Higgs boson production at the Linear Collider: SM and beyond

Joan Solà

sola@ecm.ub.es

HEP Group
Departament d'Estructura i Constituents de la Matèria
Institut de Ciències del Cosmos, Univ. Barcelona

Scalars 2011, Warsaw, August 26-29, 2011

Guidelines of the Talk

- Higgs bosons in the 2HDM and MSSM
- Higgs boson self interactions
- Quantum effects in $e^+e^- \to$ Higgs bosons
  a window to 2HDM physics?
- Single Higgs production in $\gamma\gamma$-collisions
- Conclusions

Recent works and collaborators:

Most recent works of us on Higgs physics in the Linear Collider:

- D.López-Val, JS,
  One-loop Higgs boson production at the Linear Collider within the general two-Higgs-doublet model: e^+e^- versus $\gamma\gamma$
  arXiv:1107.1305

- D.López-Val, JS,
  Single Higgs-boson production at a photon-photon collider: general 2HDM versus MSSM,
  Phys. Lett. B702 (2011) 246,
  arXiv:1106.3226

Other works of us on Higgs physics in the Linear Collider:

- D.López-Val, JS, N. Bernal,
  Quantum effects on Higgs-strahlung events at Linear Colliders within the general 2HDM.,
  Phys. Rev. D81 (2010) 113005,
  arXiv:1003.4312

- D.López-Val, JS, Neutral Higgs-pair production at Linear Colliders within the general 2HDM: quantum effects and triple Higgs boson self-interactions
  Phys. Rev. D81 (2010) 033003,
  arXiv:0908.2898

- N. Bernal, D.López-Val, JS
  Single Higgs-boson production through $\gamma\gamma$-scattering within the general 2HDM,
  Phys. Lett. B677 (2009) 39,
  arXiv:0901.2257

- R. N. Hodgkinson, D.López-Val, JS
  Higgs boson pair production through gauge boson fusion at linear colliders within the general 2HDM.,
  Phys. Lett. B673 (2009) 47,
  arXiv:0903.4978

- G. Ferrera, J. Guasch, D.López-Val, JS
  Triple Higgs boson production in the Linear Collider., Phys.Lett. B659 (2008) 297,
  arXiv:0801.3907.

Higgs bosons in the "generic" 2HDM

2HDM $\mathcal{CP}$-conserving, gauge invariant, renormalizable potential

$$V(\Phi_1,\Phi_2)=\lambda_1(\Phi_1^\dagger\Phi_1-v_1^2)^2+\lambda_2(\Phi_2^\dagger\Phi_2-v_2^2)^2+\lambda_3\left[(\Phi_1^\dagger\Phi_1-v_1^2)+(\Phi_2^\dagger\Phi_2-v_2^2)\right]^2$$

$$+\lambda_4\left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)-(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right]+\lambda_5\left[Re(\Phi_1^\dagger\Phi_2)-v_1v_2\right]^2+\lambda_6\left[Im(\Phi_1^\dagger\Phi_2)\right]^2$$

$$\Phi_1=\begin{pmatrix}\Phi_1^+\\ \Phi_1^0\end{pmatrix}\quad (Y=+1),\quad \Phi_2=\begin{pmatrix}\Phi_2^+\\ \Phi_2^0\end{pmatrix}\quad (Y=+1)$$

MSSM

$$H_1=\begin{pmatrix}H_1^0\\ H_1^-\end{pmatrix}\equiv\epsilon\,\Phi_1^*=\begin{pmatrix}\Phi_1^{0*}\\ -\Phi_1^-\end{pmatrix}\qquad (Y=-1)\qquad \epsilon=i\,\sigma_2$$

MSSM with soft-breaking terms. **SUSY** highly restricts the potential:

$$\begin{aligned}V_H \;=\;& (|\mu|^2+m_{H_1}^2)|H_1|^2+(|\mu|^2+m_{H_2}^2)|H_2|^2-\mu B\epsilon_{ij}(H_1^iH_2^j+\text{h.c.})\\ &+\frac{g_2^2+g_1^2}{8}(|H_1|^2-|H_2|^2)^2+\frac{1}{2}g_2^2|H_1^\dagger H_2|^2\end{aligned}$$

only gauge self-couplings !!

➤ Higgs couplings in 2HDM's

- Extended Higgs sector ⇒ large source of new quantum effects and also of larger Higgs boson production cross-sections

- However, one has to be careful with tree-level FCNC ⇒ two models or types of 2HDM:

Natural FC+CP

Glashow-Weinberg-Paschos Theorem (1977)

- In type I 2HDM, Φ_2 couples to all the SM fermions; Φ_1 does not couple to them at all

$$\bar{Q}_L \left[\tilde{\Phi}_2 U_R, \Phi_2 D_R\right]$$

- In type II 2HDM, Φ_2 couples only to up-like quarks; Φ_1 couples to down-like only.

$$\bar{Q}_L \tilde{\Phi}_2 U_R + \bar{Q}_L \Phi_1 D_R$$

Yukawa couplings

2HDM

	type I	type II
$h^0 t\bar{t}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
$h^0 b\bar{b}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$H^0 t\bar{t}$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
$H^0 b\bar{b}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
$A^0 t\bar{t}$	$\cot\beta$	$\cot\beta$
$A^0 b\bar{b}$	$-\cot\beta$	$\tan\beta$

$$\times \left(-\frac{g\, m_f}{2\, M_W}\right)$$

SM

➢ Triple Higgs self-couplings

$h^0h^0h^0$	$-\frac{3ie}{2M_W \sin 2\beta\, s_W}\left[M_{h^0}^2(2\cos(\alpha+\beta)+\sin 2\alpha \sin(\beta-\alpha)) - \cos(\alpha+\beta)\cos^2(\beta-\alpha)\ \frac{4\lambda_5 M_W^2\, s_W^2}{e^2}\right]$
$h^0h^0H^0$	$-\frac{ie\cos(\beta-\alpha)}{2M_W \sin 2\beta\, s_W}\left[\left(2M_{h^0}^2+M_{H^0}^2\right)\sin 2\alpha-(3\sin\ 2\alpha-\sin 2\beta)\frac{2\lambda_5 M_W^2\, s_W^2}{e^2}\right]$
$h^0H^0H^0$	$\frac{ie\sin(\beta-\alpha)}{2M_W \sin 2\beta\, s_W}\left[\left(M_{h^0}^2+2M_{H^0}^2\right)\sin 2\alpha-(3\sin 2\alpha+\sin 2\beta)\, s_W^2\ \frac{2\lambda_5 M_W^2}{e^2}\right]$
$H^0H^0H^0$	$-\frac{3ie}{2M_W \sin 2\beta\, s_W}\left[M_{H^0}^2(2\sin(\alpha+\beta)-\cos(\beta-\alpha)\sin 2\alpha) - \sin(\alpha+\beta)\sin^2(\beta-\alpha)\ s_W^2\ \frac{4\lambda_5 M_W^2}{e^2}\right]$
$h^0A^0A^0$	$-\frac{ie}{2M_W\, s_W}\left[\frac{\cos(\alpha+\beta)}{\sin 2\beta}\left(2M_{h^0}^2-\frac{4\lambda_5 M_W^2\, s_W^2}{e^2}\right)-\sin(\beta-\alpha)\ \left(M_{h^0}^2-2M_{A^0}^2\right)\right]$

➢ … more trilinear couplings

$h^0 A^0 G^0$	$\frac{ie}{2M_W\, s_W}\left(M_{A^0}^2 - M_{h^0}^2\right)\, \cos(\beta-\alpha)$
$h^0 G^0 G^0$	$-\frac{ie}{2M_W\, s_W} M_{h^0}^2\, \sin(\beta-\alpha)$
$H^0 A^0 A^0$	$-\frac{ie}{2M_W\, s_W}\left[\frac{\sin(\alpha+\beta)}{\sin 2\beta}\left(2M_{H^0}^2 - \frac{4\lambda_5 M_W^2\, s_W^2}{e^2}\right) - \cos(\beta-\alpha)\left(M_{H^0}^2 - 2M_{A^0}^2\right)\right]$
$H^0 A^0 G^0$	$-\frac{ie}{2M_W\, s_W}\left(M_{A^0}^2 - M_{H^0}^2\right)\sin(\beta-\alpha)$
$H^0 G^0 G^0$	$-\frac{ie}{2M_W s_W}\, M_{\mathrm{H}^0}^2 \cos(\beta-\alpha)$
$h^0 H^+ H^-$	$-\frac{ie}{2M_W\, s_W}\left[\frac{\cos(\alpha+\beta)}{\sin 2\beta}\left(2M_{h^0}^2 - \frac{4\lambda_5 M_W^2\, s_W^2}{e^2}\right) - \left(M_{h^0}^2 - 2M_{H^-}^2\right)\sin(\beta-\alpha)\right]$
$H^0 H^+ H^-$	$-\frac{ie}{2M_W\, s_W}\left[\frac{\sin(\alpha+\beta)}{\sin 2\beta}\left(2M_{H^0}^2 - \frac{4\lambda_5 M_W^2\, s_W^2}{e^2}\right) - \cos(\beta-\alpha)\left(M_{H^0}^2 - 2M_{H^-}^2\right)\right]$

➢ Decoupling limit

It correspons to $\alpha \to \beta - \frac{\pi}{2}$ and with all masses much larger than M_{h^0}

(In the particular case of the MSSM, this limit is correlated with $M_{A^0} \to \infty$)

In this limit, it is easy to see that

$$\lambda_{h^0 h^0 h^0} \to \lambda^{\mathrm{SM}}_{HHH} = -\frac{3\, e\, M_H^2}{2 M_W\, s_W} = -\frac{3\, g\, M_H^2}{2 M_W}$$

and similarly with the Yukawa couplings of the h^0:

	type I	type II
$h^0 t\bar{t}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
$h^0 b\bar{b}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$

→ 1

➢ Constraints on 2HDM models

➤ rho-parameter:

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

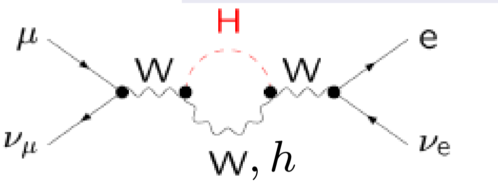
loop corrections

$$\rho = \rho_0 + \delta\rho$$

$$\delta\rho = \left.\frac{\Sigma_Z(k^2)}{M_Z^2} - \frac{\Sigma_W(k^2)}{M_W^2}\right|_{k^2=0} .$$

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

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



Experimental measurements: $|\delta\rho_{2HDM}| \lesssim 10^{-3}$
$\delta\rho_{2HDM}$ vanish for $M_A \to M_{H^\pm}$

We will demand → $M_A \sim M_{H^\pm}$

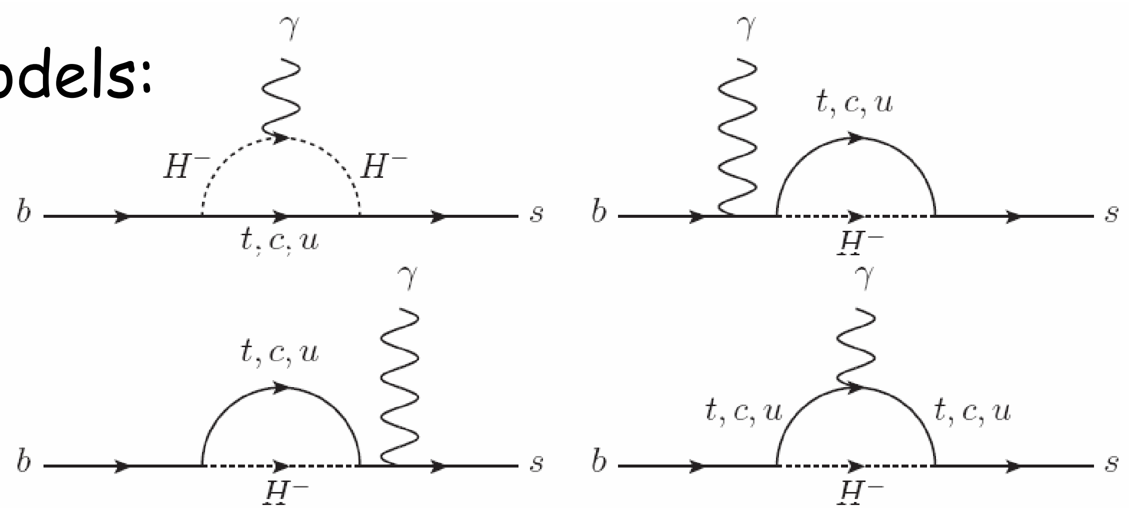
Restrictions: $\mathcal{B}(b \to s\gamma)$

- 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.

2HDM models:



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

The charged Higgs bosons contribution:

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

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

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

Update: $M_{H\pm} > 315\, GeV$ Deschamps et al, 2010

There is also an approximate limit $\tan\beta \gtrsim 1$ (from $B_d - \bar{B}_d$ mixing $\propto 1/\tan\beta$) depending on the Higgs masses

➢ Perturbativity and unitarity

- Keep the theory within a perturbative regime: $0.1 \lesssim \tan\beta \lesssim 60$

$$h_t = \frac{g m_t}{\sqrt{2} M_W \sin\beta}, \quad h_b = \frac{g m_b}{\sqrt{2} M_W \cos\beta} \to \frac{g m_b \tan\beta}{\sqrt{2} M_W}$$

- Unitarity bounds: we bound the size of the trilinear Higgs boson couplings by the value of their single SM counterpart at the scale of 1 TeV.

$$|C(HHH)| \leq \left|\lambda_{HHH}^{(SM)}(M_H = 1\ TeV)\right| = \left.\frac{3\, e\, M_H^2}{2 \sin\theta_W\, M_W}\right|_{M_H = 1\ TeV}.$$

(This would be at least the simplest unitarity requirement to start with)

➢ More strict unitarity bounds in the 2HDM

Sample of unitarity conditions:

$$
\begin{aligned}
a_\pm &= \frac{1}{16\pi}\Big\{3(\lambda_1+\lambda_2+2\lambda_3) \\
&\quad \pm(\sqrt{9(\lambda_1-\lambda_2)^2+\left(4\lambda_3+\lambda_4+\frac{\lambda_5}{2}+\frac{\lambda_6}{2}\right)^2}\Big\}\,, \\
b_\pm &= \frac{1}{16\pi}\Big\{\lambda_1+\lambda_2+2\lambda_3 \\
&\quad \pm\sqrt{(\lambda_1-\lambda_2)^2+\frac{(-2\lambda_4+\lambda_5+\lambda_6)^2}{4}}\Big\}\,, \\
c_\pm &= d_\pm = \frac{1}{16\pi}\Big\{\lambda_1+\lambda_2+2\lambda_3 \pm\sqrt{(\lambda_1-\lambda_2)^2+\frac{(\lambda_5-\lambda_6)^2}{4}}\Big\}\,,
\end{aligned}
$$

♠ $|a_\pm|, |b_\pm|, |c_\pm|, |f_\pm|, |e_{1,2}|, |f_1|, |p_1| \leq \frac{1}{2}$

➢ Vacuum stability bounds

Minimization of the Higgs potential

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

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

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

Kanemura, Kasai & Okada, 1999

➢ Higgs boson production at the Linear Colliders ILC/CLIC within the general 2HDM

- $e^+e^- \to 2H$ — D. López-Val, JS, Phys.Rev.D81 (2010) 033003 (at the **quantum level**)
- $e^+e^- \to ZH$ — D. López-Val, JS, N. Bernal, Phys.Rev.D81 (2010) 113005

- $e^+e^- \to 3H$
- $e^+e^- \to 2H + X$
- $e^+e^- \to \gamma\gamma \to H$

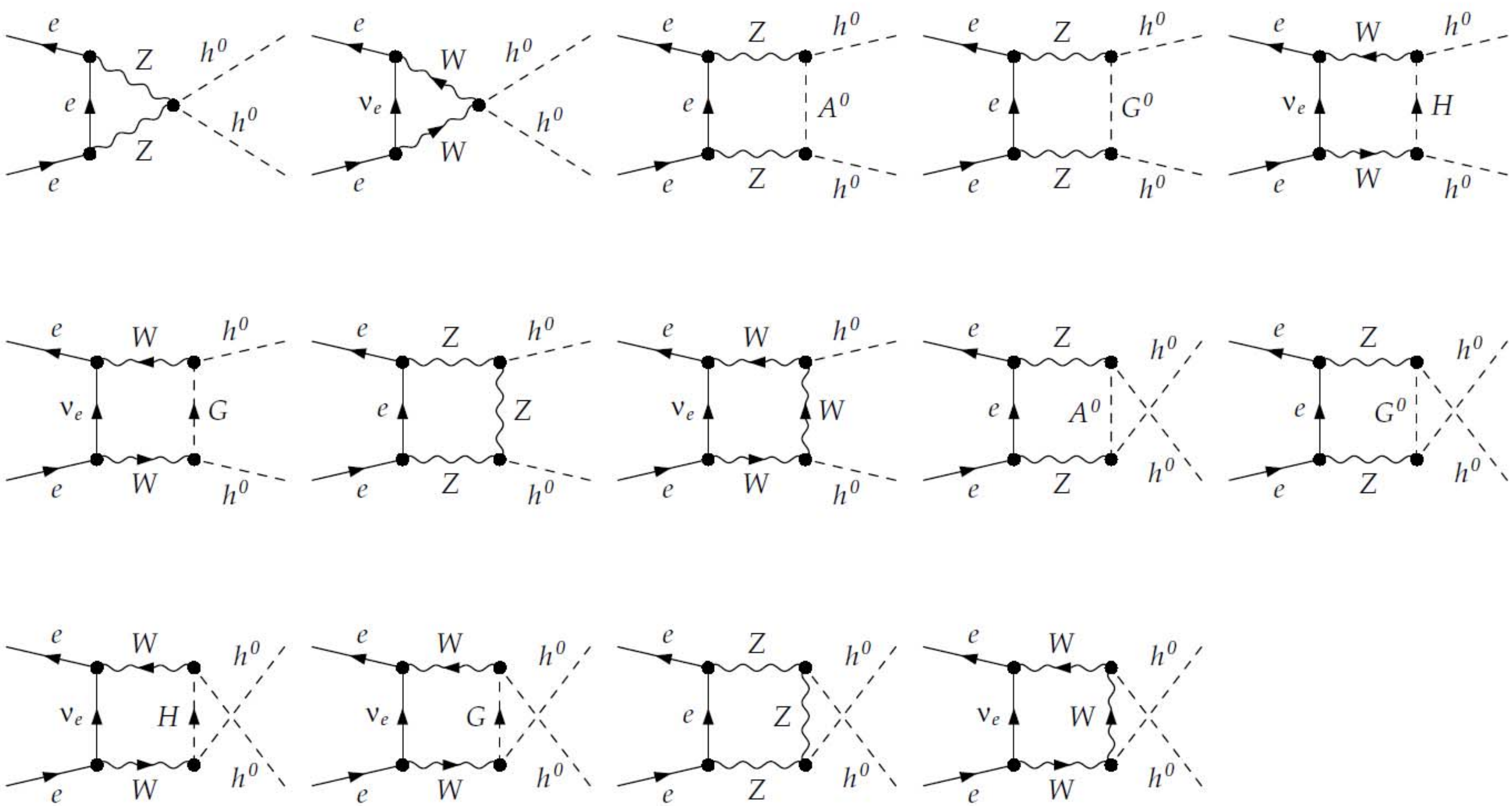
(very **promising** too!)

D. López-Val, JS, Phys.Lett.B702 (2011) 246

➢ Double-Higgs production in the SM

Two identical Higgs bosons cannot be produced through $e^+e^- \to Z \to h^0h^0$

$\sigma \sim 10^{-5}pb$ (**too small**)

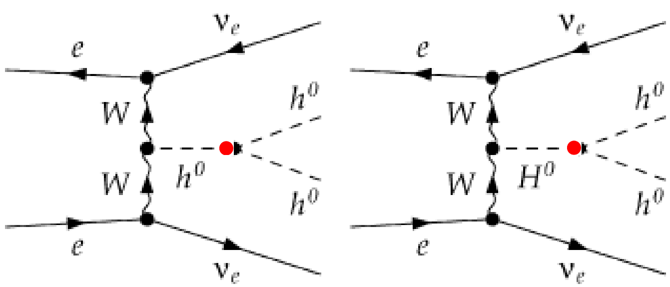


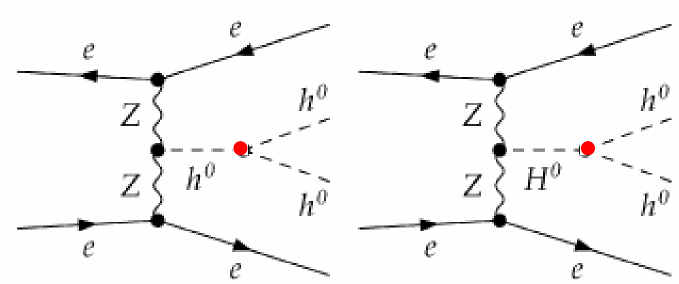
Extended strategy: $e^+e^- \to 2H + X$

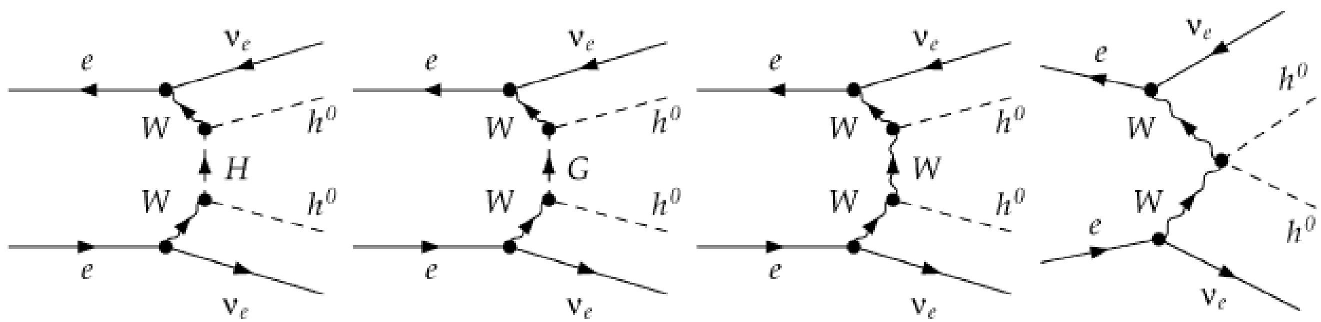
➢ Double-Higgs production through gauge boson fusion

$$e^+ e^- \to V^*V^* \to h\,h + X$$

N. Hodgkinson, D, López-Val, JS
Phys. Lett. B677 (2009) 39







+ etc.

➢ D. López-Val, JS, Phys.Rev.D81 (2010) 033003

➢ Quantum effects on $e^+e^- \to 2H$ in the 2HDM

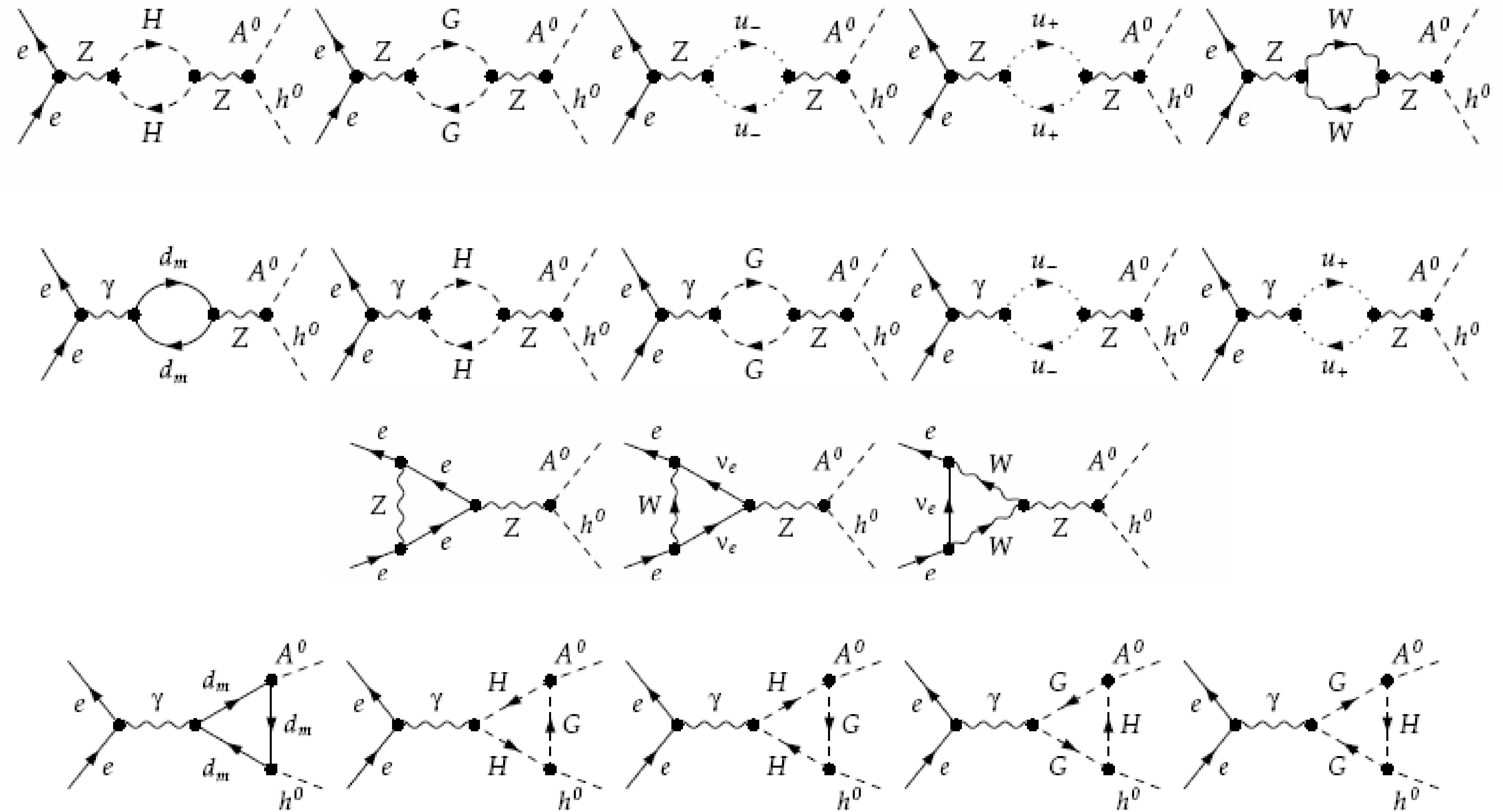
$e^+ e^- \to A^0 h^0$ (similarly with $e^+e^- \to A^0\, H^0$)

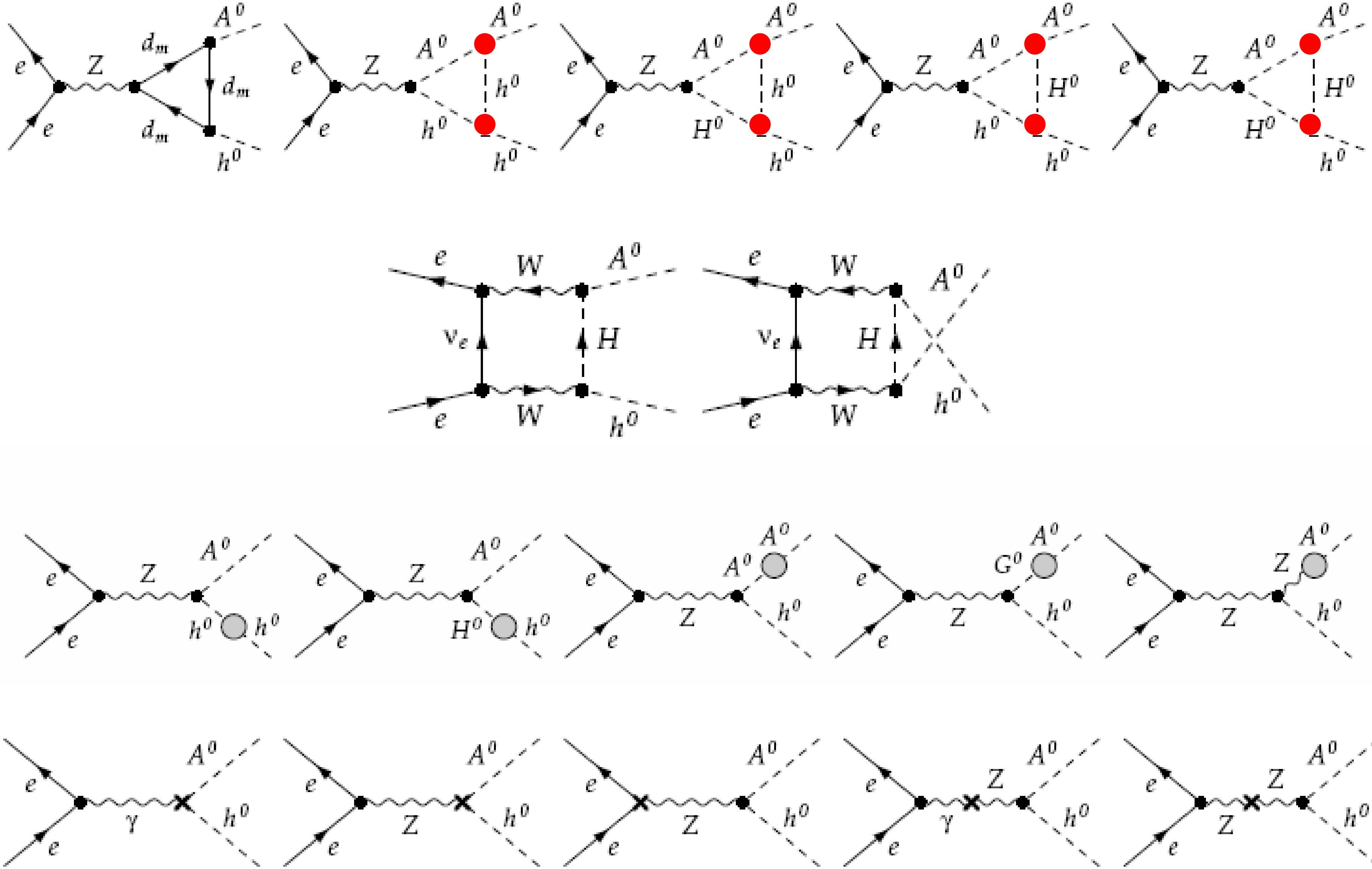
Basic one-loop amplitude:

$$
\begin{aligned}
M^1_{e^+ e^- \to A^0 h^0} \;=\; & (M^{1,Z-Z} + M^{1,\gamma-Z} \\
& + M^{1,e^+e^-Z} + M^{1,e^+e^-\gamma} \\
& + M^{1,Z^0 A^0 h^0} + M^{1,\mathrm{box}} + M^{1,\mathrm{WF}} + \delta M^1)
\end{aligned}
$$

The loop correction appears from the interference with the tree-level amplitude: $2\Re e\mathcal{M}^{(0)}\mathcal{M}^{(1)}$

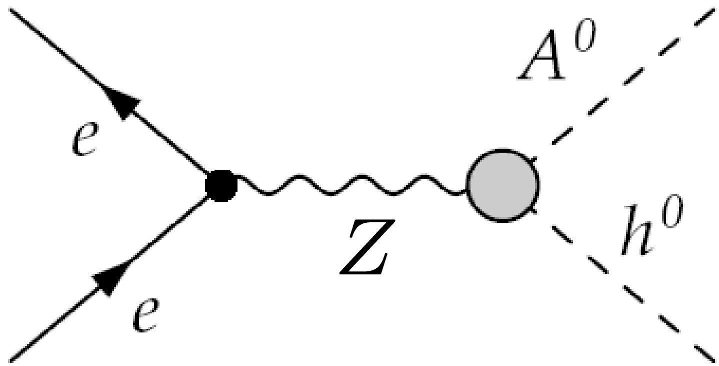
Some of the diagrams involved…





For the complete list see: D, López-Val, JS, arXiv:0908.2898 [hep-ph]

Apart from the ordinary Zee vertex counterterm, we have e.g.



$$\mathcal{L}_{A^0 h^0 Z^0} = \frac{e\,\cos(\beta-\alpha)}{2\,s_W\,c_W}\,Z^0_\mu\,A^0\,\overleftrightarrow{\partial}^\mu\,h^0$$

$$(g_i \rightarrow g_i + \delta g_i\ ,\quad \phi_i \rightarrow (1+\tfrac{1}{2}\delta Z_i)\,\phi_i)$$

♠Vertex counterterm:

$$\begin{aligned}\delta\,\mathcal{L}_{A^0\,h^0\,Z^0} \quad = \quad & \frac{e\,\cos(\beta-\alpha)}{2\,s_W\,c_W} Z^0_\mu A^0\,\overleftrightarrow{\partial^\mu}\,h^0\Big[\frac{\delta\,e}{e}+\frac{s_W^2-c_W^2}{c_W^2}\,\frac{\delta s_W}{s_W}-\\ & -\sin\beta\cos\beta\,\tan(\beta-\alpha)\,\frac{\delta\,\tan\beta}{\tan\beta}+\frac{1}{2}\,\delta\,Z_{h^0}+\frac{1}{2}\,\delta\,Z_{A^0}+\frac{1}{2}\,\delta\,Z_{Z^0}-\\ & -\frac{1}{2}\,\tan(\beta-\alpha)\,\delta Z_{H^0h^0}++\frac{1}{2}\,\tan(\beta-\alpha)\,\delta Z_{A^0\,G^0}+\frac{1}{2}\,\tan(\beta-\alpha)\,\delta Z_{A^0Z^0}\Big]\end{aligned}$$

➢ Renormalization conditions and counterterms

Renormalization of the Higgs sector OS (on-shell) scheme

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

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

$$(Z_{\Phi_i} = 1 + \delta Z_{\Phi_i})$$

♠ $\tan\beta$:

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

$$= \frac{1}{2}\left(\delta Z_{\Phi_2} - \delta Z_{\Phi_1}\right).$$

Higgs masses (OS scheme)

$$\mathrm{Re}\,\hat{\Sigma}\,(M^2_{h^0}) = 0;\ \mathrm{Re}\,\hat{\Sigma}\,(M^2_{H^0}) = 0;\ \mathrm{Re}\,\hat{\Sigma}\,(M^2_{A^0}) = 0;\ \mathrm{Re}\,\hat{\Sigma}\,(M^2_{H^\pm}) = 0$$

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

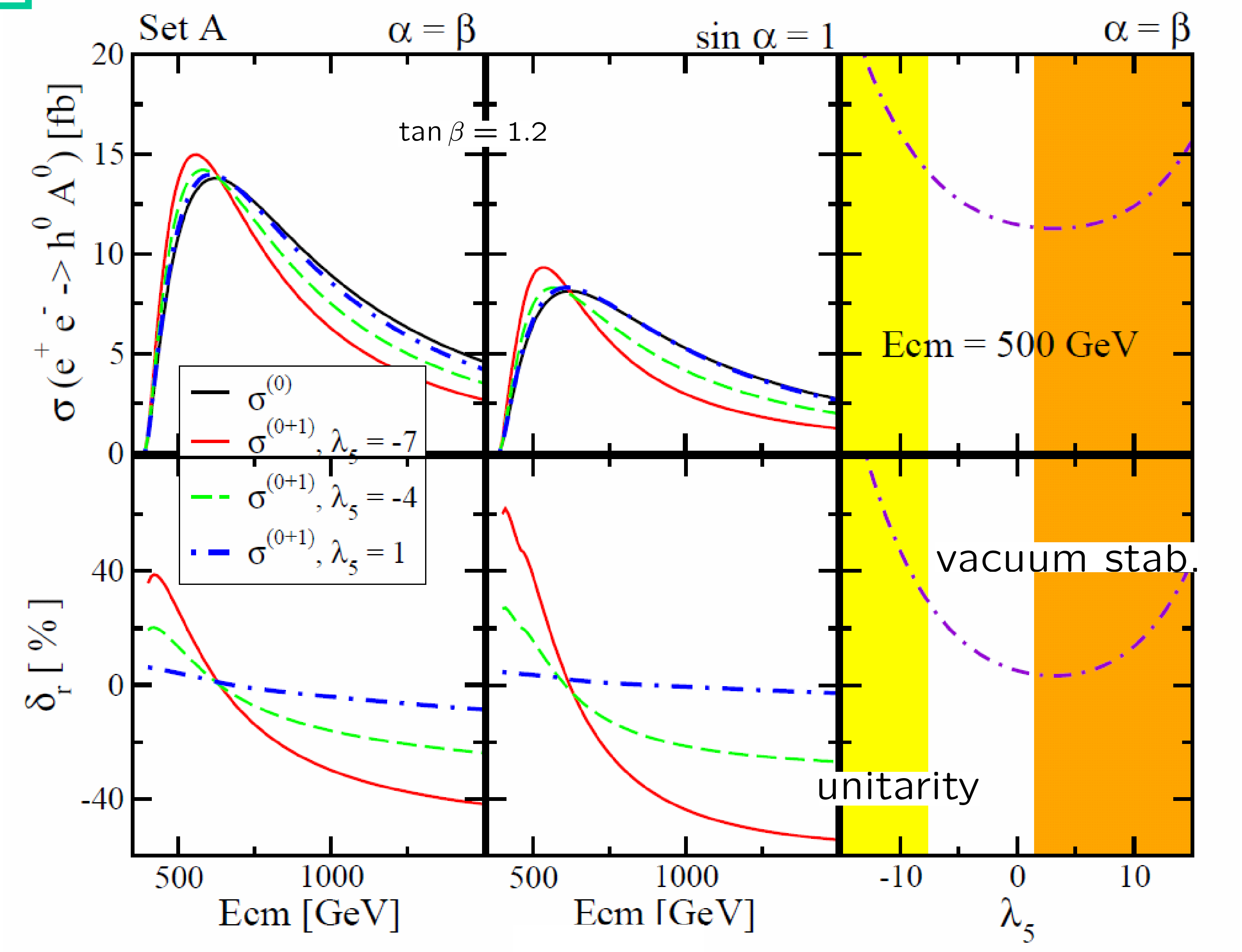
$$\delta Z_{\Phi_1} = -\mathrm{Re}\,\Sigma'_{A^0A^0}(M^2_{A^0}) - \frac{1}{M_Z\ \tan\beta}\,\mathrm{Re}\,\Sigma_{A^0\,Z^0}(M^2_{A^0})$$

$$\delta Z_{\Phi_2} = -\mathrm{Re}\,\Sigma'_{A^0A^0}(M^2_{A^0}) + \frac{\tan\beta}{M_Z}\,\mathrm{Re}\,\Sigma_{A^0\,Z^0}(M^2_{A^0})$$

$$\frac{\delta\tan\beta}{\tan\beta} = \frac{1}{M_Z\ \sin 2\beta}\Re e\Sigma_{A^0\,Z^0}(M^2_{A^0})$$

Numerical analysis

2HDM	M_{h^0} (GeV)	M_{H^0} (GeV)	M_{A^0} (GeV)	$M_{H^\pm}$(GeV)
Set A	130	200	260	300
Set B	115	165	100	105



D. López-Val, JS, arXiv:1107.1305

In our calculation we have included a fairly exhaustive collection of computational tools and phenomenological constraints by combining various packages, e.g.

FeynArts, FormCalc, LoopTools (T. Hahn et al.)

2HDMCalc (D. Eriksson et al.)

SuperISO *(F. Mahmoudi)*

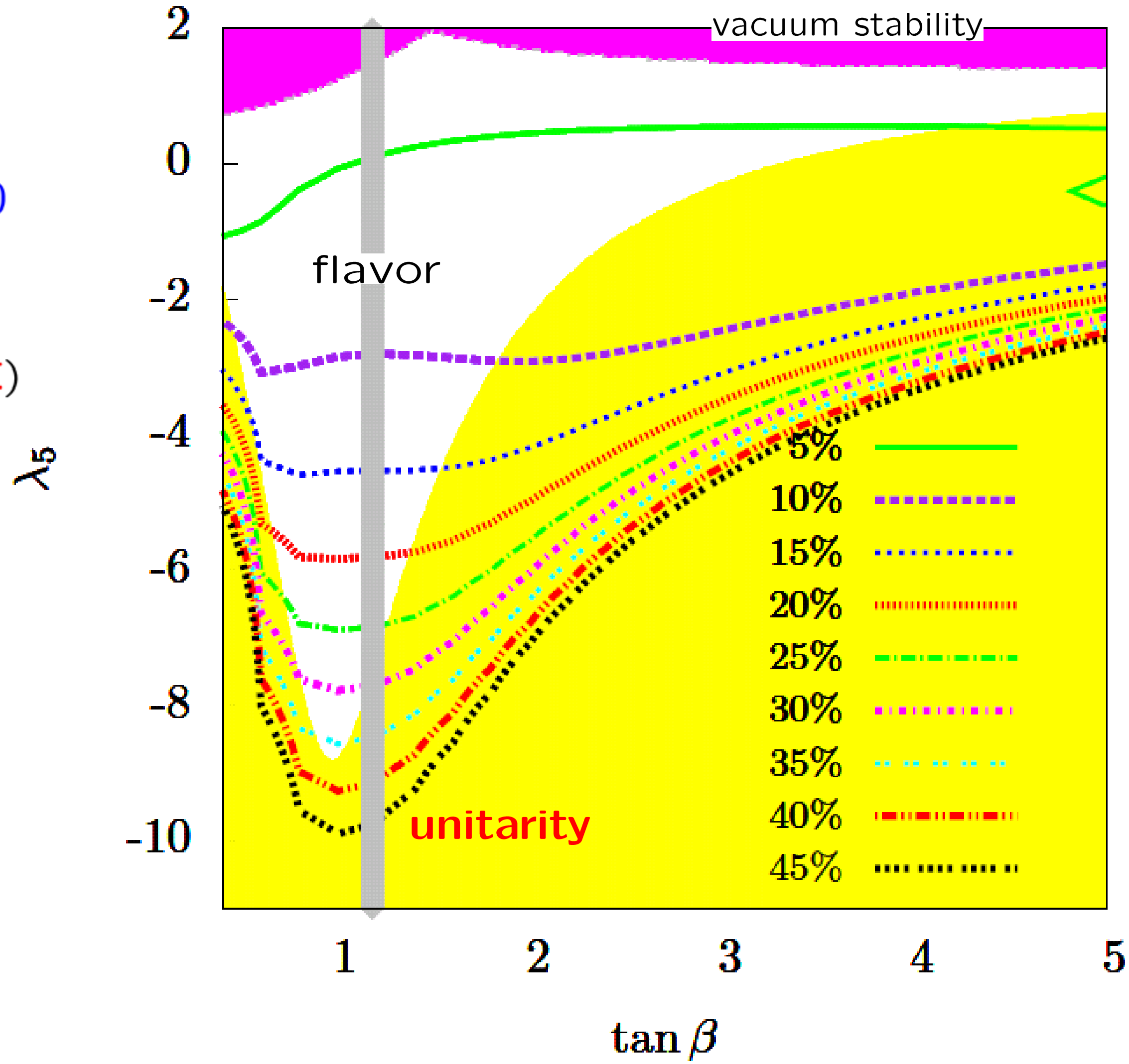
HiggsBounds (P. Bechtle et al.)

♠ Radiative corrections over the $\tan\beta - \lambda_5$ plane and its interplay with the unitarity and vacuum stability constraints.

$\sqrt{s} = 500\ \text{GeV}$

$e^+e^- \to h^0 H^0$

Set A (**Type I or II**)



D. López-Val, JS, arXiv:1107.1305

➢ N. Bernal, D. López-Val, JS, Phys.Lett..B677 (2009) 39

+ updated analysis presented here
(D. López-Val, JS)

➢ Real $\gamma\gamma$ fusion: $\gamma\gamma \to H$ in the 2HDM

D. López-Val, JS, Phys.Lett.B702 (2011) 246

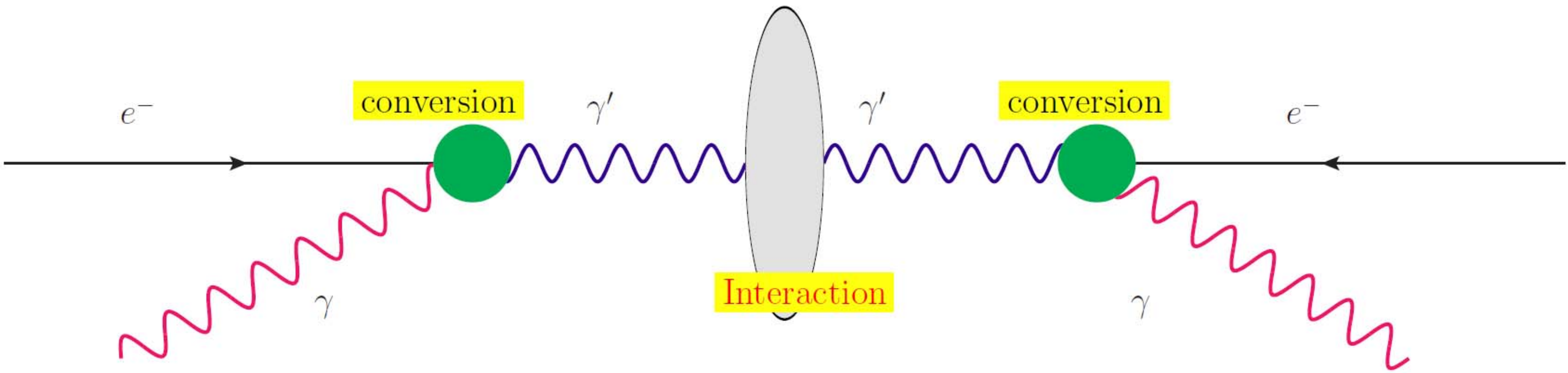
(comparison of general 2HDM **and** MSSM)

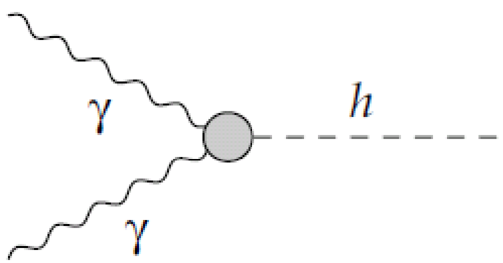
Long ago $\gamma\gamma \to H$ was considered in the MSSM by B. Grzadkowski and J.F. Gunion (1992), also by J. F. Gunion and H.E. Haber, (1993), and others.

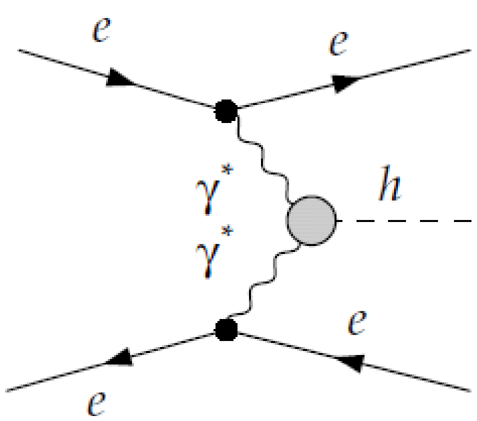
The related process $\gamma\gamma \to HH$

has been computed recently by several authors, e.g. F. Cornet and W. Hollik (2008), E. Asakawa et al. (2009), A. Arhrib et al. (2009).

➢ Compton backscattering off linac beams







➢ Gamma-Gamma fusion: $\gamma\gamma \to H$ in the 2HDM

➤ Let us recall that a photon collider is an option of a lepton collider.

It is possible to take into account the conversion $e^+e^- \to \gamma\gamma$ by the convolution

$$\sigma(e^+e^- \to \gamma\gamma \to h)(s) = \sum_{\{ij\}} \int_0^1 d\tau \, \frac{d\,\mathcal{L}_{ij}^{ee}}{d\tau} \, \hat{\sigma}_{\eta_i \eta_j}(\gamma\gamma \to h)(\tau s)$$

* $\hat{\sigma}_{\eta_i \eta_j}(\gamma\gamma \to h)$: *partonic* cross section
* τ: fraction of the energy carried by the photon
* $\mathcal{L}_{ij}^{ee}$ stands for the photon luminosity distribution

$$\frac{d\,\mathcal{L}_{ij}^{ee}}{d\tau} = \int_\tau^1 \frac{dx}{x} \frac{1}{1+\delta_{ij}} \left[f_{i/e_1}(x)\, f_{j/e_2}(\tau/x) + f_{j/e_1}(x)\, f_{i/e_2}(\tau/x)\right]$$

* f_{i/e_1} denotes the photon density functions.

➤ We use the ones provided by CompAZ   Telnov, 2006 & Żarnecki, 2003

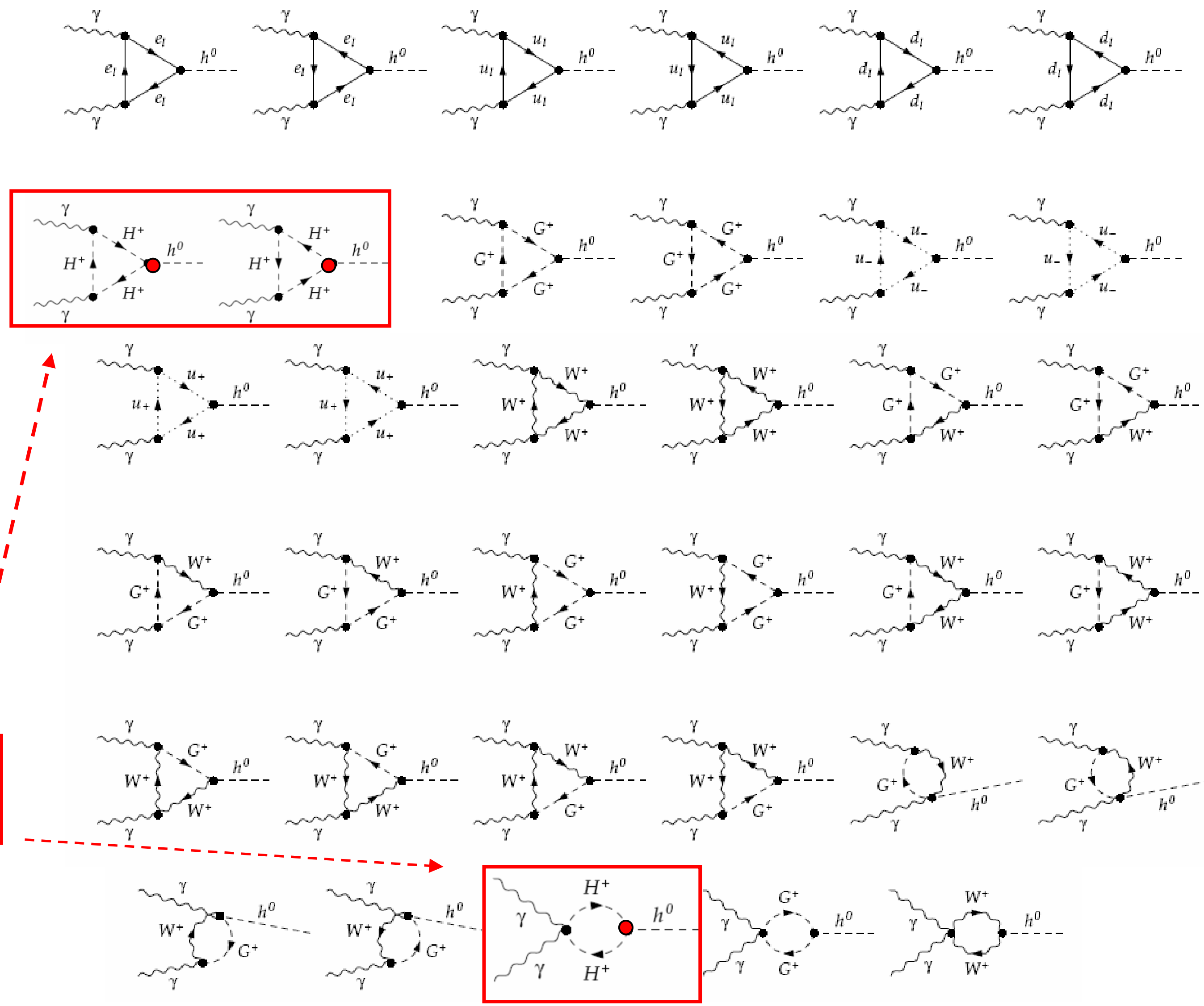
$$\sigma(\gamma\gamma \to h) = \frac{8\,\pi^2}{M_h}\,\Gamma(h \to \gamma\gamma)\,\delta(s - M_h^2)\,(1 + \eta_1\,\eta_2) = 8\pi\,\frac{\Gamma(h \to \gamma\gamma)\,\Gamma_h\,(1 + \eta_1\eta_2)}{(s - M_h^2)^2 + M_h^2\,\Gamma_h^2}$$

One-loop diagrams describing the process $\gamma\gamma \to h$, within the 2HDM

The $\gamma\gamma h^0$ interaction is generated at the quantum level

SM contributions:
* Heavy fermions t, b
* Vector bosons $W^\pm$
* Goldstone bosons $G^\pm$

+ 2HDM contributions:
* Charged Higgs $H^\pm$



Calculations performed using *FeynArts*, *FormCalc* & *LoopTools* T. Hahn

➢ Corrections to $\gamma\gamma H$ - coupling in the 2HDM

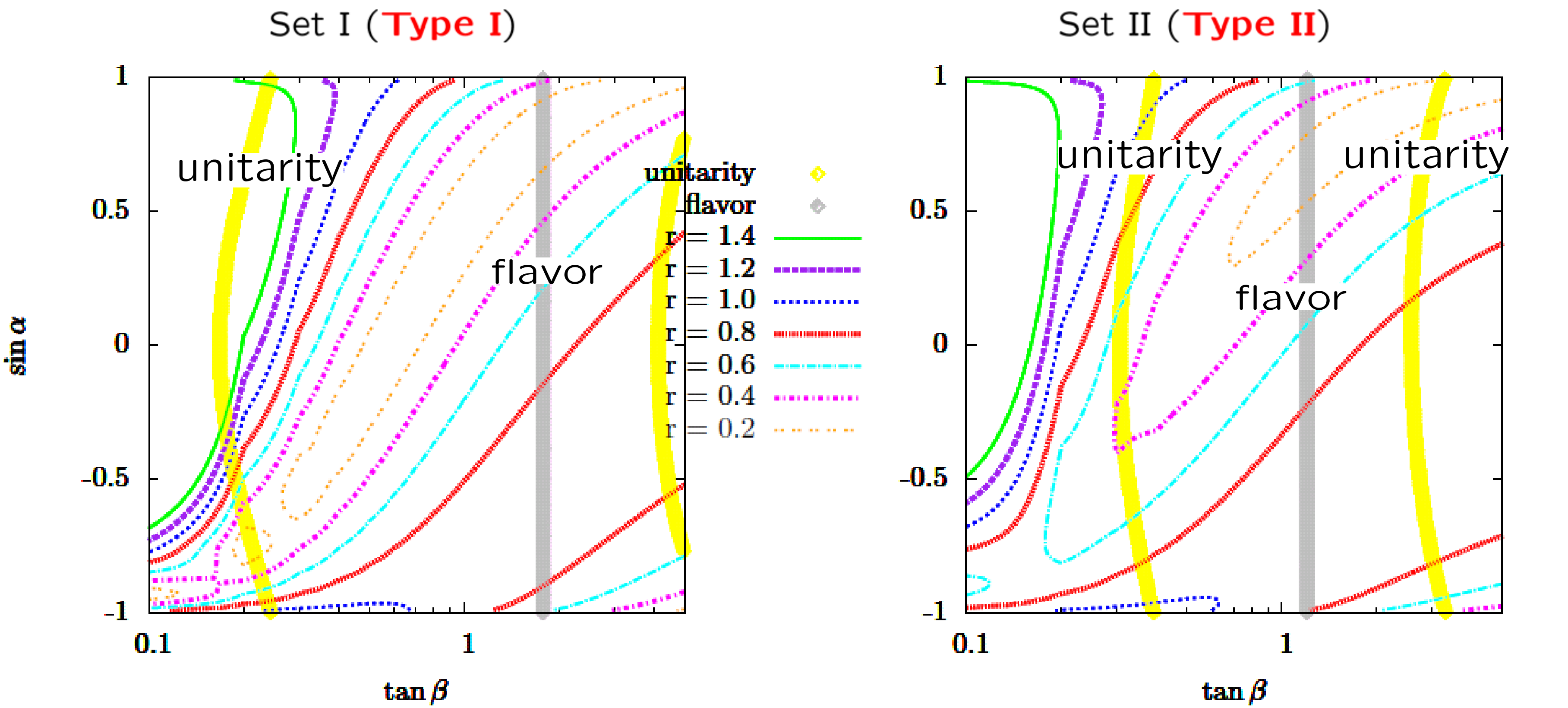
$$r \equiv \frac{g_{\gamma\gamma h}}{g_{\gamma\gamma H}} = \frac{|\mathcal{M}|^{\rm 2HDM}}{|\mathcal{M}|^{\rm SM}} = \left[\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(H\to\gamma\gamma)}\right]^{1/2}$$

2HDM	$M_{\rm h^0}$ (GeV)	$M_{\rm H^0}$ (GeV)	$M_{\rm A^0}$ (GeV)	$M_{\rm H^\pm}$(GeV)
Set I	115	165	100	105
Set II	200	250	290	300

D. López-Val, JS, arXiv:1107.1305

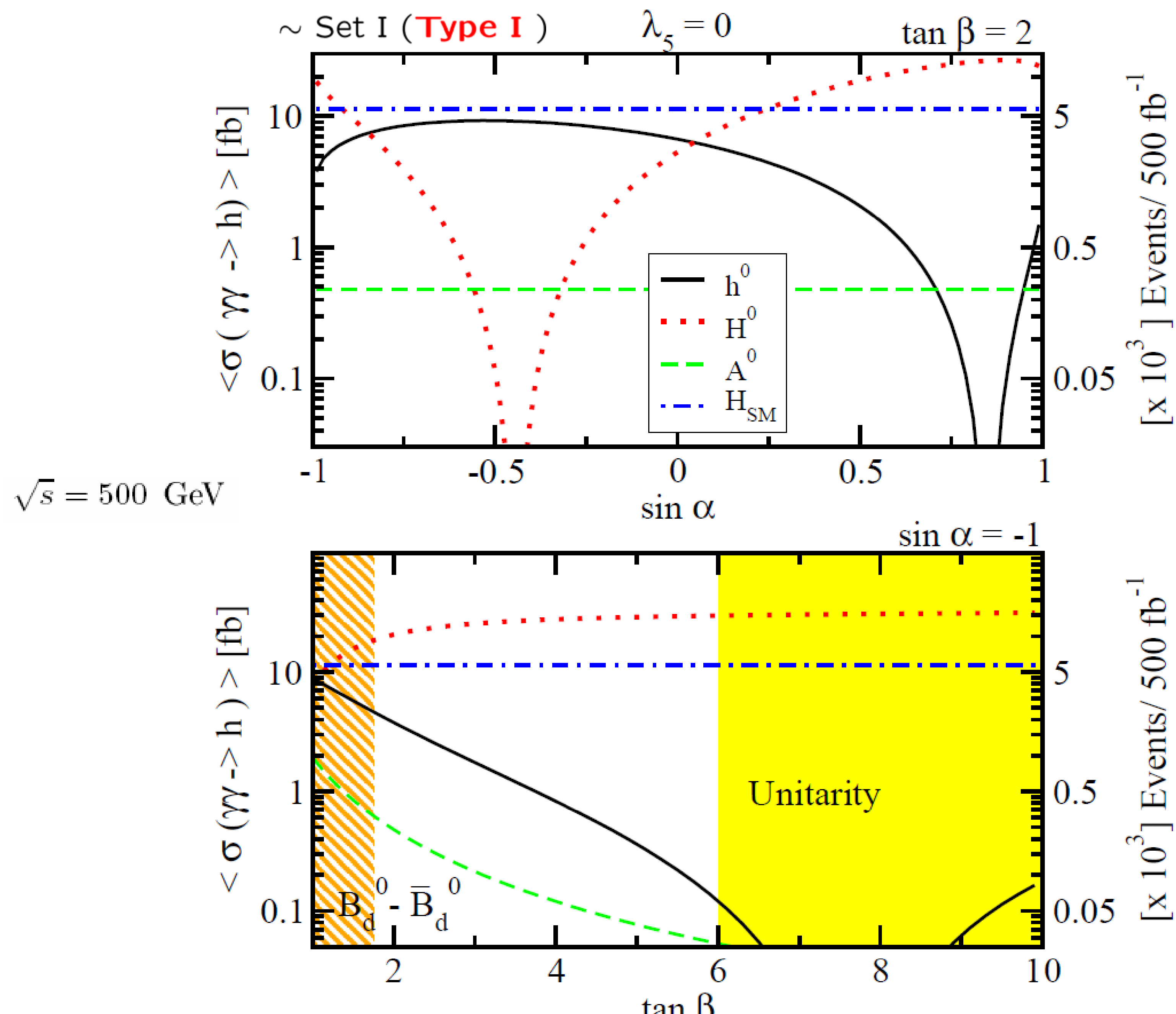
$\lambda_5 = 0$

$$r \equiv \frac{g_{\gamma\gamma h}}{g_{\gamma\gamma H}} = \frac{|\mathcal{M}|^{2HDM}}{|\mathcal{M}|^{SM}} = \left[\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(H\to\gamma\gamma)}\right]^{1/2}$$



grey band: Lower bound from $B_0 - \bar{B}_0$ ($\sim 1/\tan\beta$)

More strict unitarity bounds and limits from flavor physics $\Longrightarrow$ $r < 1$



D. López-Val, JS, arXiv:1107.1305

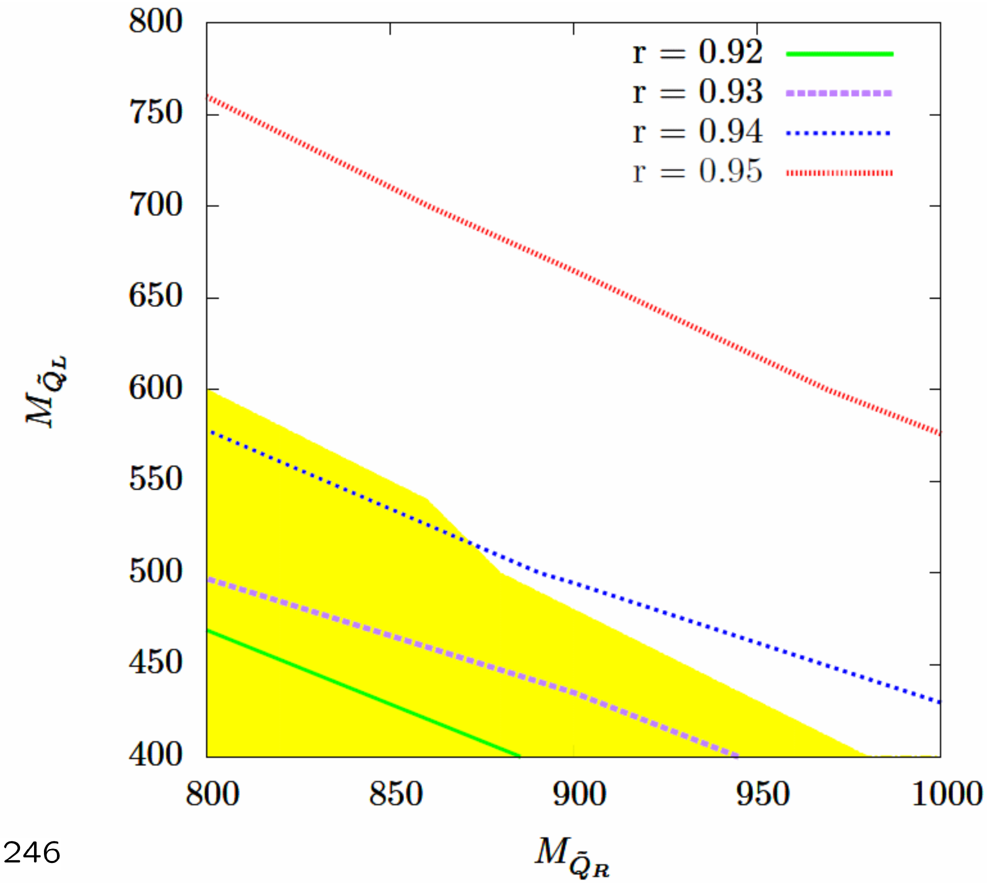
➢ Corrections to $\gamma\gamma H$ - coupling in the MSSM

$$\begin{pmatrix} M^2_{\tilde{Q}L} + m_f^2 + \cos 2\beta \,(T_3^{f_L} - Q_f \sin^2\theta_w)\, M_Z^2 & m_f\, M_{LR}^f \\ m_f\, M_{LR}^f & M^2_{\tilde{Q}R} + m_f^2 + \cos 2\beta Q_f \sin^2\theta_w M_Z^2 \end{pmatrix}$$

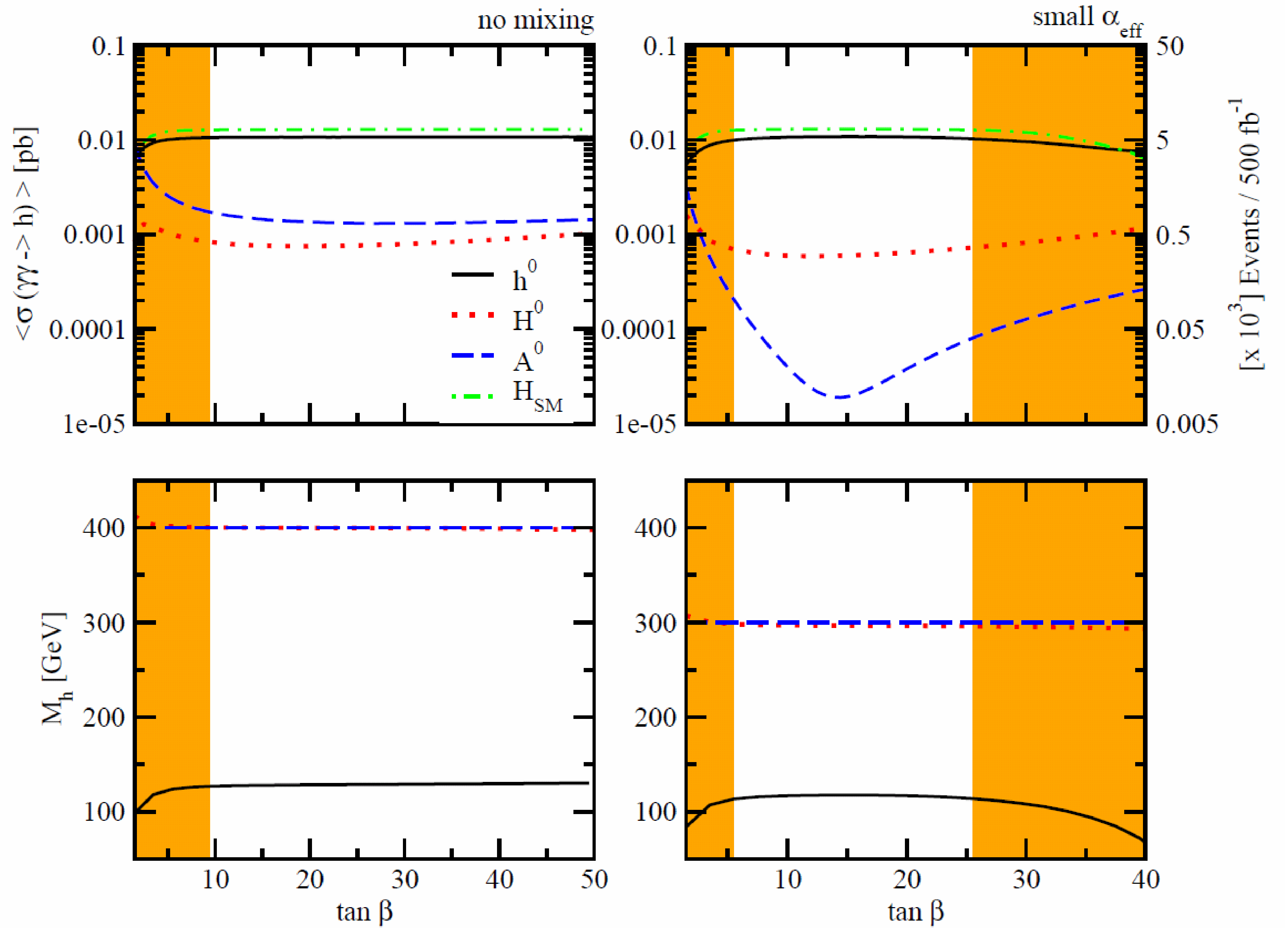
$r \lesssim 1$

Hard to distinguish

from the SM case !!

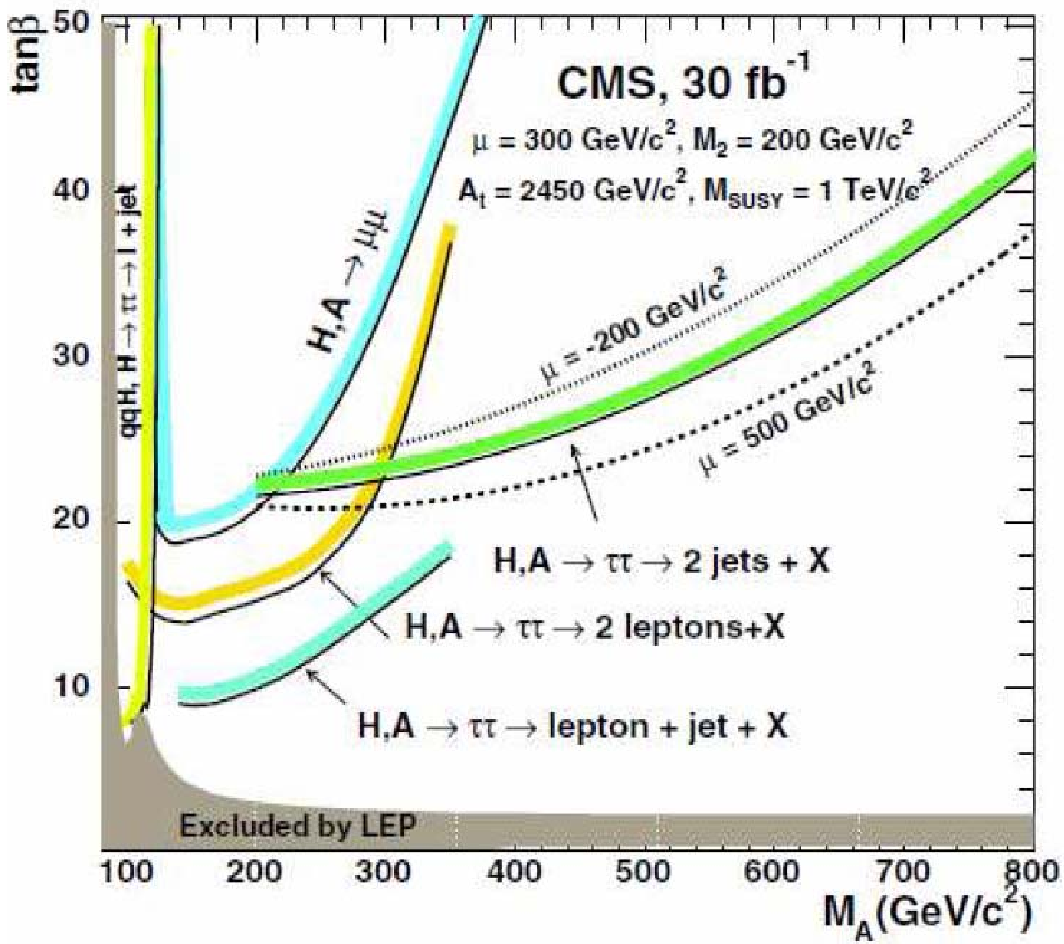


D. López-Val, JS, Phys.Lett.B702 (2011) 246



no mixing
small α_{eff}
0.1
0.01
0.001
0.0001
1e-05
<σ (γγ -> h) > [pb]
50
5
0.5
0.05
0.005
[x 10^3] Events / 500 fb^-1
h^0
H^0
A^0
H_{SM}
400
300
200
100
M_h [GeV]
10
20
30
40
50
tan β

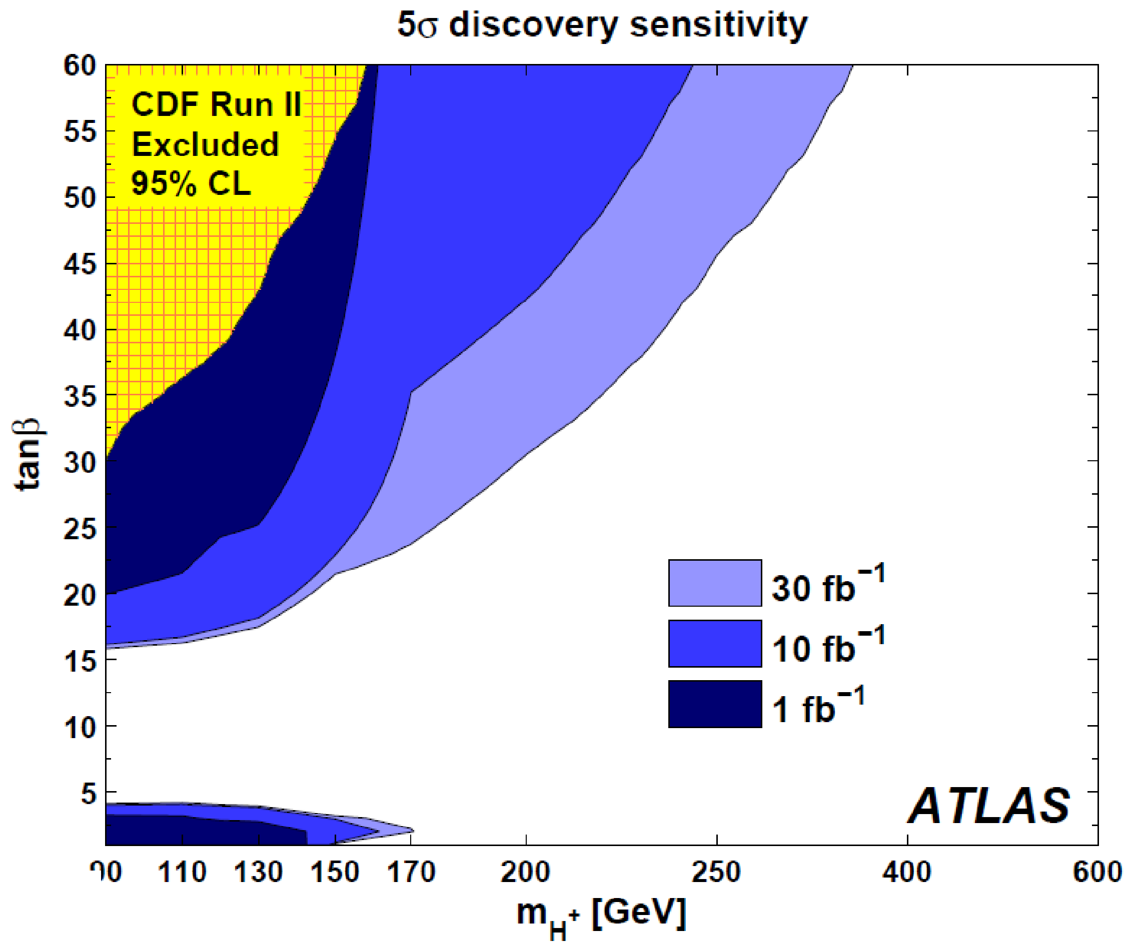
➢ The infamous "LHC wedge"



The ATLAS Collaboration:
G. Aad et al., arXiv:0901.0512

Overcoming the "LHC wedge"?

The ATLAS Collaboration:
G. Aad et al., arXiv:0901.0512



scenario	no-mixing	Small α_{eff}
M_{A^0} (GeV)	400	300
M_{SUSY} (GeV)	2000	800
μ (GeV)	200	2000
$X_t \equiv A_t - \mu/\tan\beta$ (GeV)	0	-1100
M_2 (GeV)	200	500
M_3 (GeV)	1600	500

Our points for the $\gamma\gamma \to h$ analysis are on the wedge ‼

Conclusions

- General **2HDM models** may offer a **clue** to disentangle hints of physics **beyond** the SM at the LHC and specially in the linear colliders (**ILC/CLIC**);

- Measurement of 3H and 2HX Higgs boson production should allow a first insight into the Higgs potential through a basic determination of the Higgs boson self-couplings;

- Detailed measurement of 2H and HZ processes can be crucial to **test the 2HDM** models at the **quantum level** ;

- $\gamma\gamma \to H$ (and $\gamma\gamma \to 2H$) processes could be the **cleanest** carriers of **new physics**.

$\Downarrow$

The extremely clean environment of the linear colliders should allow a comfortable tagging of these processes and might open privileged new vistas into the structure of the Higgs potential