„The theory ends here. We need help.

Experiments must clear up this mess.” **M. Veltman** 2003

Nobel 1999 "for elucidating
the quantum structure of EW interactions”

2HDM with Z_2 symmetry in light of a new data from LHC

Maria Krawczyk
IFT, Wydział Fizyki UW

I. Ginzburg, K. Kanishev (Novosibirsk U), D.Sokołowska, G. Gil,
B. Gorczyca (Świeżewska), J. Bogdanowicz (U. of Warsaw)

THE THEORY OF MATTER and STANDARD MODEL(S)

F. Wilczek, LEPFest, Nov.2000 (hep-ph/0101187)

Theory of Matter = $SU(2)_{I\ weak} \times U(1)_{Y\ weak} \times SU(3)_{color}$

Theory of Matter refers to the core concepts:
- quantum field theory
- gauge symmetry
- spontaneous symmetry breaking
- asymptotic freedom
- the assignments of the lightest quarks and leptons

Standard Models: Choose the number of Higgs (scalar) doublets
SM=1HDM, 2HDM (MSSM), 3HDM ...
Note, that the lightest scalar is often SM-like

NonStandard Models are based on more radical assumptions.

Plan

- Higgs at LHC 2012
- SM-like Higgs scenarios
- Two Higgs Doublet Models – 2HDM
- Z_2 (D) symmetry in 2HDM

  → Normal (Mixed) Model (as MSSM)

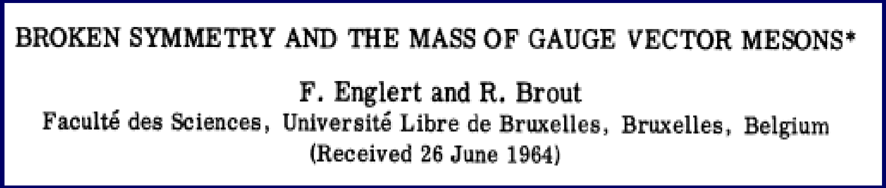
  → Dark 2HDM = 2HDM with Dark Matter

  Inert Doublet Model (IDM)

  T=0 and evolution of the Universe
- Enhancement in $\gamma\gamma$ Higgs final states

LHC

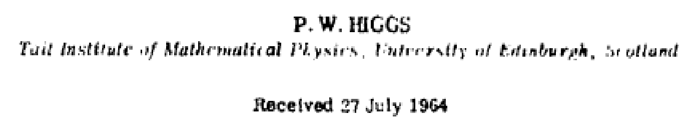
Higgs-like particle with mass125-126 GeV observed at ATLAS+CMS (+Tevatron)



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

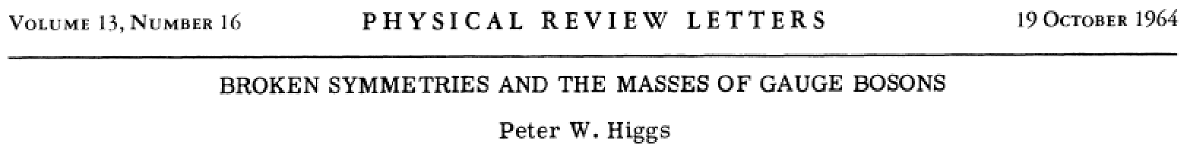
(Received 26 June 1964)



BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

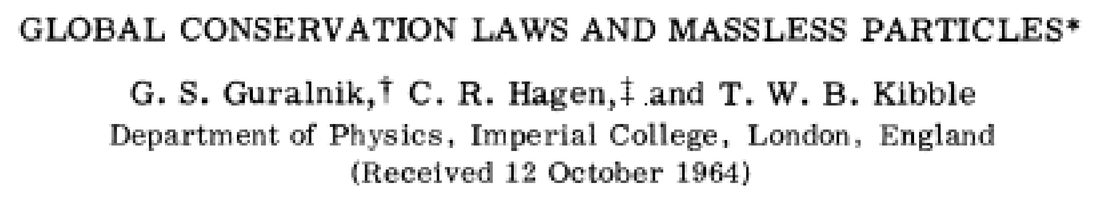


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

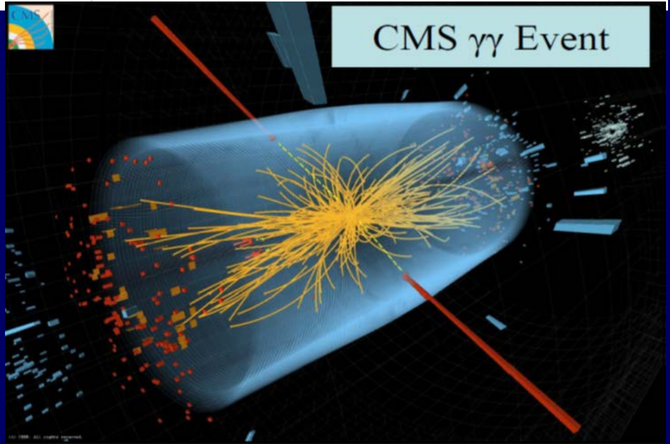
ceived 31 August 1964)



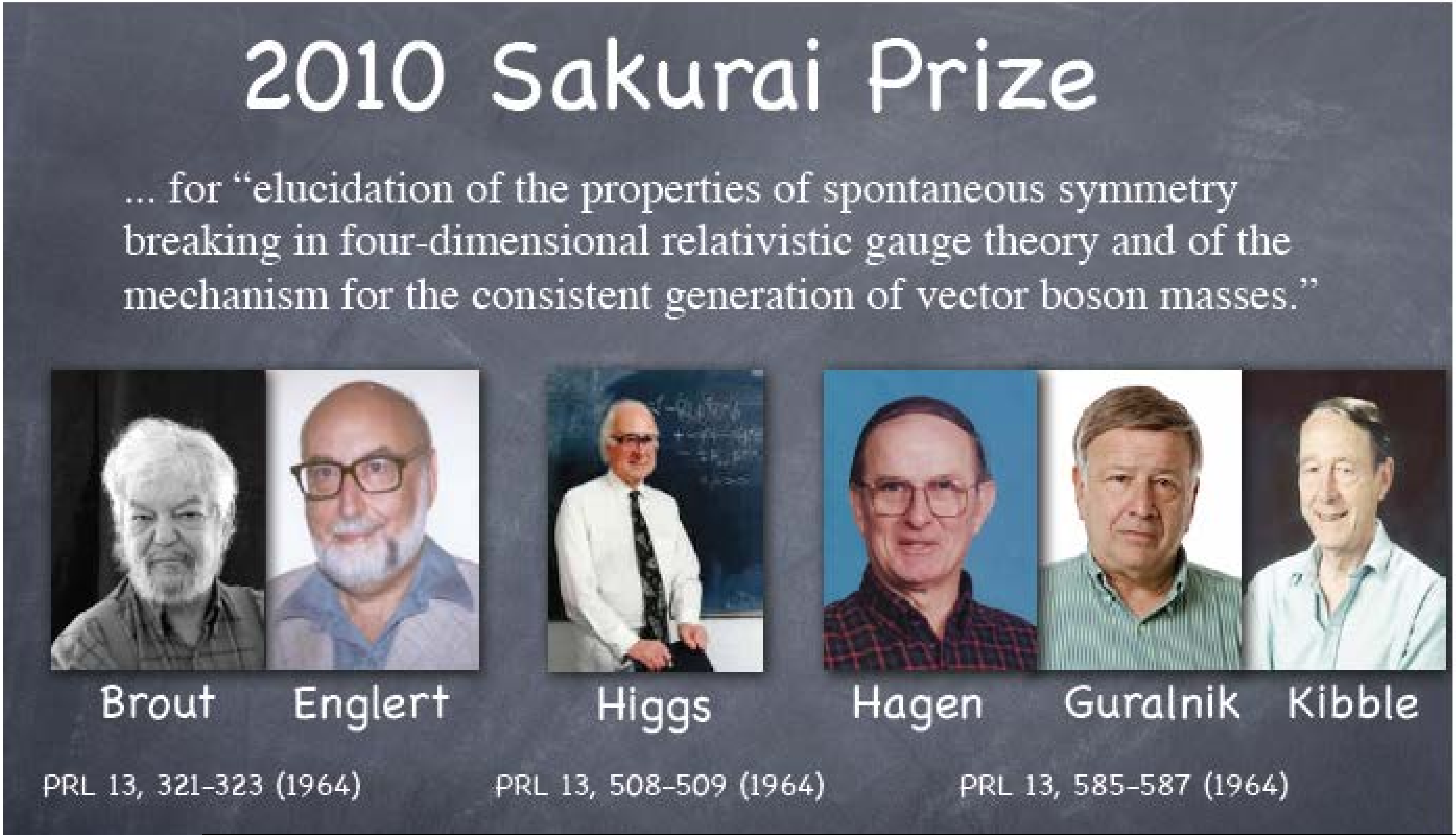
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England

(Received 12 October 1964)



Important loop couplings ggH,γγH



2010 Sakurai Prize

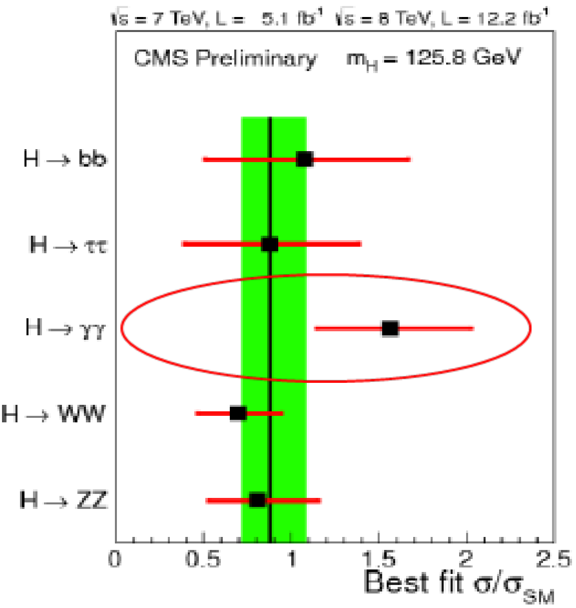
... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."

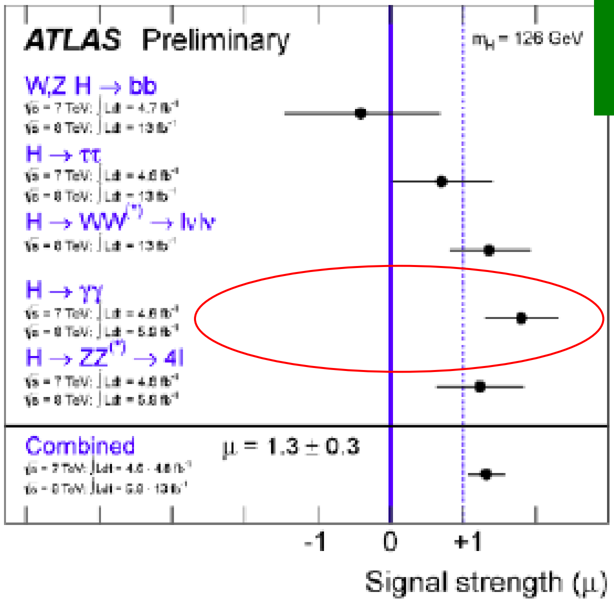
Brout Englert Higgs Hagen Guralnik Kibble

PRL 13, 321-323 (1964) PRL 13, 508-509 (1964) PRL 13, 585-587 (1964)

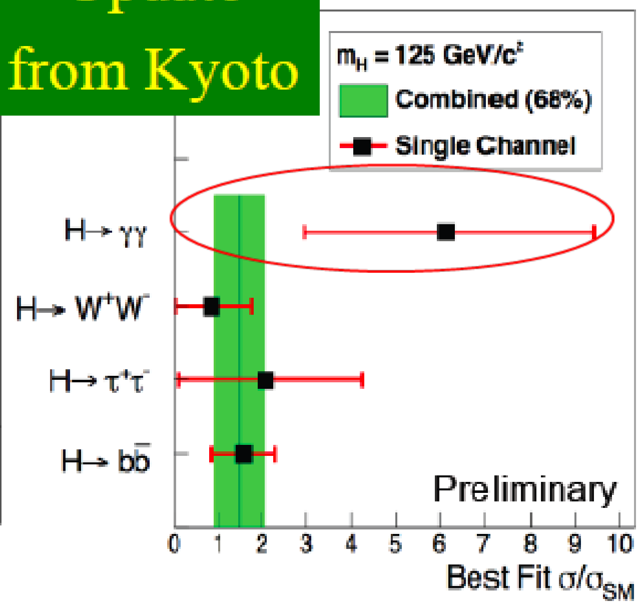
Nambu, Nobel 2008
Za wprowadzenie SSB do fizyki cząstek elementarnych

Summary of the Story so far



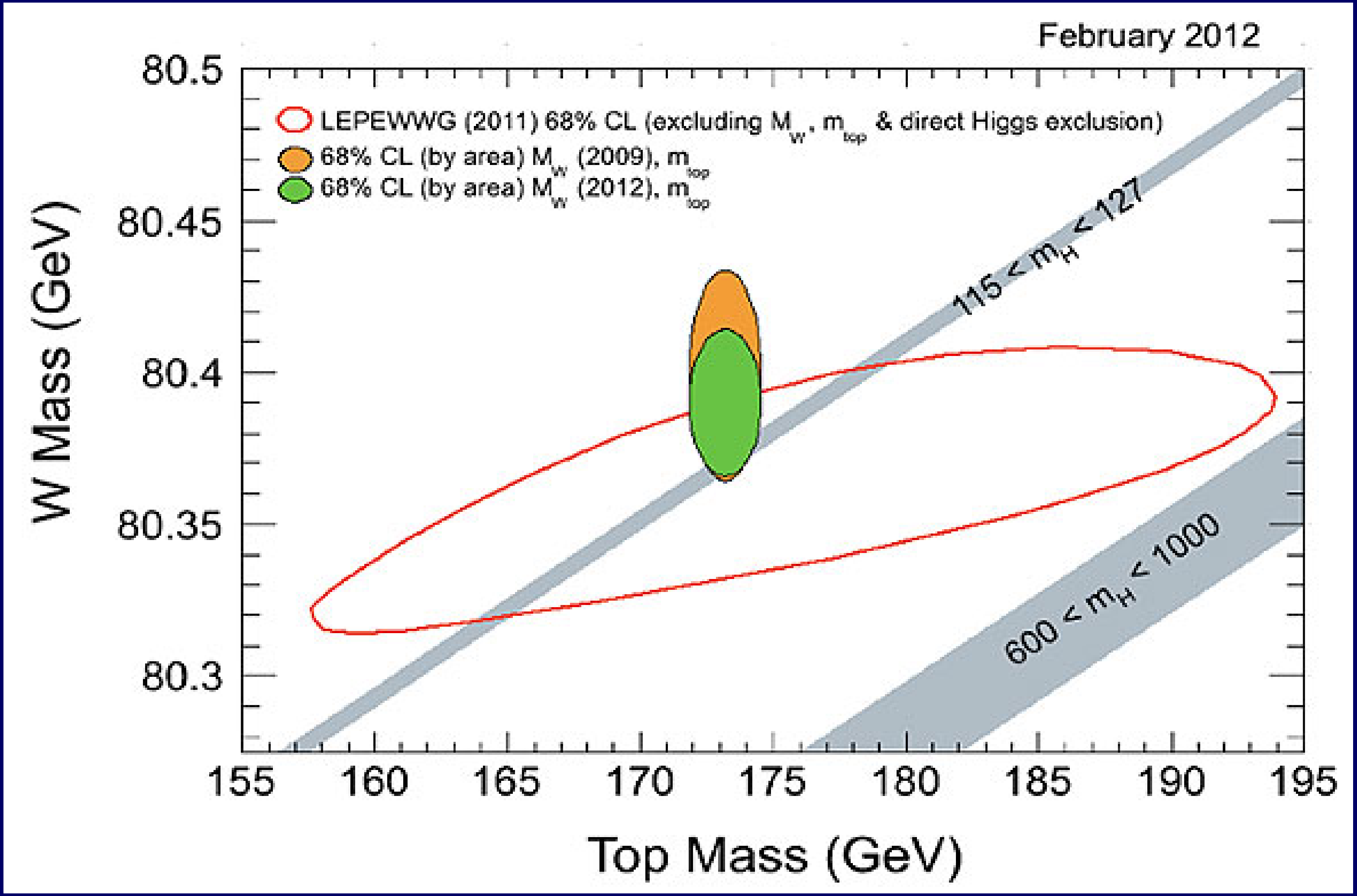


Update from Kyoto



Signals compatible (so far) with the Standard Model

Tevatron


February 2012
LEPEWWG (2011) 68% CL (excluding M_W, m_{top} & direct Higgs exclusion)
68% CL (by area) M_W (2009), m_{top}
68% CL (by area) M_W (2012), m_{top}
$115 < m_H < 127$
$600 < m_H < 1000$
W Mass (GeV)
80.5
80.45
80.4
80.35
80.3
Top Mass (GeV)
155
160
165
170
175
180
185
190
195

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow U(1)_{QED}$

Standard Model

Doublet of SU(2): $\Phi = (\varphi^{+}, v+H+i\zeta)^{T}$

Masses for $W^{+/-}$, Z (tree $\rho = 1$) , no mass for the photon

Fermion masses via Yukawa interaction

Higgs particle H_{SM} - spin 0, neutral, CP even

couplings to WW/ZZ, Yukawa couplings to fermions

unknown mass ↔ selfinteraction

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 hold (for relative couplings to SM χ)

SM-like scenarios

- In many models SM-like scenarios are possible

Our definition of SM-like scenario (2012):

Higgs h with mass ~ 125 GeV, SM tree-level couplings*
within exp. accuracy (* up to sign)
No other new particles seen …
(too heavy or too weakly interacting)

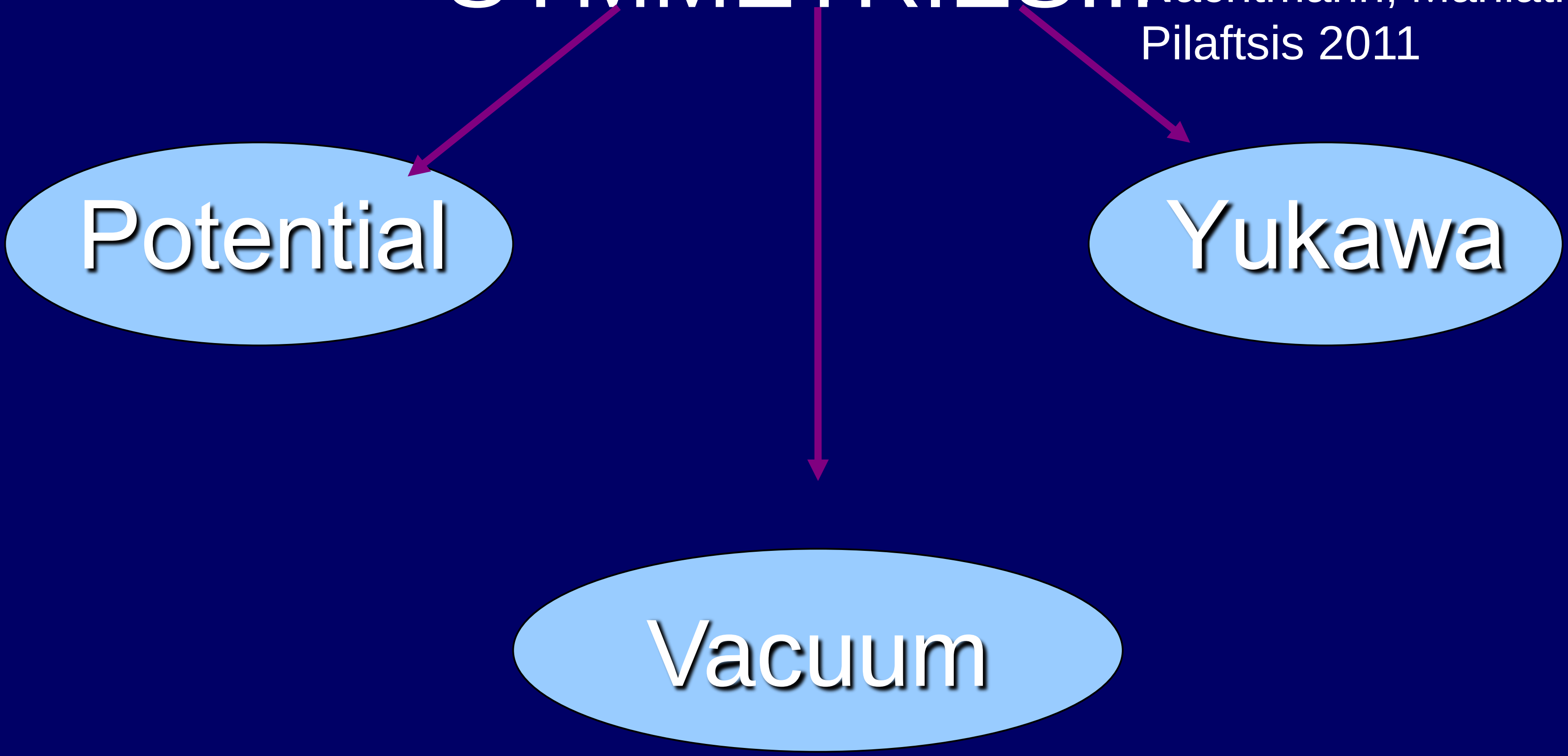
Note: Loops ggh, $\gamma\gamma$h, γZh may differ from the SM case

- In models with two SU(2) doublets:
  - MSSM with decoupling of heavy Higgses
  - 2HDM (Mixed), where *both* h or H can be SM-like
  - Intert Doublet Model, where one Higgs h *is* SM-like

2HDM's

Branco,Rebelo,Ferreira
Silva,Lavoura,Sher '12
Haber, Gunion,
Ginzburg, MK
Nachtmann, Maniatis
Pilaftsis 2011

SYMMETRIES!!!



Potential

Yukawa

Vacuum

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

Potential (Lee'73)

with $L_H=T-V$

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

$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+\tfrac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2+h.c]$$

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

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

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

(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: λ_6, λ_7, $m^2_{12}=0$ (NO CP violation)

Extrema of the 2HDM potential with explicit Z_2 symmetry

Ginzburg, Kanishev, MK, Sokołowska'09

Finding extrema: $\partial V / \partial \Phi|_{\Phi = \langle\Phi\rangle} = 0$

Finding minima → global minimum = vacuum

Positivity (stability) constraints (V with real parameters)

$$\lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R + 1 > 0$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5\,, \quad R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}\,.$$

Extremum fulfilling the positivity constraints

with the lowest energy = vacuum

Possible extrema (vacuua)

for V with Z_2 symmetry $\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$ (D symmetry)

The most general extremum state $\Phi_1 \to \Phi_S$ $\Phi_2 \to \Phi_D$

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

v_S, v_D, u - real

$v_S, u \geq 0$

$v^2 = v_S^2 + v_D^2 + u^2$

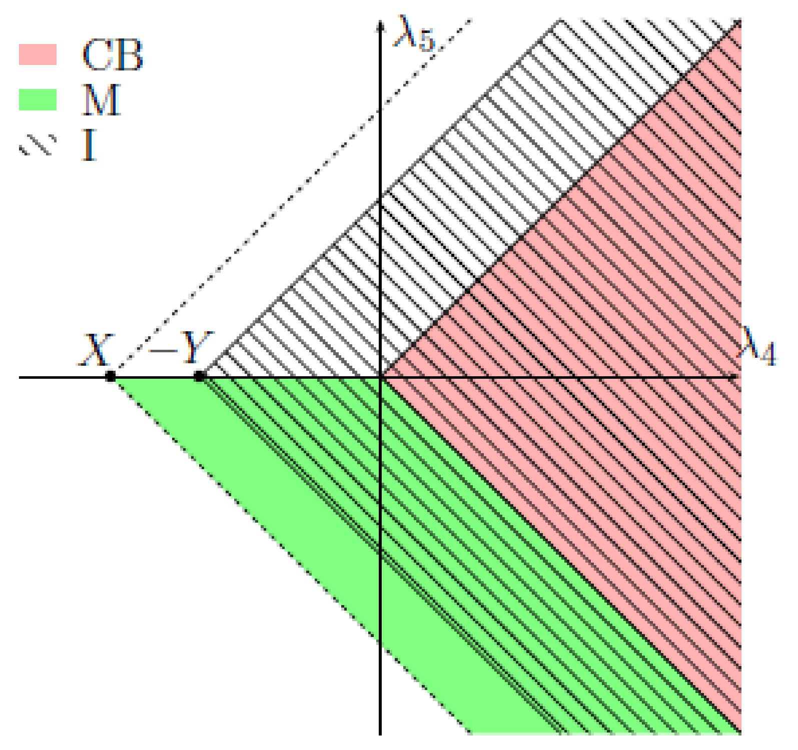
EWs	EWs	$u = v_D = v_S = 0$
Inert	I_1	$u = v_D = 0$
Inert-like	I_2	$u = v_S = 0$
Mixed (Normal, MSSM like)	M	$u = 0$
Charge Breaking	Ch	$u \neq 0 \quad v_D = 0$

D-symmetric potential - vacua

Stable vacuum (positivity)

$$\lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R+1>0, \quad R_3+1>0$$

$$\lambda_{345} = \lambda_3+\lambda_4+\lambda_5, \quad R = \lambda_{345}/\sqrt{\lambda_1\lambda_2}, \quad R_3 = \lambda_3/\sqrt{\lambda_1\lambda_2}.$$



$Y = M_{H+}^2\, 2/v^2|_{\text{Inert}}$

Neutral vacua

- Mixed M(v1 and v2 ≠ 0)
- Inert I1 (I2) [v1(v2) ≠ 0]

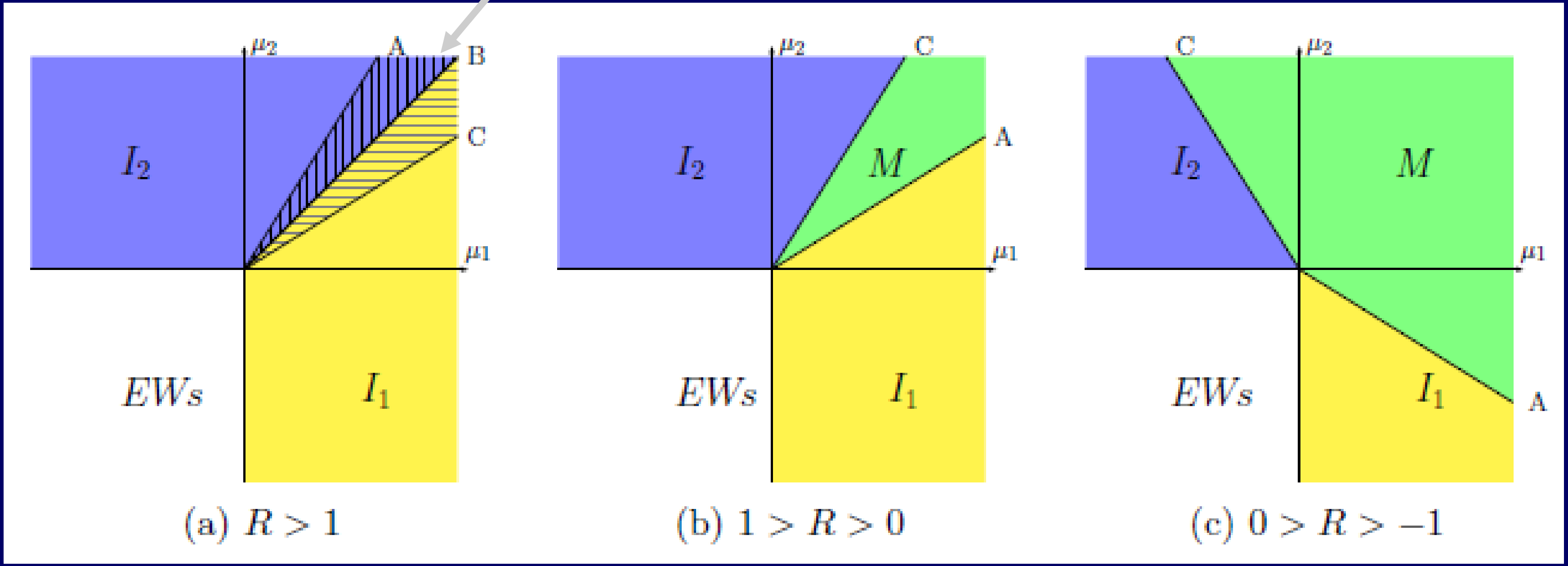
- Charged breaking vacuum CB

Inert overlaps both with Mixed and CB !

Phase diagrams D-sym. V

coexistence
of minima

$$\mu_1 = \frac{m_{11}^2}{\sqrt{\lambda_1}}, \quad \mu_2 = \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$



(a) $R > 1$ (b) $1 > R > 0$ (c) $0 > R > -1$

Inert I1 vacuum
for Mh=125 GeV

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}.$$

Various models of Yukawa inter.

typically with some Z2 type symmetry to avoid FCNC

Model I - only one doublet interacts with fermions

Model II – one doublet with down-type fermions d , l
other with up-type fermions u

Model III - both doublets interact with fermions

Model IV (X) - leptons interacts with one doublet, quarks with the other

Model Y - one doublet with down-type quarks d
other with up-type quarks u and leptons

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

Extra dim 2HDM models

Model for TODAY (LHC data..)

2HDM with explicit D symmetry (ie. in Lagrangian L)

$\Phi_S \to \Phi_S \quad \Phi_D \to -\Phi_D$

- Charge breaking phase Ch?

  photon is massive, el.charge is not conserved...

  → No

- Neutral phases:

  Mixed M in agreement with data

  here Model II (Φ_S , Φ_D interact with fermions)

  D spont. broken

  Inert I1 OK! In agreement with accelerator

  and astrophysical data (neutral DM)

  Model I (only Φ_S interacts with fermions)

  D symmetry exact

Confronting 2HDM with data

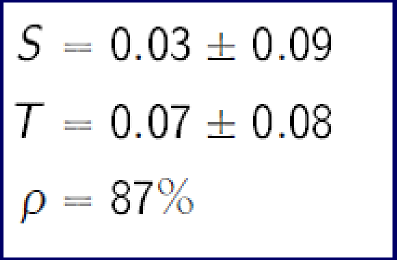
Constraints:

Vacuum stability,

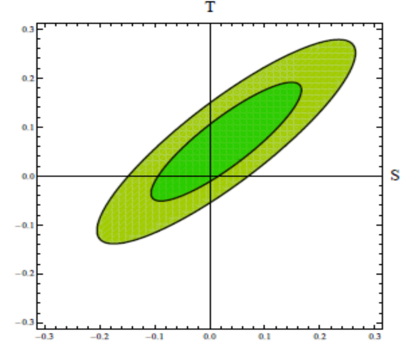
condition for a specific vacuum

Perturbative unitarity

EWPD (S and T)



$$S = 0.03 \pm 0.09$$
$$T = 0.07 \pm 0.08$$
$$\rho = 87\%$$



Mixed Model

Here 5 Higgs bosons, sum rules for relative couplings for h, H, A: eg. $(\chi^h_V)^2 + (\chi^H_V)^2 = 1$

SM-like scenario both for h and H possible

eg. $\chi_V = 1$ for h or H, V=W/Z

Inert Doublet Model: it's a SM-like scenario for h, H=DM

Unitarity constraints on parameters of V (D symmetry)

analysis by B. Gorczyca, MSc Thesis, July 2011

Full scattering matrix macierz 25x25 for scalars (including Goldstone's)

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_1 & & & & & \\ & \mathcal{M}_2 & & & & \\ & & \mathcal{M}_3 & & & \\ & & & \mathcal{M}_4 & & \\ & & & & \mathcal{M}_5 & \\ & & & & & \mathcal{M}_6 \end{pmatrix}.$$

in high energy limit

Block-diagonal form due electric charge and CP conservation

M1: G+H-, G-H+, hA, GA, GH, hH
M2: G+G-, H+H-, GG, HH, AA, hh
M3: Gh, AH
M4: G+G, G+H, G+A, G+h, GH+, HH+,AH+,hH+
M5: G+G+, H+H+
M6: G+H+

Unitarity constraints → |eigenvalues|< 8 π

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

For both the same pert. unitarity constraints on λ's

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

B. Gorczyca, MSc Thesis, July 2011

Couplings for dark particles in IDM →

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

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

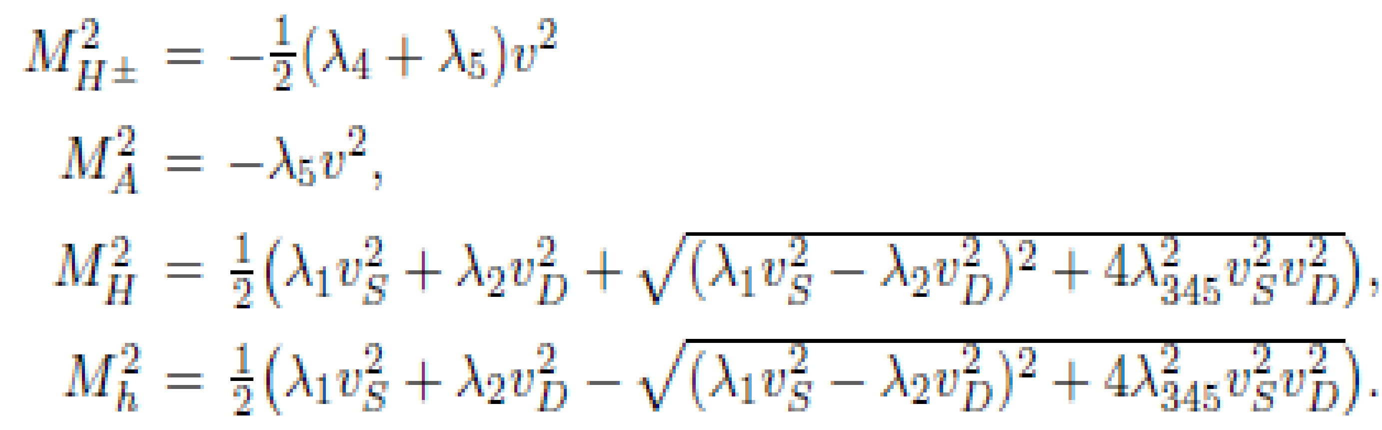
and for combinations

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

Mixed Model

(Mixed vacuum, Model II Yukawa)

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



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

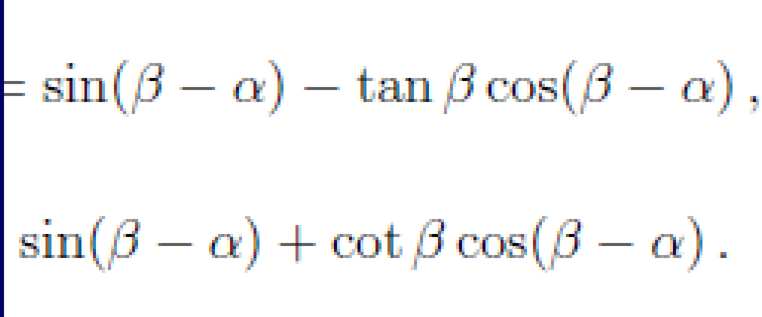
$$M_A^2 = -\lambda_5 v^2,$$

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

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

Relative couplings wrs SM ($\tan\beta = v_D/v_S$)

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



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

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

Mixed Model

Upper limits
on masses from
unitarity constraints

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

SM-like Mixed Model

also Akeroyd, Arhrib, Naimi,..

$M_h = 125$ GeV

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

V=W,Z

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

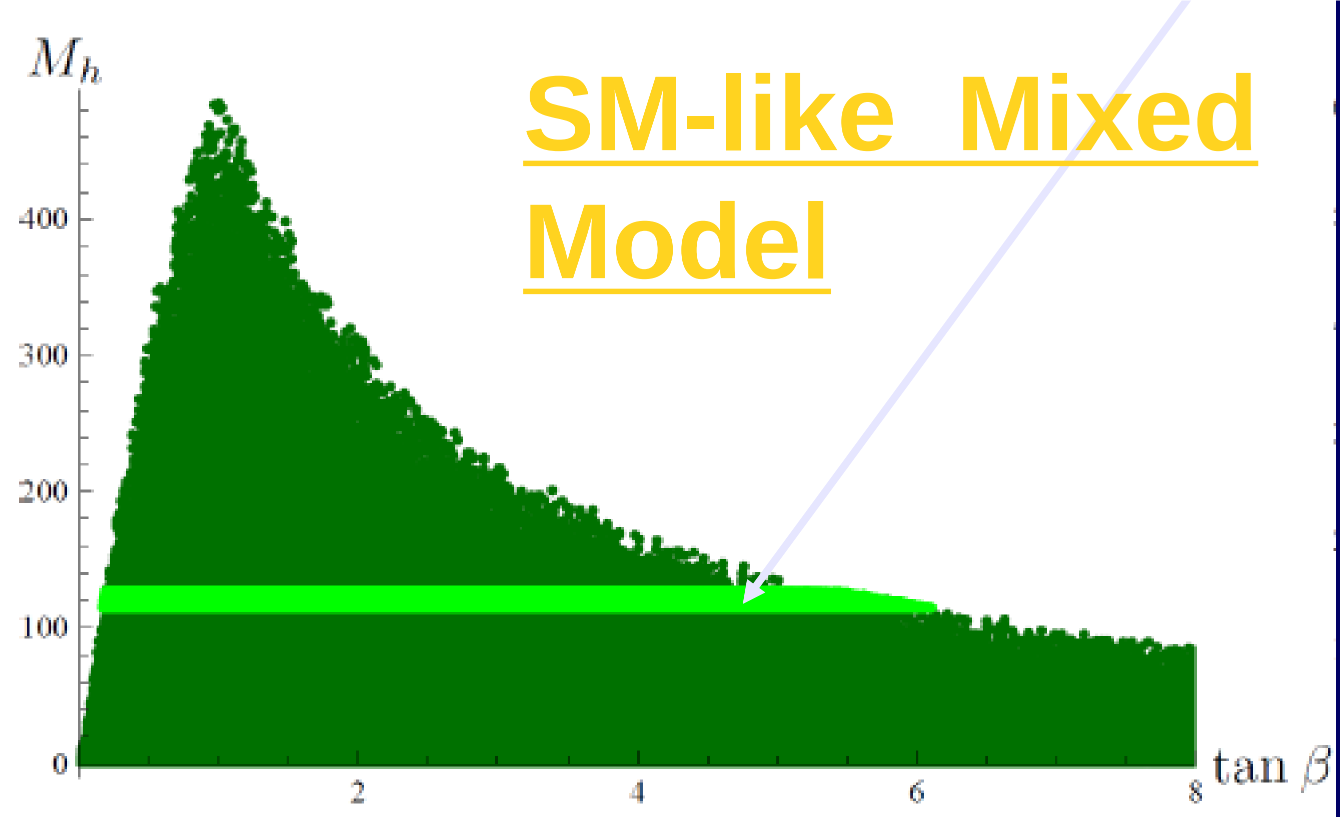
Limit on tan beta from the M_h value !

Gorczyca,MK 1112.5086

M_h vs tan β

For h mass =125 GeV

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



SM-like Mixed Model

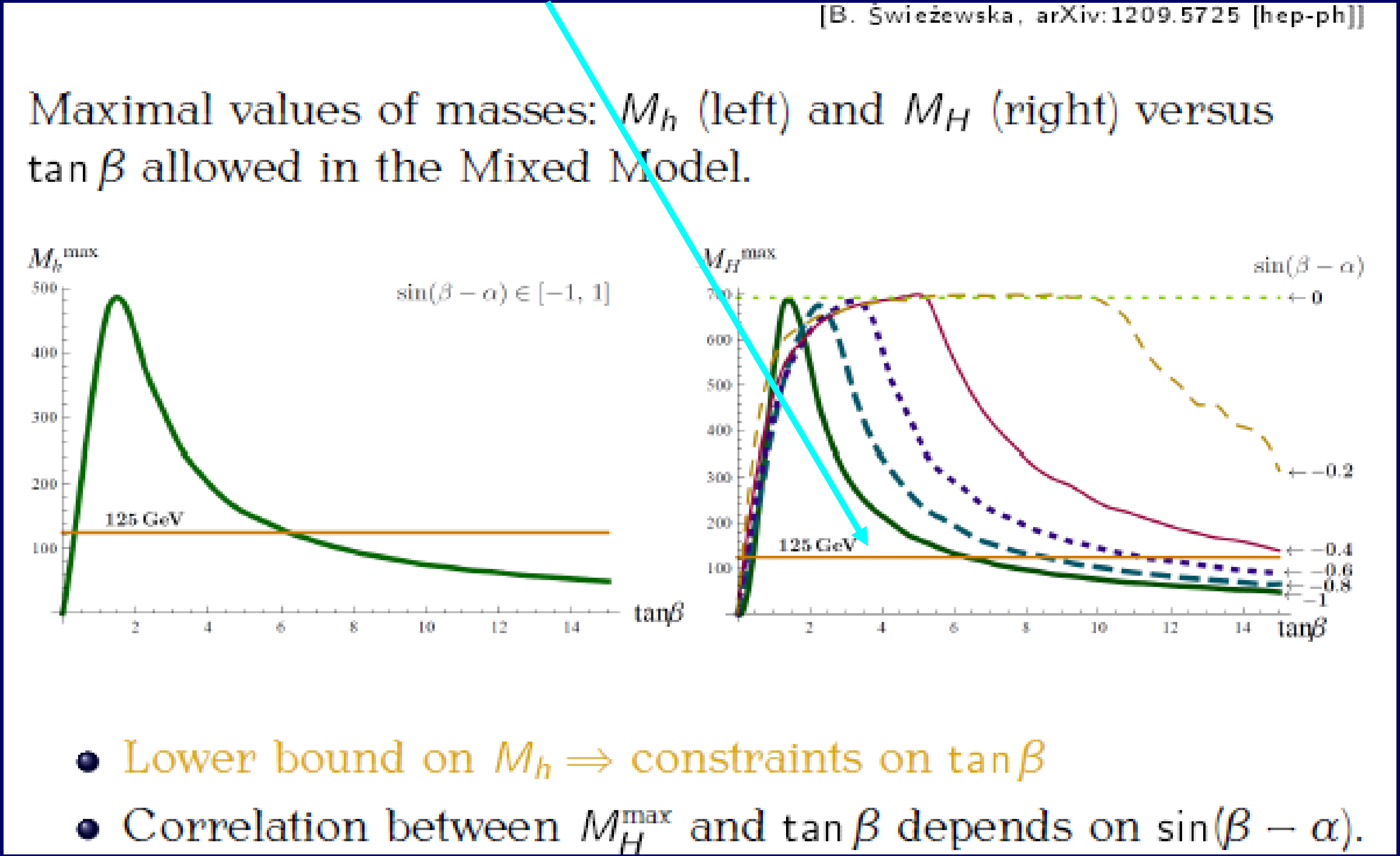
B.Gorczyca, MK

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 $\sin(\beta-\alpha)$.

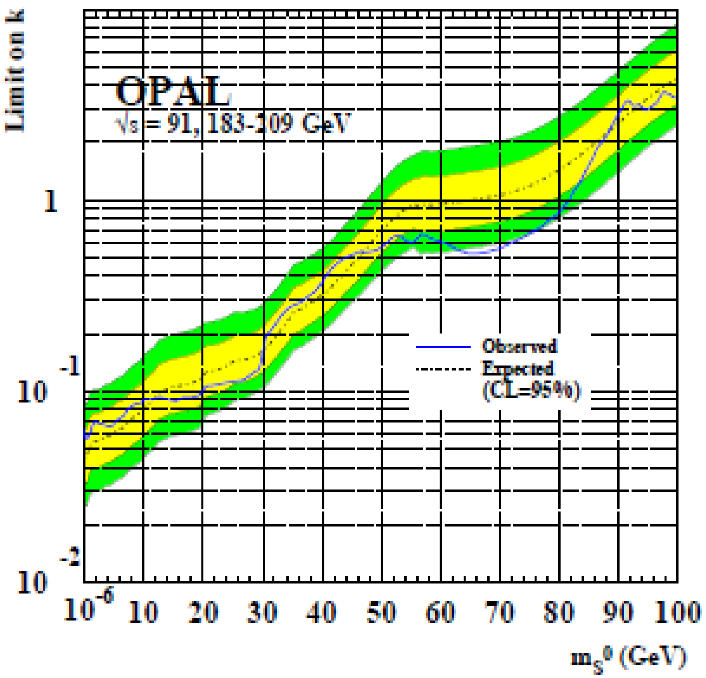
if H is SM-like then h must be lighter with the suppressed coupling to gauge bosons –> LEP data

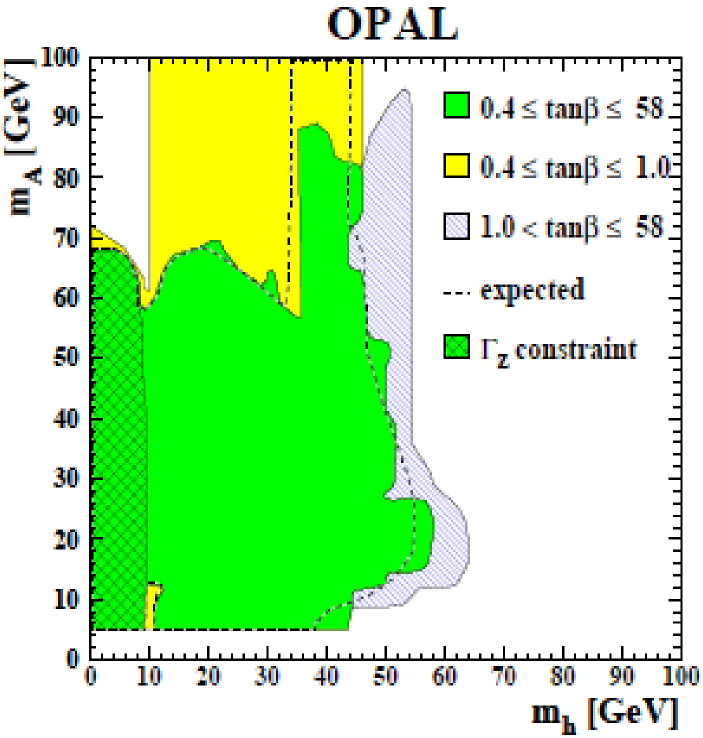
LEP data for Mixed Model

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

Light h OR light A in agreement with current data

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



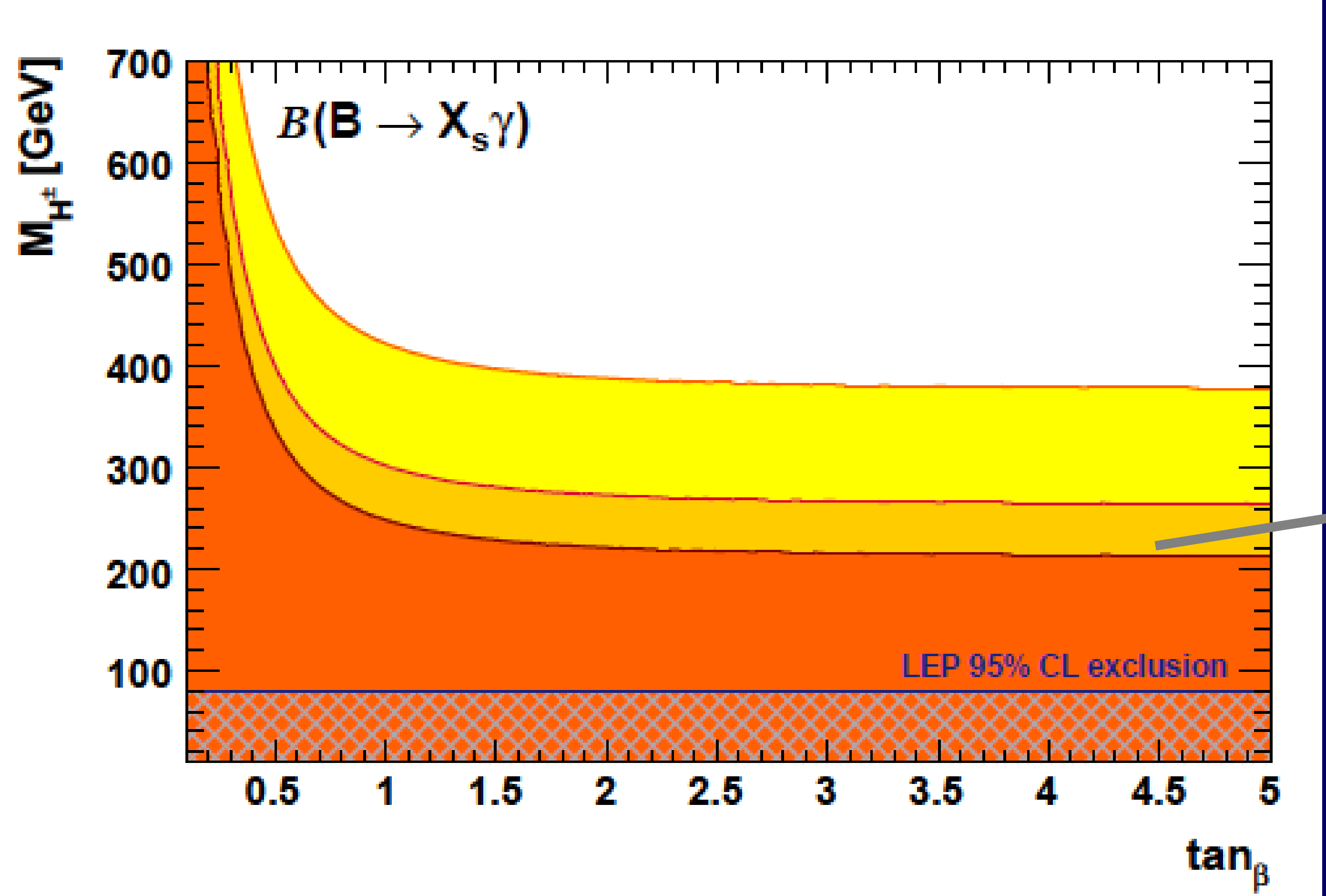


Light scalar h → small $k = sin^2(\beta-\alpha)$!

H is SM-like then !

$B \to X_s\,\gamma$ decay M_{H+} vs tan β

Mixed Model

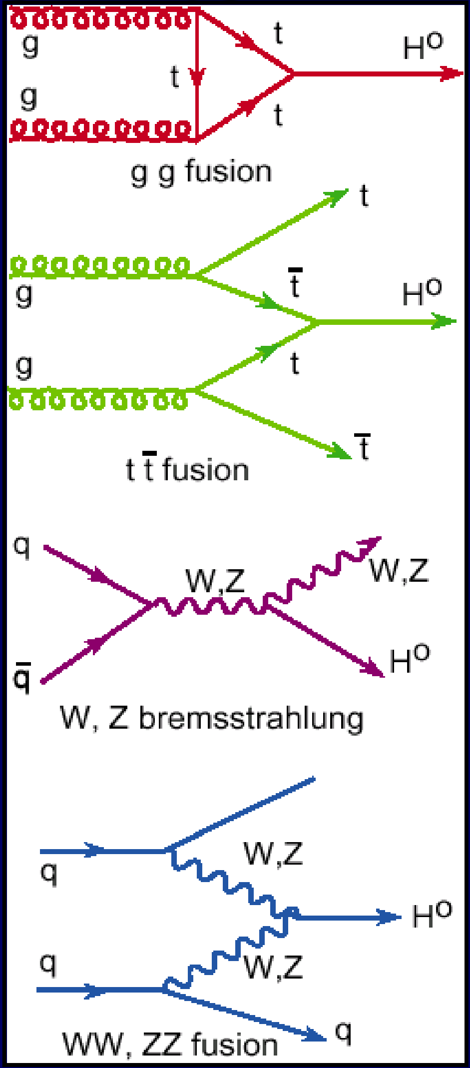


95%CL

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

Gfitter 0811.0009[hep-ph]

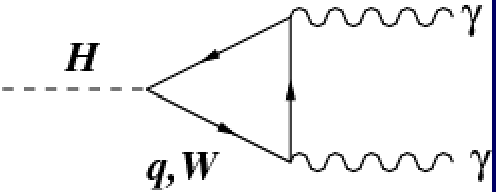
Loop couplings hgg, h$\gamma\gamma$ (hZγ)



For hgg

- b and t important

For h $\gamma\gamma$



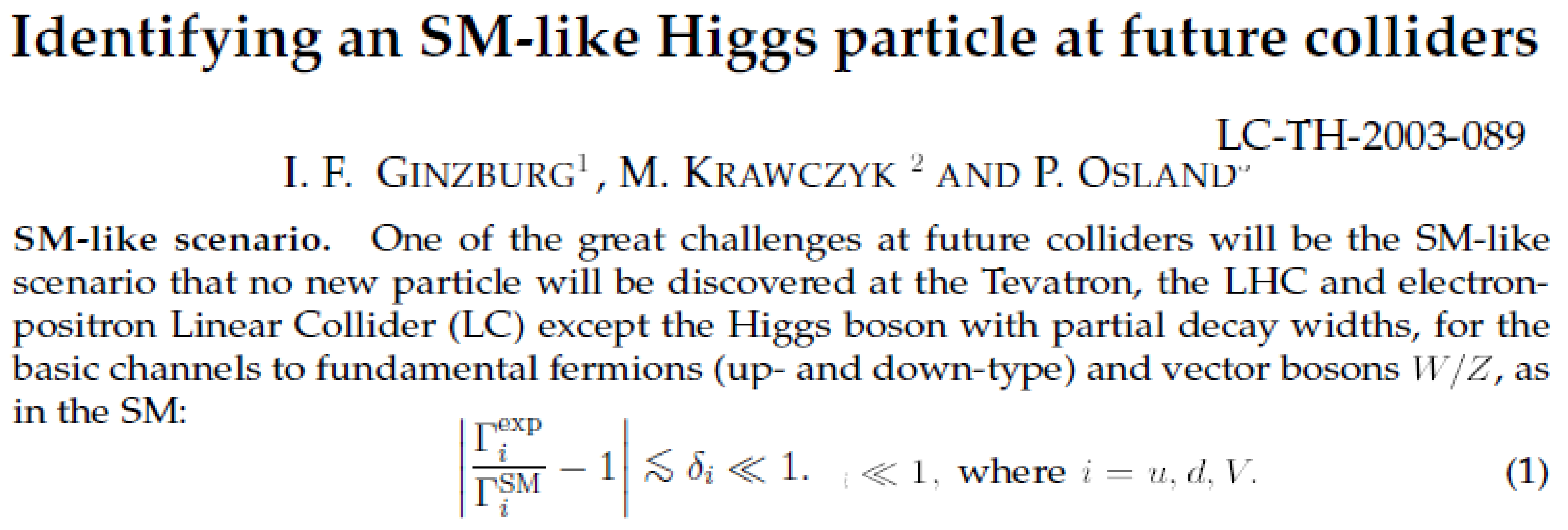
- t and b, W+, (H+ in 2HDMs)

W+ and t destructive interference in SM,

so if sign is changed for htt..

2HDM Ginzburg, MK, Olsland,2001,Carmi et al.,,,, in 2011,12

LC-TH-2001-026



Identifying an SM-like Higgs particle at future colliders

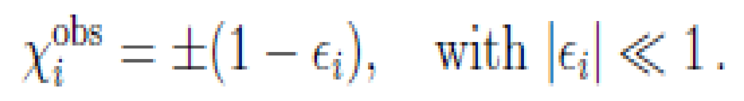
LC-TH-2003-089

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

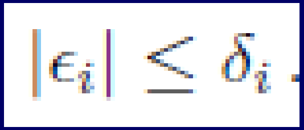
SM-like scenario. One of the great challenges at future colliders will be the SM-like scenario that no new particle will be discovered at the Tevatron, the LHC and electron-positron Linear Collider (LC) except the Higgs boson with partial decay widths, for the basic channels to fundamental fermions (up-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

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

Then for the relative basic couplings of neutral Higgses

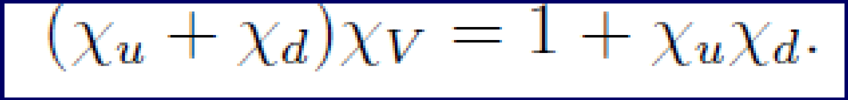


$$\chi_i^{\rm obs} = \pm(1-\epsilon_i), \quad \text{with } |\epsilon_i| \ll 1.$$

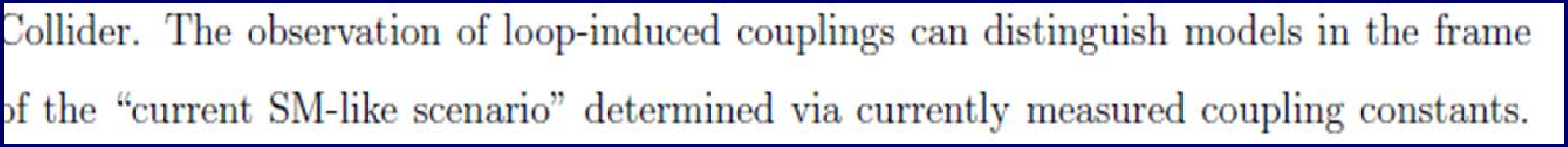


$$|\epsilon_i| \le \delta_i\,.$$

Using pattern relation
for 2HDM (II)



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



Collider. The observation of loop-induced couplings can distinguish models in the frame of the "current SM-like scenario" determined via currently measured coupling constants.

Both h and H maybe SM-like

Two solutions of pattern relation:

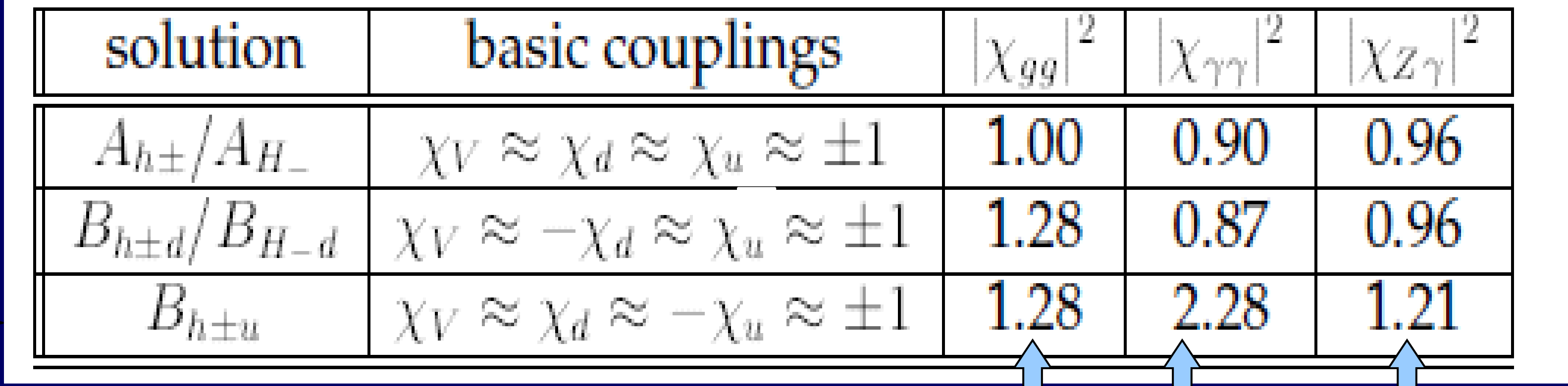
A – all couplings close to 1

B – one Yukawa coupling close to -1

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

MH+=600 GeV

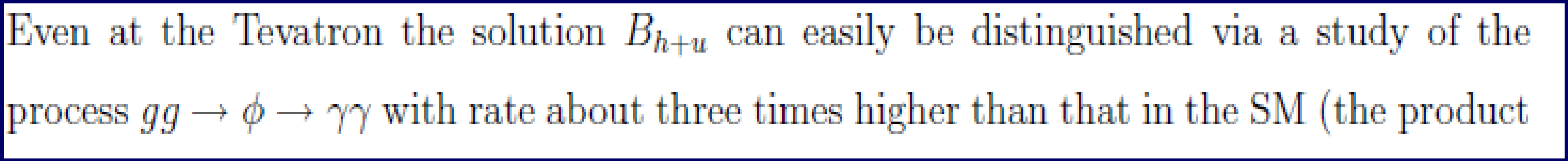
For h or H with mass 120 GeV



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

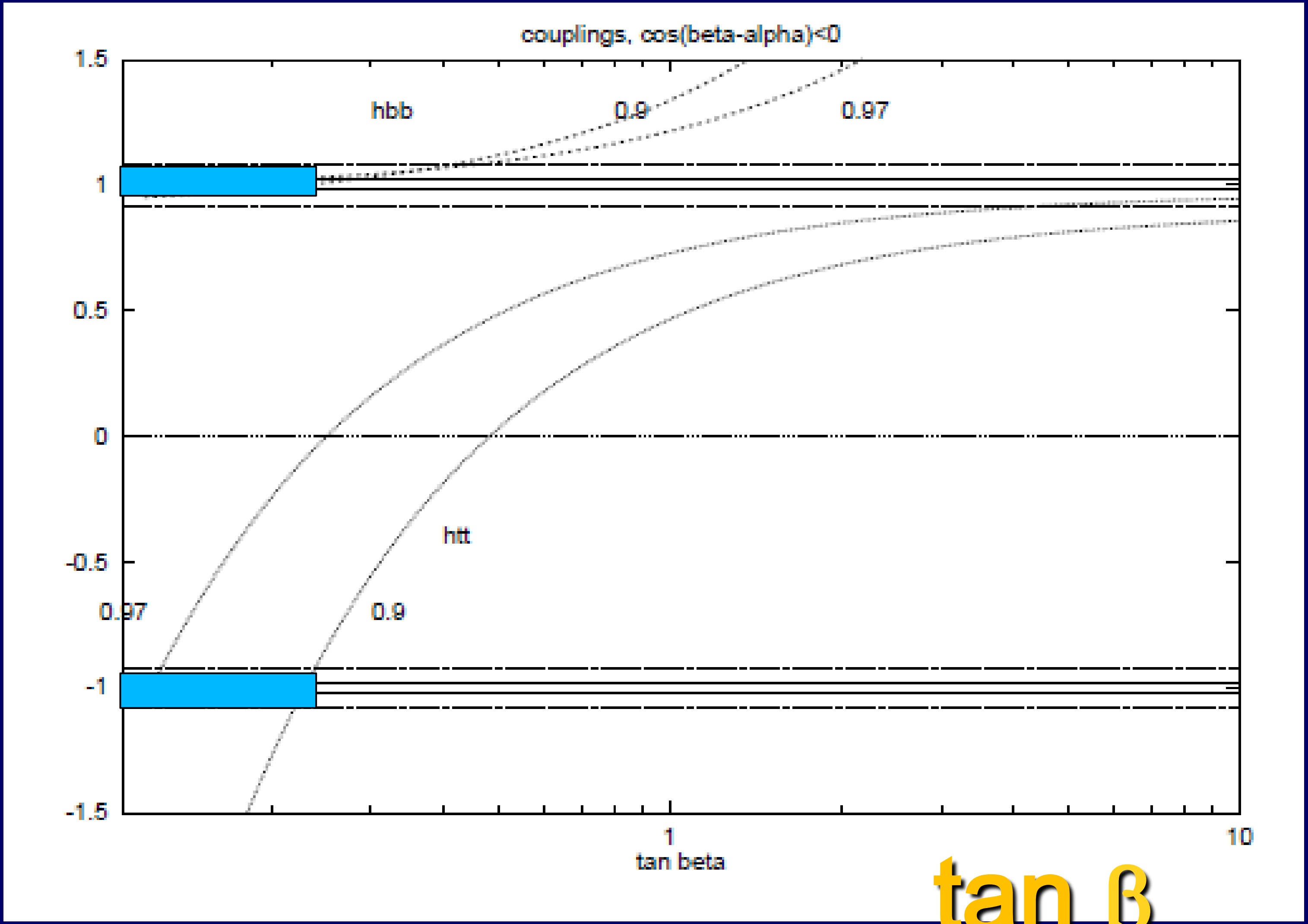
„wrong” sign of coupling to top →

large enhancement of hgg, h$\gamma\gamma$, hZγ ! and Hgg



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

htt and hbb couplings vs tan β for hVV = 0.9-0.97 (1 in SM)



hbb=1

htt=-1

tan β

Inert Doublet Model

Ma'78
Barbieri'06

Symmetry under D 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:

$$<\Phi_S> = v \qquad\qquad <\Phi_D> = 0$$

Inert
vacuum I_1

Today?

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

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

Here D symmetry exact →D parity, only Φ_D has odd D-parity
→ The lightest scalar stable -a dark matter candidate
(Φ_D dark doublet with dark D scalars) .

Φ_S Higgs doublet S

Φ_D Dark doublet D

Constraining Inert Doublet Model

- Positivity,condition for I1 vacuum ,
  pert. unitarity, S, T

(Ma'2006,..B. Świeżewska, Thesis2011, 1112.4356, 1112.5086 , Arhrib..2012)

- Considering properties of
  - the SM-like h, $M^2_h = m_{11}^2 = \lambda_1 v^2$
  - the dark scalars D always in pairs!

λ_{345}

$$M_{H^+}^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3}{2}v^2$$

$$M_H^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2}v^2$$

$$M_A^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2}v^2$$

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

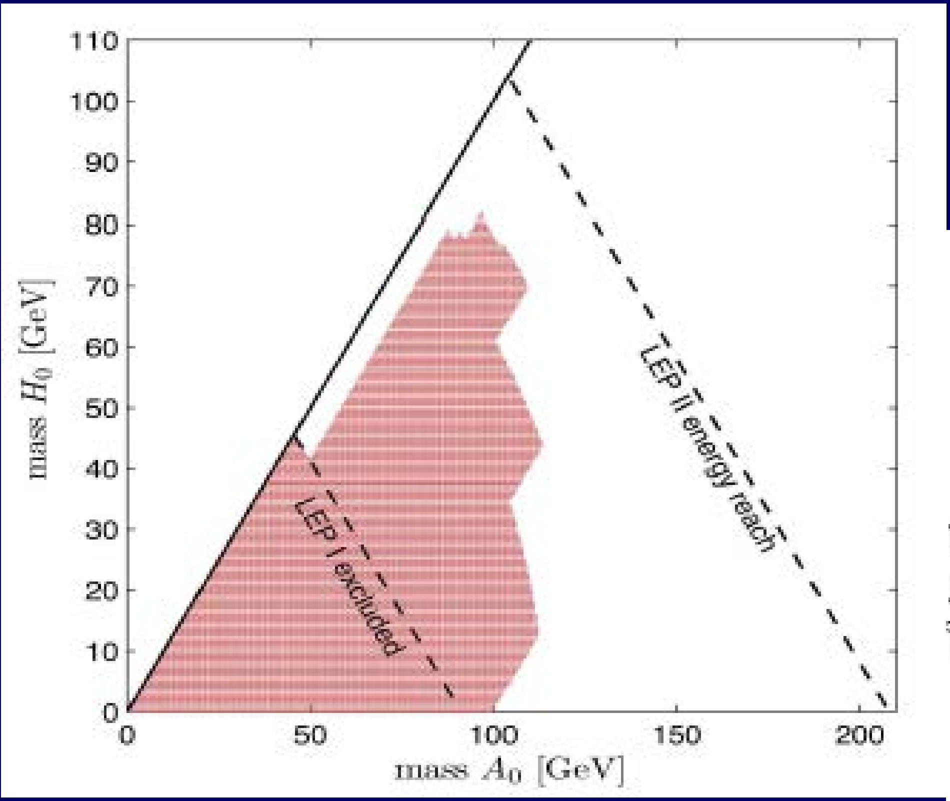
Quartic selfcouplings D^4 proportional to λ_2

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

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

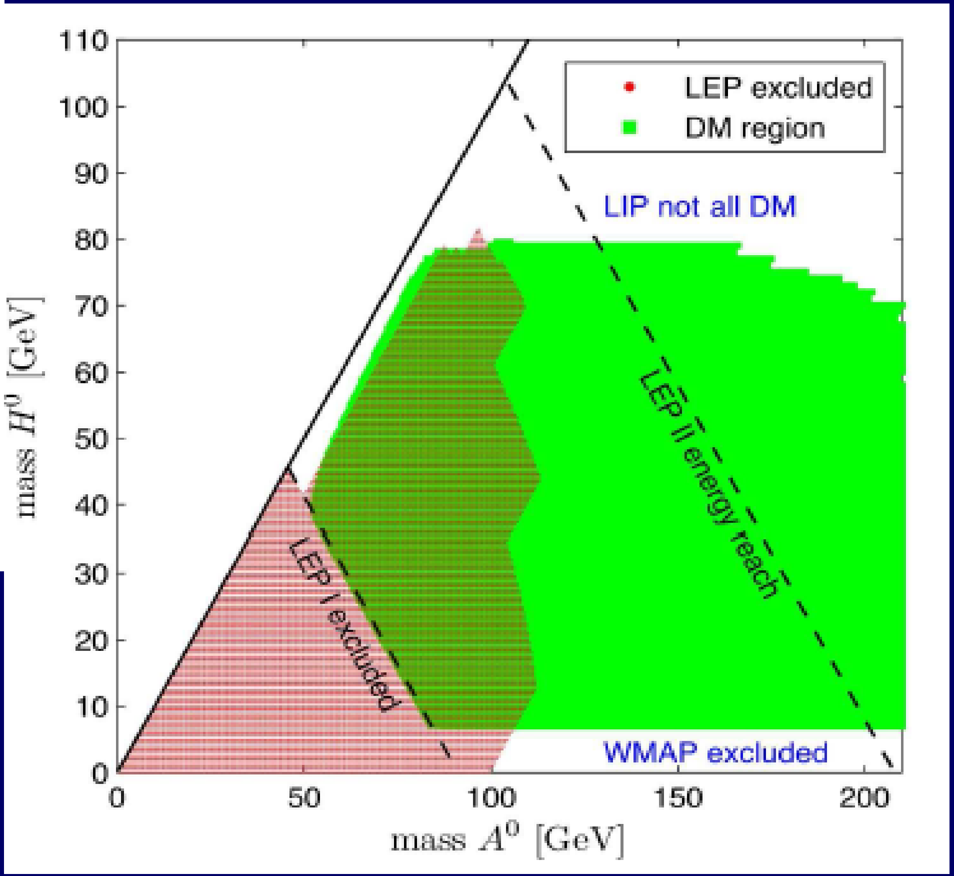
IDM: LEP II exclusion (massesH vs A)

Lundstrom... hep-ph/0810.3924



DM=H

LEP II + WIMAP



DM = low, medium, high mass

IDM constraints: LEP + S,T,U + DM relic density

D. Sokołowska 2011-12

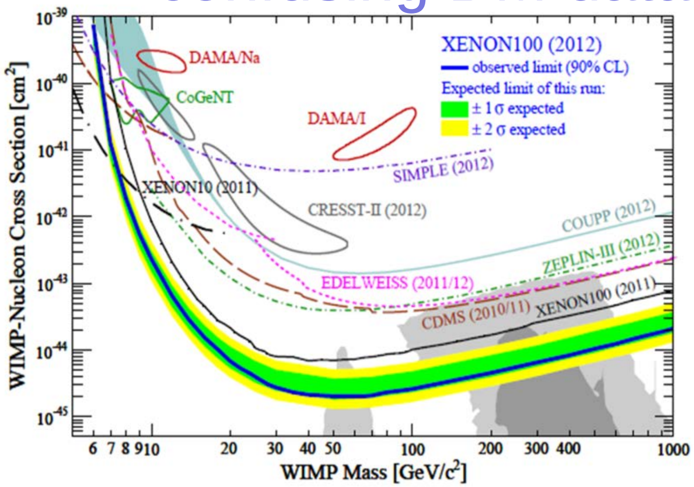
constraints for masses and $D_H D_H h_S$, $D_H D_H h_S h_S$ couplings

Dark scalars:

- **low DM mass** $M_{D_H} \lesssim 10$ GeV,
  large mass splittings: $\Delta(D_A, D_H)$ and $\Delta(D^{\pm}, D_H)$
- **medium DM mass** $M_{D_H} \approx (40 - 160)$ GeV,
  large $\Delta(D^{\pm}, D_H)$, small or large $\Delta(D_A, D$
- **high DM mass** $M_H \approx (500 - 1000)$ GeV
  small $\Delta(D_A, D_H)$ and $\Delta(D^{\pm}, D_H)$

Lopez Honorez et al. '07, Hambye et al. '08,'09, Agrawal e
al. '09, ...

confusing DM data



Higgs boson:

- both light and heavy Higgs boson possible
- LHC 2012 ⇒ $M_{h_S} \approx 125$ GeV – SM-like Higgs in IDM

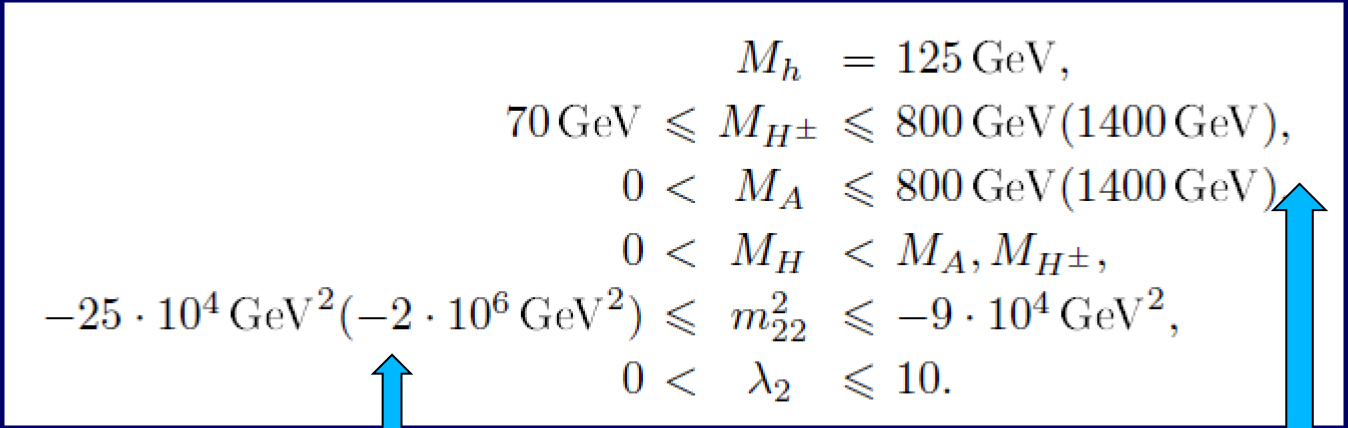
ATLAS & CMS Collaborations: 1207.7214, 1207.7235 [hep-ex]

IDM – scan (B. Świeżewska 2012)

Constraints

vacuum stability,
conditions for Inert I1 vacuum
perturbative unitarity condition
EWPT
Relic density, LEP+LHC

H – dark matter
$0 > \lambda_{45} = \lambda_4 + \lambda_5$



$$\begin{aligned} M_h &= 125\,\mathrm{GeV}, \\ 70\,\mathrm{GeV} \leqslant M_{H^\pm} &\leqslant 800\,\mathrm{GeV}\,(1400\,\mathrm{GeV}), \\ 0 < M_A &\leqslant 800\,\mathrm{GeV}\,(1400\,\mathrm{GeV}), \\ 0 < M_H &< M_A, M_{H^\pm}, \\ -25\cdot 10^4\,\mathrm{GeV}^2(-2\cdot 10^6\,\mathrm{GeV}^2) \leqslant m_{22}^2 &\leqslant -9\cdot 10^4\,\mathrm{GeV}^2, \\ 0 < \lambda_2 &\leqslant 10. \end{aligned}$$

large masses possible

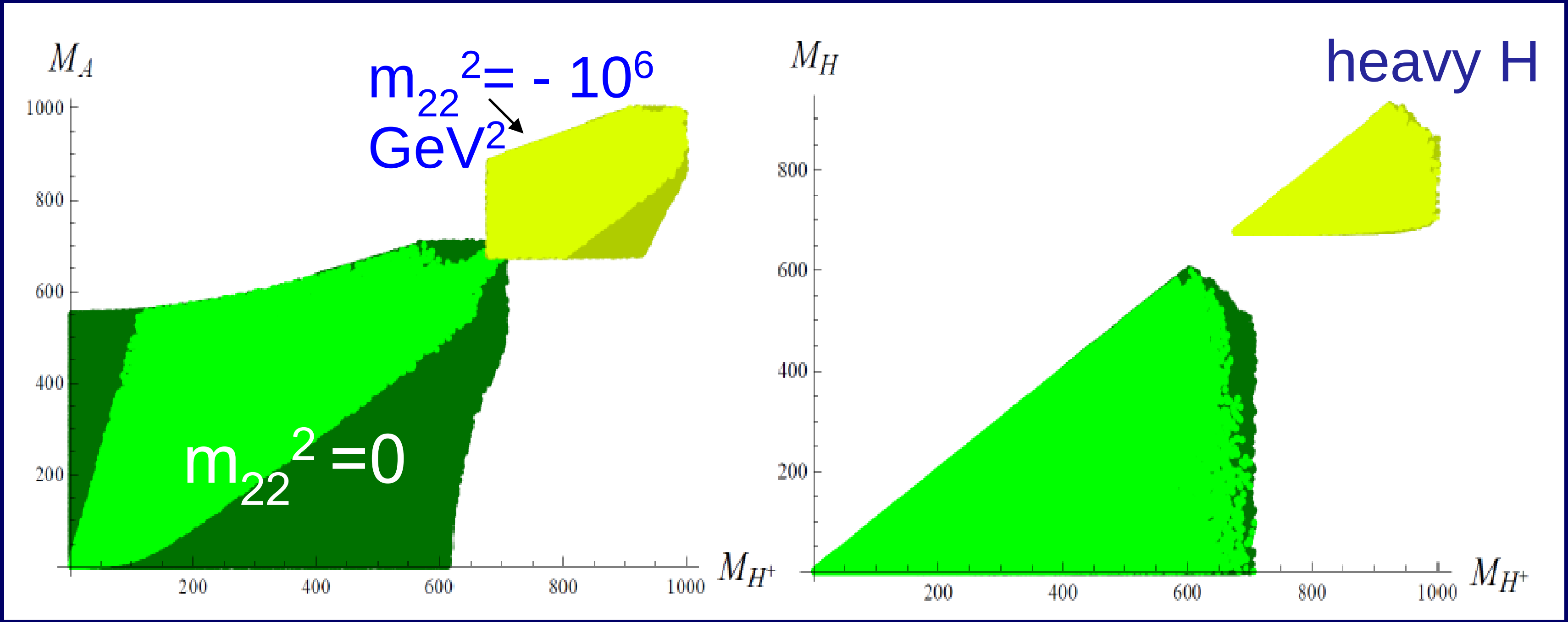
Inert Doublet Model with Mh=125 GeV

Analysis based on unitarity, positivity, EWPT constraints

Gorczyca'2011-12

$m_{22}^2 = 0$

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



$m_{22}^2 = -10^6$ GeV^2

$m_{22}^2 = 0$

heavy H

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

EWPT (pale regions)

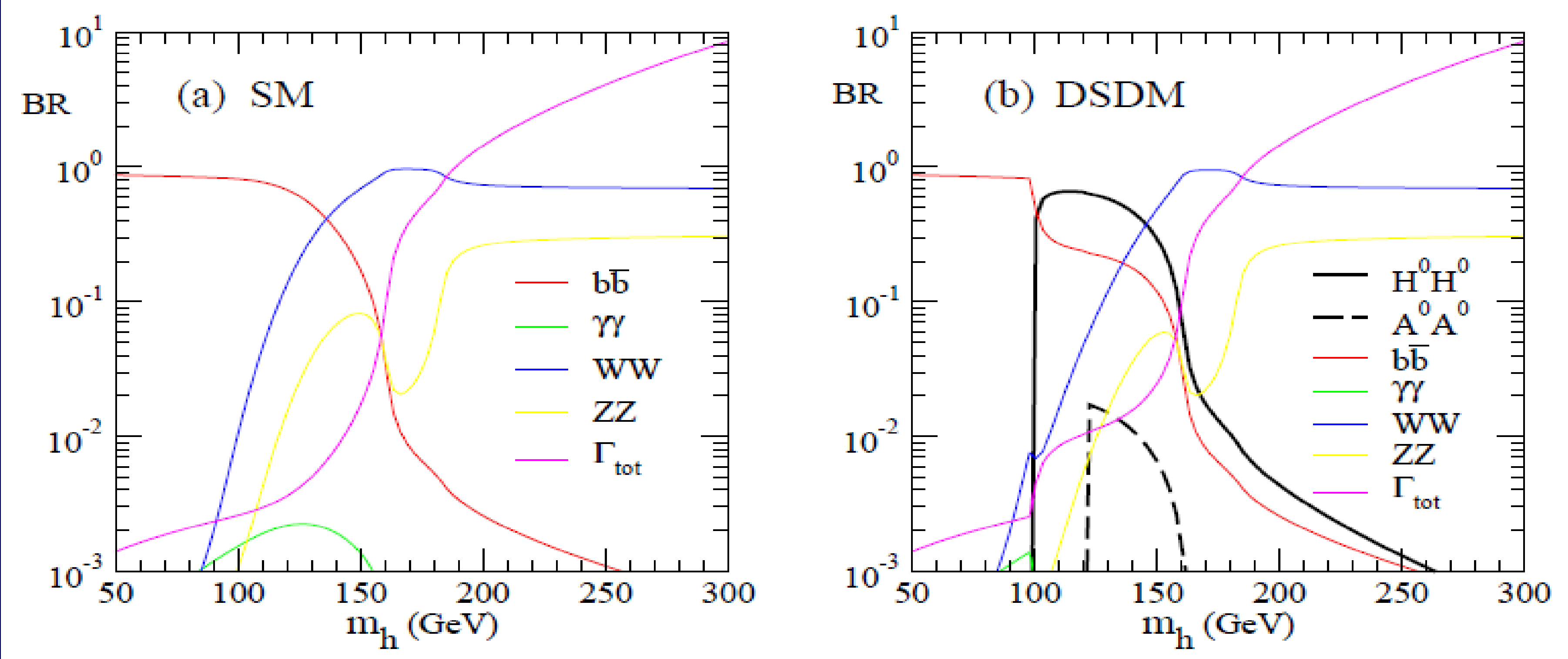
Colliders signal/constraints for IDM

Barbieri et al '2006 for heavy h; Cao, Ma, Rajasekaren' 2007 for a light h, *later many others...*

EW precision data $:(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

BR SM versus IDM

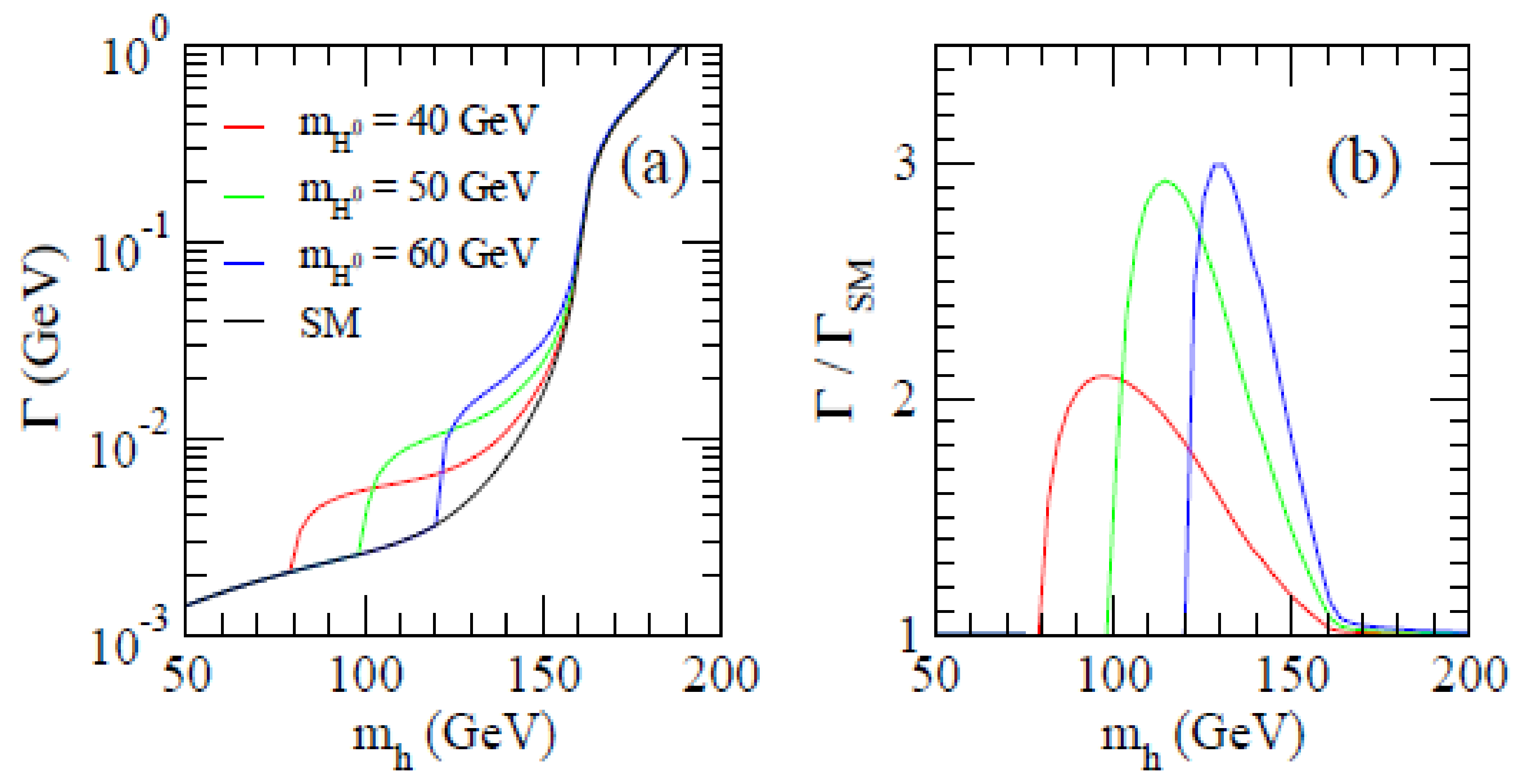
For MH=50 GeV



For $M_H = 50$ GeV, $\Delta(A,H)=10$ GeV, $M_{H+}=170$ GeV, $m_{22}=20$ GeV

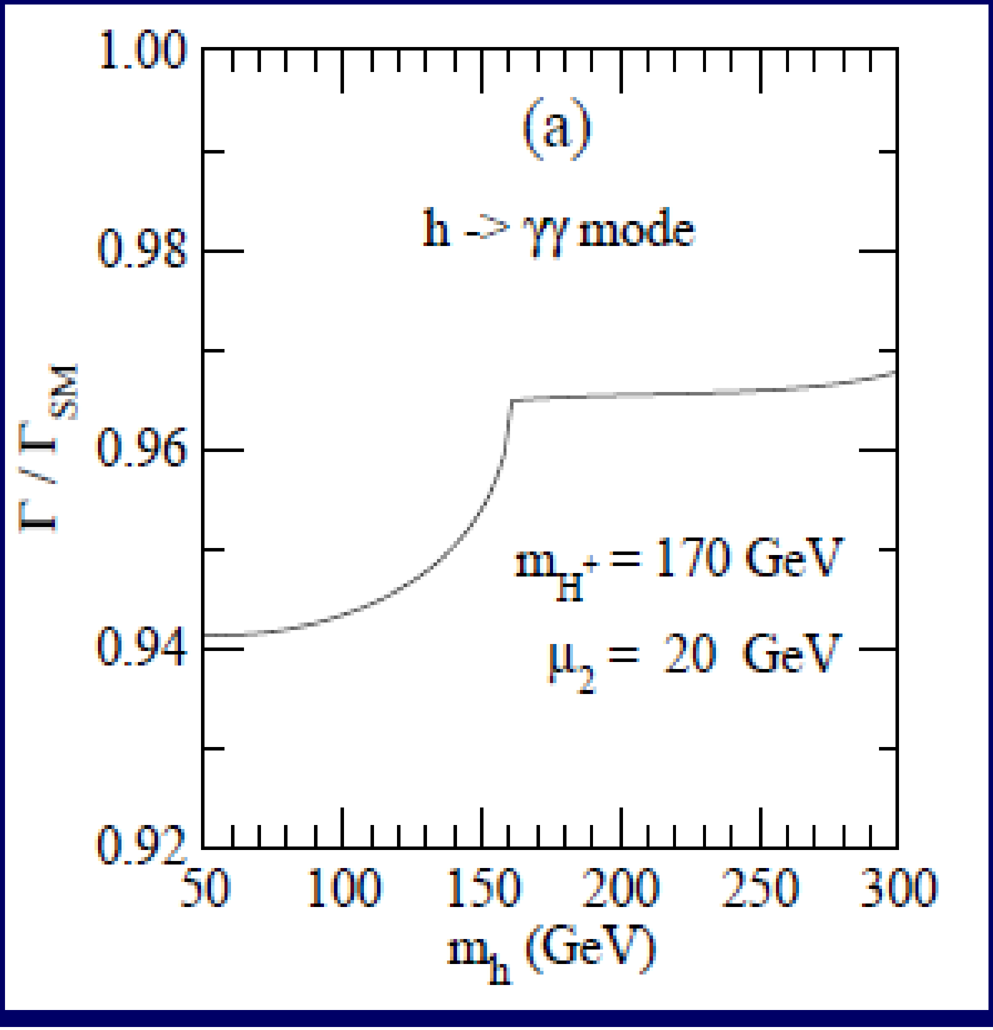
IDM – total width of h

Cao, Ma, Rajasekaren' 2007



IDM: decay width $\gamma\gamma h$

Ma'2007



For negative λ_3
It maybe larger
than in SM

$$= \frac{G_\mu \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_C Q_f^2 g_{hff} A_{1/2}(\tau_f) + g_{hWW} A_1(\tau_W) + \frac{m_{H^\pm}^2 - \mu_2^2}{\sqrt{2}\, m_{H^\pm}^2} \overset{=\lambda_3}{A_0(\tau_{H^\pm})} \right|^2 ,$$

$h \to \gamma\gamma$

Świeżewska, in preparation

[J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B 106 (1976) 292, M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, Sov. J. Nucl. Phys. 30 (1979) 711 [Yad. Fiz. 30, 1368 (1979)], P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021]

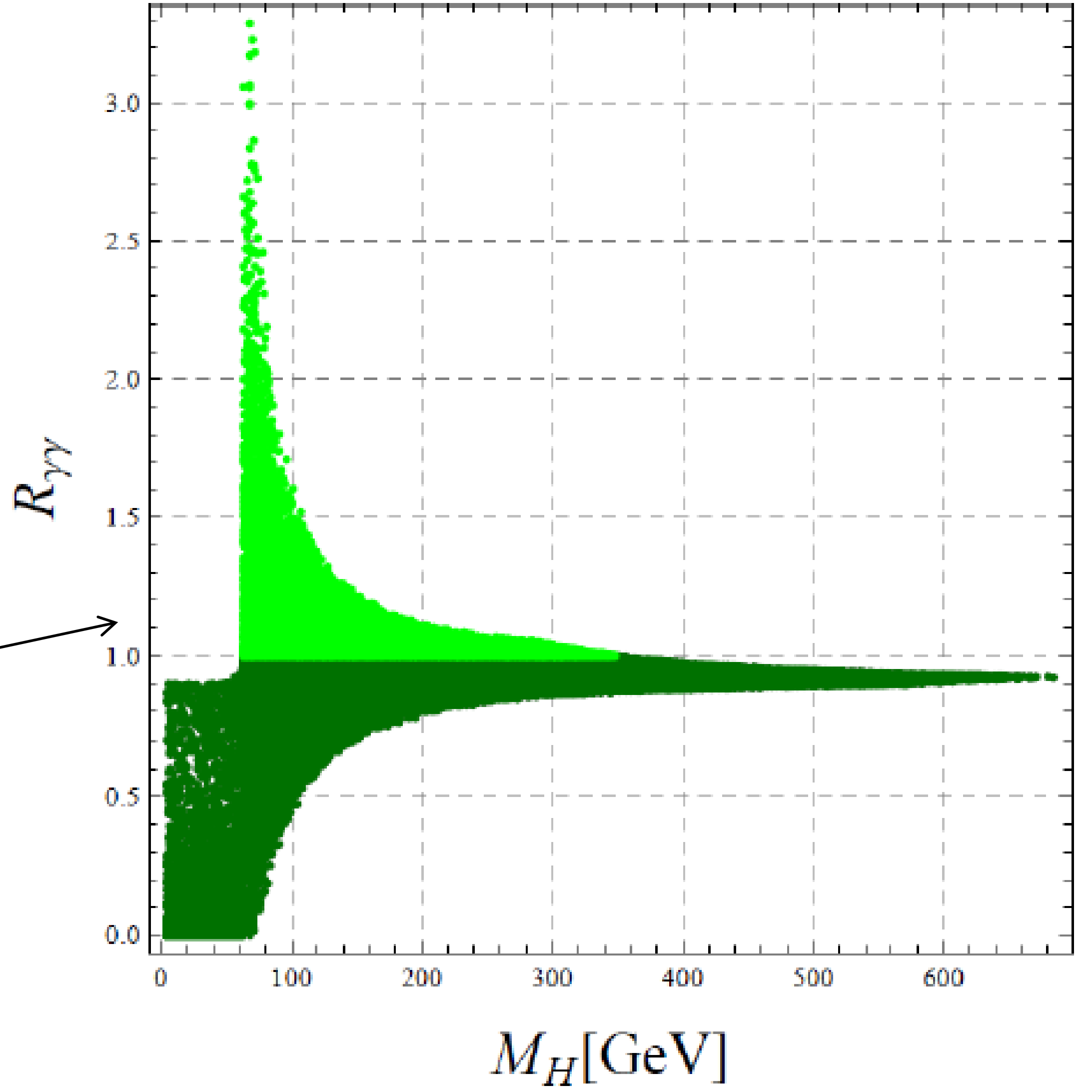
$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} = \frac{\big(\sigma(gg \to h)\mathrm{Br}(h \to \gamma\gamma)\big)^{IDM}}{\big(\sigma(gg \to h)\mathrm{Br}(h \to \gamma\gamma)\big)^{SM}} = \frac{\mathrm{Br}(h \to \gamma\gamma)^{IDM}}{\mathrm{Br}(h \to \gamma\gamma)^{SM}}$$

- Narrow width approximation
- Largest contribution to the production is from gg fusion
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$

Two sources of enhancement: modification of $\Gamma(h \to \gamma\gamma)$ or the total decay width $\Gamma(h)$.

Sources of modifications to $R_{\gamma\gamma}$ - invisible decays

Invisible decay channels open $(M_H \lessapprox M_h/2) \Rightarrow$ decay width of the Higgs boson increased so much that enhancement in $h \to \gamma\gamma$ impossible



Sources of modifications to $R_{\gamma\gamma}$ - charged scalar loop

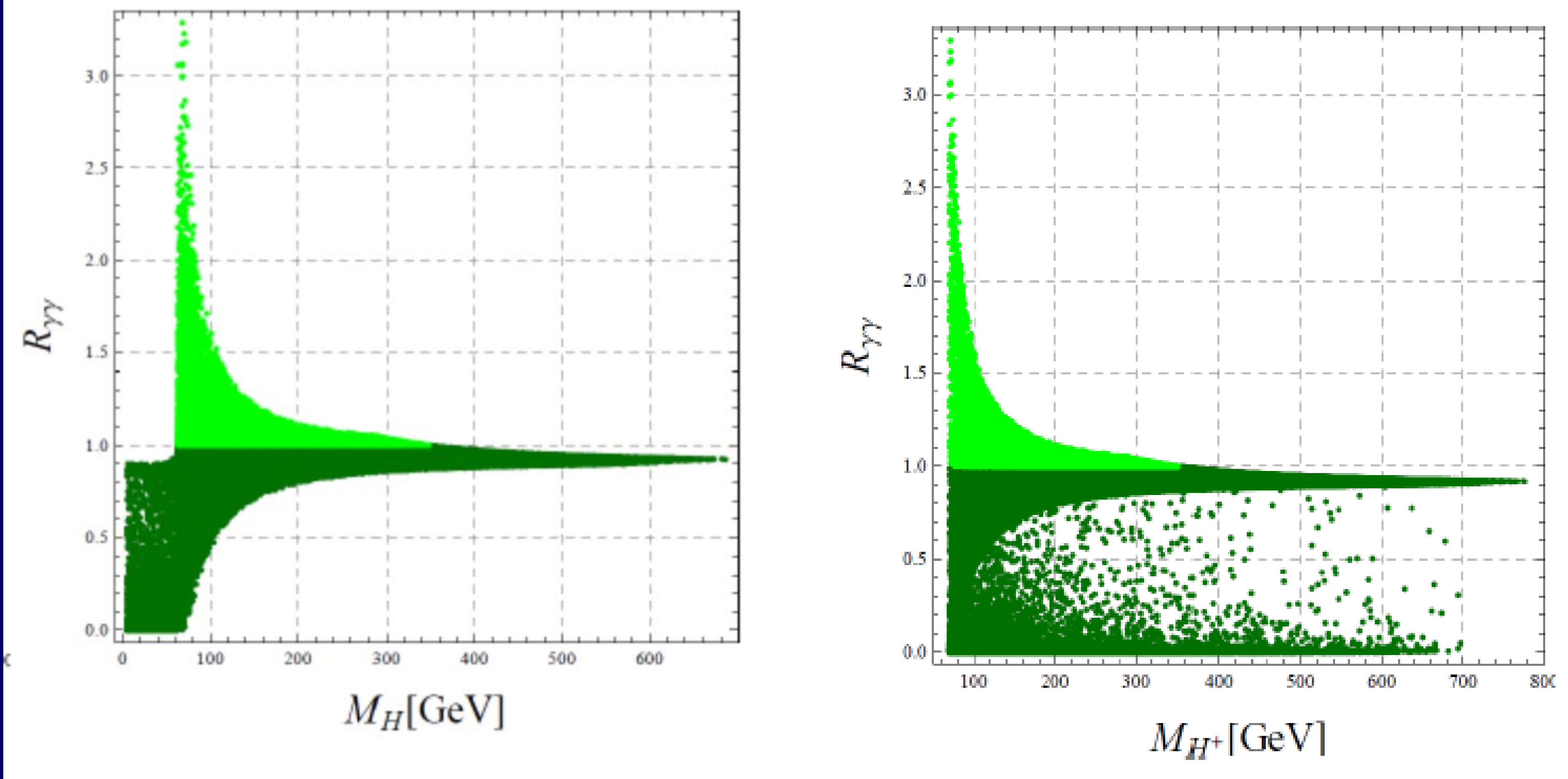
$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \frac{4}{3} g_t A_{1/2}\left(\frac{4M_t^2}{M_h^2}\right) + g_W A_1\left(\frac{4M_W^2}{M_h^2}\right) + \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

- If $h \to HH$ kinematically closed,
  $R_{\gamma\gamma} = \Gamma(h \to \gamma\gamma)^{IDM} / \Gamma(h \to \gamma\gamma)^{SM}$.
- $g_t, g_W = 1 \Rightarrow R_{\gamma\gamma}$ depends only on two of the parameters
  $M_{H^\pm}, \lambda_3, m_{22}^2$ $(M_{H^\pm}^2 = \frac{1}{2}(-m_{22}^2 + \lambda_3 v^2))$
- $R_{\gamma\gamma} > 1$ can be solved analytically

-> formula

- enhancement in $h \to \gamma\gamma$ only possible for $m_{22}^2 < -9800\ \mathrm{GeV}^2$
  $(\lambda_3 < 0)$

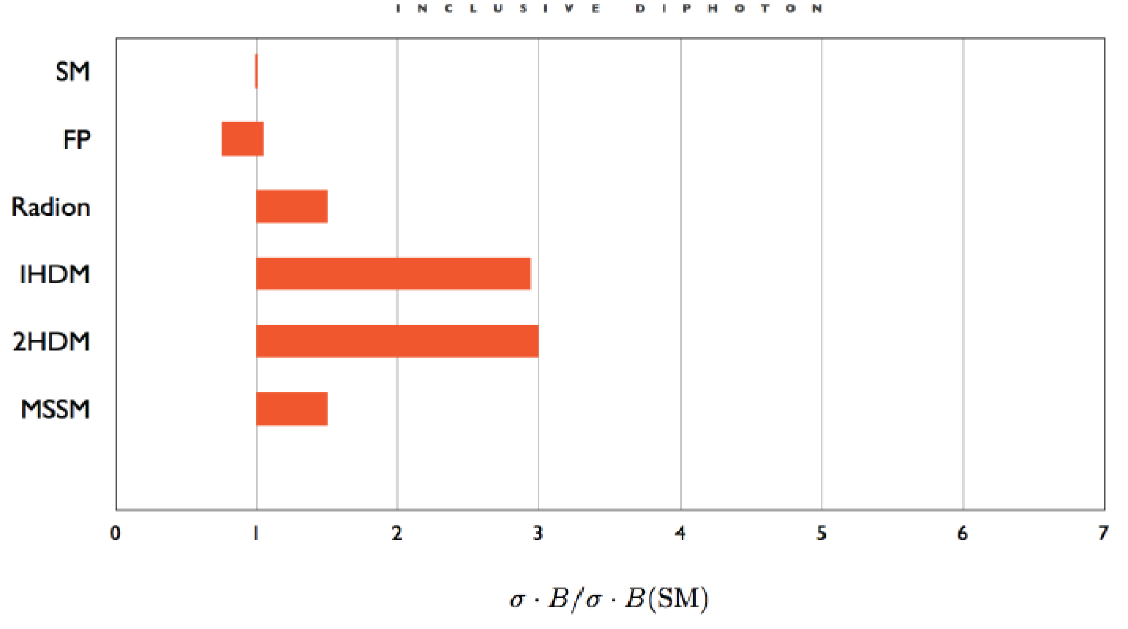
$R_{\gamma\gamma}$

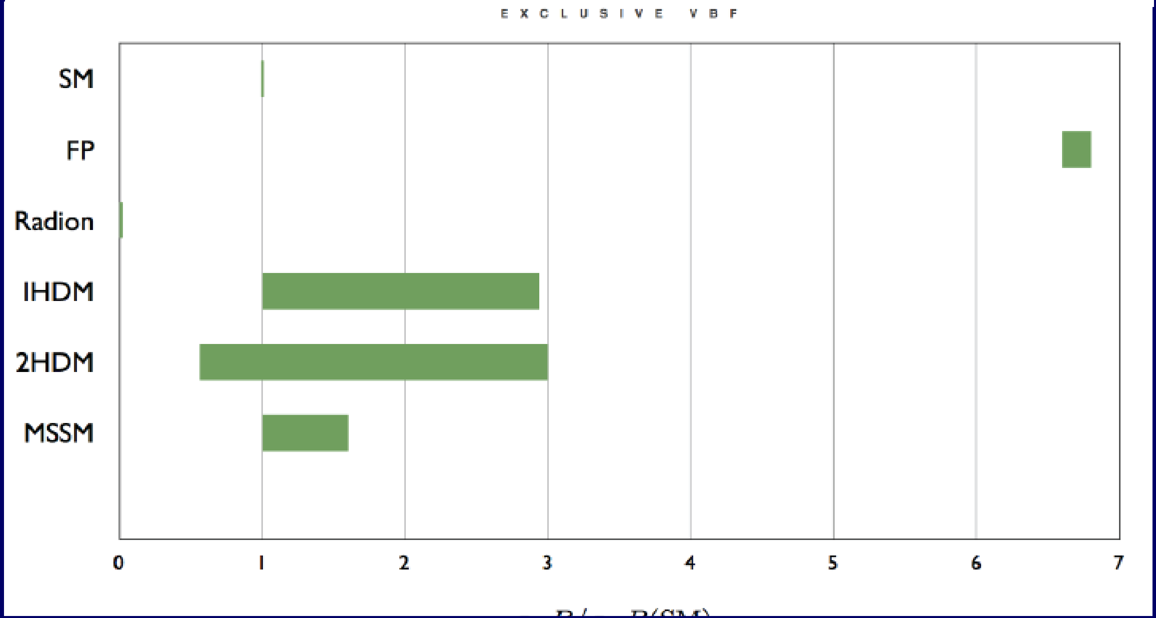


Large enhancement > 1.3 only for
M_H > 62.5 GeV and M_H+ < 130 GeV

similar result
Arhrib at al

Mimicking the SM Higgs boson-Chang..





1211.6823(29.11.2012)

inclusive

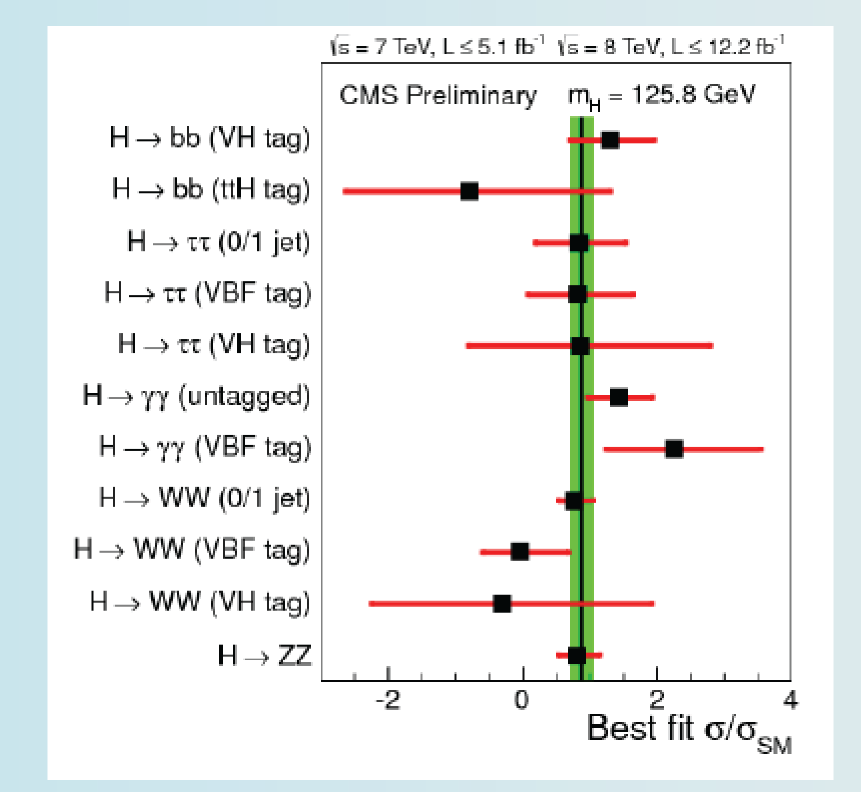
$$\frac{\sigma(X)\times B(X\to\gamma\gamma)}{\sigma(h_{\mathrm{SM}})\times B(h_{\mathrm{SM}}\to\gamma\gamma)}$$

2HDM(II), IHDM=IDM
Only taking ratio >1
(except fermiophobic)

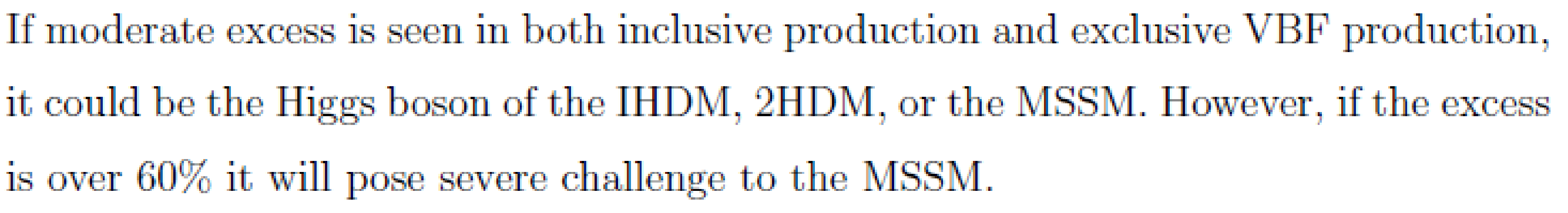
exclusive (VBF)

$$\frac{\sigma(pp\to jjX)\times B(X\to\gamma\gamma)}{\sigma(pp\to jjh_{\mathrm{SM}})\times B(h_{\mathrm{SM}}\to\gamma\gamma)}$$

Gamma-gamma enhancement



Mimicking the SM Higgs boson-Chang..


If moderate excess is seen in both inclusive production and exclusive VBF production, it could be the Higgs boson of the IHDM, 2HDM, or the MSSM. However, if the excess is over 60% it will pose severe challenge to the MSSM.

I agree

Conclusions I

- 2HDM - a great laboratory for physics BSM
- SM-like scenarios :

- 2HDM (Mixed) where *both h or H can be SM-like:*
mass of H+ between 380-600 GeV,
both for *SM-like* h (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
If $R\gamma\gamma > 1$, tan <1 and H+ heavy ~ 700 GeV
For SM-like H only ggH can >1

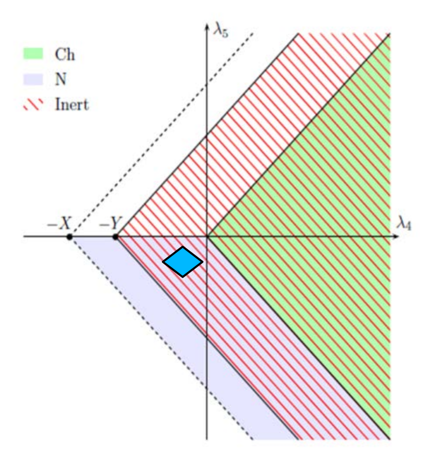
- Intert Doublet Model: h is *SM-like* and H is DM:
mass of H+ below 160 (130) GeV if $R\gamma\gamma$ >1.2 (1.3)
(Note, however that H+ has no Yukawa couplings)
If $R\gamma\gamma > 1$, H mass 62.5 GeV (below160 GeV if > 1.2)

Evolution of the Universe in 2HDM– through different vacua in the past

Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev,MK, Sokołowska PRD 2010,
Sokołowska 2011

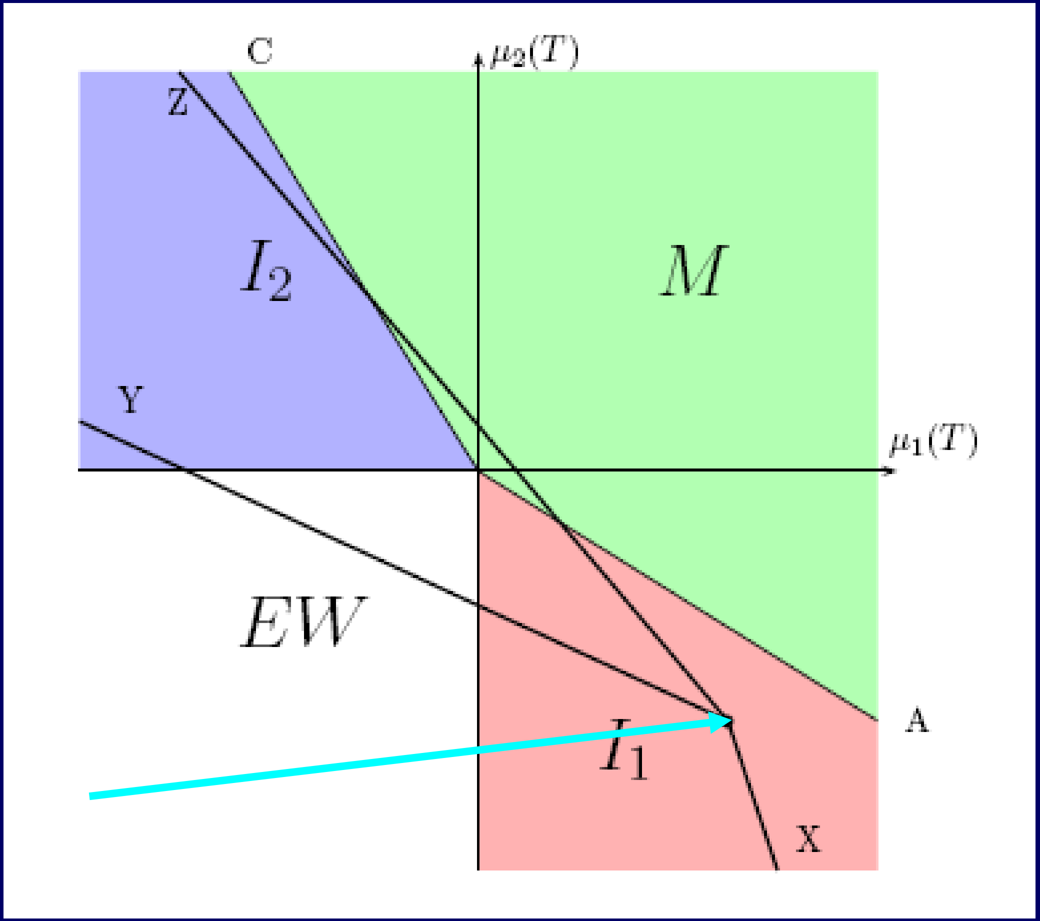
We consider 2HDM with an explicit D symmetry assuming that today the Inert Doublet Model describes reality. In the simplest approximation only *mass terms* in V vary with temperature like T^2, while λ's are fixed

Various evolution from EWs to Inert phase possible in one, two or three steps, with 1st or 2nd type phase transitions...



Non-restoration of EW symmetry R <0 possible

c_1 or $c_2 < 0$



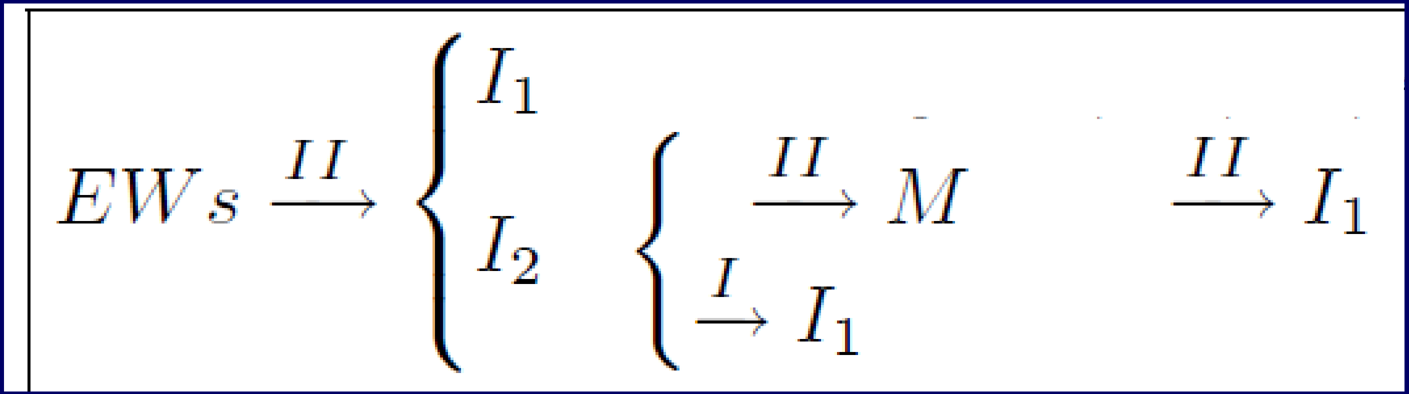
There is only one evolution with EW restoration in the past

- in one step and with $R_{\gamma\gamma} > 1$!

Sokołowska PhD,Thesis 2012

Conclusions II

- Intert Doublet Model in agreement with data
- Inert phase today - what was in the Past ?
- Various evolution scenarios :



$$EWs \xrightarrow{II} \begin{cases} I_1 \\ I_2 \begin{cases} \xrightarrow{II} M \xrightarrow{II} I_1 \\ \xrightarrow{I} I_1 \end{cases} \end{cases}$$

- Can we find clear signals ?

  -Ch breaking in the past?-excluded if DM neutral

  DM matter may appear later

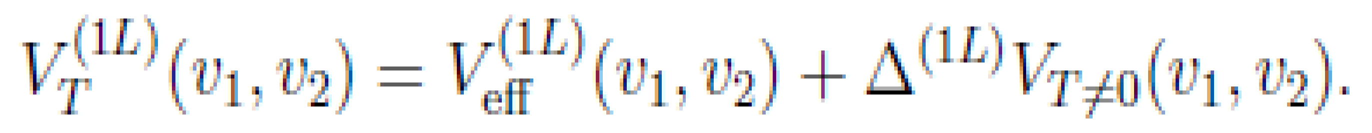
  - Inert phase today and $R_{\gamma\gamma}$ >1 for 125 GeV Higgs

  EW symmetry breaking in one step

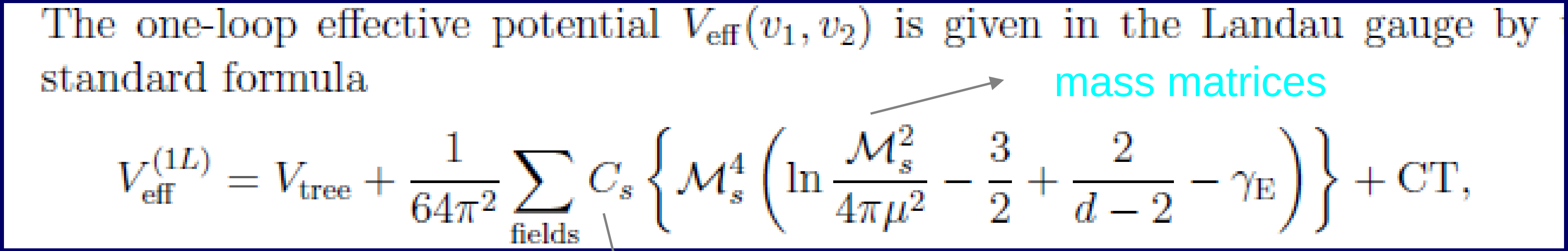
Beyond T2 corrections – strong 1st order phase transition in IDM?

G. Gil MsThesis'2011, G.Gil, P. Chankowski, MK 1207.0084 [hep-ph] PLB 2012

We applied one-loop effective potential at T=0 (Coleman-Wienberg term) and temperature dependent effective potential at T≠0 (with sum of ring diagrams)



$$V_T^{(1L)}(v_1,v_2) = V_{\rm eff}^{(1L)}(v_1,v_2) + \Delta^{(1L)}V_{T\neq 0}(v_1,v_2).$$



The one-loop effective potential $V_{\rm eff}(v_1,v_2)$ is given in the Landau gauge by standard formula

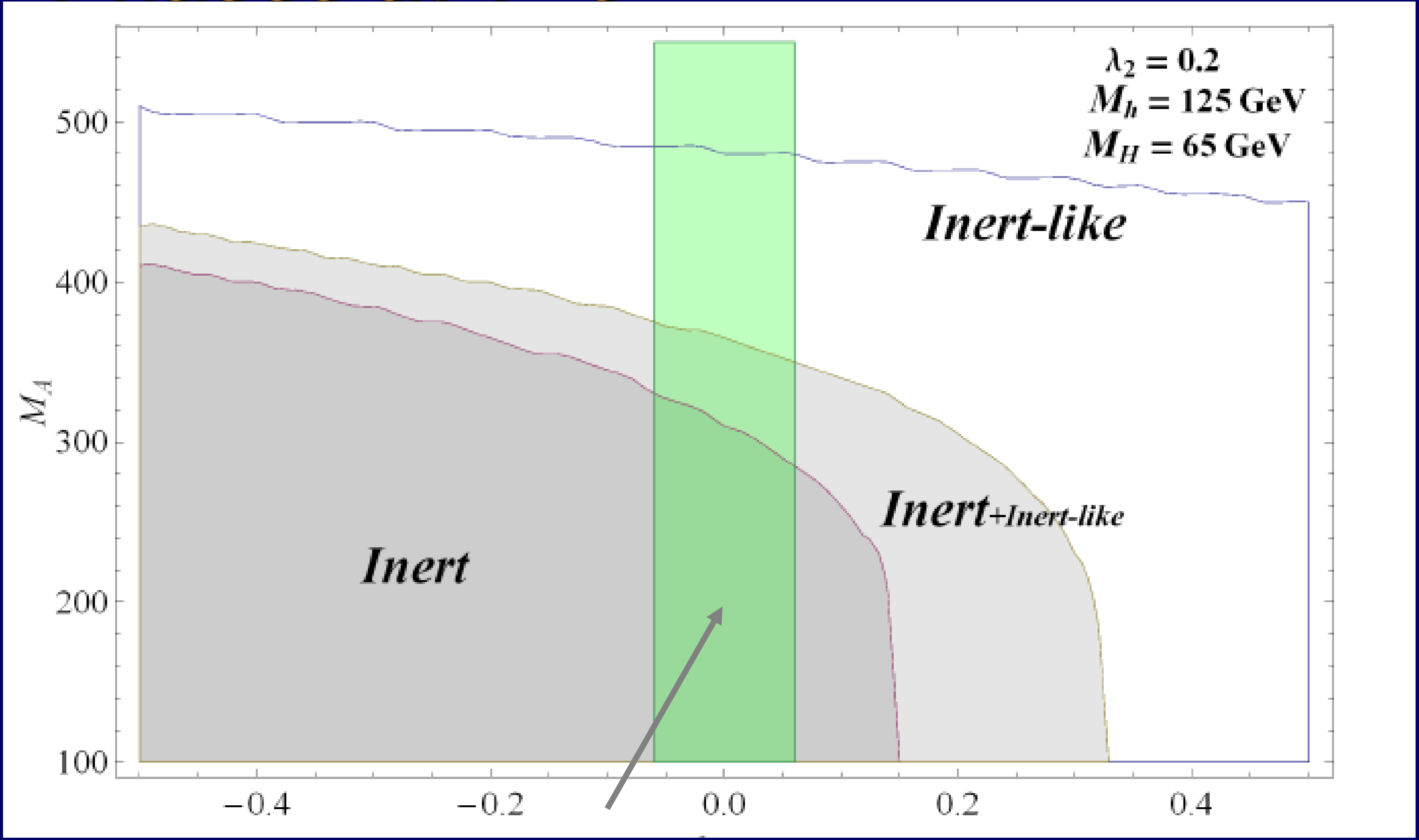
mass matrices

$$V_{\rm eff}^{(1L)} = V_{\rm tree} + \frac{1}{64\pi^2}\sum_{\rm fields} C_s \left\{ \mathcal{M}_s^4 \left(\ln\frac{\mathcal{M}_s^2}{4\pi\mu^2} - \frac{3}{2} + \frac{2}{d-2} - \gamma_{\rm E} \right) \right\} + {\rm CT},$$

number of states

counter terms →

Phases at T=0



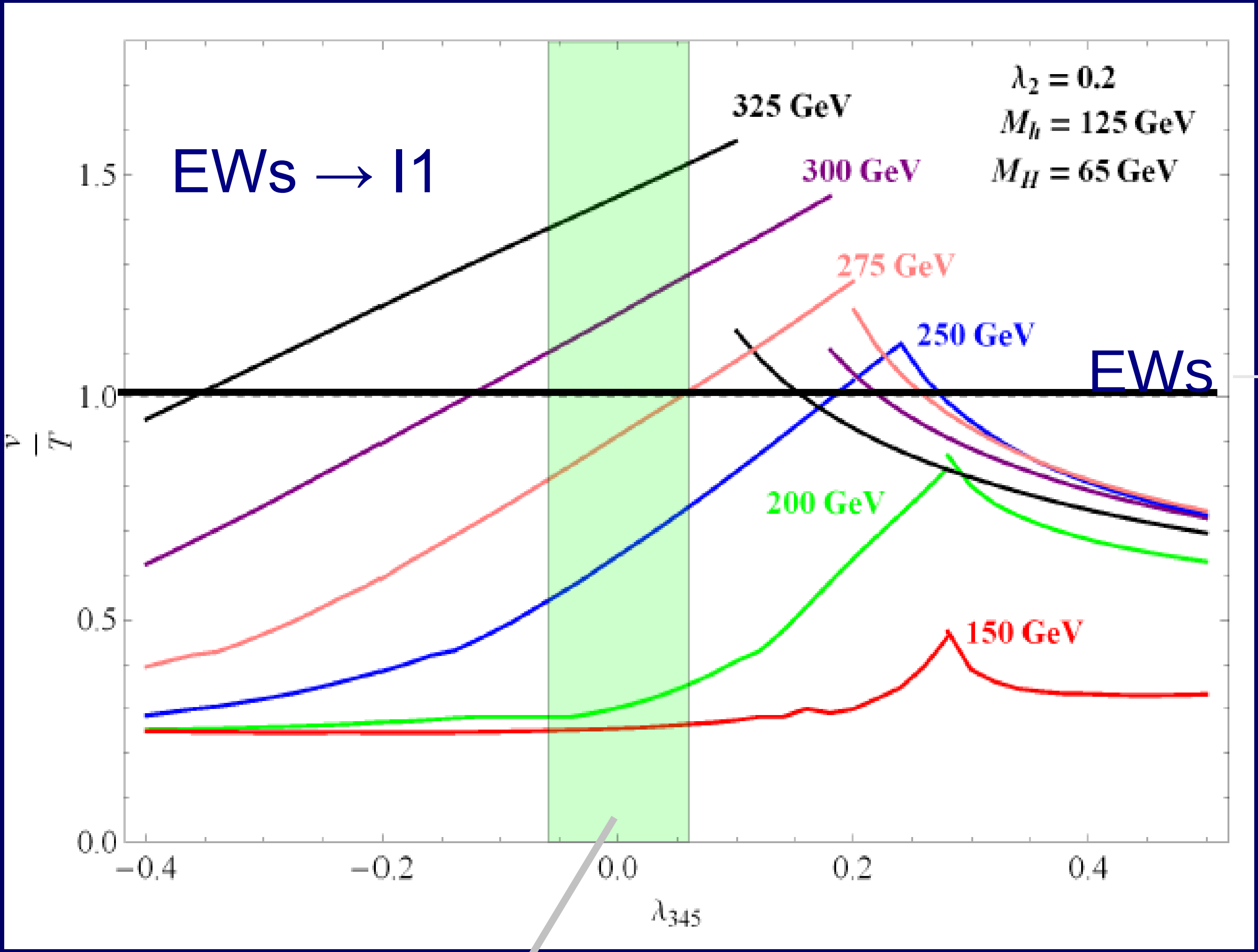
Xenon100 bound

λ_{345}

Results for $v(T_{EW})/T_{EW}$

Mh=125 GeV, MH=65 GeV, λ2=0.2

strong 1st order
phase transition
if ratio > 1



EWs → I1

EWs → I2 → I1

Allowed
MH+=MA
between 275
and 380 GeV
(one step)

λ_{345}

Xenon100 bound

Conclusion III

Strong first order phase transition in IDM possible for realistic mass of Higgs boson (125 GeV)

and DM (~65 GeV) for

1/ heavy (degenerate) H+ and A with mass

275 -380 GeV

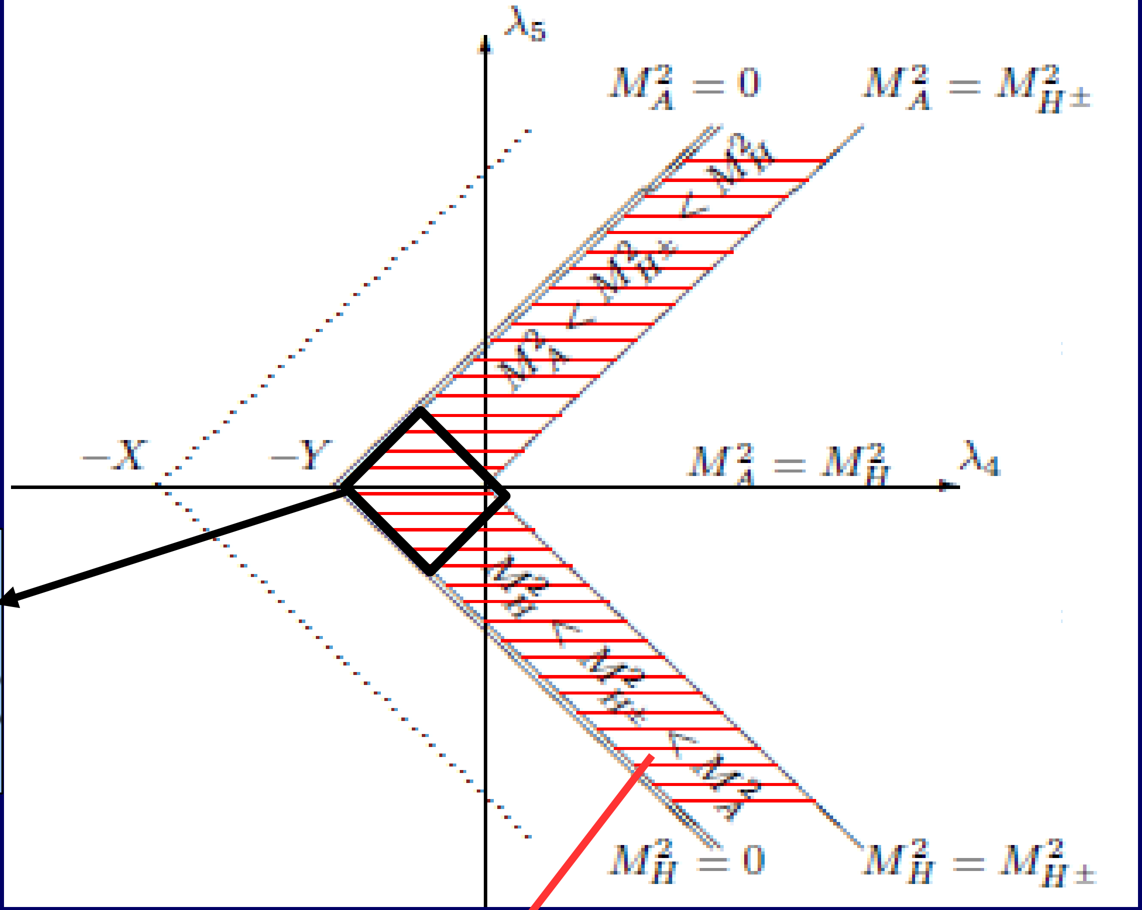
2/ low value of hHH coupling $|\lambda_{345}| < 0.1$

3/ Coleman-Weinberg term important

Our results in agreement with recent papers on IDM
Borach, Cline 1204.4722
Chowdhury et al 1110.5334 (DM as a trigger of strong EW PT)
(on 2HDM Cline et al, 1107.3559 and Kozhusko..1106.0790)

Dark scalar masses

$Y = M_{H+}^2 \, 2/v^2$



here H+
the heaviest

here H is the lightest ($\lambda_5 < 0$) – our DM

Loop couplings ggh/H, γγh/H

$\Gamma(h/H \to gg, \gamma\gamma)$

including exp. uncertainties

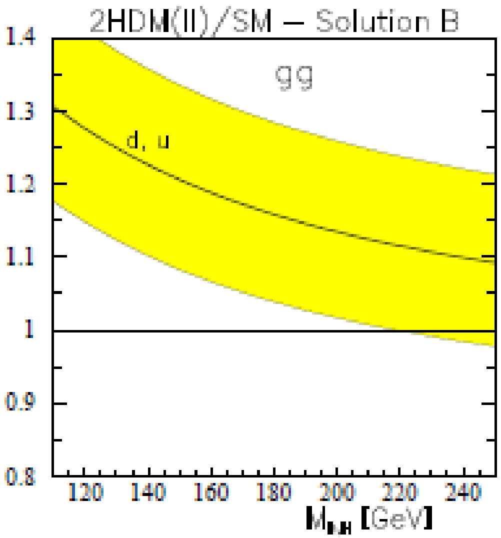
$2HDM(Z_2)$ = Mixed

Ginzburg, Osland, MK '2001

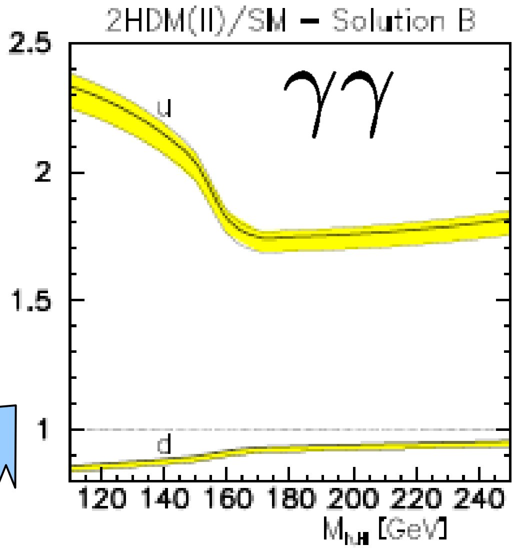
Tree couplings as in SM - close to 1 (solution A)

large non-decoupling effects due to heavy $H^\pm$. (600 GeV)

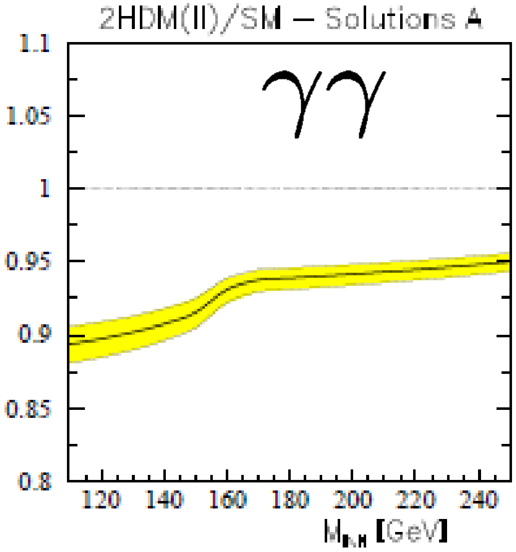
2HDM(II)/SM – Solution B



2HDM(II)/SM – Solution B

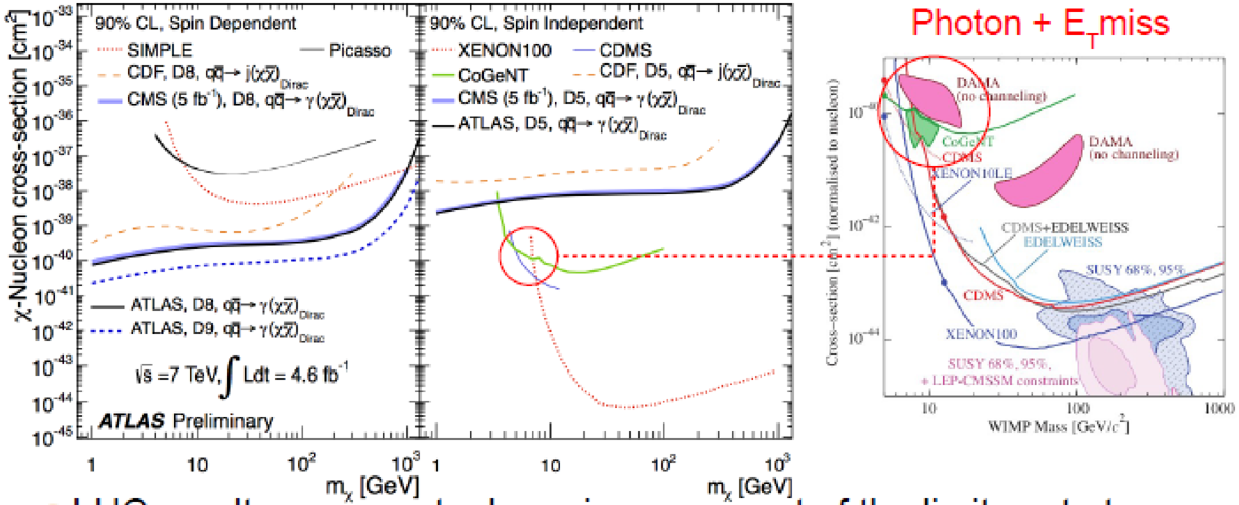


2HDM(II)/SM – Solutions A



solution B → „wrong" signs of fermion couplings

WIMP search



- LHC results represent a large improvement of the limits set at Tevatron
- Limits on scattering σ : ~10^{-40}-10^{-41} cm^2 (SD) and ~10^{-38} cm^2 (SI) for m_χ<100 GeV
- Not enough sensitivity yet to exclude/confirm CoGeNT/DAMA excess at ~10 GeV in case of D1/D5 models