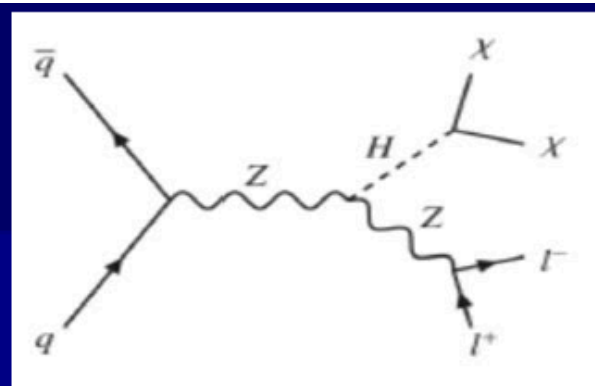
IDM(s): Dark Matter, CP compatible 2HDM

All slides taken from the following talk:

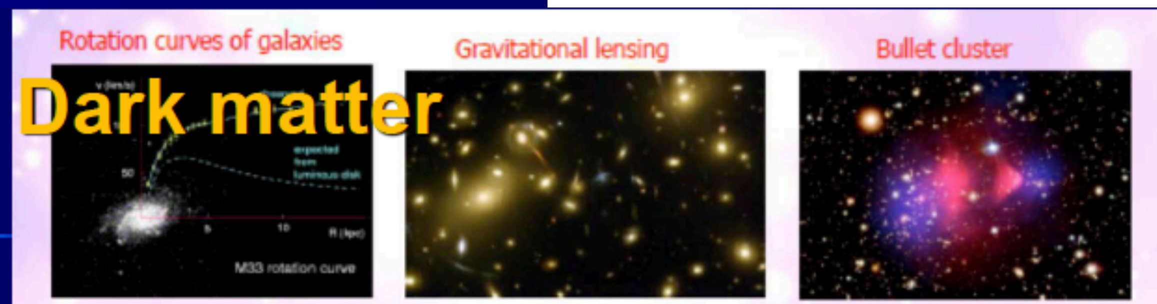
Invisible decay (Dark Matter)



- ATLAS
  BR < 0.27 (95% CL)
- CMS
  BR < 0.32 (95% CL)

M. Krawczyk, Zakopane 2015

Dark matter



Morsolli, Corfu 2014

relic density

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

3 sigma:

PLANCK $0.1118 < \Omega_{DM} h^2 < 0.128$

Inert Doublet Model (IDM)

- a model with two SU(2) doublets with *an* ***exact*** Z_2 symmetry (L & vacuum)

Higgs and Dark Matter sectors in agreement with data

Inert Doublet Model (IDM)

- a model with two SU(2) doublets with *an* ***exact*** Z_2 symmetry (L & vacuum)

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

  (T2 evolution, Ginzburg et al..PRD 2010)

- Strong enough first-order phase transition needed for baryogenesis *(G. Gil Msc'2011, G.Gil, P.Chankowski, MK PL.B 2012)*

- Metastability of vacua in IDM *(B. Świeżewska 2015)*

- IDM+complex singlet *Bonilla,DiazCruz,Sokołowska,Darvishi,MK'14*

Z_2 symmetric Lagrangian of 2HDM

Branco, Rebelo ,85: CP conserved

Potential V =

$$\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2+\tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 - \tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1)- \tfrac{1}{2}m^2_{22}(\Phi^\dagger\Phi_2)$$

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

λ_{345}

Z_2 symmetry transf.: $\Phi_1 \to \Phi_1$ $\Phi_2 \to -\Phi_2$

Yukawa interaction

Model I – one doublet Φ_1 couples to all fermions

Vacuum state ? Various possible

Extrema of the Z_2 symmetric potential

Ginzburg, Kanishev, MK, Sokołowska'09

Finding extrema: $\partial V / \partial \Phi|_{\Phi = \langle\Phi\rangle} = 0$ for $\Phi_{1,2}$

Finding minima → global minimum (vacum)

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

Extrema (vacua)

Ma78,Velhinho,Santos,Barroso..94

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)

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

v_S, v_D, u - real

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

---------------- 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	$v_D, v_S \neq 0$

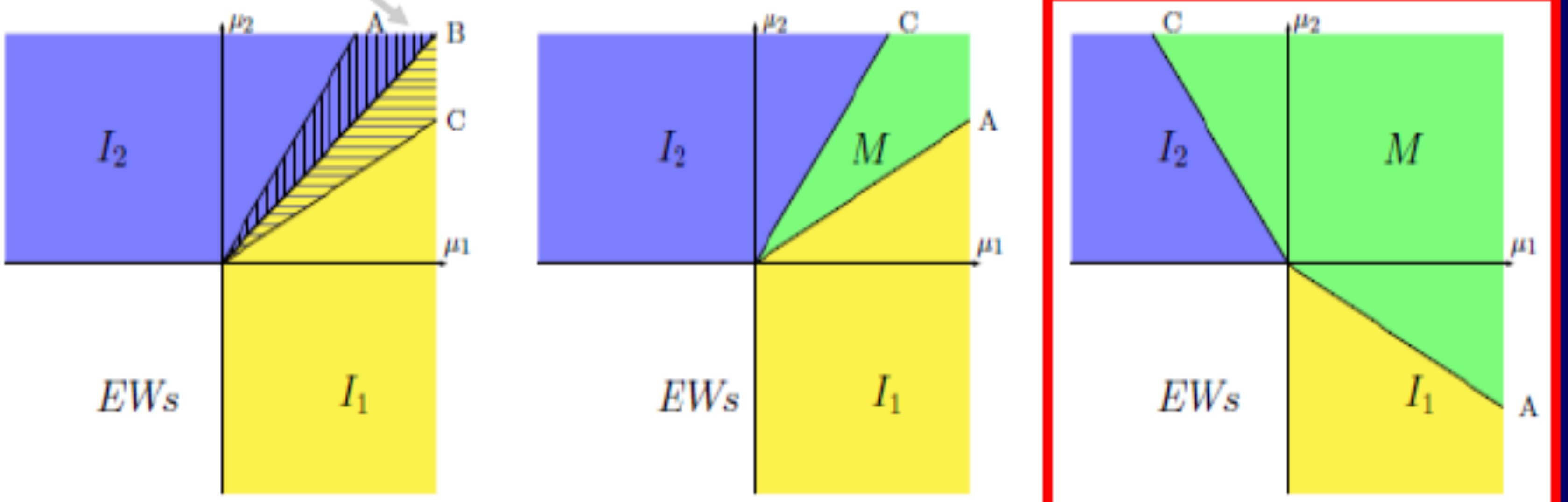
---------------- u≠0 ----------------

Charge Breaking	CB	$v_D = 0$

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
I_1 and I_2 minima



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

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

Inert (I_1) vacuum
for M_h=125 GeV → fixed μ_1

here $\lambda_{345} < 0$!

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

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

- Charge breaking phase Ch?

  photon is massive, el.charge is not conserved... → NO

- Neutral phases:

Mixed M — in agreement with data

for Model I or II (Φ_S , Φ_D interact with fermions)

D spont. broken

Inert I1 — OK! In agreement with accelerator

and astrophysical data (neutral DM)

(Model I - only Φ_S interacts with fermions)

D symmetry exact

Inert-like I2 — NO (fermions massless)

Inert Doublet Model

Ma,... '78
Barbieri..'06

Φ_S as in SM (BEH)

Φ_D – no vev

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

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

(no Higgses!)

4 scalars H+,H-,H, A
no interaction with fermions

Higgs boson h (SM-like)

D symmetry $\Phi_S \to \Phi_S$ $\Phi_D \to - \Phi_D$ exact
- D parity
  - only Φ_D has odd D-parity
    - the lightest scalar stable - DM candidate (H)
      - (Φ_D dark doublet with dark scalars)

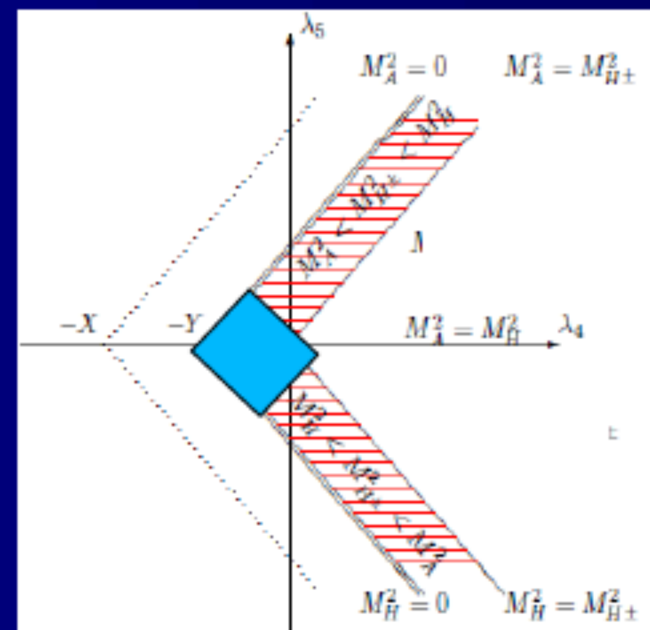
IDM: An Archetype for Dark Matter, Lopez Honorez,..Tytgat..07
LHC phenomenology (Barbieri., Ma.. 2006,…)

Masses

- SM-like Higgs scalar

$M_h^2 = m_{11}^2 = \lambda_1 v^2 = 125$ GeV

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



- Dark particles D

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

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

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

λ_{345}

m_{22}^2 – arbitrary, so if large negative → H,H+,A heavy and degenerate

H – dark matter $\lambda_5 < 0$

Testing Inert Doublet Model

Ma'2006,.Barbieri 2006, Dolle,Su, Gorczyca(Świeżewska), MSc T2011, 1112.4356, ...5086, ..1305. Posch 2011, Arhrib..2012, Chang, Stal ..2013

- Theoretical constraints
- Detailed study of
  - the SM-like h
- Study of dark scalars D
  - the dark scalars D in pairs!

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

Quartic selfcouplings D^4 proportional to λ_2

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

$\gamma\gamma$ 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]

signal strength μ

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

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

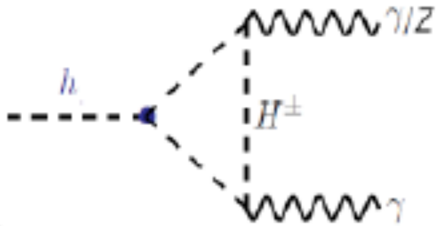
$R_{Z\gamma}$ – treated analogously

narrow width approx

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

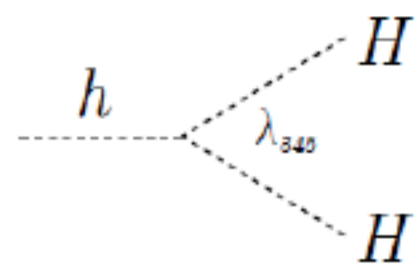
Two sources of deviation from $R_{\gamma\gamma} = 1$:

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



Invisible h decay → coupling hHH

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

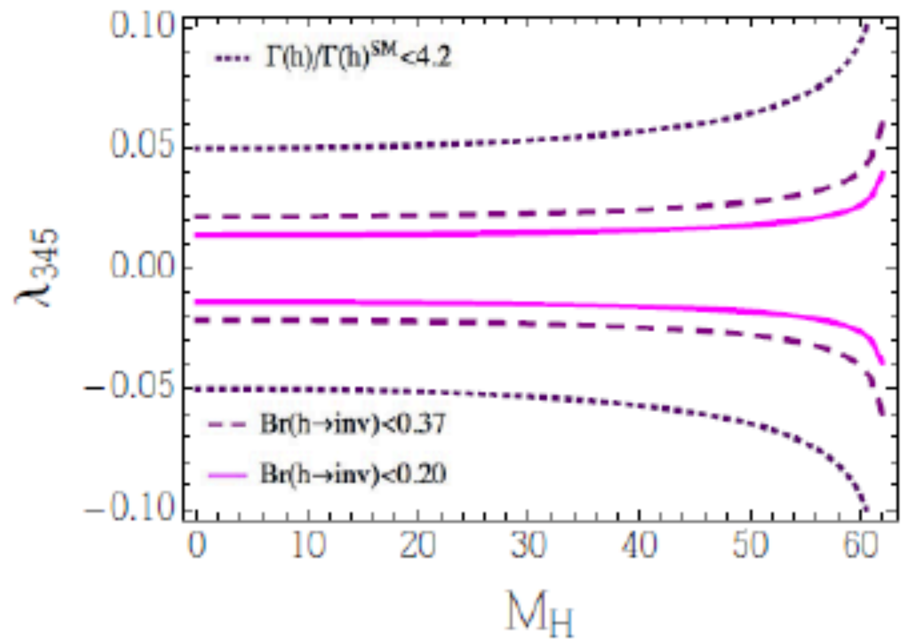


LHC:

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

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]

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

Relic DM density

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

LHC data

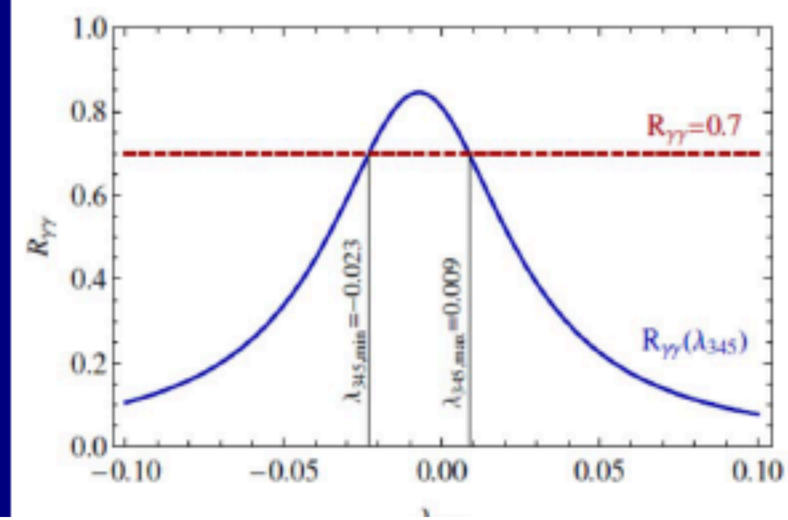
$$\text{ATLAS} : R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$$
$$\text{CMS} : R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$$

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

1.12 ± 0.24

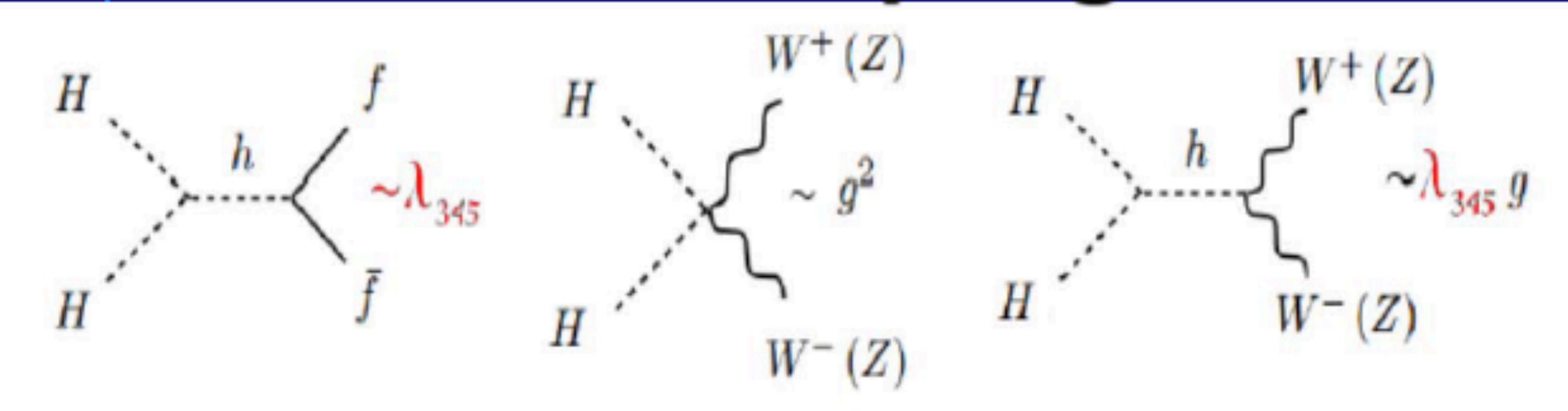
$R_{\gamma\gamma} > 1$ possible
DM mass only above 62.5 GeV allowed

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

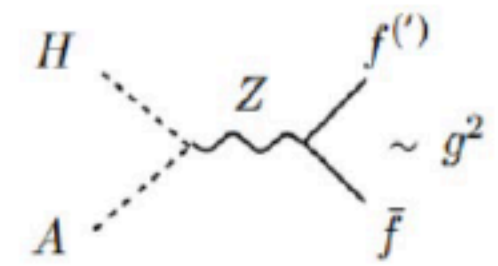


M. Krawczyk, Zakopane 2015

Relic density constraints on masses and couplings of DM



Coannihilation possible
for small (AH) mass splitting

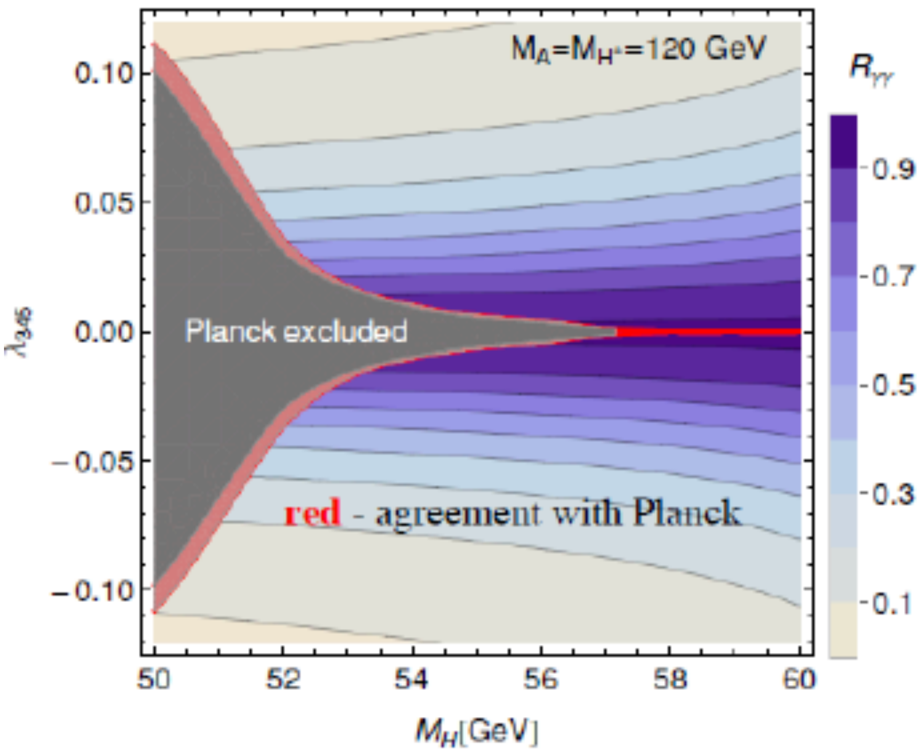


- low DM mass $M_H \lesssim 10$ GeV, $g_{HHh} \sim \mathcal{O}(0.5)$ Low DM mass excluded
- medium DM mass $M_H \approx (40 - 160)$ GeV, $g_{HHh} \sim \mathcal{O}(0.05)$
- high DM mass $M_H \gtrsim 500$ GeV, $g_{HHh} \sim \mathcal{O}(0.1)$

Using PLANCK data

[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
  ($M_H > 500\,\mathrm{GeV}$)
  $\Rightarrow R_{\gamma\gamma} \approx 1$

IDMS = IDM + complex singlet

S doublet **D doublet**

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v + \phi_1 + i\phi_6\right) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(\phi_4 + i\phi_5\right) \end{pmatrix},$$

$$\chi = \frac{1}{\sqrt{2}}(w e^{i\xi} + \phi_2 + i\phi_3).$$

complex singlet with vev

IDMS

- IDM - SM-like h and dark matter (H) in agreement with data
  - strong enough first order phase transition (baryogenesis)
  - D-symmetry = CP is conserved
- IDMS – in addition one complex singlet with complex vev. Mixing of SM doublet with a singlet -> CP violation

IDMS potential

$$U(1): \quad \Phi_1 \to \Phi_1,\ \Phi_2 \to \Phi_2,\ \chi \to e^{i\alpha}\chi$$

soft breaking U(1) assumed

IDM

$$V = -\frac{1}{2}\left[m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2\right] + \frac{1}{2}\left[\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2\right]$$

$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right]$$

$$-\frac{m_3^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2 + \Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi)$$

$$-\frac{m_4^2}{2}(\chi^{*2} + \chi^2) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3[\chi(\chi^*\chi) + \chi^*(\chi^*\chi)].$$

SM-doublet singlet interaction → $\Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi)$

no Inert doublet – singlet term (small at loop level)

Doublet-singlet mixing

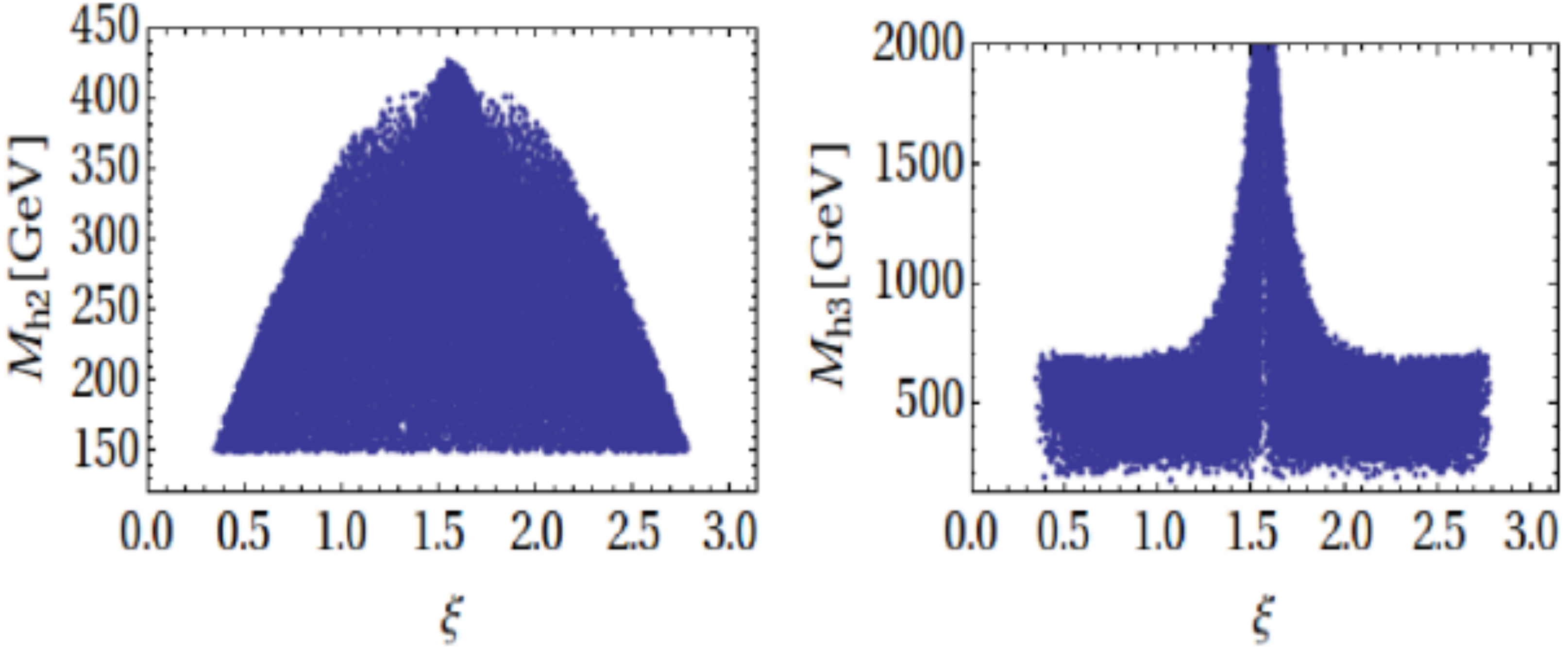
Singlet – a small modification of EWSB by a doublet

eg. $0.2 < \lambda_1 < 0.3$ if no mixing $M_{h_1}^2 = v^2\lambda_1 \Rightarrow \lambda_1 \approx 0.23$

3 Higgses

h1 ~ h in the SM with mass around 125 GeV

h2,h3 – can be heavy (we put a lower limit 150 GeV)



Summary

- SM-like scenario – still valid (June 2015)
- IDM is a very natural extension of the SM

  SM doublet → one Higgs SM-like h

  Dark doublet → 4 scalars (two charged)

  one stable (H=DM)
- IDM in agreement with LHC data and relic density/ LUX
- IDMS – towards a description of baryogenesis

Higgs as a very good probe of DM !

arXiv: 1512.06437

The Inert Doublet Model and its extensions*

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The Inert Doublet Model and its extension with an additional complex singlet is considered. The CP violation aspects are analysed in the simplified case, with one SM-like Higgs doublet and a complex singlet.