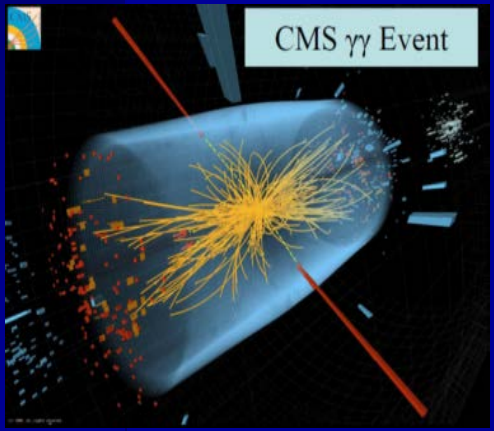
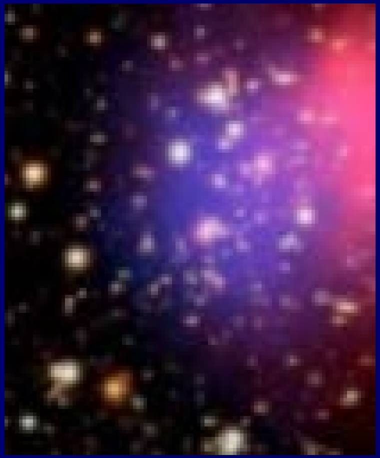
MultiHiggs Workshop, Lisbon, 9.09.2016

# The Inert Doublet Model and not only




Maria Krawczyk
University of Warsaw



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

# Inert Doublet Model (IDM) *Ma, ... '78* *Barbieri, '06*

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

Higgs & DM OK

- Evolution of Universe from EWs to Inert phase in one, two or three steps, with 1st or 2nd order phase transitions *(T2 evolution, Ginzburg ,.. PRD2010 )*
- Strong enough first-order phase transition needed for baryogenesis *(G. Gil Msc'2011, G.Gil, P.Chankowski, MK PL.B 2012); Chowdhury… Borah &Cline…*
- Metastability of vacua in IDM *(B. Świeżewska 2015)*
- IDM+complex singlet *Bonilla,DiazCruz,Sokołowska,Darvishi,MK'14*
- SM+complex singlet *Darvishi,MK'15 , Darvishi 2016(baryogenesis)*

# Higgs particle at LHC -summer 2016
## ATLAS+CMS Run 1 arXiv:1606.02266v1 [hep-ex] 7 Jun

## SM-like scenario observed

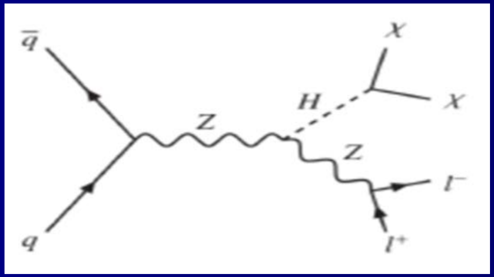
- Mass 125.09 ± 0.24 GeV   $ZZ \to 4\,l$, $\gamma\,\gamma$
- Total width < 23 MeV (95%CL); SM ~4 MeV
- Signal strengths $\mu = R = \sigma \times Br/(\sigma \times Br)|_{SM}$ ; SM = 1

  global 1.09 ± 0.11/0.10

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

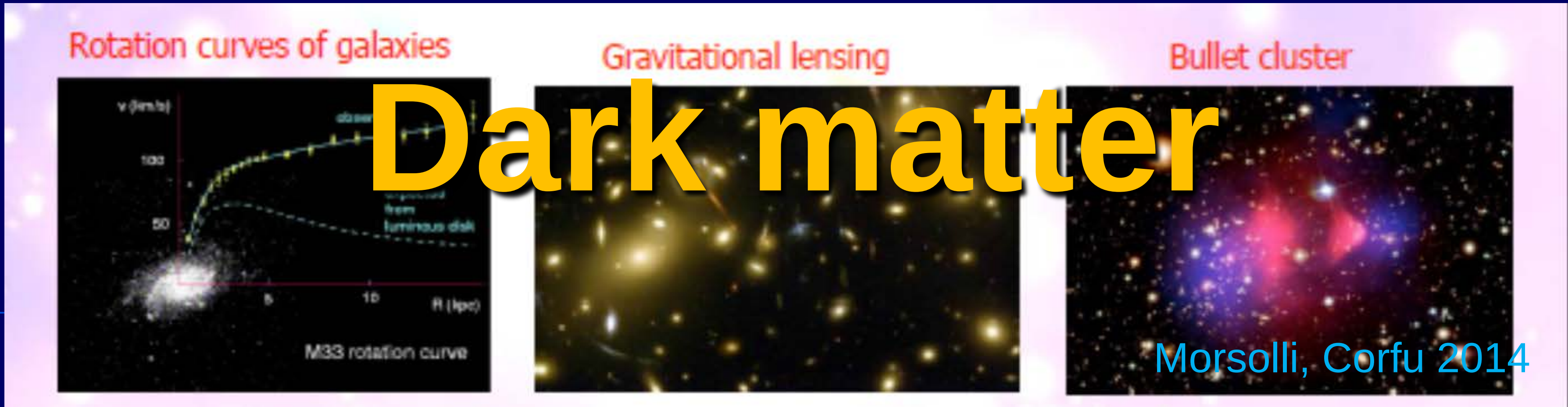
- Invisible decay

  BR < 0.34 (95% CL)




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

# Dark matter



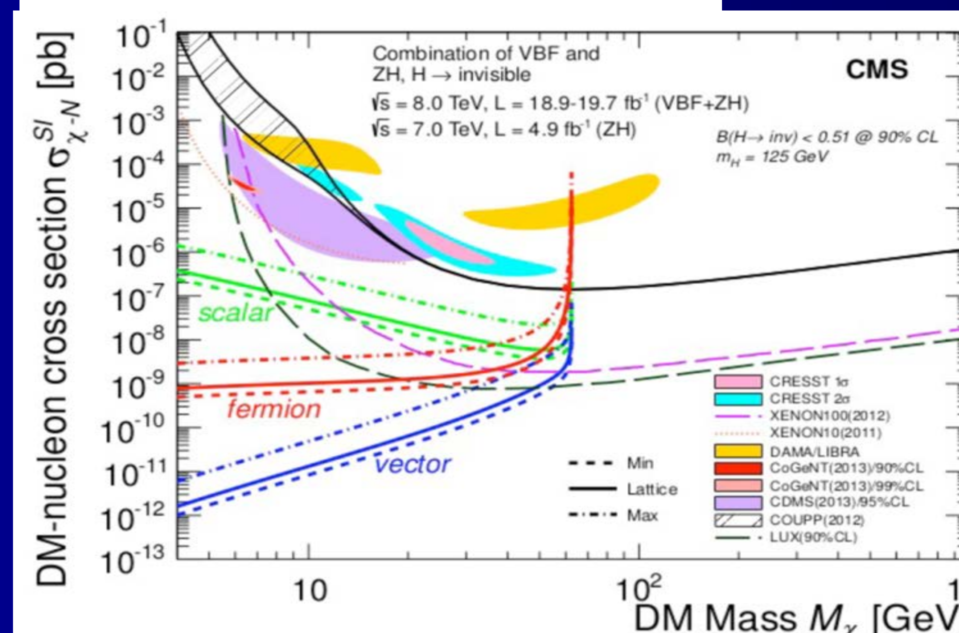

Relic DM density

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

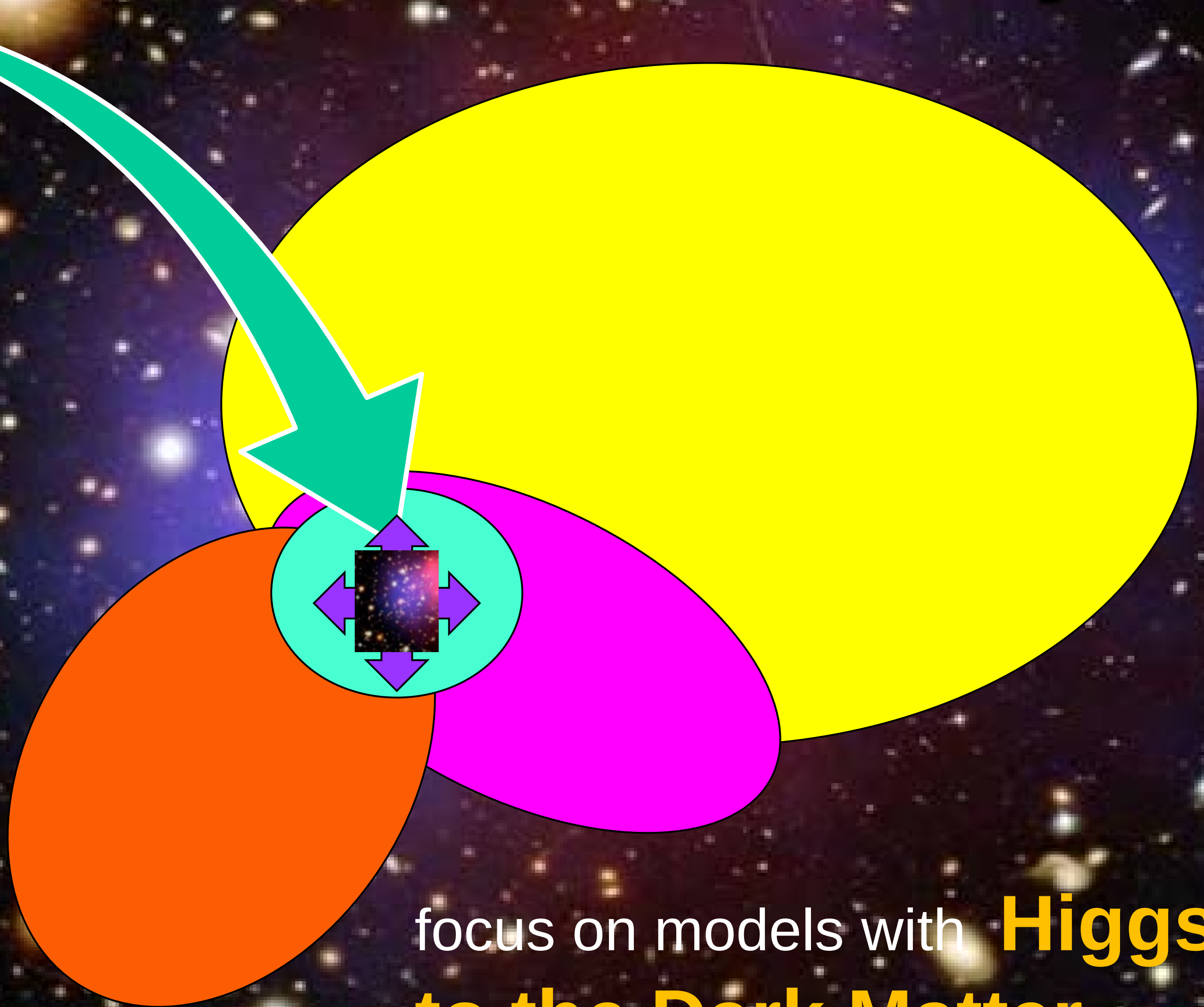
3 σ

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

Direct DM detection



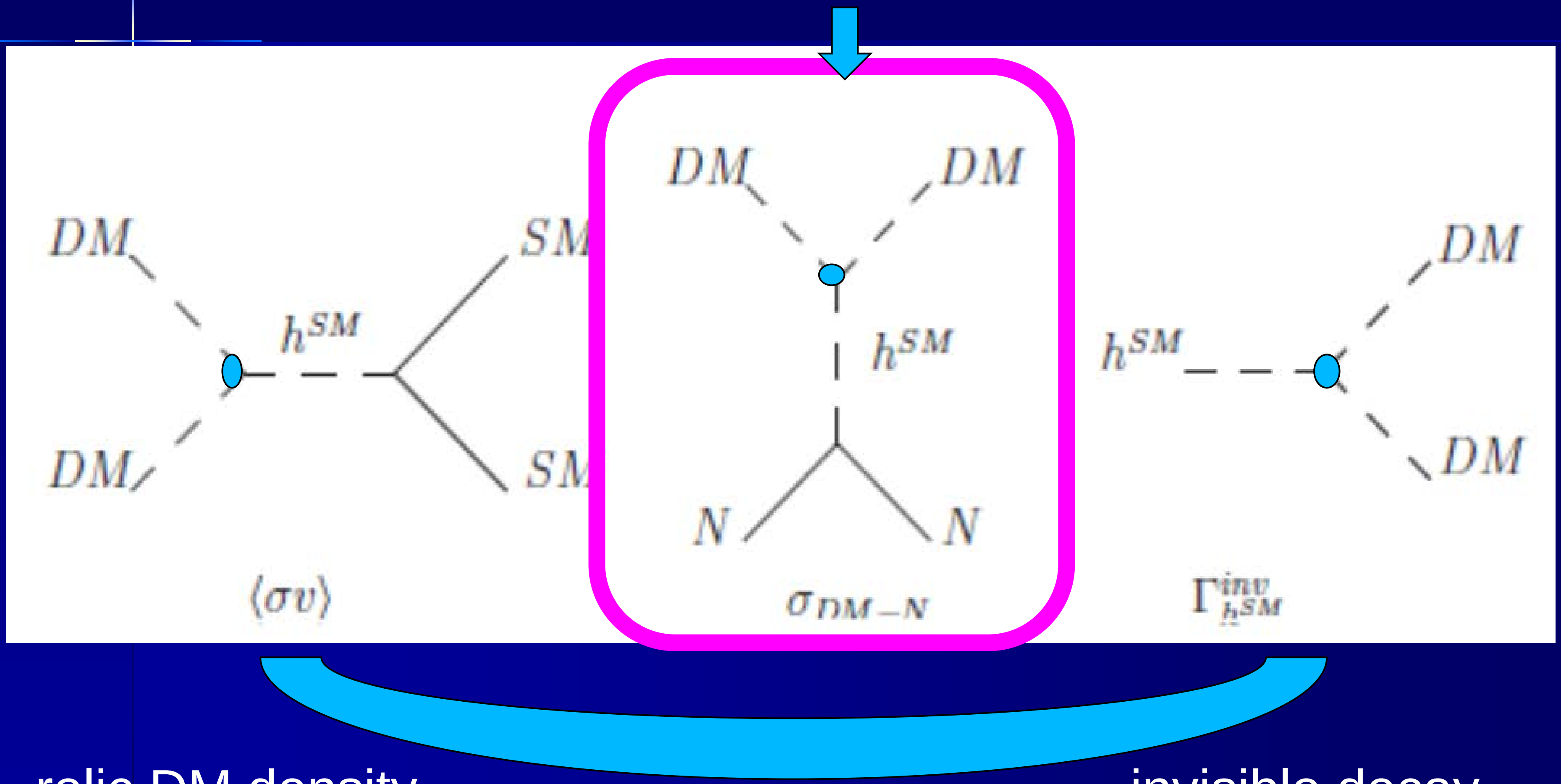
# SM - like scenario in many models



focus on models with **Higgs Portal to the Dark Matter**

# Higgs portal with the SM-like h

direct detection




relic DM density

invisible decay

*T.D. Lee 1973*
*CP violation*
*in scalar sector*

*Branco,Rebelo,Ferreira*
*Silva,Lavoura,Sher, Ma*
*Haber, Gunion, Grimus*
*Ginzburg, MK, Osland,*
*Grzadkowski, Ivanov*
*Nachtmann, Maniatis,*
*Pilaftsis,… Pich ..+*

# 2HDM's

symmetries

Potential

Vacuum

Yukawa

# Two Higgs Doublet Models

Two doublets of SU(2) (Y=1, $\rho$ =1) - $\Phi_1$ , $\Phi_2$

Masses for $W^{+/-}$, Z , no mass for photon?

Fermion masses via Yukawa interaction –
various models: Model I, II, III, IV,X,Y,...

5 scalars: 3 neutral and 2 charged

# $Z_2$ symmetric Lagrangian of 2HDM

*Branco, Rebelo ,85 (CP conserved)*

Potential V =

$$½\lambda_1(\Phi_1^\dagger\Phi_1)^2+½\lambda_2(\Phi_2^\dagger\Phi_2)^2 - ½m^2_{11}(\Phi_1^\dagger\Phi_1) - ½m^2_{22}(\Phi^\dagger\Phi_2)$$

$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+½[\lambda_5(\Phi_1^\dagger\Phi_2)^2+h.c]$$

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

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

Yukawa interaction

Model I – one doublet $\Phi_1$ 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) *Ma78,Velhinho,Santos,Barroso..94*

**$Z_2$ symmetry** $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$

new 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 | $v_D = 0$ |

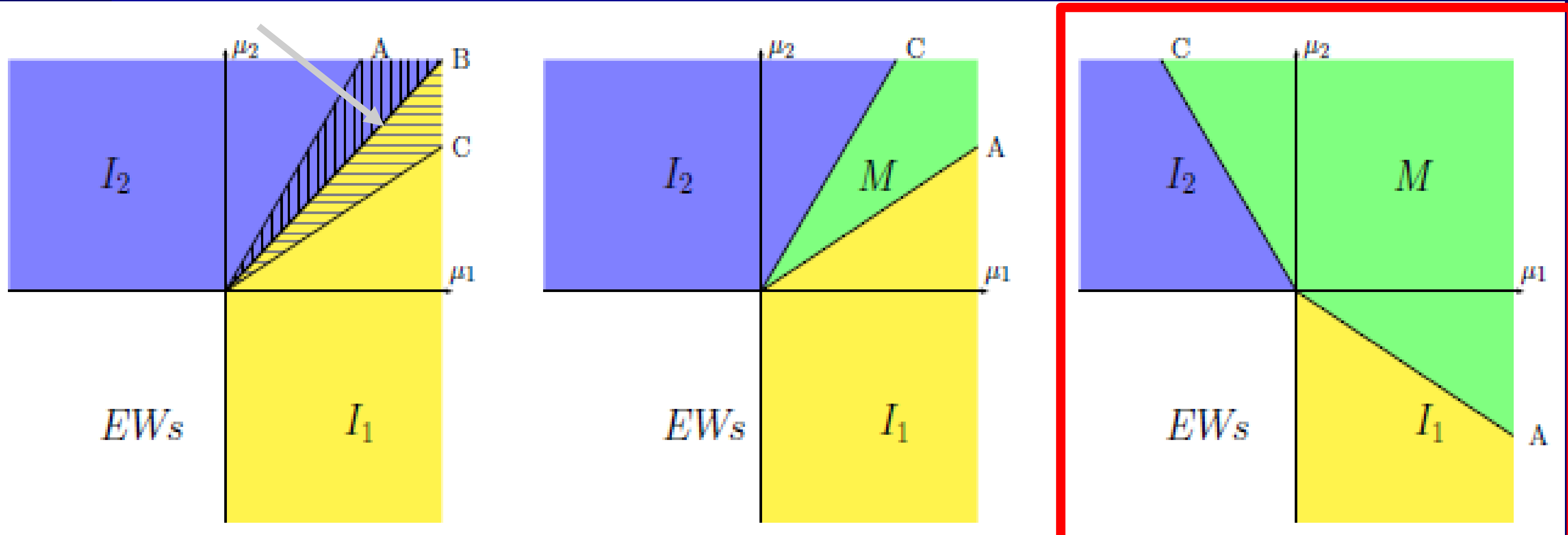
# Phase diagrams for D-sym. V

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

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

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

coexistence of
$I_1$ and $I_2$ minima




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

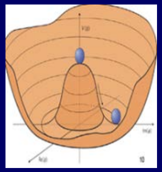
Inert ($I_1$) vacuum
for $M_h$=125 GeV → fixed $\mu_1$

here $\lambda_{345} < 0$ !

# Inert Doublet Model

*Ma,…'78*

$\Phi_S$ as in SM (BEH)



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

Higgs boson h (SM-like)

$\Phi_D$ – 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 $\Phi_S \to \Phi_S$ $\Phi_D \to -\Phi_D$ exact

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

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

*LHC phenomenology (Barbieri., Ma.. 2006,…)*

# Inert case - masses

- SM-like Higgs scalar h

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

- Dark particles D

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

$m_{22}^2$ arbitrary,

$\lambda_{345}$

so if large negative →

H,H+,A heavy, degenerate

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

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

H – dark matter

$\lambda_5 < 0$ and $\lambda_{45} < 0$

# Testing Inert Doublet Model

❖ Theoretical constraints

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

vacuum stability,

perturbative 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

❖ Study of dark scalars D = (**H**, A, H+,H-)

- 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 $\lambda_2$

Couplings with Higgs: hHH ~ $\lambda_{345}$ h H+H- ~ $\lambda_3$

# LHC – Higgs $H_{125}$ data → h (IDM)

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

Loop coupling to gg – as in SM

Loop coupling to **$\gamma\gamma$, $Z\gamma$** – extra H+ contribution

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

Invisible decay h → HH

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

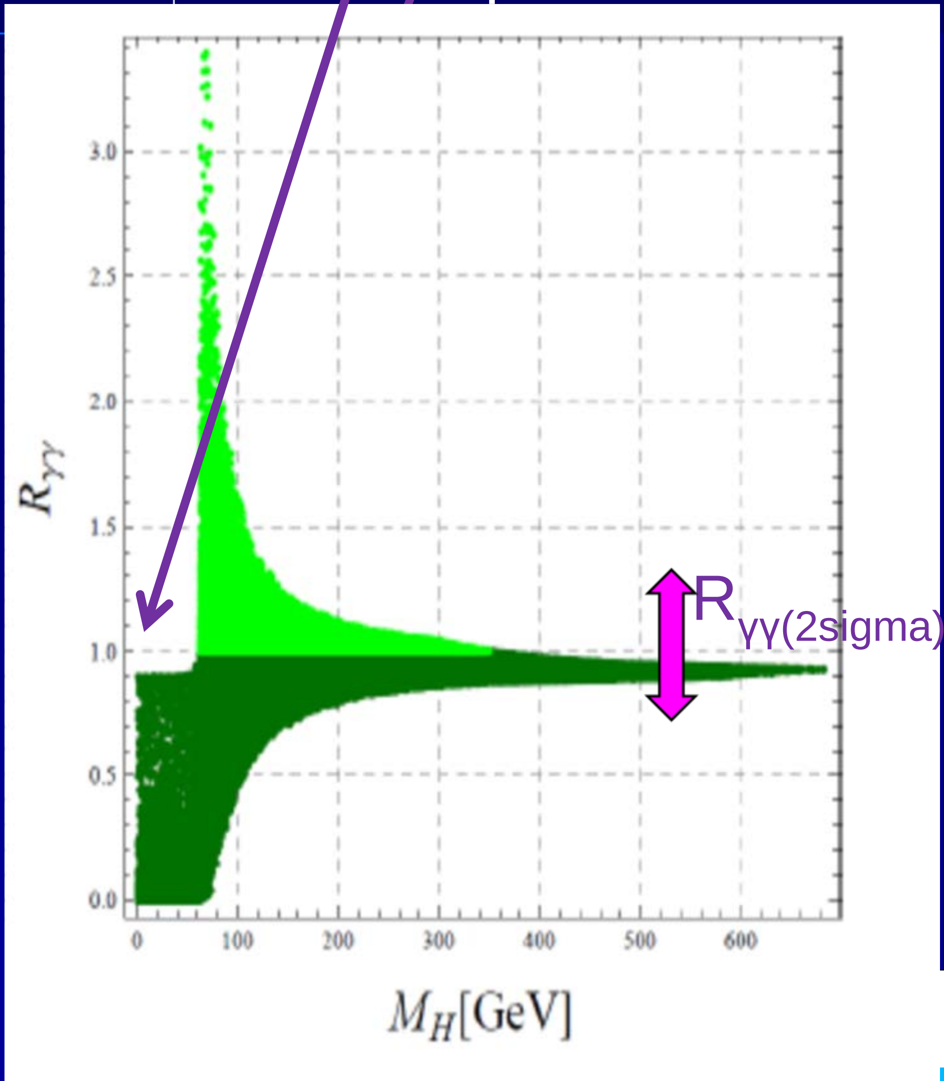
invisible decays important : $R_{\gamma\gamma} > 1$

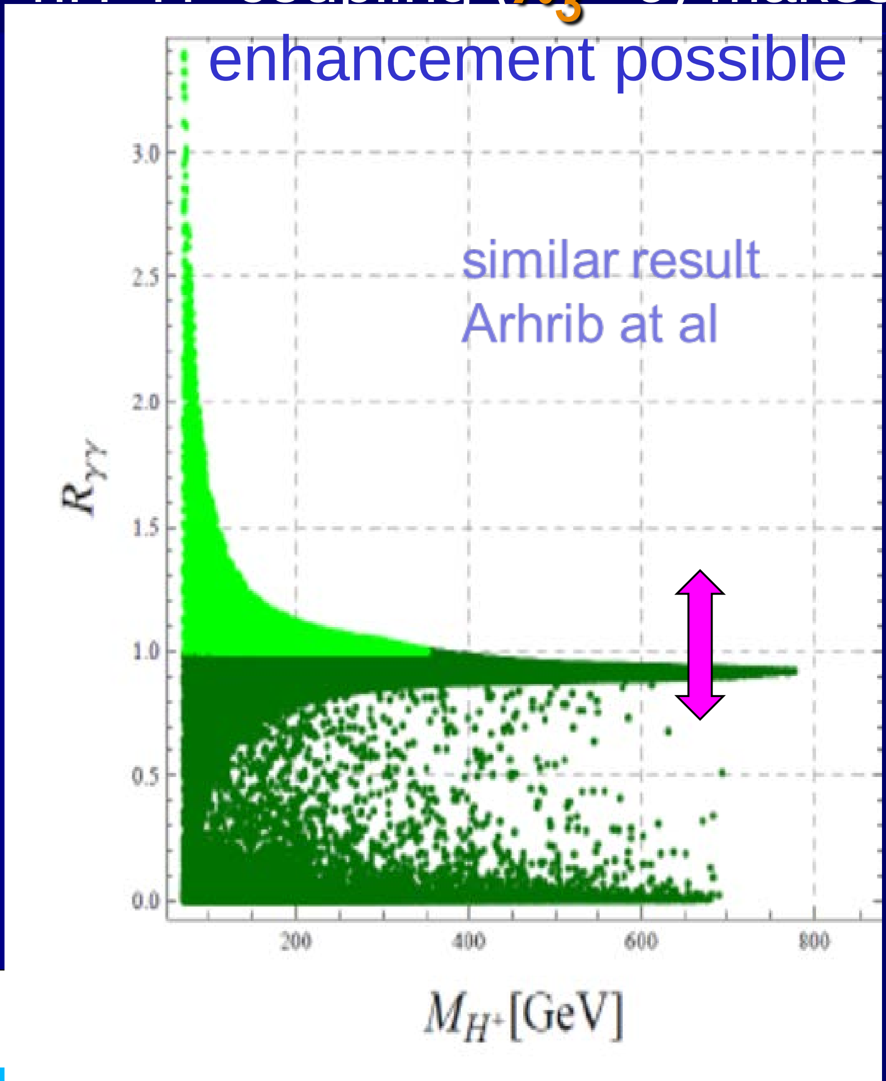
only if DM mass above 62.5 GeV

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

Invisible decays makes enhancement impossible

Light H+ with proper sign of hH+H- coupling ($\lambda_3$ <0) makes enhancement possible



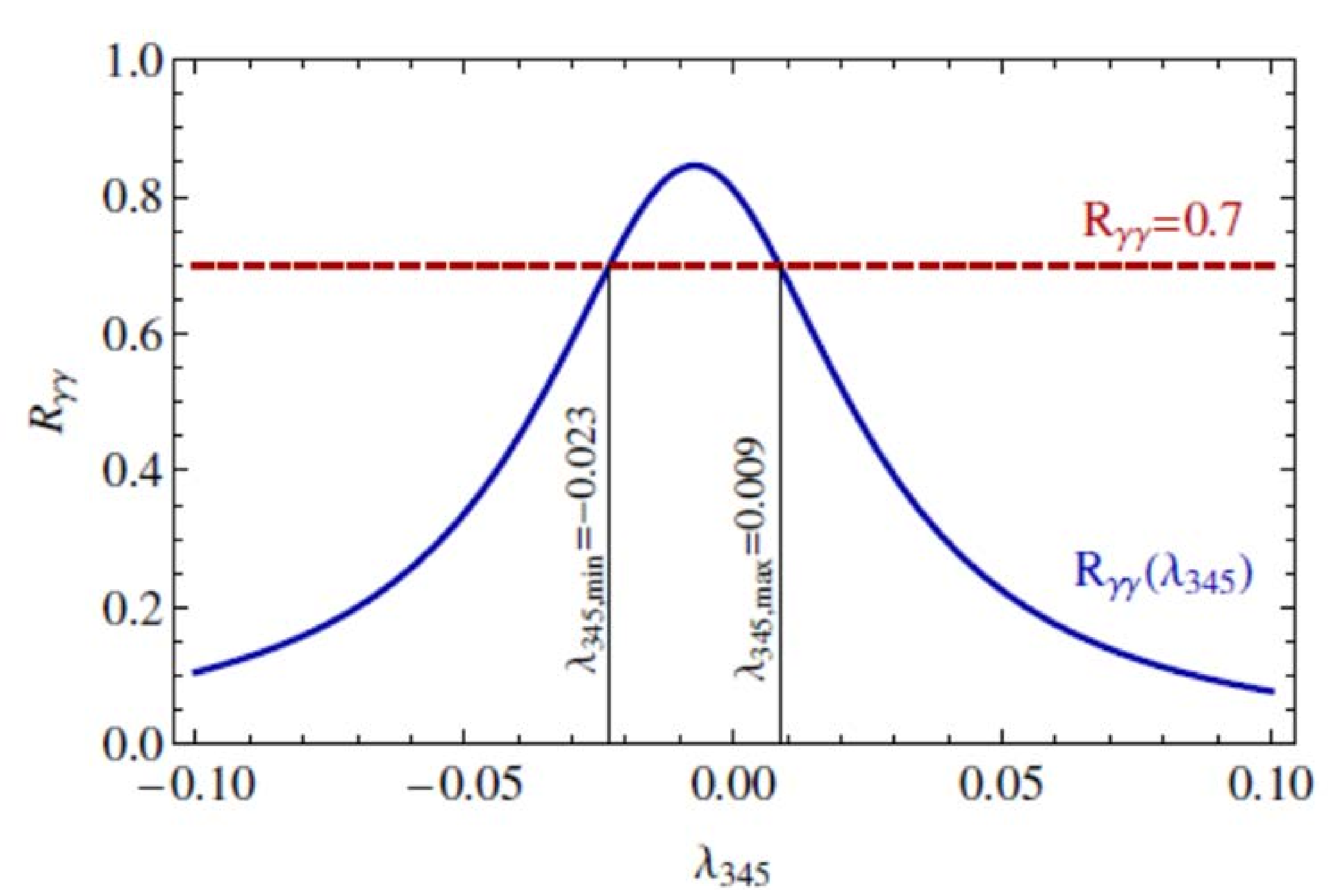



# Signal strength $R_{\gamma\gamma}$ if below 1 sensitive to hHH coupling

2013

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

CMS : $R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}$.

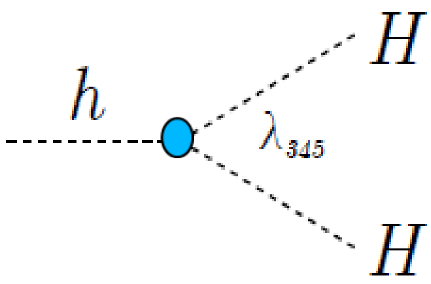



ATLAS+CMS 2016

**1.14 ± 0.19**

# Invisible h decay →coupling hHH

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

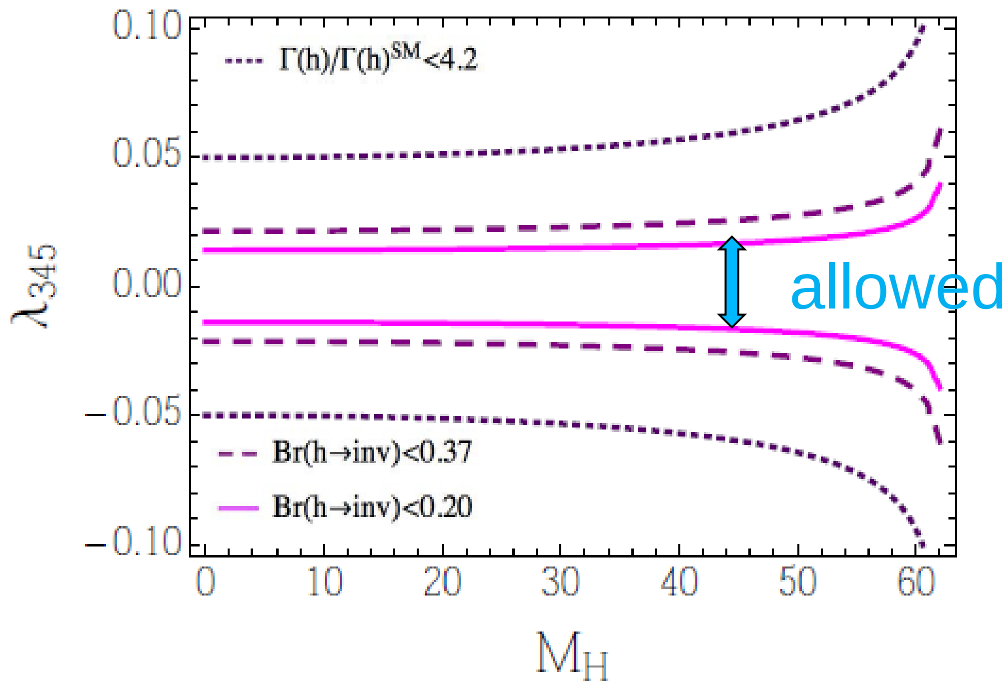



LHC:

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

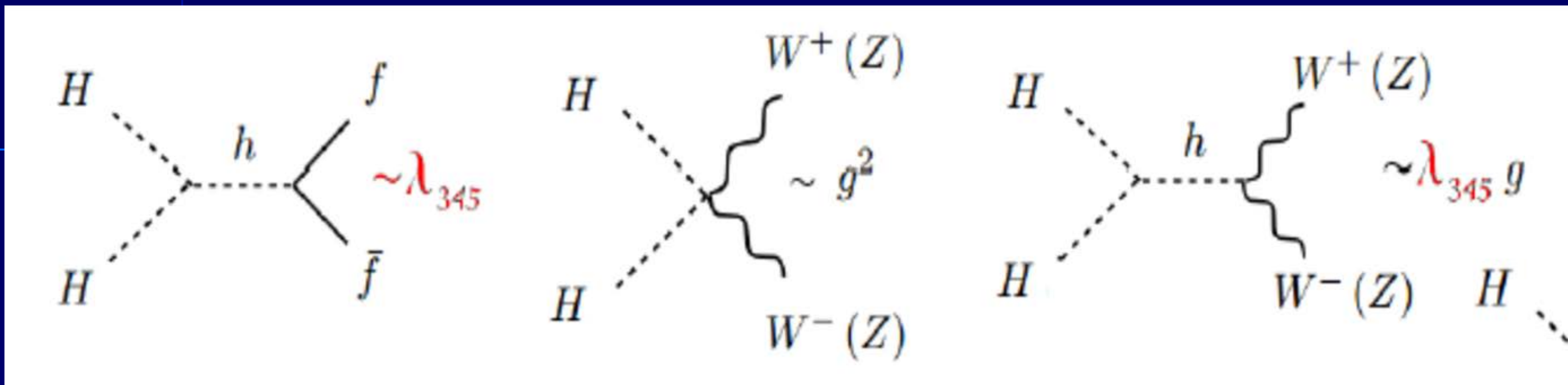
global fit:

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

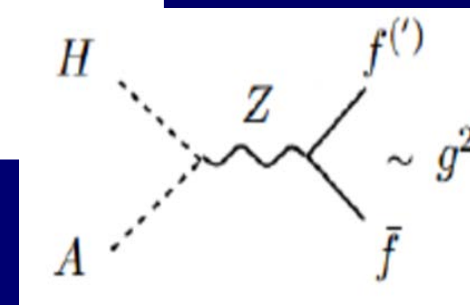



[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010, 2014, CMS-PAS-HIG-14-002]

# Relic DM density → H (IDM)




Coannihilation for small (AH) mass splitting ->

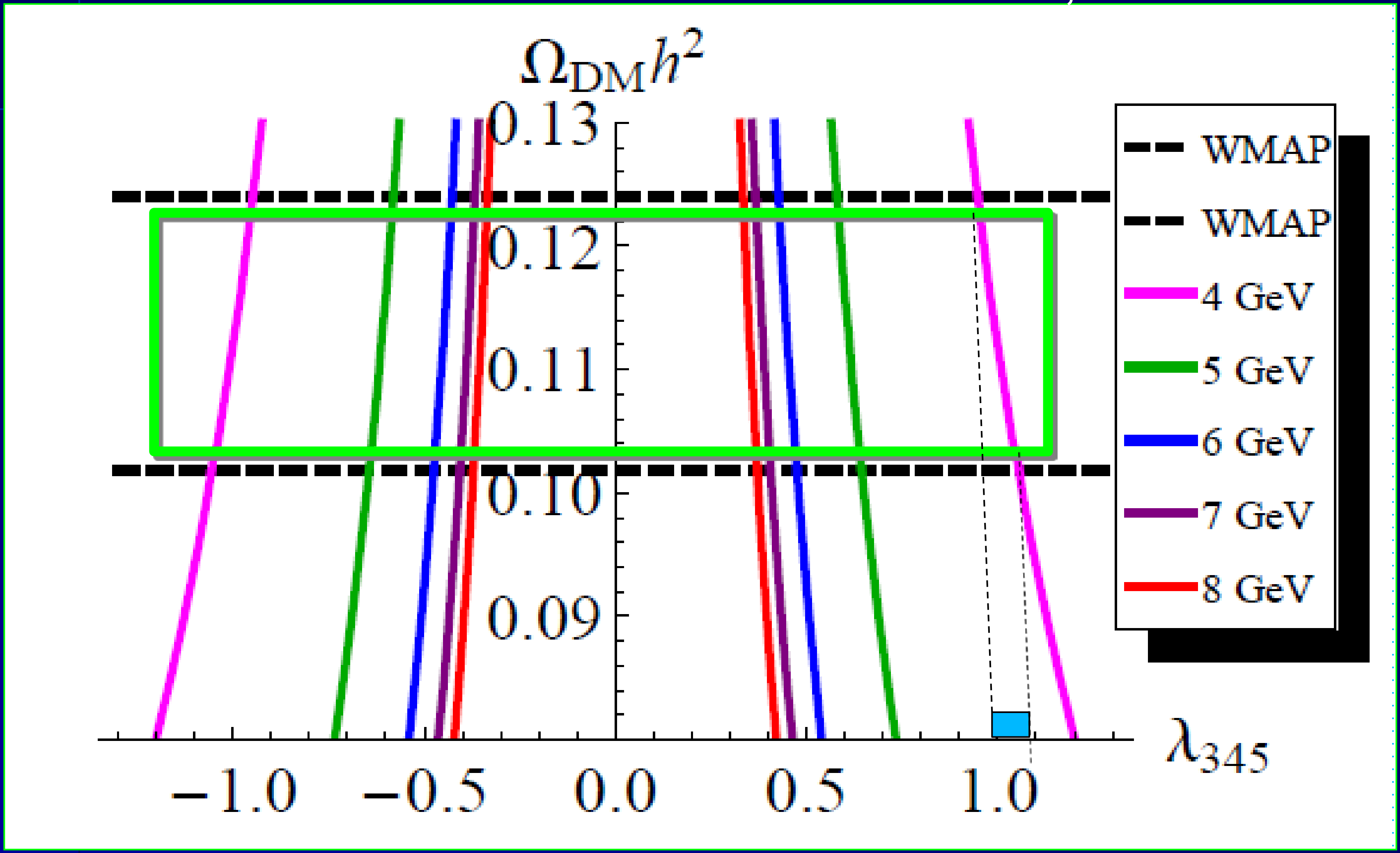



WMAP $\Omega_{DM} h^2 = 0.1126 \pm 0.0036.$

- 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)

D. Sokołowska, 2013

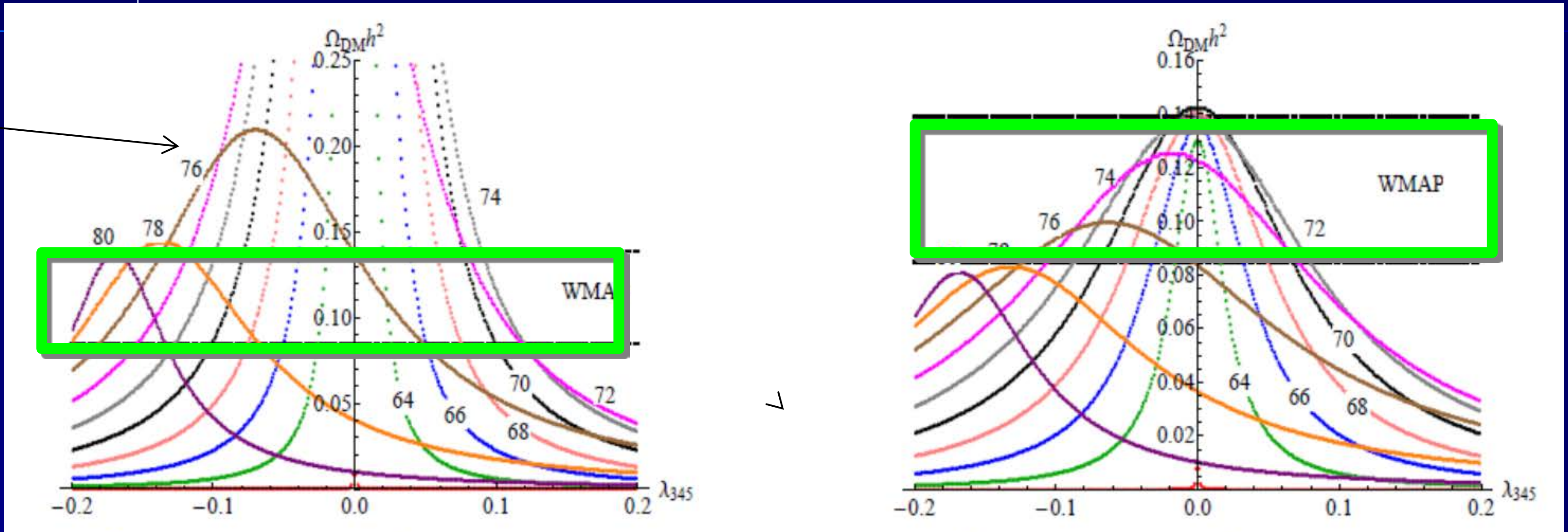



using MicrOmegas

# Relic density for DM with mass > 64 GeV

D. Sokołowska, 2013

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




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

above 76 GeV asymmetry due to annihilation to gauge bosons

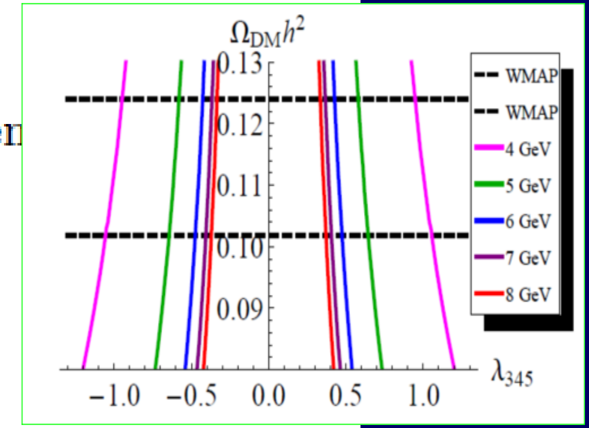
# Low mass H – excluded by LHC!

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

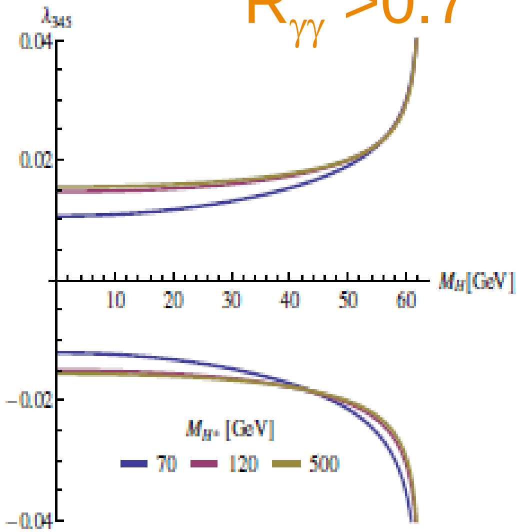
[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

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

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




$R_{\gamma\gamma}$ >0.7




- Proper relic density

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

- CDMS-II reported event:

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

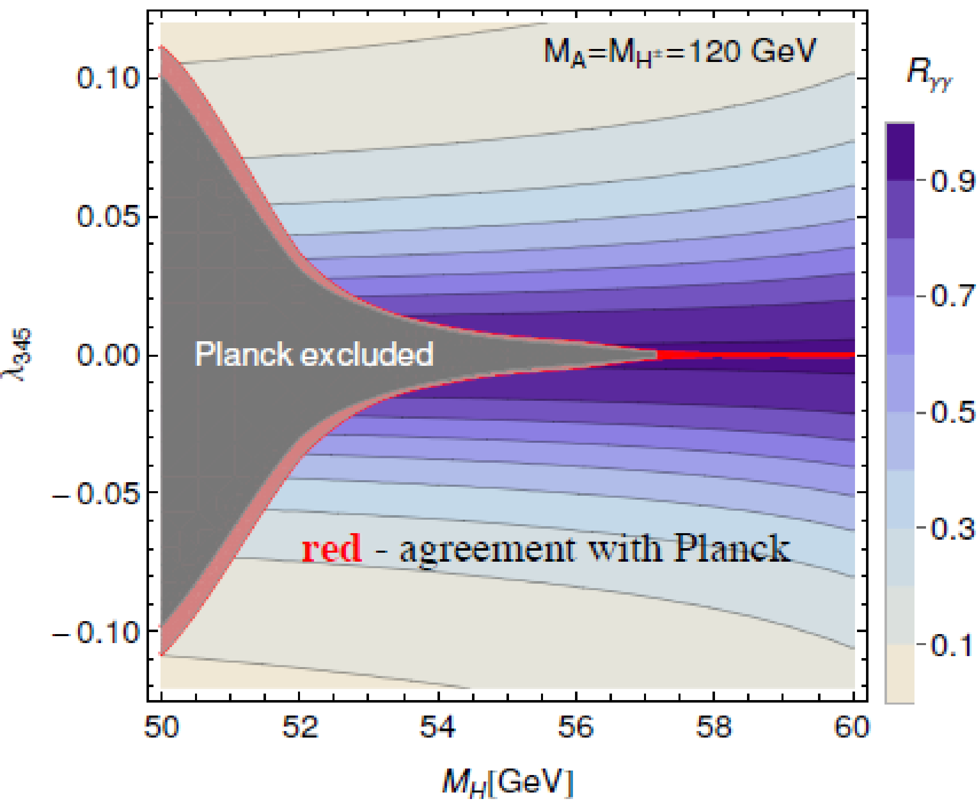
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$

Low DM mass excluded

# Using PLANCK data

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

$h \to HH$ open



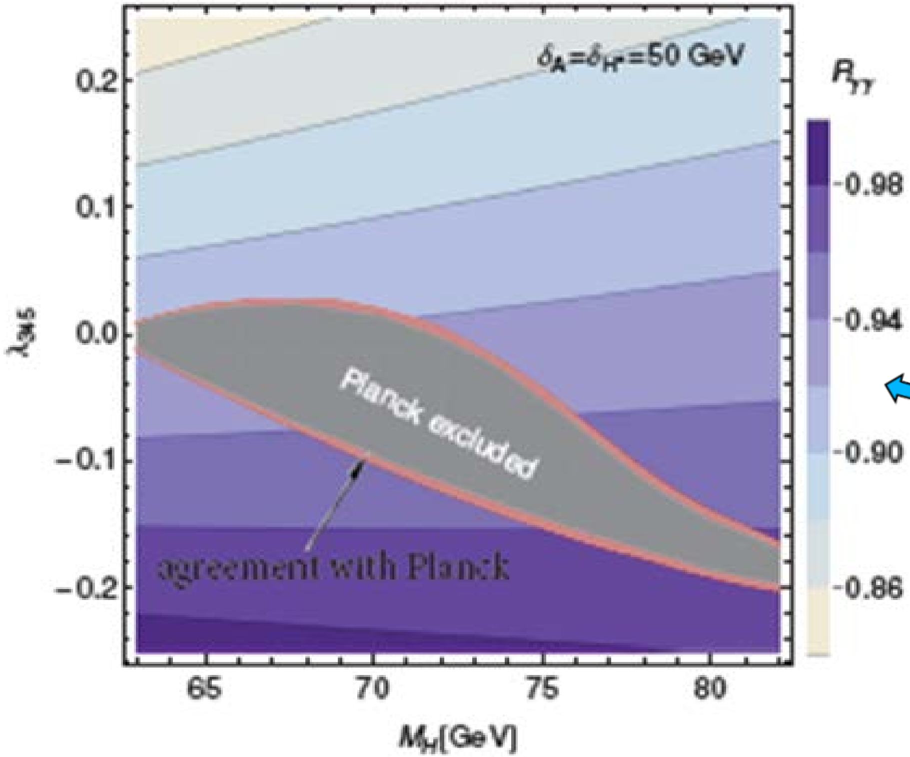

$50\,\mathrm{GeV} < M_H < M_h/2,\ M_A = M_{H^\pm} = 120\,\mathrm{GeV}$

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

# 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 (2015) → T. Robens

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

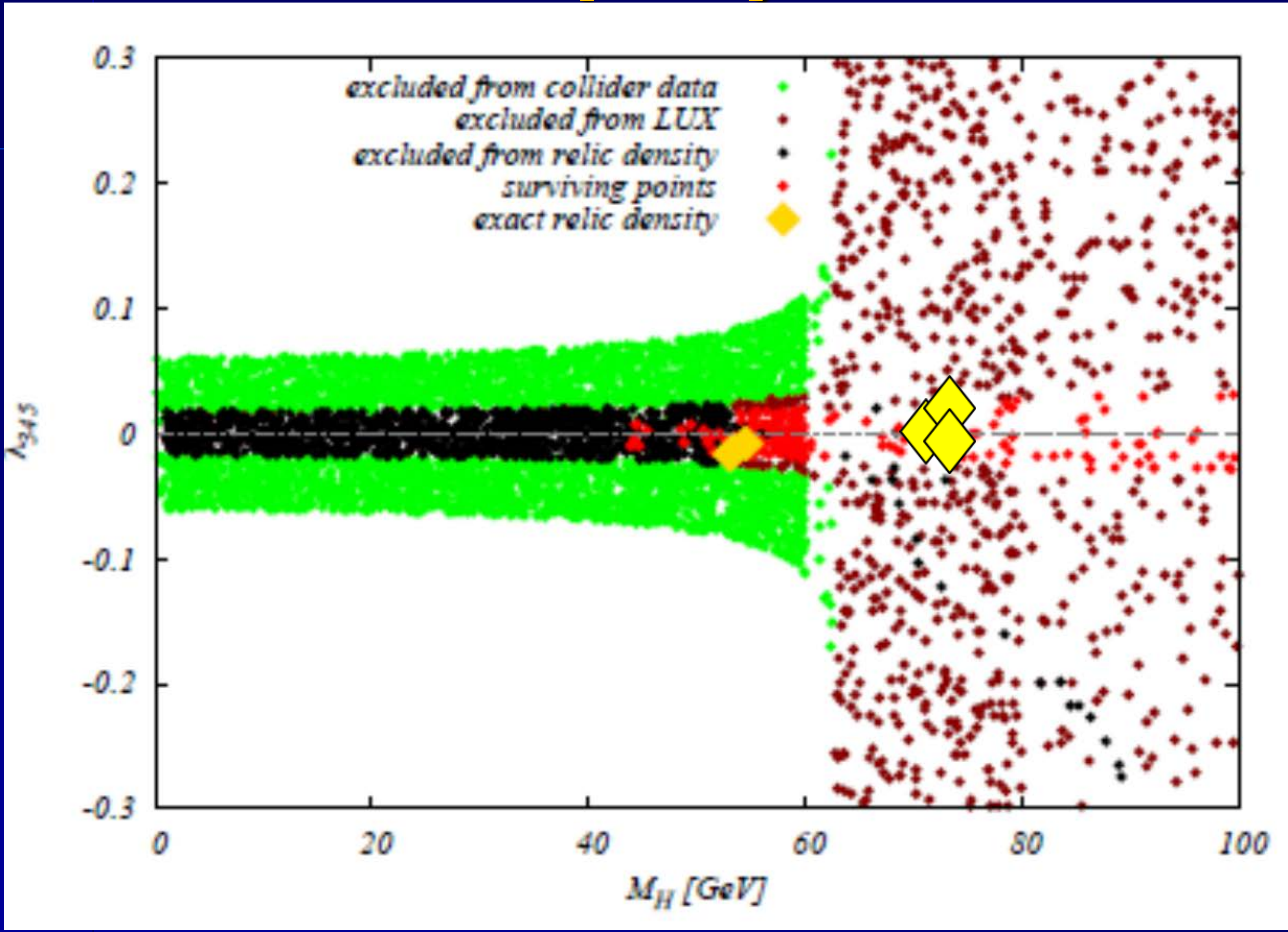
- Theor. constraints –
  stability of the potential (positivity), pert.unitarity, condition for the Inert vacuum
- STU (from 2014)
- Higgssignal/Higgs bounds
- Lifetime of H+ (< $10^{-7}$ s to decay inside detector)
- Relic density Planck **$\Omega$ < 0.1241** (95% CL)
- Direct detection LUX
- --> scan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

+LEP constraints
h total width
W/Z total width

*other analyses Stahl.., Blinov …Cline …Arhrib*

# Low mass H (DM)

1505.04734,1508.01671




exact relic density

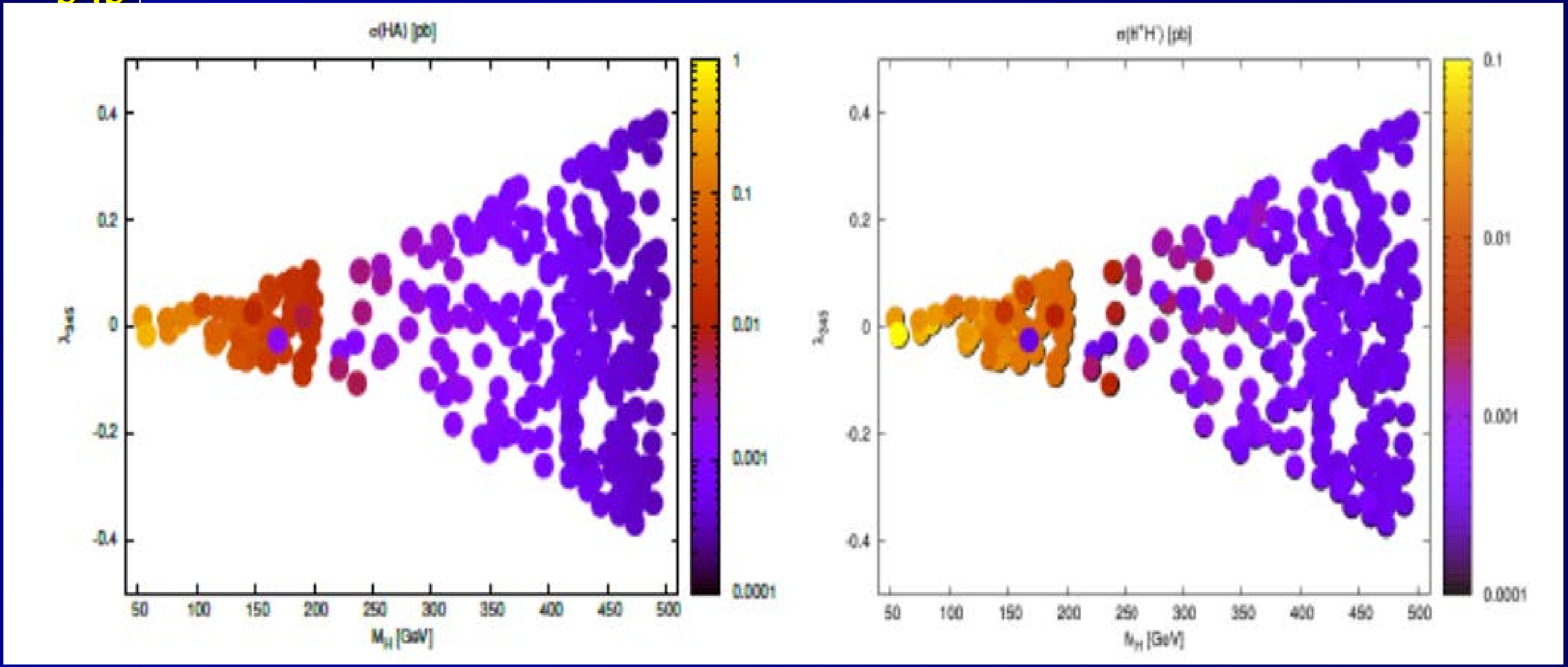
**Limit on mass of DM: $M_H$> 45 GeV !**

# Benchmarks for LHC II

$pp \to HA: \leq 0.03$ pb,
$pp \to H^{\pm}H: \leq 0.03$ pb,
$pp \to H^{\pm}A: \leq 0.015$ pb,
$pp \to H^{+}H^{-}: \leq 0.01$ pb,
$pp \to AA: \leq 0.0015$ pb.

→ T. Robens talk

$\lambda_{345}$ HA H+H-




$M_H$

Cross section in pb, mass in GeV

A → Z H = 100%

$MH^{+}$- MH > 100 MeV

# IDM at ILC/CLIC

S.Najjari, M.Hashemi, M.Krawczyk, AF. Zarnecki JHEP 1602 (2016) 187, arXiv:1512.01175

- $e^+e^- \to H^+H^-$
- $e^+e^- \to H\,A$

0.5 and 1 TeV for 500 fb$^{-1}$

Taking low mass benchmarks BP from our scan (difficult for LHC)

| BP | $m_H$ | $m_A$ | $m_{H\pm}$ |
|---|---|---|---|
| BP1 | 57.5 | 113 | 123 |
| BP2 | 85.5 | 111 | 140 |
| BP3 | 128 | 134 | 176 |

reconstruction of dark particle masses with accuracy 100 MeV possible

| | | | | |
|---|---|---|---|---|
| $m_{H\pm}$ | theo. | 123 | 140 | 176 |
| | 0.5 | $117.1 \pm 7.2$ | $136.8 \pm 10.0$ | $167.4 \pm 14.6$ |
| | 1 | $112.7 \pm 4.5$ | $131.4 \pm 5.0$ | $172.2 \pm 5.5$ |
| $m_H$ | theo. | 57.5 | 85.5 | 128 |
| | 0.5 | $58.5 \pm 3.6$ | $88.9 \pm 6.5$ | $127.2 \pm 9.5$ |
| | 1 | $53.0 \pm 2.1$ | $81.5 \pm 3.1$ | $129.1 \pm 1.2$ |
| $m_A$ | theo. | 113 | 111 | 134 |
| | 0.5 | $113.9 \pm 3.7$ | $114.3 \pm 6.6$ | $133.1 \pm 9.6$ |
| | 1 | $104.6 \pm 2.2$ | $105.0 \pm 3.2$ | $134.8 \pm 1.3$ |

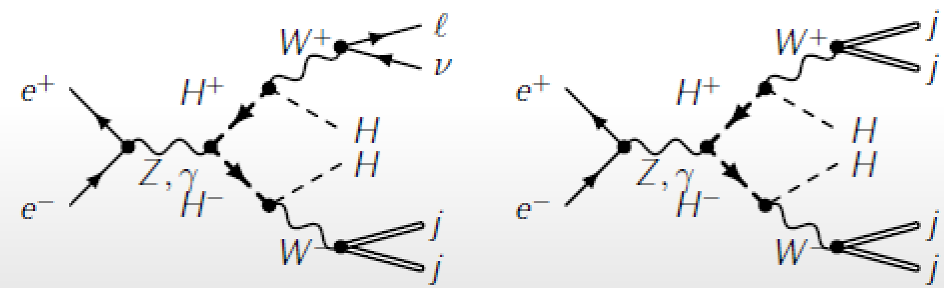
Main decays
H+→ W*+ H
A→ Z H

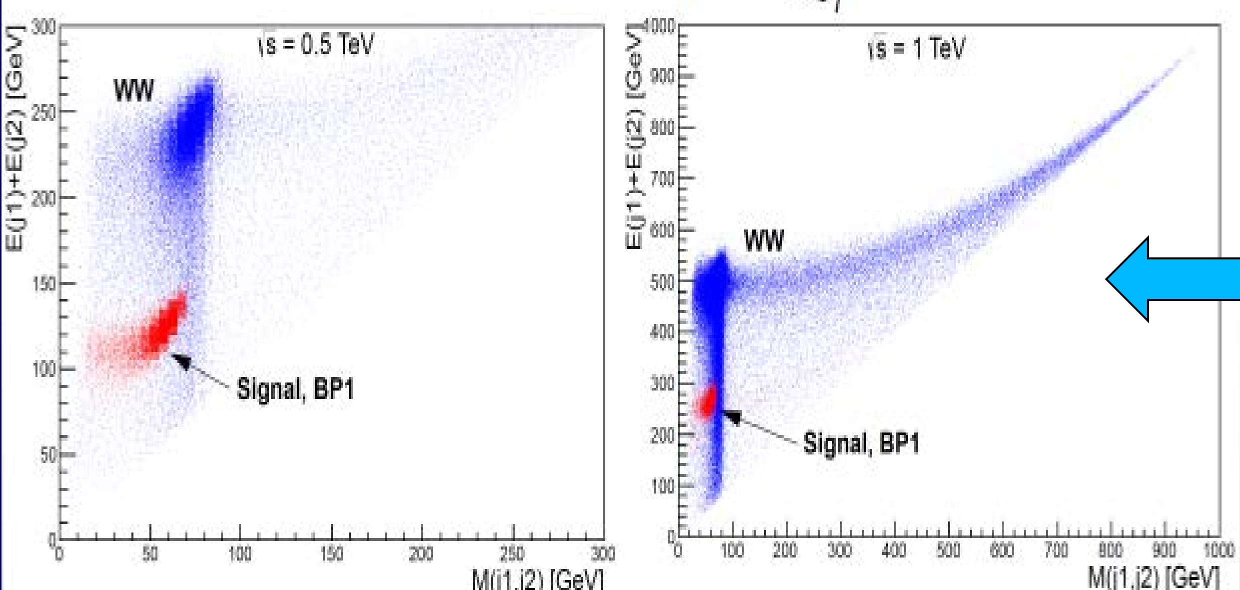
Also .. M. Aoki … PL B725 (2013) 302

Idea I. Ginzburg **J.Mod.Phys. 5 (2014) 1036**

# H+H-

| Process | Signal | | | Background | | | |
|---|---|---|---|---|---|---|---|
| | BP1 | BP2 | BP3 | WW | ZZ | Z+jets | $t\bar{t}$ |
| $\sigma$ [fb] @ 500 GeV | 82.2 | 70.9 | 44.6 | 7807 | 583 | 16790 | 595 |
| $\sigma$ [fb] @ 1 TeV | 28.1 | 27.3 | 25.3 | 3180 | 233 | 4304 | 212 |



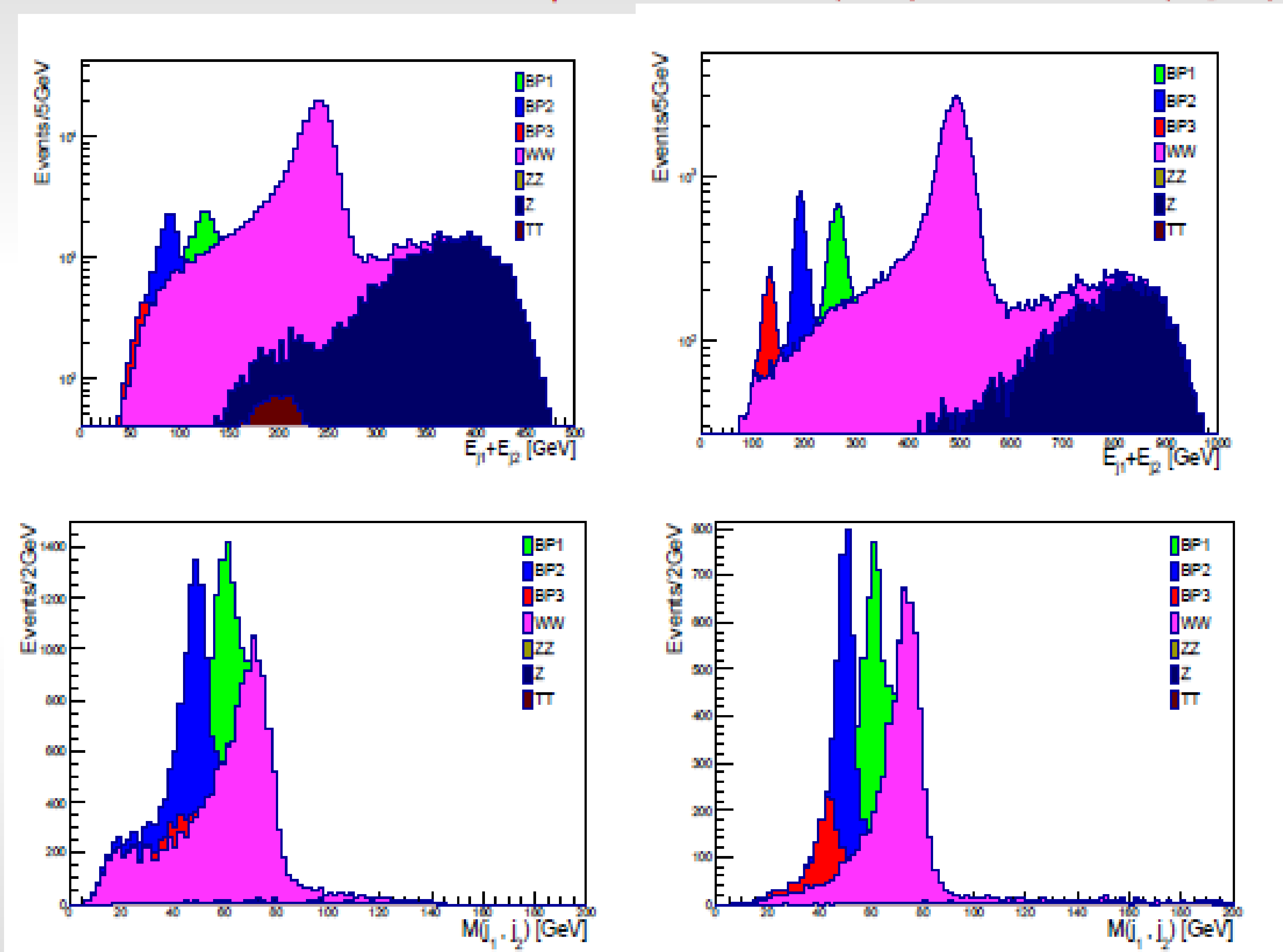




Sum of energies of two jets and their invariant mass for semileptonic events
→
cuts on sum of energies

background WW  dominated by on-shell W

# H+H-

Sum of the energies (up) and invariant mass (down) of two jets in semileptonic final state at $\sqrt{s} = 0.5$ TeV (left) and 1 TeV (right).

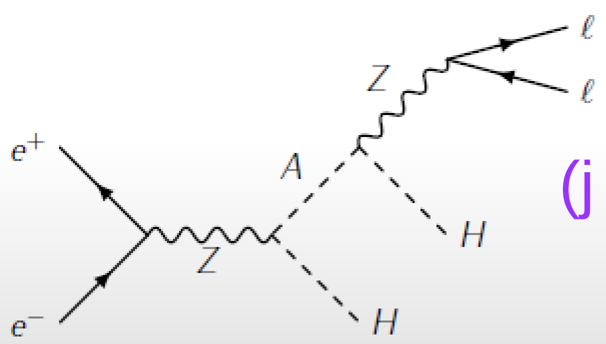



after aplying cuts on sum of energies

150(350) GeV

# HA

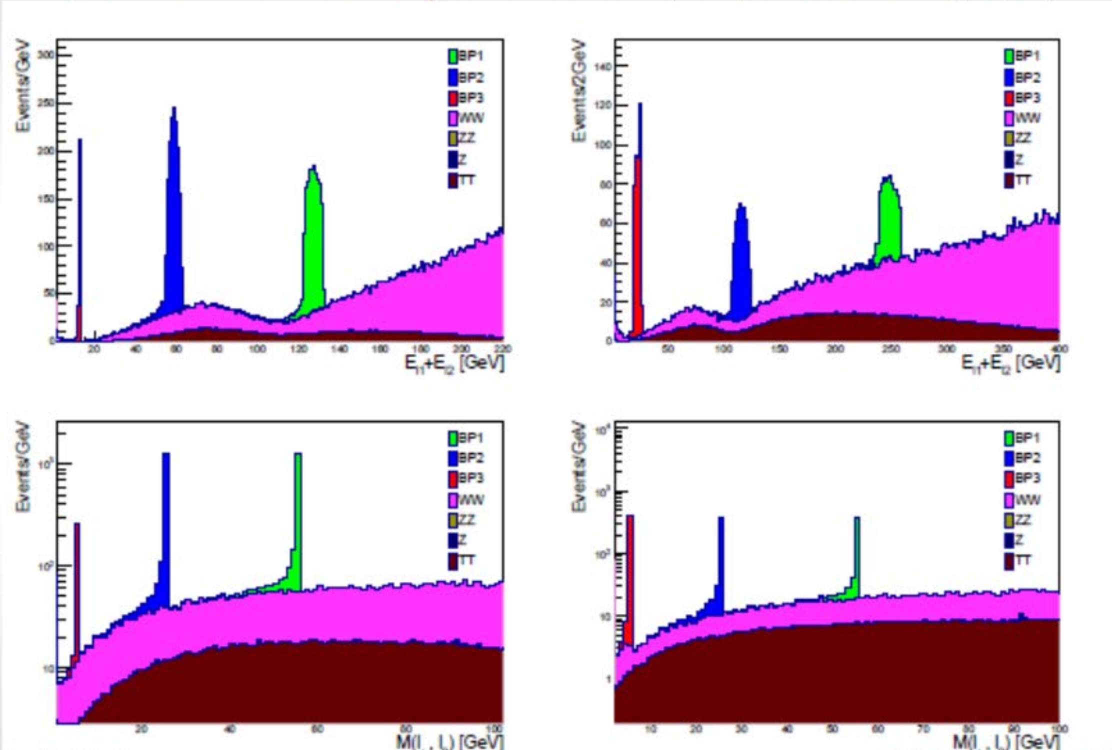
| | $\sqrt{s} = 0.5$ TeV | | | $\sqrt{s} = 1$ TeV | | |
|---|---|---|---|---|---|---|
| Process | $e^+e^- \to AH$ | | | $e^+e^- \to AH$ | | |
| Benchmark point | BP1 | BP2 | BP3 | BP1 | BP2 | BP3 |
| Cross section [fb] | 45 | 42.9 | 34.2 | 12.5 | 12.4 | 11.8 |




(j j)

Saereh Najjari

Sum of the energies (up) and invariant mass (down) of two lepton in leptonic final state at $\sqrt{s} = 0.5$ TeV (left) and 1 TeV (right).




Saereh Najjari

IDM @ Linear Colli

# IDMS Bonilla, Diaz-Cruz, Darvishi, Sokolowska, MK – J.Phys. G43 (2016) 065001

- IDM + extra neutral complex singlet $\chi$ with complex vev
- SM-like doublet - singlet interaction → CP violation in the scalar sector contaning 3 neutral Higgses: h1 (SM-like), h2, h3
- Dark doublet as before → H is good DM candidate
- Small modifications of h1 couplings to SM particles

# Potential IDMS

$\Phi_S$

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

$\Phi_D$

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

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

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

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

IDM

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

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

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

# Higgs sector – $h_1$(125 GeV), $h_2$, $h_3$

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

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

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

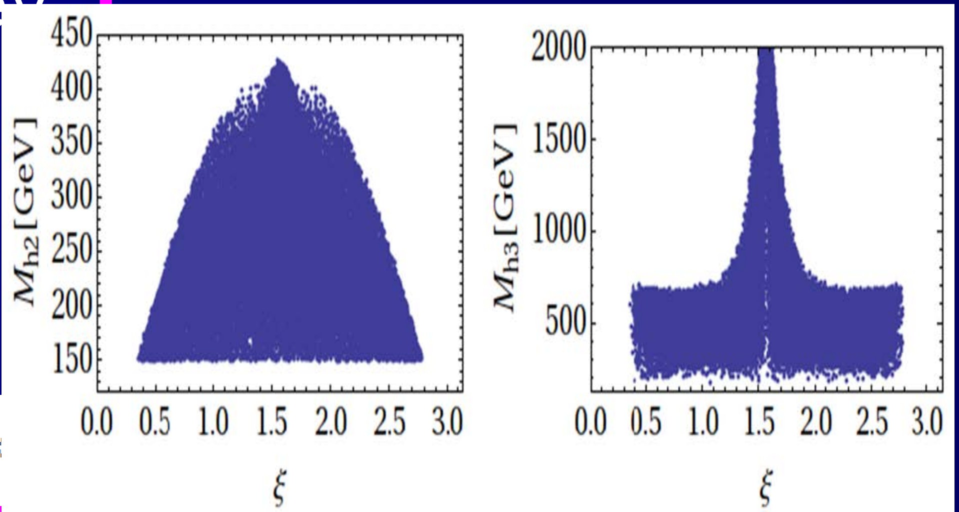
$$R_{11} = R^{-1}_{11} = c_1 c_2 \sim 1$$

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

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

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

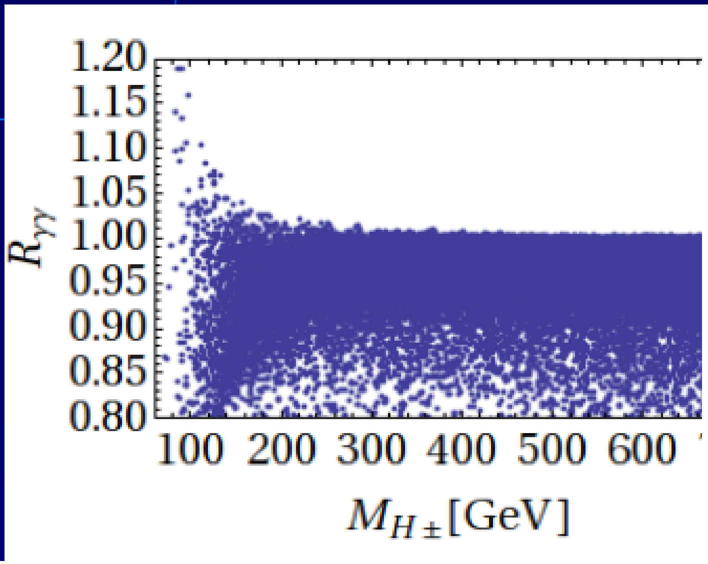
$$-1 < \Lambda_1 < 1, \quad 0 < \lambda_{s1} < 1, \quad -1 < \rho_{2,3} < 1, \quad 0 < \xi <$$

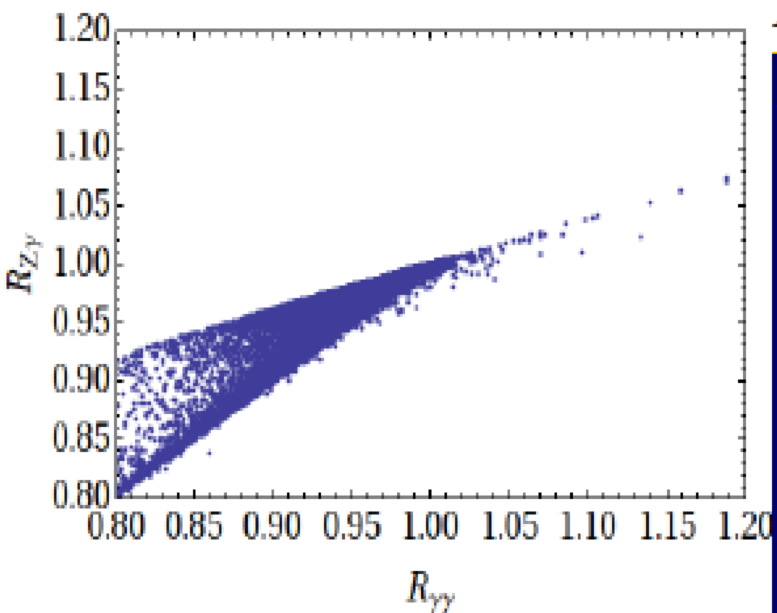


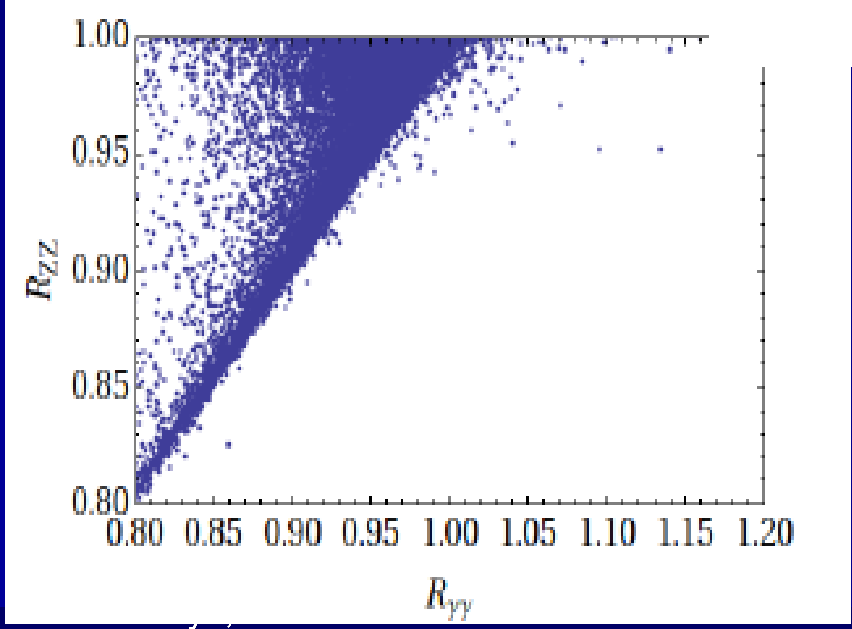
# IDMS - $h_1$(125 GeV)

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

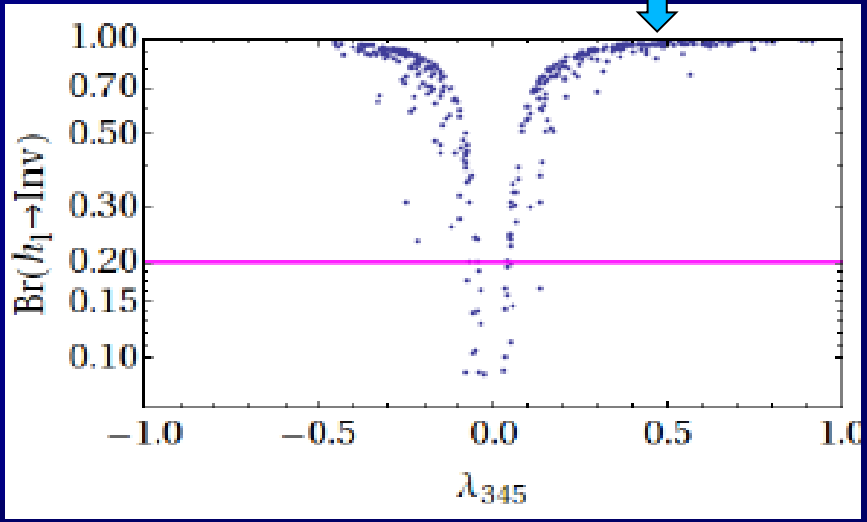
$$XX = gg, VV^*$$




**Br $h_1$ → inv**

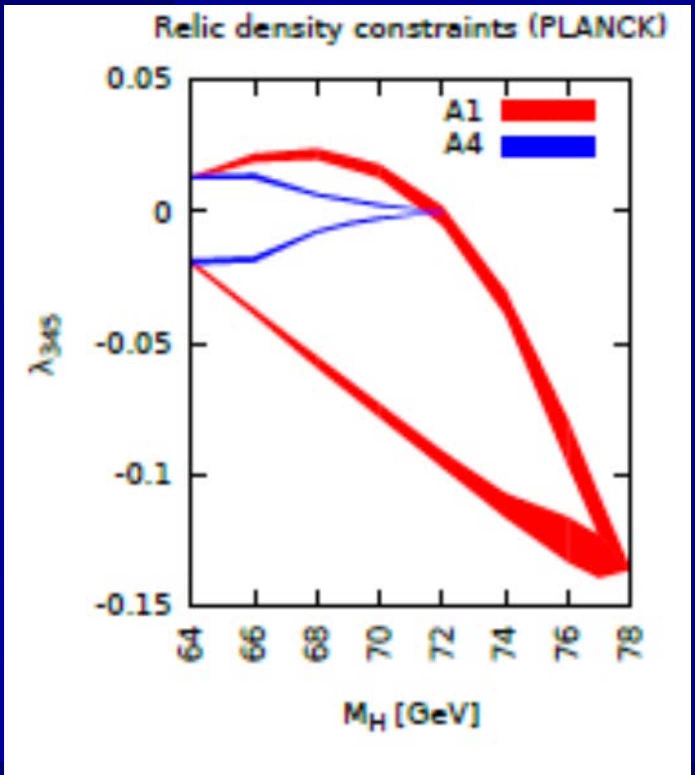


# Dark sector – Higgs portals via $h_1$, $h_2$, $h_3$ possible !

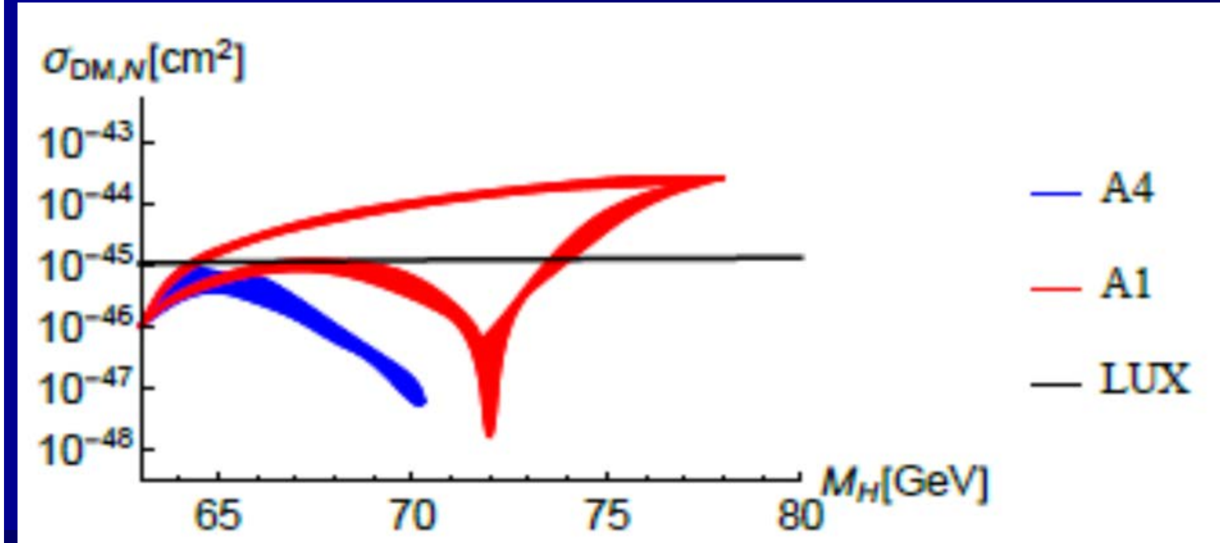
We proposed benchmarks – eg.

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

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




for A4 – Higgs portal via $h_2$



# Summary

- SM-like scenario – still valid (Sept. 2016)
- 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 + direct detection LUX data, $M_H > 45$ GeV
- Tests at LHC II , ILC/CLIC ?
- IDMS better ?
- Higgs is a sensitive probe of DM !

# SM+complex singlet

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

- Model
- Spontaneous CP violation
- Strong 1st order phase transition
- Baryogenesis with vector-like quarks (iso-doublet)

*Darvishi, 1608.02820*

# CP violation in the Standard Model with a complex singlet

## Constrained Potential

SM+CS → cSMCS

N, Darvishi,MK

$$V = -\frac{1}{2}m_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda\left(\Phi^\dagger\Phi\right)^2 - \frac{m_s^2}{2}\chi^*\chi + \lambda_s(\chi^*\chi)^2 + \Lambda(\Phi^\dagger\Phi)(\chi^*\chi)$$

$$-\frac{m_4^2}{2}(\chi^{*2}+\chi^2) + \kappa_2(\chi^3+\chi^{*3}) + \kappa_3[\chi(\chi^*\chi)+\chi^*(\chi^*\chi)] + \kappa_4\Phi^\dagger\Phi(\chi+\chi)$$

- Parameters → $m_{11}^2,\ m_s^2,\ m_4^2,\ \lambda_s,\ \lambda,\ \Lambda,\ \kappa_2,\ \kappa_3,\ \kappa_4$.
  If real → No explicit CP violation
- Vacua with spontaneous CP violation
  $\langle\Phi\rangle = \frac{1}{\sqrt{2}}v$ and $\langle\chi\rangle = \frac{1}{\sqrt{2}}we^{i\xi}$
- Spontaneous CP violation → relevant parameters $m_4^2,\ \kappa_2,\ \kappa_3\ \kappa_4$
- Positivity conditions

$$\lambda > 0, \qquad \lambda_s > 0, \qquad \Lambda + \sqrt{2\lambda\lambda_s} > 0.$$

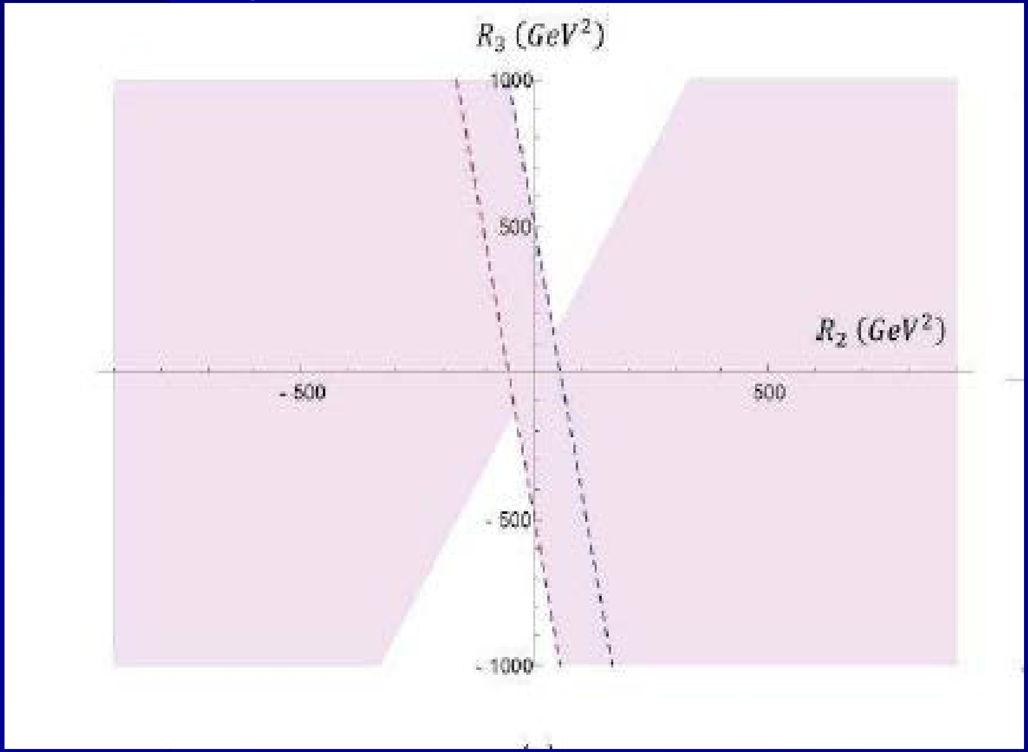
*similar study*
*Branco …98*

# Region of spont. CP violation

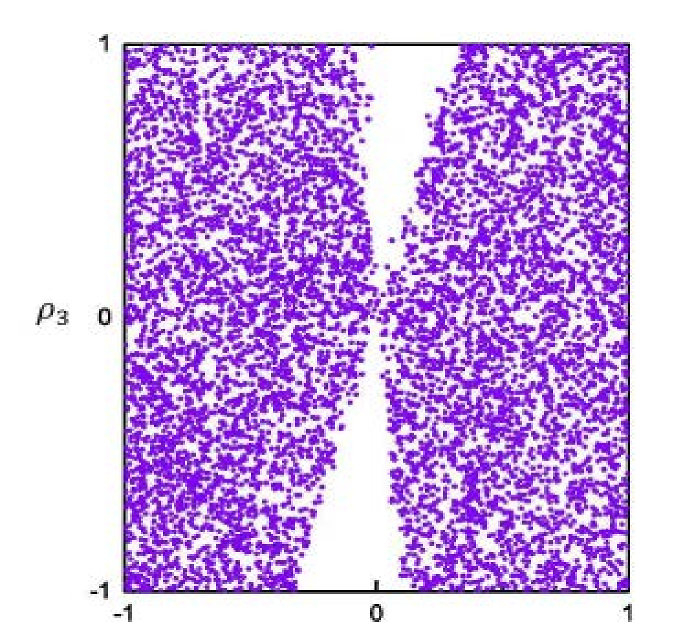
$$-4m_4^2\cos\xi + 3R_2(1+2\cos 2\xi) + R_3 + R_4 = 0,$$

$$R_2 = \sqrt{2}w\kappa_2,\ R_3 = \sqrt{2}w\kappa_3,\ R_4 = \frac{\sqrt{2}v^2\kappa_4}{w},$$

for $\kappa_4 = 0$




full scan



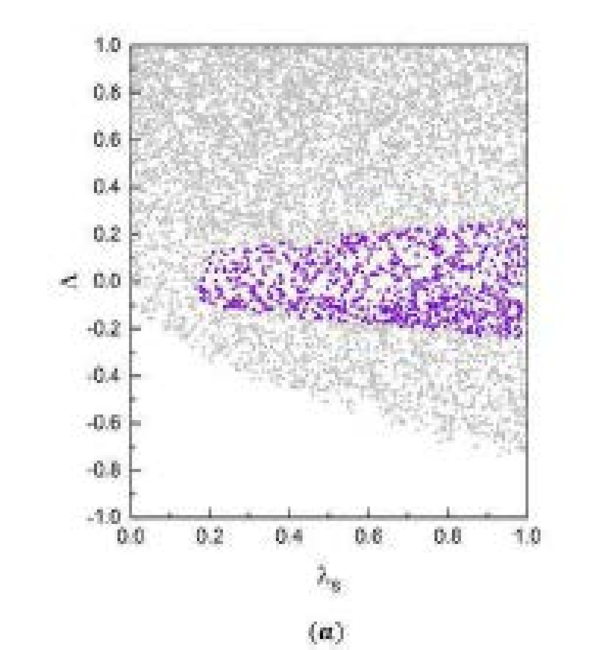
# Scan – similar to IDMS but here low < χ > ~ w possible

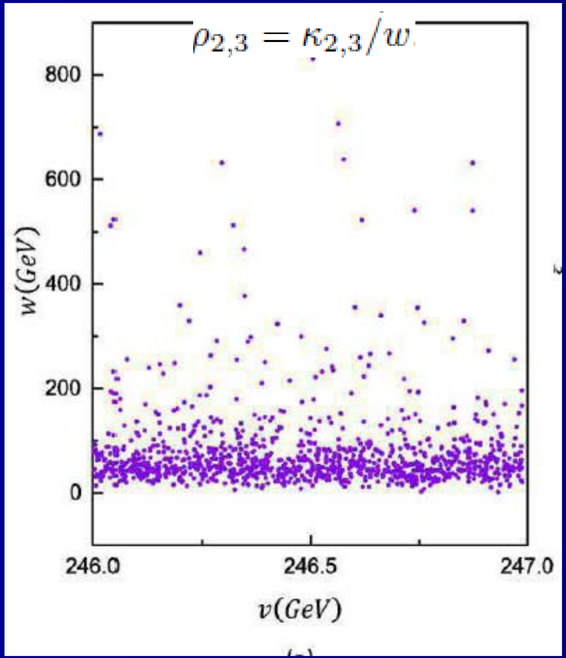
$M_{h_1} \in [124.00, 127.00]$ GeV, $M_{h_3} \gtrsim M_{h_2} > 150$ GeV

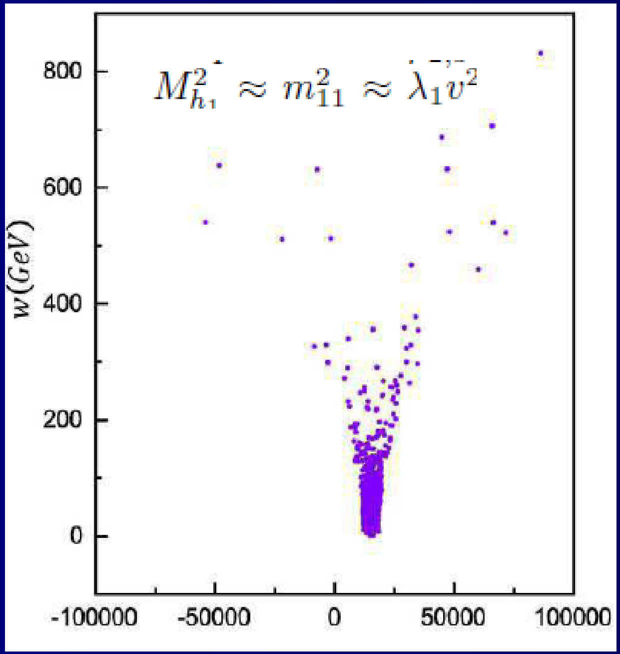
$0.2 < \lambda_1 < 0.3$

$-1 < \Lambda < 1,\ 0 < \lambda_s < 1,\ -1 < \rho_{2,3} < 1,\ 0 < \xi < \pi,$

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



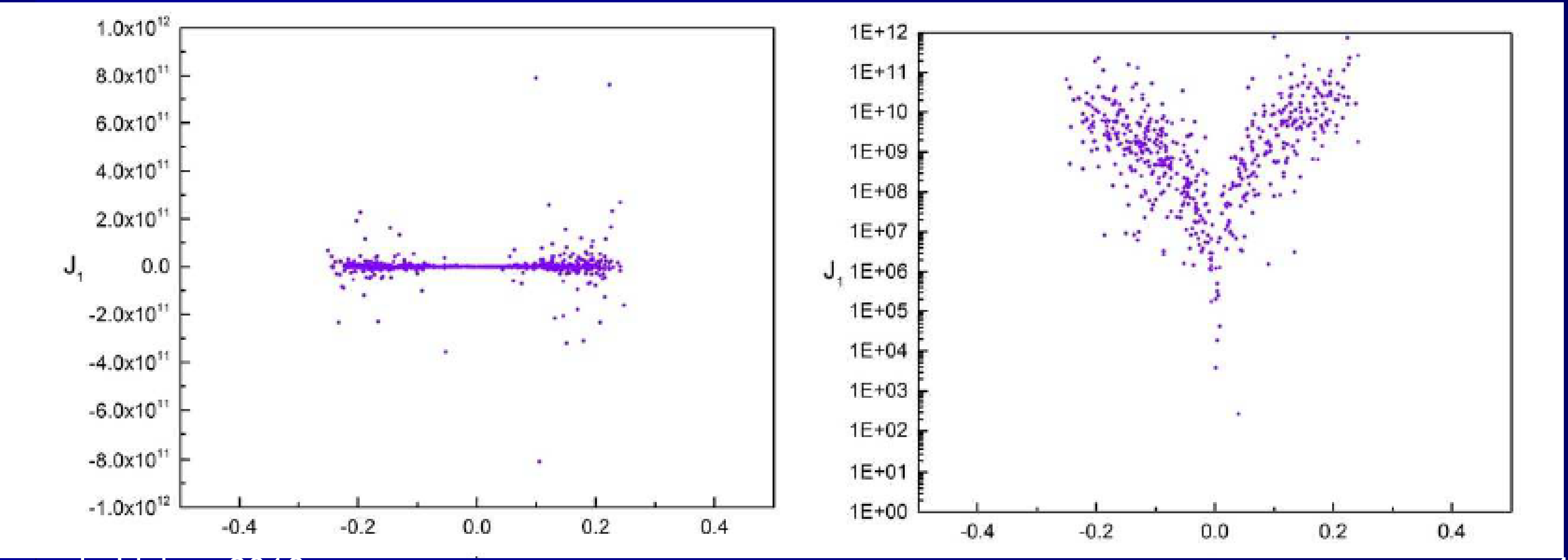
# J invariant

$$J_1 = M_{12}M_{13}(M_{22} - M_{33}) + M_{23}(M_{13}^2 - M_{12}^2),$$

$$J_1 = 2\Lambda^2 v^2 w^2 m_4^2 \sin\xi\cos\xi = 2\Lambda^2 v^2 w_1 w_2 m_4^2$$

where $$-4m_4^2\cos\xi + 3R_2(1 + 2\cos 2\xi) + R_3 + R_4 = 0,$$

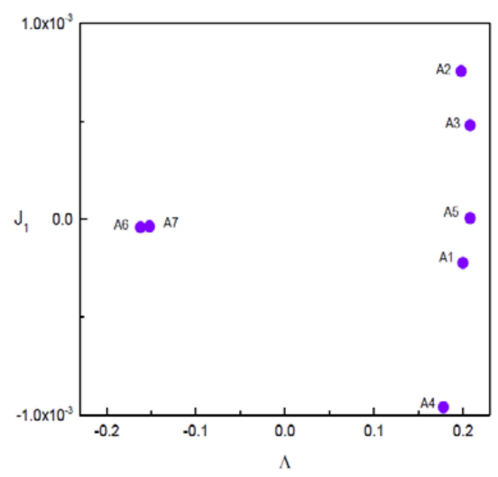
$R_{2,3,4} \sim w\,\kappa_{2,3,4}$



# Benchmarks

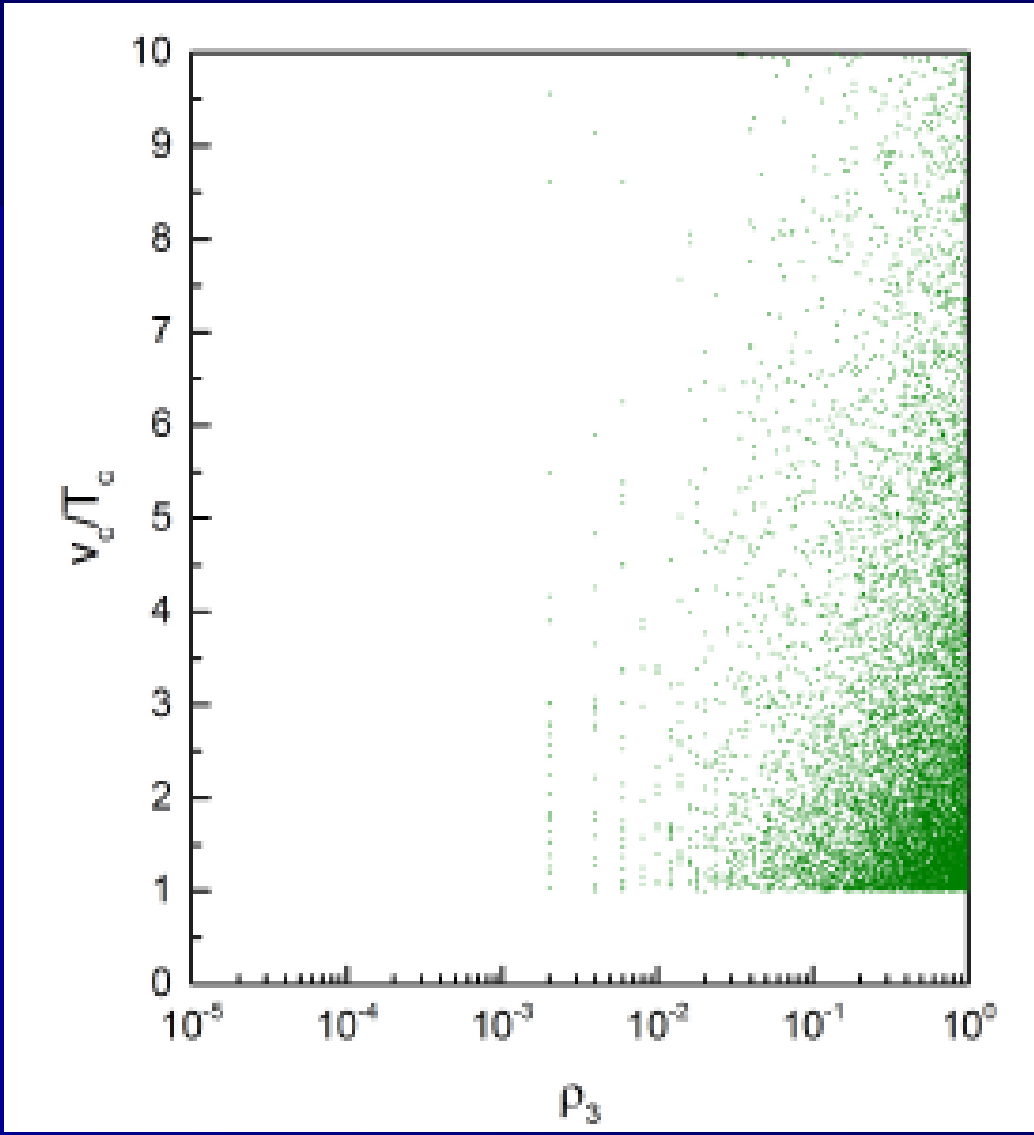
| Benchmark | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $M_{h_1}$ | $M_{h_2}$ | $M_{h_3}$ | $S$ | $T$ | $J_1/v^6$ |
|---|---|---|---|---|---|---|---|---|---|
| $A1$ | -0.047 | -0.053 | 1.294 | 124.64 | 652.375 | 759.984 | -0.072 | -0.094 | $-2.2 \times 10^{-4}$ |
| $A2$ | -0.048 | 0.084 | 0.084 | 124.26 | 512.511 | 712.407 | -0.001 | -0.039 | $7.2 \times 10^{-4}$ |
| $A3$ | 0.078 | 0.297 | 0.364 | 124.27 | 582.895 | 650.531 | 0.003 | -0.046 | $4.5 \times 10^{-4}$ |
| $A4$ | 0.006 | -0.276 | 0.188 | 125.86 | 466.439 | 568.059 | -0.013 | -0.169 | $-9.5 \times 10^{-4}$ |
| $A5$ | 0.062 | -0.436 | 0.808 | 125.21 | 303.545 | 582.496 | 0.002 | -0.409 | $5.0 \times 10^{-6}$ |
| $A6$ | -0.210 | 0.358 | 0.056 | 124.92 | 181.032 | 188.82 | 0.003 | -0.010 | $-4.0 \times 10^{-5}$ |
| $A7$ | -0.205 | 0.403 | 0.057 | 125.01 | 175.45 | 178.52 | 0.002 | -0.020 | $-3.5 \times 10^{-5}$ |

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 | $3.3 \times 10^{-5}$ | 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 |

# Strong 1st order PT




cubic term

# Baryogenesis with iso- doublet vector-like quarks

## Neda Darvishi

1608.02820

Iso-doublet vector quarks as in

McDonald, Phys. Rev. D **53** (1996) 645.

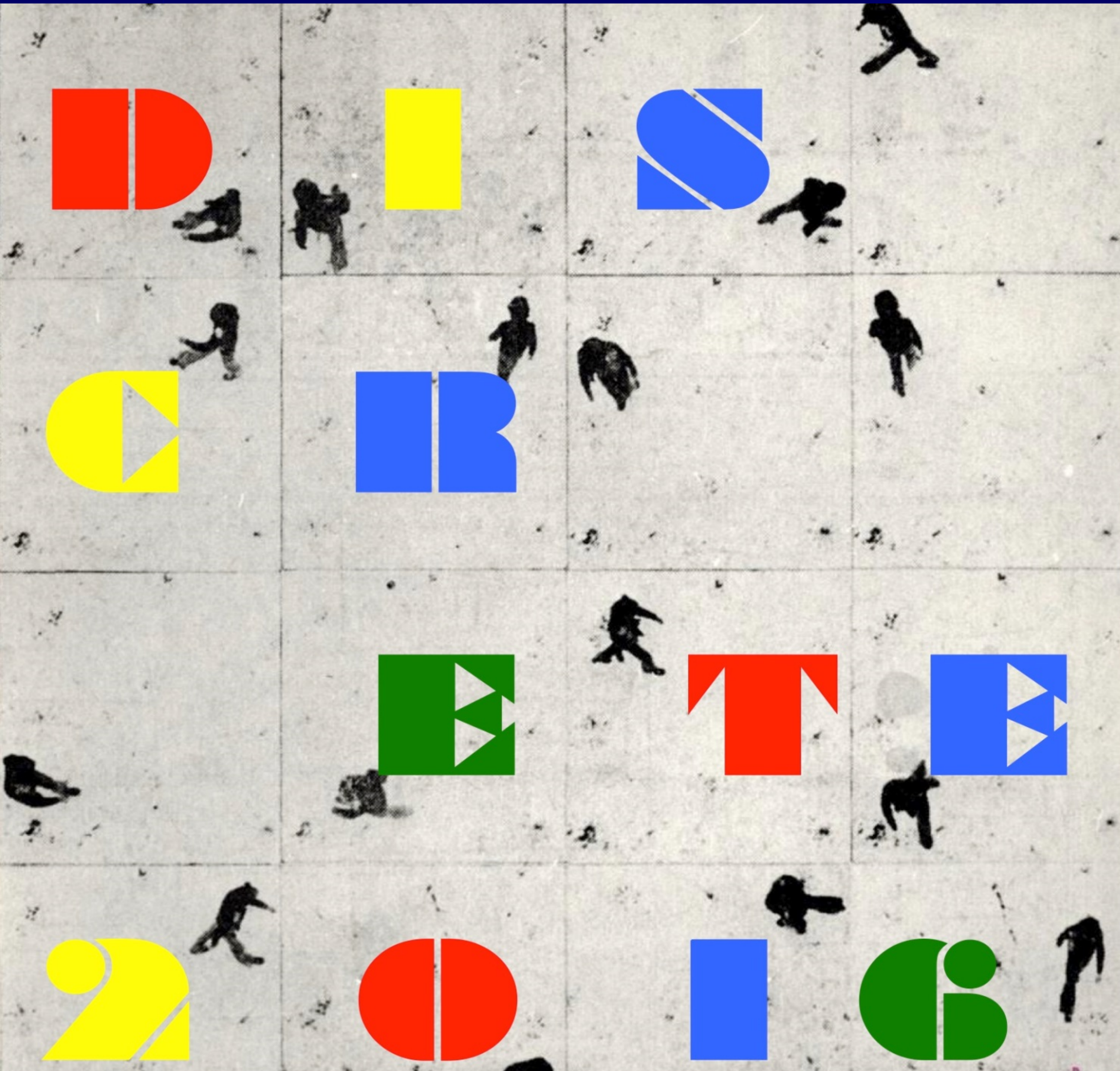



Photo by Andrzej Jórczak (1944-81), astronomer and artist specializing in experimental photography, from the series *Commutations* (1972). Courtesy of Liliana Jórczak Sarni

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- Emergence of symmetries from entanglement
- Discrete symmetries in cosmology
- Neutrino masses, mixing and discrete symmetries
- Role of symmetries beyond the SM
- Discrete symmetries and models of flavour mixing
- Strings, branes, extra dimensions, discrete symmetries
- New results from LHC, new facilities

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# Evolution of Universe to the Inert Phase

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

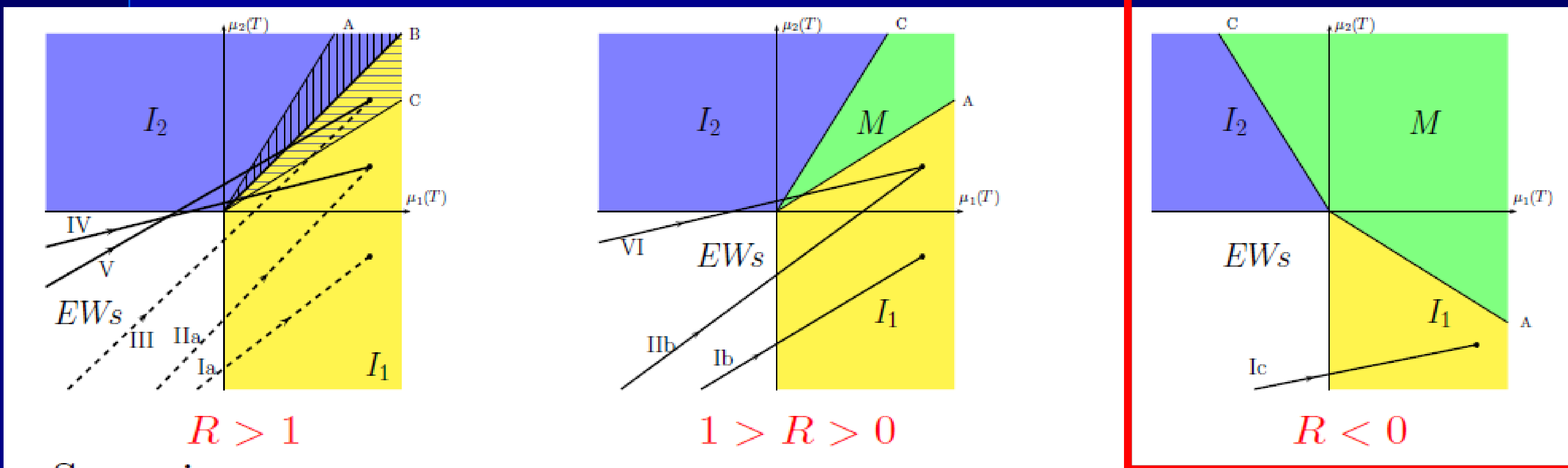
*Ginzburg, Ivanov, Kanishev 2009*
*Ginzburg, Kanishev,MK, Sokołowska PRD 2010,*
*Sokołowska 2011*

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 $\lambda$'s are fixed

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

# Evolution of vacua

$EWs \to I_2 \to I_1$



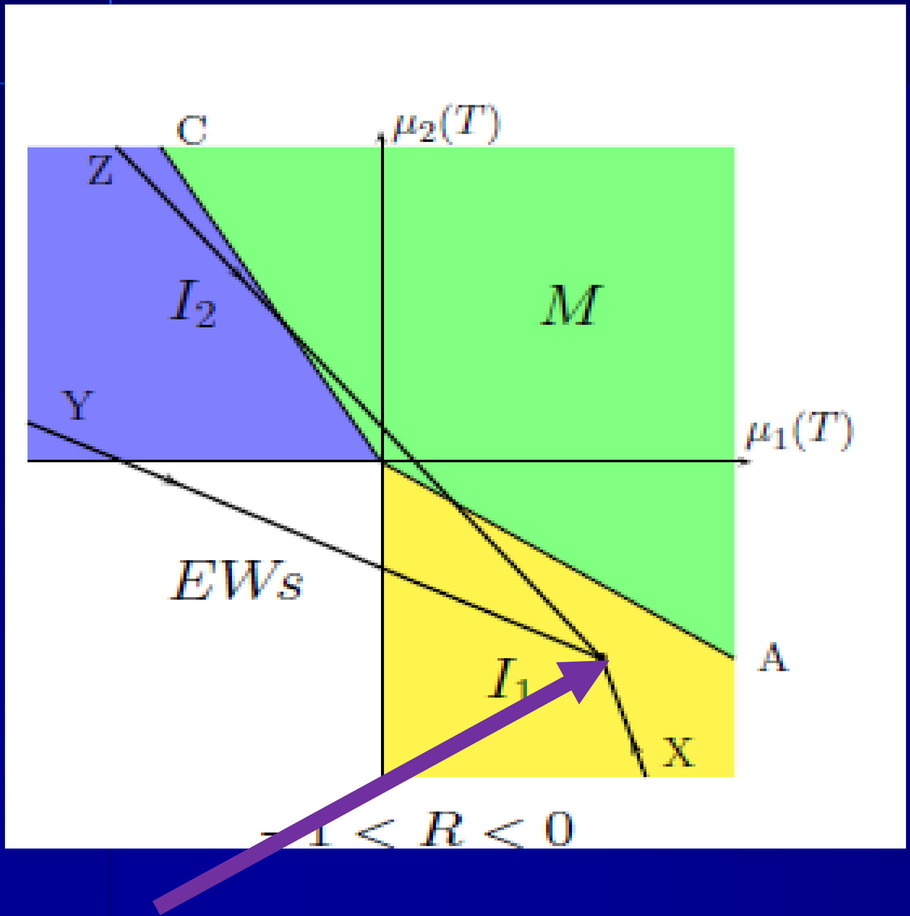

$EWs \to I_1$

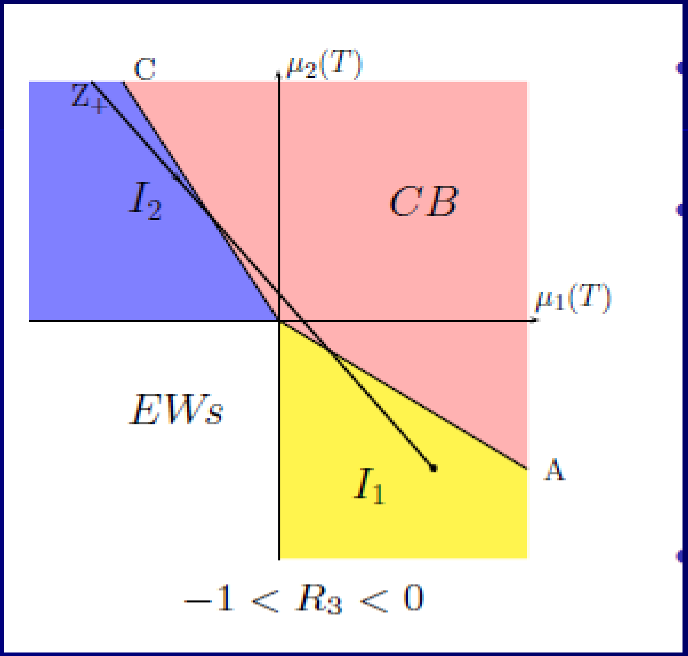
T$^2$ corrections

→ rays from EWs phase to Inert phase
one, two or three stages of Universe
(II order phase transitions, one I order)

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

# Nonrestoration of EW symmetry for $\lambda_{345} < 0$




Charged breaking phase

Only one ray with EW restoration in the past (in one step)

# Beyond $T^2$ corrections >> strong 1st order phase transition in IDM EW baryogenesis?

*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)

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

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

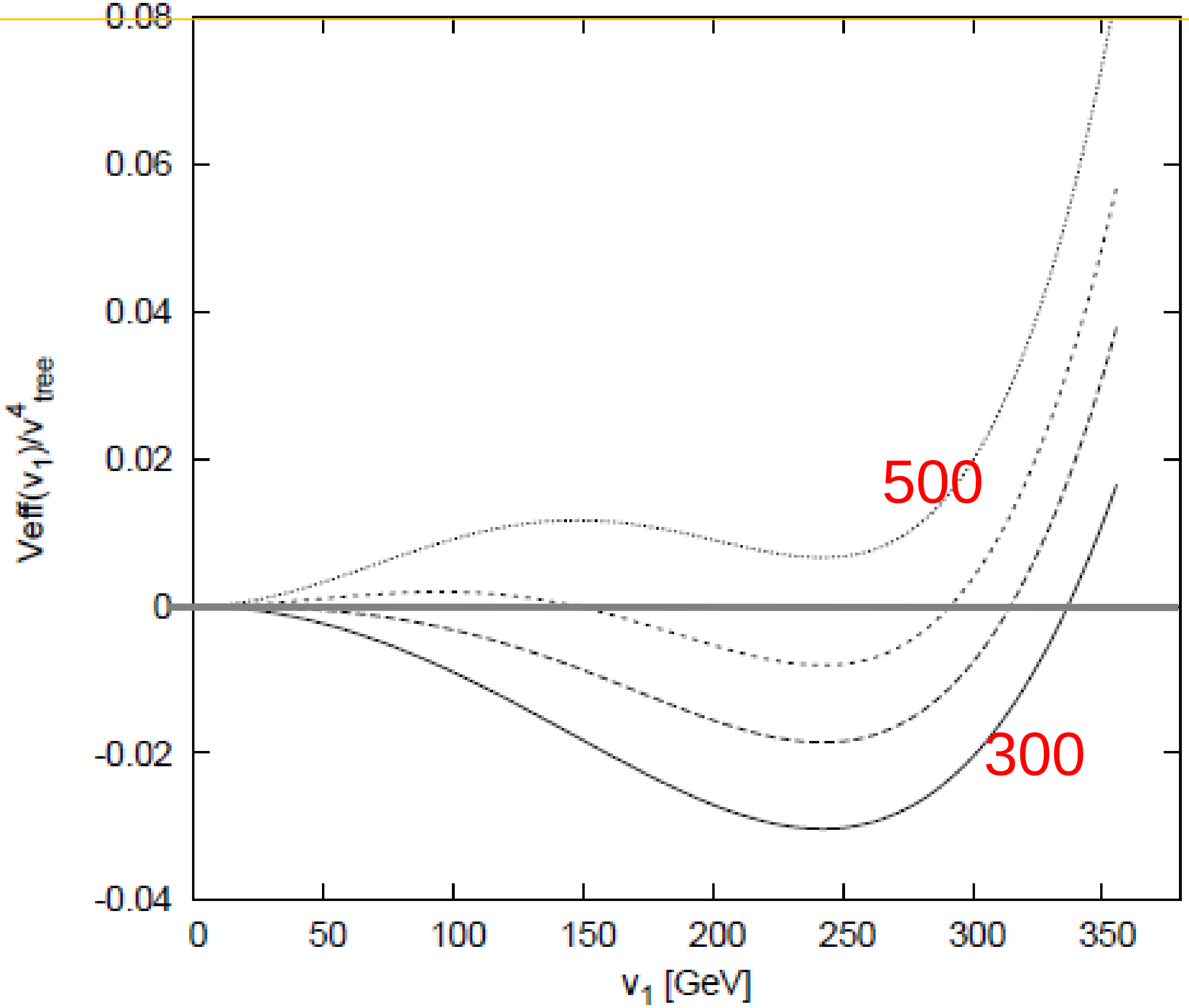
$$V_{\rm eff}^{(1L)} = V_{\rm tree} + \frac{1}{64\pi^2} \sum_{\rm fields} C_s \left\{ \mathcal{M}_s^4 \left( \ln \frac{\mathcal{M}_s^2}{4\pi\mu^2} - \frac{3}{2} + \frac{2}{d-2} - \gamma_E \right) \right\} + {\rm CT},$$

mass matrices

number of states

counter terms →

# Effective T=0 potential




Mh=125 GeV

MH=65 GeV

MH+=MA=
500,450,400,300
GeV

$\lambda_{345}$=0.2,
$\lambda_{2}$=0.2

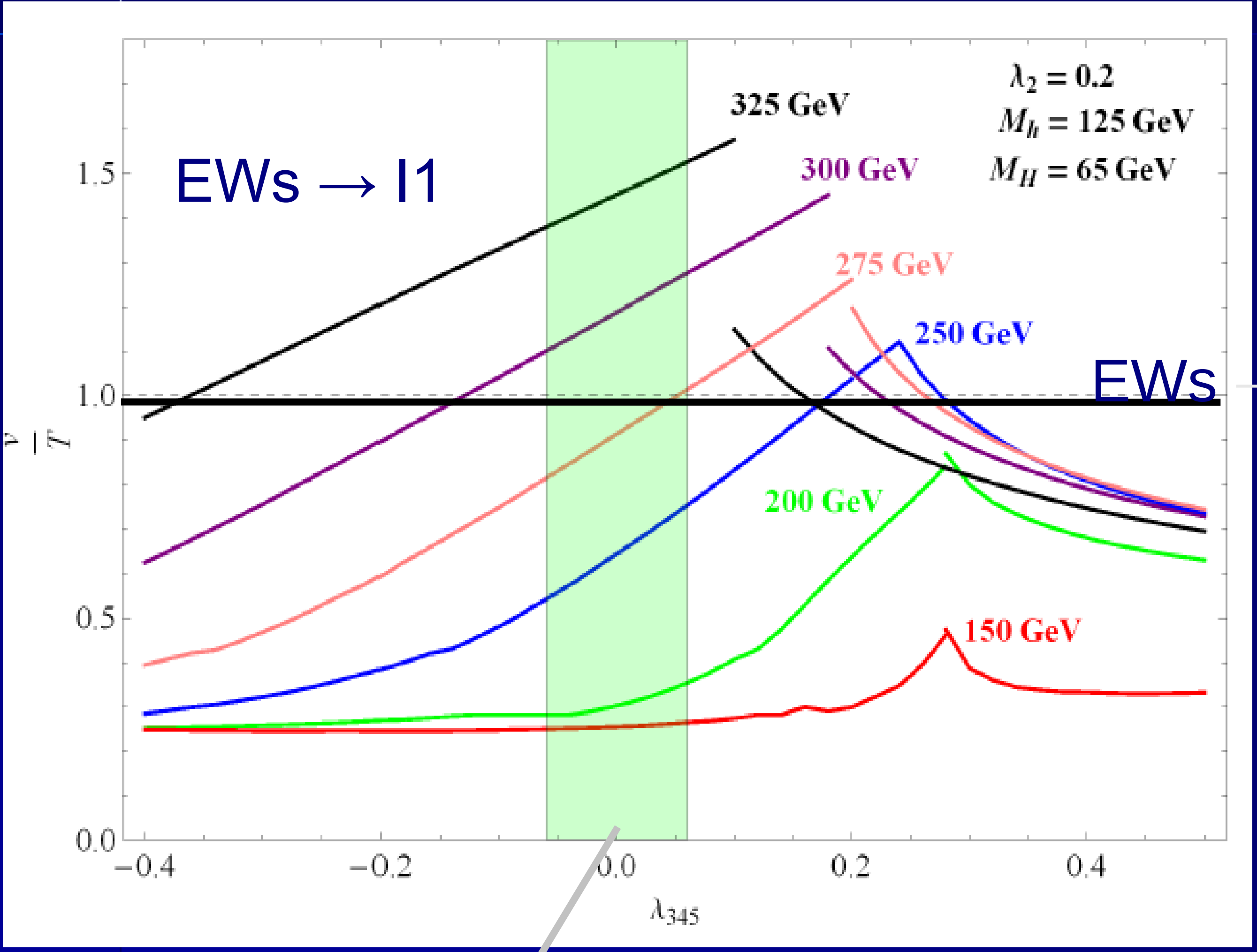
$v_{2(D)}$=0

Critical temperature $T_{EW}$: V at new minimum = V at ($v_{1(s)}$=$v_{2(D)}$=0)

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

Mh=125 GeV, MH=65 GeV, λ2=0.2

strong 1st order phase transition if ratio > 1




EWs → I2 → I1

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

$\lambda_{345}$

R<0 Xenon100 bound R>0