The 8th KIAS workshop on particle physics and cosmology

Forecast for Higgs boson self coupling measurement at the HL-100 TeV collider.

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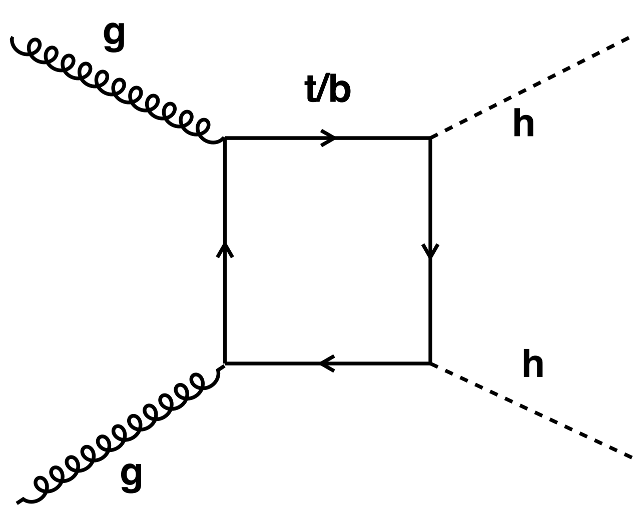
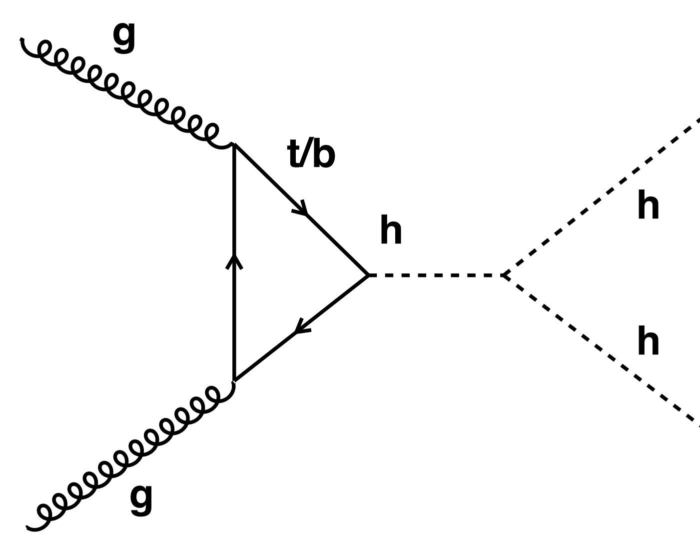
arXiv : 1804.07130 [hep-ph]
JC, Kingman Cheung (Konkuk U., NTHU, NCTS), Jae Sik Lee (CNU),
Chih-Ting Lu (NTHU), and Jubin Park (CNU)

Standard Model Di-Higgs Production

$$-\mathcal{L} = \frac{1}{3!}\left(\frac{3M_H^2}{v}\right)\lambda_{3H}\,H^3 \;+\; g_t^S\,\frac{m_t}{v}\,\bar{t}\,t\,H$$



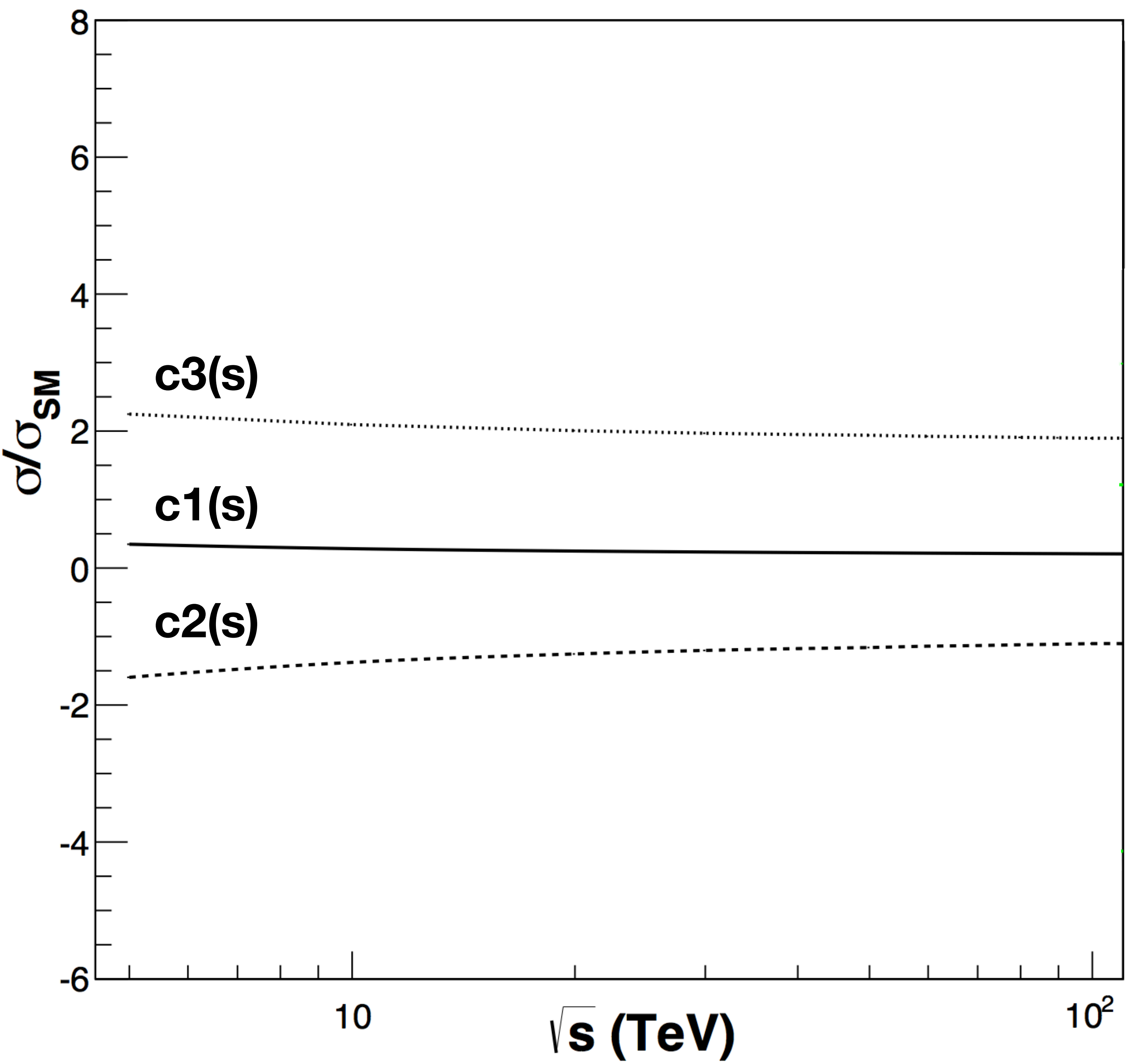


$$\frac{d\hat{\sigma}(gg\to HH)}{d\hat{t}} = \frac{G_F^2\alpha_s^2}{512(2\pi)^3}\left[\left|\lambda_{3H}g_t^S D(\hat{s})F_\triangle^S + (g_t^S)^2F_\Box^{SS}\right|^2 + \left|(g_t^S)^2G_\Box^{SS}\right|^2\right]$$

$$D(\hat{s}) = \frac{3M_H^2}{\hat{s}-M_H^2+iM_H\Gamma_H}$$

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

$$\frac{\sigma^{\rm LO}(gg \to HH)}{\sigma^{\rm LO}_{\rm SM}(gg \to HH)} = c_1(s)\,\lambda_{3H}^2\,(g_t^S)^2 + c_2(s)\,\lambda_{3H}\,(g_t^S)^3 + c_3(s)\,(g_t^S)^4$$

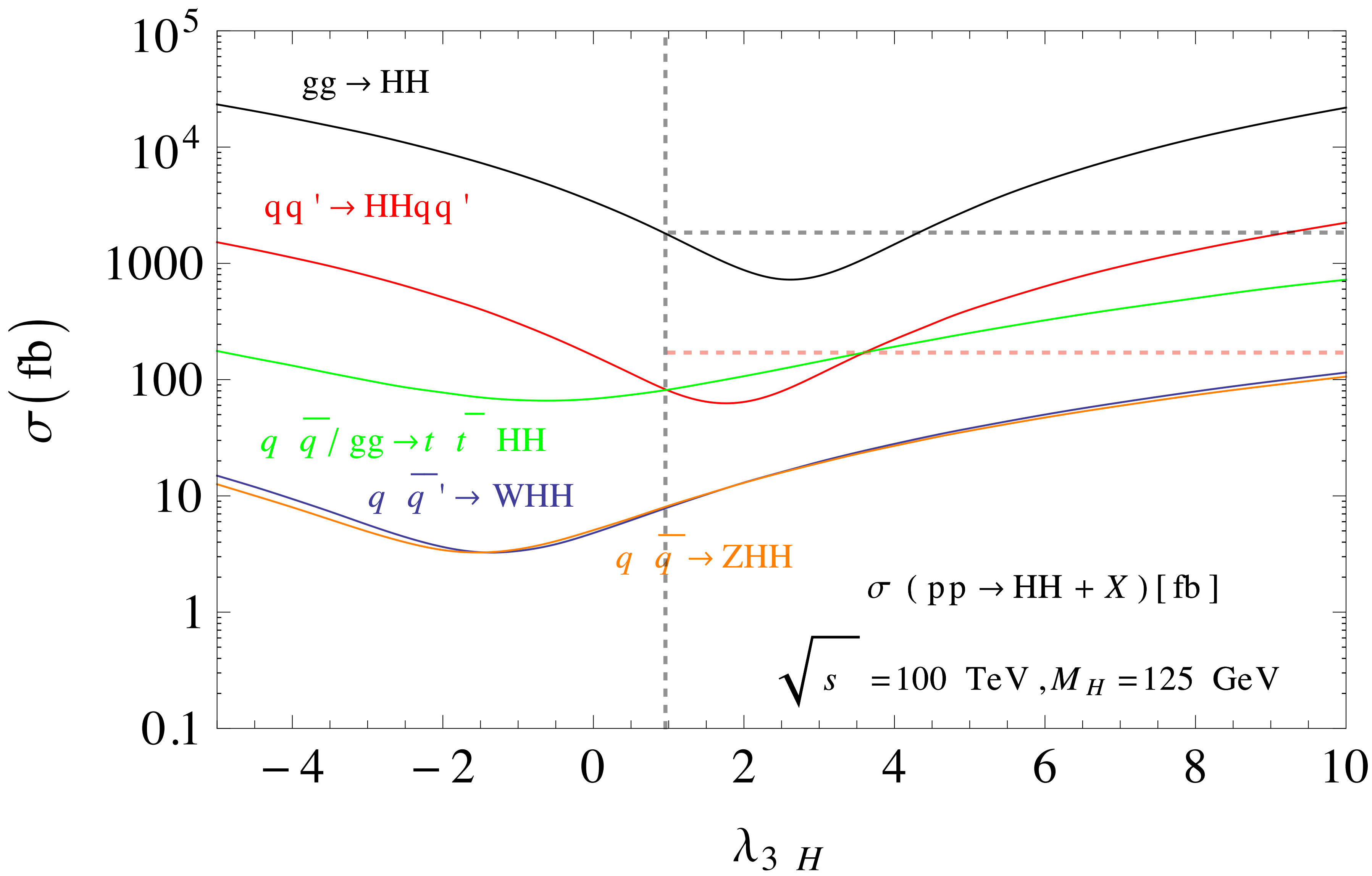


c1(s), c2(s), c3(s) are related to CM energy √s and kinematic cuts.

$\sqrt{s}$ (TeV)	$c_1(s)$ $[\lambda_{3H}^2 (g_t^S)^2]$	$c_2(s)$ $[\lambda_{3H} (g_t^S)^3]$	$c_3(s)$ $[(g_t^S)^4]$
8	0.300	−1.439	2.139
14	0.263	−1.310	2.047
33	0.232	−1.193	1.961
100	0.208	−1.108	1.900

Probe Di-Higgs Production :
Higgs boson self coupling
Top Yukawa coupling

JC, K. Cheung, J.S. Lee, C.T. Lu, JHEP08(2015)133.



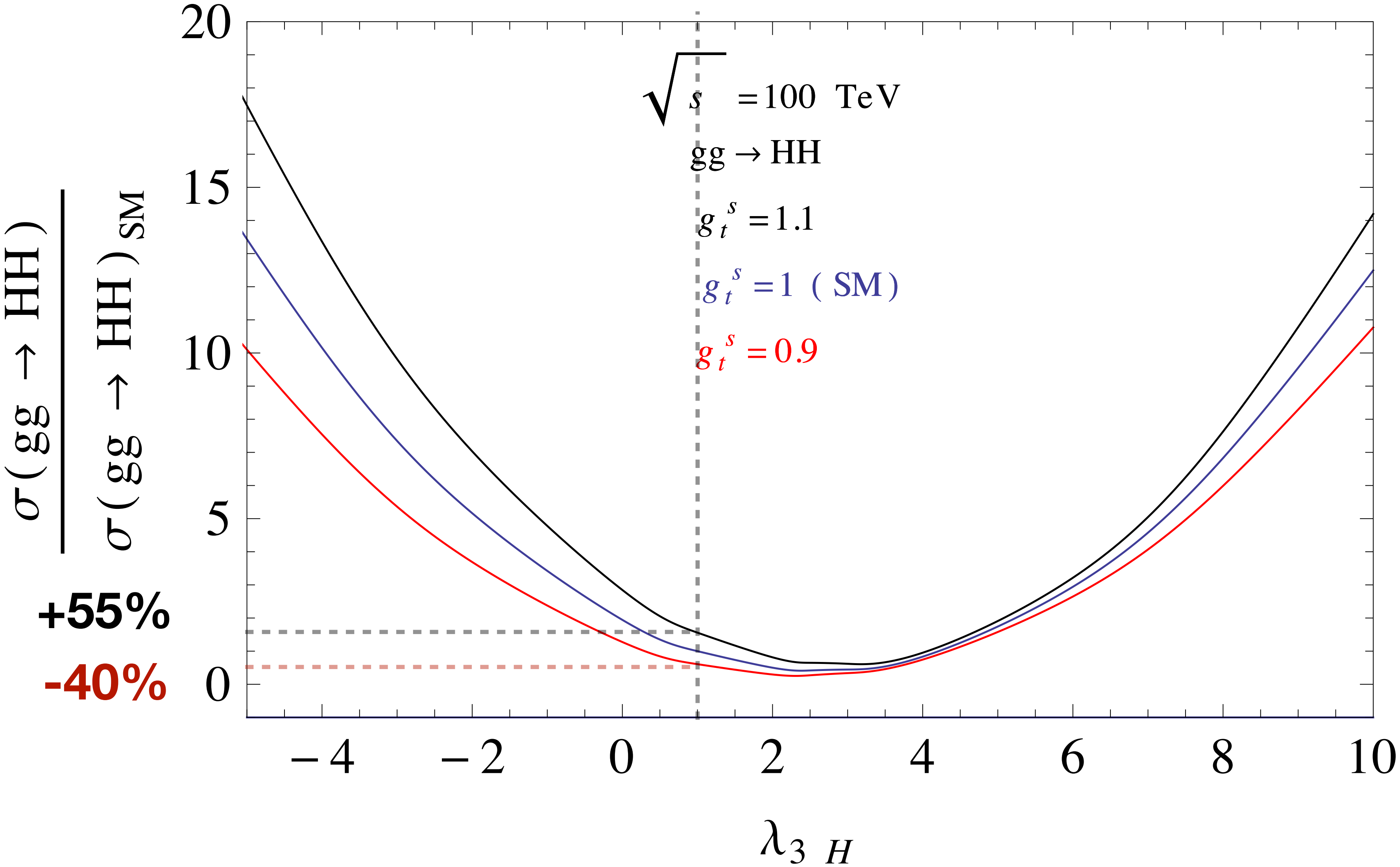
100 TeV σ(p p > h h) :
1749 fb[1], 1224 fb[2]

14 TeV σ(p p > h h) :
45.05 fb[1], 36.69 fb[2]

[1] : calculated at NNLO accuracy including NNLL gluon resummation in the infinite top quark mass approximation.

[2] : incorporate the finite top-quark mass effects at NNLO by adopting the FT (Full Theory) approximation.

[1] D. de Florian and J. Mazzitelli, JHEP 1509, 053 (2015), R. Contino et al., CERN Yellow Report, no. 3, 255 (2017).
[2] M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. M. Lindert and J. Mazzitelli, JHEP 1805 (2018) 059.



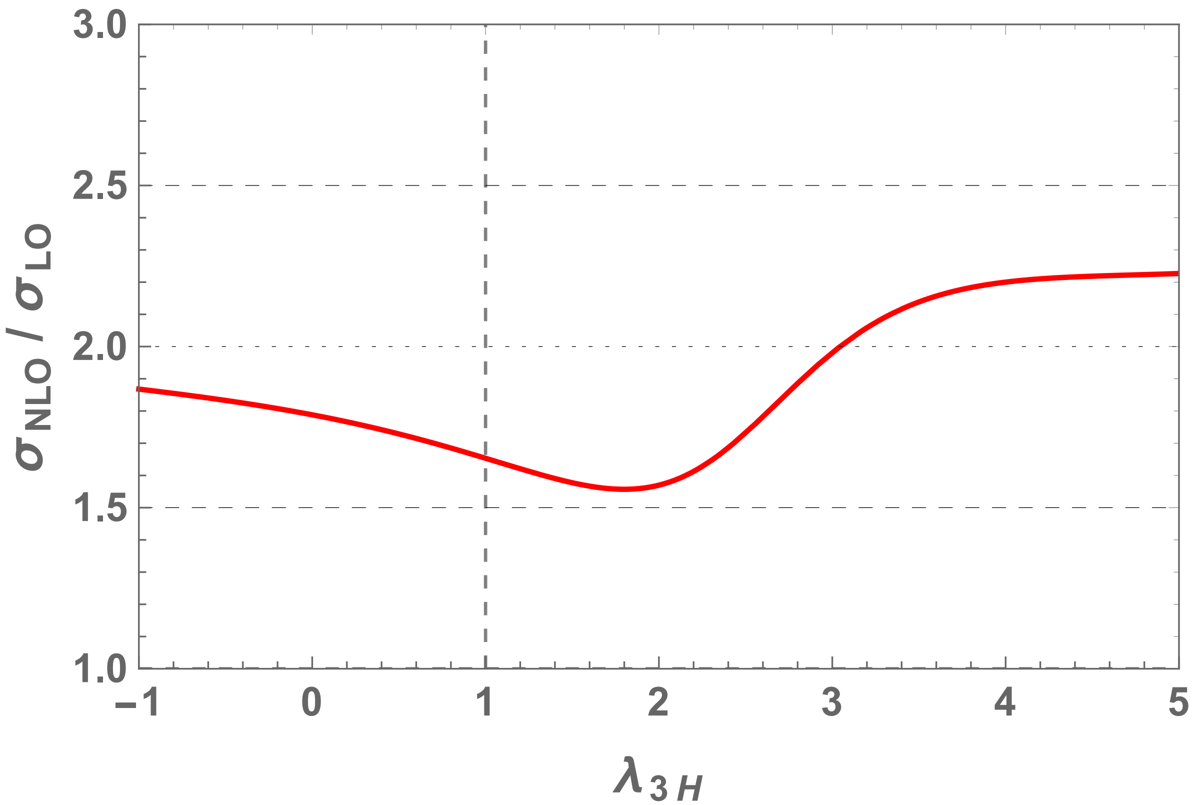
The expected Yt uncertainty is 1% at the 100-TeV pp colliders [1].

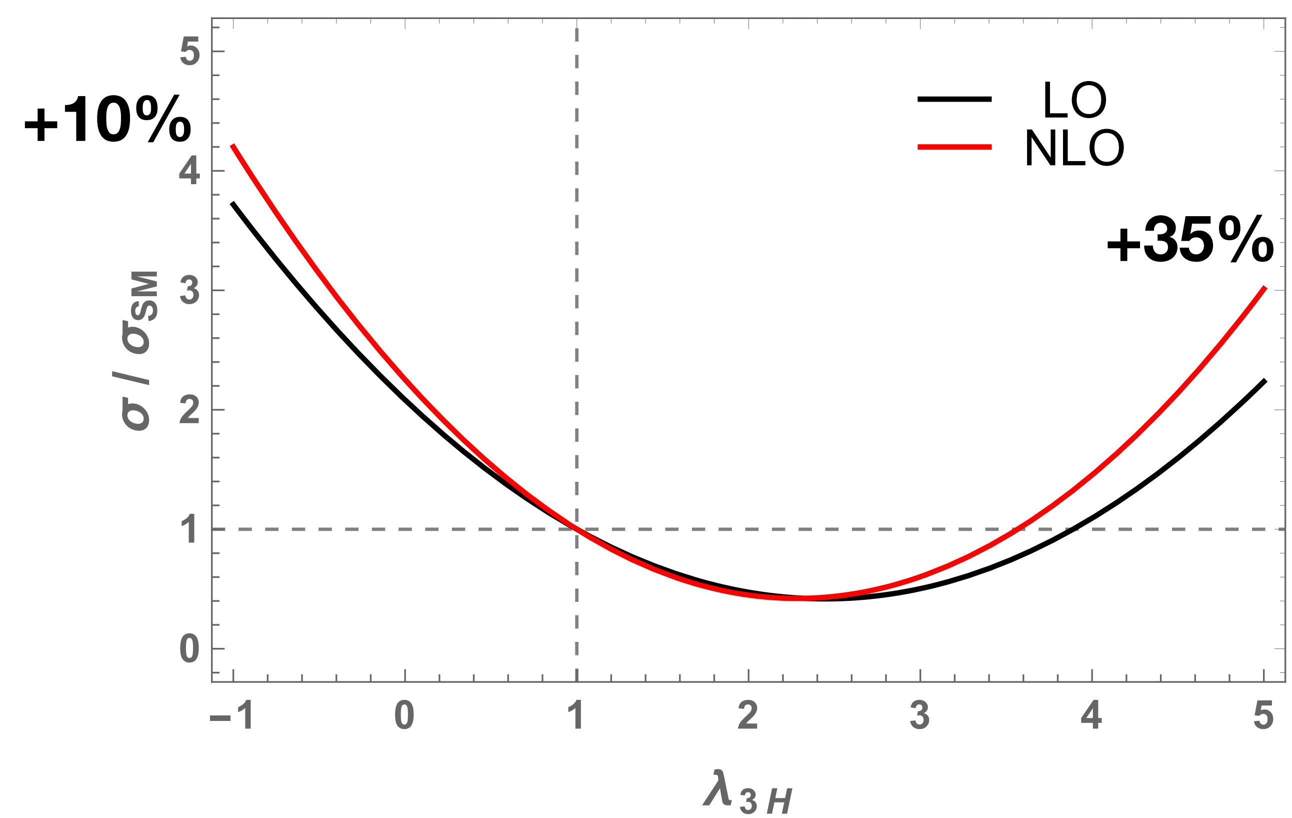
At the HL-LHC, the expected precision of measurement of the top-quark Yukawa coupling (Yt) is 10% [1].

Without knowing no better than 10% precision of the absolute Yt, we still considered 10% uncertainty for Yt at the 100-TeV pp colliders.

[1] M. Vos, arXiv:1701.06537 [hep-ex].

QCD corrections for λ_{3H}





QCD corrections are less significant than the uncertainties associated with the top-Yukawa coupling. In this respect, we have not taken account of the λ_{3H}-dependent QCD corrections on the ratio σ(HH)/σ(HH)$_{SM}$ in this work.

S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk and T. Zirke, JHEP 1610 (2016).
JC, K. Cheung, J.S. Lee, C.T. Lu and J. Park, arXiv: 1804.07130 [hep-ph].

Search for Di-Higgs production at collider

reconstruct τ / W (covering $bb\tau\tau$ and $bbWW$)

b-tagging, QCD BG (covering $bbbb$)

Decay channels	$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbWW$	$HH \to bbbb$	$\cdots$
Branching ratios	0.263%	7.29%	24.8%	33.3%	

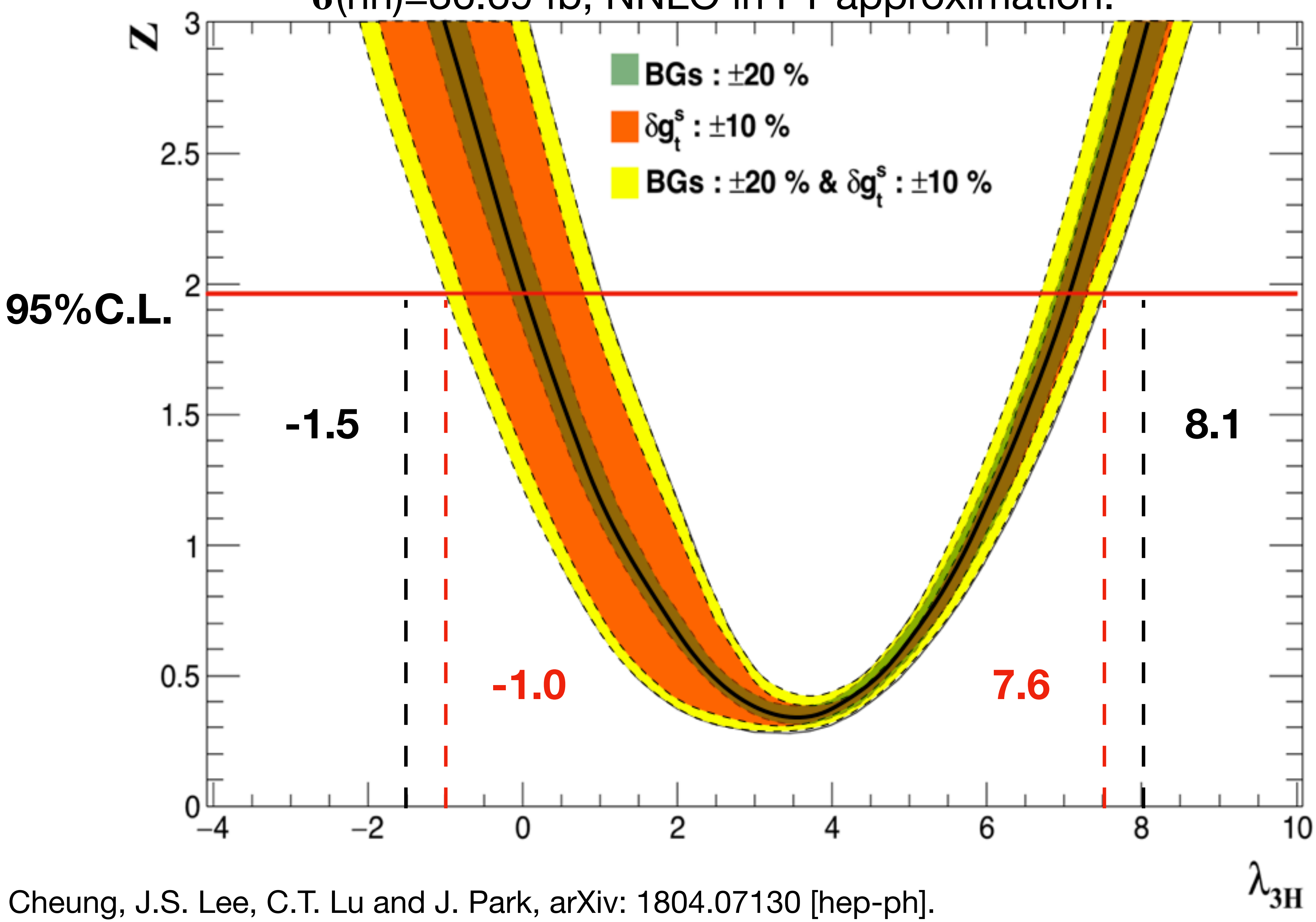
small BR (for $bb\gamma\gamma$)
relatively clean channel
dominate BGs comes from
fake photon or b-jet

In our study : bbγγ channel

HL-LHC

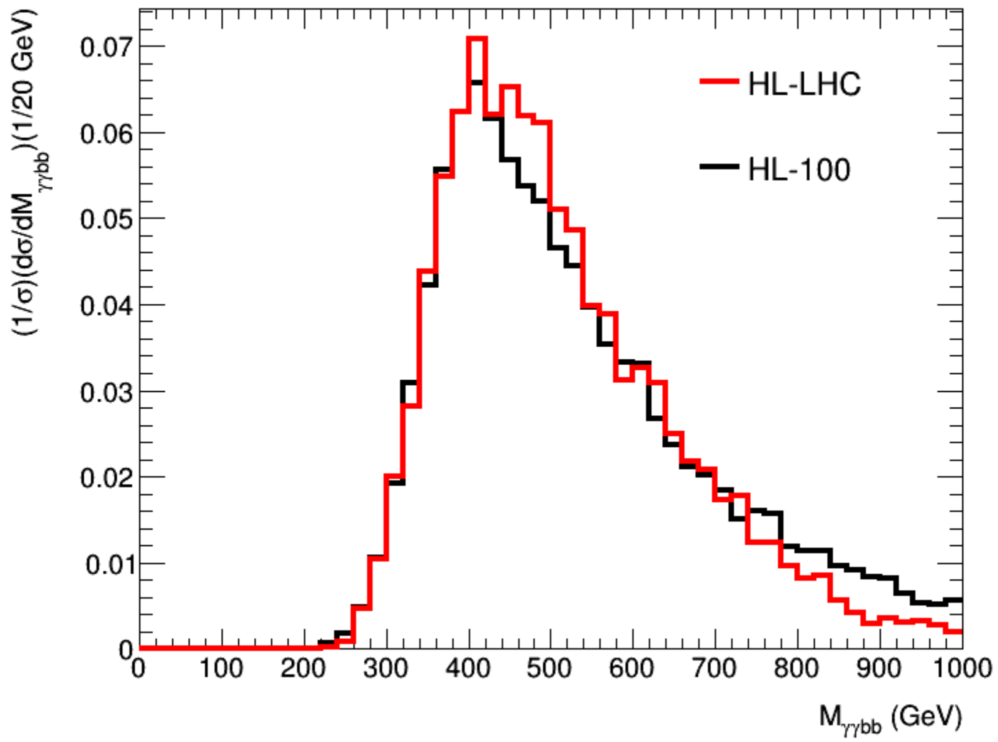
σ(hh)=45.05 fb, NNLO +NNLL.

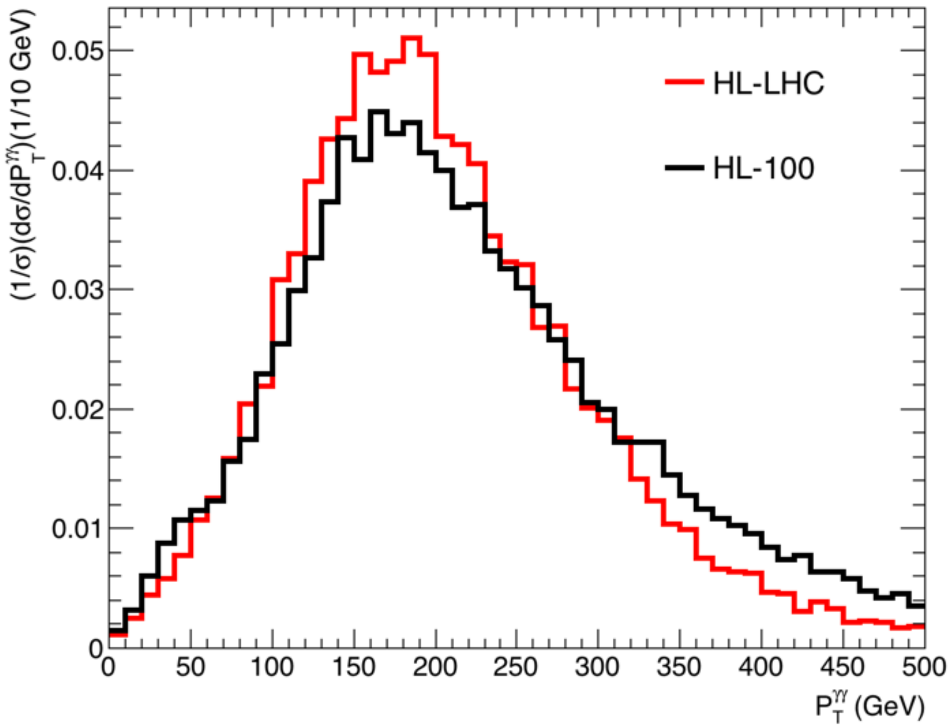
σ(hh)=36.69 fb, NNLO in FT approximation.

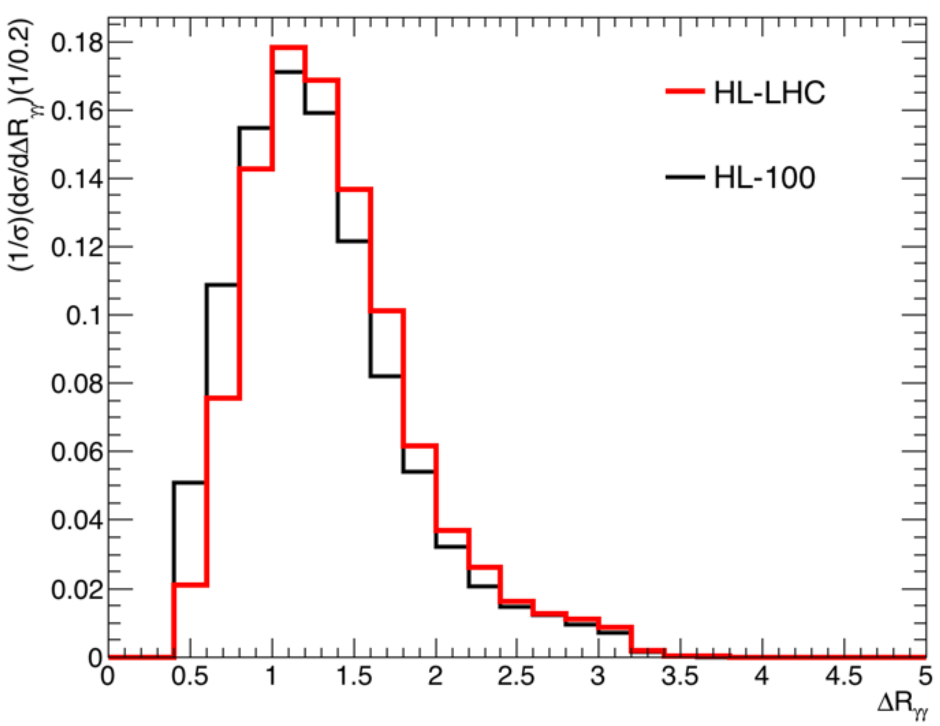


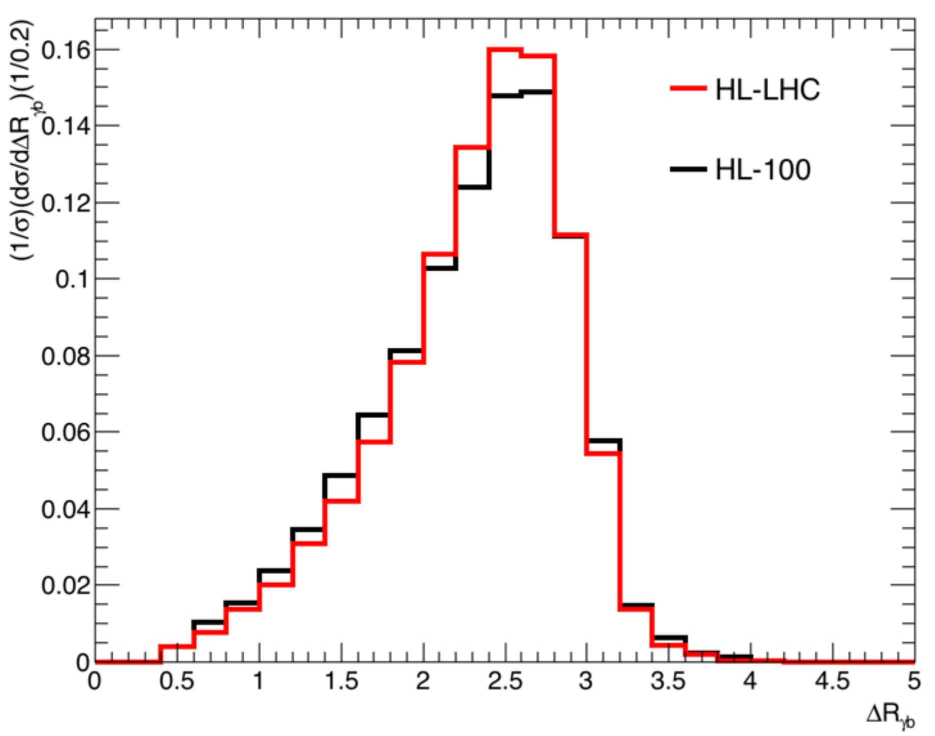
JC, K. Cheung, J.S. Lee, C.T. Lu and J. Park, arXiv: 1804.07130 [hep-ph].

HL-LHC vs HL-100









bbγγ channel BGs

single Higgs

- ggH
- ttH
- ZH
- bbH

non-resonant

- bbγγ
- ccγγ
- jjγγ
- bbjγ
- ccjγ
- bbjj

resonant

- Z(bb)γγ
- tt
- ttγ

Signal				
Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to b\bar{b}\gamma\gamma$ [20]	MG5_aMC@NLO/PYTHIA8	4.62	NNLO +NNLL	NNPDF2.3LO

Backgrounds					
Background(BG)	Process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
Single-Higgs associated BG	$ggH(\to \gamma\gamma)$ [20]	POWHEG − BOX/PYTHIA8	1.82×10^3	NNNLO	CT10
	$t\bar{t}H(\to \gamma\gamma)$ [20]	PYTHIA8/PYTHIA8	7.29×10^1	NLO	
	$ZH(\to \gamma\gamma)$ [20]	PYTHIA8/PYTHIA8	2.54×10^1	NNLO	
	$b\bar{b}H(\to \gamma\gamma)$ [37]	PYTHIA8/PYTHIA8	1.96×10^1	NNLO(5FS)	
Non-resonant BG	$b\bar{b}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	4.93×10^3	LO	CTEQ6L1
	$c\bar{c}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	4.54×10^4	LO	
	$jj\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	5.38×10^5	LO	
	$b\bar{b}j\gamma$	MG5_aMC@NLO/PYTHIA8	1.44×10^7	LO	
	$c\bar{c}j\gamma$	MG5_aMC@NLO/PYTHIA8	4.20×10^7	LO	
	$b\bar{b}jj$	MG5_aMC@NLO/PYTHIA8	1.60×10^{10}	LO	
	$Z(\to b\bar{b})\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	9.53×10^1	LO	
$t\bar{t}$ and $t\bar{t}\gamma$ BG [20] (≥ 1 lepton)	$t\bar{t}$	MG5_aMC@NLO/PYTHIA8	1.76×10^7	NLO	CT10
	$t\bar{t}\gamma$	MG5_aMC@NLO/PYTHIA8	4.18×10^4	NLO	CTEQ6L1

[20] R. Contino et al., CERN Yellow Report, no. 3, 255 (2017).
[37] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy.

Background(BG)	Process	Fake Process	Fake rate
Non-resonant BG	$b\bar{b}\gamma\gamma$	N/A	14 TeV N/A
	$c\bar{c}\gamma\gamma$	$c \to b,\ \bar{c} \to \bar{b}$	0.125 $(0.1)^2$
	$jj\gamma\gamma$	$c_s \to b,\ \bar{c}_s \to \bar{b}$	$(0.1)^2$
	$b\bar{b}j\gamma$	$j \to \gamma$	5e-4 1.35×10^{-3}
	$c\bar{c}j\gamma$	$c \to b,\ \bar{c} \to \bar{b},\ j \to \gamma$	$(0.1)^2 \cdot (1.35 \times 10^{-3})$
	$b\bar{b}jj$	$j \to \gamma,\ j \to \gamma$	$(1.35 \times 10^{-3})^2$
	$Z(\to b\bar{b})\gamma\gamma$	N/A	N/A
$t\bar{t}$	Leptonic decay	$e \to \gamma,\ e \to \gamma$	$(0.02)^2/0.02 \cdot 0.05/(0.05)^2$
	Semi-leptonic decay	$e \to \gamma,\ j \to \gamma$	$(0.02) \cdot 1.35 \times 10^{-3}/(0.05) \cdot 1.35 \times 10^{-3}$
$t\bar{t}\gamma$	Leptonic decay	$e \to \gamma$	$0.02/0.05$ **barrel/endcap**
	Semi-leptonic	$e \to \gamma$	$0.02/0.05$

here we take the separation between the barrel and endcap regions at $|\eta| = 2$

14 TeV : ATLAS Collaboration, ATL-PHYS-PUB-2017-001.
100 TeV : R. Contino et al., CERN Yellow Report, no. 3, 255 (2017).

Backgrounds: bbγγ channel

single Higgs | non-resonant | resonant

Z~S/√B

	14 TeV (fb)	100 TeV (fb)	HL-100/HL-LHC	√(HL-100/HL-LHC)
HH->bbγγ	0.12	4.62	38.82	
ggH	120.00	1820.00	15.17	3.89
ttH	1.37	72.90	53.21	7.29
ZH	2.24	25.40	11.34	3.37
bbH	1.26	19.60	15.56	3.94
bbγγ	140.00	4930.00	35.21	5.93
ccγγ	1140.00	45400.00	39.82	6.31
jjγγ	16200.00	538000.00	33.21	5.76
bbjγ	367000.00	14400000.00	39.24	6.26
ccjγ	1050000.00	42000000.00	40.00	6.32
bbjj	434000000.00	16000000000.00	36.87	6.07
Z(bb)γγ	5.17	95.30	18.43	4.29
tt	530000.00	17600000.00	33.21	5.76
ttγ	1600.00	41800.00	26.13	5.11

HL-LHC constraint
HL-100 measurement

Event generations and detector simulations

Pre-selection cut :

$$P_{T_j} > 20 \ \ \text{GeV}, \ P_{T_b} > 20 \ \ \text{GeV}, \ P_{T_\gamma} > 25 \ \ \text{GeV}, \ P_{T_l} > 10 \ \ \text{GeV},$$

$$|\eta_j| < 6, \ |\eta_\gamma| < 6, \ |\eta_l| < 6, \ \Delta R_{jj,ll,\gamma\gamma,\gamma j,jl,\gamma l} > 0.4,$$

$$M_{jj} > 25 \text{ GeV}, \ M_{bb} > 45 \text{ GeV}, \ 60 < M_{\gamma\gamma} < 200 \text{ GeV}.$$

Detector simulation : Delphes3, FCChh template.

ECAL energy resolution

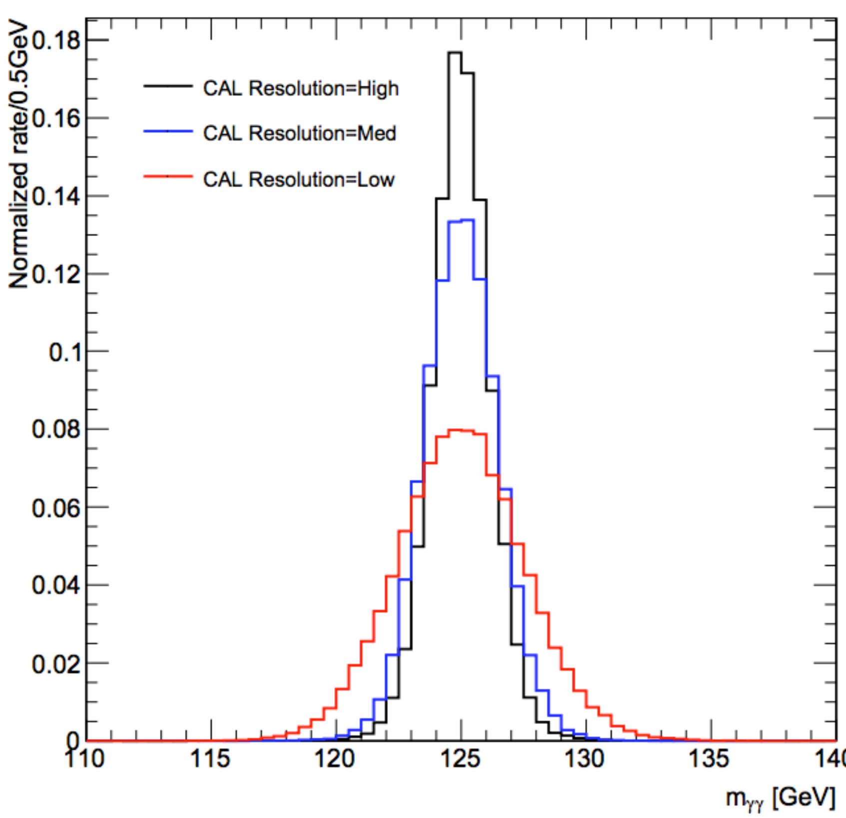
$$\Delta E/E|_{\rm ECAL} = \sqrt{0.01^2 + 0.1^2 \, \text{GeV}/E}$$

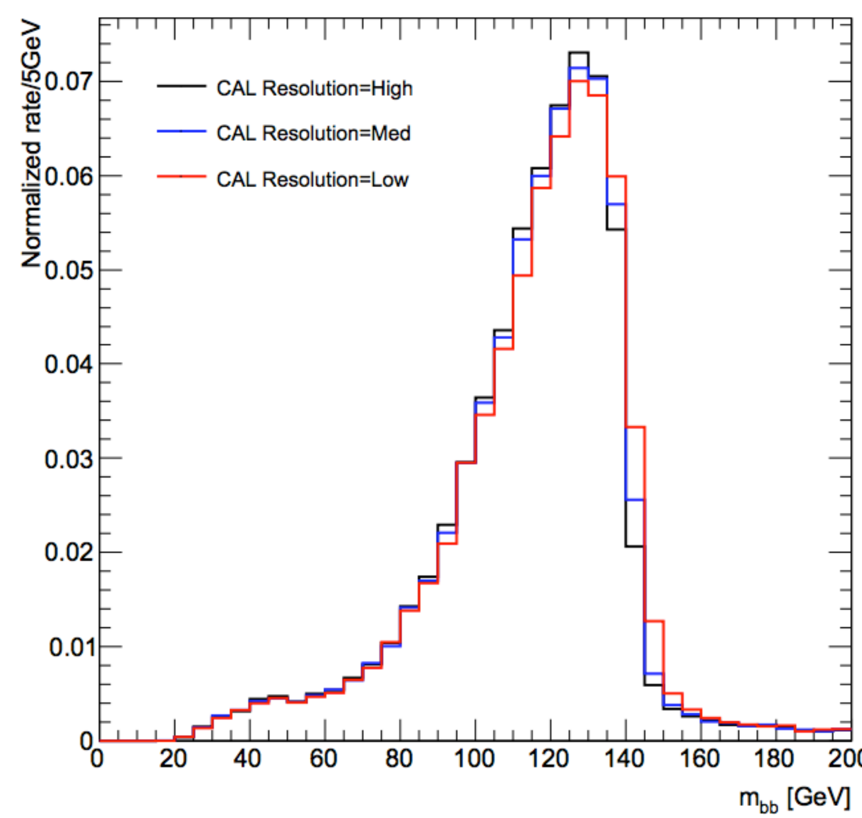
HCAL energy resolution

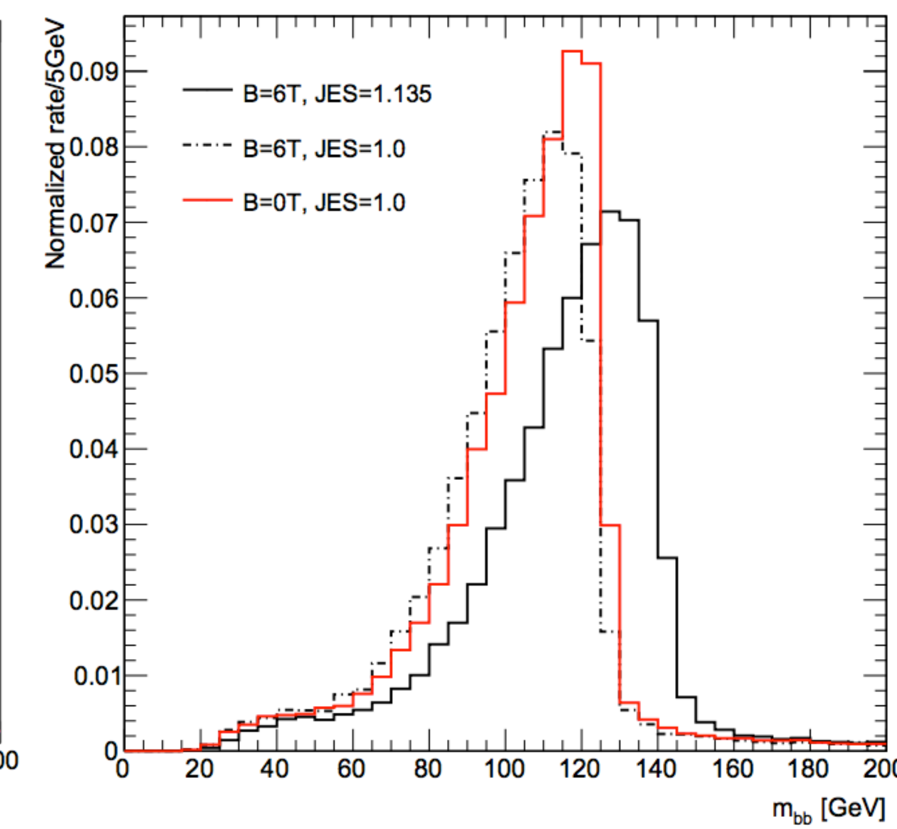
$$\Delta E/E|_{\rm HCAL} = \begin{cases} \sqrt{0.03^2 + 0.5^2 \, \text{GeV}/E} & \text{for} \ \ |\eta| \leq 4 \, , \\ \sqrt{0.05^2 + 1.0^2 \, \text{GeV}/E} & \text{for} \ \ 4 < |\eta| \leq 6 \, . \end{cases}$$

HL-100 TeV

	ECAL				HCAL			
	$\|\eta\| \leq 4$		$4 < \|\eta\| \leq 6$		$\|\eta\| \leq 4$		$4 < \|\eta\| \leq 6$	
	a	b	a	b	a	b	a	b
Low	0.02	0.2	0.01	0.1	0.05	1.0	0.05	1.0
Medium	0.01	0.1	0.01	0.1	0.03	0.5	0.05	1.0
High	0.007	0.06	0.01	0.1	0.01	0.3	0.03	0.5







R. Contino et al., CERN Yellow Report, no. 3, 255 (2017).

Detector simulation : Delphes3, FCChh template.

Magnetic field 6 T and the jet energy scale of 1.135 is taken to get the correct peak position at MH in the invariant mass distribution of the b-quark pair in the signal process.

For the b-jet tagging efficiency and related jet fake rates, we are taking $\epsilon_b = 75\ \%$, $P_{c\to b} = 10\ \%$, and $P_{j\to b} = 1\ \%$ [20].

For the photon efficiency and jet fake rate, we are taking: $\epsilon_\gamma = 95\,\%\,(|\eta_\gamma| \leq 1.5)$, $90\,\%\ (1.5 < |\eta_\gamma| \leq 4)$, $80\,\%\ (4 < |\eta_\gamma| \leq 6)$, and $P_{j\to\gamma} = 1.35\times 10^{-3}$ [20]. For the $e \to \gamma$ fake rate, with a separation between the barrel and endcap regions at $|\eta| = 2$, we take $P_{e\to\gamma} = 2\,\%\,(5\,\%)$ in the barrel (endcap) region as a reference [30] .

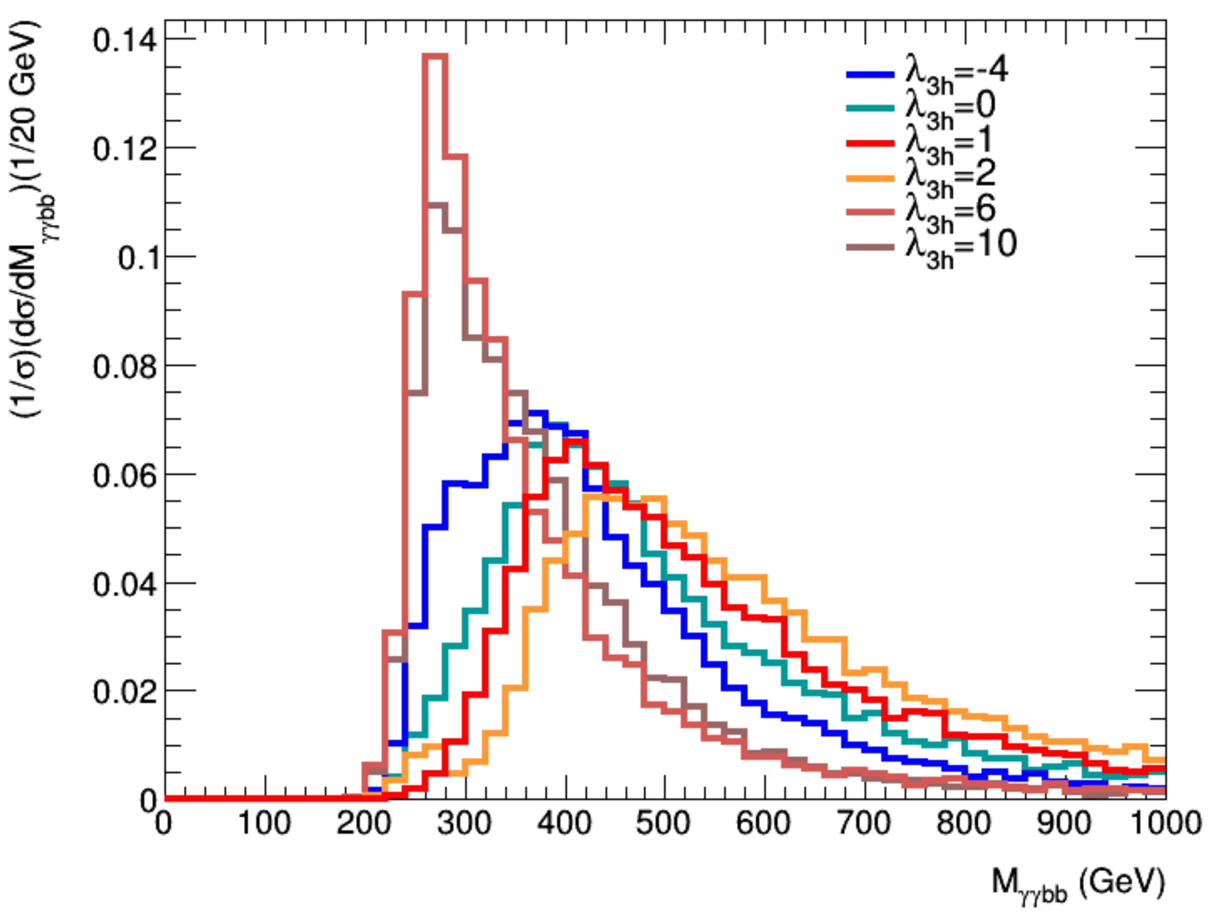
$$p_{j\to\gamma} = \alpha \exp(-p_{T,j}/\beta)\,, \tag{44}$$

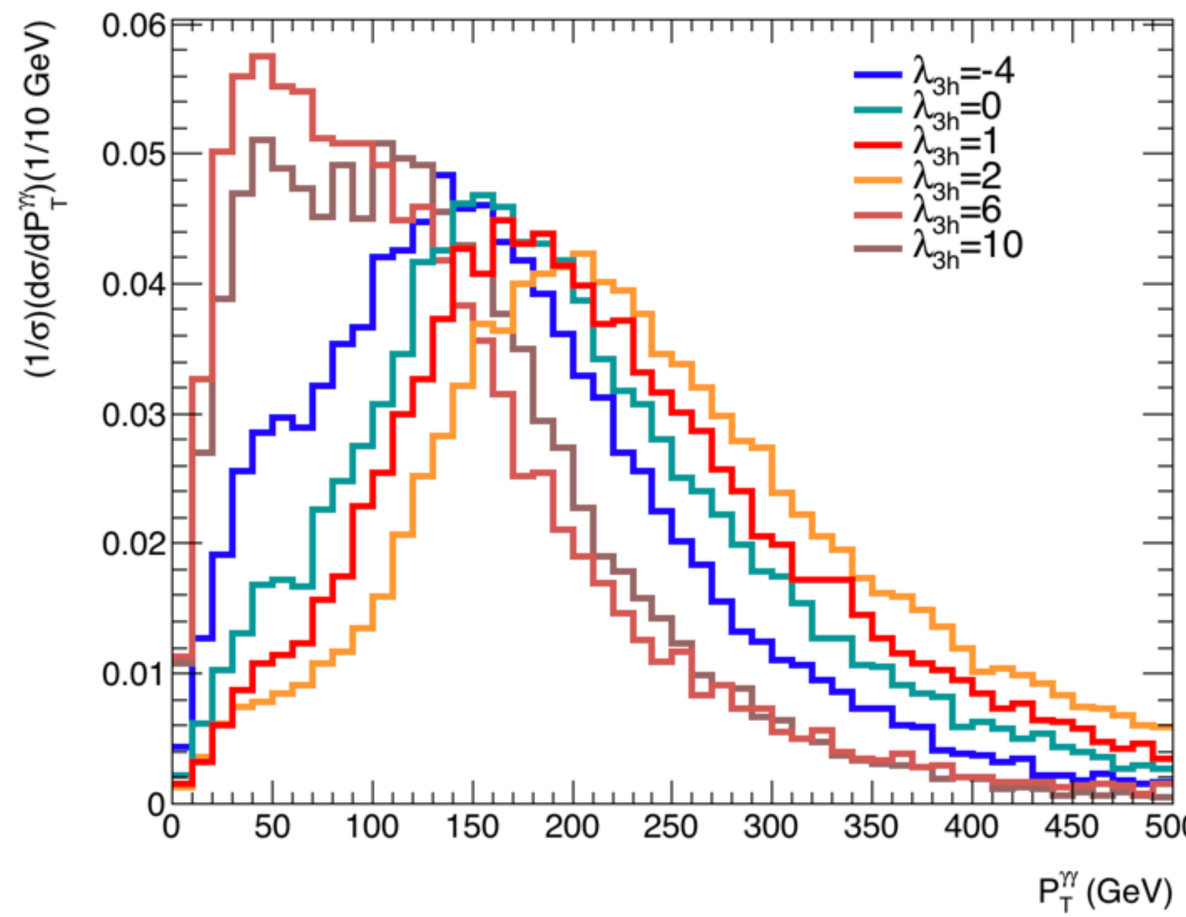
where α and β are parameters whose benchmark values are set to $\alpha = 0.01$ and $\beta = 30$ GeV. Photons

[20] R. Contino et al., CERN Yellow Report, no. 3, 255 (2017)
[30] ATLAS Collaboration, ATL-PHYS-PUB-2017-001

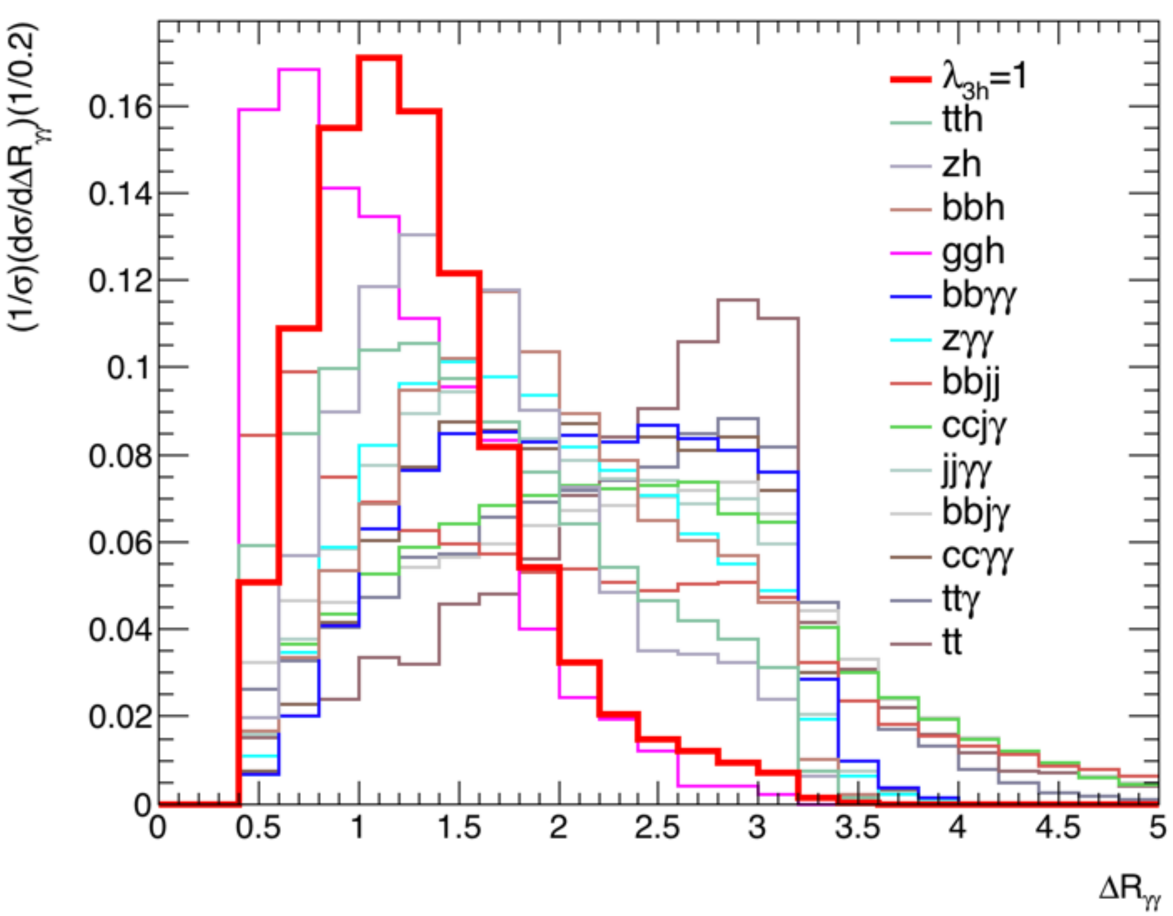
100 TeV σ(h h)$_{SM}$:1749 fb, NNLO+NNLL

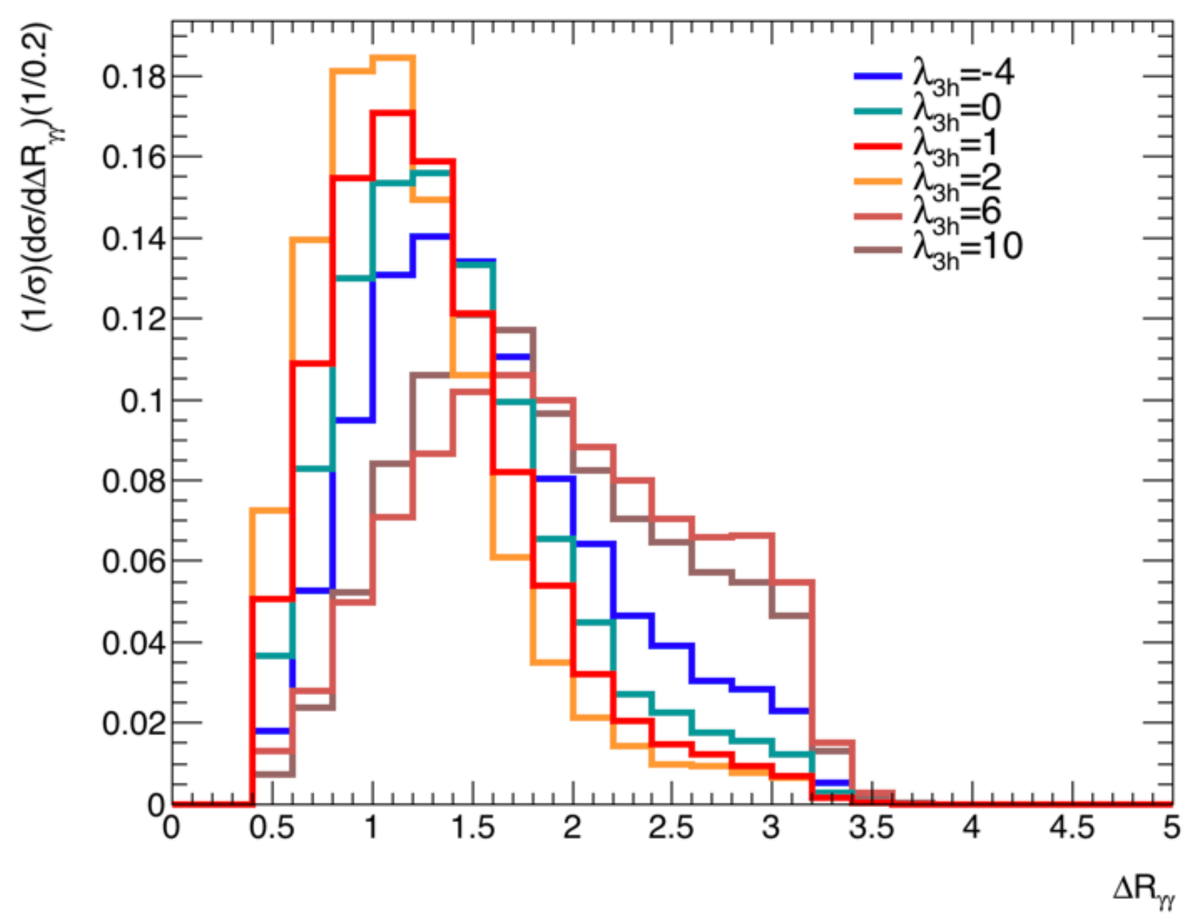
λ_{3H}	-4	0	1	2	6	10
$\sigma \cdot BR(HH \to b\bar{b}\gamma\gamma)$ [fb]	46.97	8.99	4.62	2.32	13.61	57.78





Sequence	Event Selection Criteria at the HL-100 TeV hadron collider
1	Di-photon trigger condition, ≥ 2 isolated photons with $P_T > 30$ GeV, $\|\eta\| < 5$
2	≥ 2 isolated photons with $P_T > 40$ GeV, $\|\eta\| < 3$, $\Delta R_{j\gamma} > 0.4$
3	≥ 2 jets identified as b-jets with leading(subleading) $P_T > 50(40)$ GeV, $\|\eta\| < 3$
4	Events are required to contain ≤ 5 jets with $P_T > 40$ GeV within $\|\eta\| < 5$
5	No isolated leptons with $P_T > 40$ GeV, $\|\eta\| < 3$
6	$0.4 < \Delta R_{b\bar{b}} < 3.0$, $0.4 < \Delta R_{\gamma\gamma} < 3.0$
7	$122.5 < M_{\gamma\gamma}/\text{GeV} < 127.5$ and $90 < M_{b\bar{b}}/\text{GeV} < 150$
8	$P_T^{\gamma\gamma} > 100$ GeV, $P_T^{b\bar{b}} > 100$ GeV



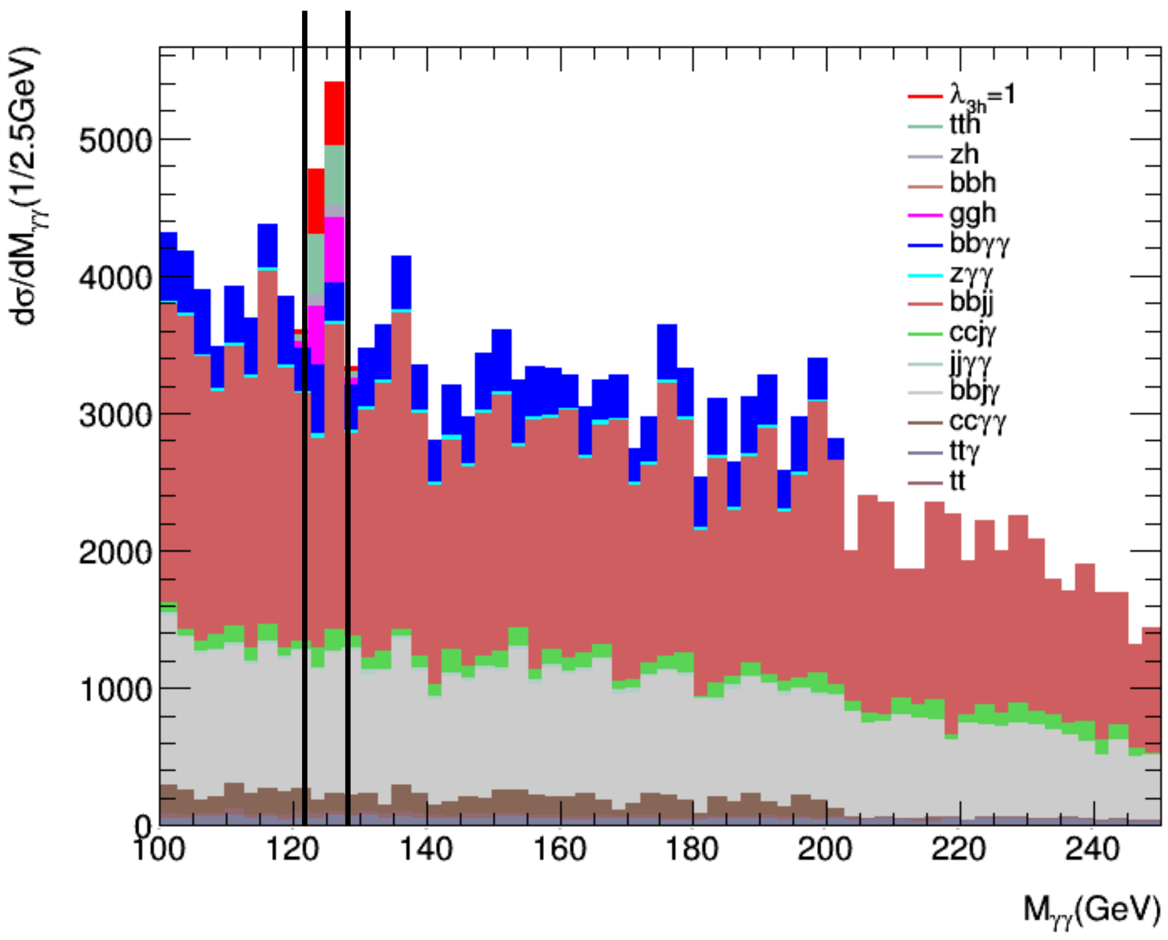


λ_{3H}	-4		0		1		2		6		10	
Cross section (fb)	46.97		8.99		4.62		2.32		13.61		57.78	
Cuts	Eff.%	No.#	%	No.#	%	No.#	%	#	%	#	%	#
1. diphoton trigger	56.06	78988	57.78	15582	58.99	8176	60.00	4176	53.44	21818	53.82	93293
2. ≥ 2 isolated photons	36.31	51158	39.21	10575	41.29	5722	43.40	3021	32.39	13225	32.94	57105
3-1. jet candidates	29.07	40965	32.77	8838	35.36	4901	37.94	2641	23.87	9746	24.74	42881
3-2 ≥ 2 two b-jet	9.57	13492	11.41	3076	12.75	1767	14.18	987	7.31	2986	7.65	13252
4. no. of jets ≤ 5	9.03	12724	10.60	2860	11.79	1634	13.04	907	6.99	2856	7.29	12638
5. lepton veto	9.03	12724	10.60	2860	11.79	1634	13.04	907	6.99	2856	7.29	12637
6. $\Delta R_{\gamma\gamma,bb}$ cut	8.32	11730	10.08	2718	11.34	1572	12.57	875	5.92	2419	6.39	11023
7-1. Higgs mass window $M_{\gamma\gamma}$	7.78	10968	9.35	2523	10.51	1456	11.57	805	5.55	2268	5.97	10341
7-2. Higgs mass window M_{bb}	6.14	8650	7.32	1974	8.23	1140	9.08	632	4.48	1830	4.77	8264
8. $p_{T_{\gamma\gamma}}, p_{T_{bb}}$ cuts	3.98	5604	5.61	1514	6.79	941	8.01	557	1.84	753	2.21	3838
other/barrel ratio	31.64%		30.14%		30.05%		29.18%		33.03%		31.26%	

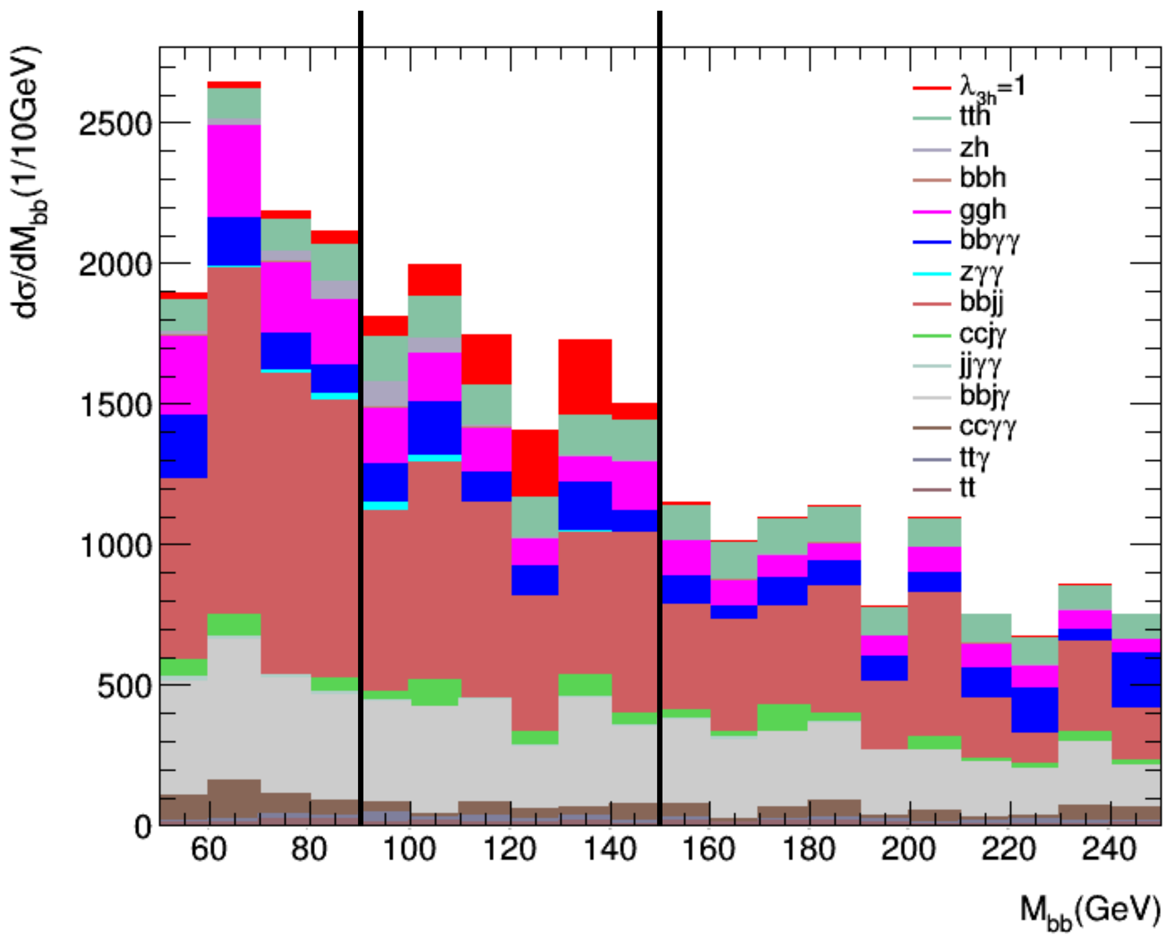
[1] : NNLO+NNLL, infinite top mass.

[2] : NNLO in FT approximation, finite top mass.

122.5 - 127.5 GeV



90 - 150 GeV



Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)	# of Gen. Events
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -4$	5604.46 ± 63.36	4257.36 ± 57.90	1347.10 ± 23.22	0.32 ± 0.007	3×10^5
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	1513.56 ± 14.81	1163.04 ± 14.09	350.52 ± 3.57	0.30 ± 0.005	3×10^5
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 1$	941.37 ± 7.65	723.86 ± 6.64	217.51 ± 3.66	0.30 ± 0.006	3×10^5
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 2$	557.36 ± 1.93	431.45 ± 1.87	125.91 ± 1.21	0.29 ± 0.003	3×10^5
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 6$	753.18 ± 6.02	566.18 ± 5.59	187.00 ± 5.33	0.33 ± 0.010	3×10^5
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 10$	3838.33 ± 36.82	2924.25 ± 32.11	914.08 ± 28.01	0.31 ± 0.010	3×10^5
$gg\,H(\gamma\gamma)$	890.47 ± 72.91	742.97 ± 58.43	147.50 ± 20.51	0.20 ± 0.03	10^6
$t\bar{t}\,H(\gamma\gamma)$	868.73 ± 8.53	659.33 ± 12.94	209.40 ± 7.04	0.32 ± 0.01	9.63×10^5
$Z\,H(\gamma\gamma)$	168.86 ± 5.91	122.91 ± 4.68	45.95 ± 1.69	0.37 ± 0.02	10^6
$b\bar{b}\,H(\gamma\gamma)$	9.82 ± 0.59	7.00 ± 0.58	2.82 ± 0.25	0.40 ± 0.05	10^6
$b\bar{b}\gamma\gamma$	770.42 ± 23.48	514.96 ± 20.81	255.46 ± 15.10	0.50 ± 0.04	1.1×10^7
$c\bar{c}\gamma\gamma$	222.88 ± 40.55	111.44 ± 32.55	111.44 ± 26.92	1.00 ± 0.38	1.1×10^7
$jj\gamma\gamma$	32.28 ± 3.23	20.98 ± 3.99	11.30 ± 2.34	0.54 ± 0.15	10^7
$b\bar{b}j\gamma$	1829.13 ± 75.08	1288.34 ± 45.27	540.79 ± 49.79	0.42 ± 0.04	1.1×10^7
$c\bar{c}j\gamma$	293.81 ± 40.11	216.49 ± 36.71	77.32 ± 32.97	0.36 ± 0.16	1.1×10^7
$b\bar{b}jj$	3569.73 ± 209.93	2294.83 ± 207.69	1274.90 ± 189.68	0.56 ± 0.10	3.43×10^6
$Z(b\bar{b})\gamma\gamma$	54.87 ± 3.79	35.72 ± 3.36	19.15 ± 2.02	0.54 ± 0.08	10^6
$t\bar{t}$ (≥ 1 leptons)	59.32 ± 7.40	38.32 ± 5.79	21.00 ± 5.61	0.55 ± 0.17	1.1×10^7
$t\bar{t}\gamma$ (≥ 1 leptons)	105.68 ± 8.22	62.53 ± 5.07	43.15 ± 7.95	0.69 ± 0.14	10^6
Total Background	8876.00 ± 243.07	6115.82 ± 227.41	2760.18 ± 202.67	0.45 ± 0.04	
Significance Z	9.823	9.082	4.087		
Combined significance		9.959			

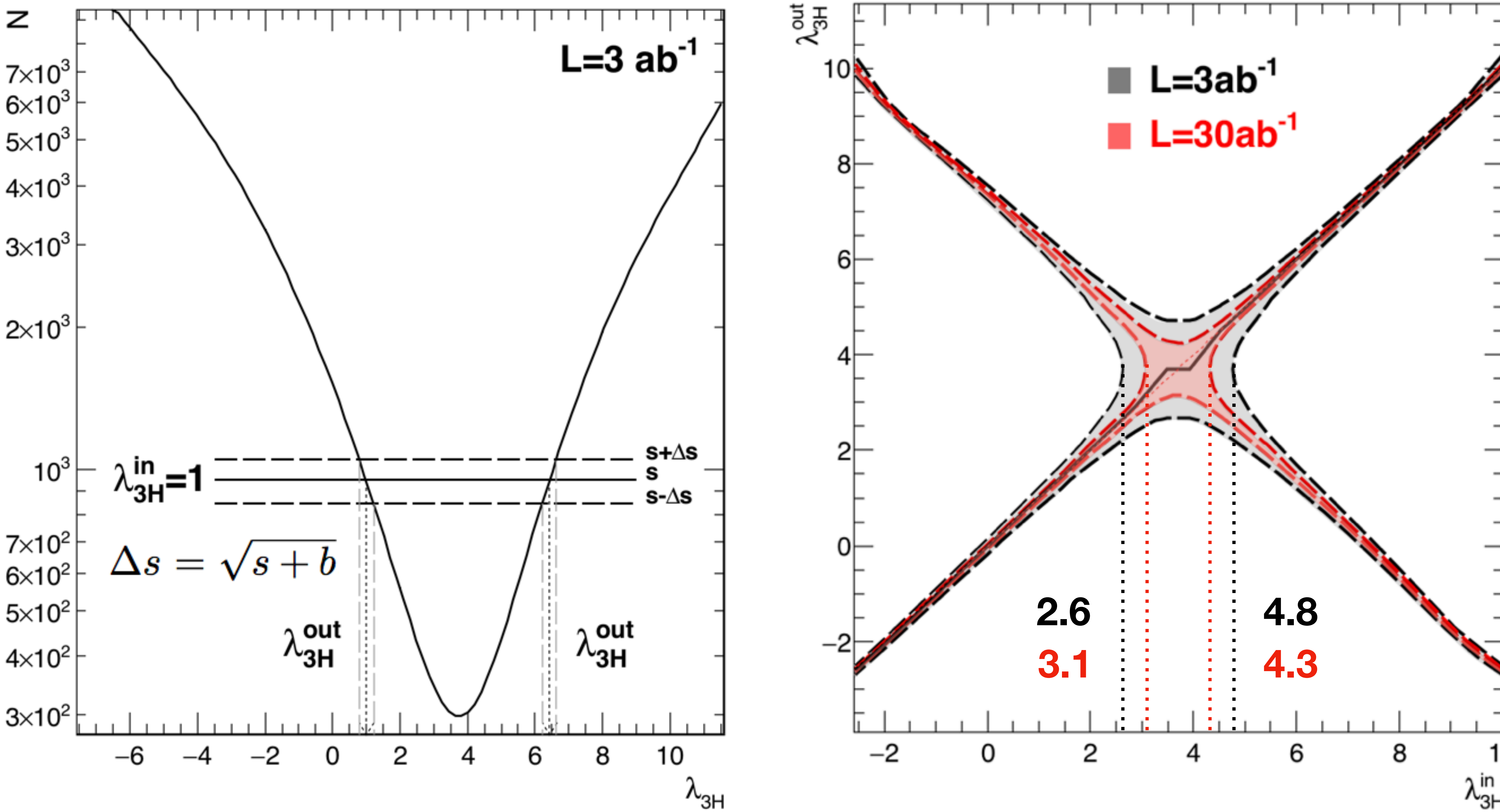
$\lambda_{3H} = 1$

λ_{3H}	-4	0	1	2	6	10
Z[1]	53.766	15.416	9.681	5.770	7.770	37.726
Z[2]	38.503	10.871	6.808	4.049	5.459	26.856

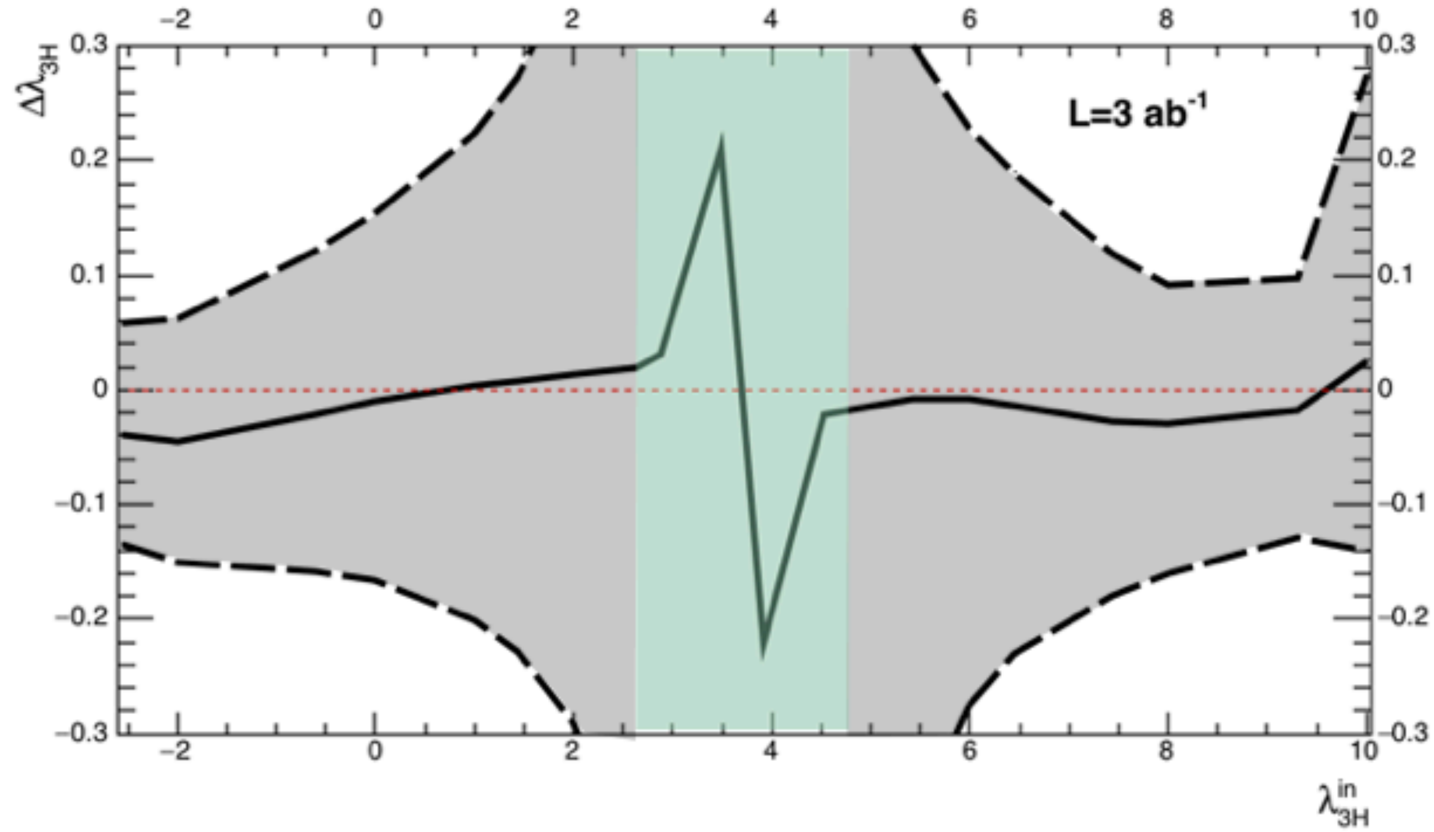
λ_{3H}	-4		0		1		2		6		10	
Cross section (fb)	46.97		8.99		4.62		2.32		13.61		57.78	
Cuts	Eff.%	No.#	%	No.#	%	No.#	%	#	%	#	%	#
1. diphoton trigger	56.06	78988	57.78	15582	58.99	8176	60.00	4176	53.44	21818	53.82	93293
2. ≥ 2 isolated photons	36.31	51158	39.21	10575	41.29	5722	43.40	3021	32.39	13225	32.94	57105
3-1. jet candidates	29.07	40965	32.77	8838	35.36	4901	37.94	2641	23.87	9746	24.74	42881
3-2 ≥ 2 two b-jet	9.57	13492	11.41	3076	12.75	1767	14.18	987	7.31	2986	7.65	13252
4. no. of jets ≤ 5	9.03	12724	10.60	2860	11.79	1634	13.04	907	6.99	2856	7.29	12638
5. lepton veto	9.03	12724	10.60	2860	11.79	1634	13.04	907	6.99	2856	7.29	12637
6. $\Delta R_{\gamma\gamma,bb}$ cut	8.32	11730	10.08	2718	11.34	1572	12.57	875	5.92	2419	6.39	11023
7-1. Higgs mass window $M_{\gamma\gamma}$	7.78	10968	9.35	2523	10.51	1456	11.57	805	5.55	2268	5.97	10341
7-2. Higgs mass window M_{bb}	6.14	8650	7.32	1974	8.23	1140	9.08	632	4.48	1830	4.77	8264
8. $p_{T_{\gamma\gamma}}, p_{T_{bb}}$ cuts	3.98	5604	5.61	1514	6.79	941	8.01	557	1.84	753	2.21	3838
other/barrel ratio	31.64%		30.14%		30.05%		29.18%		33.03%		31.26%	

[1] : NNLO+NNLL, infinite top mass.

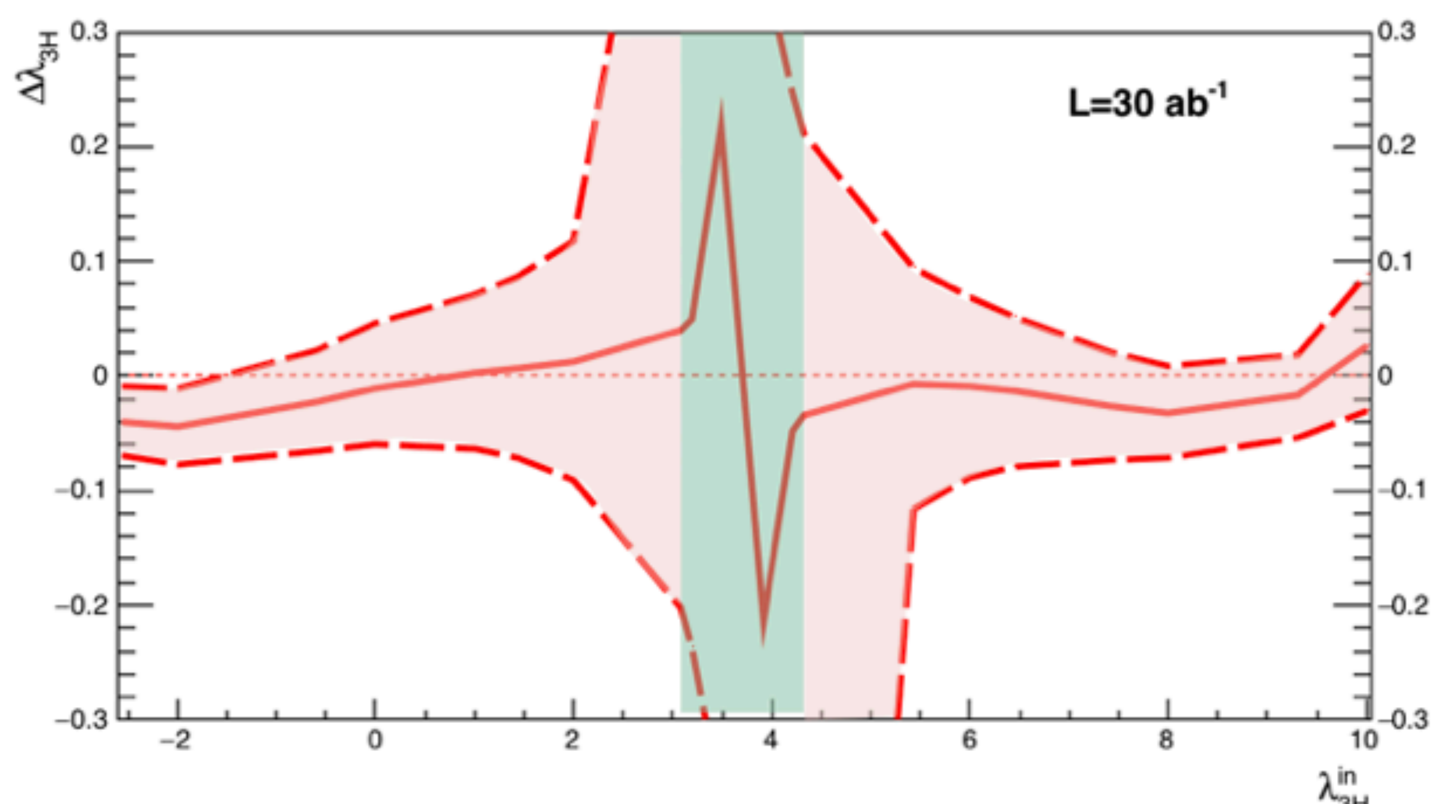
[2] : NNLO in FT approximation, finite top mass.


N
L=3 ab^{-1}
λ_{3H}^{in}=1
s+Δs
s
s-Δs
$\Delta s = \sqrt{s+b}$
λ_{3H}^{out}
λ_{3H}^{out}
λ_{3H}
λ_{3H}^{out}
L=3ab^{-1}
L=30ab^{-1}
2.6
3.1
4.8
4.3
λ_{3H}^{in}

$3ab^{-1}$: 2.6 ≲ λ_{3H} ≲ 4.8,
λ_{3H} =1 accuracy 20%

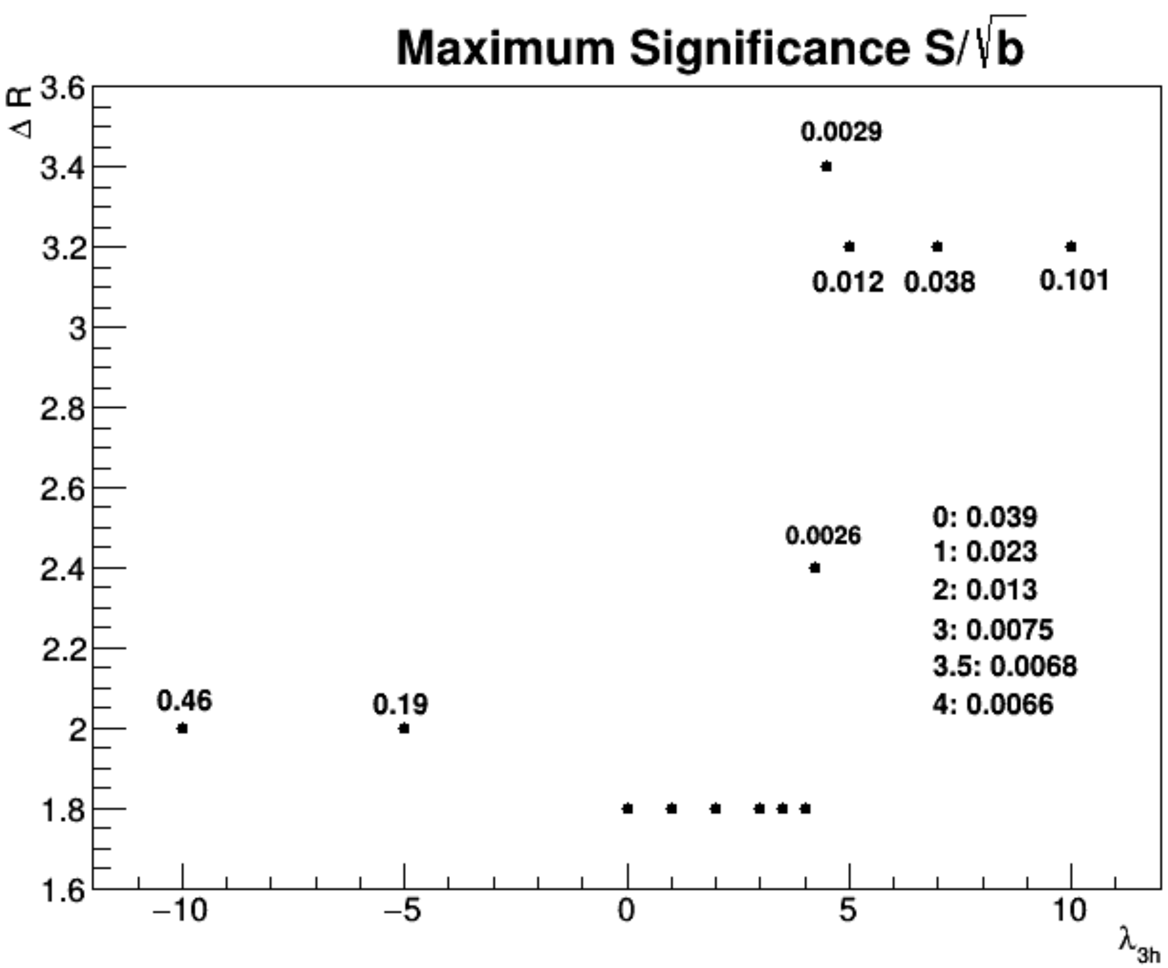


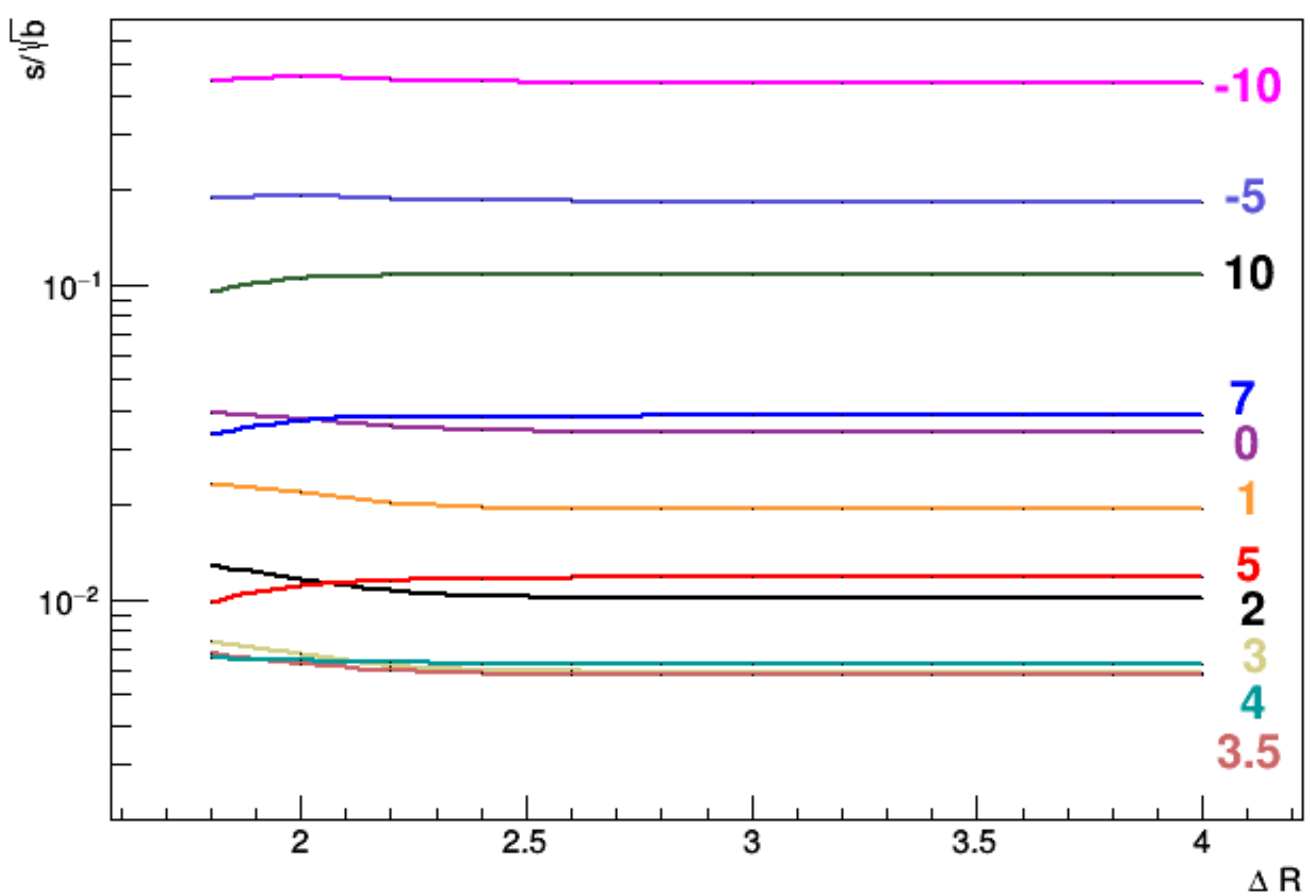
$30ab^{-1}$: 3.1 ≲ λ_{3H} ≲ 4.3,
λ_{3H} =1 accuracy 7%



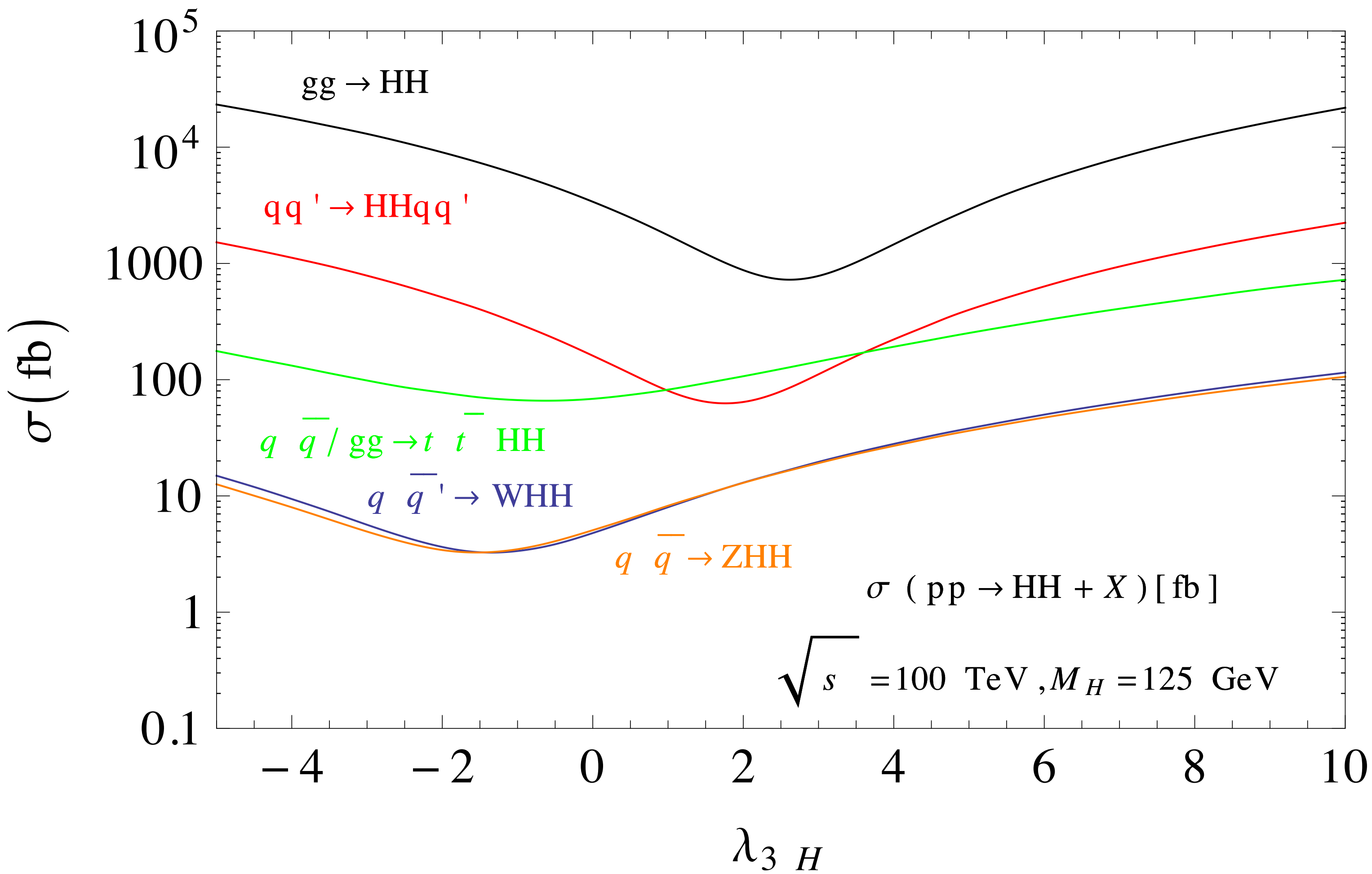
[1] : NNLO+NNLL, infinite top mass.

Significance for different λ_{3H} with varying ΔR cuts at HL-LHC





Conclusion



1. **100 TeV 3ab-1 : 2.6 ≲ λ_{3H} ≲ 4.8, λ_{3H} =1 accuracy 20%.**

2. **the σ(hh) minimum falls on different λ_{3H} for different production channel, i.e. VHH channel.**

3. **VBF channel cross section is ~O(10) smaller, but two energetic jet help to reduce BG.**

4. **Deep learning study can help to increase the efficiency, i.e. improve b-tagging, b-jet reconstruction.**

Thanks