LCWS2012

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Testing 125 GeV Higgs's from 2HDM at PLC

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Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

SU(2) x U(1) → ?

T.D. Lee 1973

Two Higgs Doublet Models

Two doublets of SU(2) (Y=1, ρ =1) - Φ_1 , Φ_2

Masses for $W^{+/-}$, Z , no mass for photon?

Fermion masses via Yukawa interaction –

various models: Model I, II, III, IV,X,Y,...

5 scalars: H+ and H- and neutrals:

- CP conservation: CP-even h, H & CP-odd A
- CP violation: h_1,h_2,h_3 with undefinite CP parity*

Sum rules (relative couplings to SM χ)

SM-like scenarios

- In many models possible SM-like scenarios

Our definition of SM-like scenario:

Higgs h with mass ~ 125 GeV, SM tree-level couplings*

(* up to sign)

No other new particles seen …

(too heavy or too weakly interacting)

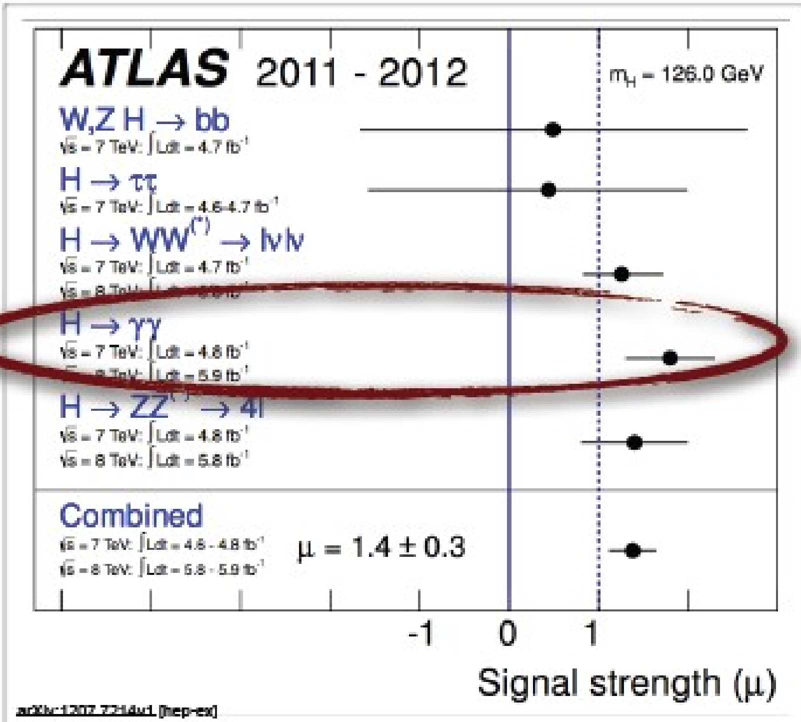
Note: Loops ggh, $\gamma\gamma$h, γZh may differ from the SM case

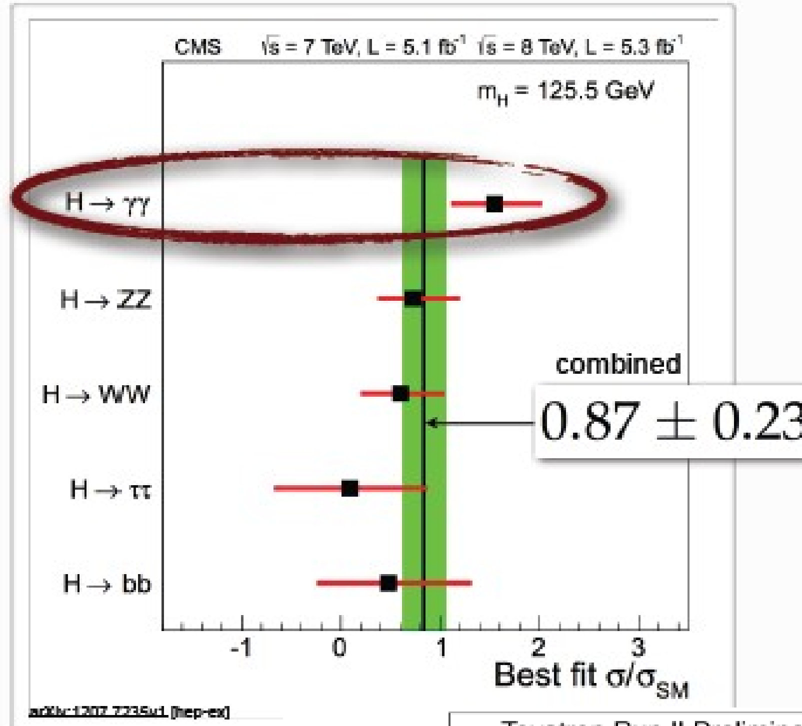
- In models with two SU(2) doublets:

  - MSSM with decoupling of heavy Higgses
  - 2HDM (Mixed), where *both h or H can be SM-like*
  - Dark 2HDM (Intert Doublet Model)

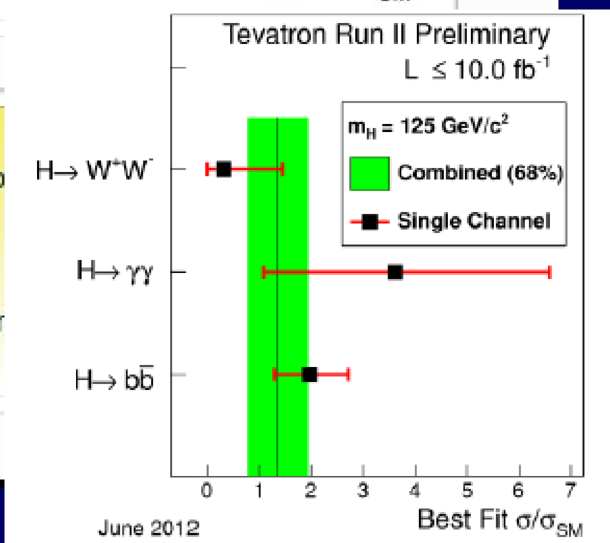
this talk

Higgs-like boson (summer 2012)





- overall, consistency with SM
- however, most striking/interesting: **high γγ rate**, in both exps and b
  - ATLAS: 1.8 ± 0.5
  - CMS: 1.6 ± 0.4
- further data highly awaited, also to see development on the fermior
- interpretation in terms of couplings: see talk by Ch. Grojean



2HDM- great laboratory of BSM

In this talk I will consider

- Mixed Model with a scalar sector as in MSSM

→ the 125 GeV Higgs boson h or H

- Inert Doublet Model (IDM) which contains DM, has one SM-type Higgs boson → the 125 GeV Higgs boson h

Will not discuss temp. evolution of the inert vacuum and sequences of different vacua in the past (one, two and three phase transitions) - with leading T^2 corrections *PRD 82(2010) Ginzburg, Kanishev,MK, Sokołowska*

- beyond T^2 corrections (to find strong enough first-order phase transition needed for baryogenesis) *(G. Gil Thesis'2011, G.Gil, P. Chankowski, MK 1207.0084 [hep-ph])*

2HDM Lagrangian $L = L_{SM} + L_H + L_Y$

Potential (Lee'73)

with $L_H = T - V$

$$V = \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}\,[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c]$$

$$+ [(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2) + h.c]$$

$$- \tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1) - \tfrac{1}{2}m^2_{22}(\Phi_2^\dagger\Phi_2) - \tfrac{1}{2}[m^2_{12}(\Phi_1^\dagger\Phi_2) + h.c.]$$

Z_2 symmetry transformation: $\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$

(or vice versa)

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12} = \mu^2$)

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12} = 0$

Consider explicit Z_2 symmetry

Z_2 symmetry of V under transformation:

$$\Phi_1 \to \Phi_1 \qquad \Phi_2 \to -\Phi_2$$

I will call it the D-symmetry,

and denote Φ_1 as Φ_S and $\Phi_2 \to \Phi_D$

Models of Yukawa inter.

with D symmetry to avoid FCNC

<u>Model I</u> - only one doublet interacts with fermions

(SM → SM)

<u>Model II</u> – one doublet with down-type fermions d , l

other with up-type fermions u

(SM' → SM', $p_R \to -p_R$)

Possible extrema (vacuum) states

The most general state **for V with Z_2 (D)**

$$\langle \phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ v_D \end{pmatrix}$$

v_S, v_D, u - real

v_S, $u \geq 0$

$v^2 = v_S^2 + v_D^2 + u^2 = (246\ \text{GeV})^2$

EWs $\quad u = 0 \quad v_D = v_S = 0$

Inert $\quad u = 0 \quad v_D = 0$

Inert-like $\quad u = 0 \quad v_S = 0$

Mixed (Normal, MSSM like) $\quad u = 0 \quad v_D \neq v_S \neq 0$

Charge Breaking $\quad u \neq 0 \quad v_D = 0$

Mixed and Inert vacuum in agreement with present data – very different phenomenology

For both the same unitarity constraints on λ's hold:

$$
\begin{aligned}
0 \leqslant \lambda_1 &\leqslant 8.38,\\
0 \leqslant \lambda_2 &\leqslant 8.38,\\
-6.05 \leqslant \lambda_3 &\leqslant 16.44,\\
-15.98 \leqslant \lambda_4 &\leqslant 5.93,\\
-8.34 \leqslant \lambda_5 &\leqslant 0.
\end{aligned}
$$

B. Gorczyca, MSc Thesis, July 2011

Couplings for dark particles in IDM →

$\lambda_{345}=\lambda_3+\lambda_4+\lambda_5$

$\lambda_{45}=\lambda_4+\lambda_5$

$$
\begin{aligned}
-8.10 \leqslant \lambda_{345} &\leqslant 12.38,\\
-7.76 \leqslant \lambda_{345}^{-} &\leqslant 16.45,\\
-8.28 \leqslant \tfrac{1}{2}\lambda_{45} &\leqslant 0,\\
-7.97 \leqslant \tfrac{1}{2}\lambda_{45}^{-} &\leqslant 6.08,
\end{aligned}
$$

Mixed Model

(Mixed vacuum, Model II Yukawa)

Masses of Higgs bosons h,H,A,H+/-

$$M_{H\pm}^2 = -\frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

$$M_A^2 = -\lambda_5 v^2,$$

$$M_H^2 = \frac{1}{2}\left(\lambda_1 v_S^2 + \lambda_2 v_D^2 + \sqrt{(\lambda_1 v_S^2 - \lambda_2 v_D^2)^2 + 4\lambda_{345}^2 v_S^2 v_D^2}\right),$$

$$M_h^2 = \frac{1}{2}\left(\lambda_1 v_S^2 + \lambda_2 v_D^2 - \sqrt{(\lambda_1 v_S^2 - \lambda_2 v_D^2)^2 + 4\lambda_{345}^2 v_S^2 v_D^2}\right).$$

Relative couplings wrs SM (tan β = v_D/v_S)

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
HW^+W^-	hW^+W^-
HZZ	hZZ

hbb, htt

$$= \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,$$

$$\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,.$$

Mixed Model

B. Gorczyca, MSc Thesis, July 2011

Upper limits on masses from unitarity constraints

$$M_{H^\pm} \leqslant 690\,\mathrm{GeV},$$
$$M_A \leqslant 711\,\mathrm{GeV},$$
$$M_H \leqslant 688\,\mathrm{GeV},$$
$$M_h \leqslant 499\,\mathrm{GeV}.$$

SM-like Mixed Model

Akeroyd, A. Arhrib, E. Naimi,

$g(hVV)=g(H_{SM}\,VV)$

$V=W,Z$

$M_h = 125$ GeV

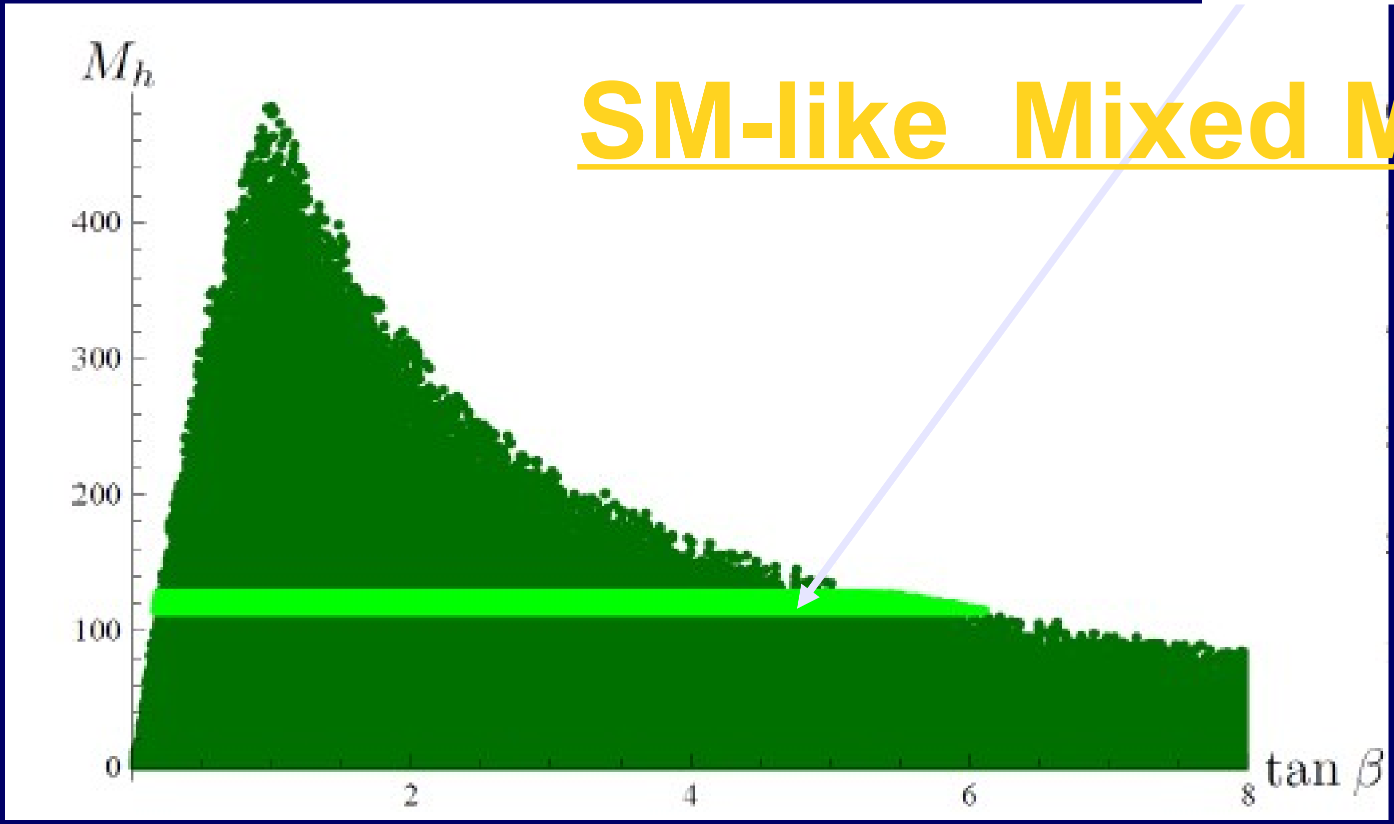
$$M_{H^\pm} \leqslant 616\,\mathrm{GeV},$$
$$M_A \leqslant 711\,\mathrm{GeV},$$
$$M_H \leqslant 609\,\mathrm{GeV},$$

Limit on tan beta from the M_h value !

M_h vs tan β

For h mass =125 GeV

$0.18 \lesssim \tan\beta \lesssim 5.59$



SM-like Mixed Model

B.Gorczyca, MK

1112.5086v2 [hep-ph]

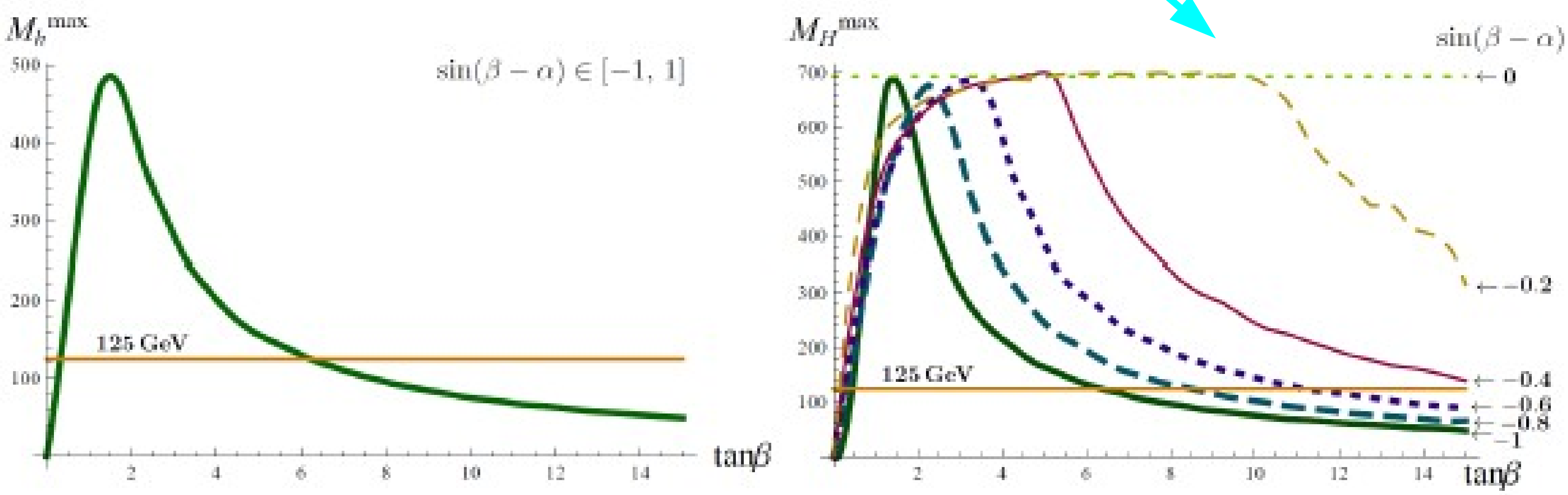
tan β

constrained by mass not Yukawa!

If H is SM-like

[B. Świeżewska, arXiv:1209.5725 [hep-ph]]

Maximal values of masses: M_h (left) and M_H (right) versus $\tan\beta$ allowed in the Mixed Model.



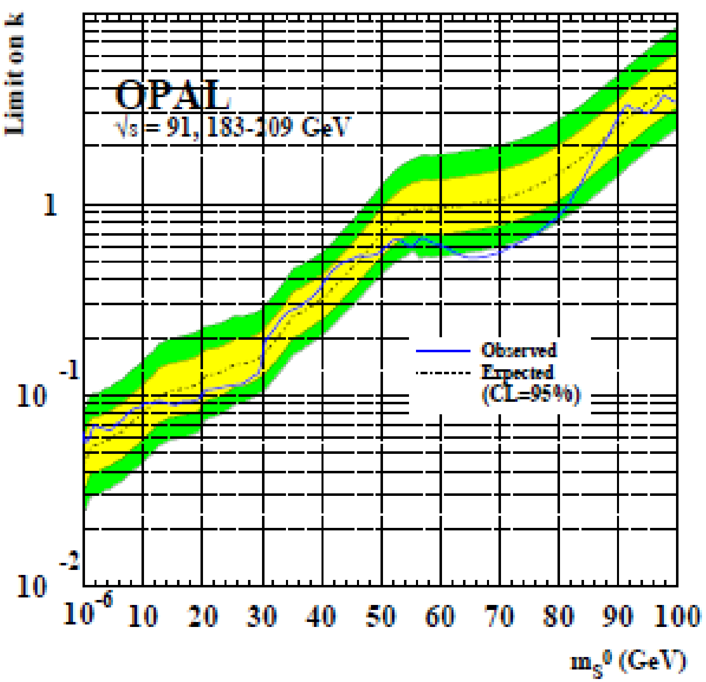
- Lower bound on $M_h \Rightarrow$ constraints on $\tan\beta$
- Correlation between M_H^{max} and $\tan\beta$ depends on $\sin(\beta-\alpha)$.

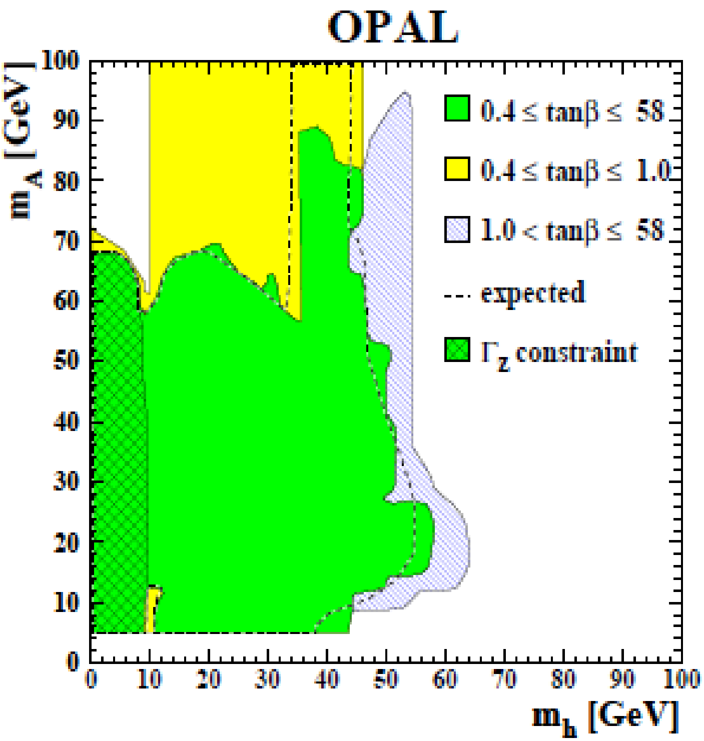
LEP data for Mixed Model

if H is SM-like then h must be lighter with the suppressed coupling to gauge boson

Light h OR light A in agreement with current data

hZZ: $sin(\beta-\alpha)$ and hAZ: $cos(\beta-\alpha)$



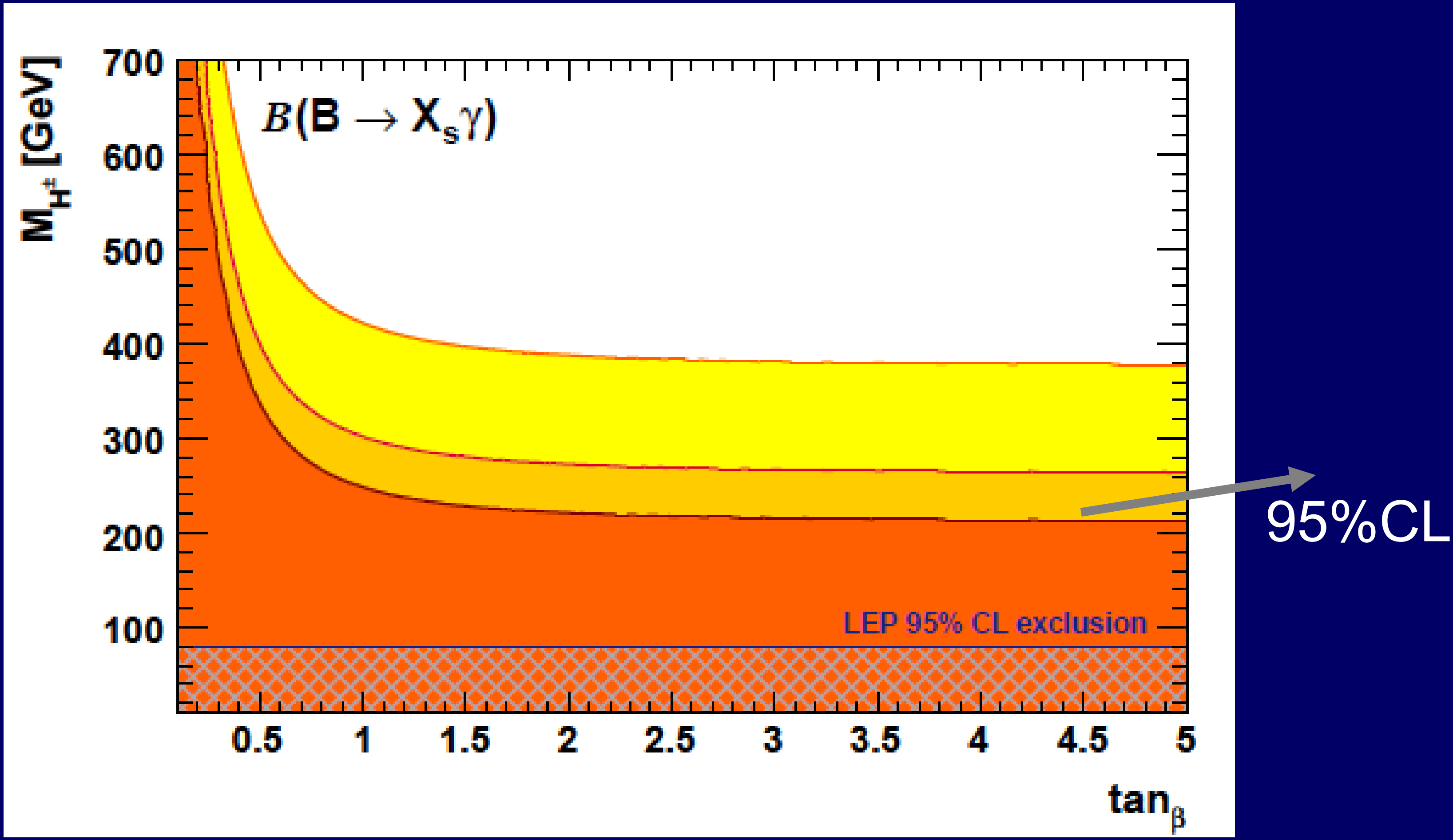


Light scalar h → small $k = sin^2(\beta-\alpha)$! **H is SM-like then !**

$B \to X_s$ gamma decay

M_{H+} vs tan β

Mixed Model



New 2012: M_{H+}> 380 GeV
Misiak

Gfitter 0811.0009[hep-ph]

Loop couplings hgg, h γ γ (hZγ)

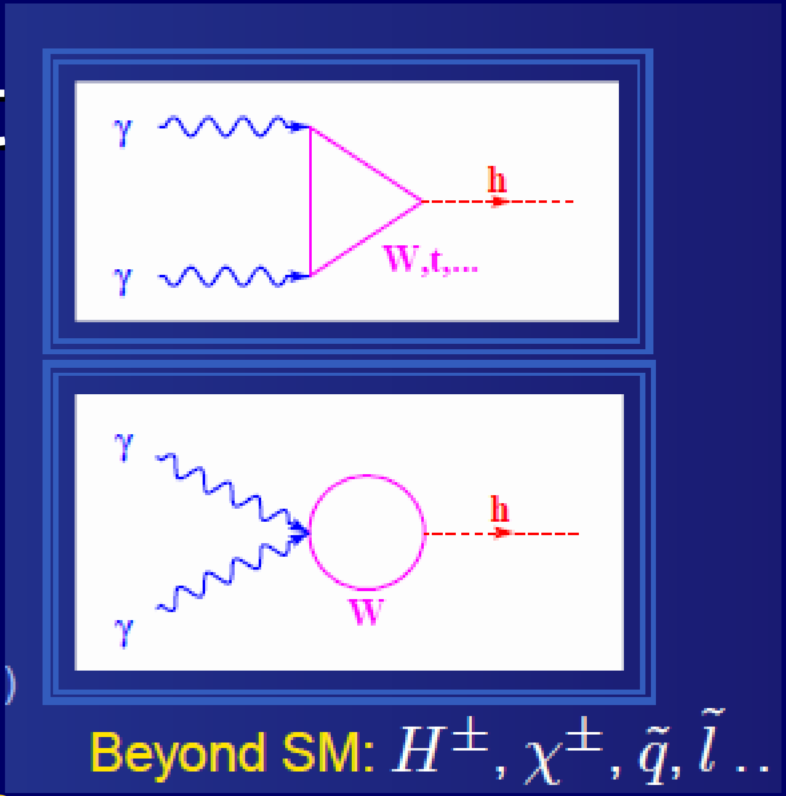
For hgg

- b and t important

For h γ γ

- t (b), W, H+

(in 2HDMs)



To be tested at PLC

W and t destructive interference in SM, so...

LC-TH-2001-026

Identifying an SM-like Higgs particle at future colliders

LC-TH-2003-089

I. F. GINZBURG[1], M. KRAWCZYK [2] AND P. OSLAND[3]

SM-like scenario. One of the great challenges at future colliders will be the SM-like scenario that no new particle will be discovered at the Tevatron, the LHC and electron-positron Linear Collider (LC) except the Higgs boson with partial decay widths, for the basic channels to fundamental fermions (up- and down-type) and vector bosons W/Z, as in the SM:

$$\left|\frac{\Gamma_i^{\rm exp}}{\Gamma_i^{\rm SM}} - 1\right| \lesssim \delta_i \ll 1. \quad \text{where } i = u, d, V. \qquad (1)$$

Then for the relative couplings of neutral Higgs (vrs SM)

$$\chi_i^{\rm obs} = \pm(1-\epsilon_i), \quad \text{with } |\epsilon_i| \ll 1.$$

$$|\epsilon_i| \le \delta_i.$$

Using pattern relation for 2HDM (II)

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

Both h and H maybe SM-like

Two solutions of pattern relation:

A – all couplings close to 1

B – one Yukawa coupling close to -1

Loop induced couplings gg, $\gamma\gamma$, $Z\gamma$ different for A and B

MH+=600 GeV

For h or H with mass 120 GeV

solution	basic couplings	$\lvert\chi_{gg}\rvert^2$	$\lvert\chi_{\gamma\gamma}\rvert^2$	$\lvert\chi_{Z\gamma}\rvert^2$
$A_{h\pm}/A_{H-}$	$\chi_V \approx \chi_d \approx \chi_u \approx \pm 1$	1.00	0.90	0.96
$B_{h\pm d}/B_{H-d}$	$\chi_V \approx -\chi_d \approx \chi_u \approx \pm 1$	1.28	0.87	0.96
$B_{h\pm u}$	$\chi_V \approx \chi_d \approx -\chi_u \approx \pm 1$	1.28	2.28	1.21

„wrong" sign of coupling to top →
large enhancement of h/H coupling to gg, $\gamma\gamma$, $Z\gamma$!

Even at the Tevatron the solution B_{h+u} can easily be distinguished via a study of the process $gg \to \phi \to \gamma\gamma$ with rate about three times higher than that in the SM (the product

Inert Doublet Model

Ma'78
Barbieri'06

Symmetry under Z_2 transf. $\Phi_S \to \Phi_S \quad \Phi_D \to - \Phi_D$

both in L (V and Yukawa interaction = Model I only Φ_S)

and in the vacuum:

$<\Phi_S> = v \qquad <\Phi_D> = 0$ Inert vacuum I_1

Today?

Φ_S as in SM (BEH), with Higgs boson h (SM-like)

Φ_D has <u>no vev</u>, with 4 scalars (no Higgs bosons!) no interaction with fermions (inert doublet)

Here Z_2 symmetry exact $\to Z_2$ parity, only Φ_D has odd Z_2-parity

$\to$ The lightest scalar stable -a dark matter candidate (Φ_D dark doublet with dark scalars) .

$\Phi_1 \to \Phi_S$ Higgs doublet S $\qquad \Phi_2 \to \Phi_D$ Dark doublet D

Constraining Inert Doublet Model

- Positivity, extrema, vacua, pert. unitarity, S, T
- By considering properties of *(Ma'2006,..B. Świeżewska, Thesis2011, 1112.4356, 1112.5086[hep-ph])*

- the SM-like h, $M^2_h = m_{11}{}^2 = \lambda_1 v^2$

- the dark scalars D always in pairs!

$$M^2_{H+} = -\frac{m^2_{22}}{2} + \frac{\lambda_3}{2} v^2$$

$$M^2_H = -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2} v^2$$

$$M^2_A = -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2} v^2$$

λ_{345}

D couple to V = W/Z (eg. AZH, $H^- W^+ H$), not DVV!

Quartic selfcouplings D^4 proportional to λ_2

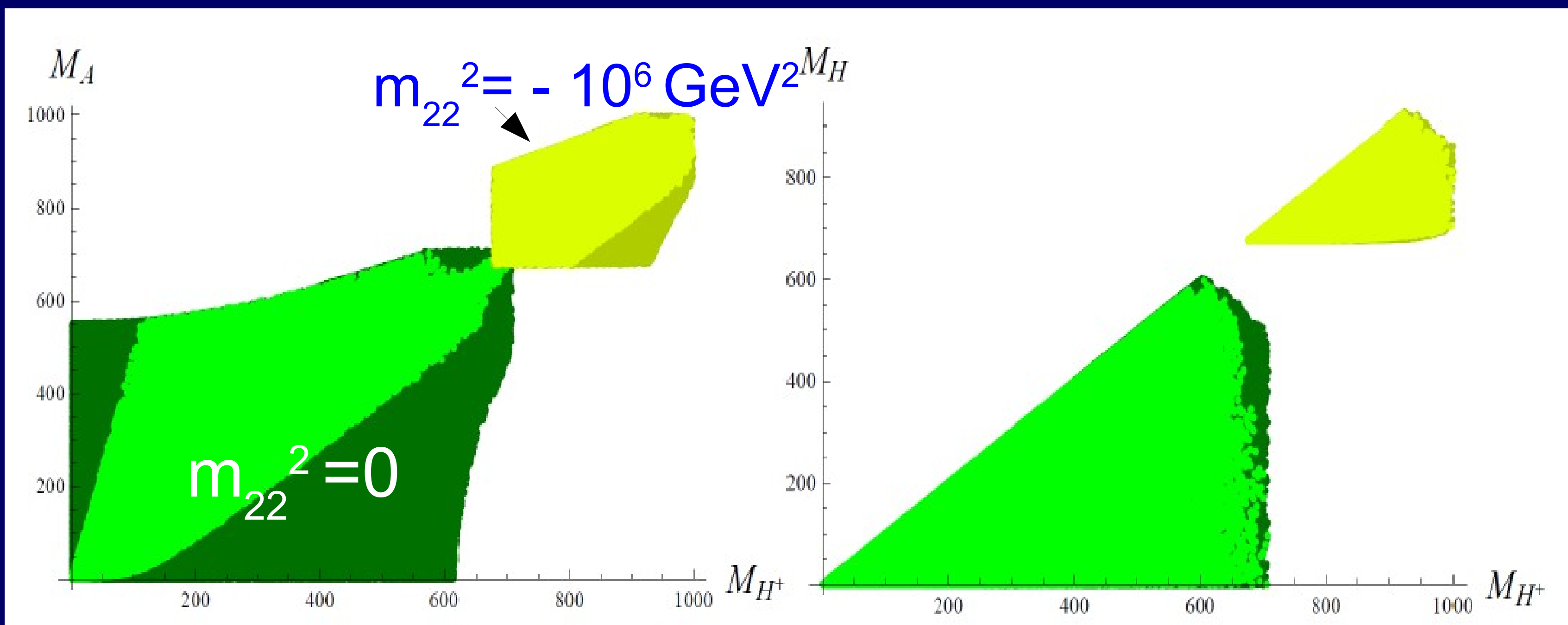
hopeless to be measured at colliders! *(→ D. Sokołowska talk)*

Couplings with Higgs: hHH ~ λ_{345} h H+H- = ~ λ_3

Inert Doublet Model with Mh=125 GeV

Analysis based on unitarity, positivity, EWPT constraints
Gorczyca'2011-12

$$M_H \leqslant 602\,\mathrm{GeV}\,,\quad M_{H^\pm} \leqslant 708\,\mathrm{GeV}\,,\quad M_A \leqslant 708\,\mathrm{GeV}\,.$$

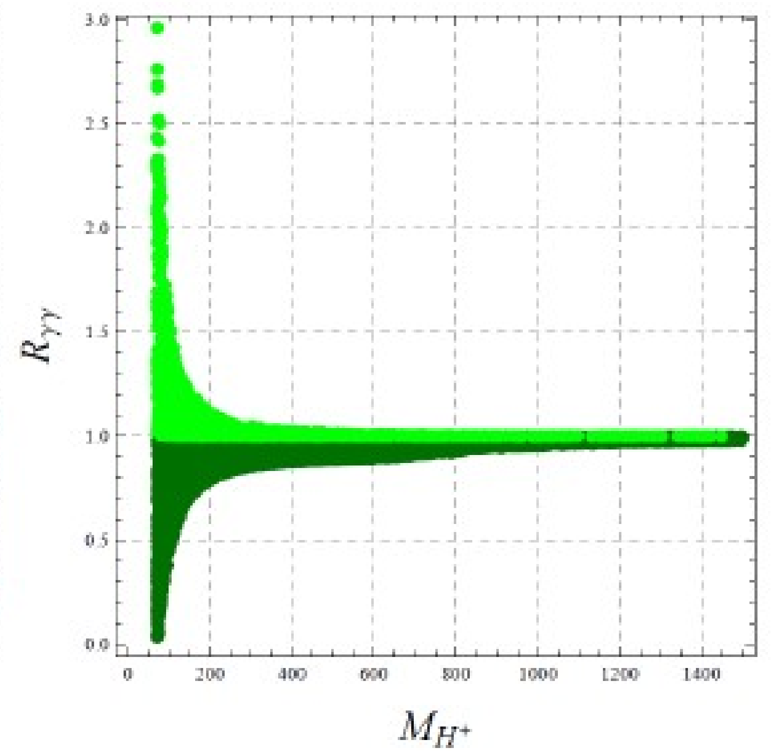


valid up to $|m_{22}^2| = 10^4 \mathrm{GeV}^2$

EWPT (pale regions)

gg → h → γγ in IDM

$$R_{\gamma\gamma} = \frac{\sigma_h^{\gamma\gamma}}{\sigma_{h_{SM}}^{\gamma\gamma}} = \frac{\sigma(gg \to h) \times Br(h \to \gamma\gamma)}{\sigma(gg \to h)^{SM} \times Br(h \to \gamma\gamma)^{SM}} = \frac{Br(h \to \gamma\gamma)}{Br(h \to \gamma\gamma)^{SM}}$$



Light green $R\gamma\gamma > 1$

$(\lambda_3 < 0)$

[B. Świeżewska, arXiv:1209.5725 [hep-ph]]

- $R_{\gamma\gamma} \gtrsim 1$ also for big $M_{H^\pm}$, e.g. $M_{H^\pm} = 1.4$ TeV
- Substantial enhancement, $R_{\gamma\gamma} \gtrsim 1.2$ only for $M_{H^\pm} \lesssim 160$ GeV $(-14 \cdot 10^4\ \mathrm{GeV}^2 \lesssim m_{22}^2 \lesssim 0.95 \cdot 10^4\ \mathrm{GeV}^2)$

also Arhrib at al

Conclusions

- 2HDM - a great laboratory for physics BSM
- SM-like scenarios can be realized in:

- 2HDM (Mixed) where *both h or H can be SM-like:*
mass of H+ between 380-600 GeV,
both for *SM-like* h (then 0.2< tan β<5.6) and *SM-like* H
large enhancement of loop couplings possible due to
wrong sign of Yukawa coupling to the top quark

- Intert Doublet Model with *SM-like h:*
mass of H+ below 160 GeV if $R_{\gamma\gamma} > 1.2$
(Note, however that H+ has no Yukawa couplings)

Photon Linear Collider can test such models

PLC

Γ (h → γ γ) ~ 3 %

$$\gamma\gamma \to h \to b\bar{b}$$

NŻK

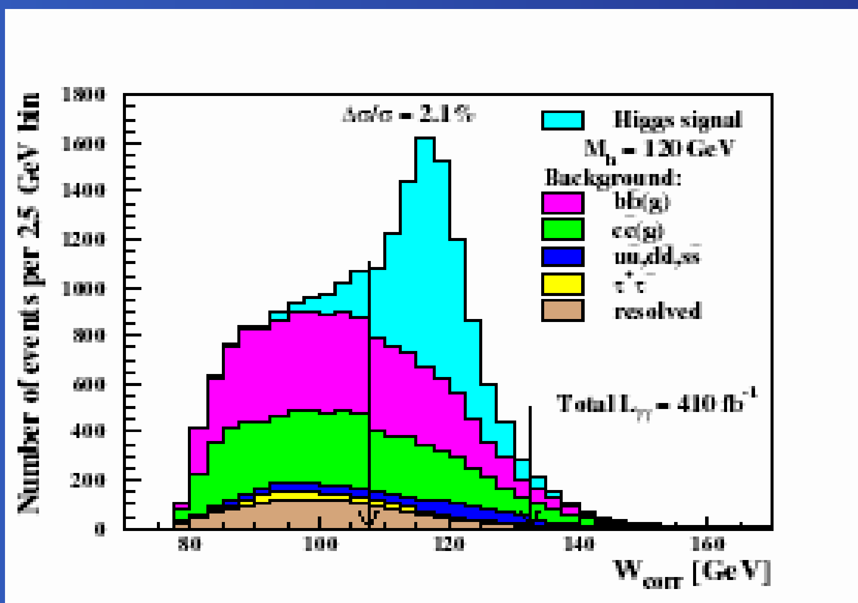
SM summary

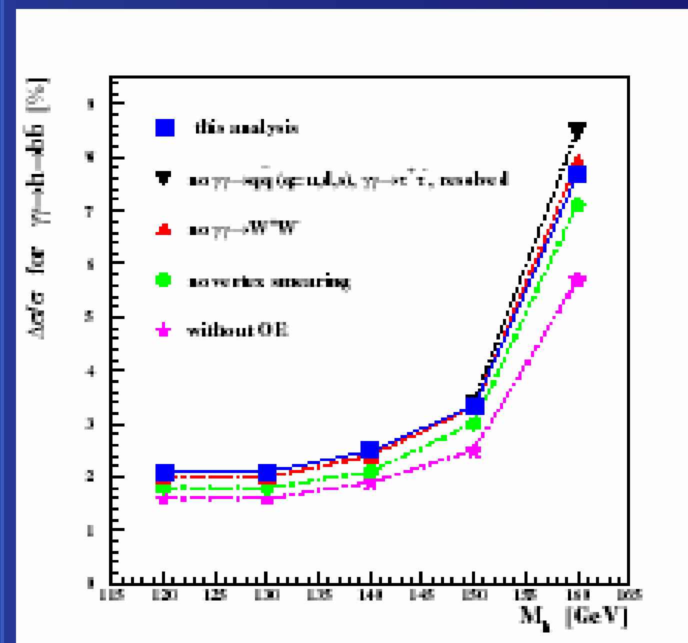
Niezurawski et al.,

Monig, Rosca

→ Results for $M_h = 120$ GeV

Results for $M_h =$ 120-160 GeV





Corrected invariant mass distributions for signal and background events

For $M_h = 150, 160$ GeV additional cuts to reduce $\gamma\gamma \to W^+W^-$

Relative couplings (w.r.s SM)

For neutral Higgs particles h_i ,i = 1,2,3

$$\chi_j^{(i)} = \frac{g_j^{(i)}}{g_j^{\mathrm{SM}}} \qquad j = V, u, d$$

V=Z,W+/-
u=up quarks (u,c,t)
d=down quarks (d,s,b)
and charged leptons

there are relations among couplings, eg.

$$\Sigma_i (\chi_j^{(i)})^2 = 1,$$

pattern relation

$$(\chi_u^{(i)} + \chi_d^{(i)})\chi_V^{(i)} = 1 + \chi_u^{(i)}\chi_d^{(i)},$$

or

$$(\chi_u^{(i)} - \chi_V^{(i)})(\chi_V^{(i)} - \chi_d^{(i)}) = 1 - (\chi_V^{(i)})^2.$$