Neutral Higgs-pair production at 1-loop from a generic 2HDM

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We investigate the pairwise 2H production processes $e^+e^- \to h^0A^0/H^0A^0$ *at 1-loop within the general 2HDM*

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- To quantify the importance of RADCOR's associated to these processes
- To evaluate the impact of the potentially enhanced 3H self-couplings.

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Based on the following references:

- DLV, J. Solà arXiv:0908.2898 [hep-ph]
- G. Ferrera, J. Guasch, DLV, J. Solà, *Phys. Lett.* **B659** (2007) 297-307, arXiv:0707.3162 [hep-ph]; PoS RADCOR 2007:043,2007, arXiv:0801.3907 [hep-ph]
- R. N. Hodgkinson, DLV, J. Solà, *Phys. Lett.* **B673** (2009) 47-56, arXiv:0901.2257 [hep-ph]

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The Two-Higgs Doublet Model: basic settings

- Canonical extension of the SM Higgs sector with a second $SU_L(2)$ doublet with weak hypercharge $Y=1$

- The Higgs potential can be written as:

$$
\begin{aligned}
V(\Phi) \quad = \quad & \lambda_1 \left(\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2}\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2}\right)^2 + \\
+ \quad & \lambda_3 \left(\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2} + \Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2}\right)^2 + \\
+ \quad & \lambda_4 \left[(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) - (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)\right] \\
+ \quad & \lambda_5 \left[\mathrm{Re}(\Phi_1^\dagger \Phi_2) - \frac{v_1 v_2}{2} \cos\chi\right]^2 + \lambda_6 \left[\mathrm{Im}(\Phi_1^\dagger \Phi_2) - \frac{v_1 v_2}{2} \sin\chi\right]^2
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The Two-Higgs Doublet Model: degrees of freedom

- 8 real degrees of freedom:

$$\Phi_1 = \begin{pmatrix} \Phi_1^0 \\ \Phi_1^- \end{pmatrix} = \begin{pmatrix} \frac{v_1+\phi_1^0+i\chi_1^0}{\sqrt{2}} \\ \phi_1^- \end{pmatrix}$$

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- 3 Goldstone bosons $(G^0, G^\pm)$
- 5 **physical** Higgs fields: 2 $\mathcal{CP}$-even Higgs bosons (h^0, H^0), 1 $\mathcal{CP}$-odd Higgs boson A^0 and 2 charged Higgs bosons $H^\pm$

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The Higgs sector in the general 2HDM: parameters

- 7 free parameters:
  - 6 couplings in the Higgs potential, $\lambda_i \qquad i = 1 \ldots 6$
  - 2 VEV's, v_1, v_2 with one constraint: $v^2 \equiv v_1^2 + v_2^2 = G_F^{-1}/\sqrt{2}$

- The masses of the physical Higgs particles ($M_{\mathrm{h}^0}, M_{\mathrm{H}^0}, M_{\mathrm{A}^0}, M_{\mathrm{H}^\pm}$)
- The ratio of the two VEV's, $\tan\beta \equiv \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle} \equiv \frac{v_2}{v_1}$
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Phenomenological and Theoretical constraints

- $\mathrm{H}^{\pm}$ contribution to $\mathcal{B}(b \to s\gamma)$: $M_{\mathrm{H}^{\pm}} > 295$ GeV (for Type-II 2HDM) Misiak et al., 2006.
- Higgs-boson one-loop corrections to ρ: $|\delta\rho_{2HDM}| \lesssim 10^{-3}$ Barbieri & Maiani, 1983
- Perturbativity on the Higgs-quark Yukawa couplings:
  $Y_t \propto \frac{m_t}{v\,\tan\beta}$ $Y_b \propto \frac{m_b\,\tan\beta}{v}$ $\Rightarrow$
  $0.3 < \tan\beta \lesssim 60$ El Kaffas, Osland & Greid, 2007
- Vacuum stability Kanemura, Kasai & Okada, 1999
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CP-allowed 2H channels

$$\left.\begin{array}{rcl} e^+e^- & \rightarrow & H^{\pm}H^{\mp} \\ e^+e^- & \rightarrow & h^0A^0 \\ e^+e^- & \rightarrow & H^0A^0 \end{array}\right\}$$ LO: tree-level diagrams ($\mathcal{O}(\alpha_{ew}^2)$, $\sigma \sim 0.01 - 0.1$ pb.)

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$$C_{\text{2HDM}}(h^0\,A^0\,Z) = \frac{e\,\cos(\beta-\alpha)}{2\,\sin\theta_W\,\cos\theta_W}$$

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♠ Dedicated studies on radiative corrections in 2H processes are hence mandatory: Chankowski, Pokorski, Driesen, Hollik, Rosiek ['96]; Arhrib, Moultaka ['98]; Guasch, Hollik, Kraft ['01]; Heinemeyer et al. ['01]

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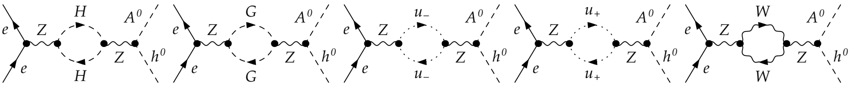
$e^+ e^- \longrightarrow A^0 h^0$

$$M^1_{e^+ e^- \to A^0 h^0} = (M^{1,Z-Z} + M^{1,\gamma-Z} + M^{1,e^+e^-Z} + M^{1,e^+e^-\gamma} + M^{1,Z^0 A^0 h^0} + M^{1,\text{box}} + M^{1,\text{WF}} + \delta M^1)$$



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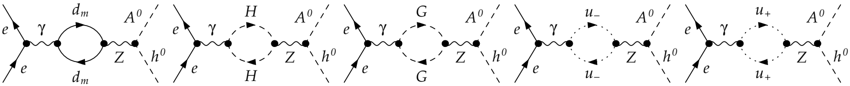

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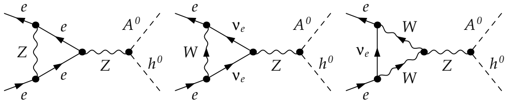

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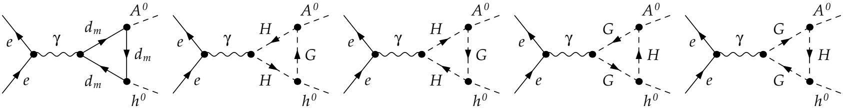

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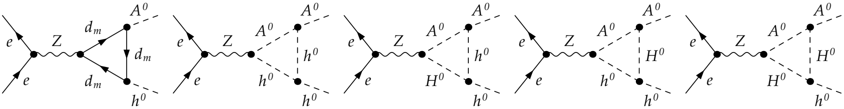

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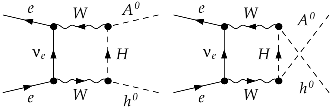

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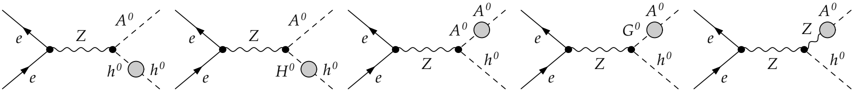

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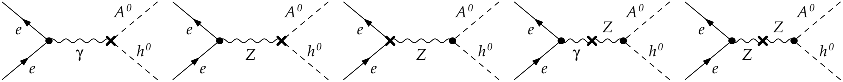

Trilinear couplings: gauge vs Yukawa-like

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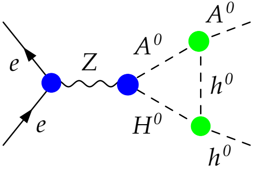

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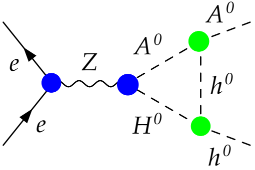

$$C[\mathrm{h^0h^0H^0}] = \frac{-ie\cos(\beta-\alpha)}{2\,M_W\;\sin\theta_W\;\sin\,2\beta}\Big[\Big(2M^2_{\mathrm{h^0}}+M^2_{\mathrm{H^0}}\Big)\sin\,2\alpha -2\,\frac{1}{e^2}\lambda_5\,M^2_W\;\sin^2\theta_W\,(3\sin2\alpha-\sin2\beta)\Big]$$

Trilinear couplings: gauge vs Yukawa-like

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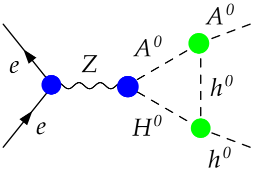

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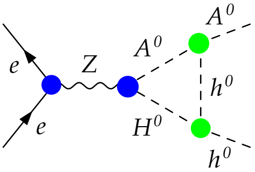

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$$\Gamma^{eff}_{\mathrm{A}^0\,\mathrm{h}^0\,\mathrm{Z}^0} \sim \Gamma^0_{\mathrm{A}^0\,\mathrm{h}^0\,\mathrm{Z}^0}\frac{\lambda^2_{3H}}{16\pi^2\,s}\,f(M^2_{\mathrm{h}^0}/s, M^2_{\mathrm{A}^0}/s)$$

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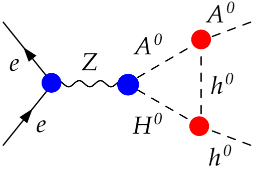

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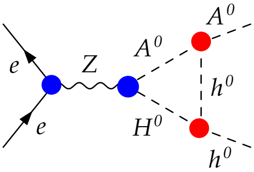

$$C_{\mathsf{MSSM}}[\mathsf{h^0h^0H^0}] = \frac{ie\,M_W}{2\,\cos\,\theta_W\,\sin\theta_W}\,(\cos 2\alpha\,\cos(\alpha+\beta) \\ -2\sin 2\alpha\,\sin(\alpha+\beta))$$

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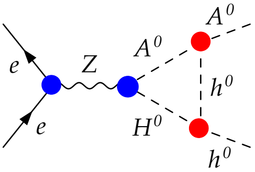

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SUSY invariance enforces the 3H couplings to be gauge-like, thus
no enhancement is present

Renormalization of the Higgs sector

- Higgs fields: 1 WF constant per $SU_L(2)$ doublet

$$\begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \to Z_{\Phi_1}^{1/2} \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix}, \qquad \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix} \to Z_{\Phi_2}^{1/2} \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix},$$

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  - In the mass-eigenstate basis:

$$\begin{aligned}
\delta Z_{\mathsf{h^0h^0}} &= \sin^2\alpha\,\delta Z_{\Phi_1} + \cos^2\alpha\,\delta Z_{\Phi_2} \\
\delta Z_{\mathsf{h^0H^0}} &= \sin\alpha\,\cos\alpha\,(\delta Z_{\Phi_2} - \delta Z_{\Phi_1}) \\
\delta Z_{\mathsf{A^0A^0}} &= \sin^2\beta\,\delta Z_{\Phi_1} + \cos^2\beta\,\delta Z_{\Phi_2} \\
\delta Z_{\mathsf{A^0-Z^0}} &= \frac{1}{2}\left(\delta Z_{\mathsf{A^0}-G^0} + \sin 2\beta\,\frac{\delta\,\tan\beta}{\tan\beta}\right)
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- $\tan\beta$ renormalization:

$$\frac{\delta v_1}{v_1} = \frac{\delta v_2}{v_2}$$

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- $\tan\beta$: $\left.\begin{array}{c} \frac{\delta v_1}{v_1} = \frac{\delta v_2}{v_2} \\ t_{h^0H^0} + \delta t_{h^0H^0} = 0 \end{array}\right\} \Rightarrow \frac{\delta \tan\beta}{\tan\beta} = \frac{1}{2}\,(\delta Z_{\Phi_2} - \delta Z_{\Phi_1})$

Renormalization of the Higgs sector

Higgs fields (OS scheme) Dabelstein ['94], Chankowski et al ['95]

$$\mathrm{Re}\,\hat{\Sigma}'_{A^0A^0}(k^2)\Big]_{k^2=M^2_{A^0}} = 0 \quad , \quad \mathrm{Re}\,\hat{\Sigma}_{A^0Z^0}(k^2)\Big]_{k^2=M^2_{A^0}} = 0$$

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Physical content of the OS conditions:

- On-shell A^0 renormalized propagators have unit residue, $1/[1 + \mathrm{Re}\,\Sigma'_{\mathrm{A}^0}(M^2_{\mathrm{A}^0})] = 1$
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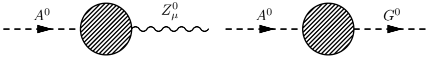

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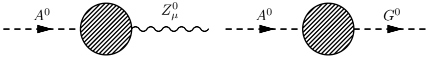

Renormalization of the Higgs sector

Higgs masses (OS scheme)

- $\text{Re}\,\hat{\Sigma}_{h^0h^0}\,(M^2_{h^0}) = 0$
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- The same condition ensures that the *CP*-even Higgs final state is on-shell, as the *physical* masses must fulfill

$$\left(p^2 - M^2_{H^0} + \hat{\Sigma}_{H^0H^0}\right)\left(p^2 - M^2_{h^0} + \hat{\Sigma}_{h^0h^0}\right) - \hat{\Sigma}^2_{h^0H^0} = 0\,.$$

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- Positive (at low energies) and negative (at high energies).
- Potentially very large:

$$\delta_r = \frac{\sigma^{(0+1)} - \sigma^{(0)}}{\sigma^{(0)}} \begin{cases} \sqrt{s} = 0.5\,\text{TeV} : 50\% \\ \sqrt{s} = 1.0\,\text{TeV} : -50\% \end{cases}$$

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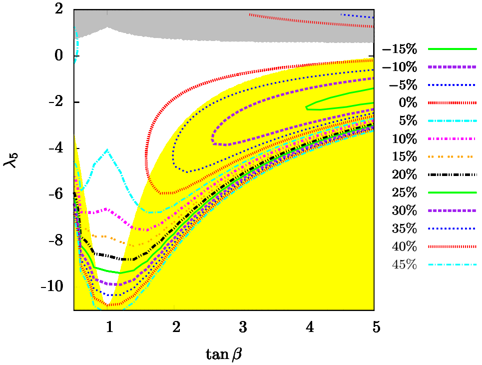
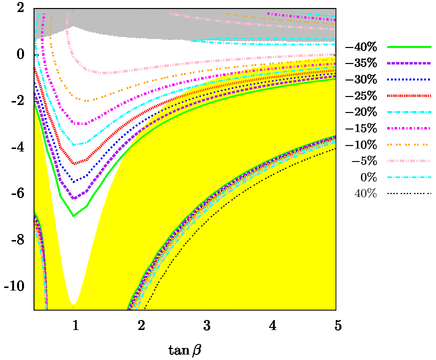
Set II



$\sqrt{s} = 500$ GeV



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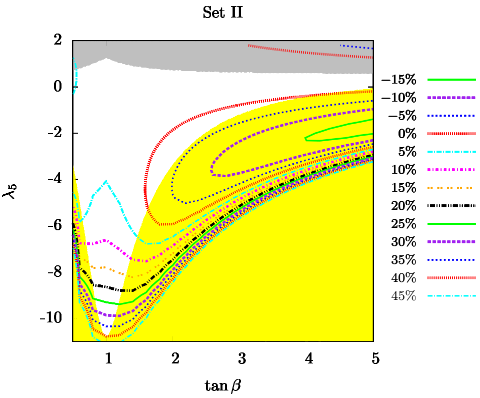

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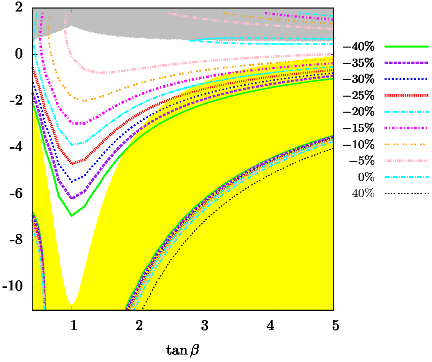

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$\sim 2 \times 10^4$ events per 500fb^{-1}

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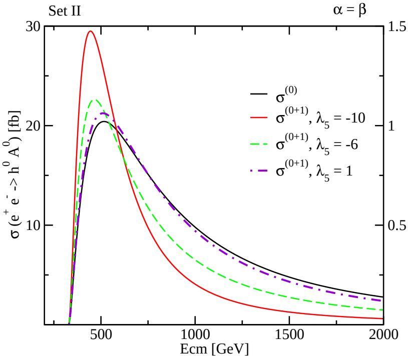

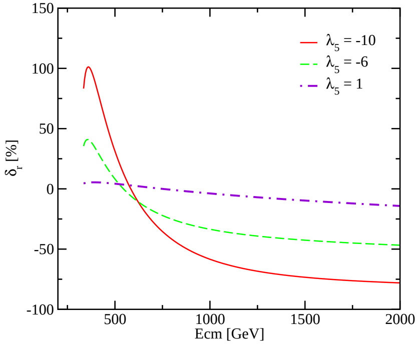

$e^+ e^- \to A^0 h^0$ phenomenology in a nutshell

- $\sqrt{s} = 500$ GeV

		$\alpha = \beta$	$\alpha = \beta - \pi/3$	$\alpha = \beta - \pi/6$	$\alpha = \pi/2$
Set II	σ_{max} [fb]	26.71	7.34	20.05	13.10
	δ_r [%]	31.32	44.43	31.42	28.81
Set III	σ_{max} [fb]	11.63	3.60	9.08	6.36
	δ_r [%]	35.17	67.59	40.68	47.86
Set IV	σ_{max} [fb]	27.44	12.12	18.37	15.41
	δ_r [%]	12.86	99.42	0.76	26.81

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	M_{h^0} [GeV]	M_{H^0} [GeV]	M_{A^0} [GeV]	$M_{H^\pm}$ [GeV]	
Set II	130	150	200	160	Type I
Set III	150	200	260	300	Type II
Set IV	95	205	200	215	Type I

$e^+ e^- \to A^0 h^0$ phenomenology in a nutshell

- $\sqrt{s} = 1$ TeV

		$\alpha = \beta$	$\alpha = \beta - \pi/3$	$\alpha = \beta - \pi/6$	$\alpha = \pi/2$
Set II	σ_{max} [fb]	4.08	0.85	2.70	1.56
	δ_r [%]	-58.42	-65.14	-63.28	-68.11
Set III	σ_{max} [fb]	6.11	1.39	4.22	2.86
	δ_r [%]	-30.16	-36.36	-35.62	-34.58
Set IV	σ_{max} [fb]	5.99	1.19	2.65	1.67
	δ_r [%]	-40.53	-52.78	-64.96	-66.81

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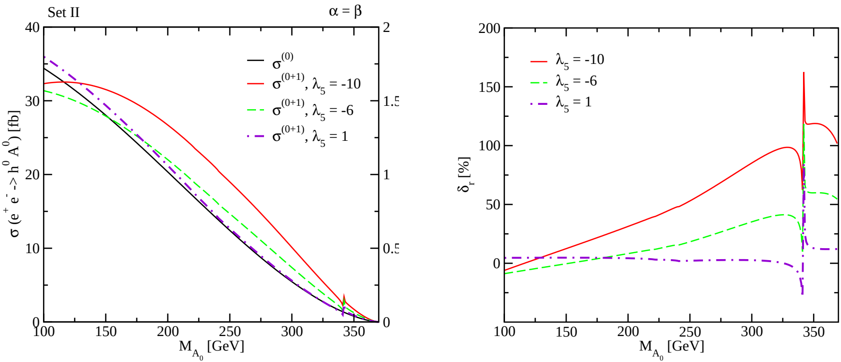

- Distinctive signature from the MSSM – wherein $\cos(\beta - \alpha)$ becomes suppressed with growing M_{A^0}.

$e^+e^- \to A^0H^0$ phenomenology in a nutshell

- The basic phenomenological trends are recovered for the H^0A^0 channel.

$\tan\beta$	α	M_{h^0} [GeV]	M_{H^0} [GeV]	M_{A^0} [GeV]	$M_{H^\pm}$ [GeV]
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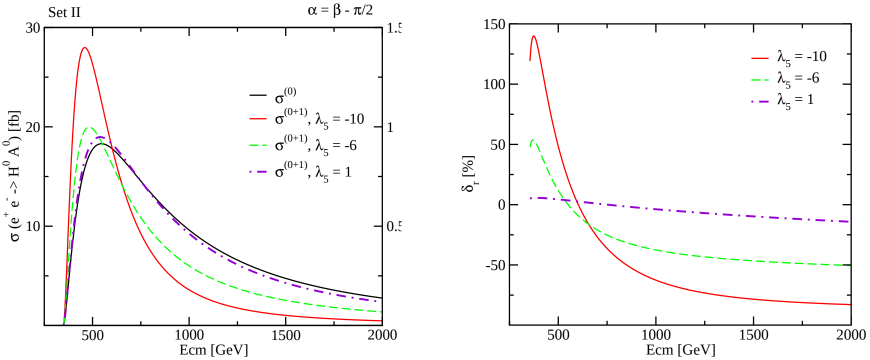

Outline

Probing the 3H self-couplings at Linear Colliders

♠ Several independent studies spotlight genuine phenomenological footprints associated to 3H self-couplings – of manifest non-SUSY nature

- Exclusive 3H production: $1)\ e^+e^- \to H^+H^-h\,,\quad 2)\ e^+e^- \to hhA^0\,,\quad 3)\ e^+e^- \to h^0H^0A^0\,,\quad (h = h^0, H^0, A^0)$, Ferrera, Guasch, DLV, Solà ['07]
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$$\left.\begin{array}{ccc} e^+e^- & \longrightarrow & H^+\,H^-\,h \\ e^+e^- & \longrightarrow & h\,h\,A^0 \\ e^+e^- & \longrightarrow & h^0\,H^0\,A^0 \end{array}\right\} \quad (h = h^0, H^0, A^0)$$

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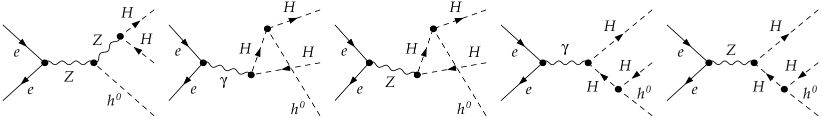

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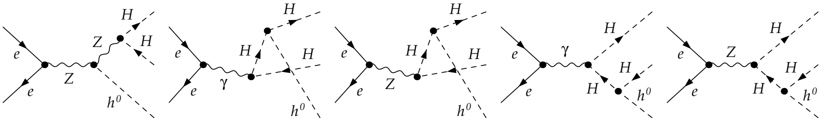

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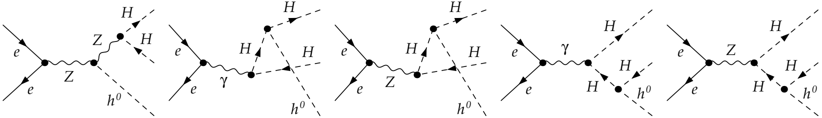

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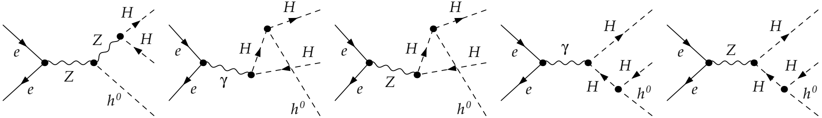

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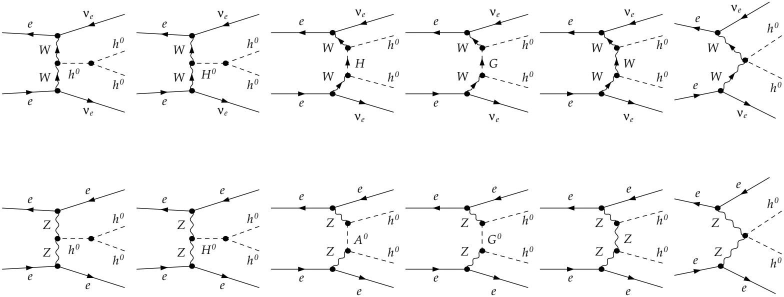

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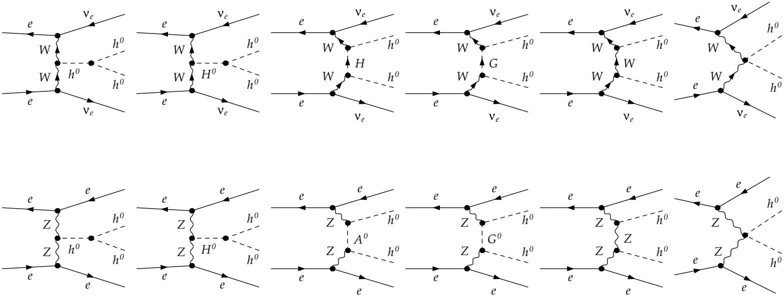

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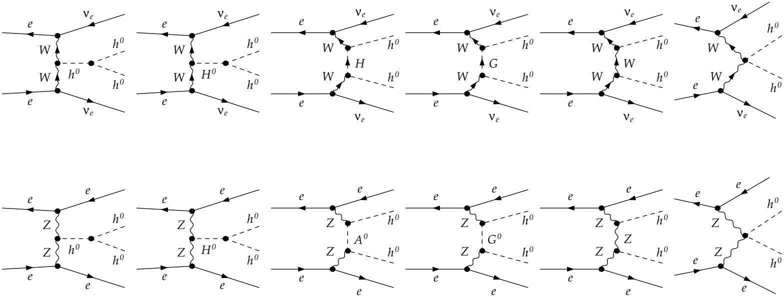

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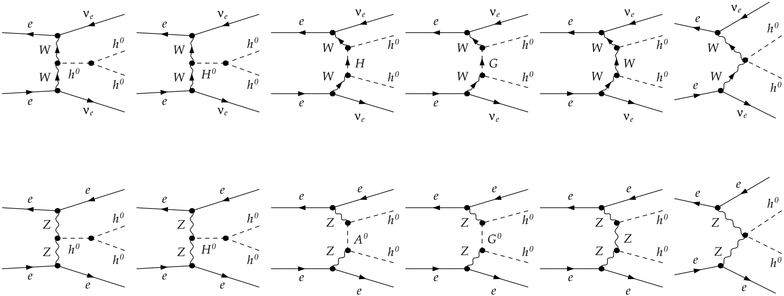

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  - in regions with $\tan\beta \sim 1$ and $|\lambda_5| \sim 5 - 10\,(\lambda_5 < 0)$
  - either positive ($\sqrt{s} = 0.5$ TeV) and negative ($\sqrt{s} = 1.0$ TeV)
  - sourced by the Higgs-mediated vertex corrections at one-loop, which are sensitive to the potentially enhanced 3H self-couplings
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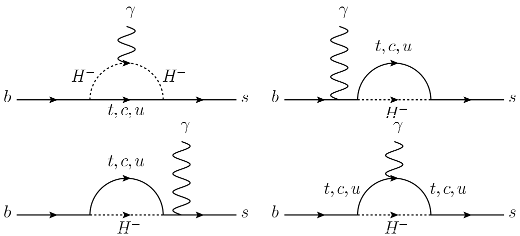
THANK YOU !

BACKUP !

Restrictions: $\mathcal{B}(b \to s\gamma)$

- We have strong constraints coming from flavor physics
  $\mathcal{B}(\bar{B} \to X_s\gamma) \sim (3.55 \pm 0.25) \cdot 10^{-4}$ from BaBar and Belle
  $\mathcal{B}(\bar{B} \to X_s\gamma) \sim (3.15 \pm 0.23) \cdot 10^{-4}$ SM NNLO prediction
- The good agreement between the SM prediction and the experimental result puts severe constraints on the flavor structure of NP models.

  New charged-particles contribute to this rare decay.



Leading-order contributions due to the charged Higgs $H^{\pm}$

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The charged Higgs bosons contribution:

- positive
- increases when $M_{\mathrm{H}^\pm}$ decreases

Type-I 2HDM: Couplings $H^{\pm}qq' \quad \propto 1/\tan\beta$
Couplings highly suppressed for $\tan\beta > 1$

Type-II 2HDM: Couplings $H^{\pm}qq' \quad \propto \tan\beta$
Couplings enhanced for $\tan\beta > 1$
Restriction $M_{\mathrm{H}^\pm} > 295$ GeV Misiak et al., 2006

Restrictions: $\delta\rho$

- rho-parameter: $\rho = \rho_0 + \delta\rho$

$$\rho = \frac{M_W^2}{M_Z^2\,\cos^2\theta_W} = 1$$

One-loop corrections induced by Higgs bosons Barbieri & Maiani, 1983

$$\begin{aligned}\delta\rho_{2HDM} \quad = \quad & \frac{G_F}{8\sqrt{2}\,\pi^2}\Bigg\{M_{H^\pm}^2\left[1-\frac{M_{A^0}^2}{M_{H^\pm}^2-M_{A^0}^2}\,\ln\frac{M_{H^\pm}^2}{M_{A^0}^2}\right] \\ & +\cos^2(\beta-\alpha)\,M_{h^0}^2\left[\frac{M_{A^0}^2}{M_{A^0}^2-M_{h^0}^2}\,\ln\frac{M_{A^0}^2}{M_{h^0}^2}-\frac{M_{H^\pm}^2}{M_{H^\pm}^2-M_{h^0}^2}\,\ln\frac{M_{H^\pm}^2}{M_{h^0}^2}\right] \\ & +\sin^2(\beta-\alpha)\,M_{H^0}^2\left[\frac{M_{A^0}^2}{M_{A^0}^2-M_{H^0}^2}\,\ln\frac{M_{A^0}^2}{M_{H^0}^2}-\frac{M_{H^\pm}^2}{M_{H^\pm}^2-M_{H^0}^2}\,\ln\frac{M_{H^\pm}^2}{M_{H^0}^2}\right]\Bigg\}\end{aligned}$$

Experimental measurements: $|\delta\rho_{2HDM}| \lesssim 10^{-3}$

$\delta\rho_{2HDM}$ vanish for $M_A \to M_{\mathrm{H}\pm}$

We will demand $M_A \sim M_{\mathrm{H}\pm}$

Restrictions: Perturbativity and Vacuum Stability

Perturbativity on the Higgs-quark Yukawa couplings

$H^{\pm}$: $Y_t \propto \frac{m_t}{v\, \tan\beta}$ $\quad Y_b \propto \frac{m_b\, \tan\beta}{v}$ $\Rightarrow$

$0.3 < \tan\beta \lesssim 60$ El Kaffas, Osland & Greid, 2007

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Vacuum stability

We assume that the quartic interaction terms in the potential do not give negative contribution for all directions of scalar fields at each energy scale up to Λ

Require a Higgs potential bounded from below

$$\lambda_1 + \lambda_3 > 0 \qquad \lambda_2 + \lambda_3 > 0$$

$$2\sqrt{(\lambda_1+\lambda_3)(\lambda_2+\lambda_3)} + 2\,\lambda_3 + \lambda_4 + \frac{1}{2}\,\text{Min}\Big(0, \lambda_5 + \lambda_6 - 2\,\lambda_4 - \big|\lambda_5 - \lambda_6\big|\Big) > 0$$

Kanemura, Kasai & Okada, 1999

Unitarity bounds

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Numerous extended analyses for the 2HDM

Higgs and Goldstone boson $2 \to 2$ S-matrix elements, S_{ij} ⇒ Unitarity condition over its eigenvalues $|\alpha_i| < 1/2\, \forall i$.

e.g.

$a_{\pm} = \frac{1}{16\pi}\Big\{3(\lambda_1+\lambda_2+2\lambda_3) \pm (\sqrt{9(\lambda_1-\lambda_2)^2+(4\lambda_3+\lambda_4+\frac{\lambda_5}{2}+\frac{\lambda_6}{2})^2}\Big\}$

Kanemura, Kubota & Takasugi, 1993; Akeroyd, Arhrib & Naimi, 2000; Horejsi & Kladiva, 2006

$e^+ e^- \longrightarrow A^0 h^0$ phenomenology in a nutshell

♠ $\sigma(e^+e^- \to A^0h^0)$ and quantum effects as a function of M_{h^0}

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