ECFA 2013 Workshop

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Higgs Physics at PLC

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9 good reasons to build PLC

Introduction to Photon2007

1. Precision measurements of the light Higgs boson production (->bb) and distinguishing SM-like scenarios
1. Testing Higgs selfinteraction
2. Higher mass reach and covering LHC wedge
3. Establishing CP property of Higgs bosons

5. Search for SUSY particles

6. Complementarity to ILC and LHC

7. Photon structure and QCD tests

8. Anomalous W and t couplings

9. New physics in $\gamma\gamma \rightarrow \gamma\gamma$

LHC

Higgs-like particle with mass~125-126 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

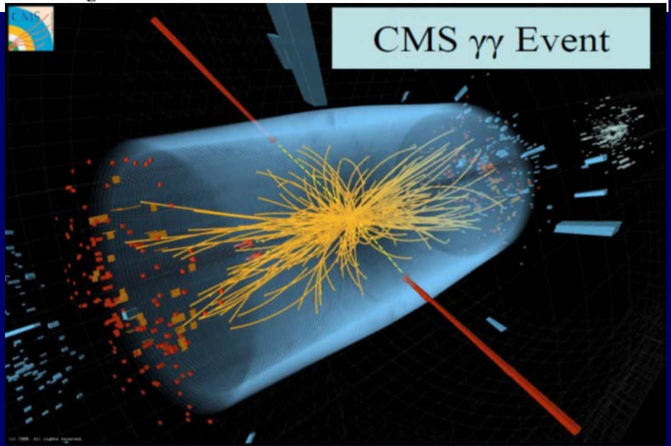
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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

125 GeV particle $\mathcal{H}$

What it is?

H_{SM} - Higgs boson of SM ?

h or H of CP-conserving 2HDM ?

other scalar particle ?

SM-like scenario observed

all measured $\mathcal{H}$ couplings are close to

the SM-prediction for *absolute value*

with I. Ginzburg

4 interpretations of these data possible

1/ with all tree-level couplings as in the SM

2/ with all these couplings close to SM-values beside $tt\mathcal{H} \sim (-)\, tt\, H_{SM}$

3/ as in 1/ but in addition new heavy charged particles contributing to the loop couplings

4/ the observed signal is not due to one particle but it is an effect of two or more particles, not resolved experimentally -- the degenerated Higgses

BSM: 2/3/4/ with modified vs SM $\mathcal{H}\gamma\gamma$, $\mathcal{H}Z\gamma$

What PLC can do for

125 GeV $\mathcal{H}$?

Heavy Higges after discovery of $\mathcal{H}$?

SM-like scenarios for 2HDMs

- In many models SM-like scenarios are possible

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*
  - Inert Doublet Model, only *one SM-like Higgs h*

Inert Doublet Model

Ma,…'78
Barbieri..'06

Symmetry under Z_2 transf. $\Phi_S \to \Phi_S$ $\Phi_D \to - \Phi_D$
both in L (V and Yukawa interaction = Model I only Φ_S)
and in the vacuum:

Today

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

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 $\Phi_2 \to \Phi_D$ Dark doublet D

The Inert Doublet Model: An Archetype for Dark Matter, Lopez Honorez,..Tytgat ..07

Confronting with data

Ma,..2006,..
**B. Gorczyca(Świeżewska), Thesis2011, 1112.4356, 1112.5086 ,*
Posch..2011, Dolle, Su…
Arhrib..2012, Chang…2012

Constraints:

vacuum stability,

perturbative unitarity

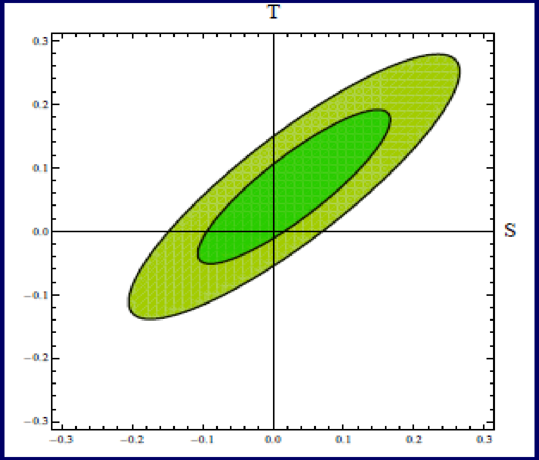
condition for a specific vacuum

Data:

EWPT (S and T)

LEP, LHC and DM data

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



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

In contrast Mixed Model (II) with 5 Higgses

sum rules for relative couplings eg. $(\chi^h{}_V)^2 + (\chi^H{}_V)^2 = 1$

can have SM-like h or H (with $\chi_V = 1$) V=W/Z

Unitarity constraints on parameters of V (D symmetry)

B. Gorczyca (Świeżewska), 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

Kanemura et al. 93; 2001
Akeroyd,Arhrib,Naimi, 2000….

Pert. unitarity constraints on lambda's

B. Gorczyca, MSc Thesis, July 2011

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

(hold for Mixed as well)

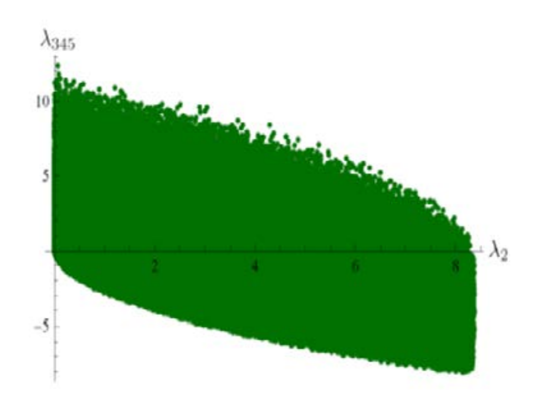
and for combinations

Couplings for dark particles in IDM

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

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

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



Condition for the Inert vacuum

IDM:

- $\langle \phi_S \rangle = \frac{v}{\sqrt{2}}$, $\langle \phi_D \rangle = 0$
- 5 physical scalars: $h, H, A, H^{\pm}$ (h - the Higgs boson)
- The Inert vacuum can be realized only if:

$$m_{11}^2 > 0, \quad \lambda_1 > 0, \quad \lambda_3 v^2 \geqslant m_{22}^2,$$
$$(\lambda_3 + \lambda_4 \pm \lambda_5) v^2 \geqslant m_{22}^2, \quad \frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}$$

For 125 GeV h: $M^2_h = m_{11}{}^2 = \lambda_1 v^2$ and max λ_2 value

upper limit: $m_{22}{}^2 < 9.\ 10^4$ GeV^2

Testing Inert Doublet Model

Ma'2006,.Barbieri 2006, Dolle,Su, Gorczyca(Świeżewska), MSc T2011, 1112.4356, 1112.5086, Posch, 2011, Arhrib..2012

Using properties of

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

Using properties of dark scalars

- masses depend on m_{22}^2
- the dark scalars D interact always in pairs!

λ_{345}

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

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

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

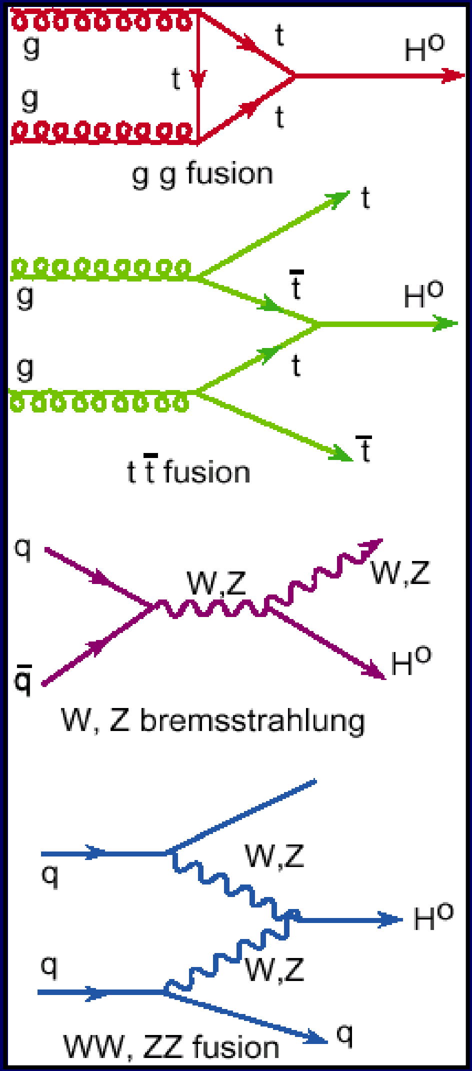
D couple to V = W/Z (eg. AZH, $H^- W^+ H$), not DVV!

Quartic selfcouplings D^4 proportional to λ_2

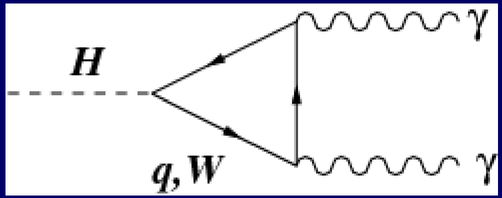
hopeless to be measured at colliders! *(→ DM D. Sokołowska)*

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

LHC: loop couplings hgg, hγγ (hZγ)



for hgg - b and t important



for h γγ

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

In SM W and t interfer destructively

so if coupling of t may change

sign an enhancement possible

2HDM (Mixed) Ginzburg, MK, Osland,2001;

Carmi et al.,,,, in 2011,12

In IDM only hγγ may differ from SM

$h \to \gamma\gamma$

Świeżewska, MK (Dec. 2012)

[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]

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

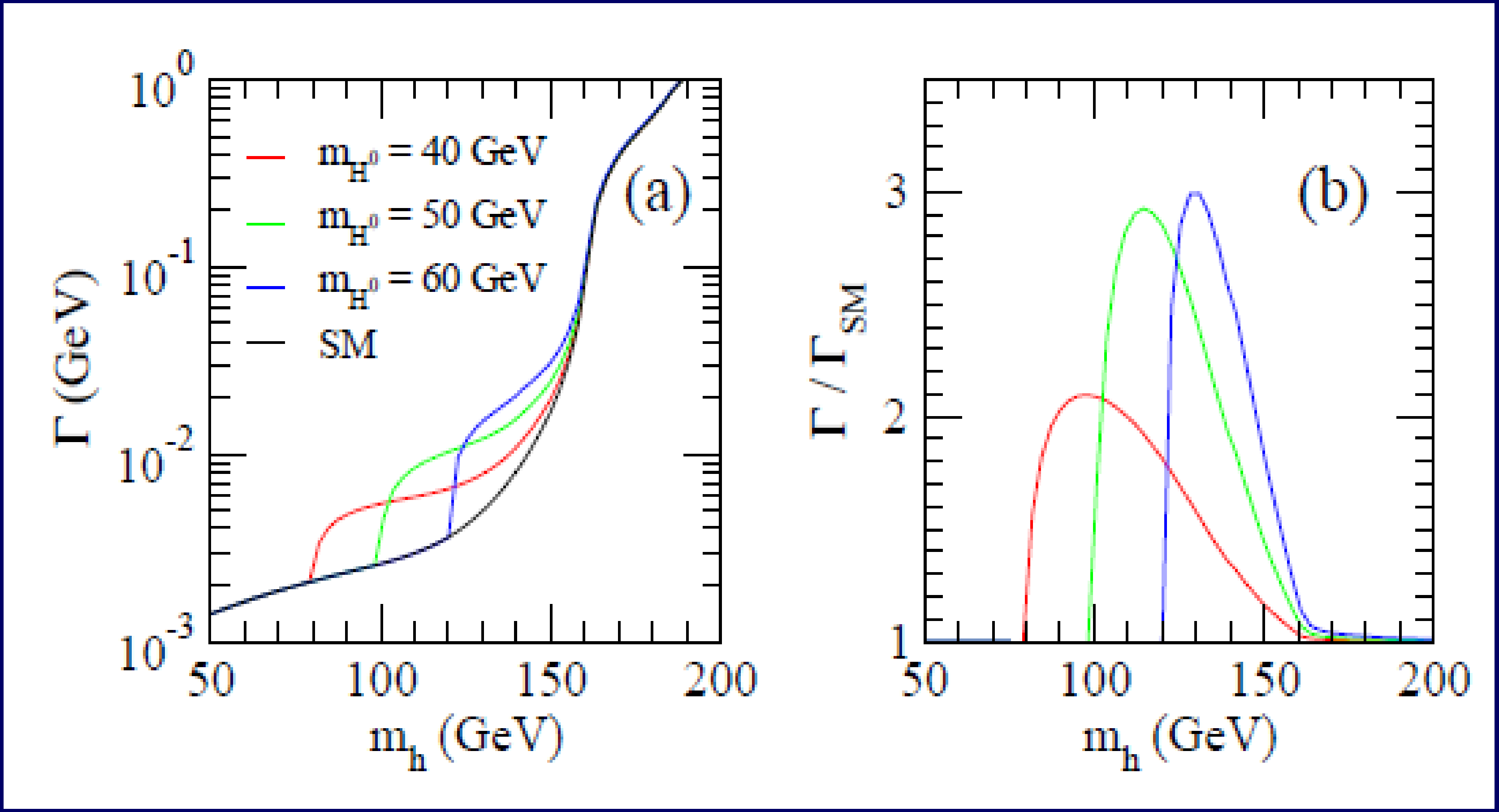
- Narrow width approximation
- Largest contribution to the production is from gg fusion
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$

Two sources of possible enhancement:

modification of the partial ($h \to \gamma\gamma$) or the total decay width ($h \to X$)

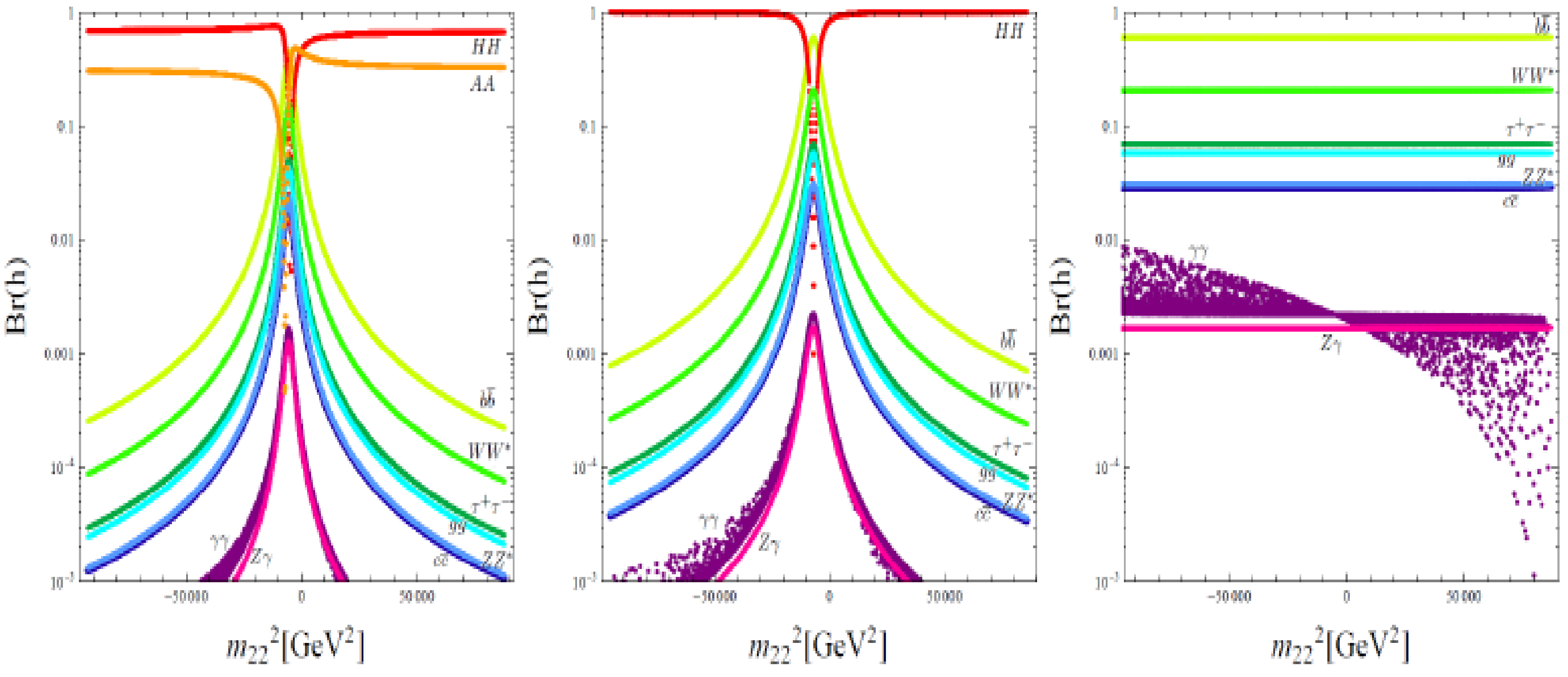
IDM – total width of h

Cao, Ma, Rajasekaren' 2007



Br of Higgs boson (125 GeV)
HH and AA channels open or closed

for positive and negative m_{22}^2 *for positive as Arhrib..'12*



H(50 GeV),A(60 GeV) both open

H open H(60 GeV),A(>63 GeV)

H(75 GeV),A(>63 GeV) both closed

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

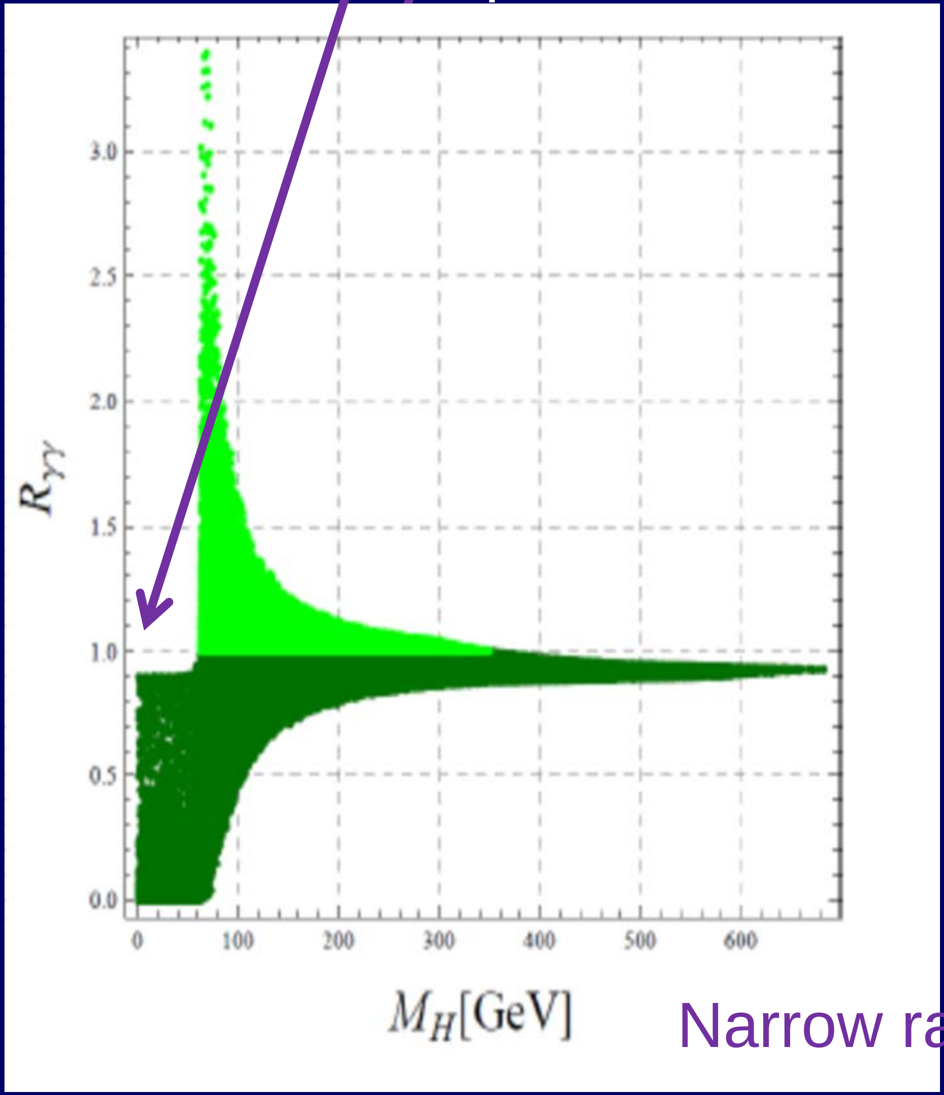
-> formula

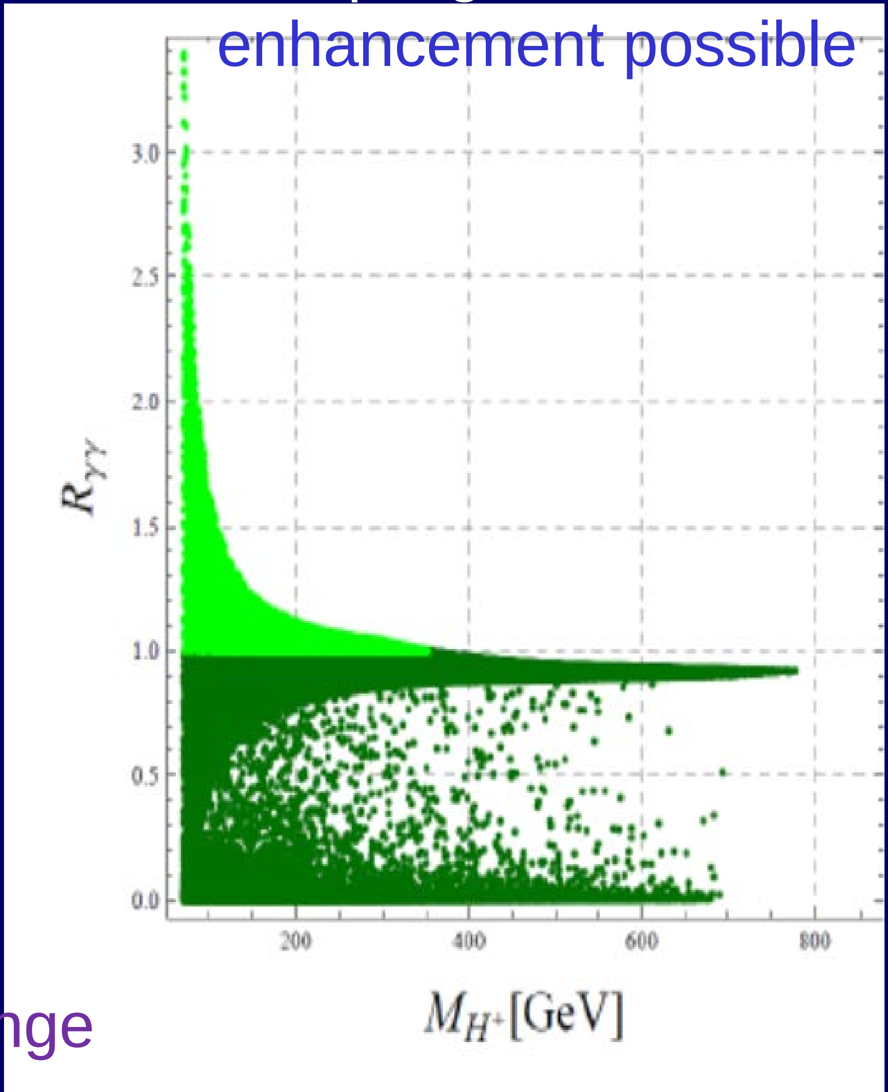
- enhancement in $h \to \gamma\gamma$ only possible for $m_{22}^2 < -9800\ \mathrm{GeV}^2$ $(\lambda_3 < 0)$

$R_{\gamma\gamma}$ as a function of mass H and H +

Invisible decays makes enhancement impossible

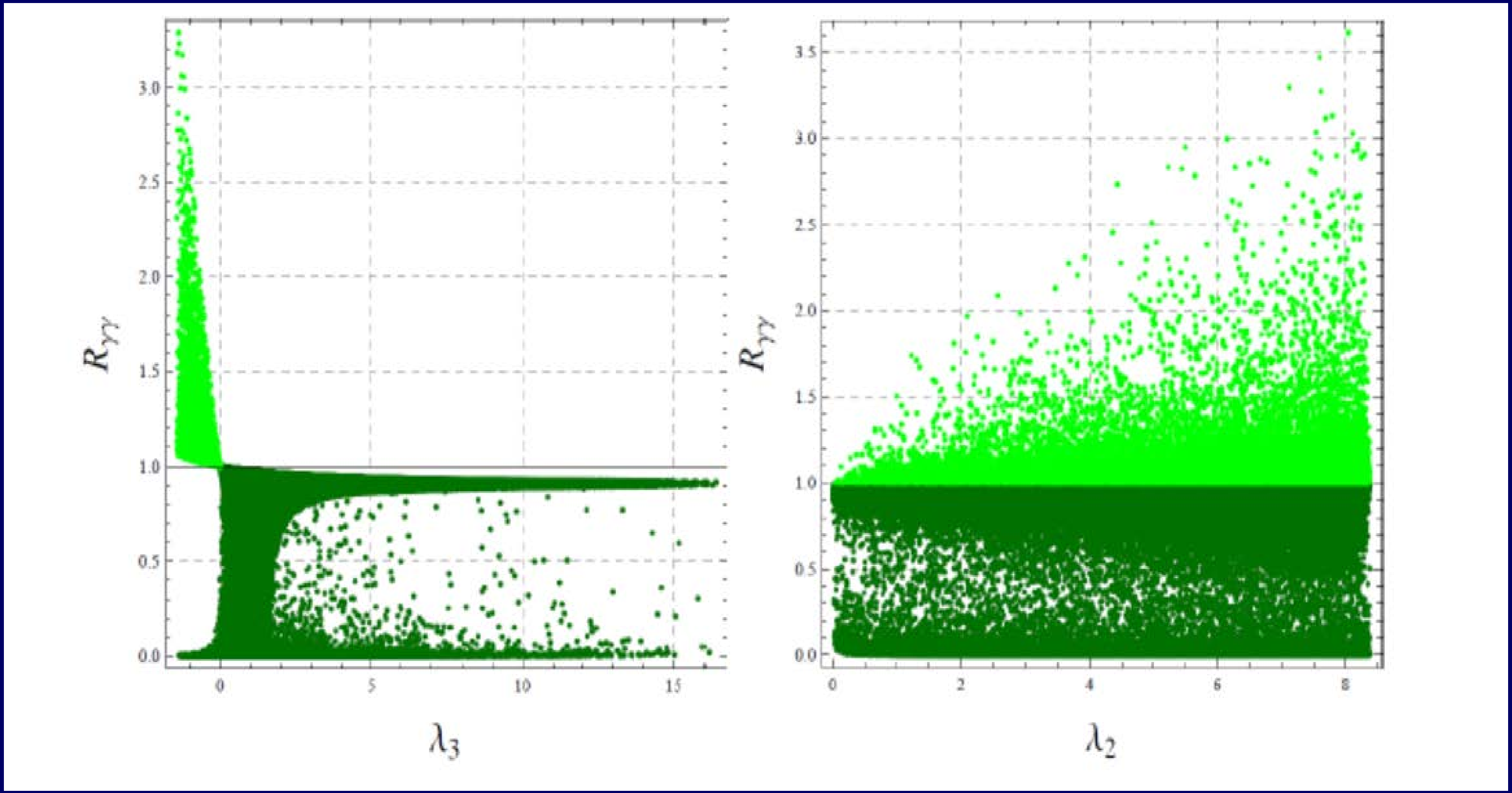
Light H+ with proper sign of hH+H- coupling makes enhancement possible





Narrow range

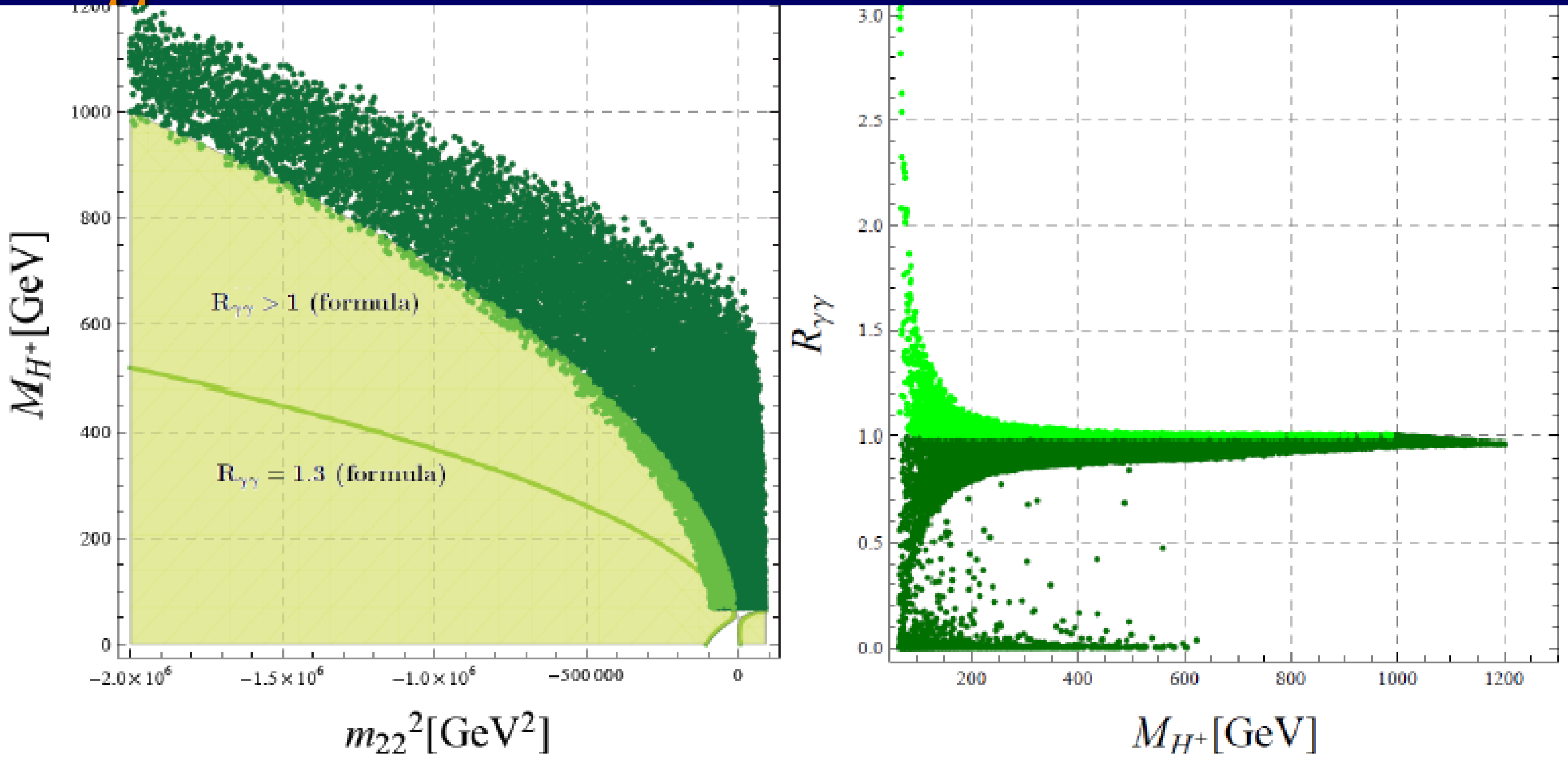
$R_{\gamma\gamma}$ as a function of λ_3 and λ_2



similar result
Arhrib at al

enhancement for negative λ_3

$R_{\gamma\gamma}$ - wide range of m_{22}^2



similar result
Arhrib at al

- $R_{\gamma\gamma} \geqslant 1$ also for big $M_{H^\pm}$, e.g. $M_{H^\pm} = 1$ TeV
- Substantial enhancement, $R_{\gamma\gamma} \geqslant 1.3$, only for $M_{H^\pm} \lesssim 130$ GeV

Conclusions

- SM-like scenarios in 2HDM

  - 2HDM (Mixed) where *both h or H can be SM-like*

  - Inert Doublet Model: h is *SM-like* and H=DM
  mass of H+ below 135 GeV if $R\gamma\gamma$ >1.3
  (H+ has no Yukawa couplings)
  If $R\gamma\gamma$ >1 H mass >62.5 GeV
  and <135 GeV, if $R\gamma\gamma$ > 1.3

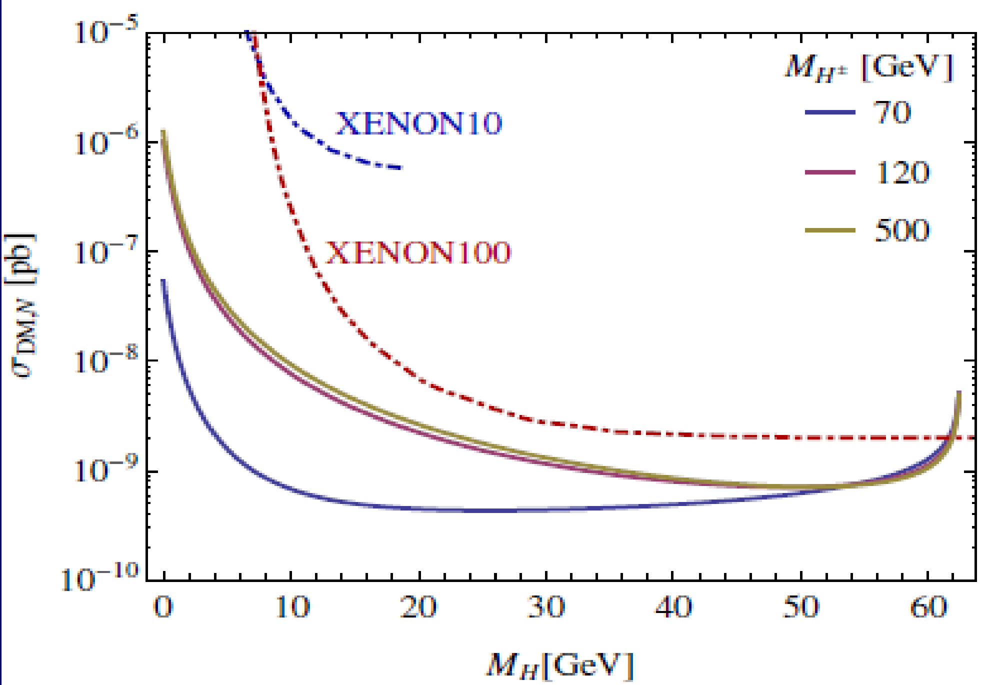
  If $R\gamma\gamma > 1.3$ $-1.46 < \lambda_3 , \lambda_{345} < -0.24$

Constraining **Inert** Dark Matter by $R_{\gamma\gamma}$ and WMAP data

M. Krawczyk, D. Sokolowska, P. Swaczyna, B. Swiezewska

$$\Omega_{DM} h^2 = 0.1126 \pm 0.0036.$$

$$\text{ATLAS} : R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$$
$$\text{CMS} : R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$$



(b) $R_{\gamma\gamma} > 0.8$

$h \to AA$ channel is closed.

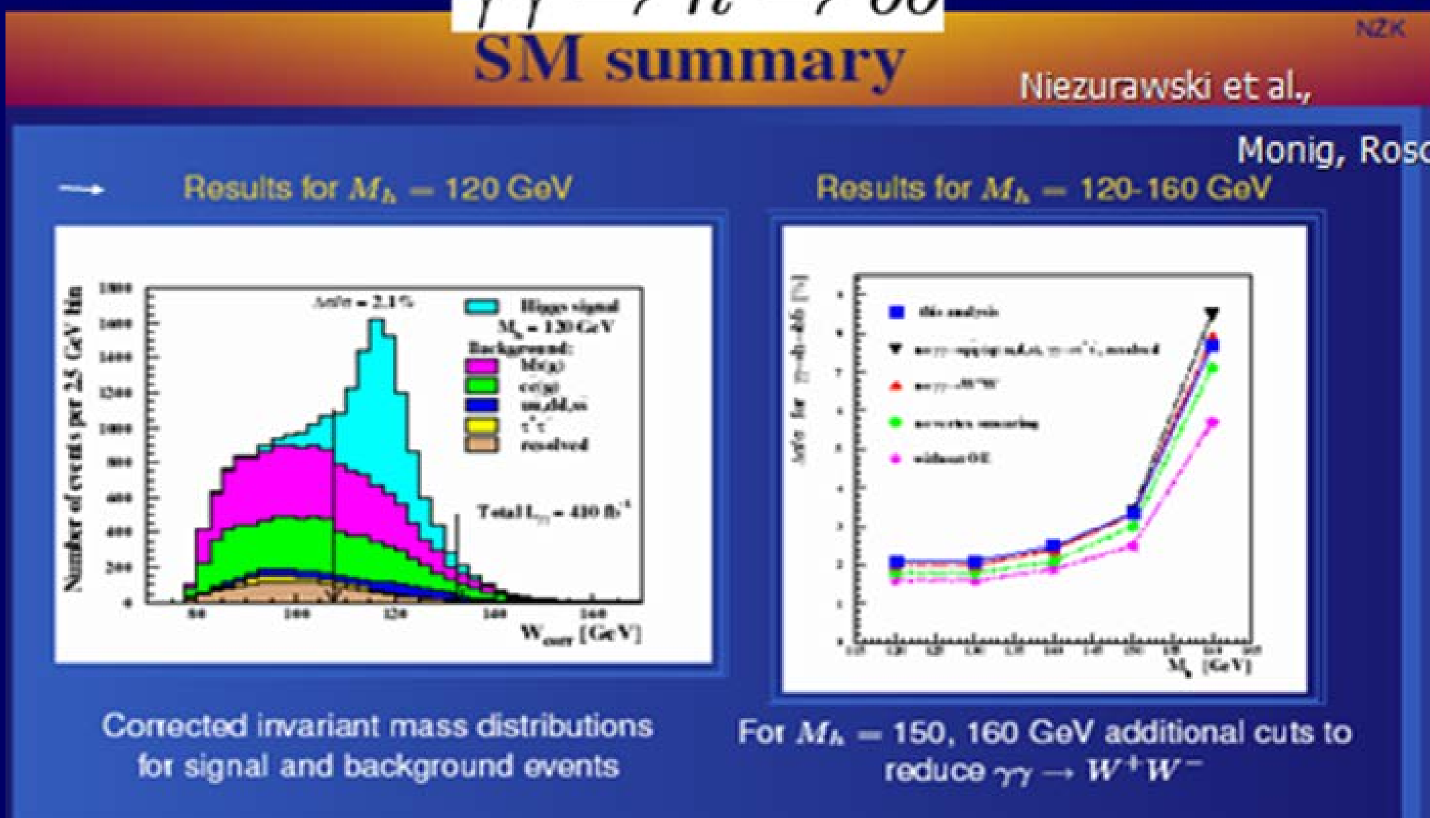
Stronger limit than Xenon100 !

No comments

PLC

Γ (h → γ γ) ~ 3 %

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



Niezurawski et al.,

Monig, Rosca