Enhanced multi-Higgs boson production in the general 2HDM

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TILC09 - 20th April 2009

- RNH, D. Lopez-Val,J. Sola : Phys. Lett. B **673** (2009) 47; arXiv:0901.2257

Outline

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What is the Higgs Sector?

$SU(2)_L \times U(1)_Y \rightarrow U(1)_\gamma$

The masses and other properties of the $W^\pm$ and Z^0 bosons are accurately descibed by a spontaneously broken gauge theory

A Higgs boson?

The nature of the so-called Higgs sector, responsible for the breaking, remains experimentally unconfirmed

Standard Model or Beyond?

- Simplest model of a single scalar doublet (the Standard Model) is not excluded
- It is not the only possibility, e.g. 2HDM, SUSY, Composite Higgs . . .

Standard Model Higgs Potential

SM Higgs boson

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

SM Higgs Potential

$$\begin{aligned} V_{\mathrm{SM}} &= \lambda \left(\Phi^2 - \frac{v^2}{2} \right)^2 \\ &= \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \end{aligned}$$

Trilinear Coupling

$$\lambda_{HHH} = \frac{3}{2} \frac{e M_H^2}{s_W M_w}$$

- small for a light Higgs

Two Higgs-Doublet Model

EW Eigenstates

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1 + ia_1 \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2 + ia_2 \end{pmatrix}$$

Coupling to Fermions?

Type-I 2HDM: $\Phi_1 (u, d, e)$
Type-II 2HDM: $\Phi_1 (d, e)$
$\Phi_2 (u)$

Mass Eigenstates

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$$v^2 = v_1^2 + v_2^2, \quad \tan\beta = \frac{v_2}{v_1}$$

2HDM Potential

General (CP-conserving) 2HDM potential

$$
\begin{aligned}
V\left(\Phi_1,\ \Phi_2\right) \quad = \quad & \lambda_1\left(\Phi_1^\dagger\Phi_1 - v_1^2\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2 - v_2^2\right)^2 \\
& + \lambda_3\left[\left(\Phi_1^\dagger\Phi_1 - v_1^2\right) + \left(\Phi_2^\dagger\Phi_2 - v_2\right)\right] \\
& + \lambda_4\left[\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) - \left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)\right] \\
& + \lambda_5\left[\Re\left(\Phi_1^\dagger\Phi_2\right) - v_1 v_2\right]^2 + \lambda_6\left[\Im\left(\Phi_1^\dagger\Phi_2\right)\right]^2
\end{aligned}
$$

Softly broken Z_2 symmetry to prevent FCNCs.

Parameters

MSSM case

Imposing SUSY severely constrains the Higgs potential

- Find $\lambda_5 = \lambda_6$
- All quartic couplings are given in terms of the electroweak gauge couplings $g,\ g'$

Two free parameters, $M_A,\ \tan\beta$

General 2HDM- Our analysis

- We impose $\lambda_5 = \lambda_6$.
- 6 free parameters

We can choose $M_{h^0},\ M_{H^0},\ M_{A^0},\ M_{H^\pm},\ \tan\beta,\ \tan\alpha$

Outline

3H Couplings

Higgs self-interactions

$$\lambda_{h^0H^0H^0} = -\frac{iec_{\beta-\alpha}}{2M_W s_W s_{2\beta}}\left[\left(2M_{h^0}^2 + M_{H^0}^2\right)s_{2\alpha} - M_{A^0}^2\left(3s_{2\alpha} - s_{2\beta}\right)\right]$$

$$\overset{\text{MSSM}}{\rightarrow} \quad \frac{ieM_Z}{2c_W s_W}\left[c_{2\alpha}c_{\alpha+\beta} - 2s_{2\alpha}s_{\alpha+\beta}\right]$$

Restrictions

- 2HDM couplings enhanced for large(small) values of tan β or large Higgs mass splittings
- Maximum enhancement limited by phenomenological and theoretical constraints

Theoretical Constraints

Perturbativity

We restrict $0.1 \lesssim \tan\beta \lesssim 60$

Unitarity

Bound all $3H$ couplings by the SM value at $M_H = 1$ TeV

$$|\lambda_{HHH}| \leq \left. \frac{3}{2} \frac{eM_H^2}{s_W M_W} \right|_{M_H = 1\text{TeV}}$$

Approximates well the range excluded by more sophisticated calculations

- Kanemura, Kubota, Takasugi; hep-ph/9303263
- Akeroyd, Arhrib, Naimi; hep-ph/0006035
- Horejsi, Kladiva; hep-ph/0510154

Phenomenological Constraints

$b \to s\gamma$

- Restricts charged Higgs mass $M_{H^\pm} \gtrsim 350$ GeV for $\tan\beta \geq 1$ in the Type-II model
- No constraint for the Type-I model as $H^\pm \bar{f} f$ couplings suppressed by $\cot\beta$

Ciuchini, Degrassi, Gambino, Giudice; hep-ph/9710335

Borzumati, Greub; hep-ph/9802391

Gambino, Misiak; hep-ph/0104034

Custodial $SU(2)$

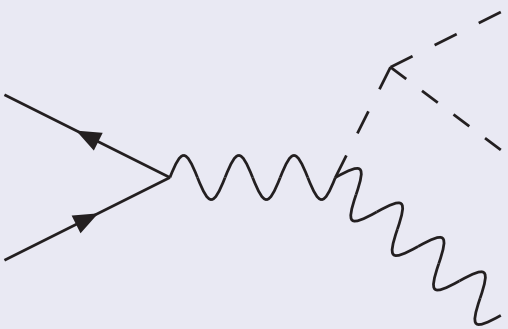
- 2HDM contributions to $\delta\rho$ vanish as $M_{A^0} \to M_{H^\pm}$
- $|\delta\rho| \leq 10^{-3}$ constrains A^0 to also be heavy in the Type-II model

Barbieri, Maiani; *Nucl. Phys.***B224** (1983) 32

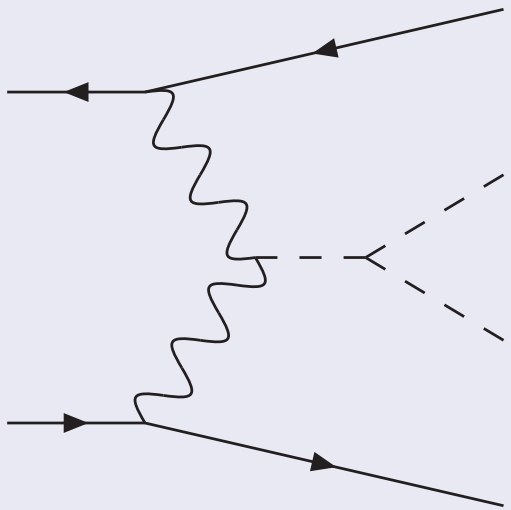
Outline

Multi-Higgs processes

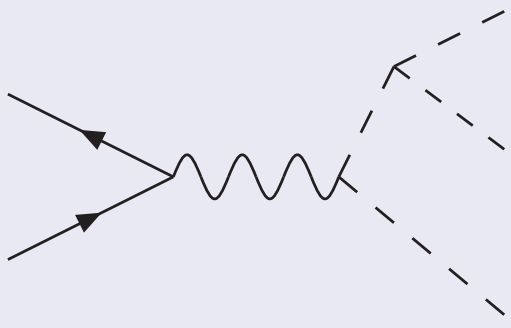
Double Higgs-strahlung



Gauge-boson fusion



Triple Higgs production



- 3H production in Ferrera, Guasch, López-Val and Solà, arXiv:0707.3162
- ZHH in Arhrib, Benbrik and Chiang, arXiv:0802.0319

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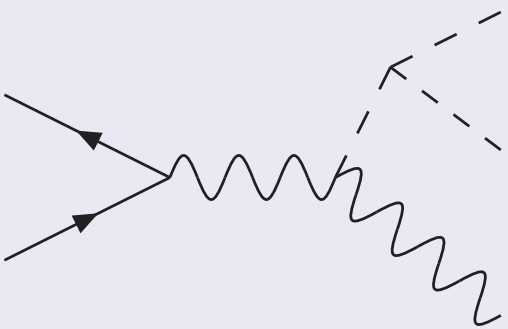

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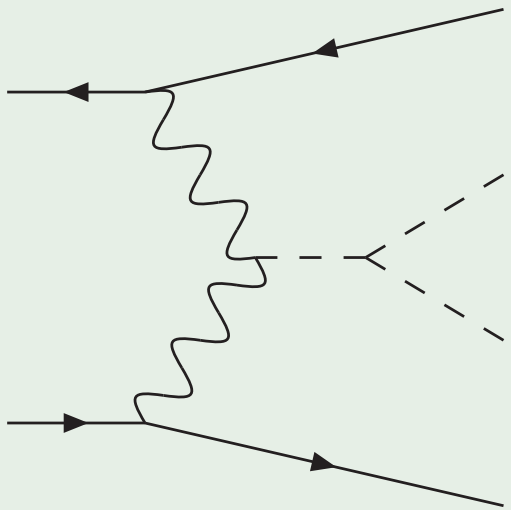

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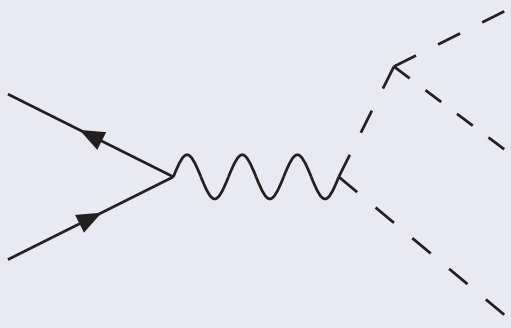

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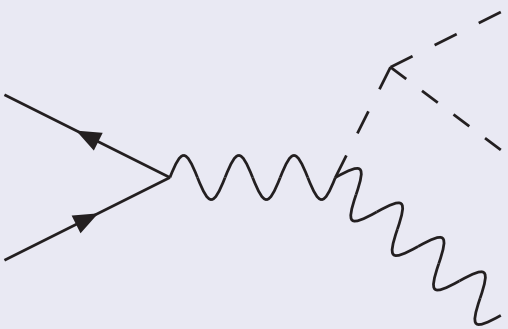

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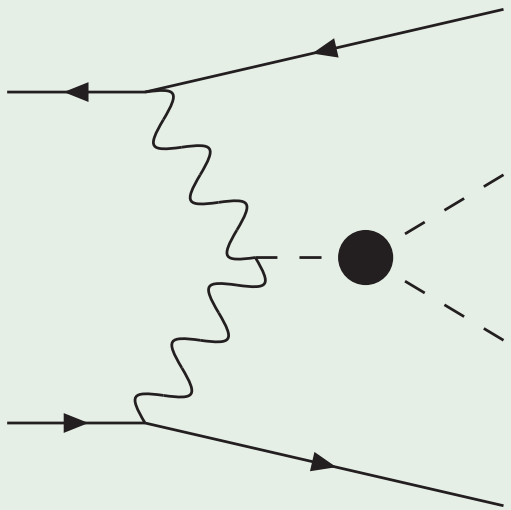

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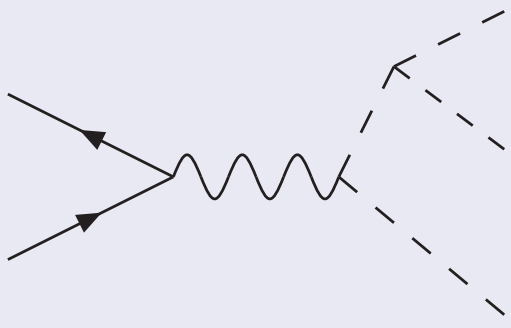

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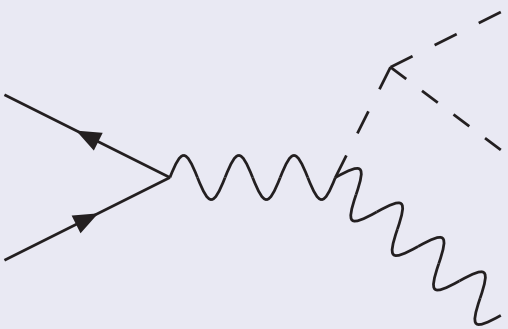

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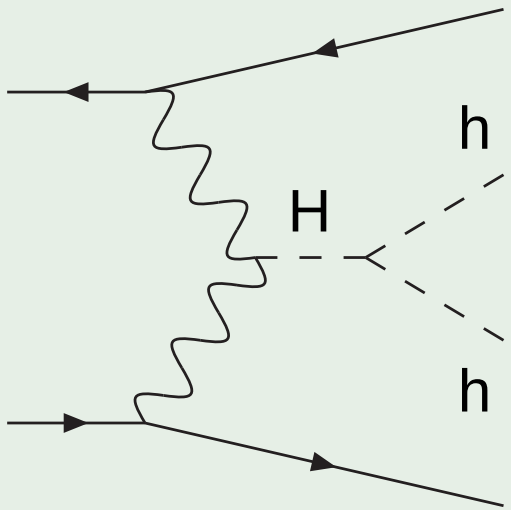

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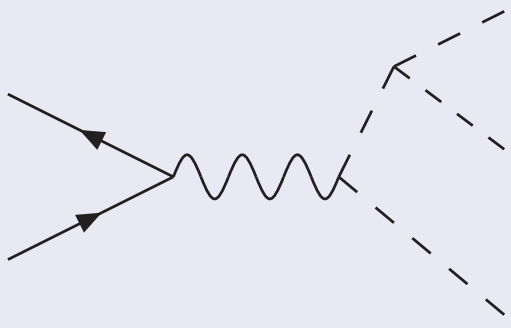

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Parameter Sets

We consider four distinct scenarios

Heavy Higgs Spectrum (Type-I and Type-II)

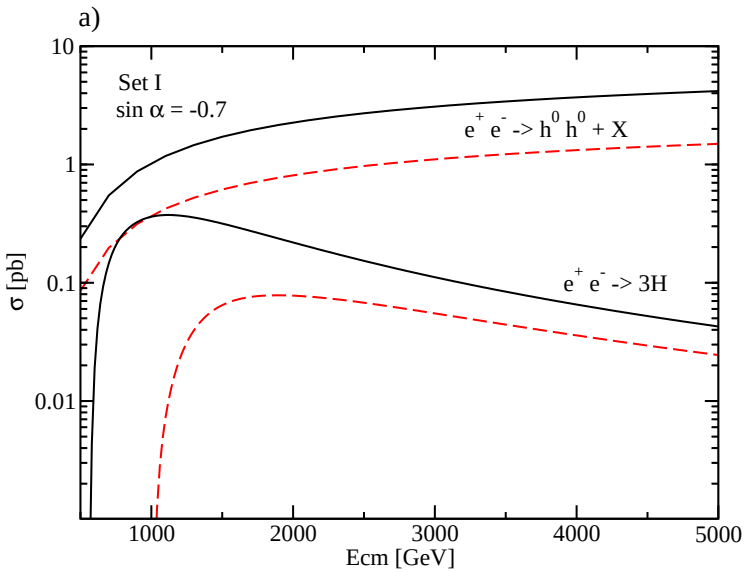
1. Non-Resonant Production
2. Resonant Production

Light Higgs Spectrum (Type-I only)

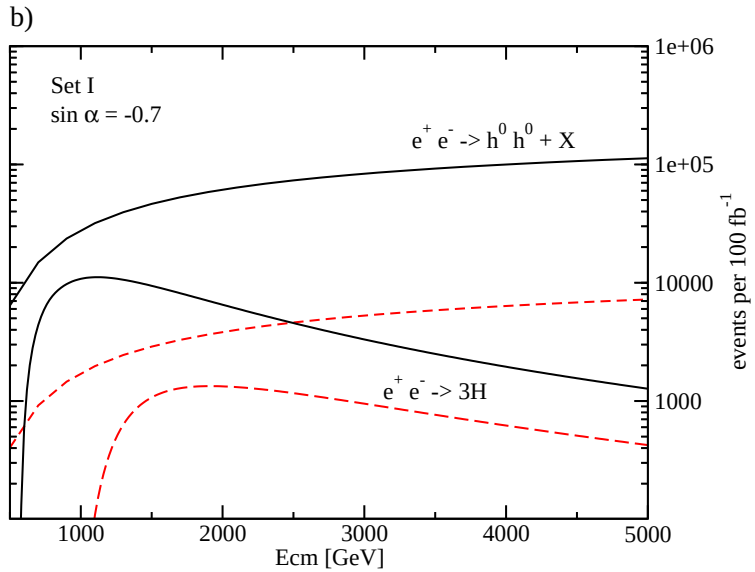
1. Non-Resonant Production
2. Resonant Production

Focus on production of light Higgs states
Numerical results using *CompHep*

Non-Resonant; Heavy Charged Higgs I



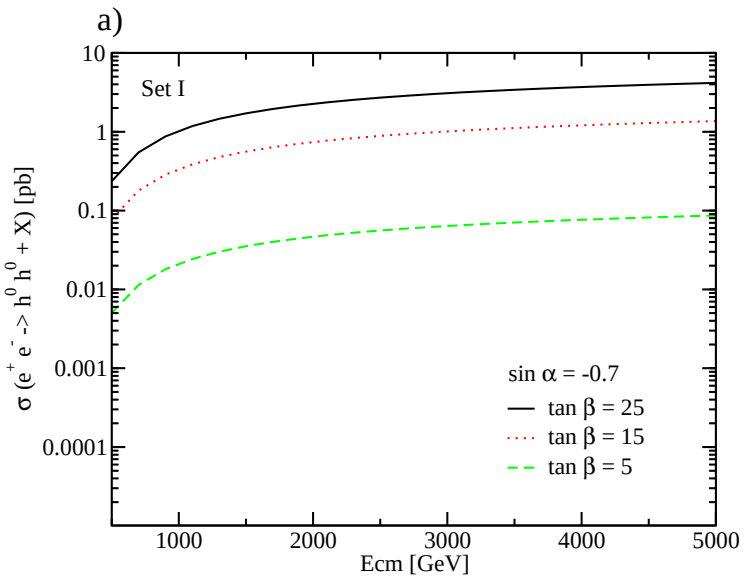
$\tan\beta \simeq 25(4)$

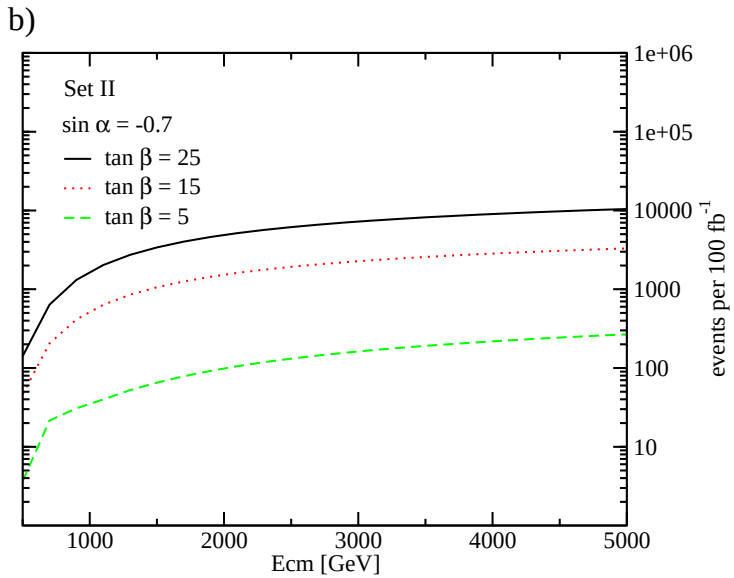


$\tan\beta \simeq 14(2)$

	M_{h^0} [/GeV]	M_{H^0} [/GeV]	M_{A^0} [/GeV]	$M_{H^\pm}$ [/GeV]
Set I (solid)	100	190	360	350
Set I' (dash)	100	190	800	800

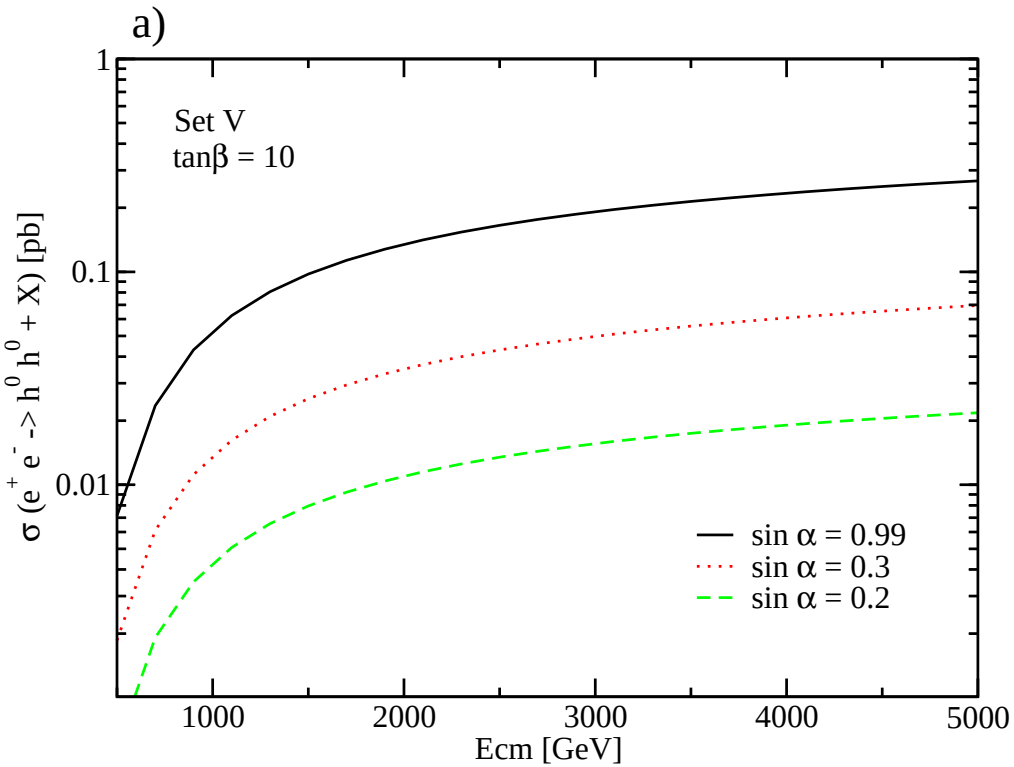
Non-Resonant; Heavy Charged Higgs II





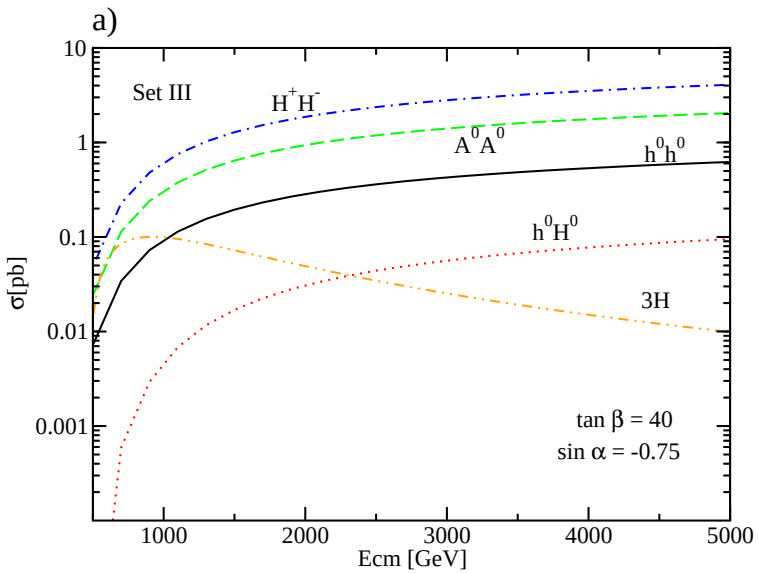
	M_{h^0} [/GeV]	M_{H^0} [/GeV]	M_{A^0} [/GeV]	$M_{H^\pm}$ [/GeV]
Set I	100	190	360	350
Set II	150	250	360	350

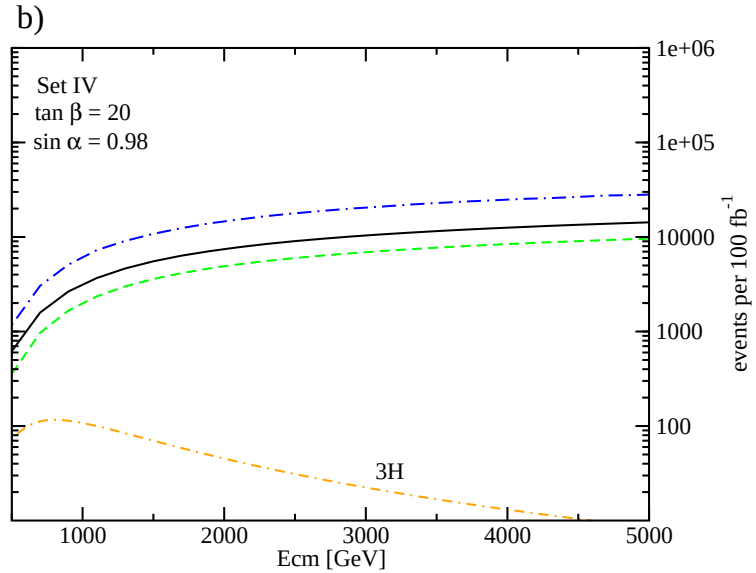
Resonant; Heavy Charged Higgs



	M_{h^0} [/GeV]	M_{H^0} [/GeV]	M_{A^0} [/GeV]	$M_{H^\pm}$ [/GeV]
Set V	125	280	300	350

Light Charged Higgs





	M_{h^0} [/GeV]	M_{H^0} [/GeV]	M_{A^0} [/GeV]	$M_{H^\pm}$ [/GeV]
Set III	150	290	150	150
Set IV	100	225	110	105

Outline

Summary and Outlook

- Even after discovery of the Higgs it will be necessary to measure its self-interactions in order to reconstruct the EW symmetry breaking potential
- If nature is described by a 2HDM the ILC or CLIC may have access to prodigious production of two-Higgs final states through gauge boson fusion
- Double Higgs-strahlung and triple Higgs production are also enhanced and give complementary measurements of the triple-Higgs vertices