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Update of the Inert Doublet Model

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Inert Doublet Model

Today

Higgs and Dark Matter in agreement with data

LHC -> Higgs
-> DM

WMAP (DM relic density)
Direct DM detection ?
Indirect DM processes (annihilation)?

LHC: strong constraints on DM from Higgs data

Plan

- SM-like Higgs scenarios AD 2013
- Great BSM laboratory:

  Two Higgs Doublet Models – 2HDM

  supersymmetric (MSSM) or not, ….
- 2HDM with exact Z_2 symmetry: Inert Doublet Model (IDM)
- LHC: enhancement/suppression in Higgs → $\gamma\gamma$
  and constraints on Dark Matter
  correlation with Higgs → $Z\gamma$
- Will not talk on evolution of the Universe in IDM (T^2 and beyond)

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 ; mass for photon possible

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

Definition of SM-like scenario (2013):

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

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

- In models with two SU(2) doublets:

  - MSSM with *SM-like h* and decoupling of heavy Higgses
  - 2HDM (Normal = Mixed), *h or H can be SM-like*
  - Inert Doublet Model, only *one SM-like Higgs h*

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

Potential (14 parameters) with L_H=T-V

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

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

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

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

- Reparametrization freedom: 11 parameters

Ginzburg, MK';Gunion,Haber'04)

- Z_2 symmetry transf.: $\Phi_1\to\Phi_1$ $\Phi_2\to -\Phi_2$ (or vice versa)

Hard Z_2 symmetry violation: λ_6, λ_7 terms *Branco,Rebelo'85*

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

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12}=0$ (NO CP violation)

Various models of Yukawa inter.

typically with some Z_2 type symmetry to avoid FCNC

Glashow-Weinberg,Paschos77

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

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling of fermions to the lightest Higgs – ruled out

and others

Extrema of the 2HDM potential with explicit Z_2 symmetry

Ginzburg, Kanishev, MK, Sokołowska'09

Extrema conditions: $\partial V / \partial \Phi|_{\Phi = \langle\Phi\rangle} = 0$

Finding extrema, minima → global minimum = vacuum

Positivity (stability) constraints (V with real parameters)

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

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

Extremum fulfilling the positivity constraints with the lowest energy = vacuum

Conditions for extrema

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

notation: $\Phi_1 \to \Phi_S$ & $\Phi_2 \to \Phi_D$ (D symmetry)

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

$$0 = u \left[\lambda_2 \left(u^2 + v_D^2 \right) + \lambda_3 v_S^2 - m_{22}^2 \right]$$

$$0 = v_D [v_S^2 \lambda_{345} - m_{22}^2 + \lambda_2 v_D^2]$$

$$0 = v_S [v_D^2 (\lambda_4 + \lambda_5) + \lambda_1 v_S^2 + \lambda_3 (v_D^2 + u^2) - m_{11}^2]$$

for $u = v_D = 0$ and $v_S \neq 0$ $\qquad \lambda_1 v_S^2 = m_{11}^2$

NOT HIGGS BASIS OF A vD ,vS ≠0 case (Mixed) !

Extrema -> vacua

(v=246 GeV)

$$\mathrm{EWs}: \quad v_D = 0, \quad v_S = 0, \qquad \mathcal{E}_{EWs} = 0;$$

$$\mathrm{I}_1: \quad v_D = 0, \quad v_S^2 = v^2 = \frac{m_{11}^2}{\lambda_1}, \quad \mathcal{E}_{I_1} = -\frac{m_{11}^4}{8\lambda_1};$$

$$\mathrm{I}_2: \quad v_S = 0, \quad v_D^2 = v^2 = \frac{m_{22}^2}{\lambda_2}, \quad \mathcal{E}_{I_2} = -\frac{m_{22}^4}{8\lambda_2};$$

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

$$\mathrm{M}: \quad v_S^2 = \frac{m_{11}^2\lambda_2 - \lambda_{345} m_{22}^2}{\lambda_1\lambda_2 - \lambda_{345}^2}, \quad v_D^2 = \frac{m_{22}^2\lambda_1 - \lambda_{345} m_{11}^2}{\lambda_1\lambda_2 - \lambda_{345}^2};$$

$$\mathcal{E}_M = -\frac{m_{11}^4\lambda_2 - 2\lambda_{345} m_{11}^2 m_{22}^2 + m_{22}^4\lambda_1}{8(\lambda_1\lambda_2 - \lambda_{345}^2)}.$$

$$\mathcal{E}_{I_1} - \mathcal{E}_M = \frac{\left(m_{11}^2\lambda_{345} - m_{22}^2\lambda_1\right)^2}{8\lambda_1^2\lambda_2(1-R^2)},$$

$$\mathrm{CB}: \quad v_S^2 = \frac{m_{11}^2\lambda_2 - \lambda_3 m_{22}^2}{\lambda_1\lambda_2 - \lambda_3^2}, \quad v_D = 0, \quad u^2 = \frac{m_{22}^2\lambda_1 - \lambda_3 m_{11}^2}{\lambda_1\lambda_2 - \lambda_3^2},$$

$$\mathcal{E}_{CB} = -\frac{m_{11}^4\lambda_2 - 2\lambda_3 m_{11}^2 m_{22}^2 + m_{22}^4\lambda_1}{8(\lambda_1\lambda_2 - \lambda_3^2)}.$$

$$R = \lambda_{345}/\sqrt{\lambda_1\lambda_2},$$

$$R + 1 > 0,$$

Types of extrema (vacuua)

Ma 78 ,Velhinho,..94

The most general extremum state v_S, v_D, u - real

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

$v_S, u \geq 0$

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

------------------ $u=0$ ------------------

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

------------------ $u\neq 0$ ------------------

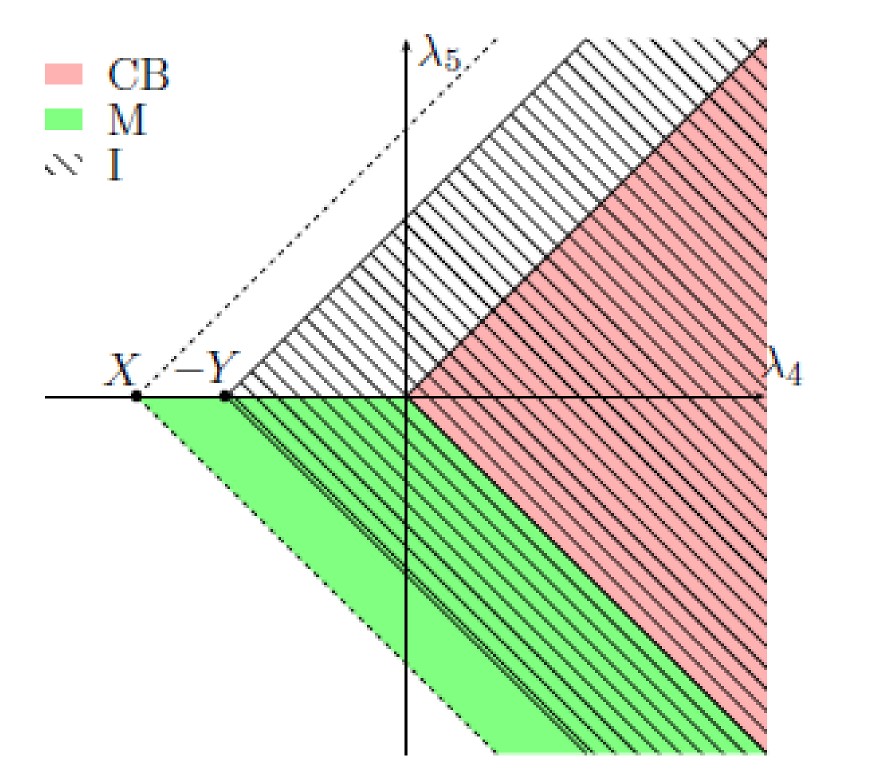
Charge Breaking	CB	$v_D = 0$

D-symmetric potential - vacua

Stable vacuum (positivity) $\lambda_4 \pm \lambda_5 > -X$, $X = \sqrt{\lambda_1\lambda_2} + \lambda_3 > 0$

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

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



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

Neutral vacua

- Mixed M [v_S and $v_D \neq 0$]
- Inert I1 (I2) [v_S or $v_D \neq 0$]

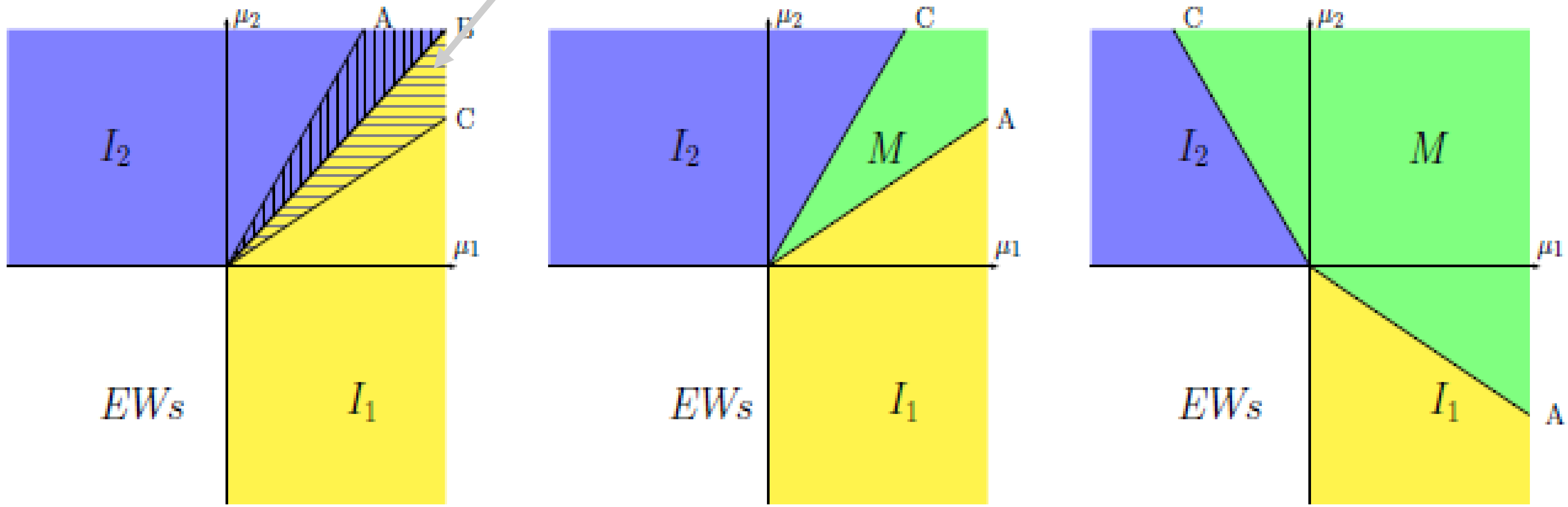
- Charged breaking vacuum CB

Inert overlaps both with Mixed and CB !

Phase diagrams for D-sym. V

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

coexistence of I1 and I2



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

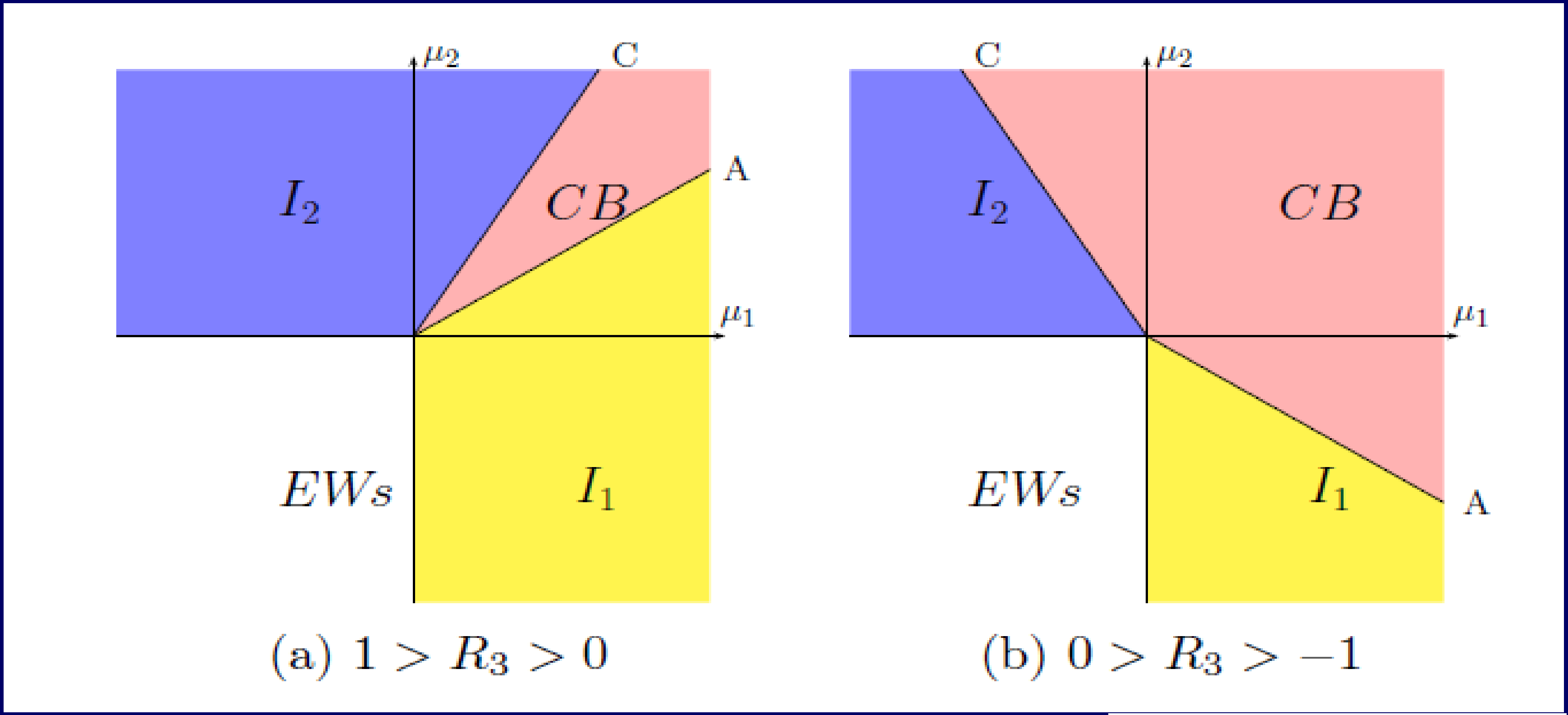
Inert (I1) vacuum

for Mh=125 GeV → fixed μ_1

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

$$R = \lambda_{345}/\sqrt{\lambda_1 \lambda_2},$$

Phase diagrams for D-sym. V Charged Breaking phase



$$R_3 + 1 > 0$$

$$R_3 = \lambda_3/\sqrt{\lambda_1\lambda_2}.$$

Inert phase for TODAY

Ma,…'78
Barbieri..'06

Inert Doublet Model

Symmetry under Z_2 (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

6 parameters , eg 4 masses + 2 couplings

Inert Doublet Model

Φ_S as in SM (BEH)

$$\Phi_S = \begin{pmatrix} \varphi^+ \\ \frac{V+h+i\,\zeta}{\sqrt{2}} \end{pmatrix}$$

Higgs boson h (SM-like)

Φ_D – no vev

$$\Phi_D = \begin{pmatrix} H^+ \\ H+i\,A \end{pmatrix}$$

4 scalars H+,H-,H, A

(no Higgs bosons!)

no interaction with fermions

D symmetry exact → D parity, only Φ_D has odd D-parity
→ the lightest scalar stable - dark matter candidate
(Φ_D **dark** doublet with dark scalars)

IDM: An Archetype for Dark Matter, Lopez Honorez,..Tytgat..07

LHC 2012

Higgs-like $\mathcal{H}$ particle with mass ~125 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

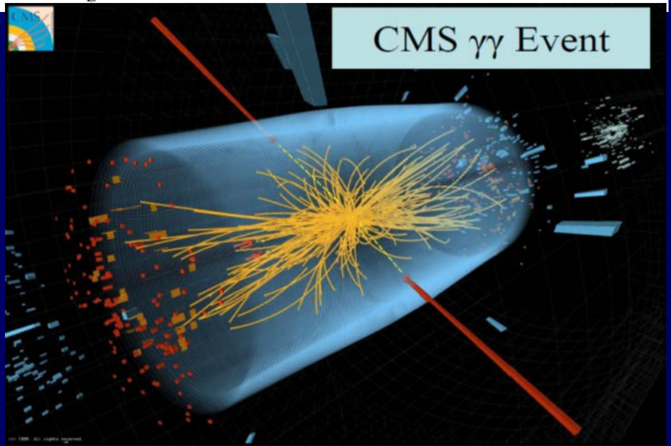
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
ceived 31 August 1964)

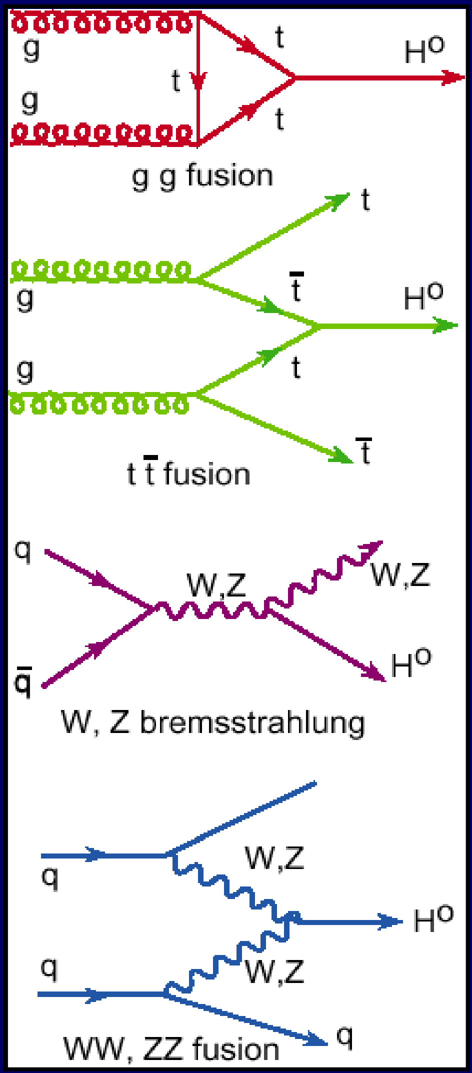
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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 gg$\mathcal{H}$, γγ$\mathcal{H}$

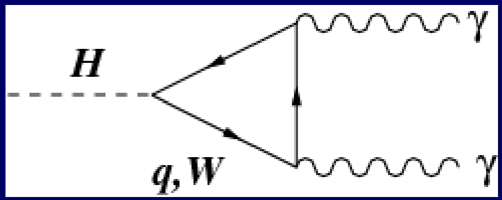


LHC: loop couplings hgg, hγγ (hZγ)



for hgg - b and t important

for hγγ, hZγ



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

W and t interfer destructively in SM

so if coupling of t may change sign in some models an enhancement possible...

2HDM (Mixed) Ginzburg, MK,Osland,2001; Carmi et al.,,,, in 2011,12

LO: In IDM only hγγ (hZγ) may differ from SM

Testing Inert Doublet Model

Ma'2006,.Barbieri 2006, Dolle,Su, Gorczyca(Świeżewska), MSc T2011, 1112.4356, 1112.5086, ..1305. Posch 2011, Arhrib..2012, Chang, Stal ..2013

- ❖ Detailed study of
  - the SM-like h

    $M^2_h = m_{11}^2 = \lambda_1 v^2$

- ❖ Study of dark scalars D
  - masses depend on m_{22}^2
  - the dark scalars

    interact 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!

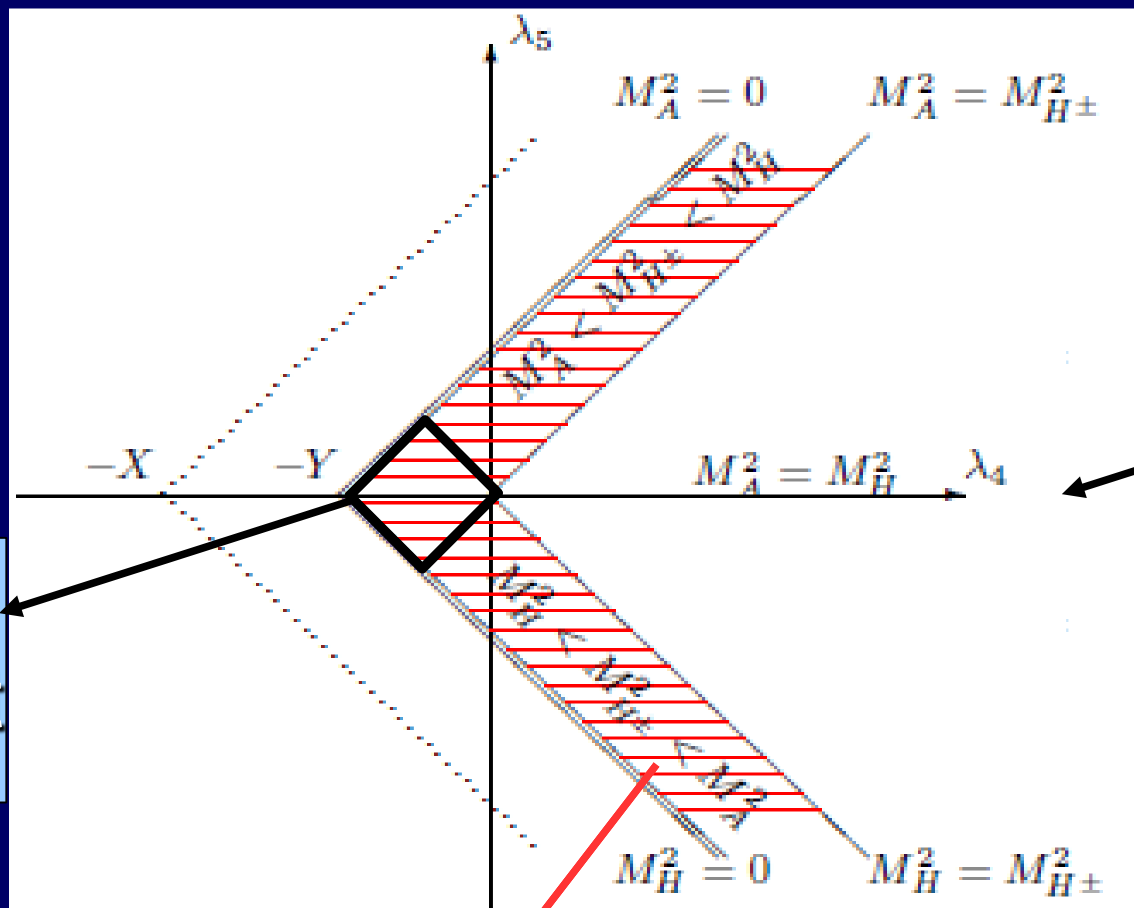
Quartic selfcouplings D^4 proportional to λ_2

hopeless to be measured at colliders!

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

IDM: Dark scalars H, A, H+/-

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



here H+
the heaviest

here H+
lightest

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

Our analysis

.
*B. Gorczyca(Świeżewska), Thesis2011, 1112.4356, 1112.5086…

Constraints:

vacuum stability,

perturbative unitarity

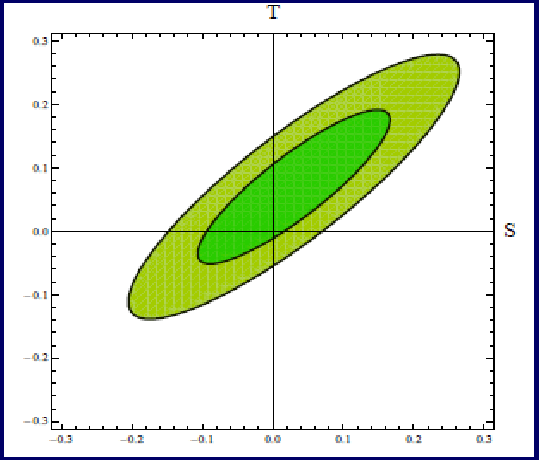
condition for Inert vacuum

Data:

EWPT (S and T)

LEP, LHC, (WMAP) data

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



New analysis

May 2013

(a) the relic density $\Omega_{DM}h^2$ (3σ WMAP)

$$0.1018 < \Omega_{DM}h^2 < 0.1234,$$

(b) diphoton decay rate $R_{\gamma\gamma}$

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

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
only quartic interaction

Block-diagonal form due electric charge and CP conservation

Unitarity constraints
→ |eigenvalues|< 8 π

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+

Kanemura et al. 93; 2001 Akeroyd,Arhrib,Naimi, 2000…, Swaczyna 2013

Limits for lambdas

for Inert model*

Mh=125 GeV

0	0.26	$\leqslant \lambda_1 \leqslant$	0.26	8.38
0	0	$\leqslant \lambda_2 \leqslant$	8.38	8.38
-6.05	-1.32	$\leqslant \lambda_3 \leqslant$	16.53	16.53
-15.98	-8.95	$\leqslant \lambda_4 \leqslant$	5.08	5.93
-8.34	-8.22	$\leqslant \lambda_5 \leqslant$	0	0

for combinations

couplings for dark particles in IDM

eg. hHH $\lambda_{345}=\lambda_3+\lambda_4+\lambda_5$

$$-1.45 \leqslant \lambda_{345} \leqslant 11.94,$$
$$-1.15 \leqslant \lambda_{345}^{-} \leqslant 16.40,$$

Important: condition for 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 (pert.unitarity)

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

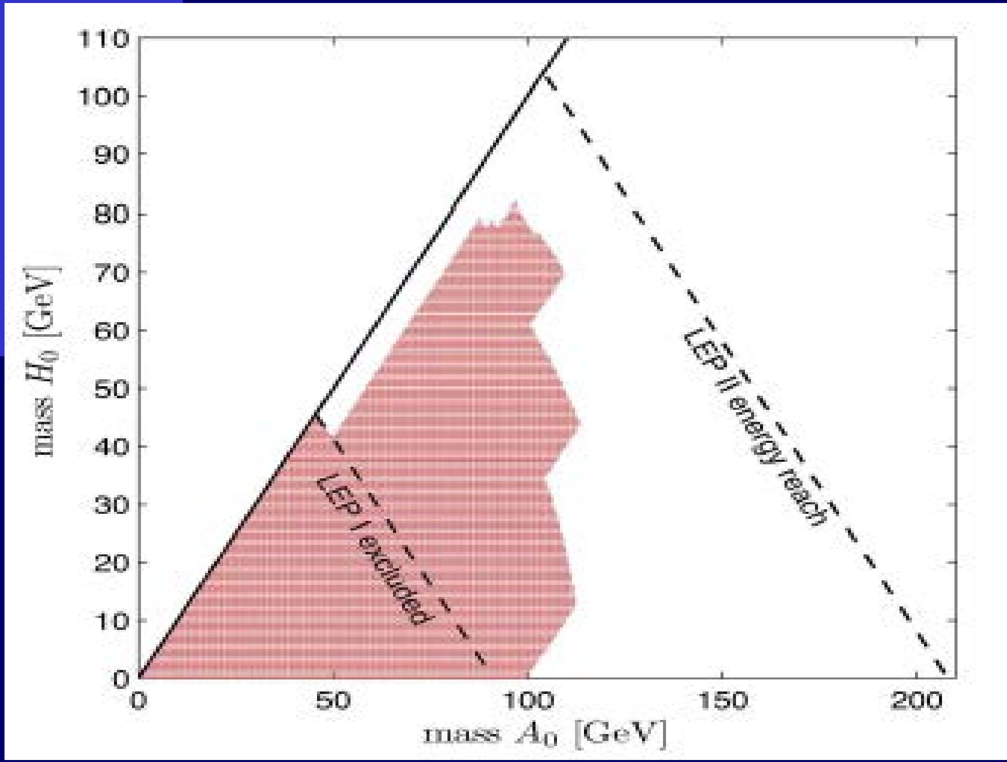
LEP exclusion

- mass of H+ > 70 GeV (model independent)

- masses H vs A

  Lundstrom...
  hep-ph/0810.3924

DM=H



IDM – scan

(B. Świeżewska 2012)

H = dark matter

$0 > \lambda_{45} = \lambda_4 + \lambda_5$

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

narrow (wide) range

condition for Inert

Correlations

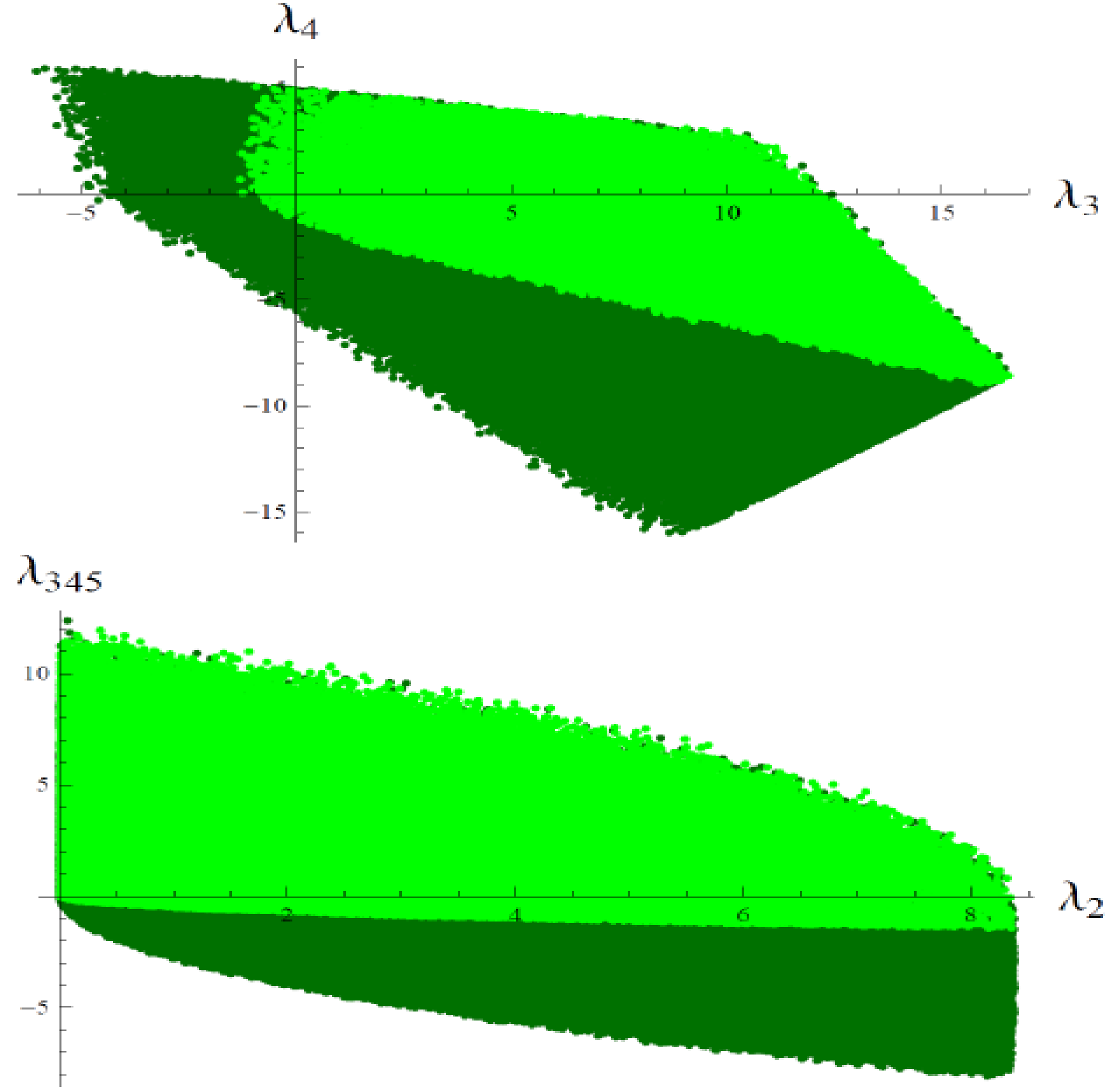


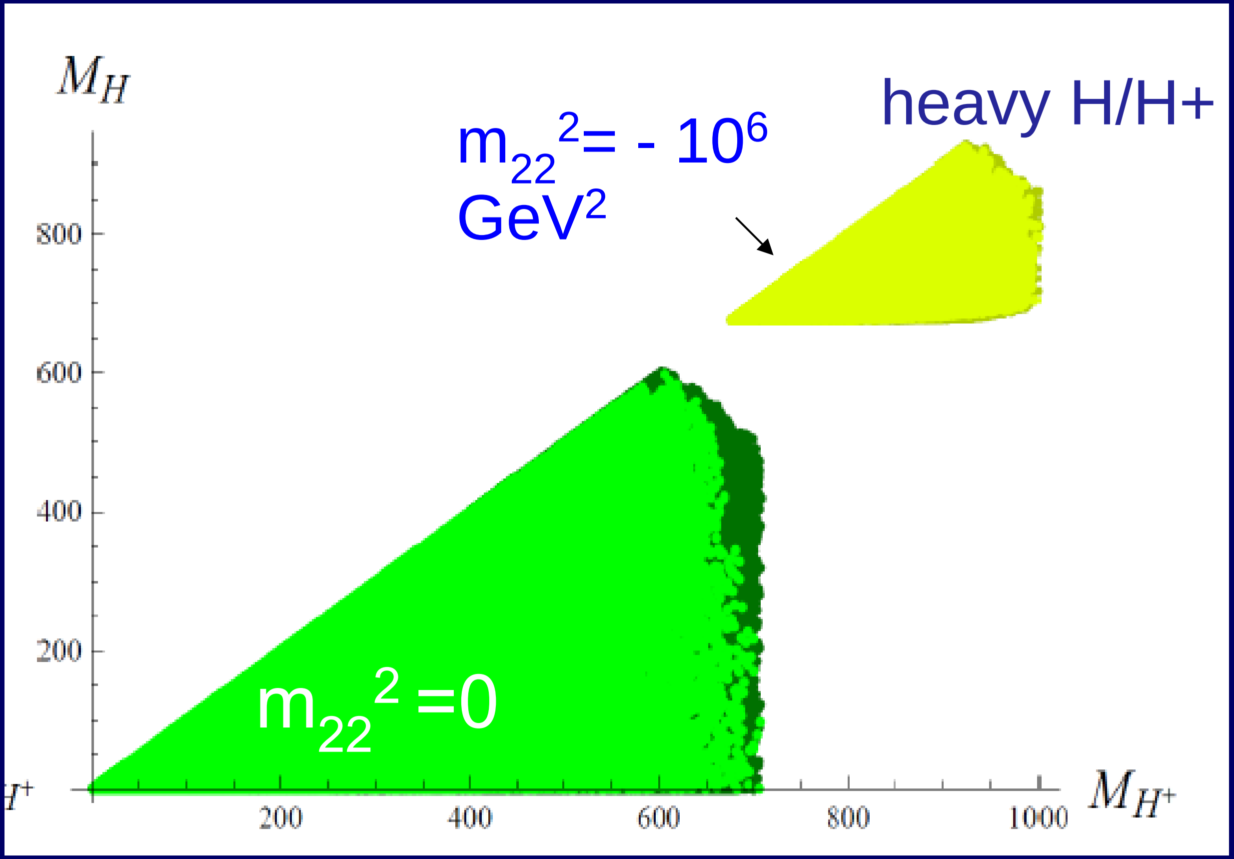
FIG. 1. Regions of parameters allowed by the constraints (13a) (without conditions determining type of the vacuum and the LEP bounds) (dark green/gray). Regions allowed in the IDM by the conditions (13a, 13b) (light green/gray).

Light green – full set of constraints for IDM

Inert Doublet Model with M_h=125 GeV

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

$m_{22}^2 = 0$



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

EWPT (pale regions)

$\gamma\gamma$ and $Z\gamma$ decay rates of the Higgs boson

[Q.-H. Cao, E. Ma, G. Rajasekaran, Phys. Rev. D 76 (2007) 095011, P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021, BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019]

$R_{\gamma\gamma}$ – 2-photon decay rate, $R_{Z\gamma}$ – $Z\gamma$ decay rate

$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

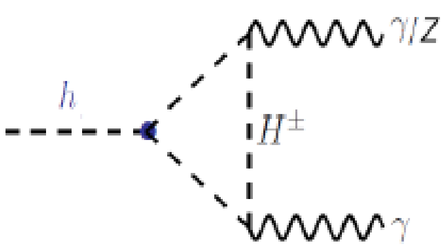
$R_{Z\gamma}$ – treated analogously

narrow width approx

- Largest contribution from gg fusion
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$ (not true in other 2HDMs)

Two sources of deviation from $R_{\gamma\gamma} = 1$:

- invisible decays $h \to HH$, $h \to AA$ in $\Gamma(h)^{IDM}$
- charged scalar loop in $\Gamma(h \to \gamma\gamma)^{IDM}$

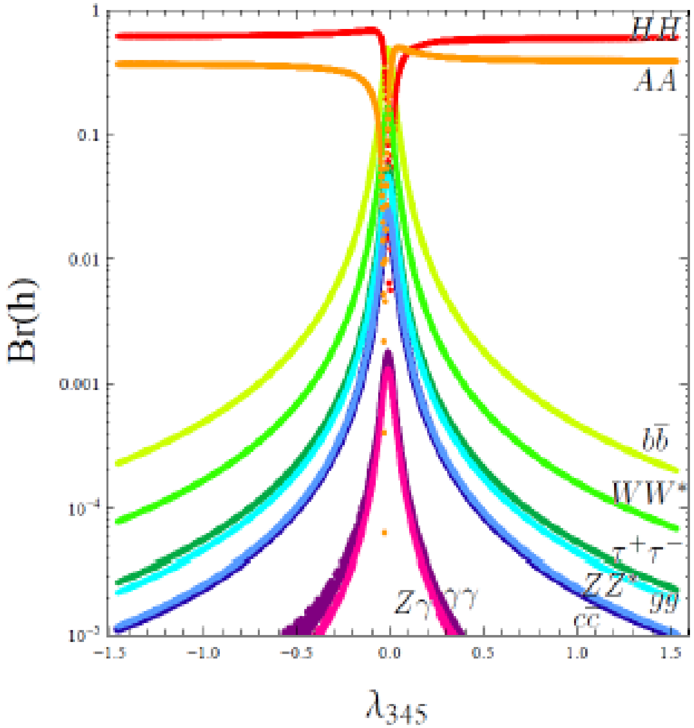


Invisible decays

$$\Gamma(h) = \Gamma(h \to b\bar{b}) + \Gamma(h \to WW^*) + \Gamma(h \to \tau^+\tau^-) + \Gamma(h \to gg)$$
$$+ \Gamma(h \to ZZ^*) + \Gamma(h \to c\bar{c}) + \Gamma(h \to Z\gamma) + \Gamma(h \to \gamma\gamma)$$
$$+ \Gamma(h \to HH) + \Gamma(h \to AA)$$

$$\Gamma(h \to HH) = \frac{\lambda_{345}^2 v^2}{32\pi M_h}\sqrt{1 - \frac{4M_H^2}{M_h^2}},$$

- Controlled by: M_H, M_A, $\lambda_{345} \sim hHH$, $\lambda_{345}^- \sim hAA$
- Invisible decays, if kinematically allowed, dominate over SM channels.
- Plot for $M_A = 58$ GeV, $M_H = 50$ GeV

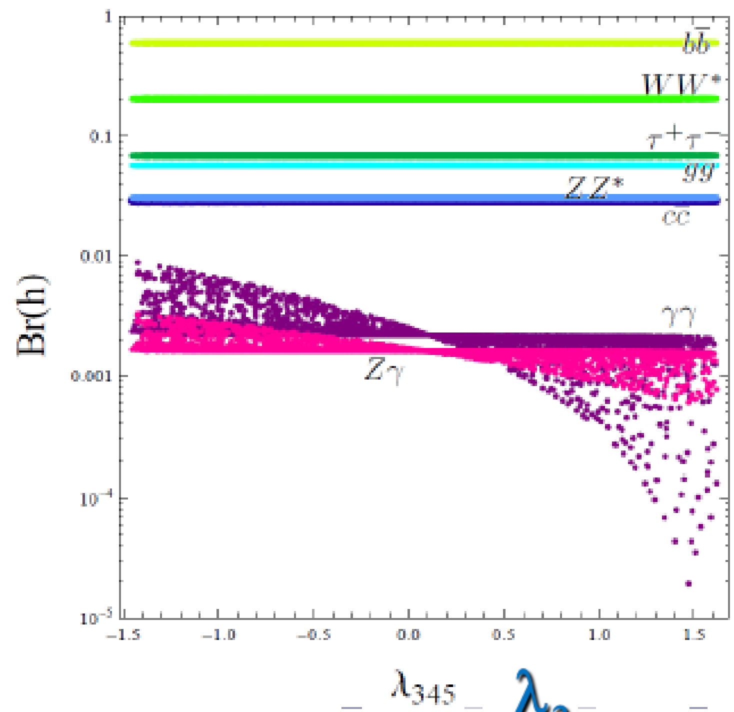


Charged scalar $H^{\pm}$ loop

[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)]

$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \frac{\overbrace{2M_{H^\pm}^2 + m_{22}^2}^{\lambda_3}}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

- Constructive or destructive interference between SM and $H^{\pm}$ contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- Invisible channels closed $\Rightarrow$ $H^{\pm}$ contribution visible



Source of modification: H+ loop

- $R_{\gamma\gamma} > 1$ can be solved analytically

$$m_{22}^2 < -2M_{H^\pm}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2 \quad \text{or}$$

$$m_{22}^2 > \frac{aM_h^2}{1-\left(\frac{2M_{H^\pm}}{M_h}\right)^2 \arcsin^2\left(\frac{M_h}{2M_{H^\pm}}\right)} - 2M_{H^\pm}^2 \gtrsim 1.8 \cdot 10^5\,\mathrm{GeV}^2,$$

Not valid (condition for Inert vacuum)

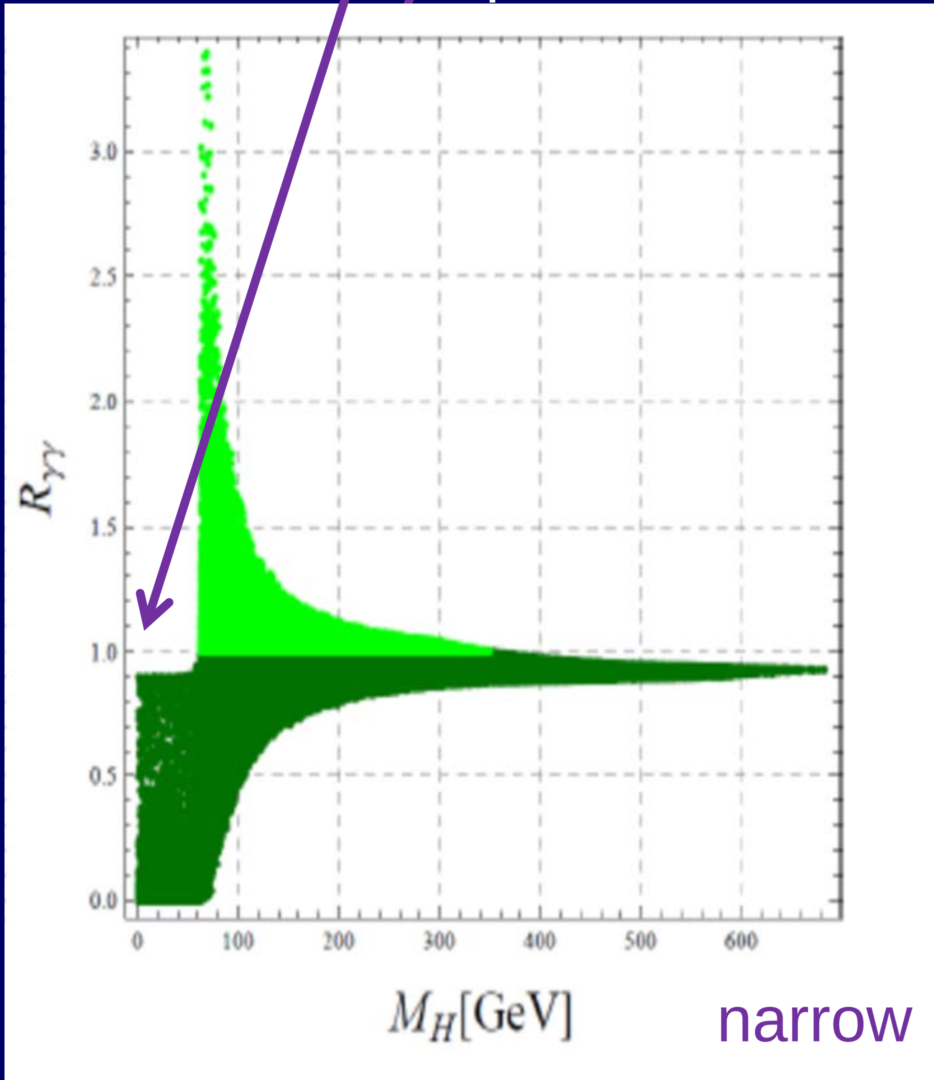
enhancement only for

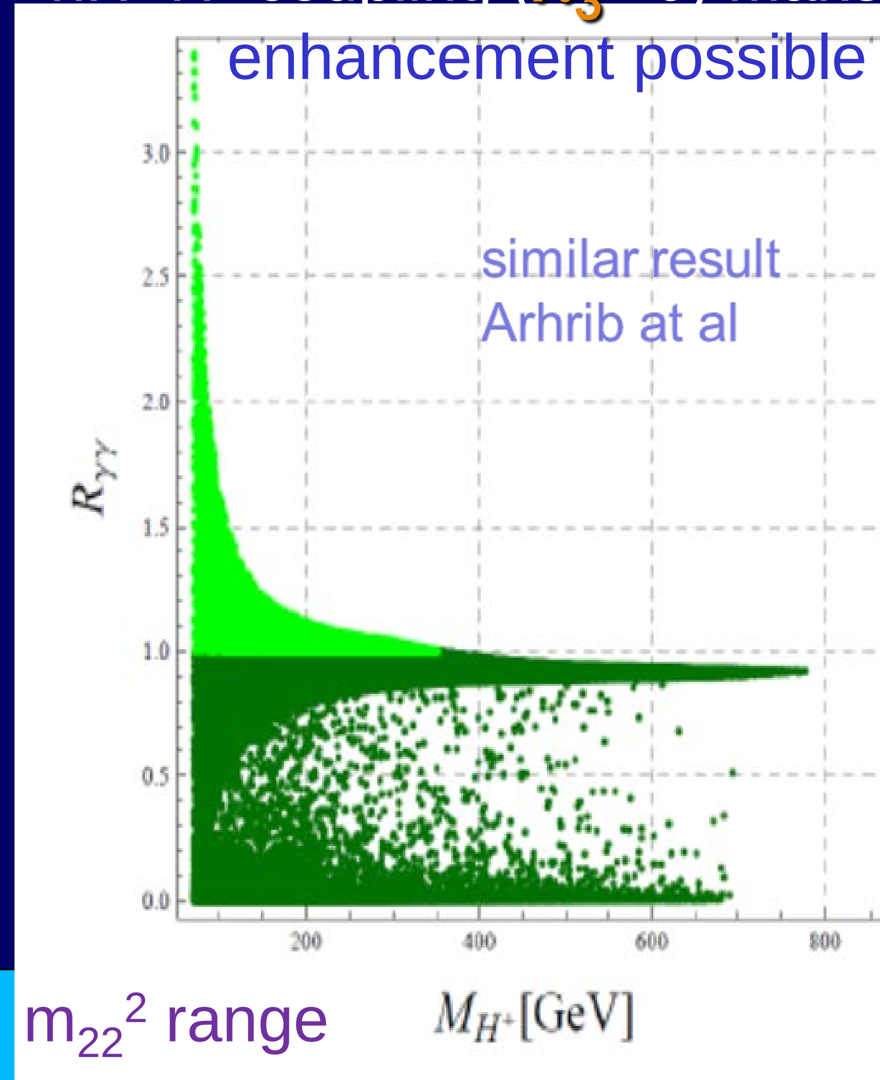
$m_{22}^2 < -9800\ \mathrm{GeV}^2$ $(\lambda_3 < 0)$

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

Invisible decays makes enhancement impossible

Light H+ with proper sign of hH+H- coupling (λ_3 <0) makes enhancement possible

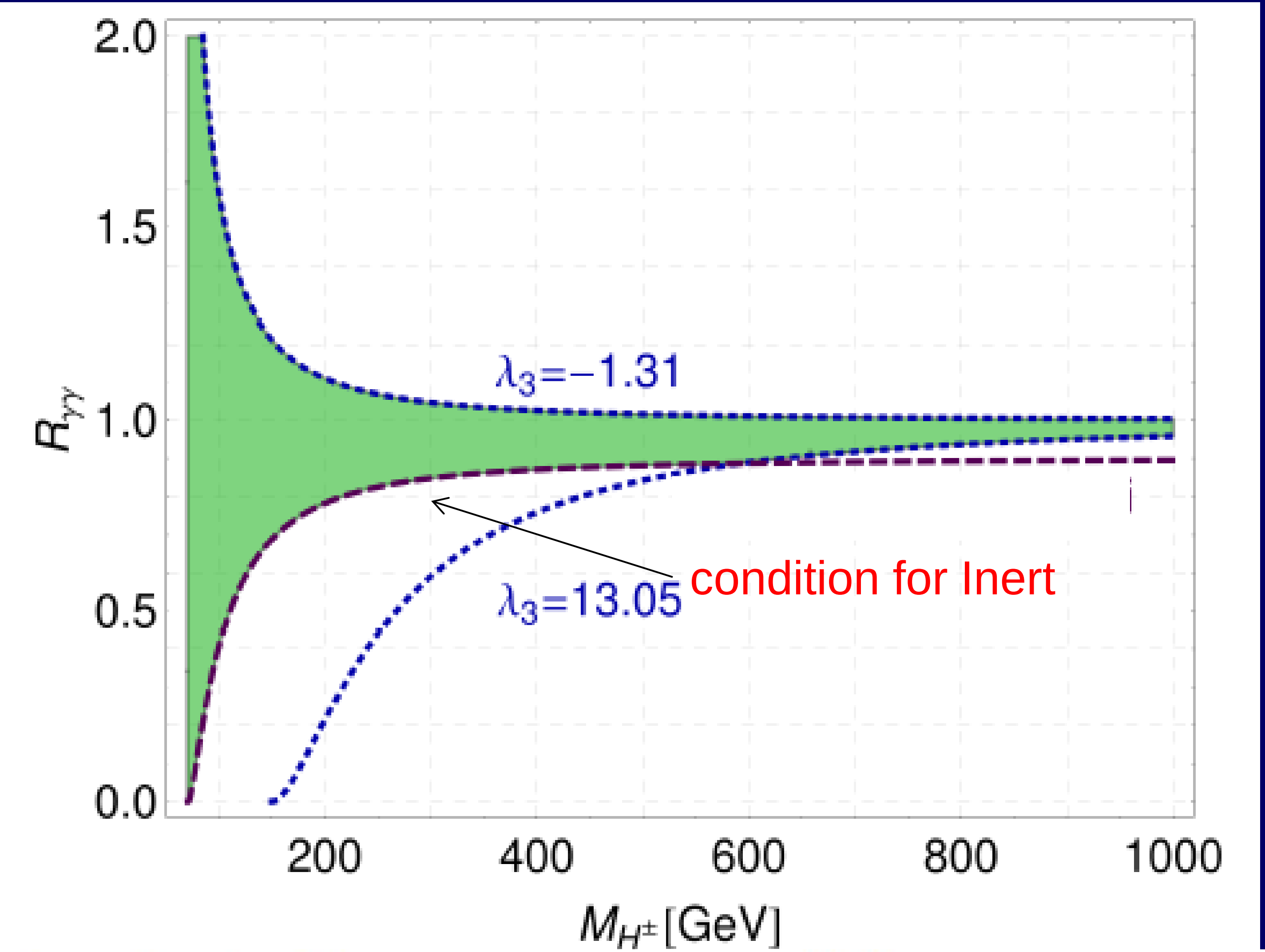




narrow m_{22}^2 range

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

invisible channel closed

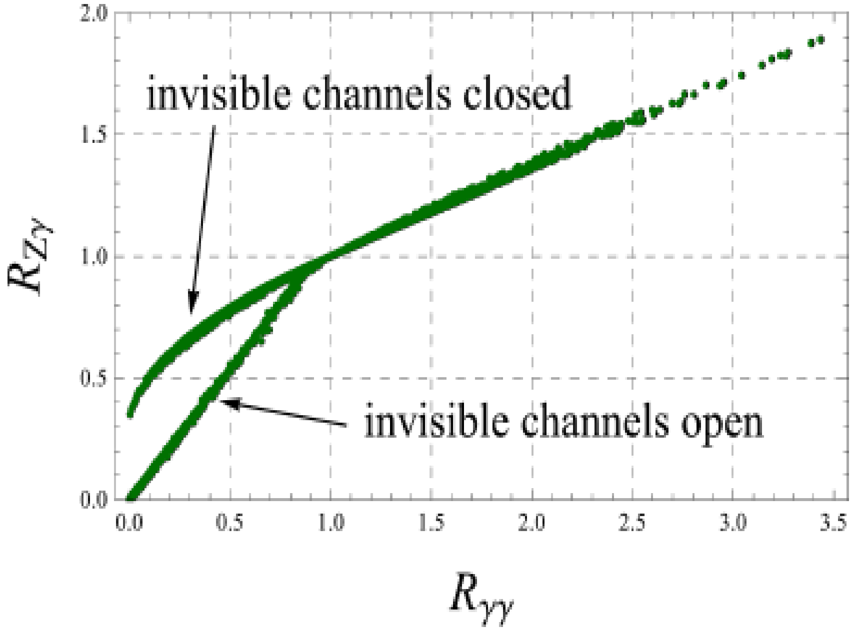


- $R_{\gamma\gamma} \geqslant 1$ also for big $M_{H^\pm}$, e.g. $M_{H^\pm} = 1$ TeV
- Substantial enhancement, $R_{\gamma\gamma} \geqslant 1.3$, only for $M_{H^\pm} \lesssim 130$ GeV

$h \to \gamma\gamma$ vs $h \to Z\gamma$

[BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019, formulas for $h \to Z\gamma$: A. Djouadi, Phys.Rept. 459 (2008) 1, C.-S. Chen, C.-Q. Geng, D. Huang, L.-H. Tsai, Phys.Rev.D 87 (2013) 075019]

- Sensitivity to invisible channels
- $R_{\gamma\gamma}$ and $R_{Z\gamma}$ positively correlated
- $R_{\gamma\gamma} > 1 \Leftrightarrow R_{Z\gamma} > 1$



DM in IDM

Relic density constraints

→ masses and couplings (g_{HHh}) of dark scalars

Direct & indirect detection of DM:

→ further constraints for (M_H, g_{HHh})

IDM can be proven/excluded once an agreement in the experimental area is reached.

Lundstrom et al. '07, '08, Barbieri et al. '06, Lopez Honorez et al. '07, Hambye et al. '08,'09, Agrawal et al. '09, Dolle et al. '09, Arina et al. '09, ...

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

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 $\Delta(D_A, D_H)$
- high DM mass $M_H \approx (500 - 1000)$ GeV,
  small $\Delta(D_A, D_H)$ and $\Delta(D^\pm, D_H)$

D. Sokołowska 2010-13

using MicroOmega's

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

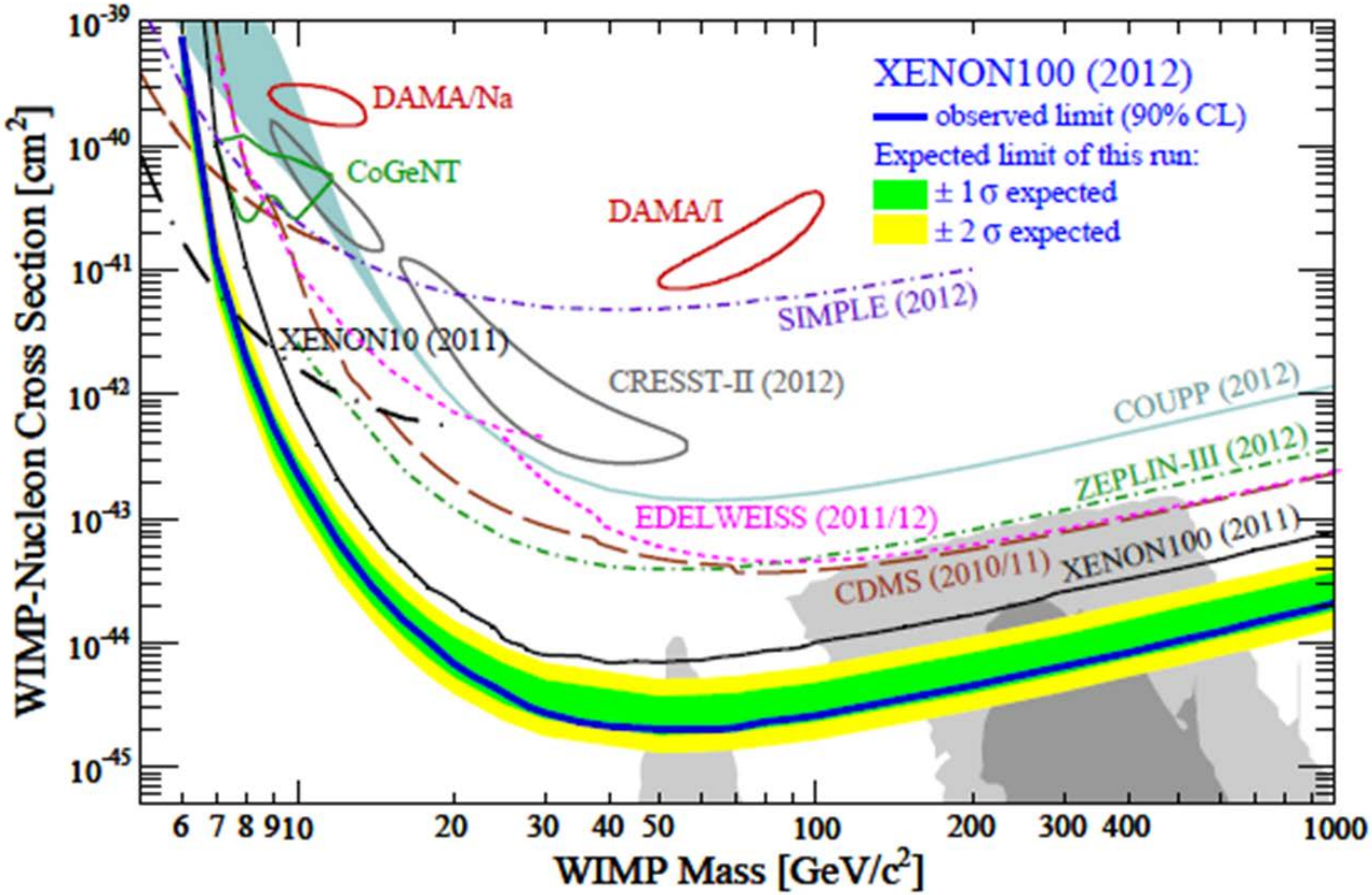
New analysis – Stahl May 2013

DATA?

Direct & indirect detection experiments do not provide a coherent picture of Dark Matter.

"One should be aware, however, that this area of investigation is at present beset with large controversies, and one should allow the dust to settle before drawing strong conclusions in either directions."

Lars Bergstrom, *Dark Matter Evidence, Particle Physics Candidates and Detection Methods,*



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

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

hep-ph/
1305.6266
JHEP 2013

Relict DM density

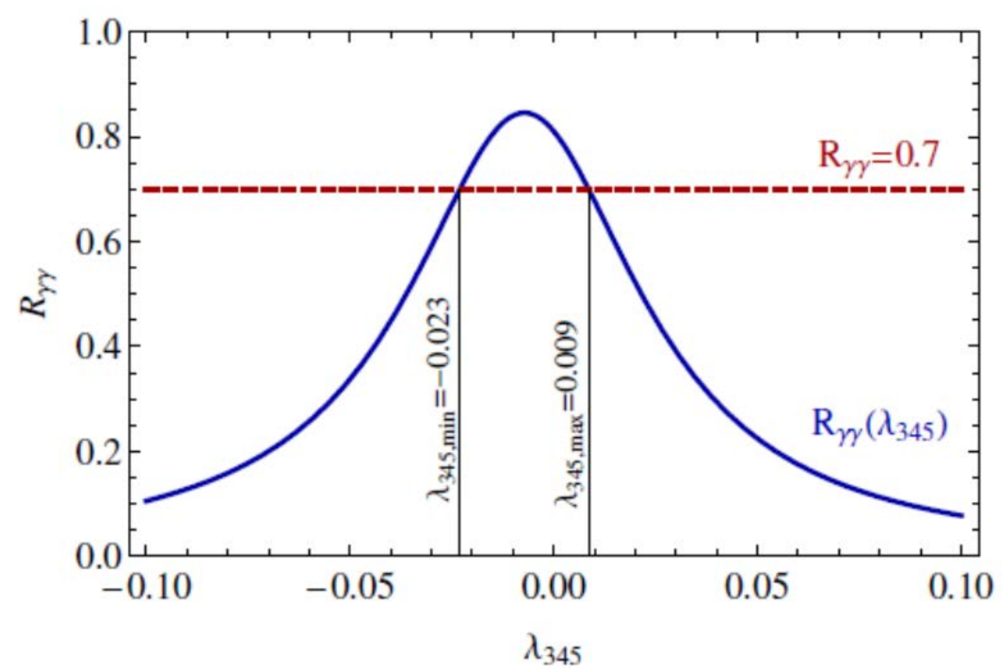
$$\Omega_{DM} h^2 = 0.1126 \pm 0.0036.$$

LHC data

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

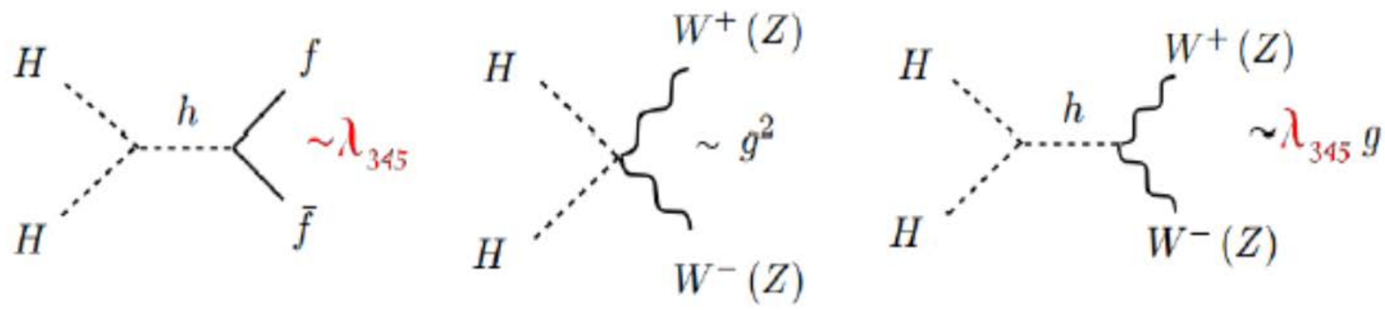
$R_{\gamma\gamma} > 1$
DM mass only above 62.5 GeV allowed

DM mass below 62.5 GeV allowed only if
$R_{\gamma\gamma} < 1$



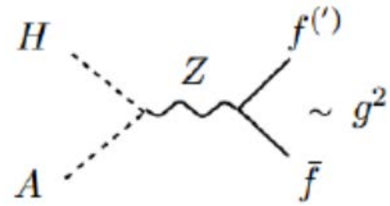
Relic density constraints on masses and couplings

Relic density constraints



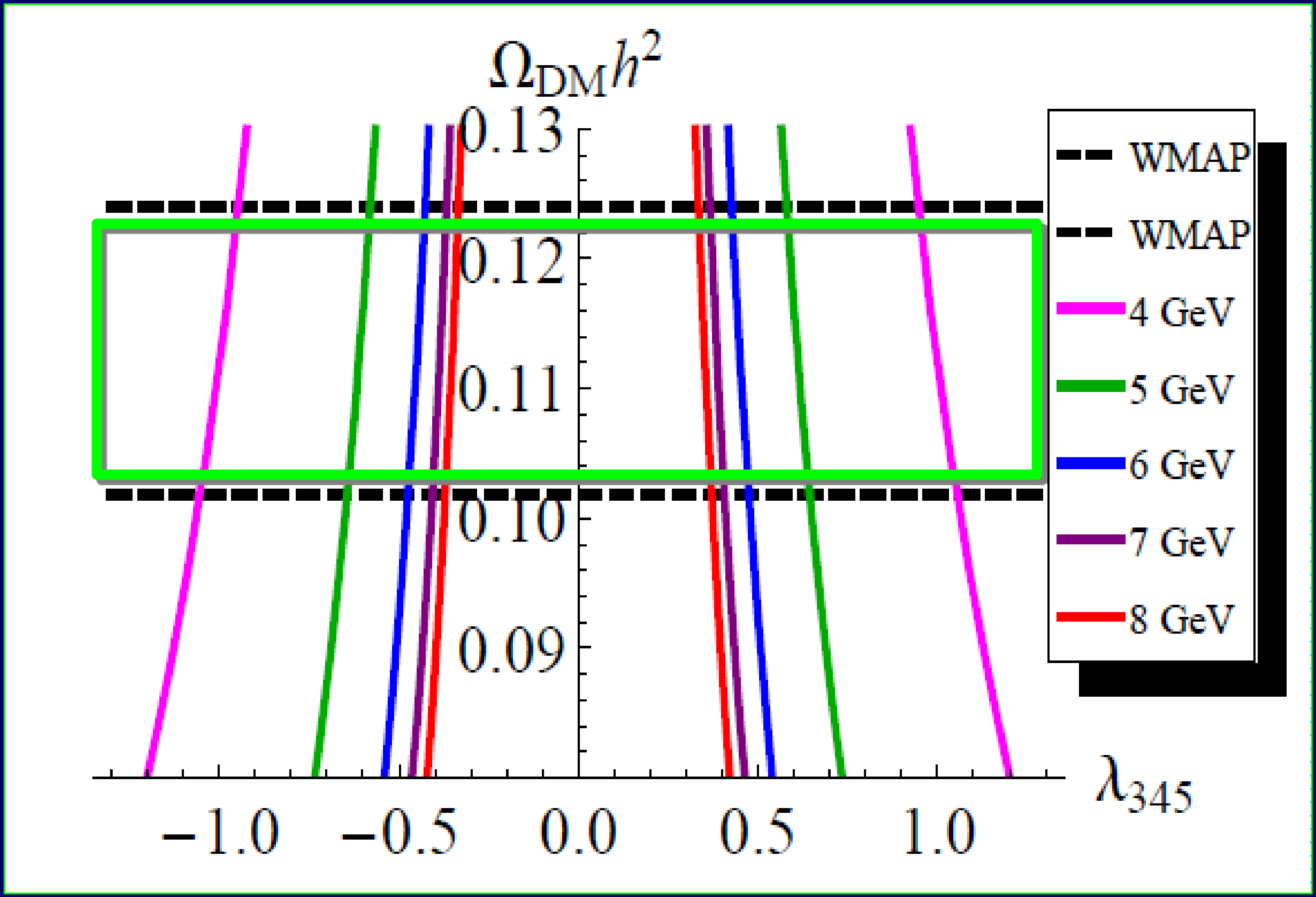
$$0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow \lambda_{345}^{\min}, \lambda_{345}^{\max}$$

Coannihilation possible
for small (AH) splitting



- low DM mass $M_H \lesssim 10$ GeV, $g_{HHh} \sim \mathcal{O}(0.5)$
- medium DM mass $M_H \approx (40 - 160)$ GeV, $g_{HHh} \sim \mathcal{O}(0.05)$
- high DM mass $M_H \gtrsim 500$ GeV, $g_{HHh} \sim \mathcal{O}(0.1)$

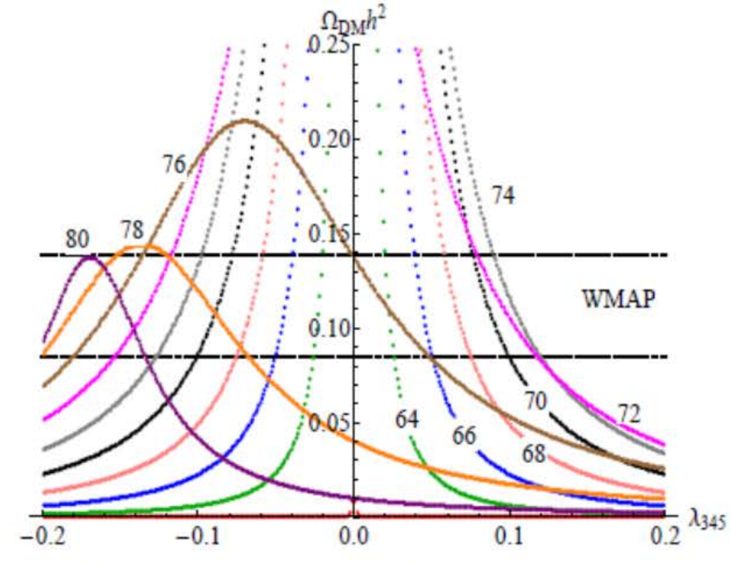
WMAP window for light H (DM)



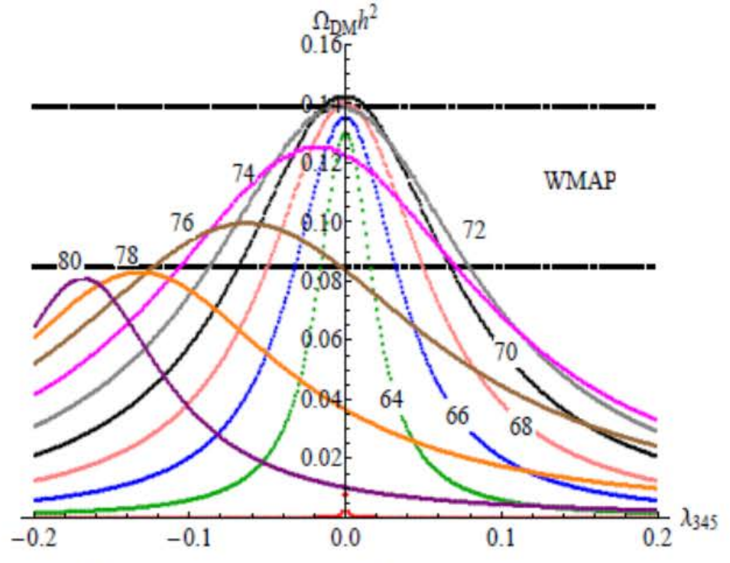
Relict density for DM with mass 62,64,…,80 GeV

D. Sokołowska, 2013

$$M_H = (62, ..., 80)\ \text{GeV},\ M_{A,H^\pm} = M_H + \delta_{A,\pm}$$



$\delta_A = 50\ \text{GeV}, \delta_\pm = 50\ \text{GeV}$



$\delta_A = 8\ \text{GeV}, \delta_\pm = 50\ \text{GeV}$

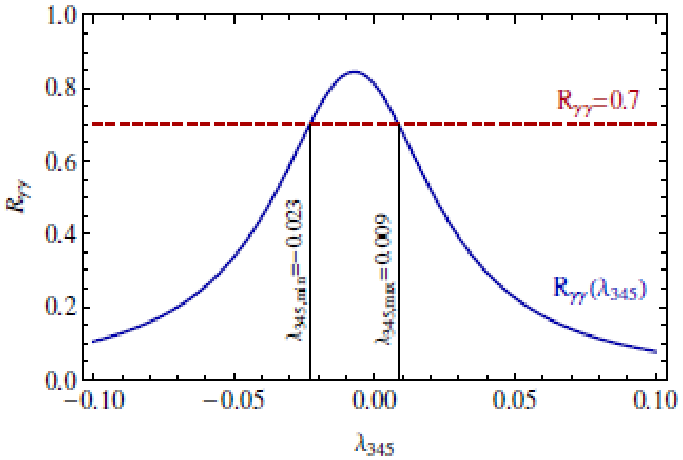
above 76 GeV asymmetry due to annihilation to gauge bosons

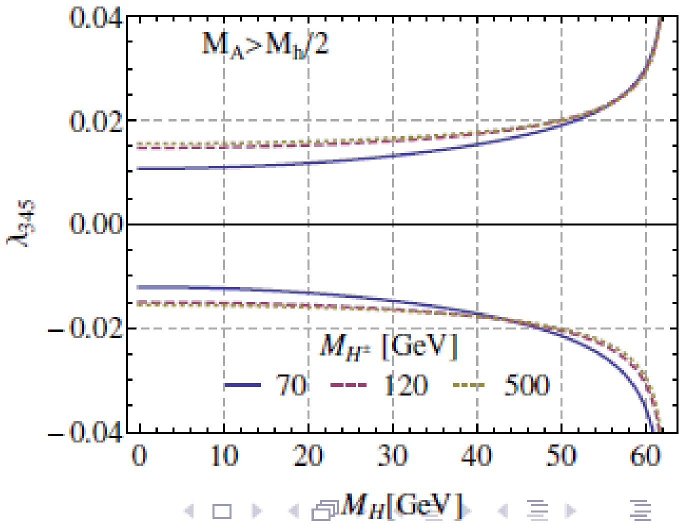
Higgs data constraining DM

$R_{\gamma\gamma}$ constraints on $\lambda_{345} \sim hHH$

[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

- Setting a lower limit on $R_{\gamma\gamma}$ constrains λ_{345}
- Upper and lower limits on λ_{345} depend on M_H
- Stronger than limits on $\mathrm{Br}(h \to \mathrm{inv})$ from LHC

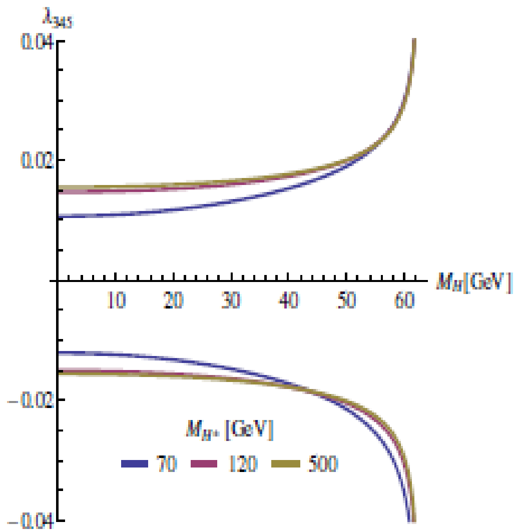




Low mass H – excluded by LHC!

$$M_H \lesssim 10\,\mathrm{GeV}, \quad M_A \approx M_{H^\pm} \approx 100\,\mathrm{GeV}$$

$h \to AA$ channel closed, $h \to HH$ channel open



- Proper relic density

  $0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$

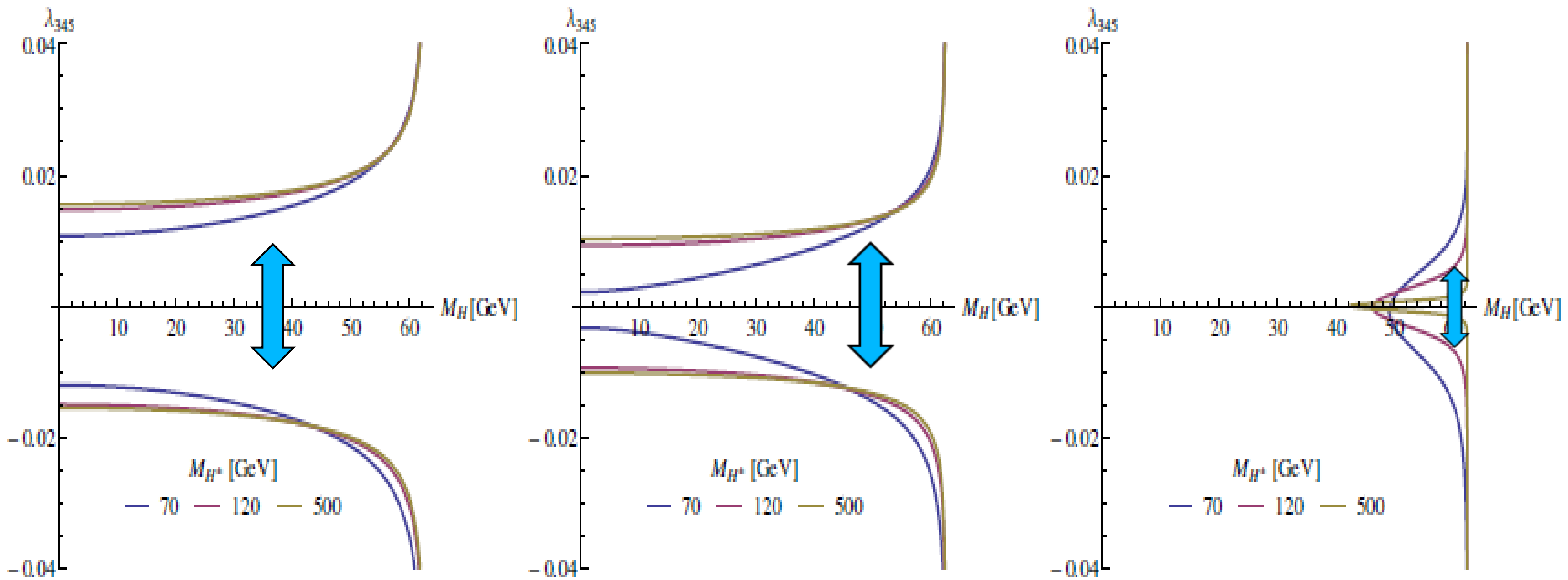
- CDMS-II reported event:

  $M_H = 8.6\ \mathrm{GeV} \Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$

Low DM mass excluded

LHC Limits on HHh coupling



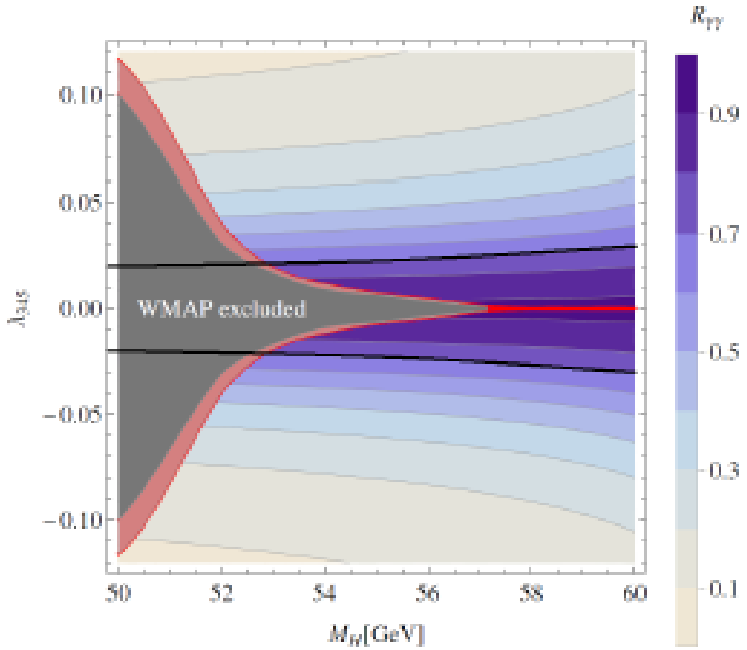
(a) $R_{\gamma\gamma} > 0.7$ (b) $R_{\gamma\gamma} > 0.8$ (c) $R_{\gamma\gamma} > 0.9$

(h->AA closed)

allowed region between lines

Medium DM mass (1) – HH channel open

$$50\,\mathrm{GeV} < M_H < M_h/2\,\mathrm{GeV}, \quad M_A = M_{H^\pm} = 120\,\mathrm{GeV}$$

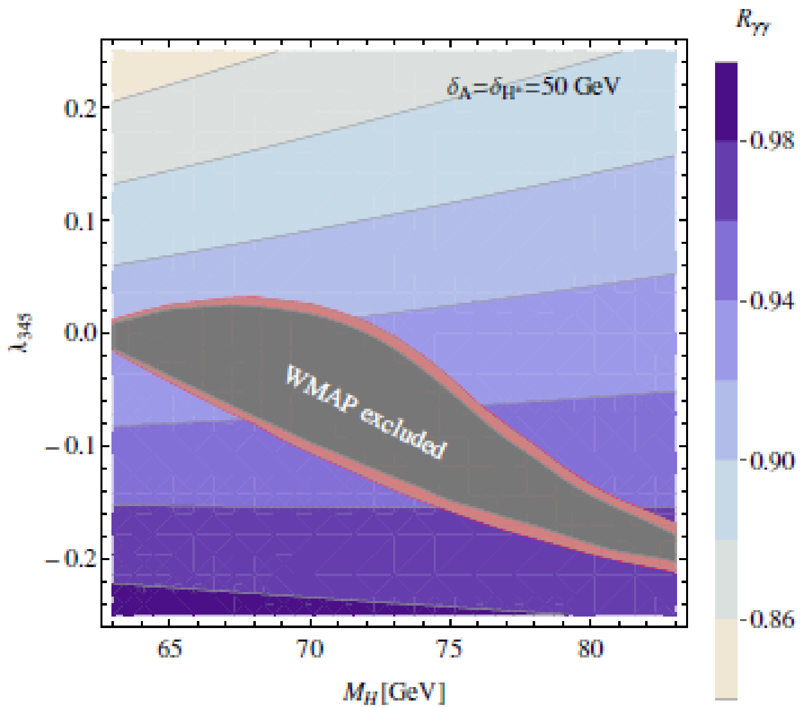


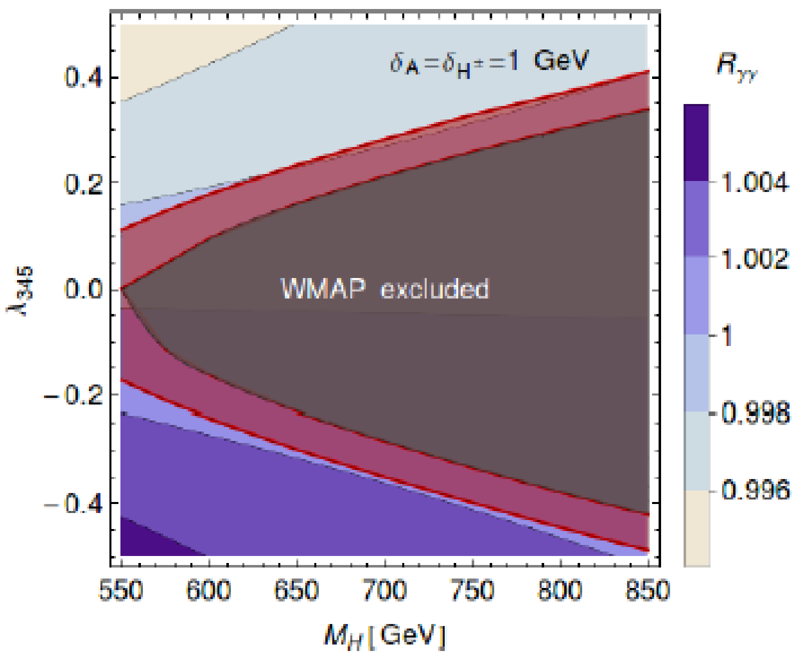
Red bound: $\Omega_{DM} h^2$ in agreement with WMAP

Black line: $R_{\gamma\gamma} = 0.7$

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow M_H \lesssim 53\,\mathrm{GeV}$ excluded
- $53\,\mathrm{GeV} \lesssim M_H \lesssim M_h/2 \Rightarrow R_{\gamma\gamma} \approx (0.8 - 0.9)$

Intermediate and heavy DM



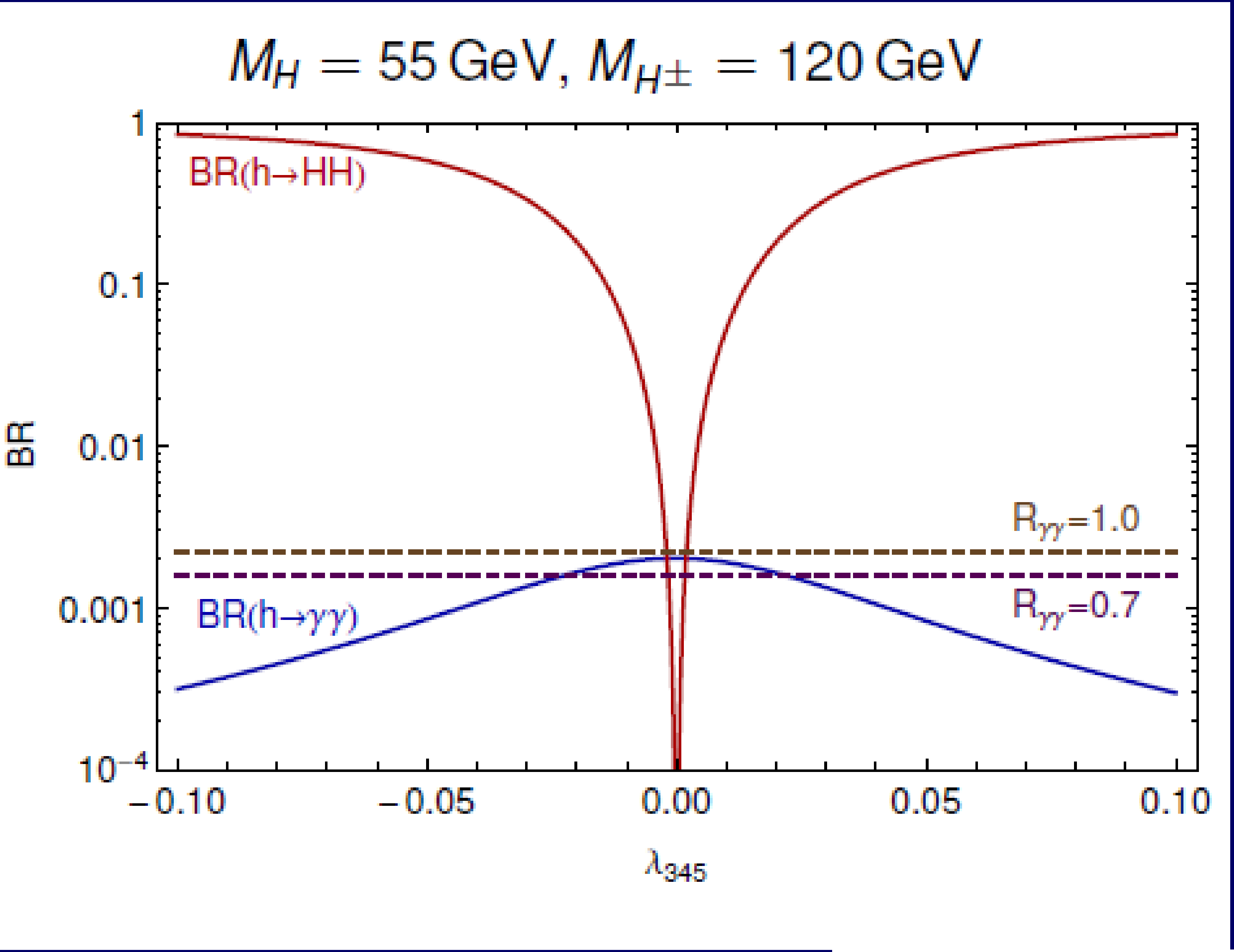


- H of intermediate mass can constitute 100% of DM
- H constituting 100% DM inconsistent with $R_{\gamma\gamma} > 1$

- For heavy DM $R_{\gamma\gamma} \approx 1$ only very small deviations allowed

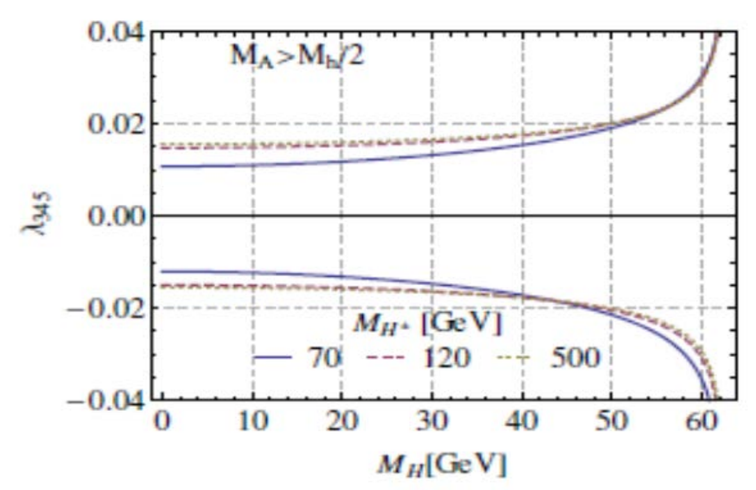
D. Sokołowska, EPS HEP 2013

Limits from BR inv

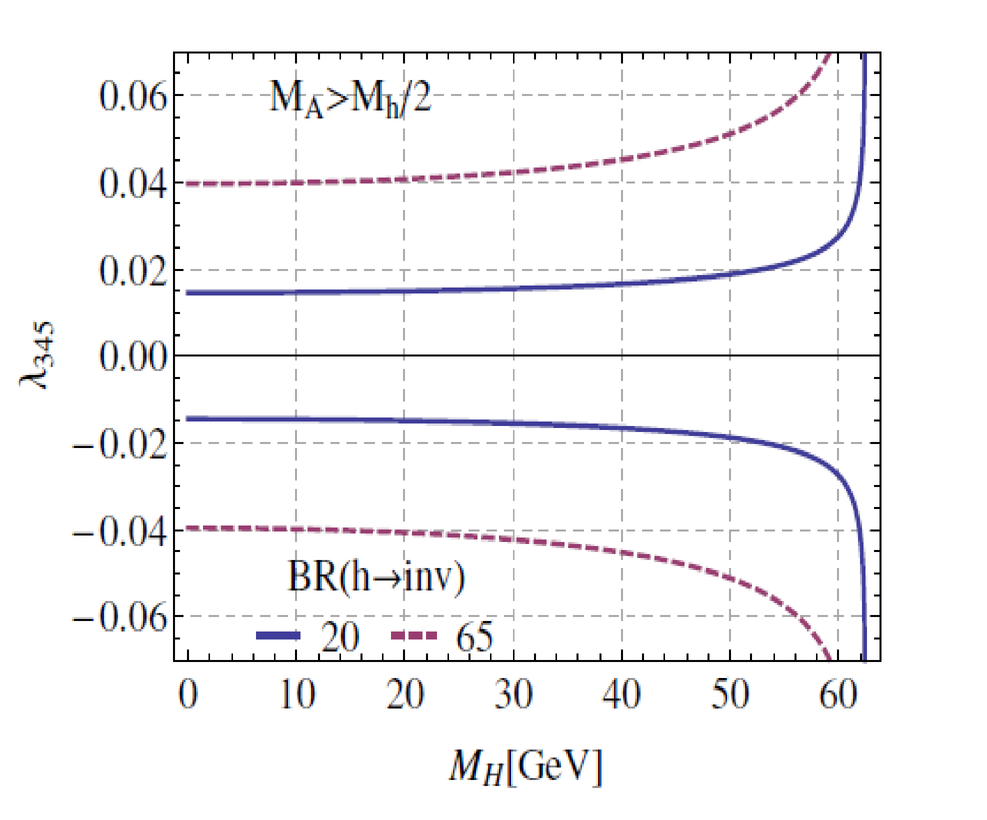


$h \to AA$ channel is closed.

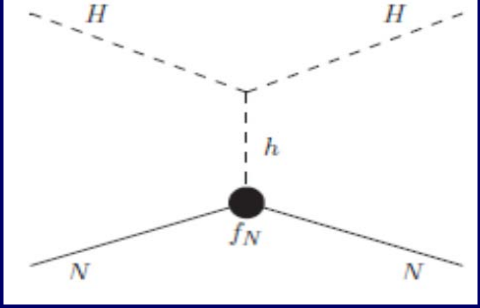
$R_{\gamma\gamma}$ vs Br(h→ inv)< 65 or 20 %



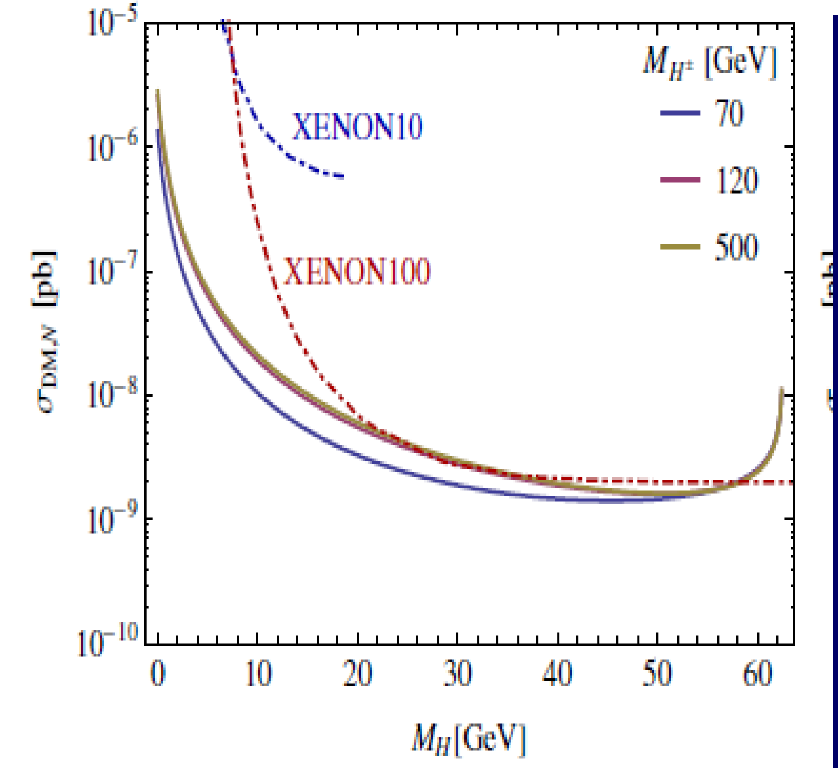
(a) $R_{\gamma\gamma} > 0.7$



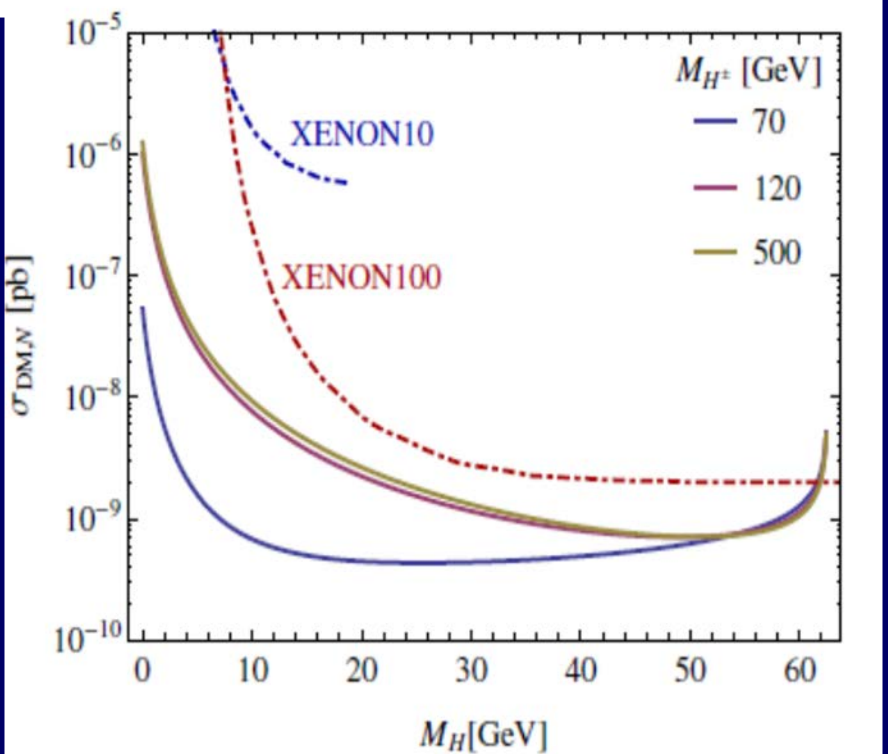
H-N cross section in IDM



$$\sigma_{\rm DM,N} = \frac{\lambda_{345}^2}{4\pi M_h^4} \frac{m_N^4}{(m_N + M_H)^2} f_N^2 \,,$$



(a) $R_{\gamma\gamma} > 0.7$



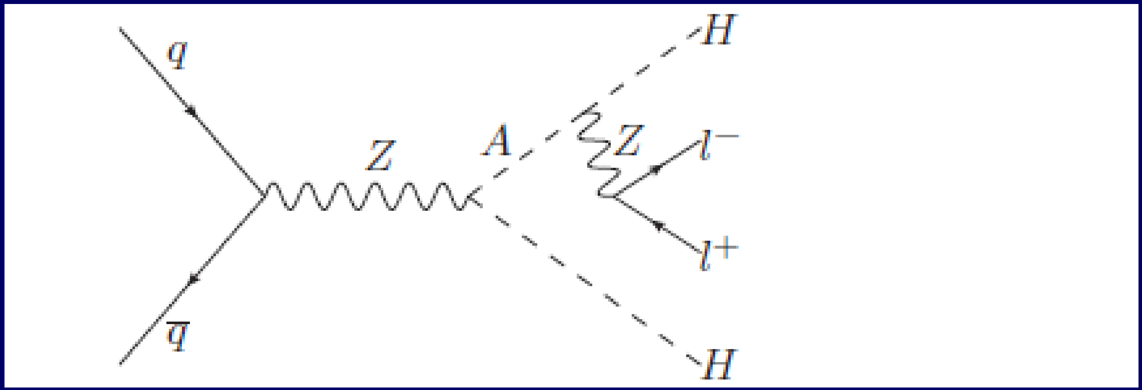
(b) $R_{\gamma\gamma} > 0.8$

$R_{\gamma\gamma}$ → stronger limit than Xenon100!

$f_N = 0.326.$

DM production at LHC

LHC at 8 TeV



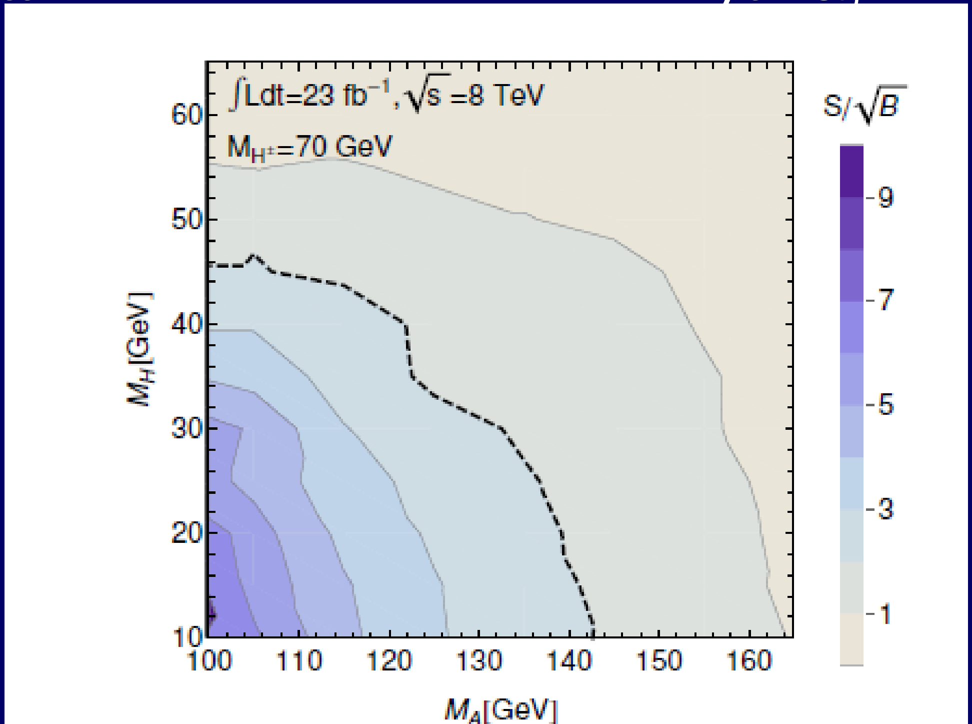
P. Swaczyna
Msc, May 2013

SM background WW,ZZ, tt

Pythia, 2HDMC

$S/\sqrt{B}$ above 2

M_H+M_A< 145 GeV
M_A>100 GeV



Conclusions

Inert Doublet Model: h is *SM-like* and H=DM

mass of H+ is below 135 GeV if $R\gamma\gamma > 1.3$
(H+ has no Yukawa couplings)
If $R\gamma\gamma > 1$ (DM) H mass >62.5 GeV
and <135 GeV, if $R\gamma\gamma > 1.3$

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

For $R\gamma\gamma < 1$ important constraints on DM (h portal)
DM mass below 10 GeV excluded!
Limits stronger than XENON100

IDM and evolution of the Universe

- Inert Doublet Model (IDM) provides DM and it is in agreement with present astrophysical and collider data including the 125 GeV Higgs boson
- If today (T=0) Universe in the Inert phase what was in the past ?
- We have studied temperature dependent Z2 sym. 2HDM potential → evolution of the Inert vacuum and sequences of different vacua in the past (one, two and three phase transitions)

- with leading T2 corrections (only m^2_{ii} (T^2))

(*PRD 82(2010) Ginzburg, Kanishev, MK, D. Sokołowska)*

- beyond T2 corrections (to find strong enough first-order phase transition needed for baryogenesis)

(G. Gil Thesis'2011, G.Gil, P. Chankowski, MK Phys. Lett. B 2012