Di- and Triple Higgs studies

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arXiv:1406.3349, C.-Y.C., S. Dawson, I. Lewis.

Q.-S. Yan, X. Zhao, Z. Zhao, Y.-M. Zhong

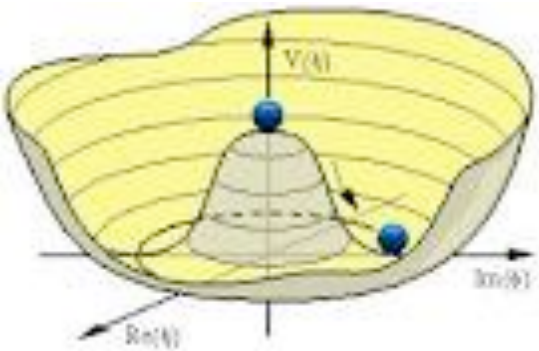
Next steps in the energy frontier - Hadron Colliders
Fermilab, August 26, 2014

Motivations

- What can we get from a 100 TeV hadron collider through Higgs productions?
  - Discovery: to find new heavy particles, such as top partners or heavy Higgs bosons …
  - Precision measurement: how well can we measure the Higgs couplings?
- Better understanding of the scalar potential
- Connection to electroweak baryogenesis

Scalar potential in SM

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda |\Phi^\dagger \Phi|^2$$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

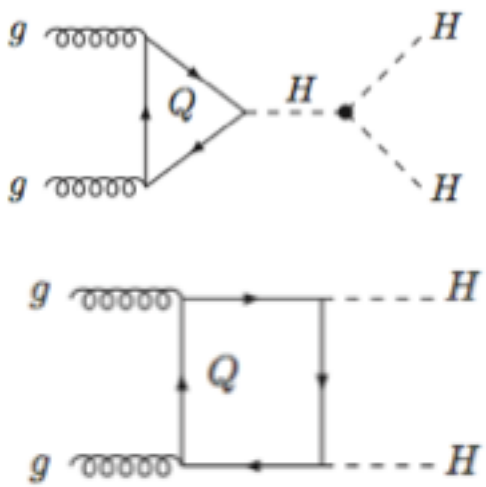
$$V \supset \tfrac{1}{2} m_H^2 H^2 + \tfrac{1}{3!} \lambda_{HHH} H^3 + \tfrac{1}{4!} \lambda_{HHHH} H^4$$

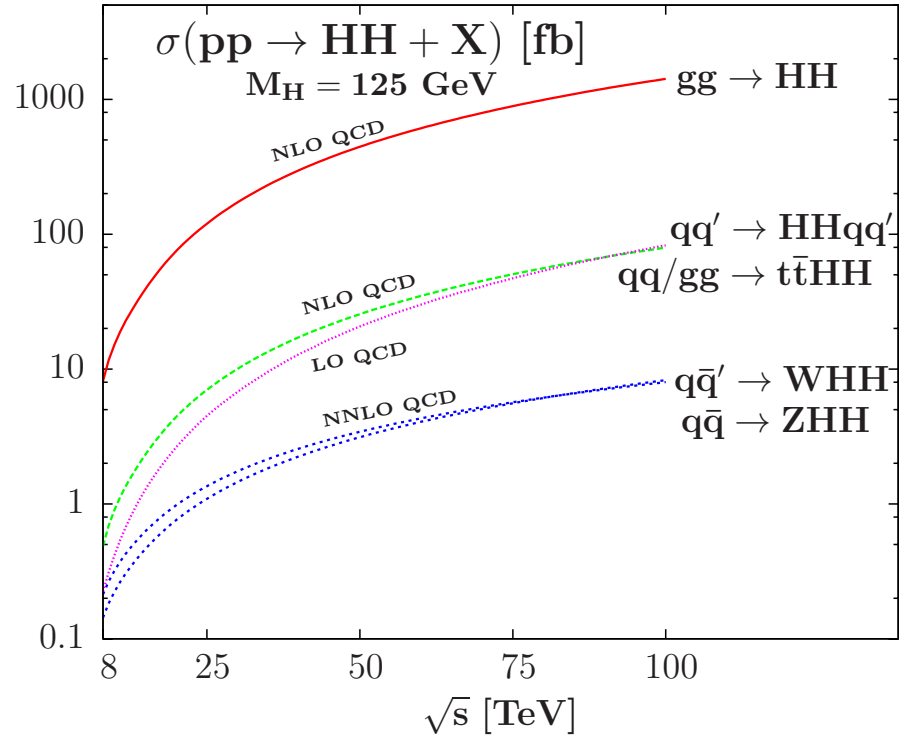
- SM predictions

$$\lambda_{HHH} = \frac{3m_H^2}{v} \sim 190.5 \text{ GeV} \qquad \lambda_{HHHH} = \frac{3m_H^2}{v^2} \sim 0.77$$

Di-Higgs production in SM

- Gluon fusion dominant:





[Snowwmass Higgs report, arXiv:1310.8361]

[Baglio et al, 1212.5581]

$\sqrt{s}$ (TeV)	Cross sections (fb) and theoretical uncertainties (%)				
	$gg \to HH$ NLO	$qq \to qqHH$ NLO	$q\bar{q} \to WHH$ NNLO	$q\bar{q} \to ZHH$ NNLO	$q\bar{q}/gg \to t\bar{t}HH$ LO
14	$33.89^{+37.2\%}_{-29.8\%}$	$2.01^{+7.6\%}_{-5.1\%}$	$0.57^{+3.7\%}_{-3.3\%}$	$0.42^{+7.0\%}_{-5.5\%}$	1.02
33	$207.29^{+33.0\%}_{-26.7\%}$	$12.05^{+6.1\%}_{-4.2\%}$	$1.99^{+3.5\%}_{-3.1\%}$	$1.68^{+7.9\%}_{-6.7\%}$	7.91
100	$1417.83^{+29.7\%}_{-24.7\%}$	$79.55^{+6.2\%}_{-4.1\%}$	$8.00^{+4.2\%}_{-3.7\%}$	$8.27^{+8.4\%}_{-8.0\%}$	77.82

Di-Higgs production in SM

- Gluon fusion dominant: leading order differential cross section

$$\frac{d\hat{\sigma}(gg \to H\,H\,)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3}\Big[|\sum_{t,b}(C_\triangle\, F_\triangle\, + C_\square\, F_\square)|^2 + |\sum_{t,b} C_\square\, G_\square|^2\Big]$$

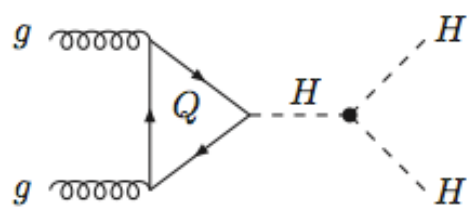
- In the heavy quark limit (Not a good approximation):

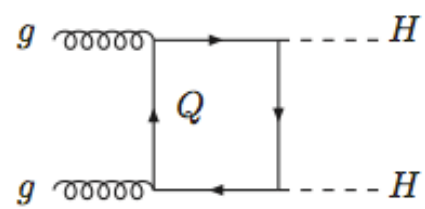
[Plehn et al., hep-ph/ 9603205]

$$C_\square = 1, \qquad C_\triangle = \frac{3M_H^2}{\hat{s} - M_H^2 + iM_H\Gamma_H} \qquad F_\triangle \to \frac{2}{3}, \quad G_\square \to 0, \qquad F_\square \to -\frac{2}{3},$$

- High order corrections are important.

LO	$16.5^{+4.6}_{-3.5}$	fb
NLO	$31.9^{+5.5}_{-4.6}$	fb
NNLO	$40.2^{+3.2}_{-3.5}$	fb

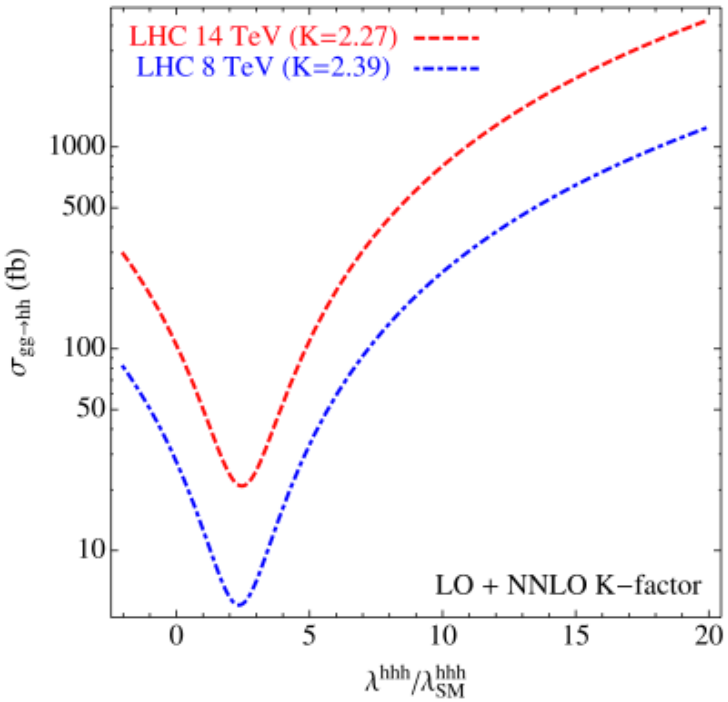


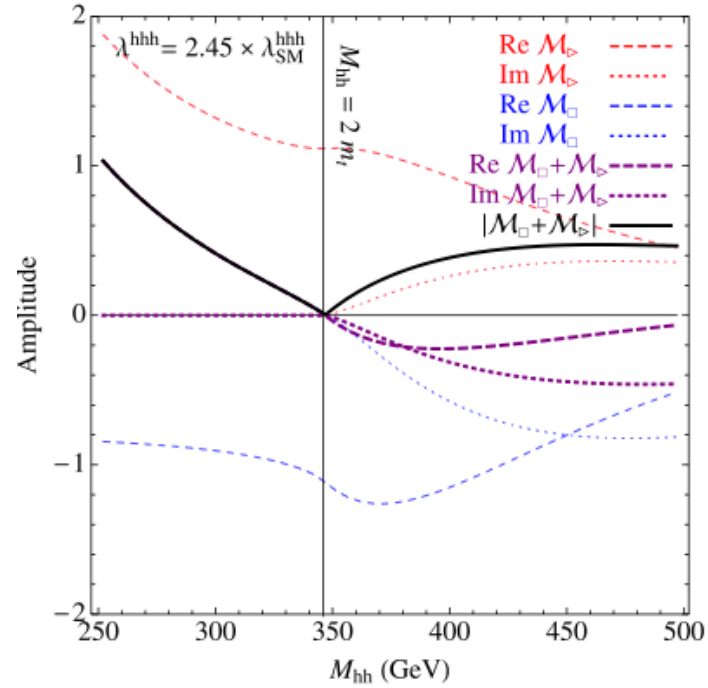


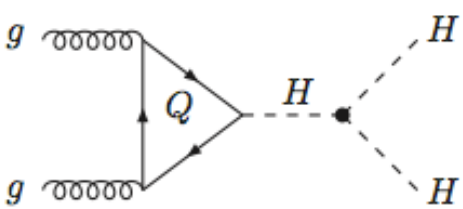
[Dawson et al, Phys.Rev. D58 (1998) 115012]
[Florian et al. Phys. Rev. Lett. 111, 201801]

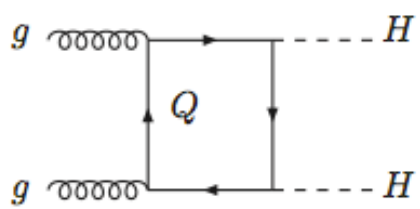
Di-Higgs production in SM

- Competition between the triangle and box diagrams.









[Barger et al., Phys. Lett. B728,433]

Collider study: di-Higgs production

- Possible channels to look at:
  - $b\bar{b}b\bar{b}$: largest rate but has large QCD background
  - $b\bar{b}\tau_h\bar{\tau}_h$: has background $b\bar{b}jj$ and light jets fake a hadronic τ
  - $b\bar{b}W^+W^-$: $t\bar{t}$ background. Small significance. Need to employ jet substructure and event reconstruction techniques.

    Papaefstathiou et al, arXiv: 1209.1489

  - $b\bar{b}\gamma\gamma$: Tiny branching fraction ~ 0.26%, but two photons in the final state can suppress the background significantly.

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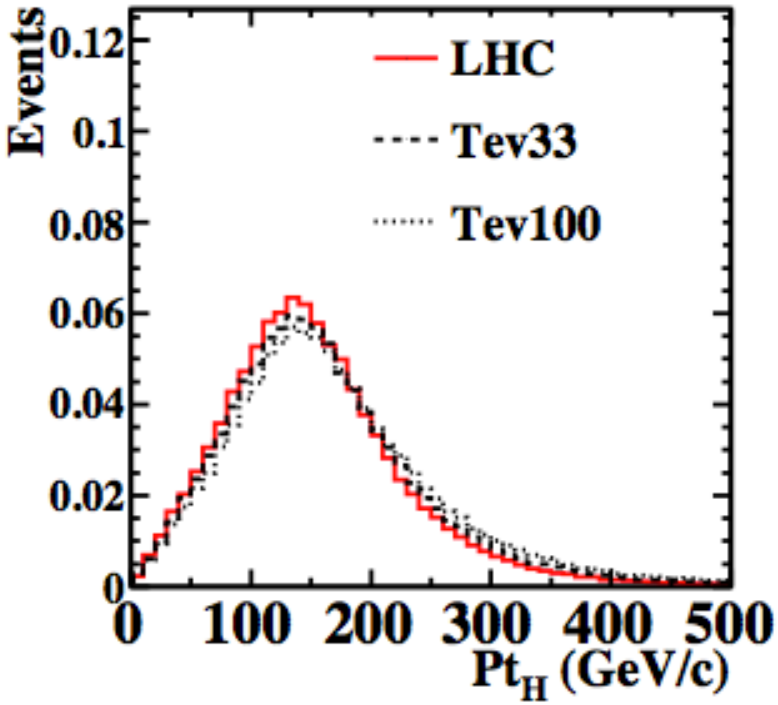
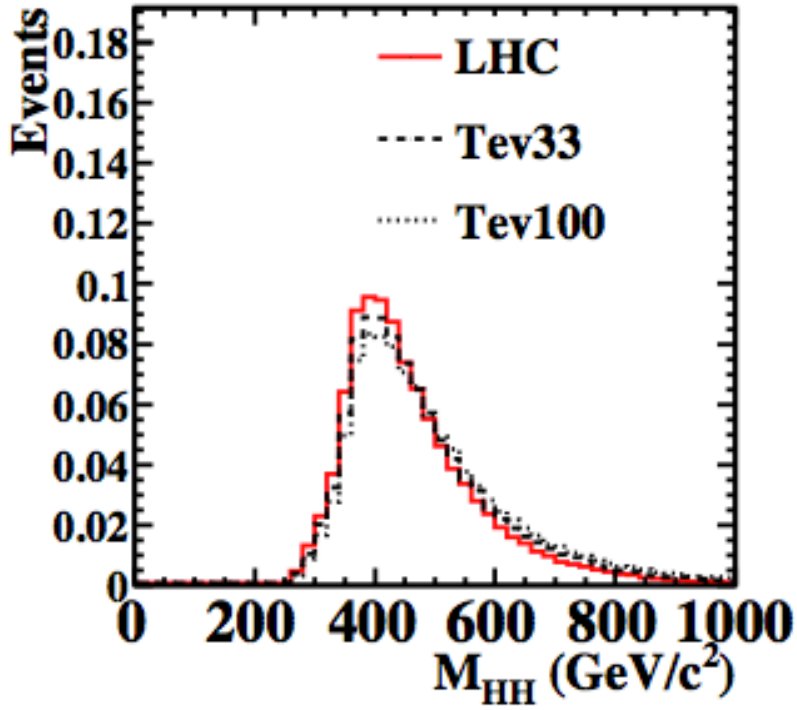
Collider study: di-Higgs production

- Normalized distributions have little energy dependence. Using the same cuts for 14 and 100 TeV.





W. Yao, arXiv: 1308.6302

Collider study: di-Higgs production

- Can measure the Higgs coupling with a 50% and 8% statistical accuracy at $\sqrt{s} = 14$ and $\sqrt{s} = 100$ TeV.

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L} dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

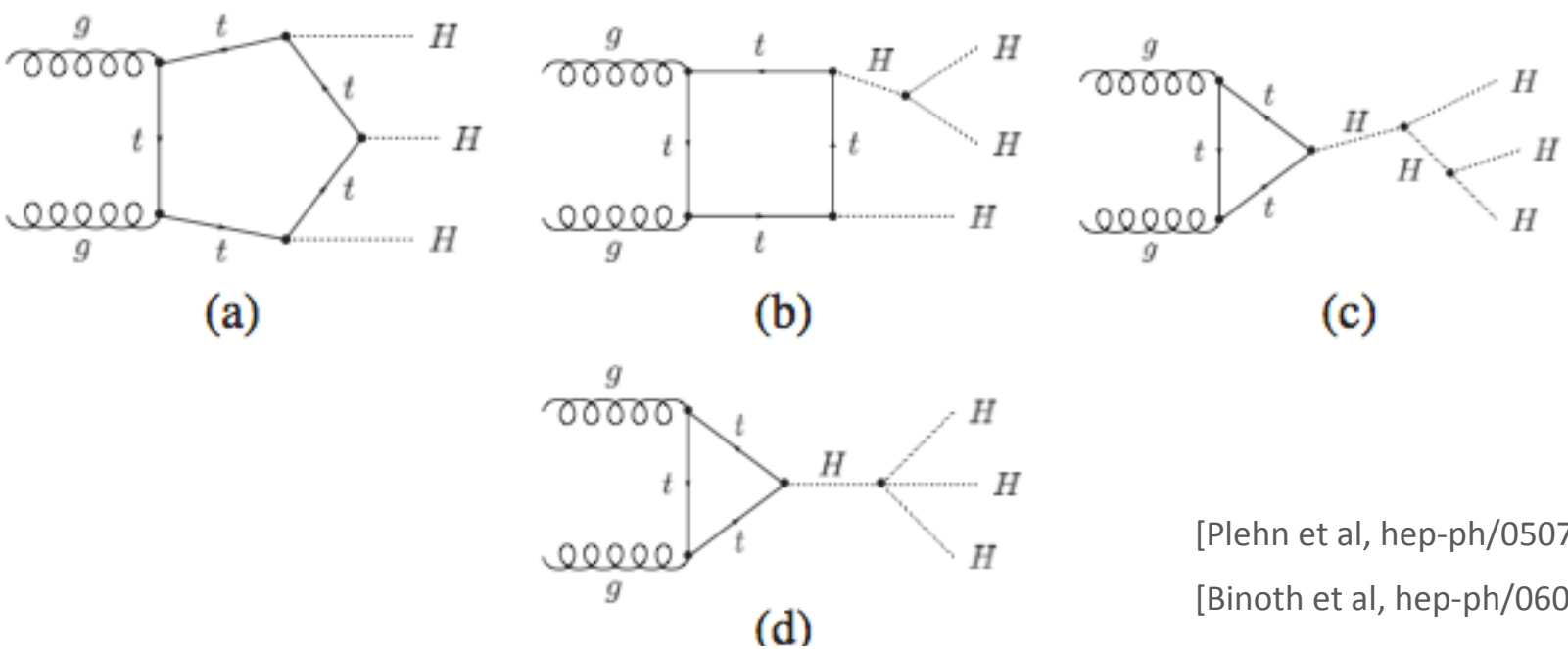
[Snowwmass Higgs report, arXiv:1310.8361]

W. Yao, arXiv: 1308.6302

Triple Higgs production

- Production cross section:
  - At 14 TeV, σ (gg -> HHH) ~ 0.044 fb (unlikely)
  - At 100 TeV, σ(gg -> HHH) ~ 4 fb (possible)

- Golden channel: $b\bar{b}b\bar{b}\gamma\gamma$ (SM background is small)

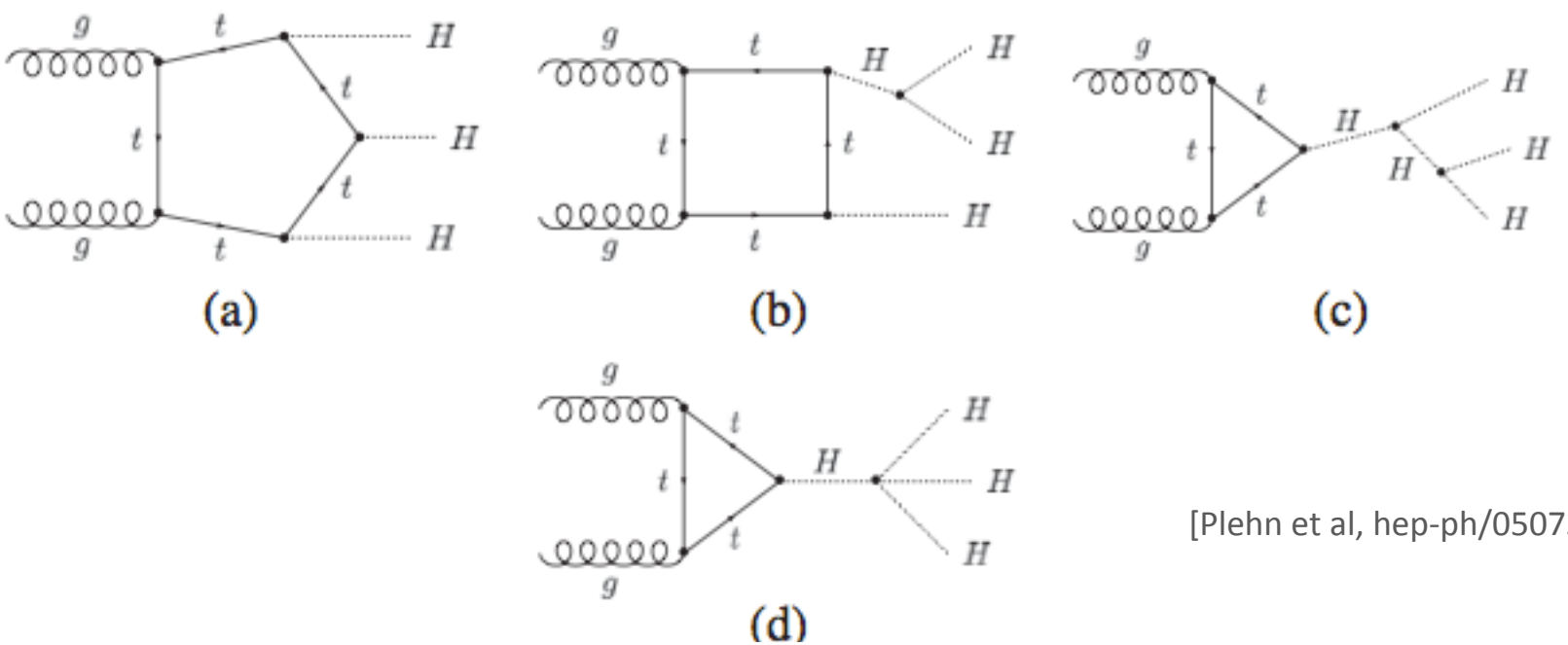


[Plehn et al, hep-ph/0507321]

[Binoth et al, hep-ph/0608057]

Triple Higgs production

- Looking at each diagram separately



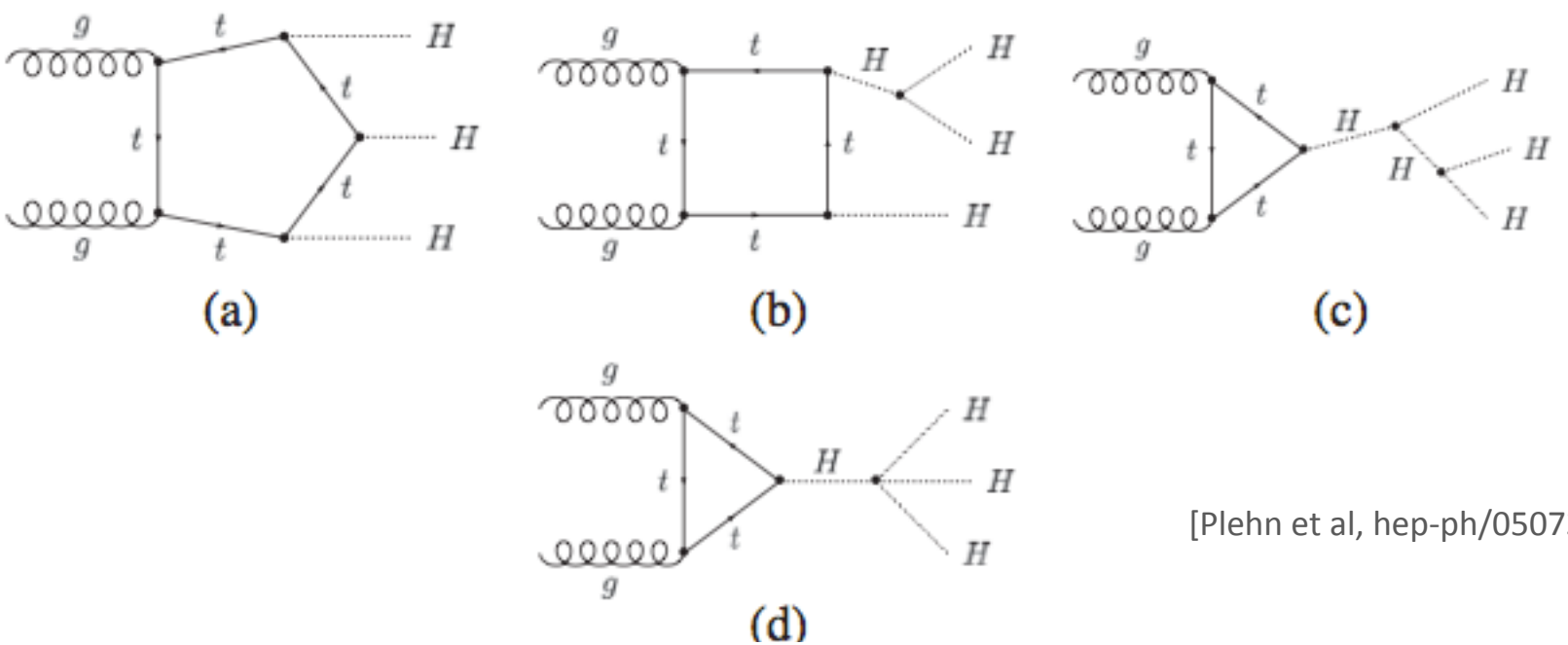
[Plehn et al, hep-ph/0507321]

Triple Higgs production

- Looking at each diagram separately (14 TeV, M_H = 120 GeV)
- Dominant contribution is from pentagon diagram

Diagrams	Pentagon (a)	Box (b)	Triangle (c,d)
Cross section (0.01 fb)	17.07	8.2	0.46

(For 14 TeV, M_H = 120 GeV)



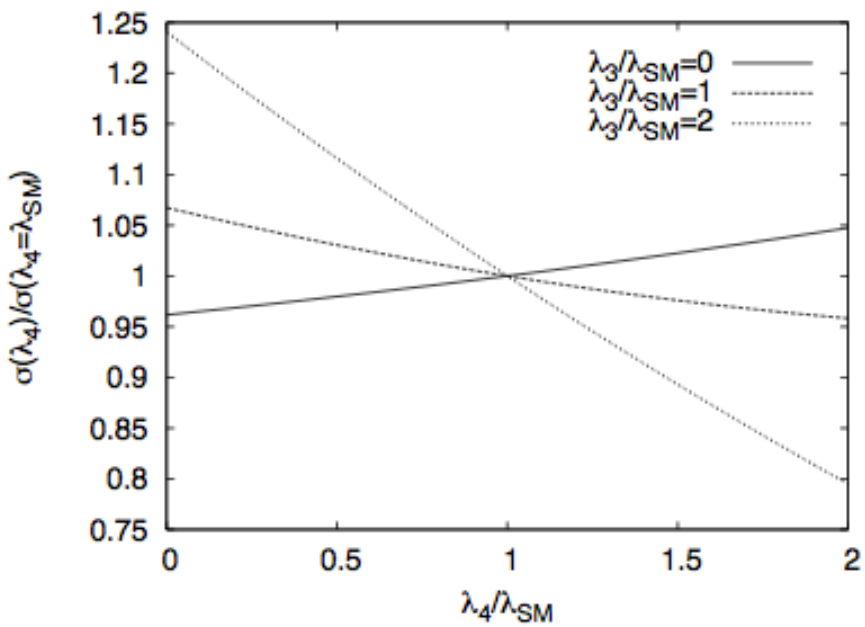
[Plehn et al, hep-ph/0507321]

Triple Higgs production

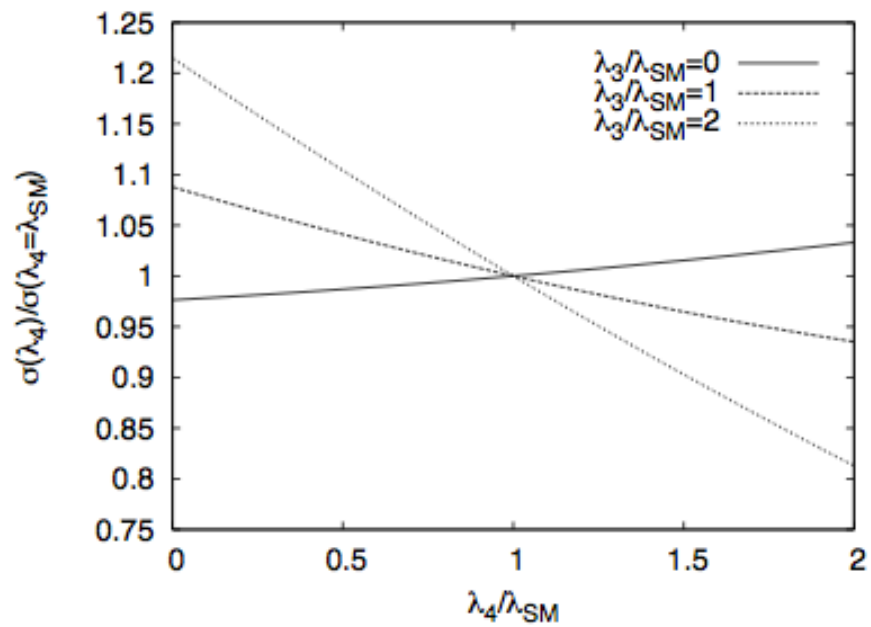
- Variation of triple and quartic self-couplings:

[Plehn et al, hep-ph/0507321]

14 TeV



200 TeV

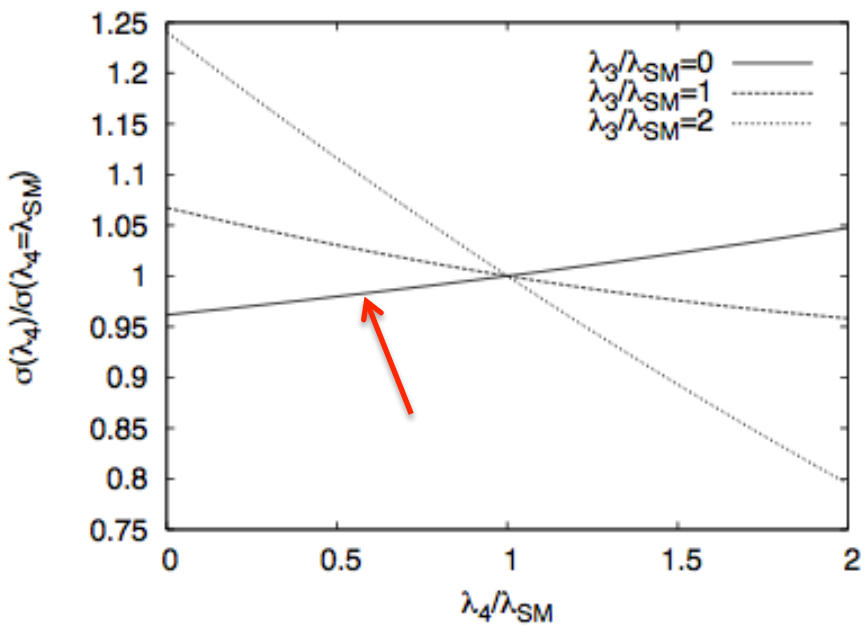


Triple Higgs production

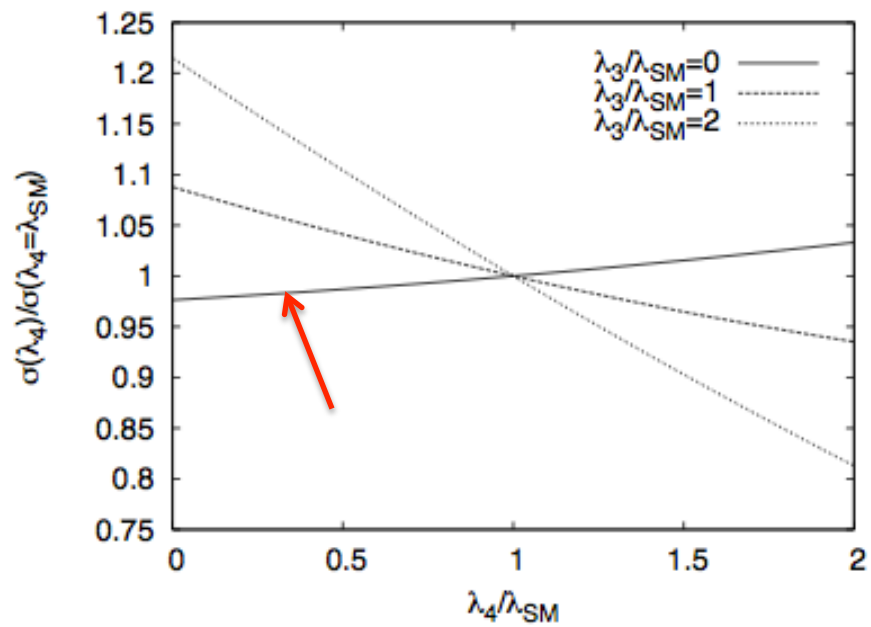
- Vary the triple and quartic self-couplings
- $\lambda_3 = 0$, pentagon diagram and triangle diagrams interfere constructively.

[Plehn et al, hep-ph/0507321]

14 TeV



200 TeV

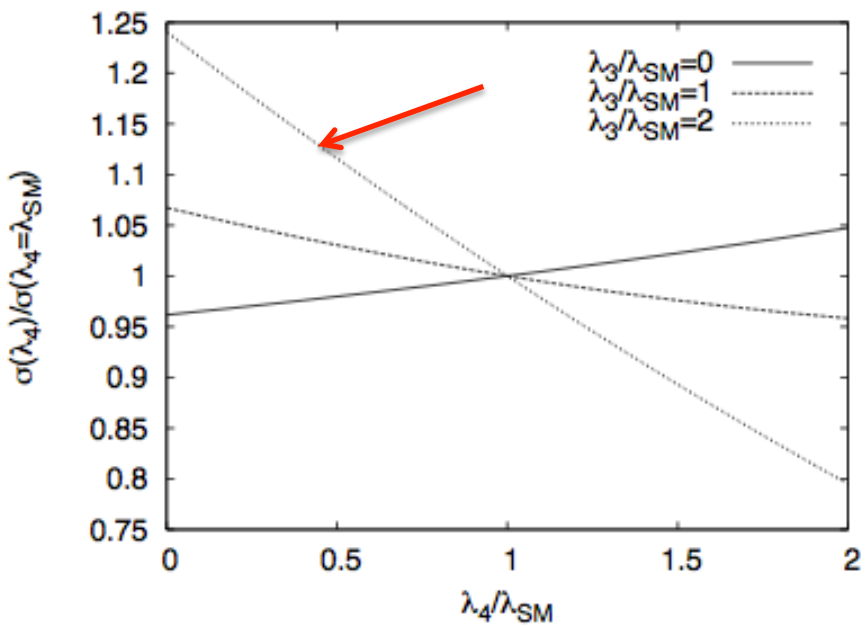


Triple Higgs production

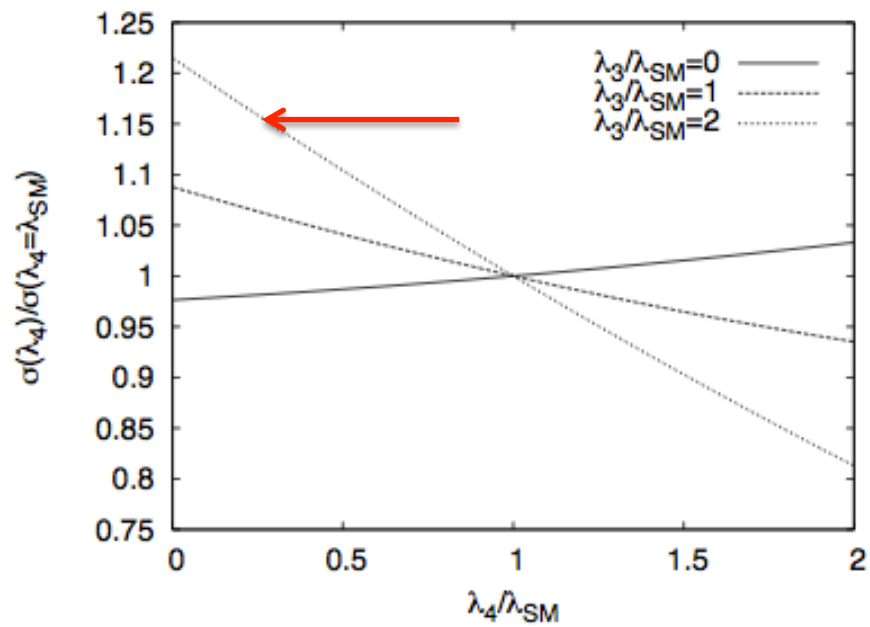
- Vary the triple and quartic self-couplings
- $\lambda_3 = 0$, pentagon diagram and triangle diagrams interfere constructively.
- $\lambda_4 \sim 0, \lambda_3 = 2\lambda_{\rm SM}$ relatively easy to discover or rule out due to larger cross section

[Plehn et al, hep-ph/0507321]

14 TeV

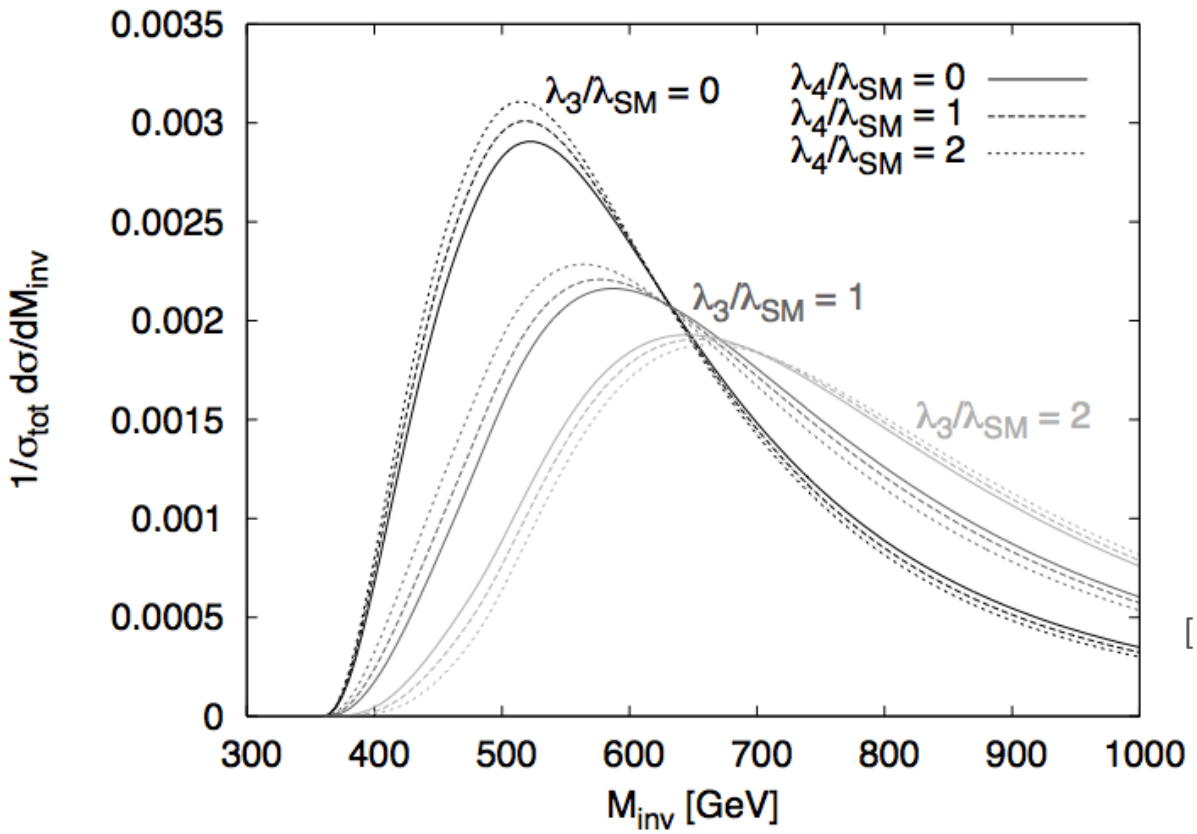


200 TeV



Triple Higgs production

- Shape is important.
- Varying λ_3 can give a sizable shift but the impact of λ_4 is an order of magnitude smaller.
- Difficult to determine λ_4 by just using shape information



[Plehn et al, hep-ph/0507321]

Collider study: tri-Higgs production

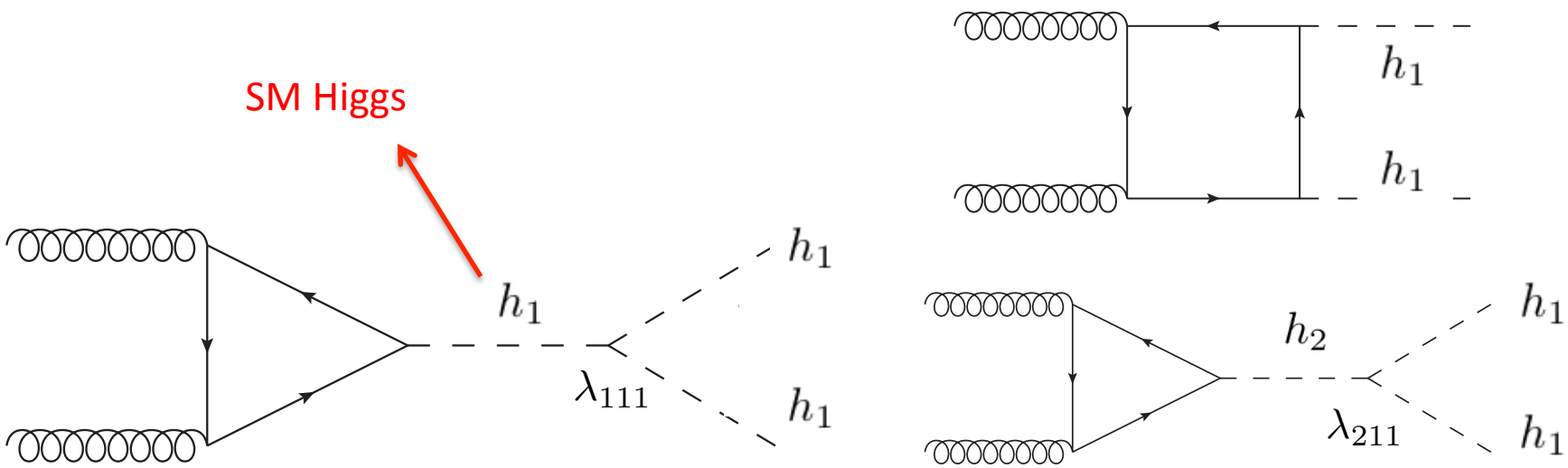
- Focusing on $b\bar{b}b\bar{b}\gamma\gamma$ channel.
- Naïve estimate of the signal at 100 TeV for an integrated luminosity of 3000/fb.

$$\text{Number of events} =$$
$$3 \times 2 \times 4 \text{ fb} \times 3000 \text{ fb}^{-1} \times 0.58^2 \times 2.3 \times 10^{-3} \times 0.7^2 \sim 13 \text{ events.}$$

- Might be able to see it if we can reduce the background.

New physics models

- New physics models may have larger rate for multi Higgs production due to the heavy resonance decay
- BSM Models
  - SM + Singlet
  - Two Higgs doublet models
  - Extra vector-like fermions



SM + Singlet

- SM Higgs doublet H mixed with an additional singlet S. The singlet doesn't couple to SM fermions and gauge bosons.

$$V = V_H + V_{HS} + V_S, \qquad V_H = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2,$$

$$V_{HS} = \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2,$$

$$V_S = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

Keep it general.
No Z_2 symmetry!

- Mixing angle:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

- Universal suppression of the Higgs couplings, $\cos\theta$.

$$V \supset \frac{\lambda^s_{111}}{3!} h_1^3 + \frac{\lambda^s_{211}}{2!} h_2 h_1^2 + \ldots$$

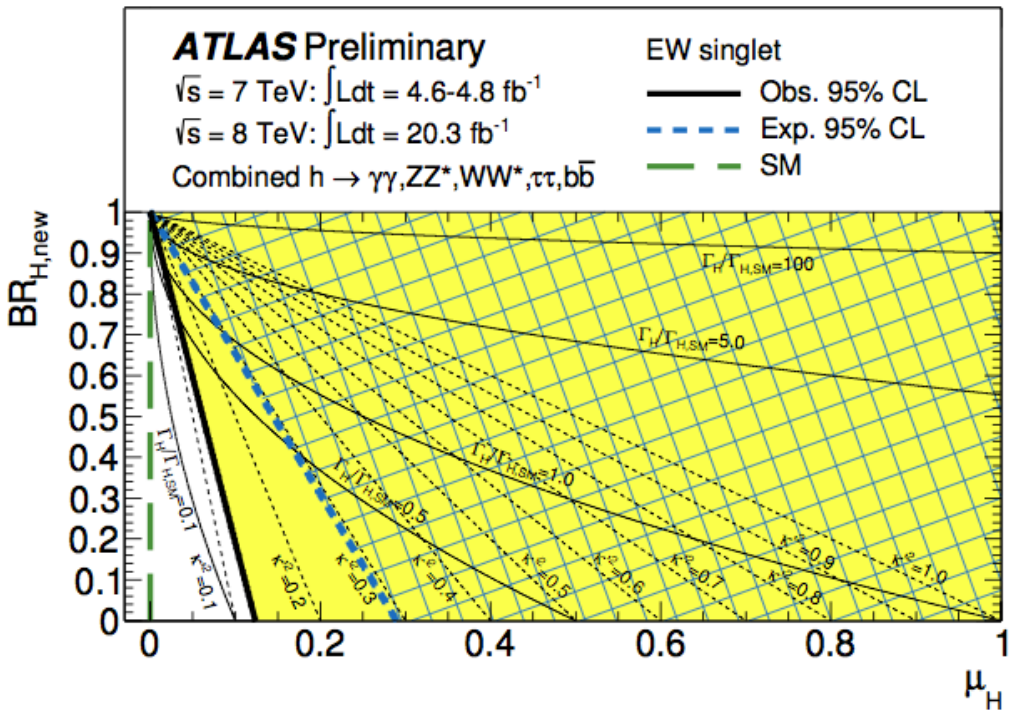
$$\lambda^s_{111} = 2s^3 b_3 + \frac{3a_1}{2} sc + 3a_2 s^2 cv + 6c^3\ \lambda v,$$

$$\lambda^s_{211} = 2s^2 c b_3 + \frac{a_1}{2} c(c^2 - 2s^2) + (2c^2 - s^2) s v a_2 - 6\lambda s c^2 v.$$

Constraints

- Constraints from LHC (observed 95% CL)

$$\kappa' \equiv \sin^2\theta < 0.12$$



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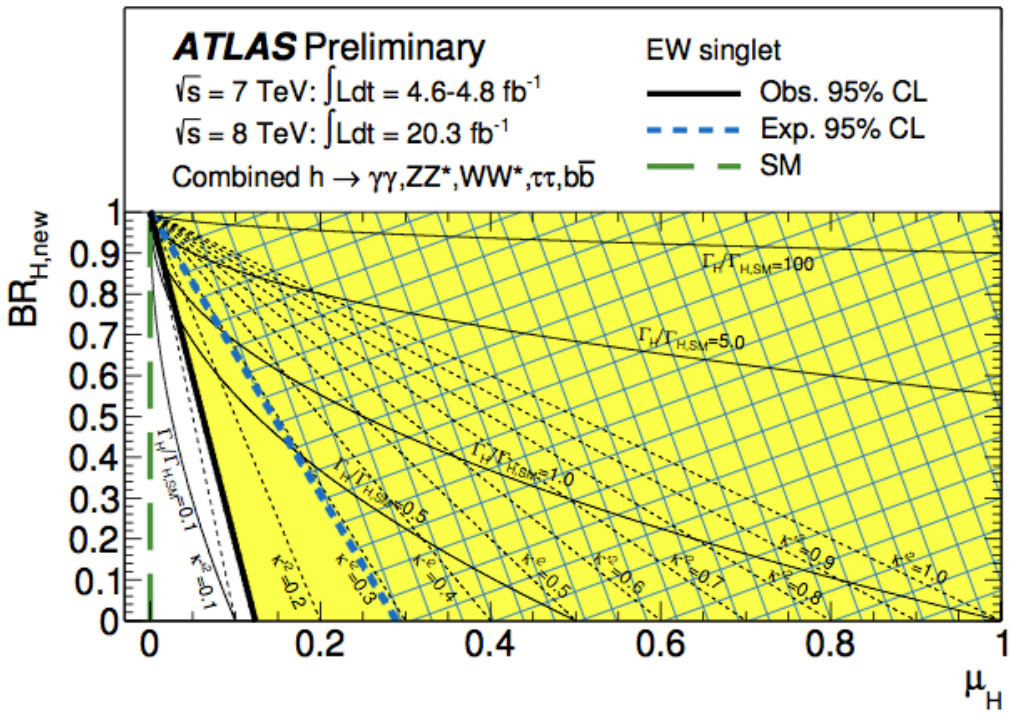
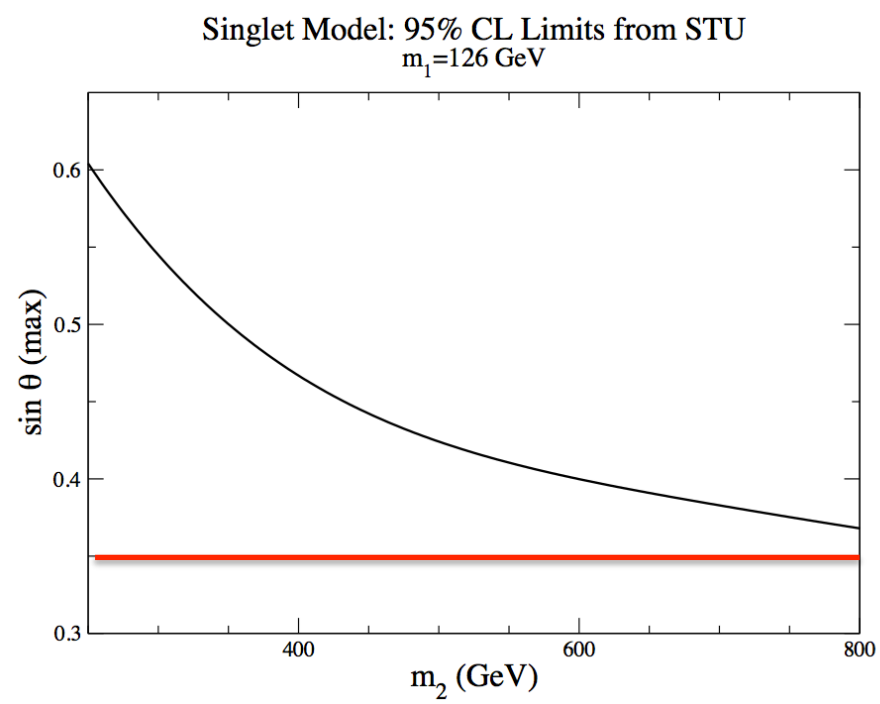
Constraints

- Constraints from LHC (observed 95% CL)

$$\kappa' \equiv \sin^2\theta < 0.12$$

- Bounds from electroweak precision measurement (STU): Not as good as the bounds from LHC





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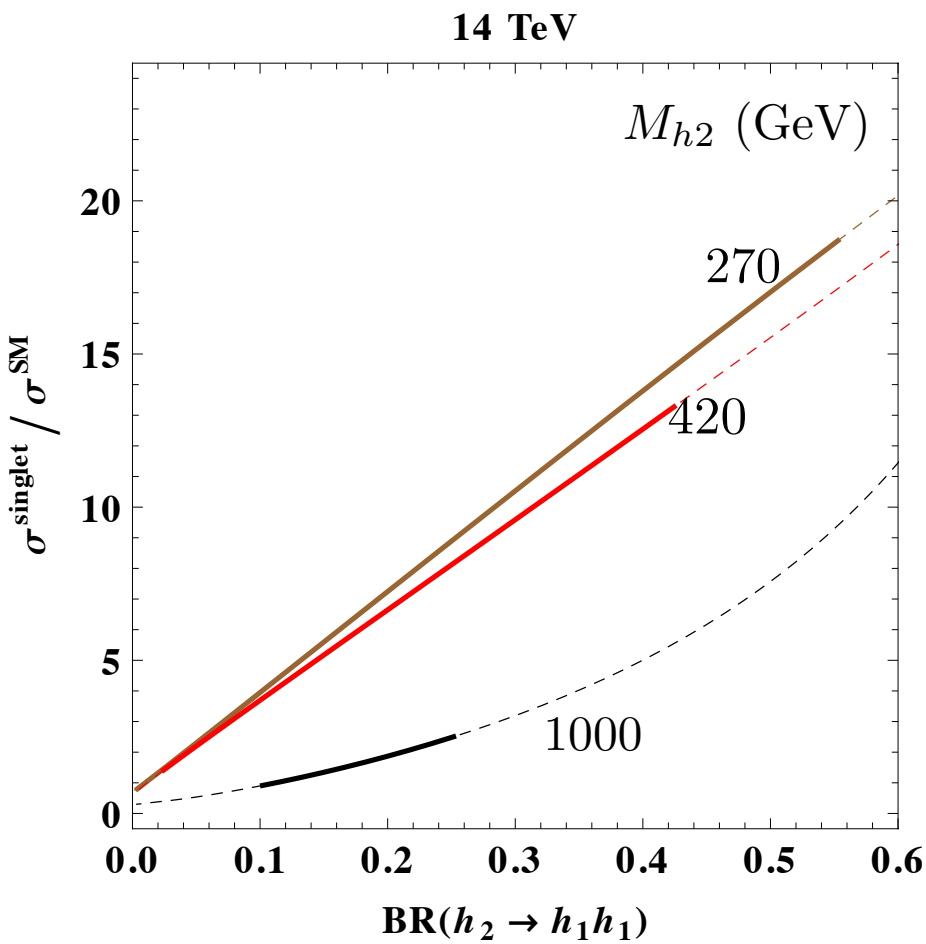
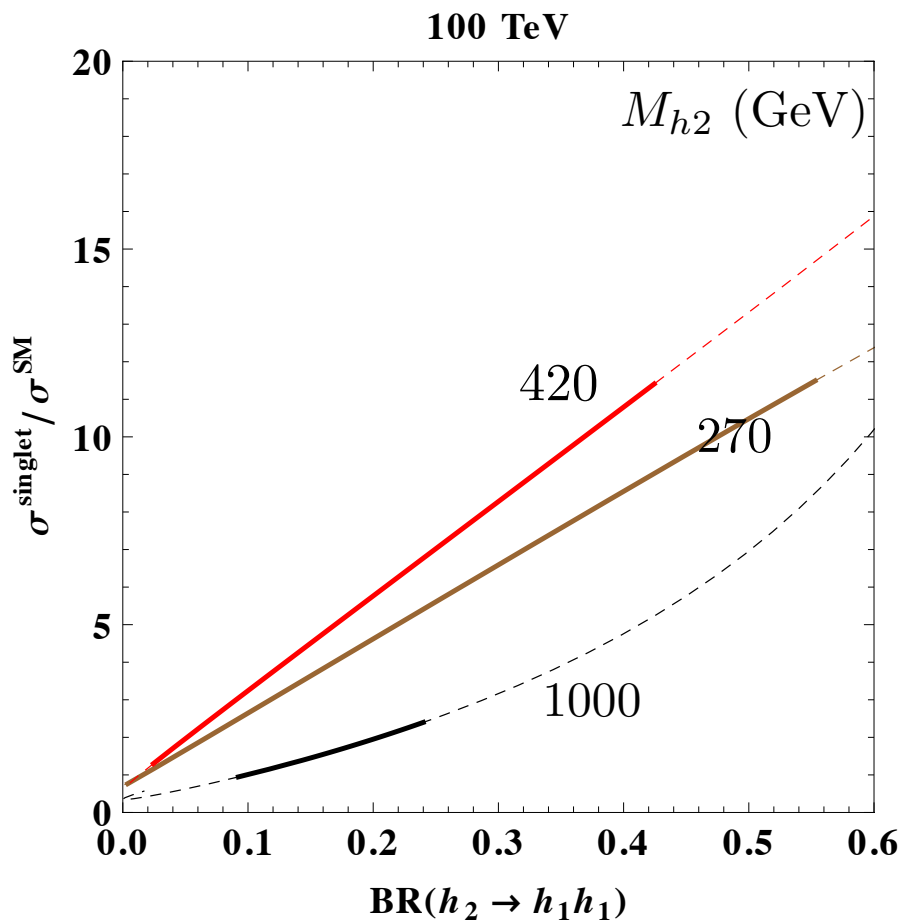
Looking for big enhancement

$a_2 = 0,$
$b_3 = -290$ GeV,
and $b_4 = 1$

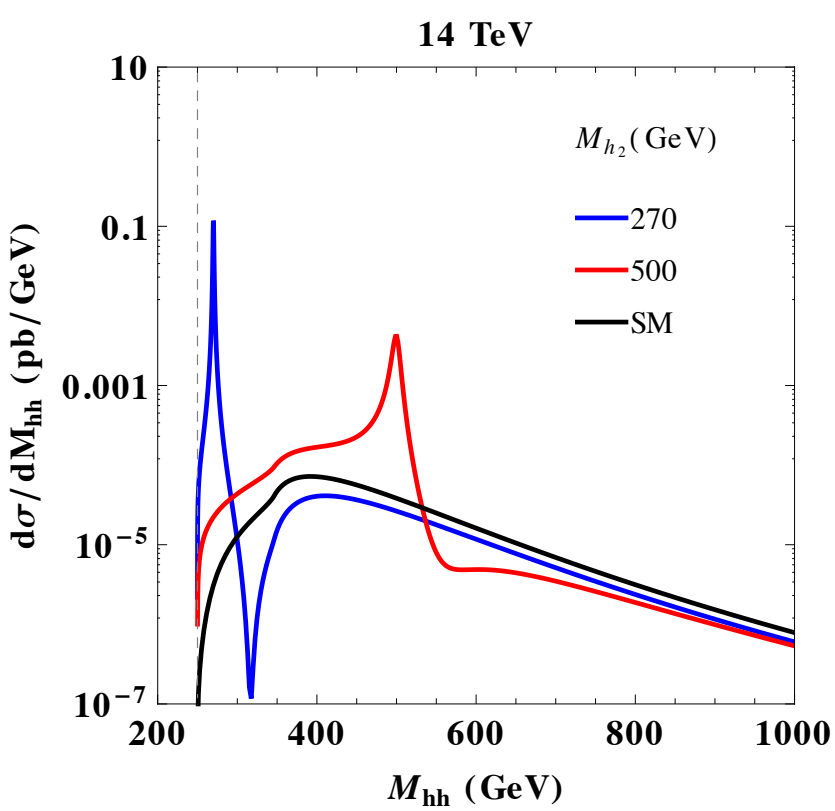


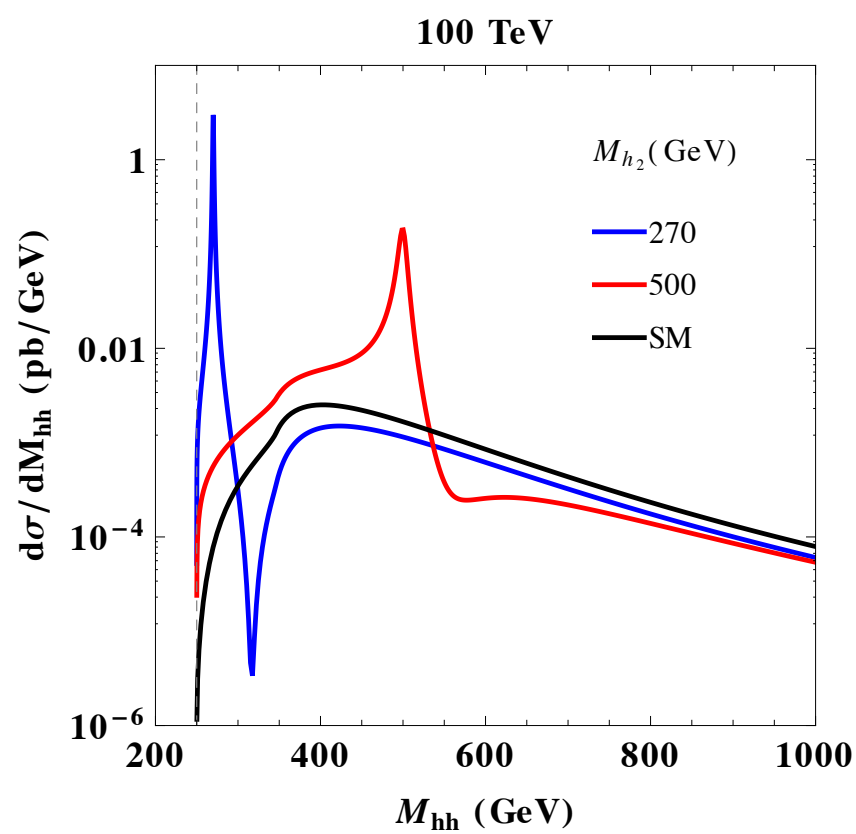


Dashed line: Excluded by the EW stability.
Solid line: Allowed range.

Differential cross section distributions

- Kinematic threshold $\sqrt{s} > 2m_h$
- Peak at M_{h_2} due to resonance decay
- Cancellations occur near $2m_t$
- Pronounced peaks are useful for discovery of the heavy resonances.





Two Higgs doublet models

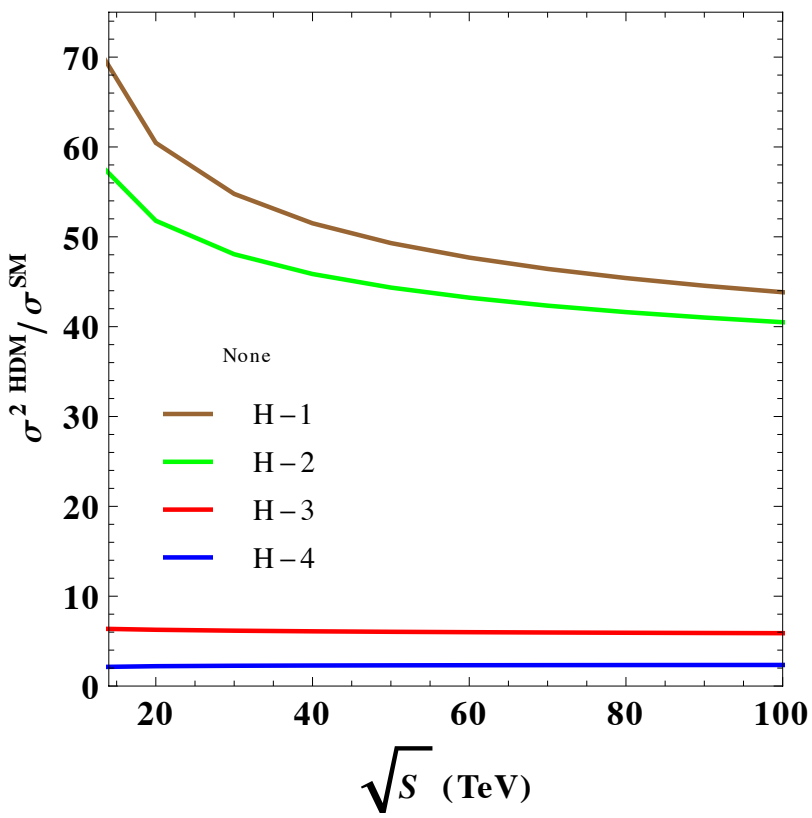
- Introduce another Higgs doublet in addition to the SM one, Φ_1 and Φ_2.
- Focus on type II: One Higgs doublet couples to up type quarks and the other to down-type quarks and leptons.

See John Stupak's talk!

- Characterized by seven parameters.

$M_h, M_H, M_{H^\pm}, M_A, \alpha, \tan\beta,$ and m_{12}

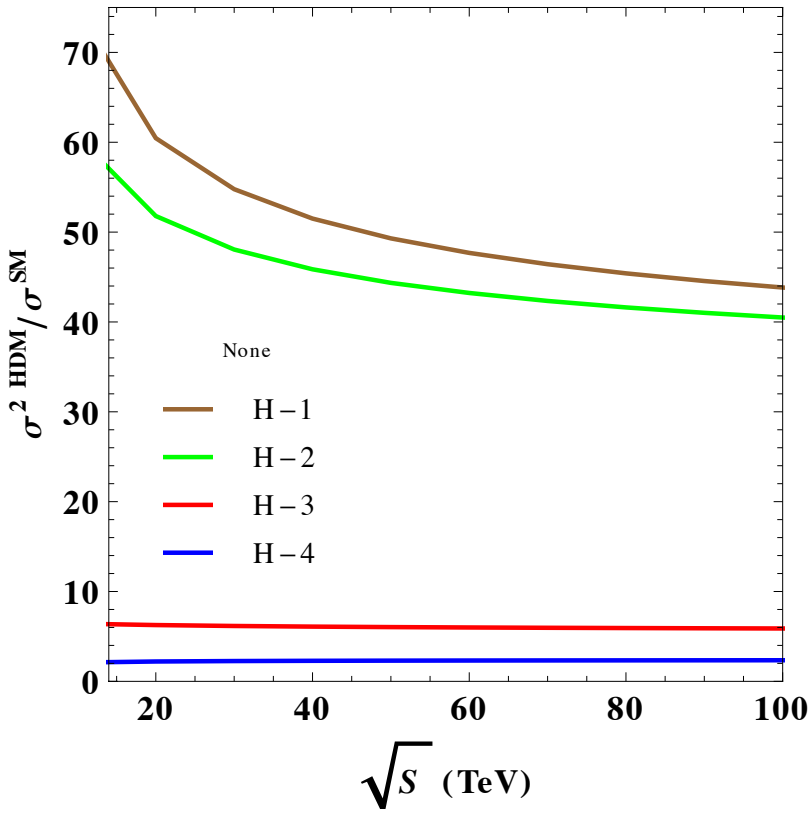
Two Higgs doublet models: branching fractions



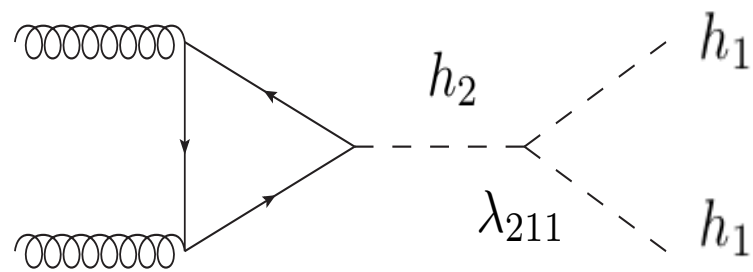
Although the total cross section increases the ratio σ^{NP}/σ^{SM} drops with the increase of the center of mass energy.

The production cross sections of the benchmarks H-3 and H-4 get enhanced by less than a factor of 10.

Two Higgs doublet models: branching fractions



Dominant contribution:



[Baglio et. al., 1403.1264]

	$\tan\beta$	$(\beta-\alpha)/\pi$	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	m_{12}^2 [GeV^2]	$BR(H \to hh)$
H-1	1.75	0.522	300	441	442	38300	59.0
H-2	2.00	0.525	340	470	471	44400	63.7
H-3	4.26	0.519	450	546	548	43200	29.0
H-4	4.28	0.513	600	658	591	76900	21.1

Differential cross section distributions

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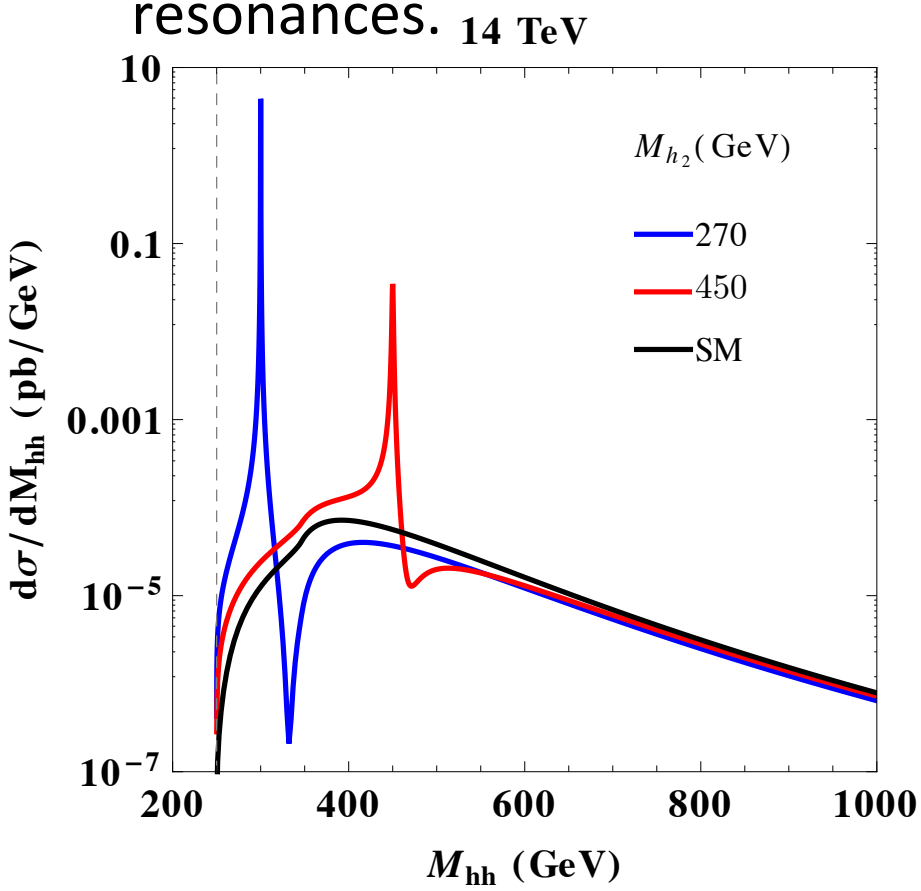
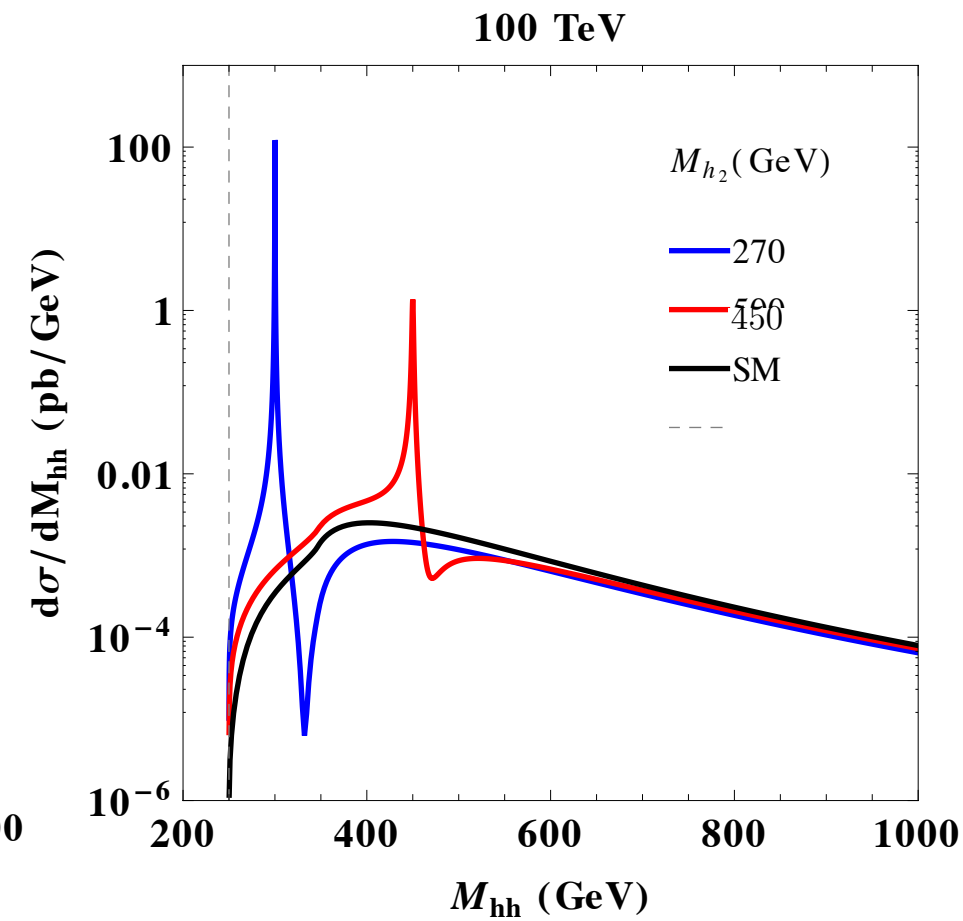
- Peak at M_{h_2} due to resonance decay
- Cancellations occur near $2m_t$
- Pronounced peaks are useful for discovery of the heavy resonances.





2HDM: collider study

Double Higgs

- For the benchmark H-1, we are be able to get $S/\sqrt{B} \sim 100$ at 14 TeV with $\mathcal{L} = 3000$ fb^{-1}.

Require $b\bar{b}\gamma\gamma$ final state
At least two b-jets and two photons with $pT > 35$ GeV
85 GeV $< M_{bb} < 135$ GeV, 120 GeV $< M_{\gamma\gamma} < 130$ GeV
$\epsilon_b = 70\%, \epsilon_{c\to b} = 10\%$, mistag rate $=1\%$

Background:

$$pp \to b\bar{b}\gamma\gamma$$
$$pp \to c\bar{c}\gamma\gamma$$
$$pp \to jj\gamma\gamma$$

Triple Higgs

- Dominant channel: g g -> hH -> hhh channel.
- Can possibly measure the Higgs couplings at HL-LHC.

Vector-like fermions

- Introduce vector-like top partners.
- Can vector-like fermions contribute to di-Higgs production and cause significant deviations from the SM prediction?

[Dawson, Furlan and Lewis, arXiv:1210.6663]

$$q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R \qquad Q = \begin{pmatrix} T \\ B \end{pmatrix}, U, D$$

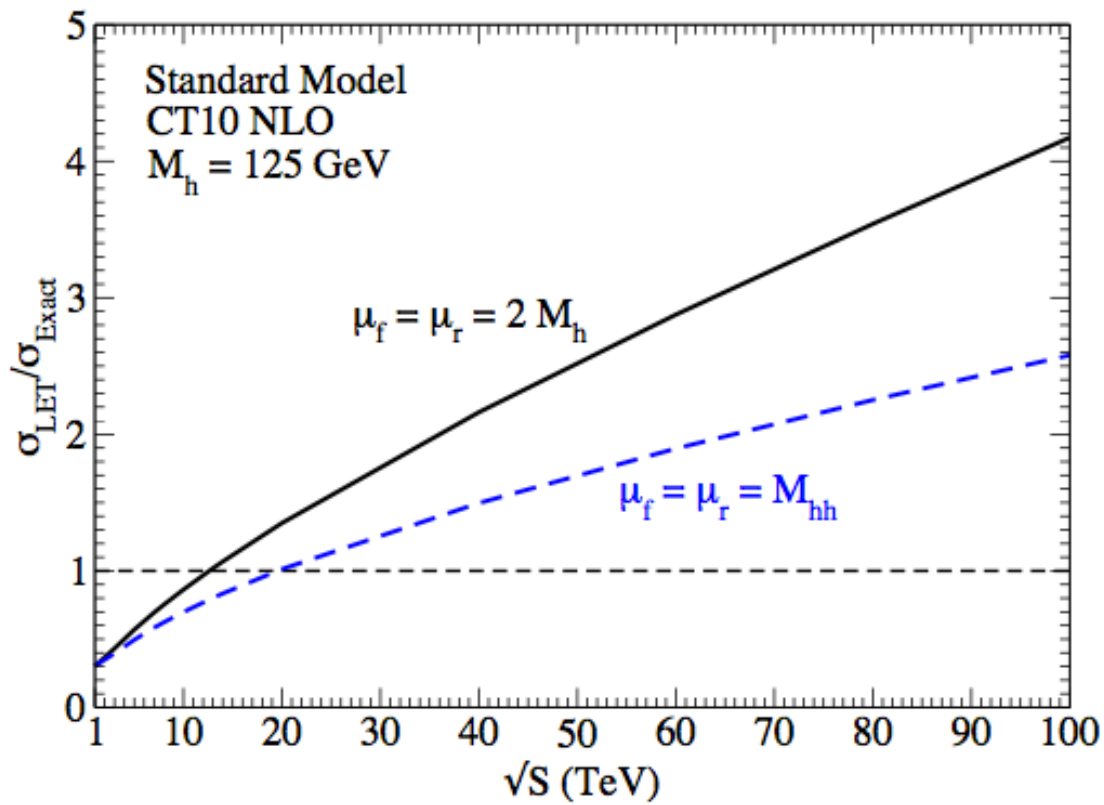
[CC, Dawson and Lewis, arXiv:1406.3349]

- Introduce extra vector-like fermions.

$$\begin{aligned}
L_{NP} &\equiv L'_M + L'_{KE} + L'_Y \\
L'_M &= -M\overline{Q}Q - M_U\overline{U}U - M_D\overline{D}D \\
L'_{KE} &= \overline{Q}(i\not{D})Q + \overline{U}(i\not{D})U + \overline{D}(i\not{D})D \\
L'_Y &= -\Big\{\lambda_1\overline{Q}_L\tilde{H}U_R + \lambda_2\overline{Q}_L H D_R + \lambda_3\overline{Q}_R\tilde{H}U_L + M_4\overline{q}_L Q_R + M_5\overline{U}_L t_R + M_6\overline{D}_L b_R \\
&\quad + \lambda_7\overline{q}_L\tilde{H}U_R + \lambda_8\overline{q}_L H D_R + \lambda_9\overline{Q}_L\tilde{H}t_R + \lambda_{10}\overline{Q}_L H b_R + \lambda_{11}\overline{Q}_R H D_L + h.c.\Big\}.
\end{aligned}$$

Vector-like fermions

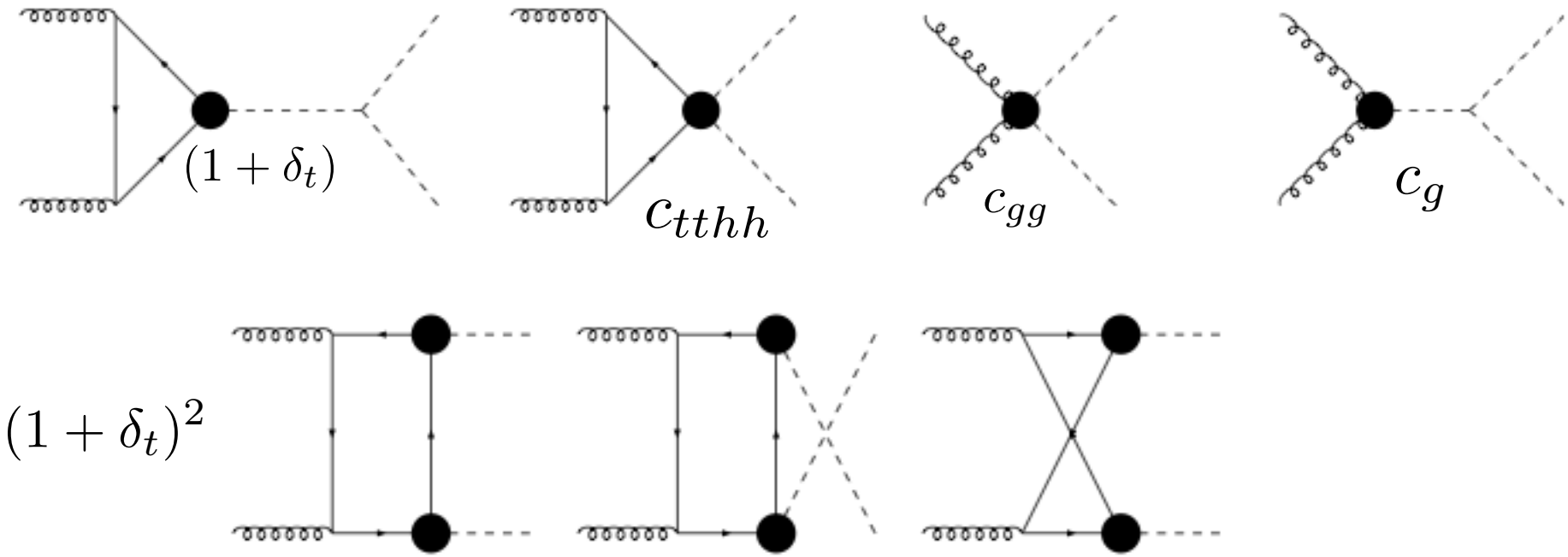
- Approach:
  - Using low energy theorem: integrated out top quark and vector-like fermions.



Bad approximation after $\sqrt{S}$ > 20 TeV

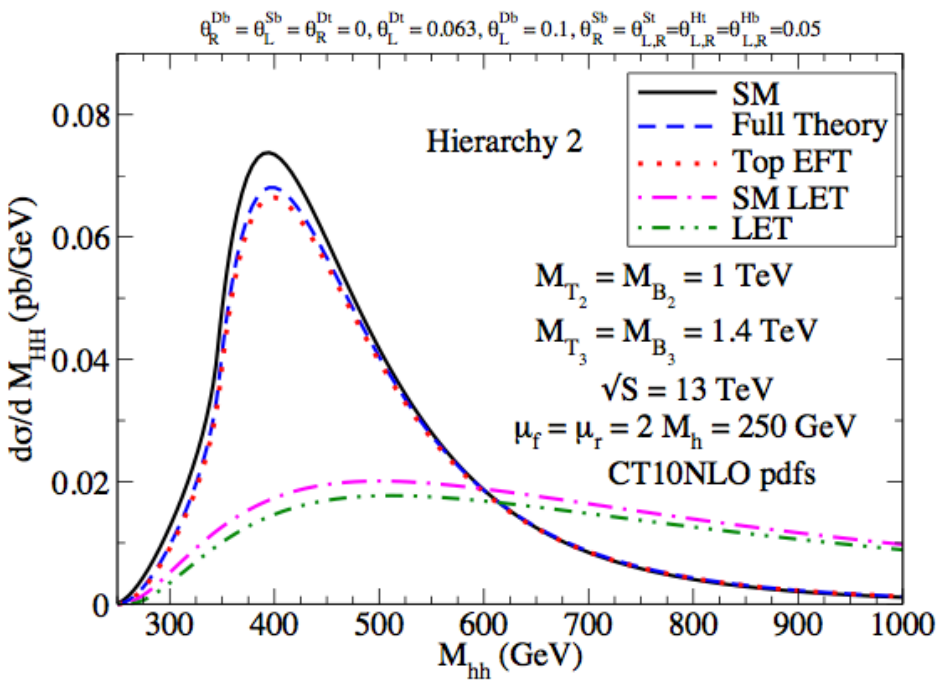
Vector-like fermions

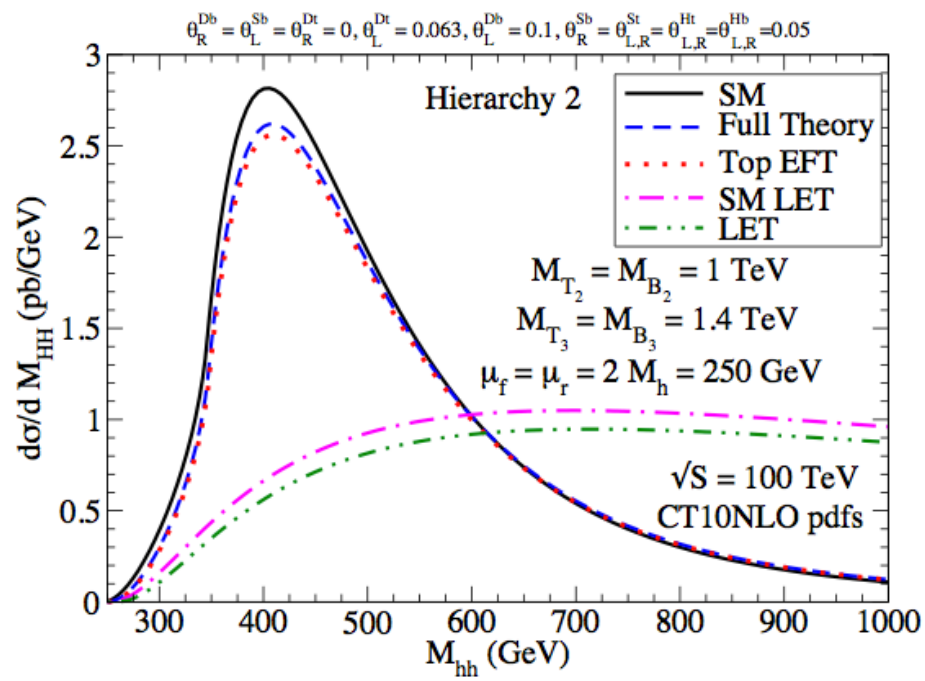
- Approach:
  - Top quark effective theory: Only integrate out heavy fermions but keep top quarks.



Top EFT matches full theory very well.
Simplify the calculation.

Top quark EFT





- Unable to find parameters consistent with electroweak precision measurements and the single Higgs production rate which gave a significant deviation from the Standard Model prediction for double Higgs production.

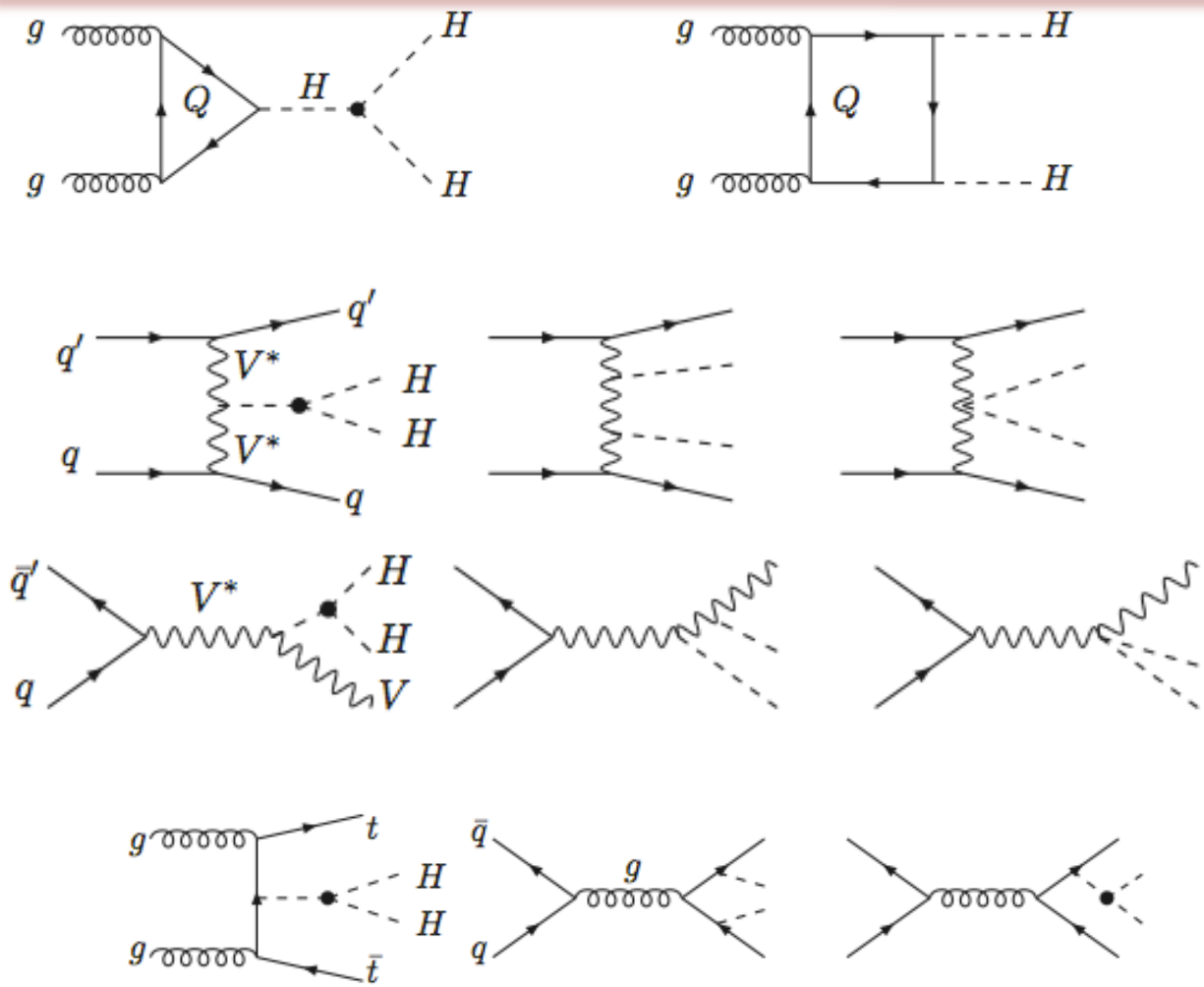
Conclusion

- Although the total cross section of the Higgs pair production increases but σ^{NP}/σ^{SM} is not enhanced at 100 collider, compared to that at 14 TeV.
- Hadron colliders can measure the Higgs coupling with a 50% and 8% statistical accuracy at $\sqrt{s} = 14$ and $\sqrt{s} = 100$ TeV through di-Higgs production.
- Small deviations from the SM for models with extra vector-like fermions.
- The Higgs self-couplings in various models can potentially be measured due to the large enhancement at HL-LHC or a 100 TeV collider.

THANK YOU!

BACKUP SLIDES

Di-Higgs production in SM



- Form factor

$$\hat{\sigma}^{(LO)}_{gg\to H^0H^0} = \int d\hat{t}\, \frac{\alpha^2\alpha_S^2}{2^{15}\pi M_W^4} \left(|C_\triangle F_\triangle + C_\square F_\square|^2\right),$$

$$|C_\triangle F_\triangle + C_\square F_\square|^2$$

[]

$$\hat{t} = -\frac{1}{2}\left[\hat{s} - 2m_H^2 - \hat{s}\sqrt{1 - \frac{4m_H^2}{\hat{s}}}\cos\theta,\right],$$

where $\tau_q = \frac{4m_q^2}{\hat{s}}$

$$F_\triangle = 2\frac{m_q^2}{\hat{s}}\left[2 + \left(4 - \frac{\hat{s}}{m_q^2}\right) m_q^2 C_{ab}\right] = \tau_q[1 + (1-\tau_q)f(\tau_q)],$$

Collider study: di-Higgs production

- Possible channels to look at:
  - $b\bar{b}b\bar{b}$: largest rate but has large QCD background
  - $b\bar{b}\tau\bar{\tau}$: large reducible background of $b\bar{b}jj$ and jets fake a τ
  - $b\bar{b}W^+W^-$: t tbar background. Small significance. Employing jet substructure and event reconstruction techniques.
  - $b\bar{b}\gamma\gamma$: Tiny branching fraction ~ 0.28%, but two photons in the final state can suppress the background significantly.

Samples	HL-LHC (3 ab^{-1})			TeV100 (3 ab^{-1})		
	$\sigma \cdot Br$	Acc.	Expect	$\sigma \cdot Br$	Acc.	Expect
	(fb)	(%)	Evnts	(fb)	(%)	Evnts
HH($b\bar{b}\gamma\gamma$)	0.089	6.2	16.6	3.73	3.61	403.9
$b\bar{b}\gamma\gamma$	294	0.0045	40.1	5037	0.00275	415.4
$z(b\bar{b})h(\gamma\gamma)$	0.109	1.48	4.86	0.875	1.57	41.2
$b\bar{b}h(\gamma\gamma)$	2.23	0.072	4.82	50.5	0.099	150.5
$t\bar{t}h(\gamma\gamma)$	0.676	0.178	3.62	37.3	0.11	124.2
Total B	-	-	53.4	-	-	731.3
S/$\sqrt{B}$	-	-	2.3	-	-	15.0

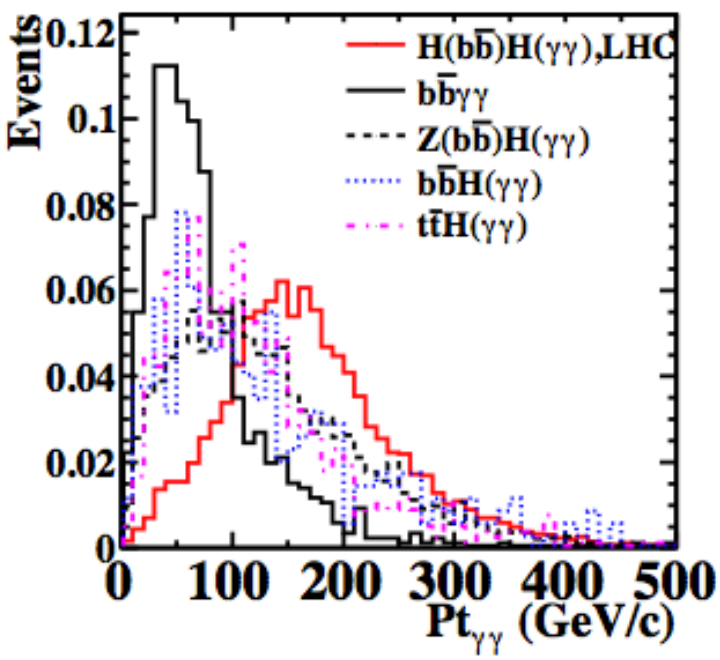
Papaefstathiou et al, arXiv: 1209.1489

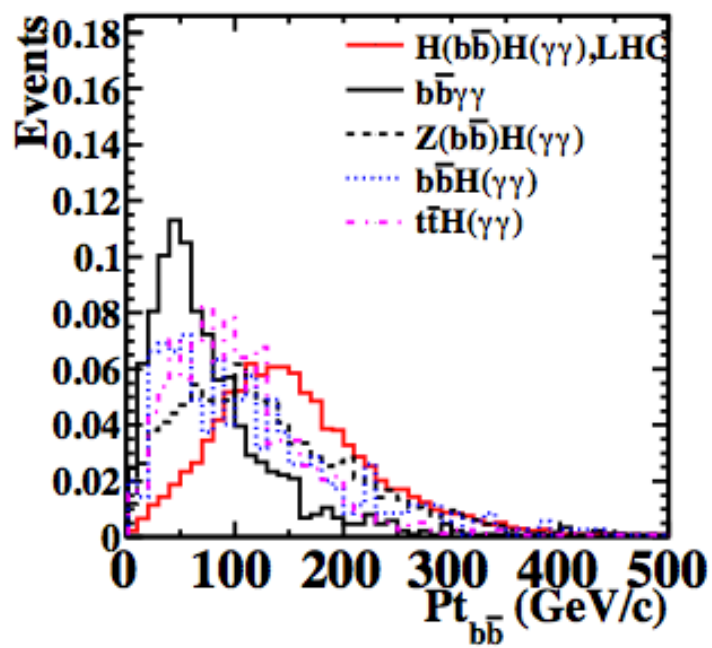
W. Yao, arXiv: 1308.6302

Collider study: selection cuts

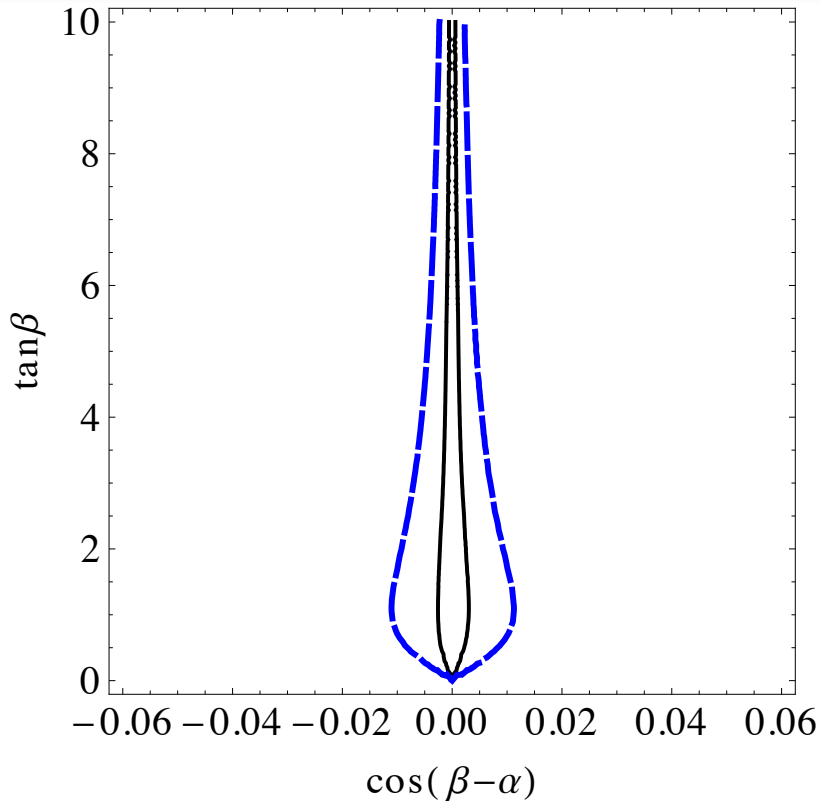
- Selection cuts
  - $\Delta R_{\gamma\gamma} < 2.5$ and $\Delta R_{b\bar{b}} < 2.0$
  - $|\eta_{\gamma\gamma}| < 2.0$ and $|\eta_{b\bar{b}}| < 2.0$
  - $Pt_{\gamma\gamma} > 100$ and $Pt_{b\bar{b}} > 100$ GeV
  - $M_{b\bar{b}\gamma\gamma} > 300$ GeV/c^2
  - $|Cos\theta_H| < 0.8$, the Higgs decay angle in the rest frame of HH.
  - $\Sigma(njets + nphos + nleps + nmet) < 7$

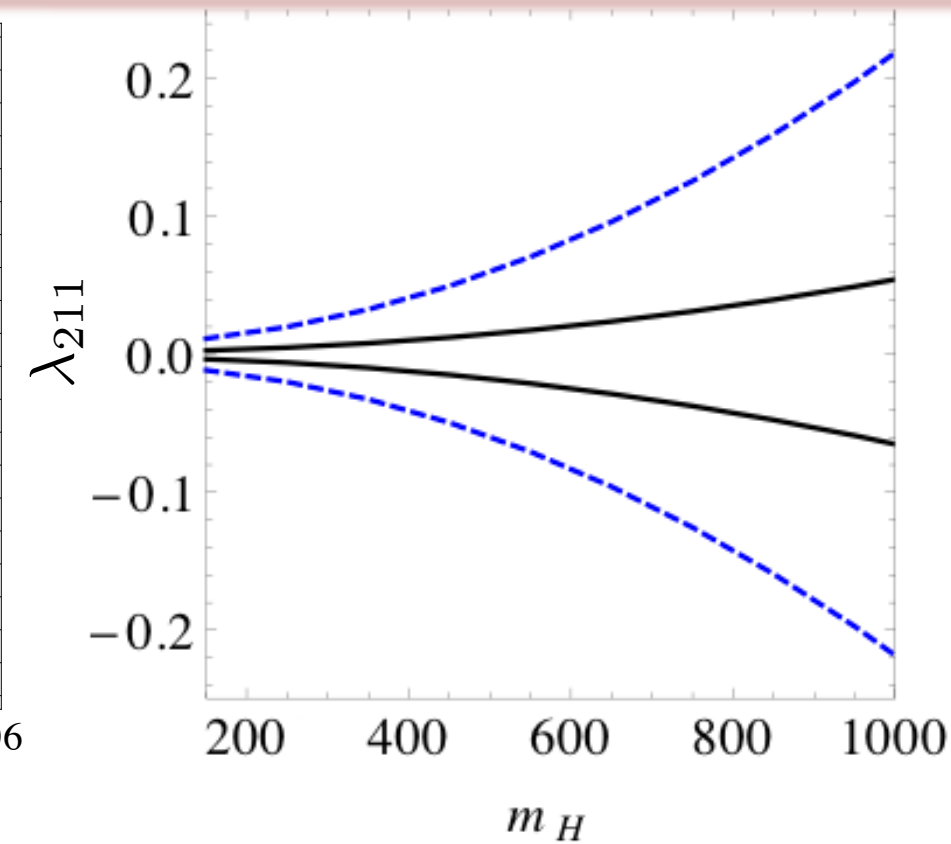
W. Yao, arXiv: 1308.6302





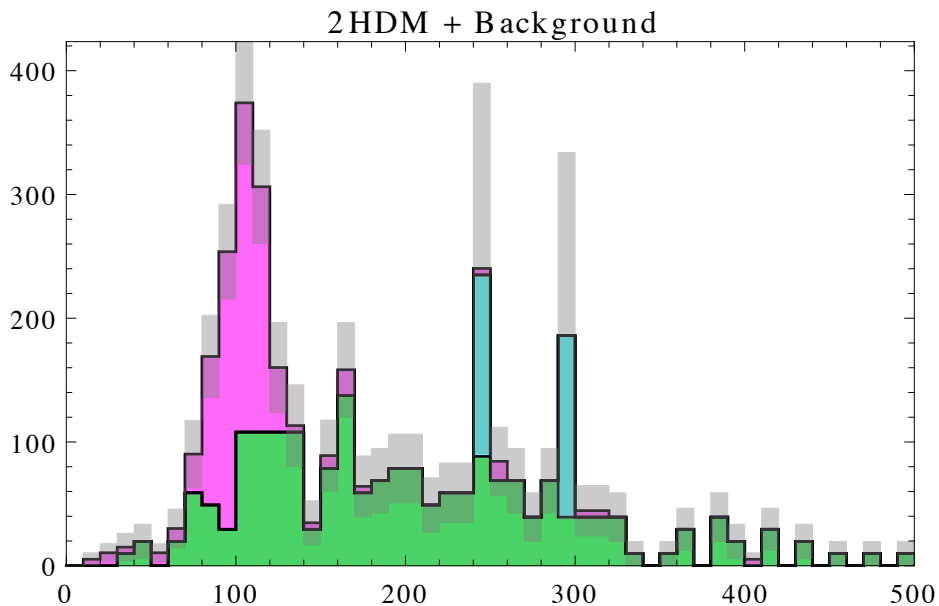
Type II 2HDMs: Constraints





- Regions between blue dashed lines and black solid lines are allowed at 95% CL at 14 TeV, 3/ab and 100 TeV, 3/ab, respectively.
- λ_{211} = 0 is the alignment limit.
- Large improvement of bounds for the mass of H > 600 GeV

Pt distribution of bb



Pink: Signal
Others: background