Higgs-Pair Production in EFT

Higgs Pair Production at Colliders
MITP Workshop

28.4.2015

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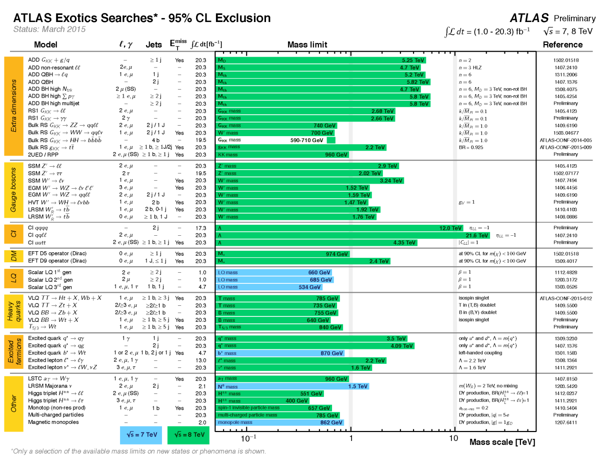
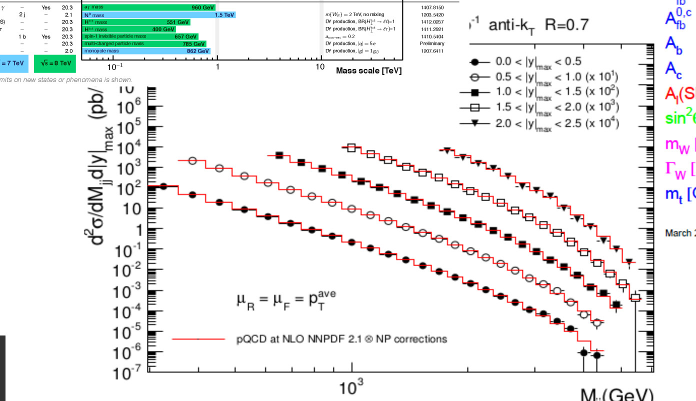
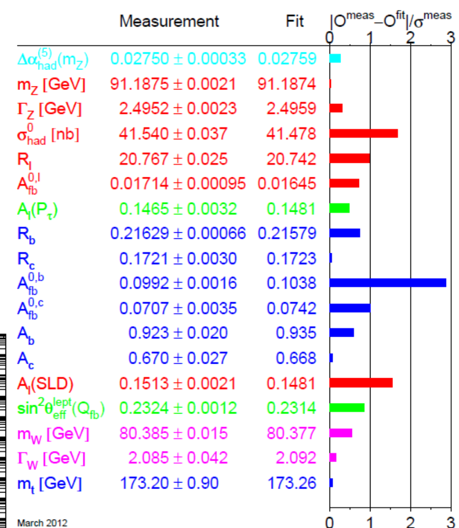
Introduction & Framework

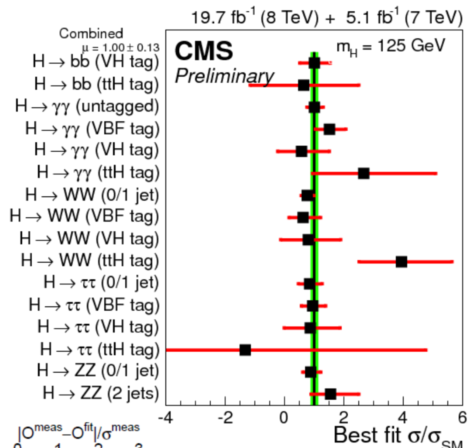
Introduction

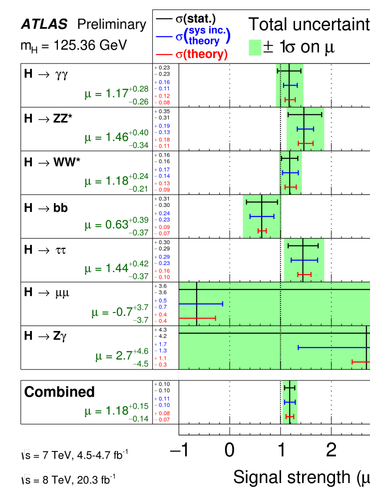
- The SM works extremely well up to energies that are currently probed at the LHC!

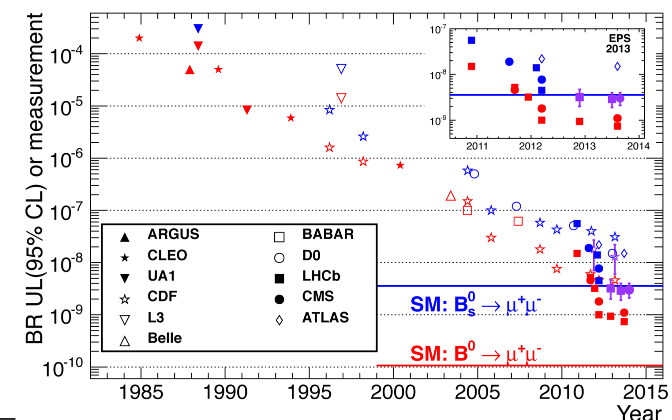






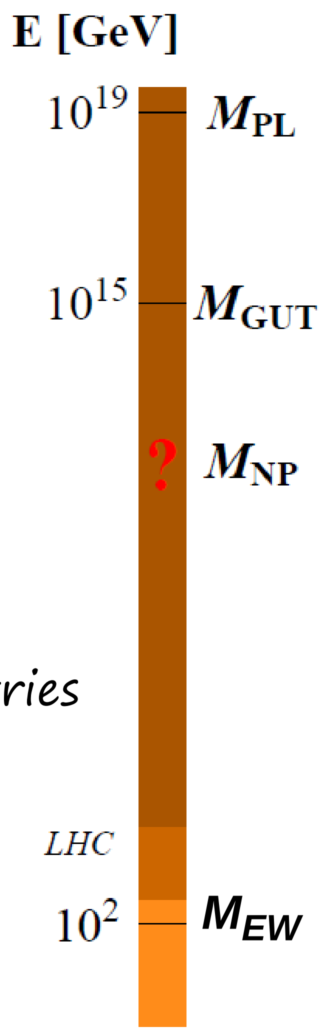






Physics Beyond the SM

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

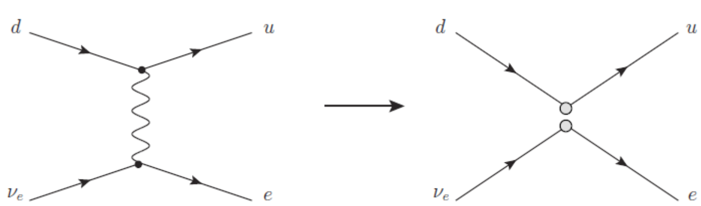


$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}^{D\,\leq\,4} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{D=6} + \ldots$$

local operators built of SM field content, respecting gauge symmetries

= New Physics

c.f. Fermi Theory



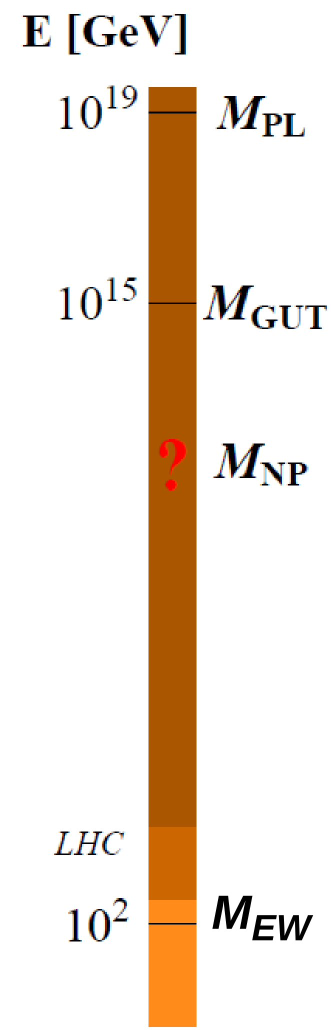
$$\mathcal{L}_{eff} = -\frac{g^2}{8m_W^2}C_1(\mu)(\bar{e}\,\nu_e)_{V-A}(\bar{u}\,d)_{V-A}$$

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

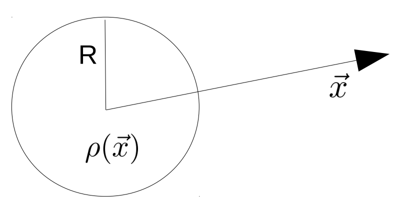
Physics Beyond the SM

- 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!

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



c.f. Multipole expansion



$$\phi(\vec{x}) = \frac{1}{4\pi} \int \frac{\rho(\vec{x}\,')}{|\vec{x} - \vec{x}\,'|} d^3x'$$

$$\frac{1}{|\vec{x} - \vec{x}\,'|} = 4\pi \sum_{l,m} \frac{1}{2l+1} \frac{r_<^l}{r_>^{l+1}} Y_{lm}^*(\theta', \phi') Y_{lm}(\theta, \phi)$$

for $|\vec{x}| \gg R$:

$$\phi(\vec{x}) = \frac{1}{4\pi} \left(\frac{q}{|\vec{x}|} + \vec{p} \cdot \frac{\vec{x}}{|\vec{x}|^3} + \frac{1}{2} \sum_{i,j} Q_{ij} \frac{x_i x_j}{|\vec{x}|^5} + \cdots \right)$$

$$q = \int \rho(\vec{x}) d^3x\,, \; \vec{p} = \int \vec{x} \rho(\vec{x}) d^3x\,,$$

$$Q_{ij} = \int (3x_i x_j - |\vec{x}|^2 \delta_{ij}) \rho(\vec{x}) d^3x$$

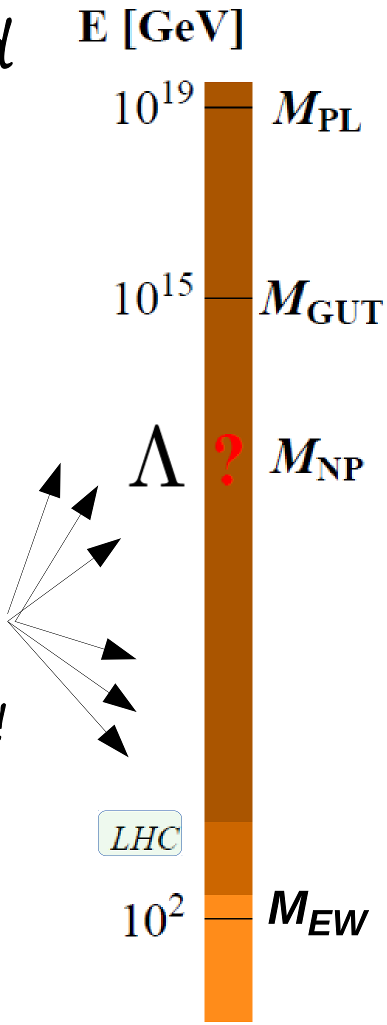
Physics Beyond the SM

- 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!

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

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

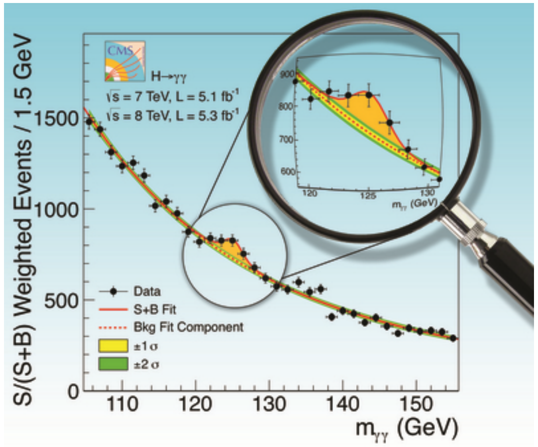
The Higgs Sector…

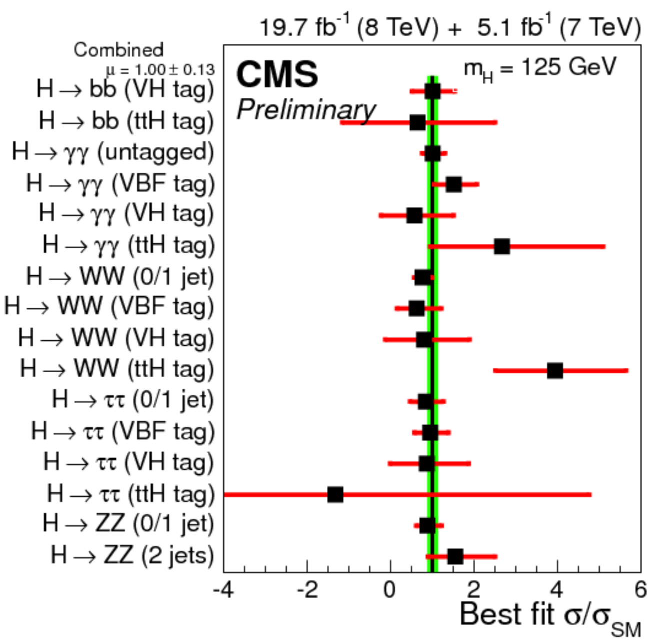
… offers a unique window to NP

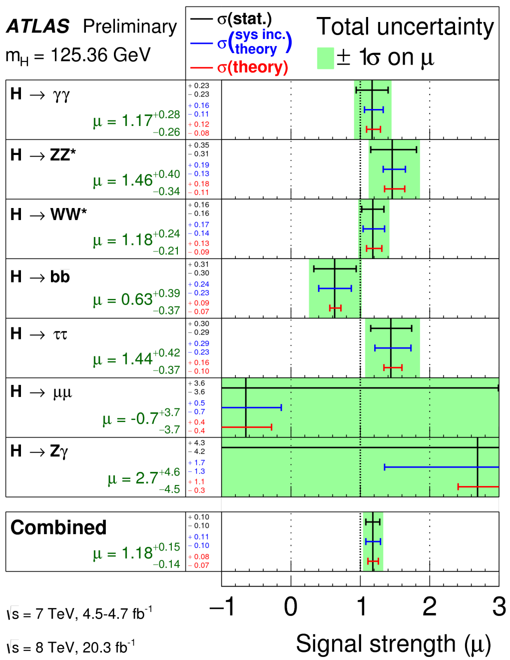
Is it the SM-Higgs Boson?

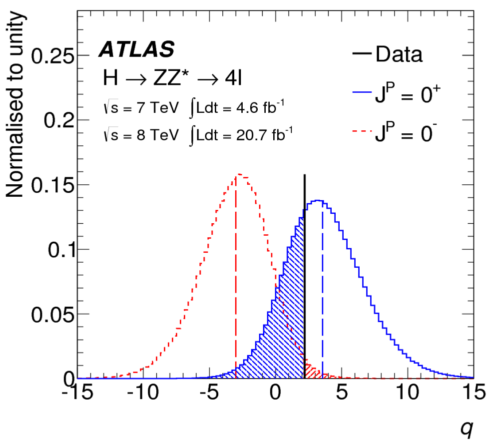
Scale of New Physics?

One of the biggest discoveries of mankind









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,...

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

$$\begin{aligned}\mathcal{O}_{WW} = & g (D^\mu H)^\dagger \sigma_k (D^\nu H) W^k_{\mu\nu} - g' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ & - g/2 (H^\dagger \sigma_k \overleftrightarrow{D}^\mu H) D^\nu W^k_{\mu\nu} + g'/2 (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}\end{aligned}$$

Use EOMs + IBP to translate between different bases

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

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

Basically unconstrainable from single-Higgs physics: c_6

→ enters Higgs potential ➡ self couplings (Important test of SM)

The Higgs Potential

The Higgs Potential

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

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

EWSB:

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

↑ $\langle |H| \rangle$

- Vacuum Stability
- Dark Matter
- Portal
- Baryogenesis
- Hierarchy Problem
- ...

The Higgs Potential

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

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

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

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

$\langle |H| \rangle$

- Vacuum Stability
- Dark Matter
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- ...

The Higgs Potential

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

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

The Higgs Potential

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

$$V(h) = \frac{\mu^2}{2}(2hv + h^2) + \frac{\lambda}{4}(4hv^3 + 6h^2v^2 + 4h^3v + h^4)$$
$$+ \frac{c_6\lambda}{8\Lambda^2}(6hv^5 + 15h^2v^4 + 20h^3v^3 + 15h^4v^2) + \ \dots$$

The Higgs Potential

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

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

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

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

The Higgs Potential

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

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

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

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

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

removes also momentum-dependent interactions

The Higgs Potential

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

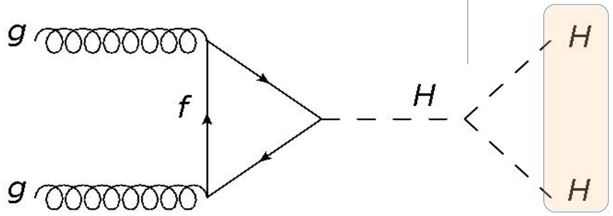
$\mathrm{m}_h \simeq 125\,\mathrm{GeV}$ established @LHC

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

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

The Higgs Potential

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

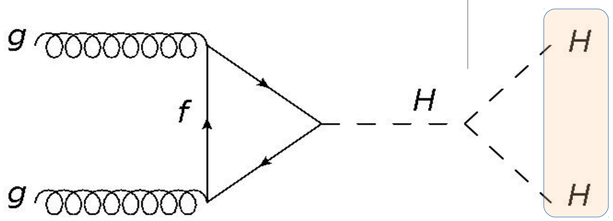


c_6 accessible in Higgs pair production: $\lambda_{3h} = \lambda_{3h}(c_6)$

Challenge: Many more operators contribute

The Higgs Potential

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



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

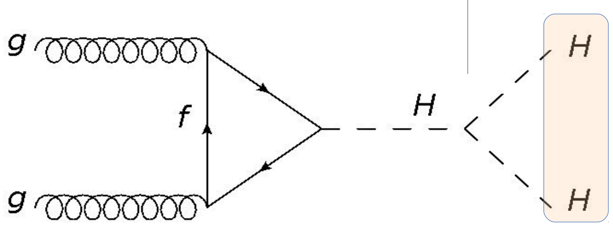
Plehn, Rauch, hep-ph/0507321

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

Challenge: Many more operators contribute

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

[test of SM]

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

FG, Papaefstathiou, Yang, Zurita
1301.3492; 1309.3805

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

Higgs Boson EFT

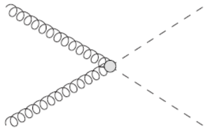
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda|H|^6$$

Pure Higgs

Yukawa type

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

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



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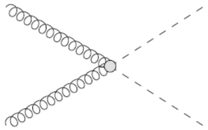
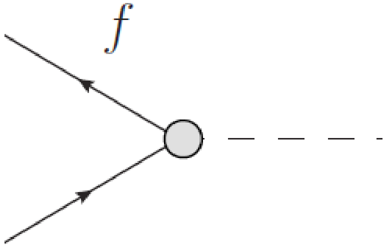
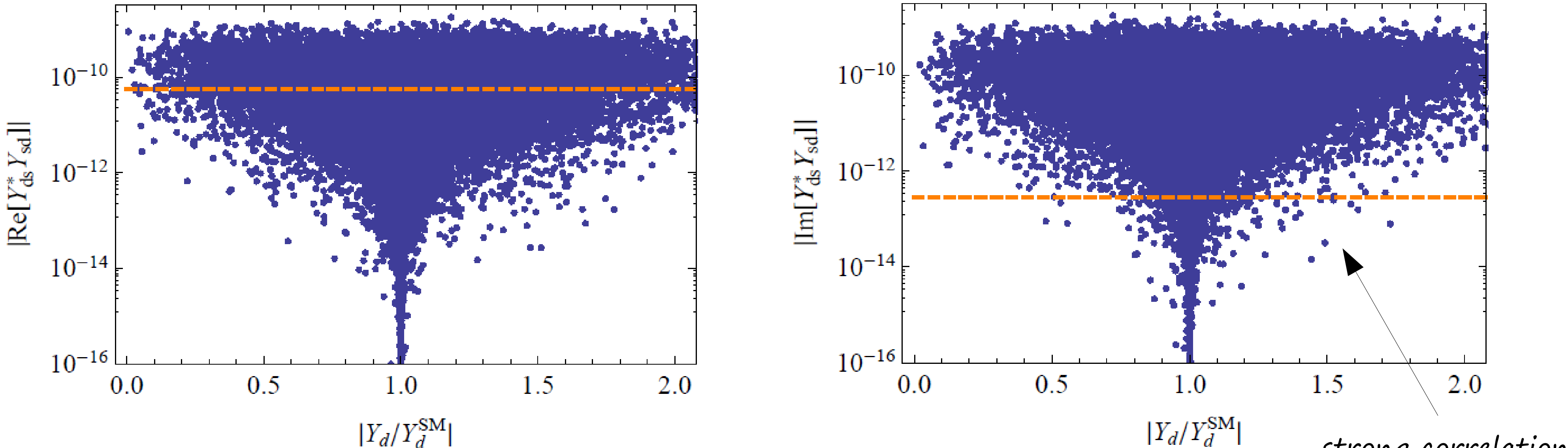


Need to consider light generations?



Strong Correlation $\Delta Y \leftrightarrow$ FCNC

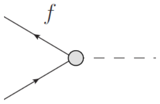
e.g.: K^0-oscillation



FG, 1406.0102

$$0.4 \lesssim |Y_d/Y_d^{\mathrm{SM}}| \lesssim 1.7$$

Need to consider light generations?



→ No!

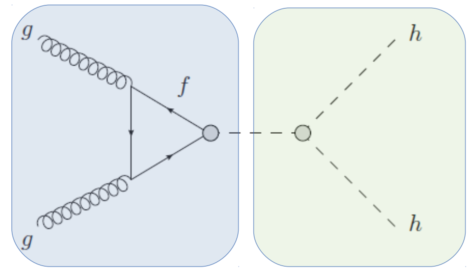
$$\mathcal{L}_6^Y = -\frac{1}{v^2}\left((H^\dagger H)\,\bar{q}_L C_u H^c u_R + (H^\dagger H)\,\bar{q}_L C_d H\, d_R\right)$$

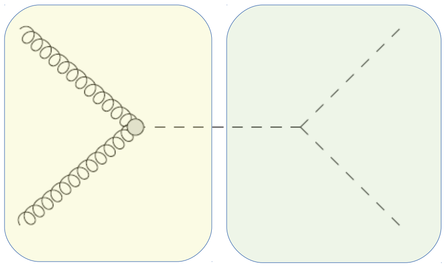
Higgs Pair Production in gg Fusion

$gg \to hh$

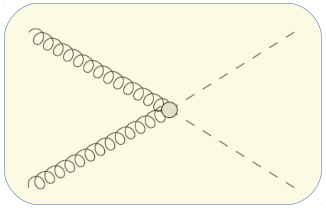
EWSB → Relevant Terms:

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

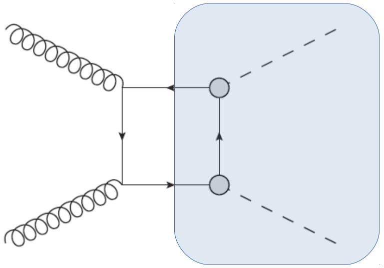




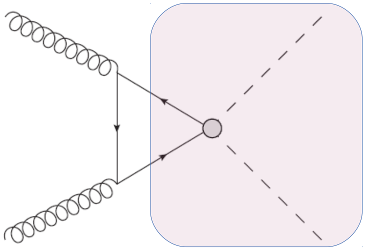
$$+ \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right) G^a_{\mu\nu} G_a^{\mu\nu}$$



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



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

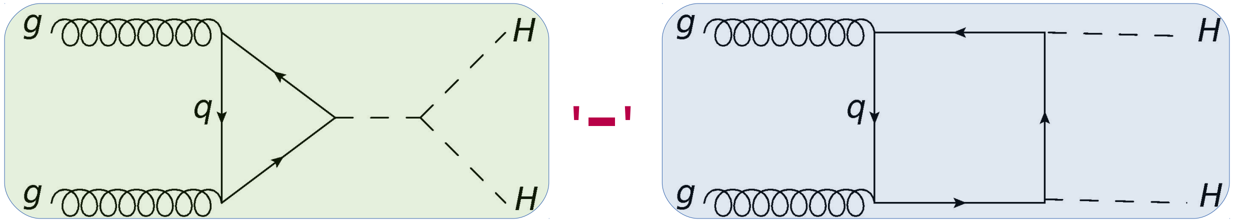


$c_i \to c_i \, \Lambda^2 / v^2$

Cross Section in SM (LO)

spin-0 spin-2

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



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

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

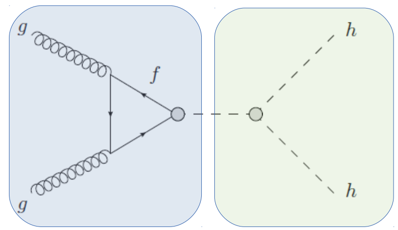
$$G_\Box = \mathcal{O}(\hat{s}/m_Q^2)$$

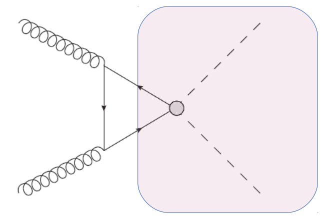
$$\sigma(gg \to hh)_{\rm LO}^{\rm LHC14} \sim 17\,{\rm fb}$$

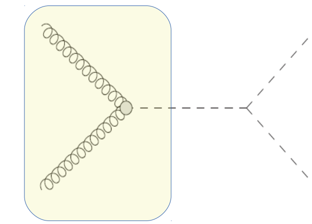
Eboli, Marques, Novaes, Natale, PLB 197(1987)269
Glover, van der Bij, NPB 309(1988)282

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

Cross Section in D=6 EFT





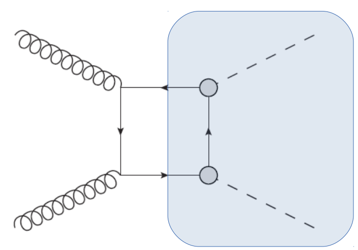


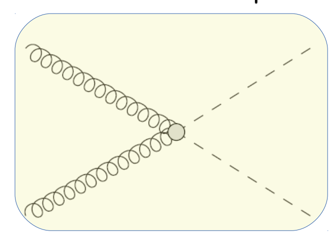
$$\left.\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}}\right|_{\mathrm{EFT}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \Bigg\{ \Big| C_\triangle F_\triangle (1 - 2c_H + c_t + c_6) + 3F_\triangle(3c_t - c_H) \; + 2c_g C_\triangle$$

$$+ C_\Box F_\Box (1 - c_H + 2c_t) + 2c_g C_\Box \Big|^2 + \Big| C_\Box G_\Box \Big|^2 \Bigg\}$$

FG, Papaefstathiou, Yang, Zurita, 1410.3471

see also Azatov, Contino, Panico, Son 1502.00539 and Roberto's talk!





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

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

Implemented in MC generator Herwig++

Normalize to NNLO: de Florian, Mazzitelli, 1309.6594

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

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_τ, c_W
$h \to WW$	c_H, ~~c_{HW}, c_W~~	-	c_H, c_W, c_b, c_t, c_τ, 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
(via eHDECAY: Contino, Ghezzi, Grojean, Muhlleitner, Spira, 1403.3381)

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

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

Unique accessibility in hh production!

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

Explicit Analysis

Explicit Analysis

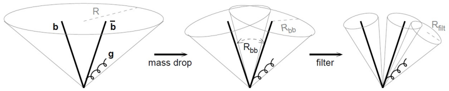
- Focus on $hh \to b\bar{b}\tau^+\tau^-$ @LHC14

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!

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

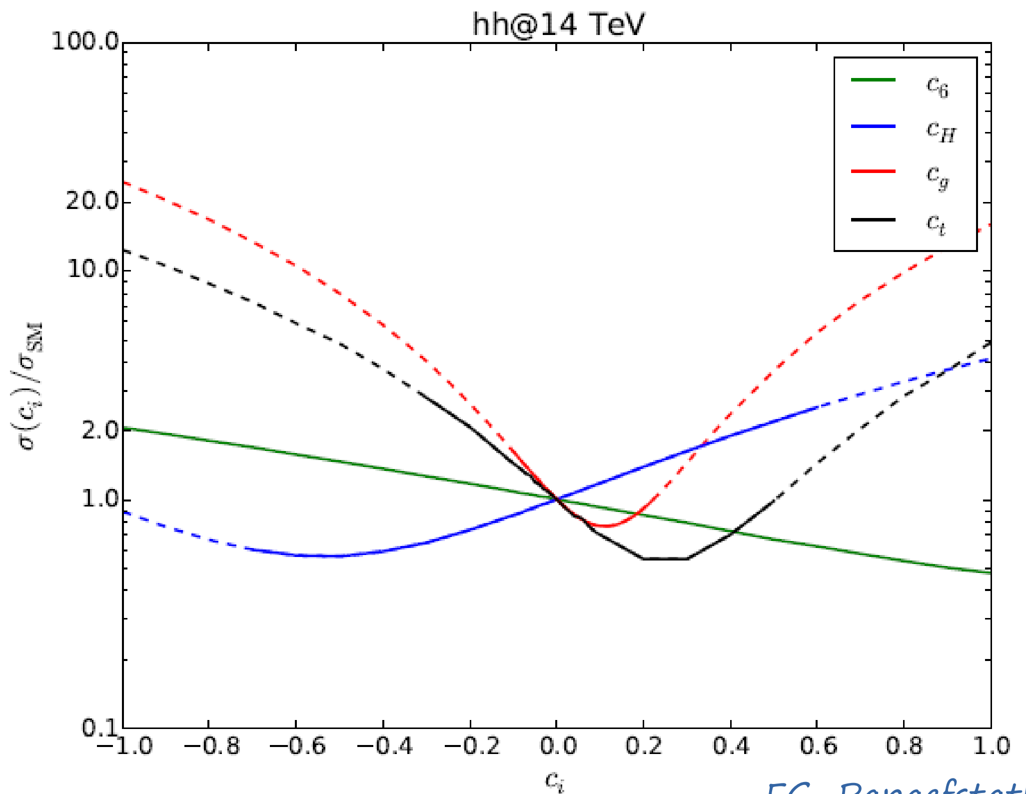
↳ Cuts:

- 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

$gg \to hh$ Cross Section in EFT



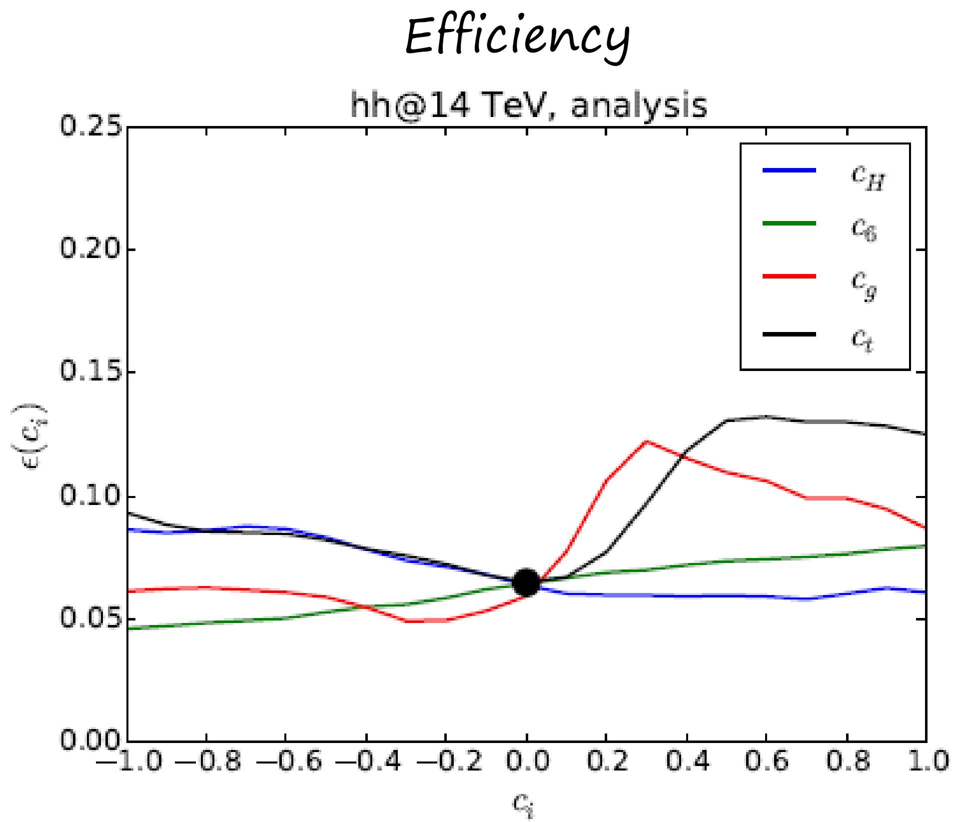
FG, Papaefstathiou, Yang, Zurita, 1410.3471

MSTW2008nlo_nf4 PDF

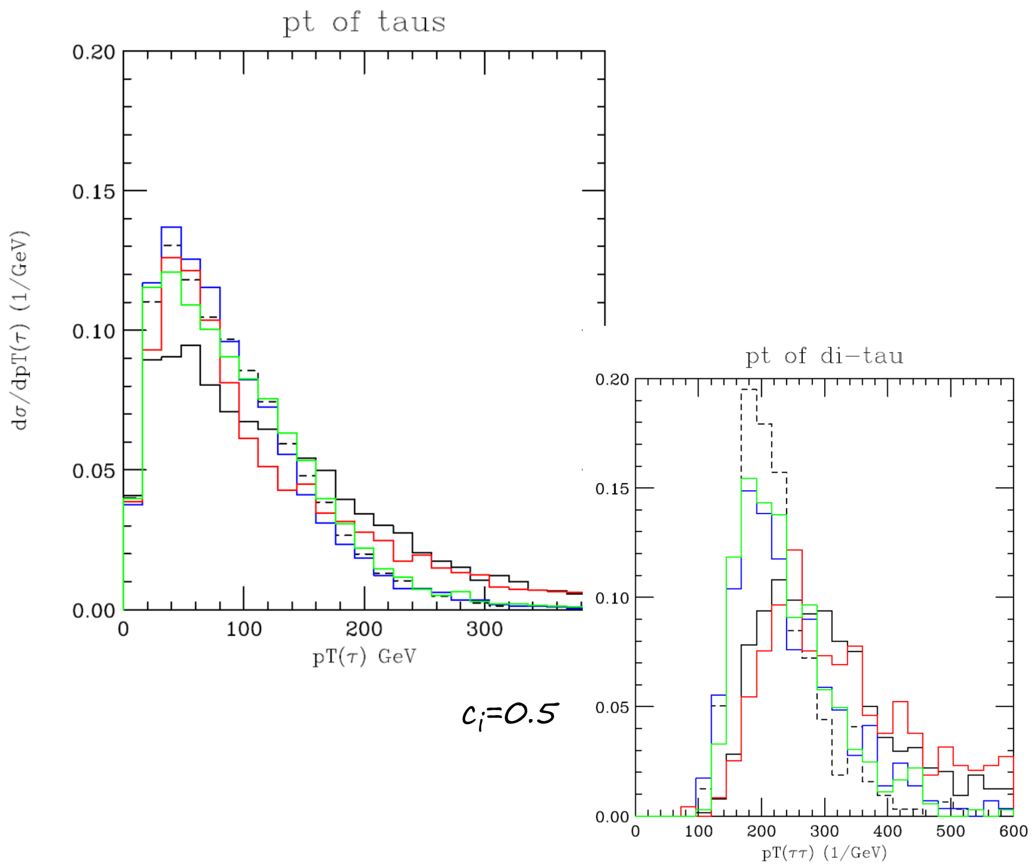
- Effect of varying individual Wilson coefficients
- Dashed: parameter-range excluded from current h data at the LHC
  → used HiggsBounds, HiggsSignals on cross sections calculated via eHDECAY

Bechtle et.al., 1311.0055, 1305.1933

$gg \to hh$ after cuts



FG, Papaefstathiou, Yang, Zurita, 1410.3471

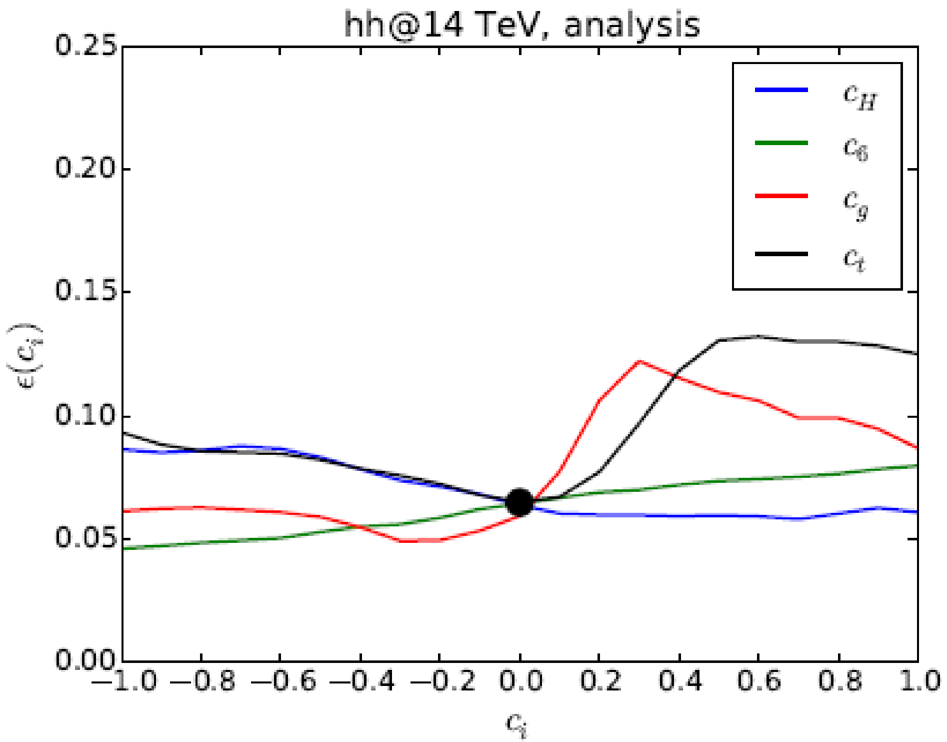


MC generator important for analysis

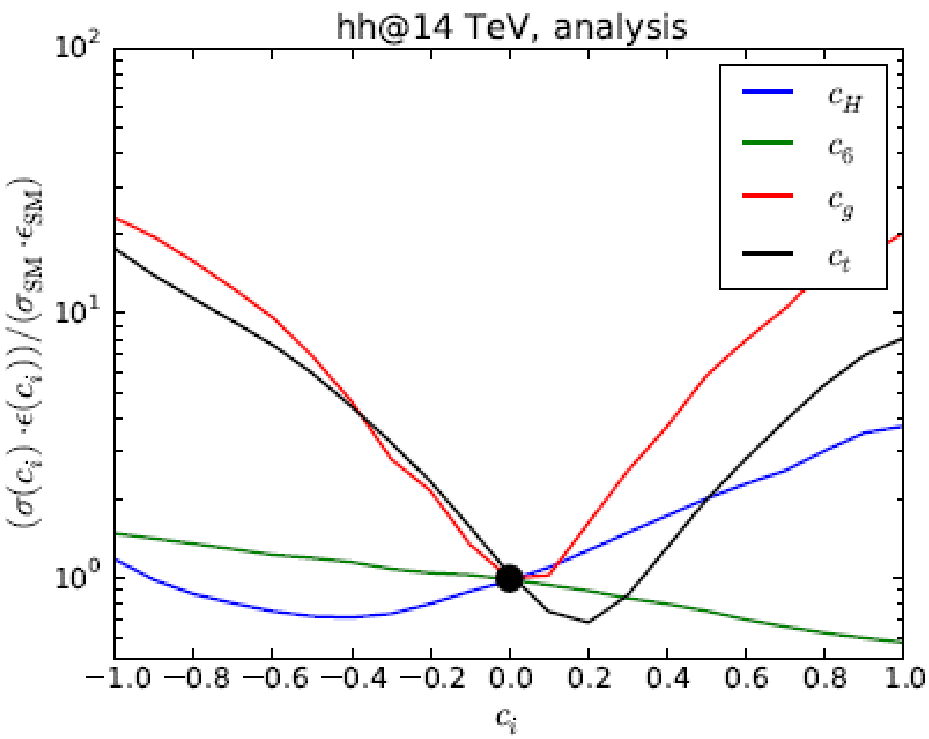
→ describe distributions, which determine efficiencies $\epsilon(c_i)$

$gg \to hh$ after cuts

Efficiency



Cross Section



FG, Papaefstathiou, Yang, Zurita, 1410.3471

MC generator important for analysis

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

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

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

$f_{\rm th}$: 30% $\sim$ 10% (scale) + 10% (pdf + α_s) + 10% (m_t)

Analysis

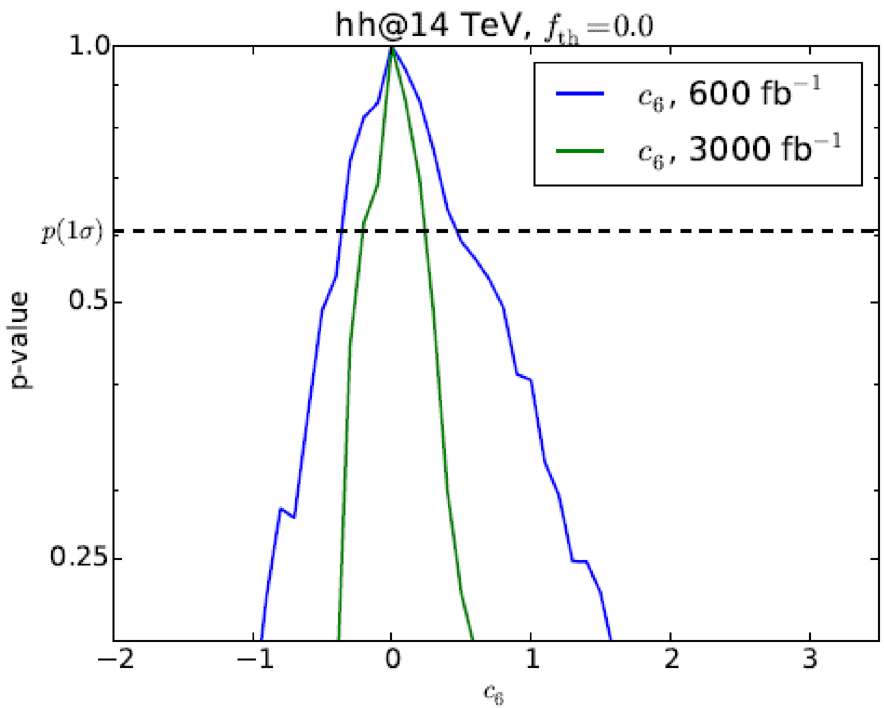
- Start with model where only $c_6 \neq 0$ (unconstrained from single h)
  - ↳ Vary only λ (as in previous studies)

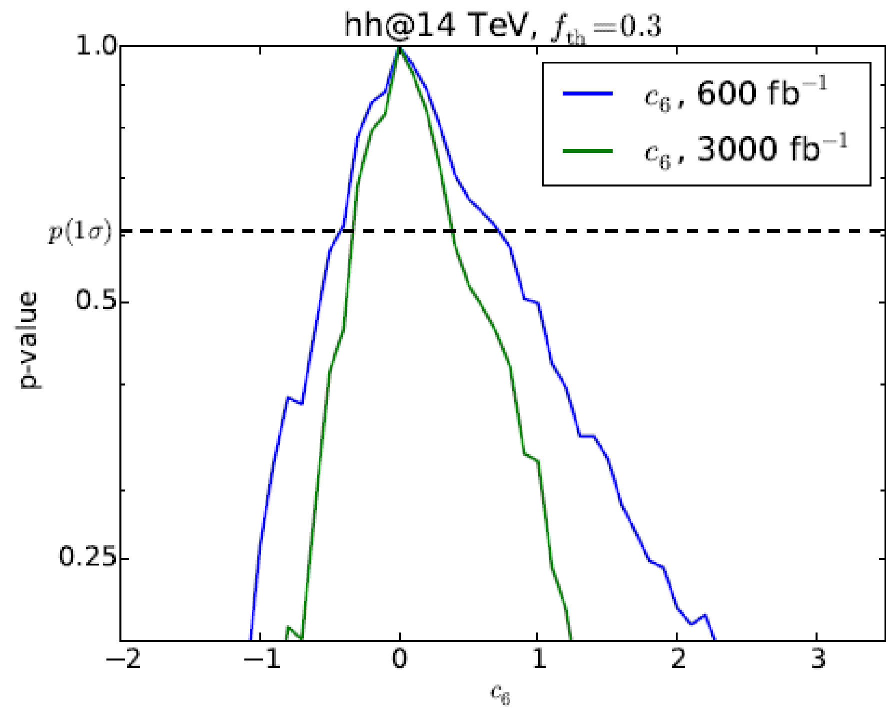
$$\delta N^2 = N + S^2 f_{\rm th}^2$$

- 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 $N(c_6 = 0)$.

Analysis





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

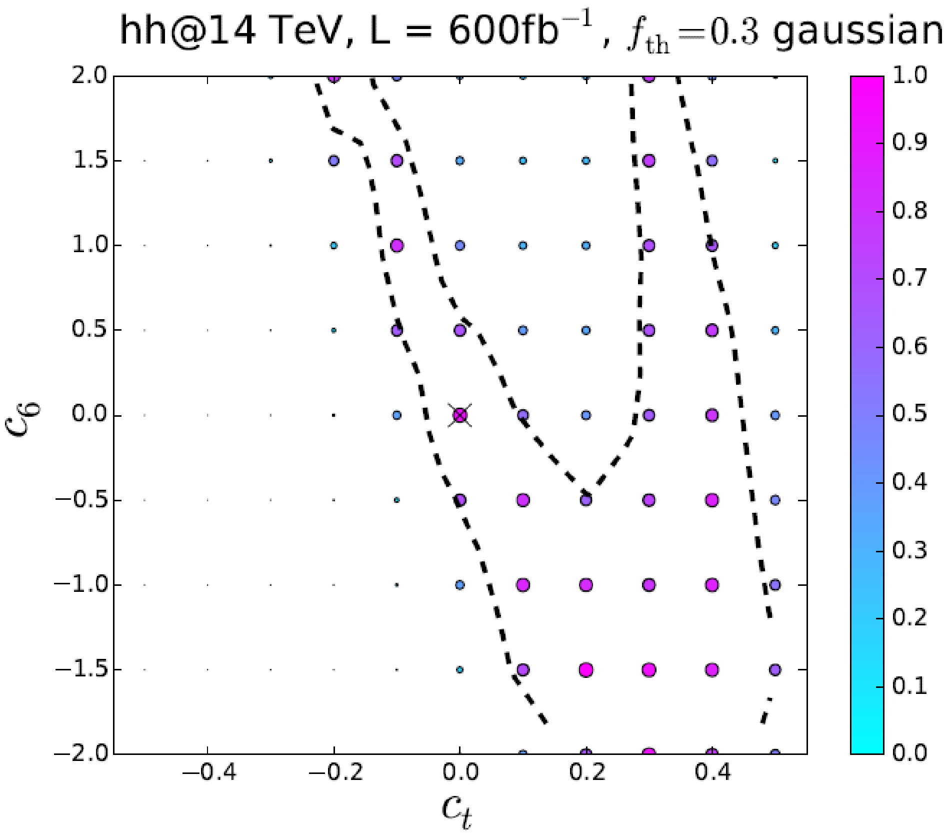
$$c_6^{1\sigma}(600\ \mathrm{fb}^{-1}) \in (-0.5, 0.8),\ \ c_6^{1\sigma}(3000\ \mathrm{fb}^{-1}) \in (-0.4, 0.4),\ \ f_{\rm th}=0.3$$

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

Full D=6 Theory

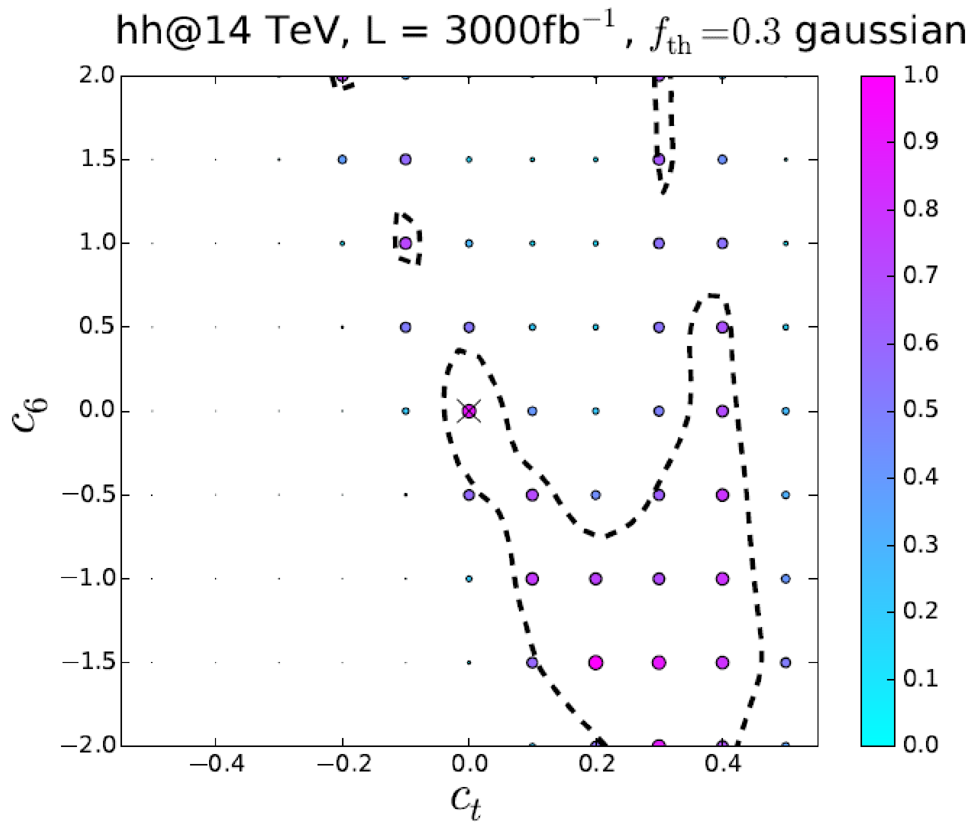
- Again assume SM (c_i=0) and calculate distance of predicted $N(c_6, .., c_b)$ from $N(c_6 = 0, .., c_b = 0)$ in units of $\delta N(c_6, .., c_b)$
- Show results in 2D grids (c_6, c_i), i=H,g,γ,t,b
- Marginalize over other directions with a Gaussian weight,
- given by projected errors on the coefficients 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

Results: c_t-c_6

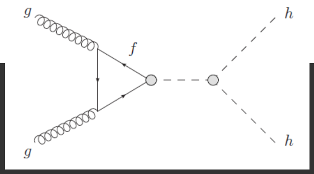


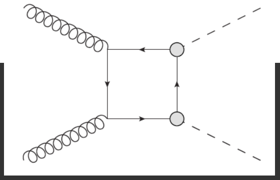
- Clear correlation visible: Enhanced hh cross section due to negative c_t can be compensated by reduction due to positive c_6

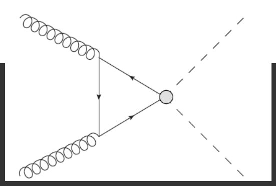
c_t-c_6



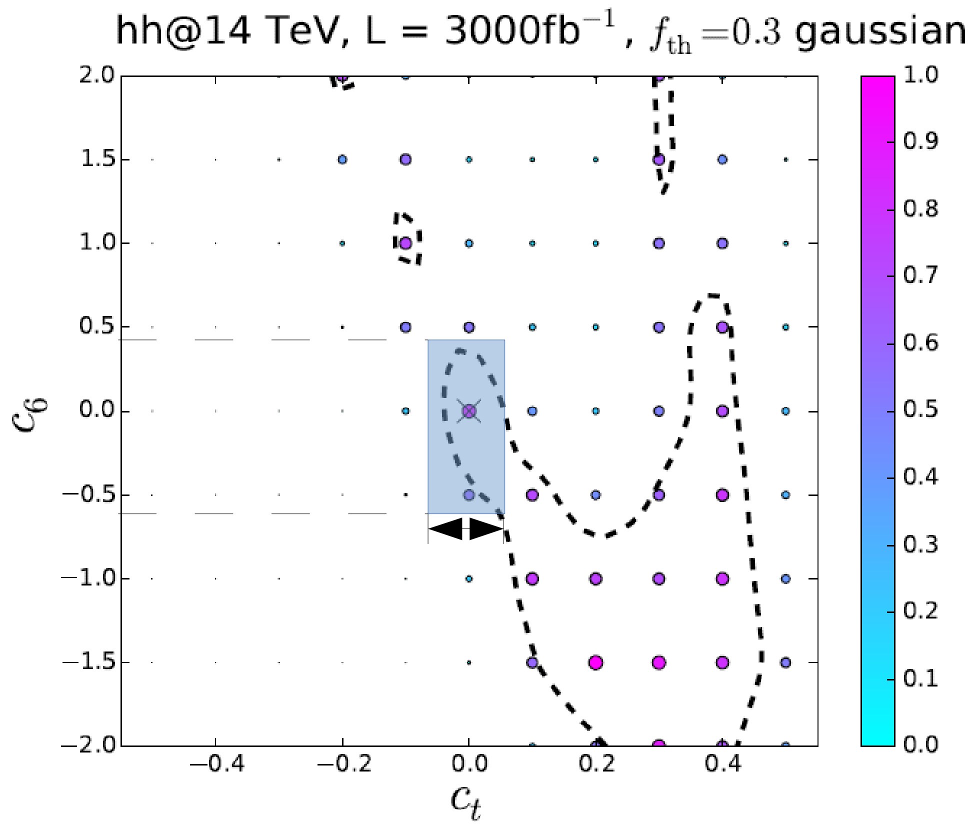
- Precise knowledge on 'top Yukawa' c_t helpful to improve the range for c_6
- On the other hand, could also obtain meaningful information on c_t in hh







c_t-c_6



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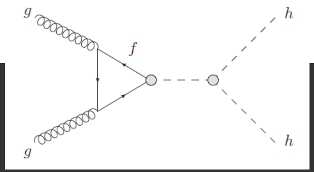
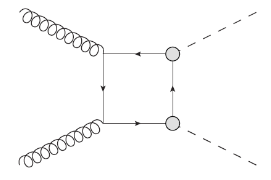
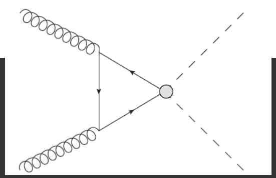
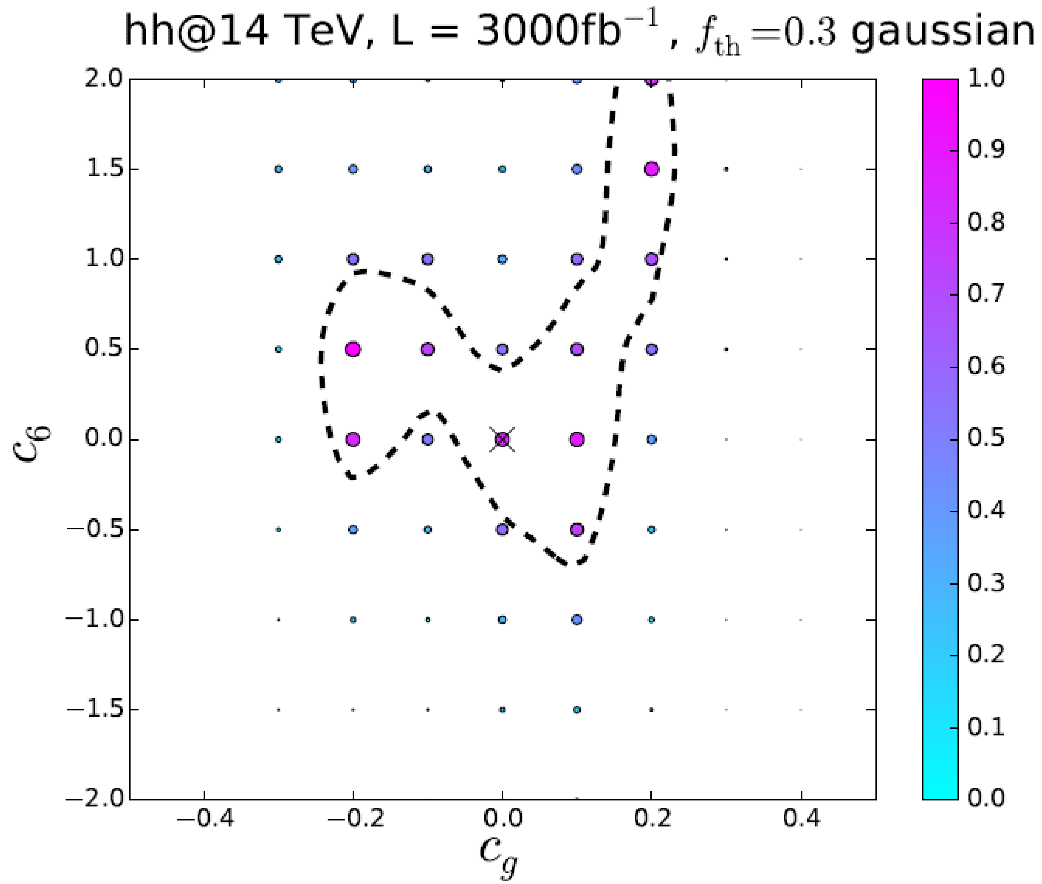




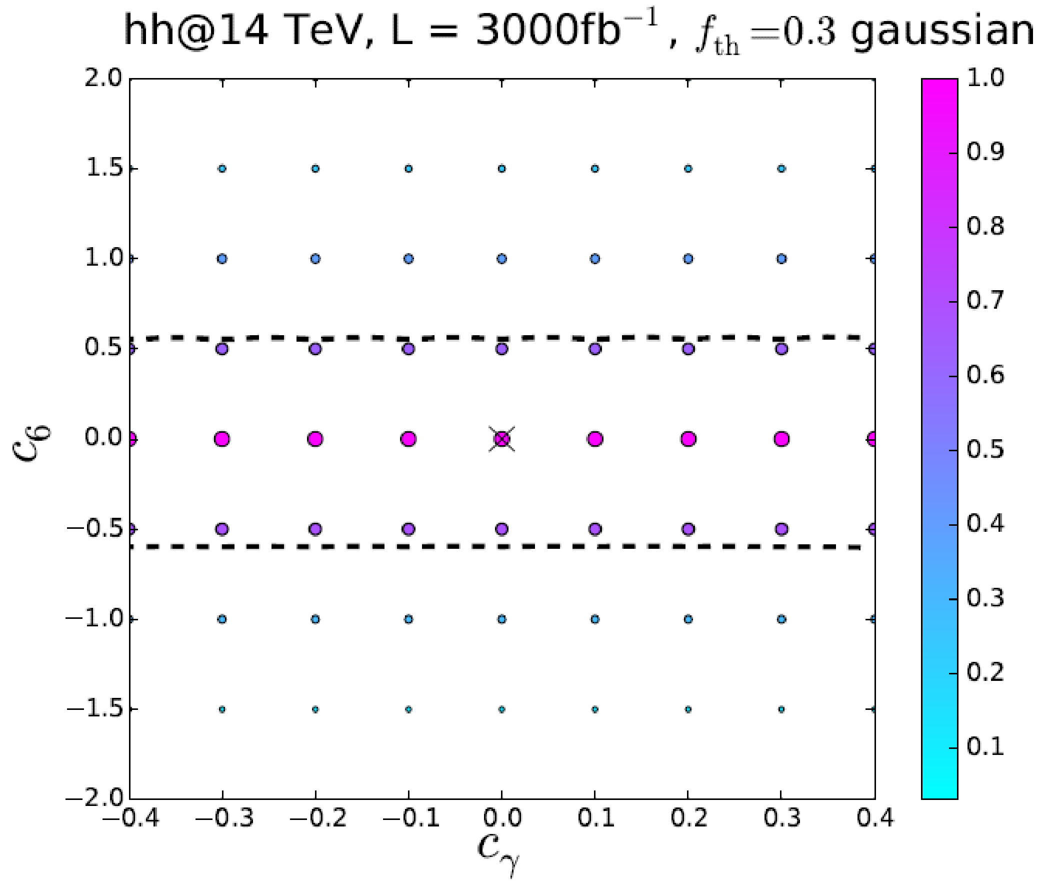


c_g-c_6



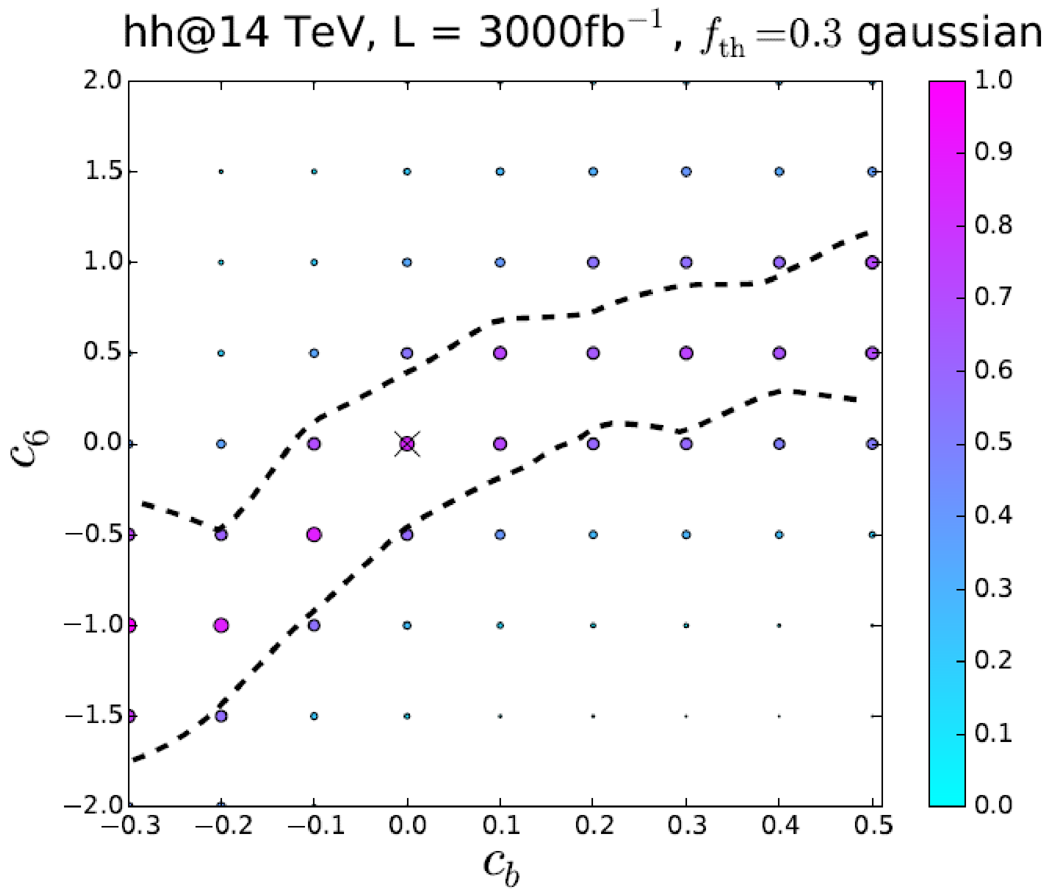
- Again compensation of effects from different operators possible
  → range for c_6 depends significantly on other coefficients

c_γ-c_6



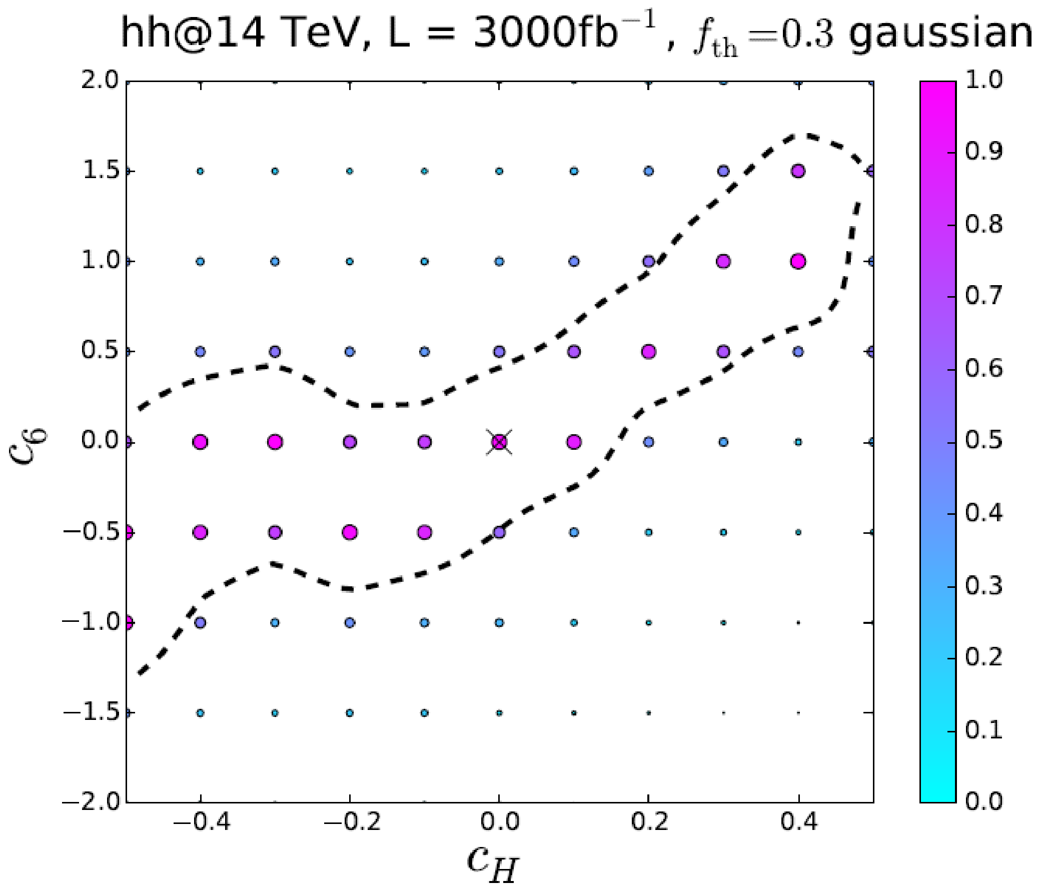
- As expected: negligible dependence on c_γ

$(c_b = c_\tau) - c_6$



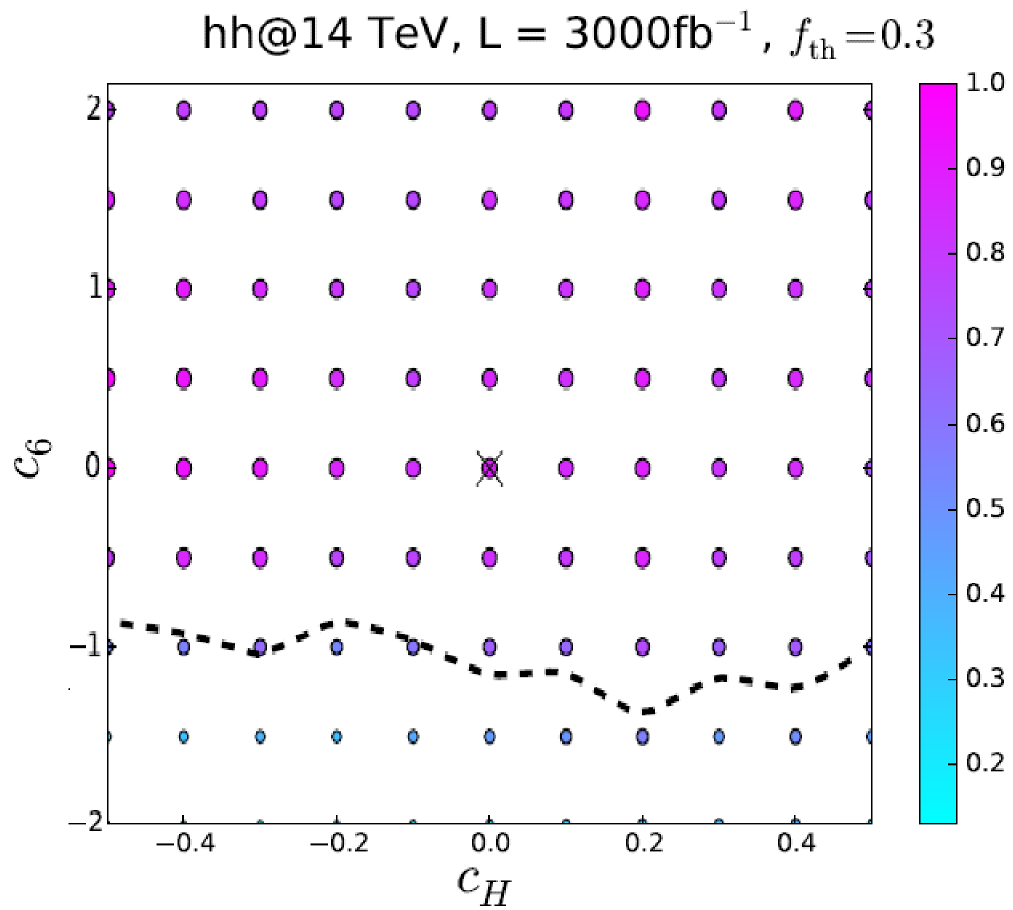
- Reduced BR due $(c_b = c_\tau) < 0$ to can be compensated by enhanced production cross section due to negative c_6 and vice versa

c_H-c_6



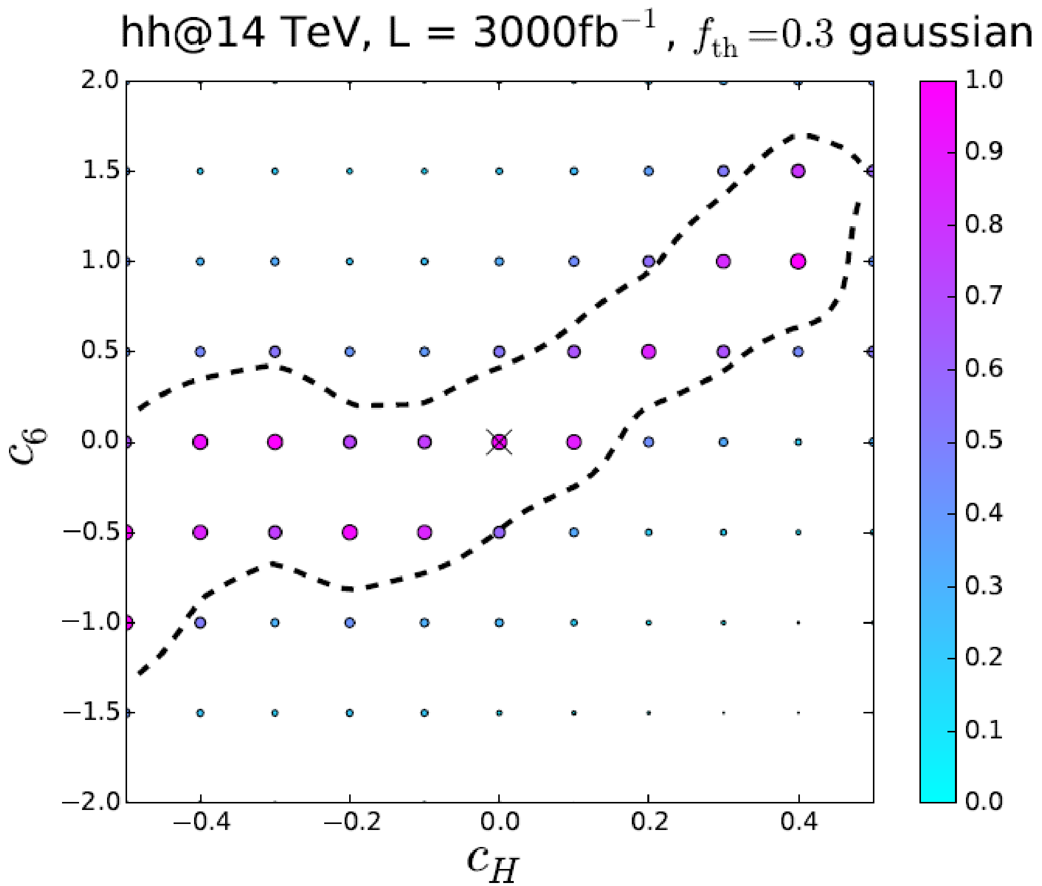
$$\lambda_{3h} = \frac{m_h^2}{2v^2}\left[1 + \frac{c_6 v^2}{\Lambda^2} - \frac{3 c_H v^2}{2\Lambda^2}\right]$$

c_H-c_6



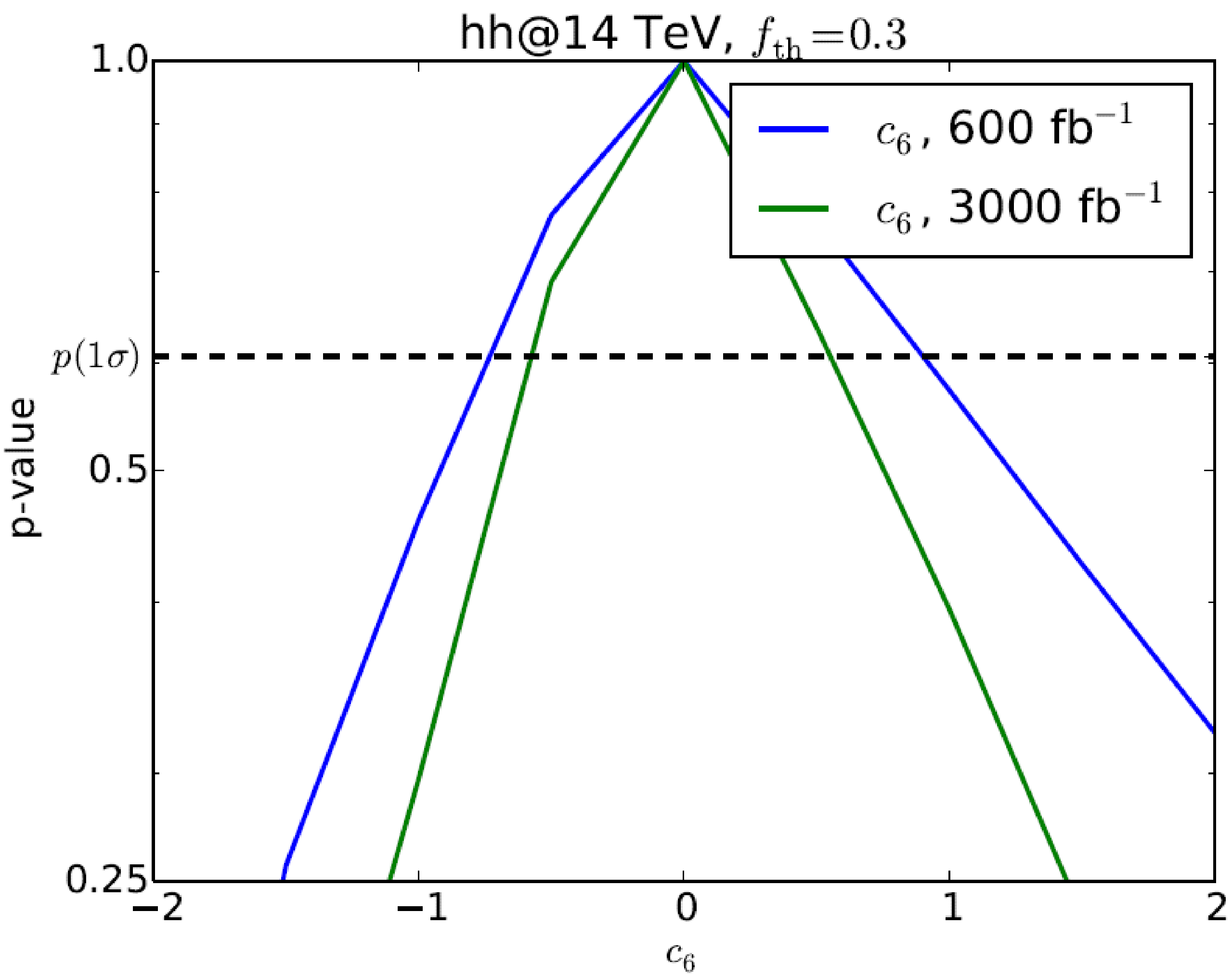
- *Marginalize over other directions with* ***current*** *p-values for coefficients from single-h measurements (using* HiggsBounds/Signals)

c_H-c_6



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

Full Marginalization → c_6



Final Results

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

model	$L = 600\ \text{fb}^{-1}$	$L = 3000\ \text{fb}^{-1}$
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 ($bb\gamma\gamma$) and Roberto's talk!

Next Steps

Some Directions to explore:

- Include other decay channels
- Optimize analysis for different regions of parameter space
- Consider distributions to improve bounds
- Include NLO QCD corrections (feasible in $m_t \to \infty$)

See yesterday's 1504.06577: Gröber, Mühlleitner, Spira, Streicher

- Sensitivity on c_t/c_g
- Test presence of μ^2

See also Roberto's talk on thursday!
→ 100 TeV Collider

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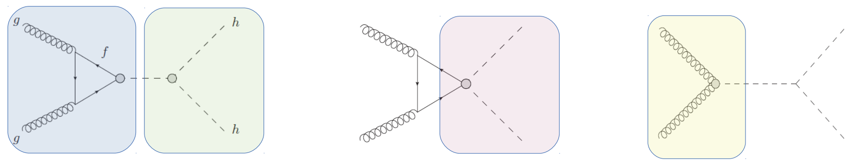
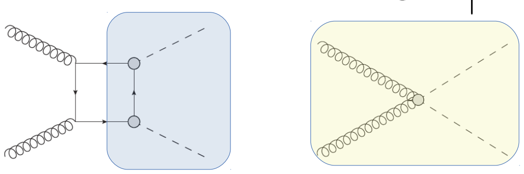
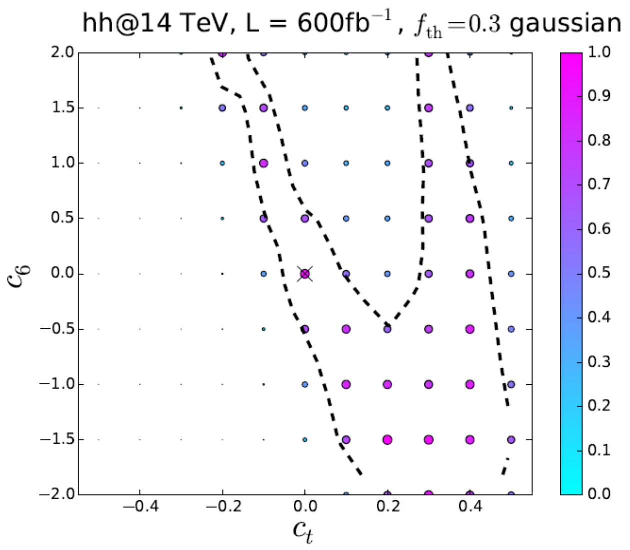
c_t-c_g

- Add additional information on c_t-c_g plane



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





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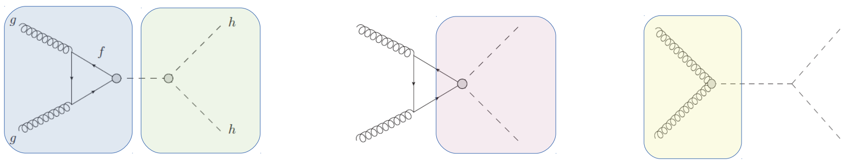

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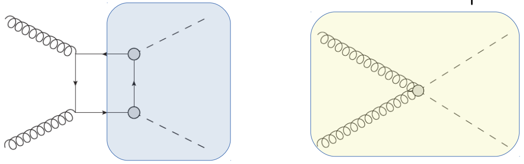
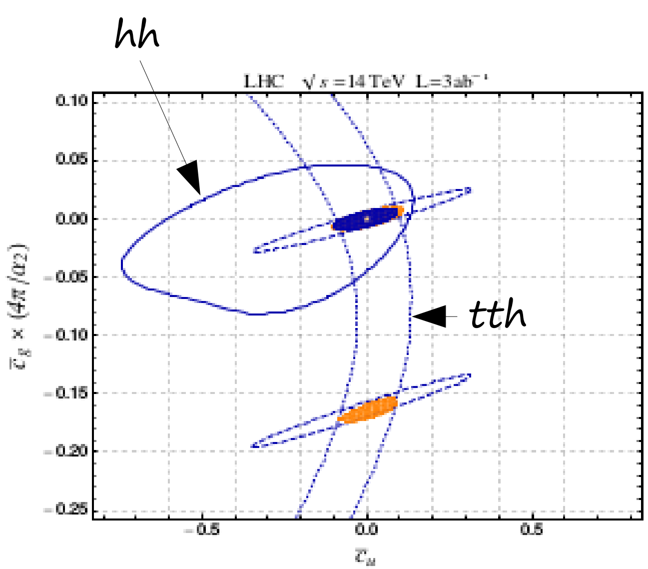
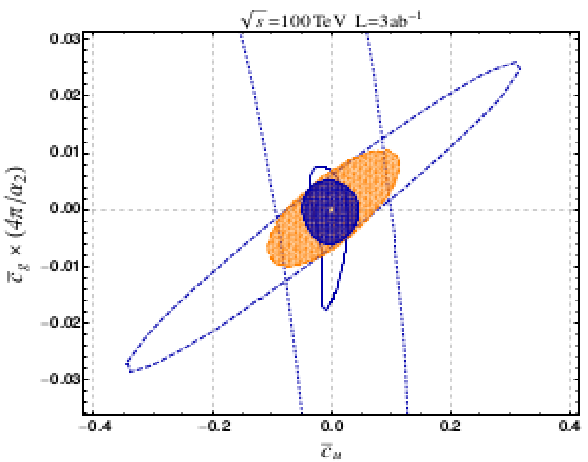




Azatov, Contino, Panico, Son, 1502.00539



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!

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

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⬇

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

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Coleman-Weinberg $$V(H) = \lambda\,|H|^4(1 + c\log(|H|^2/\mu_r^2))$$

↓

Higgs Boson much too light (in SM)

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Add NP, regenerate μ^2 again spontaneously (CSI),...

Hempfling, hep-ph/9604278;
Englert, Jaeckel, Khoze, Spannowsky, 1301.4224;
Bardeen, ...

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$$V(H) = \langle \Phi \rangle^2 \, |H|^2 + \lambda \, |H|^4 + \cdots$$

↓

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

- Alternative: replace by D=6 operator FG, 1504.00355
- $\Lambda<0$, EWSB not triggered by negative μ^2 term
- $\mu^2=0$ really possible by adding D=6 op. in consistent EFT ??

Presence of μ^2

- Yes, due to the lightness of the Higgs Boson!
- v only fixes ratio of terms

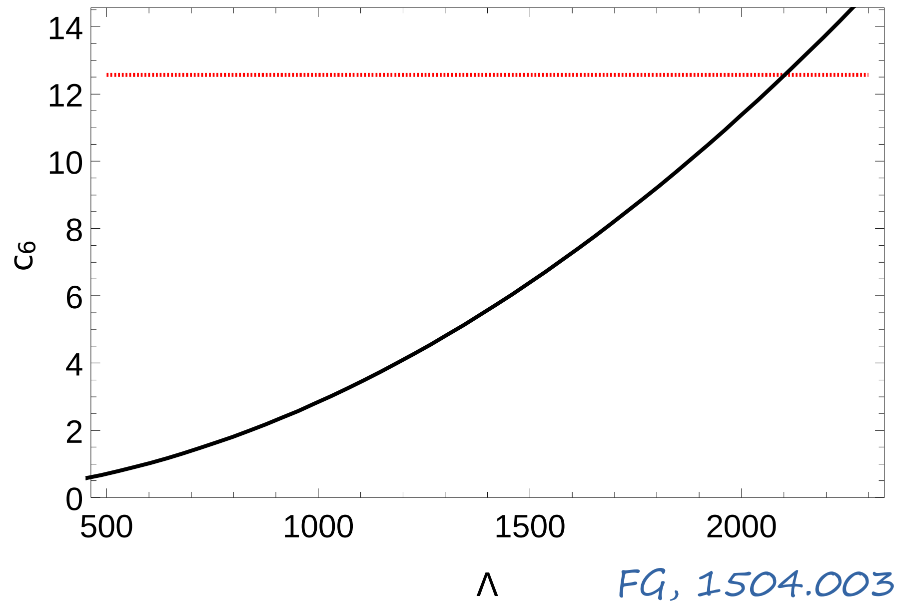
$$v^2 = -\frac{4}{3}\frac{\lambda}{c_6}\Lambda^2$$

- $$m_h^2 = 3v^2\lambda + \frac{15}{4}\frac{c_6}{\Lambda^2}v^4$$

Presence of μ²

- Yes, due to the lightness of the Higgs Boson!

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



FG, 1504.00355

SM one-loop CW → small correction:

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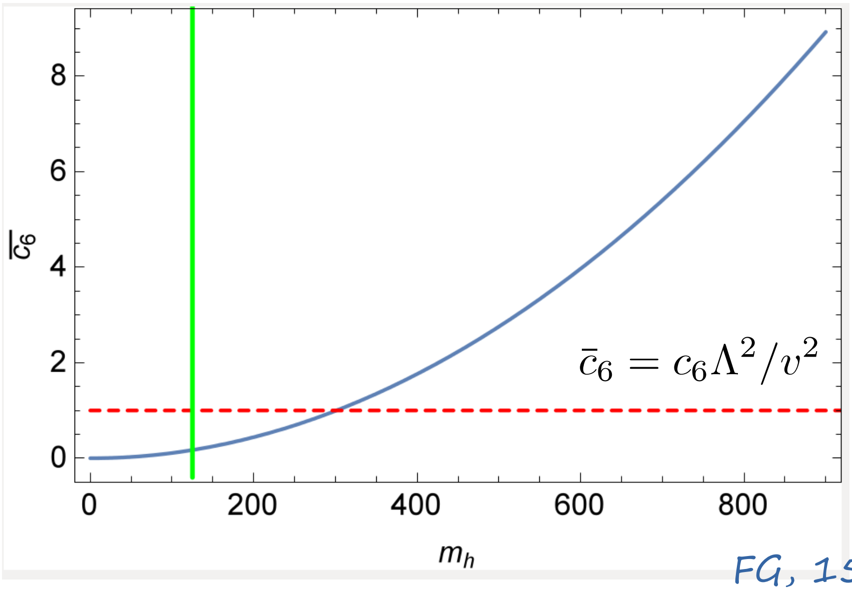
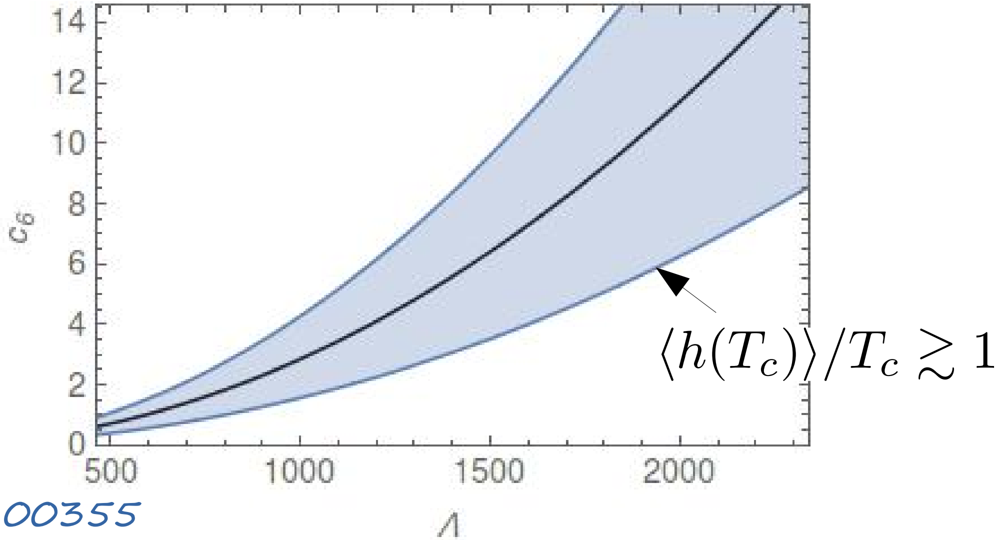


appropriate 1st order PT possible



FG, 1504.00355

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

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

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	$L = 600 \text{ fb}^{-1}$	$L = 3000 \text{ fb}^{-1}$
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	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$

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

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

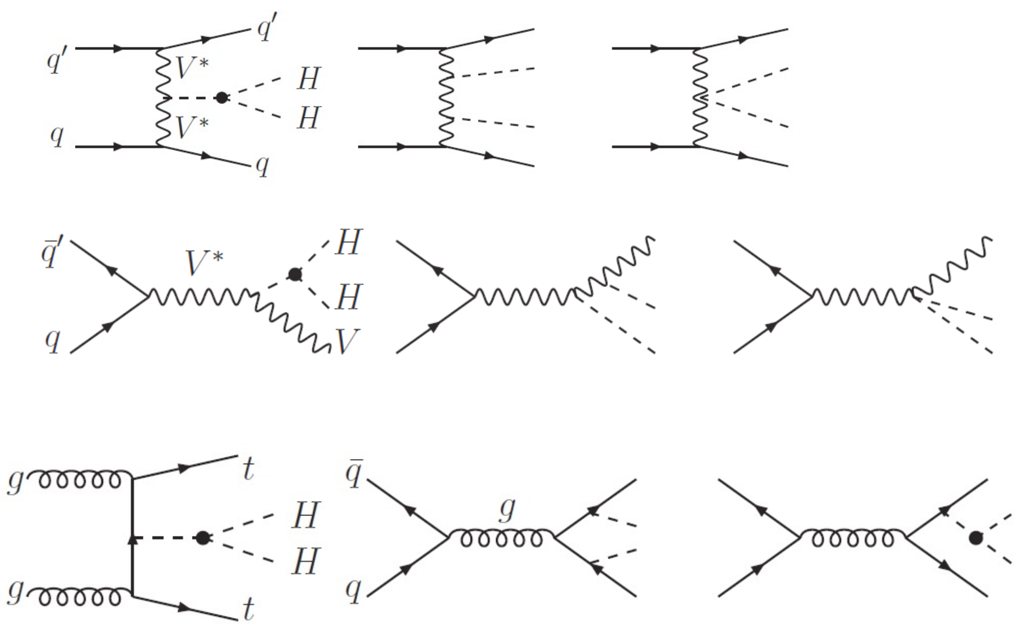
Conclusions

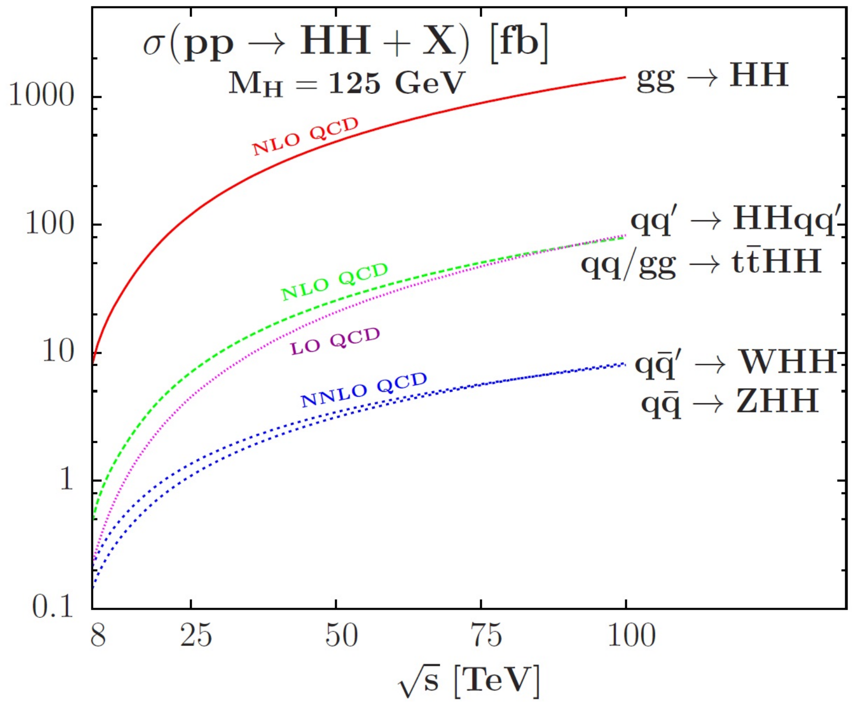
Thank you for your attention!

Backup: hh @LHC

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

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

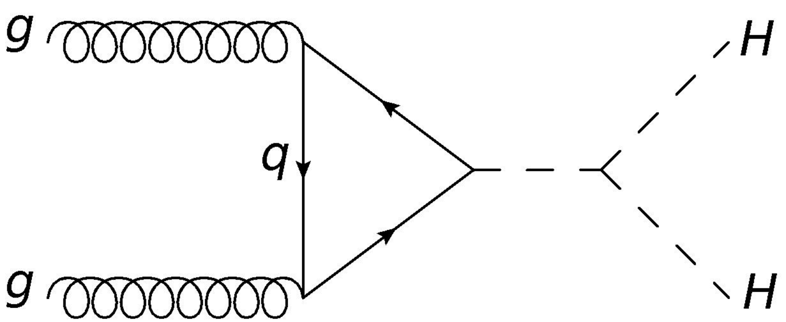


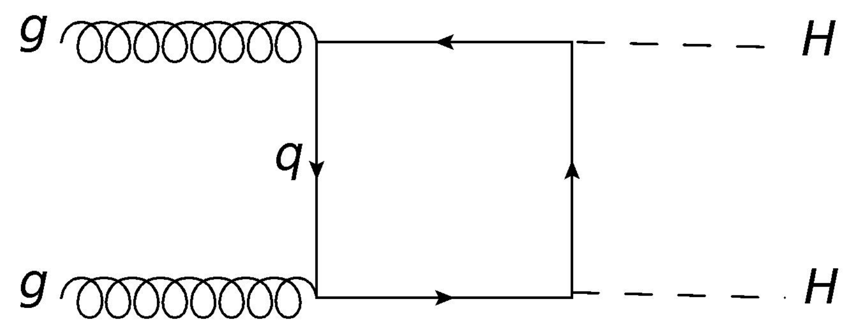


See [e.g.] Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581, and refs. therein

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

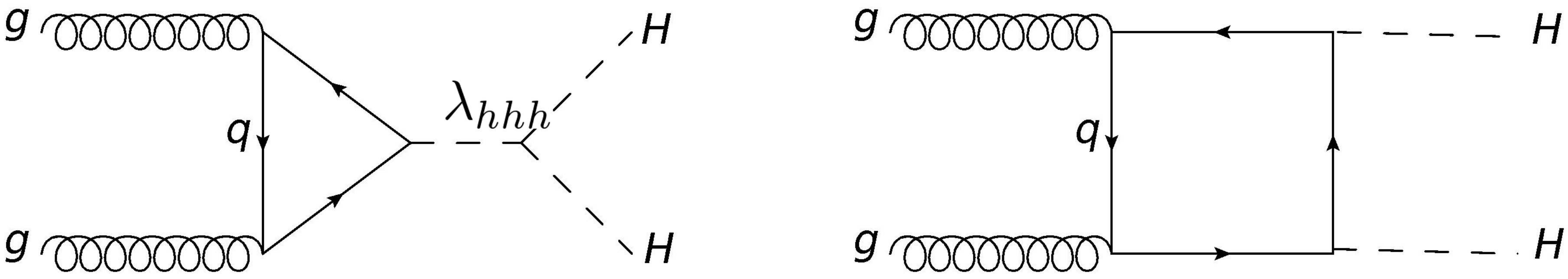
$$\sigma(gg \to hh)_{\rm LO} \sim 17\,{\rm fb}$$
$$\sigma(gg \to hh)_{\rm NLO} \sim 33\,{\rm fb}$$
$$\sigma(gg \to hh)_{\rm NNLO} \sim 40\,{\rm fb}$$

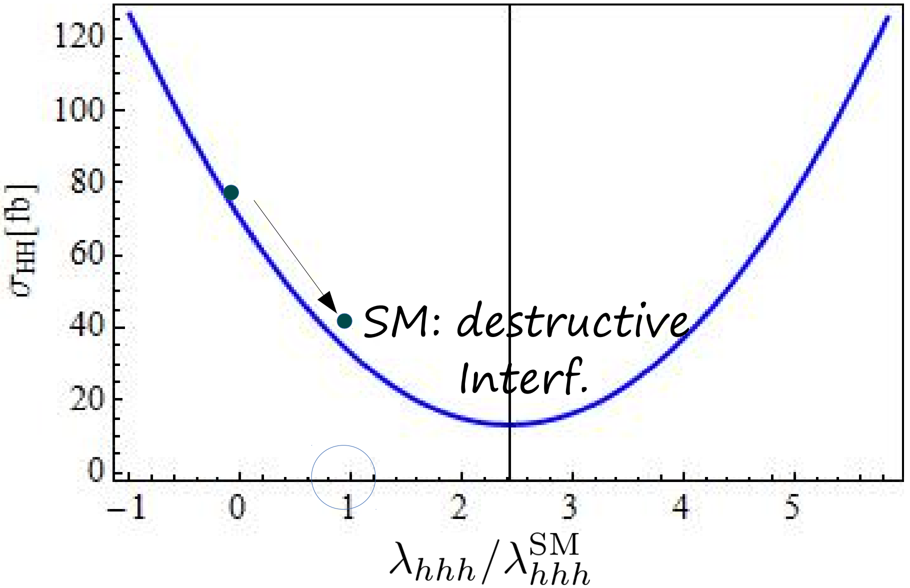
Theoretical error (NNLO): $f_{th} \sim$ 10% (scale) + 10% (pdf+α_s) + 10% (m_t^{-1})

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)

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

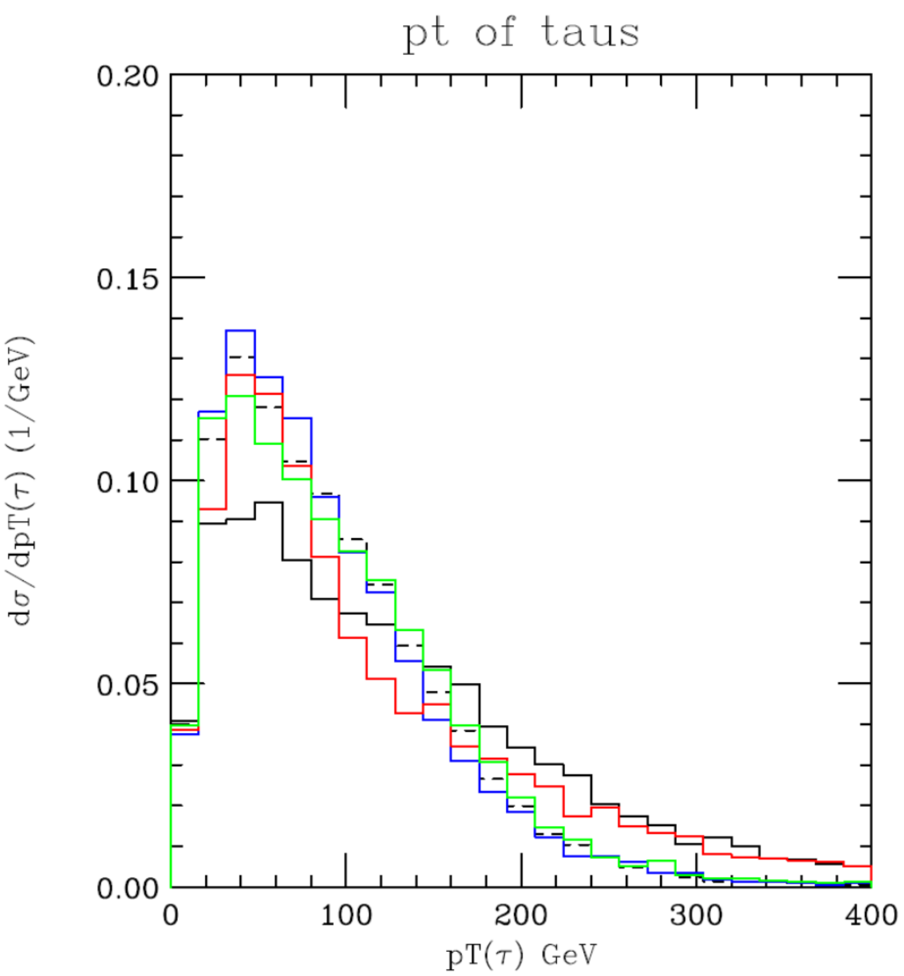
$$p_{\text{Gauss.}}(\{c_f\}) = \prod_f \frac{1}{\sigma_f \sqrt{2\pi}} \exp\left\{ -\frac{(c_f - \mu_f)^2}{2\sigma_f^2} \right\}$$

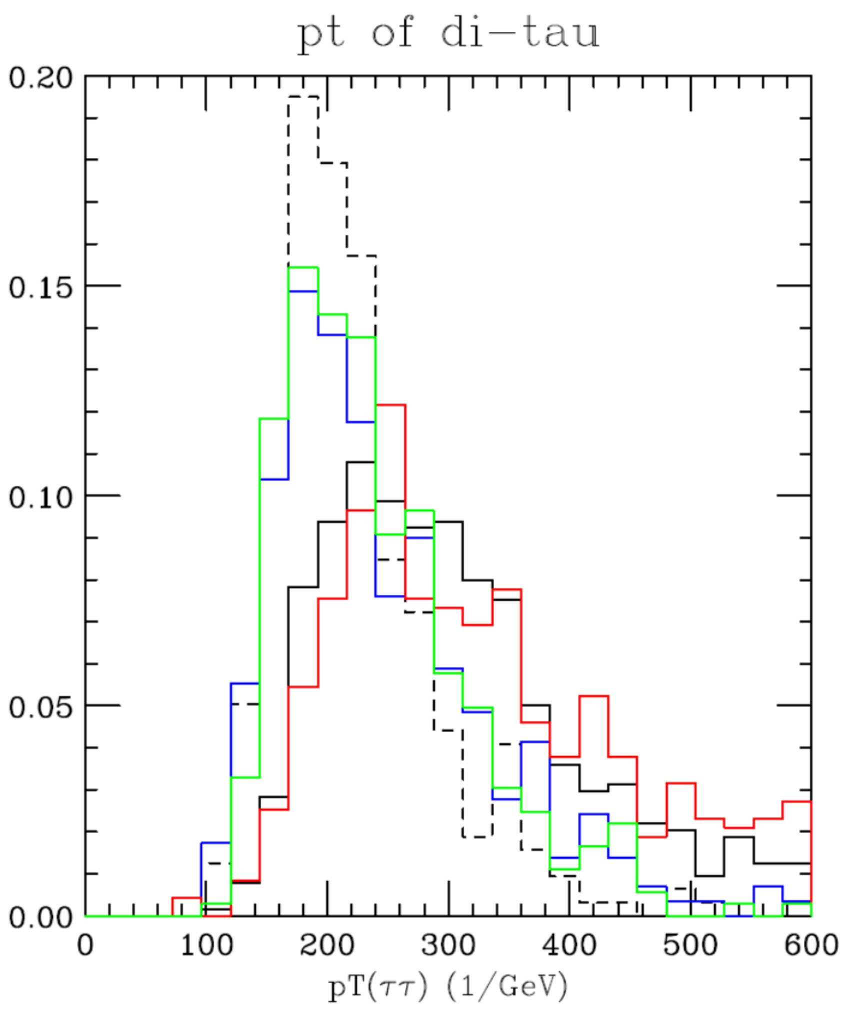
Projections:
(~10% effects)

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

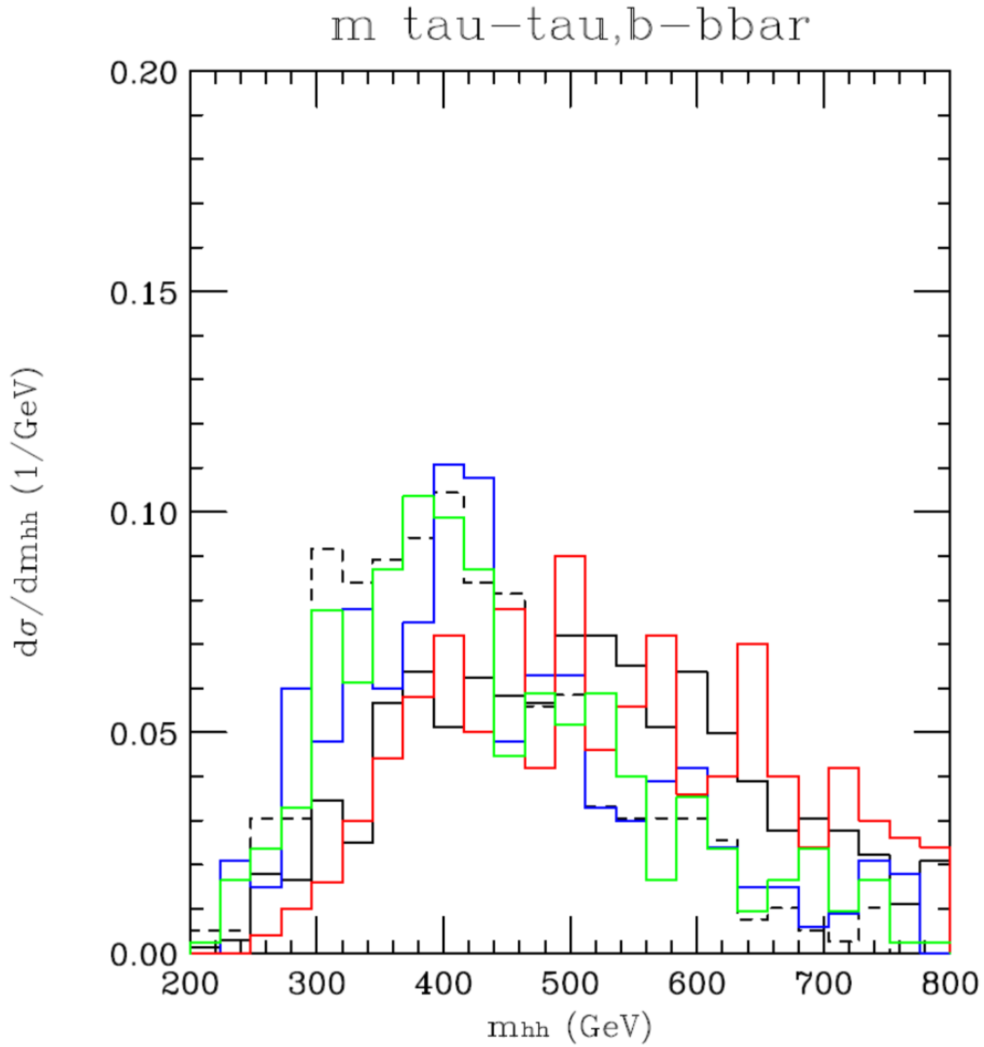
Backup: Distributions





c_i=0.5

Backup: Distributions



c_i=0.5