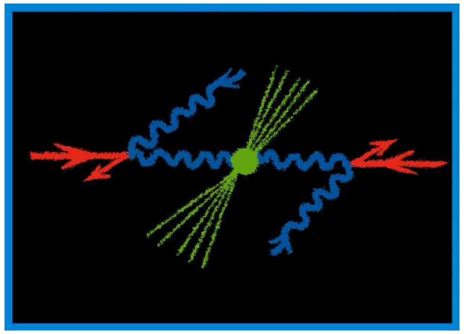


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# SM-like scenarios in 2HDM II and Photon Collider

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Based on:

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Resolving SM-like scenarios via Higgs boson production at a Photon Collider: 2HDM versus SM; Distinguishing SM-like models...

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## SM-like scenarios

Operational definition based on observation of one Higgs particle
$\rightarrow$ basic (direct) couplings to gauge boson, up- and down-quarks

SM-like version of model formulated in terms of observables (GKO'99)
There are many non-equivalent SM-like scenarios:
CP and no-CP conservation
naturally small, soft CP ($Z_2$) violation and non-decoupling effects

In 2HDM (II): pattern relation among the basic couplings may help to establish what is going on; it holds for each neutral Higgs boson

Loop coupling, like Higgs to a pair of photons, is sensitive to a particular version of the SM-like scenario

PHOTON COLLIDER as a unique machine

# Physics at a Gamma-Gamma/Electron-Gamma Collider

A Photon Collider based on laser beams back-scattered from high energy electrons allows

detailed studies of various high energy gamma-gamma and electron-gamma processes for definite polarizations

$\Longrightarrow$ It offers a unique opprtunity to study resonant production of the Higgs bosons in the process

$$\boxed{\gamma\gamma \to \mathrm{H}}$$

This process is sensitive to all charged fundamental particles of the theory!

## If LHC and $e^+e^-$ Linear Colliders will find

## **Standard-Model-like scenario**:

• One Higgs boson will be discovered with mass $M_h > 114$ GeV. Either the SM Higgs boson OR one Higgs boson: h and H ($M_h < M_H$) or $\mathrm{h}_i$ of the 2HDM or the MSSM

• The measured decay widths (or coupling constants squared) to quarks, charged leptons, EW gauge bosons and gluons in agreement with their SM values $\Gamma_i^{\mathrm{SM}}$ within the *experimental precision*

$$\left| \frac{\Gamma_i^{\mathrm{exp}}}{\Gamma_i^{\mathrm{SM}}} - 1 \right| \ll 1.$$

• No other Higgs boson will be discovered.
Either they are weakly coupled with the $Z$ boson, gluons and quarks, or they are sufficiently heavy (above O (800 GeV) to escape observation.

• All other new particles are heavier than the discovery limits of LHC and the $e^+e^-$ Linear Collider.

# Expected precision of measurements in SM-like case

Define :

$$\delta_j = \frac{\delta \Gamma_j^{\text{exp}}}{\Gamma_j^{\text{exp}}}.$$

At the TESLA $e^+e^-$ collider at $M_h \leq 140$ GeV and with integrated luminosity 500–1000 fb$^{-1}$ (Desch, Battaglia 02):

$$\begin{aligned} \delta_b &= 0.01 - 0.03 \\ \delta_t &= 0.02 - 0.06 \\ \delta_Z &= 0.01 - 0.02 \end{aligned} \tag{1}$$

At the Photon Colliders (Jikia, Söldner-Rembold, Melles et al., Nieżurawski et al, Asner at al.)

$$\delta_\gamma = 0.02 \qquad \text{for } M_h < 140 \text{ GeV}$$

# Limits on coupling constants from future data

Ratios of (in principle measurable) coupling constants of each neutral Higgs scalar $\phi$ ($h$ or $H$, $h_1, h_2, h_3$) with particle $j$ to the corresponding value for the Higgs boson in the SM,

$$\chi_j = \frac{g_j}{g_j^{\text{SM}}}\,.$$

**In the SM-like scenario, for the observed Higgs boson all $|\chi_j|$ are close to 1, i.e.,**

$$\chi_j^{\text{obs}} = \pm(1-\epsilon_j), \quad \textbf{with } |\epsilon_j| \ll 1\,.$$

**with**

$$|\epsilon_j| \leq \delta_j\,.$$

**Additional constraints to these $\epsilon_i$ follow from the considered model - 2HDM.**

# 2HDM Potential

Quartic and quadratic terms separated:

$$
\begin{aligned}
V = {} & \tfrac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \tfrac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\
& + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\
& + \tfrac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\
& + \left\{\left[\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\right](\phi_1^\dagger\phi_2) + \text{h.c.}\right\} \\
& - \left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}
\end{aligned}
$$

soft violation of $Z_2$ symmetry

No $(\phi_1, \phi_2)$ mixing if $Z_2$ symmetry satisfied:

$\phi_1 \to -\phi_1$, $\phi_2 \to \phi_2$ (or vice versa) $\Rightarrow \lambda_6 = \lambda_7 = m_{12}^2 = 0$

14 parameters: $\lambda_1, \lambda_2, \lambda_3, \lambda_4$, $\lambda_5, \lambda_6, \lambda_7$, $m_{11}^2$, $m_{22}^2$, $\mathrm{Re}\, m_{12}^2$, $\mathrm{Im}\, m_{12}^2$

Hard violation of $Z_2$ symmetry: quartic terms with $\lambda_6$, $\lambda_7$

How to get small CP and FCNC effects?

$\Rightarrow$ small $\mathrm{Re}\, m_{12}$, small $\mathrm{Im}\, m_{12} \sim \mathrm{Im}\, \lambda_5, \lambda_6, \lambda_7$ - naturalness a'la t'Hooft

## $\boxed{\text{Soft CP violation}}$

With $\lambda_6 = \lambda_7 = 0$: minimum (vacuum) at:

$$\phi_1 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{bmatrix}, \quad \phi_2 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2\, e^{i\xi} \end{bmatrix},$$

$$m_{12}^2 = [\tfrac{\mu^2}{v^2} + i\,\mathrm{Im}(\lambda_5 e^{2i\xi})] v_1 v_2 e^{-i\xi}$$
$$\mathrm{Im}(m_{12}^2 e^{i\xi}) = \mathrm{Im}(\lambda_5 e^{2i\xi}) v_1 v_2 \equiv 4\delta\, v_1 v_2$$

Naive conclusion: phase $\xi$ violates $CP$

However (eg. Branco), phase $\xi$ can be removed by suitable redefinitions of phases of Higgs fields $\phi_i$, $\lambda_5$, $m_{12}^2$ and fermion fields

With $\boxed{\delta \neq 0}$ $\Rightarrow$ CP violation
All three neutral Higgs states mix:
$h_1$, $h_2$, $h_3$

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 & \bullet \\ \mathcal{M}_{21}^2 & \mathcal{M}_{22}^2 & \bullet \\ \bullet & \bullet & \mathcal{M}_{33}^2 \end{pmatrix} \quad \bullet \Leftarrow \delta$$

## SM-like scenario from theoretical side

2HDM (II) - CP conserv.and basic couplings as in SM

For $\boxed{\delta \to 0}$ $\Rightarrow$ CP cons. w/ Higgs sector: $h$, $H$, $A$ and $H^\pm$ $(\alpha,\ \beta,\ \mu^2)$

We keep one Higgs boson, say $h$ light, other Higgs bosons have to be heavy...

How we can generate large masses? Two ways in 2HDM:

$$\boxed{\text{large } M_A^2 = \frac{1}{2}\mu^2 - \mathrm{Re}\,\lambda_5 v^2 \text{ from } \begin{cases} (i) & \text{large } \mu^2\text{, decoupling a la Haber} \\ (ii) & \text{small } \mu^2\text{, ``large'' } |\lambda_5| \end{cases} \text{ OR}}$$

Remember - naturalness (small $\mu$ or $m_{12}$) ?!

For small $\mu$ however, some $\lambda$ can be (too) large
-constraints from unitarity, perturbativity etc.
It may happend that for some cases $\mu = 0$ is not allowed.

## The simplest SM-like scenario

Consider CP cons. Model II — $d$-mass $\leftrightarrow \phi_1$, $u$-mass $\leftrightarrow \phi_2$
$\Rightarrow$ Yukawa couplings

The simplest SM-LIKE SCENARIO: light $h$ (or $H$), properties like $H_{\mathrm{SM}}$

$$g_j = g_j^{\mathrm{SM}}, \quad j = W, Z, d, u$$

Other Higgs bosons heavy, $\mathcal{O}(1\ \mathrm{TeV})$

However, loop-induced coupling like $h \to \gamma\gamma$ may differ from SM prediction

if $\mu^2 \sim M^2_{H\pm}$, no effect in $\Gamma_{\gamma\gamma}$:

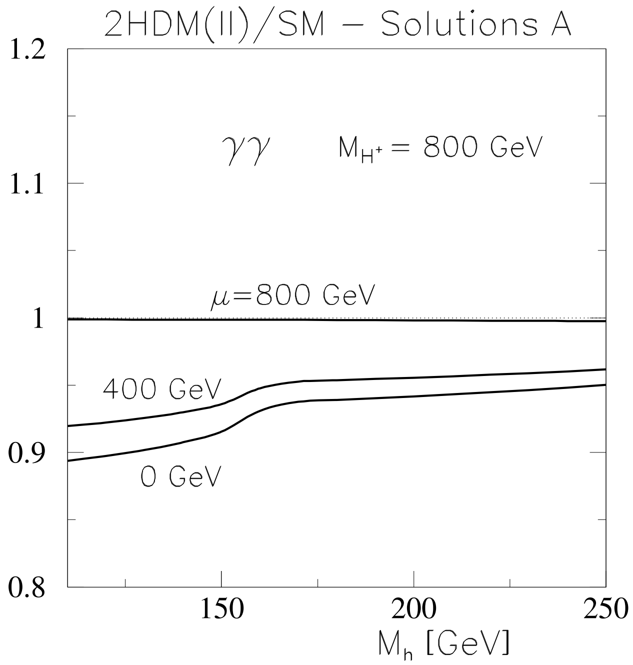
if $\mu^2 < M^2_{H\pm}$ several % difference

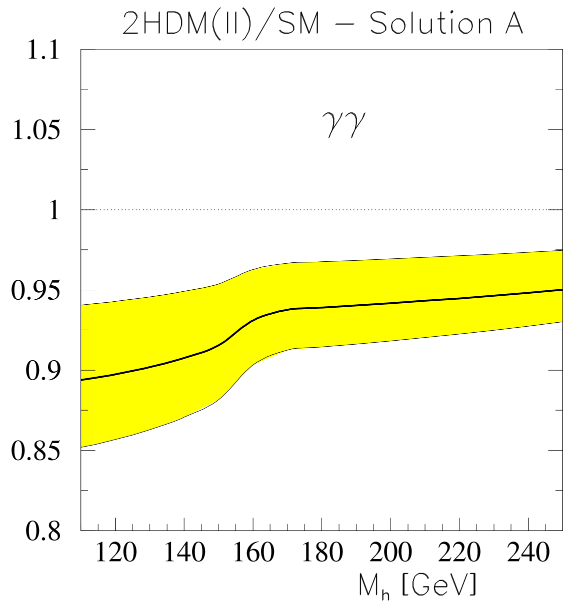
Form of the 2HDM potential e.g. (large or small $\mu$) can be tested!

Provided the accuracy of the measurement of $\Gamma_{\gamma\gamma}$ is good enough and the uncertainty of the theoretical prediction (are small.

Theoretical uncertainties include $\delta_j, \epsilon_j$ ...

## Higgs to $\gamma\gamma$ for $\delta_j = 0$ (ideal case)




on the right: old results for $\mu = 0$ from '99 (based on old estimations of $\delta_j$) - with the new estimations $\rightarrow$ bands twice smaller.

# PATTERN RELATION

We found that for CP violation and CP conservation for each neutral Higgs boson:

$$(\chi_u - \chi_V)(\chi_V - \chi_d) + \chi_V^2 = 1$$

or

$$(\chi_u + \chi_d)\chi_V = 1 + \chi_u \chi_d.$$

Also,

$$\tan^2\beta = \frac{\chi_V - \chi_d}{\chi_u - \chi_V} = \frac{1 - \chi_d^2}{\chi_u^2 - 1}$$

The pattern relation was obtained here in the tree approximation. Radiative corrections will modify it at the level of *few percents*.

# Allowed ranges for couplings in SM-like scenario

## Solutions A

The solutions near the SM point for all basic coupling constants, i.e.,

$$\chi_V = 1 - \epsilon_V, \quad \chi_d = 1 - \epsilon_d, \quad \chi_u = 1 - \epsilon_u, \qquad (A_{h+})$$
$$\chi_V = -1 + \epsilon_V, \quad \chi_d = -1 + \epsilon_d, \quad \chi_u = -1 + \epsilon_u. \qquad (A_{h-})\,.$$

Using the pattern relation and neglecting small terms of higher order in $\epsilon_i$,

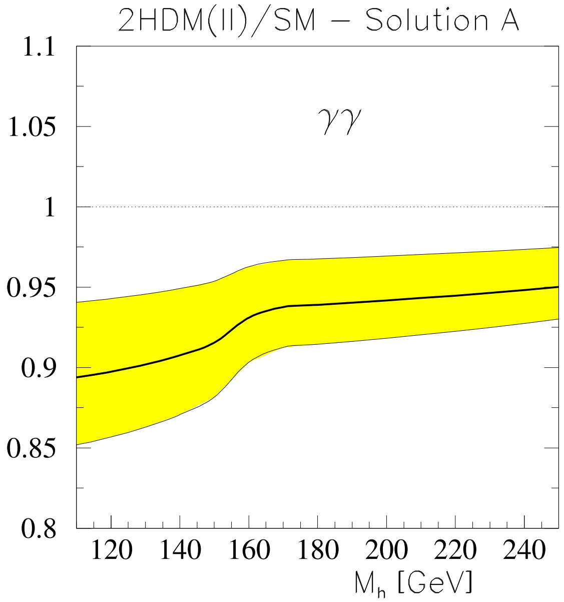
$$\tan\beta = \frac{|\epsilon_d|}{\sqrt{2\epsilon_V}} = \sqrt{\left|\frac{\epsilon_d}{\epsilon_u}\right|}$$

$$\epsilon_u = -\frac{2\epsilon_V}{\epsilon_d} \Rightarrow \epsilon_V = -\frac{\epsilon_u \epsilon_d}{2} < \frac{\delta_u \delta_d}{2}$$

Here $\epsilon_V > 0$, and the signs of $\epsilon_u$ and $\epsilon_d$ are opposite.

$\epsilon_V$ equal to the product of two other $\epsilon$'s, it should be extremely small,

# Results for Solutions A




Results are shown for $\mu = 0$ and $M_{H^\pm} = 800$ GeV. The regions above and below the thick curves correspond to 1 sigma error in couplings.

# Summary

To distinguish models in the considered SM-like scenario, we calculate loop-induced couplings of the Higgs boson with photons for solutions $A$. We study the ratios of widths $\chi^2_{\gamma\gamma}$ obtained in the 2HDM (II) and the SM. In the 2HDM (II) the couplings with photons, contributions from fermions, the charged gauge boson $W^{\pm}$, like in the SM, and in addition, from the charged Higgs, $H^{\pm}$.

In calculation

we use the ranges of the coupling constants allowed by the expected experimental inaccuracies (in numerical calculation we use $\delta_d = \delta_b$,$\delta_u = \delta_t$, and $\delta_V = \delta_Z$)

and

the constraints of the pattern relation.

The contributions of $W$ and $t$-quark loops are of opposite sign, i.e., they partially compensate each other, thus, the effect of scalar loops is enhanced here.

The coupling $\chi_{H^{\pm}}$ depends on $\mu$, the larger effect, i.e. deviation from SM prediction, is obtained for $\mu = 0$ (non-decoupling), for large $\mu$ the deviation disappears.

# SUMMARY

SM-like scenario can be realized at the LHC and $e^+e^-$ Linear Colliders. An anticipated uncertainties in future measurements of the basic couplings of the Higgs boson (in SM case) are known.

Goal: to establish how one can discriminate models, the SM and the 2HDM (II), for a Higgs boson with mass 120–250 GeV.

Method : as basic quantities we use observables: ratios of measurable couplings of the Higgs boson with quarks and electroweak gauge bosons to their SM values. We obtain a useful pattern relation among them. To establish deviation from SM we study the $\gamma\gamma$ and also $Z\gamma$ (also $gluon - gluon$) partial widths.

Conclusion: with anticipated high accuracy of measuring $\gamma\gamma$ width at a Photon Collider, this measurement could in general resolve the 2HDM (II) and the SM.