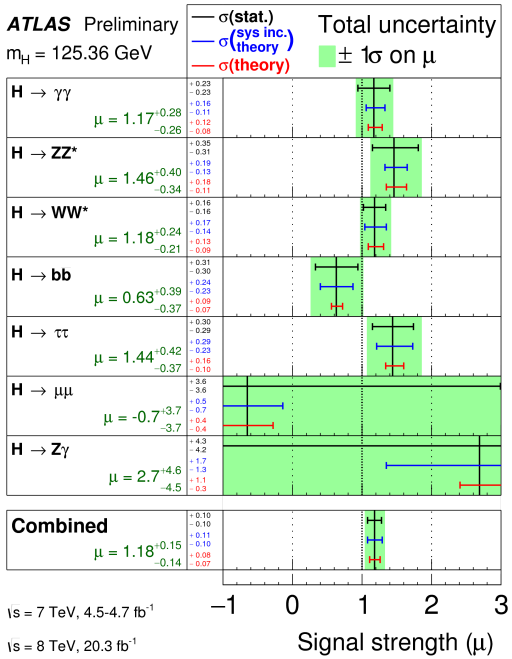
... offers a unique window to NP

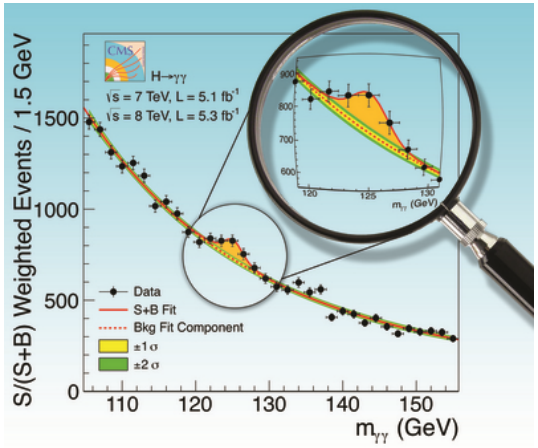
Properties of the Higgs Boson?

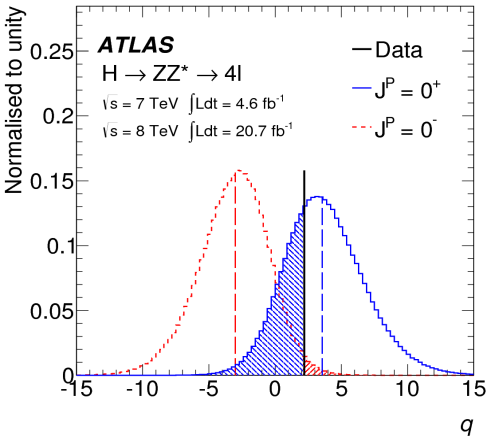
Scale of New Physics?

One of the biggest discoveries of mankind









The Higgs Potential

Very important test of SM/NP: Higgs potential → self couplings

$$V(H) = \mu^2 |H|^2 + \lambda |H|^4 \quad (+ \cdots)$$

EWSB:

$$H \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$\langle |H| \rangle$

- Vacuum Stability
- Origin of the Potential (↔ flavor)
- Dark Matter
- Portal
- Baryogenesis
- Hierarchy Problem → see later
- ...

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

SM: $\lambda_{3h} = \lambda_{4h} = m_h^2 / 2v^2$

$$H \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$\langle |H| \rangle$

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

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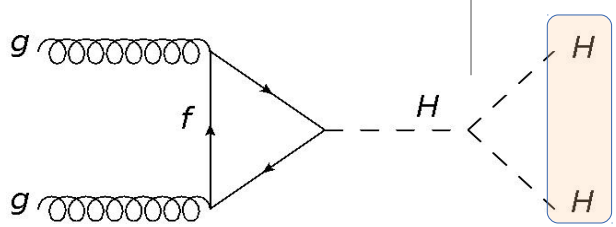

λ_{3h} accessible in <u>Higgs pair production</u>

The Higgs Potential

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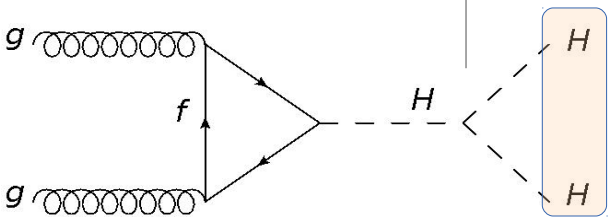


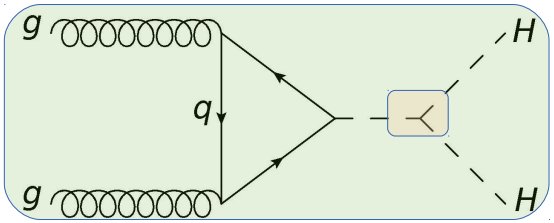
Triple Higgs production:
extremely challenging @(V)LHC
0.06 fb @LHC14; 9.45 fb @VLHC (200 TeV)

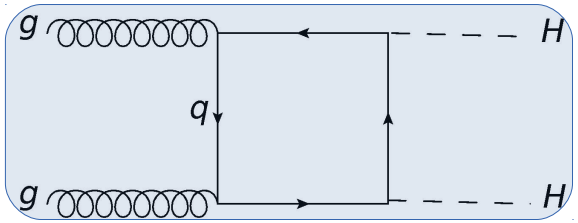
Plehn, Rauch, hep-ph/0507321

λ_{3h} accessible in <u>Higgs pair production</u>

Higgs-Pair Production in the SM (LO)

$$\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \left[|\underbrace{C_\triangle F_\triangle}_{\text{spin-0}} + \underbrace{C_\square F_\square}_{\text{spin-0}}|^2 + |\underbrace{C_\square G_\square}_{\text{spin-2}}|^2 \right]$$





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

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

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

See e.g. Plehn, Spira, Zerwas ph/9603205

$$\sigma(gg \to hh)_{\mathrm{LO}}^{\mathrm{LHC14}} \sim 17\,\mathrm{fb}$$

$$\sigma(gg \to hh)_{\mathrm{NNLO}}^{\mathrm{LHC14}} \sim 40\,\mathrm{fb}$$

Eboli, Marques, Novaes, Natale, PLB 197(1987)269
Glover, van der Bij, NPB 309(1988)282
de Florian, Mazzitelli, 1305.5206, 1309.6594
see also Maltoni, Vryonidou, Zaro, 1408.6542

Different Decay Channels

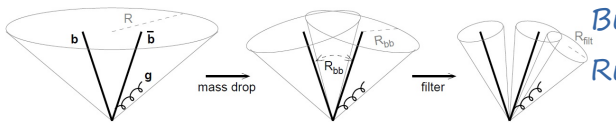
Expected Significance @ 600 fb^{-1} (SM)

$hh \to b\bar{b}\gamma\gamma$ $\lesssim 2\sigma$ (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

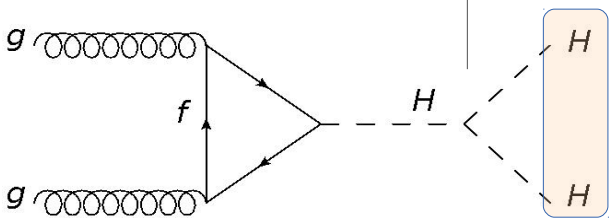
$hh \to b\bar{b}W^+W^-$ $\sim 3\sigma$ (S/B=12/8)

Papaefstathiou, Yang, Zurita, 1209.1489

Theorists' analyses!

The Higgs Potential

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



Most stringent projected constraint on λ_{3h} alone @ LHC14

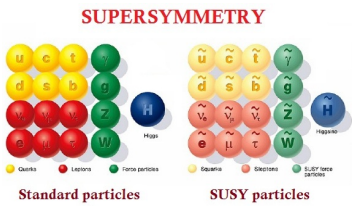
$$\Delta\lambda_{3h} = (40-50)\% \;\; @\, 600\,\mathrm{fb}^{-1}$$
$$\Delta\lambda_{3h} = \;\; 30\% \qquad\qquad @\, 3000\,\mathrm{fb}^{-1}$$

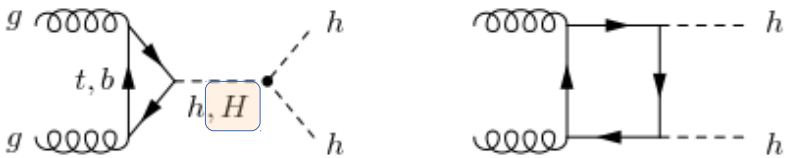
FG, Papaefstathiou, Yang, Zurita 1301.3492; 1309.3805

Baur, Plehn, Rainwater, hep-ph/0211224, hep-ph/0310056
Dolan, Englert, Spannowski 1206.5001
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira 1212.5581

New Physics in hh Production

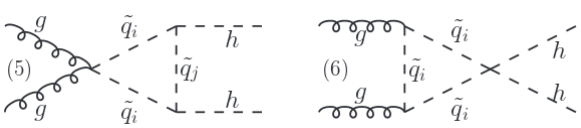
- SUSY





$$\lambda_{hhh} = 3\cos 2\alpha \sin(\beta+\alpha) + 3\frac{\epsilon}{m_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\alpha,$$

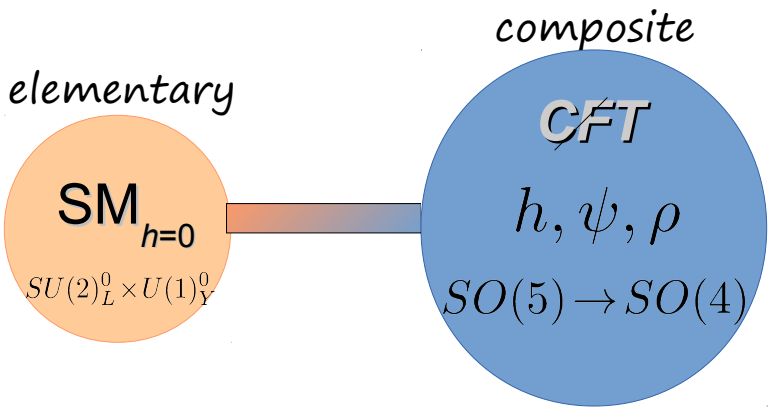
$$\lambda_{Hhh} = 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha\cos(\beta+\alpha) + 3\frac{\epsilon}{m_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\alpha,$$



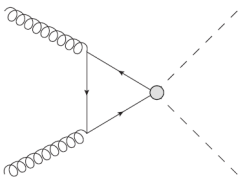
case	model	$\tan\beta$	m_h (GeV)	A (TeV)	μ (TeV)	σ (fb)	dominant mode
1	MSSM	3	104	+1	−1	2000	$gg \to H \to hh$
2	MSSM	3	100	+1	−1	20	$gg \to hh$
3	MSSM	50	105	+1	+1	5000	$gg \to hh$
4	SM	-	105	-	-	40	$gg \to hh$

Plehn, Spira, Zerwas, ph/9603205,
Djouadi, Kilian, Muhlleitner, Zerwas, ph/9904287,
Lafaye, Miller, Muhlleitner, Moretti, ph/0002238,
Cao, Heng, Shang, Wan, Yang, 1301.6437, ...

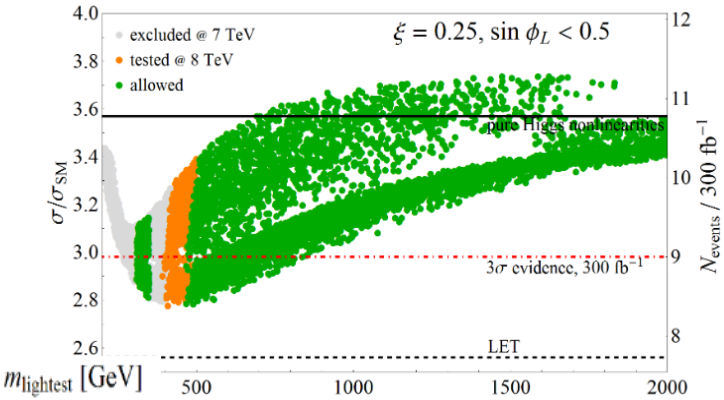
- Composite Higgs



$$\Sigma = U\,\Sigma_0\,,\;\; U = e^{i\frac{\sqrt{2}}{f_\pi}h_{\hat{a}}T^{\hat{a}}}$$



...



- etc...

Gillioz, Grober, Grojean, Muhlleitner, Salvioni, 1206.7120,
Contino, Grojean, Moretti, Piccinini, Rattazzi, 1002.1011,
Grober, Muhlleitner, 1012.1562,
Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, 1205.5444, ...

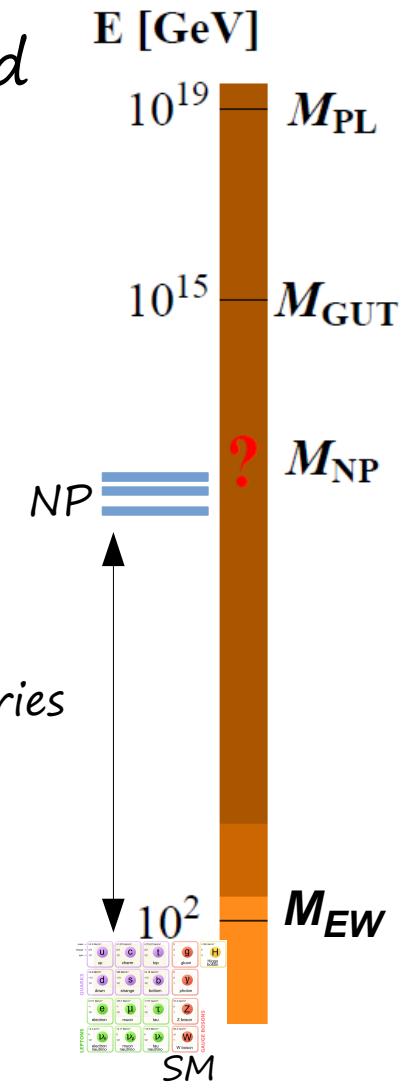
'Model Independent' Approach to NP

- If NP resides at high scale E>>M_{EW}, can be described by operators with $dim[\mathcal{O}] > 4$, independently of the concrete theory that completes the SM!

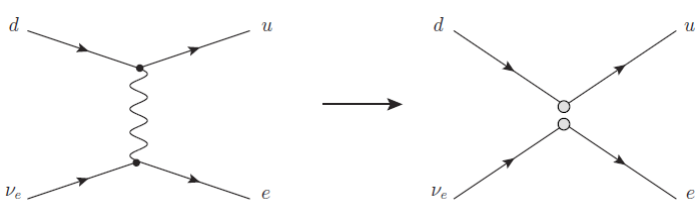
$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D \leq 4} + \boxed{\sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{D=6}} + \ldots$$

local operators built of SM field content, respecting gauge symmetries

= New Physics



c.f. Fermi Theory



$$\mathcal{L}_{eff} = -\frac{g^2}{8m_W^2} C_1(\mu)(\bar{e}\,\nu_e)_{V-A}(\bar{u}\,d)_{V-A}$$

Weinberg, Wilson, Callen, Coleman, Wess, Zumino, ...

$\hbar = c = 1$

Physics Beyond the SM

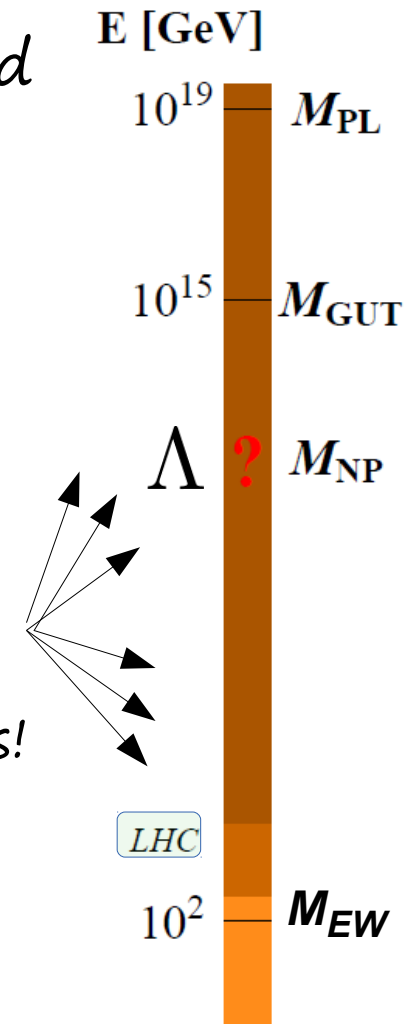
- If NP resides at high scale E>>M_{EW}, can be described by operators with $dim[\mathcal{O}] > 4$, independently of the concrete theory that completes the SM!

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D \leq 4} + \boxed{\sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{D=6}} + \ldots$$

Effects scale like E^2/Λ^2
→ suppressed by mass scale of heavy new physics

[leading effects: D=6, D=8 further suppressed]

A lot of room for new physics!



SM as IR limit, *expected* to work perfectly well at low E
– new fundamental theory takes over at large E

EFT Approach to New Physics

- Full set of non-redundant operators (i.e., basis):

59 D=6 operators (2499 including full flavor structure)

[assuming B&L conservation]

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

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

Alonso, Jenkins, Manohar, Trott, 1312.2014

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Table 3: Four-fermion operators.

- Constrain coefficients of these operators

[One way to go, given the lack of evidence in favor of concrete models]

For non-linear realization, see Grinstein, Trott 0704.1505

Contino, Grojean, Moretti, Piccinini, Rattazzi 1002.1011

Higgs Boson EFT

- Neglecting operators 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; Trott 1409.7605; Falkowski, Riva, 1411.0669; Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, Rauch 1505.05516; HXSWG; ...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6$$
$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.} \right)$$
$$+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu} + \frac{i\, c_{WW}}{16\pi^2\Lambda^2} \mathcal{O}_{WW} \; (+\mathcal{L}_{\rm CP} + \mathcal{L}_{\rm 4f})$$

Higgs Boson EFT

- Neglecting operators 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; Trott 1409.7605; Falkowski, Riva, 1411.0669; Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, Rauch 1505.05516; HXSWG; ...

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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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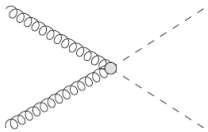

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Basically unconstrainable from single-Higgs physics: $\boxed{c_6}$

→ enters Higgs potential ➡ self couplings

The Higgs Potential

$\frac{c_6}{\Lambda^2}\lambda|H|^6$ enters Higgs potential ➡ self couplings

$$V(H) = \mu^2 |H|^2 + \lambda |H|^4 + \frac{c_6}{\Lambda^2}\lambda|H|^6$$

$$H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

The Higgs Potential

$\frac{c_6}{\Lambda^2}\lambda|H|^6$ enters Higgs potential → self couplings

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

$$\lambda_{3h} = \frac{m_h^2}{2v^2}\left[1 + \frac{c_6 v^2}{\Lambda^2}\right]$$

$$\neq \lambda_{4h} = \frac{m_h^2}{2v^2}\left[1 + \frac{6c_6 v^2}{\Lambda^2}\right]$$

The Higgs Potential

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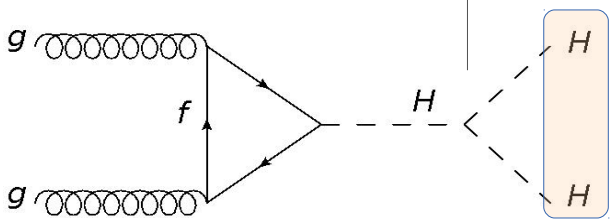

c_6 accessible in <u>Higgs pair production</u>: $\lambda_{3h} = \lambda_{3h}(c_6)$

Challenge: Many more operators contribute to gg→hh

gg→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

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

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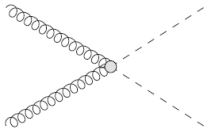
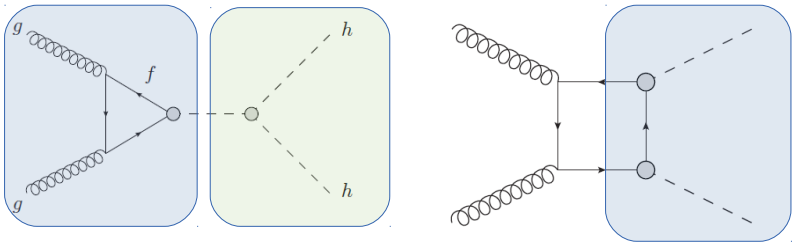
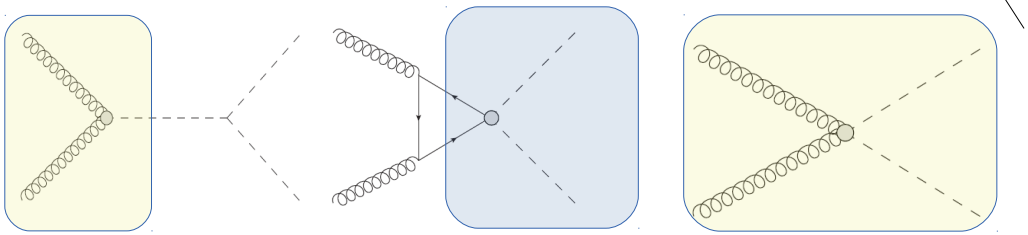


$$H \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

gg → hh

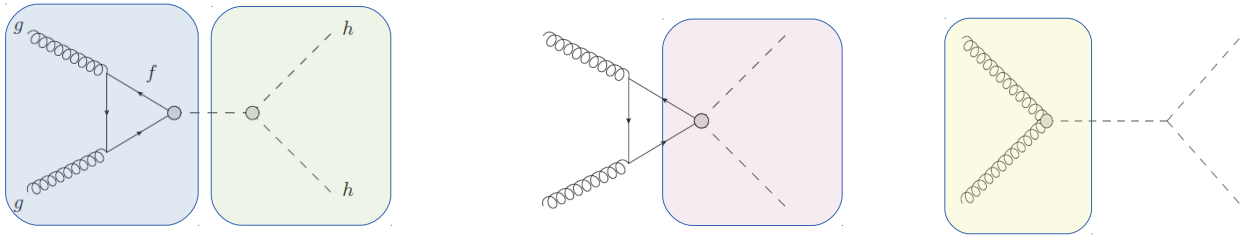


new diagrams



$$h \to \left(1 - \frac{c_H v^2}{2\Lambda^2}\right) h - \frac{c_H v}{2\Lambda^2} h^2 - \frac{c_H}{6\Lambda^2} h^3$$

gg→hh Cross Section in D=6 EFT



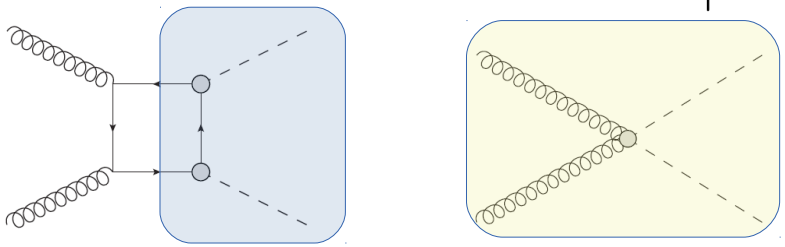
$$\left.\frac{\mathrm{d}\hat{\sigma}(gg\to hh)}{\mathrm{d}\hat{t}}\right|_{\mathrm{EFT}} = \frac{G_F^2\alpha_s^2}{256(2\pi)^3}\Big\{\Big|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)\ +2c_gC_\triangle$$

$$+C_\square F_\square(1-c_H+2c_t)+2c_gC_\square\Big|^2+\Big|C_\square G_\square\Big|^2\Big\}$$

FG, Papaefstathiou, Yang, Zurita, 1410.3471

see also Azatov, Contino, Panico, Son, 1502.00539

NLO: Gröber, Mühlleitner, Spira, Streicher, 1504.06577



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

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

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

Implemented in MC generator Herwig++

Normalize to NNLO: de Florian, Mazzitelli, 1309.6594

$c_i \to c_i\,\Lambda^2/v^2$

$\sigma(gg\to hh)^{\mathrm{LHC14}}_{\mathrm{NNLO}} \sim 40\,\mathrm{fb}$

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_τ	-	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 + $1/\Lambda^2$ suppressed wrt SM

Bold coefficients included in FG, Papaefstathiou, Yang, Zurita, 1410.3471

Don't include suppressed (loop) operators in loop topologies

Focus on

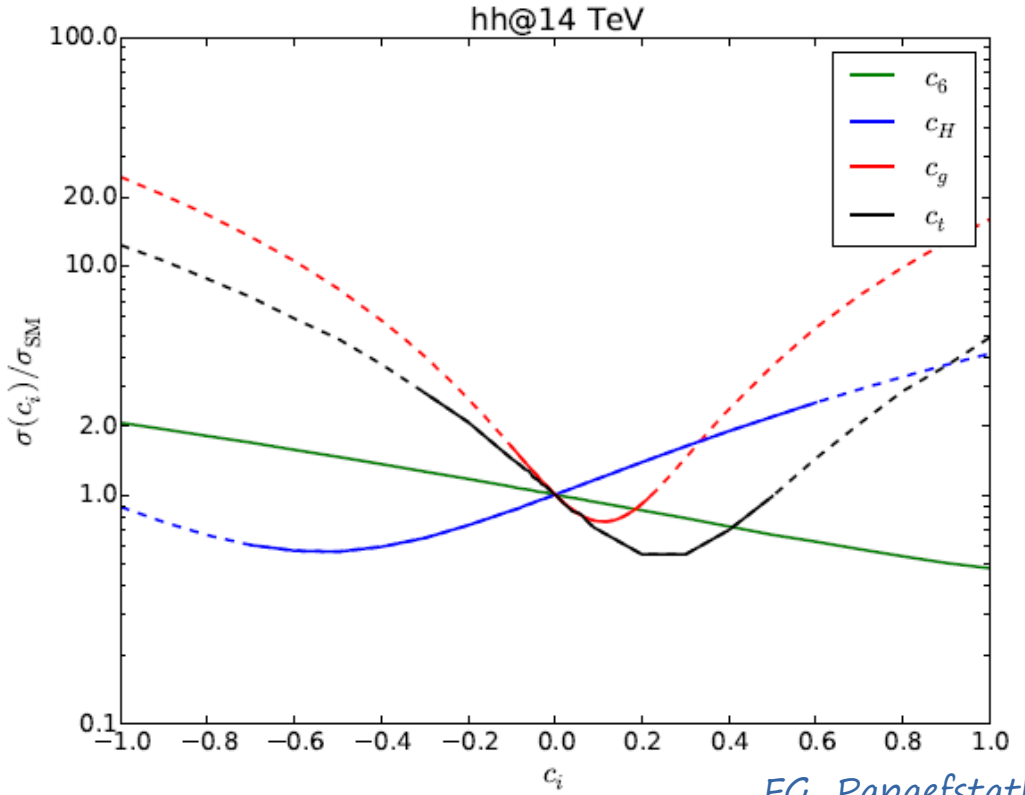
$hh \to b\bar{b}\tau^+\tau^-$ @LHC14

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

Unique accessibility in hh production!

$\mathcal{O}_{W,B,HW,HB} \in \mathcal{O}_{WW}$

gg→hh Cross Section in EFT



FG, Papaefstathiou, Yang, Zurita, 1410.3471

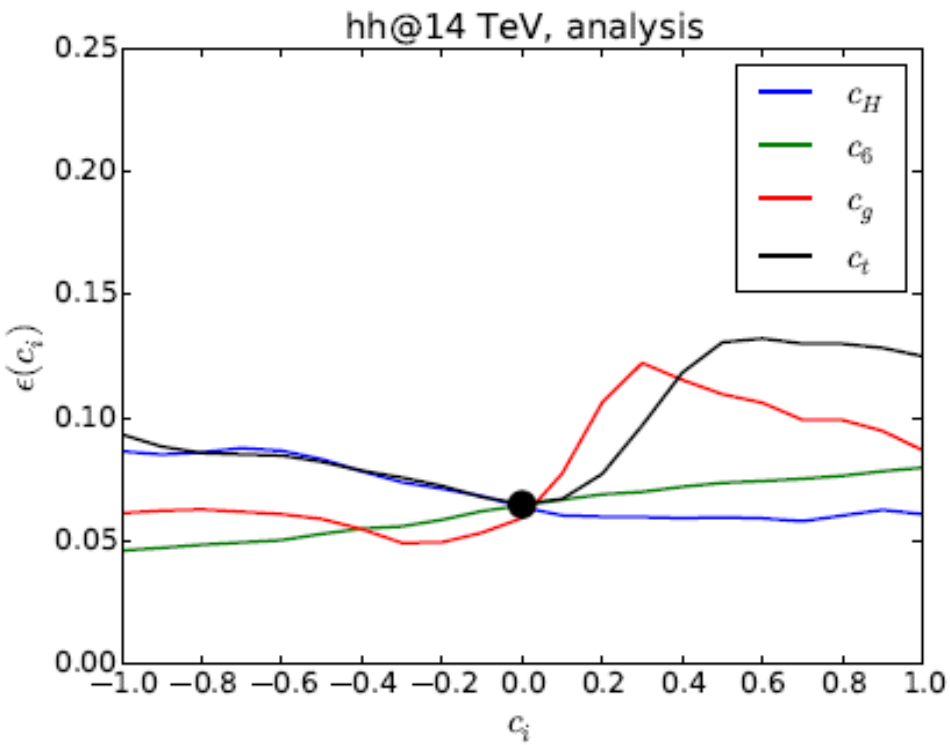
MSTW2008nlo_nf4 PDF

- Effect of varying individual Wilson coefficients
- Dashed: parameter-range excluded from current h data at the LHC
  → used HiggsBounds, HiggsSignals on cross sections calculated via eHDECAY

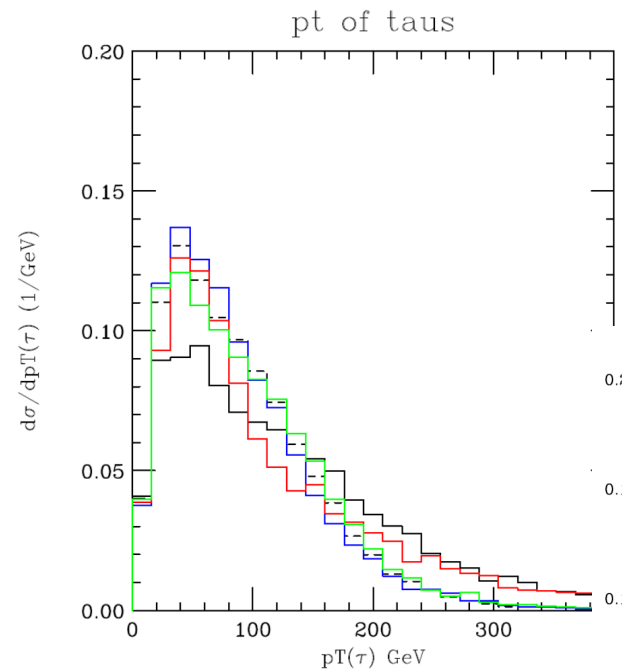
Bechtle et.al., 1311.0055, 1305.1933

gg→hh after cuts

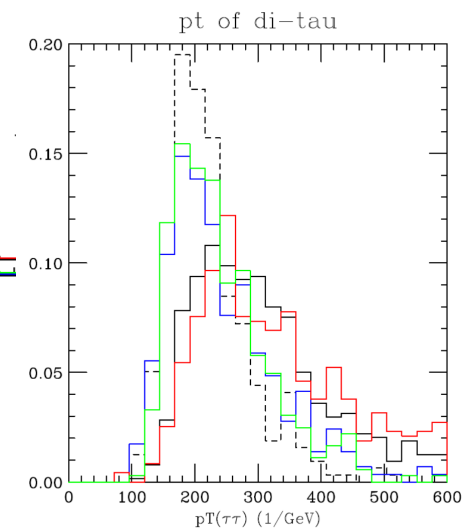
Efficiency



FG, Papaefstathiou, Yang, Zurita, 1410.3471



c_i=0.5

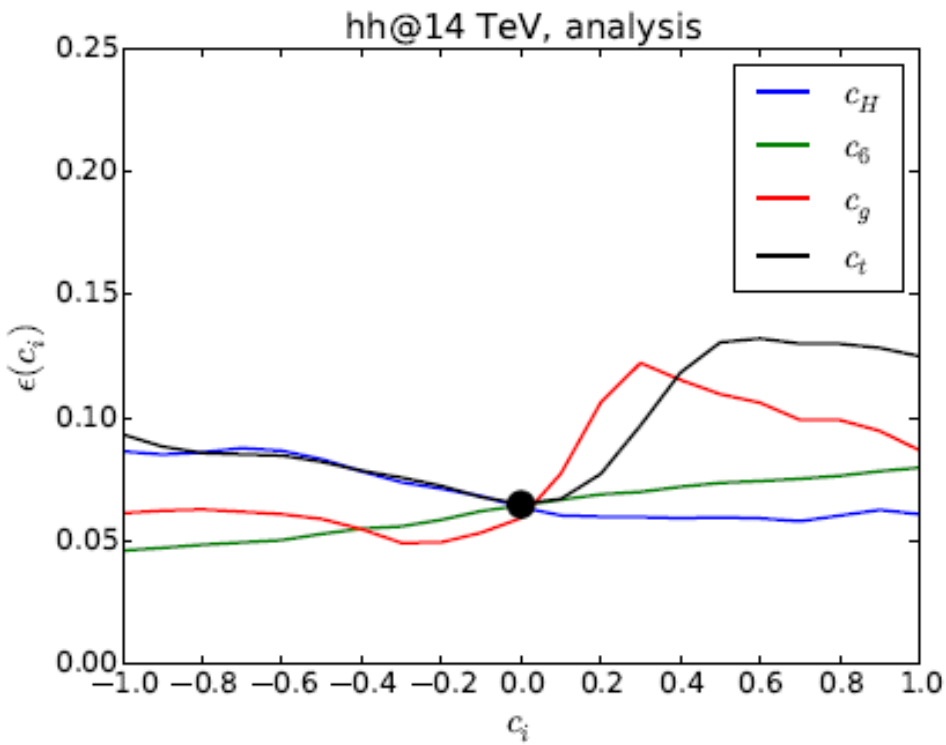


MC generator important for analysis

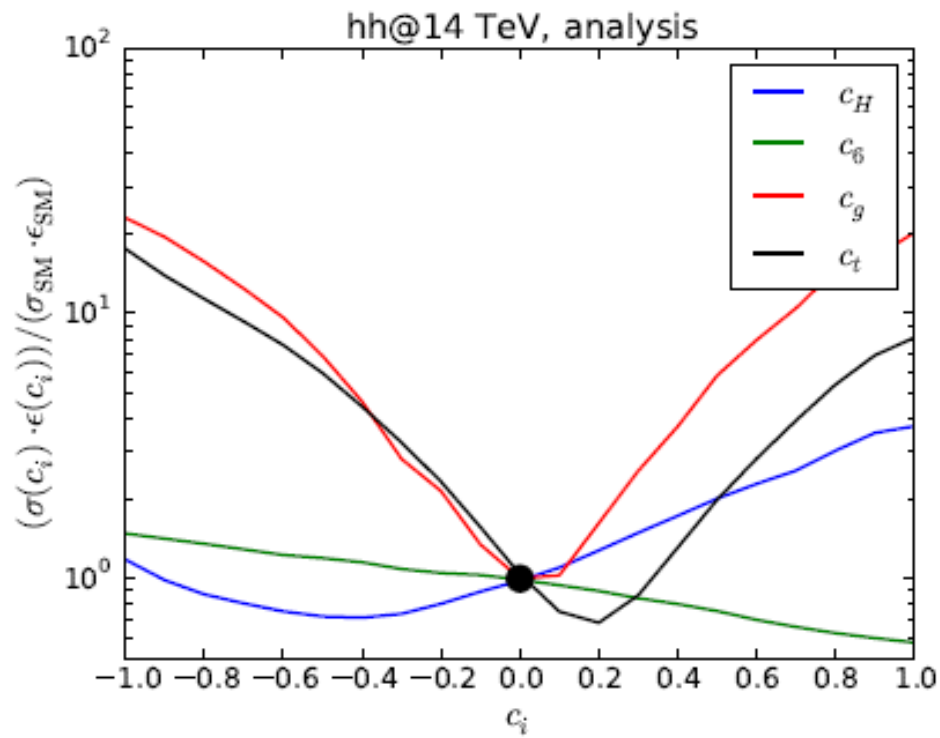
→ describe distributions, which determine efficiencies $\epsilon(c_i)$

gg→hh after cuts

Efficiency



Cross Section



FG, Papaefstathiou, Yang, Zurita, 1410.3471

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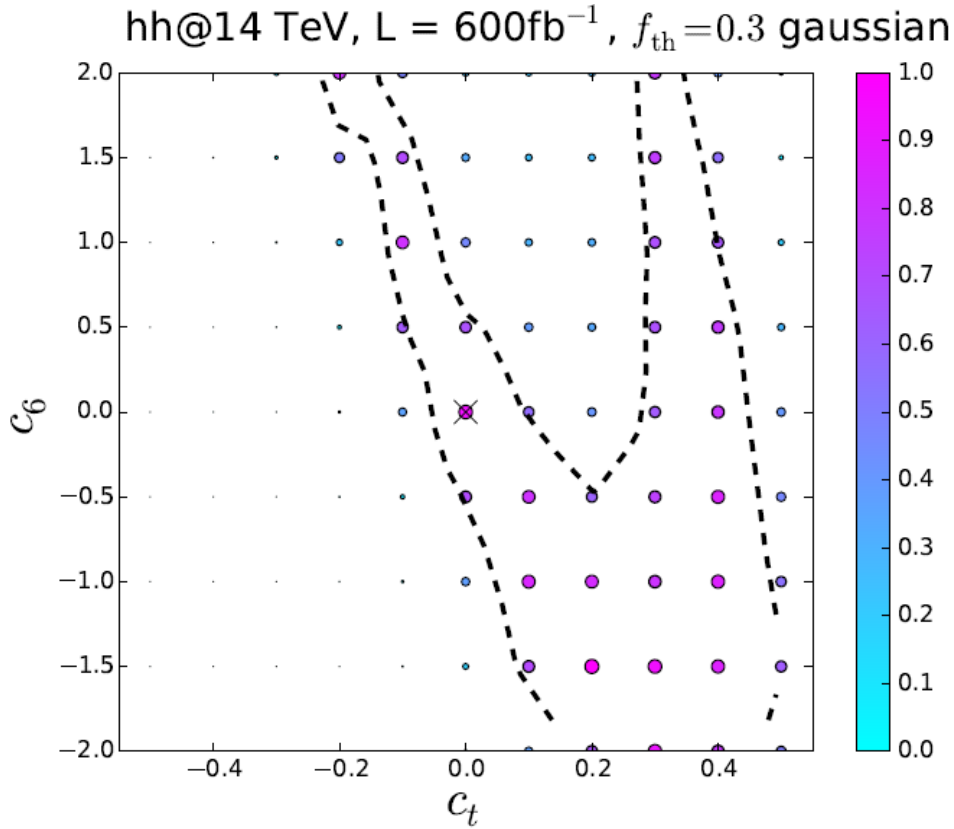
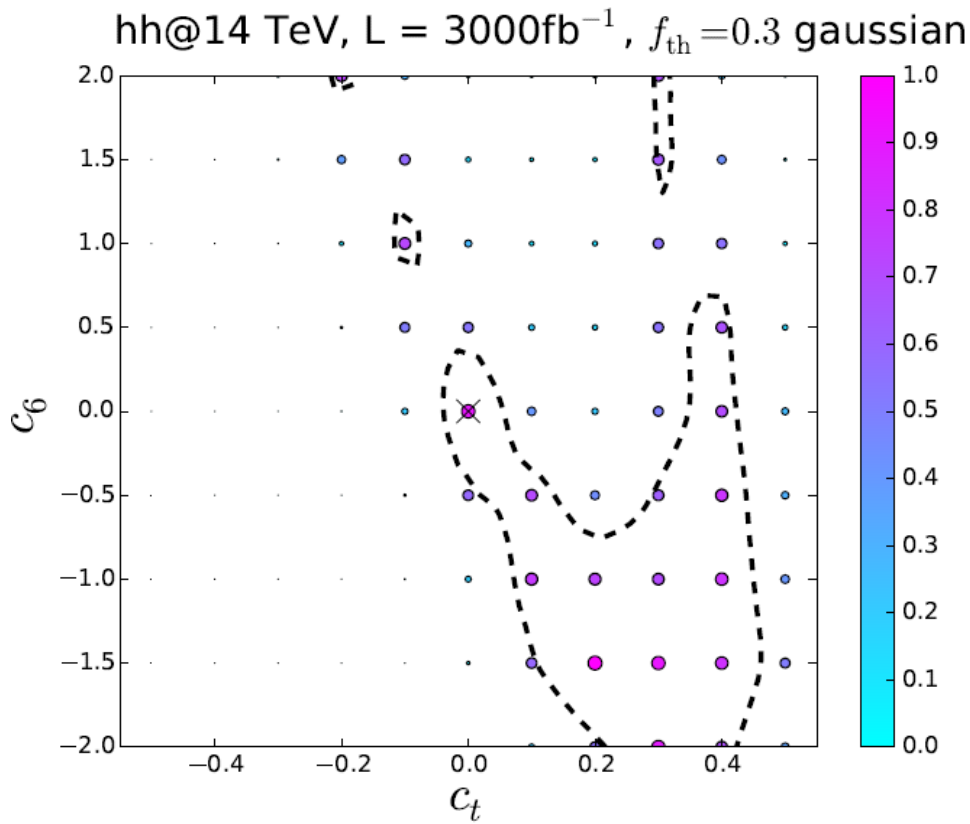
Expected Constraints after full analysis: c_t-c_6



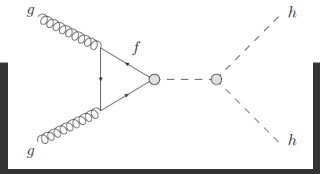
- Consider $hh \to b\bar{b}\tau^+\tau^-$
- Marginalize over other directions within projected ranges

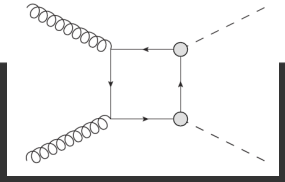
- Clear correlation visible: Enhanced hh cross section due to negative c_t can be compensated by reduction due to positive c_6

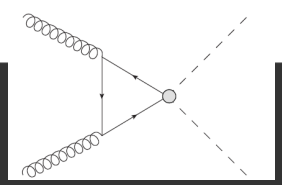
Expected Constraints after full analysis: c_t-c_6



- Precise 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







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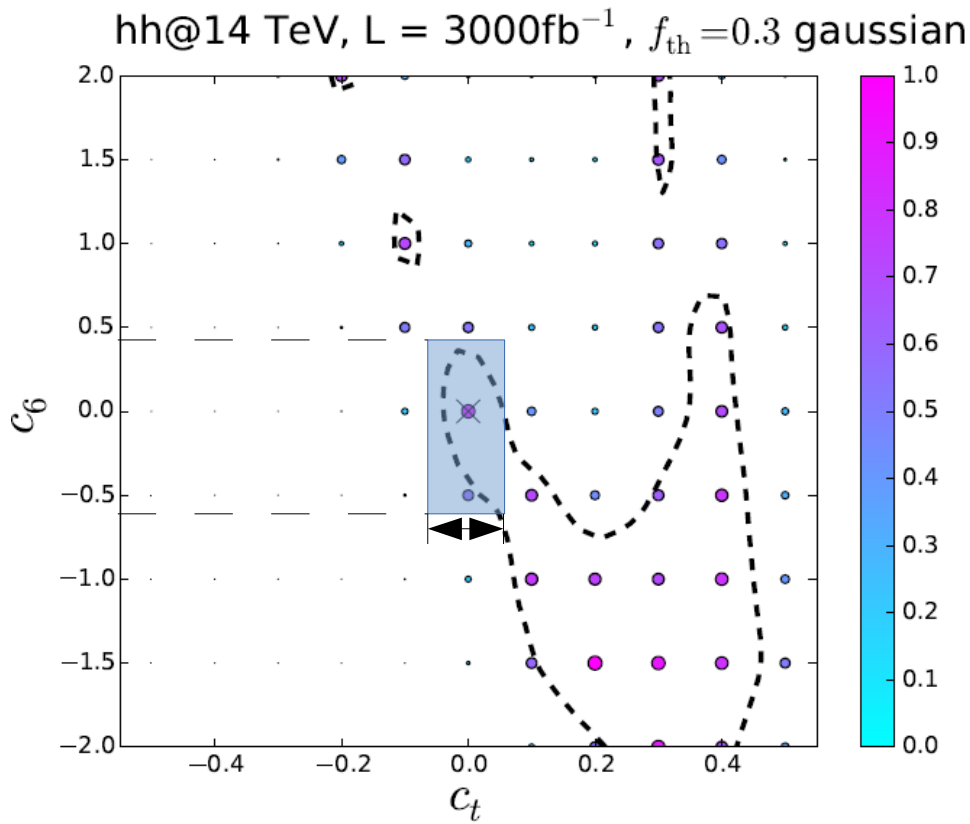

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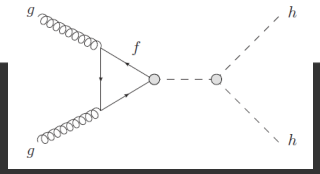

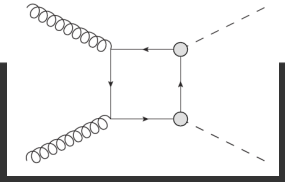

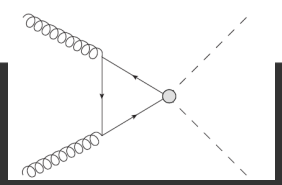

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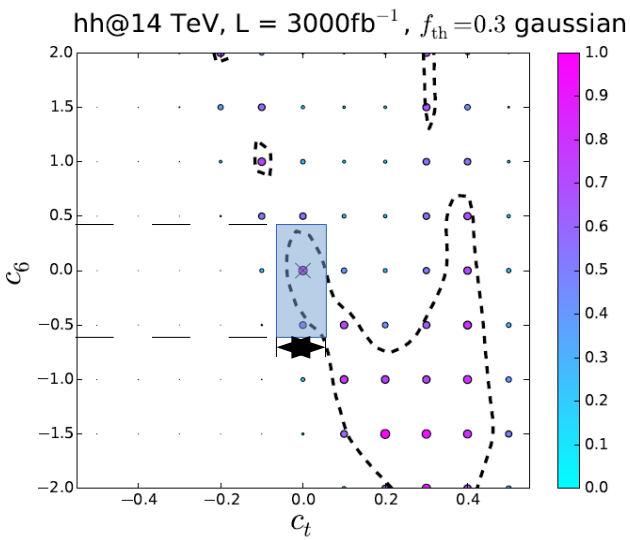

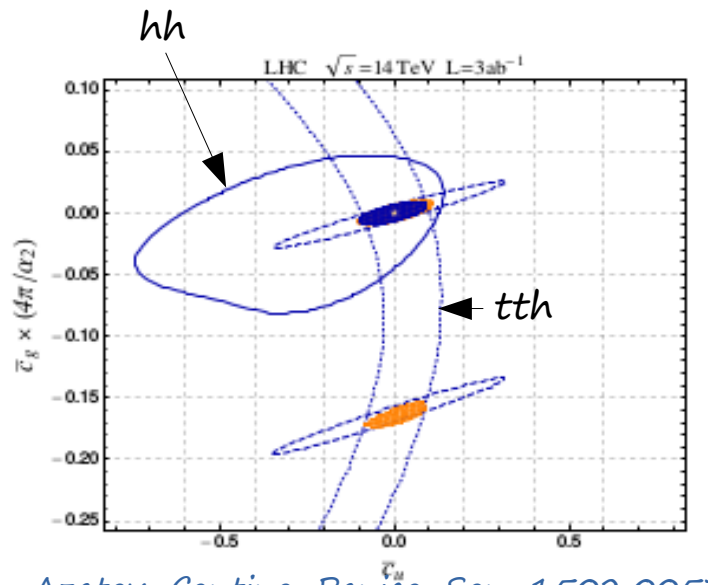

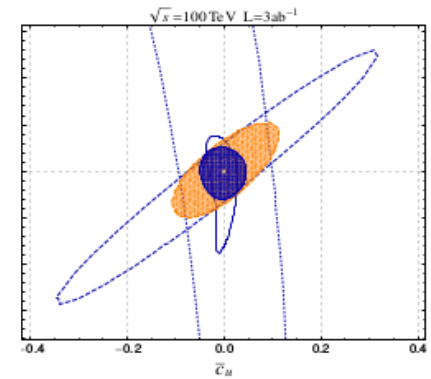

Azatov, Contino, Panico, Son, 1502.00539

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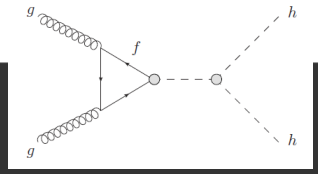

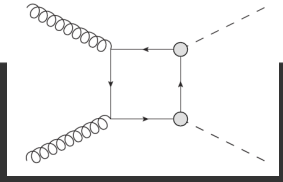

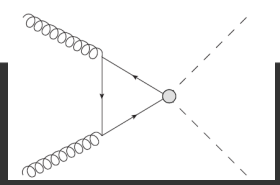

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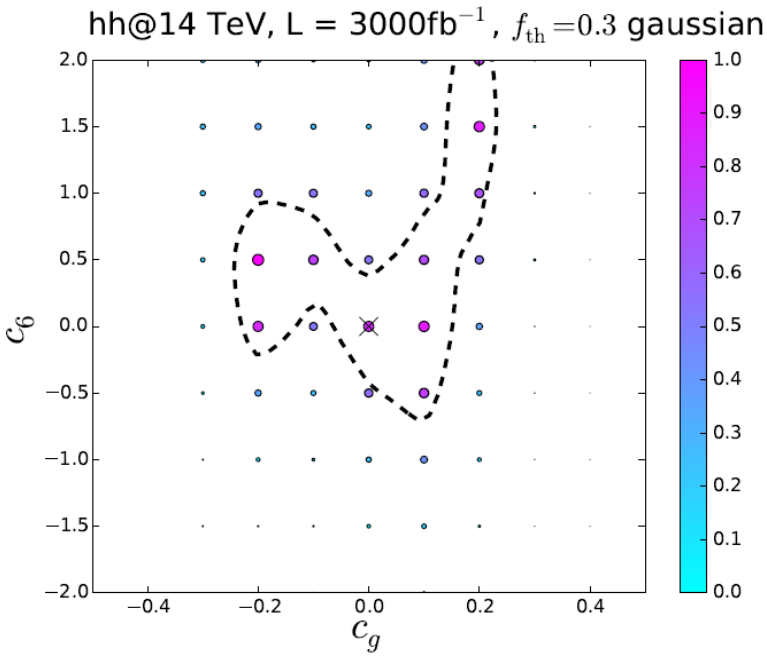
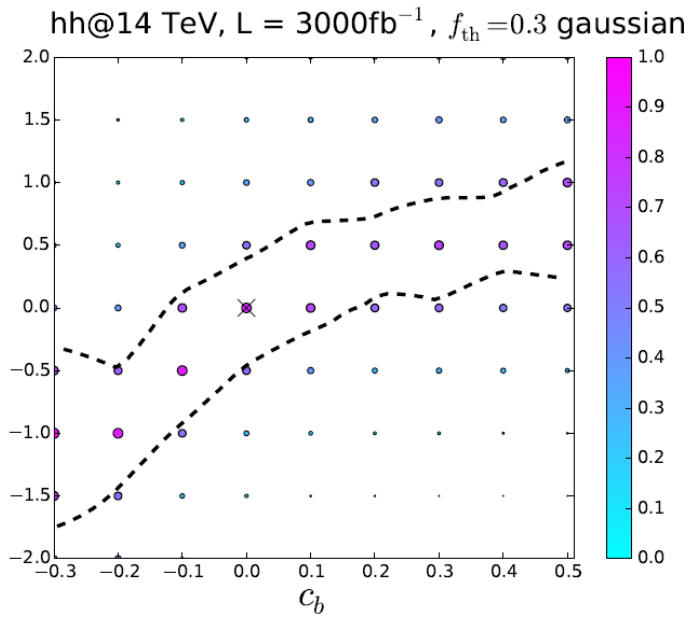
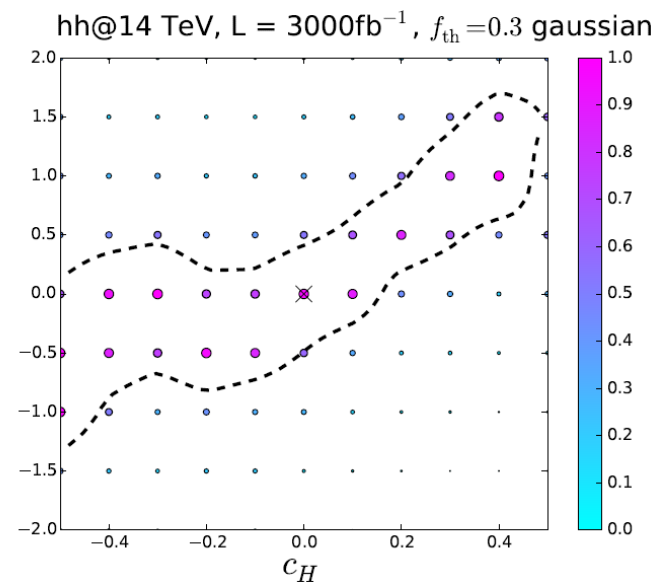






- In general significant correlations

  See also Azatov, Contino, Panico, Son, 1502.00539

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 (**future**)	$c_6 \in (-0.8, 0.9)$	$c_6 \in (-0.6, 0.6)$

FG, Papaefstathiou, Yang, Zurita, 1410.3471

- Use real p-values from *current* single Higgs measurements in marginalization:

full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$

See also Azatov, Contino, Panico, Son, 1502.00539 (bbγγ)

Presence of μ^2

- $\mu^2 |H|^2$: only relevant operator in SM
- Origin of hierarchy problem
- Have so far not tested if actually there!

$$V(H) = \lambda |H|^4$$

$$\Downarrow$$

$$v = 0, \; m_h = 0$$

Presence of μ^2

- $\mu^2 |H|^2$: only relevant operator in SM
- Origin of hierarchy problem
- Have so far not tested if actually there!

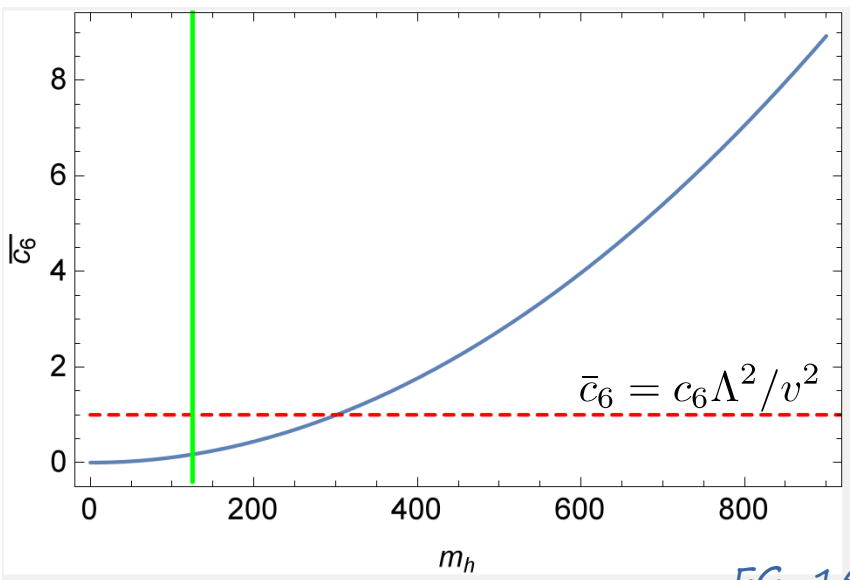
$$V(H) = \lambda |H|^4 + \frac{c_6}{\Lambda^2} |H|^6$$

- Fully replace μ term by D=6 operator FG, 1504.00355
- λ<0, EWSB not triggered by negative μ^2 term
- μ^2=0 really possible by adding D=6 op. in consistent EFT ??

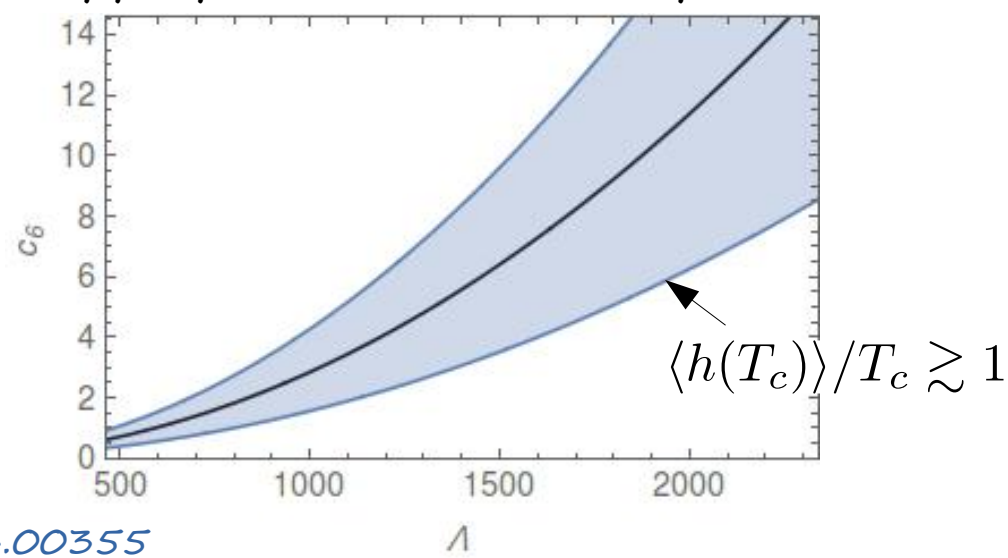
Presence of μ^2

- Yes, due to the lightness of the Higgs Boson

$$\lambda = -\frac{m_h^2}{2v^2} \approx -0.13\,, \quad c_6 = \frac{2m_h^2}{3v^2}\frac{\Lambda^2}{v^2} \approx 2.8\,\frac{\Lambda^2}{\mathrm{TeV}^2}$$



appropriate 1st order PT possible



FG, 1504.00355

SM one-loop CW → small correction: FG, 1504.00355

Limits from EWPT → see Grojean, Servant, Wells, hep-ph/0407019

μ-less SM testable at LHC

$$c_6 = \frac{2m_h^2}{3v^2} \approx 2.8\,\frac{\Lambda^2}{\mathrm{TeV}^2}$$

conventions of GPYZ, 1410.3471 → $c_6 \approx -1.2$
incl. CW shift

14TeV LHC, 1σ:

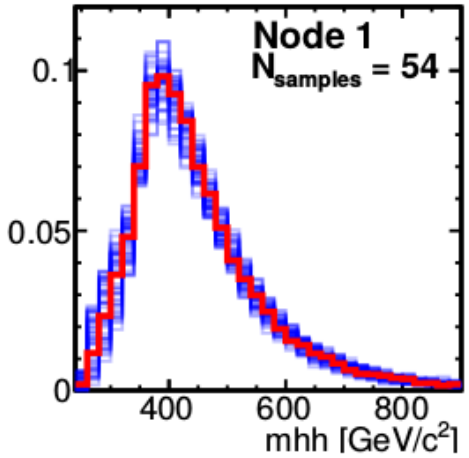
model	$L = 600\ \mathrm{fb}^{-1}$	$L = 3000\ \mathrm{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full (**future**)	$c_6 \in (-0.8, 0.9)$	$c_6 \in (-0.6, 0.6)$

- Use real p-values from *current* single Higgs measurements in marginalization:

full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$

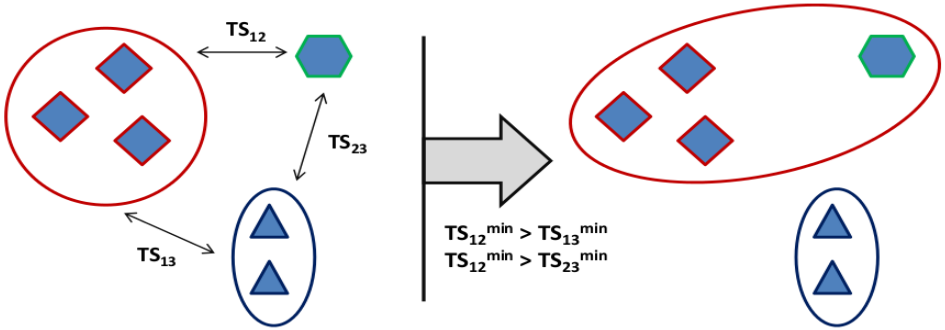
Enhance Sensitivity: Consider Distributions

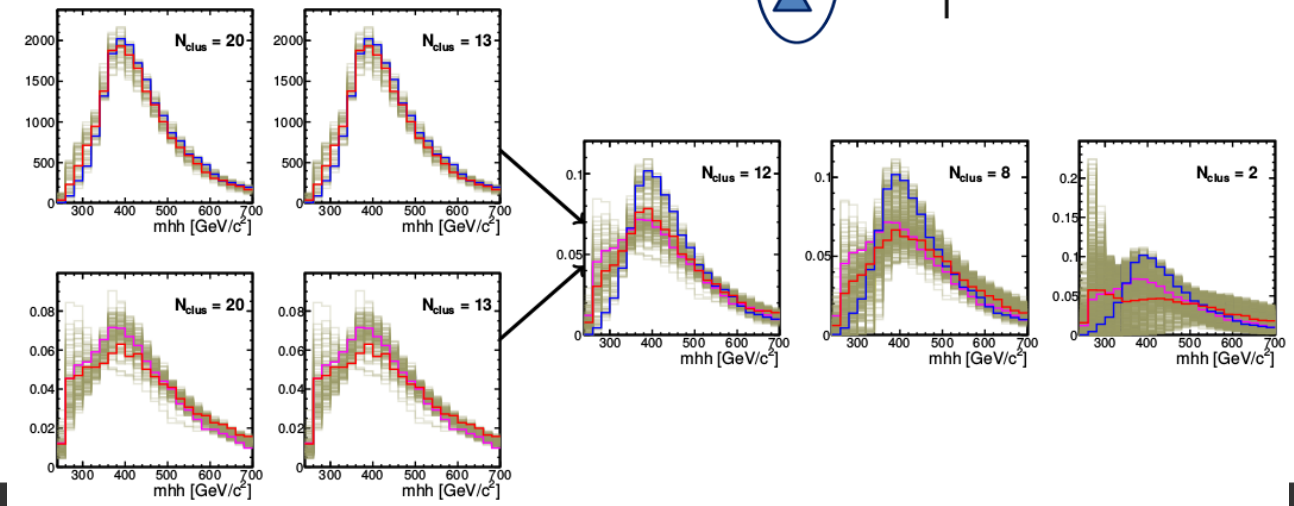
- Optimize Analysis to Kinematical Properties



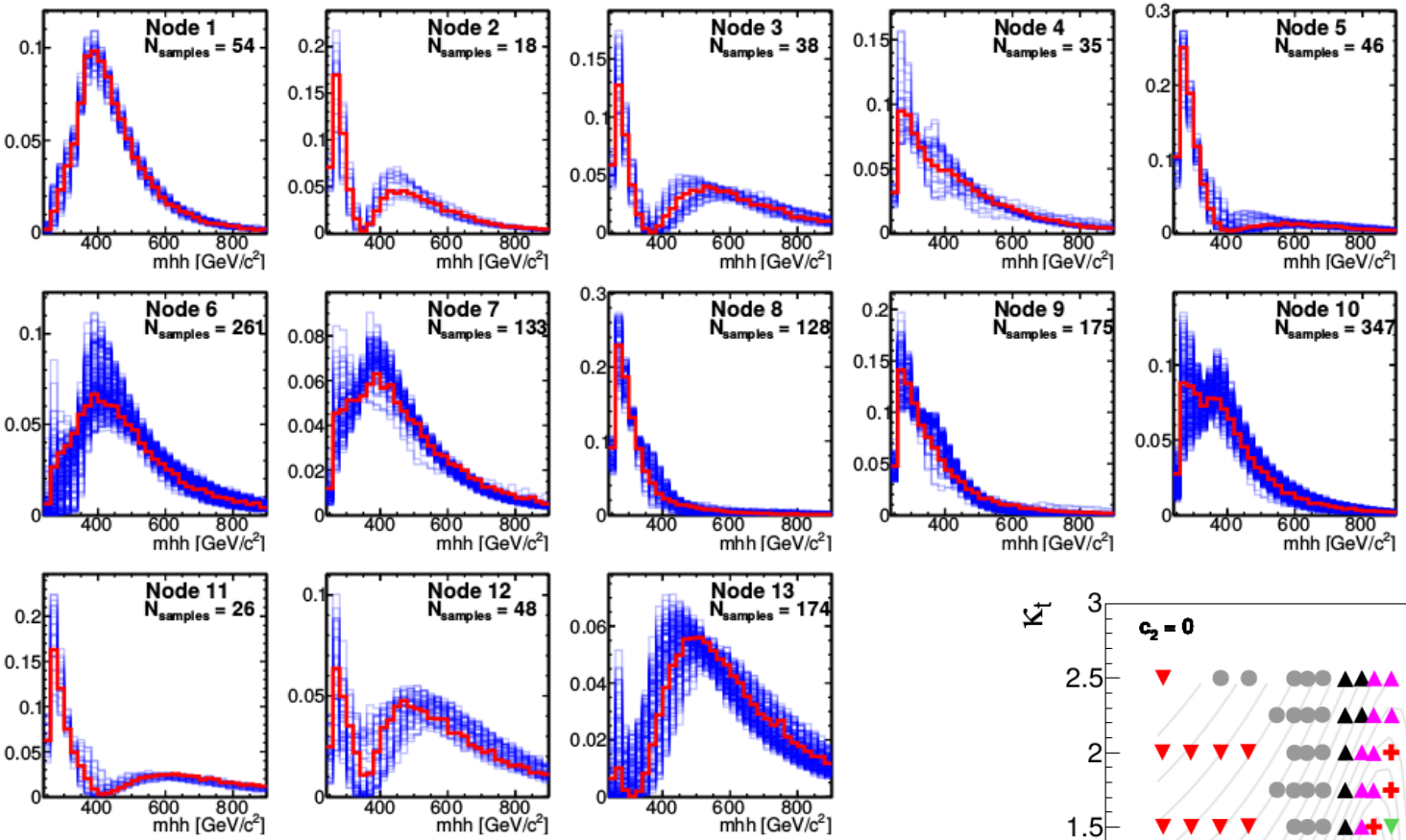
Dall'Osso, Dorigo, FG, Gottardo, Oliveira, Tosi, , 1507.02245

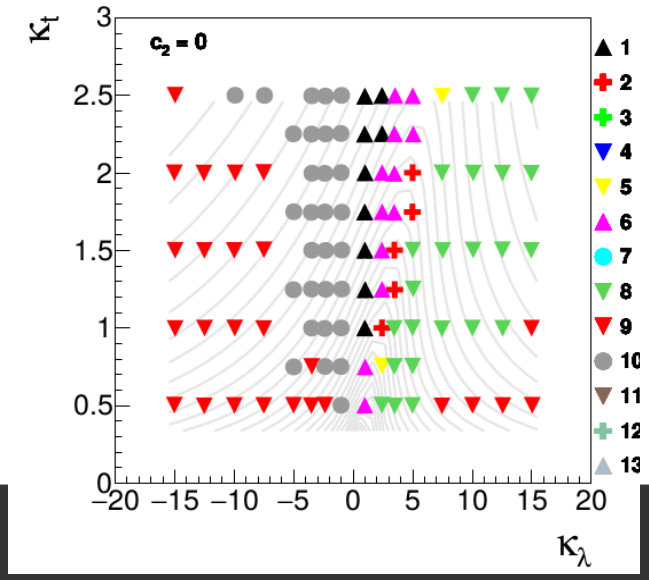
- Cluster parameter space wrt expected distributions





Enhance Sensitivity: Consider Distributions





Conclusions

- Higgs sector still contains many mysteries
- Analysis of hh production

  → unique insight on structure of (D=6) extension of SM!

The Higgs discovery is not the end,
it is just the beginning.

Backup

Backup: The Higgs Potential

$\frac{c_H}{2\Lambda^2}(\partial^\mu|H|^2)^2$ enters after canonical normalization of kinetics

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

$$\lambda_{3h} = \frac{m_h^2}{2v^2}\left[1 + \frac{c_6 v^2}{\Lambda^2} - \frac{3c_H v^2}{2\Lambda^2}\right]$$

$$\neq \lambda_{4h} = \frac{m_h^2}{2v^2}\left[1 + \frac{6c_6 v^2}{\Lambda^2} - \frac{25c_H v^2}{3\Lambda^2}\right]$$

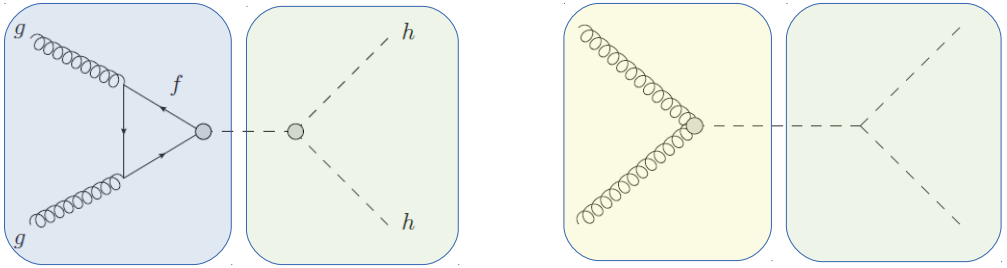
$$h \to \left(1 - \frac{c_H v^2}{2\Lambda^2}\right) h - \frac{c_H v}{2\Lambda^2} h^2 - \frac{c_H}{6\Lambda^2} h^3$$

removes also momentum-dependent interactions

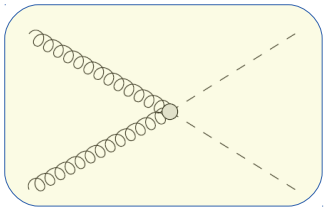
Backup: $gg \to hh$

EWSB → Relevant Terms:

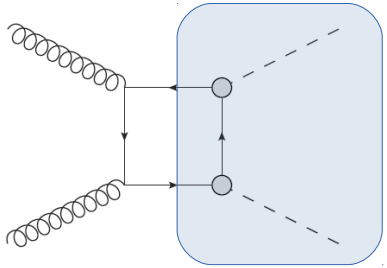
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3$$



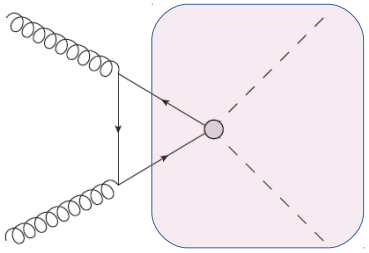
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$



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

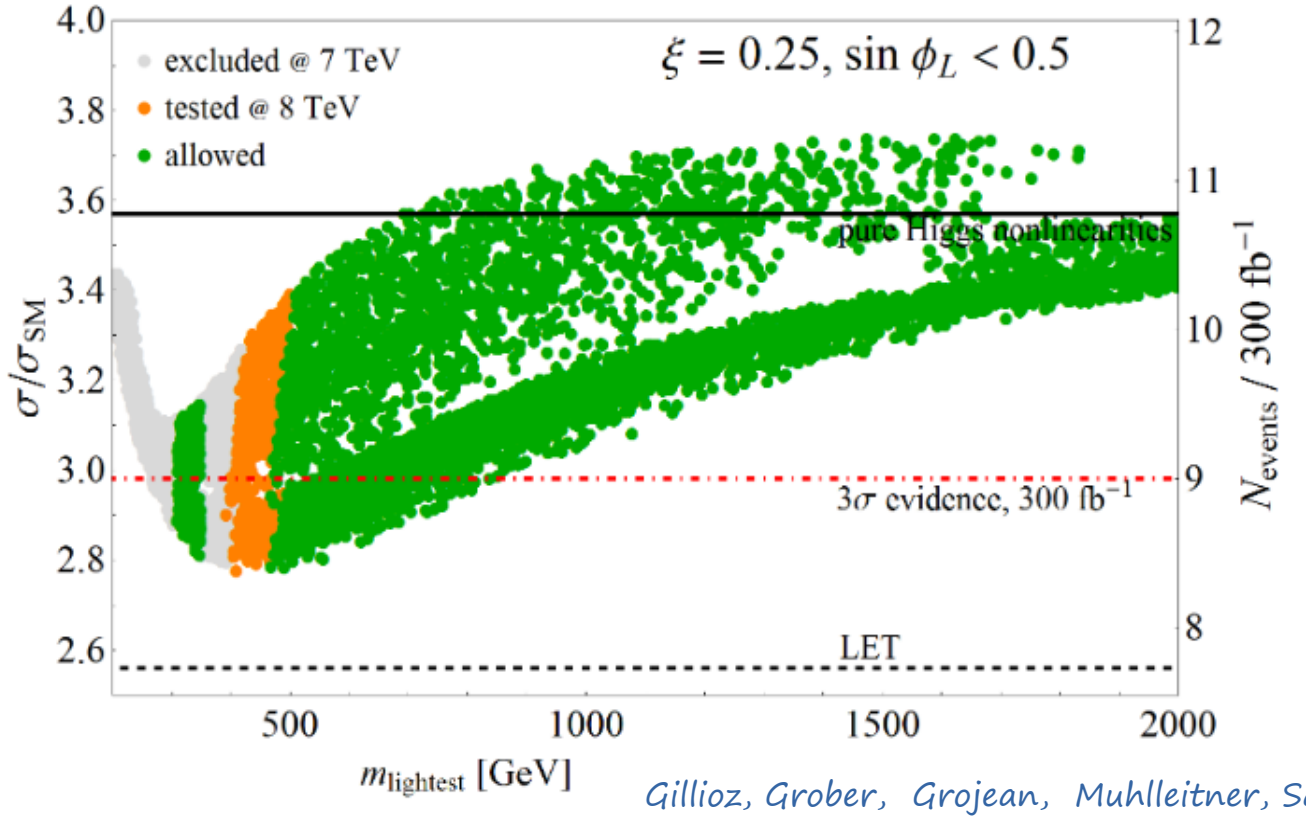


$$-\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$



$c_i \to c_i\,\Lambda^2/v^2 \quad h \to \left(1 - \frac{c_H v^2}{2\Lambda^2}\right)h - \frac{c_H v}{2\Lambda^2}h^2 - \frac{c_H}{6\Lambda^2}h^3$

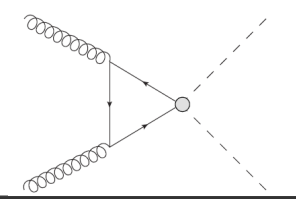
Backup: HH Production: $MCHM_5$



Gillioz, Grober, Grojean, Muhlleitner, Salvioni, 1206.7120

See also Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, 1205.5444

- Important contribution:



Backup: Explicit Analysis

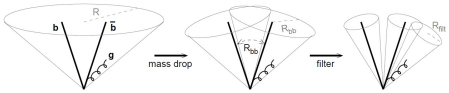
- Focus on $hh \to b\bar{b}\tau^+\tau^-$ @LHC14

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

Significance @ 600 fb^{-1} (SM)

$hh \to b\bar{b}\gamma\gamma$ — $\lesssim 2\sigma$ (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!

Backup: 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 ($|\eta| < 2.5$)
- $m_{\tau^+\tau^-}, m_{\rm fat} \in [m_h - 25\,\text{GeV}, m_h + 25\,\text{GeV}]$
- $p_\perp^{\rm fat}, p_\perp^{\tau\tau} > 100\ \text{GeV},\ \ \Delta R(h,h) > 2.8,\ \ p_\perp^{hh} < 80\ \text{GeV}$

b,τ–tagging efficiencies: 70 %

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

Backup: Analysis

- Start with model where only $c_6 \neq 0$ (unconstrained from single h)
  - Vary only λ (as in previous studies)

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

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

30% ~ 10% (scale) + 10% (pdf + α_s) + 10% (m_t)

Backup: Analysis

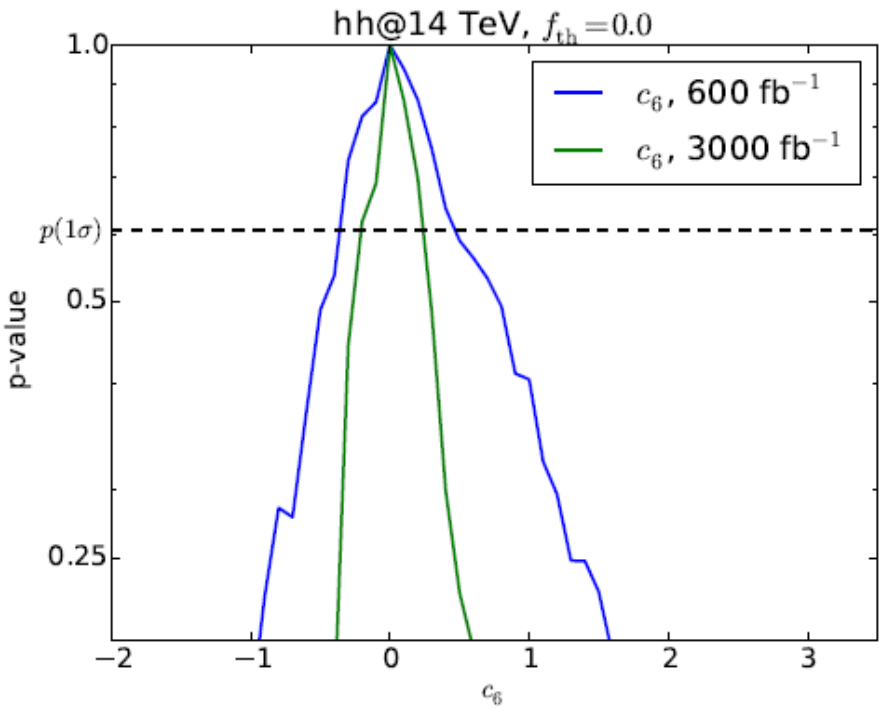
- Start with model where only $c_6 \neq 0$ (unconstrained from single h)
  - Vary only λ (as in previous studies)

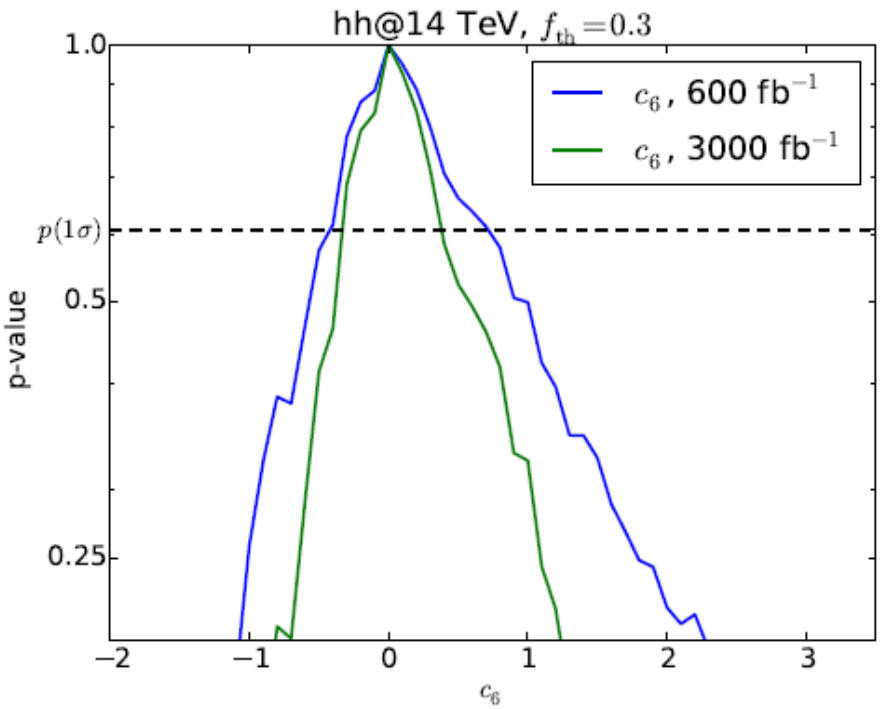
$$\delta N^2 = N + S^2 f_{\mathrm{th}}^2$$

- 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 $N(c_6 = 0)$.

Backup: Analysis





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

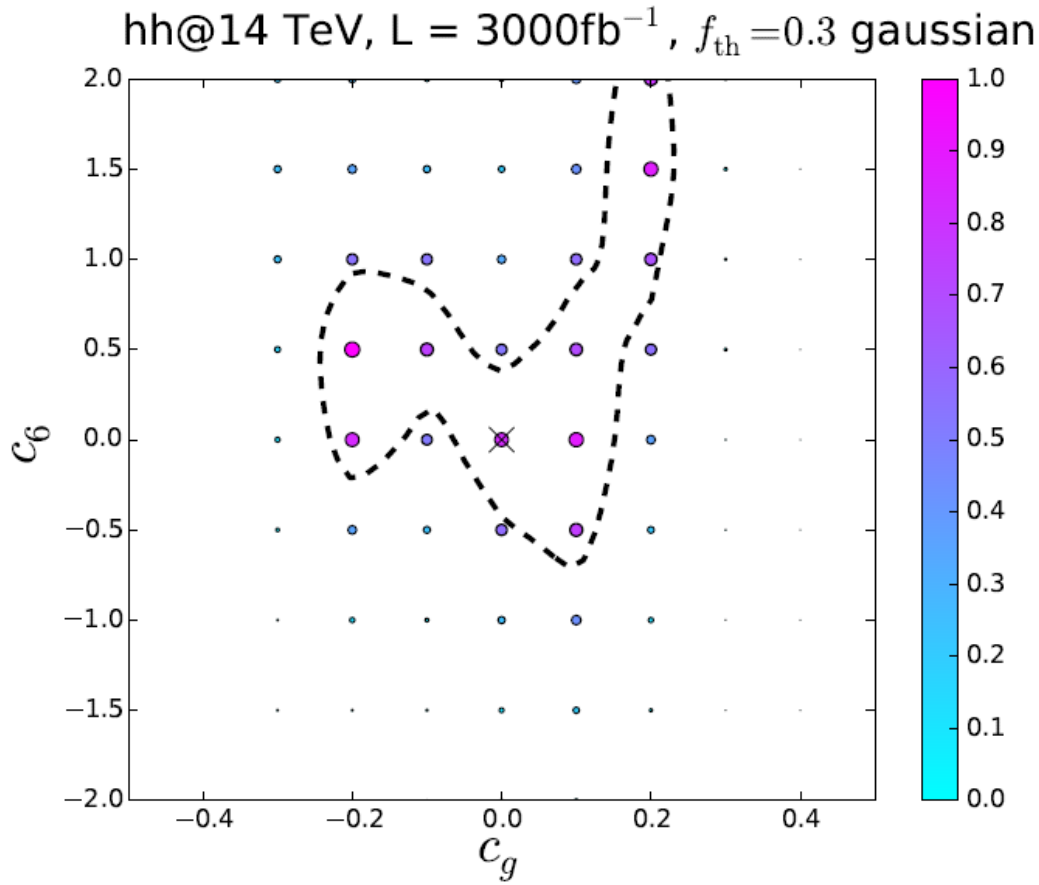
$$c_6^{1\sigma}(600\ \mathrm{fb}^{-1}) \in (-0.5, 0.8),\ c_6^{1\sigma}(3000\ \mathrm{fb}^{-1}) \in \boxed{(-0.4, 0.4)},\ f_{\rm th}=0.3$$

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

Backup: Full D=6 Theory

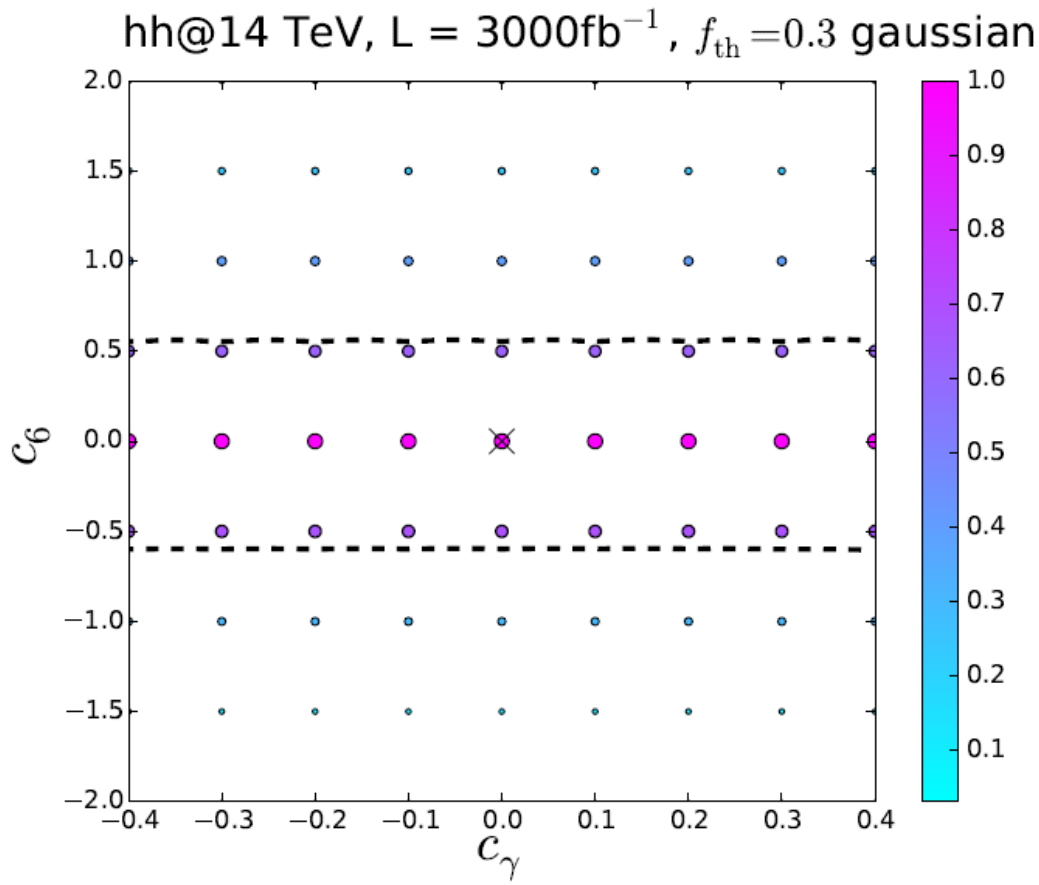
- Again assume SM (c_i=0) and calculate distance of predicted $N(c_6, .., c_b)$ from $N(c_6 = 0, .., c_b = 0)$ in units of $\delta N(c_6, .., c_b)$
- Show results in 2D grids (c_6, c_i), i=H,g,γ,t,b
- Marginalize over other directions with a Gaussian weight,
- given by projected errors on the coefficients from single h (~10% @ (600-3000) fb^{-1})
  - ➡ in the future use real constraints (like p-values from HiggsBounds/Signals)
- Draw iso-contours corresponding to probability-drop of 1σ

Backup: c_g-c_6



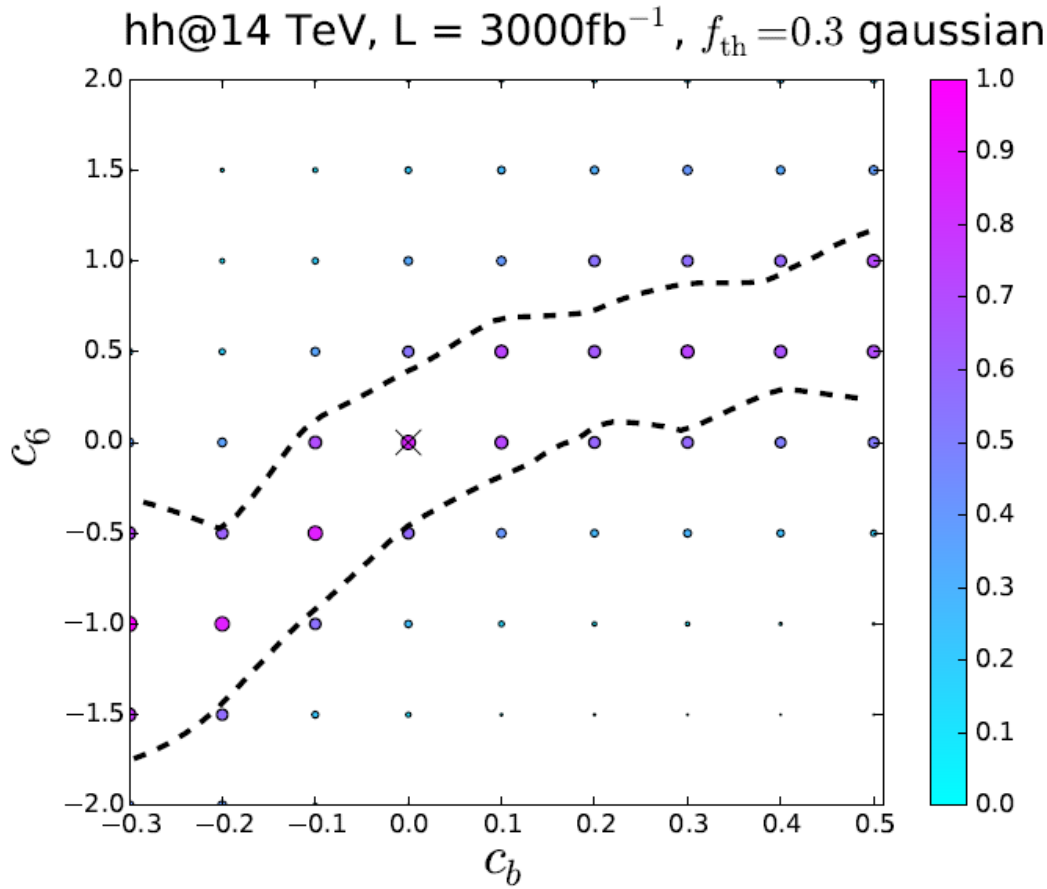
- Again compensation of effects from different operators possible
  → range for c_6 depends significantly on other coefficients

Backup: c_γ-c_6



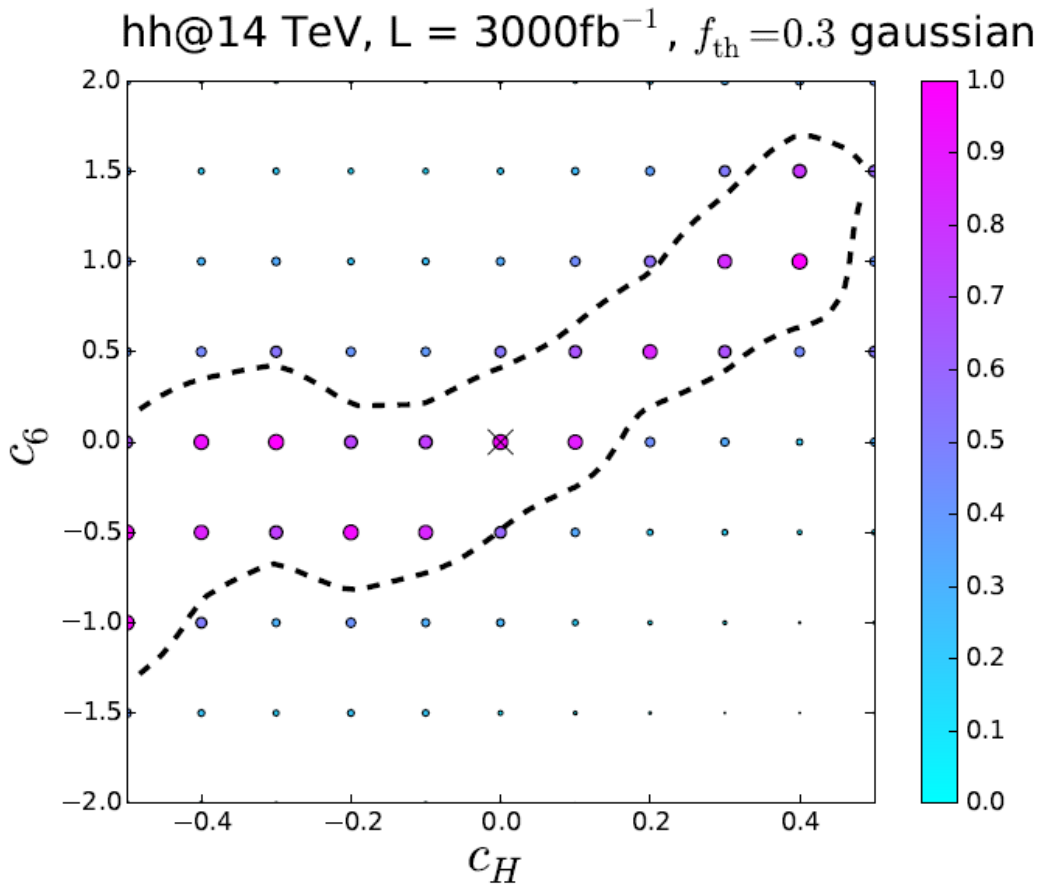
- As expected: negligible dependence on c_γ

Backup: $(c_b=c_\tau)$-c_6



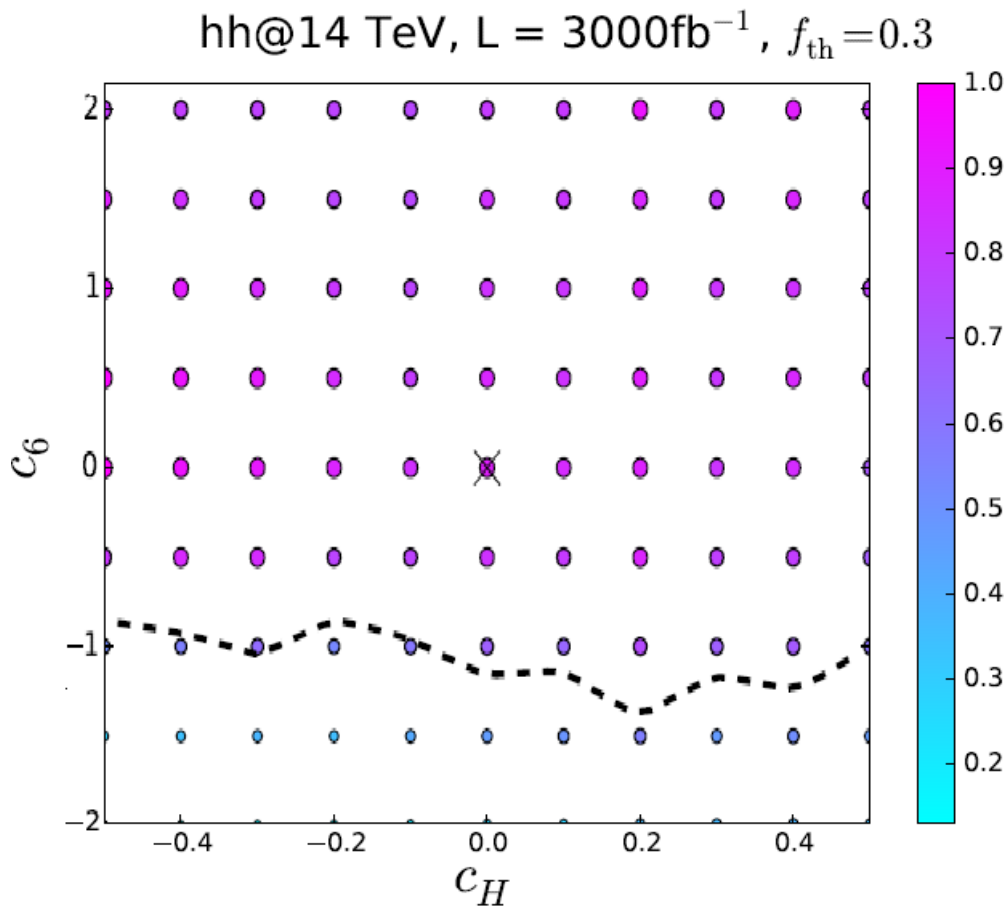
- Reduced BR due $(c_b=c_\tau)<0$ to can be compensated by enhanced production cross section due to negative c_6 and vice versa

Backup: c_H-c_6



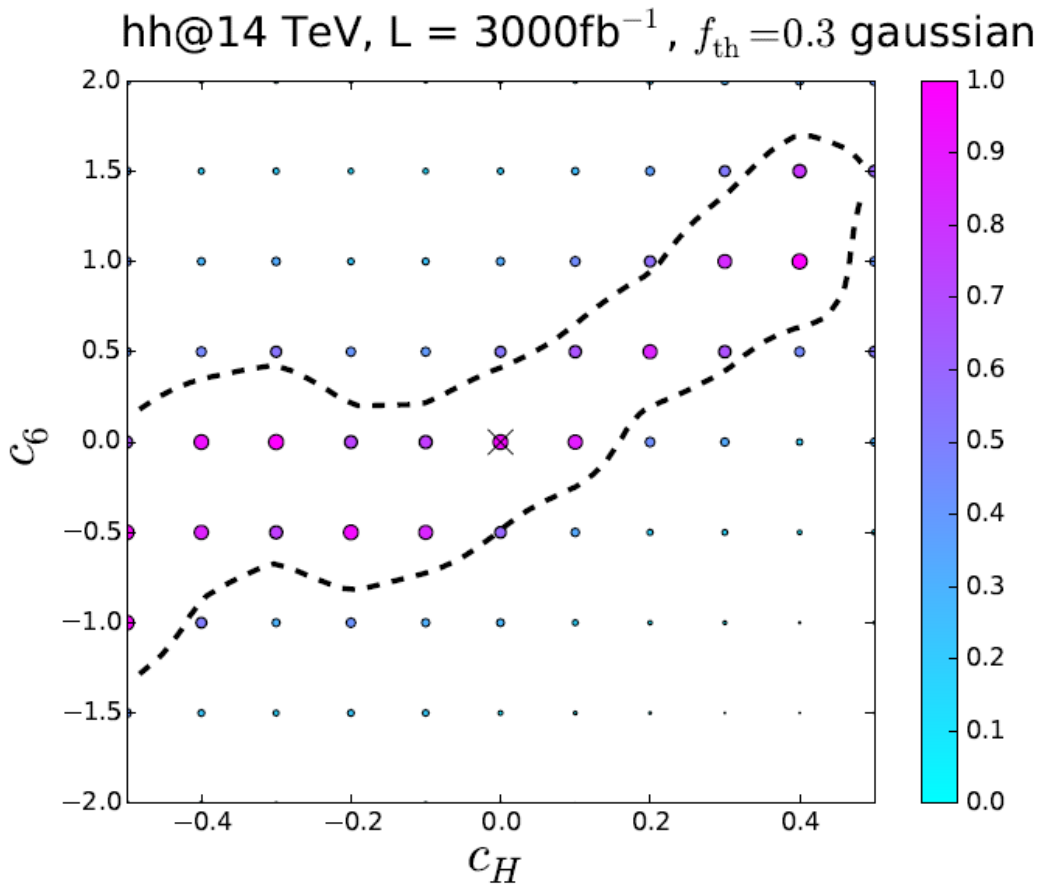
$$\lambda_{3h} = \frac{m_h^2}{2v^2}\left[1 + \frac{c_6 v^2}{\Lambda^2} - \frac{3 c_H v^2}{2\Lambda^2}\right]$$

Backup: c_H-c_6



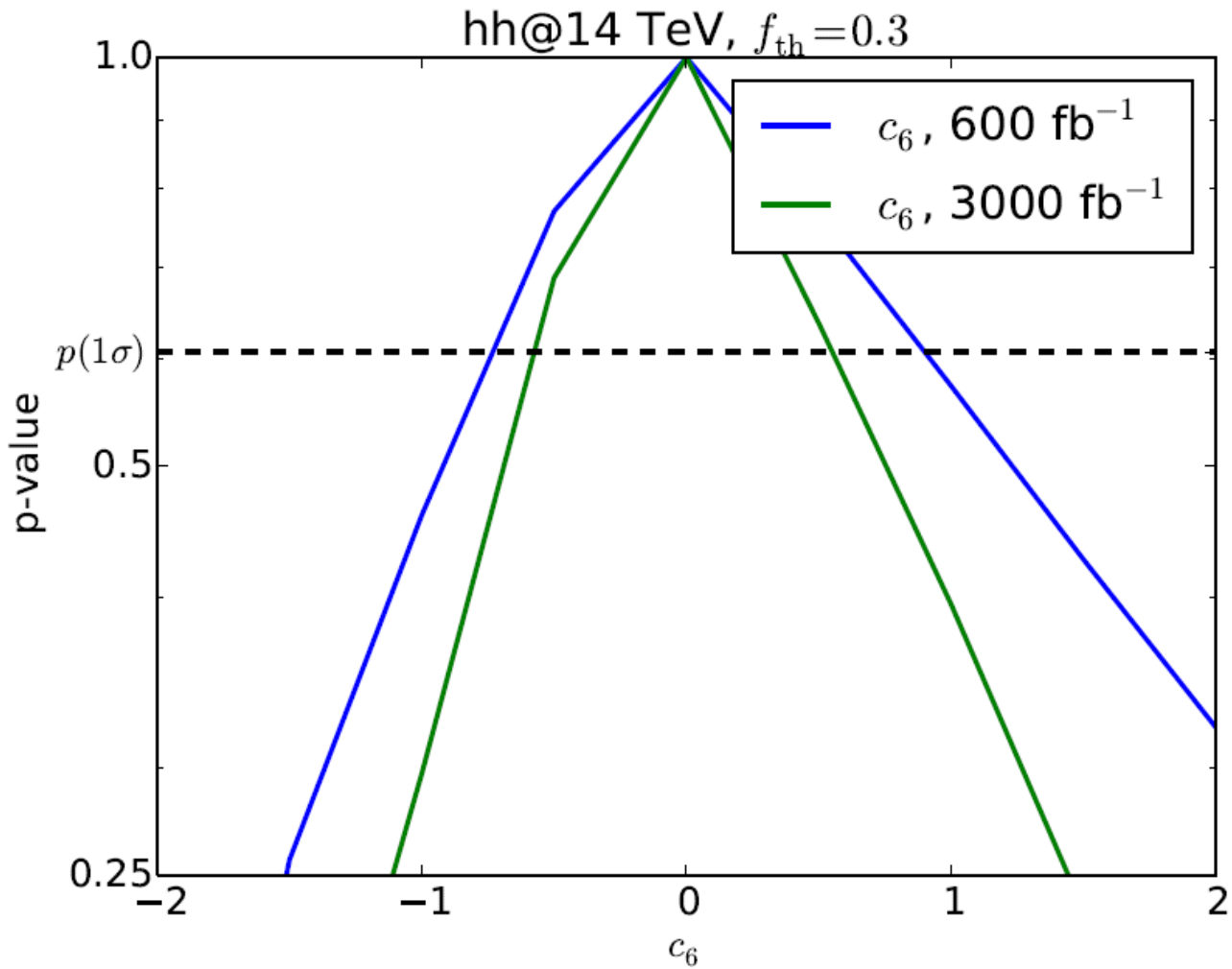
- Marginalize over other directions with **current** p-values for coefficients from single-h measurements (using HiggsBounds/Signals)

Backup: c_H-c_6



- Precise knowledge of other Wilson coefficients necessary for reasonable bounds on c_6

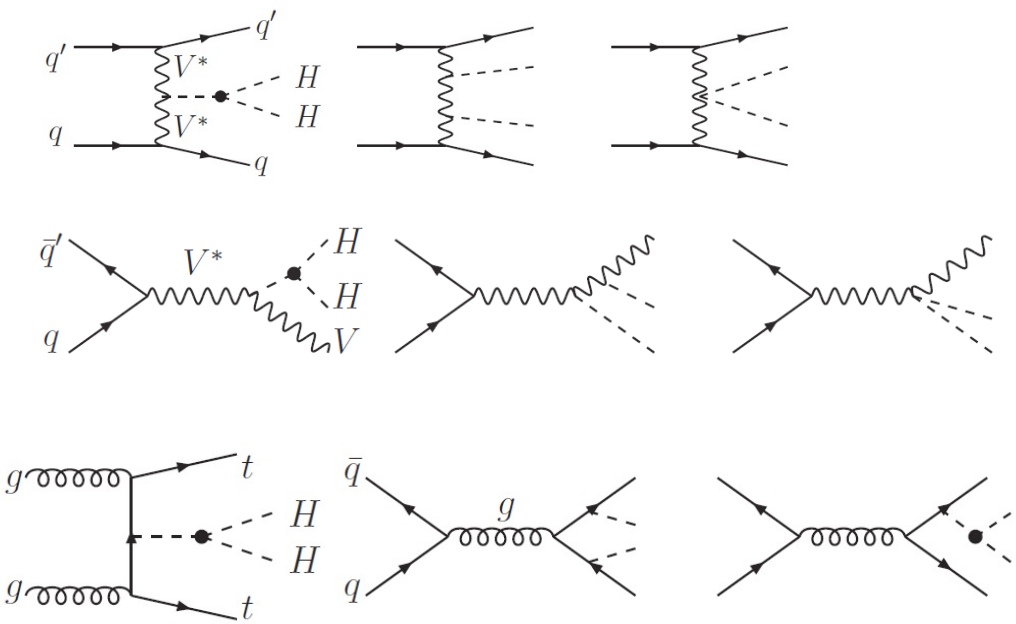
Backup: Full Marginalization → c_6

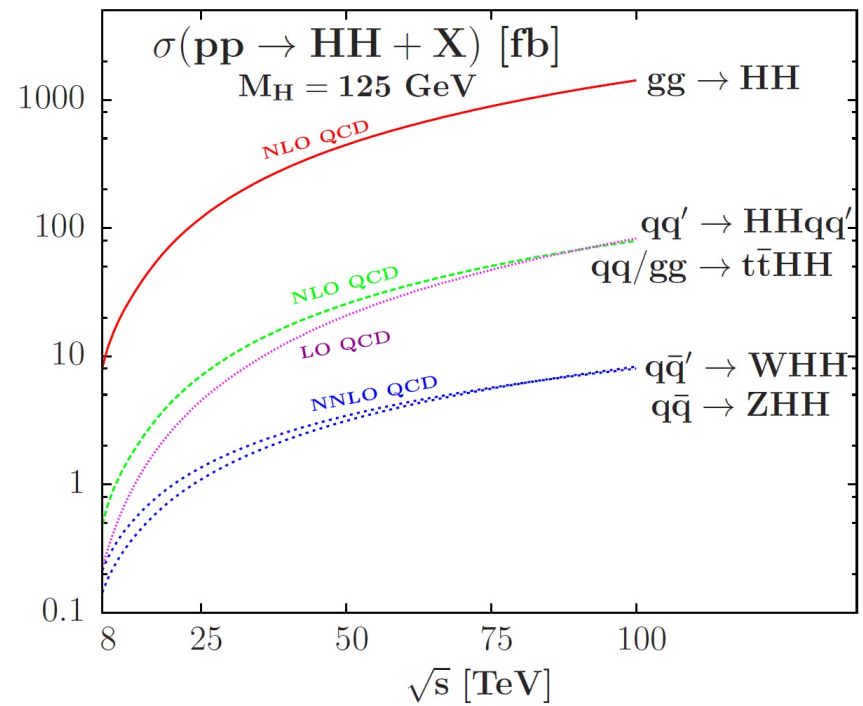


Backup: hh @LHC

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

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

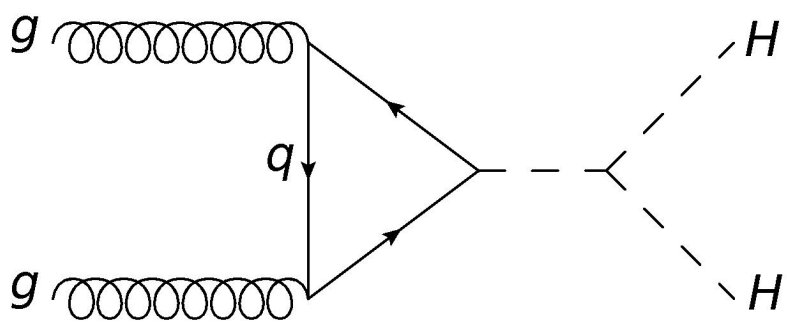


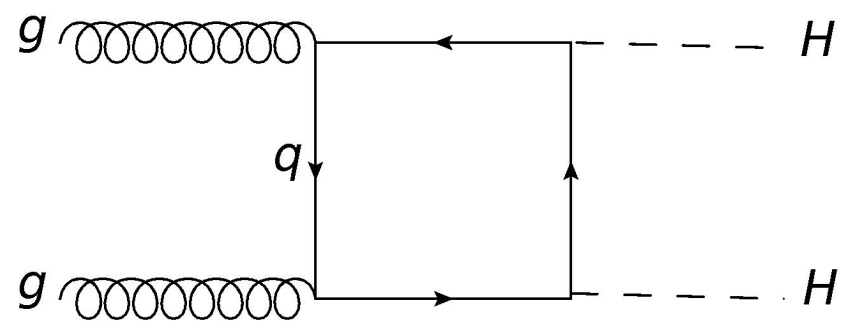


See [e.g.] Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581, and refs. therein

Backup: hh @ 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

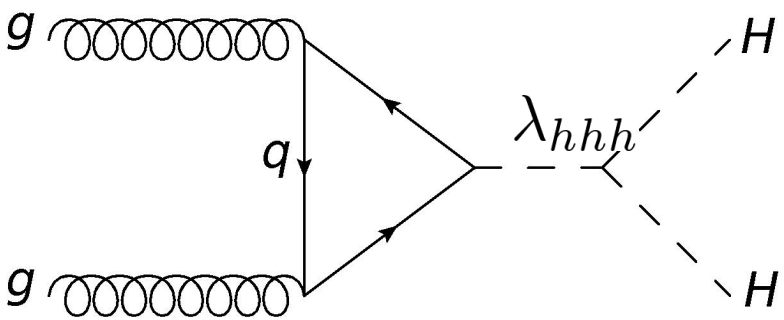
$$\sigma(gg \to hh)_{\rm LO} \sim 17\,{\rm fb}$$
$$\sigma(gg \to hh)_{\rm NLO} \sim 33\,{\rm fb}$$
$$\sigma(gg \to hh)_{\rm NNLO} \sim 40\,{\rm fb}$$

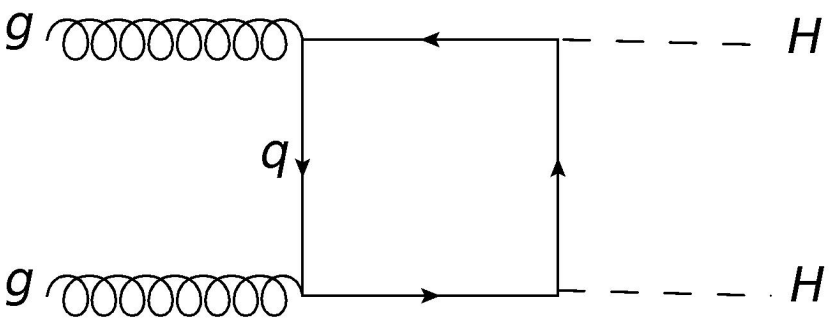
Theoretical error (NNLO): $f_{th} \sim 10\%$ (scale) + 10% (pdf+α_s) + 10% (m_t^{-1})

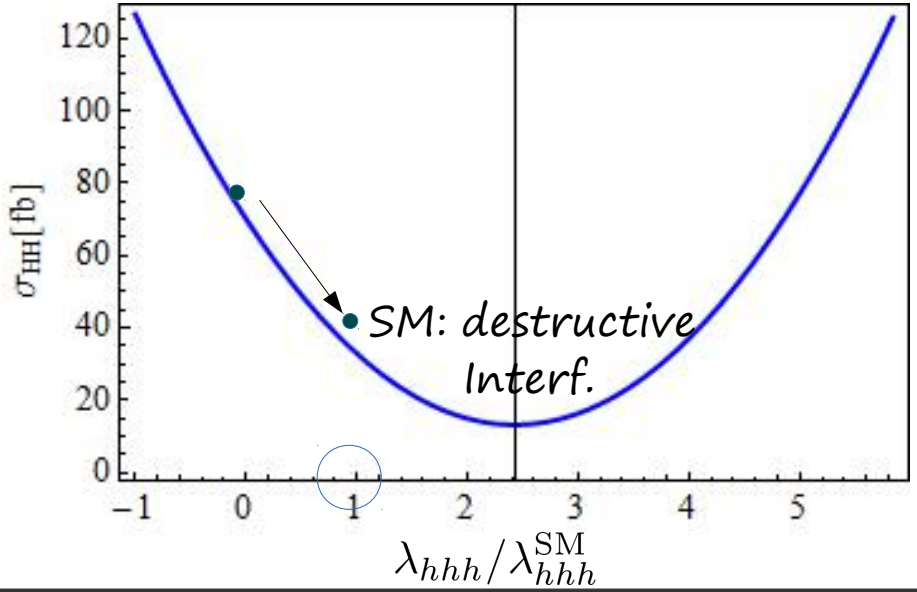
LHC@14TeV
$m_h \sim 125$ GeV

Backup: hh @ LHC

- Most important mechanism: $gg \to hh$







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

assuming gaussian distributions

Backup: Parameter-Space Scan

- 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)

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

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

Projections:
(~10% effects)

c_f	Δc_f
c_g	$0.05 \times \frac{1}{3}$
c_H	0.05×2
c_t, c_b, c_τ	0.05
c_γ	$0.05 \times \frac{47}{18}$

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

Backups: Couplings, Benchmarks, Test Statistics

$$\mathcal{L}_h = \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}(v + \kappa_t h + \frac{1}{v} c_2 h h)(\bar{t_L} t_R + h.c.)$$
$$+ \frac{\alpha_s}{\pi v}(c_g h - \frac{c_{2g}}{2v} h h) G^{\mu\nu} G_{\mu\nu} ,$$

Node	κ_λ	κ_t	c_2	c_g	c_{2g}
1	1.0	1.0	0.0	0.0	0.0
2	7.5	2.5	-0.5	0.0	0.0
3	15.0	1.5	-3.0	-0.0816	0.3010
4	5.0	2.25	3.0	0.0	0.0
5	10.0	1.5	-1.0	-0.0956	0.1240
6	1.0	0.5	4.0	-1.0	-0.3780
7	2.4	1.25	2.0	-0.2560	-0.1480
8	7.5	2.0	0.5	0.0	0.0
9	10.0	2.25	2.0	-0.2130	-0.0893
10	15.0	0.5	1.0	-0.0743	-0.0668
11	-15.0	2.0	6.0	-0.1680	-0.5180
12	2.4	2.25	2.0	-0.0616	-0.1200
13	-15.0	1.25	6.0	-0.0467	-0.5150

$$p\left(n_{i,1}, n_{i,2} \,|\, \mu_i = \frac{n_{i,1} + n_{i,2}}{2}\right) = e^{-2\mu_i} \frac{\mu_i^{-n_{i,1}-n_{i,2}}}{n_{i,1}! n_{i,2}!}$$

$$TS = log(L)_{12} = log \Sigma_{i=1}^{N_{bin}^{tot}} [-2\mu_i - (n_{i,1} + n_{i,2}) log\mu_i - log(n_{i,1}!) - log(n_{i,2}!)]$$