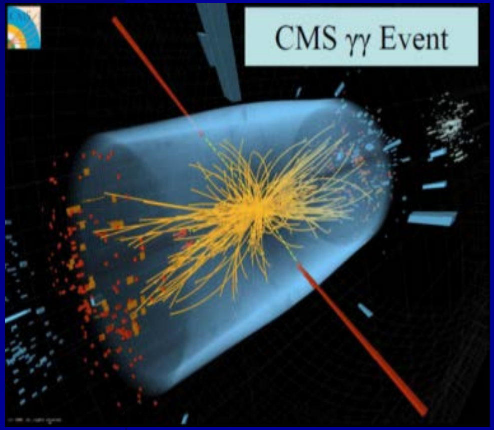
BSM, Corfu, 2.09.2016

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

Plan

- Inert Doublet Model (IDM):Higgs & Dark Matter
- Constraints from LHC, WMAP/PLANCK&LUX
- Future tests at LHC and ILC

Towards baryogenesis (Sacharow conditions):

IDM provides a strong 1st order PT

but no CP violation

- Extensions of IDM: IDMS = IDM+Singlet
- SM+Singlet

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 → 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

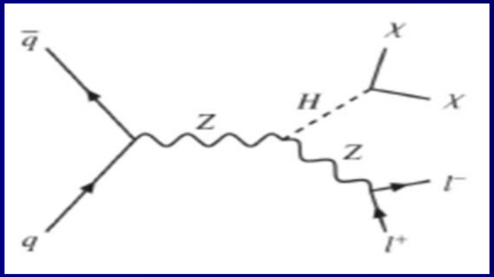
  global 1.09 ± 0.11/0.10

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

- Invisible decay

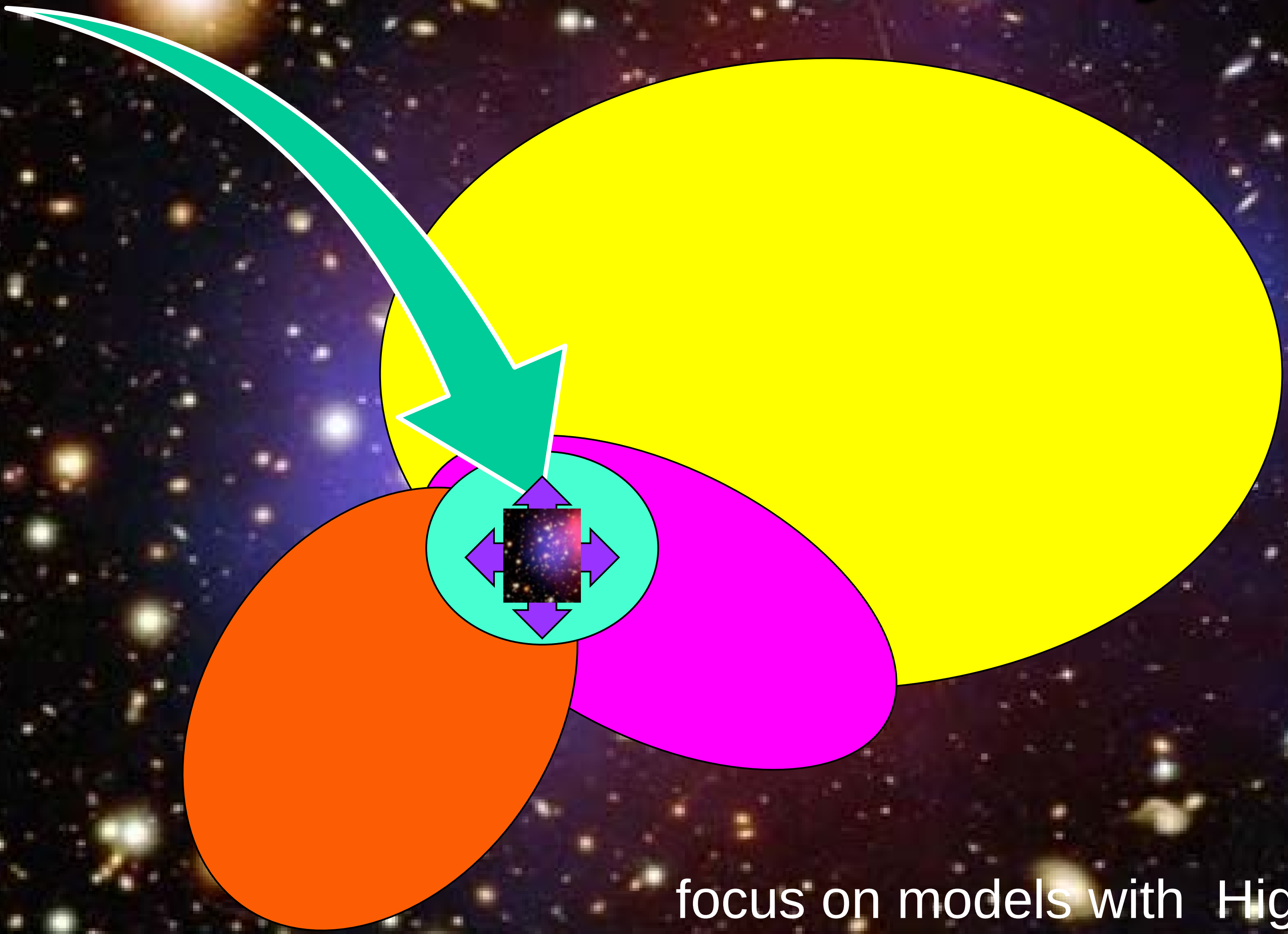
  BR < 0.34 (95% CL)

- Spin/CP J^{CP} 0 +



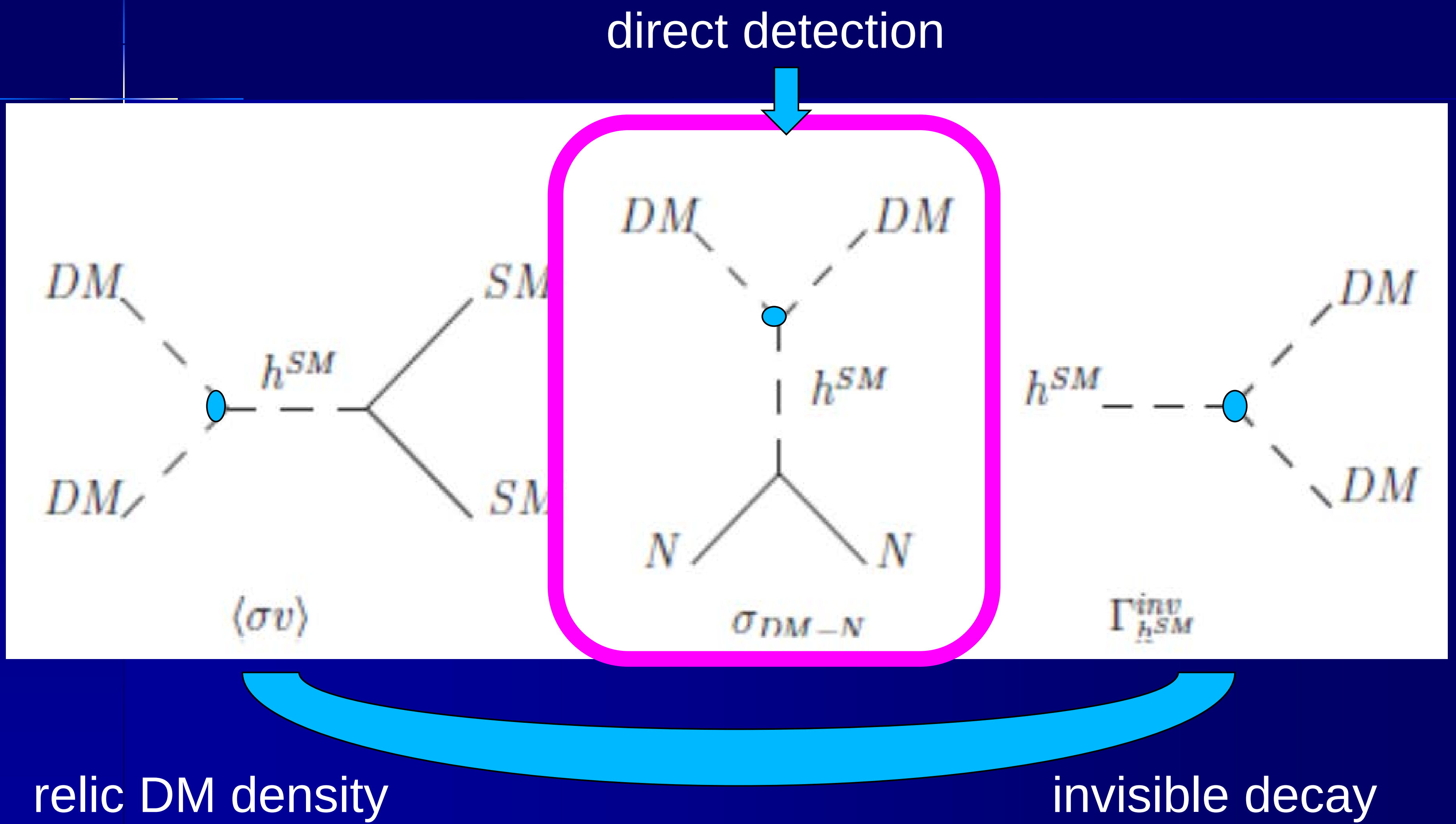
But what it is ?

SM - like scenario in many models



focus on models with Higgs Portal to the Dark Matter

Higgs portal with the SM-like h



Dark matter

Relic DM density

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

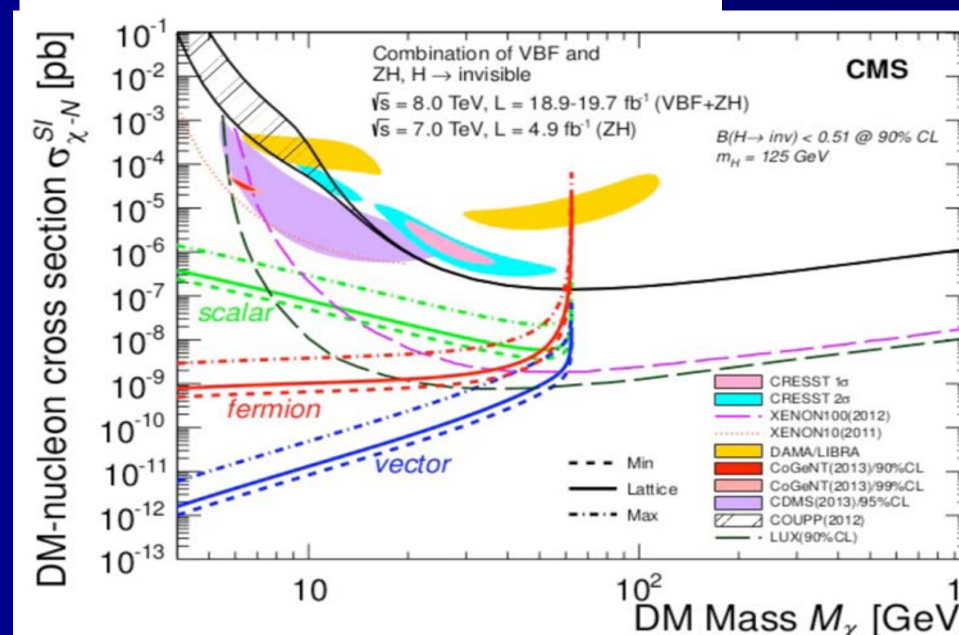
WMAP

3 σ

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

PLANCK

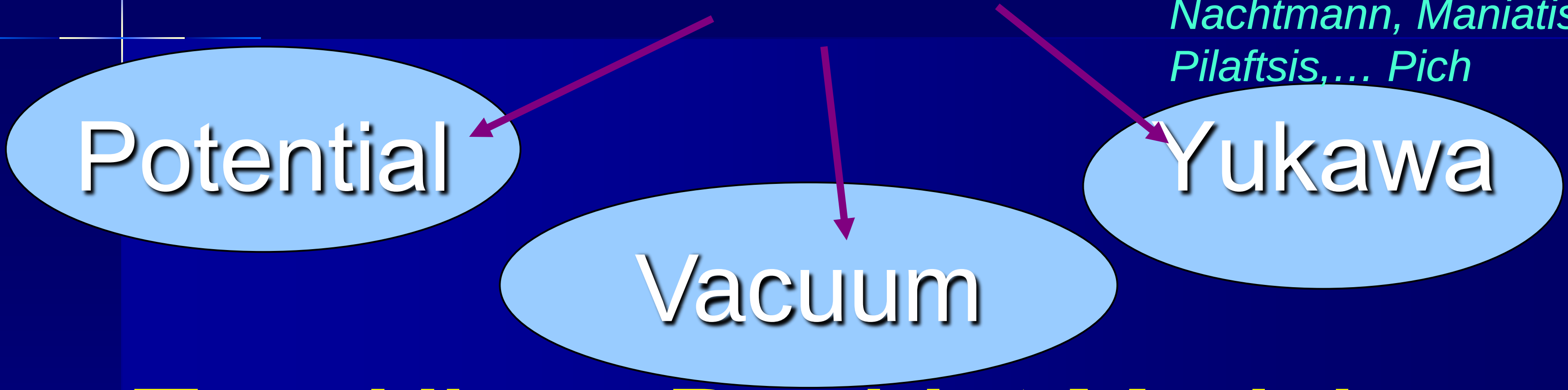
Direct DM detection



T.D. Lee 1973
CP violation
in scalar sector

2HDM's

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



Two Higgs Doublet Models

Two doublets of SU(2) (Y=1, ρ =1) - Φ_1 , Φ_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

Potential V = *Branco, Rebelo ,85 (CP conserved)*

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

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

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

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) *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	$v_D, v_S \neq 0$

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

Charge Breaking	CB	$v_D = 0$

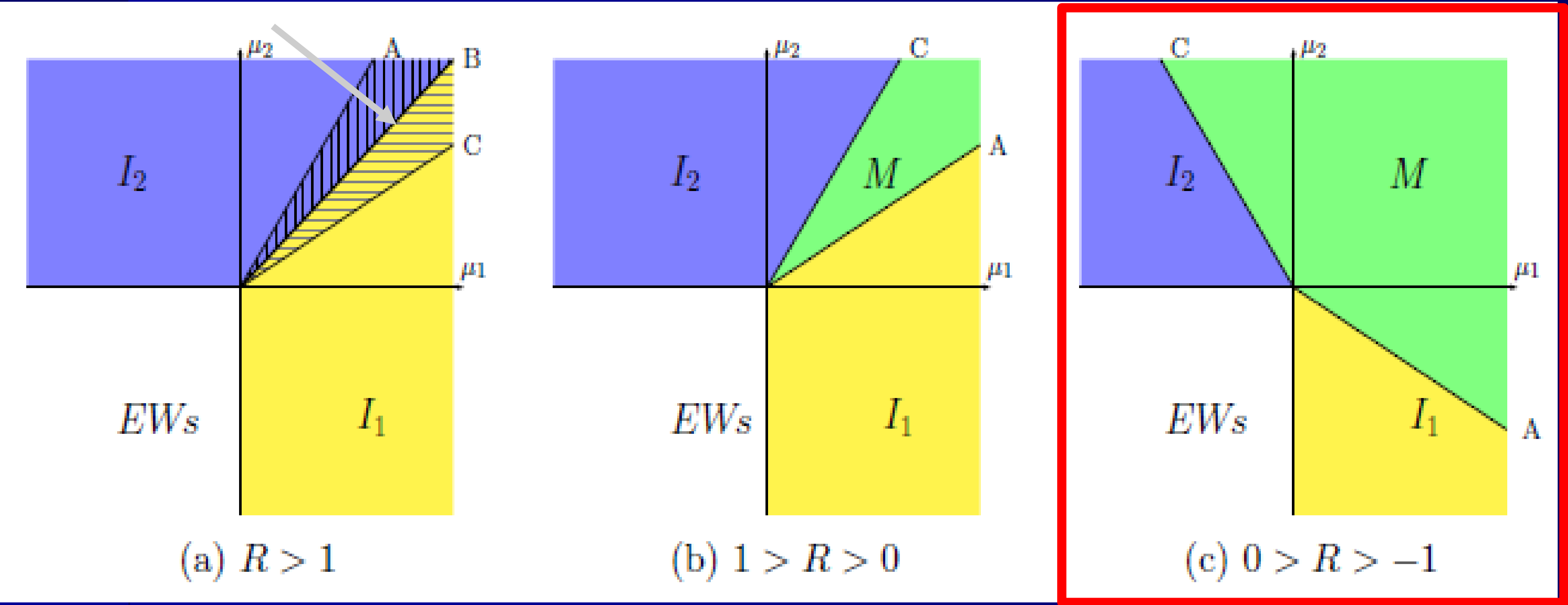
Phase diagrams for D-sym. V

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

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

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

coexistence of I_1 and I_2 minima



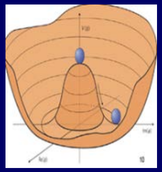
Inert (I_1) vacuum
for M_h=125 GeV → fixed μ_1

here $\lambda_{345} < 0$!

Inert Doublet Model

Ma,…'78

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 $\Phi_S \to \Phi_S$ $\Phi_D \to - \Phi_D$ 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,…)

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,

so if large negative →

H,H+,A heavy, degenerate

λ_{345}

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

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

H – dark matter

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

Testing Inert Doublet Model

- Theoretical constraints
  vacuum stability,
  perturbative unitarity
  condition for Inert vacuum

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

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

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 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 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

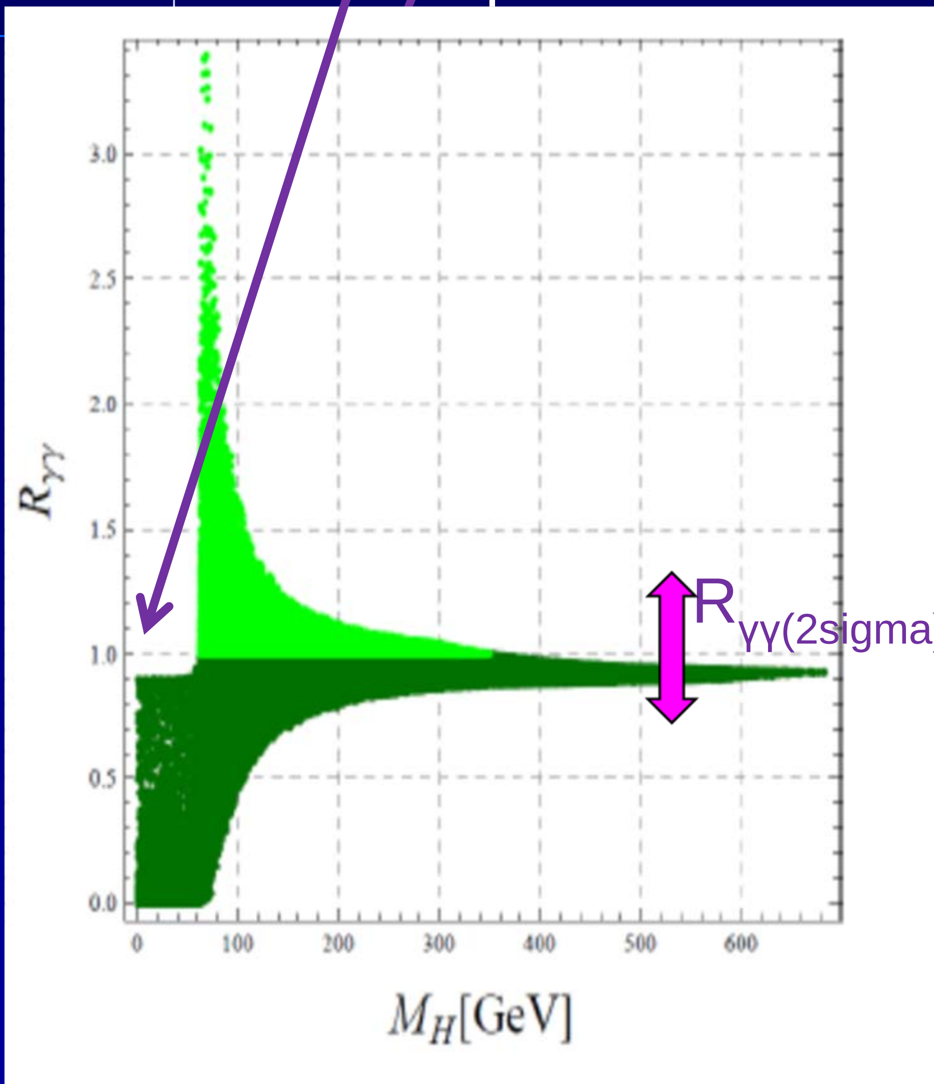
$$R_{\gamma\gamma} = [\Gamma_{\gamma\gamma} / \Gamma^{SM}_{\gamma\gamma}] \times [\Gamma^{SM}_{tot} / \Gamma_{tot}] > 1$$

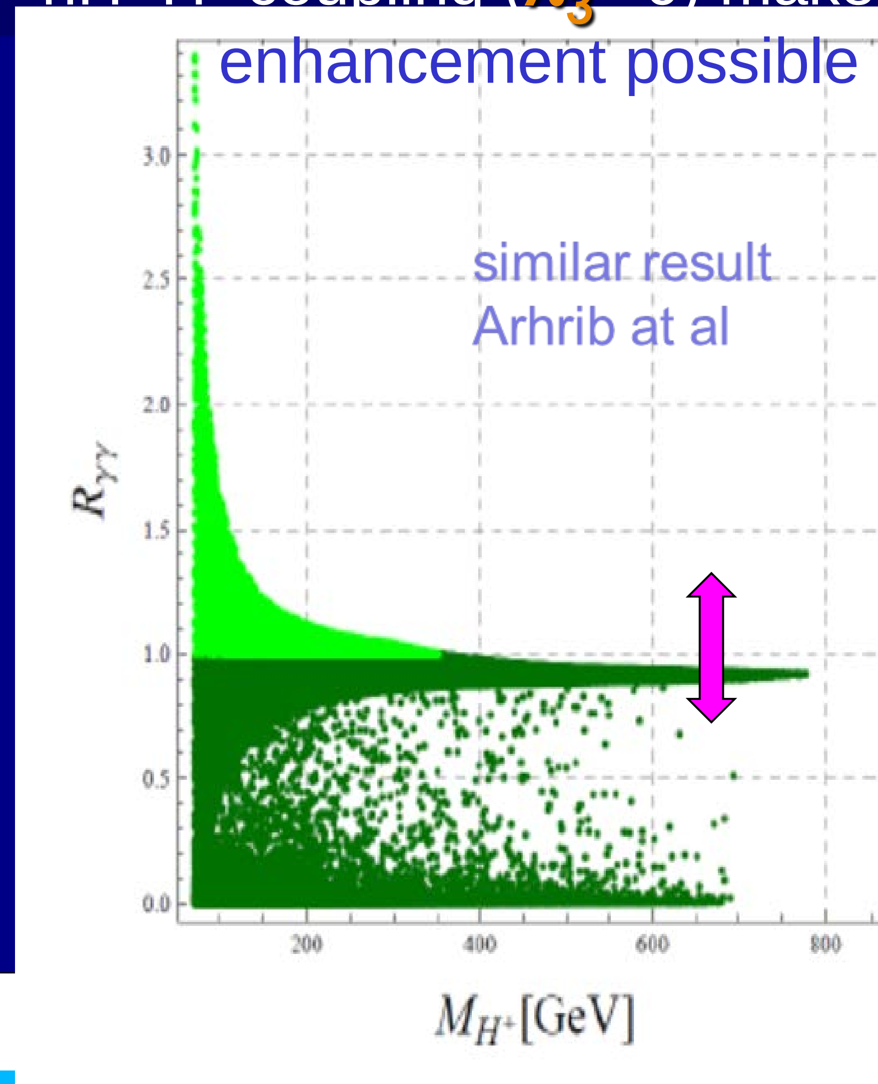
possible if DM mass above 62.5 GeV

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

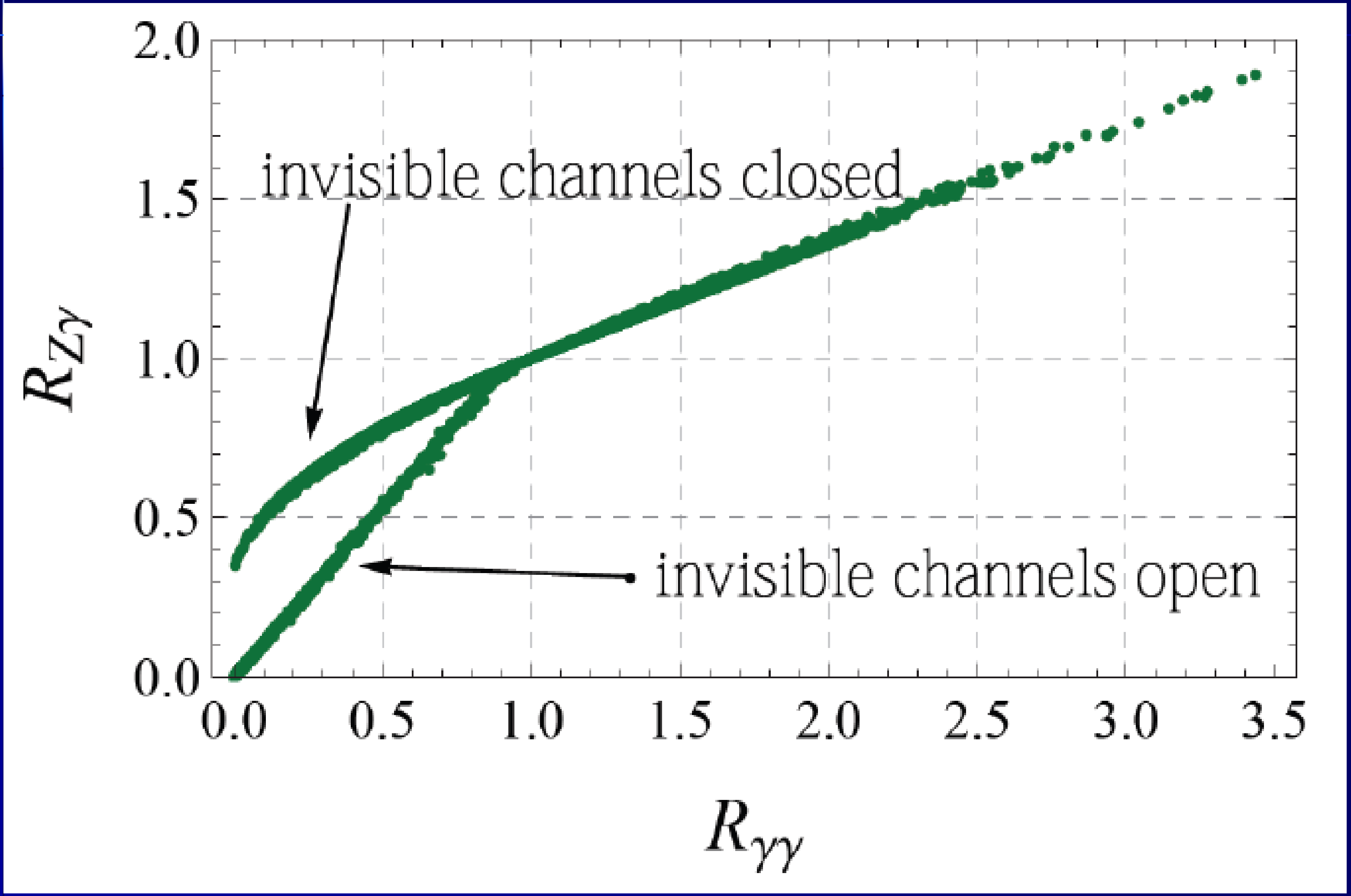
Invisible decays makes enhancement impossible

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



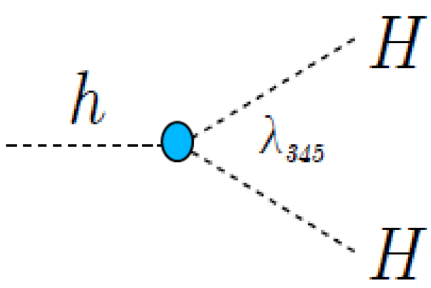


γγ versus Zγ in IDM



Invisible h decay →coupling hHH

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

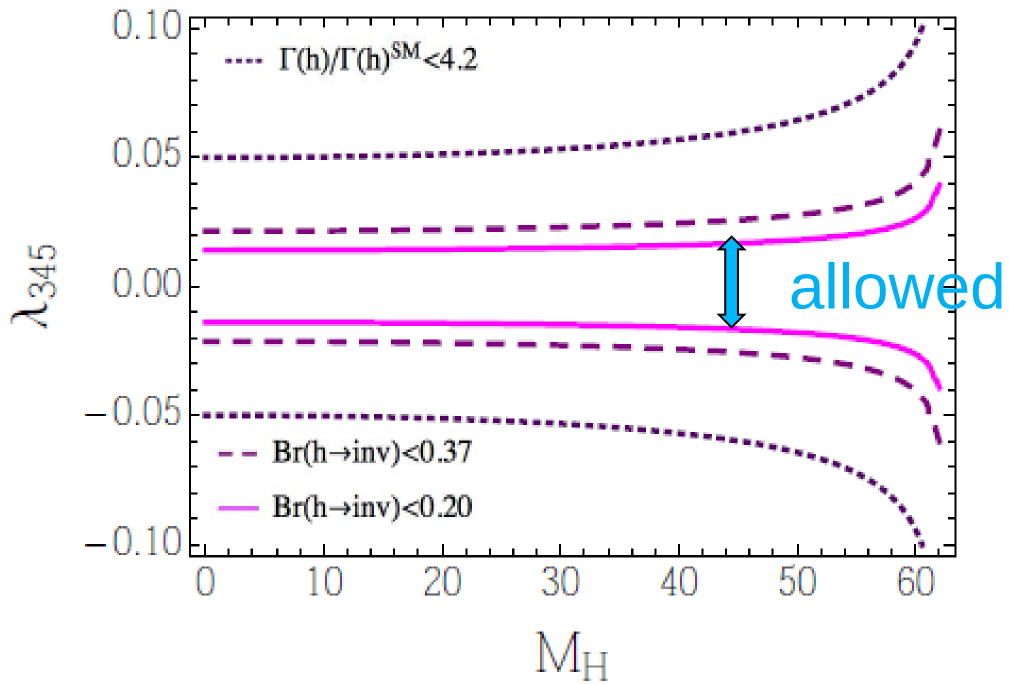


LHC:

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

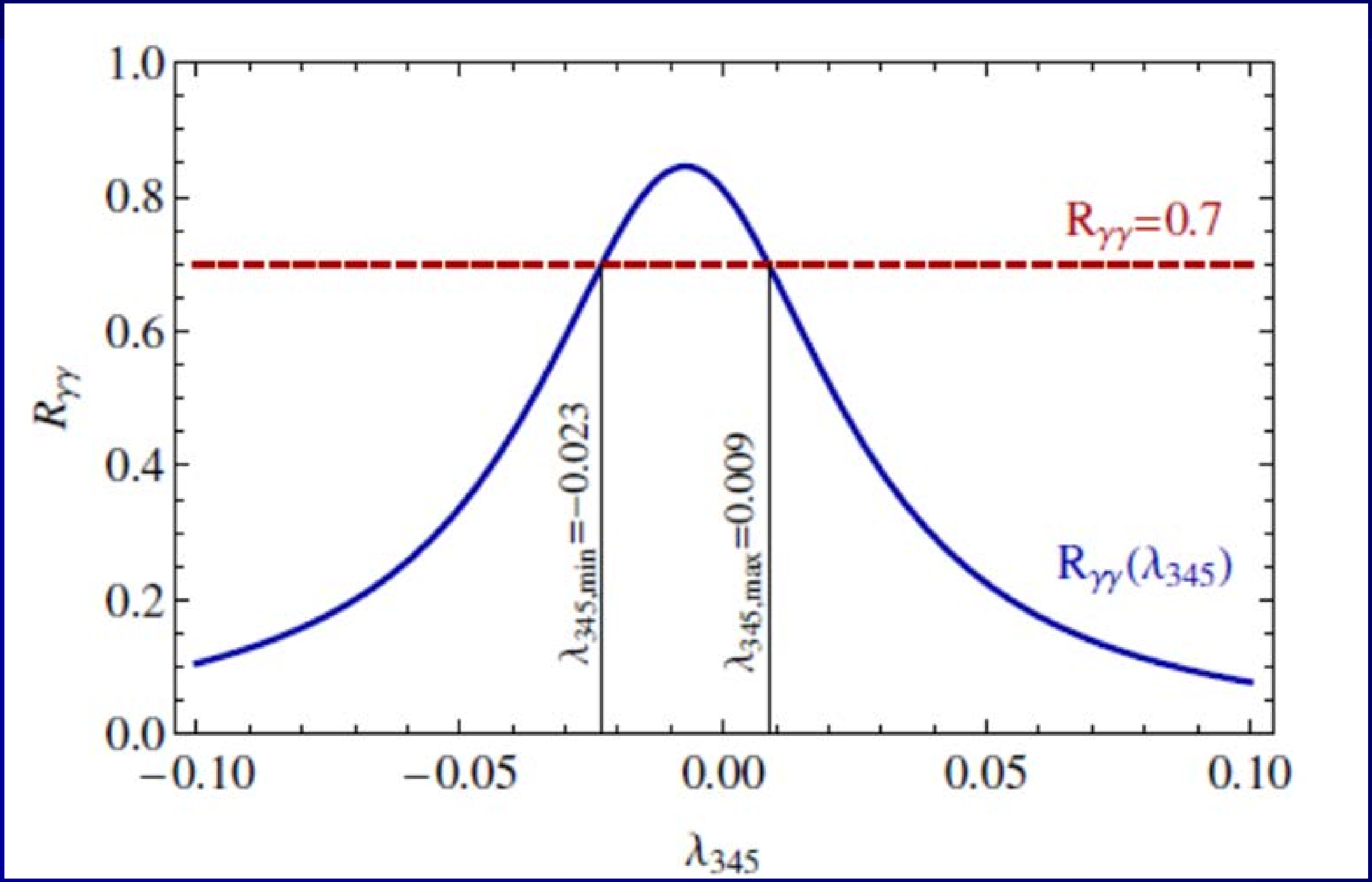
global fit:

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



[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]

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



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

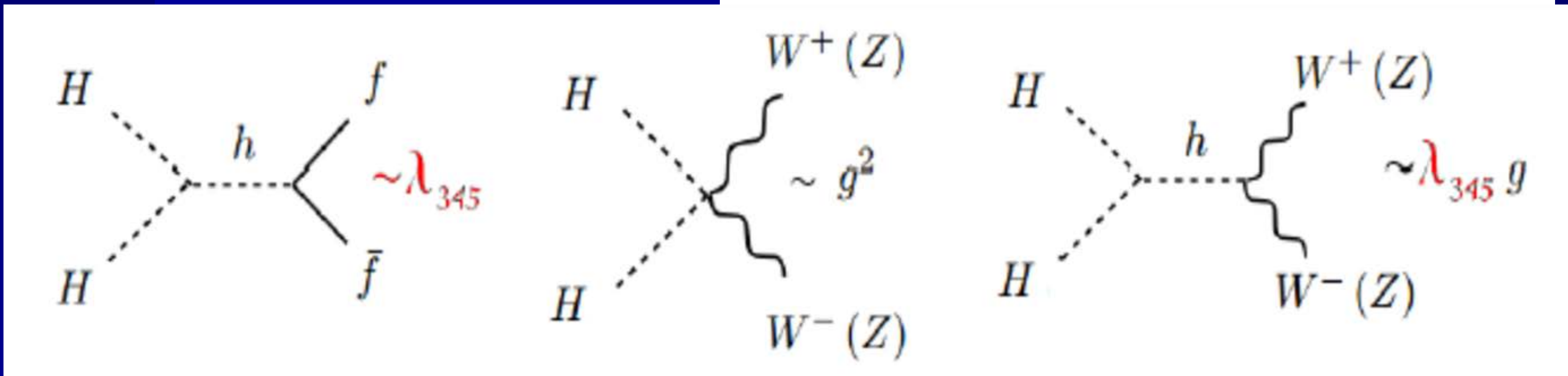
LHC data

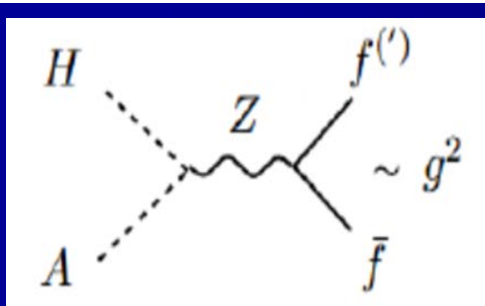
$$\text{ATLAS} : R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$$
$$\text{CMS} : R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$$

ATLAS+CMS 2016 1.14 ± 0.19

Relic DM density

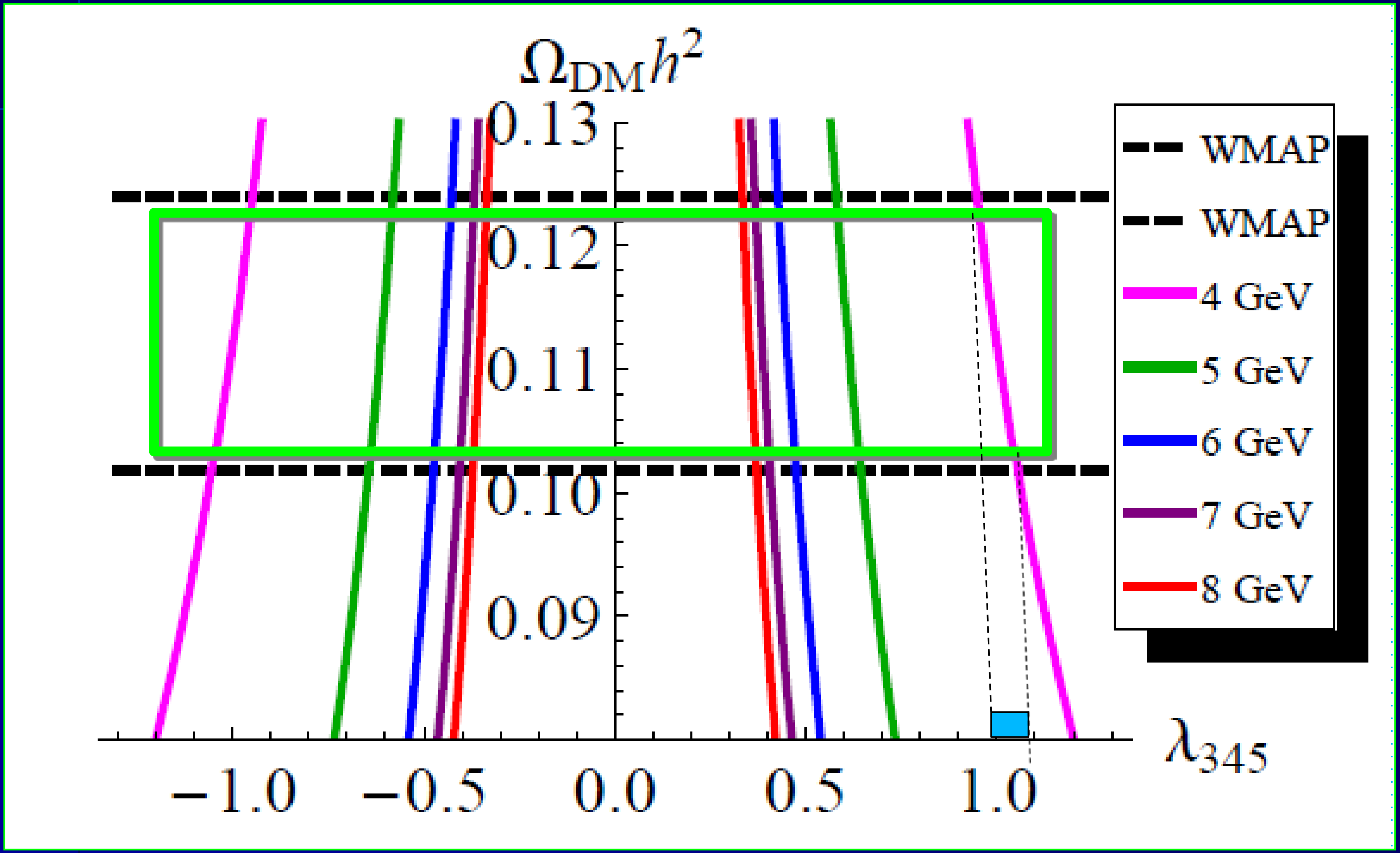
$$\Omega_{DM} h^2 = 0.1126 \pm 0.0036.$$





Coannihilation possible
for small (AH) mass splitting

WMAP window for light H (DM)

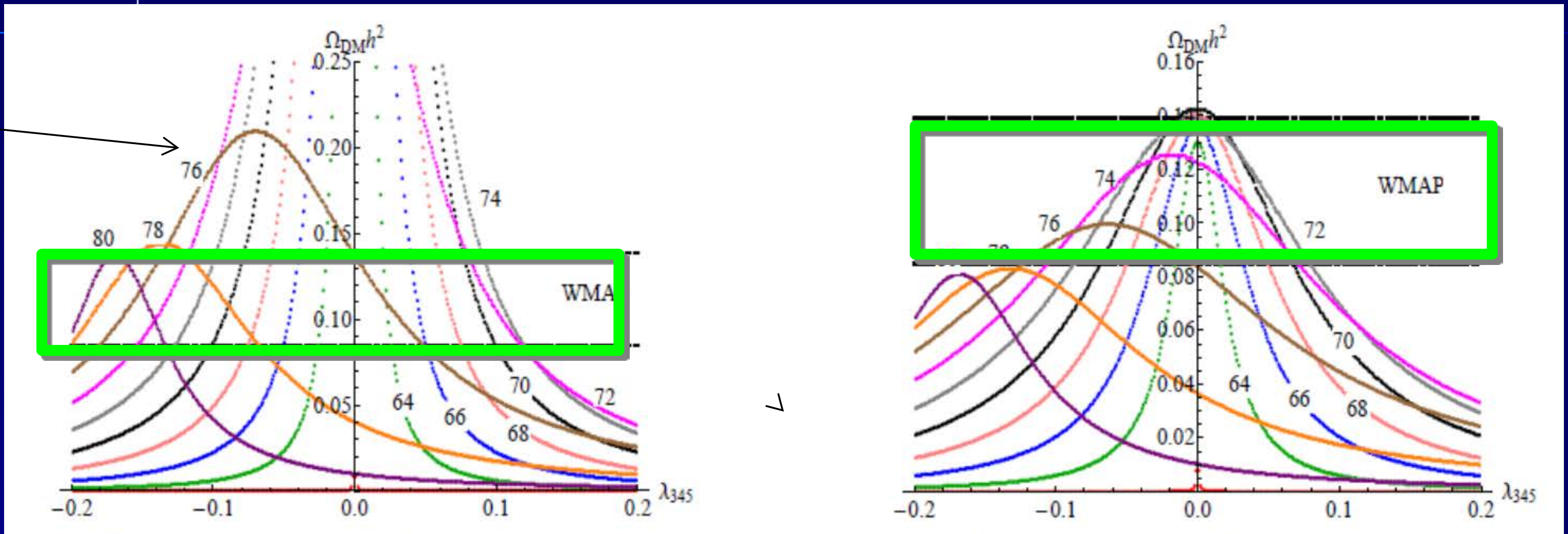


using MicrOmega

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

allowed regions

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

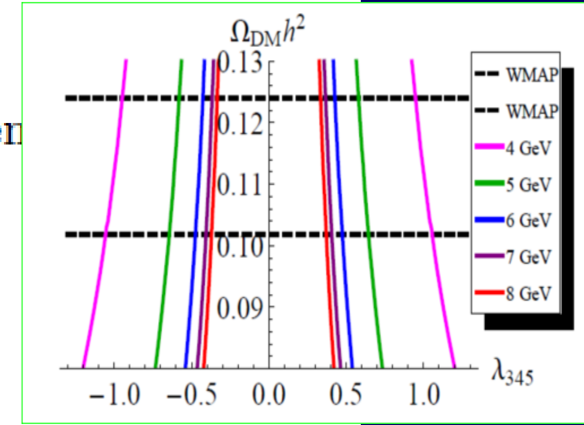
Low mass H – excluded by LHC!

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

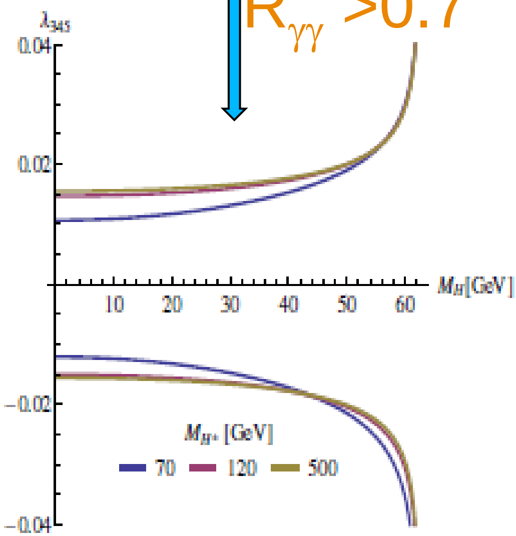
[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

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

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



$R_{\gamma\gamma}$ >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:

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

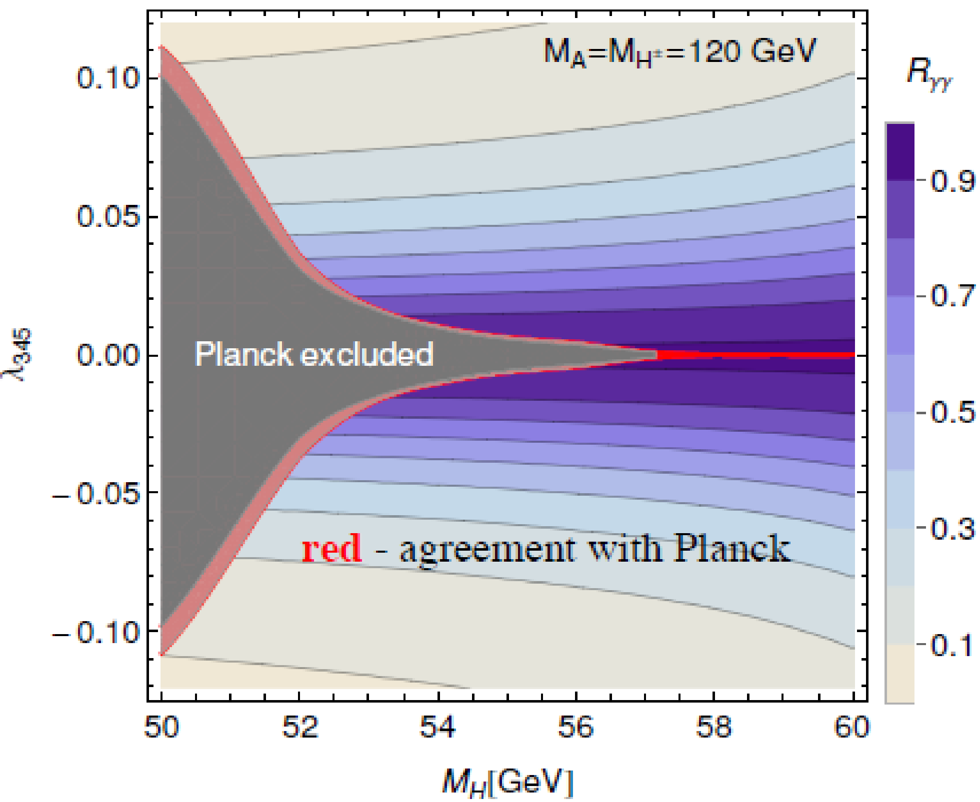
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$

Low DM mass excluded

Using PLANCK data

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

$h \to HH$ open



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

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

Full scan for IDM (2015)

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

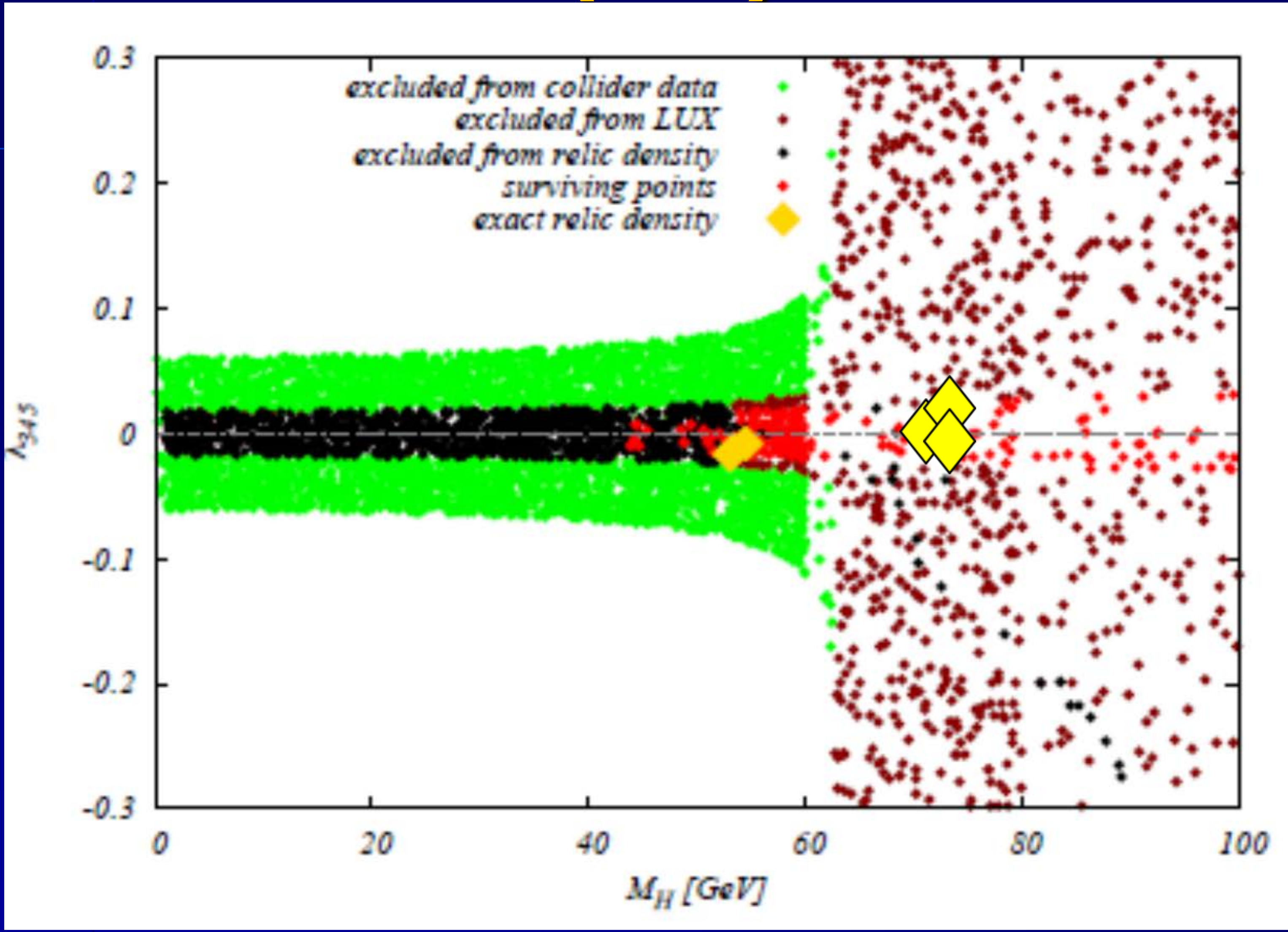
- Theor. constraints –
  stability of the potential (positivity), pert.unitarity, condition for the Inert vacuum
- STU (from 2014)
- Higgssignal/Higgs bounds
- Lifetime of H+ (< 10^{-7} s to decay inside detector)
- Relic density Planck **Ω < 0.1241** (95% CL)
- Direct detection LUX
- --> scan over M_H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

+LEP constraints
h total width
W/Z total width

other analyses Stahl.., Blinov …Cline

Low mass H (DM)

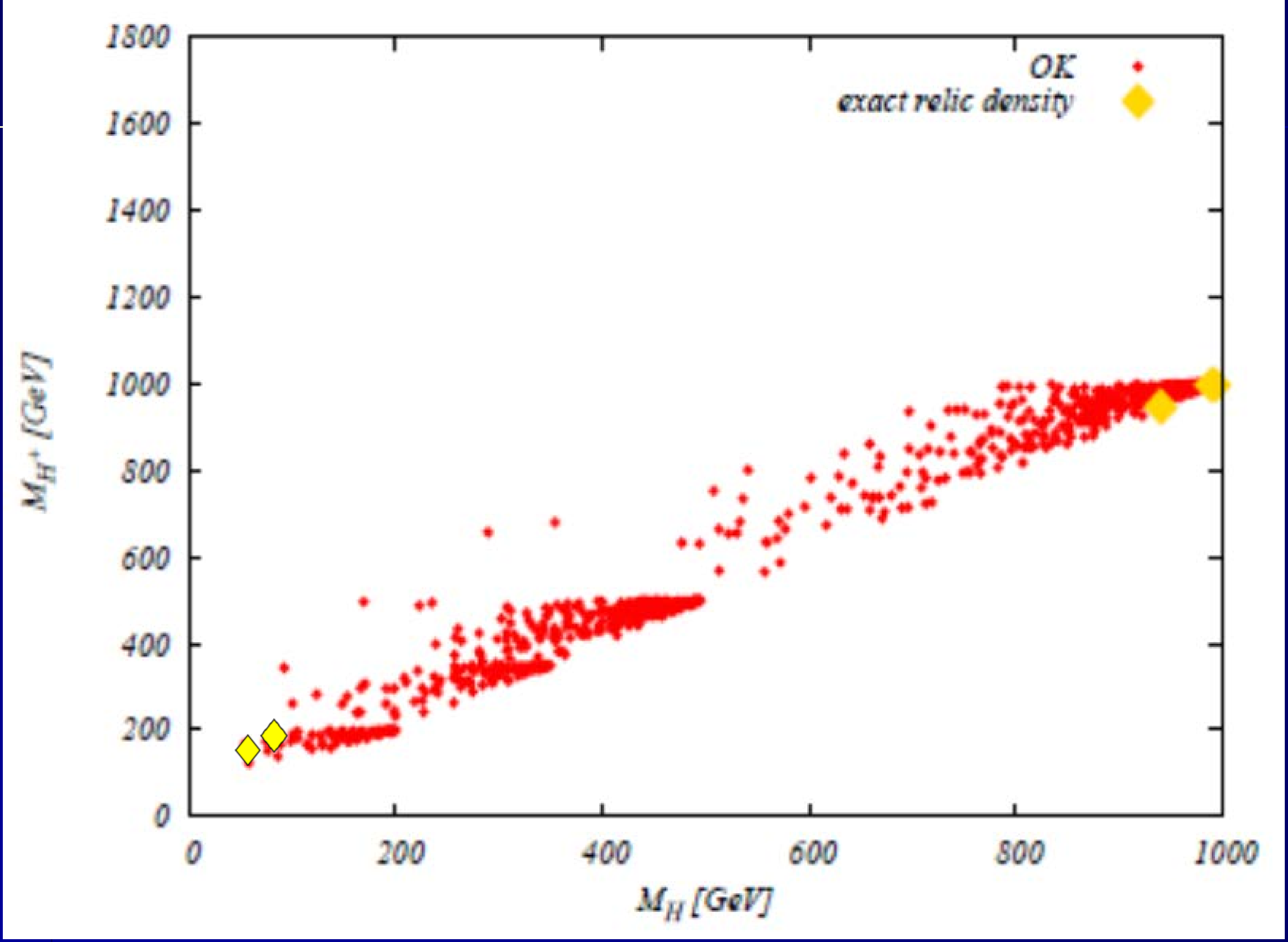
1505.04734,1508.01671



exact relic density

Limit on mass of DM: M_H> 45 GeV !

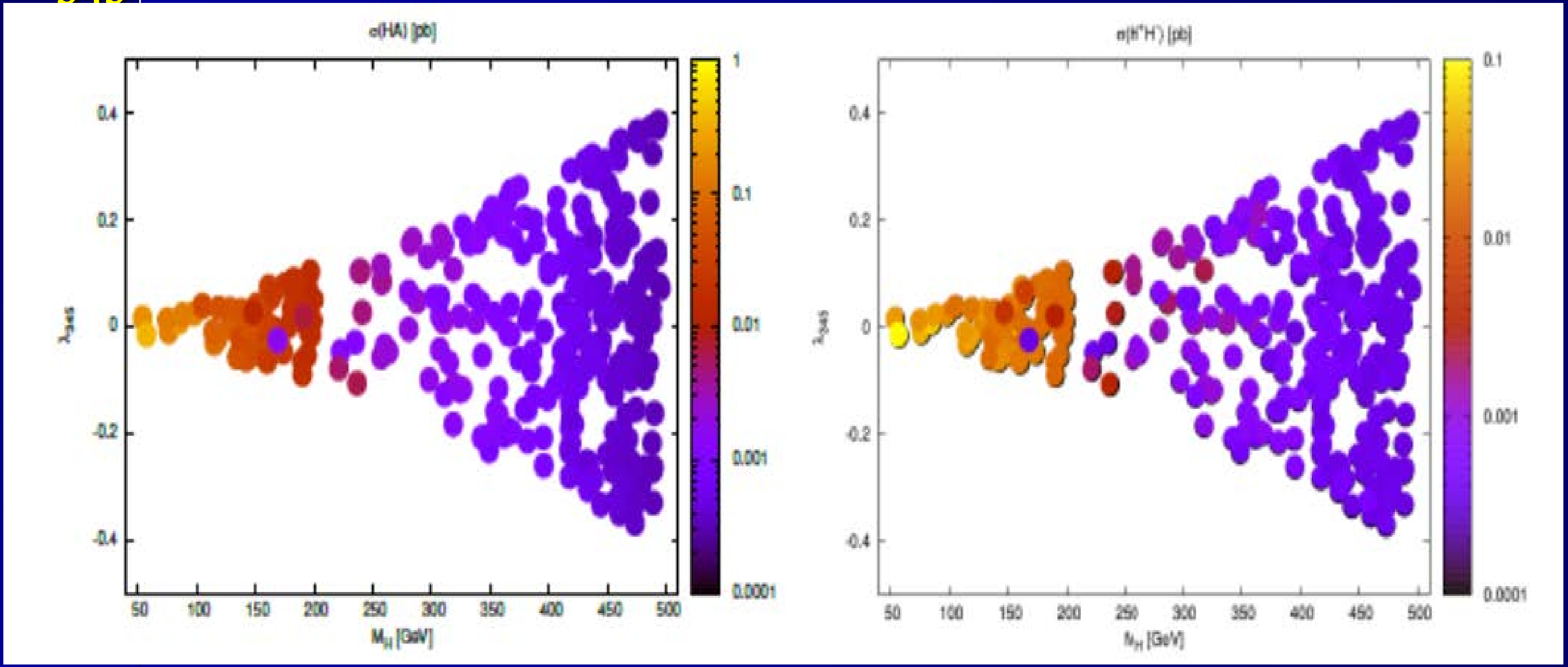
dark particles masses



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.

λ_{345} HA H+H-



M_H

A → Z H = 100%

MH^{+}- MH > 100 MeV

Cross section in pb, mass in GeV

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 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

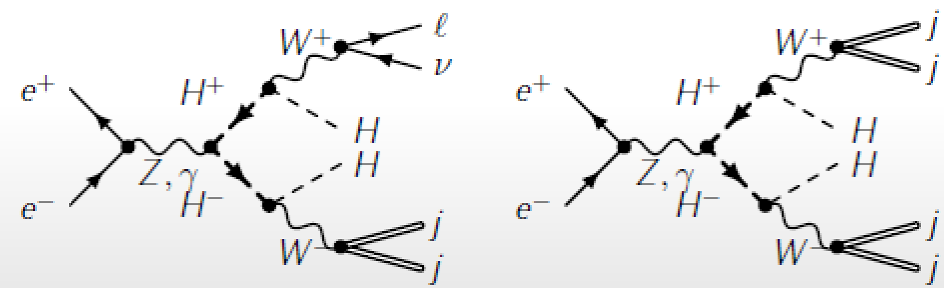
$m_{H^\pm}$	theo.	123	140	176
	0.5	117.1 ± 7.2	136.8 ± 10.0	167.4 ± 14.6
	1	112.7 ± 4.5	131.4 ± 5.0	172.2 ± 5.5
m_H	theo.	57.5	85.5	128
	0.5	58.5 ± 3.6	88.9 ± 6.5	127.2 ± 9.5
	1	53.0 ± 2.1	81.5 ± 3.1	129.1 ± 1.2
m_A	theo.	113	111	134
	0.5	113.9 ± 3.7	114.3 ± 6.6	133.1 ± 9.6
	1	104.6 ± 2.2	105.0 ± 3.2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

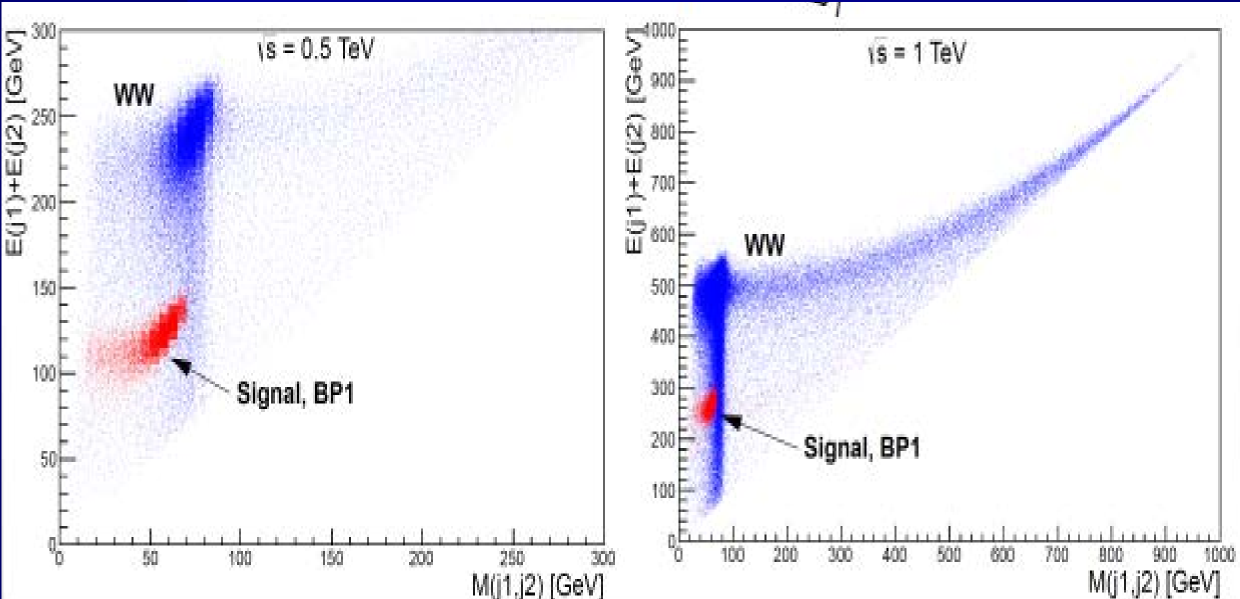
Main decays
H+→ W*+ H
A→ Z H

Also .. M. Aoki … PL B725 (2013) 302

H+H-

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



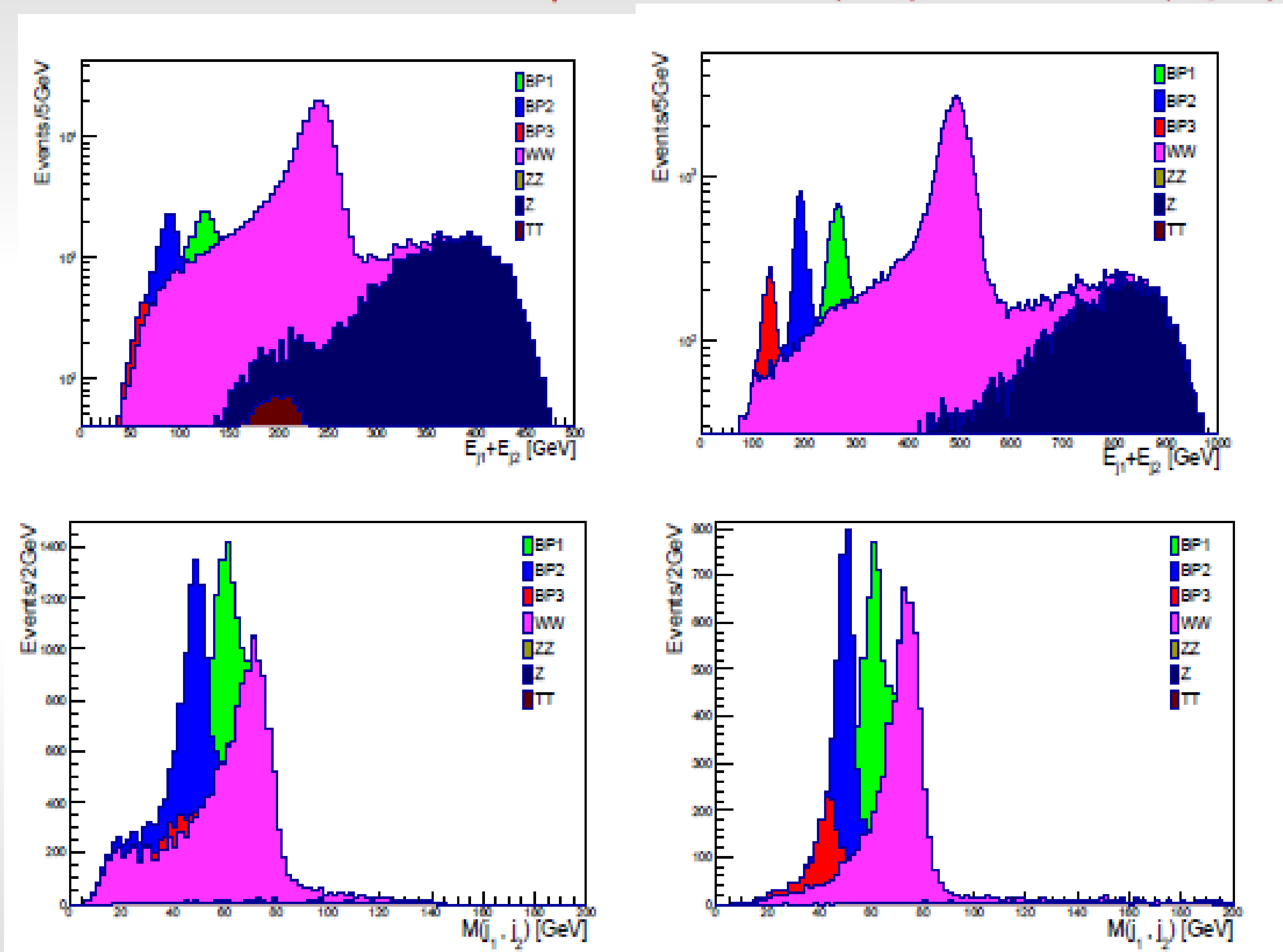


Sum of energies of two jets and their invariant mass for semileptonic events -> cuts on sum of energies

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).

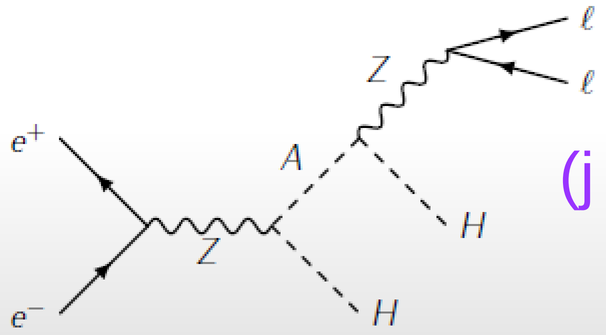


after aplying cuts on sum of energies

150(350) GeV

HA

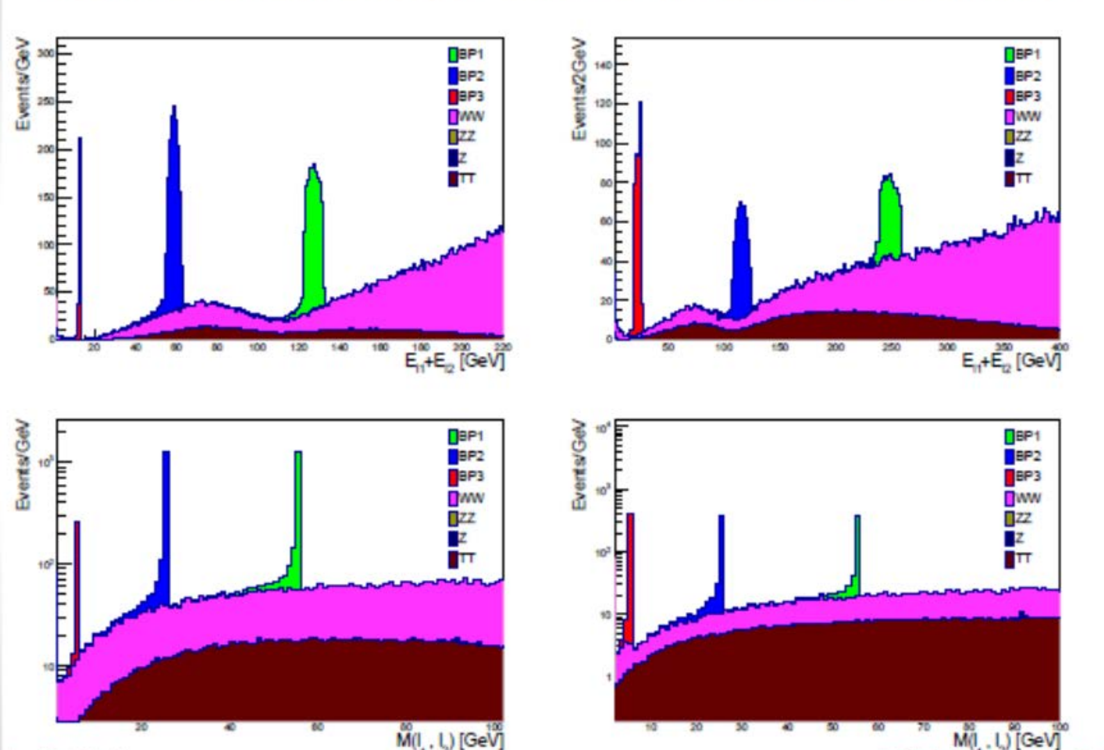
	$\sqrt{s} = 0.5$ TeV			$\sqrt{s} = 1$ TeV		
Process	$e^+e^- \to AH$			$e^+e^- \to AH$		
Benchmark point	BP1	BP2	BP3	BP1	BP2	BP3
Cross section [fb]	45	42.9	34.2	12.5	12.4	11.8



(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, DiazCruz,Darvishi, Sokolowska, MK – J.Phys. G43 (2016) 065001

- IDM + extra neutral complex singlet χ 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 good DM candidate
- Small modifications of h1 couplings to SM particles

Potential IDMS

Φ_S

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

Φ_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

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

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

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

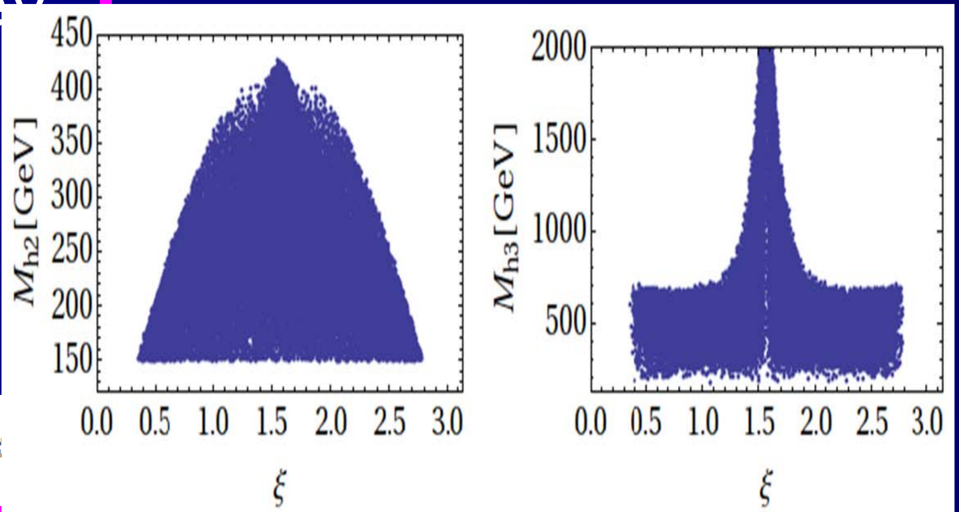
$$R_{11} = R^{-1}_{11} = c_1 c_2.$$

Mh1 ~125 GeV w=300-1000 GeV

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

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

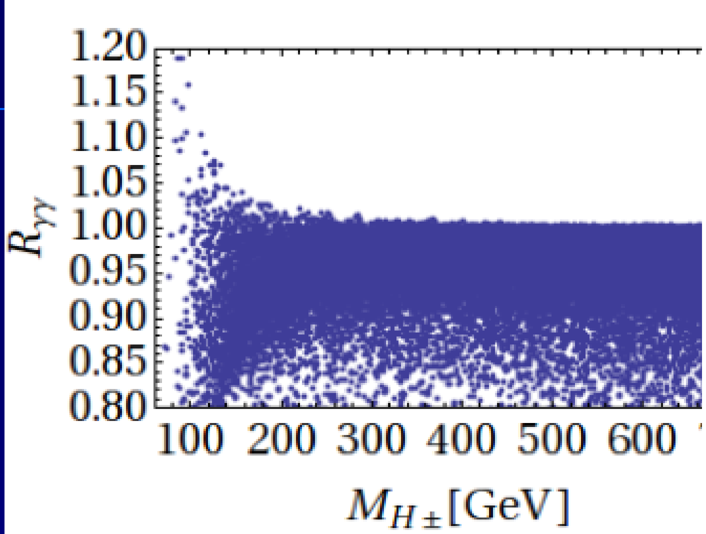
$$-1 < \Lambda_1 < 1, \quad 0 < \lambda_{s1} < 1, \quad -1 < \rho_{2,3} < 1, \quad 0 < \xi <$$

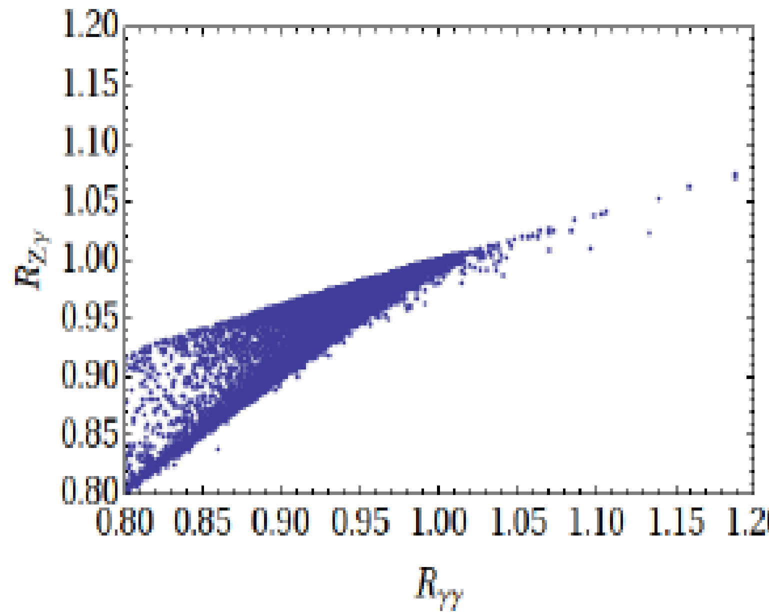


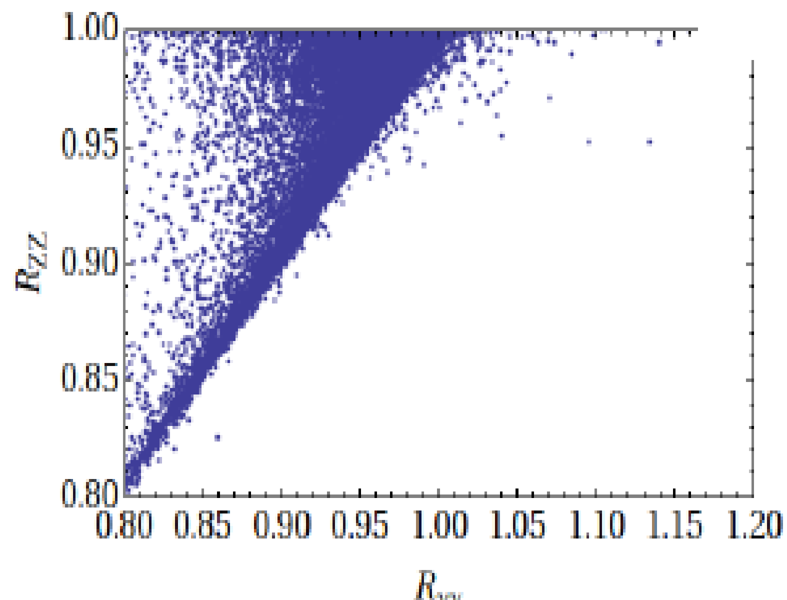
IDMS vs LHC data

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

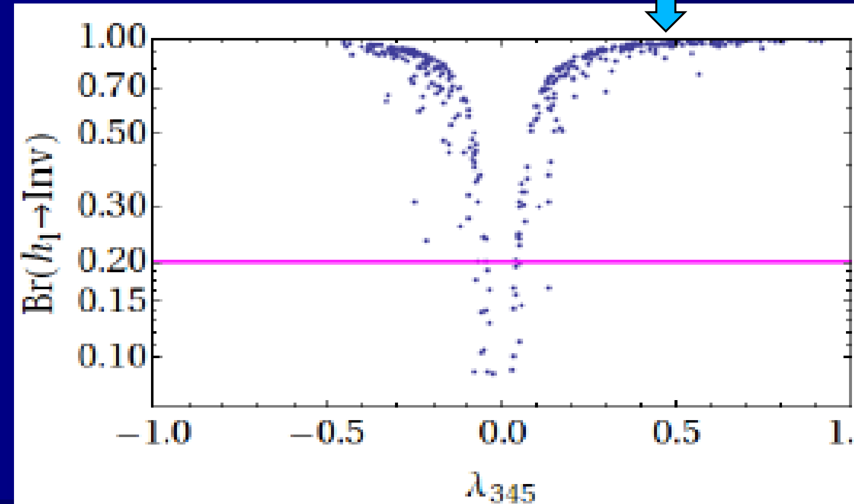
$$XX = gg, VV^*$$







Br h_1 → inv



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

We proposed benchmarks – eg.

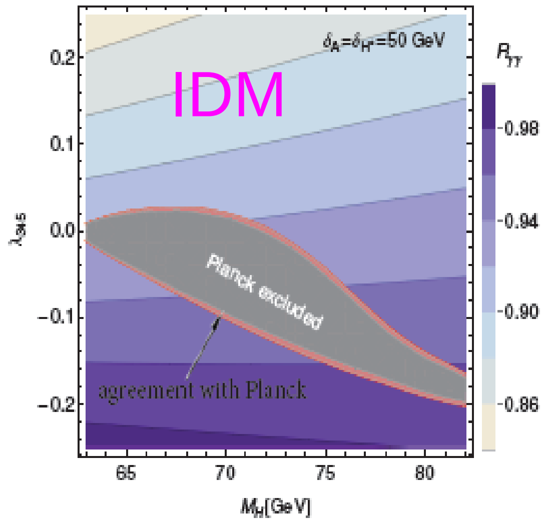
$$\textbf{A1}: \; M_{h_1} = 124.83\text{GeV}, \; M_{h_2} = 194.46\text{GeV}, \; M_{h_3} = 239.99\text{GeV},$$

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

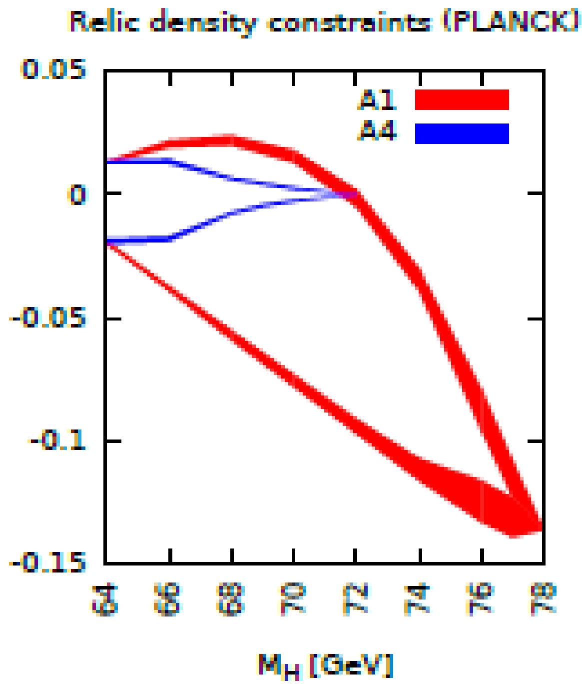
If one of extra Higgs is lighter than 2 M_W as for A4 – difference with IDM! Higgs portal via h_2

NEW . CP violation in the Higgs sector changes the annihilation channels; for example, channels like $HH \to h_i \to Zh_j$ can appear and significantly change the relic density value if DM particle is heavy enough.

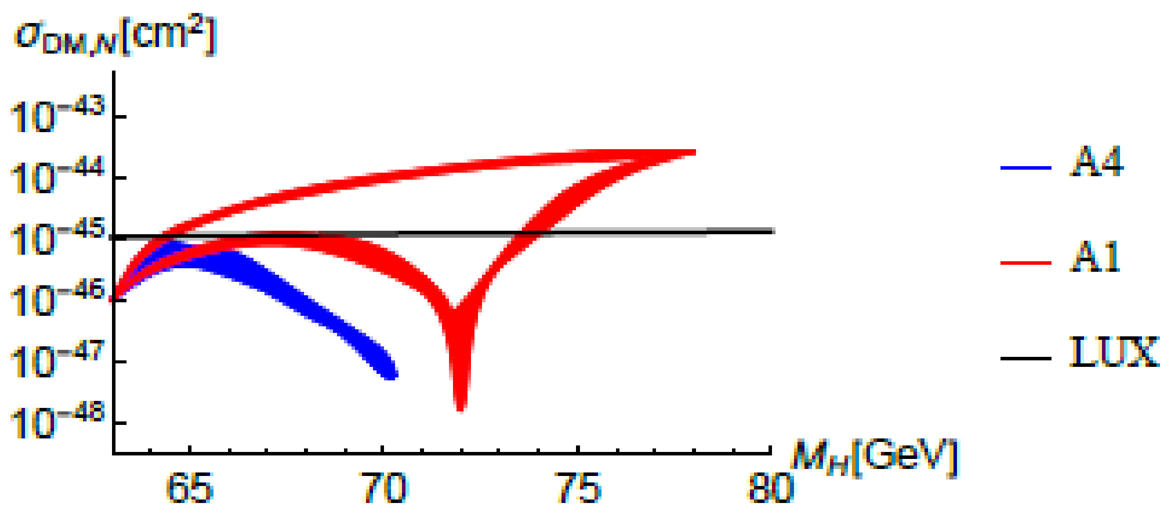
IDMS



IDM
$\delta_A=\delta_{H^\pm}=50$ GeV
$R_{\gamma\gamma}$
Planck excluded
agreement with Planck
λ_{345}
M_H[GeV]



Relic density constraints (PLANCK)
A1
A4
M_H [GeV]



$\sigma_{DM,N}$[cm^2]
A4
A1
LUX
M_H[GeV]

Evolution of Universe to the Inert Phase

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

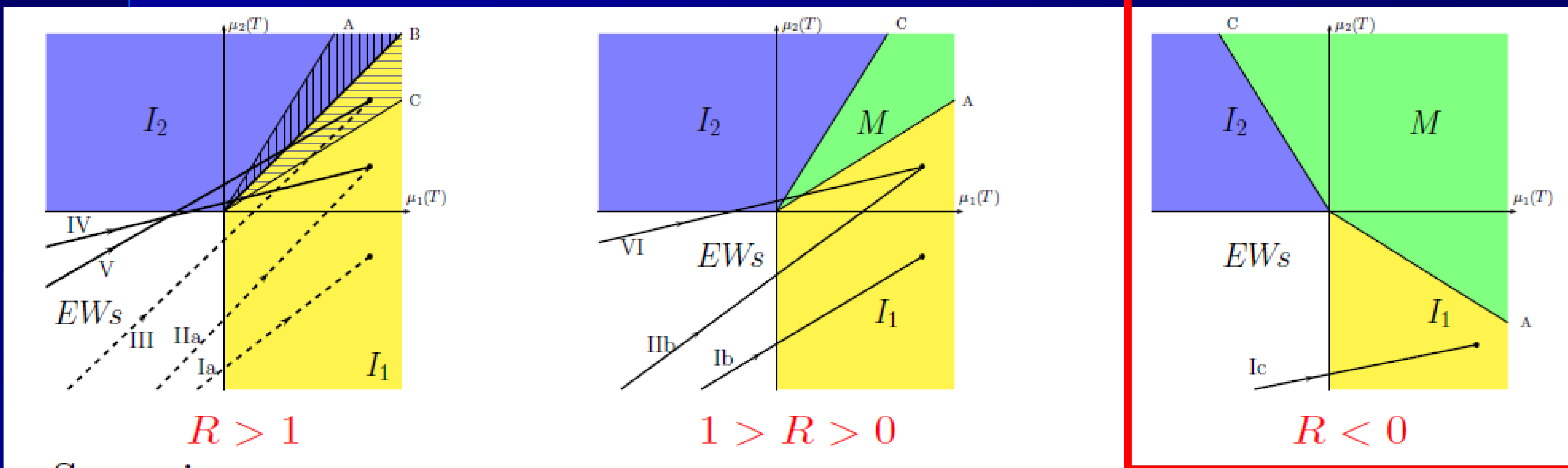
Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev,MK, Sokołowska PRD 2010,
Sokołowska 2011

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 λ'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

$EWs \to I_2 \to I_1$



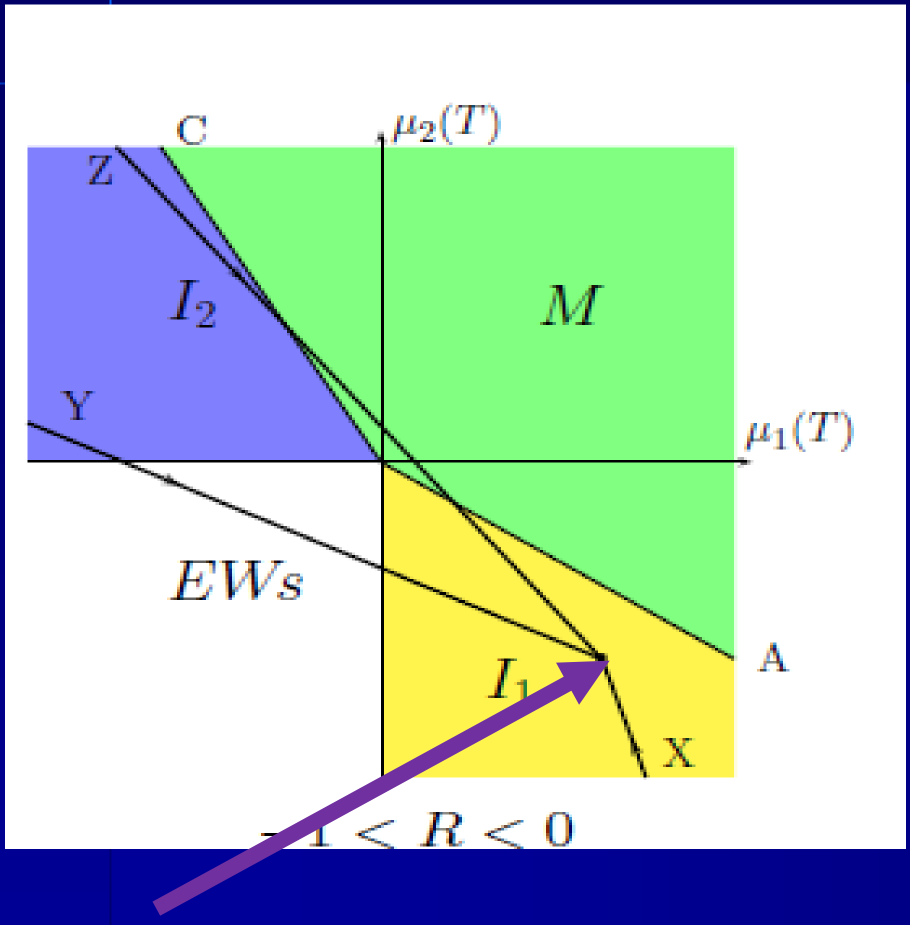
$EWs \to I_1$

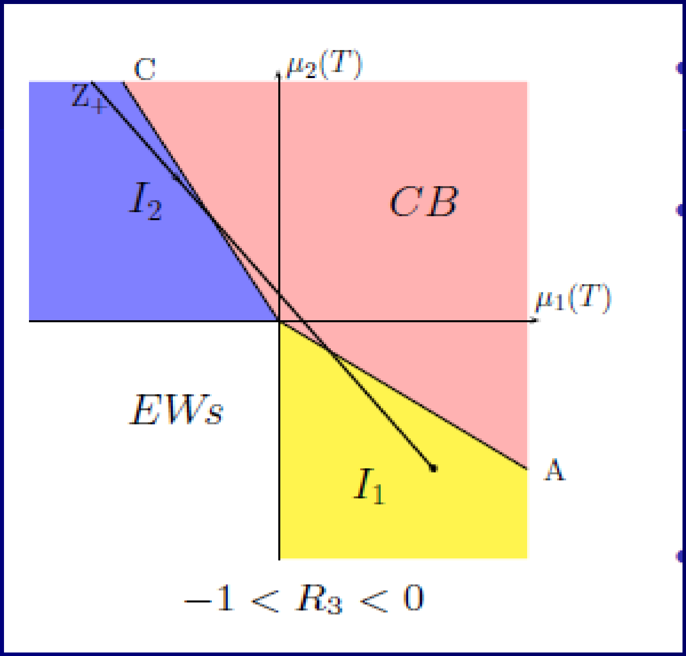
T[2] corrections

→ 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)

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

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

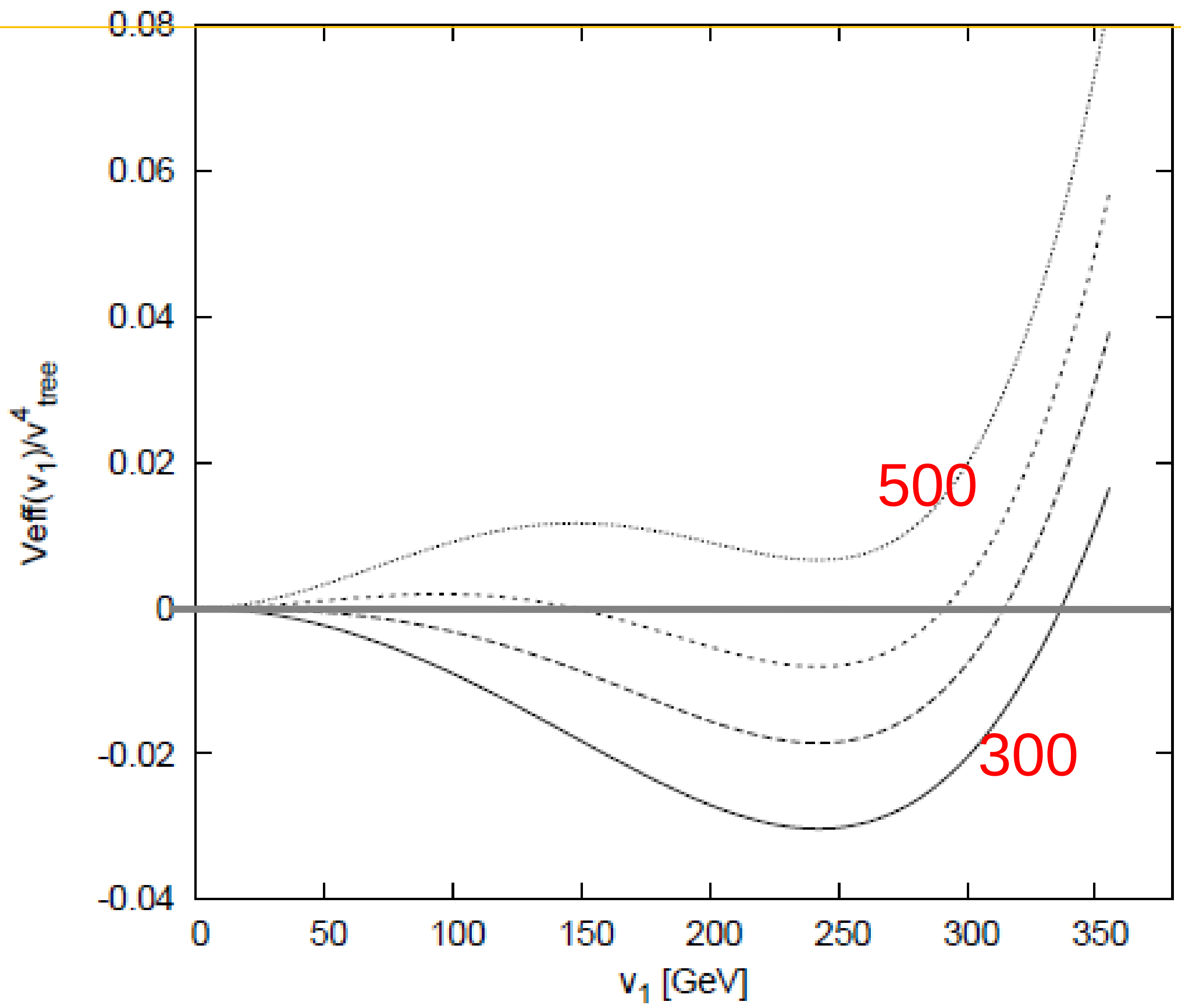
mass matrices

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

number of states

counter terms →

Effective T=0 potential



Mh=125 GeV

MH=65 GeV

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

λ_{345}=0.2,
λ_2=0.2

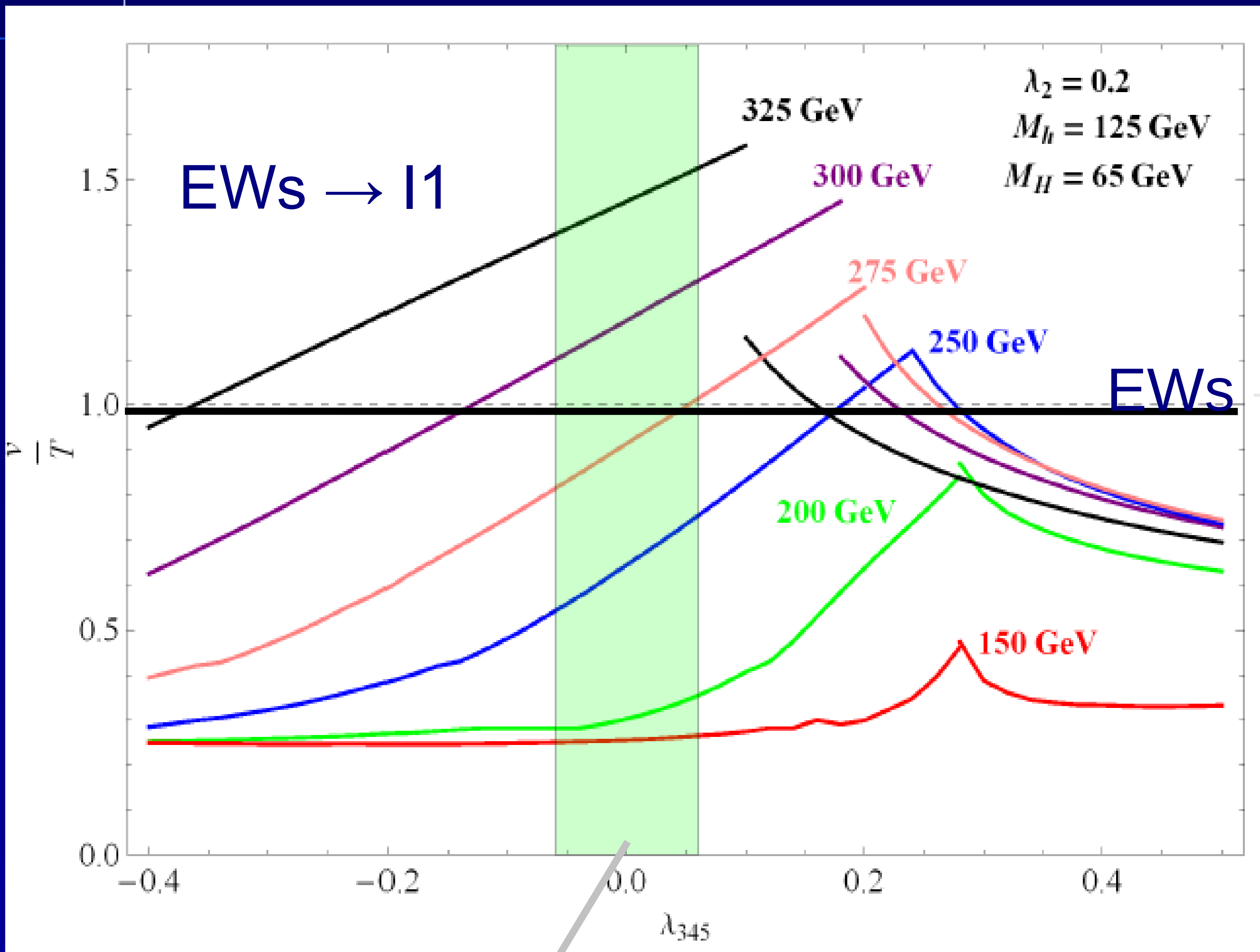
$v_{2(D)}=0$

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



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

λ_{345}

R<0 Xenon100 bound R>0

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 !