How to distinguish two mass-degenerate 125 GeV Higgs boson(s) from one?

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Outline

- Can we have more than one (or two) resonances at 125 GeV (degenerate Higgs)? Yes, it is possible.

- How to distinguish the degenerate Higgs scenario from the conventional single Higgs scenario?

    - precise signal fit cannot offer an answer

    - to look for the BSM effects: self-interactions or pair productions at LHC/ILC, the searches for CP-odd scalars.

The 2HDM

$$\mathcal{L} = \sum_{i=1,2} |D\Phi_i|^2 - V(\Phi_1, \Phi_2)$$

$$V(\Phi_1, \Phi_2) = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + H.c.) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4$$
$$+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + H.c.\right]$$

with m_{12}^2 and λ_5 being complex.

$$\Phi_1 = \begin{pmatrix} -s_\beta H^+ \\ \frac{1}{\sqrt{2}}(v_1 + H_1^0 - is_\beta A) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} c_\beta H^+ \\ \frac{1}{\sqrt{2}}(v_2 e^{i\xi} + H_2^0 + ic_\beta A), \end{pmatrix}$$

Neutral Higgs masses

- Masses and mixings of the CP-even Higgs boson:

$$\mathcal{M}_0^2 = \begin{pmatrix} m_{12}^2 t_\beta + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2 / t_\beta + \lambda_2 v_2^2 \end{pmatrix},$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Neutral Higgs couplings

$$\mathcal{L} \supset \sum_{h_i=h,H} \Big[-\frac{m_f}{v}\xi_i^f \bar{f} f + a_i \Big(2\frac{m_W^2}{v} W_\mu^+ W^{-\,\mu} + \frac{m_Z^2}{v} Z_\mu Z^\mu \Big) \Big] h_i$$
$$- \frac{m_f}{v}\xi_A^f \bar{f} i\gamma_5 f A \,,$$

$$\text{Type-I} : \xi_h^f = s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta} \,, \qquad \xi_H^f = c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$$
$$\xi_A^u = \frac{1}{t_\beta} \,, \qquad \xi_A^{d,\ell} = -\frac{1}{t_\beta} \,,$$
$$\text{Type-II} : \xi_h^u = s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta} \,, \qquad \xi_h^{d,\ell} = s_{\beta-\alpha} - c_{\beta-\alpha} t_\beta \,,$$
$$\xi_H^u = c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta} \,, \qquad \xi_H^{d,\ell} = c_{\beta-\alpha} + s_{\beta-\alpha} t_\beta \,,$$
$$\xi_A^u = \frac{1}{t_\beta} \,, \qquad \xi_A^{d,\ell} = t_\beta \,,$$
$$a_h = s_{\beta-\alpha} \,, \qquad a_H = c_{\beta-\alpha} \,.$$

Global signal fit to the degenerate Higgs

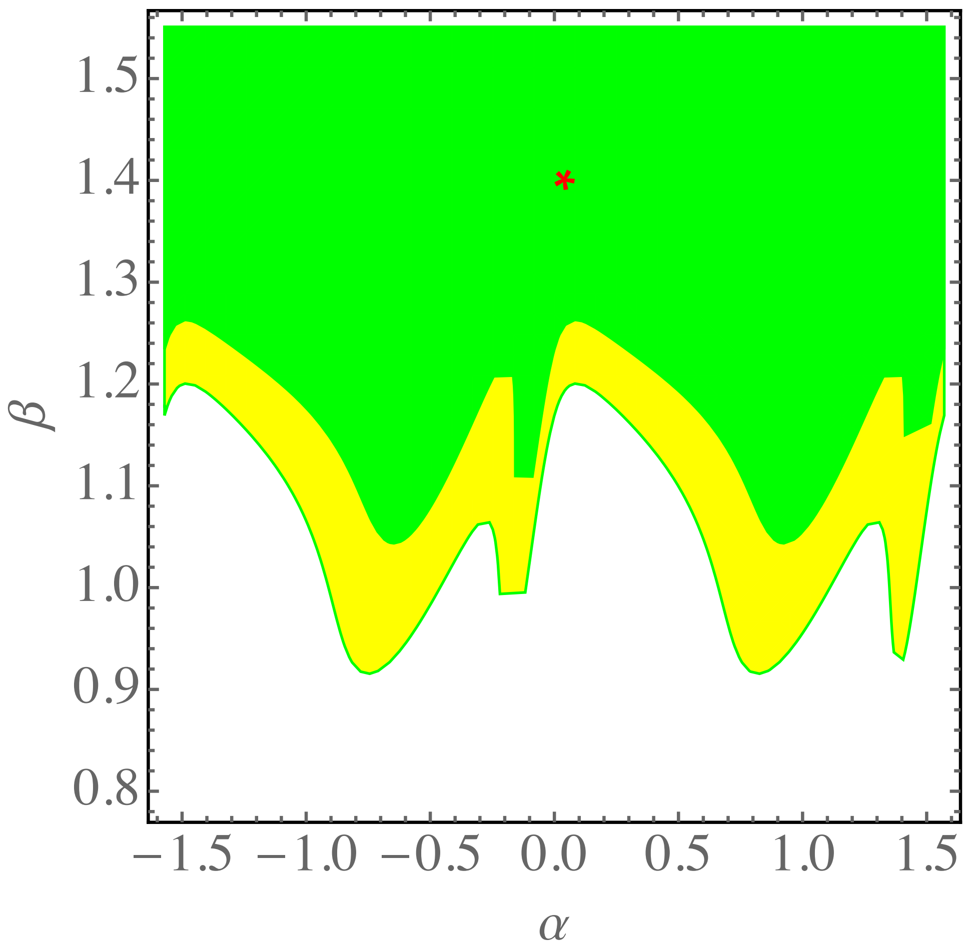
The Higgs signals @LHC run-I

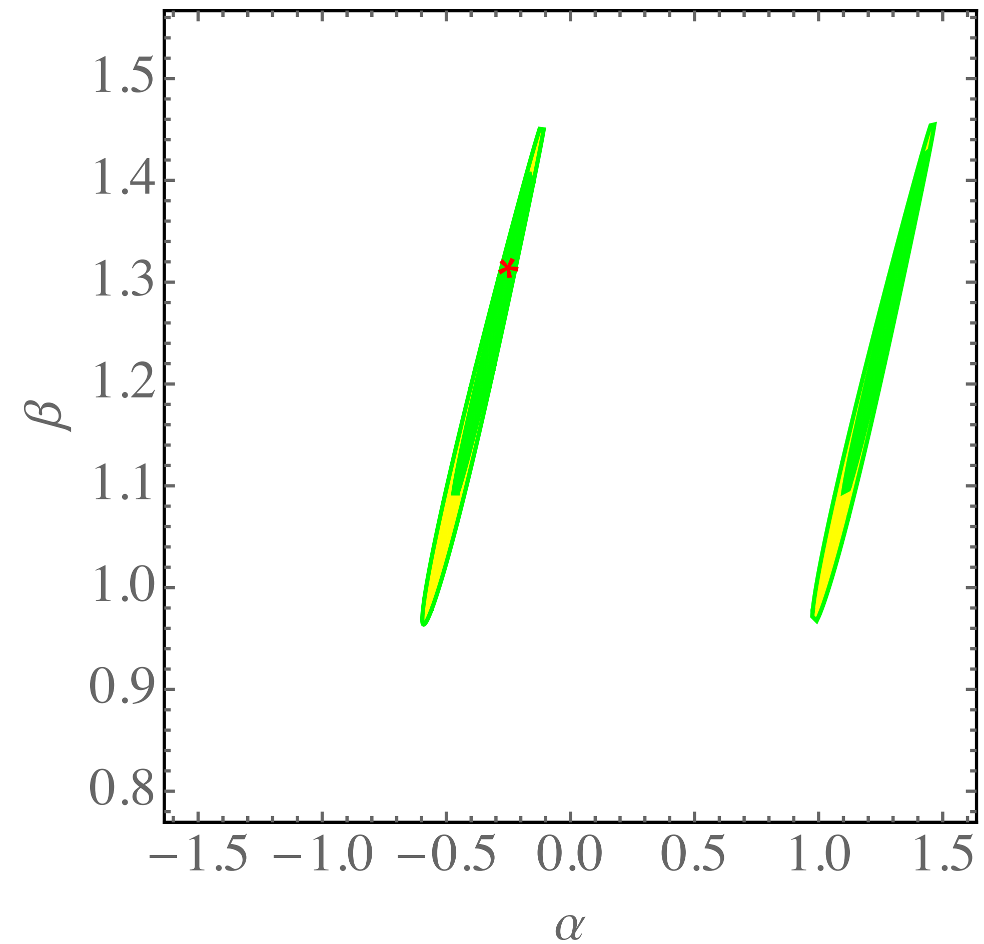
Decays	Productions	ATLAS	Ref	CMS	Ref
$\gamma\gamma$	ggF	1.32 ± 0.38	[31]	$1.12^{+0.37}_{-0.32}$	[32]
$\gamma\gamma$	VBF	0.8 ± 0.7	[31]	$1.58^{+0.77}_{-0.68}$	[32]
$\gamma\gamma$	WH	1.0 ± 1.6	[31]	-	-
$\gamma\gamma$	ZH	$0.1^{+3.7}_{-0.1}$	[31]	-	-
$\gamma\gamma$	VH	-	-	$-0.16^{+1.16}_{-0.79}$	[32]
$\gamma\gamma$	ttH	$1.6^{+2.7}_{-1.8}$	[31]	$2.69^{+2.51}_{-1.81}$	[32]
ZZ	ggF,ttH,bbH	$1.7^{+0.5}_{-0.4}$	[33]	-	-
ZZ	ggF,ttH	-	-	$0.80^{+0.46}_{-0.36}$	[34]
ZZ	VBF,VH	$0.3^{+1.6}_{-0.9}$	[33]	$1.7^{+2.2}_{-2.1}$	[34]
W^+W^-	ggF	$1.02^{+0.29}_{-0.26}$	[35]	$0.74^{+0.22}_{-0.20}$	[36]
W^+W^-	VBF	$1.27^{+0.53}_{-0.45}$	[35]	$0.60^{+0.57}_{-0.46}$	[36]
W^+W^-	VH	-	-	$0.39^{+1.97}_{-1.87}$	[36]
$b\bar{b}$	ttH	1.5 ± 1.1	[37]	$1.2^{+1.6}_{-1.5}$	[38]
$b\bar{b}$	VH	$0.51^{+0.40}_{-0.37}$	[39]	1.0 ± 0.5	[40]
$\tau^+\tau^-$	ggF	$2.0^{+1.5}_{-1.2}$	[41]	1.07 ± 0.46	[42]
$\tau^+\tau^-$	VBF,VH	$1.24^{+0.59}_{-0.54}$	[41]	-	-
$\tau^+\tau^-$	VBF	-	-	0.94 ± 0.41	[42]
$\tau^+\tau^-$	VH	-	-	-0.33 ± 1.02	[42]

The Higgs signals @LHC run-II

Decays	Productions	ATLAS	Ref	CMS	Ref
$\gamma\gamma$	ggF	$0.80^{+0.19}_{-0.18}$	[43, 44]	$1.11^{+0.19}_{-0.18}$	[45]
$\gamma\gamma$	VBF	2.1 ± 0.6	[43, 44]	$0.5^{+0.6}_{-0.5}$	[45]
$\gamma\gamma$	VH	$0.7^{+0.9}_{-0.8}$	[43, 44]	$2.3^{+1.1}_{-1.0}$	[45]
$\gamma\gamma$	ttH	0.5 ± 0.6	[43, 44]	$2.2^{+0.9}_{-0.8}$	[45]
ZZ	ggF	$1.11^{+0.25}_{-0.22}$	[44, 46]	$1.20^{+0.22}_{-0.21}$	[47]
ZZ	VBF	$4.0^{+1.8}_{-1.5}$	[44, 46]	$0.05^{+1.03}_{-0.05}$	[47]
ZZ	VH	0 ± 1.9	[44, 46]	0 ± 2.83 ,or 0 ± 2.66	[47]
ZZ	ttH	0 ± 3.9	[44, 46]	0 ± 1.19	[47]
W^+W^-	ggF	-	-	1.02 ± 0.27	[48]
W^+W^-	VBF	$1.7^{+1.2}_{-0.9}$	[49]	-	-
W^+W^-	WH	$3.2^{+4.4}_{-4.2}$	[49]	-	-
W^+W^-	VBF+VH	-	-	0.89 ± 0.67	[48]
$b\bar{b}$	VH	$1.20^{+0.42}_{-0.36}$	[50]	-	-
$\tau^+\tau^-$	ggF	-	-	0.84 ± 0.89	[51]
$\tau^+\tau^-$	VBF	-	-	$1.11^{+0.34}_{-0.35}$	[51]
$\tau^+\tau^-$	ttH	-	-	$0.72^{+0.62}_{-0.53}$	[52]

Global signal fit





$$\chi^2 = \sum_{\rm PD} \left(\frac{\mu_{\rm th}^{\rm PD} - \mu_{\rm exp}^{\rm PD}}{\sigma_{\rm exp}^{\rm PD}} \right)^2,$$

$$\mu[XX \to h/H \to YY] = \frac{|\kappa_{hXX}\kappa_{hYY}|^2}{\Gamma_h/\Gamma_h^{\rm SM}} + \frac{|\kappa_{HXX}\kappa_{HYY}|^2}{\Gamma_H/\Gamma_h^{\rm SM}}.$$

$$\Delta M \equiv M_H - M_h \gg \Gamma_H + \Gamma_h$$

Best-fit points

$M_h \approx M_H$	Type-I	Type-II
$(c_{\beta-\alpha}\,, t_\beta\,, \Gamma_{\rm tot})$	$(0.21\,, 5.8\,, 4.2~\rm MeV)$	$(0.01\,, 3.8\,, 41.4~\rm MeV)$
$(\Gamma_h\,, \Gamma_H)$	$(4.11~\rm MeV\,, 0.05~\rm MeV)$	$(3.89~\rm MeV\,, 37.49~\rm MeV)$
$(\rm Br[h \to b\bar{b}]\,, Br[H \to b\bar{b}])$	$(58.80\,\%\,, 8.68\,\%)$	$(56.23\,\%\,, 89.85\,\%)$
$(\rm Br[h \to \tau^+\tau^-]\,, Br[H \to \tau^+\tau^-])$	$(6.44\,\%\,, 0.95\,\%)$	$(6.16\,\%\,, 9.84\,\%)$
$(\rm Br[h \to W^+W^-]\,, Br[H \to W^+W^-])$	$(20.35\,\%\,, 77.86\,\%)$	$(22.50\,\%\,, -)$
$(\rm Br[h \to ZZ]\,, Br[H \to ZZ])$	$(2.50\,\%\,, 9.56\,\%)$	$(2.76\,\%\,, -)$
$(\rm Br[h \to \gamma\gamma]\,, Br[H \to \gamma\gamma])$	$(0.21\,\%\,, 1.22\,\%)$	$(0.24\,\%\,, -)$
$(\rm Br[h \to gg]\,, Br[H \to gg])$	$(8.73\,\%\,, 1.29\,\%)$	$(9.04\,\%\,, 0.28\,\%)$

Table: The best-fit points of $(\alpha\,, \beta)$ for the mass-degenerate Higgs bosons of $M_h \approx M_H = 125~\rm GeV$ in both Type-I and Type-II 2HDM. The decay widths of $(\Gamma_h\,, \Gamma_H)$, and decay branching ratios are listed, where the decay branching ratios smaller than 10^{-4} are neglected.

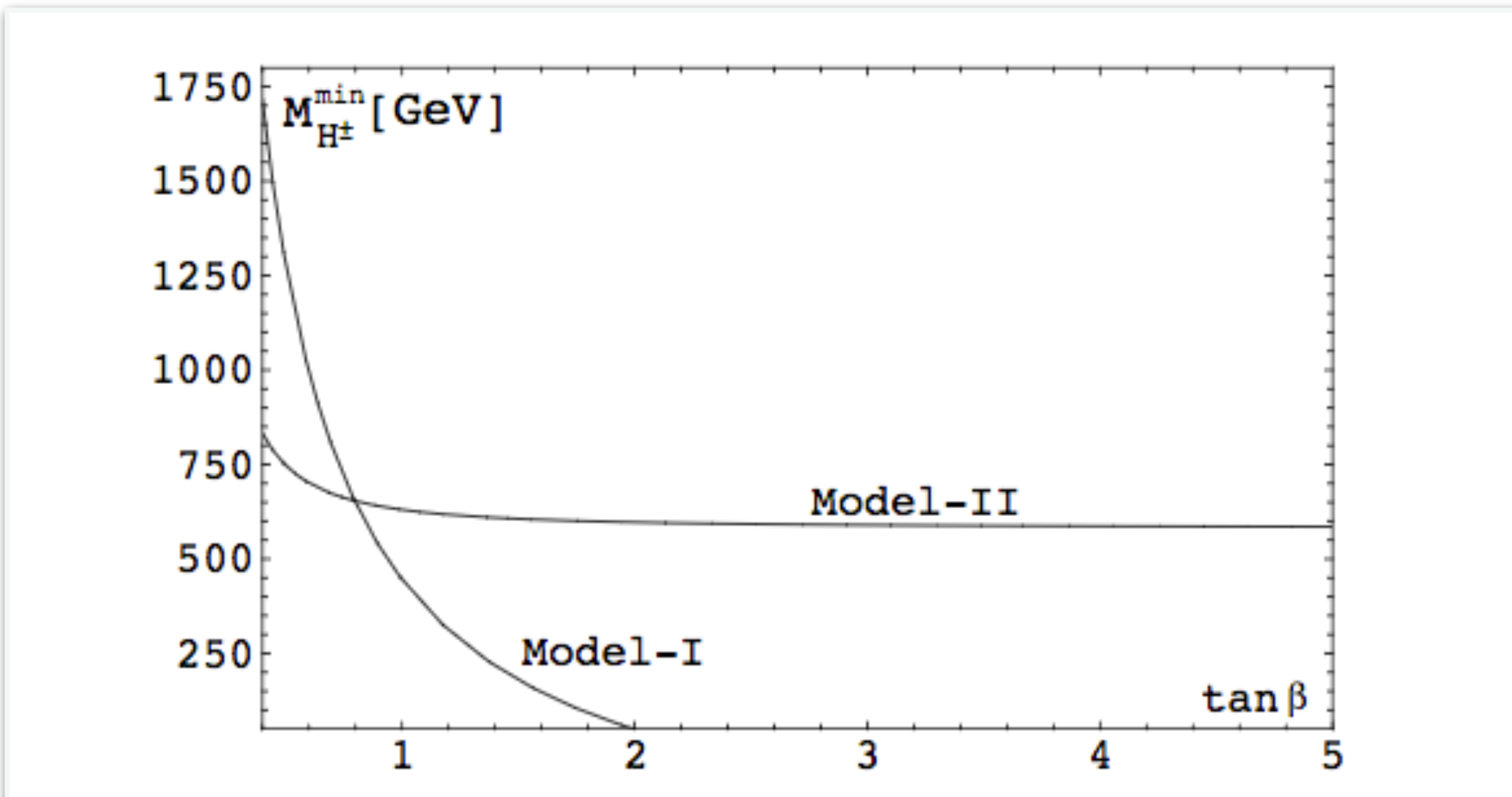
The constraints to the 2HDM with degenerate Higgs

A set of constraints

- The charged Higgs boson mass bounds: from FCNC decays
- The unitarity && stability constraints to the 2HDM potential
- The EW precision tests: can be easily alleviated
- LHC direct searches for CP-odd scalar A

The charged Higgs boson

The Belle measurements of b>
s+gamma decay: 1608.02344



Misiak && Steinhauser, 1702.04571

No constraints to $M_\pm$ in Type-I, while $M_\pm \geq 590$ GeV in Type-II.

The unitarity && stability

- The perturbative unitarity constraints require the following quantities:

$$a_\pm = \frac{3}{2}(\lambda_1 + \lambda_2) \pm \frac{1}{2}\sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2},$$
$$b_\pm = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right],$$
$$c_\pm = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}\right],$$
$$f_+ = \lambda_3 + 2\lambda_4 + 3\lambda_5, \qquad f_- = \lambda_3 + \lambda_5, \qquad f_1 = f_2 = \lambda_3 + \lambda_4,$$
$$e_1 = \lambda_3 + 2\lambda_4 - 3\lambda_4, \qquad e_2 = 2\lambda_3 - \lambda_5, \qquad p_1 = \lambda_3 - \lambda_4,$$

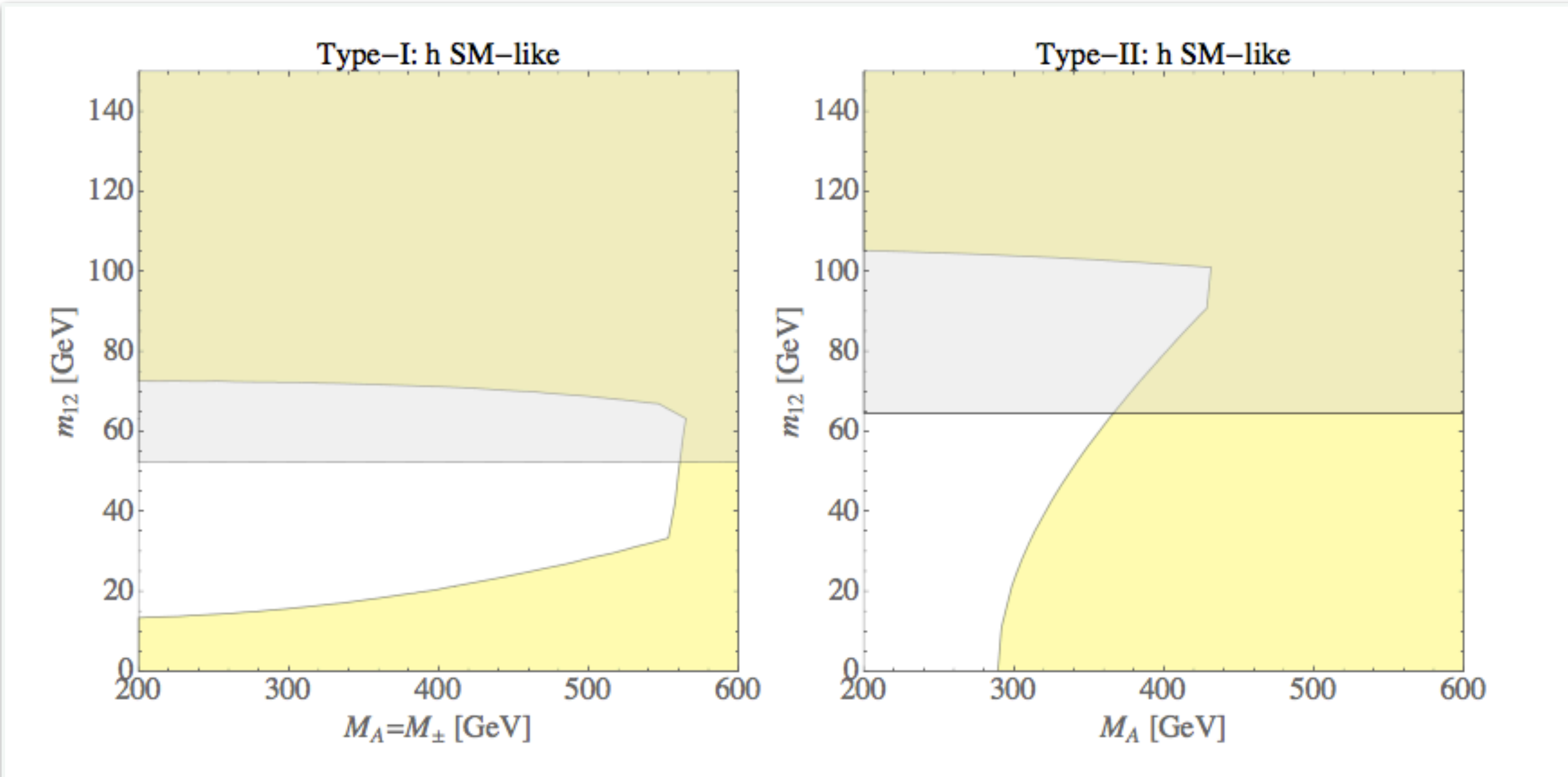
  to be $\leq 8\pi$.
- The stability constraints: $\lambda_{1,2} \geq 0$, $\lambda_3 \geq -\sqrt{\lambda_1\lambda_2}$, and $\lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1\lambda_2}$.

The unitarity && stability

- The quartic Higgs self couplings can be traded into physical inputs as:

$$
\begin{aligned}
\lambda_1 &= \frac{M_h^2 s_\alpha^2 + M_H^2 c_\alpha^2 - m_{12}^2 t_\beta}{v^2 c_\beta^2}\,, \\
\lambda_2 &= \frac{M_h^2 c_\alpha^2 + M_H^2 s_\alpha^2 - m_{12}^2 / t_\beta}{v^2 s_\beta^2}\,, \\
\lambda_3 &= \frac{1}{v^2}\Big[\frac{(M_H^2 - M_h^2) s_\alpha c_\alpha}{s_\beta c_\beta} + 2M_\pm^2 - \frac{m_{12}^2}{s_\beta c_\beta}\Big]\,, \\
\lambda_4 &= \frac{1}{v^2}(M_A^2 - 2M_\pm^2 + \frac{m_{12}^2}{s_\beta c_\beta})\,, \\
\lambda_5 &= \frac{1}{v^2}(\frac{m_{12}^2}{s_\beta c_\beta} - M_A^2)\,.
\end{aligned}
$$

The unitarity && stability



$$\text{Type-I} \quad : \quad 20 \lesssim m_{12} \lesssim 50 \text{ GeV}, \quad \text{with } M_A = M_\pm \in (200\,, 280) \text{ GeV},$$

$$\text{Type-II} \quad : \quad 0 \leq m_{12} \lesssim 60 \text{ GeV},$$

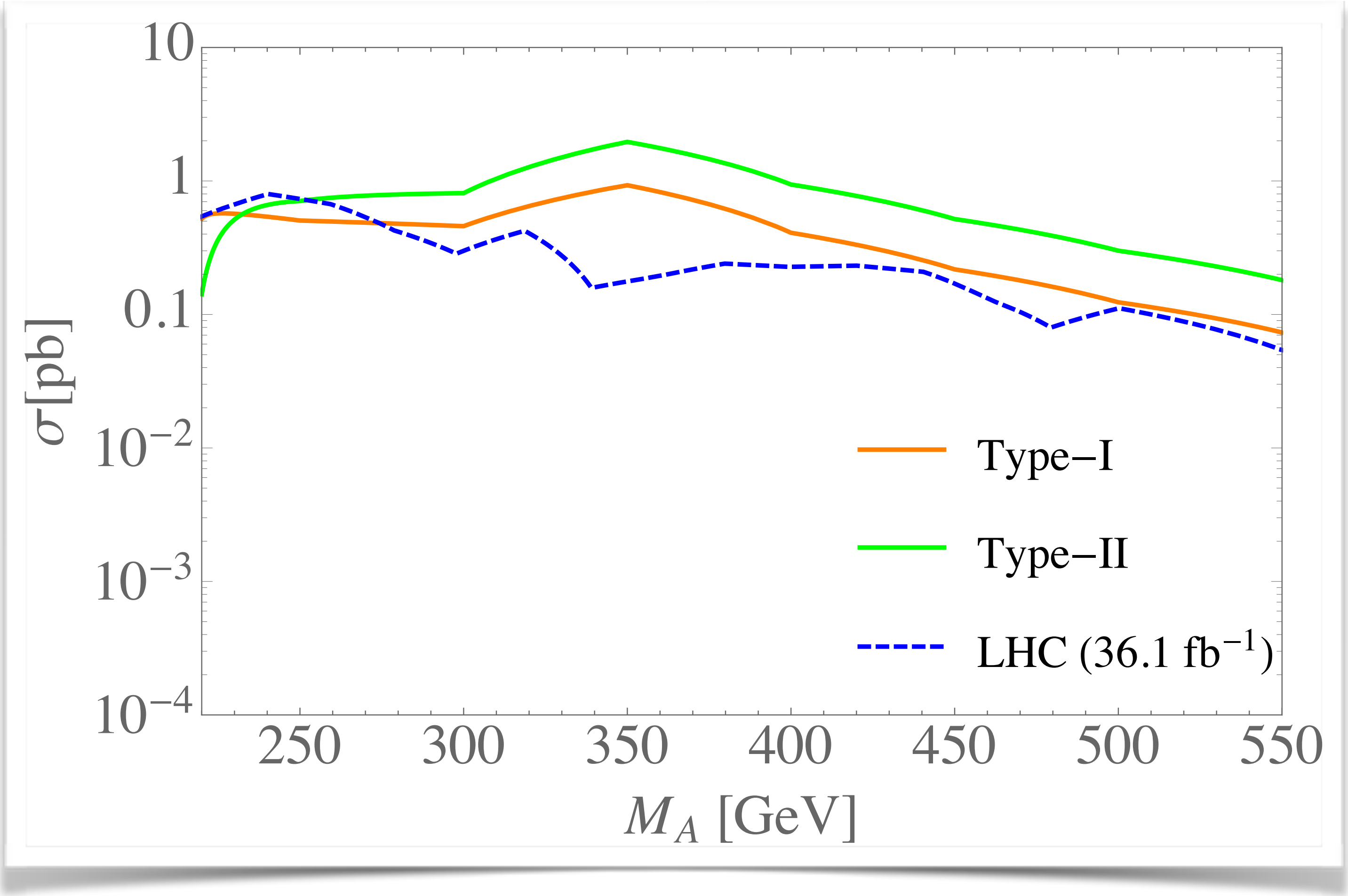
$$\text{with } M_A \in (200\,, 250) \text{ GeV and } M_\pm = 600 \text{ GeV}.$$

Experimental tests of the degenerate Higgs

Indirect tests at LHC

- In the single $M_h \approx 125$ GeV 2HDM, the decay branching fraction of $A \to h + Z$ is suppressed by the alignment factor of $c_{\beta-\alpha} \sim \mathcal{O}(0.1) - \mathcal{O}(0.01)$.
- In the h/H mass-degenerate case, one has decay modes of $A \to h/H + Z$. The signal rates with the $b\bar{b} + \ell^+\ell^-$ final states are obtained as

$$\begin{aligned}\sigma_{\rm tot} &= \sigma[pp \to AX] \times \Big(\mathrm{BR}[A \to hZ] \times \mathrm{BR}[h \to b\bar{b}] \\ &+ \mathrm{BR}[A \to HZ] \times \mathrm{BR}[H \to b\bar{b}]\Big) \times \mathrm{BR}[Z \to \ell^+\ell^-]\,.\end{aligned}$$



Direct tests: Higgs self-couplings && Higgs pairs

- The Higgs self-couplings can be measured through the Higgs pair productions at both LHC and future electron-positron colliders.

- There are more than one triple Higgs self-couplings involved for degenerate Higgs:

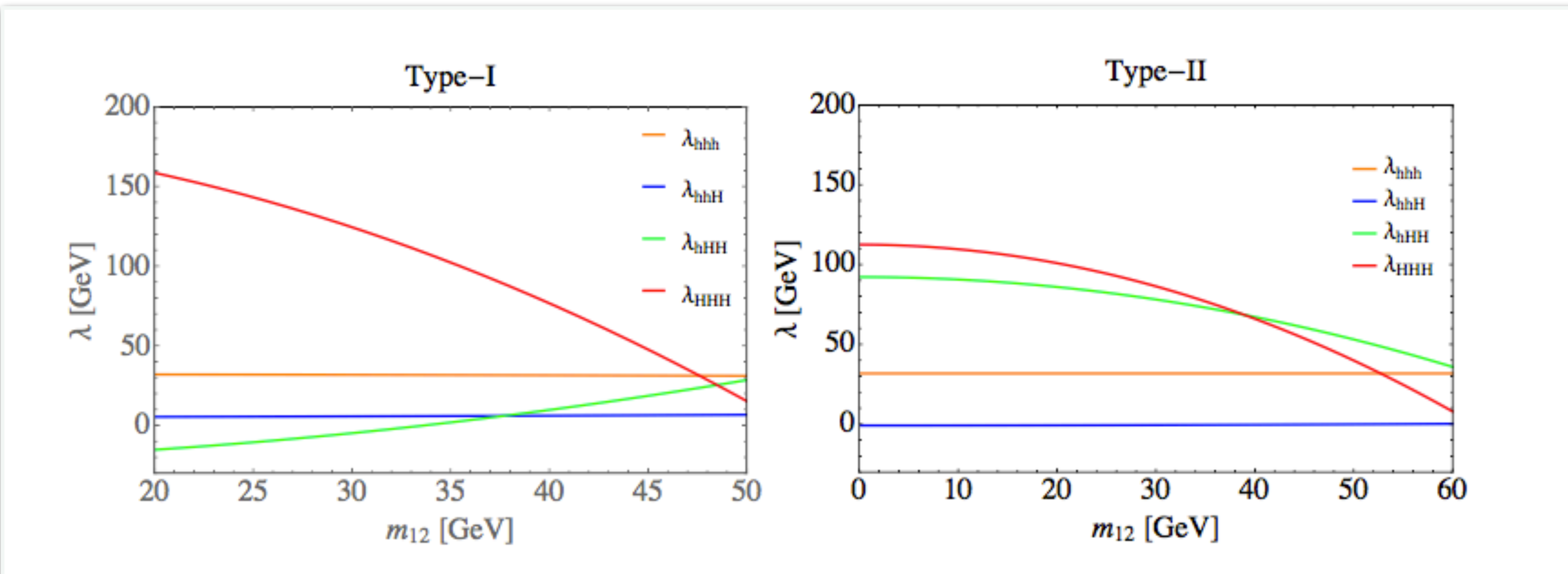
$$\lambda_{hhh} = -\frac{1}{32 v s_\beta^2 c_\beta^2}\Big[M_h^2(3s_{\alpha-\beta} + s_{3(\alpha-\beta)} - s_{3\alpha+\beta} - 3s_{\alpha+3\beta}) + 4m_{12}^2(c_{3\alpha-\beta} + c_{\alpha-3\beta} + 2c_{\alpha+\beta})\Big],$$

$$\lambda_{hhH} = \frac{c_{\alpha-\beta}}{2 v s_\beta c_\beta}\Big[(2M_h^2 + M_H^2)s_\alpha c_\alpha + m_{12}^2(1 - 3\frac{s_{2\alpha}}{s_{2\beta}})\Big],$$

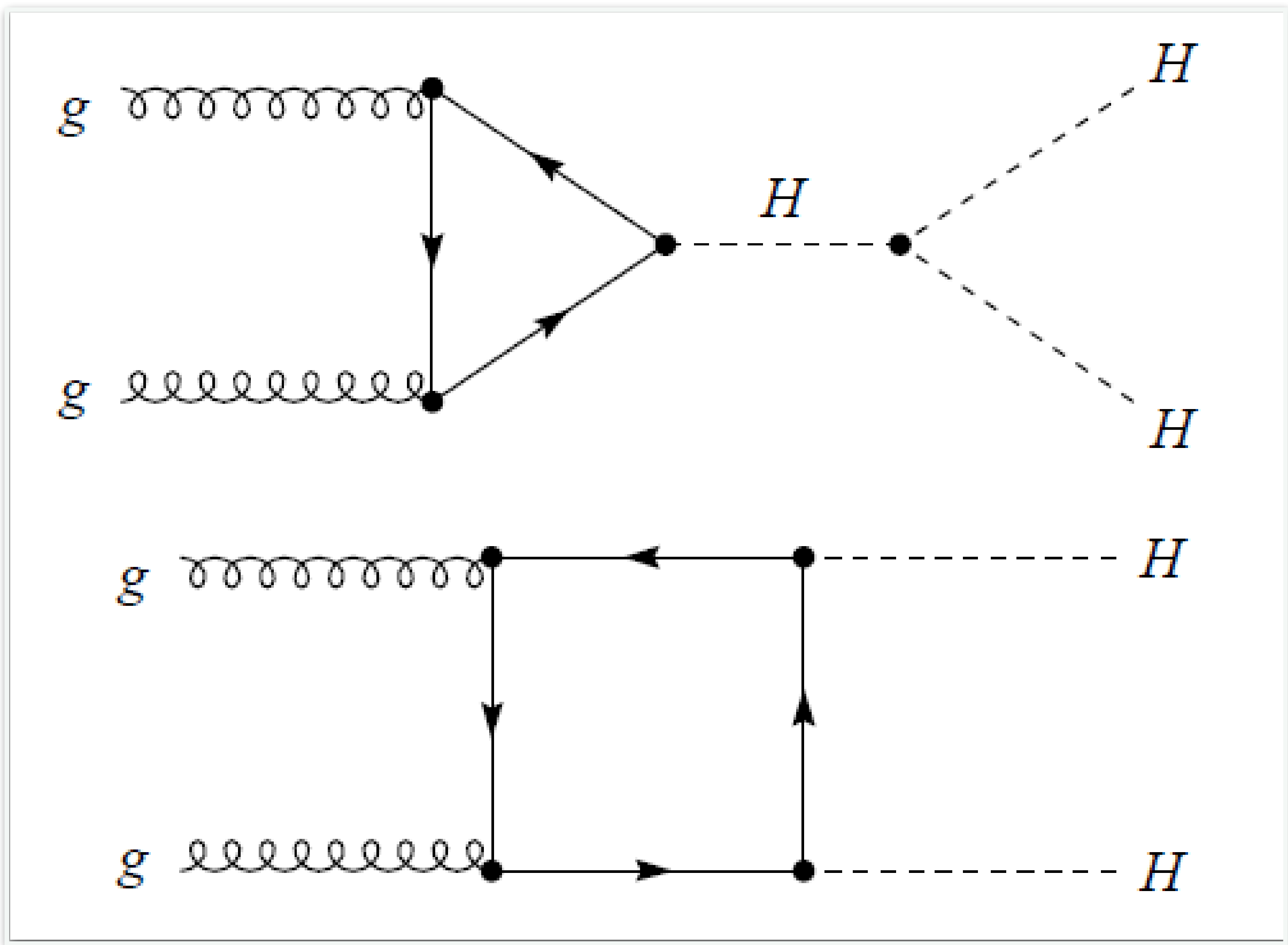
$$\lambda_{hHH} = \frac{s_{\beta-\alpha}}{2 v s_\beta c_\beta}\Big[-(M_h^2 + 2M_H^2)s_\alpha c_\alpha + m_{12}^2(1 + 3\frac{s_{2\alpha}}{s_{2\beta}})\Big],$$

$$\lambda_{HHH} = -\frac{1}{32 v s_\beta^2 c_\beta^2}\Big[M_H^2(c_{3(\alpha-\beta)} - c_{3\alpha+\beta} - 3c_{\alpha-\beta} + 3c_{\alpha+3\beta}) + 4m_{12}^2(s_{\alpha-3\beta} - s_{3\alpha-\beta} + 2s_{\alpha+\beta})\Big].$$

Higgs self-couplings



Direct tests at the LHC: SM-like case



Direct tests at the LHC

- The relevant Higgs pair productions at the LHC are:

$$\sigma[gg \to hh]\,, \qquad \sigma[gg \to hH]\,, \qquad \sigma[gg \to HH]$$

- The parton-level cross section reads

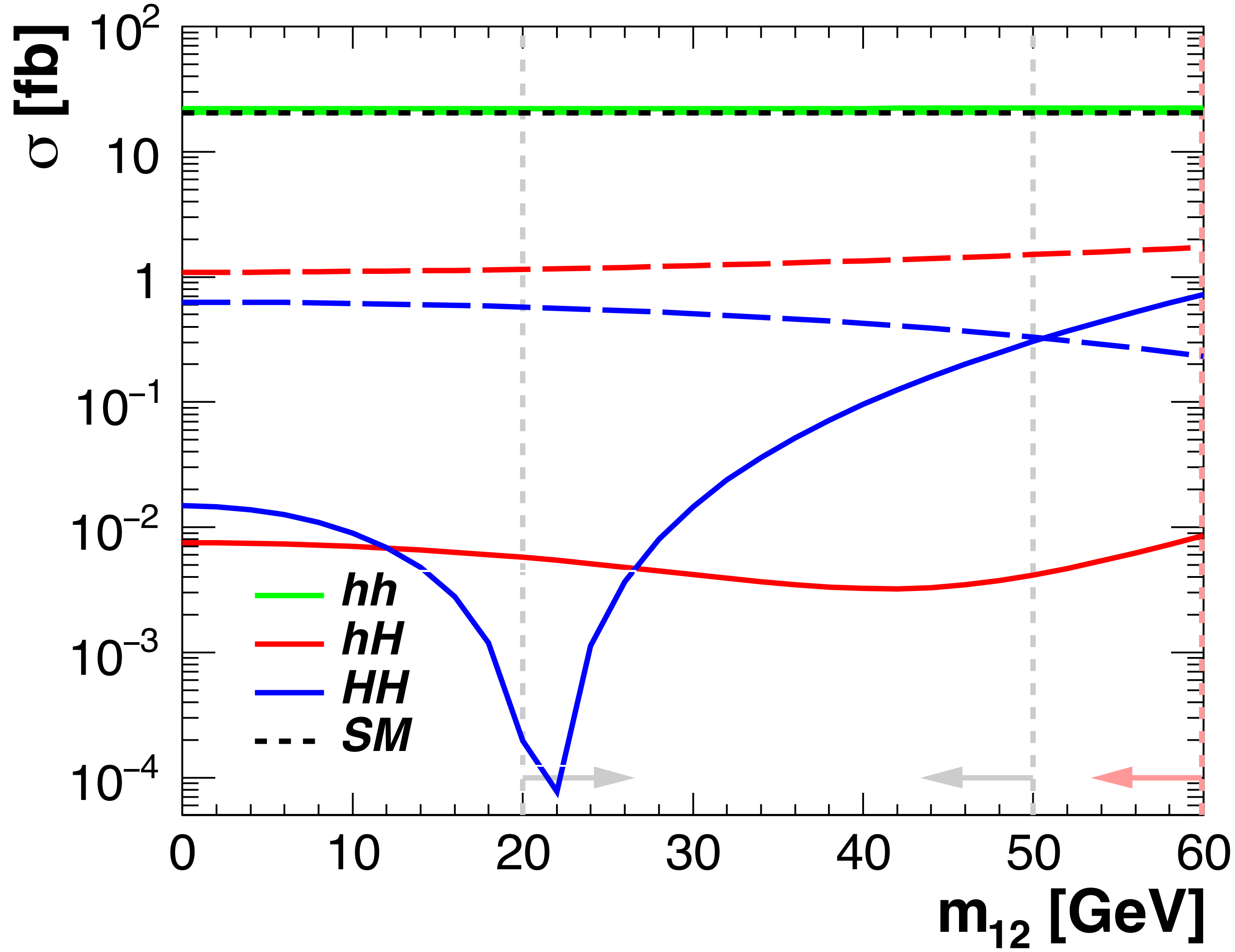
$$\frac{d\hat{\sigma}}{d\hat{t}} = K\, c^{ij}\, \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \left\{ \Big| \sum_{q=t\,,b} (C_\triangle^{ij} F_\triangle + C_\Box^{ij} F_\Box) \Big|^2 + \Big| \sum_{q=t\,,b} C_\Box^{ij} G_\Box \Big|^2 \right\}$$

with $K \approx 2$.

- The lab-frame cross section

$$\frac{d^2\sigma}{dM_{hh} dp_T} = \int_\tau^1 \frac{dx}{x} f_g(x\,, \mu_F) f_g(\frac{\tau}{x}\,, \mu_F) \frac{2M_{hh}}{s} \frac{d\hat{\sigma}}{dp_T}$$

Direct tests at the LHC



Direct tests at the LHC

- The signal rate estimations

$$\begin{aligned}\sigma[gg\to(hh\,,hH\,,HH)\to(XXYY)] &= \sigma[gg\to hh](\kappa_{XY}\mathrm{Br}[h\to XX]\mathrm{Br}[h\to YY])\\ &+ \sigma[gg\to hH]\times\Big(...\Big)\\ &+ \sigma[gg\to HH](\kappa_{XY}\mathrm{Br}[H\to XX]\mathrm{Br}[H\to YY])\end{aligned}$$

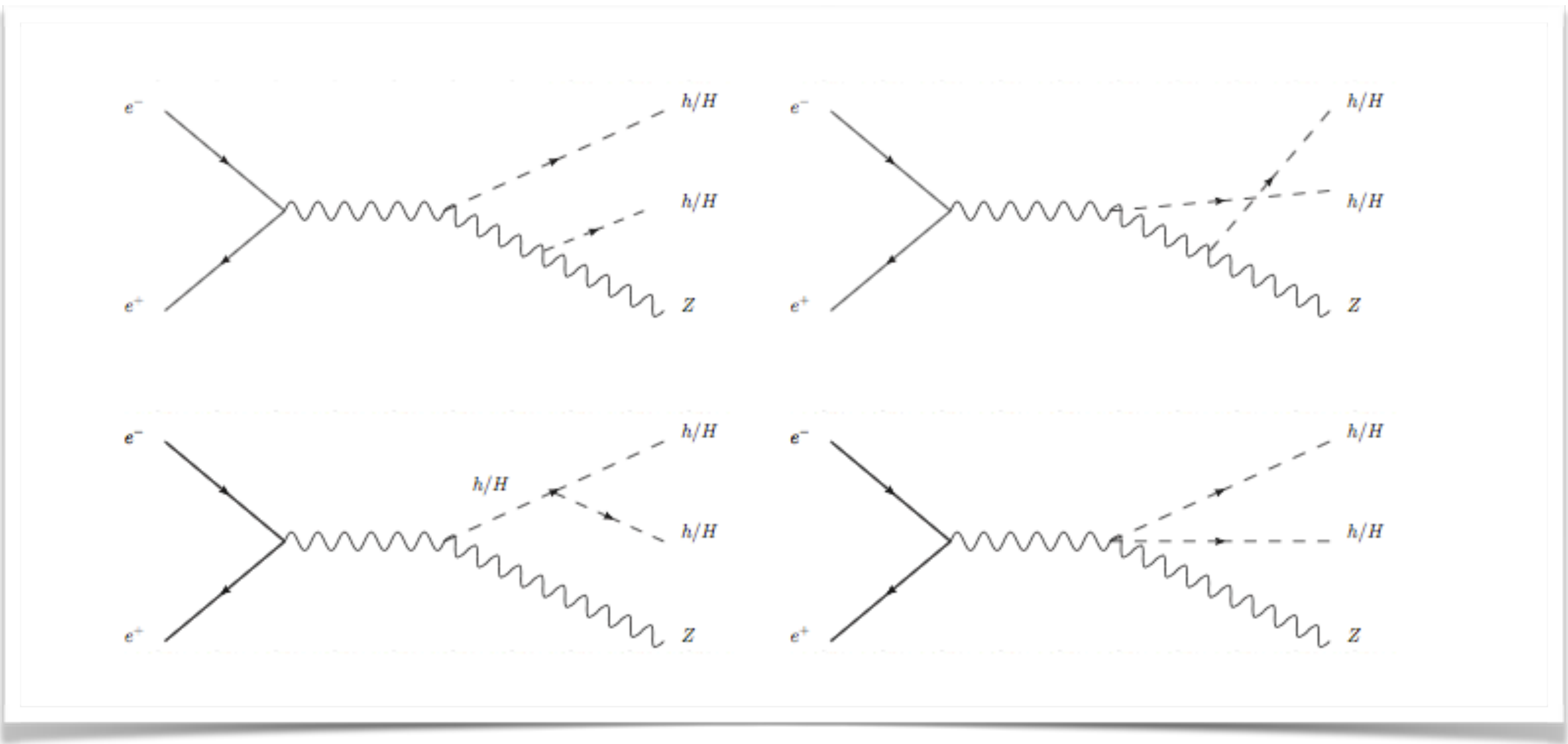
- The conservative estimations of significances for SM Higgs boson pairs at the HL-LHC:

$$\begin{aligned}&\text{ATLAS}: 1.05\,\sigma \quad \text{for} \quad 2b2\gamma\\ &\text{CMS}: (0.39\,\sigma\,,1.6\,\sigma) \quad \text{for} \quad (4b\,,2b2\gamma)\end{aligned}$$

- Not optimistic to probe the h/H mass-degenerate at the LHC:

	$4b$	$2b2\gamma$
Type-I (m_{12})	$\sim 0.44\,\sigma\,(20-50\ \text{GeV})$	$1.61\,\sigma\,(20\ \text{GeV})$ $1.64\,\sigma\,(50\ \text{GeV})$
Type-II (m_{12})	$\sim 0.43\,\sigma\,(0-60\ \text{GeV})$	$1.71\,\sigma\,(0\ \text{GeV})$ $1.75\,\sigma\,(60\ \text{GeV})$

Higgs pairs at the ILC



Higgs pairs at the ILC

- The cross sections at the ILC can be expressed as (Hikasa: Phys.Rev. D33 (1986) 3203)

$$\begin{aligned}\sigma &= \frac{1}{4}\Big[(1+P_{e^-})(1+P_{e^+})\sigma_{\rm RR} + (1-P_{e^-})(1-P_{e^+})\sigma_{\rm LL} \\ &+ (1+P_{e^-})(1-P_{e^+})\sigma_{\rm RL} + (1-P_{e^-})(1+P_{e^+})\sigma_{\rm LR}\Big]\,,\end{aligned}$$

  where $\sigma_{\rm LR}$: $(P_{e^+}, P_{e^-}) = (+1, -1)$ config.
- The ILC run at $\sqrt{s} = 500$ GeV with $\mathcal{L}_{\rm int} = 4$ ab^{-1} shared by $(P_{e^+}, P_{e^-}) = (\pm 0.3, \mp 0.8)$:

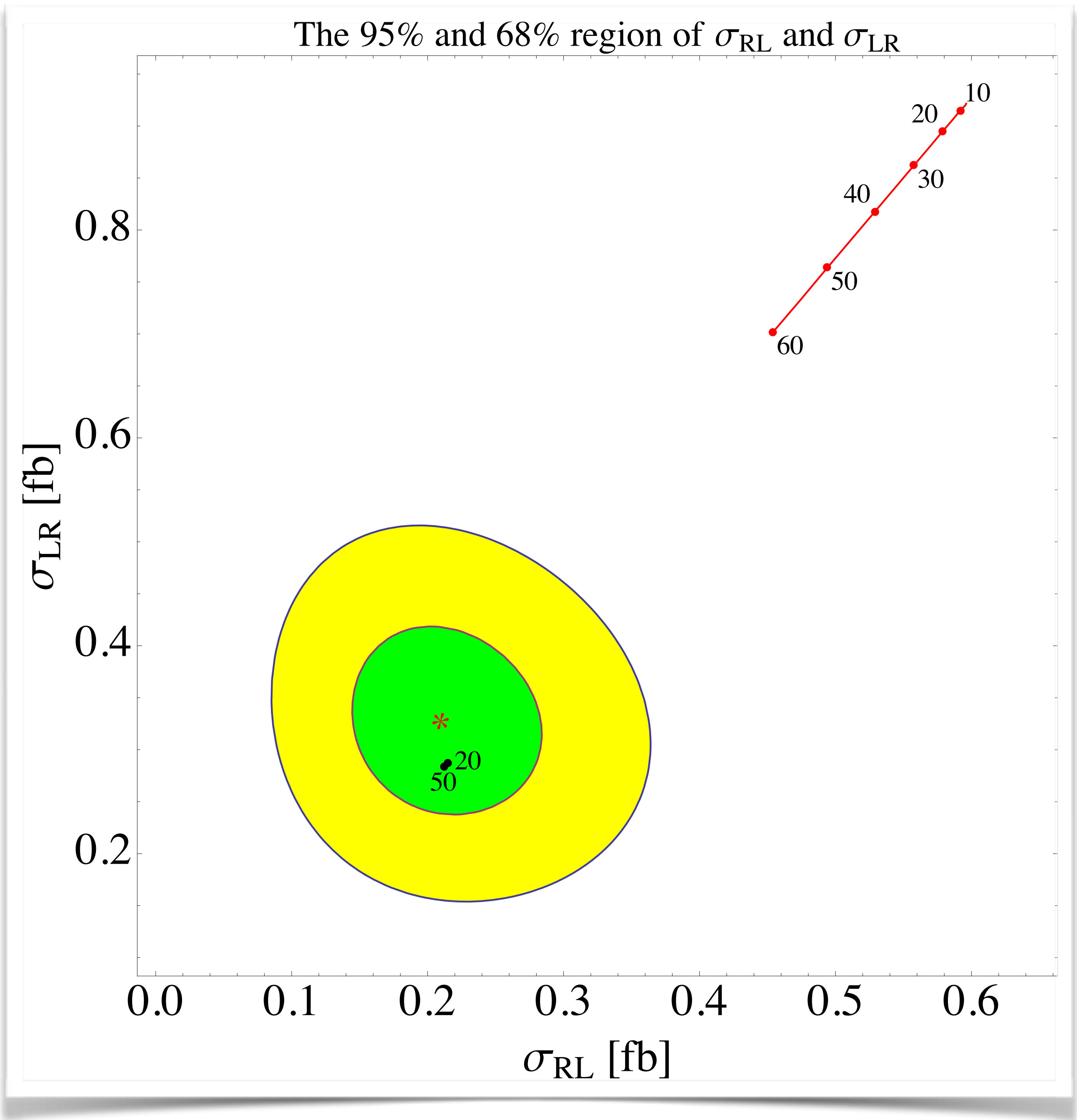
$$\begin{aligned}\sigma_{(+0.3,-0.8)} &= 0.585\,\sigma_{\rm LR} + 0.035\,\sigma_{\rm RL}\,, \\ \sigma_{(-0.3,+0.8)} &= 0.035\,\sigma_{\rm LR} + 0.585\,\sigma_{\rm RL}\,.\end{aligned}$$

Higgs pairs at the ILC

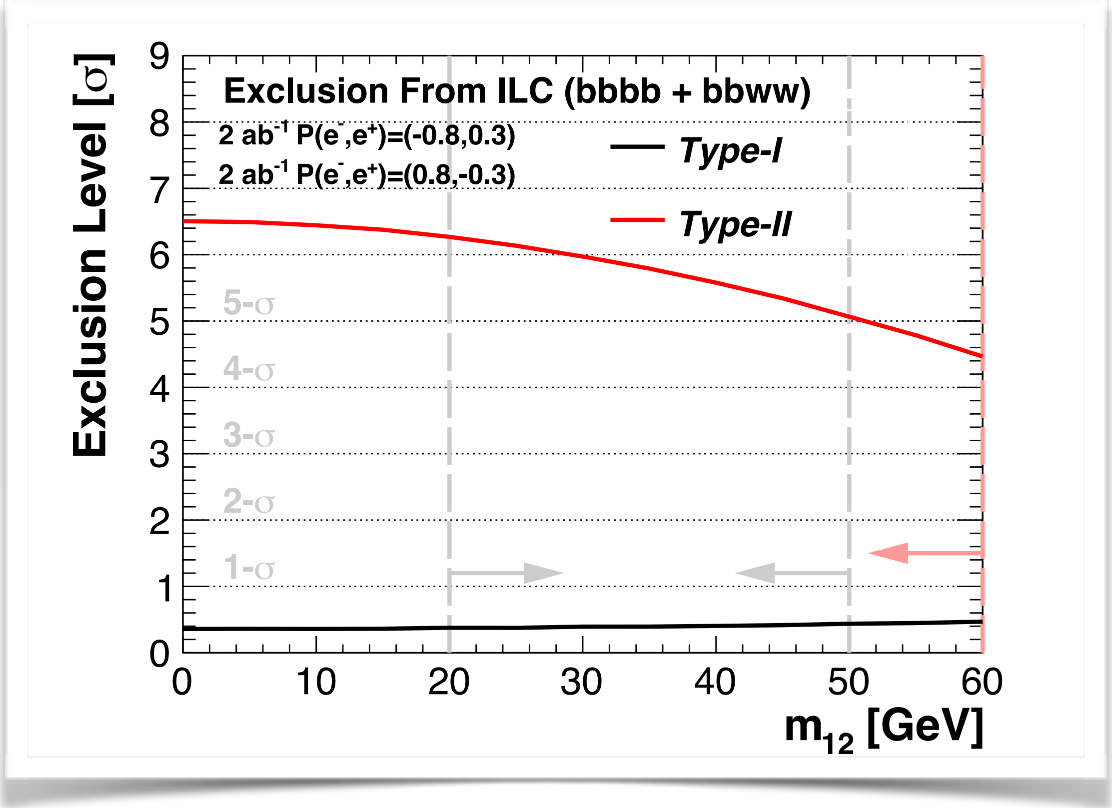
- The prospects (Claude Dürig: PhD thesis):

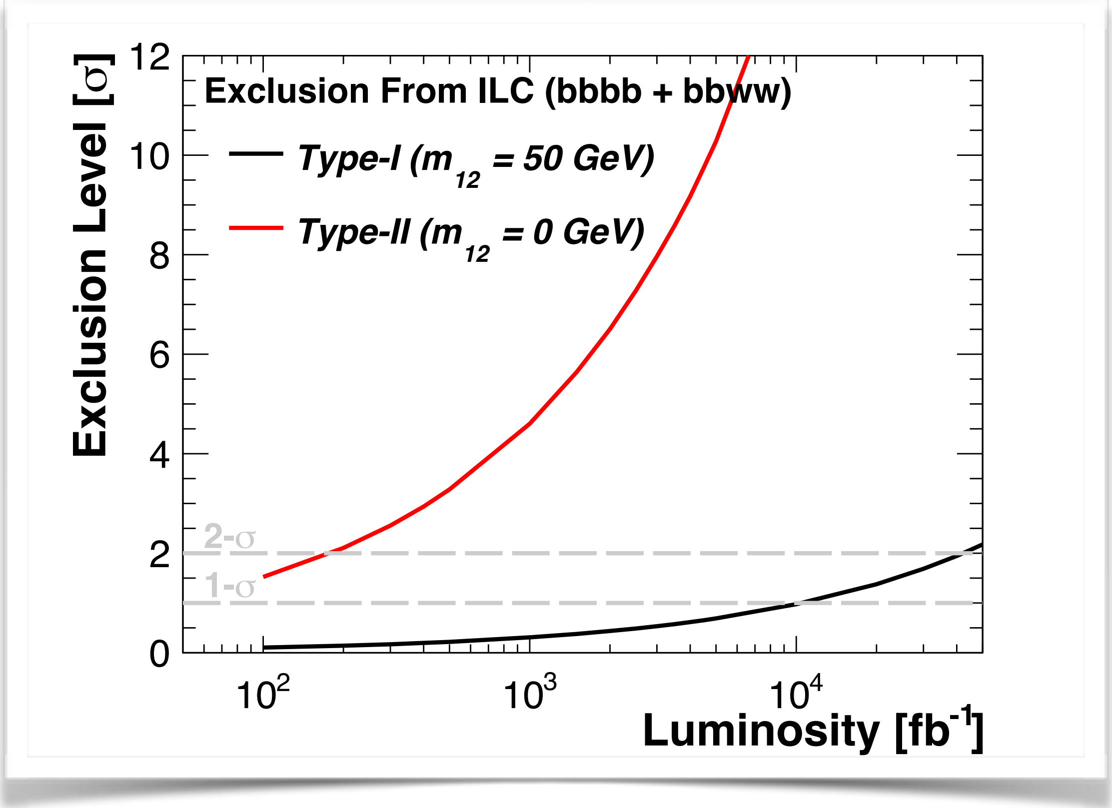
$P(e^+, e^-)$	Channel	Excess significance	Precision on σ_{ZHH}
(0.3,-0.8)	$HH \to b\bar{b}b\bar{b}$	3.5 σ	30.3%
(-0.3,0.8)	$HH \to b\bar{b}b\bar{b}$	4.8 σ	29.4%
(0.0,-0.8)	$HH \to b\bar{b}b\bar{b}$	3.5 σ	34.7%
(0.0,0.8)	$HH \to b\bar{b}b\bar{b}$	4.2 σ	33.7%
(0.6,-0.8)	$HH \to b\bar{b}b\bar{b}$	4.2 σ	28.7%
(-0.6,0.8)	$HH \to b\bar{b}b\bar{b}$	5.5 σ	27.8%
(0.3,-0.8)	$HH \to b\bar{b}W^+W^-$	1.91 σ	–

Higgs pairs at the ILC



Higgs pairs at the ILC





Summary

- The future prospects of distinguishing the mass-degenerate Vs. the single resonance case, in the 2HDM.
- Direct measurements of Higgs signals: Higgs Yukawa && gauge couplings. We suggest to probe the Higgs self-couplings through Higgs pair productions.
- LHC: not likely to probe the scenario from the Higgs pairs, but can rule out this scenario by searching for A (very soon at run-II).
- Electron-positron colliders (ILC): direct measurements, can fully justify the Type-II case.

Thank you!