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

LHC Higgs XS
HH Subgroup Meeting

CERN, 8.12.2014

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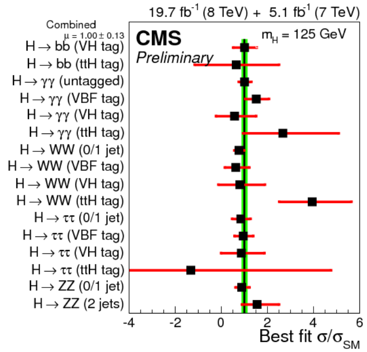
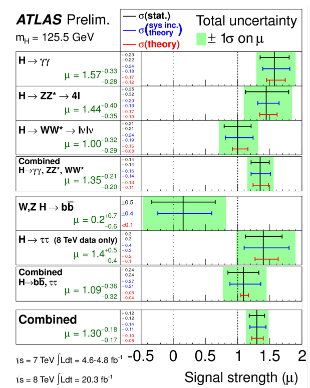
CERN

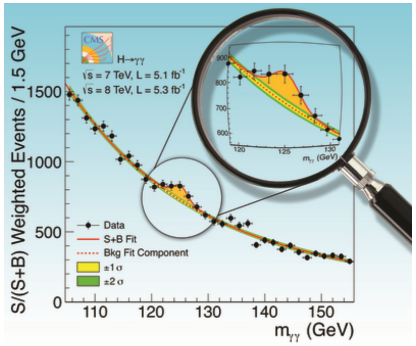
arXiv: 1410.3471
FG, Papaefstathiou, Yang, Zurita

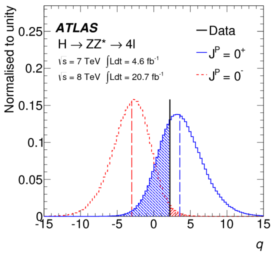
Introduction

- *Is it the SM-Higgs Boson?*
  - *Scale of New Physics?*



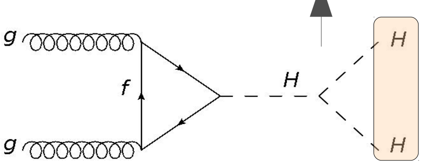






Important test: *<u>Higgs potential</u>* $V(h) = \frac{1}{2} m_h^2\, h^2 + \boxed{\lambda_{hhh}} v\, h^3 + \frac{1}{4} \lambda_{hhhh}\, h^4$

self couplings



$(D \leq 4)$

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

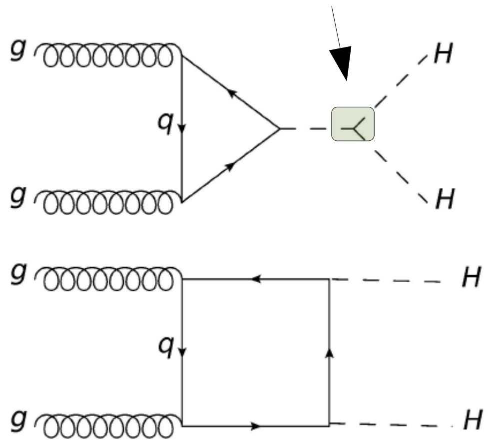
Measuring λ_{hhh}

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

- Simple approach: addition of a single D=6 operator $\leftrightarrow$ $\lambda_{hhh} \neq \lambda_{hhh}^{\mathrm{SM}}$

Process	600 fb^{-1} (1σ)	3000 fb^{-1} (1σ)
$b\bar{b}\tau^+\tau^-$	$(0.57, 1.64)$	$(0.69, 1.40)$
$b\bar{b}W^+W^-$	$(0.46, 1.95)$	$(0.65, 1.46)$
$b\bar{b}\gamma\gamma$	$(0.09, 4.83)$	$(0.48, 1.87)$

from FG, Papaefstathiou, Yang, Zurita, 1301.3492



- assumed $\lambda_{\mathrm{true}} = 1$
- Reduce error by employing ratio $\mathrm{C}_{hh} = \frac{\sigma(gg\to hh)}{\sigma(gg\to h)} \equiv \frac{\sigma_{hh}}{\sigma_h}$

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

Full Analysis: Higgs EFT

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

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

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

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

Here:

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

- Neglected operators that are strongly constrained from precision tests

See e.g.: Elias-Miro, Espinosa, Masso, Pomarol, 1308.1879; Pomarol, Riva, 1308.2803; Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia 1207.1344, 1211.4580, 1304.1151; Falkowski, Riva, Urbano, 1303.1812; Contino, Ghezzi, Grojean, Muhlleitner, Spira, 1303.3876; Dumont, Fichet, von Gersdorff 1304.3369; Falkowski, Riva, 1411.0669, Trott 1409.7605, ...

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

$$\mathcal{O}_{WW} = \tilde{c}_{HW}(D^\mu H)^\dagger \sigma_k (D^\nu H) W^k_{\mu\nu} + \tilde{c}_{HB}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} + \tilde{c}_W (H^\dagger \sigma_k \overleftrightarrow{D}^\mu H) D^\nu W^k_{\mu\nu} + \tilde{c}_B (H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

Only one free parameter

Higgs Boson EFT

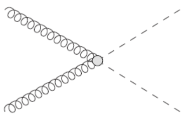
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6$$

Pure Higgs

Yukawa type

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

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



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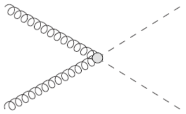
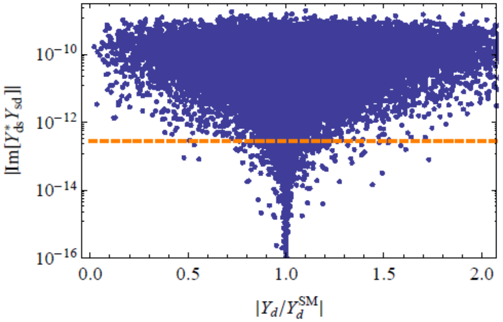


- What about light-quark Yukawas
  → can assume MFV, but even should be negligible on more general grounds: FCNCs



FG, 1406.0102

$gg \to hh$

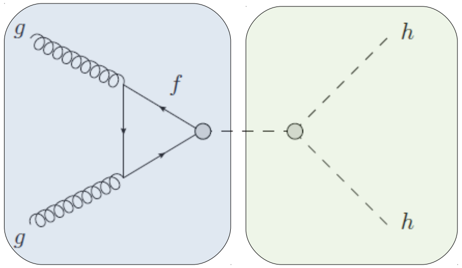
Relevant Terms:

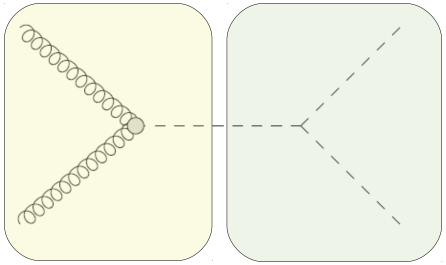
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3$$

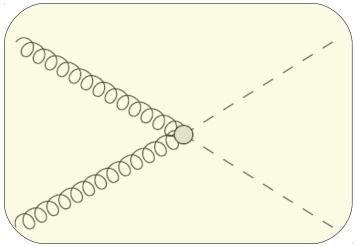
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G_a^{\mu\nu}$$

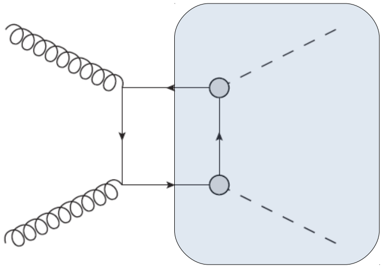
$$-\left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \text{h.c.}\right]$$

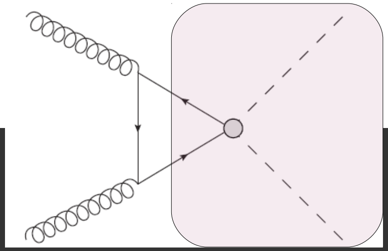
$$-\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$











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

$$H = \exp\left(-i\frac{T\cdot\xi}{v}\right)\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix}$$

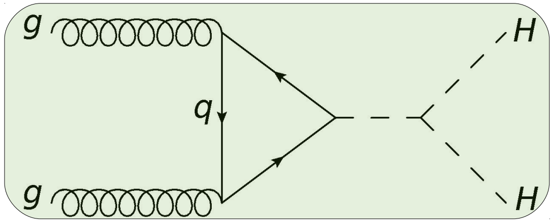
$$h \to \left(1-\frac{c_H v^2}{2\Lambda^2}\right)h - \frac{c_H v}{2\Lambda^2}h^2 - \frac{c_H}{6\Lambda^2}h^3$$

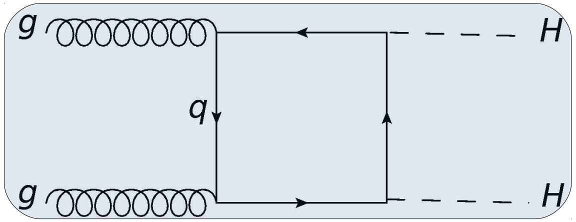
non-linear redefinition:
removes momentum-dependent interactions

Cross Section in SM (LO)

spin-0 spin-2

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





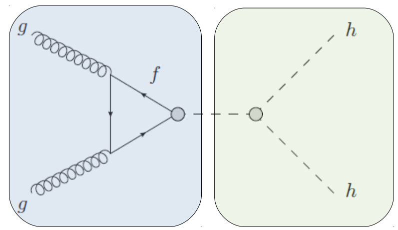
$$C_\triangle = \frac{3m_h^2}{\hat{s} - m_h^2}, \qquad C_\Box = 1$$

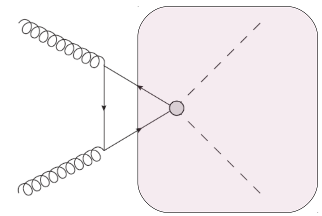
$$F_\triangle = \frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2), \quad F_\Box = -\frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2),$$

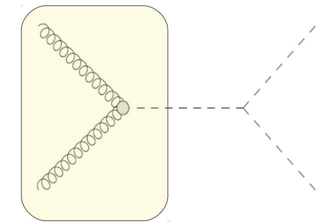
$$G_\Box = \mathcal{O}(\hat{s}/m_Q^2)$$

See Plehn, Spira, Zerwas ph/9603205

Cross Section in D=6 EFT

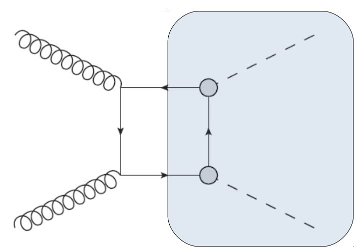


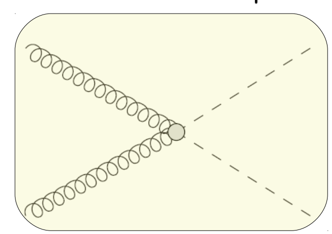




$$\left.\frac{\mathrm{d}\hat{\sigma}(gg\to hh)}{\mathrm{d}\hat{t}}\right|_{\mathrm{EFT}} = \frac{G_F^2\alpha_s^2}{256(2\pi)^3}\left\{\left|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)\ +2c_g C_\triangle \right.\right.$$

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





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

Implemented in MC generator Herwig++

See Plehn, Spira, Zerwas ph/9603205

Normalize to NNLO: de Florian, Mazzitelli, 1309.6594

Higgs Decays in D=6 EFT

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

Loop + $1/\Lambda^2$ suppressed wrt SM

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

Bold coefficients included in analysis

(via eHDECAY: Contino, Ghezzi, Grojean, Muhlleitner, Spira, 1403.3381)

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

Unique accessibility in hh production!

HH in D=6 EFT

Reminder:

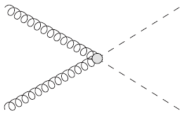
$$\mathcal{L} = \mathcal{L}_{\rm SM} \boxed{+ \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6}$$

Pure Higgs

Yukawa type

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

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



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Unique accessibility in hh production!

Analysis

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

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

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

Generated with aMC@NLO (+ HERWIG++)

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

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

- **Main backgrounds:**
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Generated with aMC@NLO (+ HERWIG++)

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

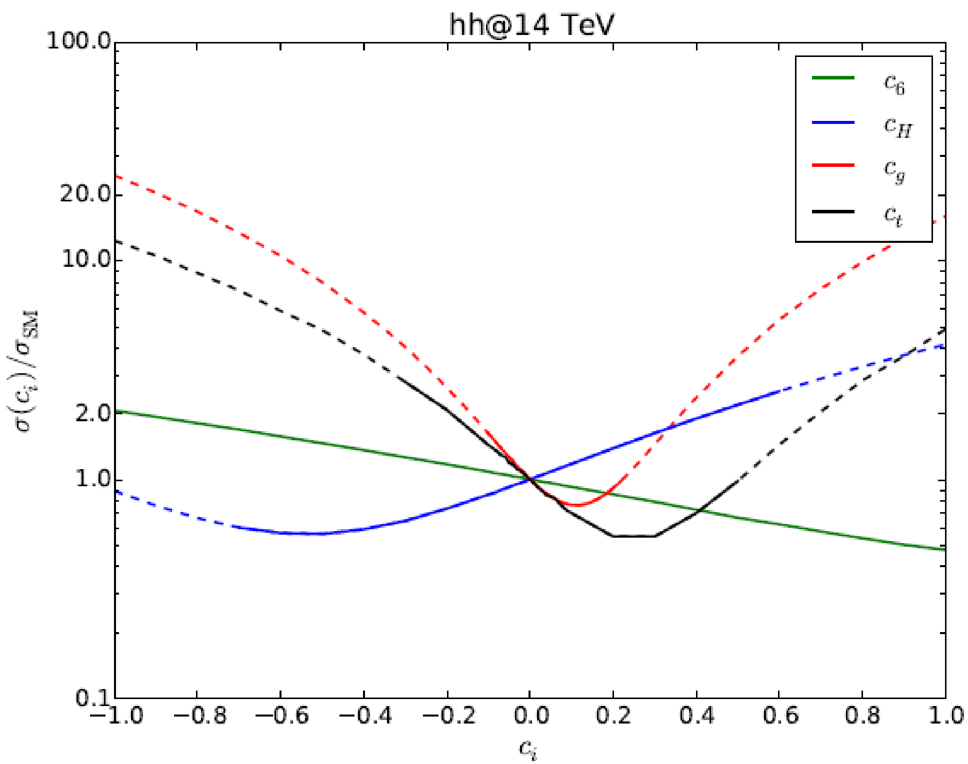
Cuts:

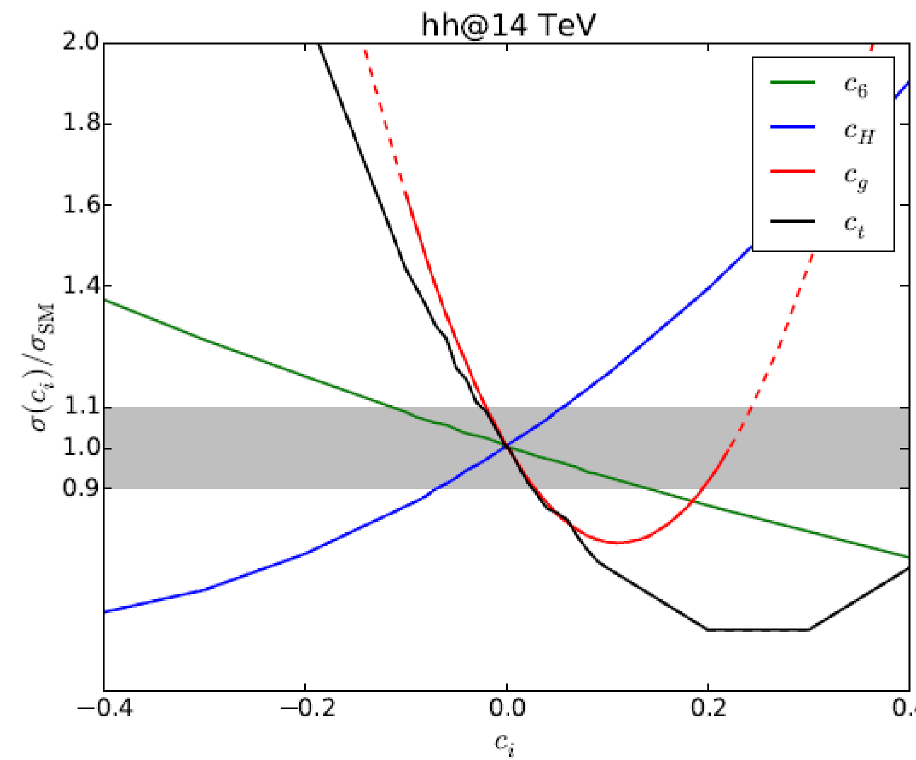
- Two τ-tagged jets with $p_\perp > 20\,\mathrm{GeV}$
- one fat jet with $R = 1.4$ (CA), two hardest sub-jets b-tagged ($|\eta| < 2.5$)
  Butterworth, Davison, Rubin, Salam, 0802.2470
- $m_{\tau^+\tau^-}, m_{\rm fat} \in [m_h - 25\,\mathrm{GeV}, m_h + 25\,\mathrm{GeV}]$
- $p_\perp^{\rm fat}, p_\perp^{\tau\tau}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

b,τ–tagging efficiencies: 70 %

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

$gg \rightarrow hh$ Cross Section in EFT





MSTW2008nlo_nf4 PDF

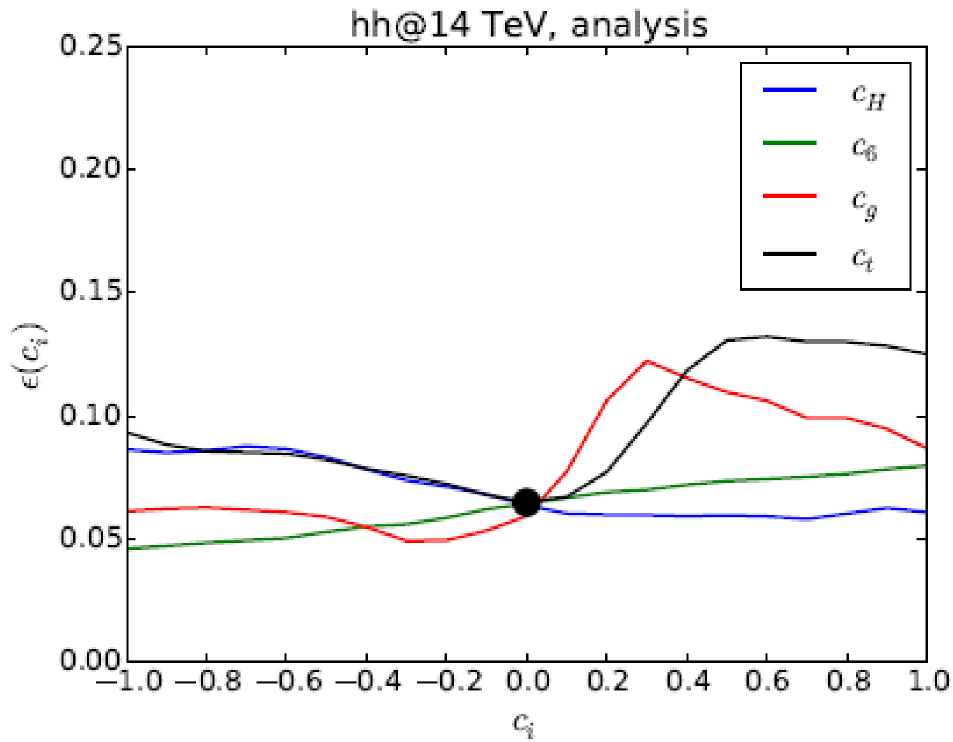
- Effect of varying individual Wilson coefficients
- Dashed: parameter-range excluded from current h data at the LHC

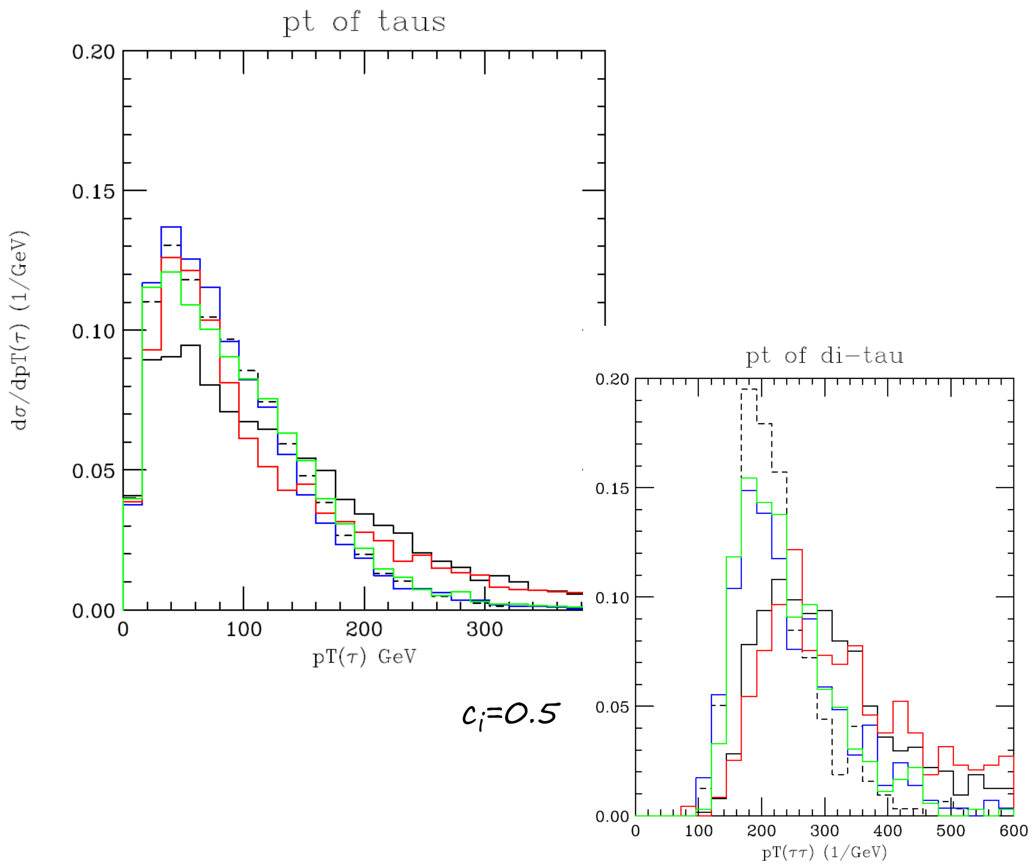
  → used HiggsBounds, HiggsSignals on cross sections calculated via eHDECAY

Bechtle et.al., 1311.0055, 1305.1933

$gg \to hh$ after cuts

Efficiency



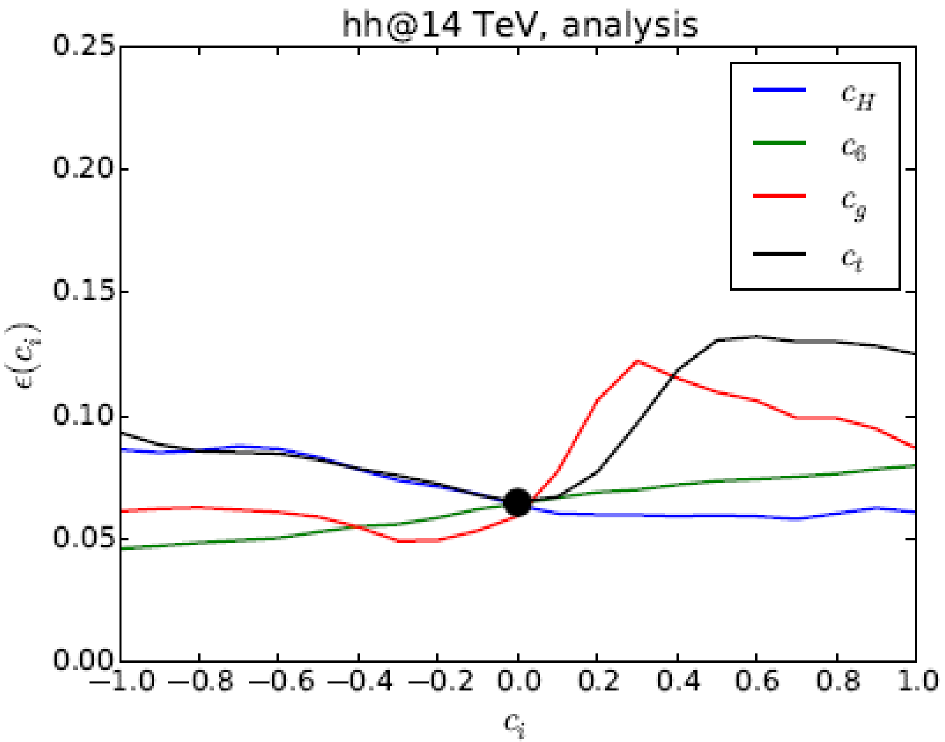


MC generator important for analysis

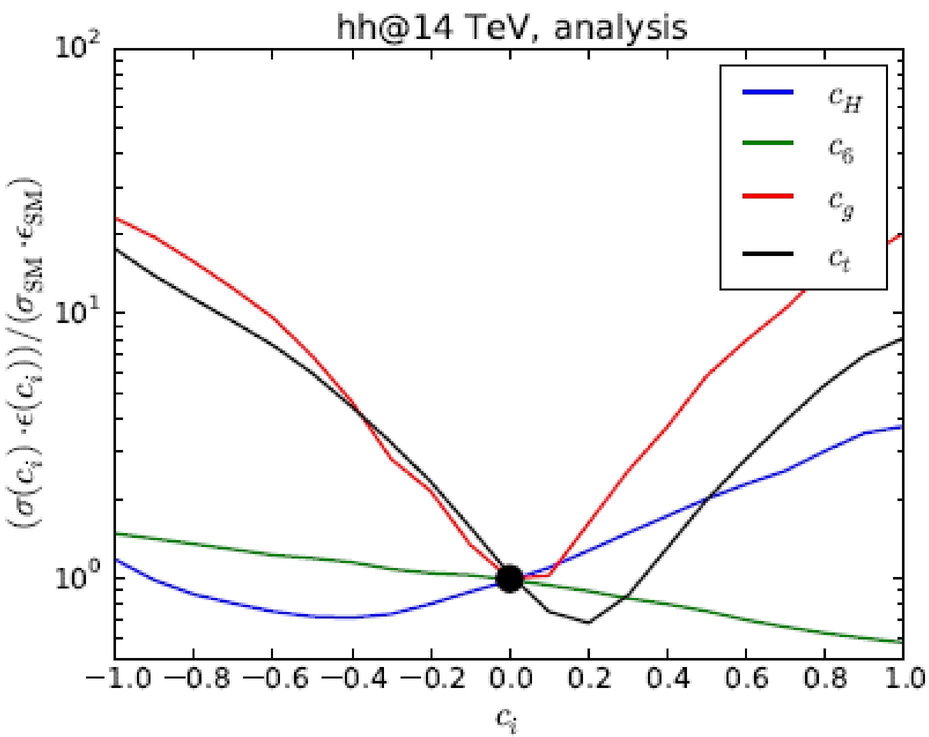
→ describe distributions, which determine efficiencies $\epsilon(c_i)$

$gg \to hh$ after cuts

Efficiency



Cross Section



MC generator important for analysis

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

Full Analysis

- Start with model where only $\boxed{c_6 \neq 0}$ (unconstrained from single h)
  - ↳ Vary only λ as done in previous studies (→ BRs unchanged)

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

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

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

Full Analysis

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

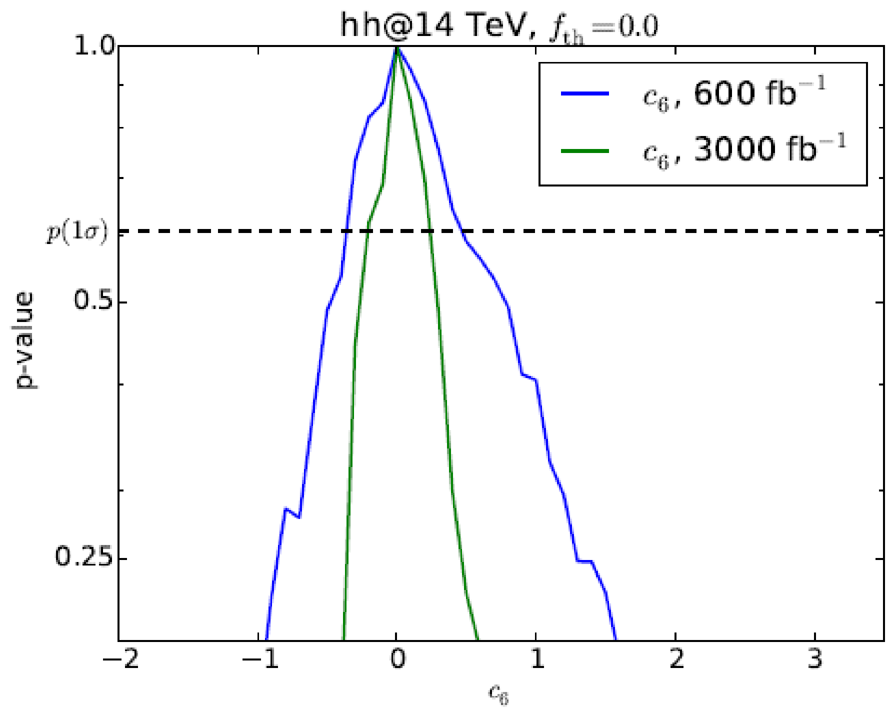
  ↳ Vary only λ as done in previous studies (→ BRs unchanged)

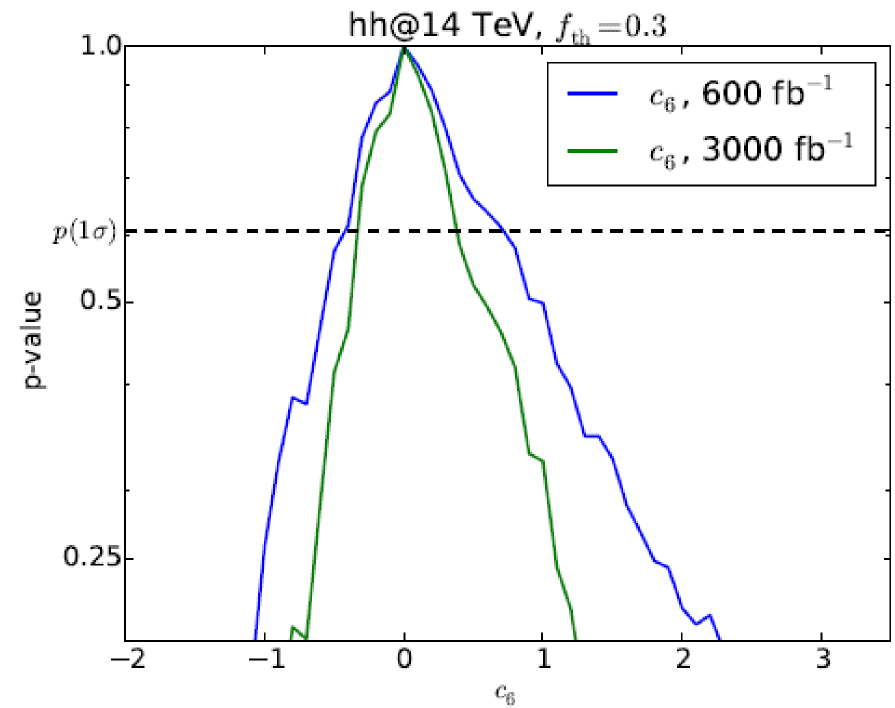
$$\delta N^2 = N + S^2 f_{\mathrm{th}}^2$$

- 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 $N(c_6 = 0)$.

Full Analysis





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

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

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

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 $\delta N(c_6,..,c_b)$

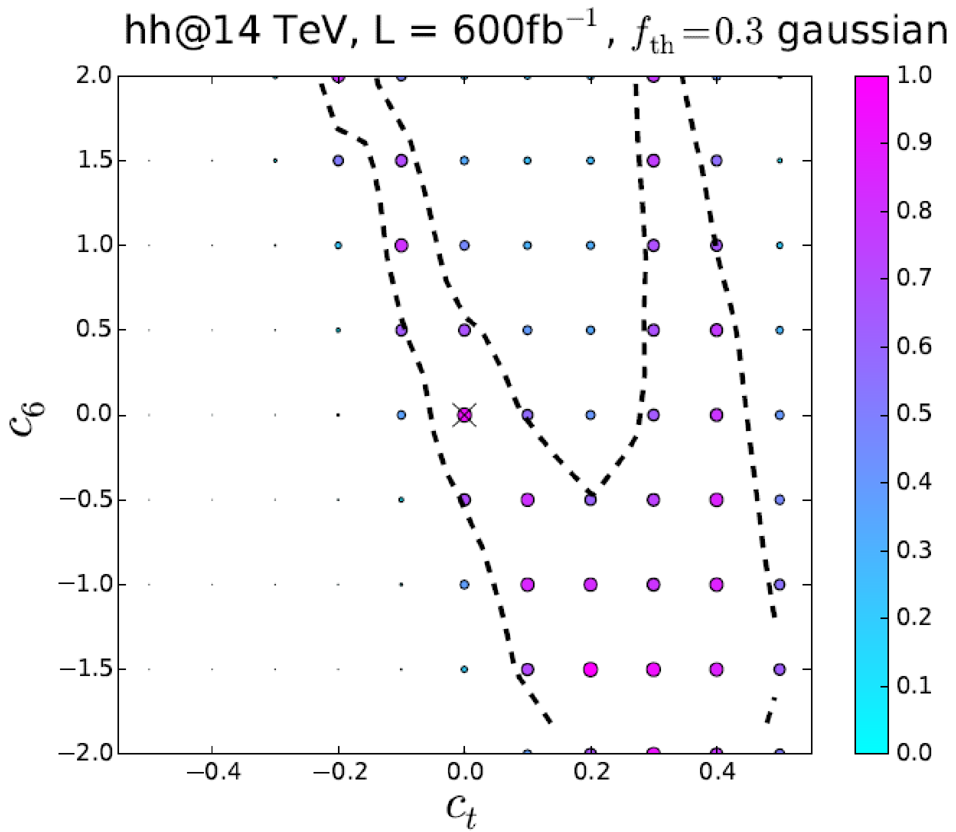
- Show results in 2D grids (c_6, c_i), i=H,g,γ,t,b

- Marginalize over other directions with a Gaussian weight, given by projected errors on the coefficients from single h measurements (~10% @ (600-3000) fb^{-1})

  ⇒ in the future use real constraints (like p-values from HiggsBounds/Signals)

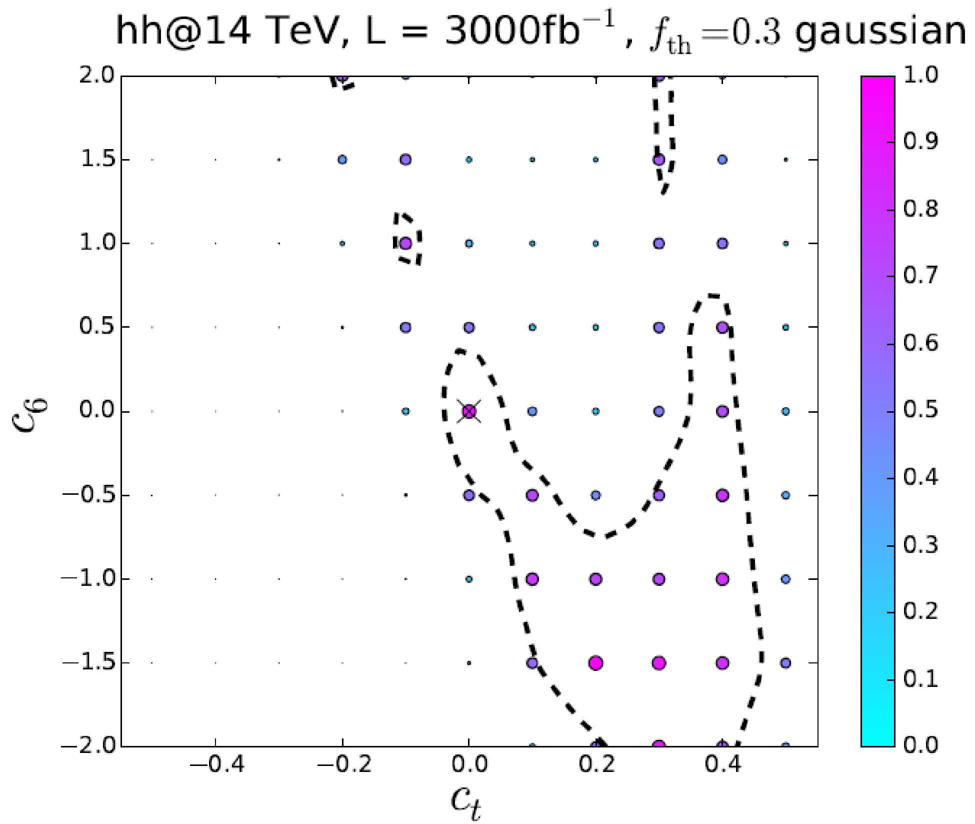
- Draw iso-contours corresponding to probability-drop of 1σ

Results: c_t-c_6

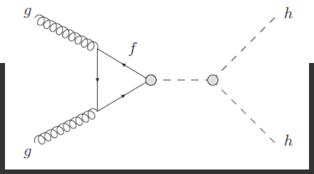


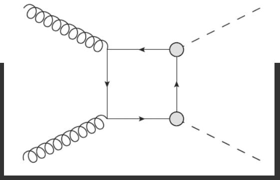
- Clear correlation visible: Enhanced hh cross section due to negative c_t can be compensated by reduction due to positive c_6

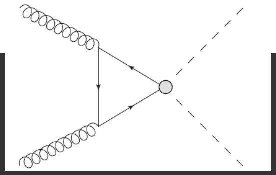
c_t–c_6



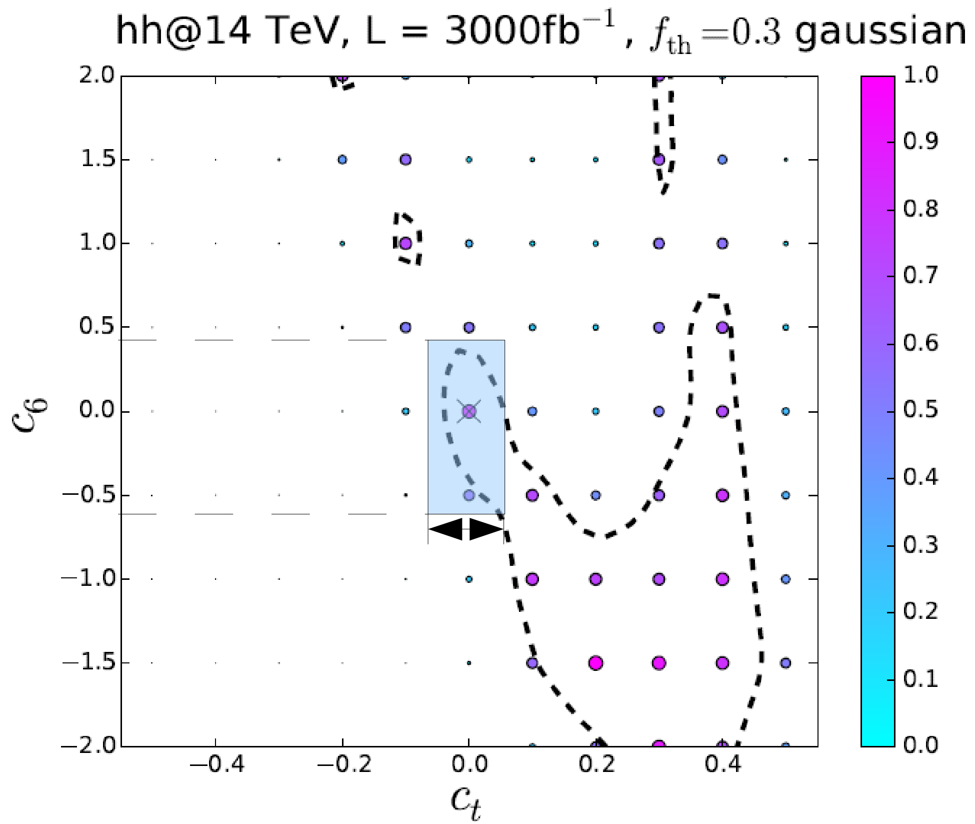
- Precise knowledge on 'top Yukawa' c_t helpful to improve the range for c_6
- On the other hand, could also obtain meaningful information on c_t in hh







c_t-c_6



- Precise knowledge on 'top Yukawa' c_t helpful to improve the range for c_6
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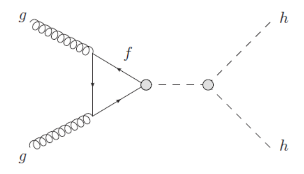
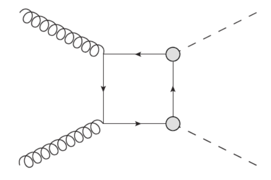
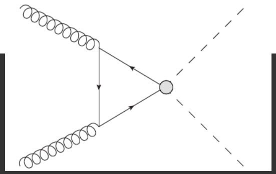
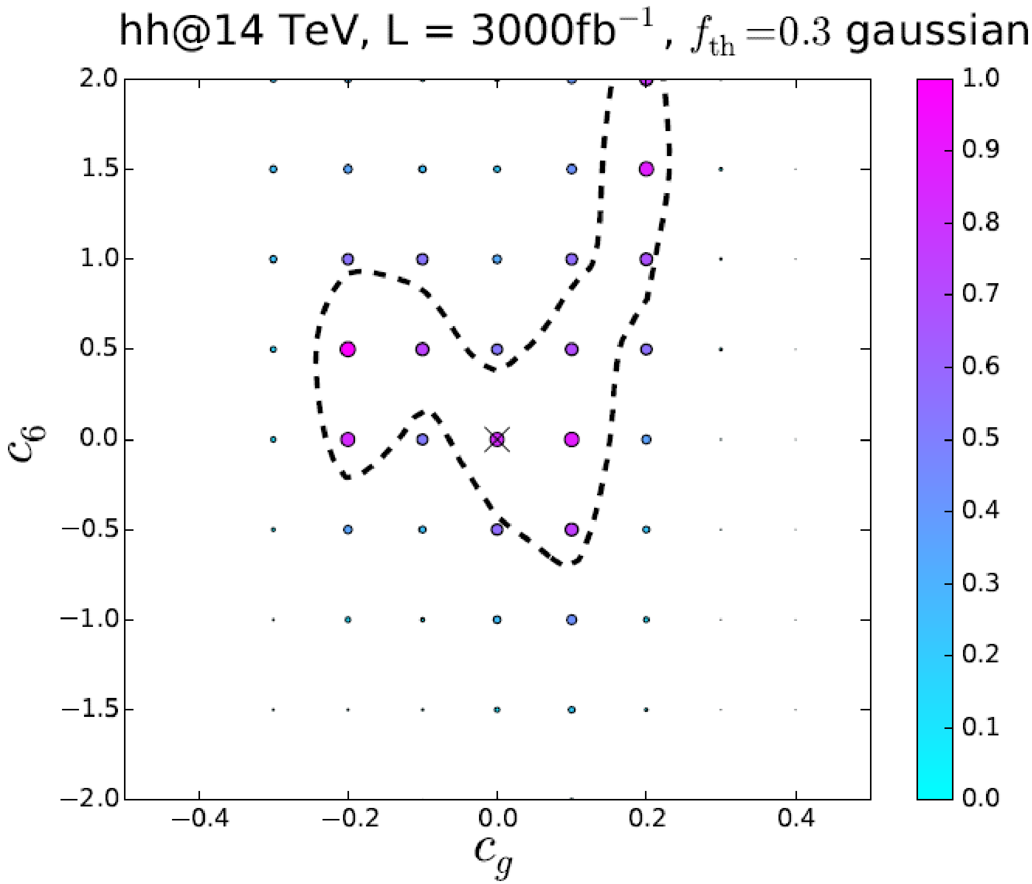




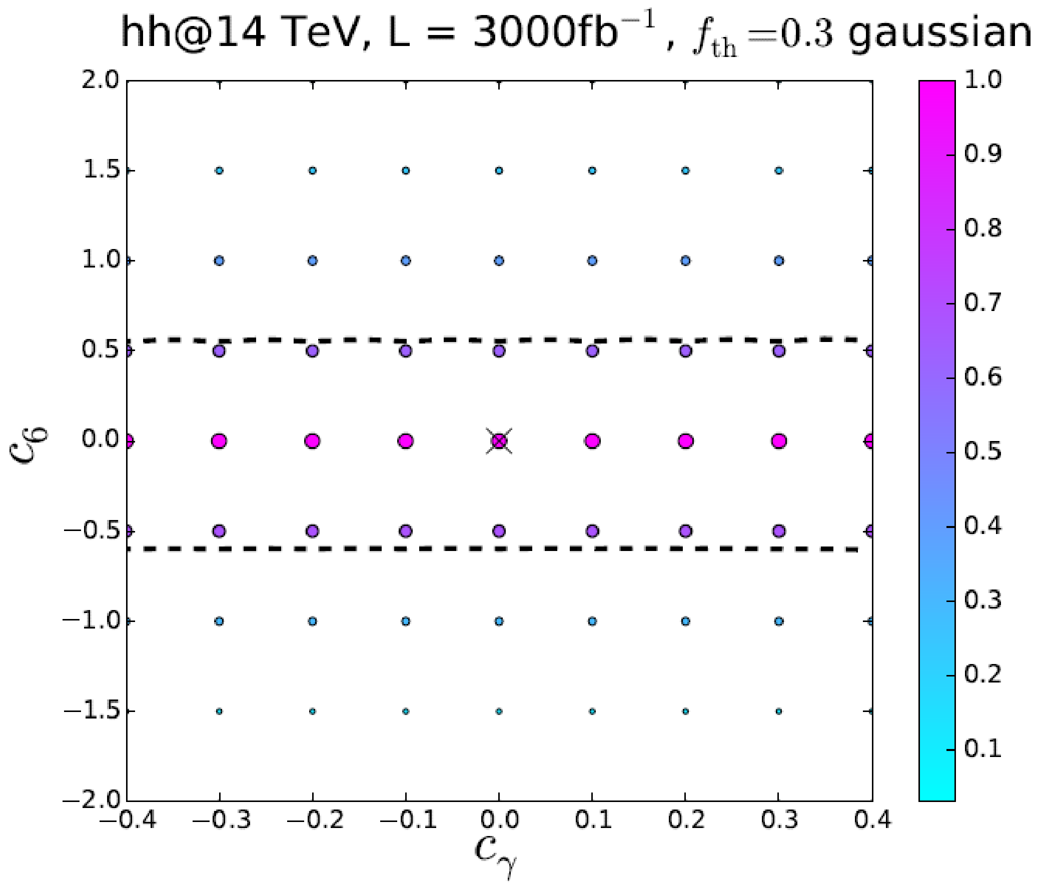


c_g-c_6



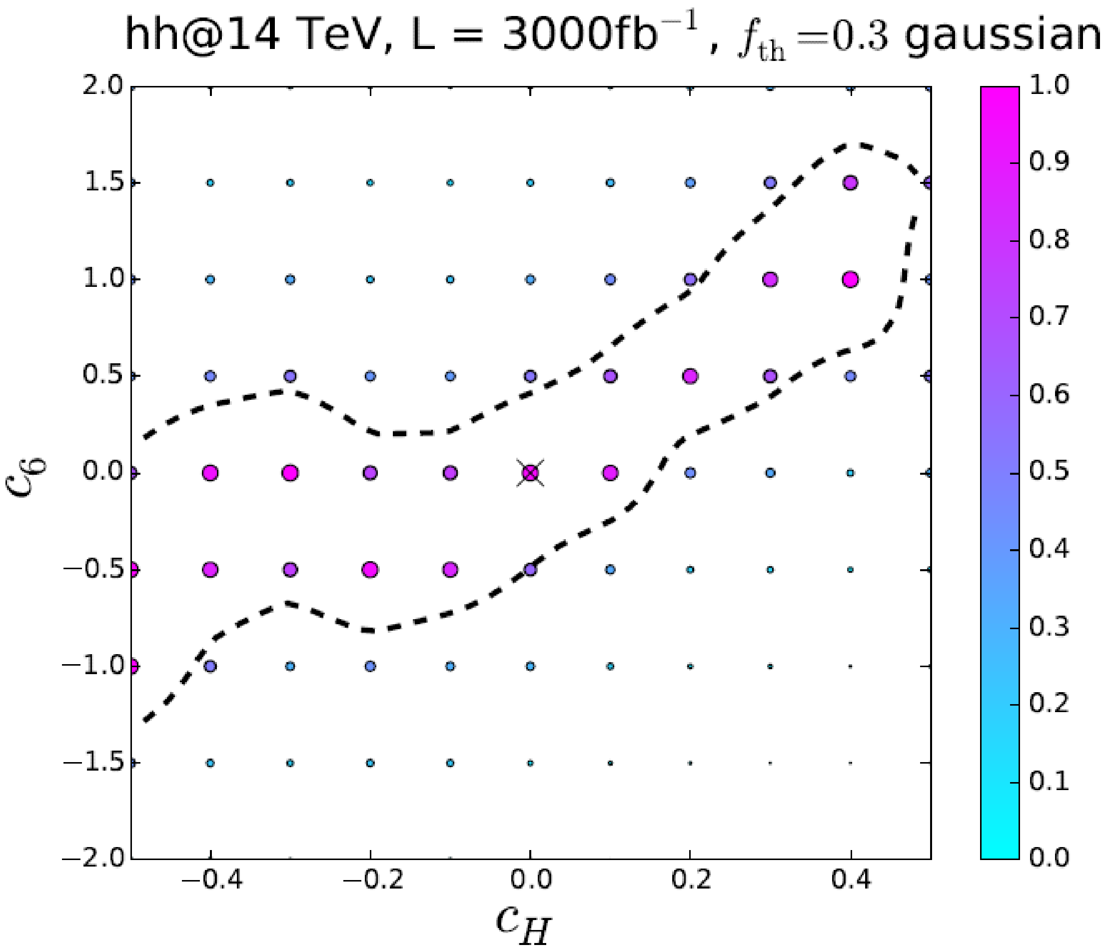
- Again compensation of effects from different operators possible
  → range for c_6 depends significantly on other coefficients

c_γ-c_6



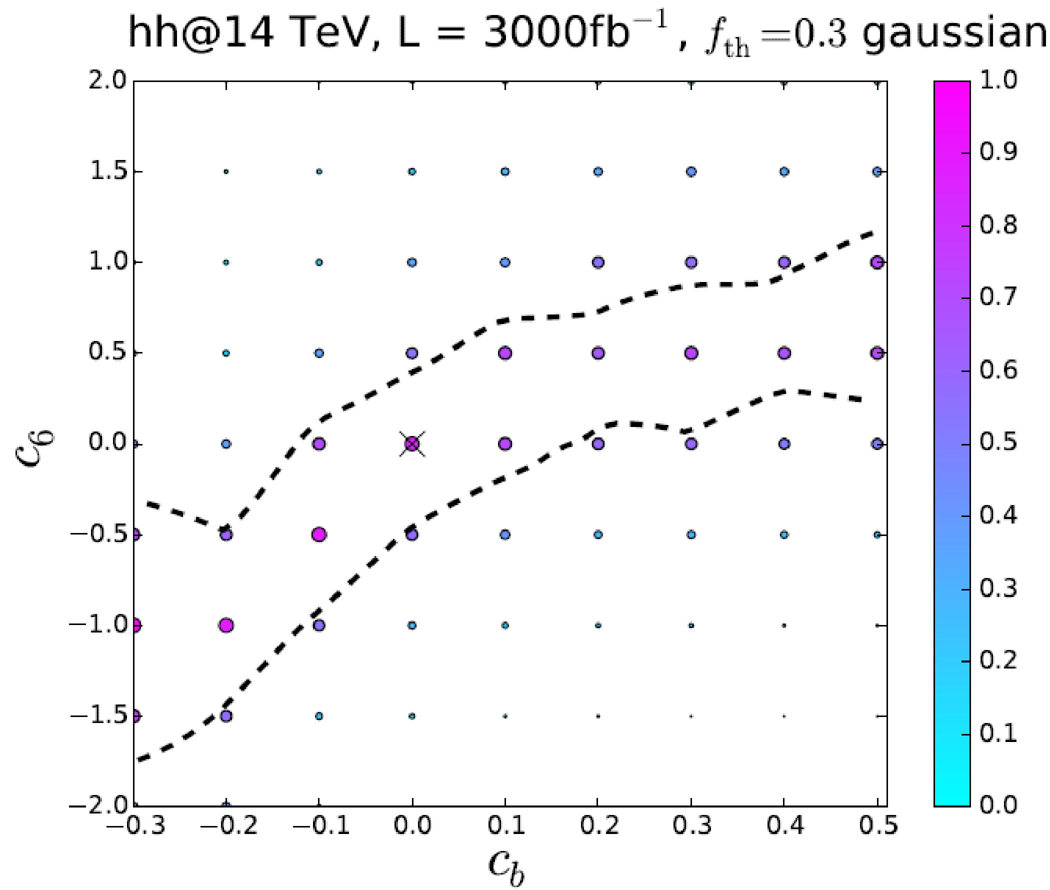
- As expected: negligible dependence on c_γ

c_H-c_6



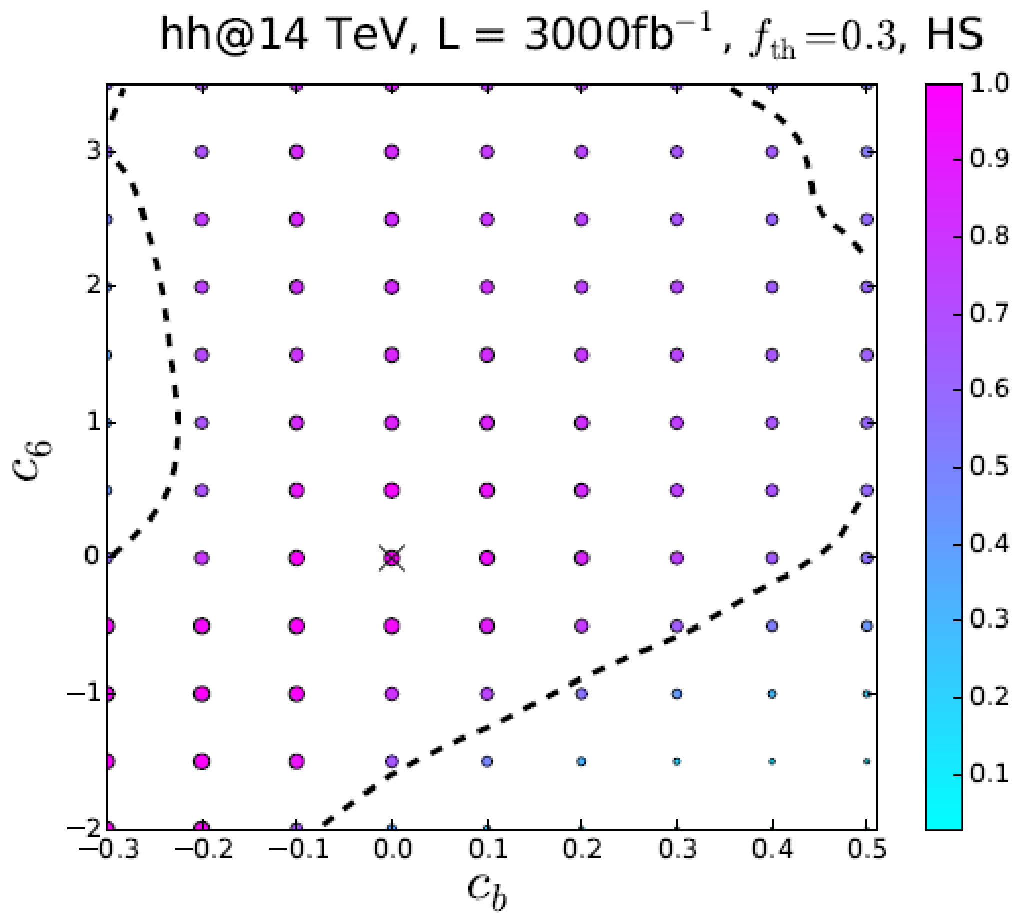
hh@14 TeV, L = 3000fb^{-1} , $f_{\rm th}$ =0.3 gaussian
c_6
c_H
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−0.4
−0.2
0.0
0.2
0.4
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

$(c_b = c_\tau) - c_6$



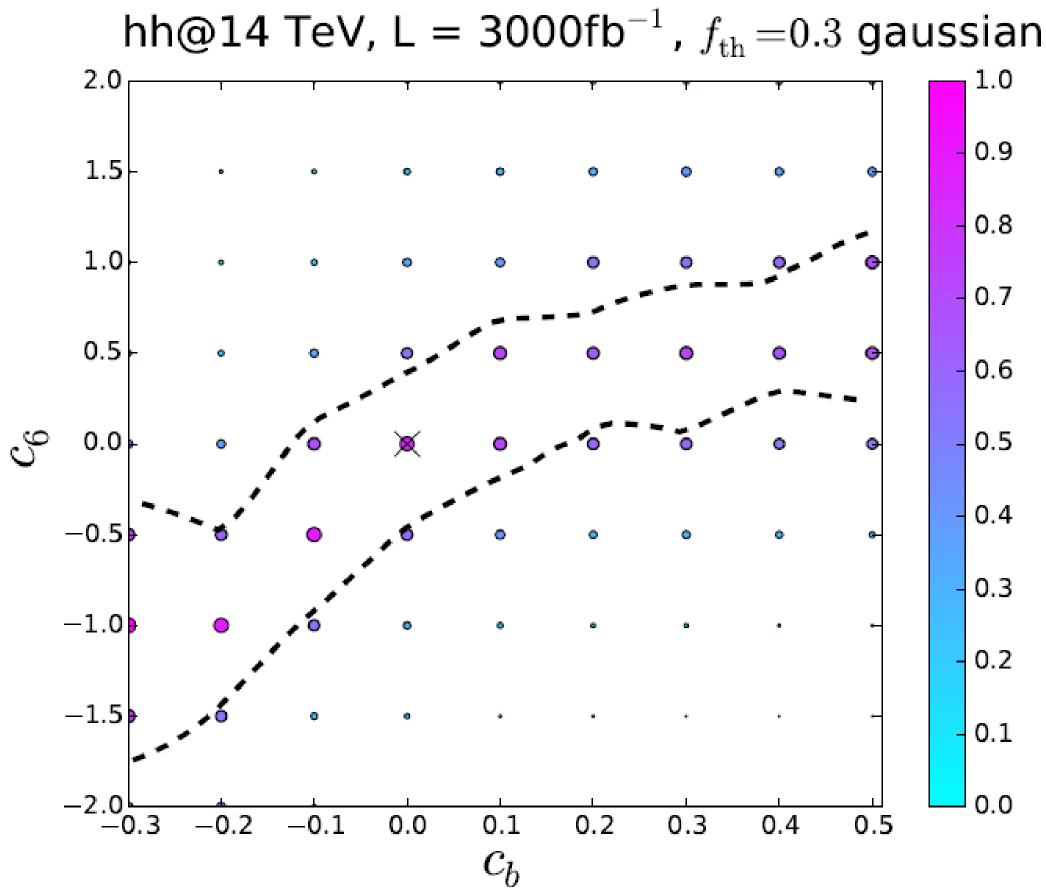
- Reduced BR due $(c_b = c_\tau) < 0$ to can be compensated by enhanced production cross section due to negative c_6 and vice versa

$(c_b = c_\tau) - c_6$



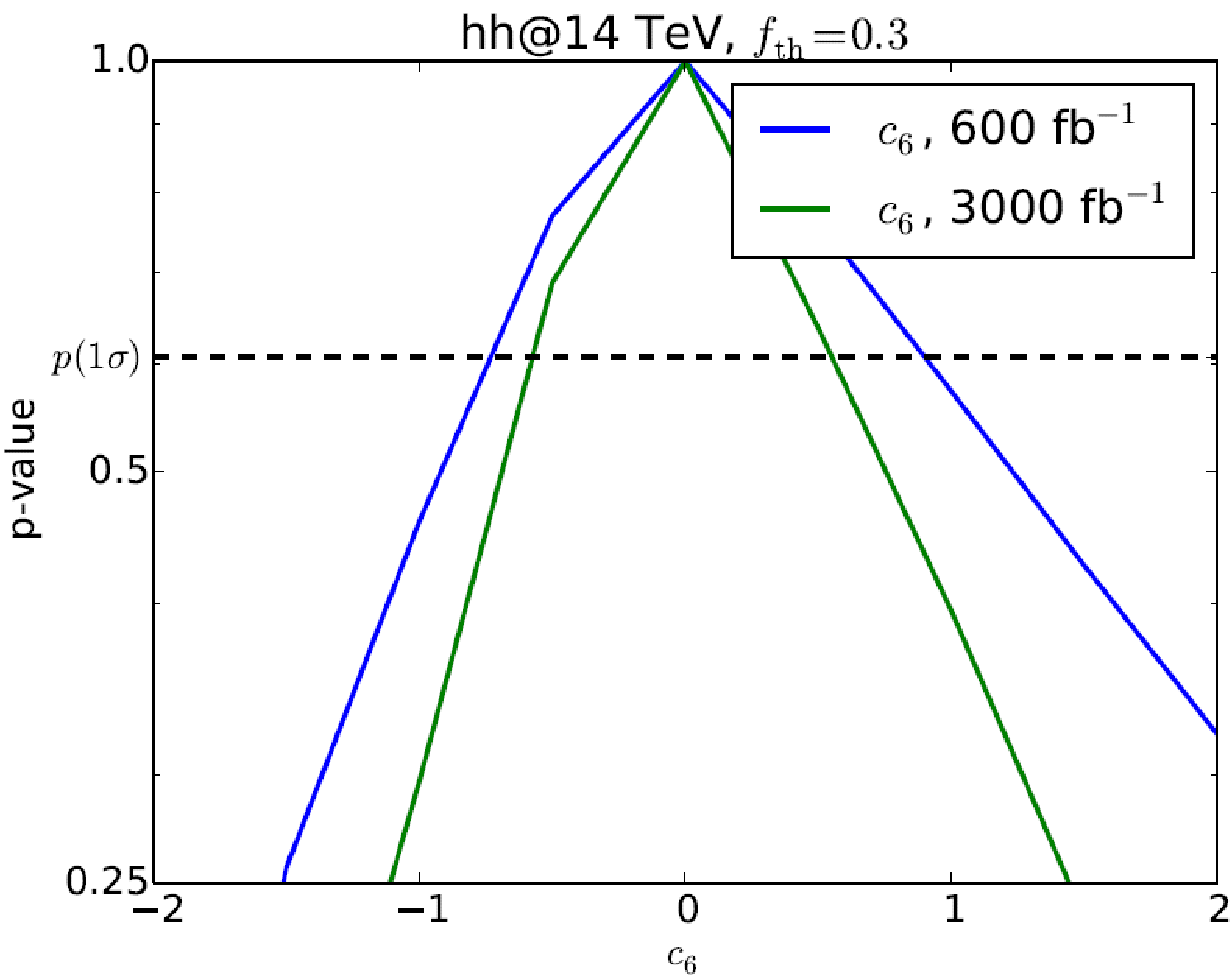
- *Marginalize over other directions with* ***current*** *p-values for coefficients from single-h measurements (using* HiggsBounds/Signals)

$(c_b = c_\tau) - c_6$



- 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	$c_6 \in (-0.5, 0.8)$	$\boxed{c_6 \in (-0.4, 0.4)}$
full (**future**)	$c_6 \in (-0.8, 0.9)$	$\boxed{c_6 \in (-0.6, 0.6)}$
$c_6 - c_t - c_\tau - c_b$ (**future**)	$c_6 \in (-0.8, 0.8)$	$c_6 \in (-0.6, 0.5)$

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$c_6 - c_t - c_\tau - c_b$ (**future**)	$c_6 \in (-0.8, 0.8)$	$c_6 \in (-0.6, 0.5)$

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

full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$
$c_6 - c_t - c_\tau - c_b$	$c_6 \gtrsim -2.0$	$c_6 \in (-1.8, 2.3)$

Conclusions and Outlook

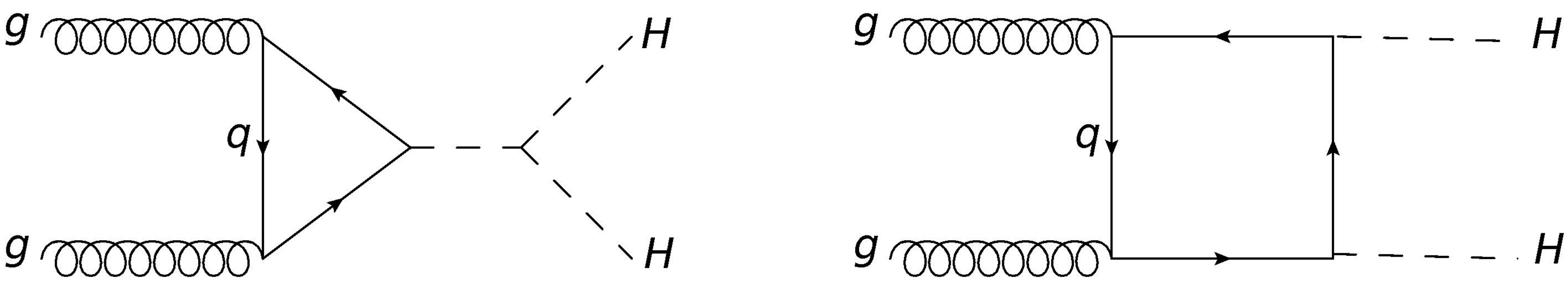
Analysis of hh productions can offer viable additional information on the D=6 extension of the SM

Some Current/Future Directions:

- Break degeneracy $c_b = c_\tau$ + consider different projections
- Optimize analysis for different regions of parameter space
- Include other decay channels
- Consider distributions to improve bounds

Backup: HH @ LHC

- Most important mechanism: $\boxed{gg \to hh}$



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

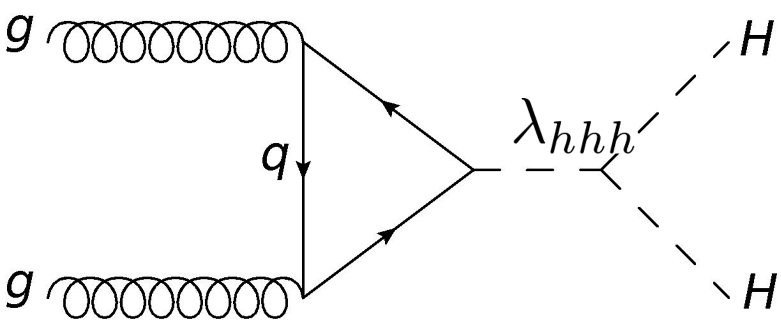
$$\sigma(gg \to hh)_{\mathrm{LO}} \sim 17\,\mathrm{fb}$$
$$\sigma(gg \to hh)_{\mathrm{NLO}} \sim 33\,\mathrm{fb}$$
$$\sigma(gg \to hh)_{\mathrm{NNLO}} \sim 40\,\mathrm{fb}$$

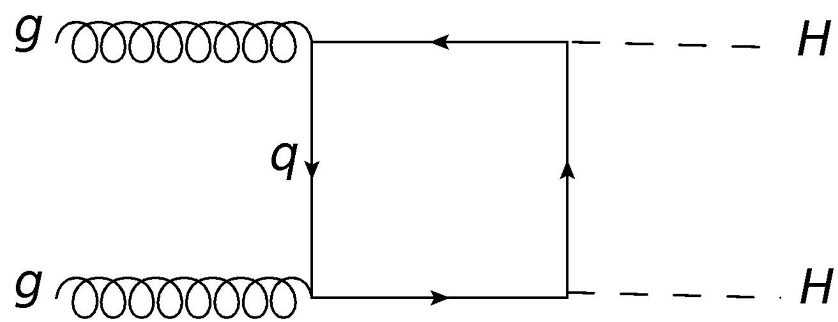
Theoretical error (NNLO): $f_{th} \sim 10\%$ (scale) + 10% (pdf+α_s) + 10% (m_t^{-1})

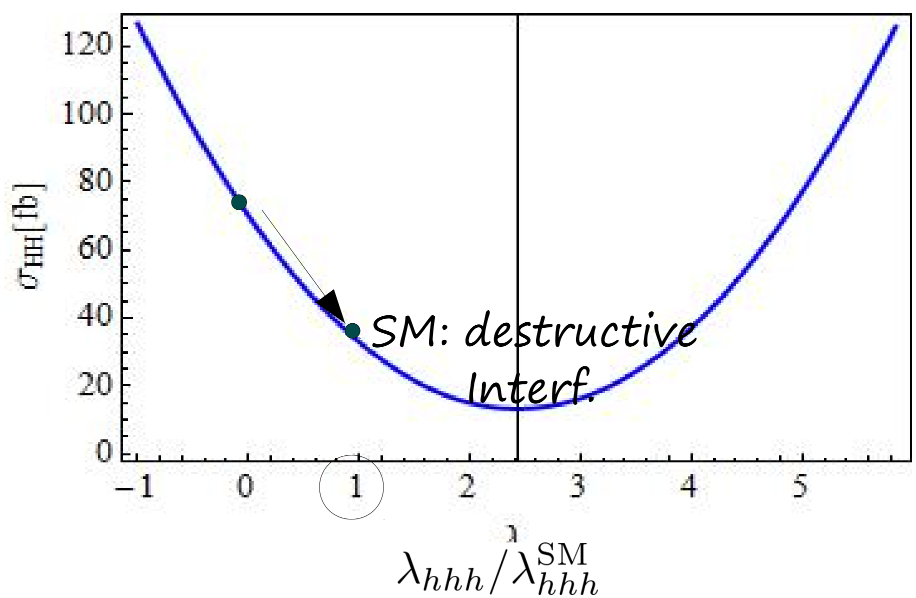
LHC@14TeV
$m_h \sim 125$ GeV

Backup: HH @ LHC

- Most important mechanism: $gg \to hh$







Backup: Decay Channels

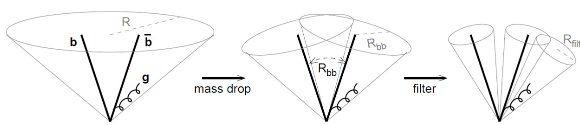
Significance @ 600 fb^{-1}

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

Baur, Plehn, Rainwater, hep-ph/0310056

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

Dolan, Englert, Spannowsky, 1206.5001



Butterworth, Davison, Rubin, Salam, 0802.2470

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

Papaefstathiou, Yang, Zurita, 1209.1489

Theorists' analyses!

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)

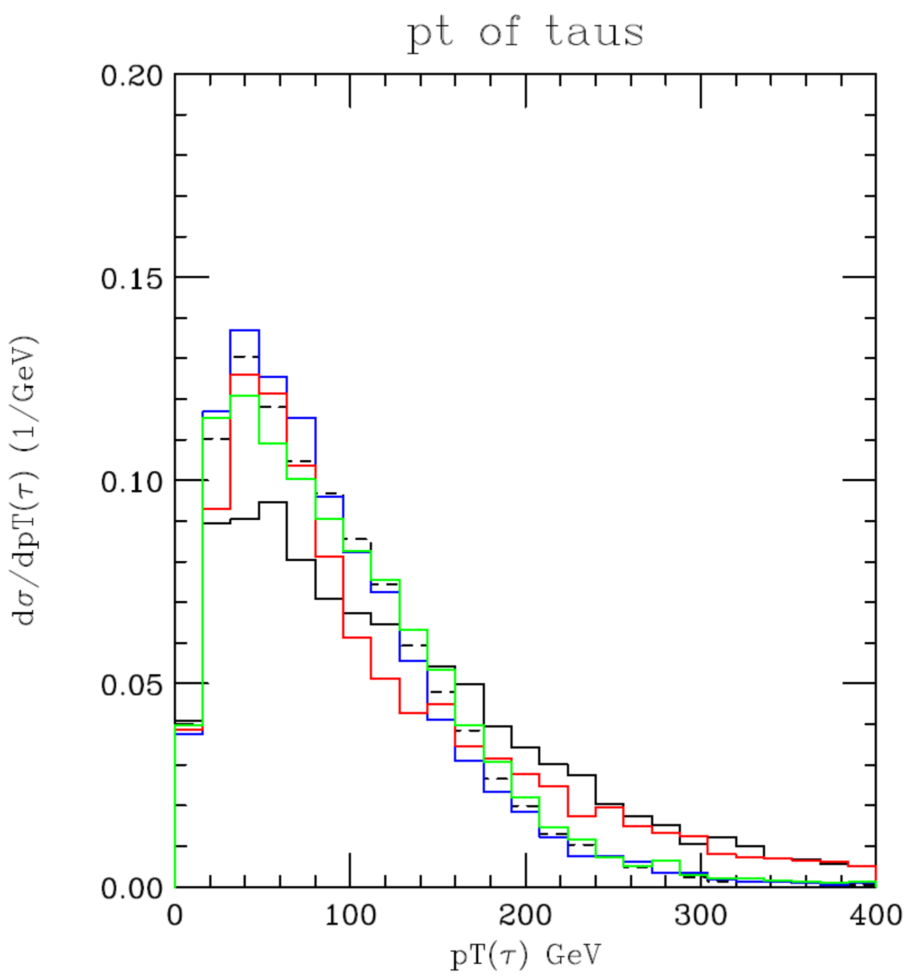
$$p(c_i, c_6) = \frac{\bar{p}(c_i, c_6)}{\max(\bar{p}(c_i, c_6))}, \ \bar{p}(c_i, c_6) = \frac{\sum_{\{c_f\}} p(c_6, c_i, \{c_f\}) \times p_{\text{Gauss.}}(\{c_f\})}{\sum_{\{c_f\}} p_{\text{Gauss.}}(\{c_f\})}$$

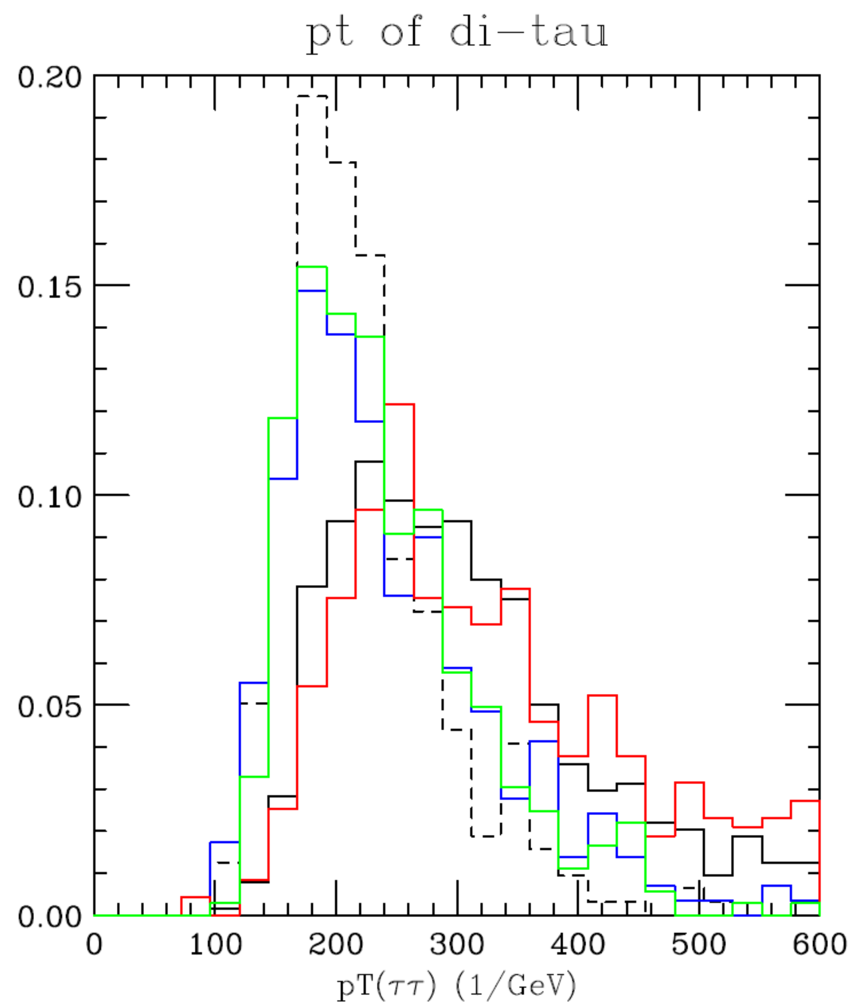
$$p_{\text{Gauss.}}(\{c_f\}) = \prod_f \frac{1}{\sigma_f \sqrt{2\pi}} \exp\left\{-\frac{(c_f - \mu_f)^2}{2\sigma_f^2}\right\}$$

Projections: $\mu_f = 0, \ \sigma_H = 0.1 \, , \sigma_{b,\tau,t} = 0.05 \, , \sigma_g = 0.017 \, , \sigma_\gamma = 0.13$ (~10% effects)

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

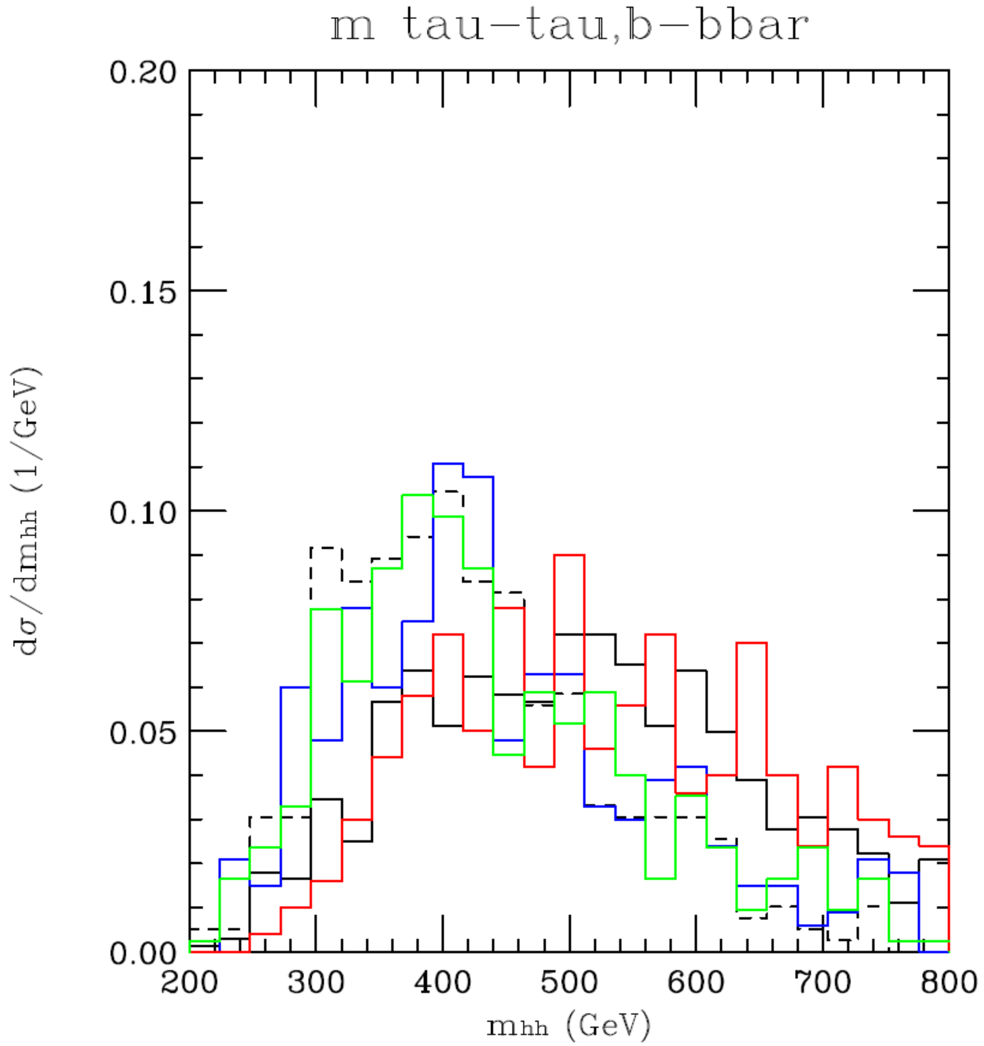
Backup: Distributions





c_i=0.5

Backup: Distributions



c_i=0.5