New Physics in Higgs Pair Production at the LHC

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(NTNU)

9/29/2017 @ NTU

Outline

New physics effects in Higgs pair production at the LHC

couplings

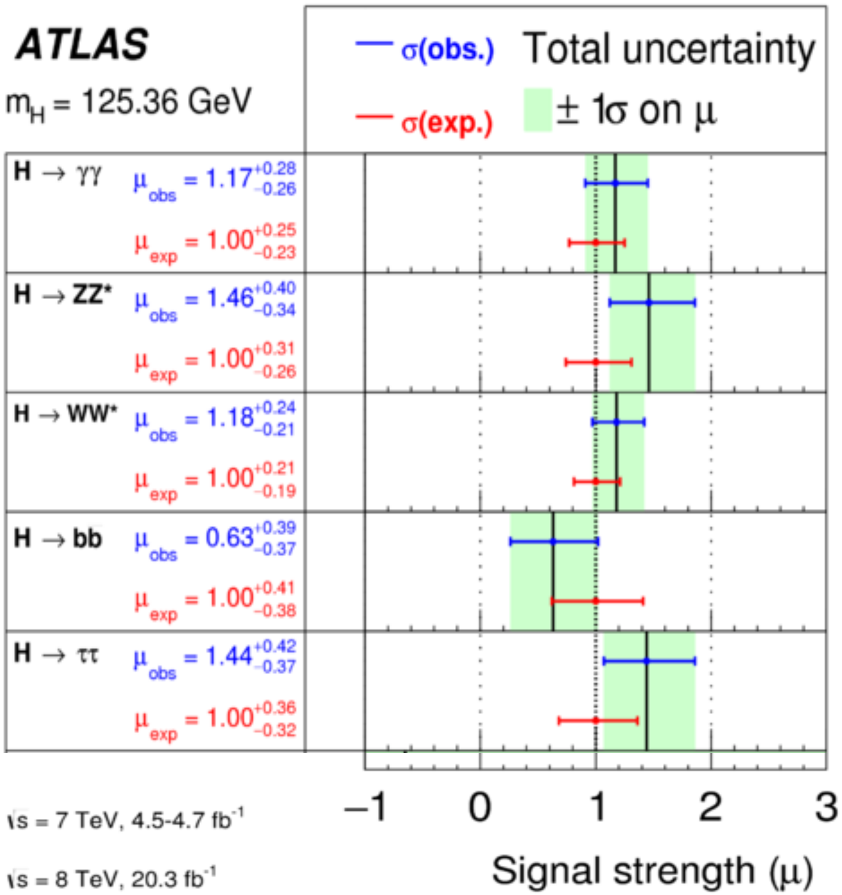
resonance

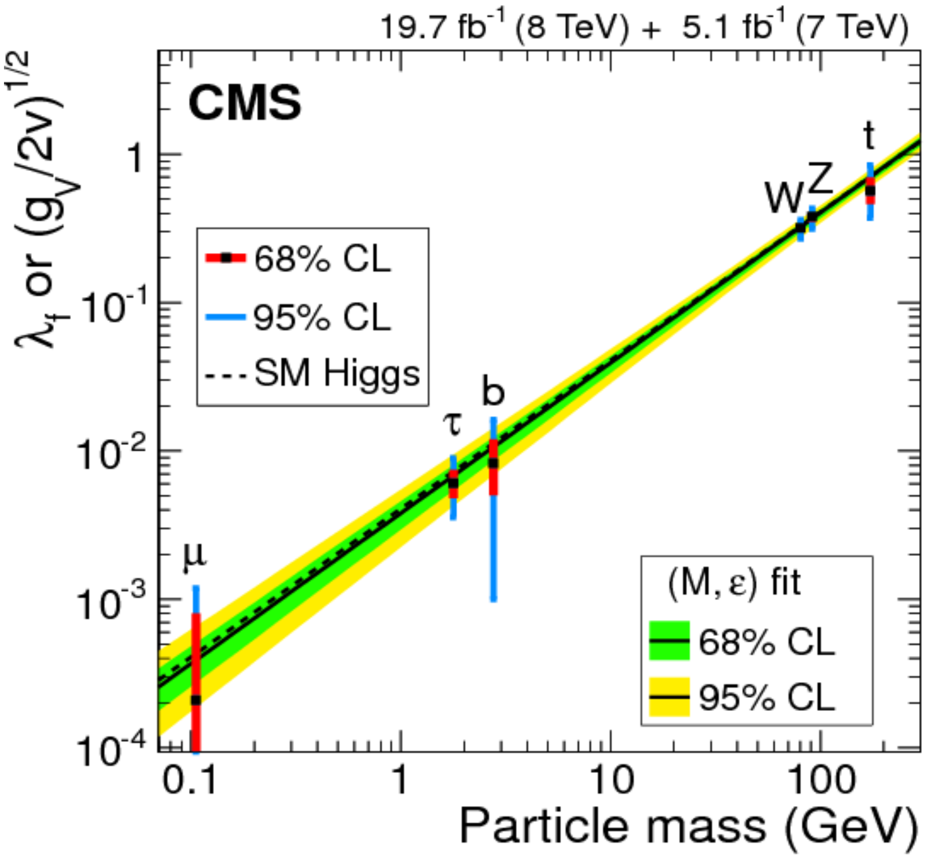
associated with other particles

See Jason's talk!!

Summary

Higgs boson @ LHC

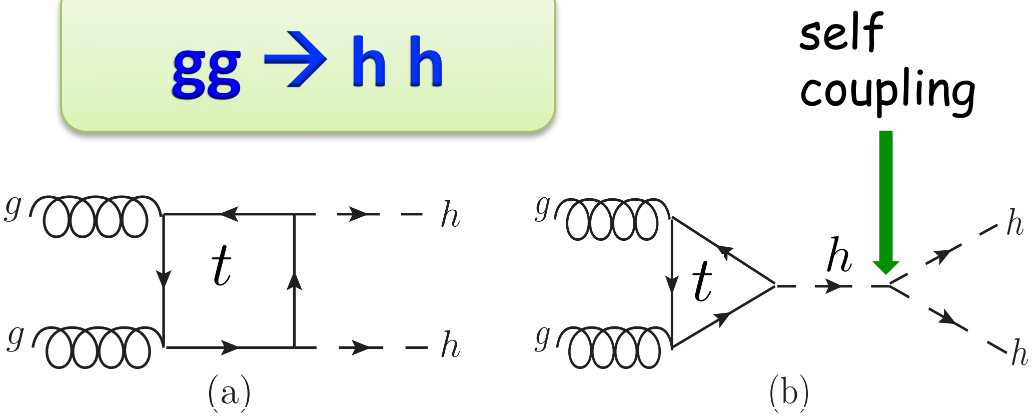


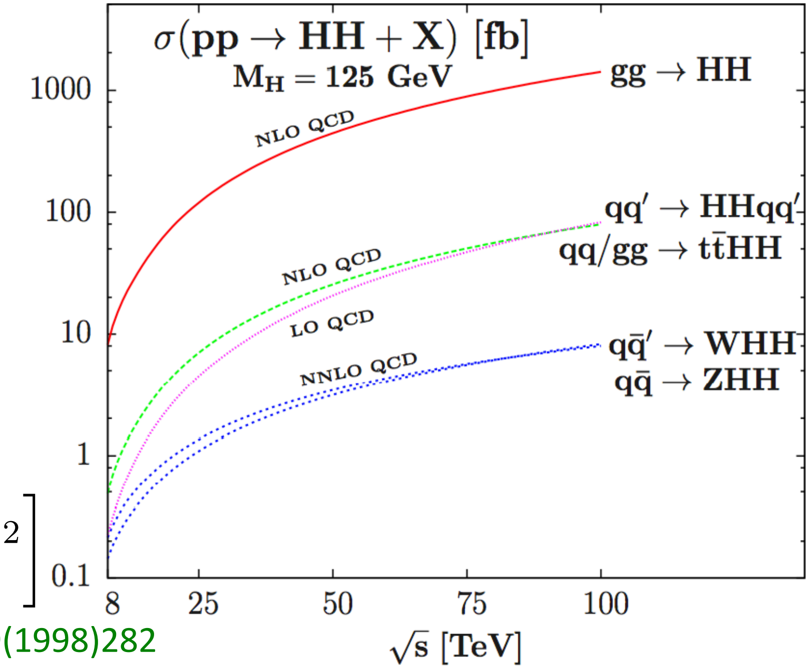


get information of interactions between
Higgs boson and other SM particles

HOWEVER, can NOT test/determine the Higgs boson self coupling!!

$gg \to h\,h$





$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3}\left[\left|\frac{3m_h^2}{\hat{s}-m_h^2}F_\triangle + F_\Box\right|^2 + |G_\Box|^2\right]$$

Plehn, Spira, Zerwas, NPB 479(1996)46 Glover, van der BIJ, NPB 309(1998)282

Dawson, Dittmaier, Spira, hep-ph/9805244 Djouadi, Kilian, Muhlleitner, Zerwas, hep-ph/9904287

Asakawa, Harada, Kanemura, Okada, Tsumura, 1009.4670 Dawson, Furlan, Lewis, 1210.6663

Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581 Yao, 1308.6302

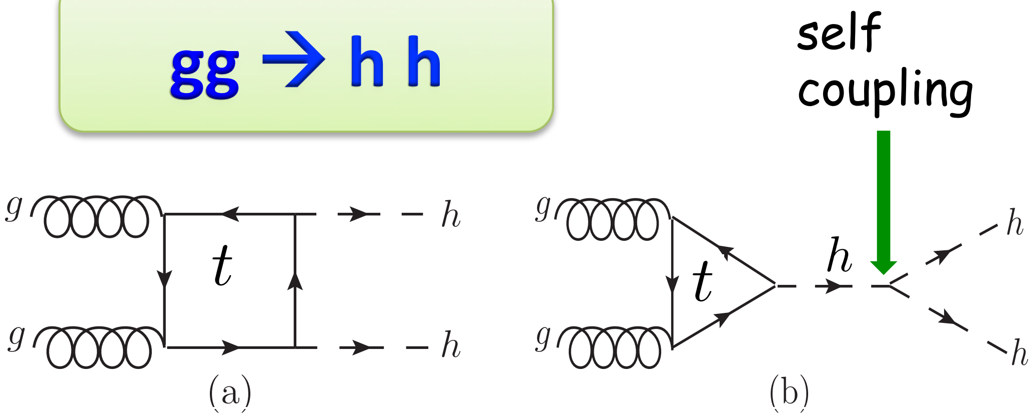
$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

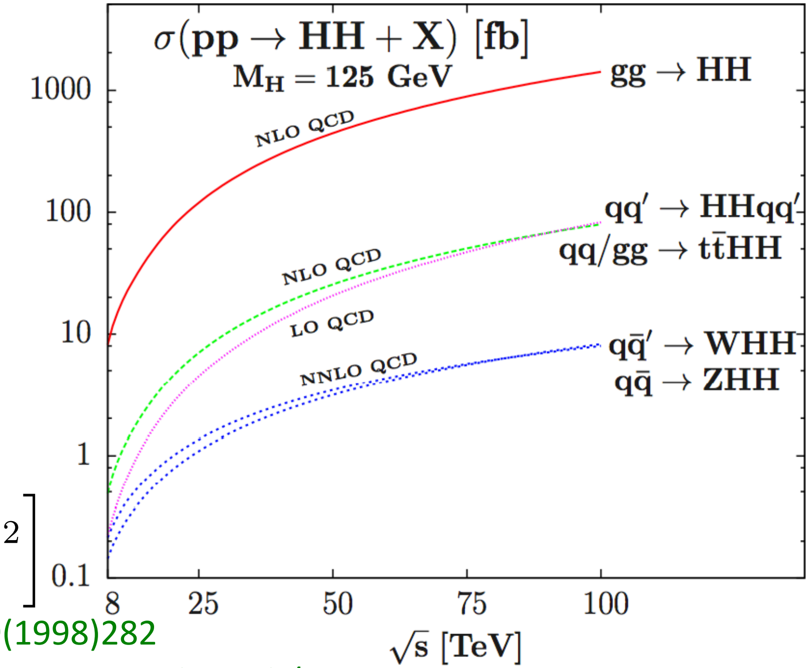
* quite promising that one can discover $gg \to hh \to \gamma\gamma b\bar{b}$

* w/ 3000 fb^{-1} @ 100 TeV pp collider, hhh coupling can be measured with 8 % accuracy

Yao, 1308.6302

gg → h h





$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3}\left[\left|\frac{3m_h^2}{\hat{s}-m_h^2}F_\triangle + F_\Box\right|^2 + |G_\Box|^2\right]$$

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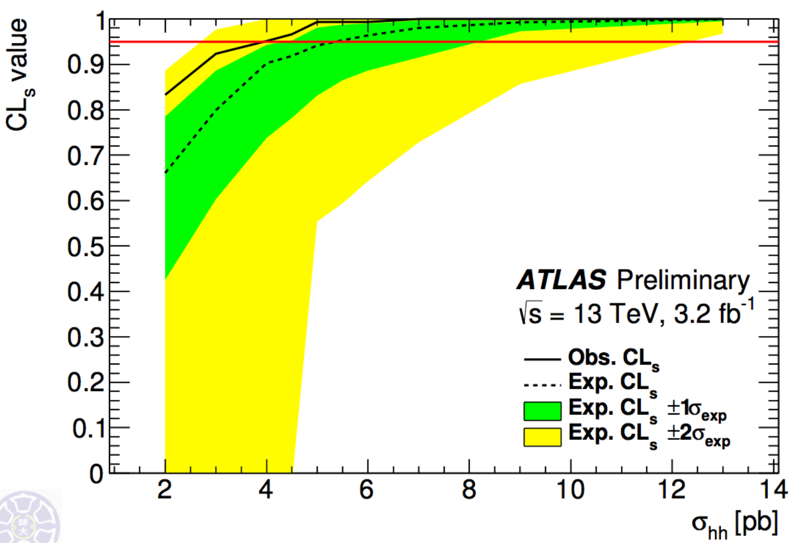


ATLAS:
"an upper limit of 3.9 pb on the cross section for non-resonant is extracted at 95% confidence level"

tri-H coupling at ILC

$e^+e^- \rightarrow Zhh$

250 GeV, 1150 fb^{-1} +
500 GeV, 1600 fb^{-1} : ~46%

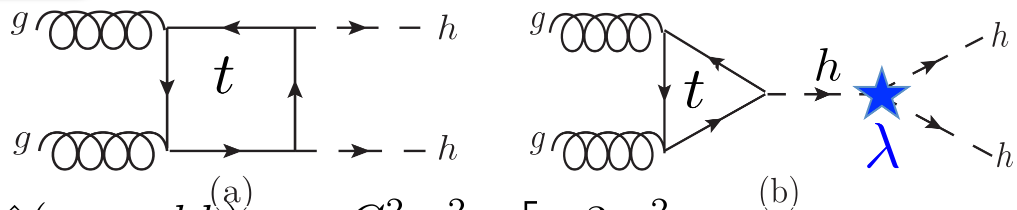
+ 1 TeV, 2500 fb^{-1}: ~13%

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250 + 500	250 + 500 + 1000	250 + 500 + 1000
L (ab^{-1})	0.25	0.25 + 0.5	0.25 + 0.5 + 1	1.15 + 1.6 + 2.5
$\gamma\gamma$	18%	8.4%	4.0%	2.4%
gg	6.4%	2.3%	1.6%	0.9%
WW	4.8%	1.1%	1.1%	0.6%
ZZ	1.3%	1.0%	1.0%	0.5%
$t\bar{t}$	–	14%	3.1%	1.9%
$b\bar{b}$	5.3%	1.6%	1.3%	0.7%
$\tau^+\tau^-$	5.7%	2.3%	1.6%	0.9%
$c\bar{c}$	6.8%	2.8%	1.8%	1.0%
$\mu^+\mu^-$	91%	91%	16%	10%
$\Gamma_T(h)$	12%	4.9%	4.5%	2.3%
HHH	–	83%	21%	13%
BR(invis.)	<0.9%	<0.9%	<0.9%	<0.4%

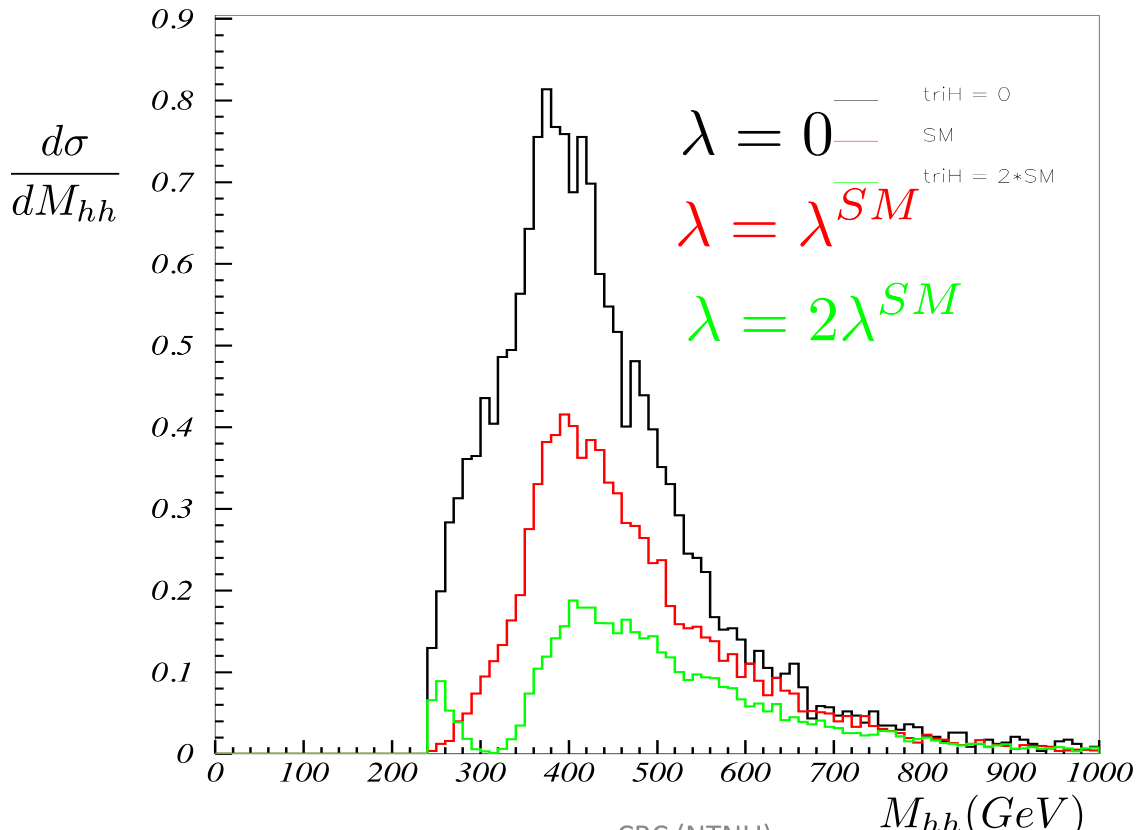
For these estimates the value $m_H = 120$ GeV was used.

The measurement of the hhh coupling for mh ≃ 126 GeV is very challenging at the LHC and even at the high luminosity upgrade of the LHC. At the ILC, the hhh coupling can be measured via e+e− → Zhh and e+e− → hhνν̄ . As indicated in Chapter 9, for the combined data taken at the ILC with √s = 250 with 1150 fb−1 and 500 GeV with 1600 fb−1, the hhh coupling can be measured with an accuracy of about 46%. By adding additional data from a run of √s = 1 TeV with 2500 fb−1, one can determine the hhh coupling to an accuracy of about 13%. Therefore, the scenario for electroweak baryogenesis would be testable by measuring the triple Higgs boson coupling at the ILC.

NP effects in gg → h h

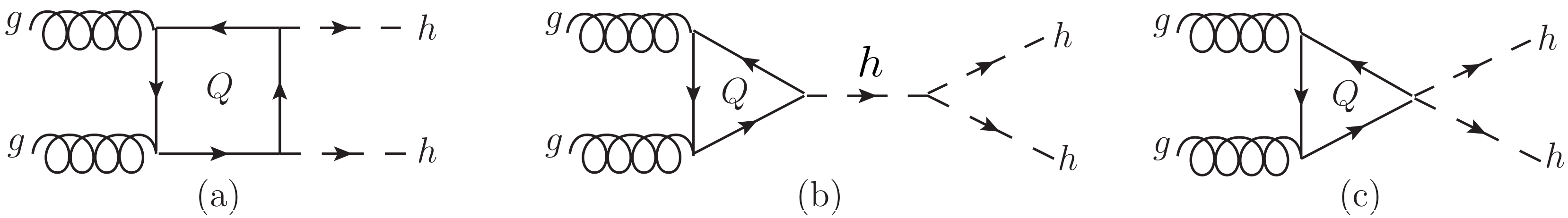


$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3}\left[\left|\frac{3m_h^2}{\hat{s} - m_h^2} F_\triangle + F_\Box\right|^2 + |G_\Box|^2\right]$$

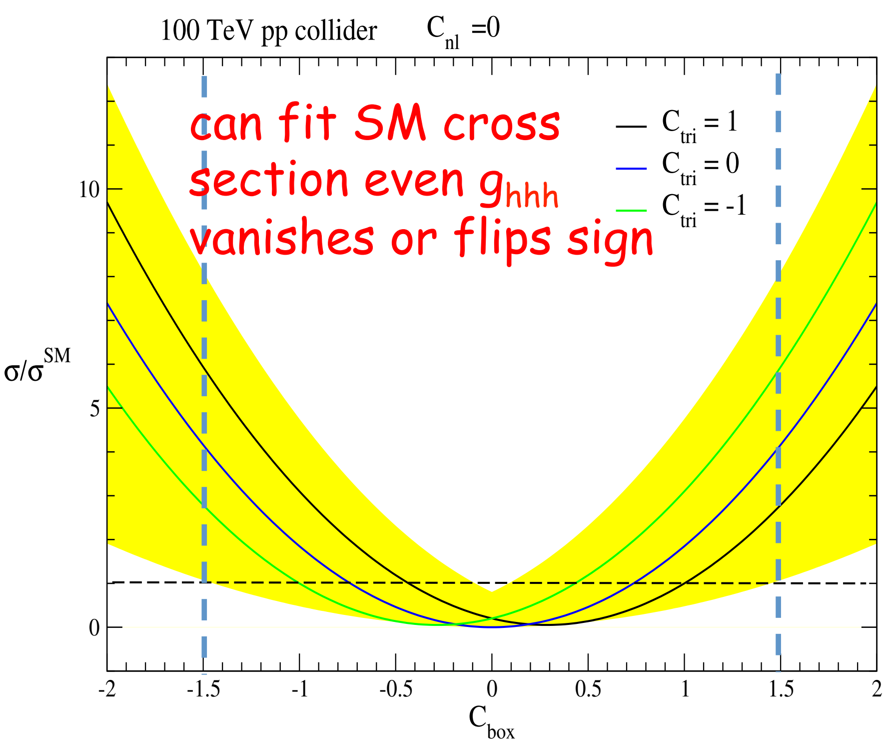


NP effects in gg → h h (I)

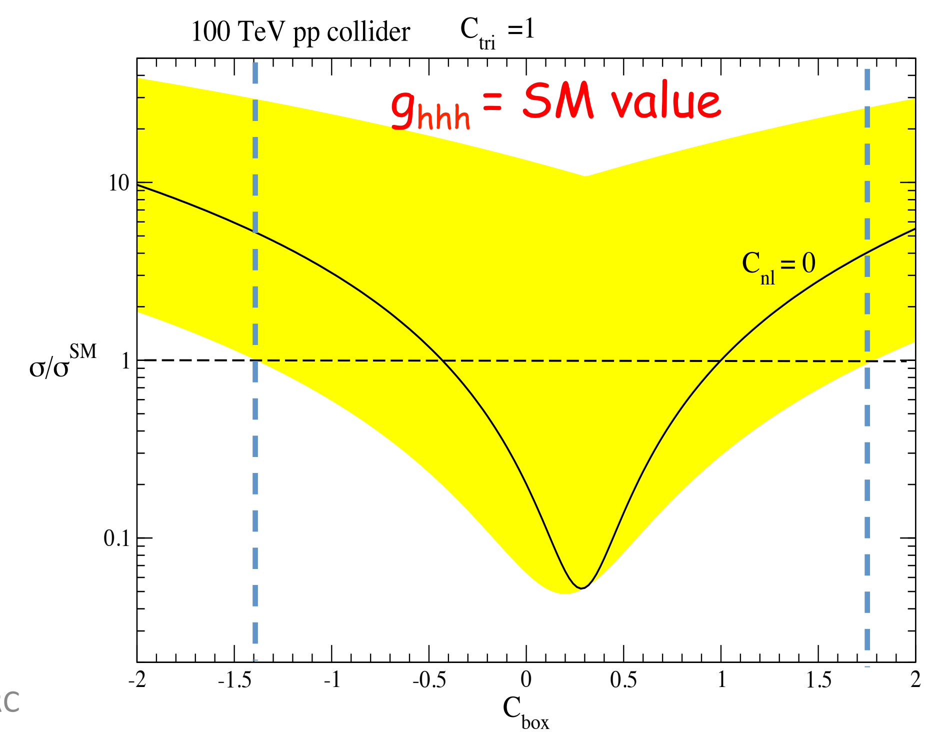
CRC and Low, PRD 90. 013018



$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \left(\boxed{c_{tri}} \frac{3m_h^2}{\hat{s} - m_h^2} + \boxed{c_{nl}} \right) F_\triangle + \boxed{c_{box}} F_\square \right|^2 + \left| \boxed{c_{box}} G_\square \right|^2 \right]$$

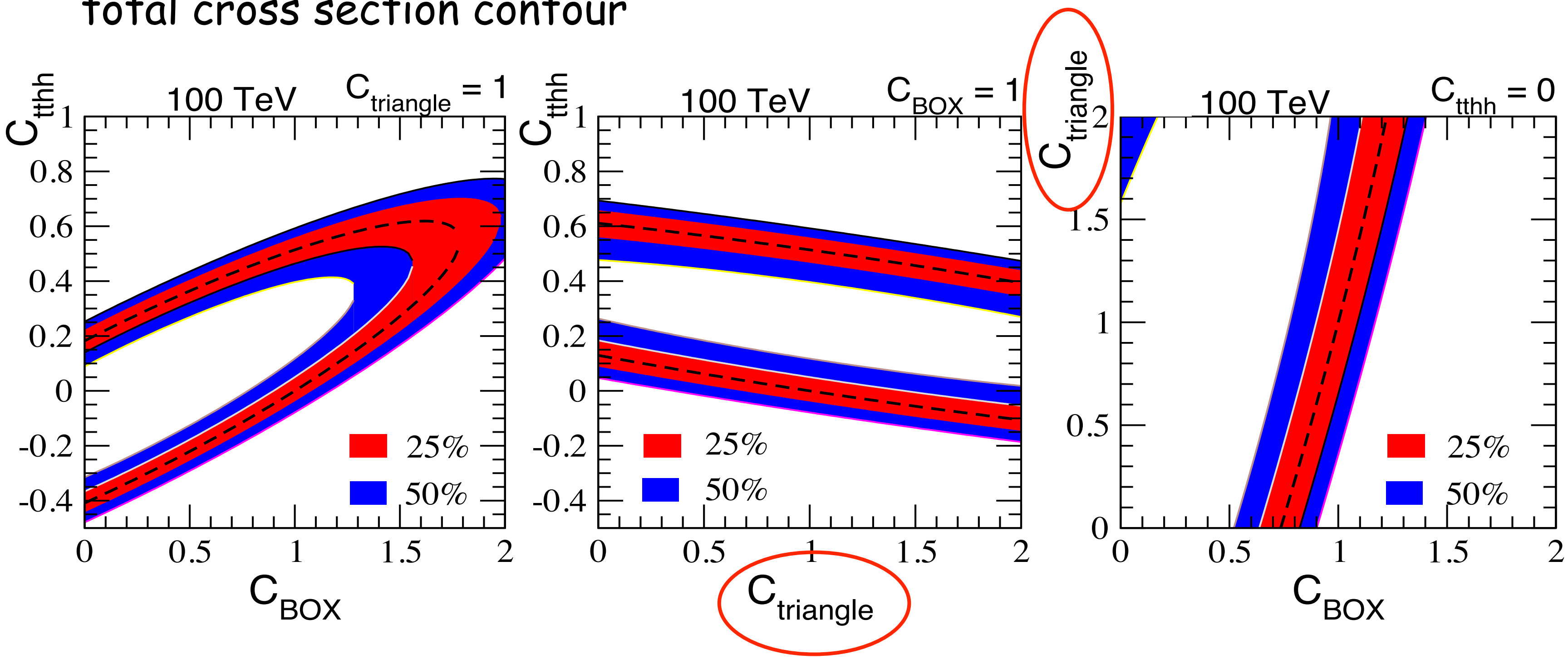


RC



gg → h h

total cross section contour



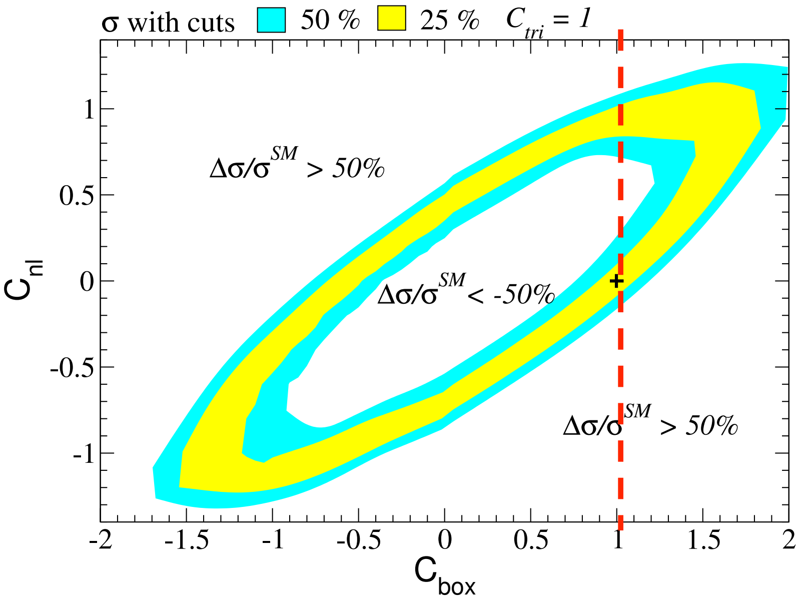
total cross section itself is insensitive to Higgs trilinear coupling!!

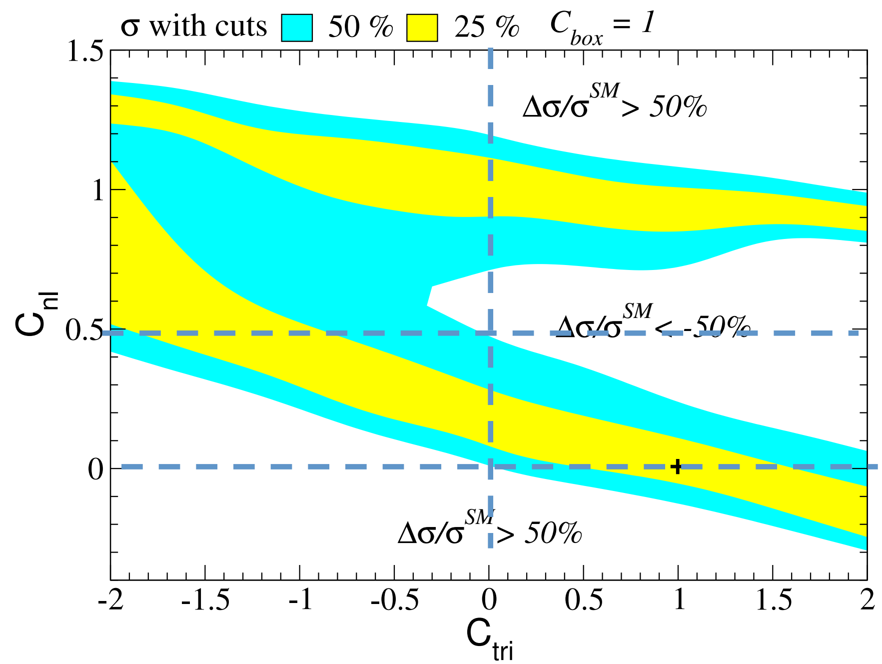
gg → h h

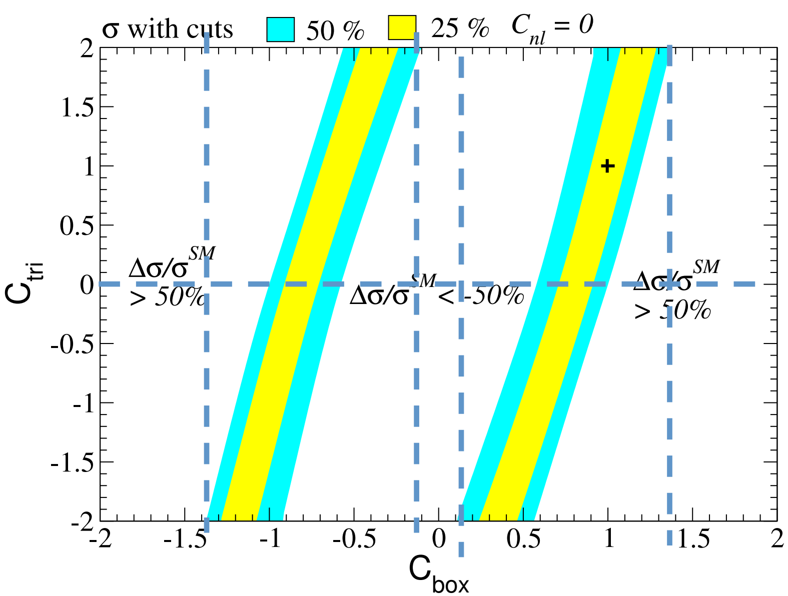
$$p_T^b > 35\text{ GeV},\quad |\eta_b| < 2,\quad 2.5 > \Delta R(b,b) > 0.4,$$

$$p_T^\gamma > 35\text{ GeV},\quad |\eta_\gamma| < 2,\quad 2.5 > \Delta R(\gamma,\gamma) > 0.4,\quad \Delta R(\gamma,b) > 0.4,$$

$$|\cos\theta_{\gamma\gamma}| < 0.8,\quad p_T^h > 100\text{ GeV and } m_{hh} > 350\text{ GeV},$$



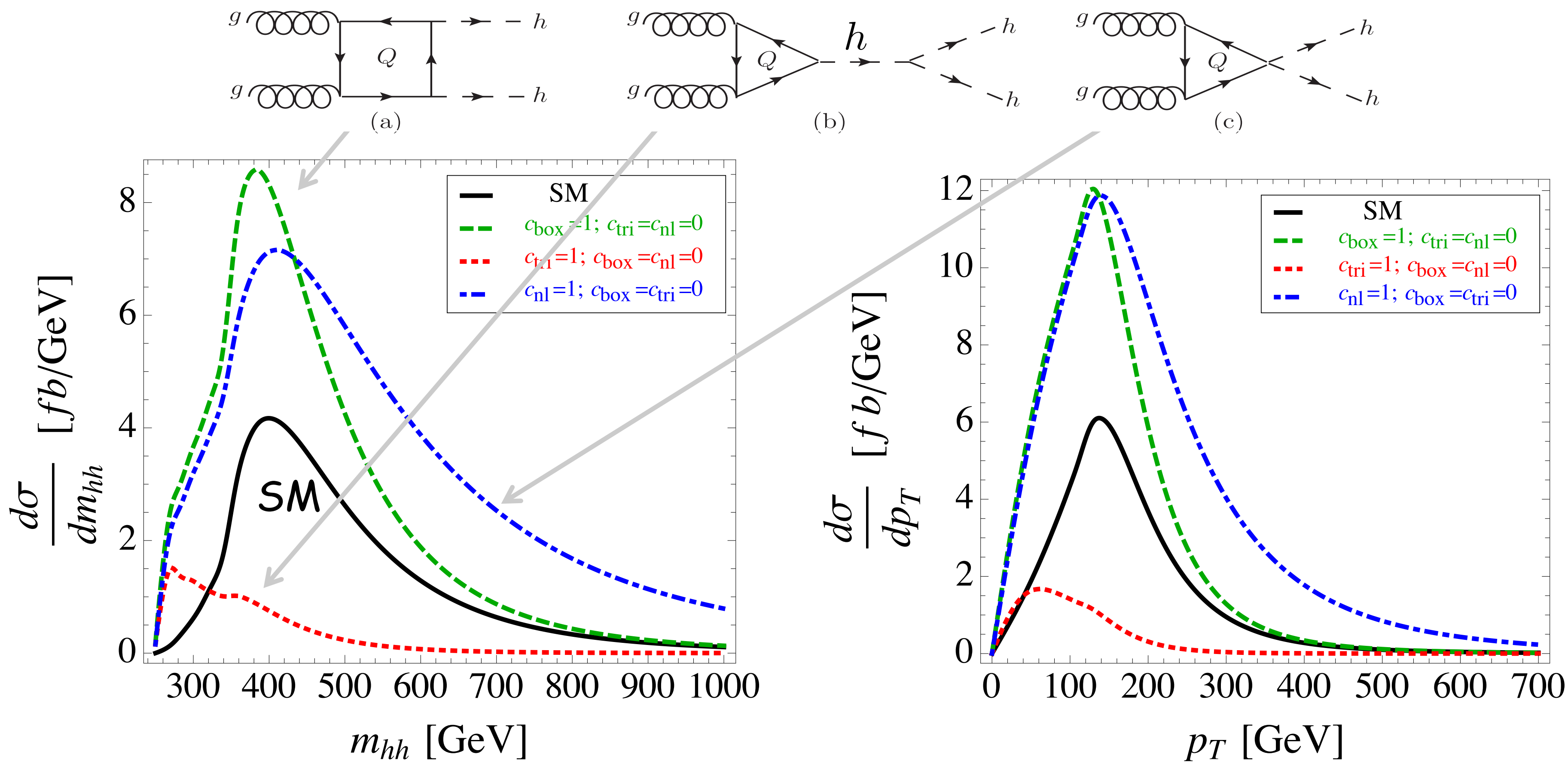




constrain on C_{tri} is weak

w/ more assumptions, we can have more implications

gg → h h



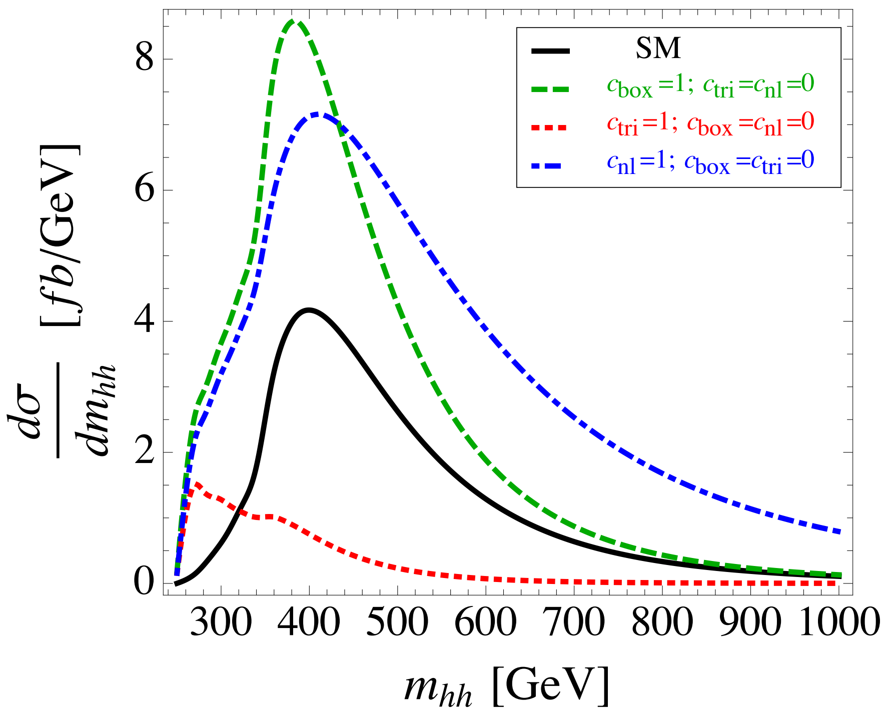
triangle → low M_{hh} and low p_t

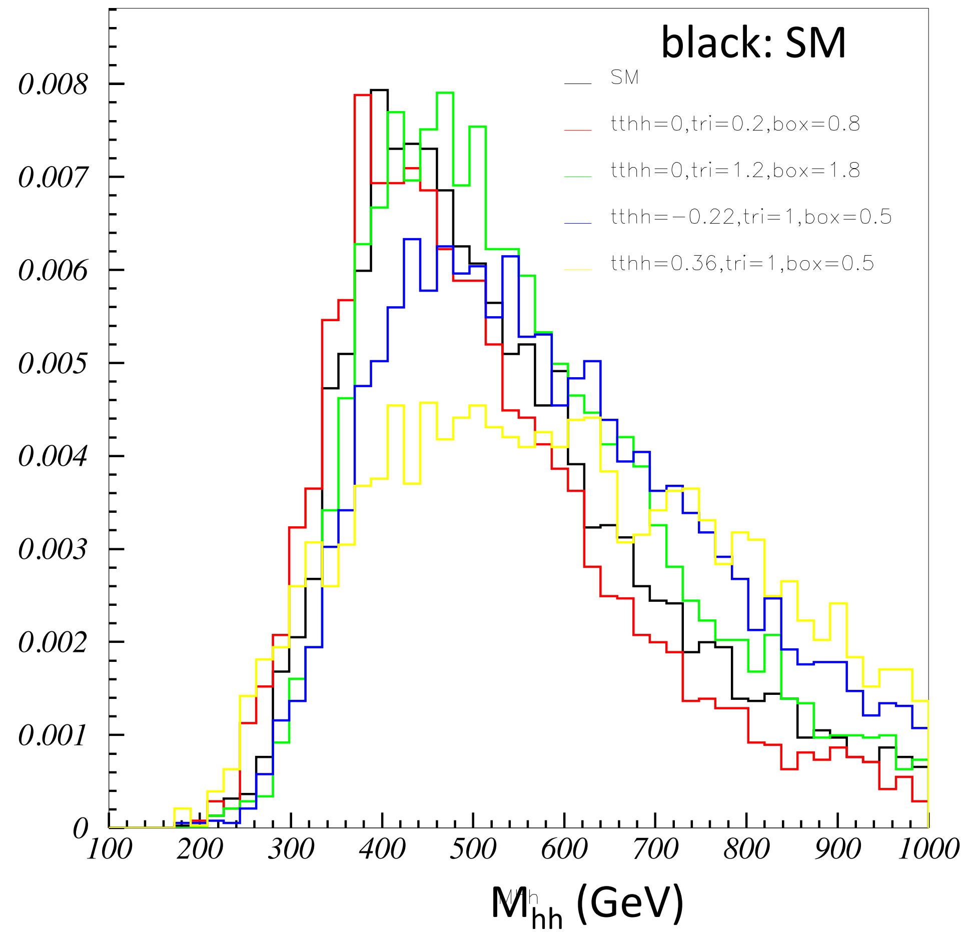
box diagram → higher M_{hh} and higher p_t

tthh diagram →even higher M_{hh} and even higher p_t

gg → h h

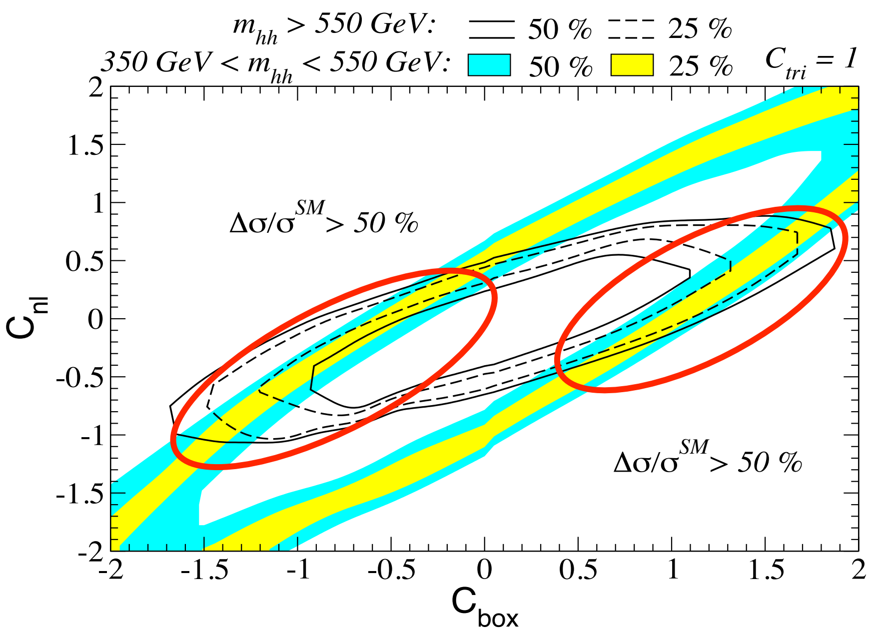
red: C_{nl}=0, C_{tri}=0.2, C_{box}=0.8
green: C_{nl}=0, C_{tri}=1.2, C_{box}=1.8
blue: C_{nl}=-0.22, C_{tri}=1, C_{box}=0.5
yellow: C_{nl}=0.36, C_{tri}=1, C_{box}=0.5

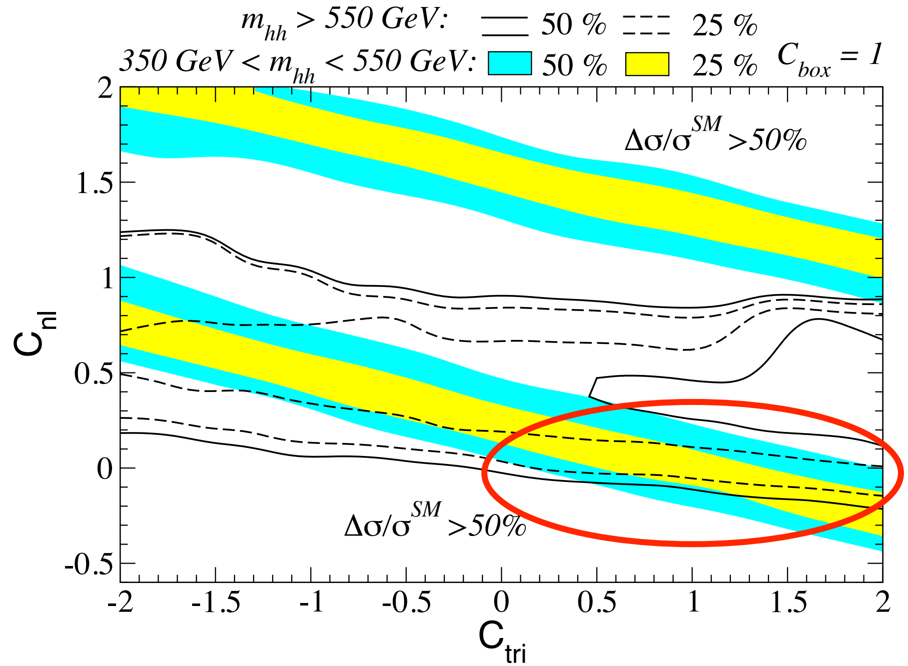




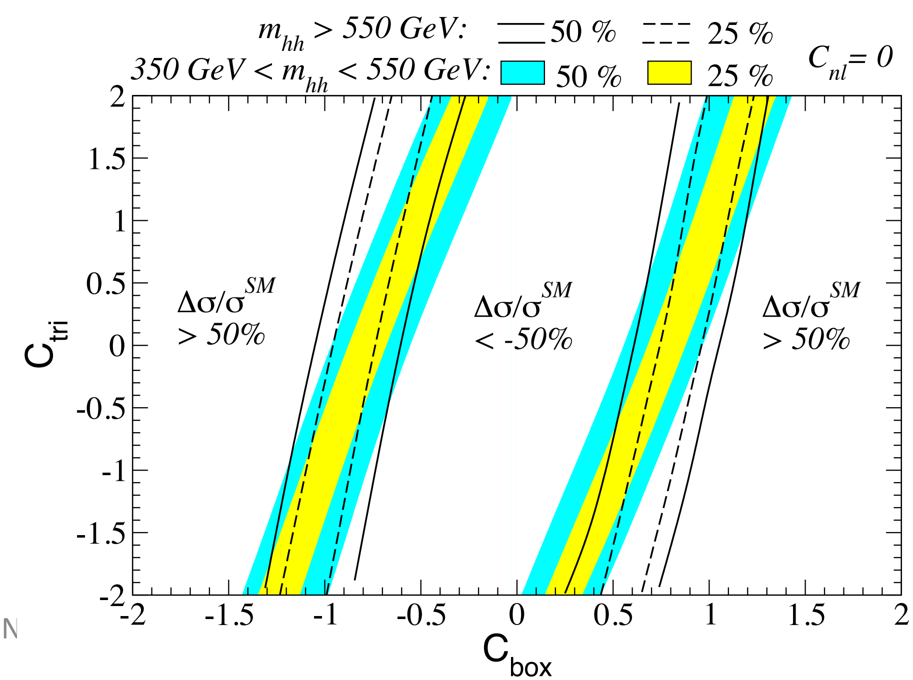
different combinations give same cross section, but
different M_{hh} and P_t distributions

gg → h h

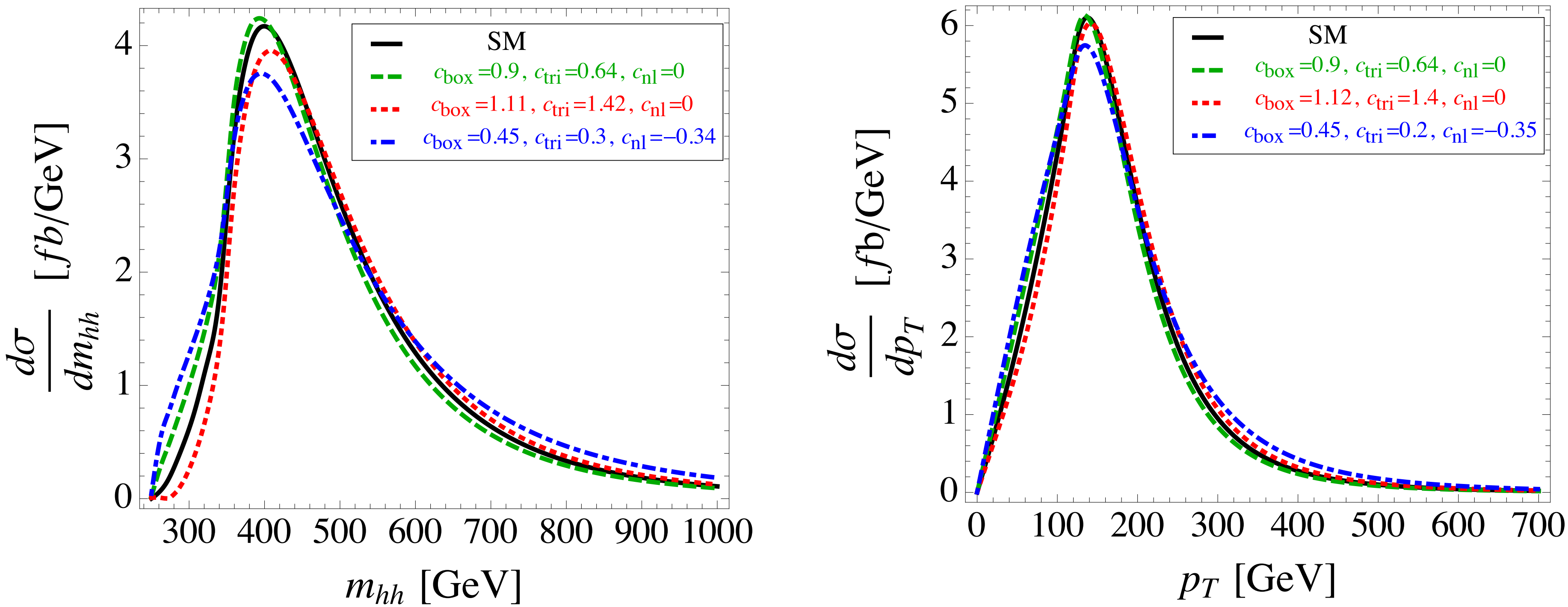




constrain some parameter space



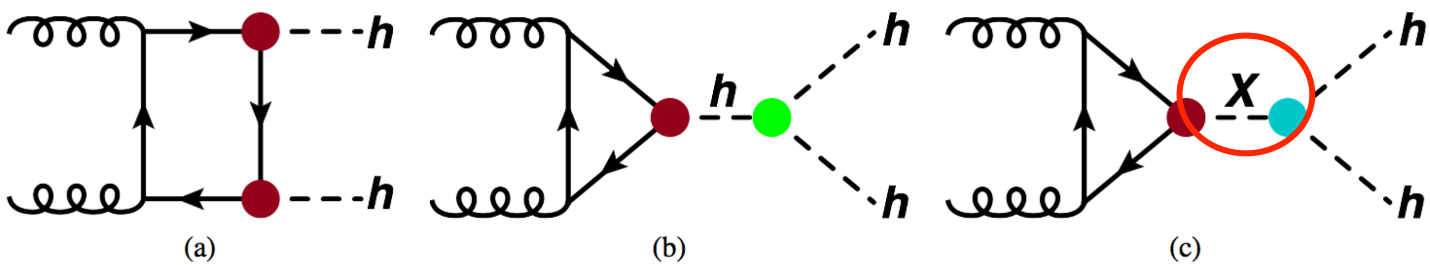
$gg \rightarrow h\,h$



different combinations of C_{tri}, C_{box} and C_{NL} produce similar distributions

→ need more information to break the degeneracy

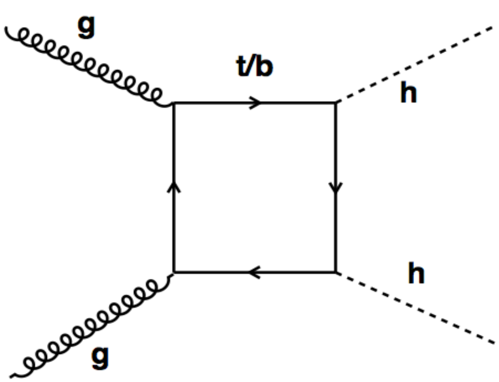
NP effects in gg → h h (II)

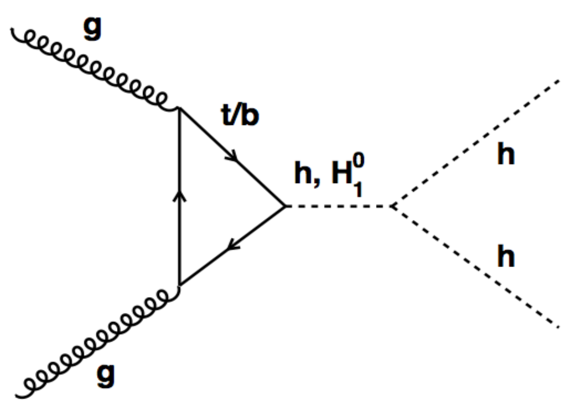


existence of a new resonance that decays into Higgs boson pair!

e.g. two doublet Higgs model, Gerogi-Machacek model, Gauged 2HDM…

Chang, **CRC**, Chiang, JHEP 1703,137 **CRC**, Lin, Tran, Yuan 1710.*****





NP effects in gg → h h (II)

GM model : neutrino generation, extension in scalar sector

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -(\phi^{+})^{*} & \phi^{0} \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -(\chi^{+})^{*} & \xi^{0} & \chi^{+} \\ (\chi^{++})^{*} & -(\xi^{+})^{*} & \chi^{0} \end{pmatrix};$$

$$\begin{aligned} V(\Phi,\Delta) =& \frac{1}{2}m_1^2 \mathrm{tr}[\Phi^\dagger\Phi] + \frac{1}{2}m_2^2 \mathrm{tr}[\Delta^\dagger\Delta] + \lambda_1(\mathrm{tr}[\Phi^\dagger\Phi])^2 + \lambda_2(\mathrm{tr}[\Delta^\dagger\Delta])^2 \\ &+\lambda_3 \mathrm{tr}[(\Delta^\dagger\Delta)^2] + \lambda_4 \mathrm{tr}[\Phi^\dagger\Phi]\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_5 \mathrm{tr}\left[\Phi^\dagger\frac{\sigma^{\mathrm{a}}}{2}\Phi\frac{\sigma^{\mathrm{b}}}{2}\right]\mathrm{tr}\left[\Delta^\dagger \mathrm{T}^{\mathrm{a}}\Delta\mathrm{T}^{\mathrm{b}}\right] \\ &+\mu_1 \mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right](P^\dagger\Delta P)_{ab} + \mu_2 \mathrm{tr}\left[\Delta^\dagger T^a\Delta T^b\right](P^\dagger\Delta P)_{ab}\ , \end{aligned}$$

$$P = \frac{1}{\sqrt{2}}\begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix}$$

NP effects in gg → h h (II)

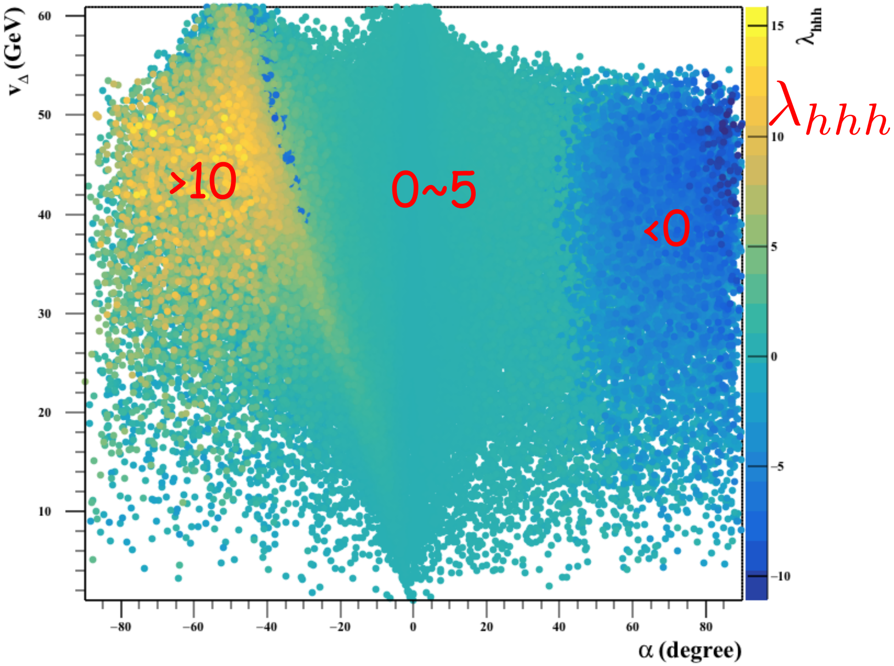
$$h = \cos\alpha H_\Phi^1 - \sin\alpha H_\Delta^1, \quad H_1^0 = \sin\alpha H_\Phi^1 + \cos\alpha H_\Delta^1$$

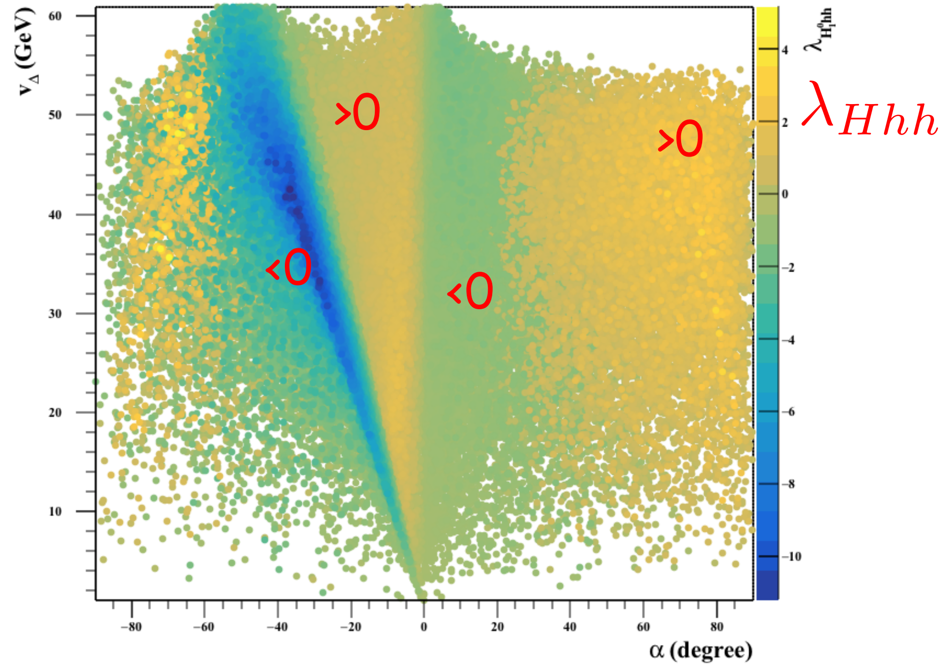
$$g_{hf\bar f} = \frac{c_\alpha}{s_\beta} g_{hf\bar f}^{\rm SM}, \qquad g_{hVV} = \left(s_\beta c_\alpha - \sqrt{\frac{8}{3}} c_\beta s_\alpha \right) g_{hVV}^{\rm SM},$$

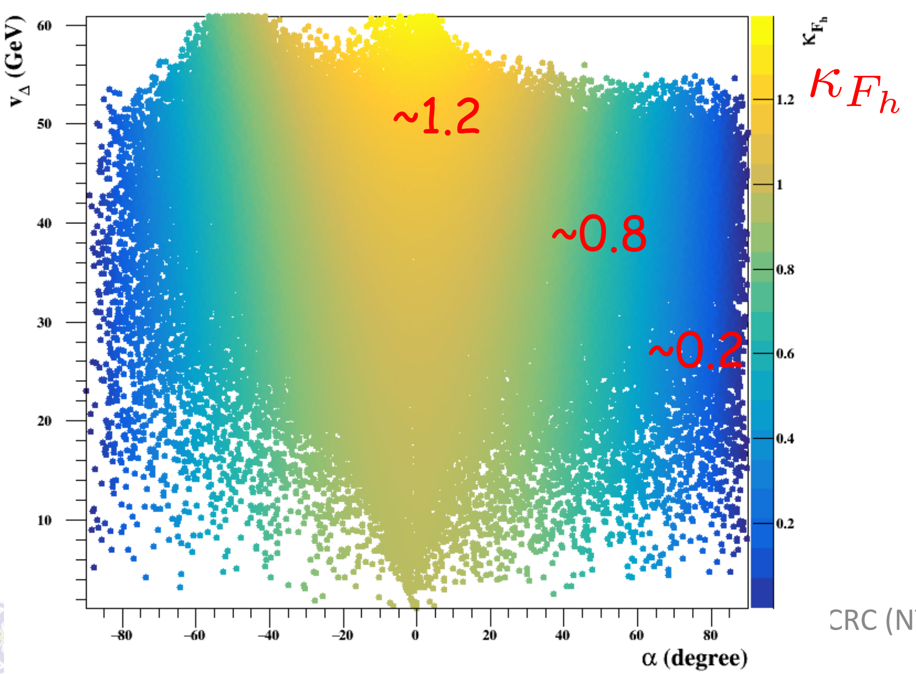
$$g_{H_1^0 f\bar f} = \frac{s_\alpha}{s_\beta} g_{hf\bar f}^{\rm SM}, \qquad g_{H_1^0 VV} = \left(s_\beta s_\alpha + \sqrt{\frac{8}{3}} c_\beta c_\alpha \right) g_{hVV}^{\rm SM}.$$

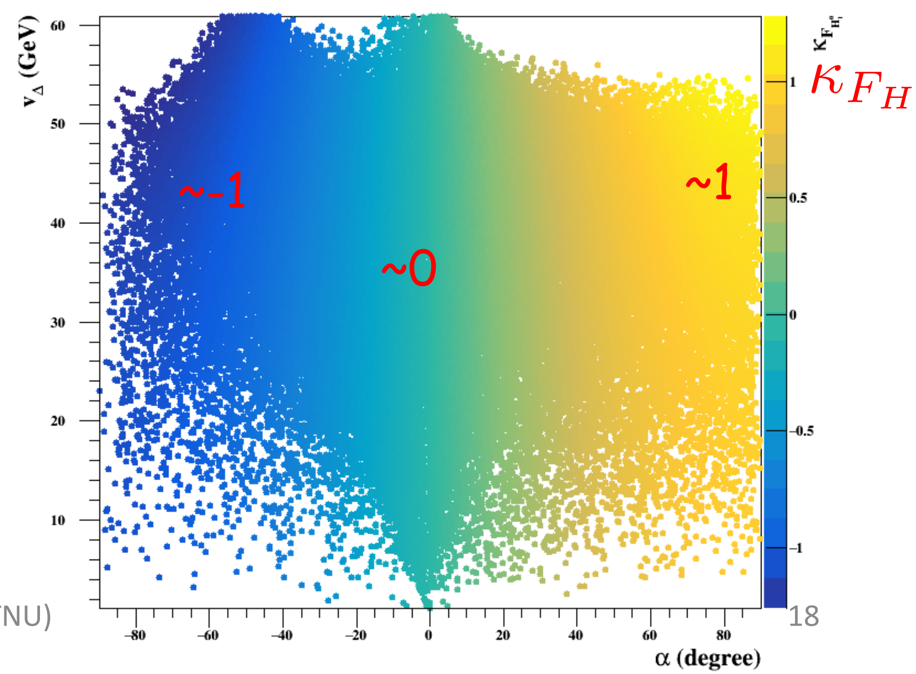
$$g_{hhh} \simeq \left\{ 1 - \frac{\mu_1^2 v^2}{m_2^4} \left[\frac{7}{8} - \frac{3}{2} \frac{v^2}{m_h^2} \left((2\lambda_4 + \lambda_5) + \frac{\mu_1 \mu_2}{m_2^2} \right) \right] \right\} g_{hhh}^{\rm SM},$$

$$g_{H_1^0 hh} = 24\lambda_1 c_\alpha^2 s_\alpha v_\phi + 2\left[\sqrt{3} c_\alpha v_\Delta (3c_\alpha^2 - 2) + s_\alpha v_\phi (1 - 3c_\alpha^2) \right] (2\lambda_4 + \lambda_5)$$
$$+ 8\sqrt{3} c_\alpha s_\alpha^2 v_\Delta (\lambda_3 + 3\lambda_2) + \frac{\sqrt{3}}{2} \mu_1 c_\alpha (3c_\alpha^2 - 2) + 4\sqrt{3} \mu_2 c_\alpha s_\alpha^2.$$


v_Δ (GeV)
α (degree)
λ_{hhh}
>10
0~5
<0

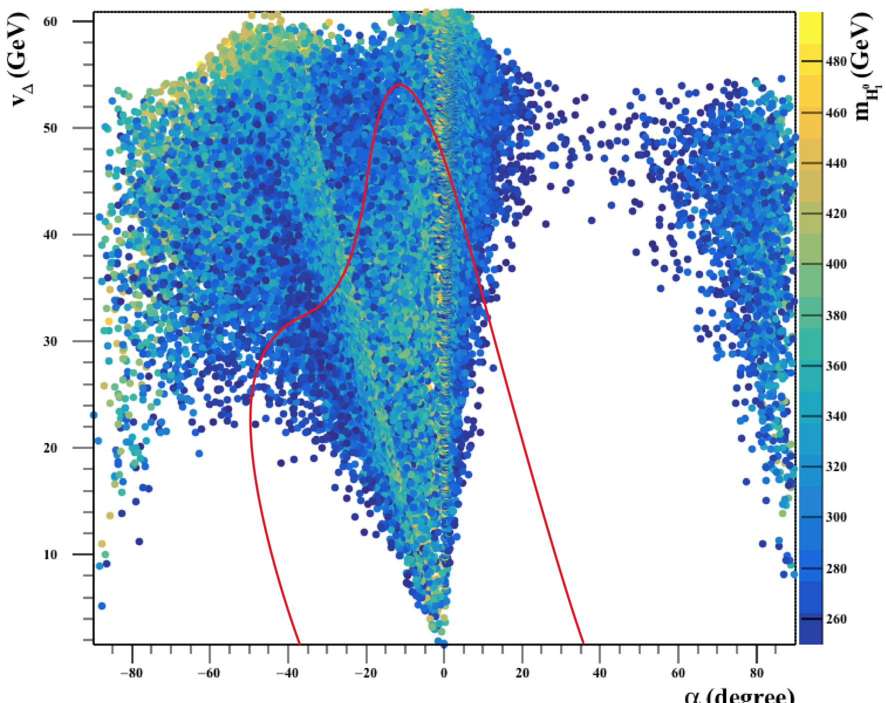

v_Δ (GeV)
α (degree)
λ_{Hhh}
>0
>0
<0
<0


v_Δ (GeV)
α (degree)
κ_{F_h}
~1.2
~0.8
~0.2

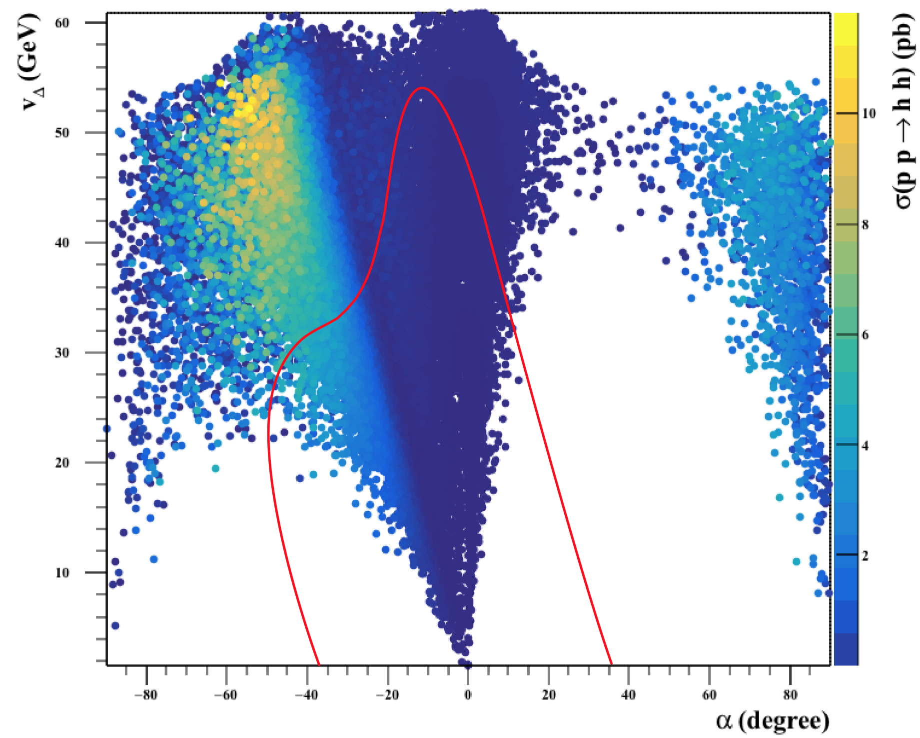

v_Δ (GeV)
α (degree)
κ_{F_H}
~-1
~0
~1

$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3}\left[\left|\lambda_{hhh}\kappa_{F_h} D(\hat{s}) F_\triangle + \lambda_{H_1^0 hh}\kappa_{F_{H_1^0}} \bar{D}(\hat{s}) F_\triangle + \kappa_{F_h}^2 F_\Box\right|^2 + \left|\kappa_{F_h}^2 G_\Box\right|^2\right]$$

$$D(\hat{s}) = \frac{3m_h^2}{\hat{s} - m_h^2 + i m_h \Gamma_h}\ , \quad \bar{D}(\hat{s}) = \frac{3m_h^2}{\hat{s} - m_{H_1^0}^2 + i m_{H_1^0}\Gamma_{H_1^0}}$$



M_H



$pp \to H_0 \to hh$

$$\sigma(pp \to H_1^0 \to hh) = \sigma(gg \to h)_{m_h \to m_{H_1^0}} \times \kappa_{F_{H_1^0}}^2 \times BR(H_1^0 \to hh)$$

NP effects in gg → h h (II)

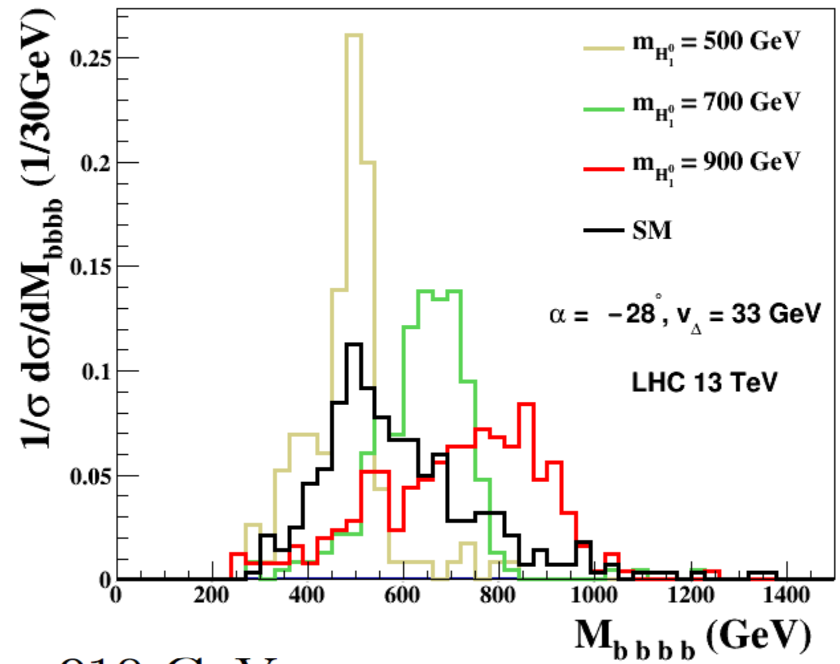
some benchmark points

benchmark point	A	B	C	D	E	F	G	H
(α, v_Δ)	$(10,30)$	$(-10,50)$	$(-10,20)$	$(-30,20)$	$(-40,30)$	$(-45,20)$	$(-28,33)$	$(-1,1)$
κ_{F_h}	1.049	1.204	1.012	0.889	0.816	0.727	0.954	0.999
$\kappa_{F_{H_1^0}}$	0.185	−0.212	−0.178	−0.514	−0.685	−0.727	−0.507	−0.018
κ_{V_h}	0.827	0.969	1.024	1.031	1.081	0.954	1.108	1.00
$\kappa_{V_{H_1^0}}$	0.718	0.782	0.201	−0.161	−0.172	−0.423	0.113	1.32×10^{-3}
$m_{H_1^0}$	250–301	250–455	250–954	250–315	250–402	250–273	250–1373	250–492
$BR(H_1^0 \to hh)$	0.004–0.16	0.0014–0.133	0.009–0.186	0.244–0.954	2×10^{-4}–0.96	2×10^{-5}–0.5	7×10^{-3}–0.81	0.6–0.99

$500\ \mathrm{GeV} > m_H \geq 250\ \mathrm{GeV}$ ➡ using bbγγ channel

$m_H \geq 500\ \mathrm{GeV}$ ➡ using 4 b channel

NP effects in gg → h h (II)



$$N_b \geq 4\ ,\ |\eta(j)| < 2.5\ ,\ P_T(b) > 40\ \text{GeV}\ ,$$

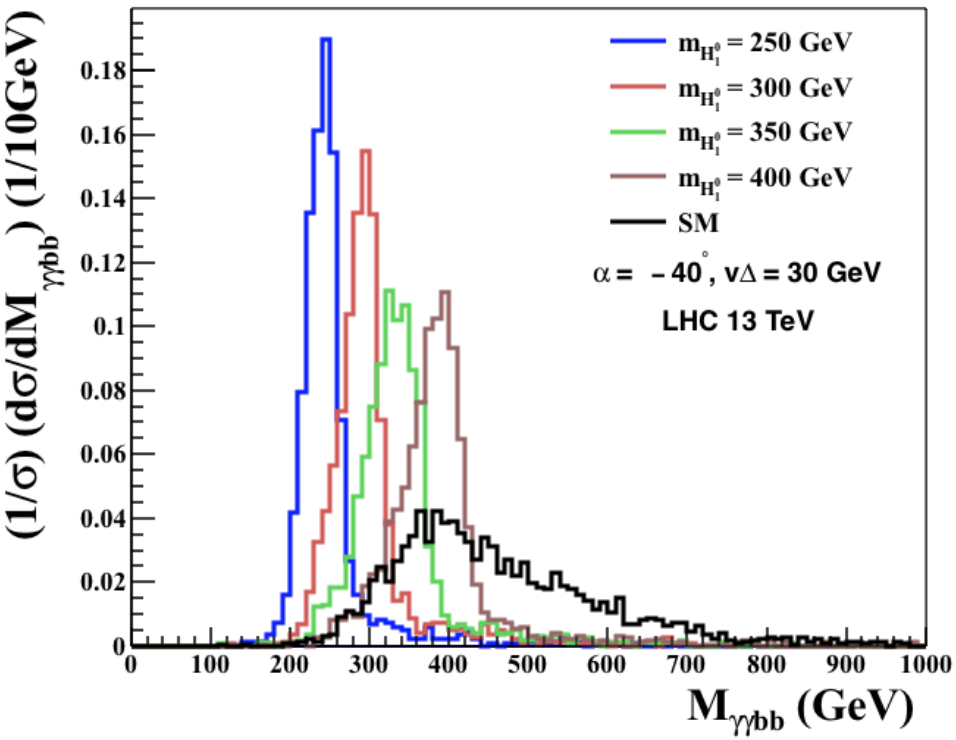
$$\Delta R(jj) < 1.5,\ P_T(jj)^{\text{lead,subl}} > 200, 150\ \text{GeV}$$

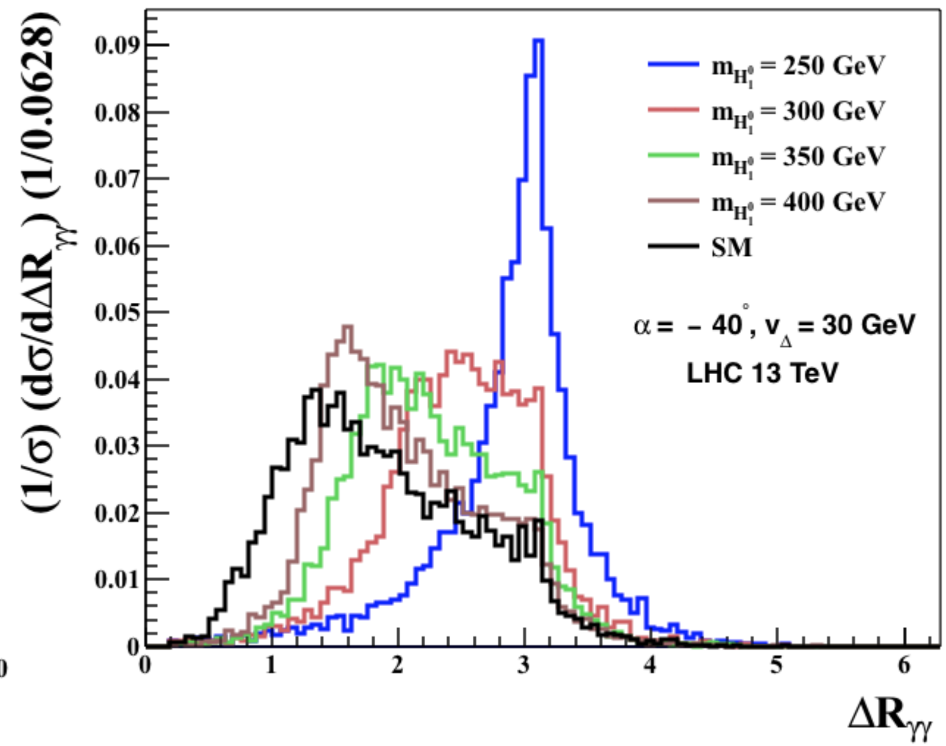
$$P_T^{\text{lead}}(jj) > \begin{cases} 400\ \text{GeV} & \text{if } M_{4j} > 910\ \text{GeV}\ , \\ 200\ \text{GeV} & \text{if } M_{4j} < 600\ \text{GeV}\ , \\ 0.65 M_{4j} - 190\ \text{GeV} & \text{otherwise}\ ; \end{cases}$$

$$P_T^{\text{subl}}(jj) > \begin{cases} 260\ \text{GeV} & \text{if } M_{4j} > 990\ \text{GeV}\ , \\ 150\ \text{GeV} & \text{if } M_{4j} < 520\ \text{GeV}\ , \\ 0.23 M_{4j} + 30\ \text{GeV} & \text{otherwise}\ ; \end{cases}$$

$$|\Delta\eta(jj)| < \begin{cases} 1.0 & \text{if } M_{4j} < 820\ \text{GeV}\ , \\ 1.6 \times 10^{-3} M_{4j} - 0.28 & \text{otherwise}\ . \end{cases}$$

NP effects in gg → h h (II)





$$N_\gamma \geq 2,\ N_b = 2\ ,\ P_T(j) > 25\ \text{GeV}\ ,\ P_T(b)^{\text{lead,subl}} > 55,\ 35\ \text{GeV}\ ,$$

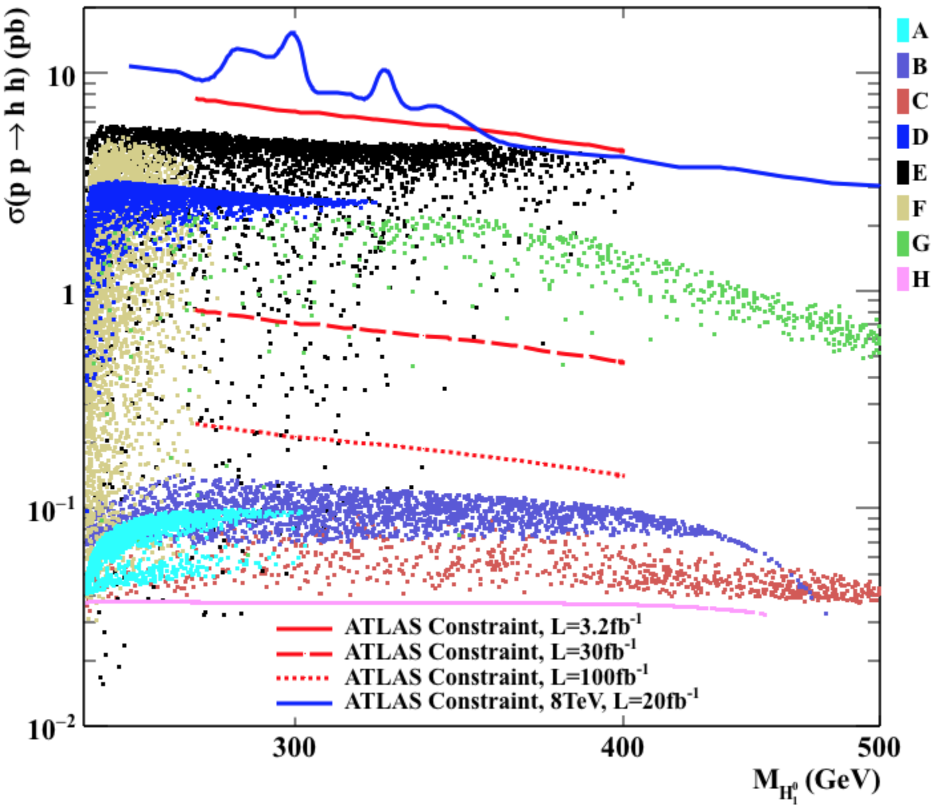
$$105\ \text{GeV} < M_{\gamma\gamma} < 160\ \text{GeV},\ 95\ \text{GeV} < M_{bb} < 135\ \text{GeV}\ .$$

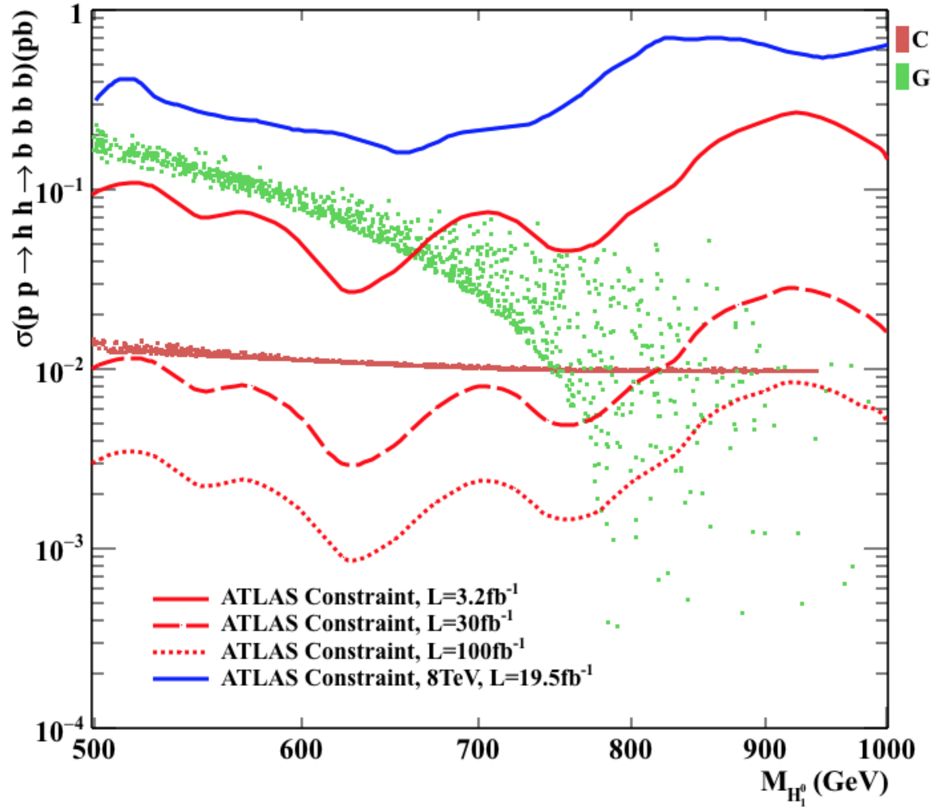
NP effects in $gg \to h\,h$ (II)

Benchmark point	E				G						SM
(α, v_Δ)	$(-40^\circ,\ 30\ \text{GeV})$				$(-28^\circ,\ 33\ \text{GeV})$						
$m_{H_1^0}$ (GeV)	250	300	350	400	500	600	700	800	900	1000	
$\Gamma_{H_1^0}$ (GeV)	0.68	5.37	10.62	8.05	6.75	9.04	18.91	27.83	34.67	51.00	
$BR(H_1^0 \to hh)$	0.82	0.954	0.955	0.76	0.57	0.45	0.62	0.66	0.65	0.71	
$\sigma(pp \to hh)_{13\text{–TeV}}$ (pb)	3.62	3.28	3.32	2.68	0.56	0.25	0.18	0.11	0.11	0.078	
Efficiency	5.6%	6.4%	7.2%	8.8%	2.57%	4.15%	3.65%	2.45%	0.86%	0.97%	9.2%

$bb\gamma\gamma$

$bbbb$





8 TeV, 20 fb^{-1}

13 TeV, 3.2 fb^{-1}

13 TeV, 30 fb^{-1}

13 TeV, 300 fb^{-1}

*current data excludes part of parameter space of BP G

*with 30 fb^{-1}, most of parameter space of BP C (M>500 GeV), D, E, F, G can be probed

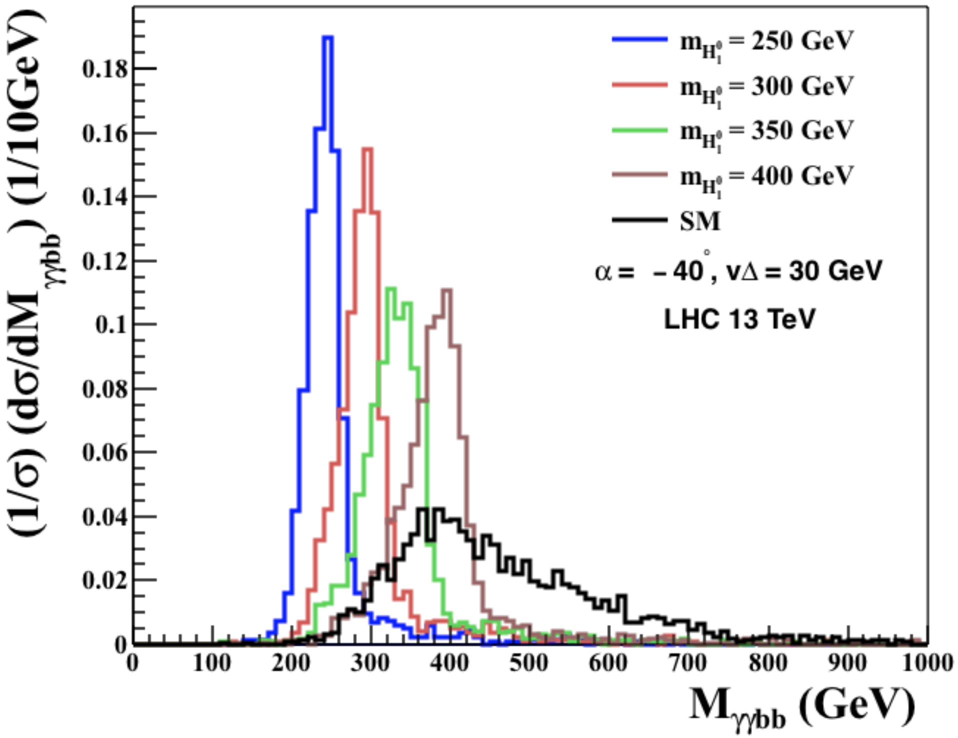
IF the SM-like Higgs pair production signal is discovered, could we tell whether there is new physics?

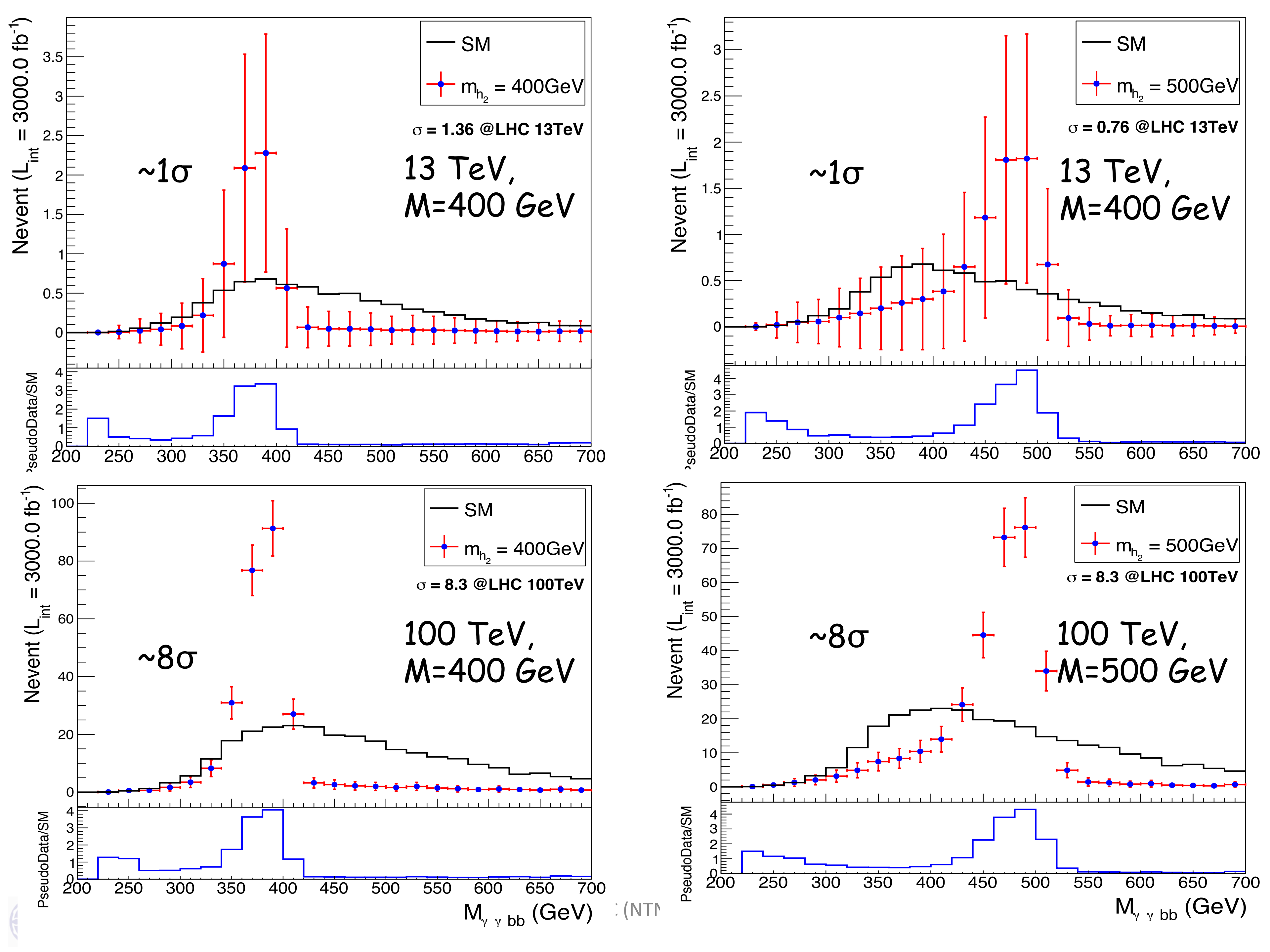
Assuming:

cross section is consistent with SM prediction

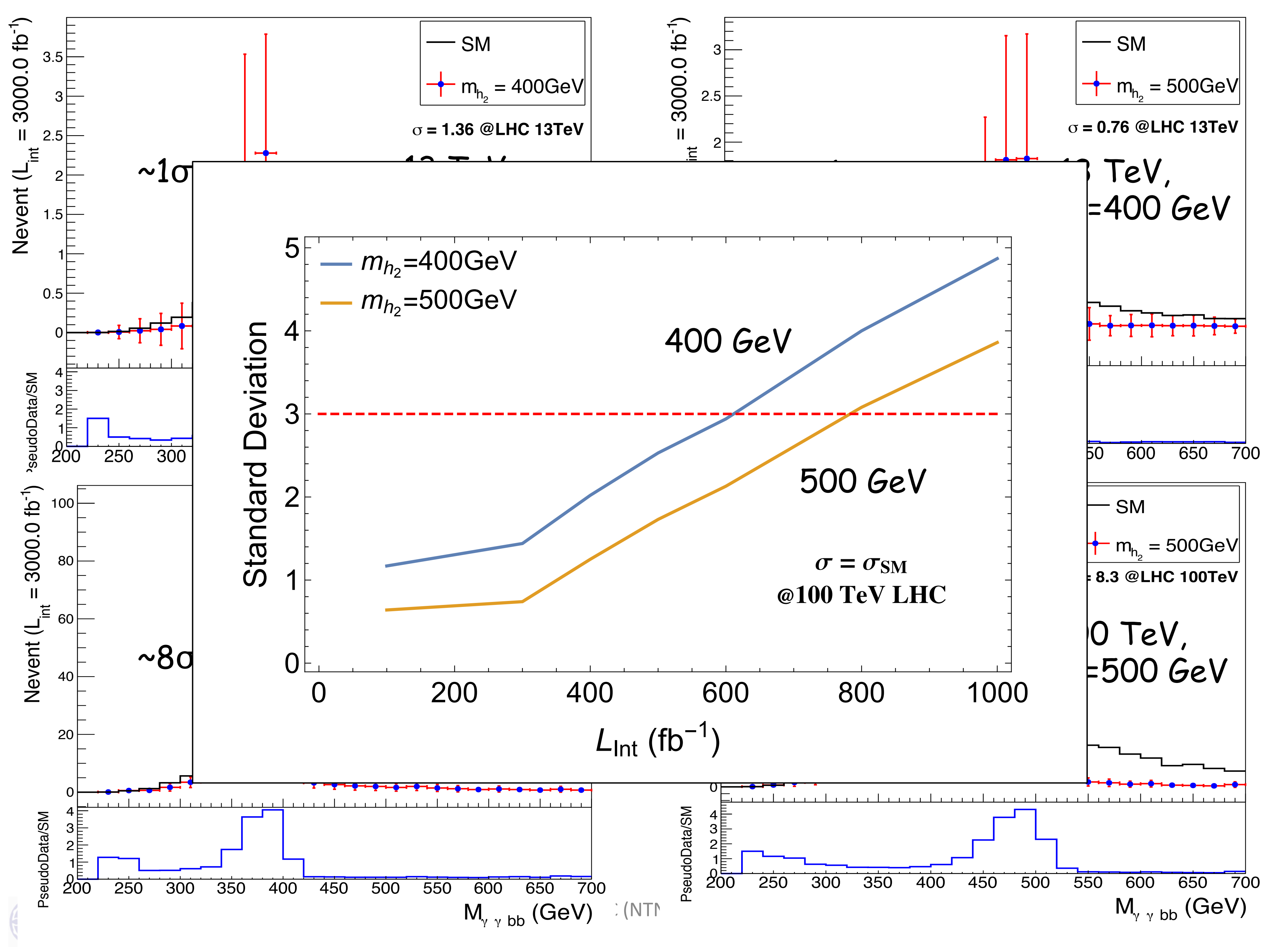
No “obvious” bump in high invariant mass of hh

→ similar distribution as SM, peaks around 400 ~ 500 GeV





SM
m_{h_2} = 400GeV
σ = 1.36 @LHC 13TeV
~1σ
13 TeV,
M=400 GeV
Nevent (L_{int} = 3000.0 fb^{-1})
PseudoData/SM
SM
m_{h_2} = 500GeV
σ = 0.76 @LHC 13TeV
~1σ
13 TeV,
M=400 GeV
Nevent (L_{int} = 3000.0 fb^{-1})
PseudoData/SM
SM
m_{h_2} = 400GeV
σ = 8.3 @LHC 100TeV
~8σ
100 TeV,
M=400 GeV
Nevent (L_{int} = 3000.0 fb^{-1})
PseudoData/SM
$M_{\gamma\gamma bb}$ (GeV)
SM
m_{h_2} = 500GeV
σ = 8.3 @LHC 100TeV
~8σ
100 TeV,
M=500 GeV
Nevent (L_{int} = 3000.0 fb^{-1})
PseudoData/SM
$M_{\gamma\gamma bb}$ (GeV)



SM
m_{h_2} = 400GeV
σ = 1.36 @LHC 13TeV
~1σ
SM
m_{h_2} = 500GeV
σ = 0.76 @LHC 13TeV
=400 GeV
~8σ
SM
m_{h_2} = 500GeV
8.3 @LHC 100TeV
=500 GeV
Nevent (L_{int} = 3000.0 fb^{-1})
PseudoData/SM
$M_{\gamma\gamma bb}$ (GeV)
m_{h_2}=400GeV
m_{h_2}=500GeV
400 GeV
500 GeV
Standard Deviation
$\sigma = \sigma_{SM}$
@100 TeV LHC
L_{Int} (fb^{-1})

Summary

* A new scalar with mass ~ 125 GeV is discovered and its properties are consistent with SM Higgs boson.

* Higgs self-coupling is crucial to test SM and find NP!! → not measured yet.

* Higgs pair production is important for the Higgs self-coupling, however, total cross section is not that sensitive to it, and NP may hide there.

* Kinematic distributions can break some degeneracy but more information is needed for a significant improvement!!

* With new resonance, the Higgs pair production can be significantly enhanced!!

* current data could be sensitive to heavy resonance production

* future collider (e.g. 100 TeV p-p) could probe the structure of scalar potential through Higgs pair production

backup

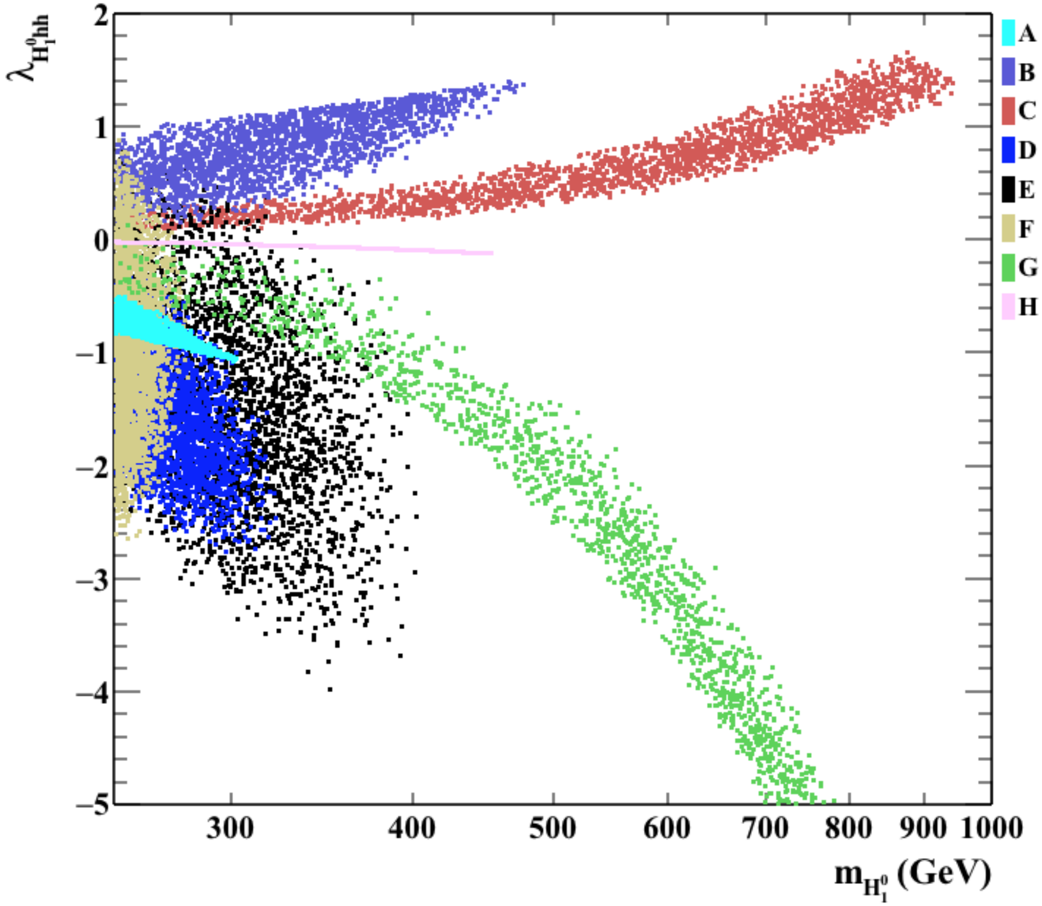
$$\phi^0 = \frac{1}{\sqrt{2}}(v_\phi + \phi_r + i\phi_i) \ , \ \chi^0 = v_\chi + \frac{1}{\sqrt{2}}(\chi_r + i\chi_i) \ , \ \xi^0 = v_\xi + \xi_r \ ,$$

$$v_\chi = v_\xi \equiv v_\Delta, \ \ v^2 \equiv v_\phi^2 + 8v_\Delta^2 = (246 \text{ GeV})^2, \tan\beta \equiv v_\phi/(2\sqrt{2}v_\Delta).$$

$$H_\Phi^1 = \phi_r \quad H_\Delta^1 = \sqrt{1/3}\xi_r + \sqrt{2/3}\chi_r$$

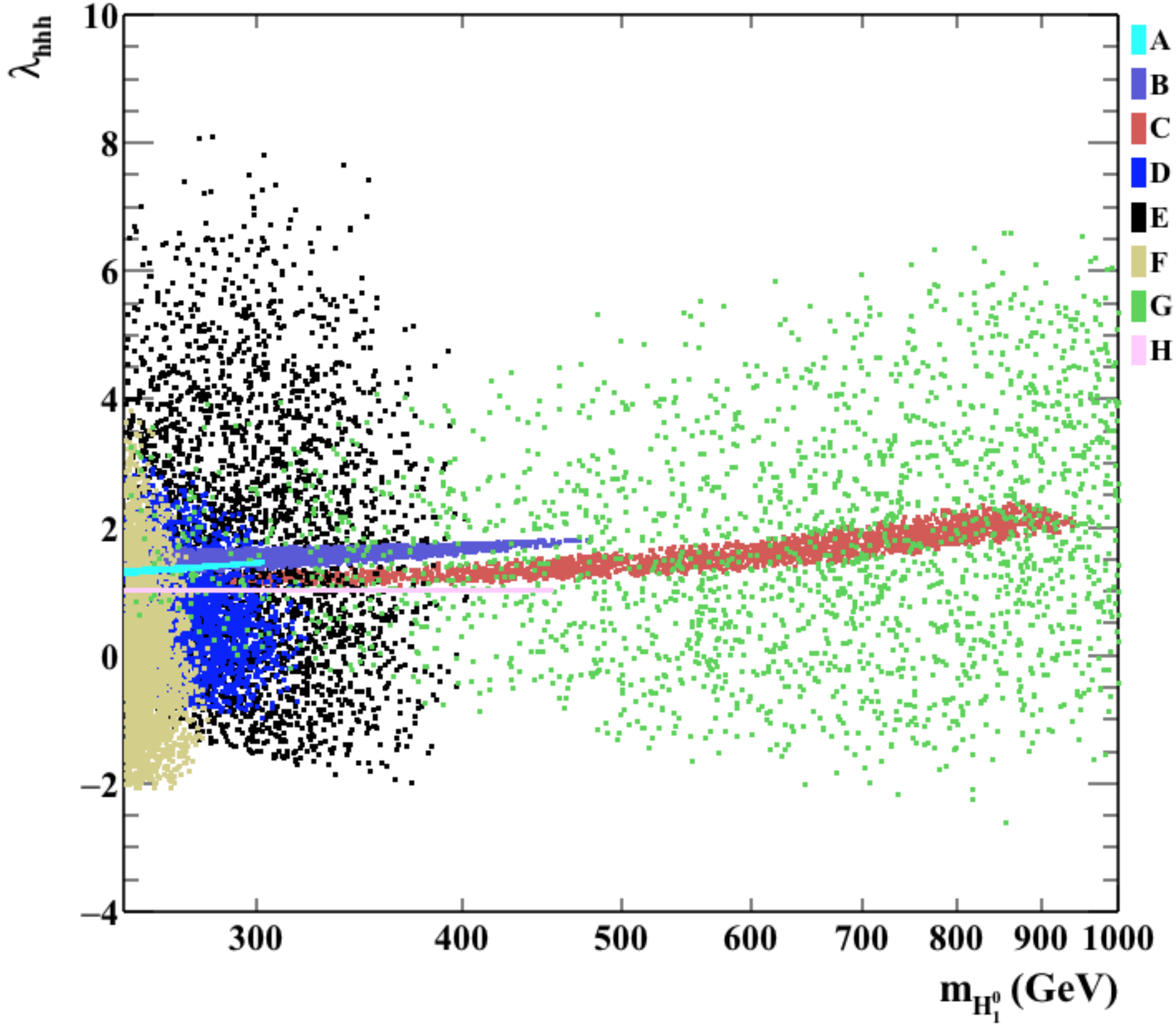
$$h = \cos\alpha H_\Phi^1 - \sin\alpha H_\Delta^1, \qquad H_1^0 = \sin\alpha H_\Phi^1 + \cos\alpha H_\Delta^1$$

backup

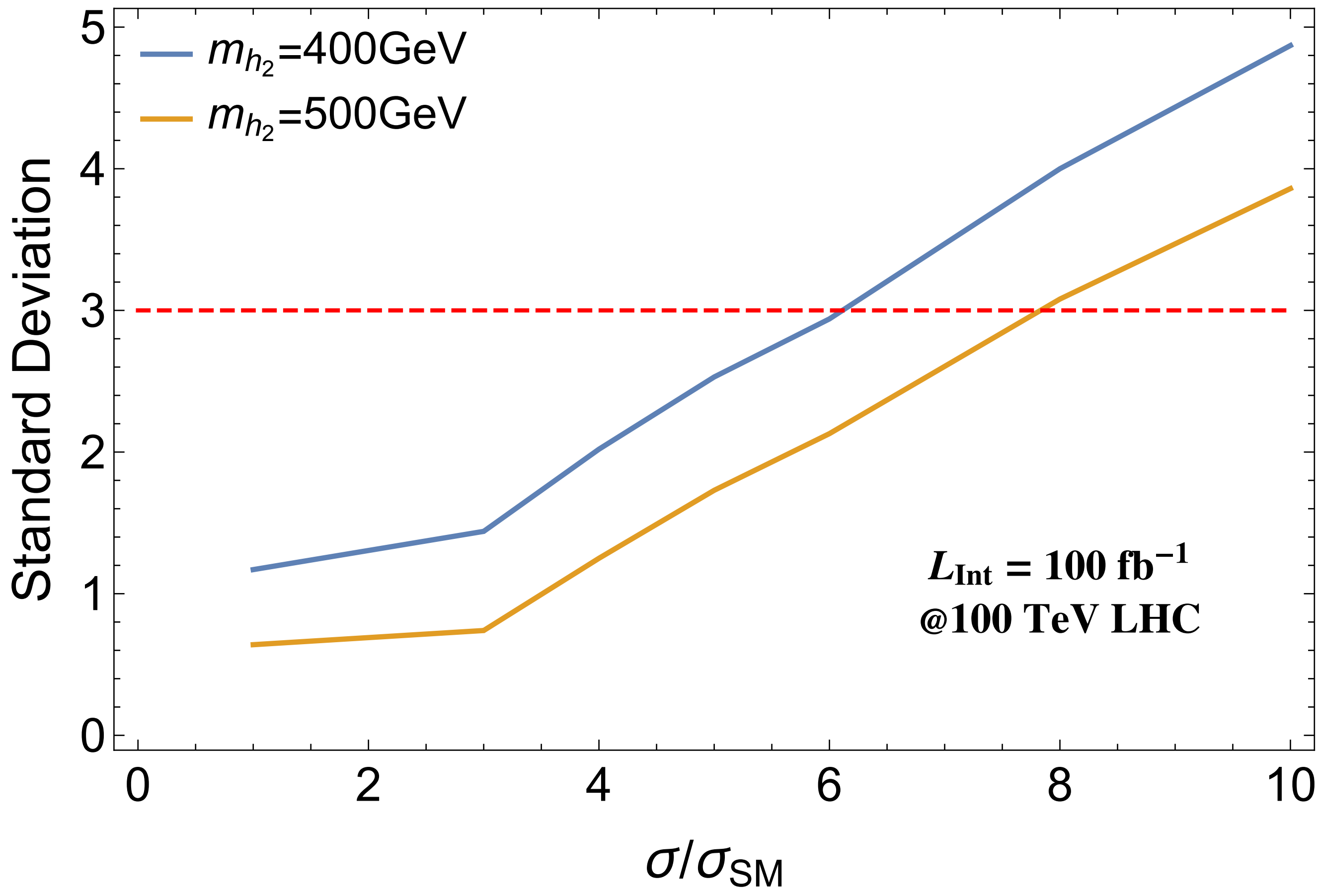


$\lambda_{H_1^0 hh}$
2
1
0
−1
−2
−3
−4
−5
300
400
500
600
700
800
900
1000
$m_{H_1^0}$ (GeV)
A
B
C
D
E
F
G
H

backup


λ_{hhh}
10
8
6
4
2
0
−2
−4
300
400
500
600
700
800
900
1000
$m_{H_1^0}$ (GeV)
A
B
C
D
E
F
G
H

backup



m_{h_2}=400GeV
m_{h_2}=500GeV
Standard Deviation
σ/σ_{SM}
L_{Int} = 100 fb^{-1}
@100 TeV LHC
0
1
2
3
4
5
0
2
4
6
8
10