Triple Higgs boson production at a 100 TeV proton-proton collider

$(bb)(bb)(\gamma\gamma)$ channel

Kazuki Sakurai

UNIVERSITY OF WARSAW

In collaboration with: Andreas Papaefstathiou

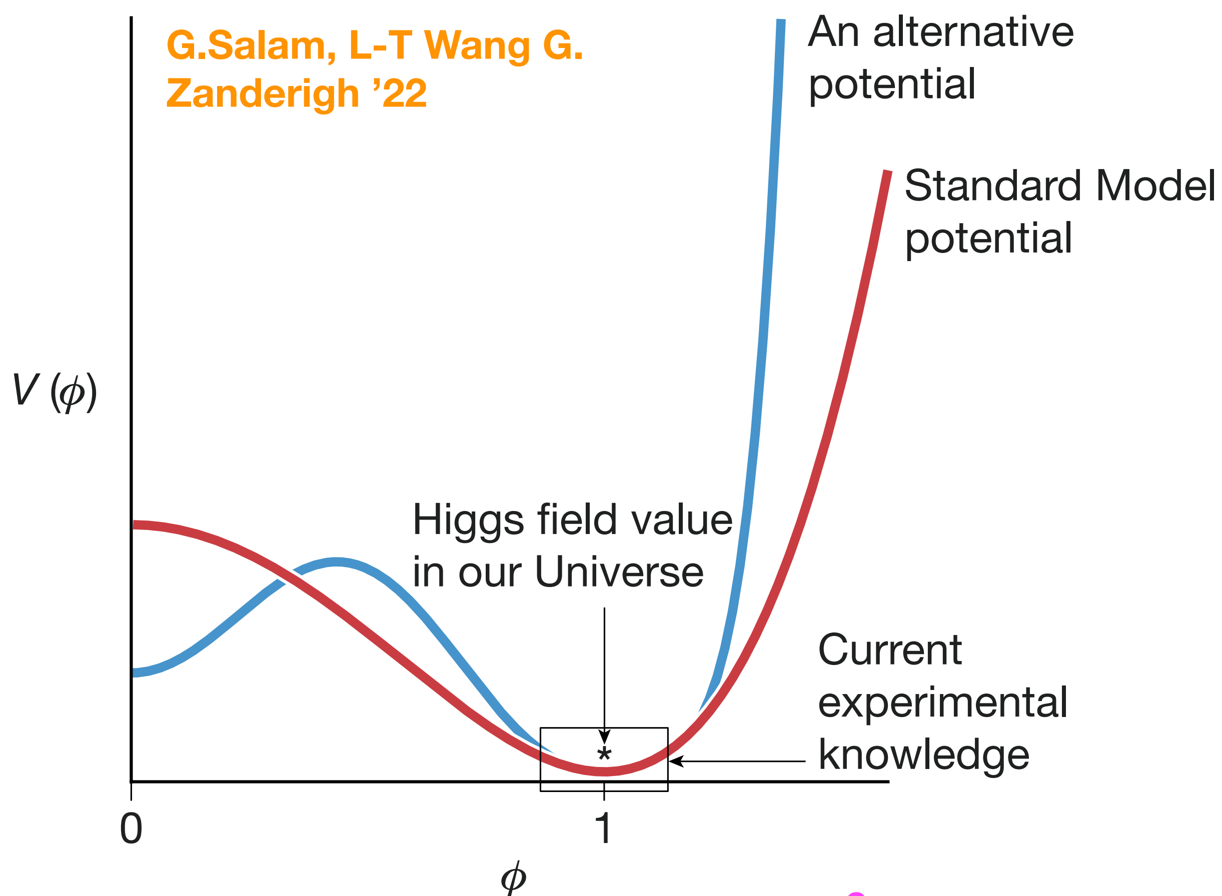
Based on: JHEP 02 (2016) 006 [1508.06524]

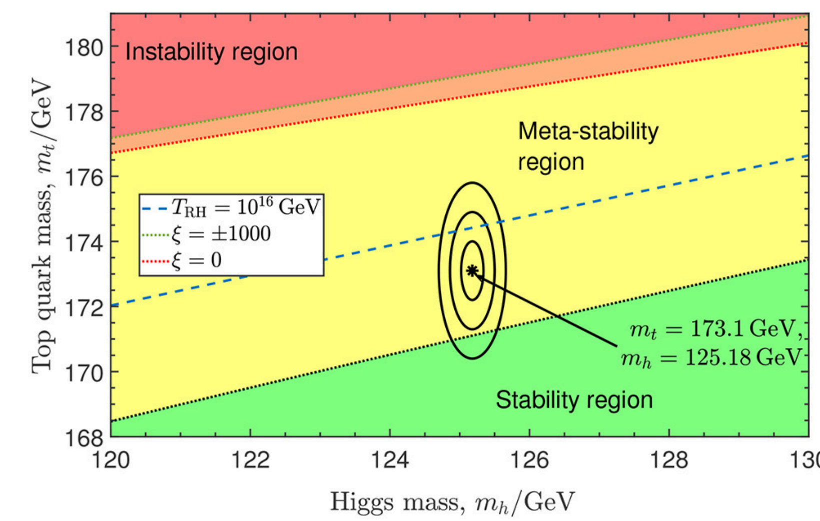
16/7/2023, HHH workshop @ Dubrovnik

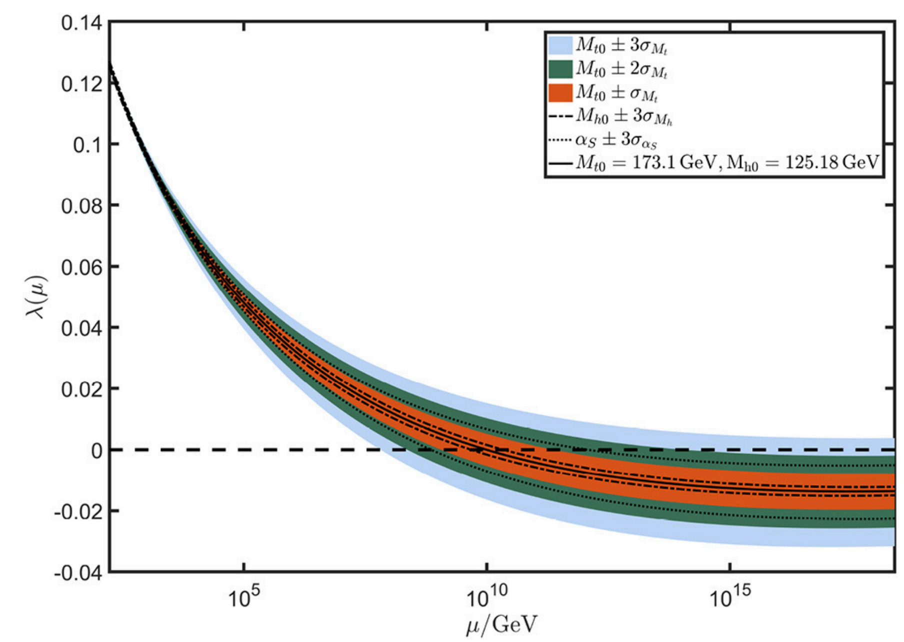
Why HHH?

- Some properties of the Higgs boson is well measured, e.g. mass, couplings to heavy fermions and gauge-bosons
- However, we do not know much about the shape of the Higgs potential.
- To constrain the potential, we must measure the higher order terms in the expansion, such as triple and quartic self-couplings.

T.Markkanen, A.Rajantie, S.Stopyra '18







$$V(h)\big|_{V'=0} = \frac{m_h^2}{2!}h^2 + \frac{a_3}{3!}h^3 + \frac{a_4}{4!}h^4 + \cdots$$

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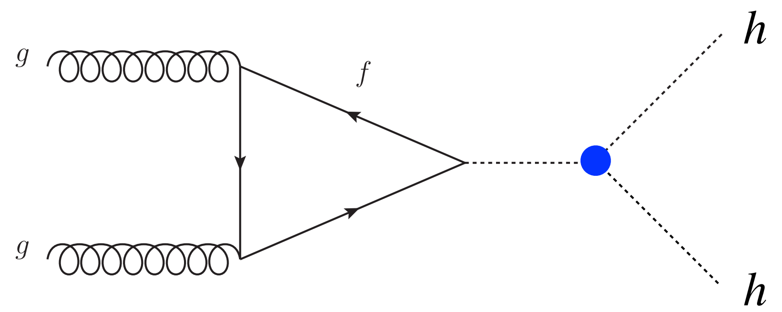
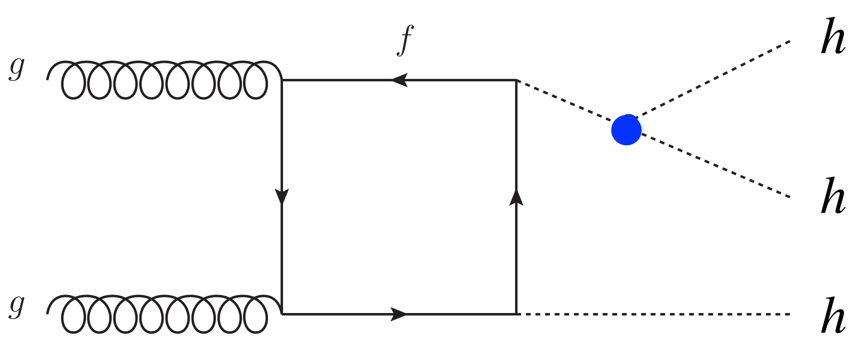
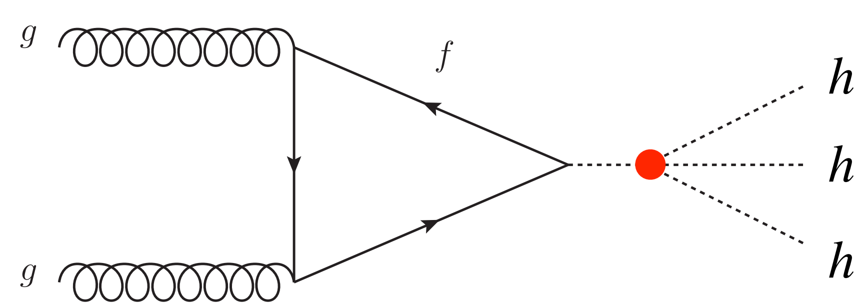
- HH production is the lowest multiplicity process to probe a_3



- HHH production is the lowest multiplicity process to probe a_4





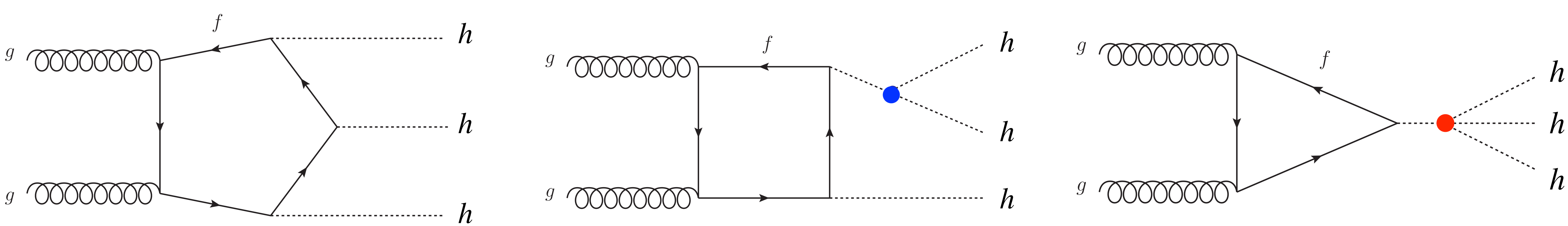
- $H^{(n-1)}$ production is the lowest multiplicity process to probe a_n

HHH cross section

- HHH cross section in the SM is generally very small due to the large total mass ($> 3m_h$) and loop suppression.

$$\sigma(pp \to hhh)^{14\mathrm{TeV}}_{\mathrm{NLO}} \sim 0.1\ \mathrm{fb} \quad \Longrightarrow \quad N^{\mathrm{HLLHC}}_{hhh}|_{3\mathrm{ab}^{-1}} \sim 300$$

$$\boxed{\sigma(pp \to hhh)^{100\mathrm{TeV}}_{\mathrm{NLO}} \sim 5\ \mathrm{fb} \quad \Longrightarrow \quad N^{\mathrm{HLLHC}}_{hhh}|_{30\mathrm{ab}^{-1}} \sim 1.5 \cdot 10^5}$$



“promising” channels A.Papaefstathiou, KS ‘16

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\mathrm{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125

$$m_h = 125.5\,\mathrm{GeV}$$

A.Papaefstathiou, G.Tetlalmatzi-Xolocotzi, M.Zaro ‘19

W.Kilian, S.Sun, Q-S.Yan, X.Zhao, Z.Zhao ‘16

B.Fuks, J.H.Kim, Seung.Lee ‘16

A.Papaefstathiou, KS ‘16

C-Y.Chen, Q-S.Yan, X.Zhao, Z.Zhao, Y-M.Zhong ‘16 “promising” channels **A.Papaefstathiou, KS ‘16**

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$m_h = 125.0\,\text{GeV}$

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\text{ab}^{-1}}$
$(bb)(bb)(bb)$	19.754	1141.805	34254
$(bb)(bb)(W_jW_j)$	9.937	574.367	17231
$(bb)(bb)(gg)$	8.331	481.523	14445
$(bb)(bb)(\tau\tau)$	6.382	368.891	11066
$(bb)(bb)(W_jW_\ell)$	6.174	356.855	10705
$(bb)(bb)(W_jW_\tau)$	3.293	190.323	5709
$(bb)(bb)(cc)$	2.942	170.036	5101
$(bb)(gg)(W_jW_j)$	2.794	161.482	4844
$(bb)(bb)(Z_jZ_j)$	2.611	150.919	4527
$(bb)(\tau\tau)(W_jW_j)$	2.14	123.71	3711
$(bb)(W_jW_j)(W_jW_\ell)$	2.07	119.674	3590
$(bb)(\tau\tau)(gg)$	1.794	103.713	3111
$(bb)(gg)(W_jW_\ell)$	1.736	100.329	3009
$(bb)(W_jW_j)(W_jW_j)$	1.666	96.309	2889
$(bb)(\tau\tau)(W_jW_\ell)$	1.33	76.861	2305
$(bb)(gg)(gg)$	1.171	67.689	2030
$(bb)(W_jW_\tau)(W_jW_j)$	1.104	63.826	1914
$(bb)(cc)(W_jW_j)$	0.987	57.023	1710
$(bb)(bb)(W_\ell W_\ell)$	0.959	55.429	1662
$(bb)(gg)(W_jW_\tau)$	0.926	53.509	1605
$(bb)(W_jW_j)(Z_jZ_j)$	0.876	50.612	1518
$(bb)(cc)(gg)$	0.827	47.805	1434
$(bb)(bb)(Z_jZ_\nu)$	0.746	43.125	1293
$(bb)(gg)(Z_jZ_j)$	0.734	42.43	1272
$(bb)(\tau\tau)(W_jW_\tau)$	0.709	40.993	1229
$(bb)(\tau\tau)(\tau\tau)$	0.687	39.727	1191
$(bb)(W_jW_\tau)(W_jW_\ell)$	0.686	39.655	1189
$(bb)(W_jW_\ell)(W_jW_\ell)$	0.643	37.177	1115
$(bb)(cc)(\tau\tau)$	0.634	36.623	1098
$(bb)(cc)(W_jW_\ell)$	0.613	35.428	1062
$(bb)(\tau\tau)(Z_jZ_j)$	0.562	32.506	975
$(bb)(W_jW_\ell)(Z_jZ_j)$	0.544	31.445	943
$(bb)(cc)(W_jW_\tau)$	0.327	18.895	566
$(bb)(W_jW_j)(W_\ell W_\ell)$	0.322	18.588	557
$(gg)(\tau\tau)(W_jW_j)$	0.301	17.39	521
$(gg)(W_jW_j)(W_jW_\ell)$	0.291	16.823	504
$(bb)(Z_jZ_j)(W_jW_\tau)$	0.29	16.771	503
$(bb)(gg)(W_\ell W_\ell)$	0.27	15.584	467
$(bb)(cc)(Z_jZ_j)$	0.259	14.983	449
$(bb)(W_jW_j)(Z_jZ_\nu)$	0.25	14.462	433
$(bb)(bb)(Z_jZ_\ell)$	0.249	14.388	431
$(gg)(W_jW_j)(W_jW_j)$	0.234	13.538	406
$(bb)(bb)(\gamma\gamma)$	0.231	13.351	400

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BR(4b+jets) = 49.8%

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- The minimal and general modification of the Higgs potential is:

$$V_{\text{self}}(h) = \frac{m_h^2}{2v}\left(1 + c_3\right) h^3 + \frac{m_h^2}{8v^2}\left(1 + d_4\right) h^4$$

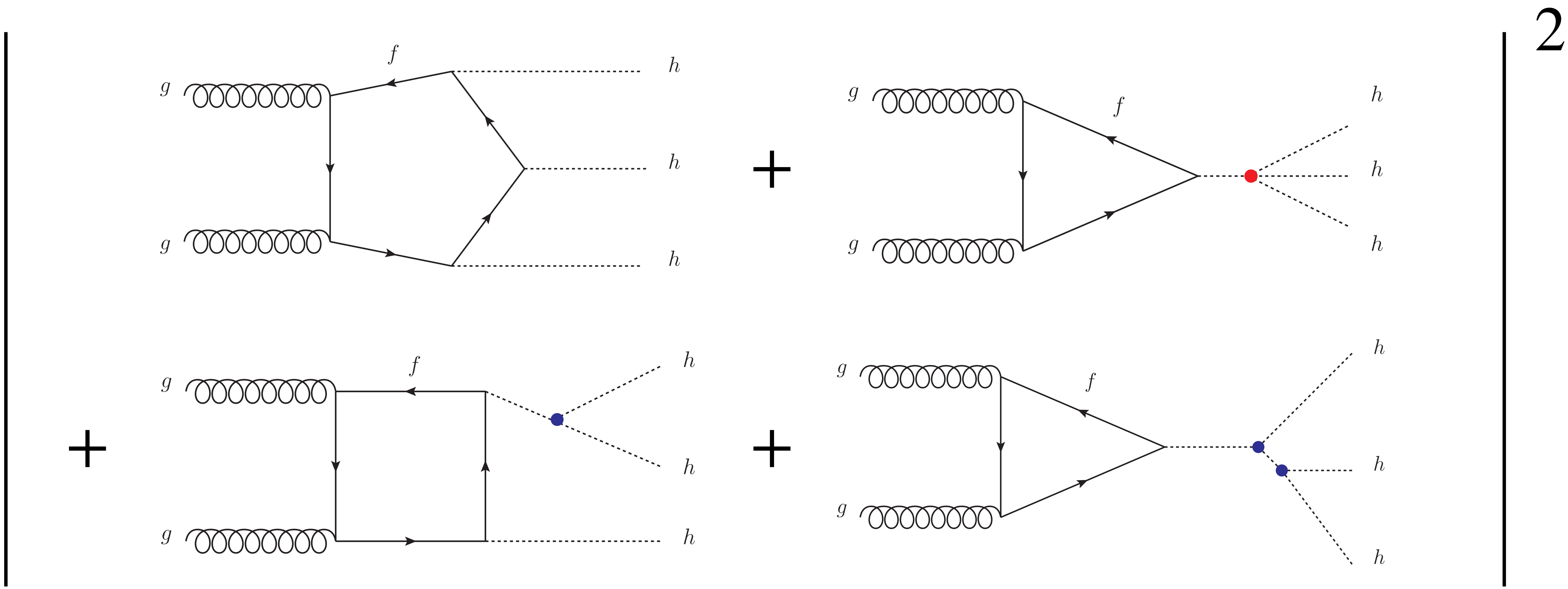
$$\text{SM} \implies (c_3, d_4) = (0,0)$$

- In terms of $\mathcal{O}_6$ coefficient:

$$\mathcal{O}_6 \equiv \frac{c_6}{v^2}\lambda |H|^6 \implies \frac{d_4}{c_3} = 6, \quad (c_3, d_4) = (1, 6) \cdot c_6$$

- In terms of $\mathcal{O}_8$ coefficient:

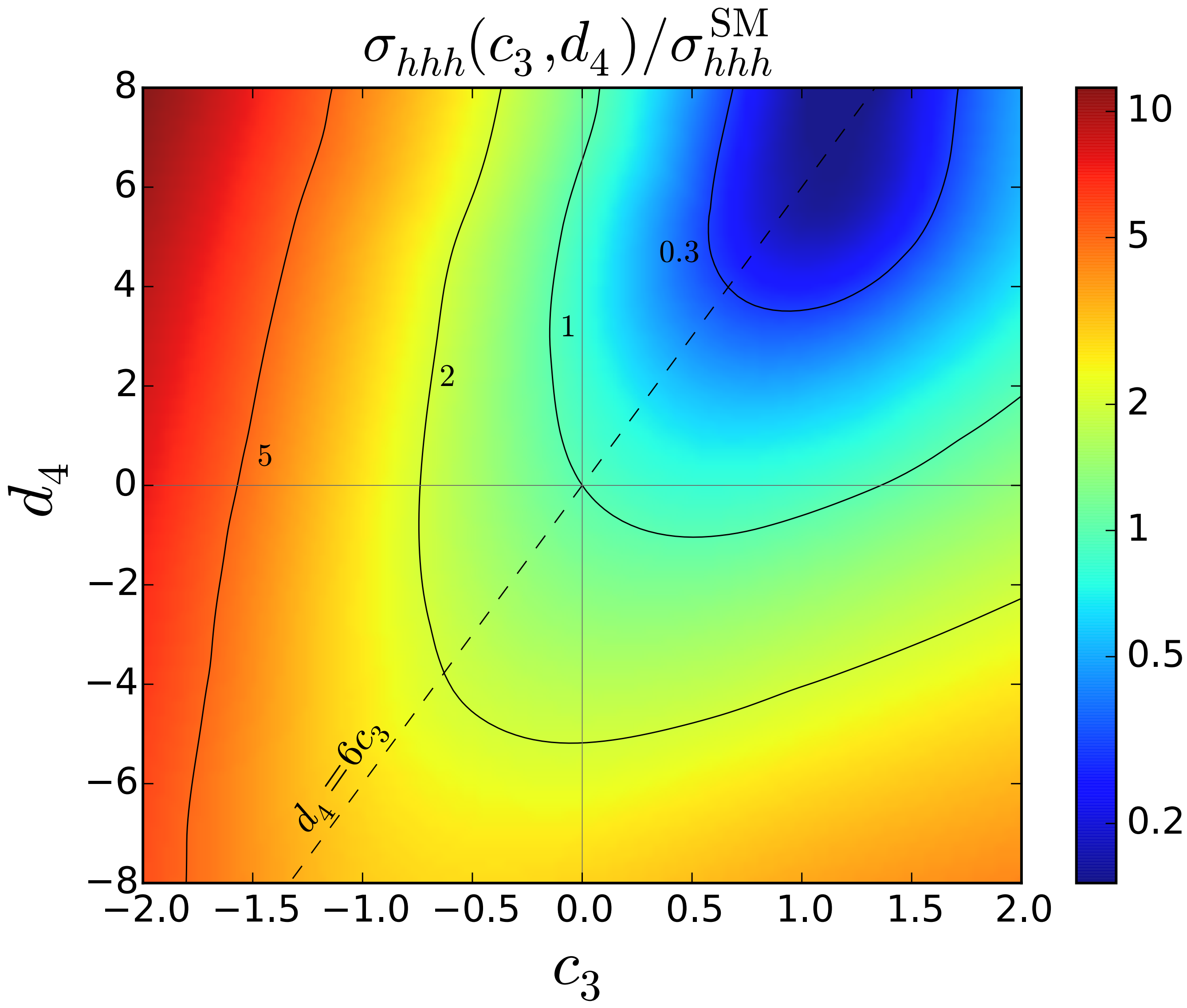
$$\mathcal{O}_8 \equiv \frac{c_8}{v^4}\lambda |H|^8 \implies \frac{d_4}{c_3} = \frac{31}{3}, \quad (c_3, d_4) = \left(\frac{3}{2}, \frac{31}{2}\right) \cdot c_8$$

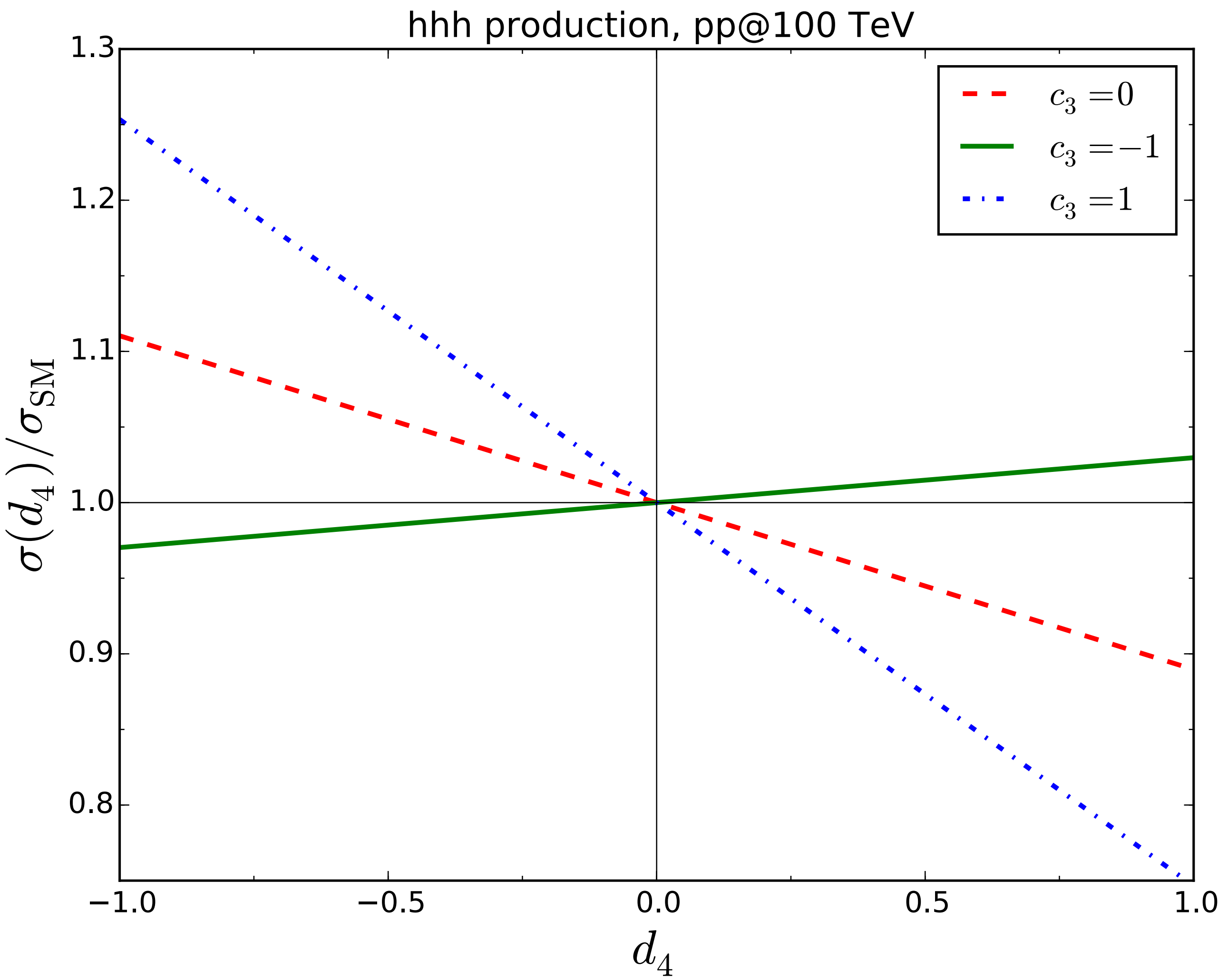


$$\frac{\sigma(c_6)_{hhh}}{\sigma(\mathrm{SM})_{hhh}} = 1 - 1.31 \cdot c_6 + 0.43 \cdot c_6^2 + 0.03 \cdot c_6^3 + 0.03 \cdot c_6^4$$

$$\mathcal{O}_6 \equiv \frac{c_6}{v^2} \lambda |H|^6$$

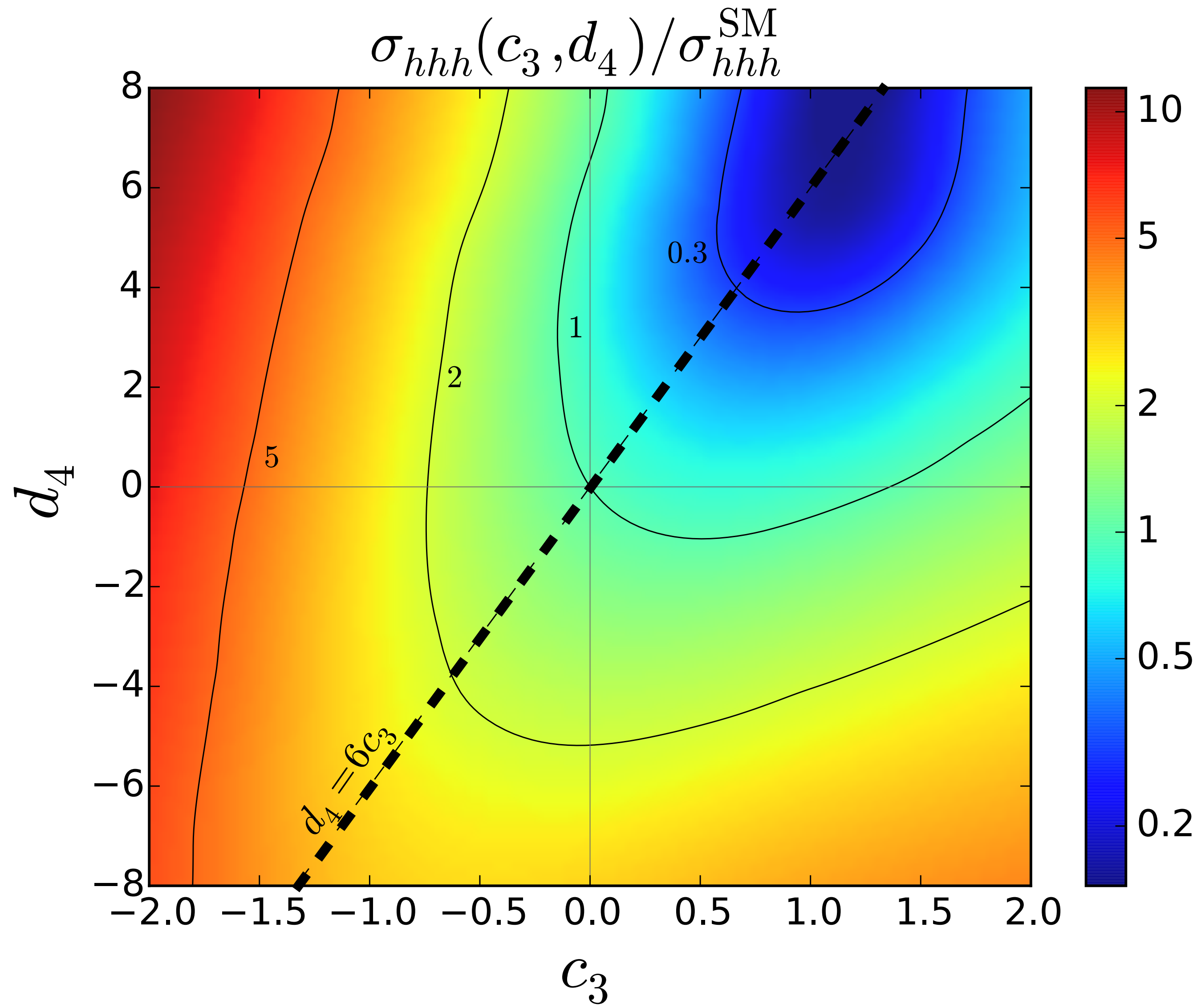
c_3, d_4 dependence on σ_{hhh}

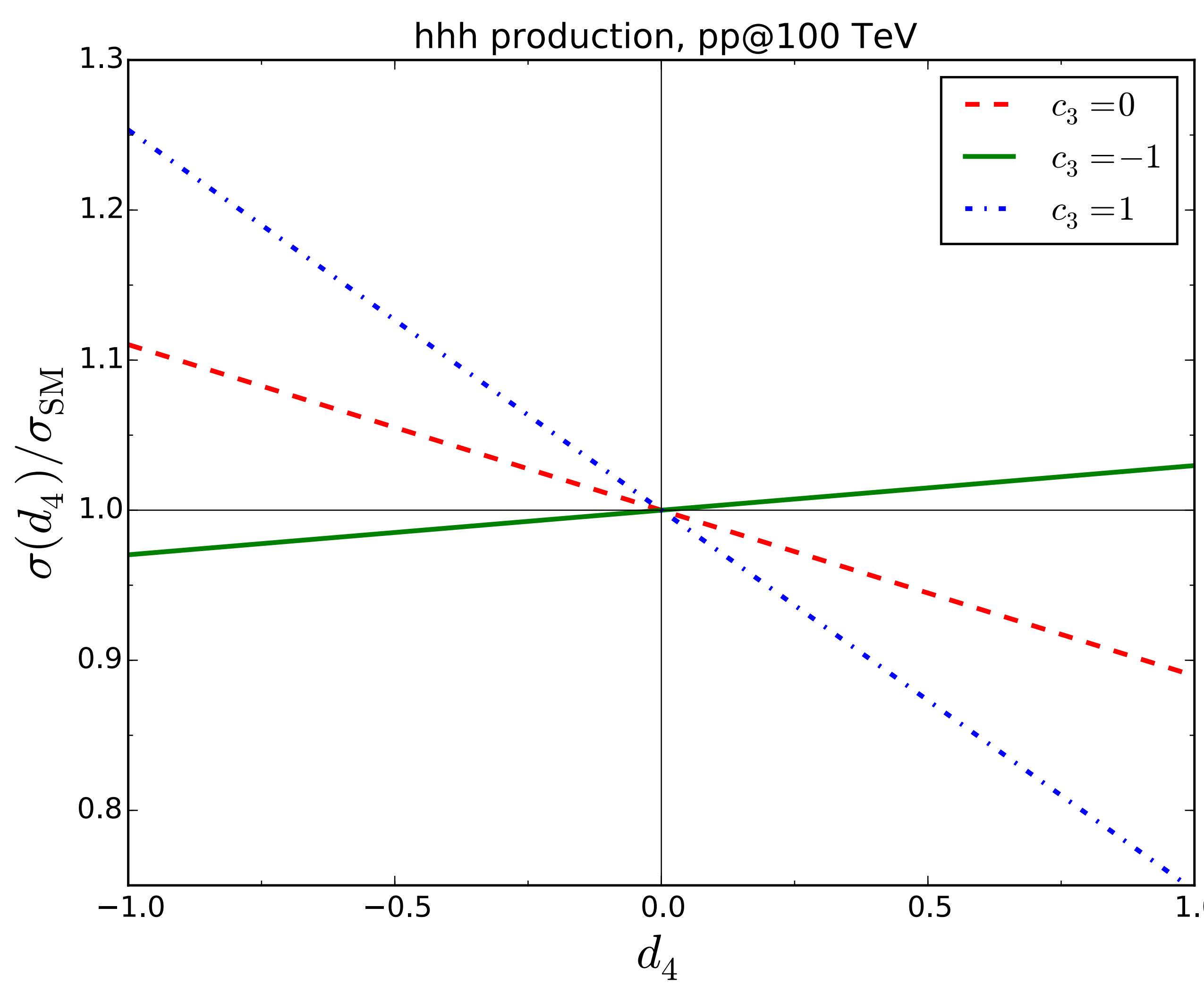




$$V_{\mathrm{self}}(h) = \frac{m_h^2}{2v}\left(1 + c_3\right) h^3 + \frac{m_h^2}{8v^2}\left(1 + d_4\right) h^4$$

c_3, d_4 dependence on σ_{hhh}





$\mathcal{O}_6 \equiv \frac{c_6}{v^2} \lambda |H|^6 \qquad (c_3, d_4) = (1, 6) \cdot c_6$

$V_{\mathrm{self}}(h) = \frac{m_h^2}{2v} \left(1 + c_3\right) h^3 + \frac{m_h^2}{8v^2} \left(1 + d_4\right) h^4$

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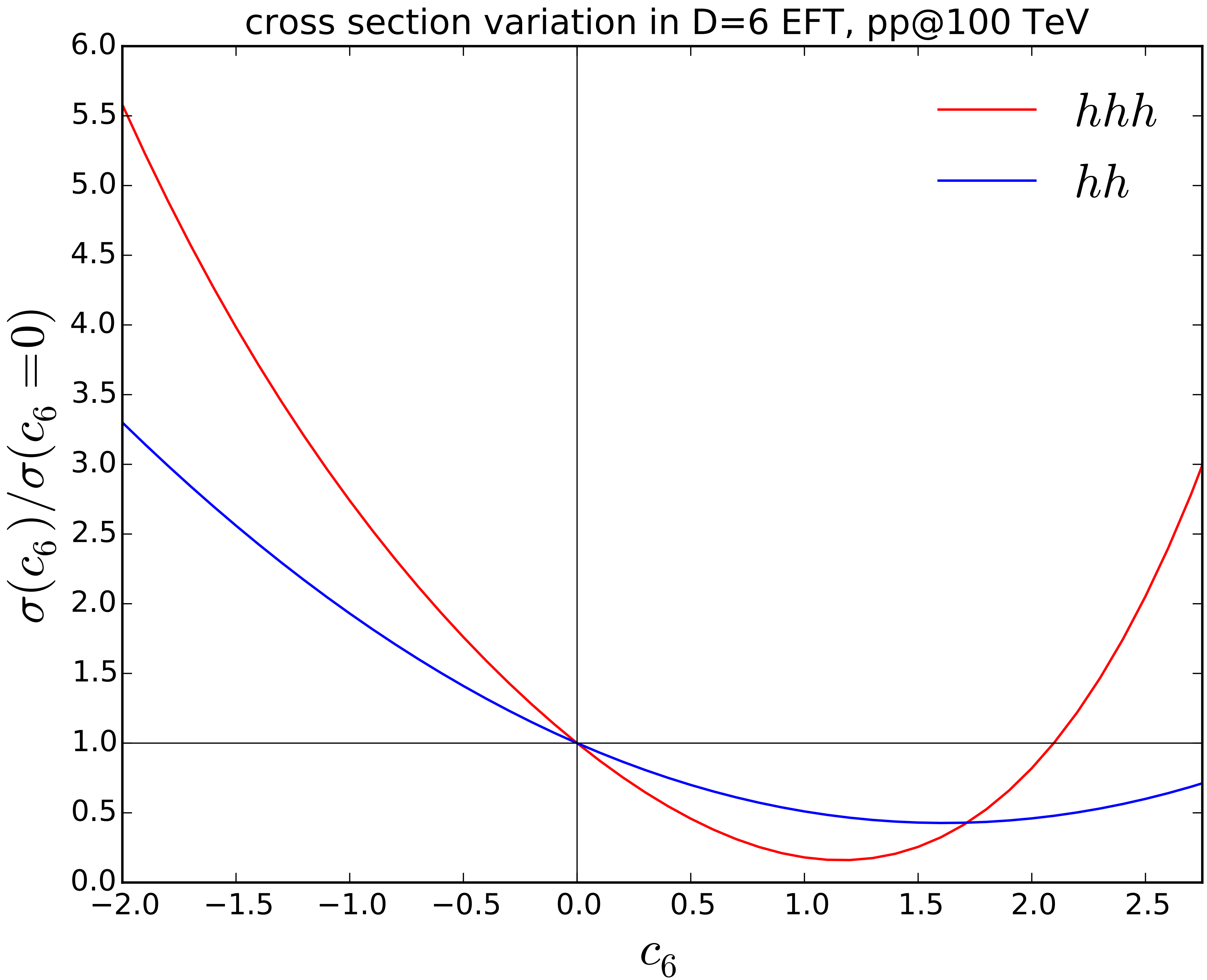
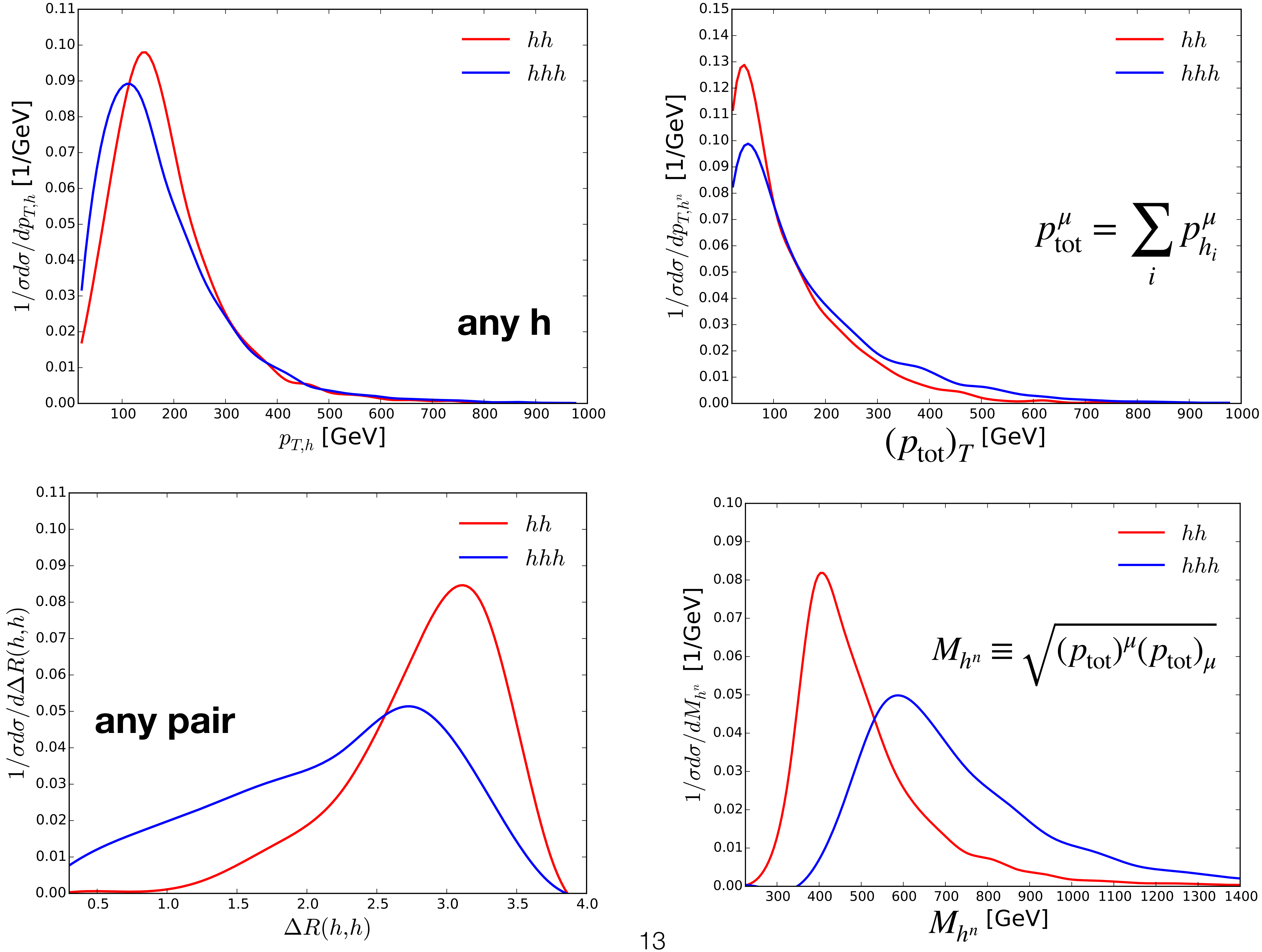


Distributions



Background to $4b + 2\gamma$

Background processes:

$bbbb\gamma\gamma$

$h_{\gamma\gamma}Z_{bb}Z_{bb}$

$h_{\gamma\gamma}h_{bb}Z_{bb}$

$$\left.\begin{array}{ll} h_{\gamma\gamma}Z_{bb} + \text{jets} & \times\ [\mathscr{P}_{j\to b}]^2 \\ bbbb\gamma + \text{jets} & \times\ \mathscr{P}_{j\to\gamma} \\ bbbb + \text{jets} & \times\ [\mathscr{P}_{j\to\gamma}]^2 \\ bb\gamma\gamma + \text{jets} & \times\ [\mathscr{P}_{j\to b}]^2 \\ h_{\gamma\gamma}h_{bb} + \text{jets} & \times\ [\mathscr{P}_{j\to b}]^2 \end{array}\right\} 4b + 2\gamma$$

mis-tag rates:

$$\boxed{\begin{array}{l} \mathscr{P}_{j\to b} = 10^{-2} \\ \mathscr{P}_{j\to\gamma} = 10^{-3} \end{array}}$$

b-tag rate:

$\mathscr{P}_{b\to b} = 80\,\%$

photon reco eff: 100%

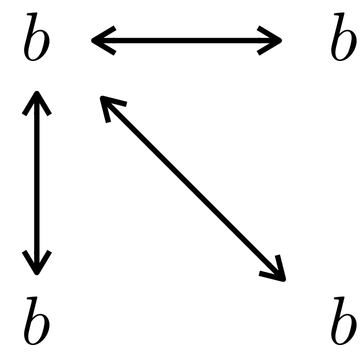
Generator level cuts

observable	PS cut
$p_{T,b}$	> 35 GeV, at least one > 70 GeV
$\lvert\eta_b\rvert$	< 3.2
$p_{T,\gamma}$	> 35 GeV, at least one > 70 GeV
$\lvert\eta_\gamma\rvert$	< 3.5
$\Delta R_{\gamma\gamma}$	> 0.2
$m_{\gamma\gamma}$	$\in [90, 160]$ GeV

	process	$\sigma_{\text{NLO}} \times \text{BR} \times \mathcal{P}_{\text{tag}}$ (ab)
Signal	$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, SM	5.4
	$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, $c_6 = 1.0$	0.9
	$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, $c_6 = -1.0$	15.0
BG	$b\bar{b}b\bar{b}\gamma\gamma$	1050
	hZZ, (NLO) $(ZZ \to (b\bar{b})(b\bar{b}))$	0.8
	hhZ, (NLO)$(Z \to (b\bar{b}))$	0.8
	hZ, (NLO) $(Z \to (b\bar{b}))$	1129
	$b\bar{b}b\bar{b}\gamma$ + jets	2420
	$b\bar{b}b\bar{b}$ + jets	4460
	$b\bar{b}\gamma\gamma$ + jets	4.0
	hh + jets, SM	592.7
	hh + jets , $c_6 = 1.0$	331.5
	hh + jets , $c_6 = -1.0$	1116.9

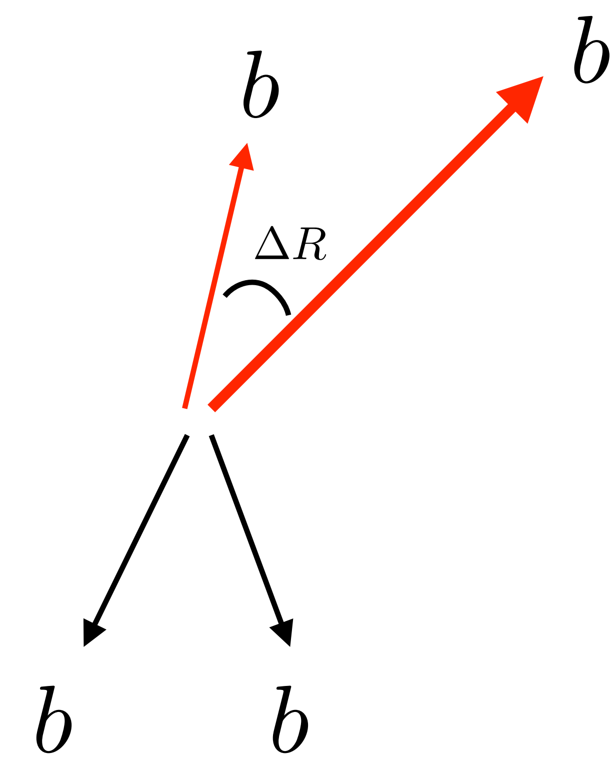
Combinatorics

There are 3 ways to pair 4 b-jets:



Algorithm 1:

1. take the highest pT b-jet
2. pair it with the *closest* one in terms of ΔR
3. the rest is fixed



Algorithm 2:

1. take the combination that minimises

$$[m(b_{i_1}, b_{i_2}) - m_h]^2 + [m(b_{i_3}, b_{i_4}) - m_h]^2$$

$\Longrightarrow$ combinations found from the two algorithms differ with O(1)% chance

$\Longrightarrow$ we use Algorithm 1.

Event selection

observable	selection cut
$p_{T,b_{\{1,2,3,4\}}}$	$> \{80, 50, 40, 40\}$ GeV
$\lvert\eta_b\rvert$	< 3.0
$m_{bb}^{\text{close},1}$	$\in [100, 160]$ GeV
$m_{bb}^{\text{close},2}$	$\in [90, 170]$ GeV
$\Delta R_{bb}^{\text{close},1}$	$\in [0.2, 1.6]$
$\Delta R_{bb}^{\text{close},2}$	no cut
$p_{T,\gamma_{\{1,2\}}}$	$> \{70, 40\}$ GeV
$\lvert\eta_\gamma\rvert$	< 3.5
$\Delta R_{\gamma\gamma}$	$\in [0.2, 4.0]$
$m_{\gamma\gamma}$	$\in [124, 126]$ GeV

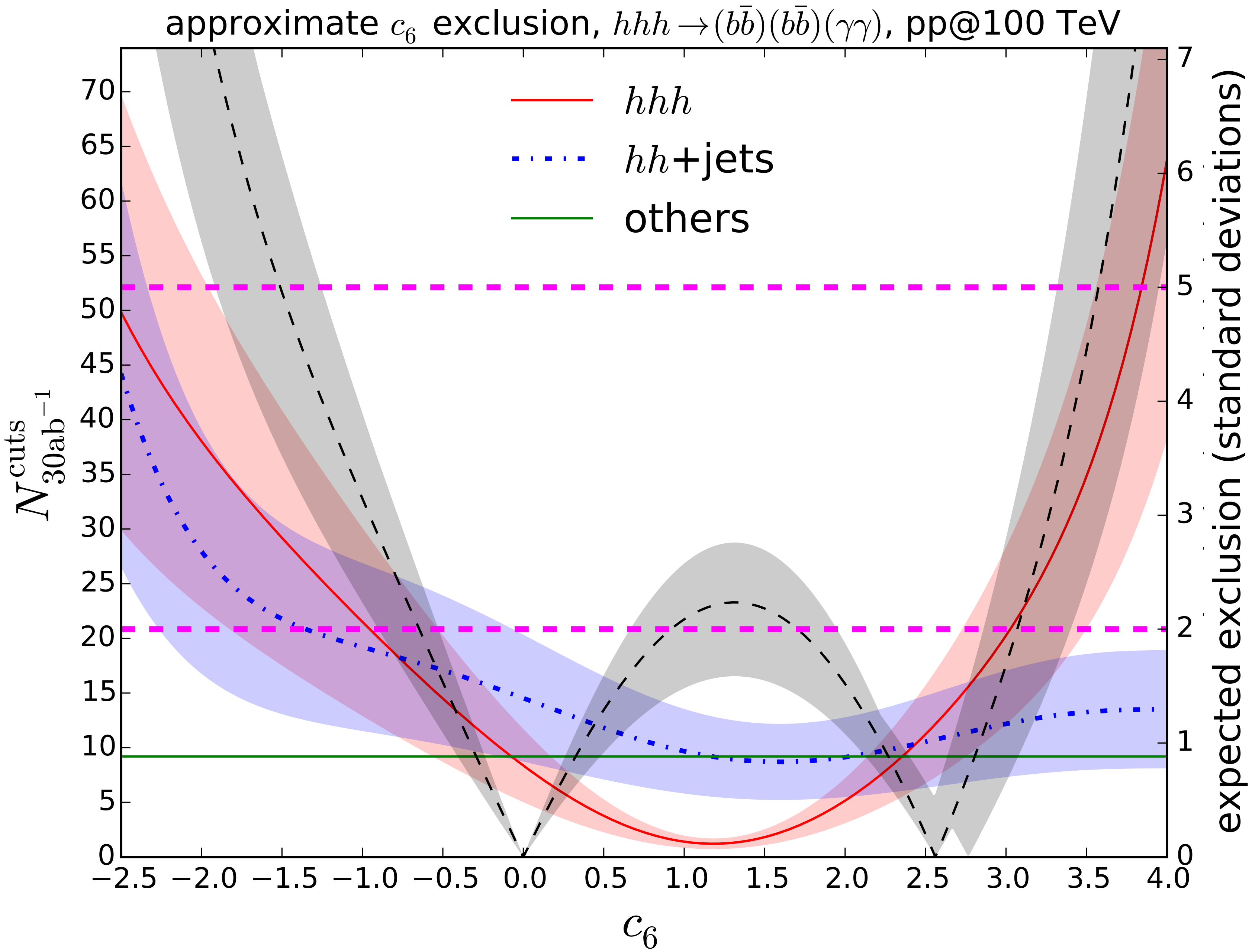
Analysis results

	process	$\sigma_{\rm NLO} \times {\rm BR} \times \mathcal{P}_{\rm tag}$ (ab)	$\epsilon_{\rm analysis}$	$N^{\rm cuts}_{30\ {\rm ab}^{-1}}$
	$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, SM	5.4	0.06	9.7
Signal	$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, $c_6 = 1.0$	0.9	0.04	1.1
	$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, $c_6 = -1.0$	15.0	0.05	22.5
	$b\bar{b}b\bar{b}\gamma\gamma$	1050	2.6×10^{-4}	8.2
	hZZ, (NLO) $(ZZ \to (b\bar{b})(b\bar{b}))$	0.8	0.002	$\ll 1$
	hhZ, (NLO)$(Z \to (b\bar{b}))$	0.8	0.007	$\ll 1$
BG	hZ, (NLO) $(Z \to (b\bar{b}))$	1129	$\mathcal{O}(10^{-5})$	$\ll 1$
	$b\bar{b}b\bar{b}\gamma$ + jets	2420	$\mathcal{O}(10^{-5})$	$\mathcal{O}(1)$
	$b\bar{b}b\bar{b}$ + jets	4460	$\mathcal{O}(10^{-6})$	$\ll 1$
	$b\bar{b}\gamma\gamma$ + jets	4.0	$\mathcal{O}(10^{-5})$	$\ll 1$
	hh + jets, SM	592.7	7×10^{-4}	12.4
	hh + jets , $c_6 = 1.0$	331.5	0.001	9.9
	hh + jets , $c_6 = -1.0$	1116.9	4×10^{-4}	13.4

c_6 sensitivity

$$\mathcal{O}_6 \equiv \frac{c_6}{v^2}\lambda |H|^6$$

red and blue curves

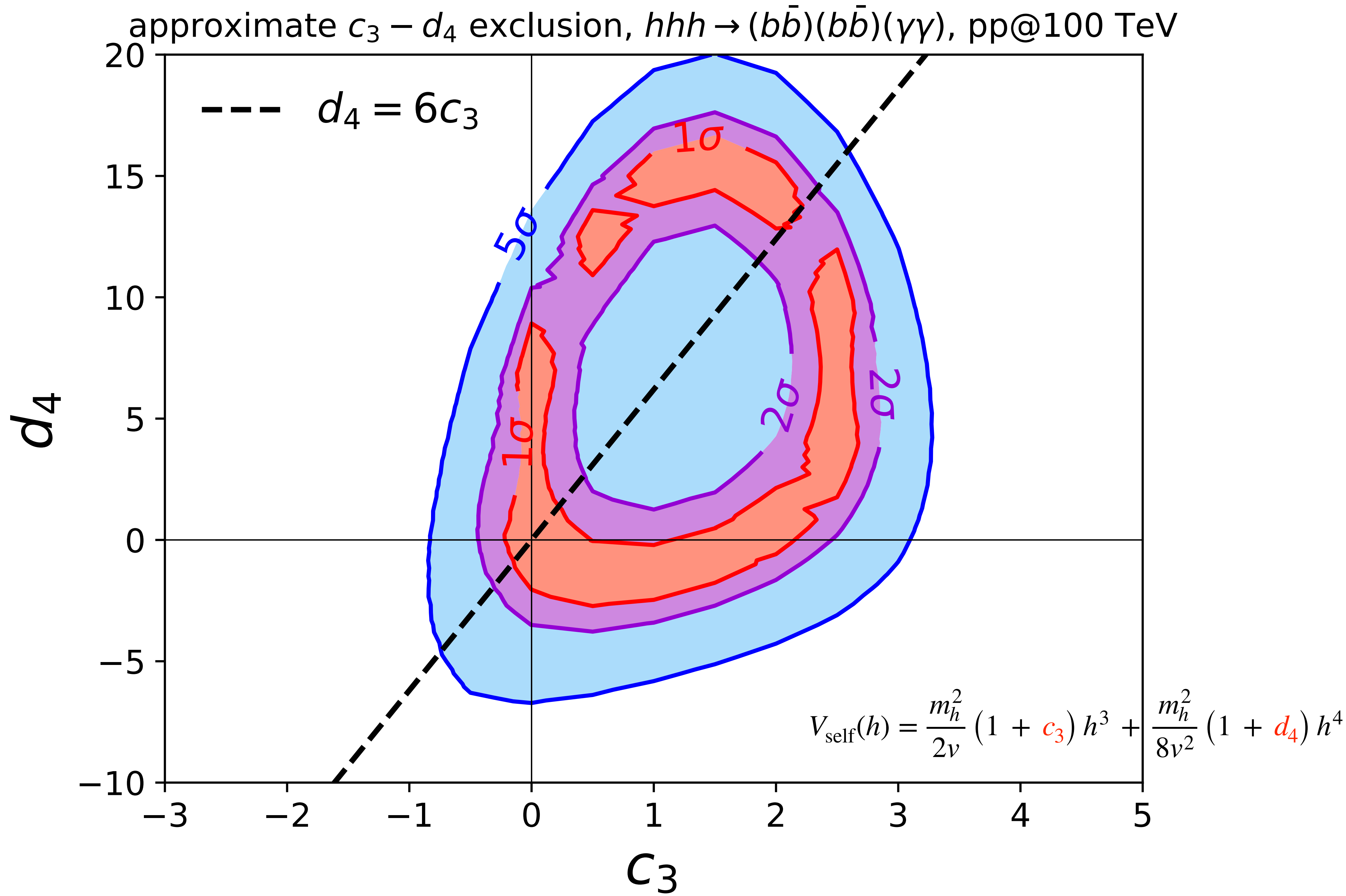


black curve

40% theory uncertainty

	hhh	total	$\frac{\lvert N(\text{SM})-N(c_6)\rvert}{\sqrt{N(\text{SM})}}$
SM	9.7	31.3	
$c_6 = 1.0$	1.1	20.2	~ 2.0
$c_6 = -1.0$	22.5	45.1	~ 2.5

c_3, d_4 constraints



$\mathcal{O}(1)$ **constraints on** c_3, d_4, c_6 **can be obtained at a 100TeV collider with** $30\,\mathrm{ab}^{-1}$

Discussion and Conclusion

- HHH production is practically the only way to directly probe the h^4 interaction.
- The cross section is small, ~0.1/fb @LHC and ~5/fb @FCChh, and the signal is diluted into many different final states: $\sigma \to \sigma \cdot BR_1 \cdot BR_2 \cdot BR_2$
- In the $(bb)(bb)(\gamma\gamma)$ channel @FCChh, O(1) deviation from the SM h^3 and h^4 couplings can be detected.
- The signal efficiency is sensitive to the b-tagging efficiency: $\epsilon_b = 80\,\% \to 70\,\%$ reduces the signal efficiency by ~40%.
- A very good photon energy resolution (~ 1GeV) is necessary.
  We required $m_{\gamma\gamma} = [124,126]\,\mathrm{GeV}$
- There should be a lot of room to improve the analysis: boosted merged jets, ML methods, different final states, combination of multiple channels.

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