Higgs-boson-pair production $H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ from gluon fusion at the HL-LHC and HL-100 TeV hadron collider

Collaborators : Prof. Kingman Cheung, Prof. Jae Sik Lee, Dr. Chih-Ting Lu, Dr. Jung Chang

Ref : 1. An exploratory study of Higgs-boson pair production (JHEP 1508(2015) 133)

2. Higgs-boson-pair production $H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ from gluon fusion at the HL-LHC and HL-100 TeV hadron collider (arxiv :1804.07130)

3. Higgs-boson-pair production $H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ from gluon fusion with multivariate techenique (Work in Progress)

24 August @ ACADEMIA SINICA, TAIWAN

Jubin Park (Chonnam National University)

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  1. NLO and NNLO QCD corrections….
  2. TMVA is used. The BTD method can give a better result.
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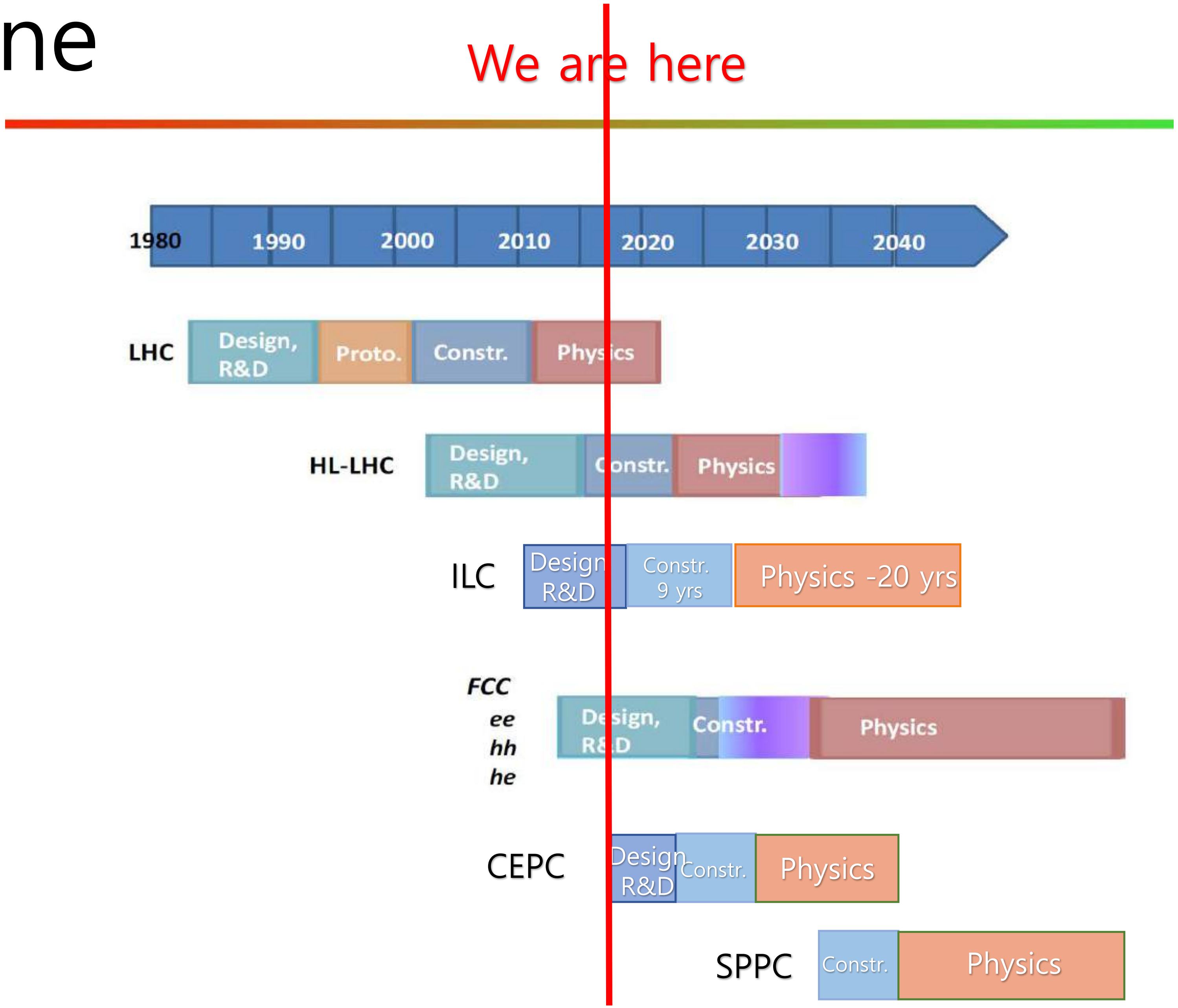
Motivations

- Self-coupling of the Higgs boson is a crucial property which depends on the dynamics of the electroweak symmetry breaking sector.
- One of the probes of Higgs self-coupling is the Higgs-boson-pair production at the LHC.
- In this work, we perform the most up-to-date comprehensive signal-background analysis for Higgs-pair production through gluon fusion and the $H(\to b\bar{b})H(\to \gamma\gamma)$ channel at the HL-LHC and HL-100 TeV hadron collider, with the goal of probing the self-coupling λ_{3H} of the Higgs boson.

Timeline


We are here
1980
1990
2000
2010
2020
2030
2040
LHC
Design, R&D
Proto.
Constr.
Physics
HL-LHC
Design, R&D
Constr.
Physics
ILC
Design R&D
Constr. 9 yrs
Physics -20 yrs
FCC
ee
hh
he
Design, R&D
Constr.
Physics
CEPC
Design R&D
Constr.
Physics
SPPC
Constr.
Physics

Understanding the process

in the effective Lagrangian

$$-\mathcal{L} = \frac{1}{3!}\left(\frac{3M_H^2}{v}\right)\lambda_{3H} H^3 + \frac{m_t}{v}\bar{t}\left(g_t^S + i\gamma_5 g_t^P\right) t\, H + \frac{1}{2}\frac{m_t}{v^2}\bar{t}\left(g_{tt}^S + i\gamma_5 g_{tt}^P\right) t\, H^2$$

★ In the SM, $\lambda_{3H} = g_t^s = 1$ and $g_{tt}^s = g_{tt}^P = 0$

SM Higgs self couplings

$$\mathcal{L} = -\frac{1}{2}m_H^2 H^2 - \frac{g_{HHH}}{3!}H^3 - \frac{g_{HHHH}}{4!}H^4$$

$$g_{HHH} = \frac{3m_H^2}{v}, \quad g_{HHHH} = \frac{3m_H^2}{v^2}$$

In the gluon fusion process at the hadron collide

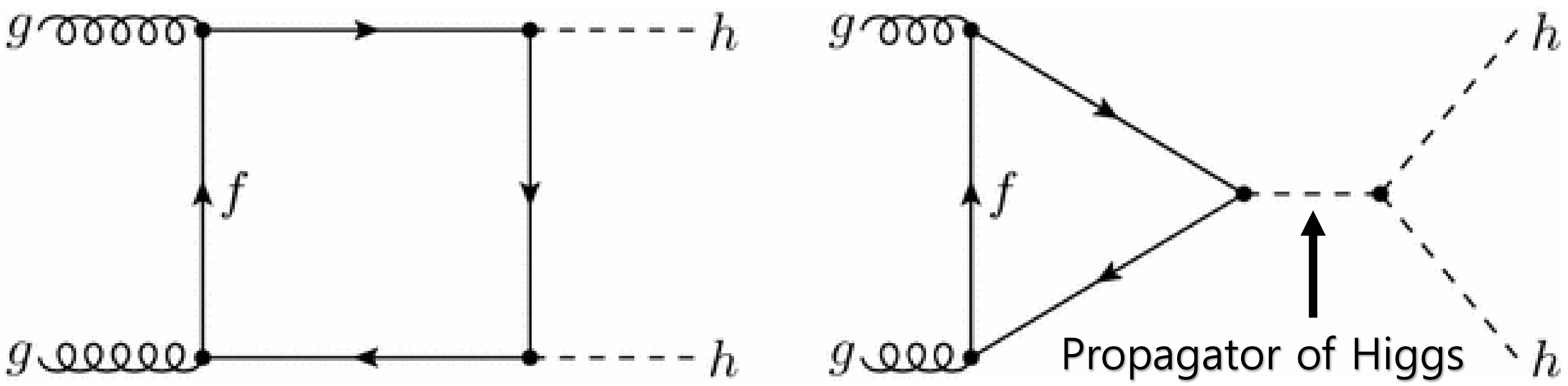
$$g(p_1)g(p_2) \rightarrow H(p_3)H(p_4)$$

The differential cross section is given by

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

Feynman diagrams

Only QCD Leading Order (LO)

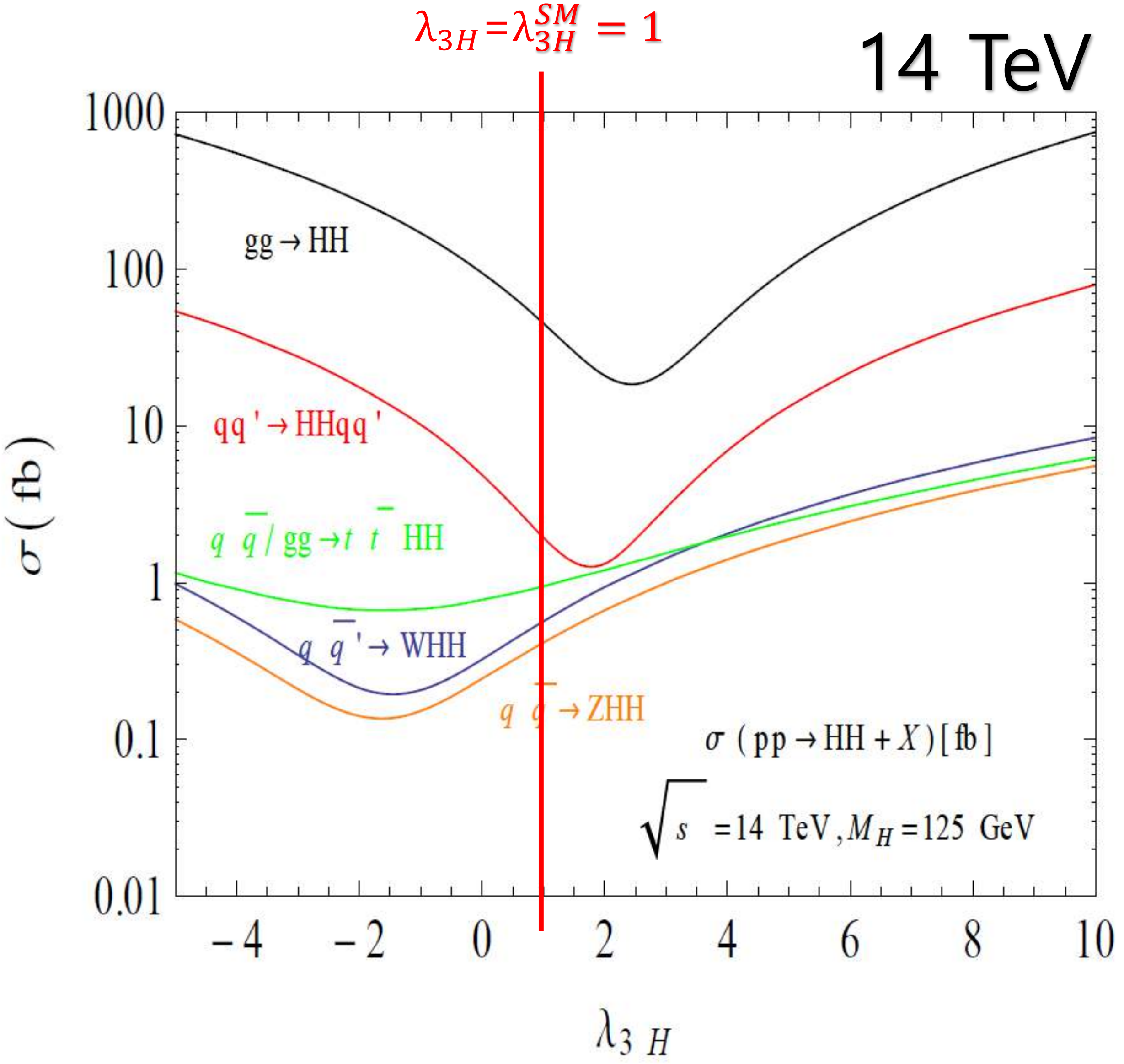


$$D(\hat{s}) = \frac{3M_H^2}{\hat{s} - M_H^2 + iM_H\Gamma_H}$$

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

Important Interference term !!! $\leftrightarrow$ λ_{3H}^{Non-SM}

For the reference, there are various production modes

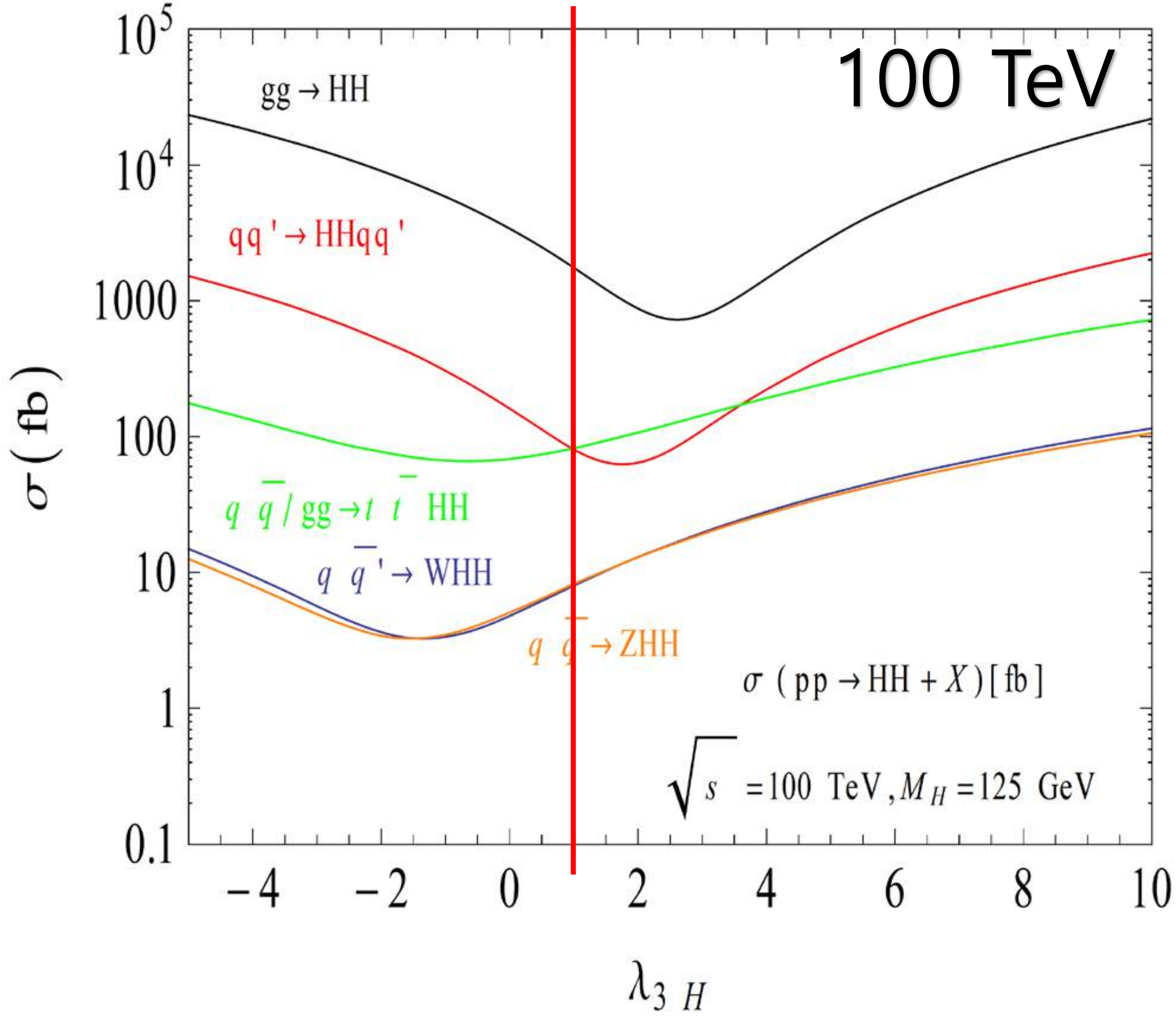


The gluon fusion production mode is dominant one !

(gg -> HH) = 45.05 fb,
(qq_0 -> $HHqq_0$) = 1.94 fb,
($qq_{(0)}$) -> V HH =0.567(V = W) =0.415(V = Z) fb,
(gg/qq -> ttHH) = 0.949 fb
are calculated at
NNLO+NNLL, NLO, NNLO, and NLO, respectively

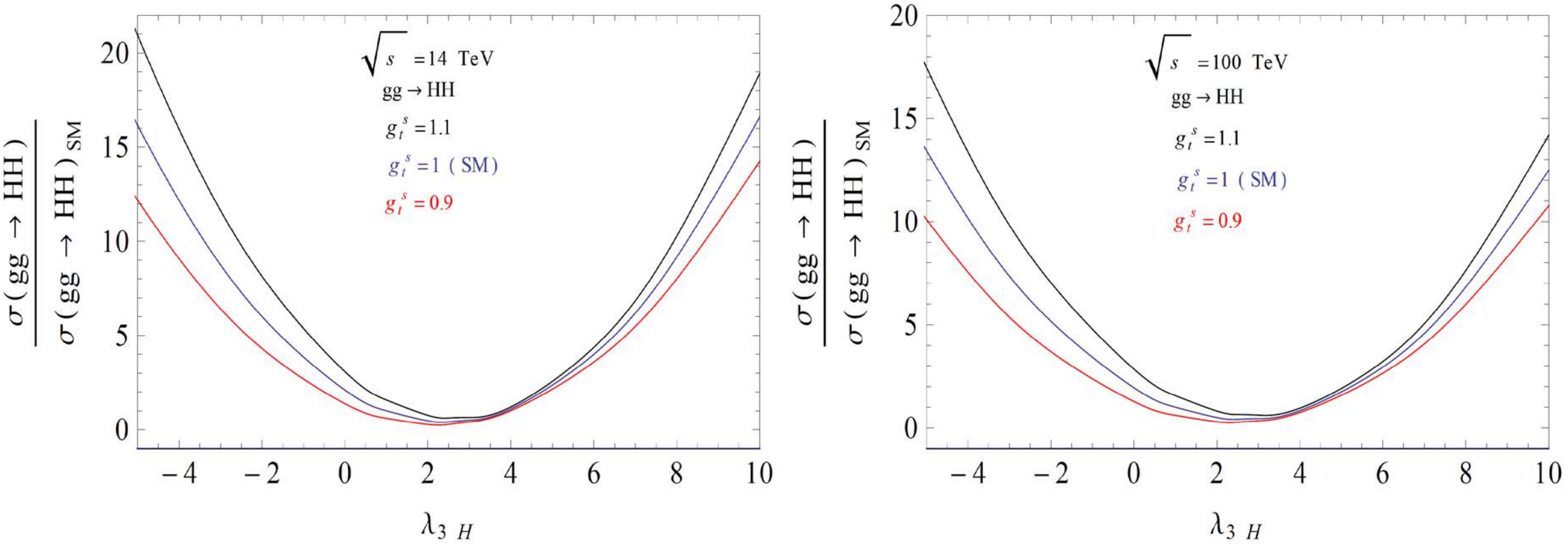
continue ....

$\lambda_{3H} = \lambda_{3H}^{SM} = 1$



The 100 TeV cross sections
(gg -> HH) = 1749 fb,
(qq0 -> HHqq0) = 80.3 fb,
(qq(0) -> V HH = 8.00(V =W) =8.23(V = Z) fb,
(gg/qq -> ttHH) = 82.1 fb
are calculated at the same orders as at 14 TeV.

Including top Yukawa uncertainty !



Ratio of cross sections (gg -> HH)=(gg -> HH)$_{SM}$ versus $_{3H}$ taking account of 10% uncertainty of the top-Yukawa coupling: g$_{St}$ = 1:1 (black), 1 (blue), and 0:9 (red) for sqrt(s) = 14 TeV (left) and sqrt(s) = 100 TeV (right).

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

In the heavy quark limit

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

There is large cancellation between the triangle and box diagrams

The production cross section normalized to the corresponding SM cross section :

★Interference term

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

$c_1(s)$	$c_2(s)$	$c_3(s)$	
0.263	-1.310	2.047	14 TeV
0.208	-1.108	1.900	100 TeV

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Outline of simulations and event selections

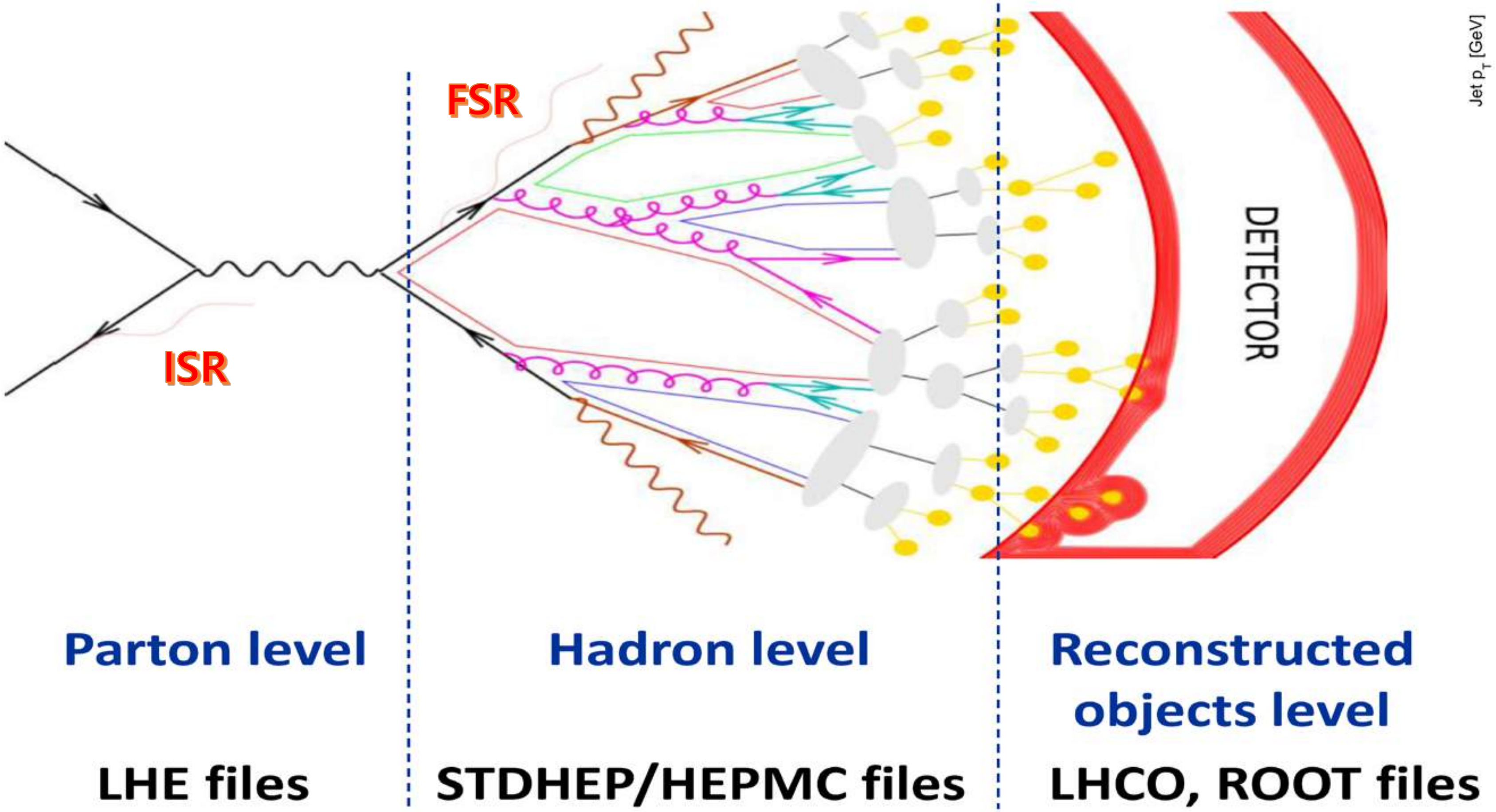
- Our goal is to disentangle the effects of the trilinear Higgs coupling, which is present in the triangle diagram, in Higgs pair production.
- We vary the value of the trilinear coupling λ_{3H} between -5 and 10 to visualize the effects of λ_{3H}.
- We consider the full set of backgrounds.

Outline of simulations

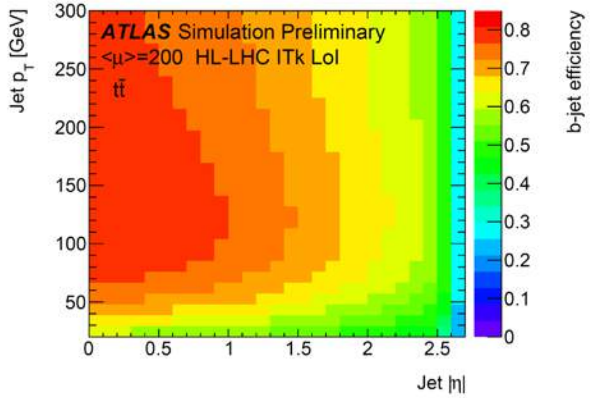
Hard Scattering Part

Hadronization and showering Processes

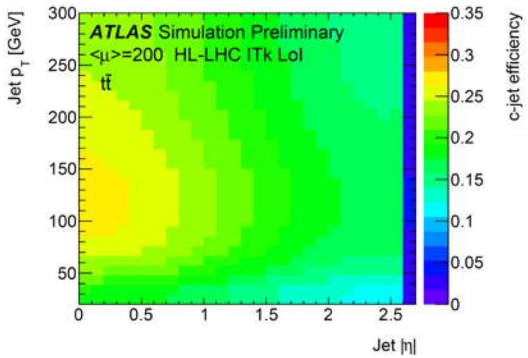
Reconstruction level



b-jet efficiency



c-jet efficiency



ATL-PHYS-PUB-2016-026

HL-LHC 14 TeV

Signal

Signal				
Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to b\bar{b}\gamma\gamma$ [15]	MG5_aMC@NLO/PYTHIA8	0.119	NNLO +NNLL	NNPDF2.3LO

Backgrounds

Backgrounds					
Background(BG)	Process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
Single-Higgs associated BG [15]	$ggH(\to \gamma\gamma)$	POWHEG − BOX/PYTHIA6	1.20×10^2	NNNLO	CT10
	$t\bar{t}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.37	NLO	
	$ZH(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	2.24	NLO	
	$b\bar{b}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.26	NLO	
Non-resonant BG	$b\bar{b}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.40×10^2	LO	CTEQ6L1
	$c\bar{c}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.14×10^3	LO	
	$jj\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.62×10^4	LO	
	$b\bar{b}j\gamma$	MG5_aMC@NLO/PYTHIA8	3.67×10^5	LO	
	$c\bar{c}j\gamma$	MG5_aMC@NLO/PYTHIA8	1.05×10^6	LO	
	$b\bar{b}jj$	MG5_aMC@NLO/PYTHIA8	4.34×10^8	LO	
	$Z(\to b\bar{b})\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	5.17	LO	
$t\bar{t}$ and $t\bar{t}\gamma$ BG	$t\bar{t}$ [18]	POWHEG − BOX/PYTHIA8	5.30×10^5	NNLO +NNLL	CT10
(≥ 1 lepton)	$t\bar{t}\gamma$ [19]	MG5_aMC@NLO/PYTHIA8	1.60×10^3	NLO	CTEQ6L1

Main fake processes and the corresponding rates

HL-LHC 14 TeV

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

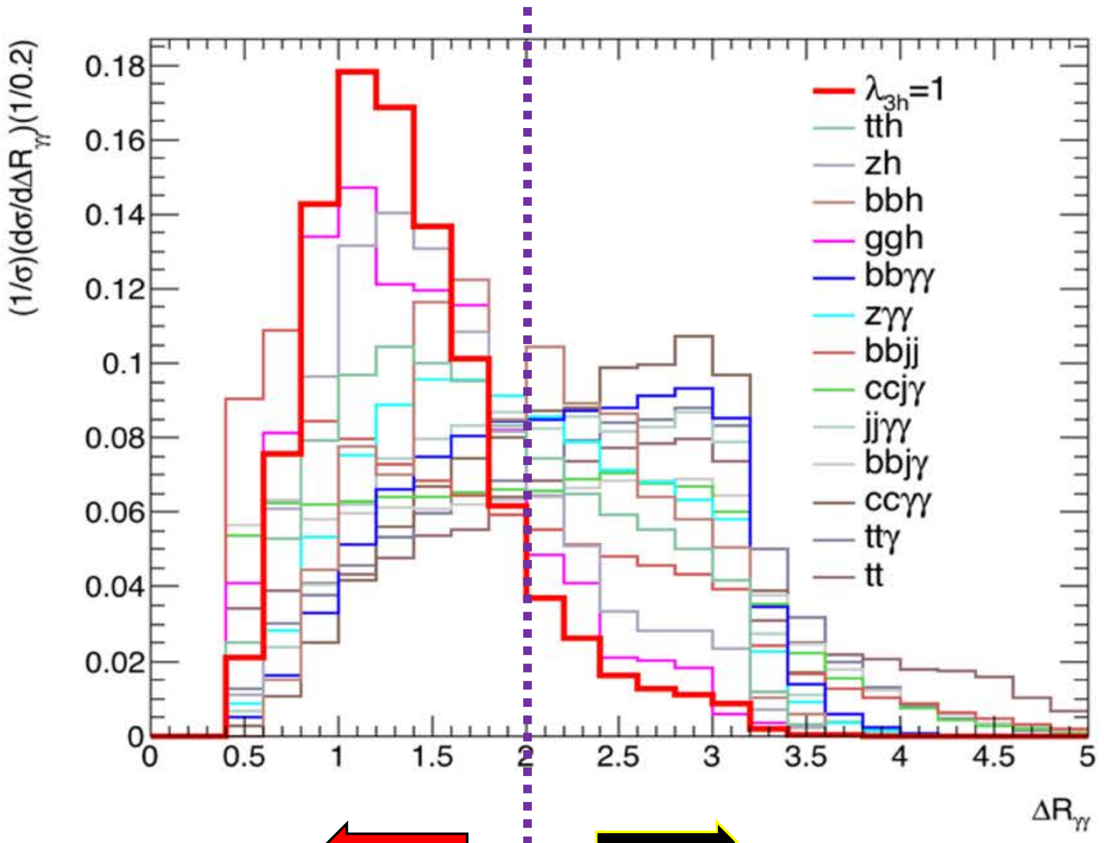
Event selection

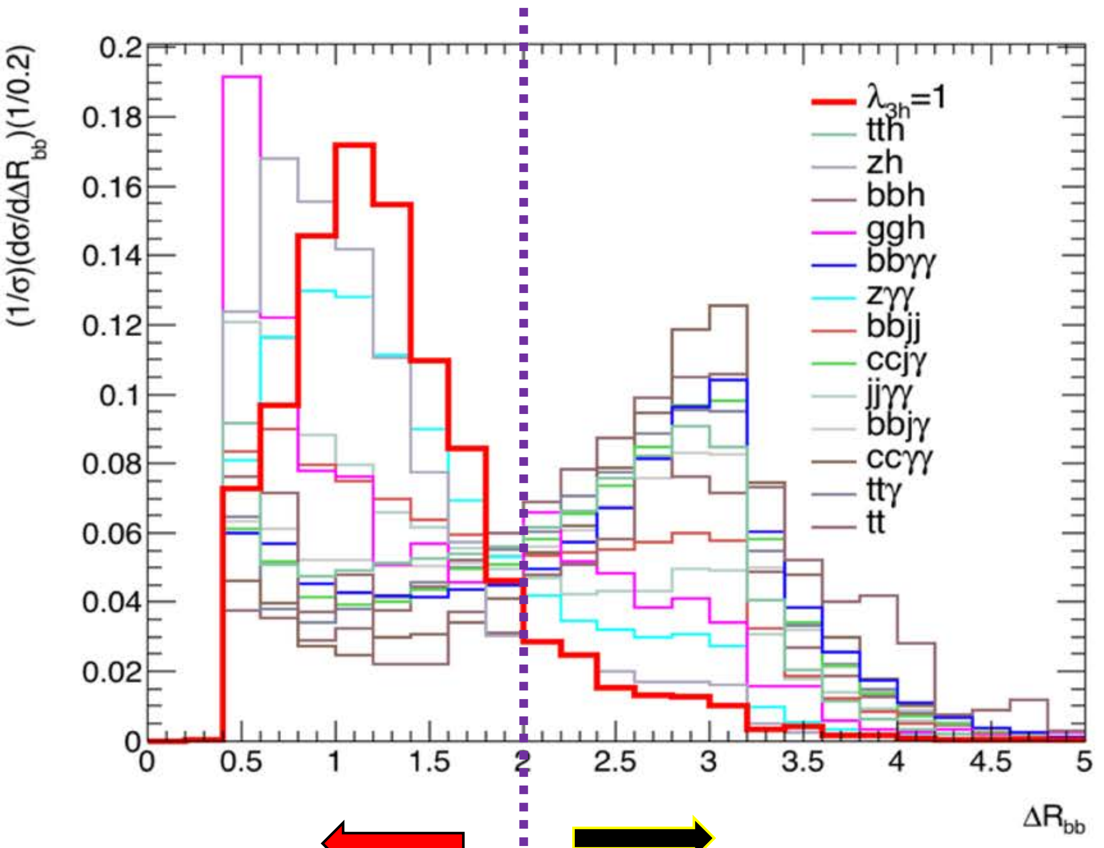
Sequence	Event Selection Criteria at the HL-LHC
1	Di-photon trigger condition, ≥ 2 isolated photons with $P_T > 25$ GeV, $\|\eta\| < 2.5$
2	≥ 2 isolated photons with $P_T > 30$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$, $\Delta R_{j\gamma} > 0.4$
3	≥ 2 jets identified as b-jets with leading(subleading) $P_T > 40(30)$ GeV, $\|\eta\| < 2.4$
4	Events are required to contain ≤ 5 jets with $P_T > 30$ GeV within $\|\eta\| < 2.5$
5	No isolated leptons with $P_T > 25$ GeV, $\|\eta\| < 2.5$
6	$0.4 < \Delta R_{b\bar{b}} < 2.0$, $0.4 < \Delta R_{\gamma\gamma} < 2.0$
7	$122 < M_{\gamma\gamma}/\text{GeV} < 128$ and $100 < M_{b\bar{b}}/\text{GeV} < 150$
8	$P_T^{\gamma\gamma} > 80$ GeV, $P_T^{b\bar{b}} > 80$ GeV

These conditions of cuts are very important to distinguish signal and background !!!!!

$$0.4 < \Delta R_{\gamma\gamma} < 2.0$$

$$0.4 < \Delta R_{b\bar{b}} < 2.0$$

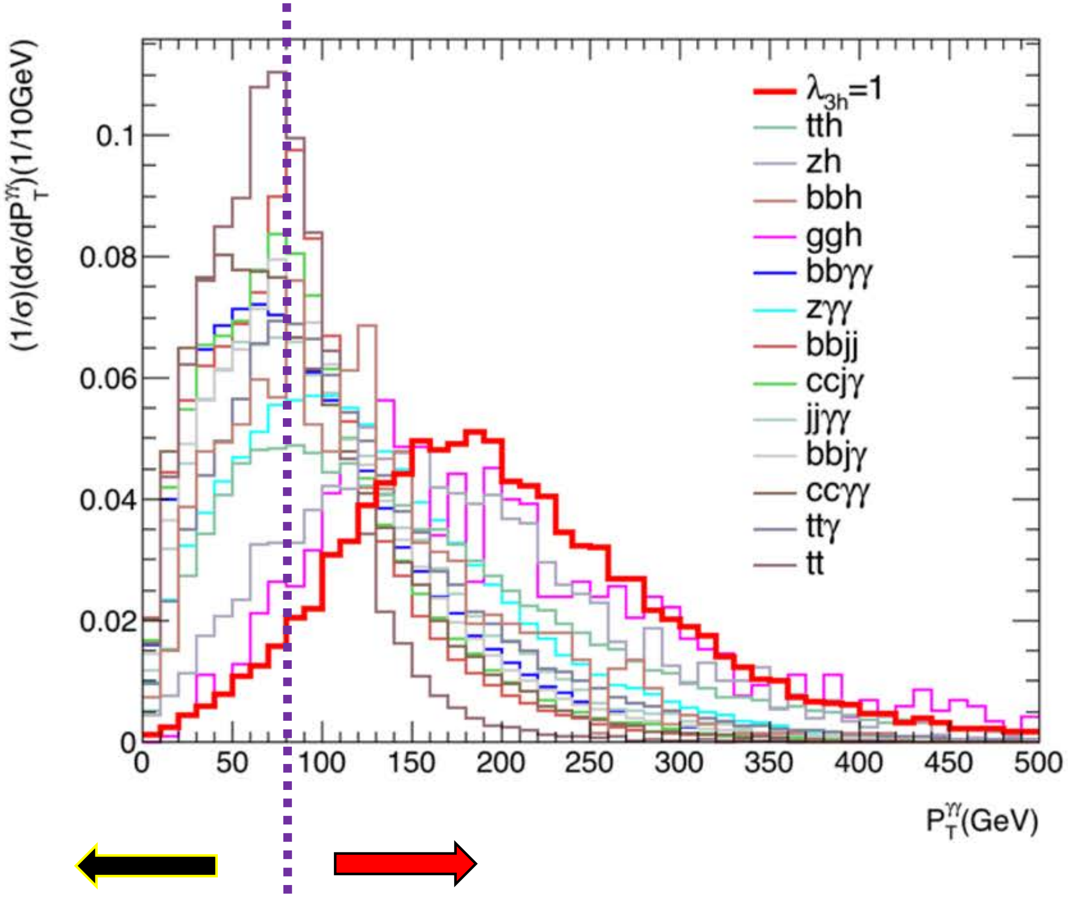




Signal-region-like | Background-region-like

Signal-region-like | Background-region-like

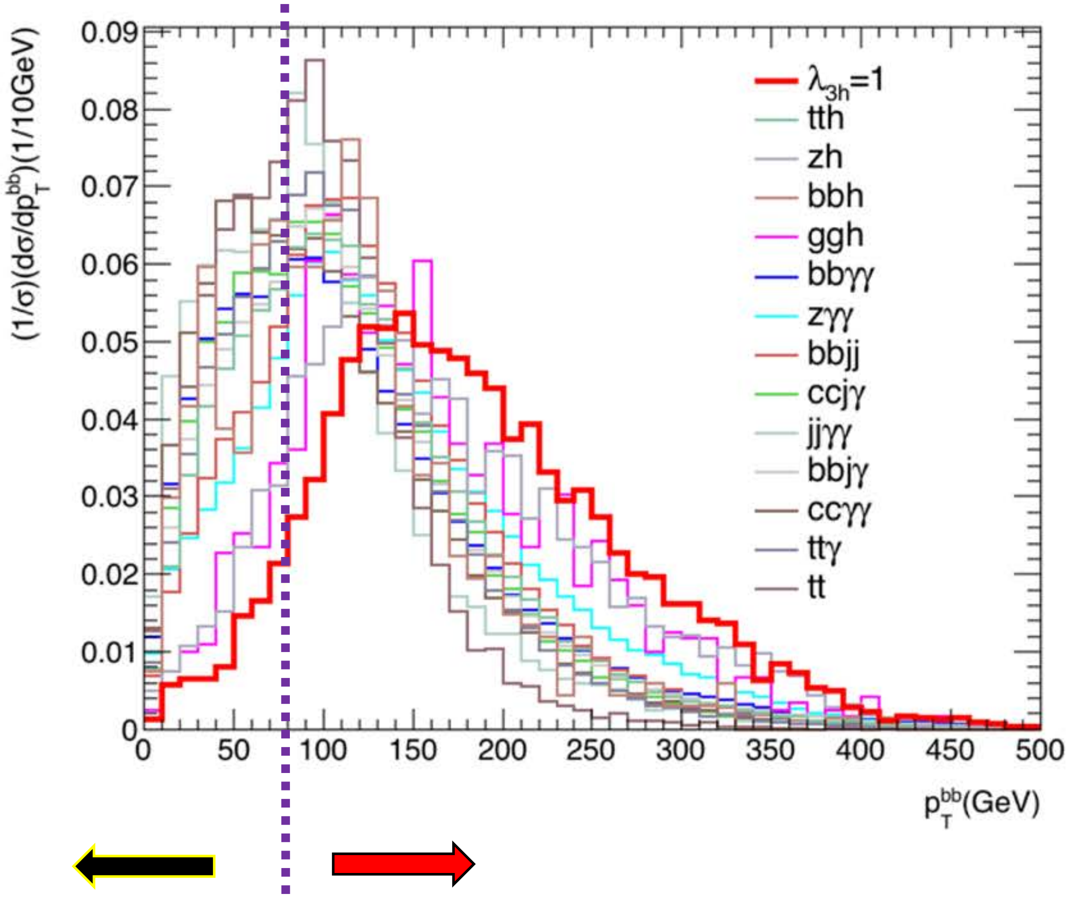
$P_T^{\gamma\gamma} > 80$ GeV



Background-region-like

Signal-region-like

$P_T^{b\bar{b}} > 80$ GeV



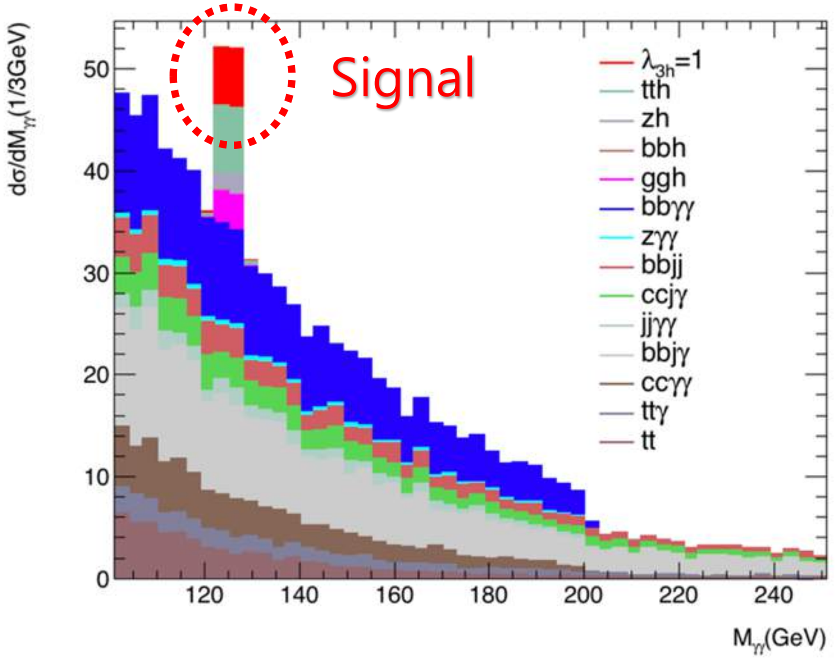
Background-region-like

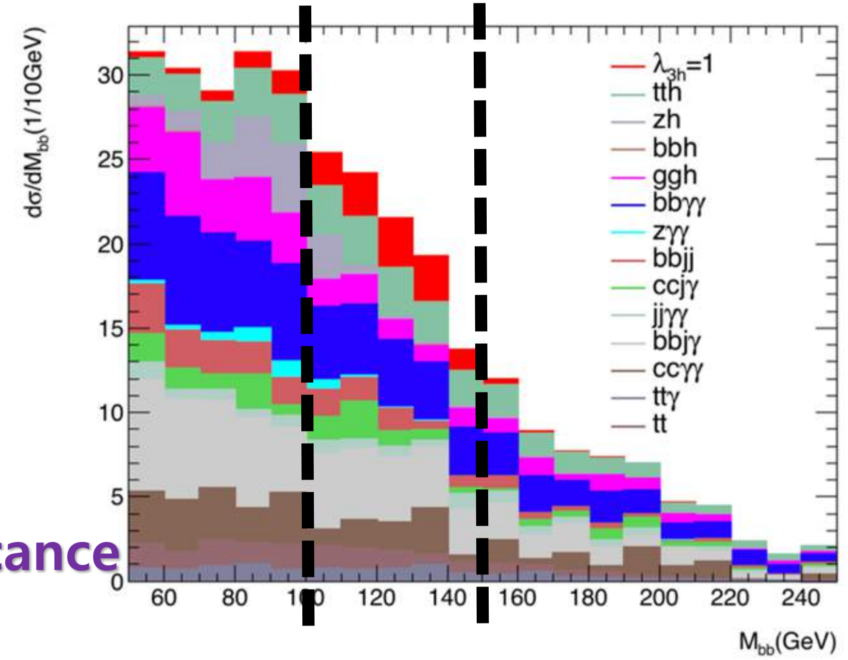
Signal-region-like

Final Results I :
Expected Yields and Kinematic distributions of $M_{\Upsilon\Upsilon}$(GeV) and $M_{b\bar{b}}$(GeV)

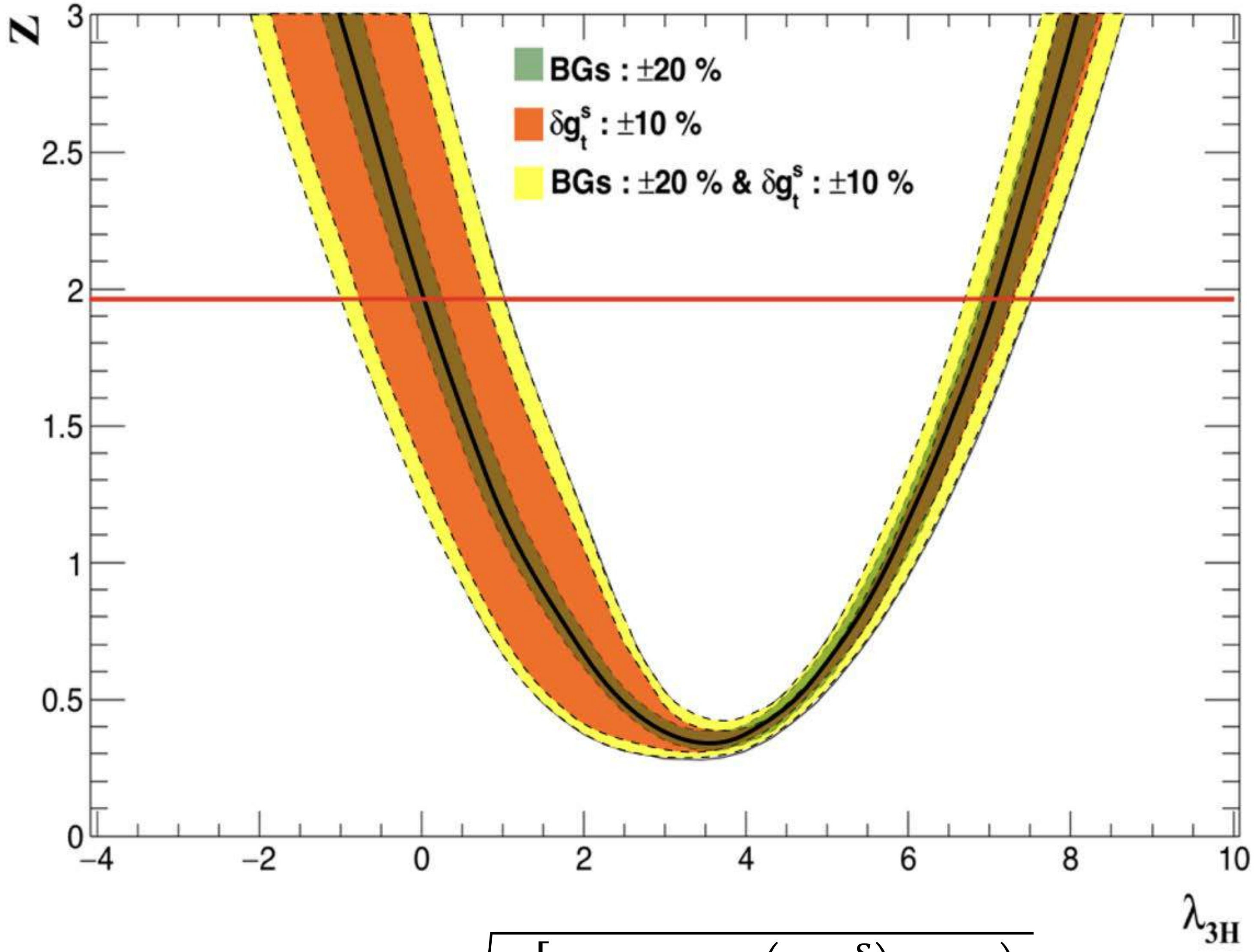
Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -4$	77.14	57.03	20.11	0.35
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	19.50	14.33	5.17	0.36
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 1$	11.42	8.53	2.89	0.34
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 2$	6.82	5.14	1.68	0.33
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 6$	11.03	7.91	3.12	0.39
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 10$	57.46	41.94	15.52	0.37
$gg\,H(\gamma\gamma)$	6.60	4.50	2.10	0.47
$t\bar{t}\,H(\gamma\gamma)$	13.21	9.82	3.39	0.35
$Z\,H(\gamma\gamma)$	3.62	2.44	1.18	0.48
$b\bar{b}\,H(\gamma\gamma)$	0.15	0.11	0.04	0.40
$b\bar{b}\gamma\gamma$	18.86	11.15	7.71	0.69
$c\bar{c}\gamma\gamma$	7.53	4.79	2.74	0.57
$jj\gamma\gamma$	3.34	1.59	1.75	1.10
$b\bar{b}j\gamma$	18.77	10.40	8.37	0.80
$c\bar{c}j\gamma$	5.52	3.94	1.58	0.40
$b\bar{b}jj$	5.54	3.81	1.73	0.45
$Z(b\bar{b})\gamma\gamma$	0.90	0.54	0.36	0.67
$t\bar{t}$ ($\geq$ 1 leptons)	4.98	3.04	1.94	0.64
$t\bar{t}\gamma$ ($\geq$ 1 leptons)	3.61	2.29	1.32	0.58
Total Background	92.63	58.42	34.21	0.59
Significance Z	1.163	1.090	0.487	
Combined significance		1.194		

Combined significance = 1.194



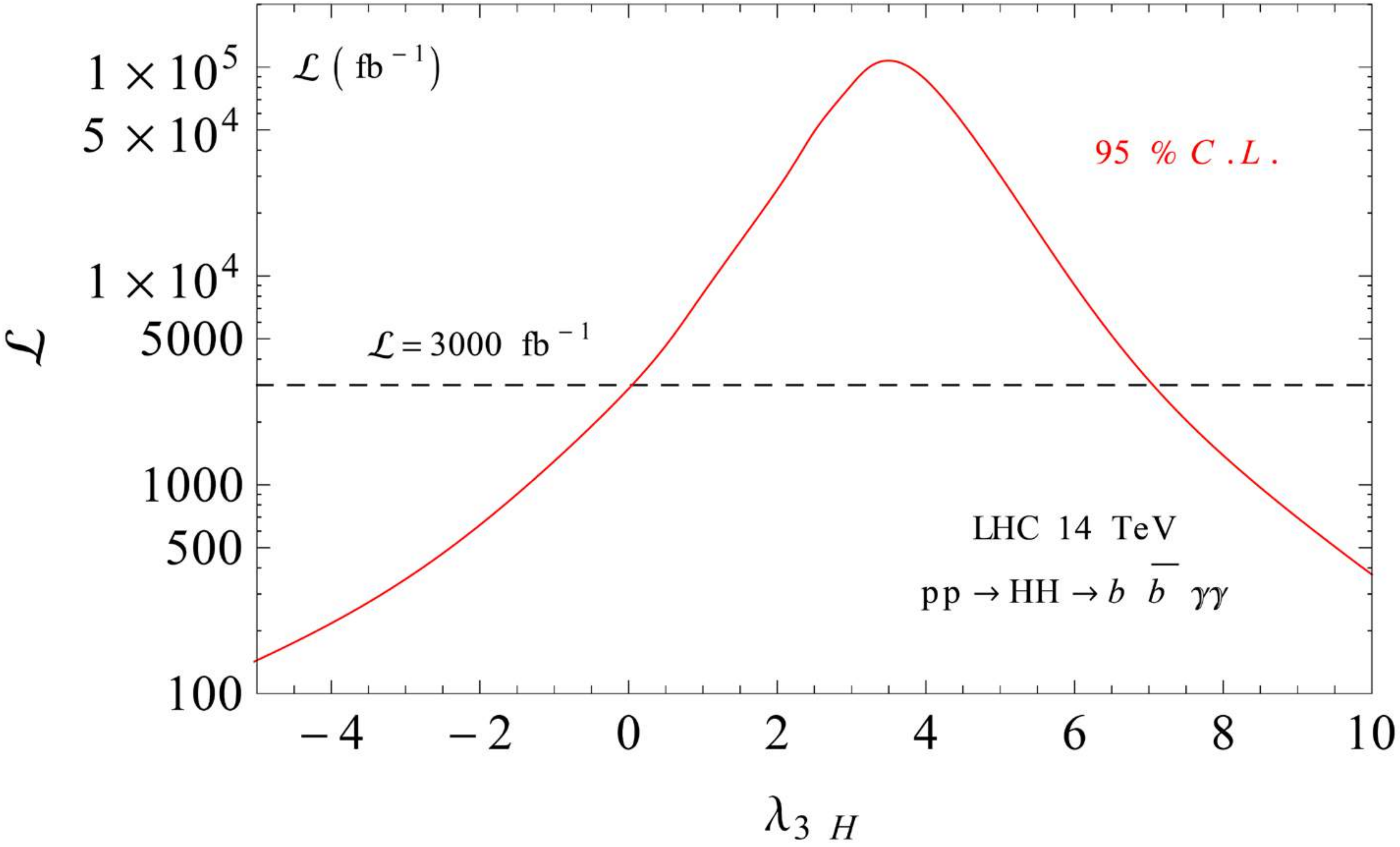


Essence of analysis results at the HL-LHC



$$Z = \sqrt{2\left[\left(\left(s+b\right)\ln\left(1+\frac{s}{b}\right)-s\right)\right]}$$

Required luminosity for 95% confidence level sensitivity at the 14 TeV HL-LHC v.s λ_{3H}.



HL-100 TeV hadron collider

TABL V. … same as … T ble … for … … the row for … HH(…
5FS st nds … th … -flavor sch … e.

Signal

Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to b\bar{b}\gamma\gamma$ [16]	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	$ggH(\to \gamma\gamma)$ [16]	POWHEG – BOX/PYTHIA8	1.82×10^3	NNNLO	CT10
	$t\bar{t}H(\to \gamma\gamma)$ [16]	PYTHIA8/PYTHIA8	7.29×10^1	NLO	
	$ZH(\to \gamma\gamma)$ [16]	PYTHIA8/PYTHIA8	2.54×10^1	NNLO	
	$b\bar{b}H(\to \gamma\gamma)$ [30]	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 [16] ($\geq$ 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

Main fake processes and the corresponding rates

HL 100 TeV hadron collider

Background(BG)	Process	Fake Process	Fake rate
Non-resonant BG	$b\bar{b}\gamma\gamma$	N/A	N/A
	$c\bar{c}\gamma\gamma$	$c \to b,\ \bar{c} \to \bar{b}$	$(0.1)^2$
	$jj\gamma\gamma$	$c_s \to b,\ \bar{c}_s \to \bar{b}$	$(0.1)^2$
	$b\bar{b}j\gamma$	$j \to \gamma$	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	$e \to \gamma$	$0.02/0.05$
	Semi-leptonic	$e \to \gamma$	$0.02/0.05$

Event selection at the 100 TeV Hadron collider

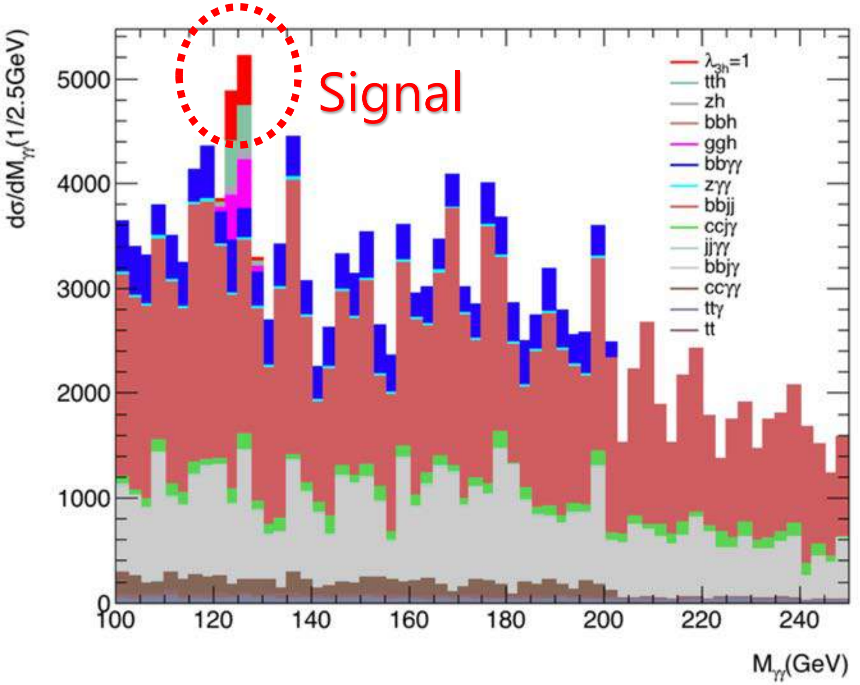
Sequence	Event Selection Criteria at the HL-100 TeV hadron collider
1	Di-photon trigger condition, ≥ 2 isolated photons with $P_T > 30$ GeV, $\|\eta\| < 5$
2	≥ 2 isolated photons with $P_T > 40$ GeV, $\|\eta\| < 3$, $\Delta R_{j\gamma} > 0.4$
3	≥ 2 jets identified as b-jets with leading(subleading) $P_T > 50(40)$ 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	$122.5 < M_{\gamma\gamma}/\mathrm{GeV} < 127.5$ and $90 < M_{b\bar{b}}/\mathrm{GeV} < 150$
8	$P_T^{\gamma\gamma} > 100$ GeV, $P_T^{b\bar{b}} > 100$ GeV

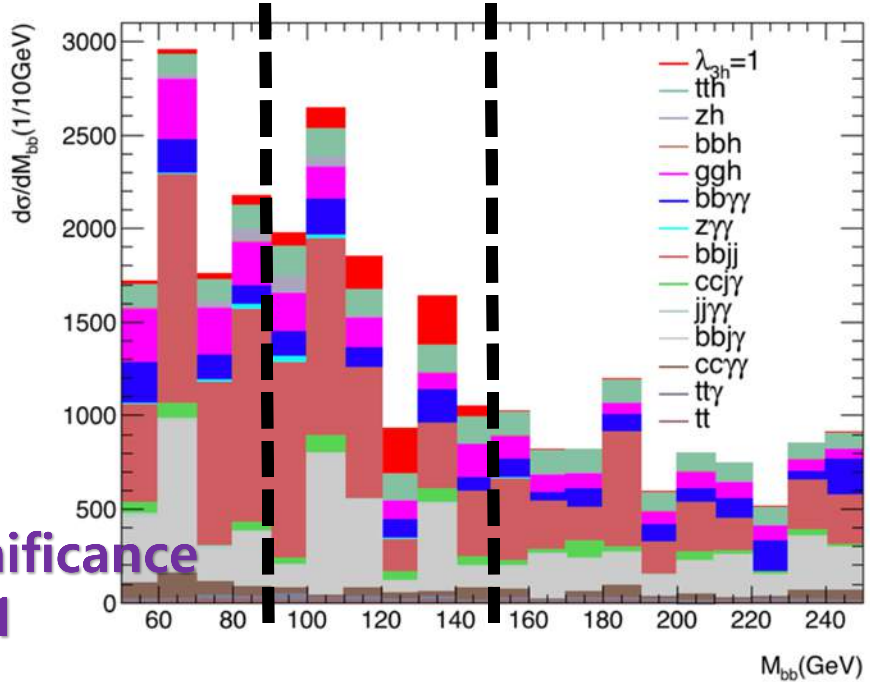
We relaxed these two conditions to enhance the signal yields !

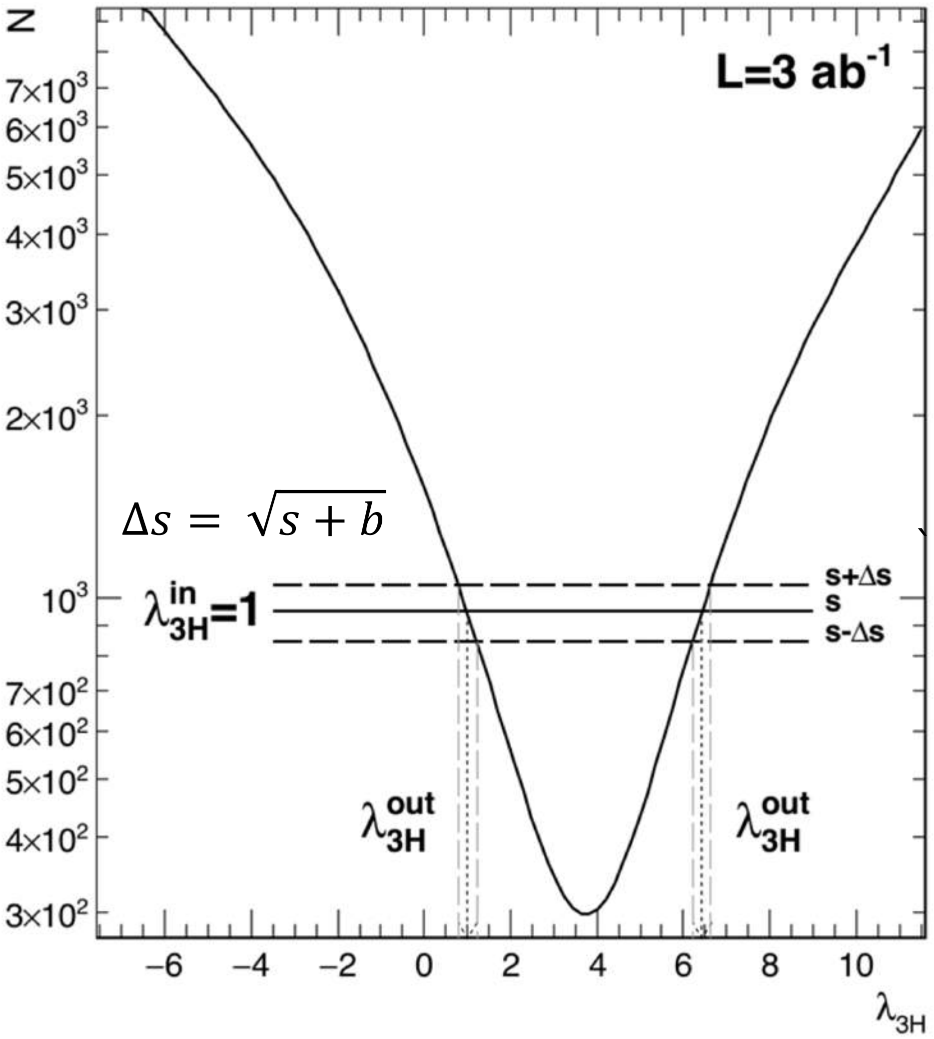
Final Results II : Expected Yields and Kinematic distributions of $M_{\gamma\gamma}$(GeV) and $M_{b\bar{b}}$(GeV) at HL-100 TeV collider

Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -4$	5604.46	4257.36	1347.10	0.32
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	1513.56	1163.04	350.52	0.30
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 1$	941.37	723.86	217.51	0.30
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 2$	557.36	431.45	125.91	0.29
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 6$	753.18	566.18	187.00	0.33
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 10$	3838.33	2924.25	914.08	0.31
$gg\,H(\gamma\gamma)$	890.47	742.97	147.50	0.20
$t\bar{t}\,H(\gamma\gamma)$	868.73	659.33	209.40	0.32
$Z\,H(\gamma\gamma)$	168.86	122.91	45.95	0.37
$b\bar{b}\,H(\gamma\gamma)$	9.82	7.00	2.82	0.40
$b\bar{b}\gamma\gamma$	783.87	443.70	340.17	0.77
$c\bar{c}\gamma\gamma$	222.88	111.44	111.44	1.00
$jj\gamma\gamma$	32.28	20.98	11.30	0.54
$b\bar{b}j\gamma$	1982.88	1516.32	466.56	0.31
$c\bar{c}j\gamma$	293.81	216.49	77.32	0.36
$b\bar{b}jj$	3674.16	1924.56	1749.60	0.91
$Z(b\bar{b})\gamma\gamma$	54.87	35.72	19.15	0.54
$t\bar{t}$ ($\geq$ 1 leptons)	59.32	38.32	21.00	0.55
$t\bar{t}\gamma$ ($\geq$ 1 leptons)	105.68	62.53	43.15	0.69
Total Background	9147.63	5902.27	3245.36	0.55
Significance Z	9.681	9.239	3.777	
Combined significance		9.981		

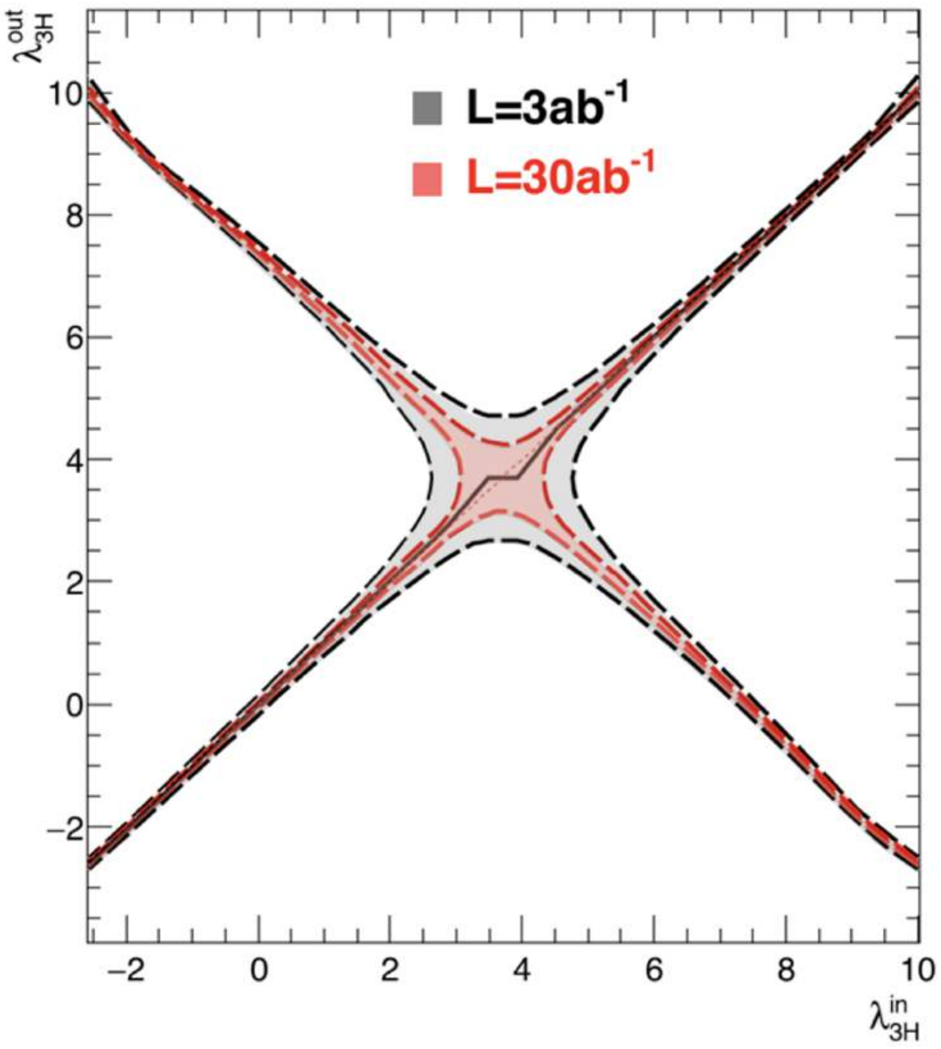
Combined significance = 9.981







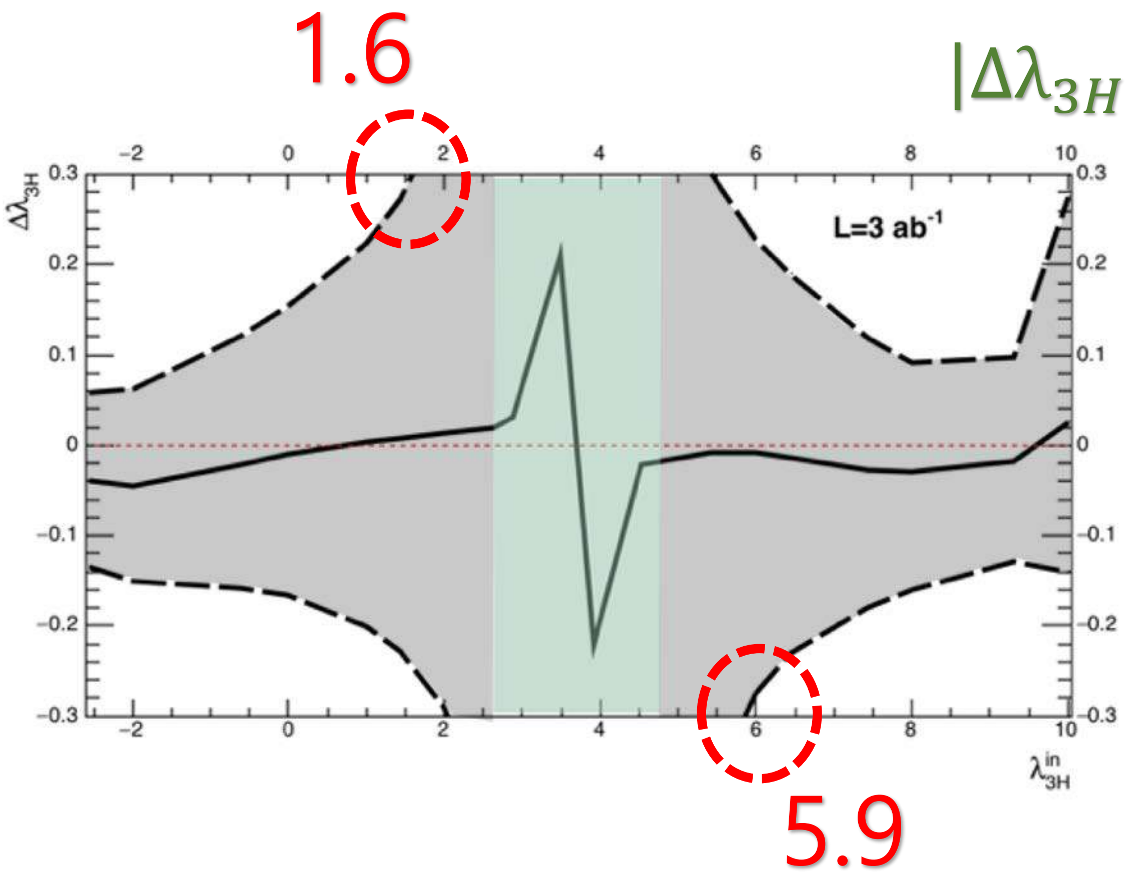
The number of signal event N v.s λ_{3H} with 3 ab^{-1}

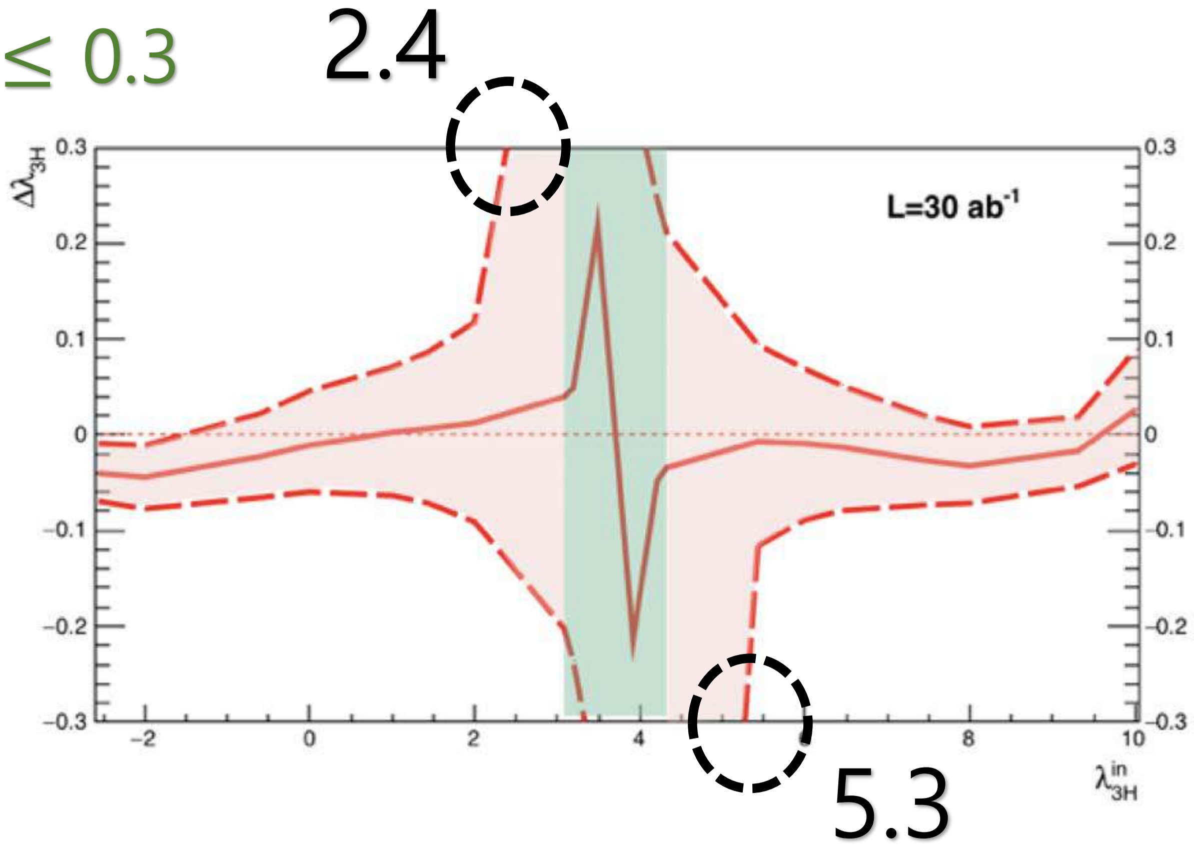


The 1-σ error regions v.s the input values of λ_{3H}^{in} assuming **3** $\boldsymbol{ab^{-1}}$ **(black)** and **30** $\boldsymbol{ab^{-1}}$ **(red)**

HL-100 TeV hadron collider

$|\Delta\lambda_{3H}| \leq 0.3$





$\Delta\lambda_{3H} = \lambda_{3H}^{out} - \lambda_{3H}^{in}$ v.s λ_{3H}^{in} along the $\lambda_{3H}^{out} = \lambda_{3H}^{in}$ line
with 3 ab^{-1} (left) and 30 ab^{-1}(right)

Conclusion I [HL-LHC]

- We find that even for the most promising channel H($\rightarrow$ bb)H($\rightarrow$ γγ) at the HL-LHC with a luminosity of 3000 fb^{-1}, the significance is still not high enough to establish the Higgs self-coupling at the SM value.
- Instead, we can only constrain the self-coupling to $-1.0 < \lambda_{3H} <$ 7.6 at 95% confidence level after considering the uncertainties associated with the top-Yukawa coupling and the estimation of backgrounds.

Conclusion II [HL-100 TeV hadron collider]

- With a luminosity of 3 ab^{-1}, we find there exists a bulk region of $2.6 < \lambda_{3H} < 4.8$ in which one can not pin down the trilinear coupling.
- At the SM value, we show that the coupling can be measured with about 20% accuracy.
- While assuming 30 ab^{-1}, the bulk region reduces to $3.1 < \lambda_{3H} < 4.3$ and the trilinear coupling can be measured with about 7% accuracy at the SM value.

Machine learning approaches to the Higgs boson self coupling

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Why Higgs pair production so difficult ?

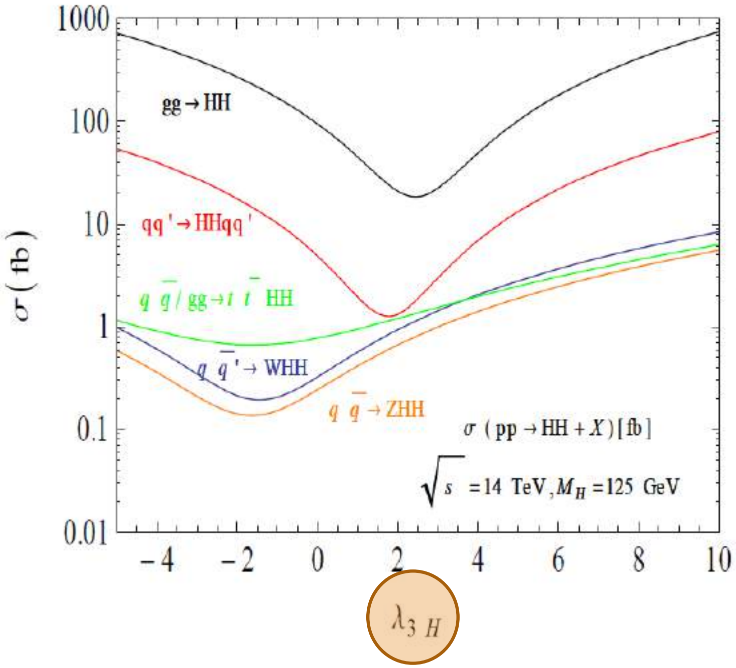
Why Higgs pair production so interesting ?

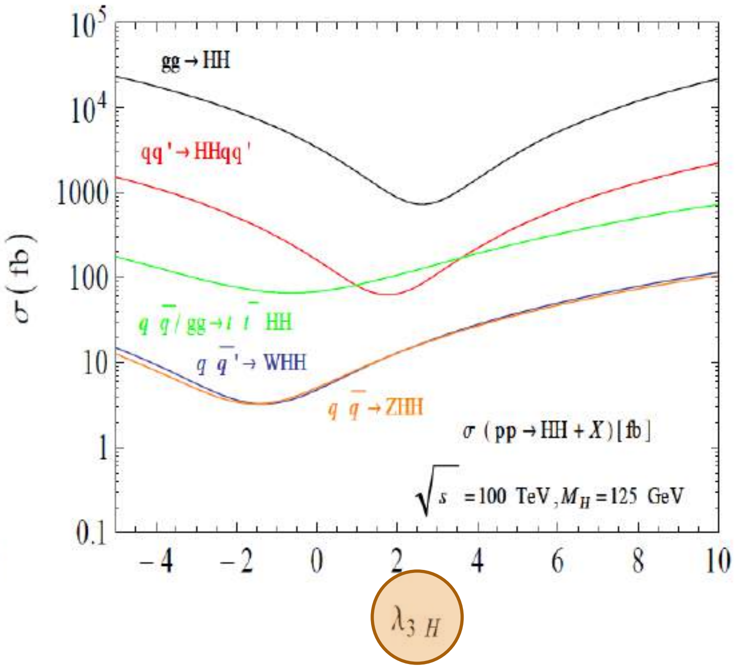
Machine Learning approaches to the Higgs boson self coupling

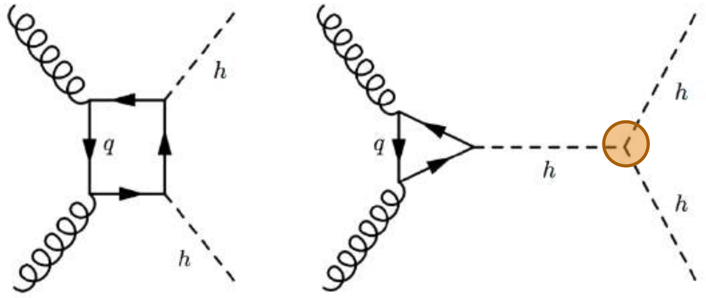
Summary Table

Conclusion

Why Higgs pair production so difficult ?







Distrcuctive interference !

In the SM, hh rates are small : In the leading gluon fusion production mode, the cross section at 14 TeV is only 40 fb, further suppressed by each decay branching fractions.

Why Higgs pair production so difficult ?

· Xsec(gg -> hh) = $39.64\ ^{+4.4}_{-6.0}$ (scale) $\pm 2.1\ (PDF)\ \pm 2.2\ (\alpha_s)$ fb @ [14 TeV, $m_h = 125$ GeV]

NNLO cross sections including top quark mass effects to NLO
Phys. Rev. Lett. 117, 012001 [S.Borowka, et al.]

· O (10^-3) smaller than the single Higgs production (SM)

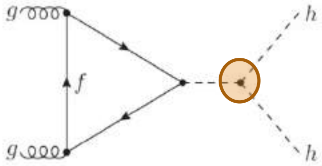
Xsec(gg -> hh) ~ 40 fb ⟷ Xsec(gg -> h) ~ 50 fb @ 14 TeV

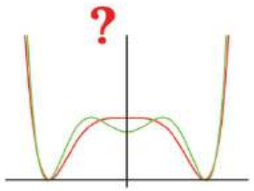
· For the reference, with Xsec ~ 33 fb at 13 TeV,
2017 LHC @ 13 TeV with 40 fb^-1 → 1320 Events
14 TeV with 40 fb^-1 → 1600 Events

Why Higgs pair production so interesting ?

Allows accessing crucial components of the Higgs sector !!!

can probe the Higgs self-coupling





can help to reconstruct the electroweak symmetry breaking potential

may reveal the doublet nature of the Higgs by means of the hhVV coupling

Search channel for Higgs pair production

Channel	BR(%)	Events with 3 ab^-1
bbbb	~ 33	40080 Huge hadronic BG
bbWW	~ 25	30000 Huge ttbar BG
bbττ	~ 7.3	9000
WWWW	~ 4.3	5200
bbYY	~ 0.27	5200
bbZZ(eemm)	~ 0.015	19

Machine Learning approaches to the Higgs boson self coupling

① BDT(Boosted Decision Tree) : bbYY

1. Phys.Rev. D96 (2017) no.3, 035022 (Alves, Alexandre et al.) arXiv:1704.07395 [hep-ph]

BDT + kinematic cuts → 5 σ (4.6 σ) significance with 10 %(20%) systematics and 3 ab^-1

② (Supervising) Deep Neural Networks (DNN) : bbWW + bbττ

1. "Supervising Deep Neural Networks with topological augmentation in search for di-Higgs production at the LHC (Won Sang Cho, next speaker)

   5 classes by the number of leptonic taus

   Optimass & its compatibility distance with dim. Of vars ~ 40

→ AUC of ROC = 0.991

Eff(sig)

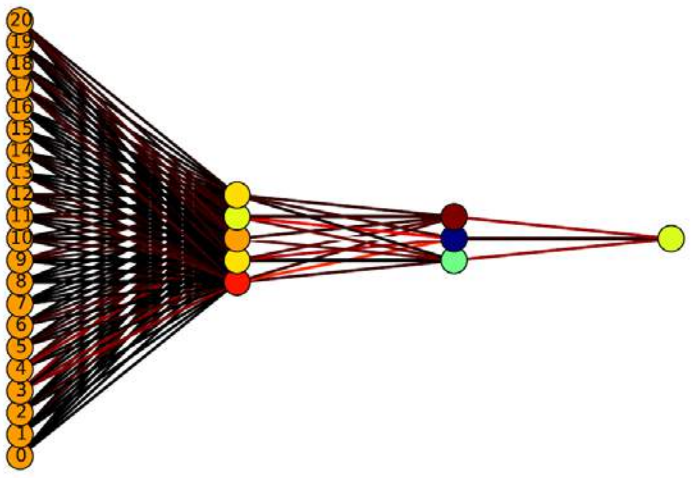
@(Background purity=0.01) = 0.84

Machine Learning approaches to the Higgs boson self coupling

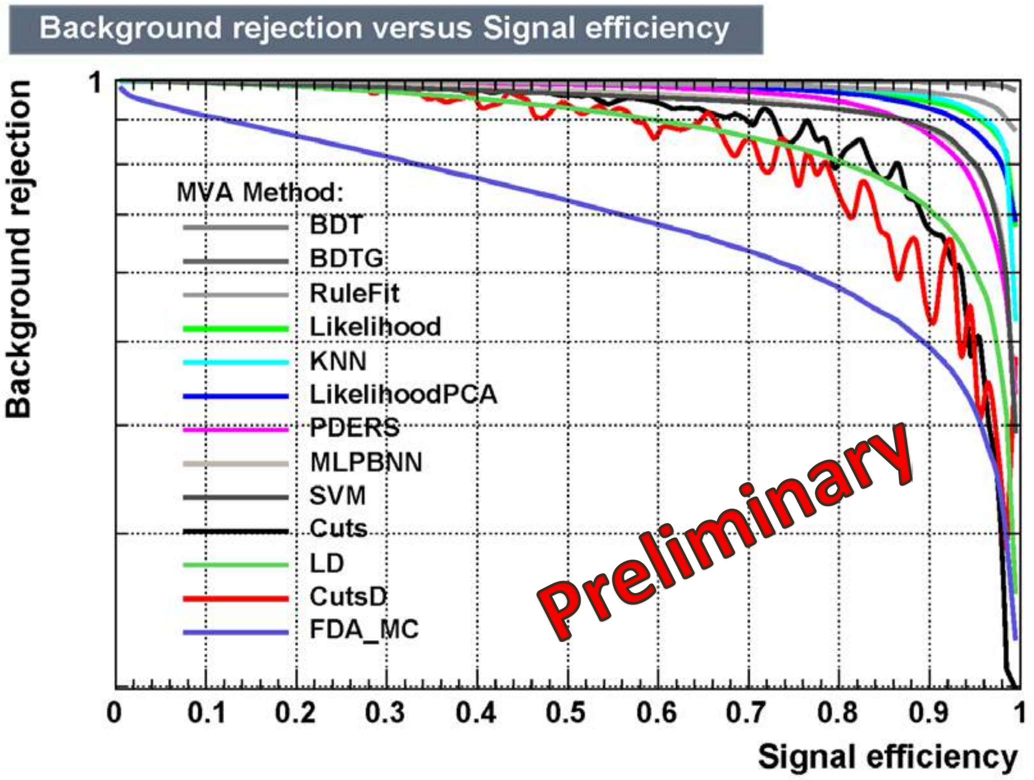
③ DNN (ANN : a multi-layer feed-forward artificial neural network) : bbbb

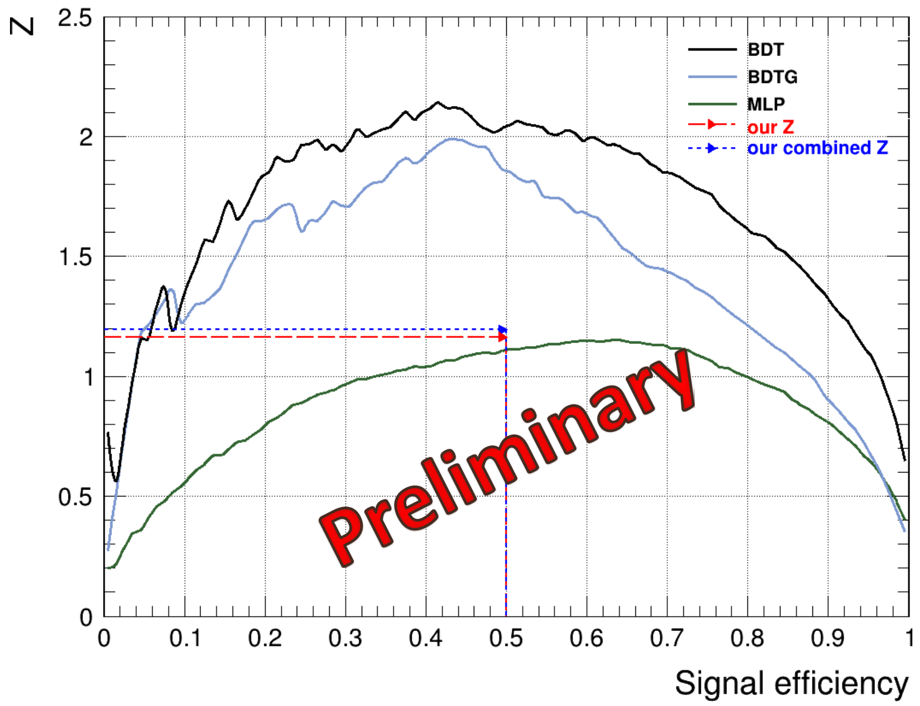
1. Eur. Phys. J. C (2016) 76:386 (Katharina Behr, Bortoletto et al.) arXiv:1512.08928 [hep-ph]

DNN + kinematic cuts → $\frac{S}{\sqrt{B}} \sim$ 3 σ significance with 3 ab^-1



Machine Learning approaches to the Higgs boson self coupling





Summary Table

Channel	Achievable Significance (σ)	Methods	Papers	Remarks
bbbb	~ 3	Kinematic Cuts+ DNN	Eur. Phys. J. C (2016) 76:386	HL-LHC (3 ab^-1)
	~ (3.1 ~ 5.7)	DNN	Arxiv: 1609.002541	100 TeV FCC (10 ab^-1)
bbWW		DNN	Recnt Dr. Won Sang Cho work	HL-LHC (3 ab^-1)
bbττ				
WWWW				
bbYY	~ 5 (4.6)	Kinematic Cuts + BDT	Phys.Rev. D96 (2017) no.3, 035022	HL-LHC (3 ab^-1),
	~ 2.1	Kinematic Cuts + BDT	Preriminary	With full BGs.
bbZZ(eemm)				

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bbZZ(eemm)				

Conclusion

1. Higgs pair production can allow us to reconstruct the EWSB potential
   and to understand the nature of the EWSB mechanism !
2. The bbYY channel can offer the appropriate yields and clean(?) signal.
3. Various multivariate classification methods based on machine learning techniques are used to consider the enhancement of significance in measuring the Higgs self coupling.
4. We found that the BDT-related methods (+ cut-based analysis) can give the best results compared with other methods.
5. Presently, we are checking consistencies of our methods.

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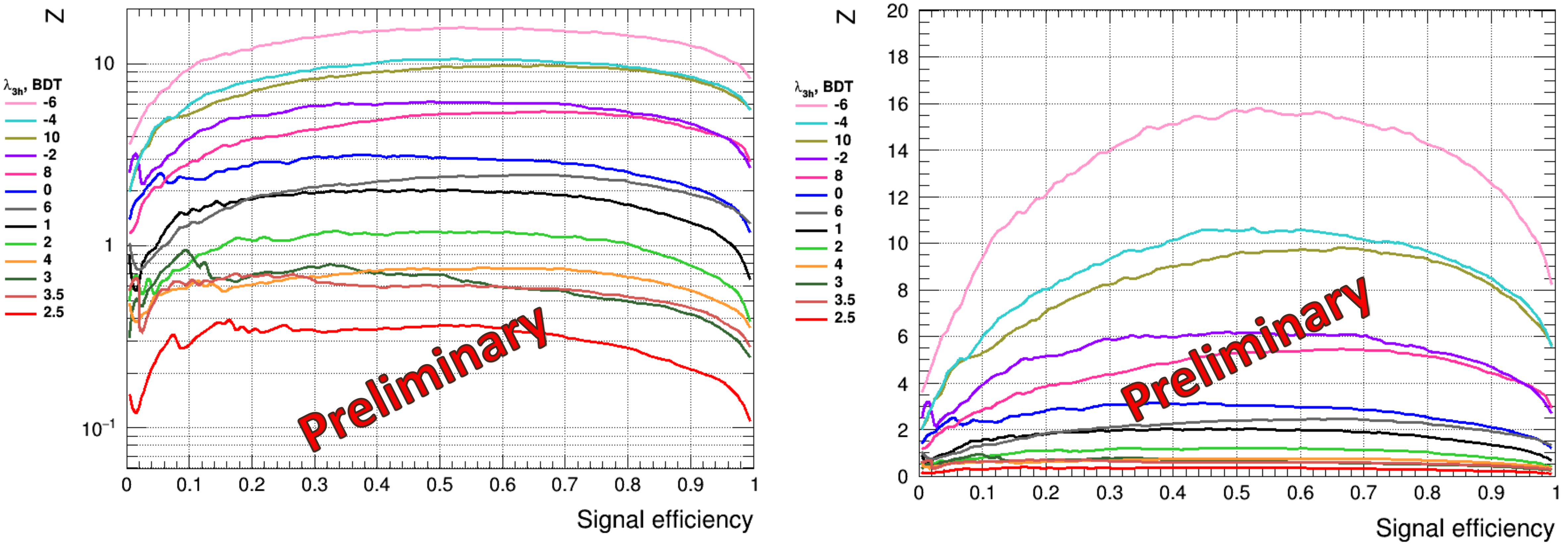
5. Presently, we are checking consistencies of our methods.

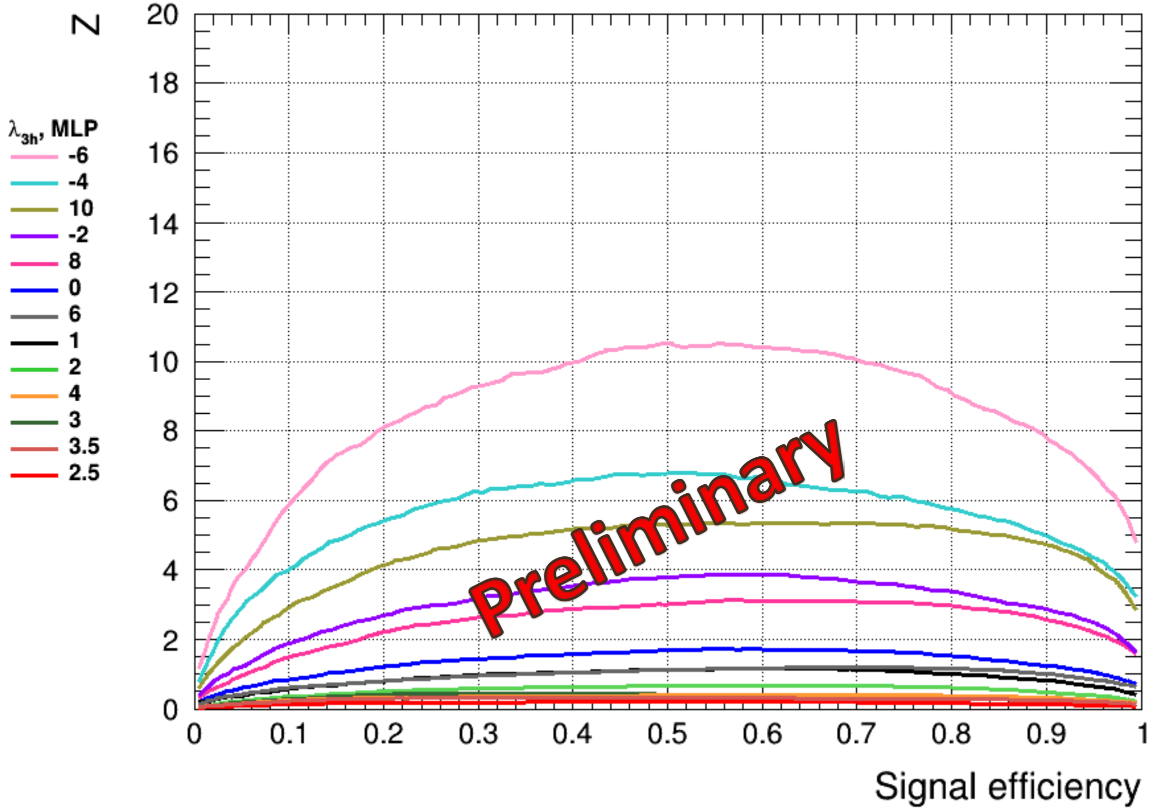
Thank you for your attention !

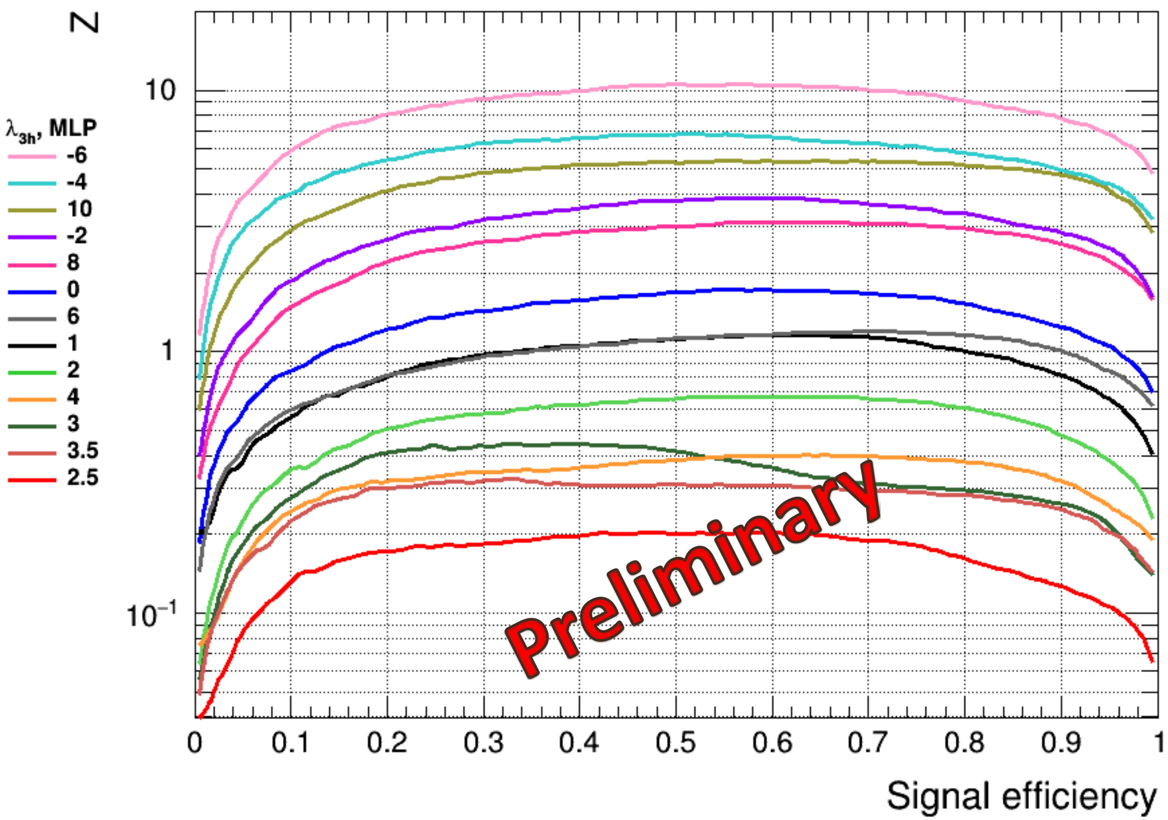
BACKUP SLIDES

λ dependency with BDT



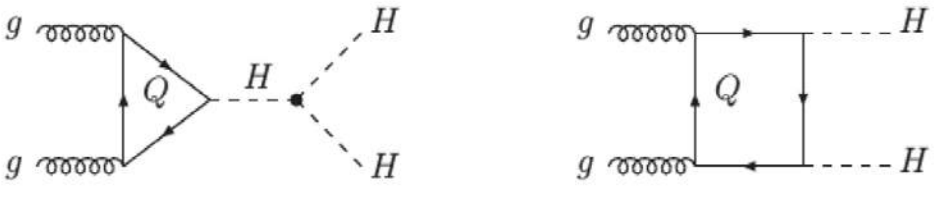
λ dependency with MLP



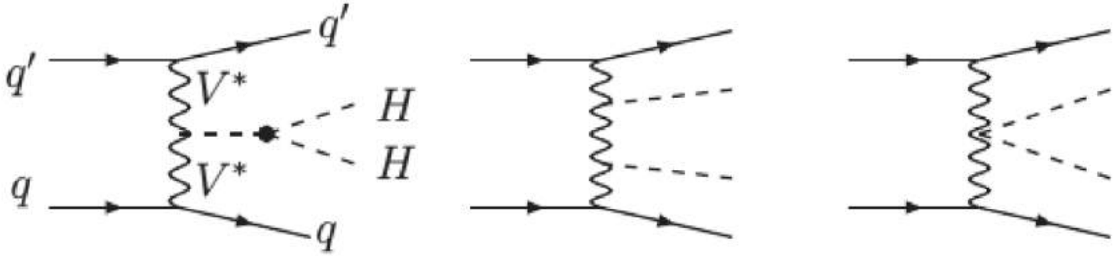


Higgs pair productions

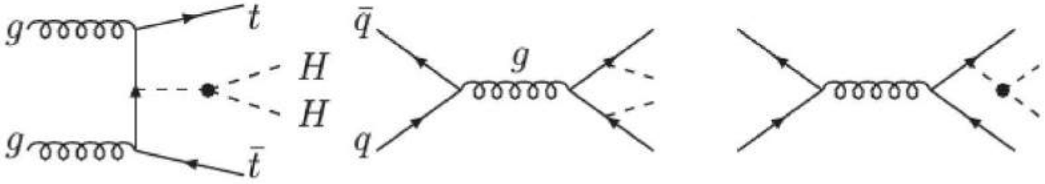
Gluon Fusion



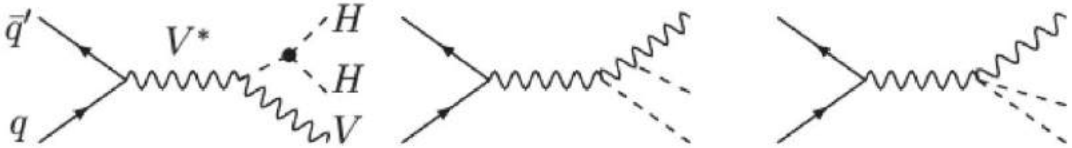
Vector Boson Fusion



Top associated productions



Higgs strahlung



Future colliders

LHC series

→ HL-LHC (High luminosity LHC) → HE-LHC , (High Energy LHC) VHE-LHC (Very High Energy LHC) → FCC-hh

FCC series

(TLEP)

China collider series

CEPC
(Circular Electron Positron Collider)
SPPC
(Super Proton Proton Collider)

Linear Collider Series

ILC
(International Linear Collider)

CLIC
(Compact Linear Collider)

Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

FCC-ee

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

Snowmass 1310.8361