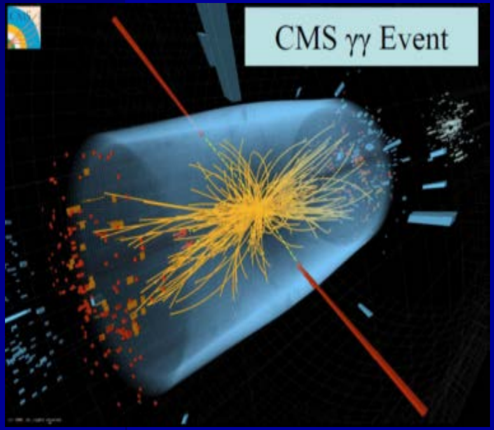
Extensions of the IDM



Maria Krawczyk
University of Warsaw

In coll. with I. Ginzburg, K. Kanishev, D.Sokołowska, B. Świeżewska, G. Gil, P.Chankowski, N. Darvishi, A. Ilnicka, T. Robens, L. Diaz-Cruz, C. Bonilla

Higgs particle at LHC -summer 2016

ATLAS+CMS Run 1

arXiv:1606.02266v1 [hep-ex]

SM-like scenario observed

- Mass 125.09 ± 0.24 GeV ZZ → 4 l, $\gamma\,\gamma$
- Total width < 23 MeV (95%CL); SM ~4 MeV
- Signal strengths μ = R = $\sigma\times Br/(\sigma\times Br)|_{SM}$; SM =1

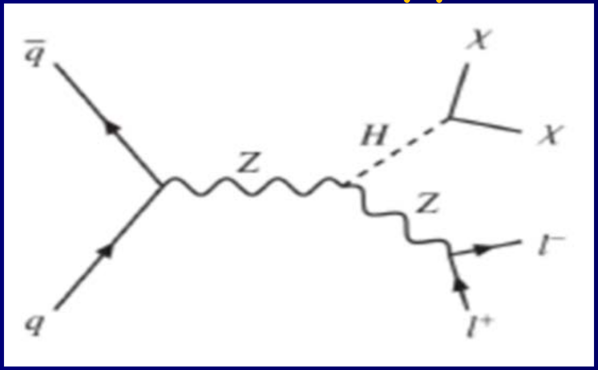
  global 1.09 ± 0.11/0.10

  $\gamma\gamma$ 1.14 ± 0.19/0.18 → $R_{\gamma\gamma}$

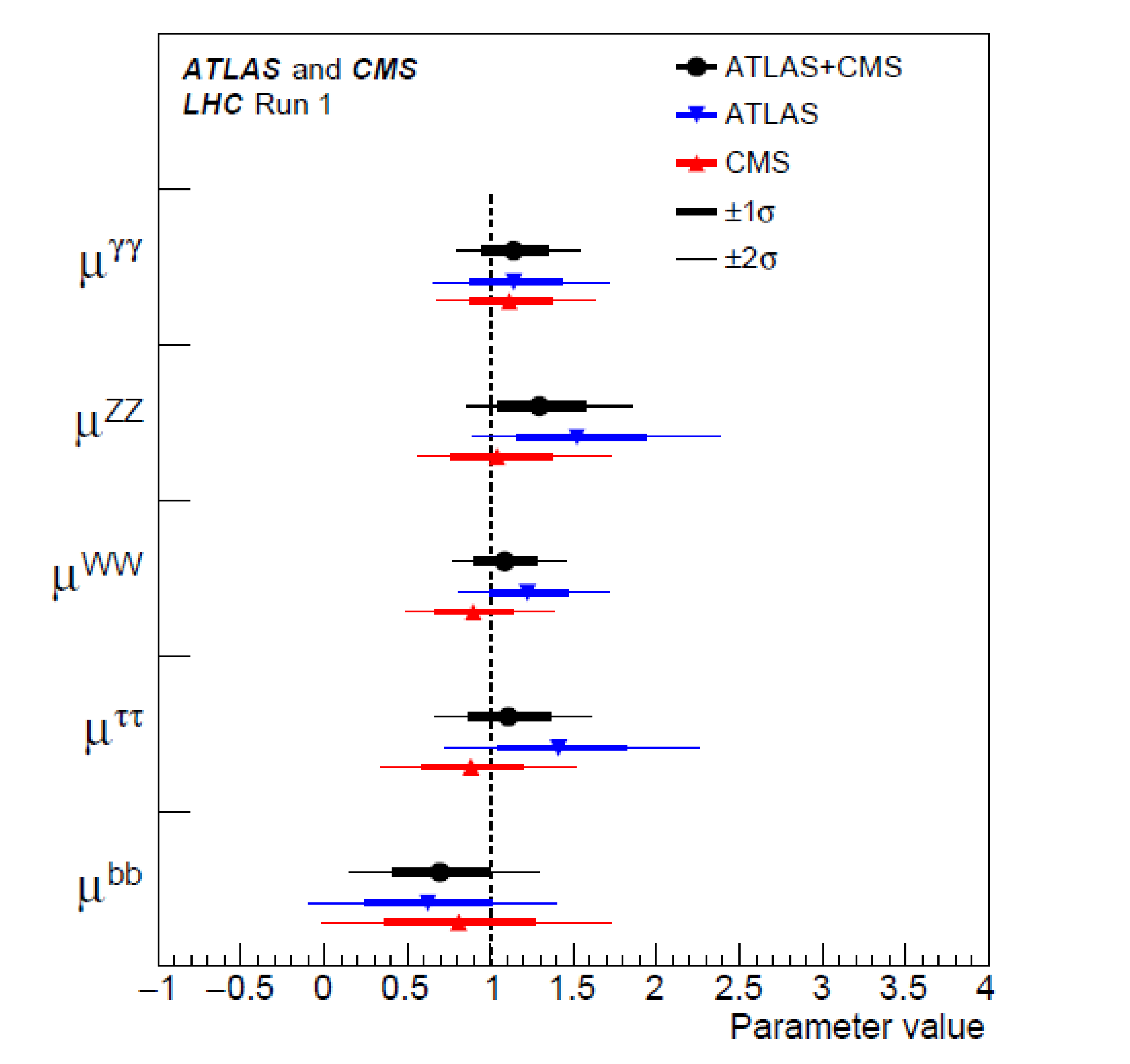
- Invisible decay

  BR = $0.00^{+0.16}$ (< 0.32 at 95% CL)

- Spin/CP J^{CP} 0^{+}

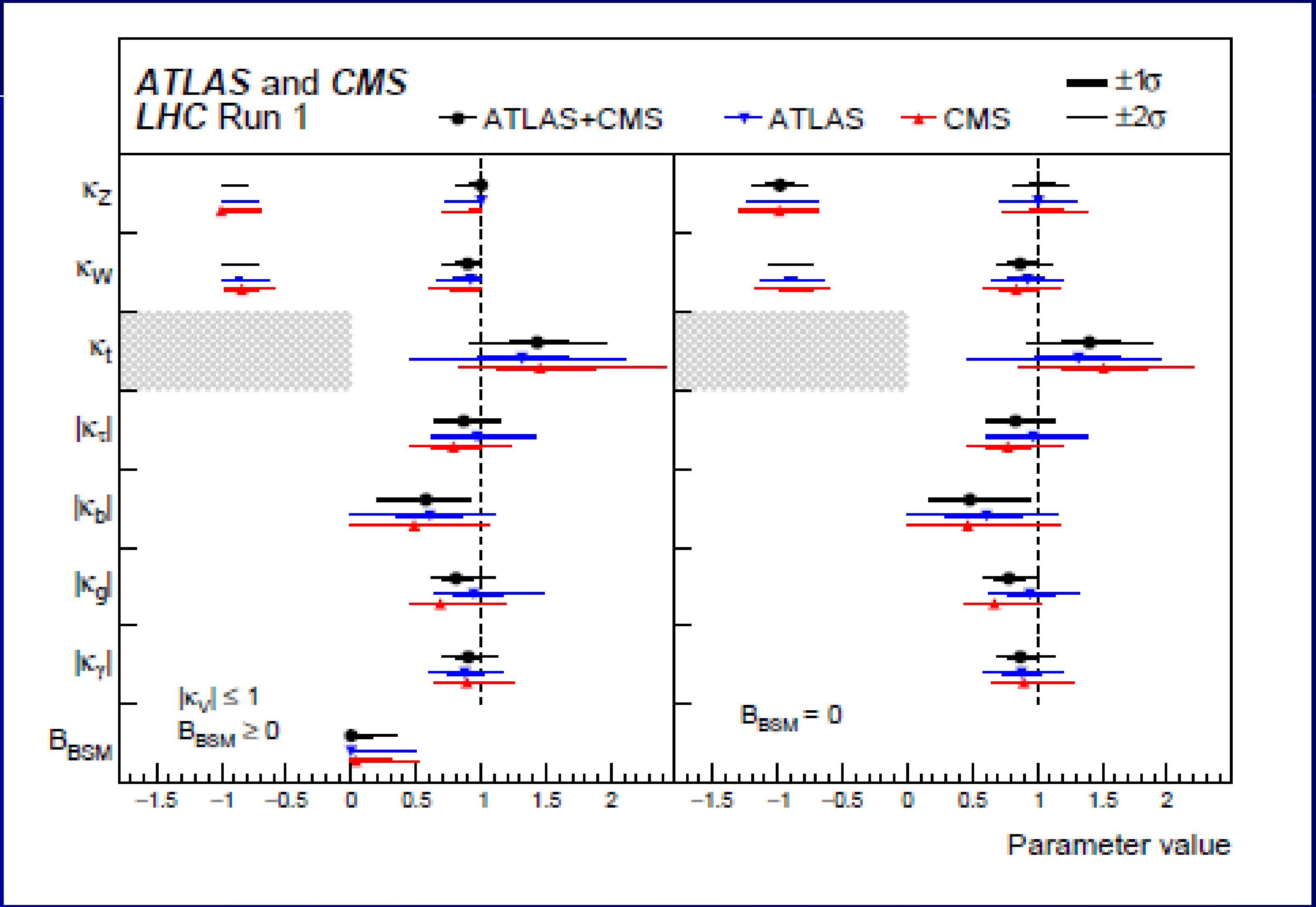


LHC 2016

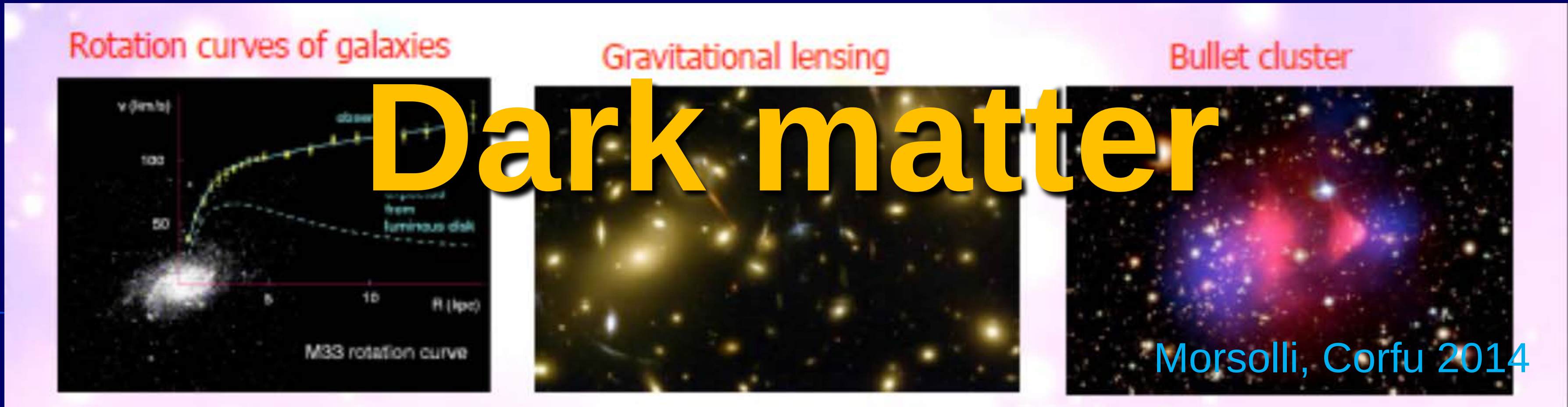


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
μγγ
μZZ
μWW
μττ
μbb
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

LHC 2016


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
κZ
κW
κt
|κτ|
|κb|
|κg|
|κγ|
BBSM
|κV| ≤ 1
BBSM ≥ 0
BBSM = 0
−1.5 −1 −0.5 0 0.5 1 1.5 2
−1.5 −1 −0.5 0 0.5 1 1.5 2
Parameter value

Dark matter



Morsolli, Corfu 2014

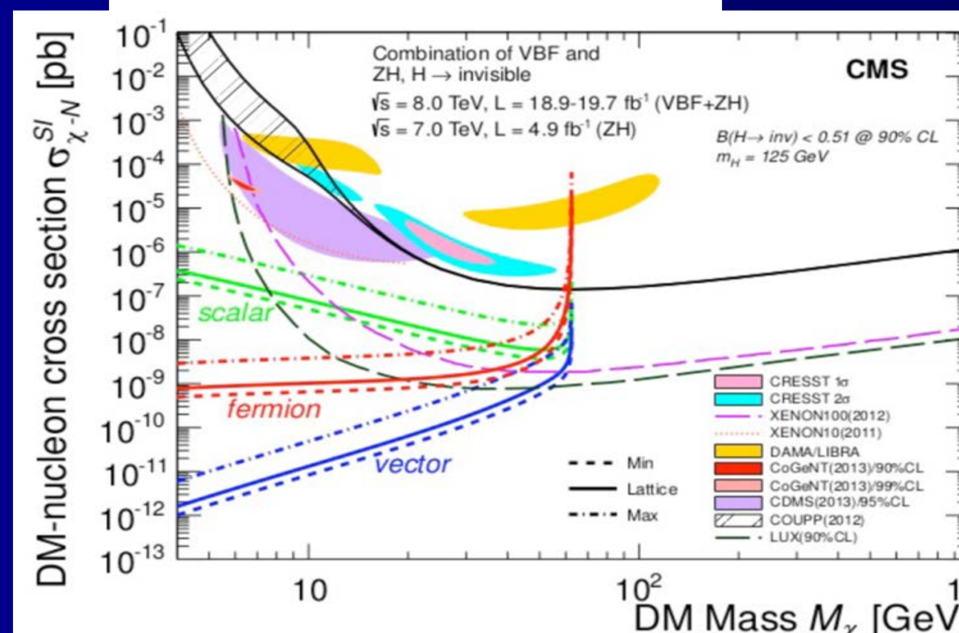
Relic DM density

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

3 σ

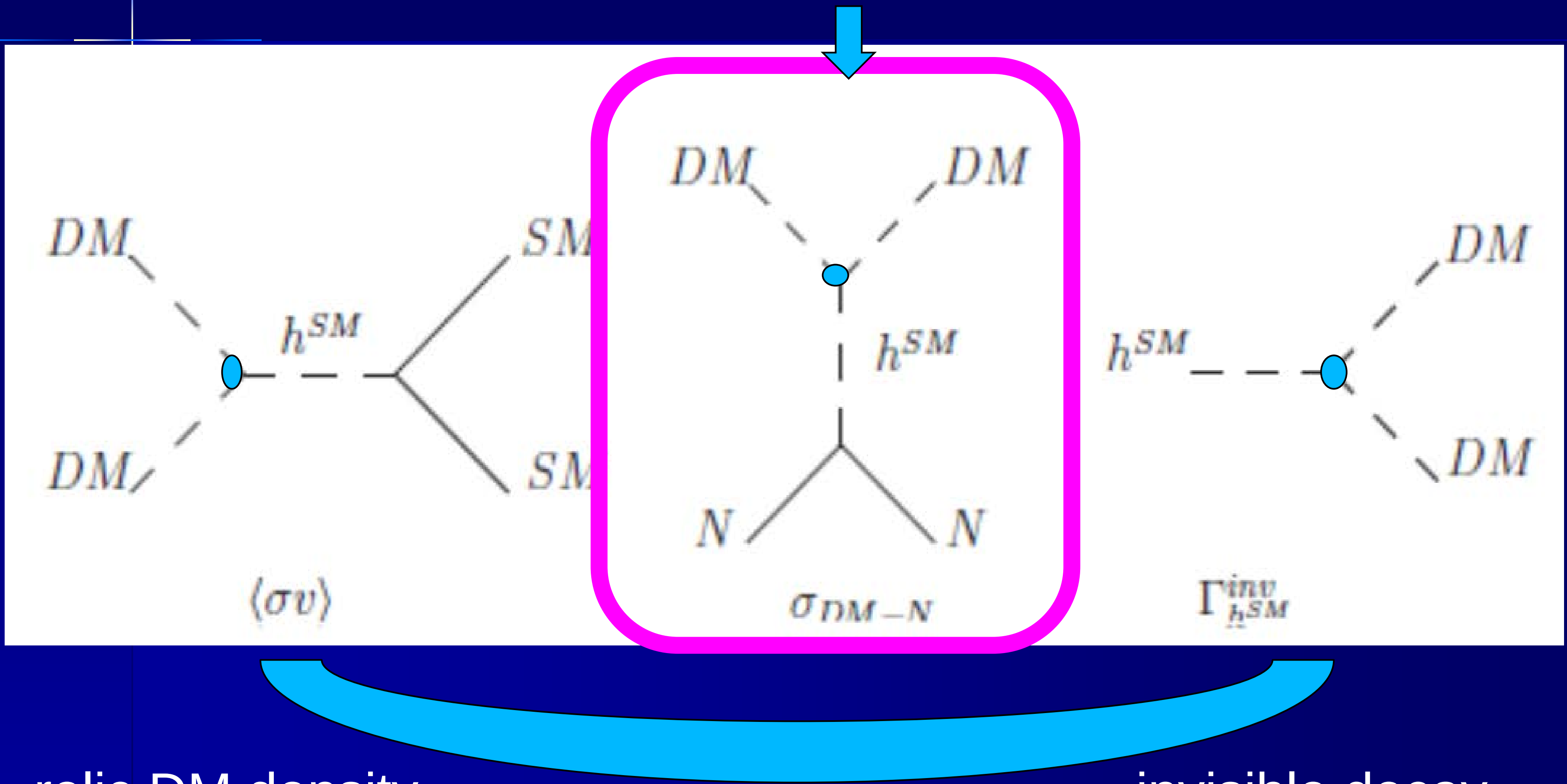
$$0.1118 < \Omega_{DM} h^2 < 0.128$$ PLANCK

Direct DM detection



Higgs portal with the SM-like h

direct detection



relic DM density

invisible decay

IDM: Z_2 2HDM potential for 2HDM

Branco, Rebelo ,85 (CP conserved)

Potential V =

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

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

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

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

Yukawa interaction

Model I – one doublet Φ_1 couples to all fermions

Vacuum state ?

various possible

positivity (stability) constraints

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

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

Extrema → vacua

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

Symmetry

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

Inert

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

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

u=0

u=0

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

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

Mixed as in MSSM

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

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

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

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

Charge Breaking

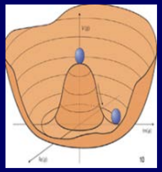
u≠0

Inert Doublet Model

Ma,…'78

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!)

Higgs boson h (SM-like)

4 scalars H+,H-,H, A

no interaction with fermions

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,…)

Testing IDM

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

- Theoretical constraints:

  vacuum stability, pert.unitarity

  condition for Inert vacuum

  $$\frac{m_{11}^2}{\sqrt{\lambda_1}} \geq \frac{m_{22}^2}{\sqrt{\lambda_2}}$$

  Swiezewska

- Detailed study of the SM-like h

  $M^2_h = m_{11}^2 = \lambda_1 v^2 = (125\text{ GeV})^2$

- Study of dark scalars D = (**H**, A, H+,H-) - in pairs!

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

λ_{345}

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

m_{22}^2 arbitrary ! (decoupling…)

H – dark matter ($\lambda_5 < 0$)

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

LHC – Higgs H_{125} data → h (IDM)

Direct couplings to W/Z and fermions - as in SM

Loop coupling hgg – as in SM

Loop coupling $h\gamma\gamma$,h $Z\gamma$ – extra H^+ (λ_3) contribution

Total width – extra contributions h→ HH,AA,H+H-

Invisible decay h → HH (~λ_{345})

$$R_{\gamma\gamma} = \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \frac{\Gamma^{SM}_{tot}}{\Gamma_{tot}}$$

invisible decays important : $R_{\gamma\gamma} > 1$

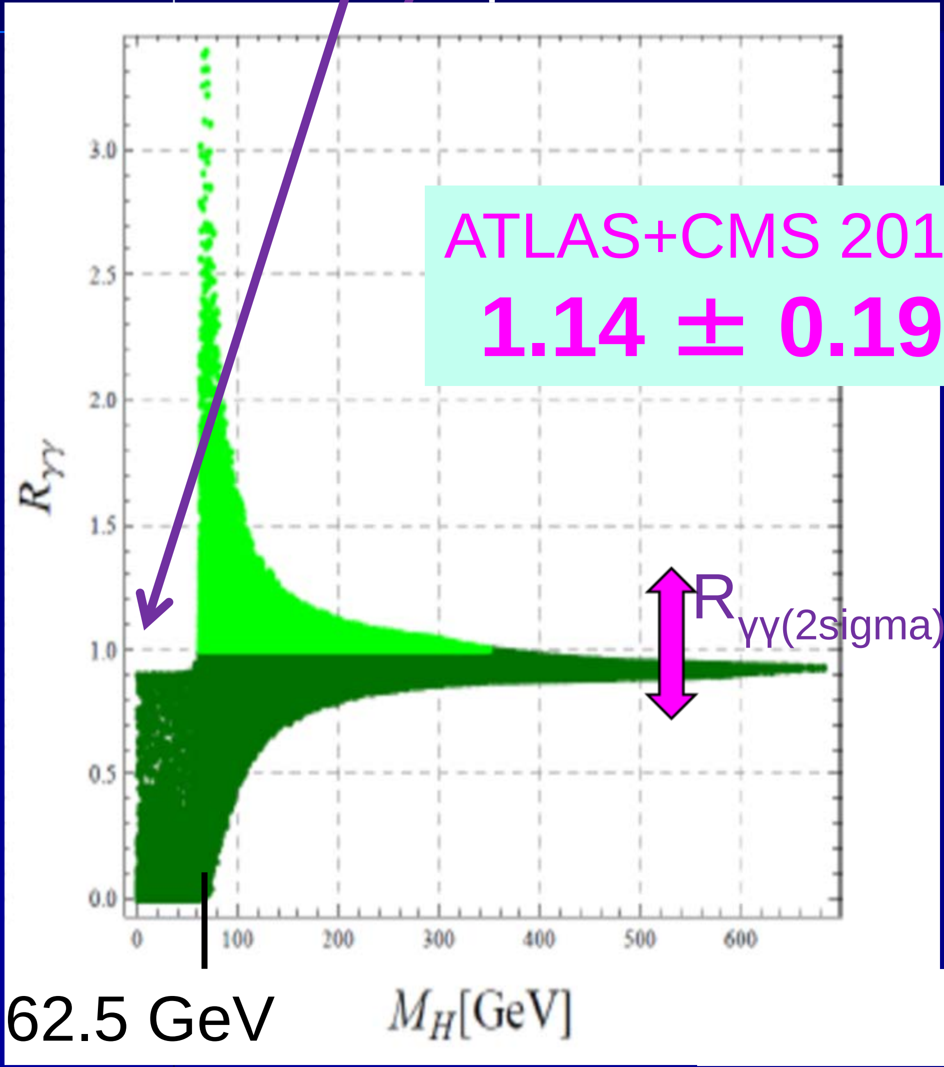
only if DM mass above 62.5 GeV

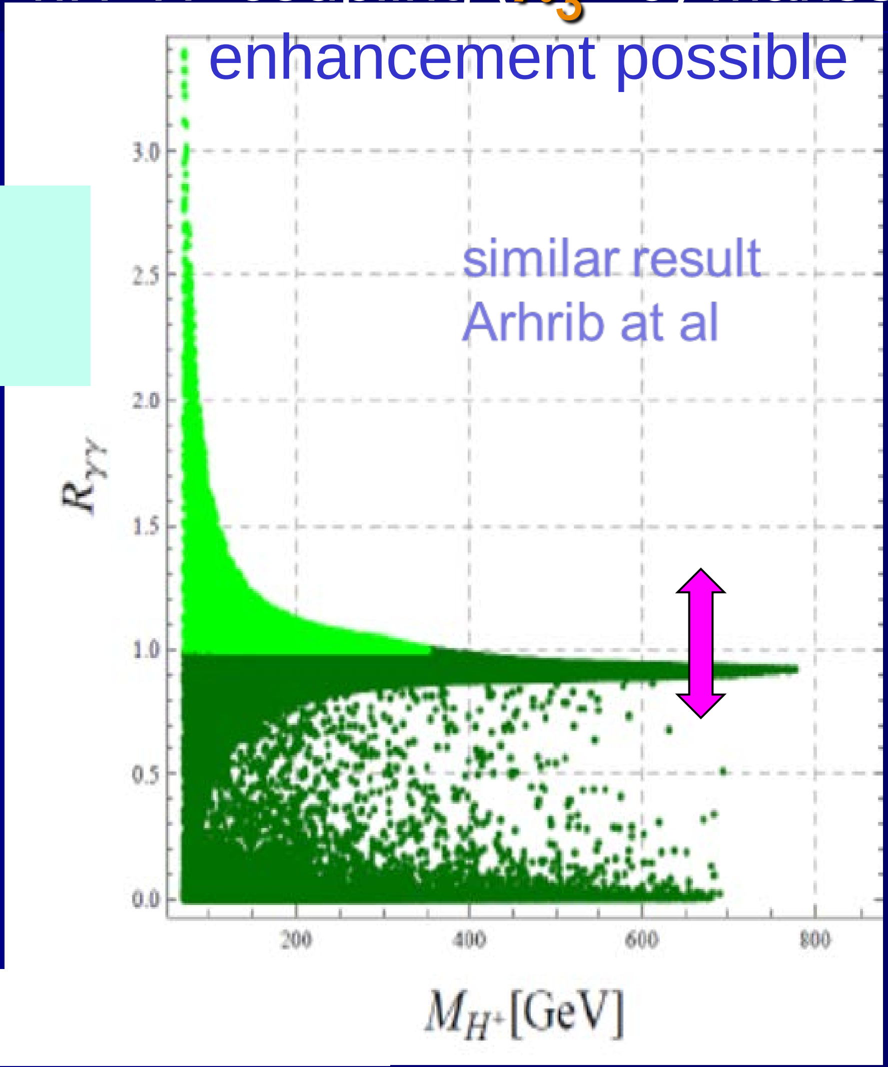
$R_{\gamma\gamma}$ as a function of mass H, H +

Invisible decays makes enhancement impossible

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

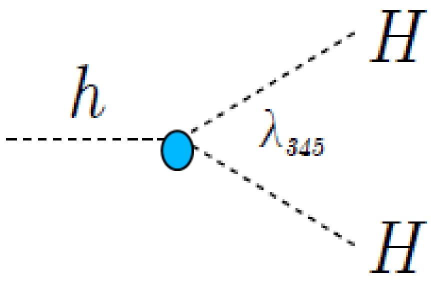
ATLAS+CMS 2016
1.14 ± 0.19





Invisible h decay →coupling hHH

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

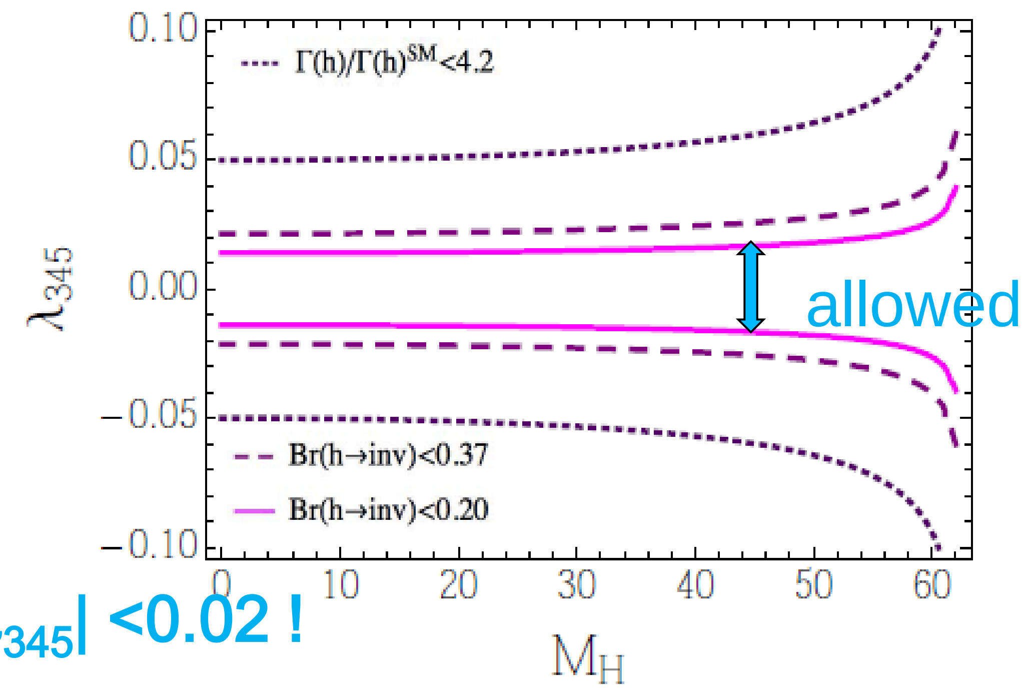


LHC:

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

global fit:

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



→ only very small $|\lambda_{345}| < 0.02$!

[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]

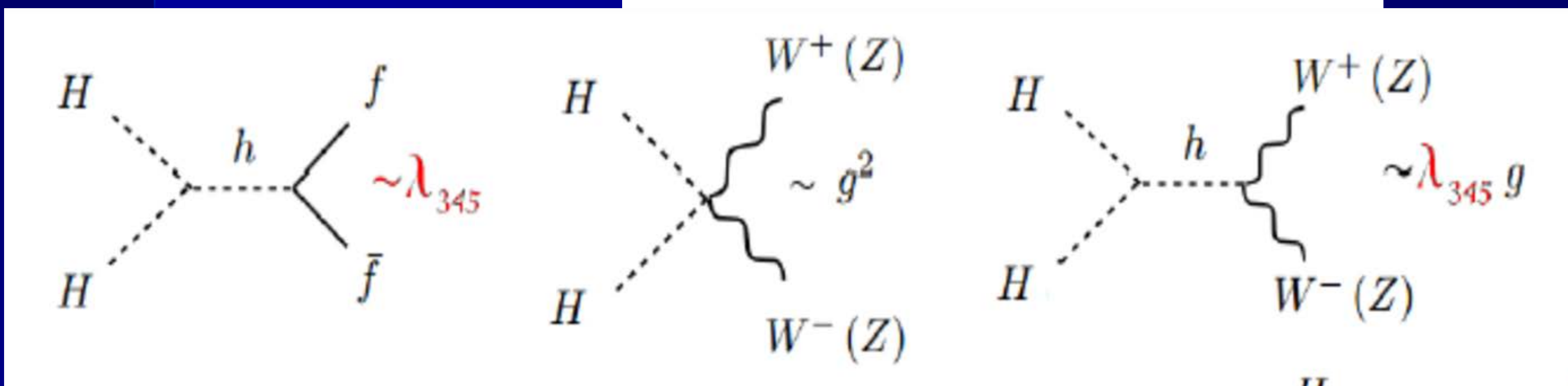
Constraining Inert Dark Matter by $R_{\gamma\gamma}$ and WMAP data

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

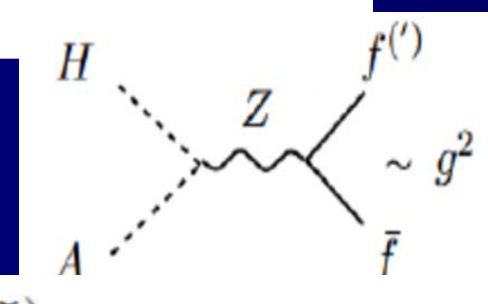
hep-ph/1305.6266
JHEP 2013

LHC data ATLAS+CMS 2016 1.14 ± 0.19

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



Coannihilation possible
for small (AH) mass splitting

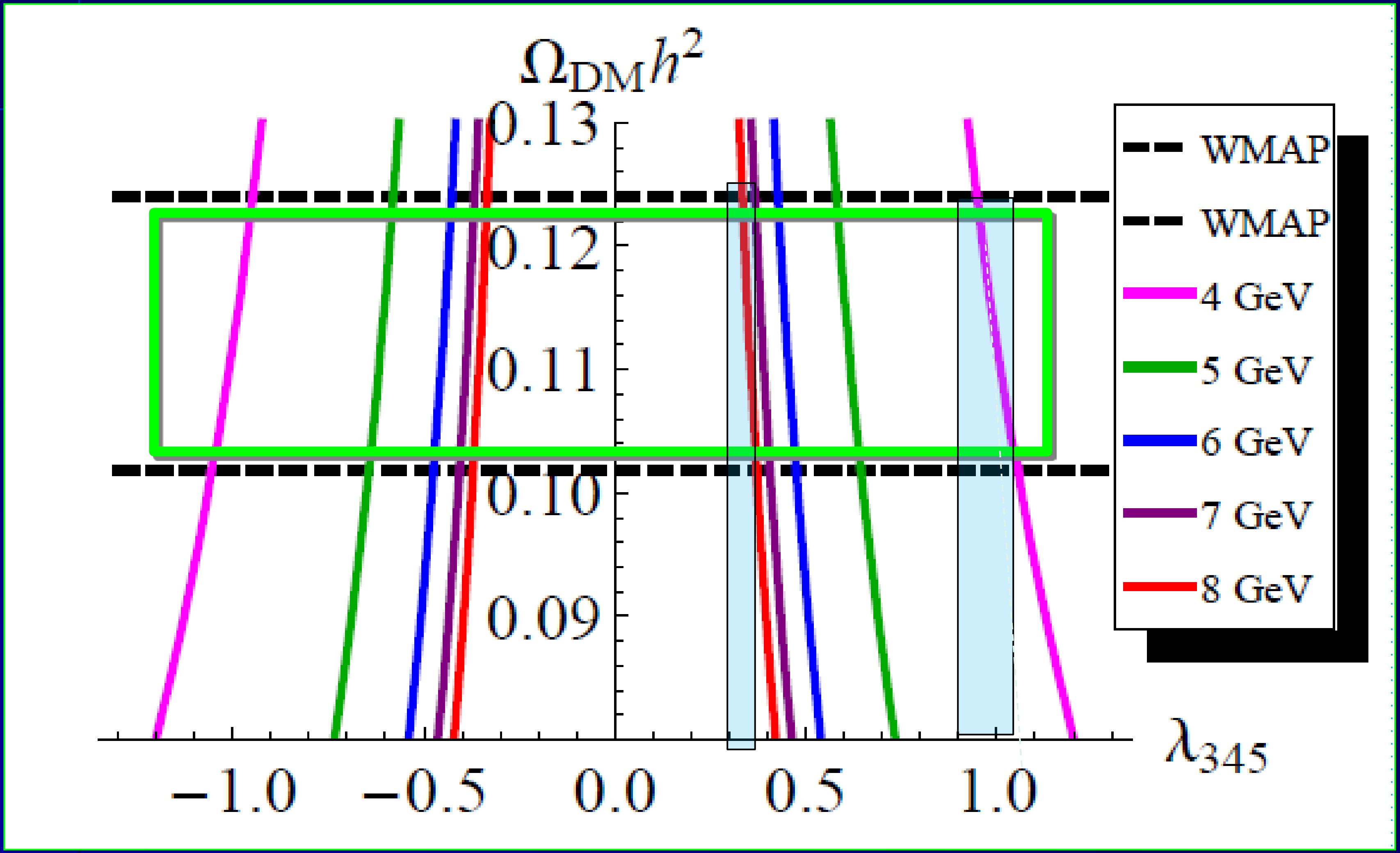


Results:

- 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 very light H (DM)

using MicrOmegas

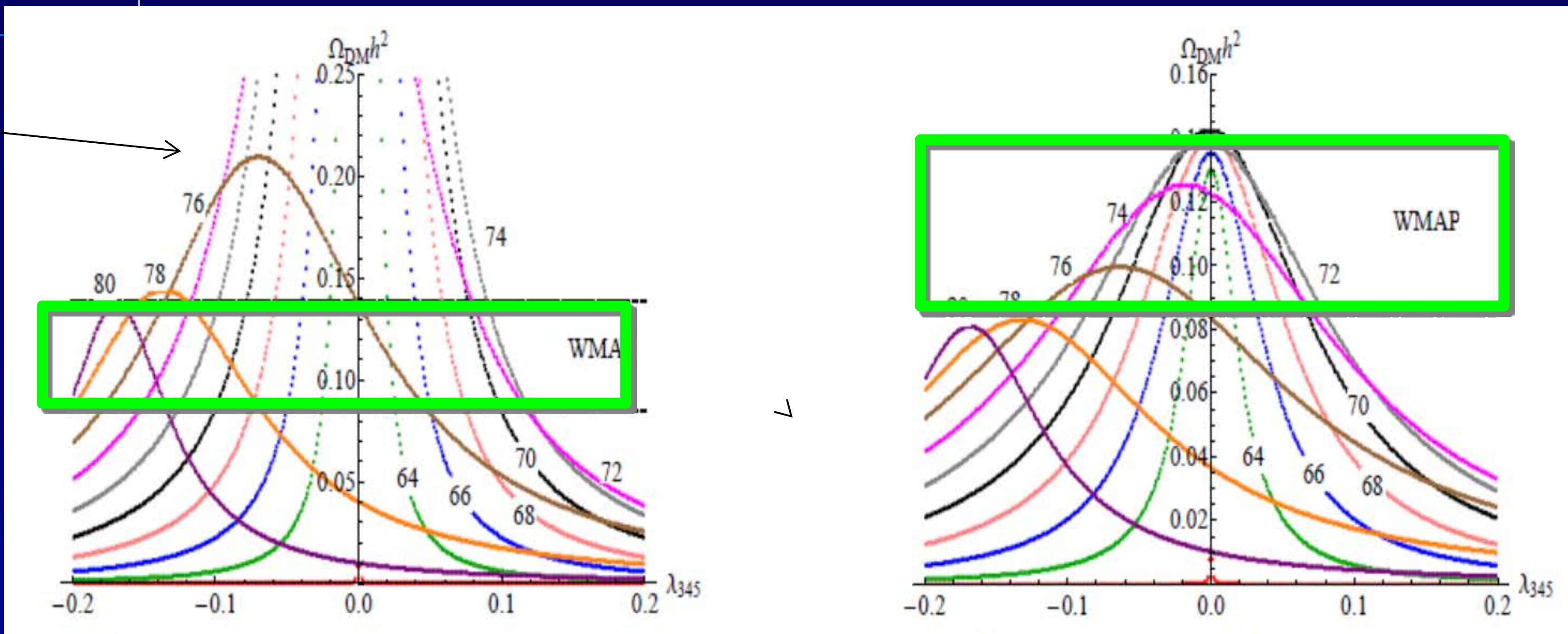


here $\lambda_{345} \sim 0.5$ in contradiction to LHC!

Relic density for DM with mass > 64 GeV

D. Sokołowska

$$M_{A,H^\pm} = M_H + \delta_{A,\pm}$$



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

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

For 64 GeV distribution still symmetric, above 76 GeV asymmetry due to annihilation to gauge bosons

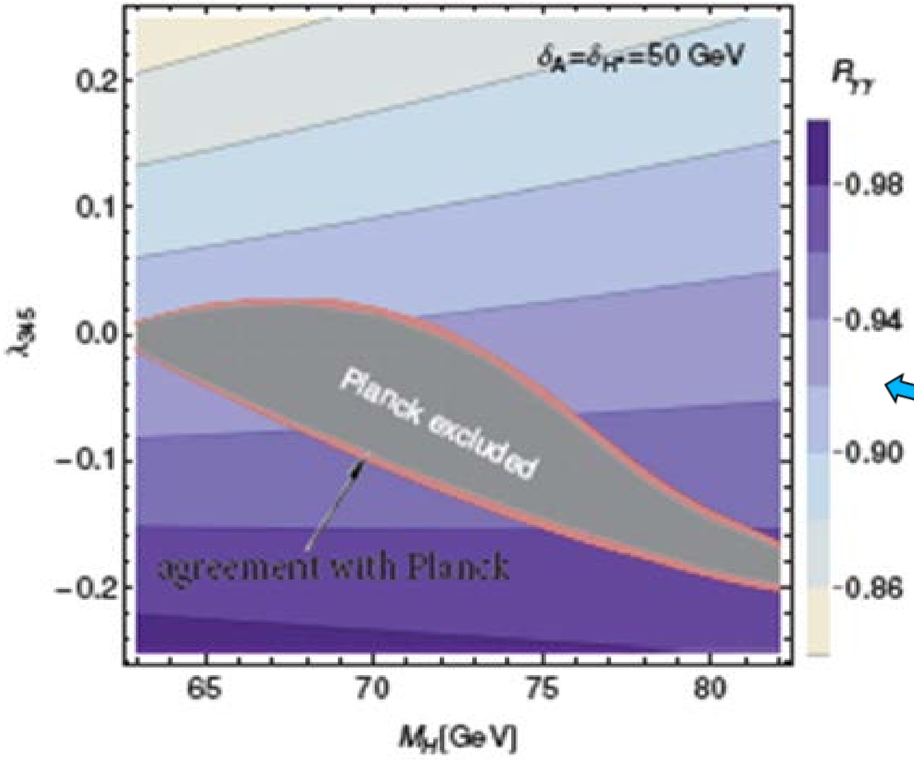
Two scales:

$M_h/2$ and M_W

Using PLANCK data

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

$h \to HH$ open



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

Full scan for IDM

A. Ilnicka, T. Robens, MK Phys.Rev. D93 (2016)

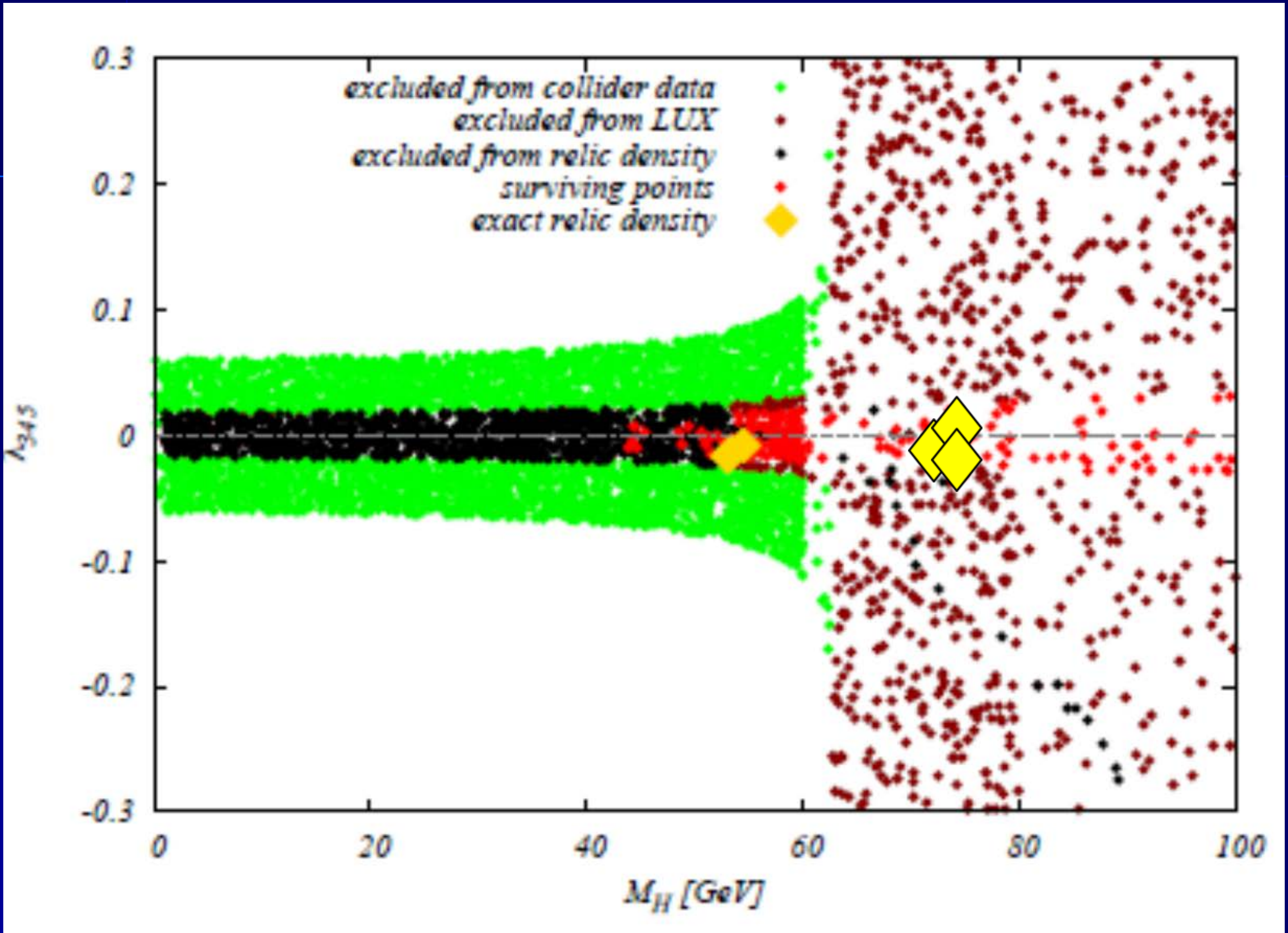
- Theor. constraints –
  stability of the potential (positivity), pert.unitarity,
  condition for the Inert vacuum
- STU (from 2014)
- Higgssignal/Higgs bounds
- Lifetime of H+ (< 10^{-7} s to decay inside detector)
- Relic density Planck **Ω < 0.1241** (95% CL) and **„exact"**
- Direct detection LUX (2015)
- → scan over M_H up to 1 TeV
- ➡ Benchmarks

+LEP constraints
h total width
W/Z total width

other analyses Stahl.., Blinov …Cline …Arhrib, ..Belayev…,Poulose, …Banerjee

Low mass H (DM)

1505.04734,1508.01671



„exact" relic density

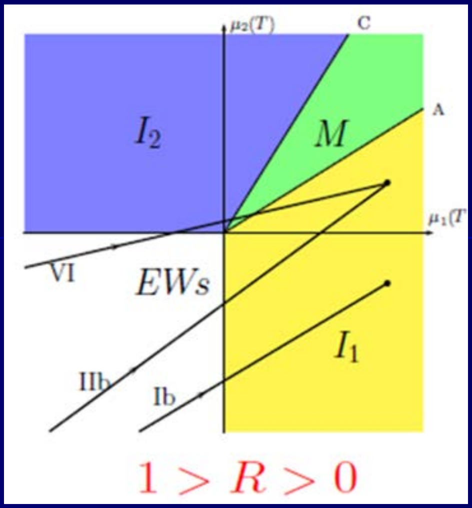
Limit on mass of DM: M_H > 45 GeV !

T^2 corrections:evolution of the Universe

→ rays from EWs phase to Inert phase
one, two or three stages of Universe
(2nd order PT, one 1st order)

Ginzburg, Kanishev,MK, Sokołowska PRD 2010

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



beyond T^2 corrections: strong 1st order PT

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

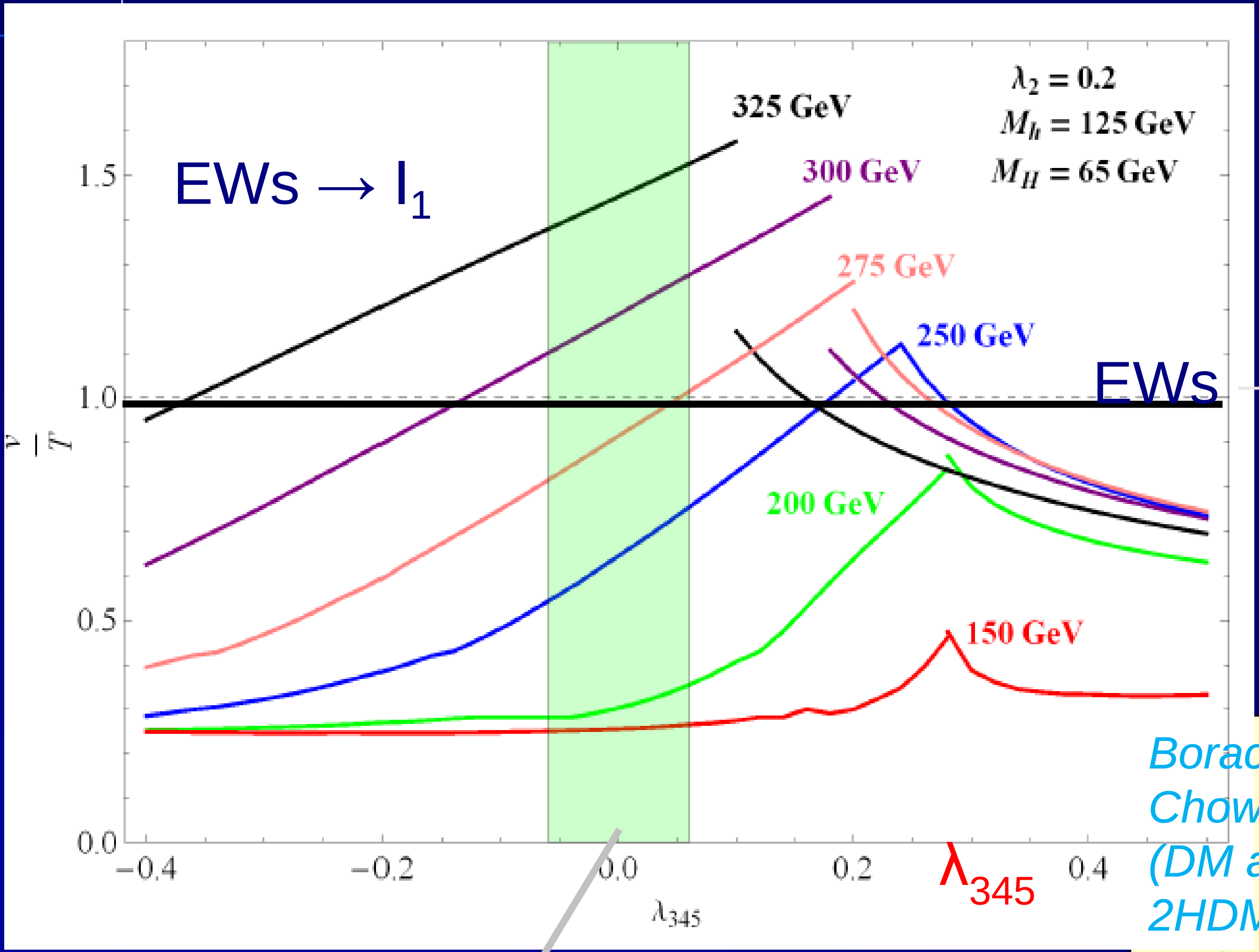
We applied one-loop effective potential at T=0 (Coleman-Wienberg term) and temperature dependent effective potential at T≠0 (with sum of ring diagrams)

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

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

strong 1st order phase transition

Mh=125 GeV, MH=65 GeV, λ2=0.2



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

also

Borach, Cline 1204.4722
Chowdhury et al 1110.5334
(DM as a trigger of strong PT)
2HDM Cline et al, 1107.3559
and Kozhusko..1106.0790)

R<0 Xenon100 bound R>0

IDMS Bonilla, Diaz-Cruz, Darvishi, Sokołowska, MK – J.Phys. G43 (2016)

- IDM + extra neutral complex singlet χ with a complex vev

  → towards CP violation and baryogenesis
- SM-like doublet - singlet interaction →

  mixing in the neutral scalar sector

  3 neutral Higgses: h1 (SM-like), h2, h3

- Small change in h_1 couplings to SM particles
- Dark doublet as before → H is a good DM candidate, modifications due to h2 and h3

Fields and potential of the IDMS

Φ_S

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

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

Φ_D

χ

$$Z_2 \; : \; \Phi_1 \to \Phi_1, \; \Phi_2 \to -\Phi_2, \text{ SM fields} \to \text{SM fields}, \; \chi \to \chi.$$

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

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

IDM

$$-\frac{m_s^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2$$

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

$$+\Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi)$$

with softly broken U(1) $\quad U(1): \; \Phi_1 \to \Phi_1, \, \Phi_2 \to \Phi_2, \, \chi \to e^{i\alpha}\chi.$

Remarks

$Z_2 \; : \; \Phi_1 \to \Phi_1, \; \Phi_2 \to -\Phi_2, \; \text{SM fields} \to \text{SM fields}, \; \chi \to \chi,$

respected by vacuum –> no domain problem

The general singlet part of the potential is equal to:

$$V_S = -\frac{m_s^2}{2}\chi^*\chi - \frac{m_4^2}{2}(\chi^{*2}+\chi^2) + \lambda_{s1}(\chi^*\chi)^2 + \lambda_{s2}(\chi^*\chi)(\chi^{*2}+\chi^2) + \lambda_{s3}(\chi^4+\chi^{*4})$$
$$+\kappa_1(\chi+\chi^*) + \kappa_2(\chi^3+\chi^{*3}) + \kappa_3(\chi(\chi^*\chi)+\chi^*(\chi^*\chi)).$$

The doublet-singlet interaction terms are:

CP transformation $\Phi_{1,2} \to \Phi_{1,2}^\dagger, \chi \to \chi^*$

$$V_{DS} = \Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi) + \Lambda_2(\Phi_2^\dagger\Phi_2)(\chi^*\chi) + \Lambda_3(\Phi_1^\dagger\Phi_1)(\chi^{*2}+\chi^2) + \Lambda_4(\Phi_2^\dagger\Phi_2)(\chi^{*2}+\chi^2)$$
$$+\kappa_4(\Phi_1^\dagger\Phi_1)(\chi+\chi^*) + \kappa_5(\Phi_2^\dagger\Phi_2)(\chi+\chi^*).$$

To simply model we use U(1)

$\Phi_1 \to \Phi_1, \; \Phi_2 \to \Phi_2, \; \chi \to e^{i\alpha}\chi.$

But with non-zero vev for singlet → massless Nambu-Goldstone boson. So we softly break it…

In order to have DM ~ IDM we neglect terms with dark doublet

κ_4 and Λ_2 - generated at one-loop (→ small)

Higgs sector – h_1(125 GeV), h_2, h_3

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix},$$

$$R = R_1 R_2 R_3 = \begin{pmatrix} c_1 c_2 & c_3 s_1 - c_1 s_2 s_3 & c_1 c_3 s_2 + s_1 s_3 \\ -c_2 s_1 & c_1 c_3 + s_1 s_2 s_3 & -c_3 s_1 s_2 + c_1 s_3 \\ -s_2 & -c_2 s_3 & c_2 c_3 \end{pmatrix}$$

$$h_1 = c_1 c_2 \phi_1 + (c_3 s_1 - c_1 s_2 s_3)\phi_2 + (c_1 c_3 s_2 + s_1 s_3)\phi_3,$$

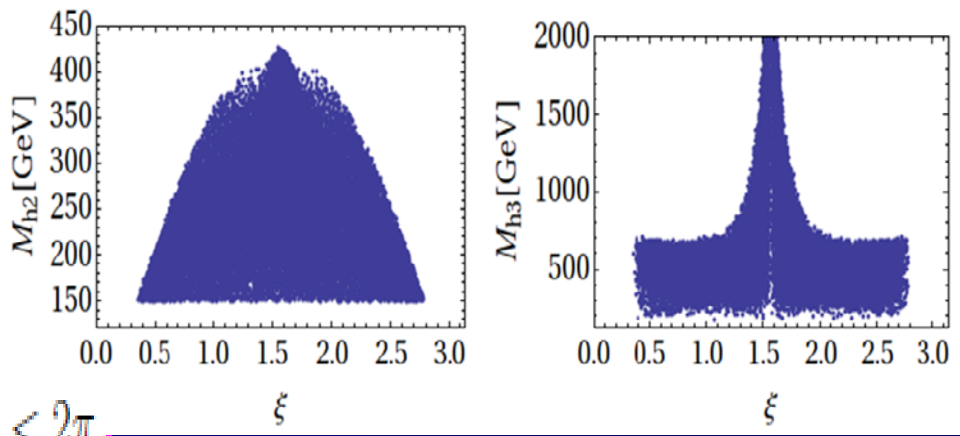
$$R_{11} = R_{11}^{-1} = c_1 c_2 \sim 1$$

M h_1 ~125 GeV, w=300-1000 GeV

$$M_{h_3} > M_{h_2} > 150\ \mathrm{GeV}.$$

$$\kappa_{2,3} = w\rho_{2,3},$$

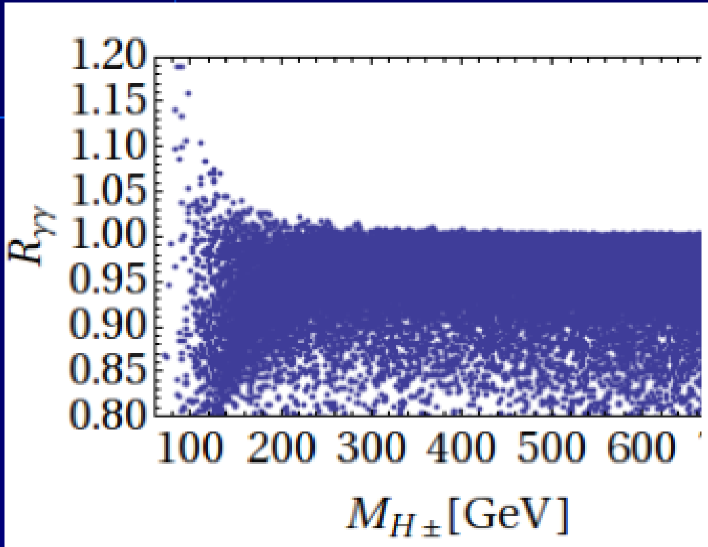
$$-1 < \Lambda_1 < 1, \quad 0 < \lambda_{s1} < 1, \quad -1 < \rho_{2,3} < 1, \quad 0 < \xi < 2\pi.$$

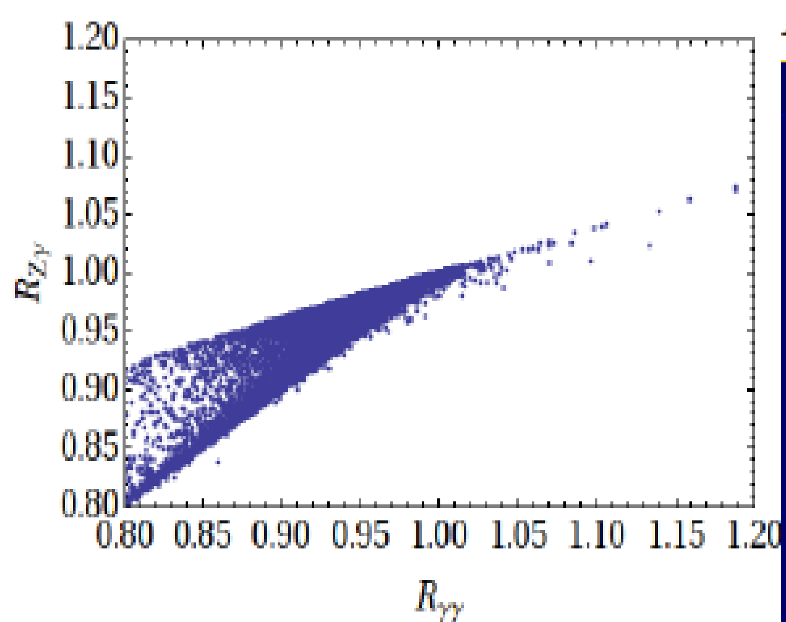


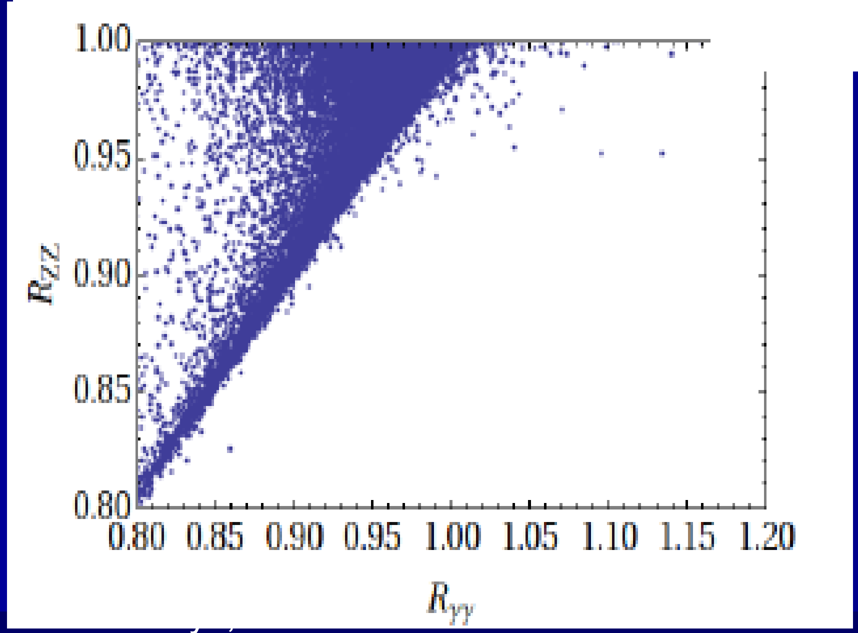
IDMS - h_1(125 GeV)

$$\Gamma(h_1 \to XX) = R_{11}^2 \Gamma(\phi_{SM} \to XX$$

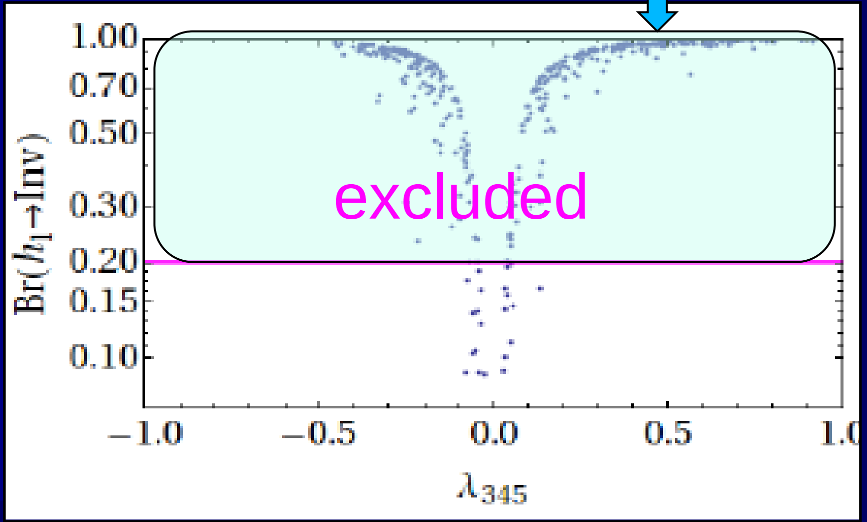
$$XX = gg, VV^*$$



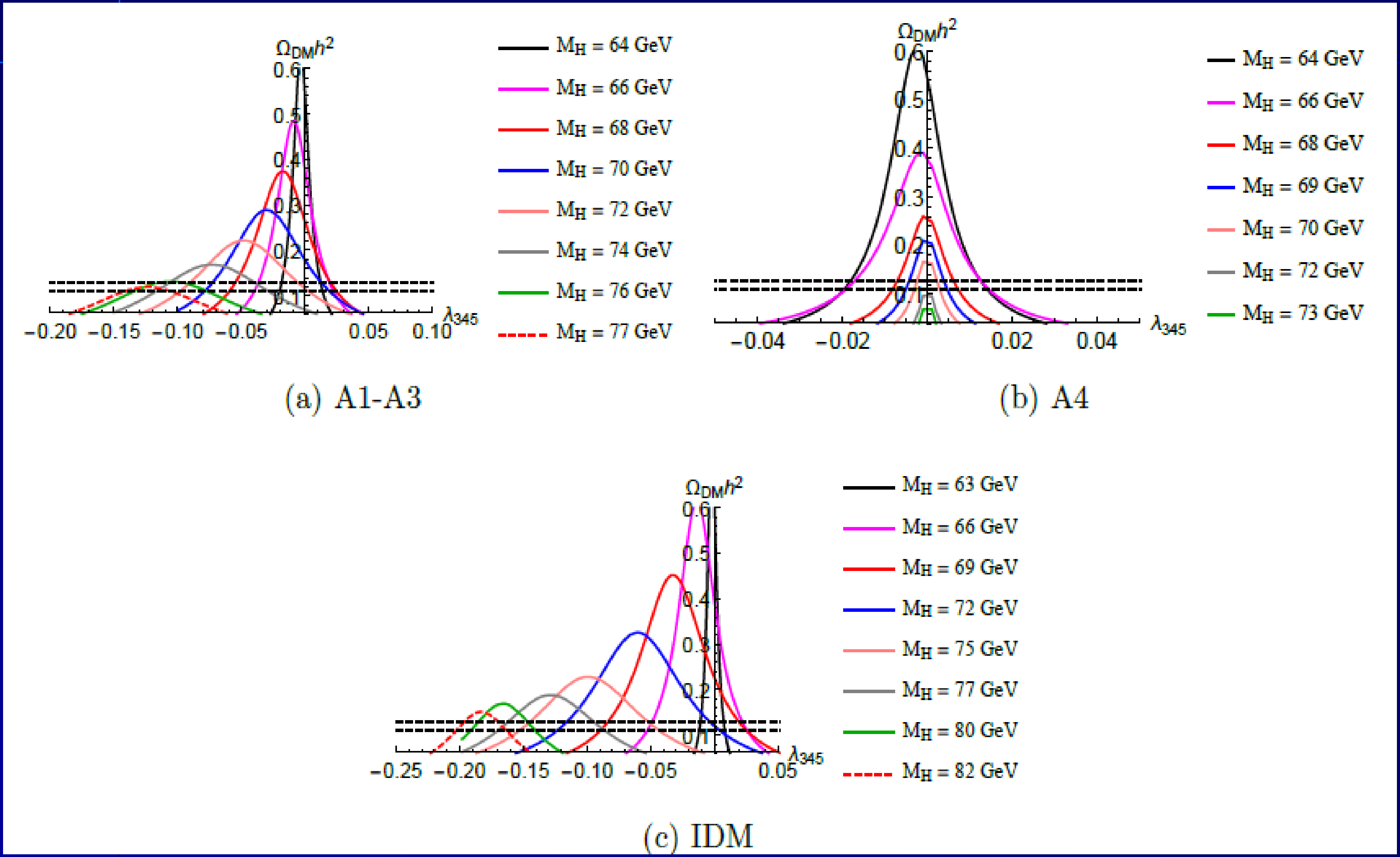




Br h_1 → inv



Relic density - interference and second light Higgs

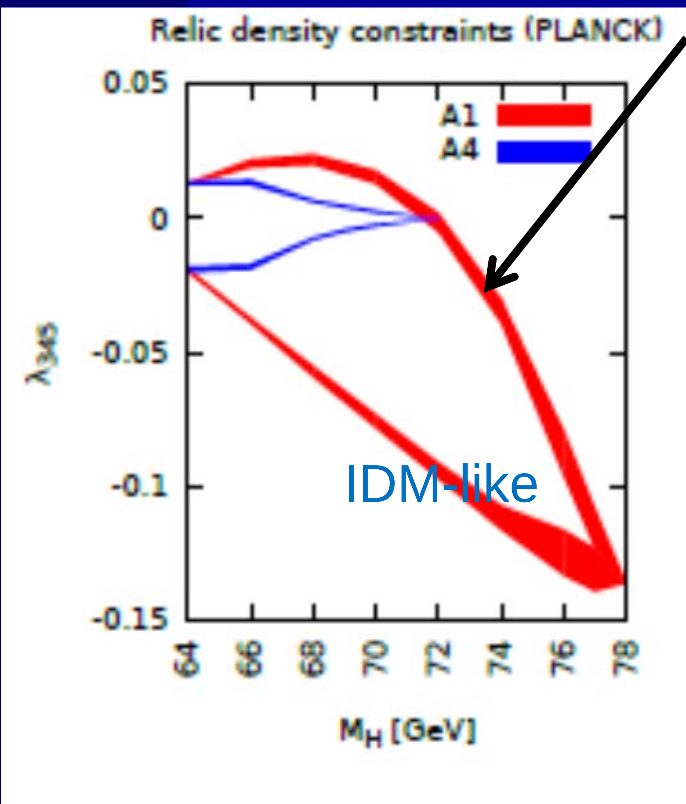


Dark sector – Higgs portals via h_1, h_2, h_3 possible !

We proposed benchmarks – eg.

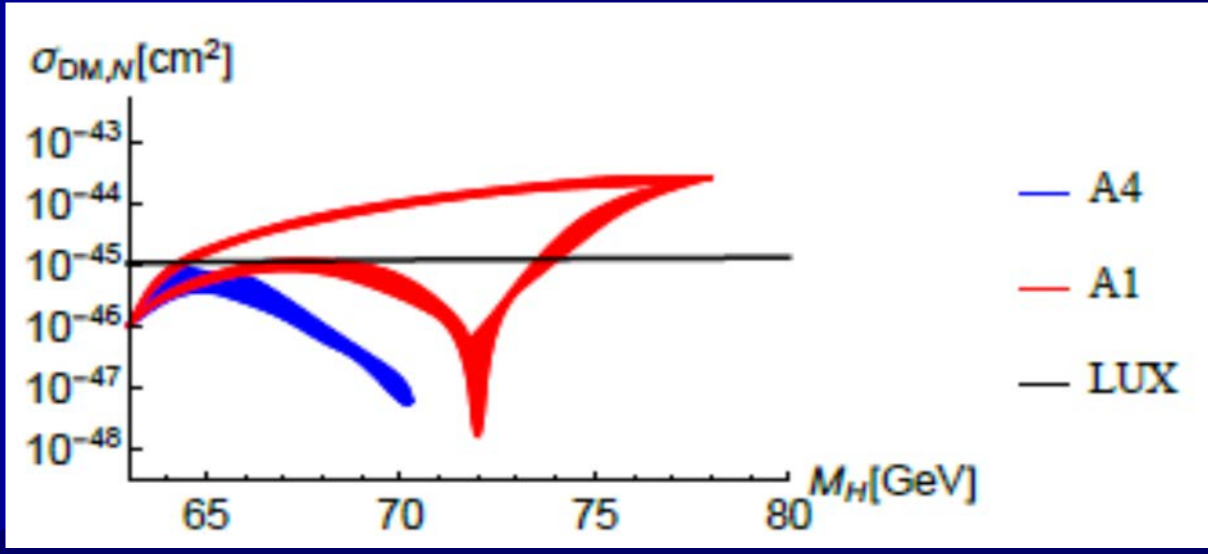
$$\mathrm{A1:}\ M_{h_1} = 124.83\mathrm{GeV},\ M_{h_2} = 194.46\mathrm{GeV},\ M_{h_3} = 239.99\mathrm{GeV}$$

$$\mathrm{A4:}\ M_{h_1} = 125.36\mathrm{GeV},\ M_{h_2} = 149.89\mathrm{GeV},\ M_{h_3} = 473.95\mathrm{GeV}$$



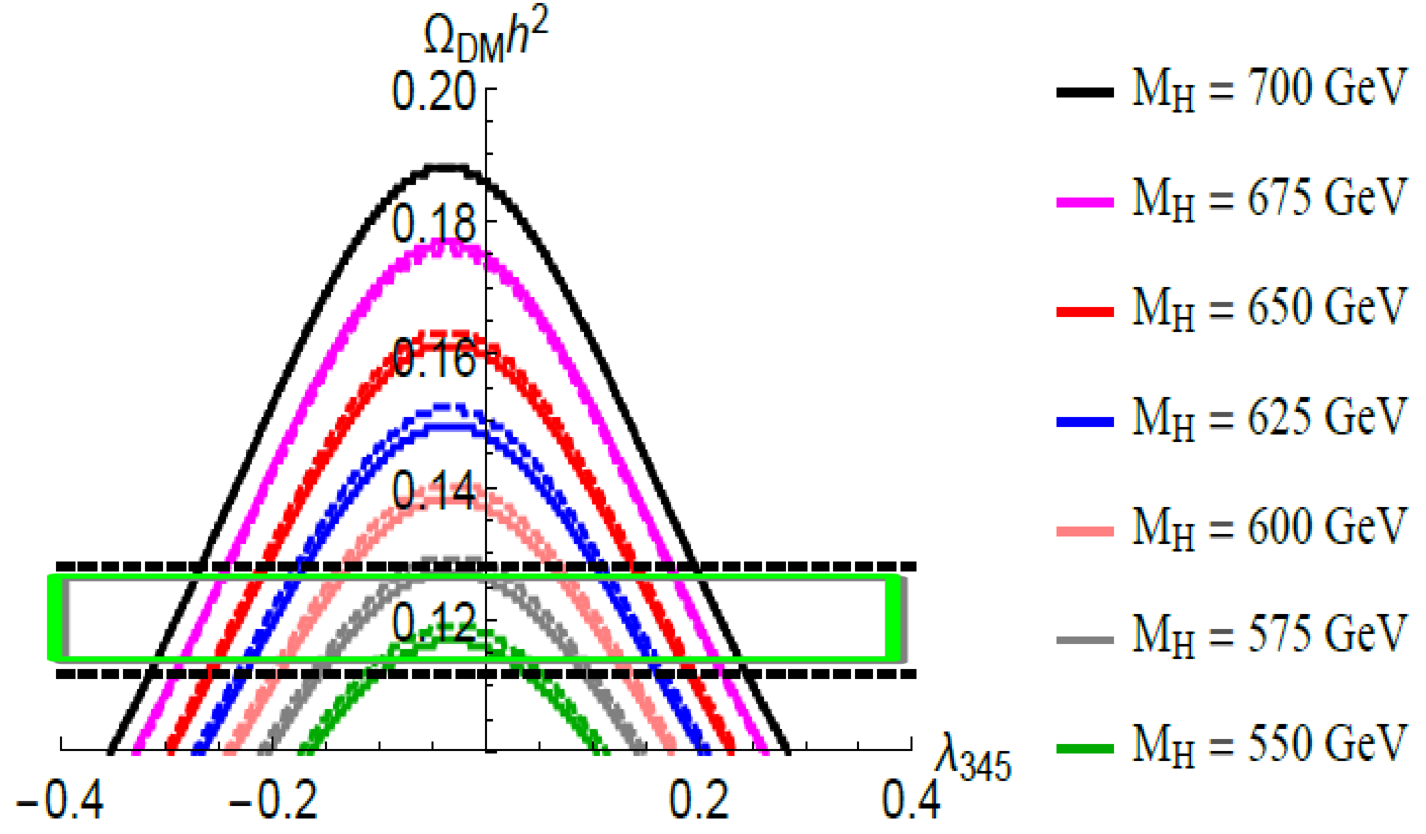
A1:only h_1 lighter than $2M_W$ – like IDM

A4: h_2 portal up to M_H ~70 GeV (h_2 resonance); $2M_W > M\_h_1, M\_h_2$



IDMS – heavy DM

$M_A = M_{H\pm} = M_H + 1\,\mathrm{GeV}.$



A1-A4 –> similar results

SM+complex singlet

Branco .. Espinosa

Darvishi, Sokolowska,MK ***1512.06437 (APP B47 2016)****;* ***Darvishi, MK 1603.00598***

- SM SU(2) doublet + complex singlet with non-zero complex vev

  (in agreement with LHC)

- Important cubic terms
- Possibility of spontaneous CP violation
- Strong 1st order phase transition

  Darvishi, JHEP 2016

- Baryogenesis with vector-like quarks (iso-doublet) *Darvishi, JHEP 2016; McDonald 1996*

Fields and potential of the SMCS

Φ_S $$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1 + i\phi_6) \end{pmatrix},$$

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

w1 = w cos

w2 = w sin

Symmetry transformation $\chi \to \chi^*$

$$V = -\frac{1}{2}\left[m_{11}^2 \Phi_1^\dagger \Phi_1\right. \quad + \frac{1}{2}\left[\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2\right.$$

SM

cubic terms

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

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

$$+\Lambda_1(\Phi_1^\dagger \Phi_1)(\chi^*\chi)$$

with softly broken U(1) $U(1): \quad \Phi_1 \to \Phi_1, \quad \chi \to e^{i\alpha}\chi.$

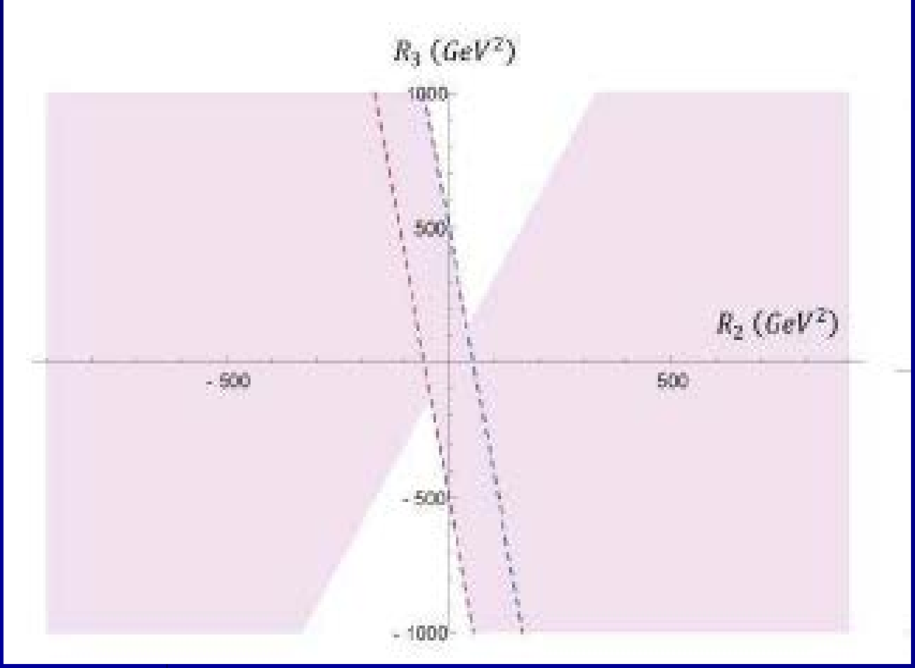
Vacuum: v, $w_1=\cos\xi$, $w_2=\sin\xi \neq 0$
Spont. CP violation in region

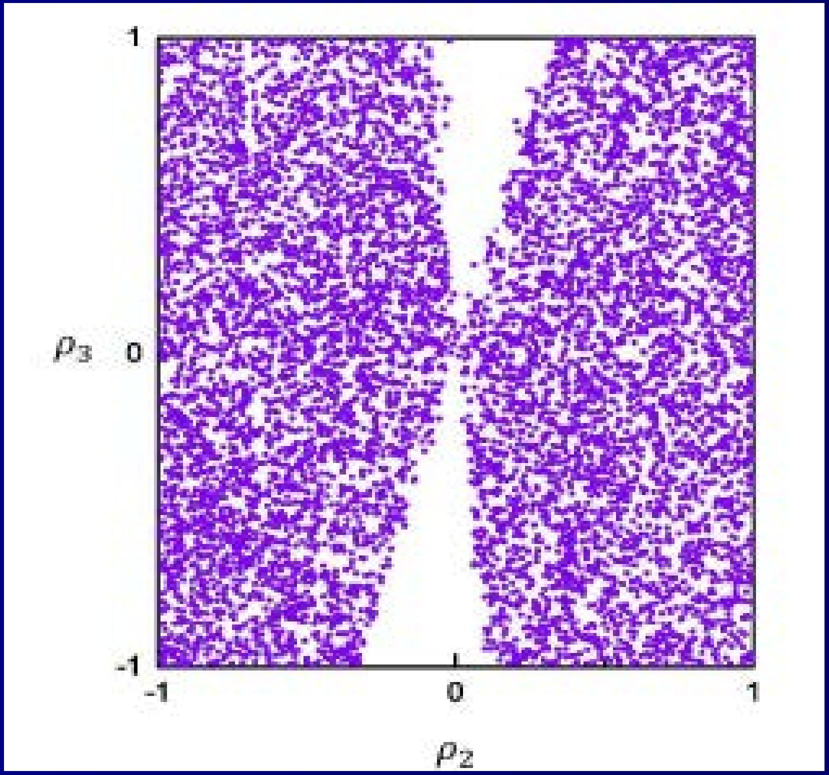
$$-4m_4^2\cos\xi + 3R_2(1+2\cos 2\xi) + R_3 \cdot \quad = 0$$

$$R_2 = \sqrt{2}w\kappa_2,\ R_3 = \sqrt{2}w\kappa_3,$$

cubic terms

full scan





$$\rho_{2,3} = \kappa_{2,3}/w$$

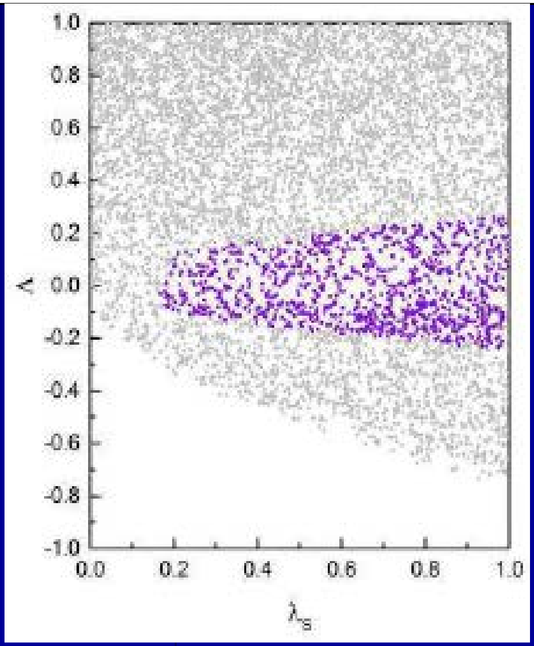
Scan – results similar to IDMS but here low < χ > ~ w possible

$$M_{h_1} \in [124.00, 127.00]\ \mathrm{GeV}, \quad M_{h_3} \gtrsim M_{h_2} > 150\,\mathrm{GeV}$$

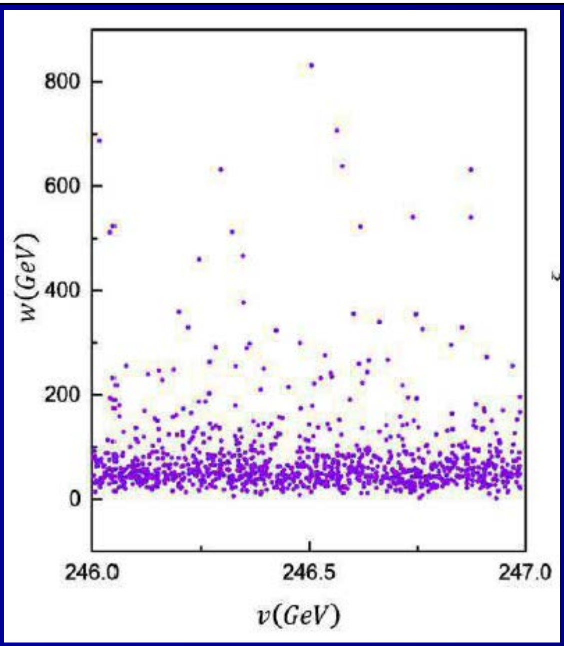
$$0.2 < \lambda_1 < 0.3 \qquad \rho_{2,3} = \kappa_{2,3}/w$$

$$-1 < \Lambda < 1,\ 0 < \lambda_s < 1,\ -1 < \rho_{2.3} < 1,\ 0 < \xi < \pi,$$

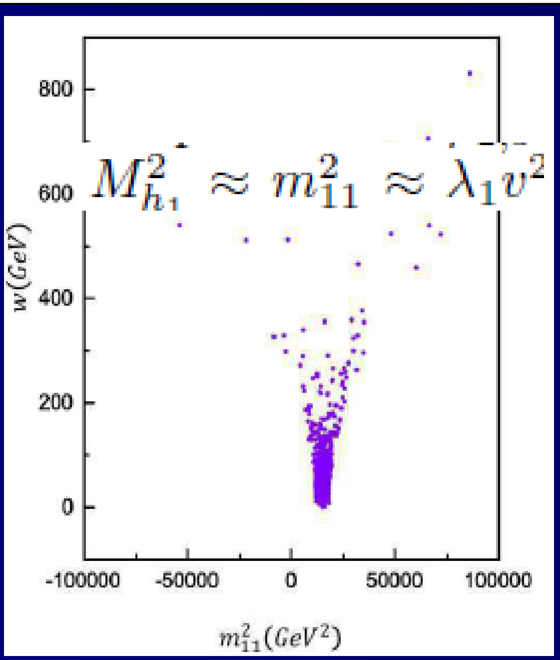
$$-90000\ \mathrm{GeV}^2 < \mu_1^2, \mu_2^2, m_{11}^2 < 90000\ \mathrm{GeV}^2. \quad \mu_1^2 = m_s^2 + 2m_4^2, \quad \mu_2^2 = m_s^2 - 2m_4^2.$$



singlet self coupling λ_s, to be greater than 0.2,
the doublet-singlet coupling $|\Lambda|$, to be below 0.2.



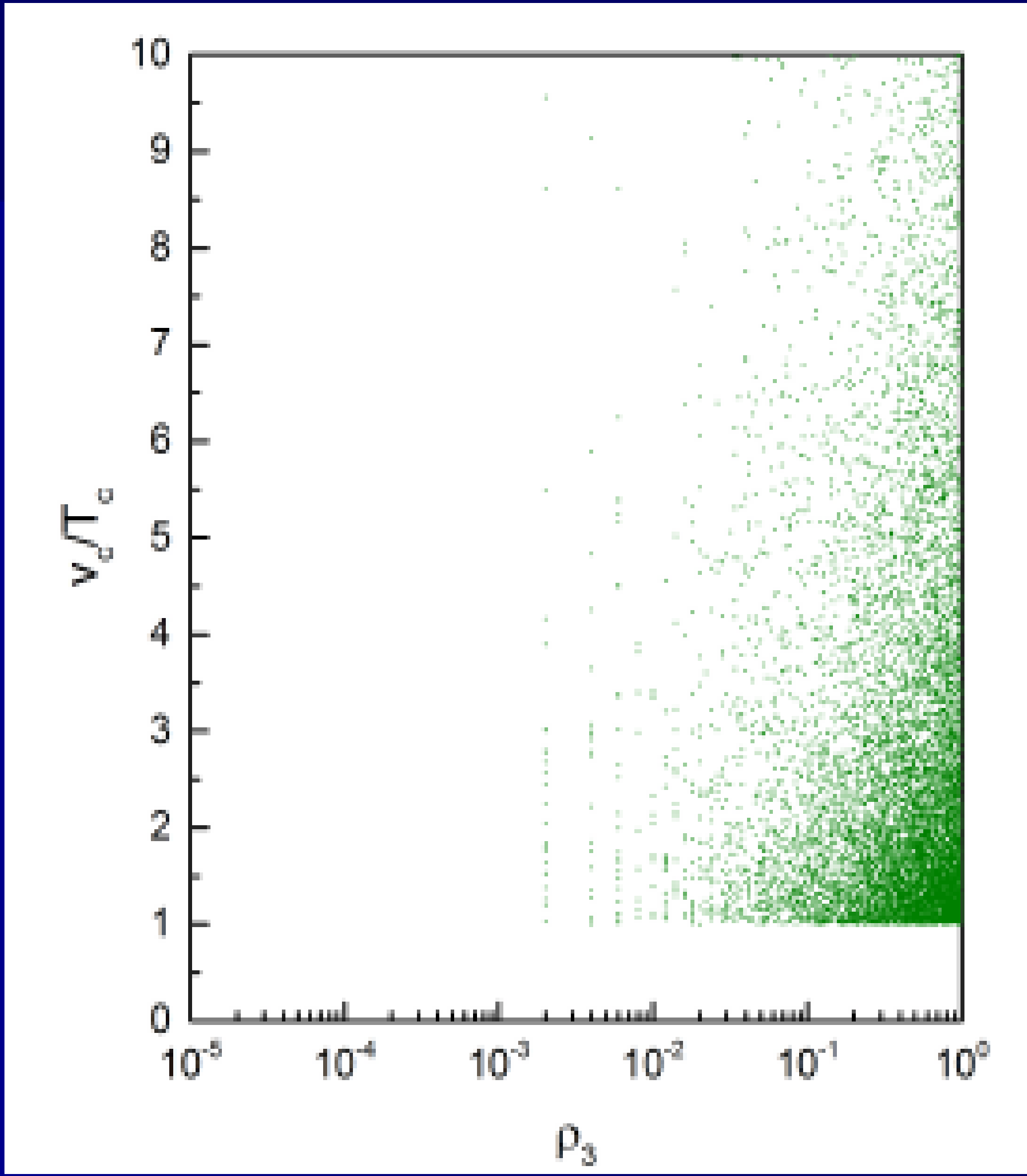
w not too large



mass 125 GeV

Strong 1st order PT

T2 – corrections



cubic term

Benchmarks

Benchmark	α_1	α_2	α_3	M_{h_1}	M_{h_2}	M_{h_3}	S	T	J_1/v^6
$A1$	-0.047	-0.053	1.294	124.64	652.375	759.984	-0.072	-0.094	-2.2×10^{-4}
$A2$	-0.048	0.084	0.084	124.26	512.511	712.407	-0.001	-0.039	7.2×10^{-4}
$A3$	0.078	0.297	0.364	124.27	582.895	650.531	0.003	-0.046	4.5×10^{-4}
$A4$	0.006	-0.276	0.188	125.86	466.439	568.059	-0.013	-0.169	-9.5×10^{-4}
$A5$	0.062	-0.436	0.808	125.21	303.545	582.496	0.002	-0.409	5.0×10^{-6}
$A6$	-0.210	0.358	0.056	124.92	181.032	188.82	0.003	-0.010	-4.0×10^{-5}
$A7$	-0.205	0.403	0.057	125.01	175.45	178.52	0.002	-0.020	-3.5×10^{-5}

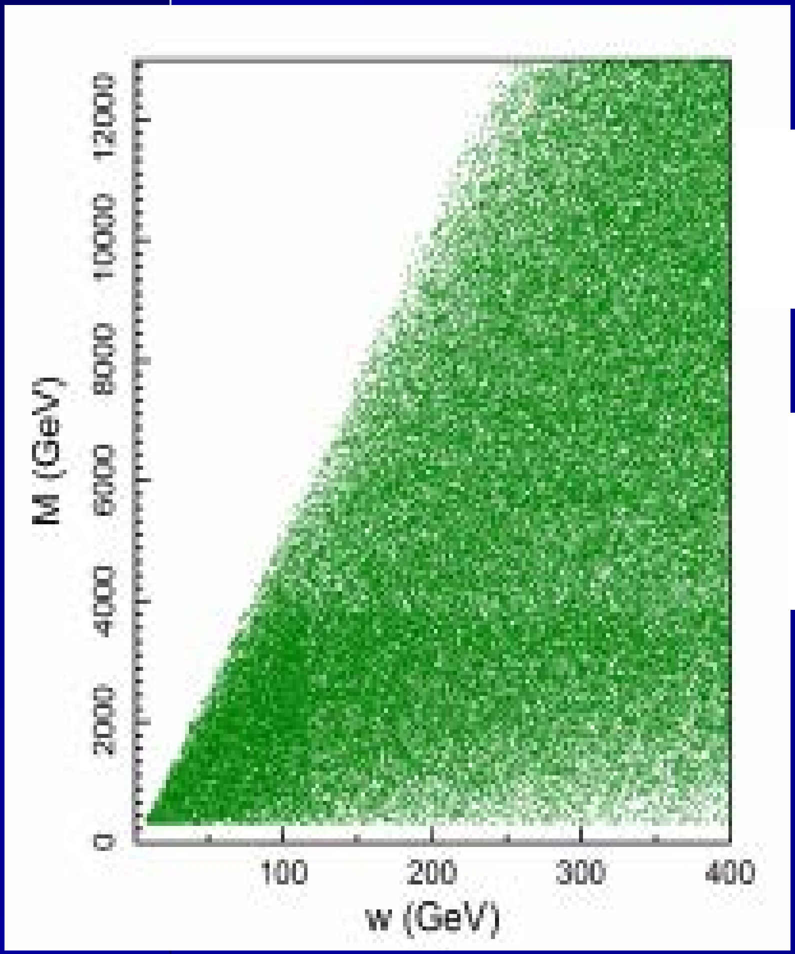
Table I. Benchmark points $A1 - A7$, masses are given in GeV.

Benchmark	$R^{h_1}_{\gamma\gamma}$	$R^{h_2}_{\gamma\gamma}$	$R^{h_3}_{\gamma\gamma}$	$\Gamma^{h_1}_{tot}$	$\Gamma^{h_2}_{tot}$	$\Gamma^{h_3}_{tot}$
$A1$	0.98	0.0021	0.0028	0.0042	0.304	0.781
$A2$	0.98	0.0021	0.0070	0.0042	0.145	1.31
$A3$	0.98	0.0055	0.085	0.0042	0.566	12.24
$A4$	0.92	3.3×10^{-5}	0.074	0.0043	0.001	7.08
$A5$	0.81	0.0029	0.17	0.0043	0.002	17.51
$A6$	0.82	0.19	0.11	0.0043	0.119	0.163
$A7$	0.81	0.18	0.15	0.0043	0.871	0.083

McDonald, PRD (1996)

Baryogenesis with heavy iso - doublet vector - like quarks

Neda Dravishi,
JHEP 2016 (1608.02820)



$$\mathcal{L}_Y(V_q,\chi) = \lambda_V \chi \overline{Q}_L V_R + M \overline{V}_L V_R + h.c,$$

$$\Delta\mathcal{L}_k = -\frac{\lambda_V^2 w^2}{M^2}\dot{\xi}(\overline{Q'}_L \gamma^0 Q'_L - \overline{V'}_L \gamma^0 V'_L).$$

$$\frac{n_B}{s} = \frac{225 K \alpha_W^4}{4\pi^2 g^*}\frac{\lambda_V^2 w^2}{M^2}\delta\xi,$$

Summary

- Doublets and singlets extensions of SM – rich phenomenology
- Higgs and Dark Matter in IDM and IDMS - in agreement with data

- Various stages of the Universe ?
- Strong first order phase transition → baryogenesis with vector - quarks