Corfu Workshop 2014

9.09.2014

Vacuum (stability) in IDM

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I Ginzburg, K. Kanishev (Novosibirsk)

Plan

- SM-like Higgs scenarios AD 2014
- 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 → $Z\gamma$
- Evolution of the Universe in IDM (T^2 and beyond)
- Veltman condition (2HDM, 2HDM+singlets)

LHC

SM-like Higgs 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

Nobel 2013 (Englert, Higgs)

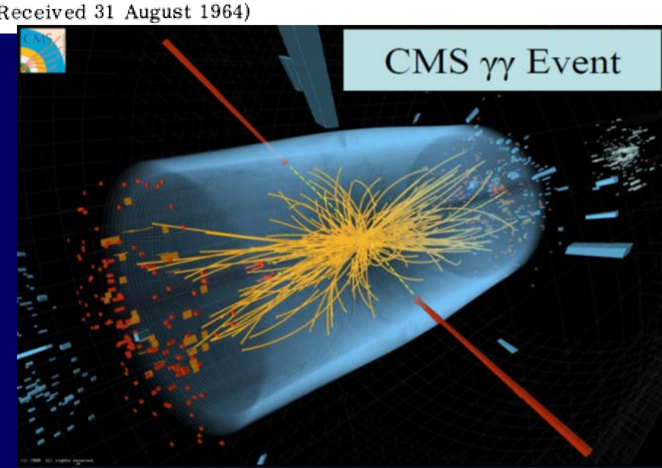
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

125 GeV particle $\mathcal{H}$

What it is?

H_{SM} - Higgs boson of SM ?

h or a heavier scalar

(eg. H of CP-conserving 2HDM (MSSM))?

other state ?

SM-like scenario is observed - so

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

the SM-prediction for *absolute value*

I. Ginzburg, MK , P. Osland 2001

SM-like scenarios

- In many models SM-like scenarios are possible

Definition of SM-like scenario (2014):

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 by LHC

and others

Inert Doublet Model

Today

Higgs and Dark Matter in agreement with data

LHC -> SM-like Higgs
4 dark scalars (no coupling with fermions)
-> DM candidate

WMAP/PLANCK (DM relic density)
Direct DM detection
Indirect DM processes (annihilation)

LHC: strong constraints on DM from Higgs data

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)

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

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

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

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

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

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

$$R = \lambda_{345}/\sqrt{\lambda_1\lambda_2}, \quad R+1>0,$$

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

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

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

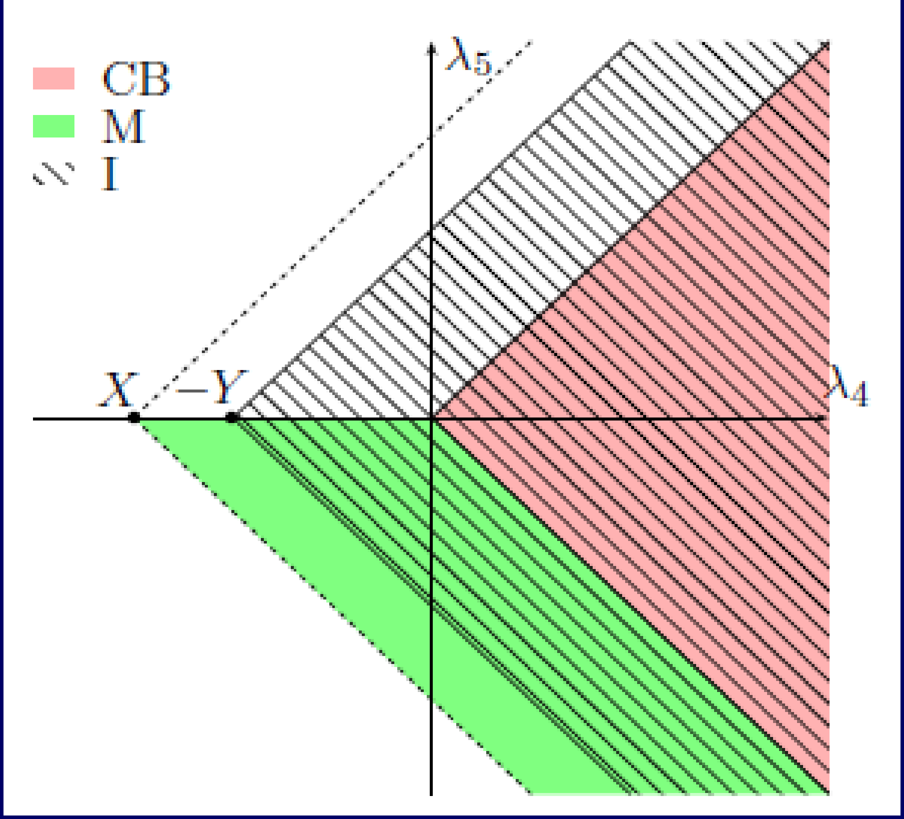
$\sim 1/(1-R_3^2)$

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 $v_D \neq 0$]

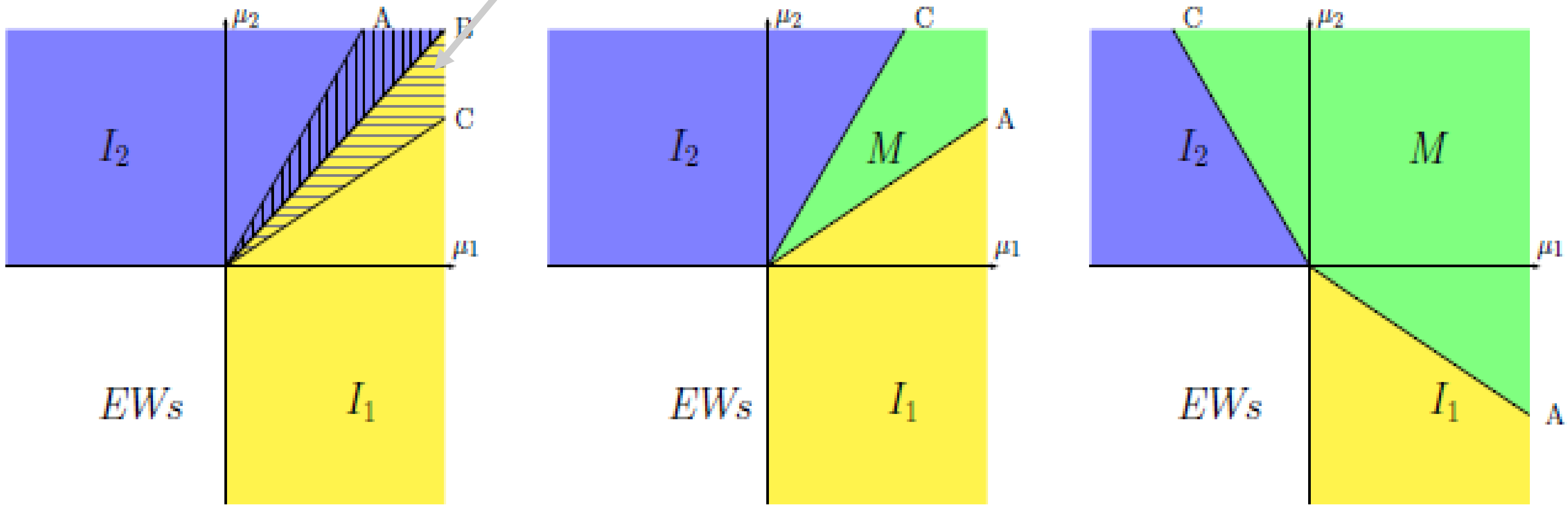
- Charged breaking vacuum CB

Inert overlaps both with Mixed and CB !

Phase diagrams for D-sym. V

coexistence of I1 and I2

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



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

Inert (I1) vacuum

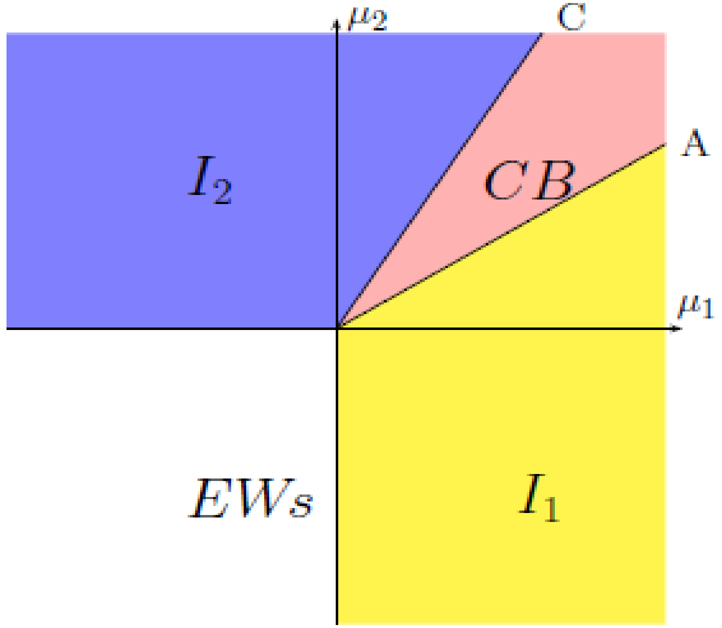
for Mh=125 GeV → fixed μ_1

condition to avoid I2 minimum

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

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

Phase diagrams for D-sym. V Charged Breaking phase



(a) $1 > R_3 > 0$ (b) $0 > R_3 > -1$

$$R_3 + 1 > 0$$

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

Inert phase for TODAY

Ma,…'78
Barbieri..'06

Inert Doublet Model

Symmetry under Z_2 (D) transf. $\Phi_S \to \Phi_S$ $\Phi_D \to - \Phi_D$
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

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

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

(no Higgses!)

4 scalars H+,H-,H, A

no interaction with fermions

D symmetry exact →

- D parity
  - only Φ_D has odd D-parity
    - the lightest scalar stable - DM candidate (H)
      - (Φ_D dark doublet with dark scalars)

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

LHC phenomenology (Barbieri., Ma.. 2006)

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!

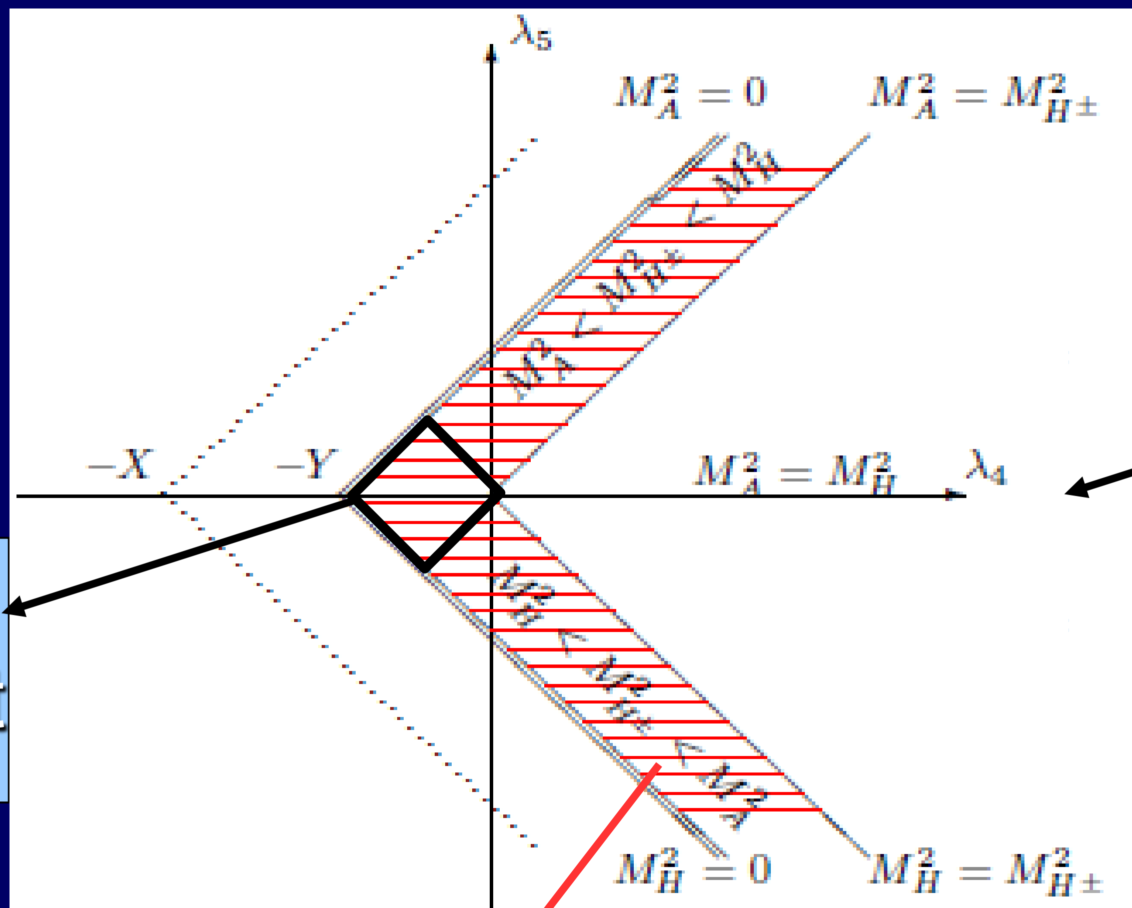
Quartic selfcouplings D^4 proportional to λ_2

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+ lightest

here H+ the heaviest

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 the Inert vacuum

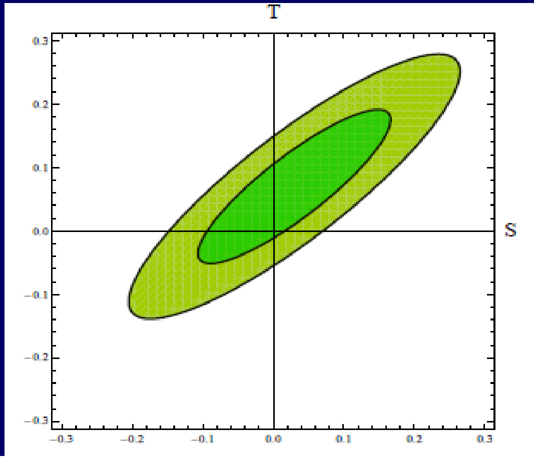
Data:

EWPT (S and T)

LEP, LHC, (WMAP/ PLANCK) data

May 2013

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



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

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

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

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

For now: $R_{\gamma\gamma} = 1.17 \pm 0.27$ (ATLAS), $R_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}$ (CMS)

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

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

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

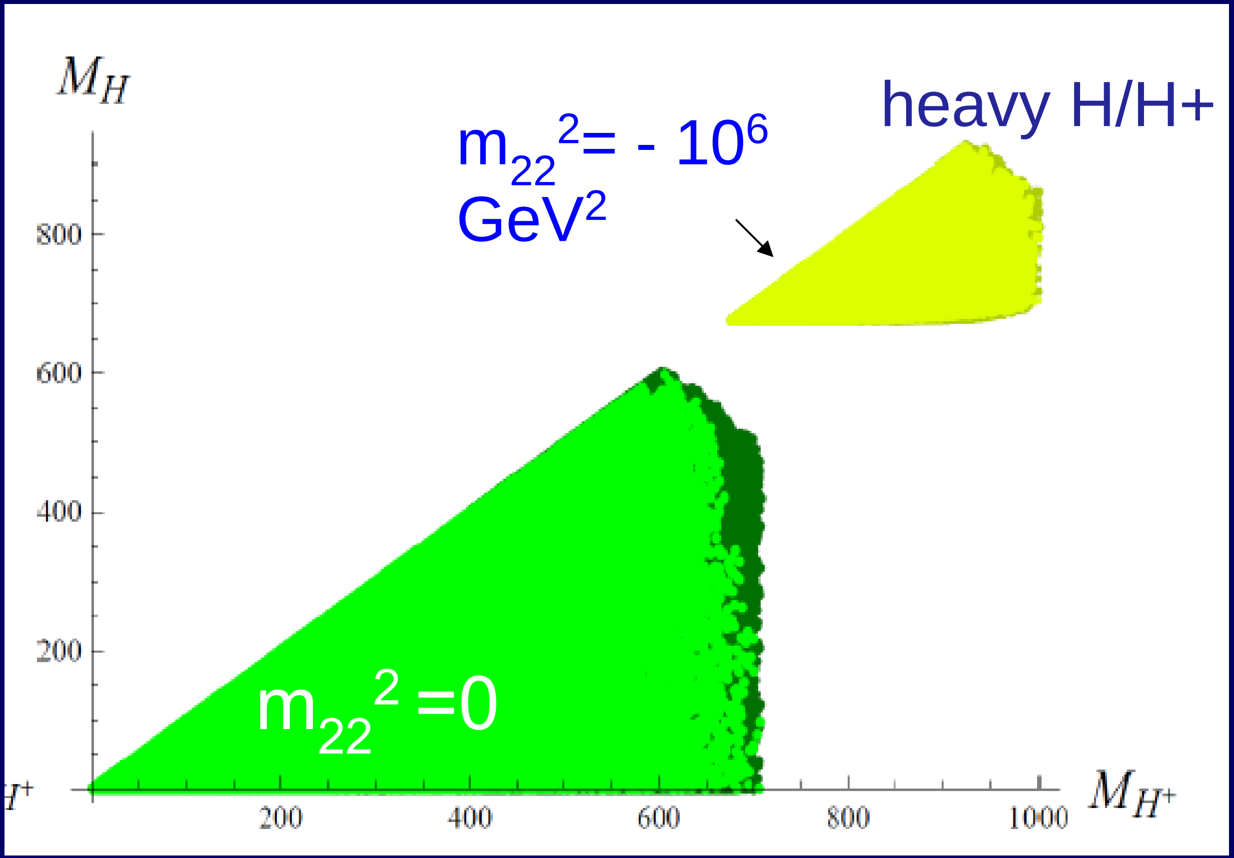
condition for Inert $\frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}$

for 125 GeV h: $M^2_h = m_{11}{}^2 = \lambda_1 v^2$ and max value (pert.unitarity) upper limit: $< 9 \times 10^4\ \mathrm{GeV}^2$

Inert Doublet Model with M_h=125 GeV

$m_{22}^2 = 0$

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



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

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

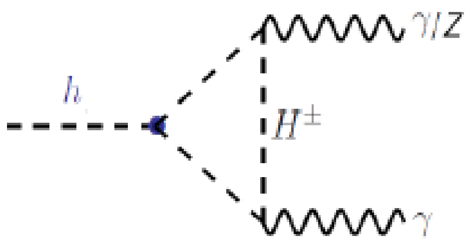
$R_{Z\gamma}$ – treated analogously

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 $\Gamma(h \to \gamma\gamma)^{IDM}$

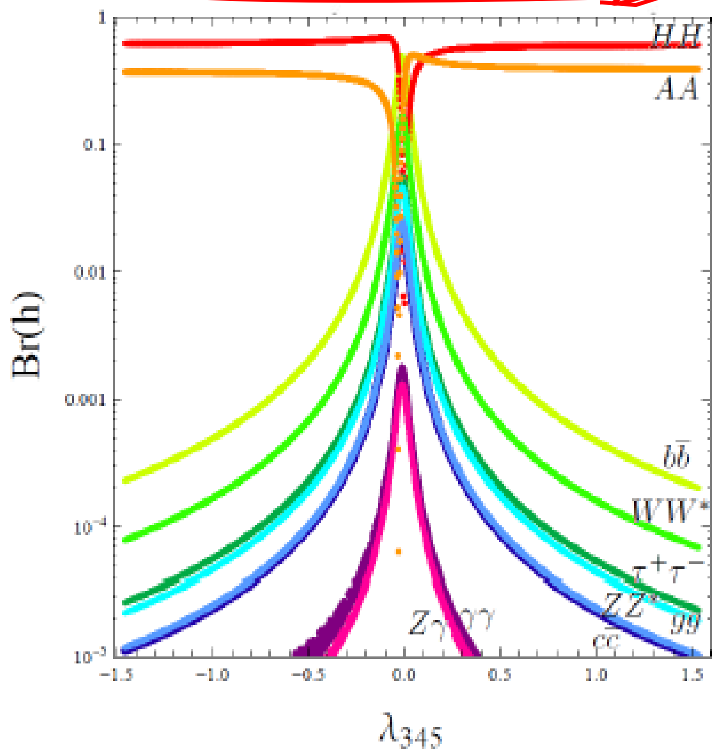


Invisible decays

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

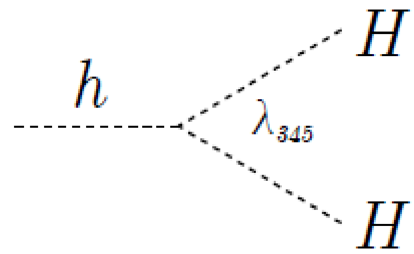
$$\Gamma(h \to HH) = \frac{\lambda_{345}^2 v^2}{32\pi M_h}\sqrt{1 - \frac{4M_H^2}{M_h^2}},$$

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



Invisible decays of the Higgs boson in the IDM

- $h \to HH$ – invisible decay (H is stable)
- augmented total width of the Higgs boson, $\Gamma(h \to HH) \sim \lambda_{345}^2$

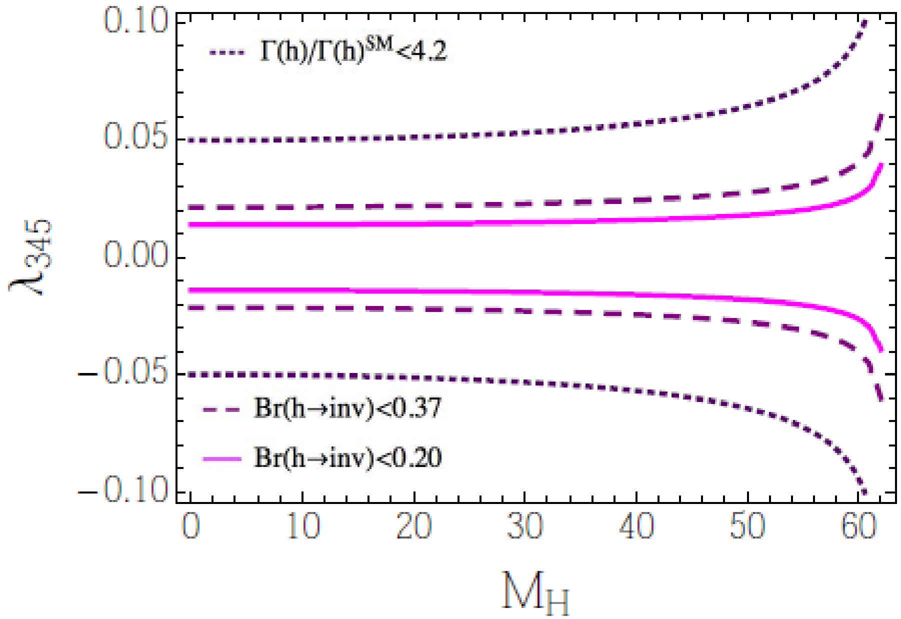


LHC:

- $\mathrm{Br}(h \to \mathrm{inv}) < 37\%$,
- $\Gamma(h)/\Gamma(h)^{SM} < 4.2$

global fit:

- $\mathrm{Br}(h \to \mathrm{inv}) \lesssim 20\%$



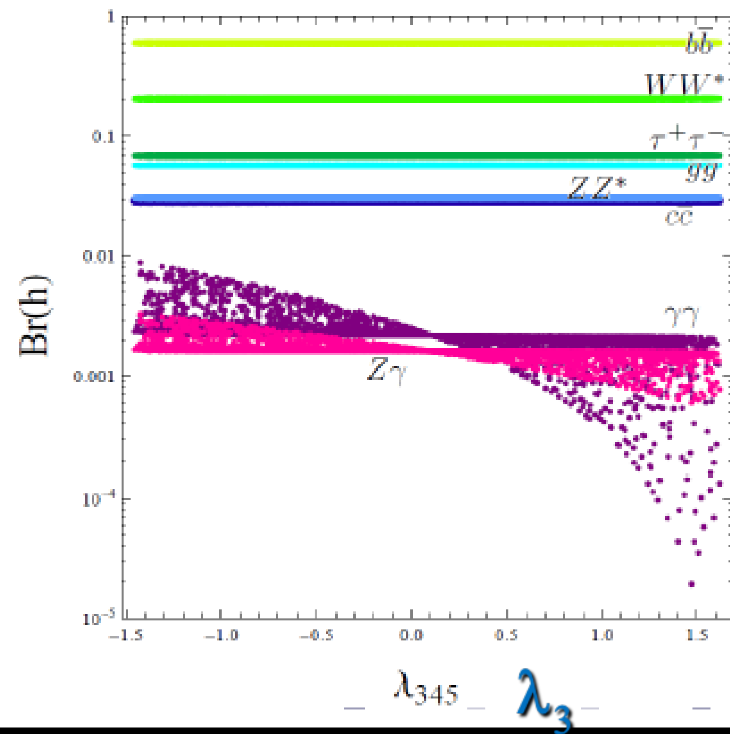
[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010, 2014; CMS-PAS-HIG-14-002]

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

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

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

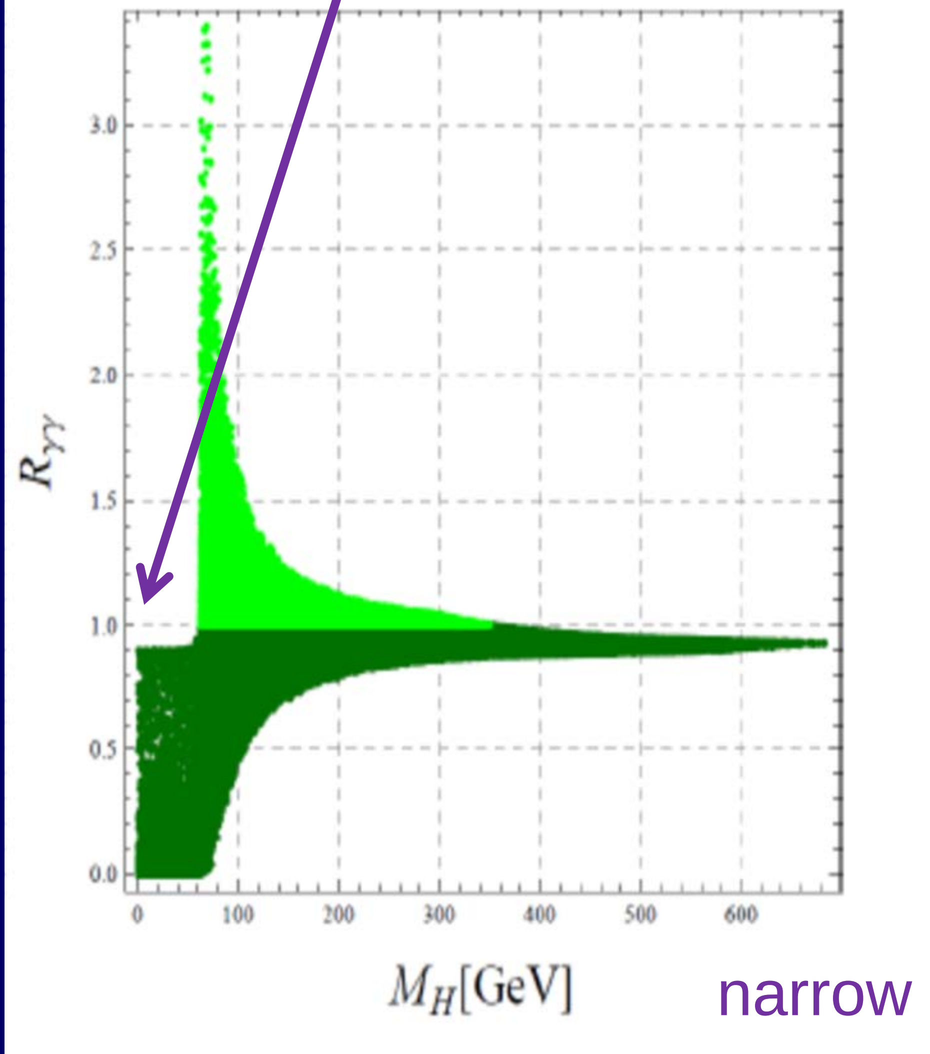
enhancement only for

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

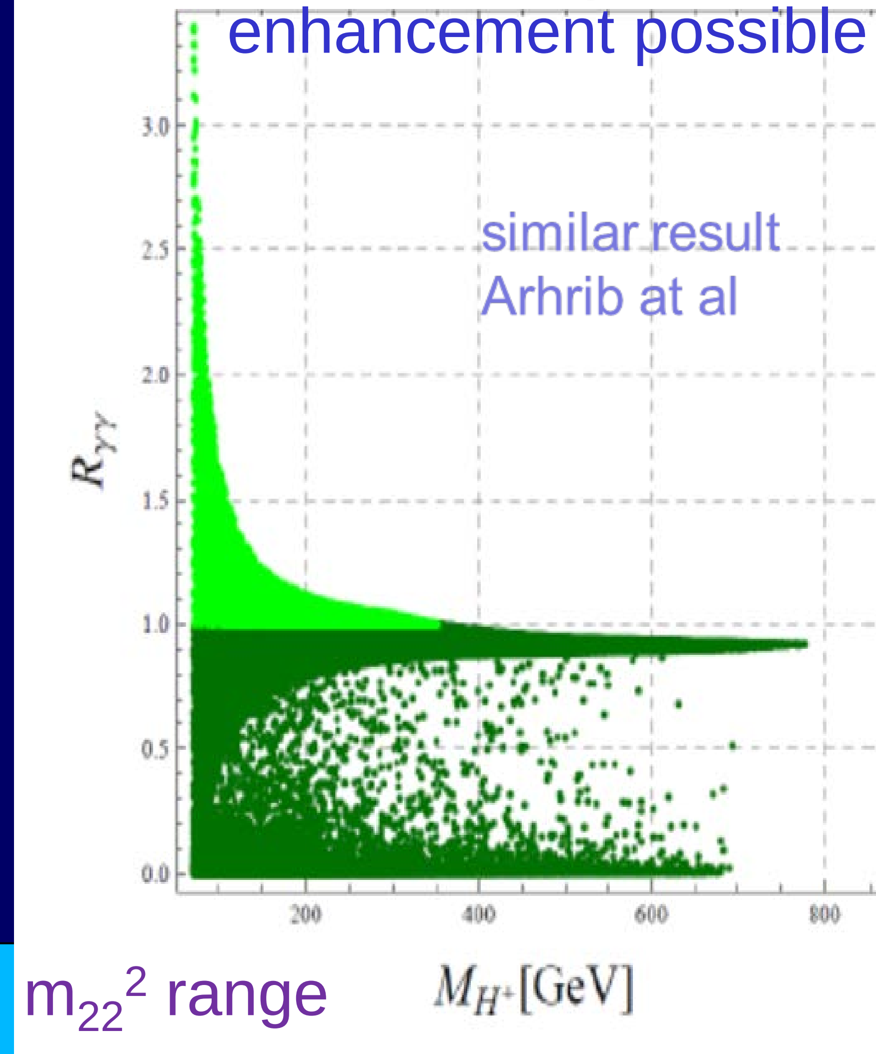
Not valid (condition for Inert vacuum)

$R_{\gamma\gamma}$ 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



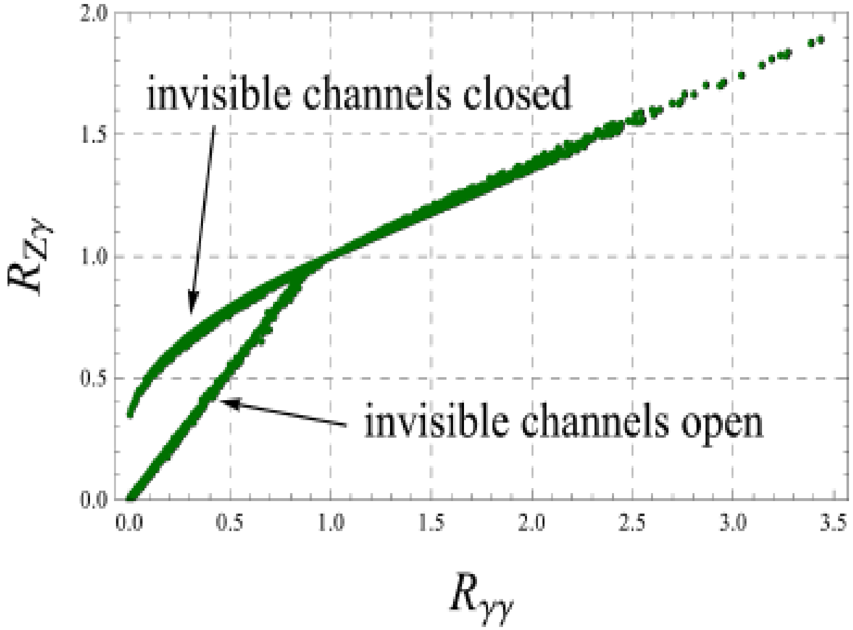
similar result Arhrib at al

narrow m_{22}^2 range

$h \to \gamma\gamma$ 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, ...

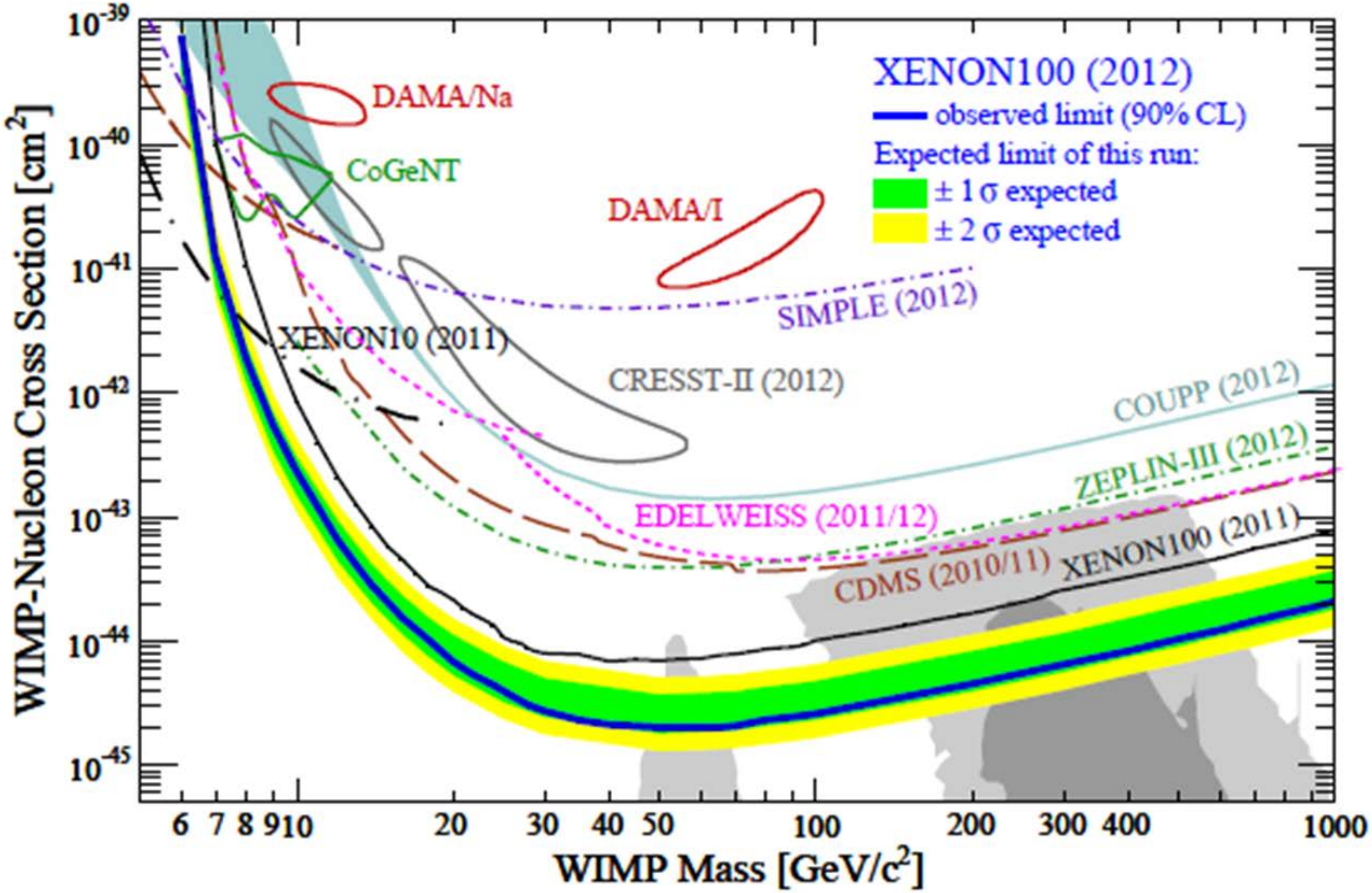
New analysis – Stahl May 2013

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

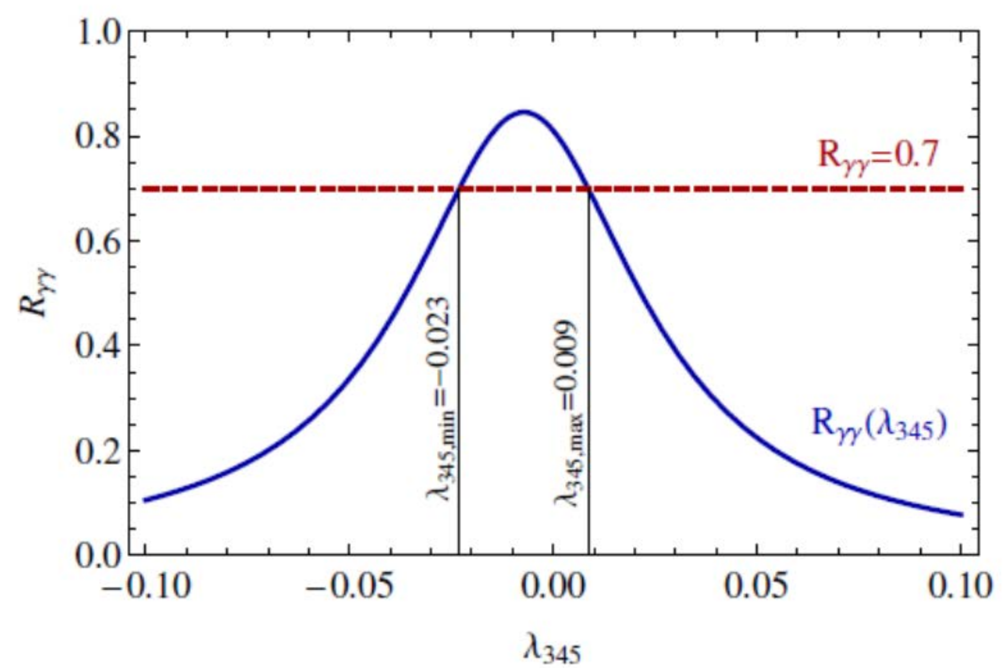
$$\Omega_{DM} h^2 = 0.1126 \pm 0.0036.$$

LHC data

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

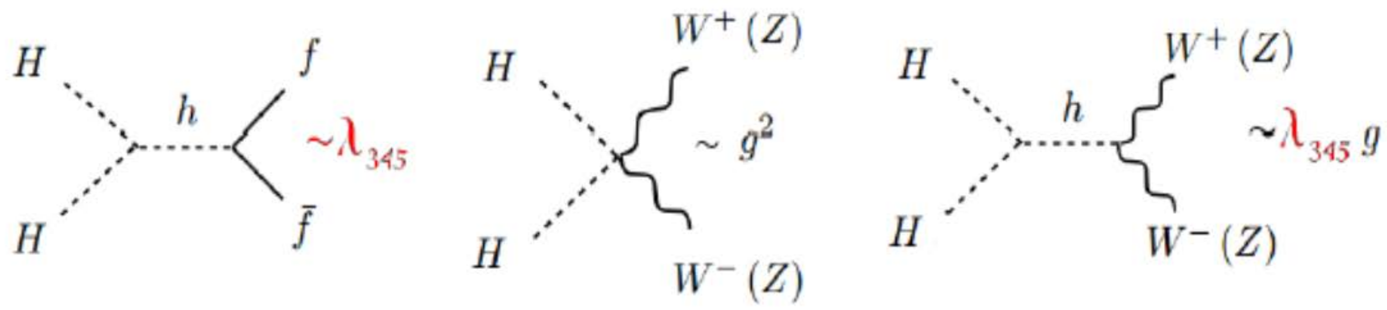
$R_{\gamma\gamma} > 1$
DM mass only above 62.5 GeV allowed

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



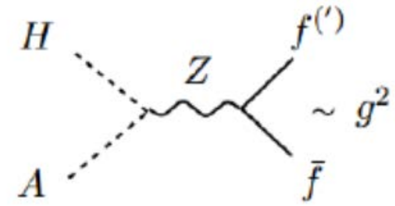
Relic density constraints on masses and couplings

Relic density constraints



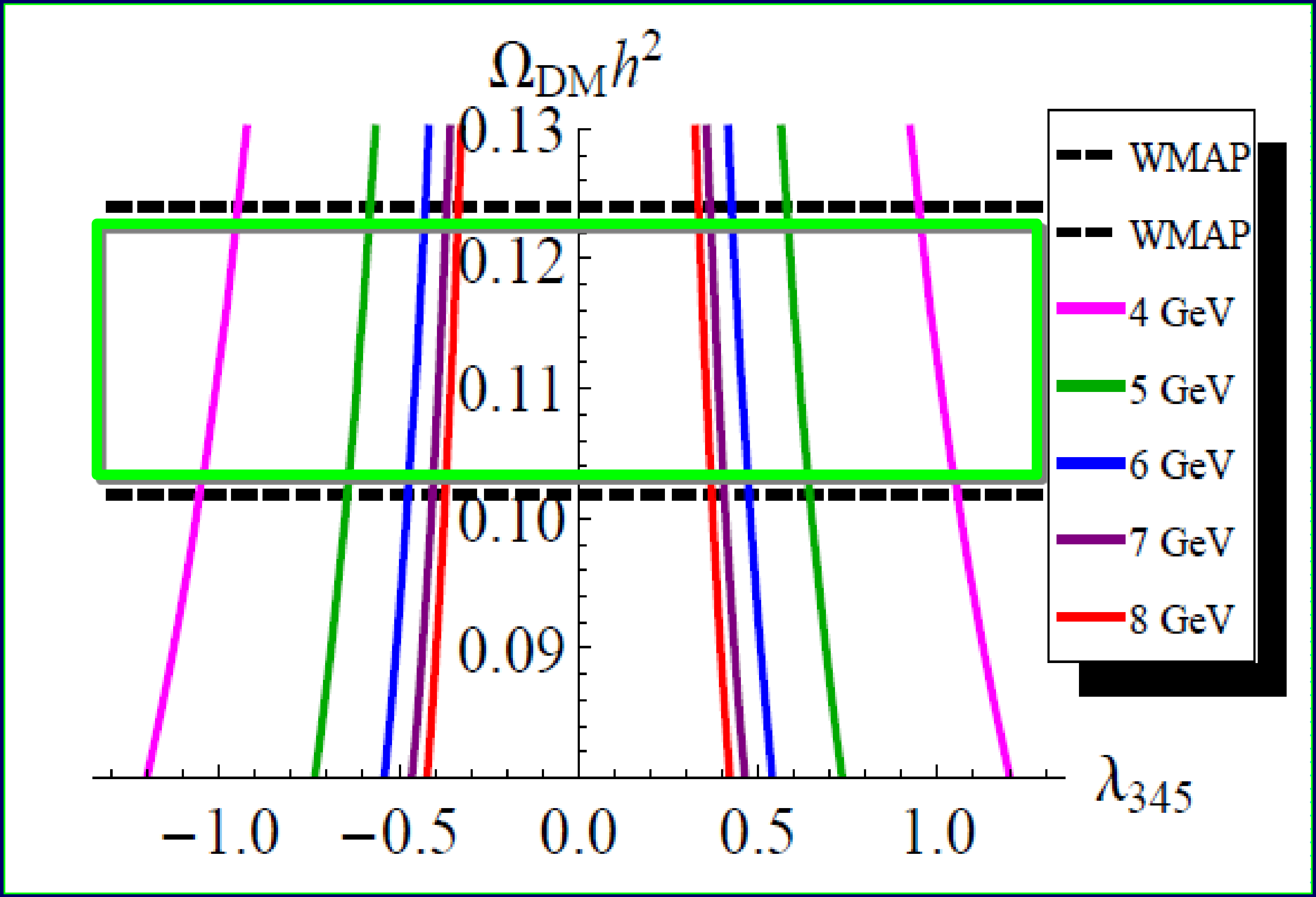
$$0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow \lambda_{345}^{\min}, \lambda_{345}^{\max}$$

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, $g_{HHh} \sim \mathcal{O}(0.1)$

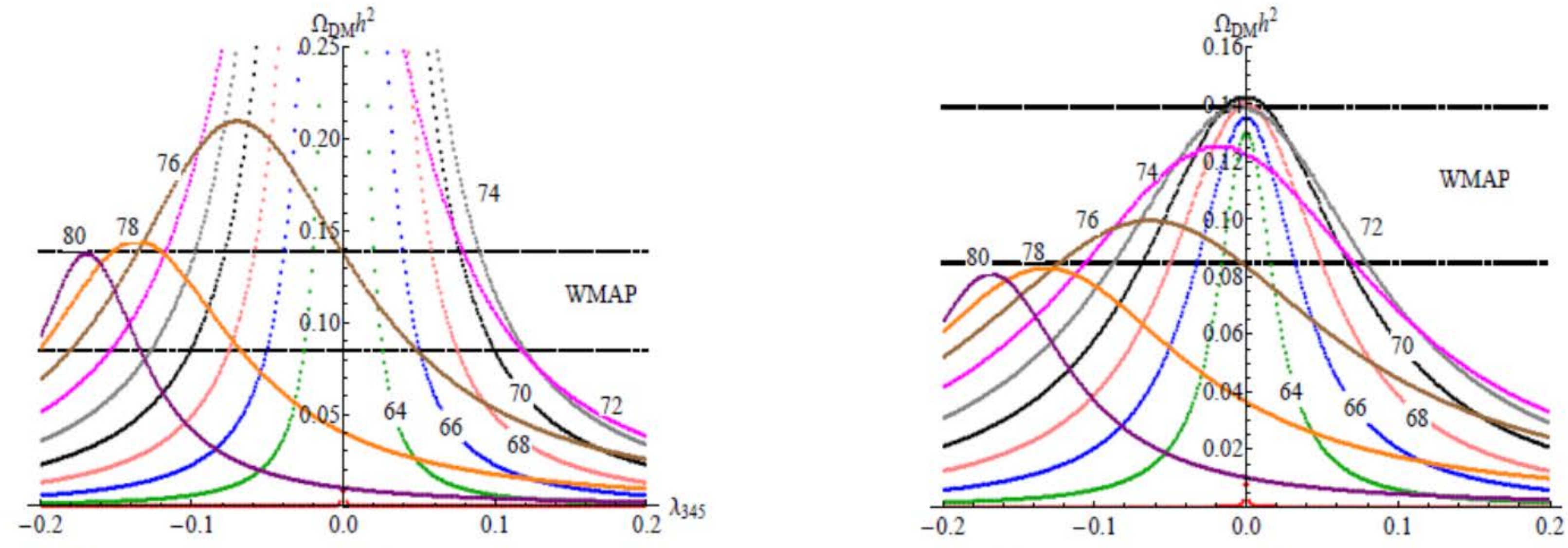
WMAP window for light H (DM)



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

D. Sokołowska, 2013

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



$\delta_A = 50$ GeV, $\delta_\pm = 50$ GeV

$\delta_A = 8$ GeV, $\delta_\pm = 50$ GeV

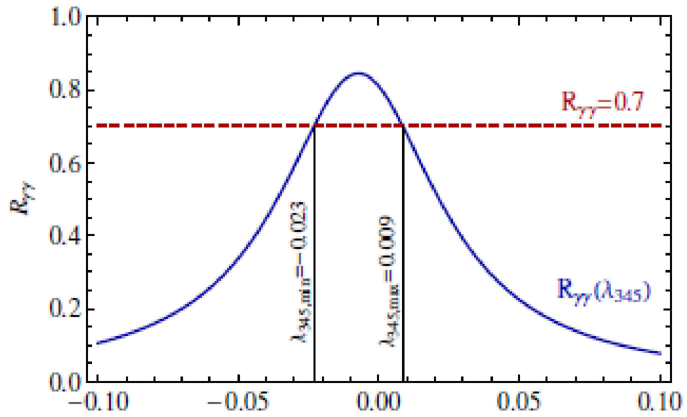
above 76 GeV asymmetry due to annihilation to gauge bosons

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}

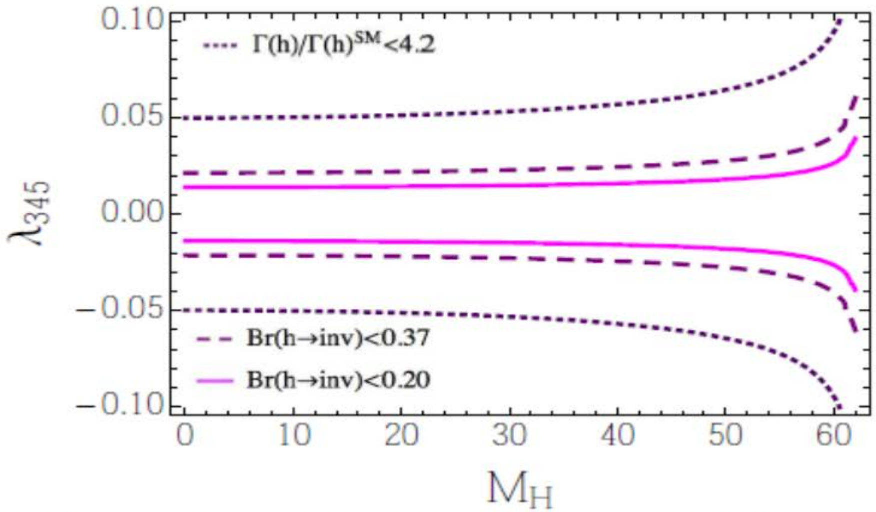


LHC:

- $\mathrm{Br}(h \to \mathrm{inv}) < 37\%$,
- $\Gamma(h)/\Gamma(h)^{SM} < 4.2$

global fit:

- $\mathrm{Br}(h \to \mathrm{inv}) \lesssim 20\%$

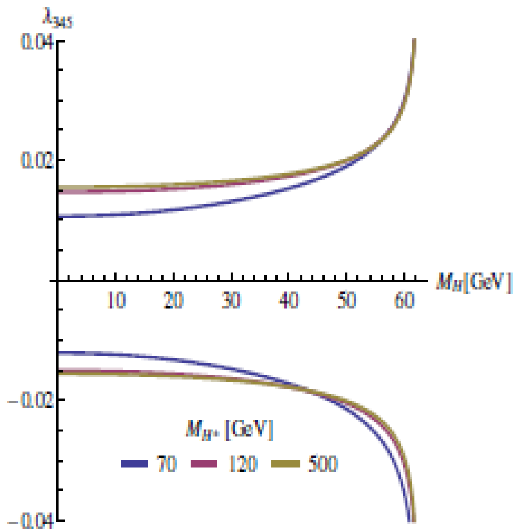


[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010; 2014 CMS-PAS-HIG-14-002]

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

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

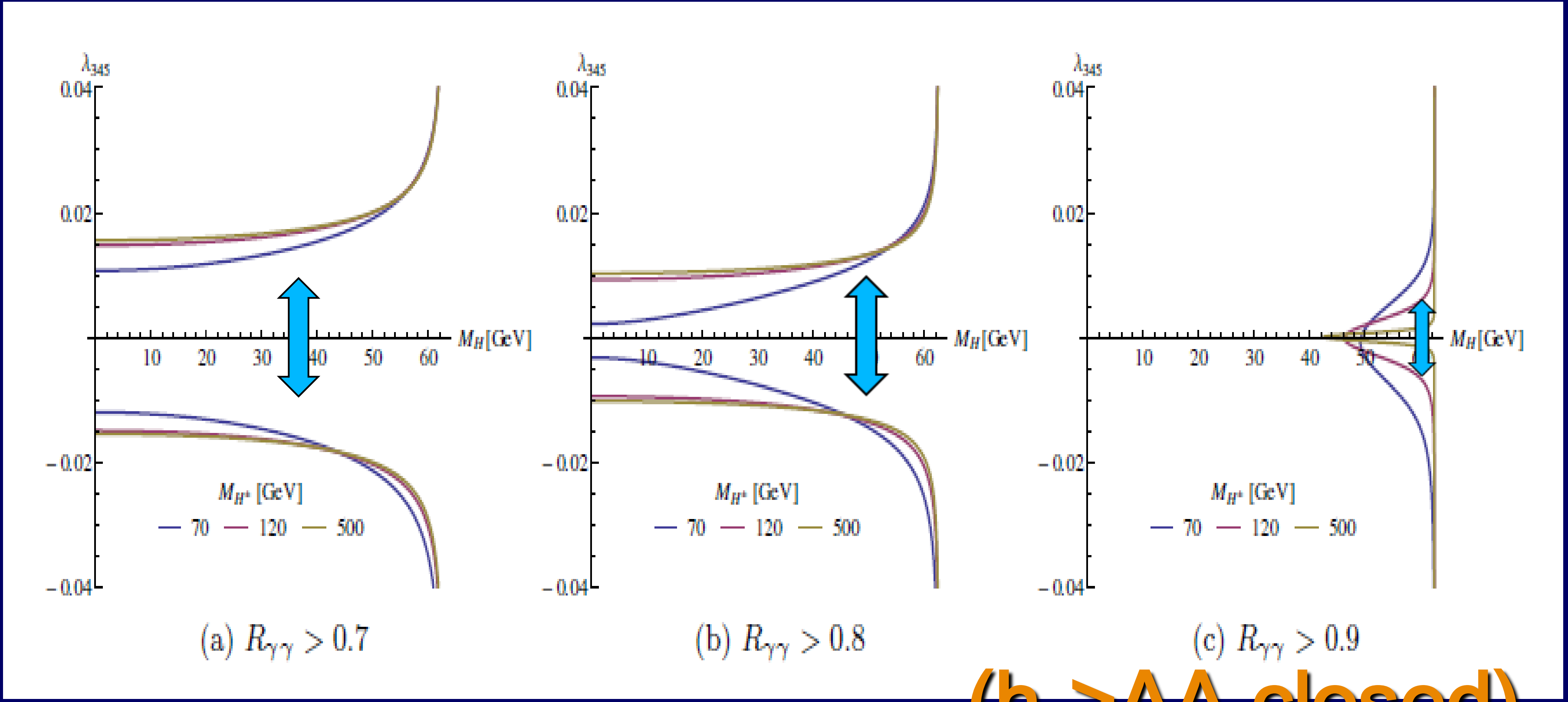
- CDMS-II reported event:

  $M_H = 8.6$ 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

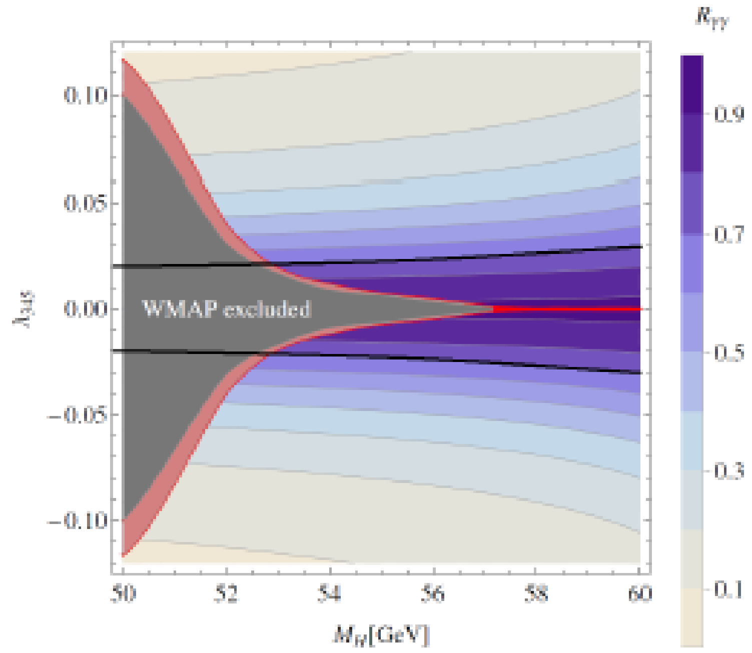


(h->AA closed)

allowed region between lines

Medium DM mass (1) – HH channel open

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

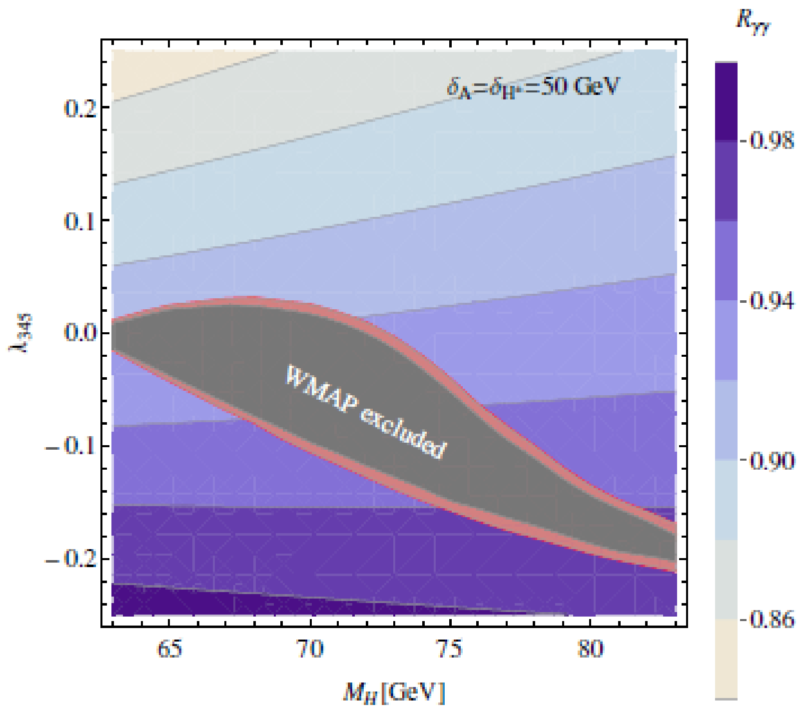


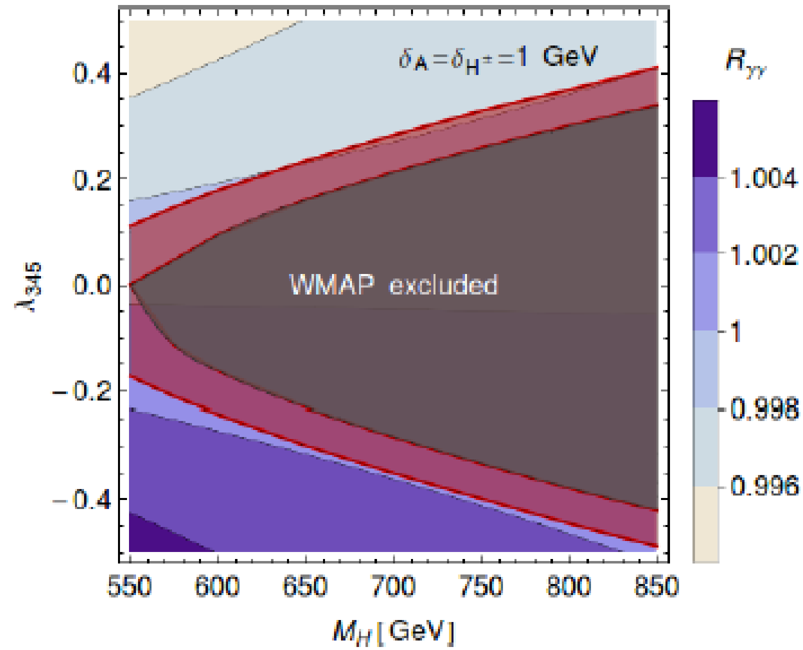
Red bound: $\Omega_{DM} h^2$ in agreement with WMAP

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





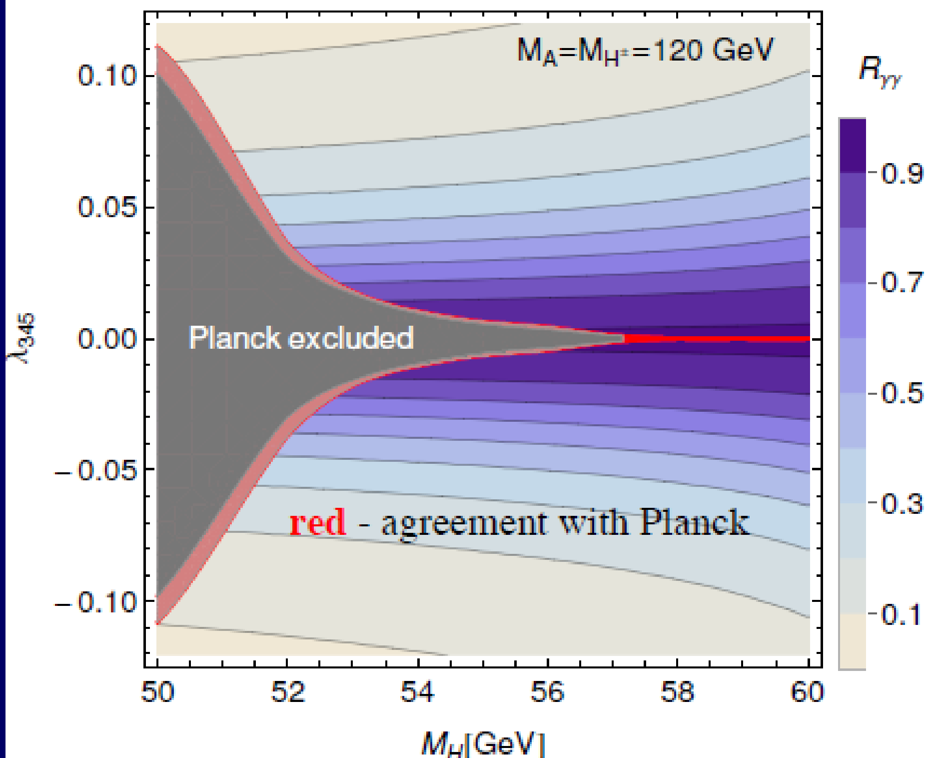
- H of intermediate mass can constitute 100% of DM
- H constituting 100% DM inconsistent with $R_{\gamma\gamma} > 1$

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

New (Planck)

[Planck update: D. Sokołowska, P. Swaczyna, 2014]

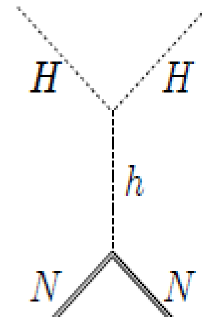
$h \to HH$ open



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

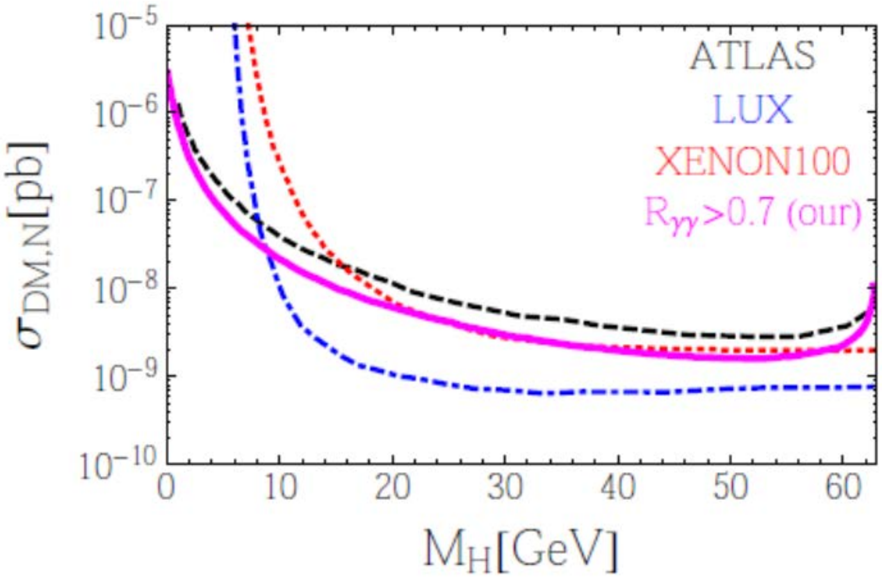
- light DM ($M_H < 10\,\mathrm{GeV}$)
  $\Rightarrow$ excluded
- intermediate DM 1
  ($50\,\mathrm{GeV} < M_H < M_H/2$)
  $\Rightarrow M_H > 53\,\mathrm{GeV}$
- intermediate DM 2
  ($M_h/2 < M_H \lesssim 82\,\mathrm{GeV}$)
  $\Rightarrow R_{\gamma\gamma} < 1$
- heavy DM
  ($M_H > 500\,\mathrm{GeV}$)
  $\Rightarrow R_{\gamma\gamma} \approx 1$

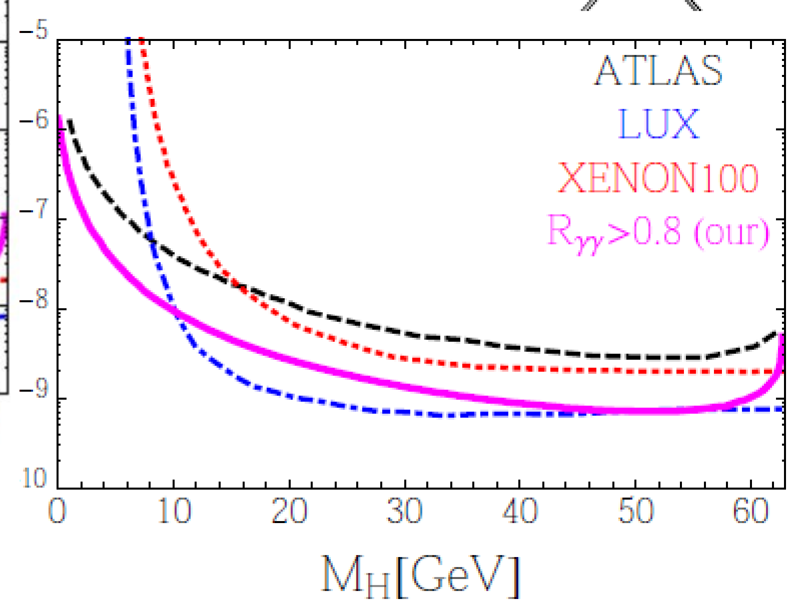
Direct detection – comparison with XENON/LUX

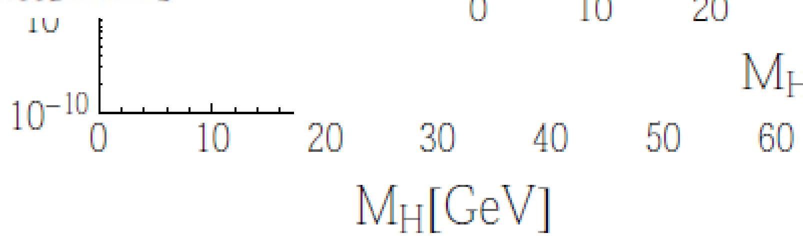


- DM-nucleon scattering cross section $\sigma_{\mathrm{DM,N}} \sim \lambda_{345}^2$

$(M_H,\ \sigma_{\mathrm{DM},N})$ plane





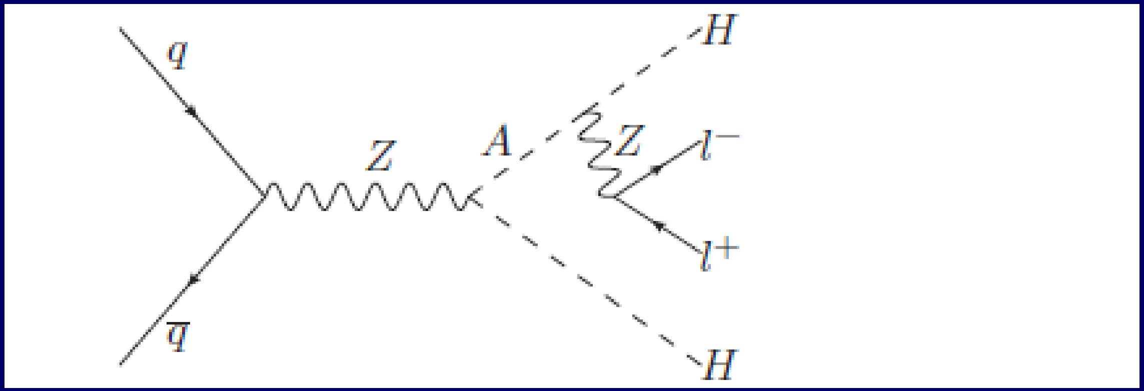


Limits stronger/comparable to those from XENON100

DM production at LHC

LHC at 8 TeV

P. Swaczyna
MSc, May 2013

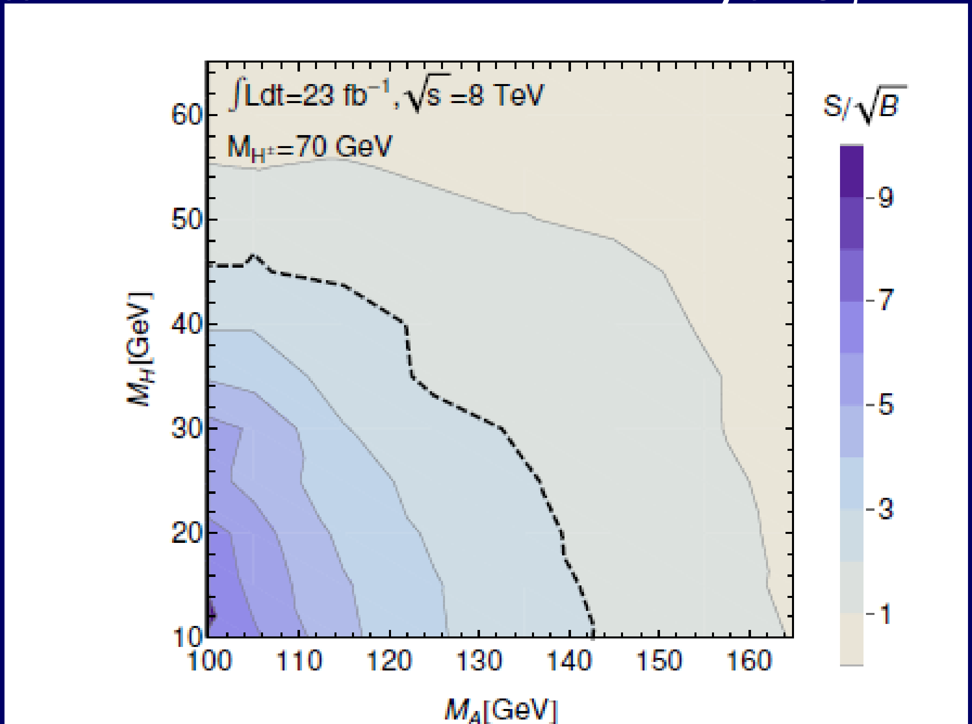


SM background WW,ZZ, tt

Pythia, 2HDMC

$S/\sqrt{B}$ above 2

M_H+M_A< 145 GeV
M_A>100 GeV



Conclusions I

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 $R_{\gamma\gamma} > 1.3$

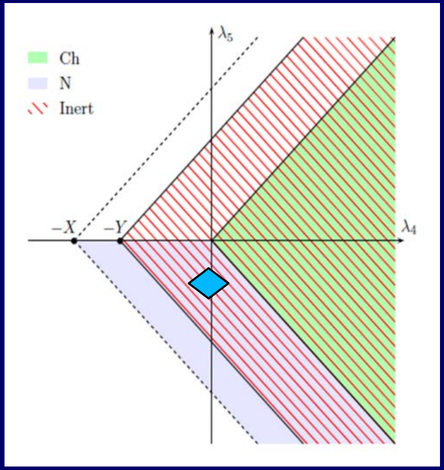
For $R_{\gamma\gamma} < 1$ important constraints on DM (h portal)
DM mass below 10 GeV excluded!
Limits stronger than XENON100/LUX

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

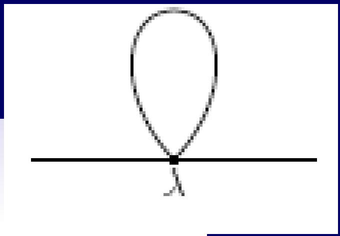
Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev,MK, Sokołowska PRD 2010,
Sokołowska 2011

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...



Termal corrections



Evolution of the Universe

Scalar, bosonic and fermionic contributions to $\Delta V \to m_{ii}^2(T)$:

$$m_{11}^2(T) = m_{11}^2 - c_1 T^2\,, \quad m_{22}^2(T) = m_{22}^2 - c_2 T^2$$

$$c_1 = \frac{3\lambda_1+2\lambda_3+\lambda_4}{6} + \frac{3g^2+g'^2}{8} + \frac{g_t^2+g_b^2}{2}, \quad c_2 = \frac{3\lambda_2+2\lambda_3+\lambda_4}{6} + \frac{3g^2+g'^2}{8}$$

- fermionic contribution in c_1 (Model I)
- $c_1 + c_2 > 0$ from positivity constrains
- c_1 and c_2 positive to restore EW symmetry in the past

For a given T we determine:

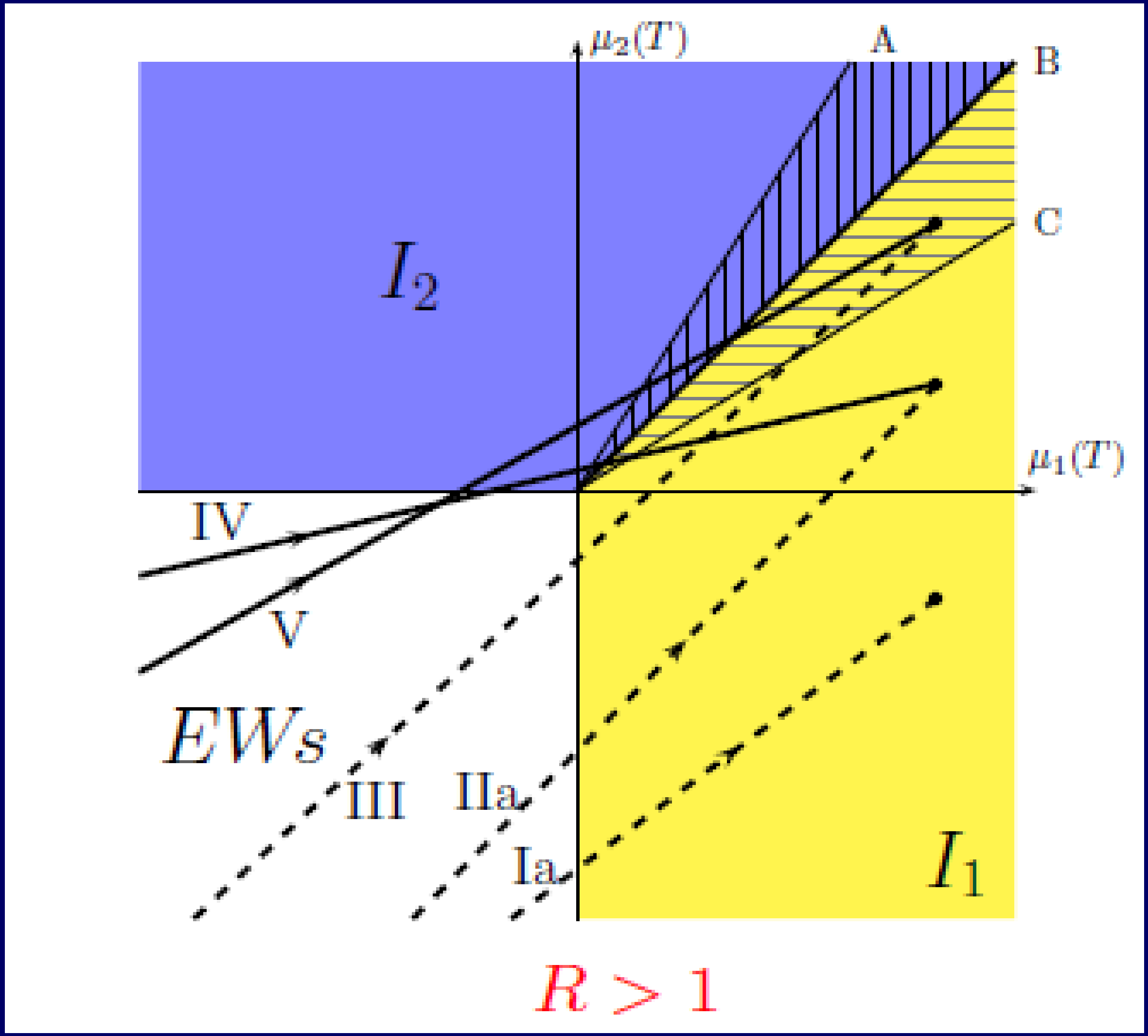
- sign of $v_i^2\big|_{I_1, I_2, M}(T) \to$ possible existence of a given extremum
- values of λ_i (fixed) $\to$ existence of a local minimum
- value of extremum energy $\to$ global minimum

$\Rightarrow$ sequences of possible phase transitions

For $u = 0$ (neutral extrema) three separate cases of $EWs \to \ldots \to I_1$:

$$R = \lambda_{345}/\sqrt{\lambda_1\lambda_2}: \quad R > 1, \quad 1 > R > 0, \quad 0 > R > -1$$

Phase diagram (μ_1,μ_2)



$\mu_i = m_{ii}^2/\sqrt{\lambda_i}$

$$R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}$$

Stability condition

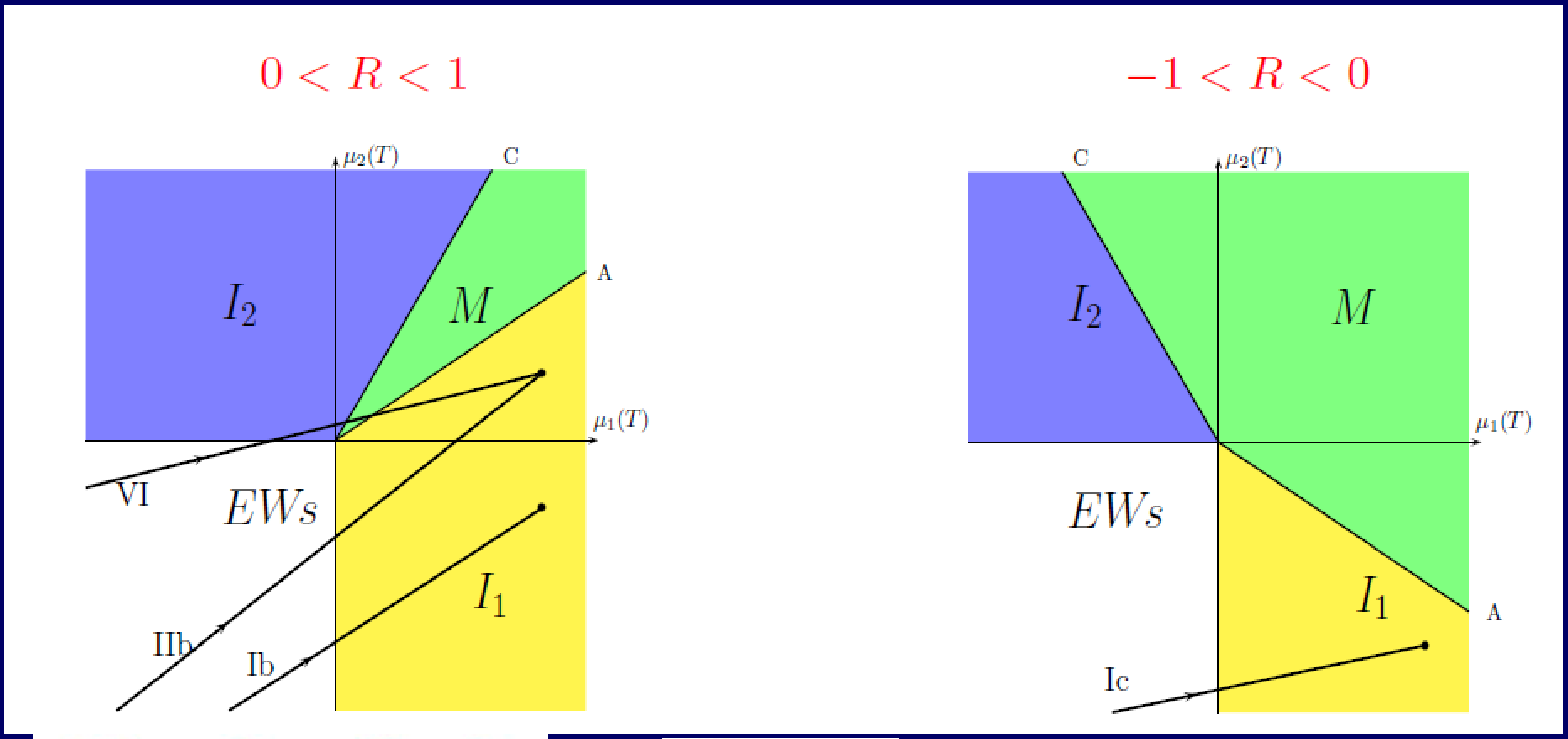
$EWs \to I_1$

$EWs \to I_2 \to I_1$

T^2 corrections → rays from EWs to the Inert phase

unique possibility: 1st order phase transition $I_2 \to I_1$

Sequences of phases

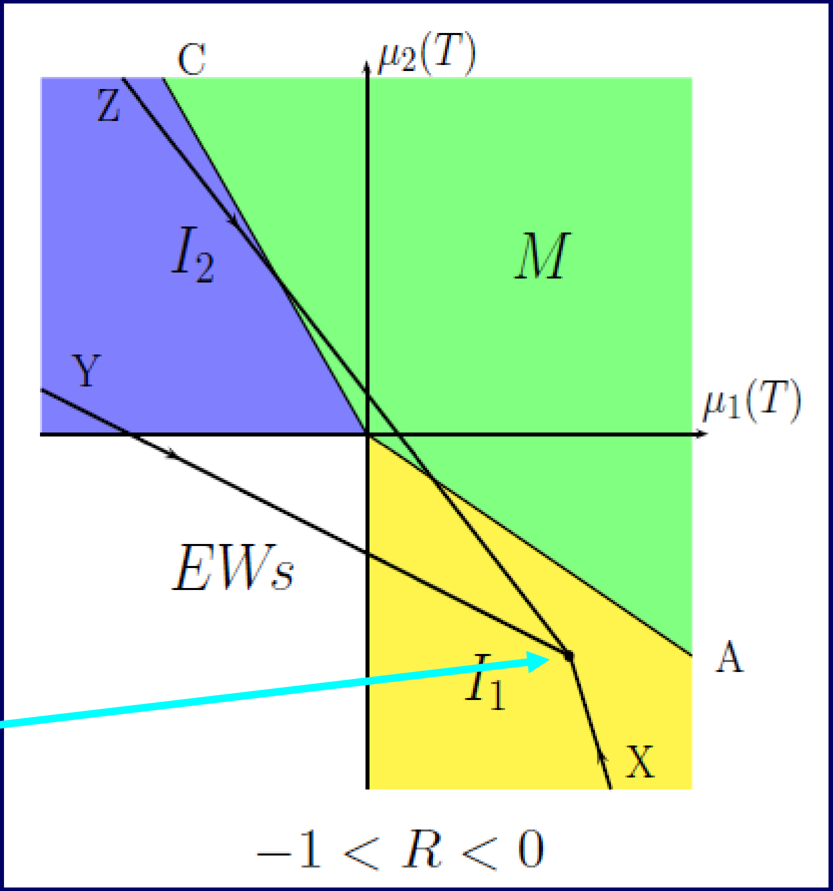


$EWs \to I_2 \to M \to I_1$

$EWs \to I_1$

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

Sensitivity to HHHH coupling λ_2 medium DM mass - example

- fixed values of scalars' masses $\rightarrow (\lambda_{345}, \lambda_2)$ phase space:

$$M_{D_H} = 50 \text{ GeV}, \; M_{D_A} = 120 \text{ GeV}, \; M_{D^\pm} = 120 \text{ GeV}, \; M_{h_S} = 120 \text{ GeV}$$

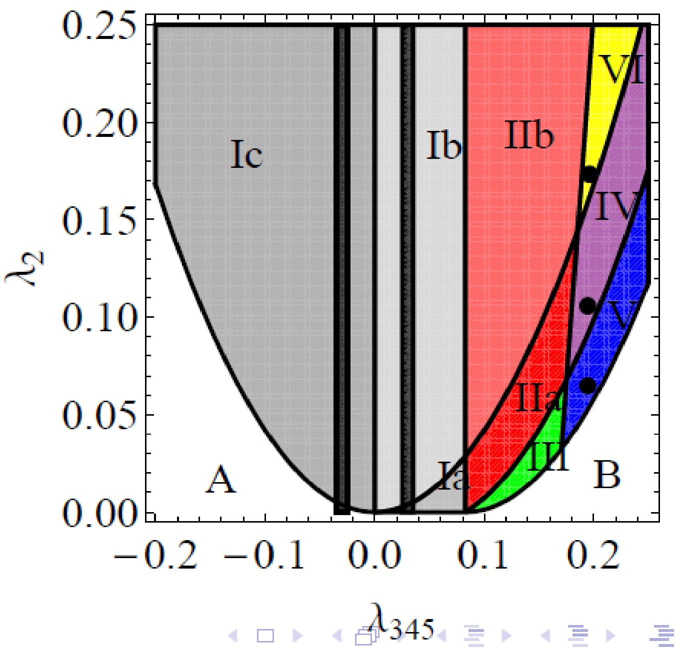
- fixed value of λ_{345}:

$$\lambda_{345} = 0.1945$$

- **rays may differ only by value of λ_2**

vertical bounds – WMAP-allowed region

Ray no.	λ_2
$EWs \rightarrow I_2 \rightarrow I_1$	
IV	$\lambda_2 = 0.1031$
V	$\lambda_2 = 0.0684$
$EWs \rightarrow I_2 \rightarrow M \rightarrow I_1$	
VI	$\lambda_2 = 0.1672$



limits on λ_2
-positivity
-Inert vacuum

Conclusions II

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

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

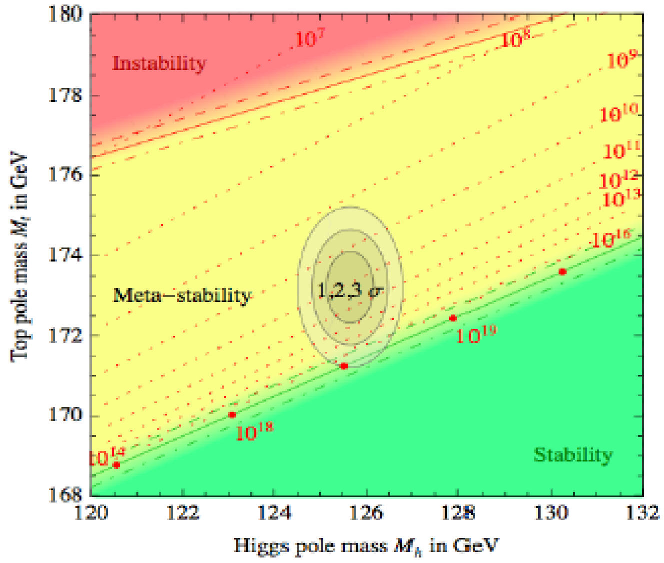
- Can we find clear signals ?

  - 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

Inert vacuum beyond tree-level

Vacuum stability – the SM picture

- measurement of the Higgs mass allows to localize the SM in the phase diagram
- SM vacuum – metastable but with long lifetime
- new interactions modify the picture
- what is the impact of additional scalars?



from: Butazzo et al., JHEP 1312 (2013) 089

[see also: V. Branchina et al., PRL 111 (2013) 241801, arXiv:1407.4112, arXiv:1408.5302]

Swiezewska

Stability of Inert vacuum

$\Longrightarrow$ for $m_{22}^2 \gtrsim 9 \cdot 10^4$ GeV^2 Inert and Inert-like minima can coexist – **necessary computation of the Inert vacuum lifetime**

- *common sense:* "scalar contribution to the effective potential is positive, so IDM vacuum should be more stable than in the SM" – is it true?
- *simple approach:* consider the tree level positivity conditions with running couplings inserted

$$\lambda_1(\mu) > 0, \quad \lambda_2(\mu) > 0, \quad \lambda_3(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0,$$

$$\lambda_{345}(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0,$$

$\Longrightarrow$ the instability scale is higher than in the SM

[A. Goudelis, B. Herrmann, O. Stål, JHEP 09 (2013) 106]

- *refined approximate approach:* consider effective potential of the IDM, keeping only one vev $\neq 0$ (additional scalars are "integrated out")

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

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

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

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

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

mass matrices

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

number of states

counter terms →

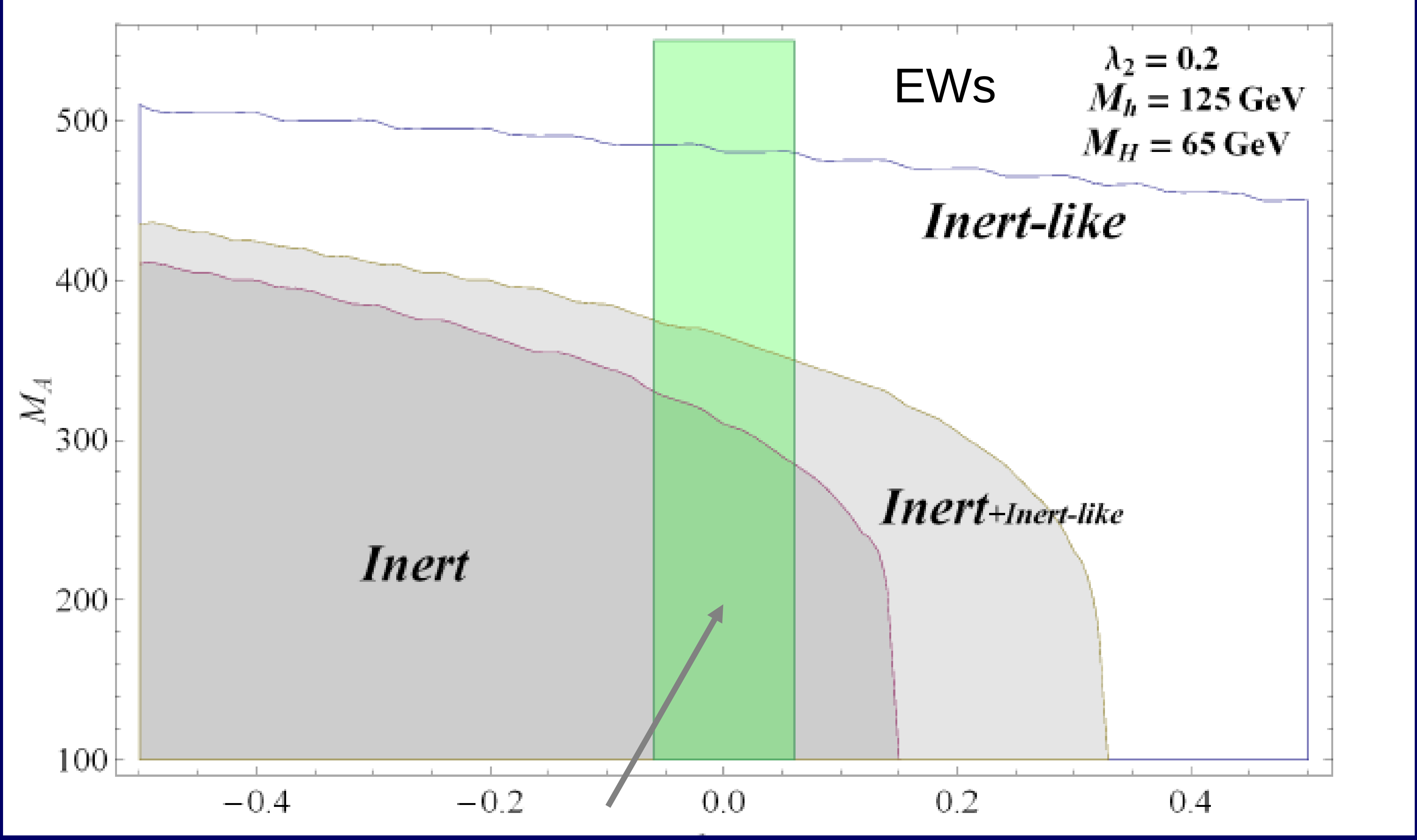
Fixing counterterms

We require that v1=v1(tree)
and that h field propagator has a pole for tree-level mass-squared M_h^2

Then we put conditions on λ_{345} (hHH), λ_2(HHHH)

subtract the divergences of $V_{\text{eff}}^{(1L)}$ proportional to v_2^4 and $v_1^2 v_2^2$ using the $\overline{\text{MS}}$ scheme. This fixes the combinations $\delta\lambda_2 + 2\lambda_2\delta Z_2$ and $\delta\lambda_{345} + \lambda_{345}(\delta Z_1 + \delta Z_2)$. Once the latter counterterm is fixed the last necessary combination $\delta m_{22}^2 + m_{22}^2 \delta Z_2$ is determined by renormalizing the H^0 propagator on-shell. The counterterms $\delta\lambda_3$ and $\delta\lambda_5$ can be then used to enforce that the tree-level masses M_{A^0} and $M_{H^\pm}$ remain unchanged by one-loop corrections (they do not need to be determined explicitly).

Phases at T=0 (one-loop eff. V) for $M_{H+}=M_A$



One-loop temperature dependent effective potential

$$\Delta^{(1L)}V_{T\neq 0} = \frac{T^4}{2\pi^2}\sum_{\text{fields}} C_s \int_0^\infty dx\, x^2 \ln\left[1-(-1)^{2s}\exp\left(-\sqrt{x^2+\mathcal{M}_s^2/T^2}\right)\right].$$

For $T^2 \gg \mathcal{M}_s^2$ the contribution of $\mathcal{M}_s^2$ to (12) can be expanded:

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_B = |C_s|\left\{-\frac{\pi^2}{90}T^4 + \frac{1}{24}T^2\mathcal{M}_s^2 - \frac{T}{12\pi}|\mathcal{M}_s^3| - \frac{\mathcal{M}_s^4}{64\pi^2}\left(\ln\frac{\mathcal{M}_s^2}{T^2} - C_B\right)\right.$$

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_F = |C_s|\left\{-\frac{7\pi^2}{720}T^4 + \frac{1}{48}T^2\mathcal{M}_s^2 + \frac{\mathcal{M}_s^4}{64\pi^2}\left(\ln\frac{\mathcal{M}_s^2}{T^2} - C_F\right)\right\}$$

($C_B = 5.40762$, $C_F = 2.63503$). In the opposite limit $T^2 \ll \mathcal{M}_s^2$ one has

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_s = -|C_s|\, T^4\left(\frac{|\mathcal{M}_s|}{2\pi T}\right)^{3/2}\left(1+\frac{15}{8}\frac{T}{|\mathcal{M}_s|}+\dots\right)\exp\left(-\frac{|\mathcal{M}_s|}{T}\right),$$

both for B and F

Strength of the phase transition

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

We are looking for parameter space of IDM which allows for a strong first order phase transition

$$v(T_{EW})/T_{EW} > 1$$

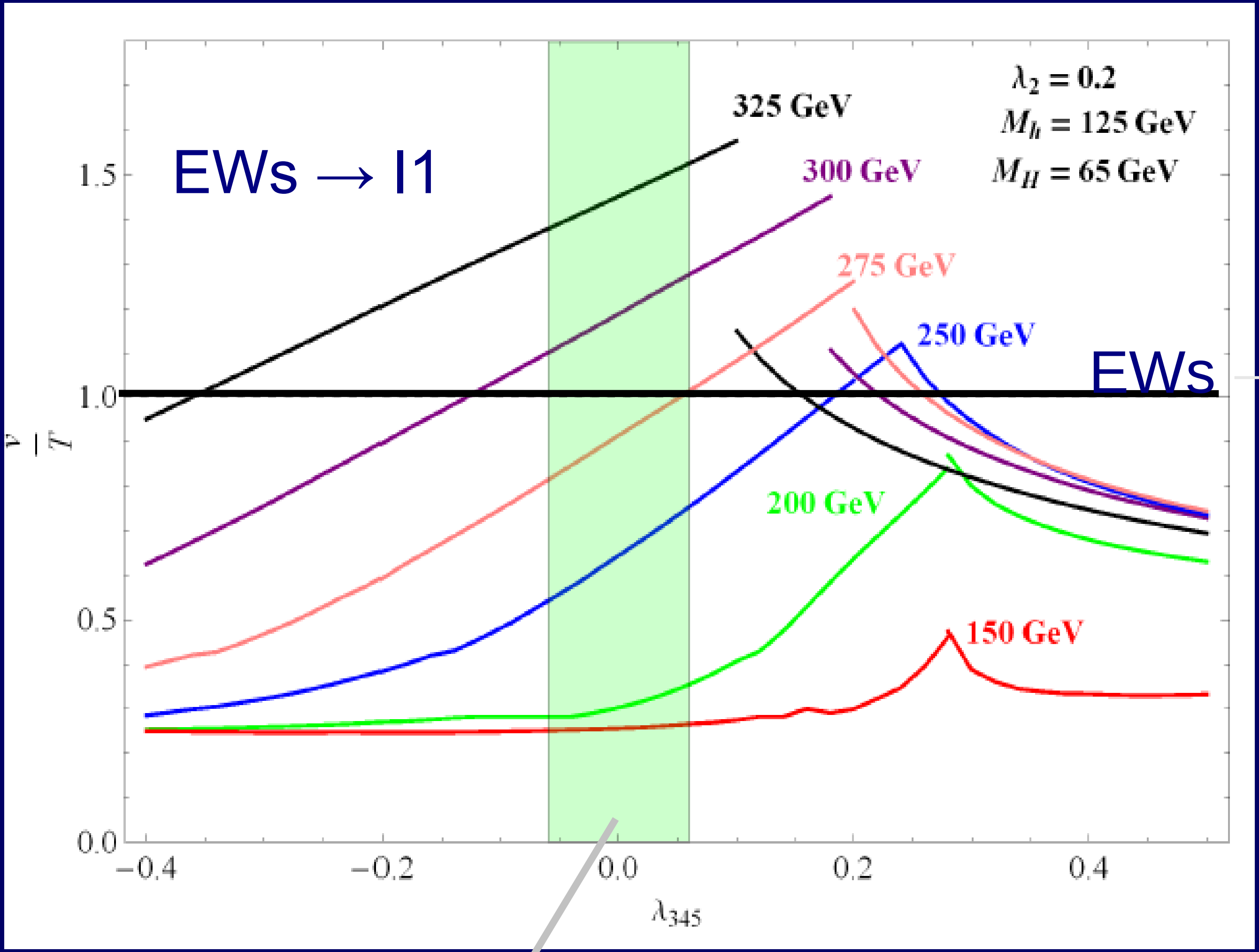
being in agreement with collider and astro-physical data

We focus on medium DM, with $M_H \ll v$, heavy degenerated A and H+ and M_h=125 GeV

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

Mh=125 GeV, MH=65 GeV, λ2=0.2

strong 1st order phase transition if ratio > 1



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

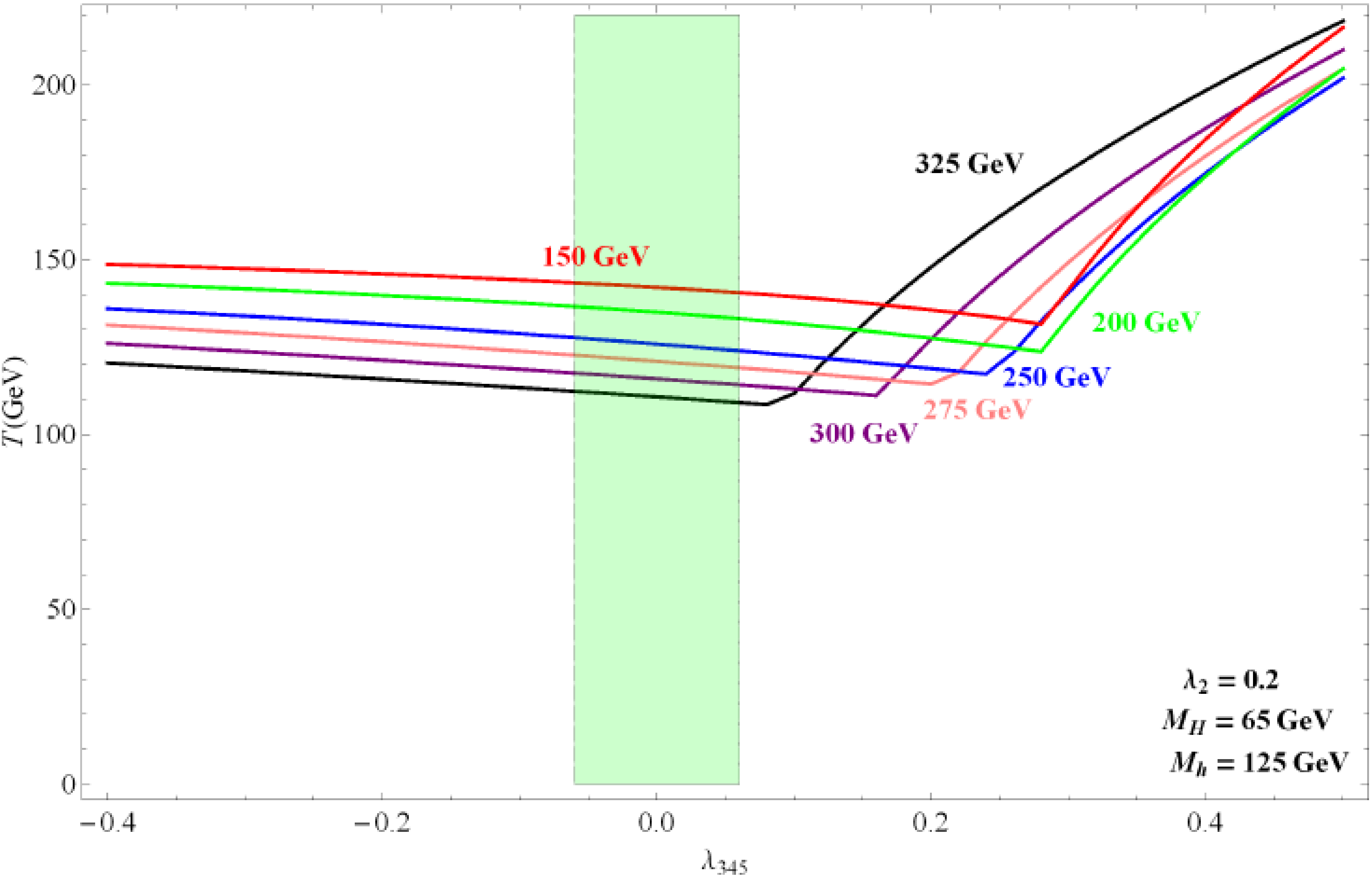
λ_{345}

R<0

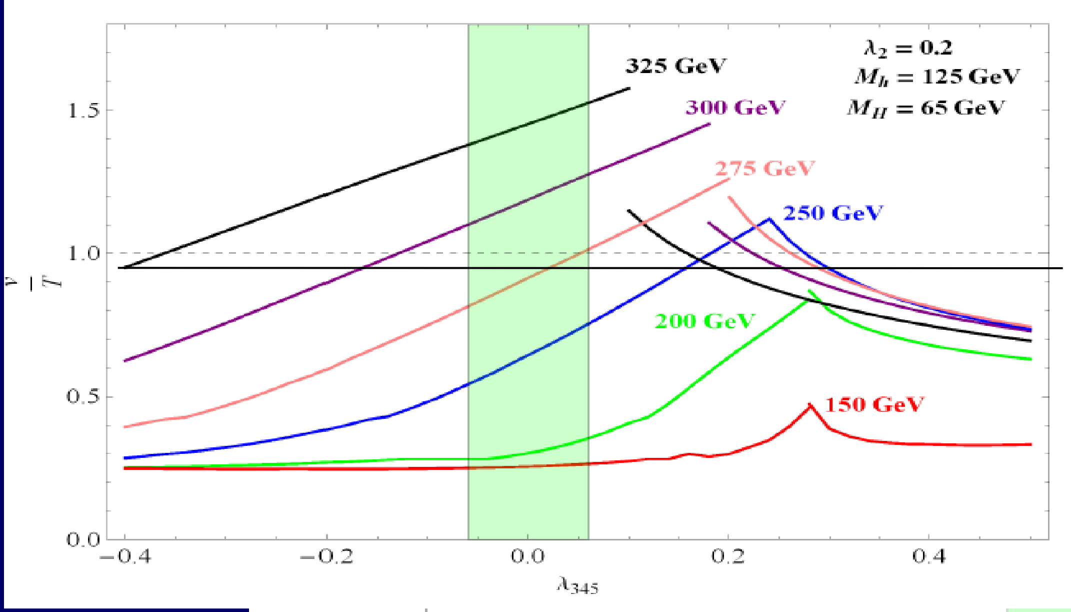
Xenon100 bound

R>0

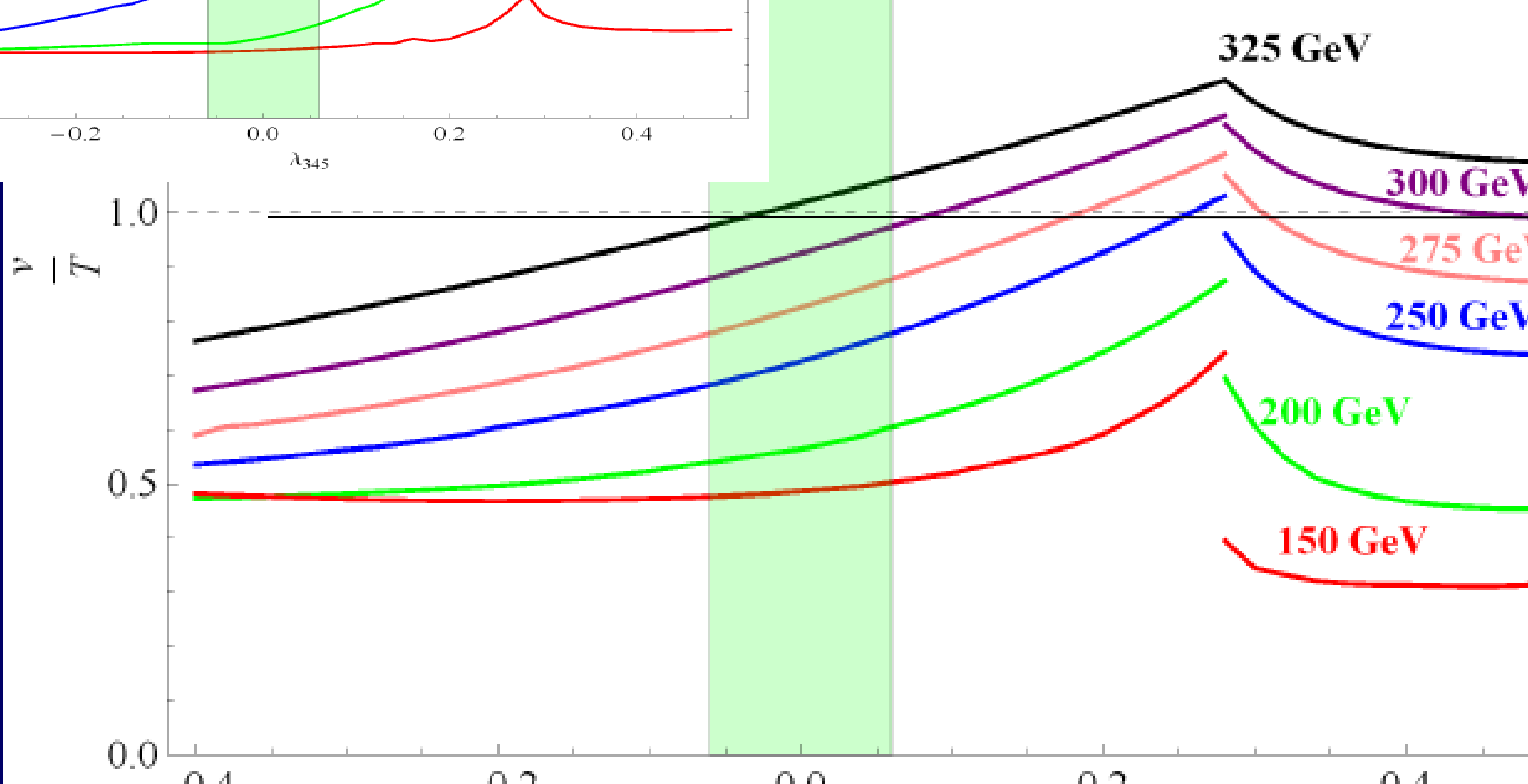
T_{EW} as a function of λ_{345}



Role of Coleman-Weinberg term



with and without CW term



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: mass 275-380 GeV
2/ low value of hHH coupling $|\lambda_{345}| < 0.1$
3/ Coleman-Weinberg term important

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)

Cancelation of quadratic divergencies

Veltman condition - one-loop SM

or

$$Q_1 = \lambda + \frac{1}{8}g'^2 + \frac{3}{8}g^2 - y_t^2.$$

$$Q_1' = 2Q_1 v^2 = m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2,$$

cancelation Q_1=0 -> M_H(SM) ~ 314 GeV

2HDM: Wu, Osland, Newton ~2000; Ma, 2001

Grządkowski, Osland ~ 2010

(soft Z_2 viol, two-loop, heavy Higgses)

Our work: one-loop, 2HDM (Mixed) SM-like h, H

2HDM+singlets, IDM+singlets

(Ma 2013, Darvishi, Ilnicka 2014)

Veltman condition for 2HDM (II)

$$6M_W^2 + 3M_Z^2 + v^2\left(3\lambda_1 + 2\lambda_3 + \lambda_4\right) = \frac{12}{\cos^2\beta} {m_D}^2$$

$$6M_W^2 + 3M_Z^2 + v^2\left(3\lambda_2 + 2\lambda_3 + \lambda_4\right) = \frac{12}{\sin^2\beta} {m_U}^2$$

$$\lambda_1 - \lambda_2 = \frac{4}{v^2}\left(\frac{m_b^2}{\cos^2\beta} - \frac{m_t^2}{\sin^2\beta}\right) = \frac{4m_b^2}{v^2}\left(1 - \frac{m_t^2/m_b^2}{\tan^2\beta}\right)(1 + \tan^2\beta).$$

From 2HDM

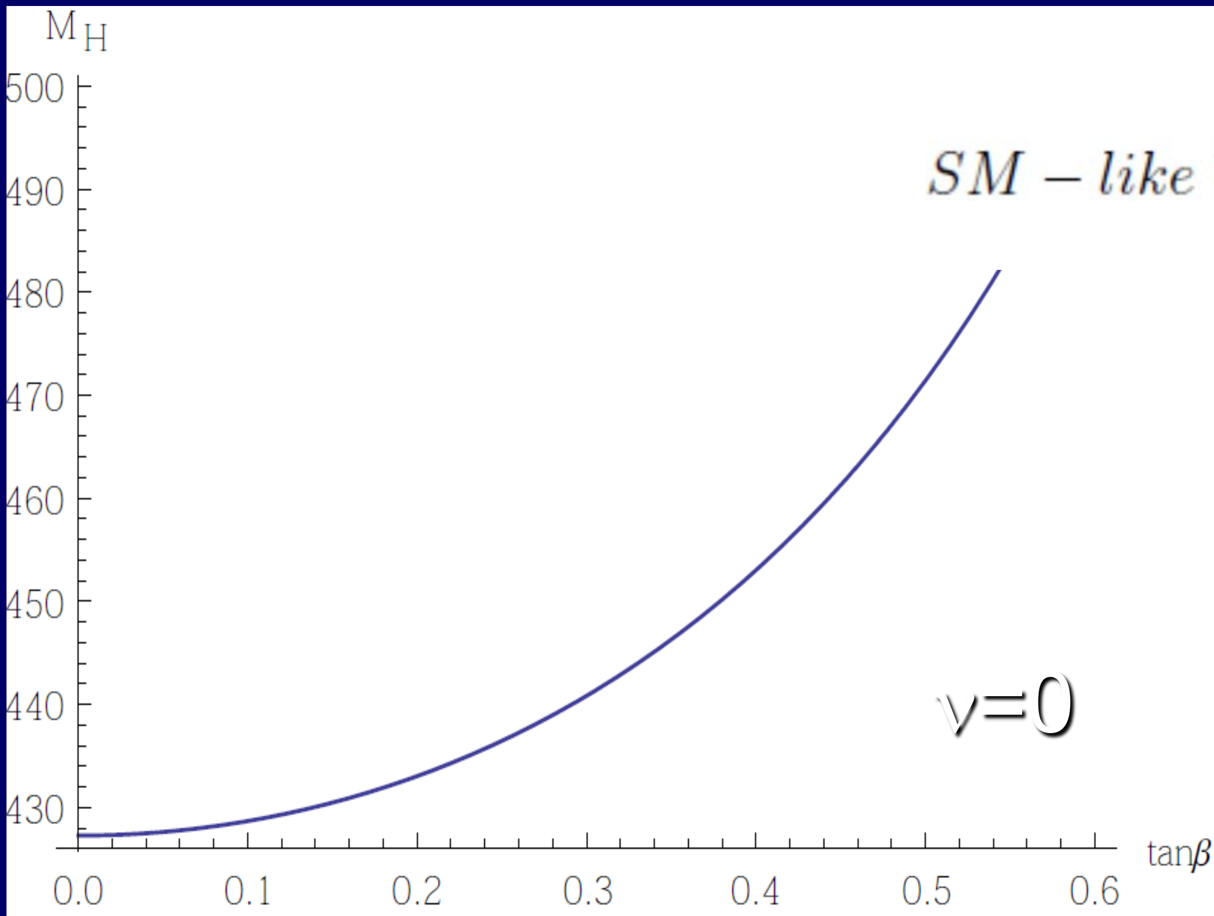
$$SM - like\ h : \lambda_1 - \lambda_2 = \left(\tan^2\beta - \frac{1}{\tan^2\beta}\right)\left(\frac{M_H^2}{v^2} - \nu\right),$$

Results for SM-like h

$$SM - like\ h : M_H^2 = 4m_b^2 \frac{\tan^2\beta - \frac{m_t^2}{m_b^2}}{\tan^2\beta - 1} + \nu v^2.$$

For SM-like H

$$M_h^2 = 4m_b^2 \frac{\tan^2\beta - \frac{m_t^2}{m_b^2}}{\tan^2\beta - 1} + \nu v^2,$$



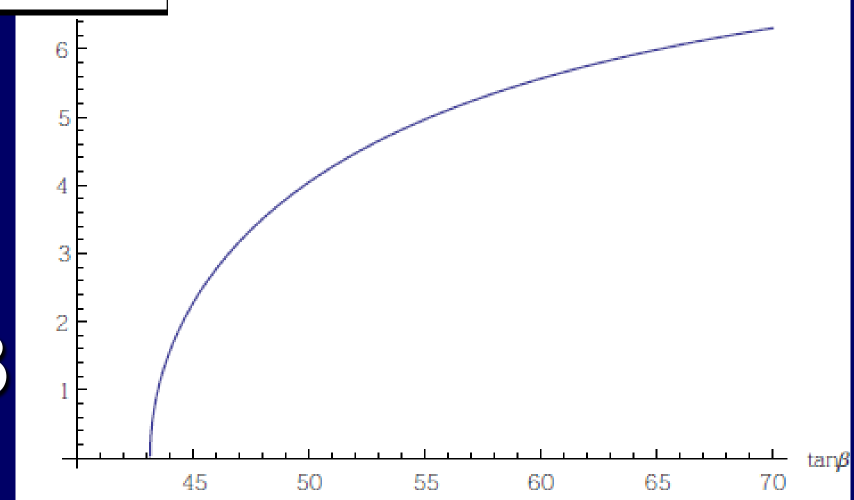
$$SM-like\ h:\ M_H^2 = 4m_b^2 \frac{\tan^2\beta - \frac{m_t^2}{m_b^2}}{\tan^2\beta - 1}$$

only very small tan β

min $M_H = 2\ m_t$

$\nu=0$

gure 2: SM-like H scenario, $m_{12} = 0$



SM-like H

$$M_h^2 = 4m_b^2 \frac{\tan^2\beta - \frac{m_t^2}{m_b^2}}{\tan^2\beta - 1}$$

only very large tan β

min $M_h = 2\ m_b$

Masses (Mixed)

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

$$\mathcal{M}^2 = \begin{bmatrix} \cos^2\beta\lambda_1 + \sin^2\beta\nu & (\lambda_{345} - \nu)\cos\beta\sin\beta \\ (\lambda_{345} - \nu)\cos\beta\sin\beta & \sin^2\beta\lambda_2 + \cos^2\beta\nu \end{bmatrix} v^2.$$

$$\mathcal{M}^2 = \begin{bmatrix} M_h^2\sin^2\alpha + M_H^2\cos^2\alpha & (M_H^2 - M_h^2)\sin\alpha\cos\alpha \\ (M_H^2 - M_h^2)\sin\alpha\cos\alpha & M_H^2\sin^2\alpha + M_h^2\cos^2\alpha \end{bmatrix}$$

We assume:

$M_H > M_h$, Δ M2/v2 (sin 2α /sin2β)= $\lambda_{345} - \nu$

α range (- $\pi/2$, $\pi/2$) (cos α>0)

β range (0, $\pi/2$)

so $\beta-\alpha$ from $-\pi/2$ to π (in 2HDMC only to $\pi/2$!)

Scan

- SM-like h, $M_h = 125$ GeV, $\sin(\beta-\alpha) \sim +1$ $(\beta - \alpha = \pi/2)$
- SM-like H, $M_H = 125$ GeV, $\cos(\beta-\alpha) \sim +1$ $(\beta = \alpha)$

  $\cos(\beta-\alpha) \sim -1 (\beta - \alpha = \pi)$

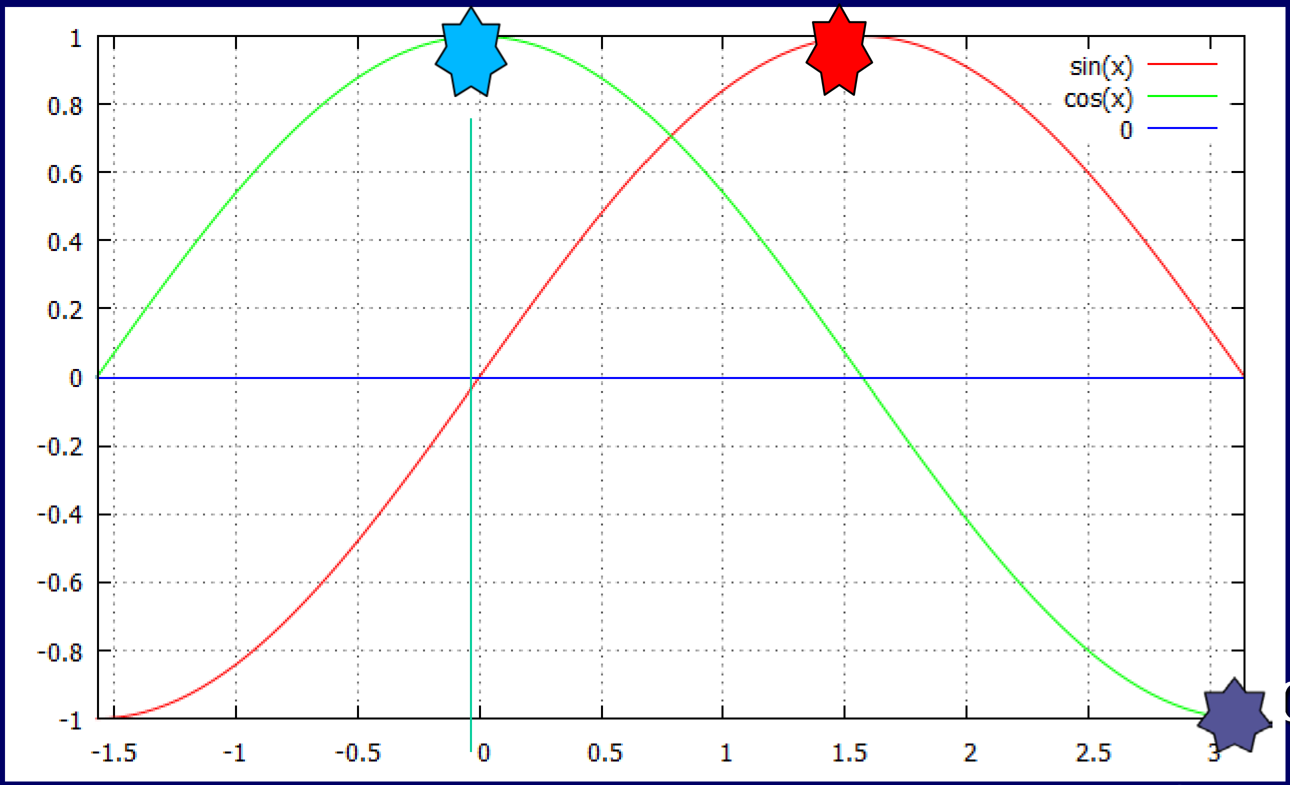
Scan for masses 124-127 GeV, tan beta 0.2 – 100,
$M_{\pm} > 300$ GeV.

Mathematica and C++ (N. Darvishi)
2HDMC (not for SM-H_)

Cross check re unitarity limits on lambdas,
some exp. constraints

SM-like scenarios h_+, H_+, H_-

defined by couplings to gauge bosons in terms of 'relative' couplings $\sin(\beta-\alpha)\sim +1$, $\cos(\beta-\alpha)\sim\pm 1$



β-α

α <0

$\beta \sim \alpha = \pi/2$

SM-H_+ (solution only for ν=0)

B mark	α	β	t_β	$s_{\beta-\alpha}$	$c_{\beta-\alpha}$	M_h	M_H	M_A	$M_H^\pm$
H+1	1.57000	1.5470	42.012	-0.020	0.999	2.36	126.28	230.00	310.00
H+2	1.56972	1.5515	52.012	-0.018	0.999	5.08	125.67	200.00	320.00
H+3	1.56765	1.5608	100.041	-0.006	0.999	7.31	125.84	136.50	330.00
H+4	1.56765	1.5498	47.632	-0.017	0.999	4.29	126.47	100.00	340.00
H+5	1.56765	1.5483	44.314	-0.019	0.999	3.41	124.58	136.50	335.00
H+6	1.55972	1.5470	42.012	-0.012	0.999	1.88	125.39	200.00	310.00
H+7	1.55823	1.5592	86.453	0.001	0.999	6.90	126.85	136.50	310 .00

B mark	λ_1	λ_2	λ_3	λ_{345}	λ_4	λ_5
H+1	0.16	0.26	3.18	0.008	-2.30	-0.87
H+2	1.15	0.26	3.39	0.014	-2.72	-0.66
H+3	8.87	0.26	3.68	0.08	-3.29	-0.30
H+4	0.69	0.26	3.86	0.03	-3.65	-0.16
H+5	0.38	0.25	3.74	0.03	-3.40	-0.30
H+6	0.15	0.25	3.29	0.12	-2.51	-0.30
H+7	6.16	0.26	3.46	0.28	-2.86	-0.66

t b

$\frac{g_t^H}{g_t^{H\,SM}}$	$\chi_t^H(1)$	$\frac{g_b^H}{g_b^{H\,SM}}$	$\chi_b^H(1)$
1.00	0.99	0.15	0.15
1.00	0.99	0.05	0.06
1.00	0.99	0.35	0.39
0.99	0.99	0.18	0.18
1.00	0.99	0.15	0.15
1.00	0.99	0.49	0.49
0.99	0.99	1.85	1.08

t b

$\frac{g_t^h}{g_t^{h\,SM}}$	$\chi_t^h(1)$	$\frac{g_b^h}{g_b^{h\,SM}}$	$\chi_b^h(1)$
0.0058	0.0037	-72.08	-41.99
0.0014	0.0012	-75.58	-51.94
0.0043	0.0039	-88.70	-99.94
0.0058	0.0039	-71.58	-47.60
0.0043	0.0035	-69.75	-44.28
0.0203	0.0117	-76.83	-41.98
0.0291	0.0125	-119.41	-86.36

for partner h

SM-H_ (solution only for ν=0)

B mark	α	β	t_β	$s_{\beta-\alpha}$	$c_{\beta-\alpha}$	M_h	M_H	M_A	$M_H^{\pm}$
H-1	-1.56137	1.5609	100.03	0.019	-0.999	7.23	125.93	130	360
H-2	-1.55815	1.5560	67.98	0.027	-0.999	6.23	125.23	120	360
H-3	-1.55800	1.5541	60.06	0.029	-0.999	5.72	124.24	110	360
H-4	-1.54566	1.5556	65.81	0.040	-0.998	5.49	125.39	248	348
H-5	-1.54566	1.5484	44.81	0.047	-0.998	1.61	125.68	200	348
H-6	-1.54566	1.5482	44.31	0.047	-0.998	1.19	126.31	150	360
H-7	-1.53566	1.5569	72.00	0.049	-0.998	4.94	126.37	300	360
H-8	-1.52053	1.55923	86.45	0.061	-0.998	3.33	124.35	350	360

B mark	λ_1	λ_2	λ_3	λ_{345}	λ_4	λ_5
H-1	8.87	0.26	4.03	-0.24	-4.00	-0.27
H-2	3.12	0.25	4.06	-0.22	-4.04	-0.23
H-3	.10	0.25	4.08	-0.19	-4.08	-0.19
H-4	2.87	0.25	3.48	-0.42	-2.88	-1.02
H-5	0.41	0.26	3.70	-0.29	-3.34	-0.66
H-6	0.38	0.26	3.98	-0.29	-3.91	-0.37
H-7	3.77	0.26	3.24	-0.66	-2.42	-1.48
H-8	6.19	0.25	3.17	-1.10	-2.25	-2.02

t b

$\chi_t^H(1)$	$\chi_b^H(1)$
-0.99	0.90
-0.99	0.83
-0.99	0.74
-0.99	1.63
-0.99	1.10
-0.99	1.08
-0.99	2.53
-0.99	4.27

wrong sign Htt

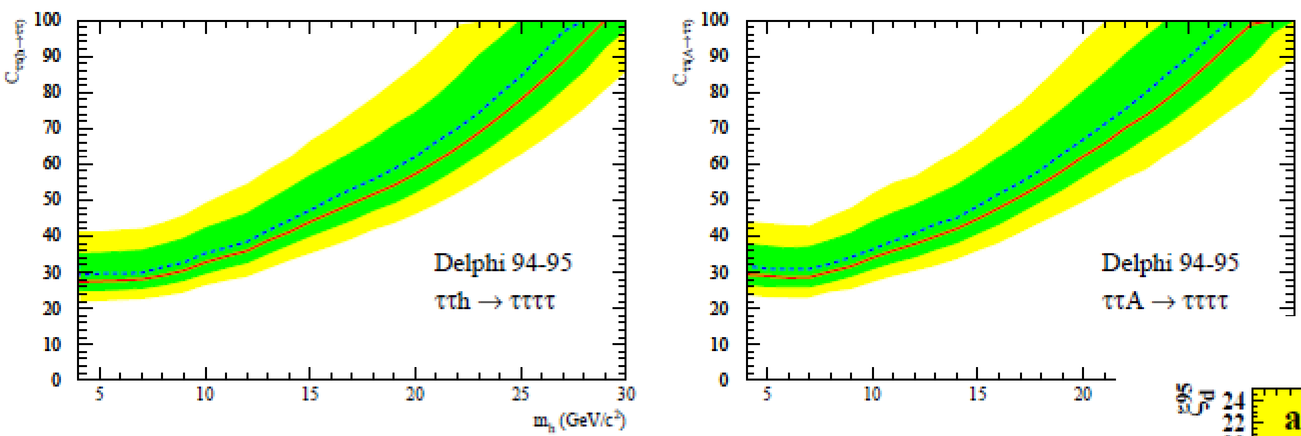
t b

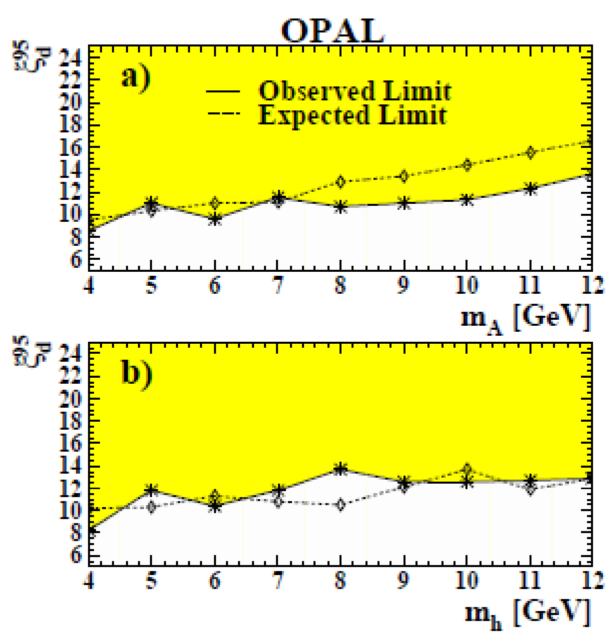
$\chi_t^h(1)$	$\chi_b^h(1)$
0.009	99.94
0.012	67.93
0.012	60.02
0.024	64.72
0.024	44.76
0.024	44.26
0.035	71.90
0.049	86.33

for partner h

LEP

Yukawa couplings 2HDM (II) with CP conservation





SM-like h (solutions only for $\nu>0$)

B mark	α	t_β	$s_{\beta-\alpha}$	$c_{\beta-\alpha}$	M_h	M_H	M_A	$M_H^\pm$	$\lvert m_{12}\rvert$	ν
h+1	-1.15	0.36	0.99	0.07	125.24	445.91	136.5	360	178	0.82
h+2	-1.05	0.48	0.99	0.07	125.56	489.89	136.5	360	223	1.05
h+3	-0.85	0.68	0.99	0.12	124.71	711.74	136.5	360	342	2.07
h+4	-0.85	0.68	0.99	0.12	126.55	739.21	300.0	360	377	2.52
h+5	-0.85	0.68	0.99	0.12	124.89	795.49	500.0	360	443	3.48

B mark	λ_1	λ_2	λ_3	λ_{345}	λ_4	λ_5
h+1	0.75	17.89	-0.07	-2.71	-3.15	0.51
h+2	1.20	11.70	-0.86	-3.04	-2.92	0.74
h+3	4.58	10.80	-6.44	-6.57	-1.89	1.77
h+4	4.80	11.02	-7.58	-6.82	-0.27	1.03
h+5	5.26	11.48	-10.07	-7.38	3.33	-0.64

t b

$\frac{g_t^h}{g_t^{h_{SM}}}$	$\chi_t^h(1)$	$\frac{g_b^h}{g_b^{h_{SM}}}$	$\chi_b^h(1)$
1.38	1.18	0.91	0.96
1.28	1.13	0.91	0.95
1.19	1.16	0.83	0.90
1.19	1.16	0.83	0.90
1.19	1.16	0.83	0.90

$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h_{SM}\to\gamma\gamma)}$	$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h_{SM}\to Z\gamma)}$	$\frac{\Gamma(h\to gg)}{\Gamma(h_{SM}\to gg)}$	$\frac{\Gamma_h^{tot}}{\Gamma_h^{tot\,SM}}$
0.78	0.86	1.55	0.99
0.86	0.98	1.72	0.98
0.89	0.92	1.46	0.90
0.88	1.09	1.16	0.95
0.89	0.94	1.11	0.90

S	T	U
-0.006	-0.288	-0.03
-0.001	0.438	-0.004
0.015	-1.113	-0.008
0.023	-0.366	-0.002
0.032	1.009	0.004

exp. 3σ

$$-0.27 \le S \le 0.33,$$
$$-0.31 \le T \le 0.41,$$
$$-0.26 \le U \le 0.40.$$

Relative couplings (w.r.s SM)

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

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

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

there are relations among couplings, eg $\Sigma_i(\chi_j^{(i)})^2 = 1,$

Haber

	χ_V(W and Z)	χ_u(up-type quarks)	χ_d(down-type quarks)
h	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)+\frac{1}{\tan\beta}\cos(\beta-\alpha)$	$\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)$
H	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)-\frac{1}{\tan\beta}\sin(\beta-\alpha)$	$\cos(\beta-\alpha)+\tan\beta\sin(\beta-\alpha)$
A	0	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$

SM-like h

in GeV

t b

B mark	$\frac{g_t^H}{g_t^{H\,SM}}$	$\chi_t^H(1)$	$\frac{g_b^H}{g_b^{H\,SM}}$	$\chi_b^H(1)$
h+1	-2.35	-2.68	0.41	0.42
h+2	-1.72	-1.99	0.50	0.54
h+3	-1.14	-1.33	0.66	0.79
h+4	-1.14	-1.33	0.66	0.79
h+5	-1.14	-1.33	0.66	0.79

$\Gamma(H \to \gamma\gamma)$	$\Gamma(H \to Z\gamma)$	$\Gamma(H \to gg)$	$\Gamma(H \to hh)$	Γ_H^{tot}
8.19e-4	3.04e-4	0.22	0.53	1.32
5.58e-4	2.29e-4	0.14	0.58	1.07
5.38e-4	2.96e-4	0.09	1.40	2.60
8.28e-4	5.09e-4	0.10	1.57	2.56
1.01e-3	6.55e-4	0.10	1.94	2.71

for partner H

Summary of results of application of Veltman condition for 2HDM (II)

SM-like $H_{\pm}$: solutions only for $\nu=0, |\chi_V| \sim 0.999$, very light h (1- 8 GeV), $\tan\beta > 40$

- H_+ M_H 124.6-126.8 GeV, Mh 1.9-7.3 GeV
  M_A 100-230 GeV, $M_{\pm} <$ 310-340 GeV,
  $\tan\beta > 42.4$
- H_- M_H 124.2-126.3 GeV, Mh 1.2-7.2 GeV
  M_A 110-350 GeV, $M_{\pm}$ 350-360 GeV $\tan\beta > 44$

Problem with couplings to b both for SM-like H and a partner h – excluded !!

Results for SM-h

SM-h: solutions only for $\nu > 0$, $\chi_V \sim 0.99$,
heavy H > 450 GeV, $\tan\beta < 1$

- M_h 124.7-125.6 GeV, M_H 446- 795 GeV
  M_A 135.6-500 GeV, $M_\pm$ ~360 GeV,
  m_{12} 178-443 GeV, $\tan\beta$ <0.68,
  at 3σ in agreement with S,T,U

OK ?

Veltman condition for other models

Two scalar doublets (2,1) of SU(2)xU(1)
One singlet (1,Y_φ) of SU(2)xU(1)

A. Ilnicka

Potential (2 doublet + real singlet)

V= V_2HDM(soft viol.Z_2) + $m\varphi^2\ \varphi^2$

$$+\lambda_\varphi \varphi^4 + \eta_1 \varphi^2 \Phi_1^\dagger \Phi_1 + \eta_2 \varphi^2 \Phi_2^\dagger \Phi_2 + etc(\varphi)$$

if complex singlet $\varphi^2 \to \varphi^\dagger \varphi$

Vacuum structure

Mixed(s)

$$< \phi_1^0 >= \frac{v_1}{\sqrt{2}} \neq 0 \text{ and } < \phi_2^0 >= \frac{v_2}{\sqrt{2}} \neq 0$$

$$\langle \varphi \rangle = 0 \quad \text{or} \quad \langle \varphi \rangle = \frac{v_\varphi}{\sqrt{2}}$$

Inert(s)

$$< \phi_1^0 >= \frac{v_1}{\sqrt{2}} \neq 0 \text{ and } < \phi_2^0 >= 0$$

$$\langle \varphi \rangle = 0 \quad \text{or} \quad \langle \varphi \rangle = \frac{v_\varphi}{\sqrt{2}}$$

For Inert case Z_2 symmetry $\Phi_2 \to -\Phi_2$
for singlet with zero vev Z_2'

Positivity conditions

$$\lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R + 1 > 0, \quad R_3 + 1 > 0$$
$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad R = \lambda_{345}/\sqrt{\lambda_1 \lambda_2}, \quad R_3 = \lambda_3/\sqrt{\lambda_1 \lambda_2}.$$

$$\lambda_\varphi \geq 0 \;\;\&\;\; \eta_1, \eta_2 \geq 0$$

Veltman condition

$$(\frac{3}{2}\lambda_1 + \lambda_3 + \frac{1}{2}\lambda_4 + \frac{1}{2}\eta_1)\frac{v^2}{2} + \frac{3}{4}(2m_W^2 + m_Z^2) = 3(\frac{m_t^2}{\cos^2\beta} + \frac{m_b^2}{\cos^2\beta})$$

$$(\frac{3}{2}\lambda_2 + \lambda_3 + \frac{1}{2}\lambda_4 + \frac{1}{2}\eta_2)\frac{v^2}{2} + \frac{3}{4}(2m_W^2 + m_Z^2) = 0$$

$$\Rightarrow \quad 3\lambda_\varphi + \eta_1 + \eta_2 = 0$$

Mixed(s)
Type I
(real s)

$$(\frac{3}{2}\lambda_1 + \lambda_3 + \frac{1}{2}\lambda_4 + \frac{1}{2}\eta_1)\frac{v^2}{2} + \frac{3}{4}(2m_W^2 + m_Z^2) = 3\frac{m_b^2}{\cos^2\beta}$$

$$(\frac{3}{2}\lambda_2 + \lambda_3 + \frac{1}{2}\lambda_4 + \frac{1}{2}\eta_2)\frac{v^2}{2} + \frac{3}{4}(2m_W^2 + m_Z^2) = 3\frac{m_t^2}{\sin^2\beta}$$

$$\Rightarrow \quad 3\lambda_\varphi + \eta_1 + \eta_2 = 0$$

Mixed(s)
Type II
(real s)

A. Ilnicka

Veltman condition

$$(\frac{3}{2}\lambda_1 + \lambda_3 + \frac{1}{2}\lambda_4 + \frac{1}{2}\eta_1)\frac{v^2}{2} + \frac{3}{4}(2m_W^2 + m_Z^2) = (m_t^2 + m_b^2)\cdot 3$$

$$(\frac{3}{2}\lambda_2 + \lambda_3 + \frac{1}{2}\lambda_4 + \frac{1}{2}\eta_2)\frac{v^2}{2} + \frac{3}{4}(2m_W^2 + m_Z^2) = 0$$

$\Uparrow$ ALSO CONTRADICTION

$$(\lambda_3 + \frac{1}{2}\lambda_4) \geq \frac{2}{v^2}((m_t^2 + m_b^2)\cdot 3 - \frac{3}{4}m_h^2 - \frac{3}{4}(2m_W^2 + m_Z^2)) = 1.86$$

$3\lambda_\varphi + \eta_1 + \eta_2 = 0 \Leftarrow$ CONTRADICTION (positivity conditions)

Inert(s) real singlet

Veltman condition

Case of two doublets with complex singlet

- The conditions for cancellation of quadratic divergences for doublets stay the same
- Two additional neutral scalars ($Y_\varphi = 0, v_\varphi \neq 0$) or charged scalars ($Y_\varphi \neq 0, v_\varphi = 0$)
- For charged particles with non-zero hypercharge:

$$3\lambda_\varphi + \eta_1 + \eta_2 + \frac{3}{4}(g' Y_\varphi)^2 = 0 \Leftarrow \text{STILL CONTRADICTION}$$

Conclusions III

We investigated consequences of cancelation of quadratic divergencies (Veltman condition) at one loop

- for SM-like scenarios for Mixed 2HDM
  with ~125 GeV h for $\chi_V \sim 1$ OK?
  ~125 GeV H for $\chi_V \sim +1, -1$ NO
- difficult to get solution for other models with two doublets and singlets