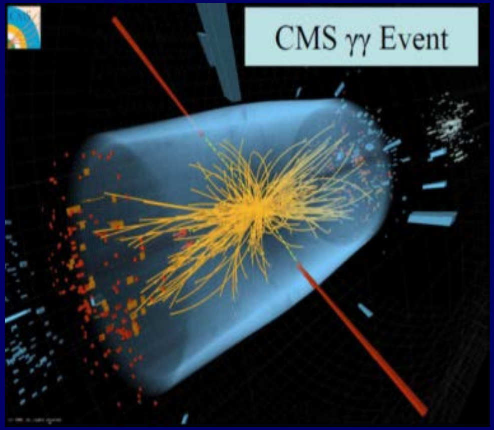
Humboldth Kolleg, Kitzbuhel,1.07.2016

The Universe in the light of LHC data



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

Higgs particle at LHC – July,1 2016
ATLAS+CMS Run 1

arXiv:1606.02266v1 [hep-ex] 7 Jun

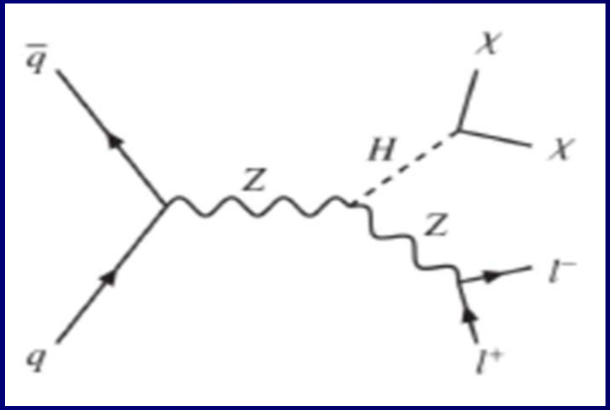
- Mass 125.09 ± 0.24 GeV   ZZ → 4 l, $\gamma\,\gamma$
- Total width < 23 MeV (95%CL); SM ~4 MeV
- Signal strengths ; SM = 1

→ global 1.09 ± 0.11/0.10

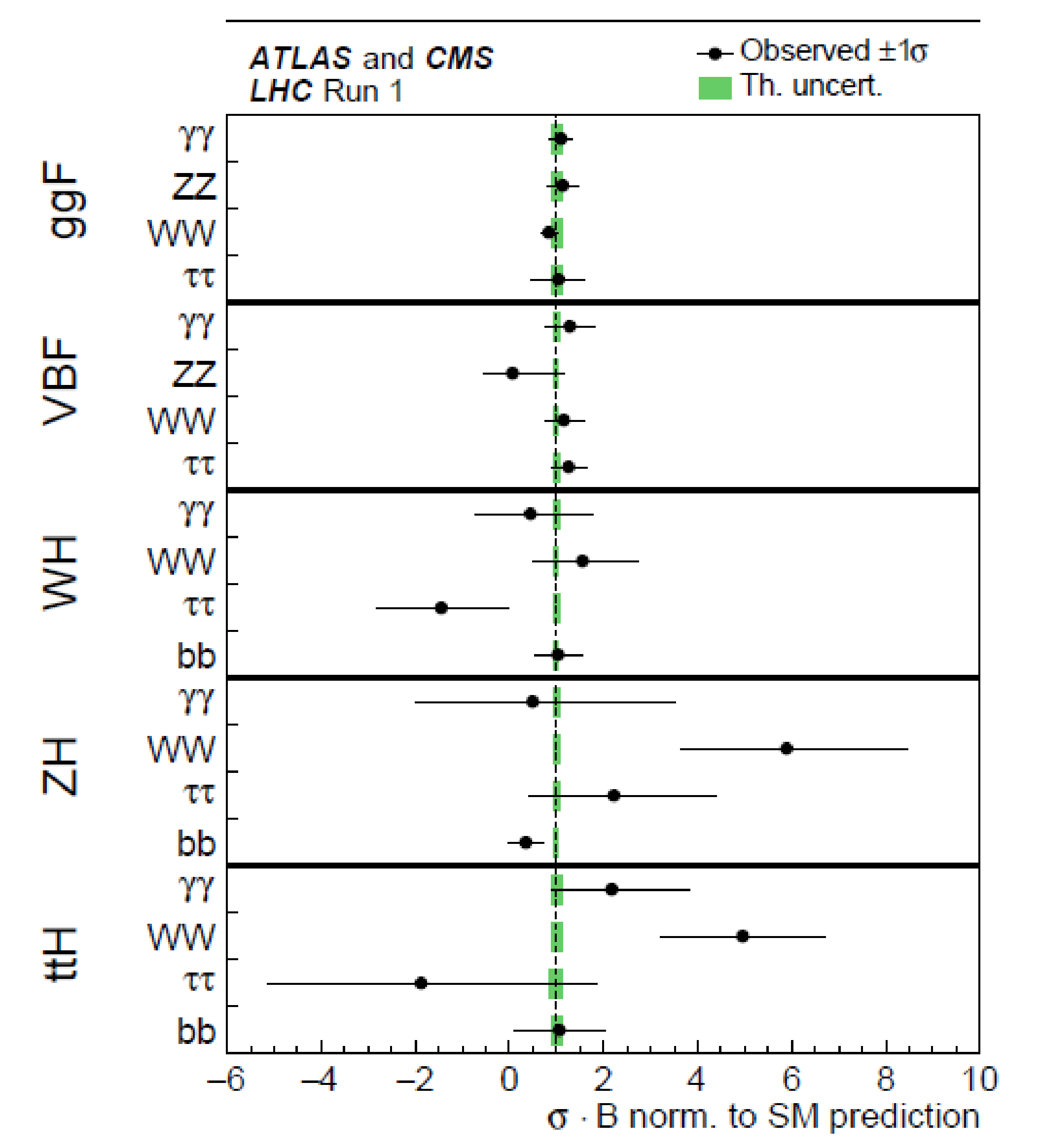
$\gamma\gamma$ 1.14 ± 0.19/0.18

- Invisible decay

  BR < 0.34 (95% CL)
- Spin/CP J^{CP} 0 +



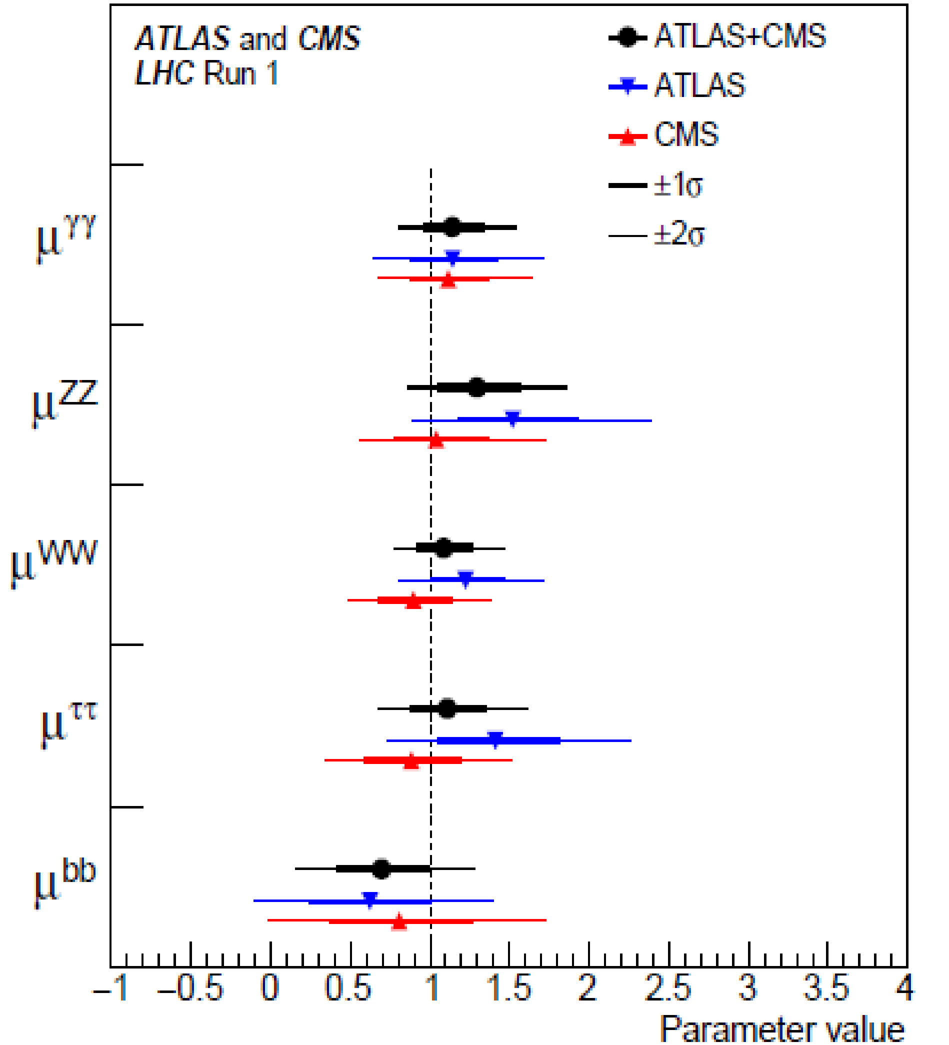
ATLAS+CMS (June 2016)



signal strength
(run 1 = 7+8 TeV)

ATLAS+CMS (June 2016)

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.14^{+0.19}_{-0.18}$ $\left(^{+0.18}_{-0.17}\right)$
μ^{ZZ}	$1.29^{+0.26}_{-0.23}$ $\left(^{+0.23}_{-0.20}\right)$
μ^{WW}	$1.09^{+0.18}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$
$\mu^{\tau\tau}$	$1.11^{+0.24}_{-0.22}$ $\left(^{+0.24}_{-0.22}\right)$
μ^{bb}	$0.70^{+0.29}_{-0.27}$ $\left(^{+0.29}_{-0.28}\right)$
$\mu^{\mu\mu}$	$0.1^{+2.5}_{-2.5}$ $\left(^{+2.4}_{-2.3}\right)$



Signal strength, 7+8 TeV, assuming production as in the SM

125 GeV particle

What it is?

h_{SM} - Higgs boson of SM ?

h or H of CP-conserving 2HDM, MSSM ?

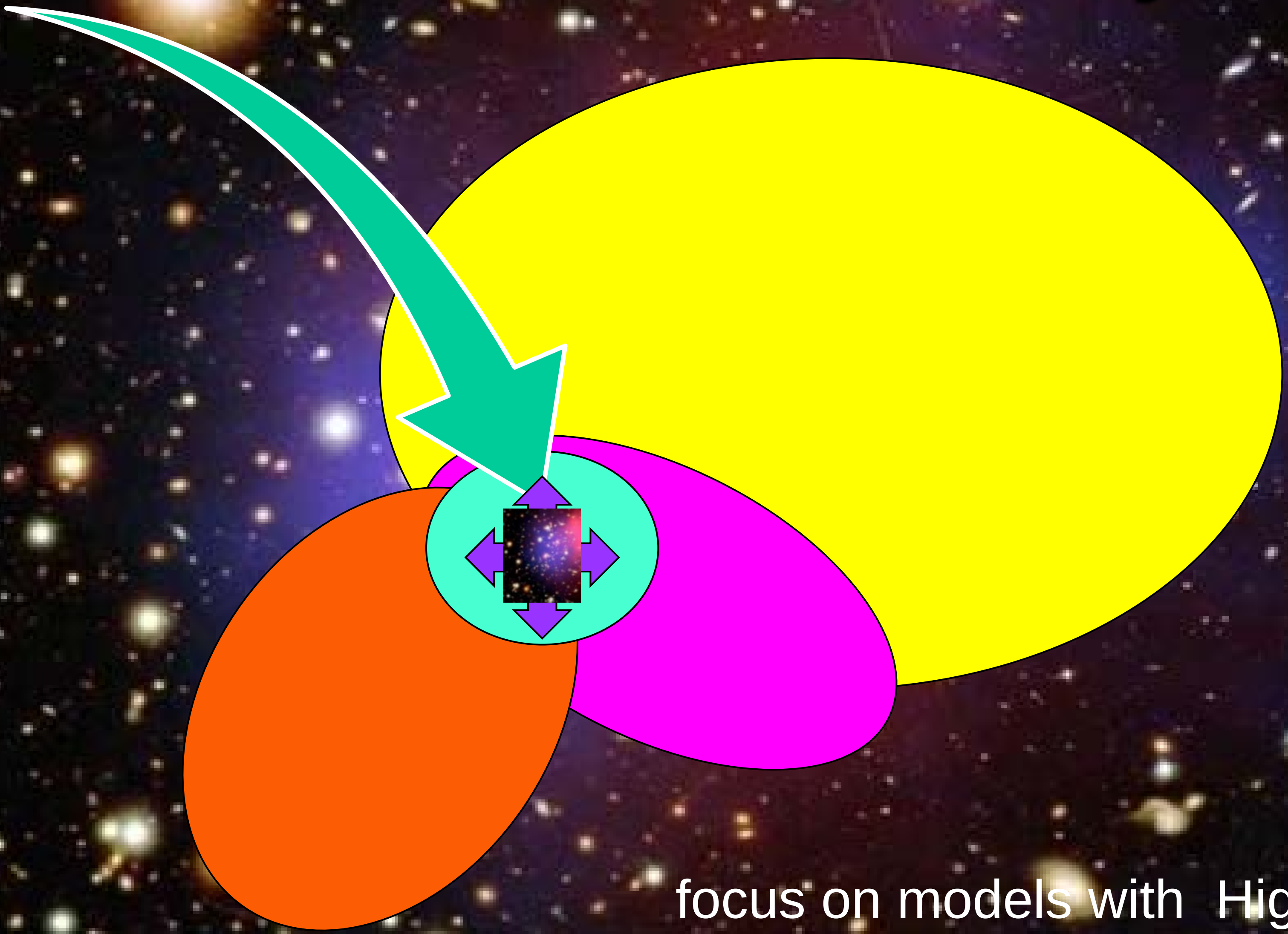
other scalar particle ?

SM-like scenario observed: all direct couplings are close to the SM predictions

(*for absolute value*)

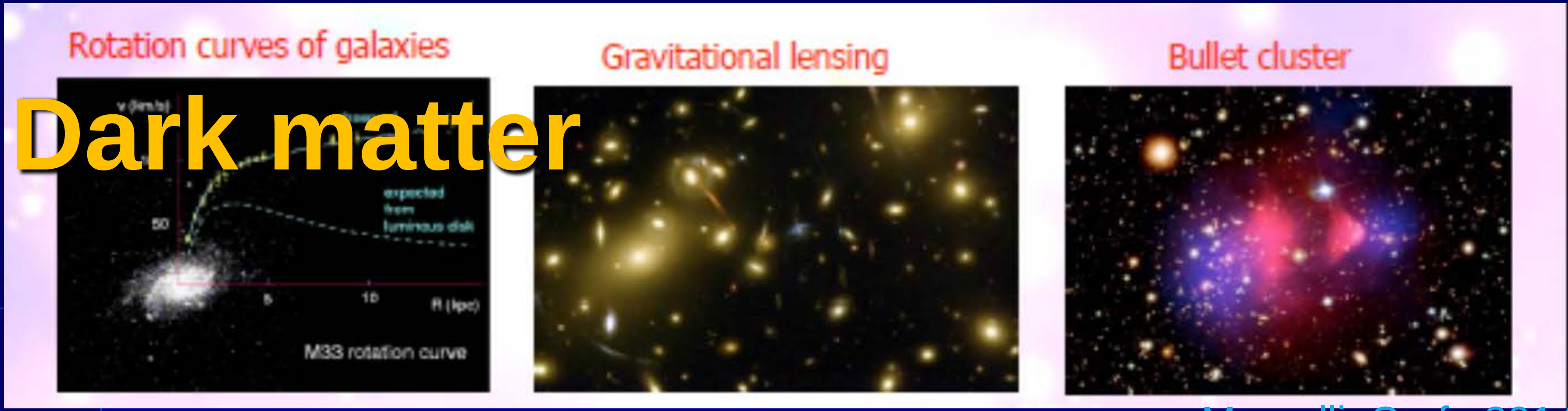
look at decay to **$\gamma\gamma$**, **$Z\gamma$** *- 2001 I. Ginzburg, P. Osland , MK*

SM - like scenario in many models



focus on models with Higgs Portal to the Dark Matter

Dark matter



Morsolli, Corfu 2014

Relic DM density

3 sigma:

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

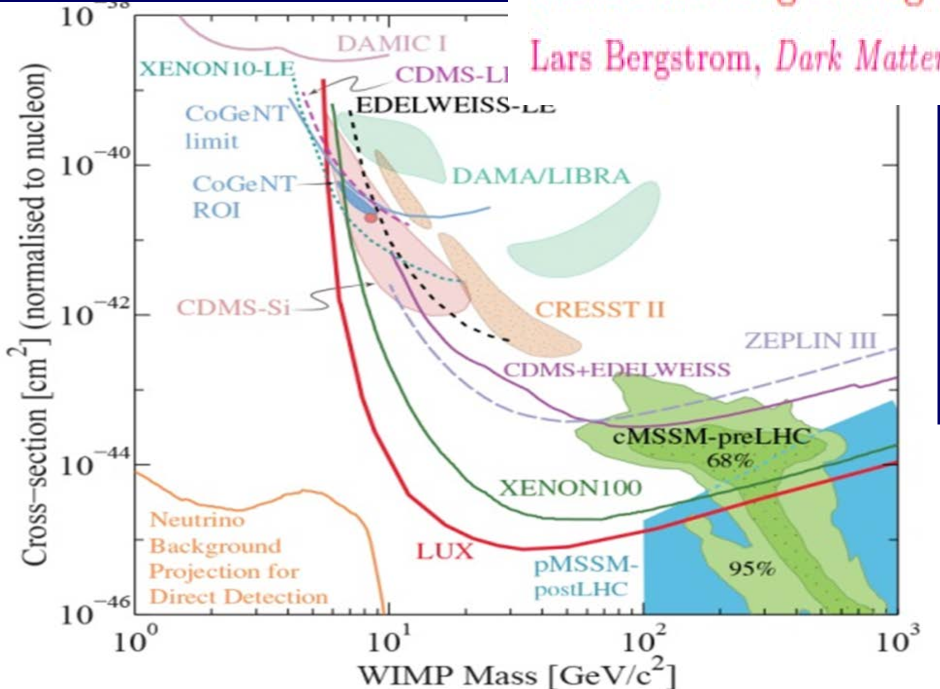
PLANCK $$0.1118 < \Omega_{DM} h^2 < 0.128$$

Direct detection

"One should be aware, however, that this area of investigation is at present beset with large controversies, and one should allow the dust to settle before drawing strong conclusions in either directions."

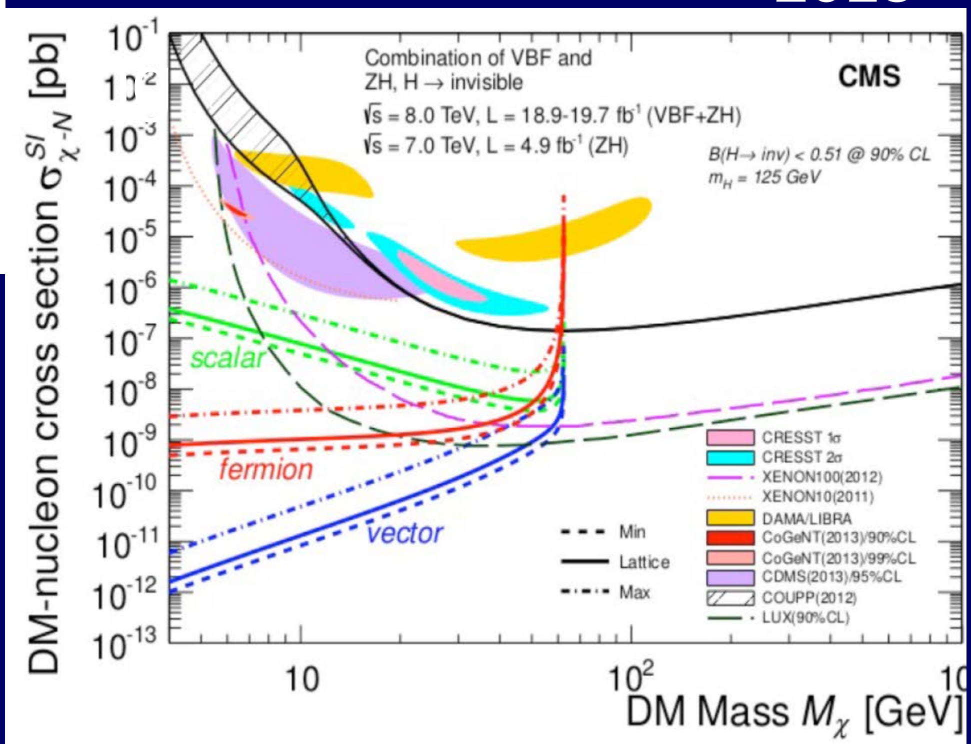
2012

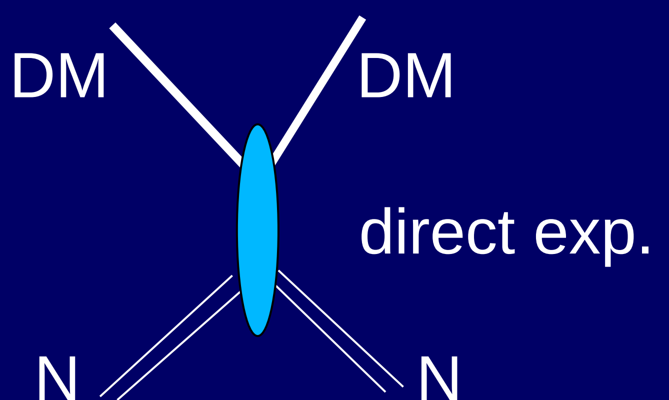
Lars Bergstrom, *Dark Matter Evidence, Particle Physics Candidates and Detection Methods,*



DM N → DM N

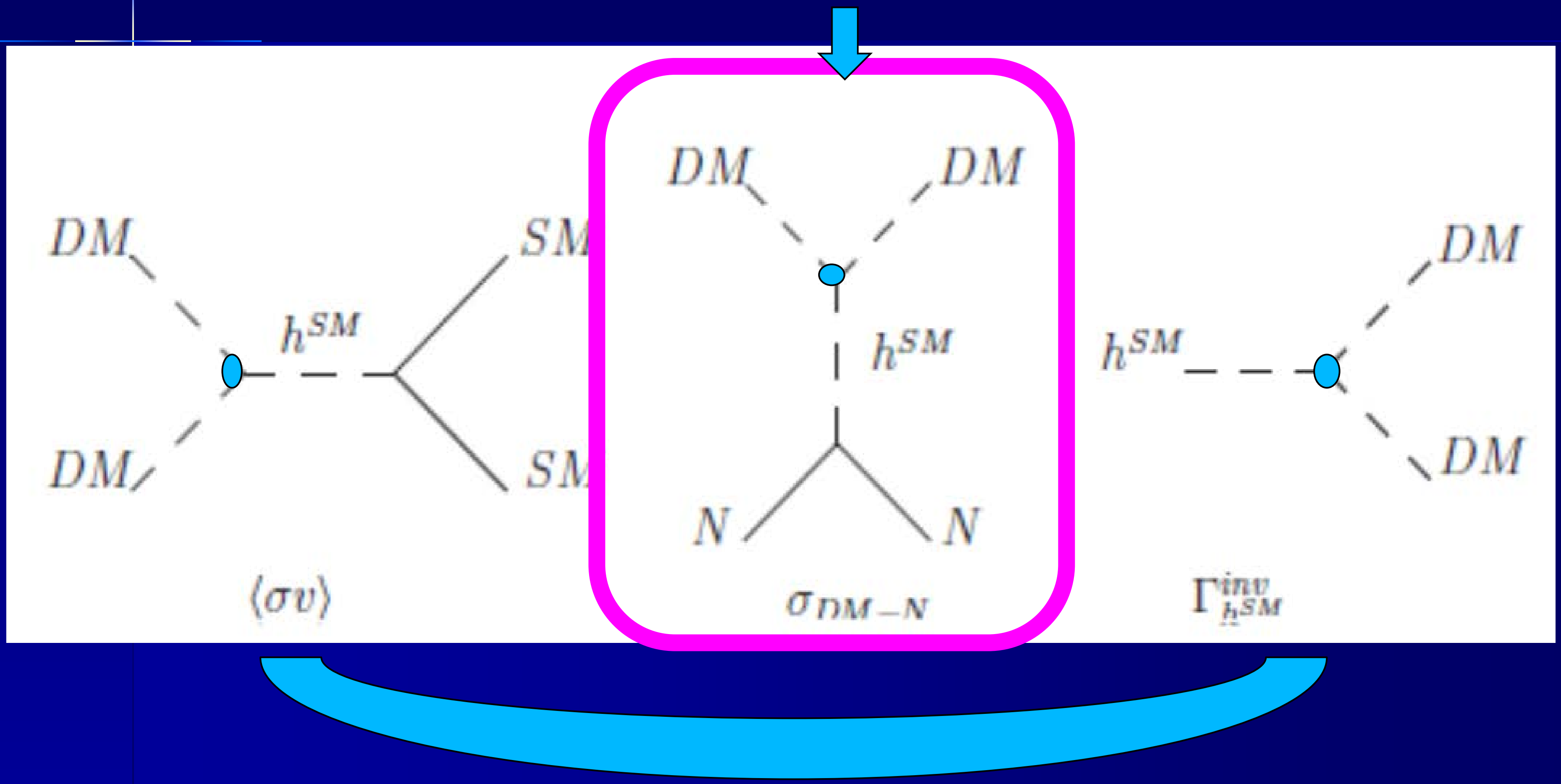
2015



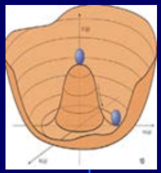


Higgs portal with the SM-like h

direct detection



T.D. Lee 1973



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

2HDM's

Potential

Vacuum

Yukawa

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

Inert Doublet Model (IDM)

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

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

Higgs and Dark Matter sectors 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)*
- 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 =

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

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

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

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

Yukawa interaction

Model I – one doublet 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 $\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2$

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	$v_D = 0$

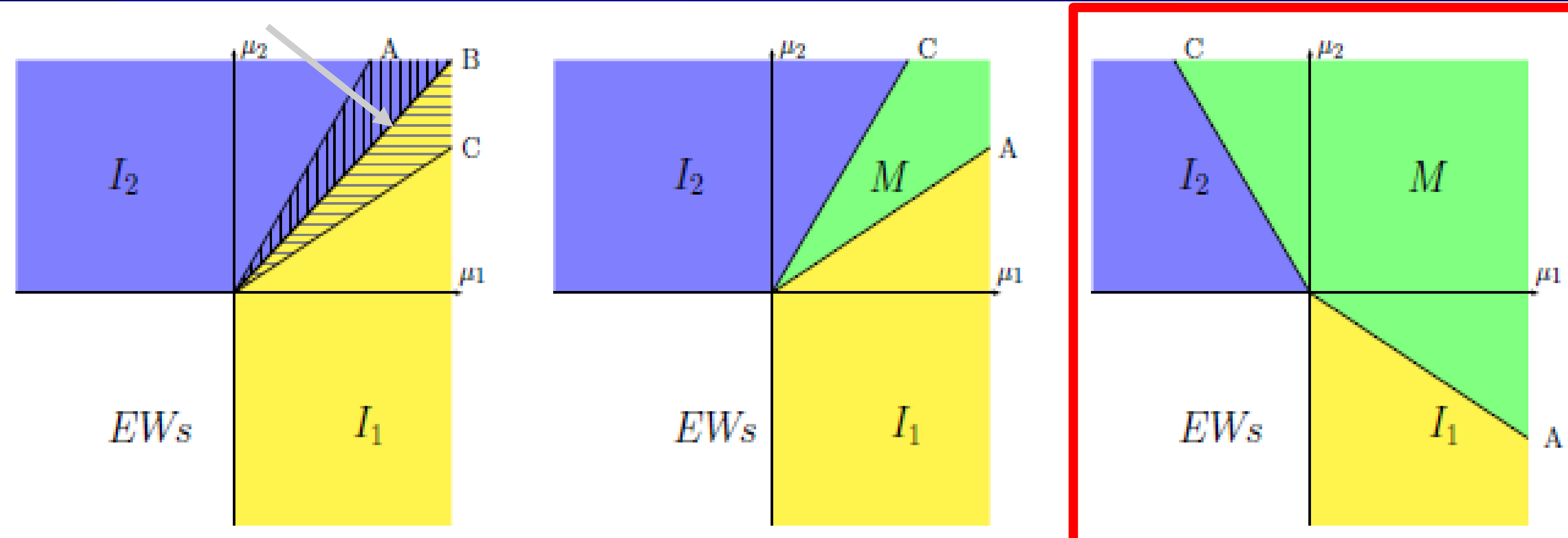
Phase diagrams for D-sym. V

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

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

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

coexistence of
I_1 and I_2 minima



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

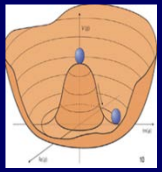
Inert (I_1) vacuum
for M_h=125 GeV → fixed μ_1

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 $\Phi_S \rightarrow \Phi_S$ $\Phi_D \rightarrow - \Phi_D$ 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

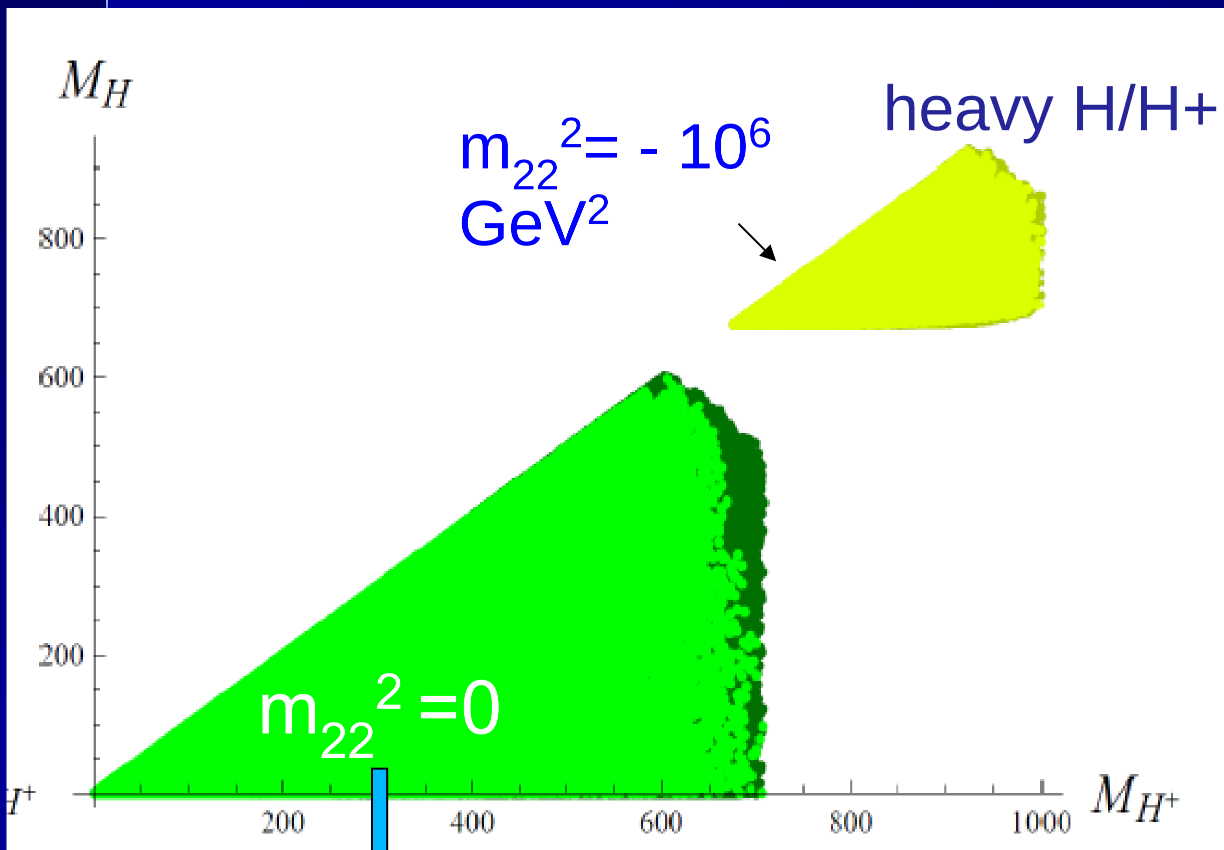
Couplings with Higgs: hHH ~ λ_{345} h H+H- ~ λ_3

Inert Doublet Model with M_h=125 GeV

Świeżewska 2011

m_{22}^2 =0

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



valid up to $|m_{22}^2|$= 10^4GeV^2

Data:

EWPT (S and T)

$S = 0.03 \pm 0.09$

$T = 0.07 \pm 0.08$

$\rho = 87\%$

LEP, no LHC yet

MH+ > 70 GeV

EWPT (pale regions)

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 **γγ**, **Zγ** – extra contributions due to H+

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

Invisible decay

$\gamma\gamma$ 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

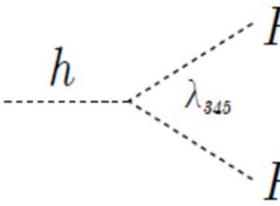
$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

$R_{Z\gamma}$ – treated analogously

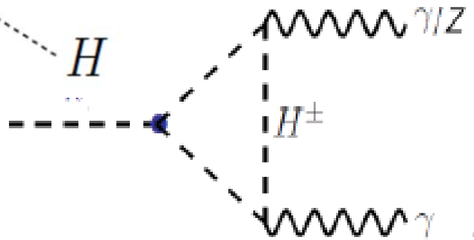
narrow width approx

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



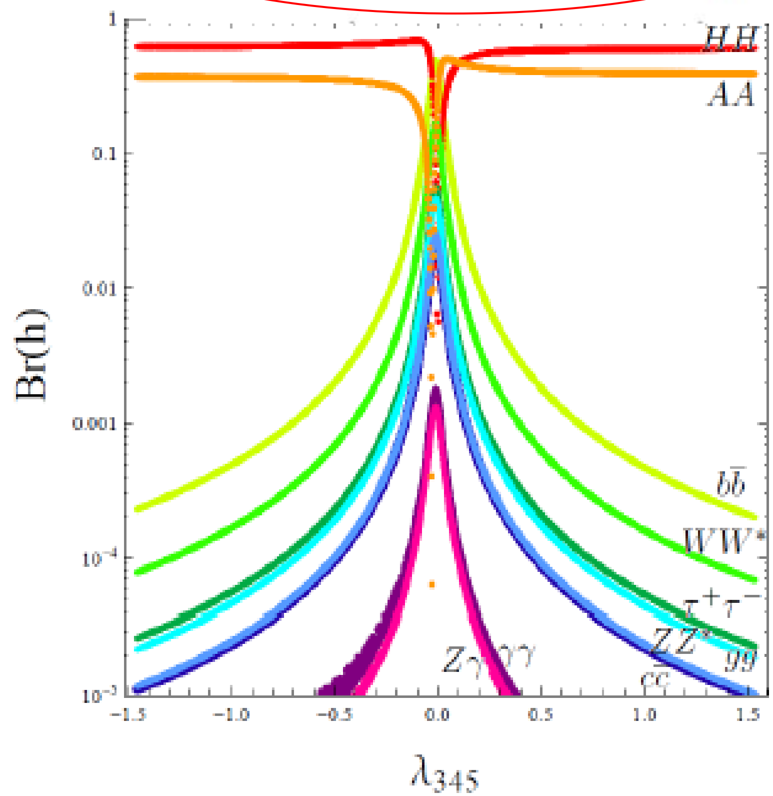
Invisible decays

B. Świeżewska

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

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

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



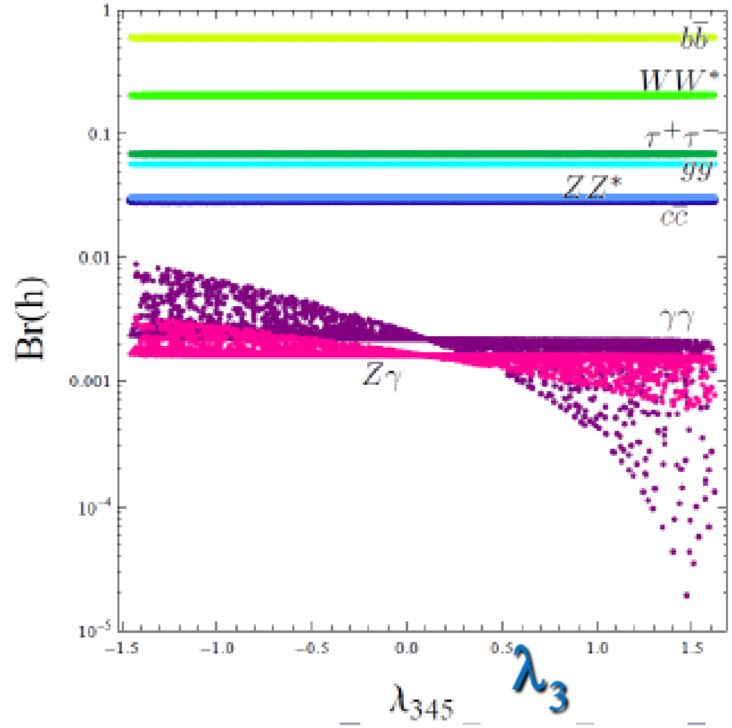
Charged scalar $H^{\pm}$ loop

B. Świeżewska

[J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B 106 (1976) 292, M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, Sov. J. Nucl. Phys. 30 (1979) 711 [Yad. Fiz. 30, 1368 (1979)]

$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \overbrace{\frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2}}^{\lambda_3} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

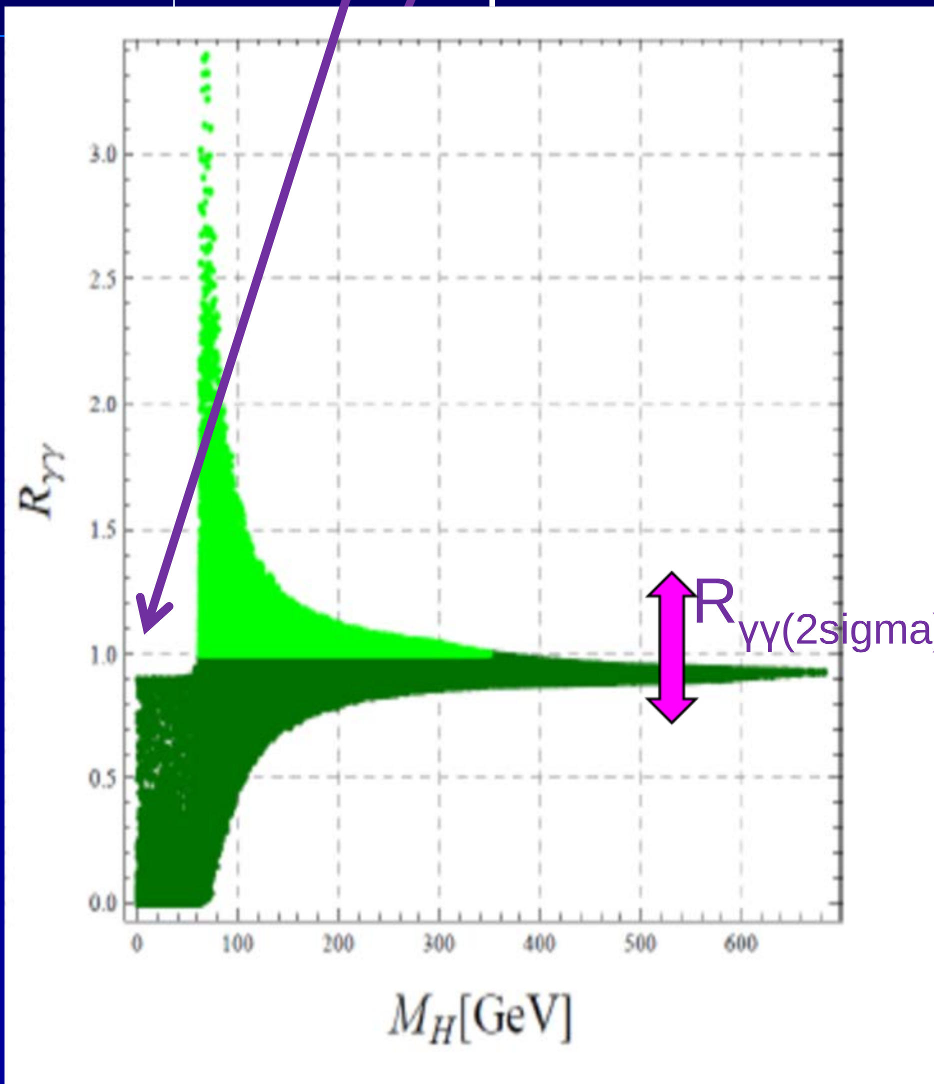
- Constructive or destructive interference between SM and $H^{\pm}$ contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- Invisible channels closed $\Rightarrow H^{\pm}$ contribution visible

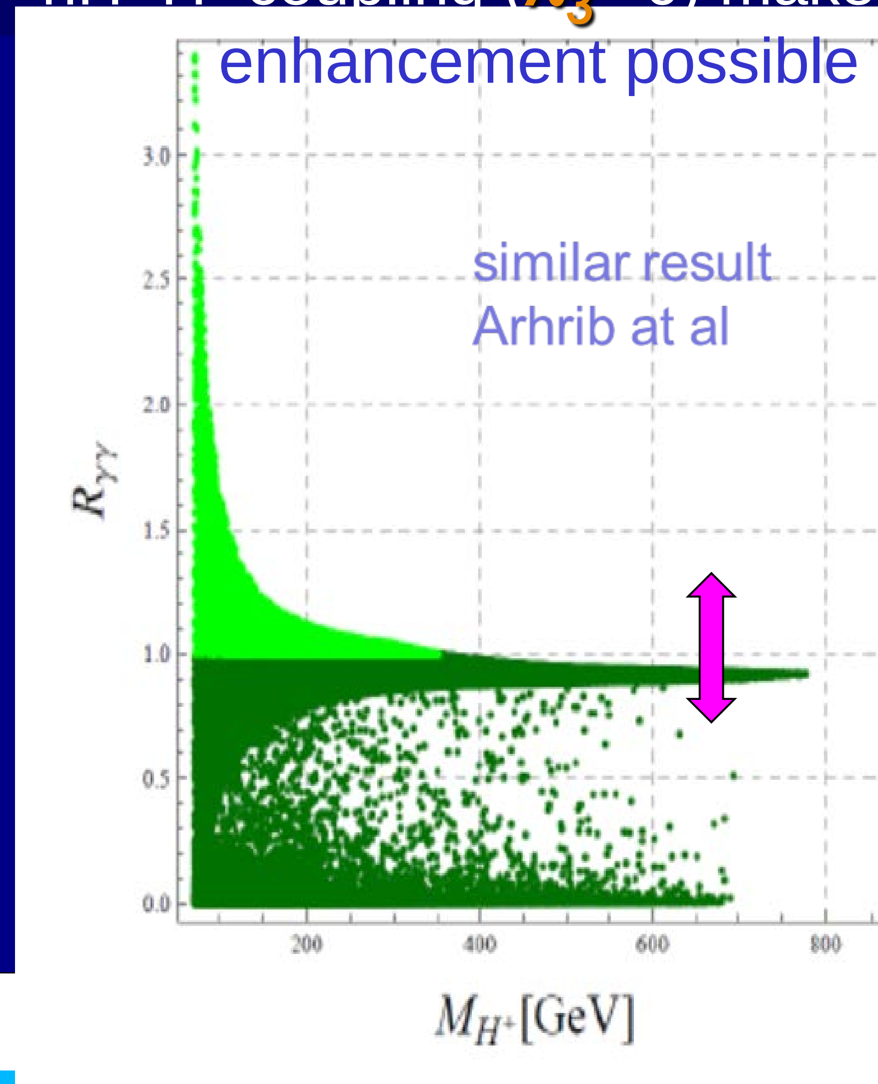


$R_{\gamma\gamma}$ as a function of mass H, H +

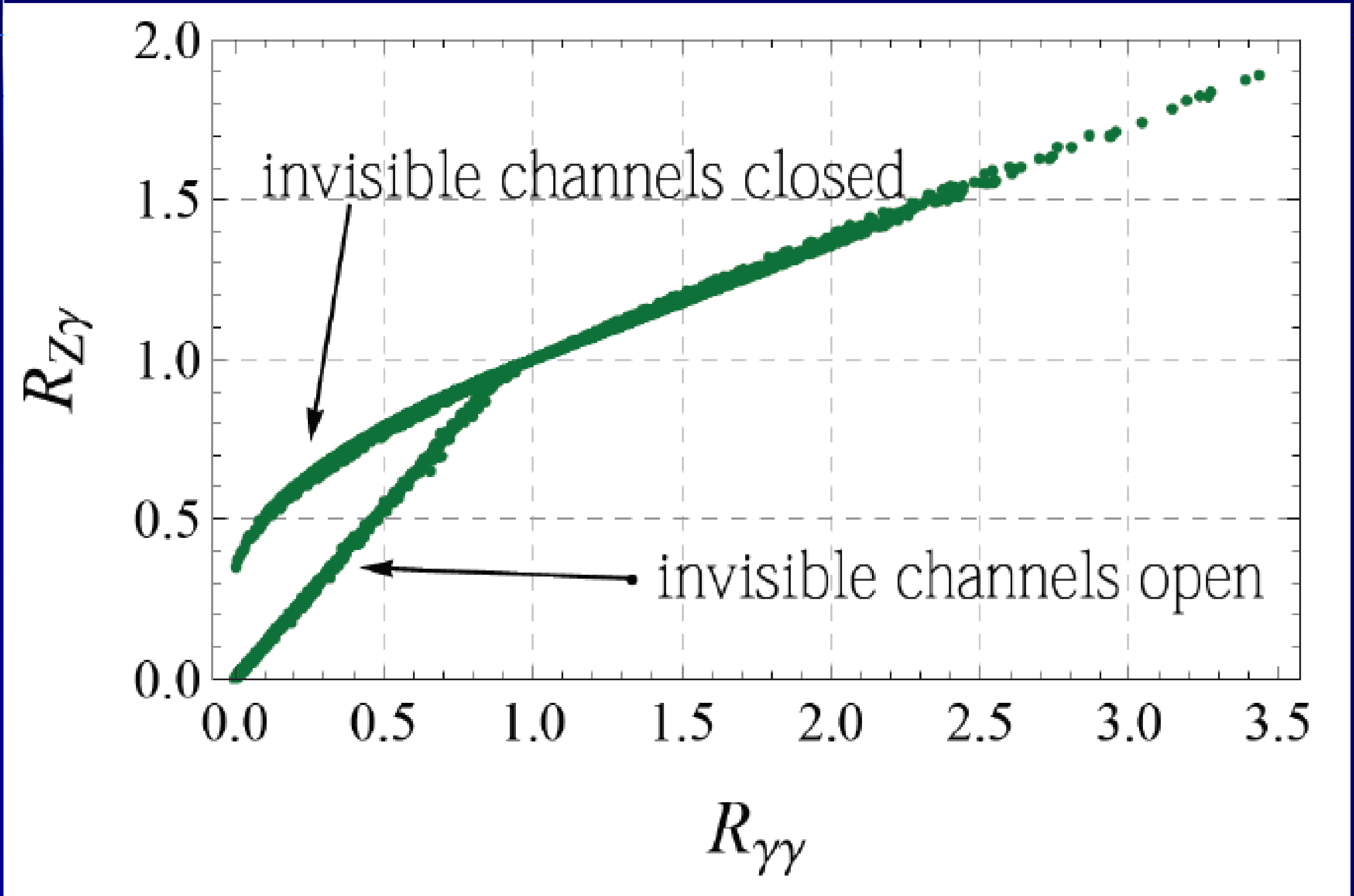
Invisible decays makes enhancement impossible

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



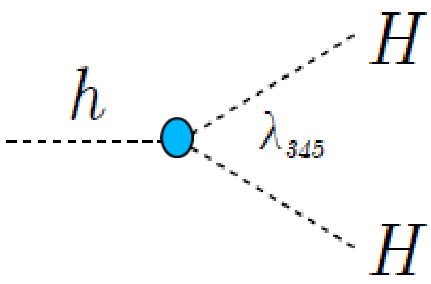


γγ versus Zγ in IDM



Invisible h decay →coupling hHH

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

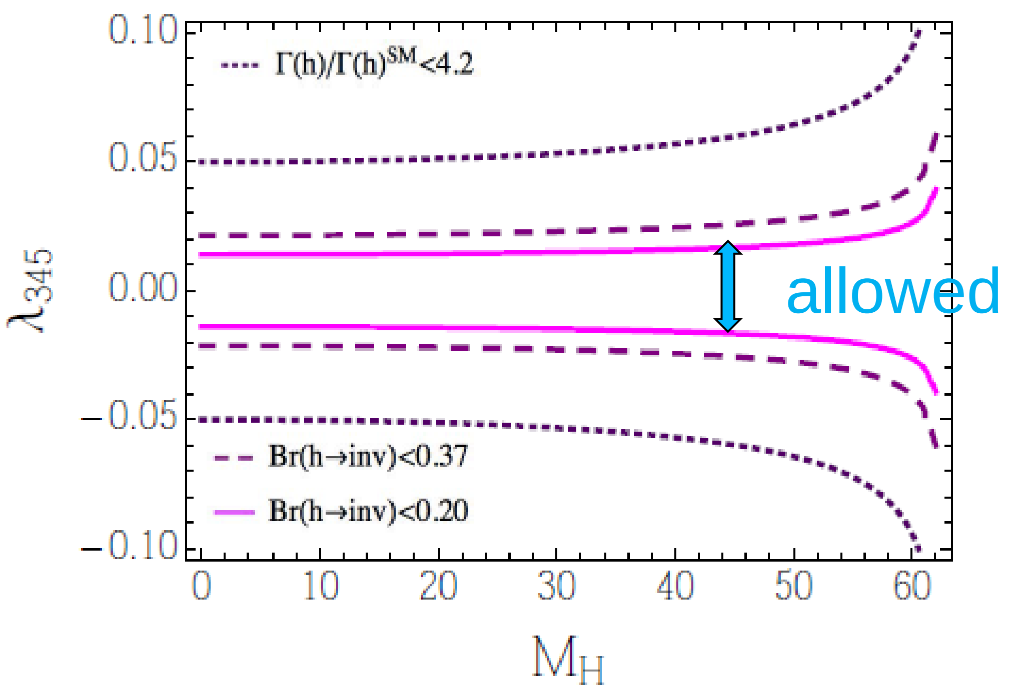


LHC:

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

global fit:

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



[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

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

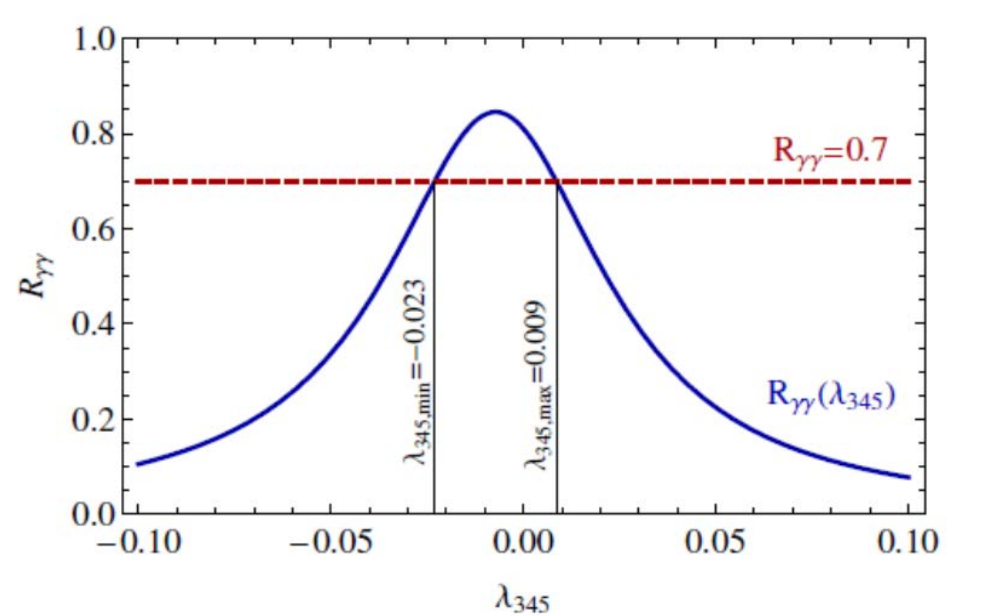
LHC data

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

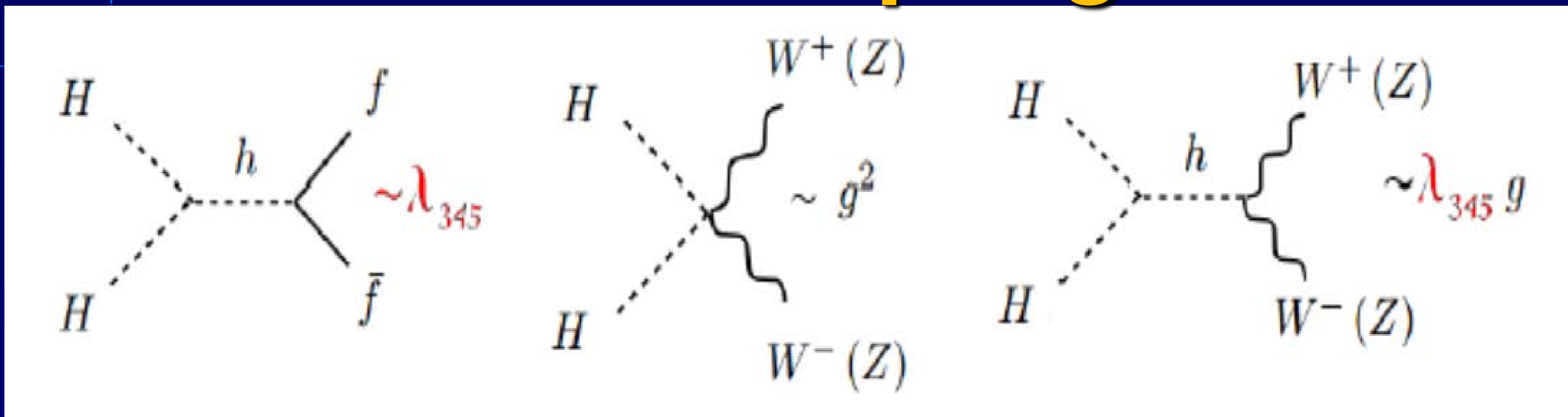
ATLAS+CMS 2016 1.14 ± 0.19

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

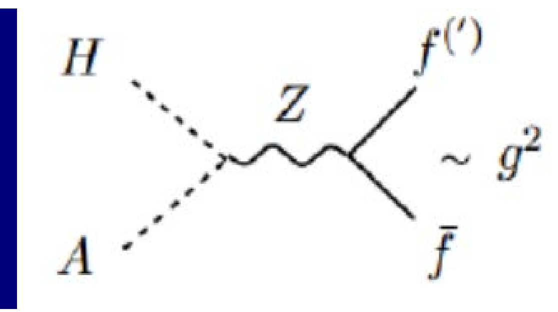
DM mass below 62.5 GeV allowed only if
$R_{\gamma\gamma}$ < 1



Relic density constraints on masses and couplings of DM

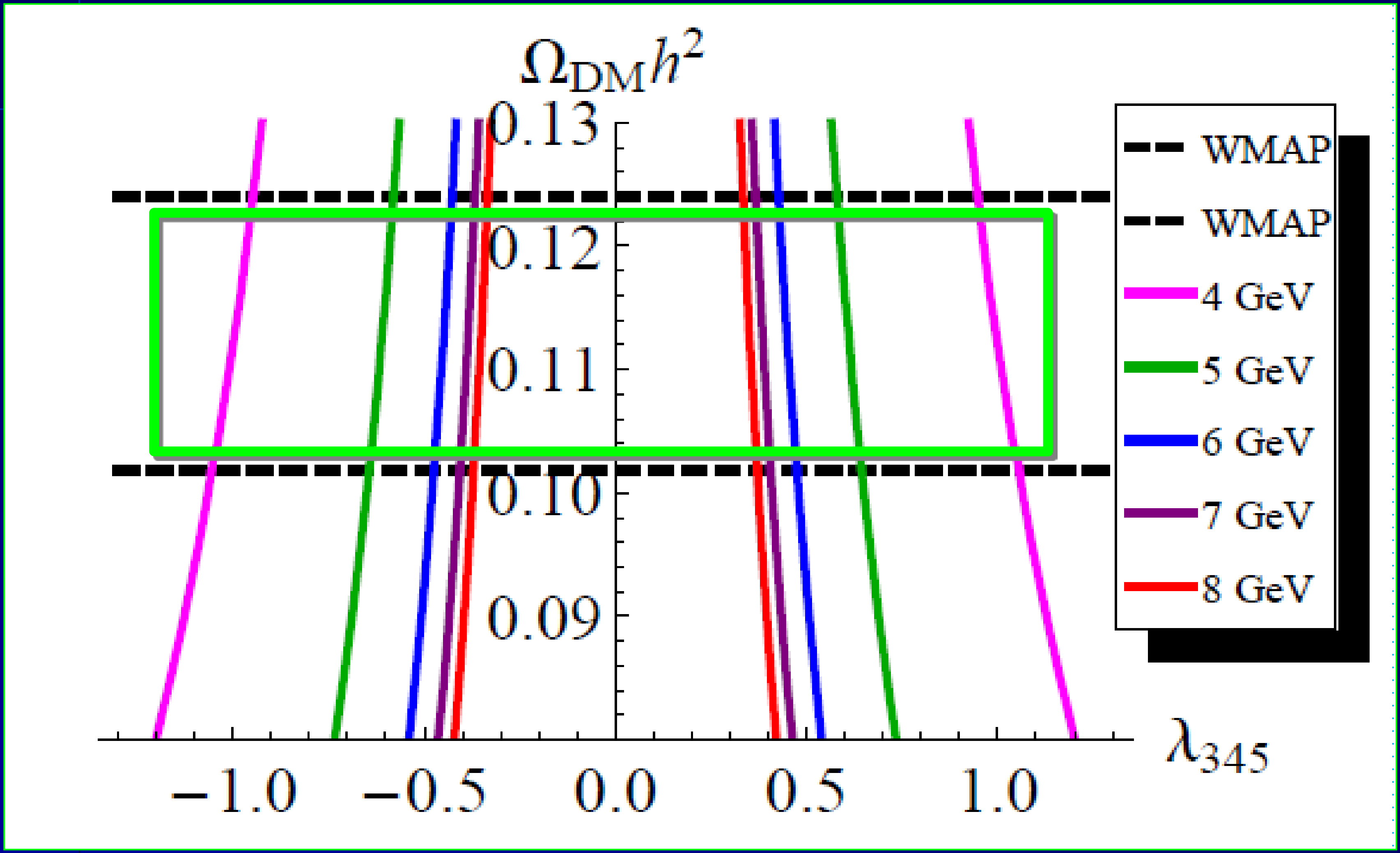


Coannihilation possible
for small (AH) mass splitting



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

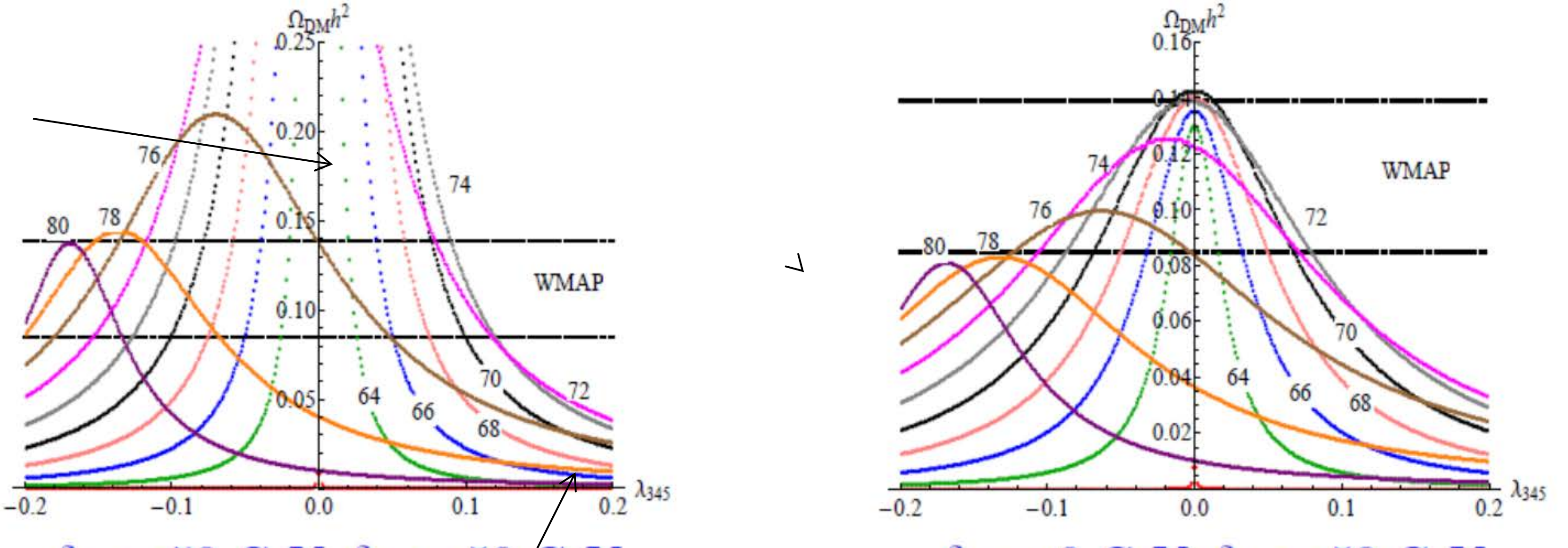
WMAP window for light H (DM)



Relic density for DM with mass 64,…,80 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

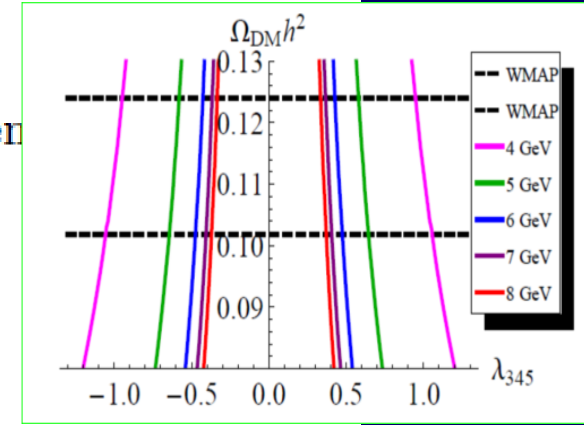
Low mass H – excluded by LHC!

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

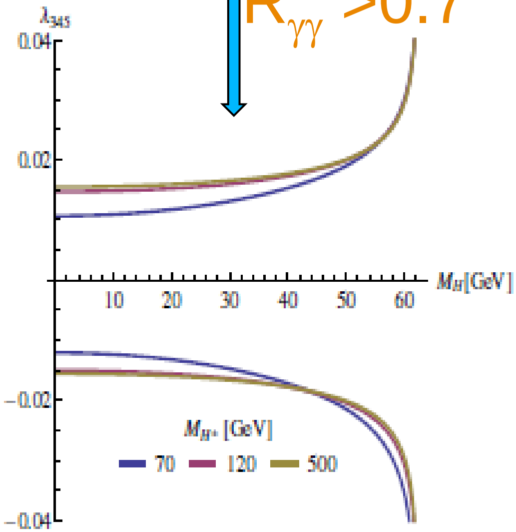
[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

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

$h \to AA$ 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:

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

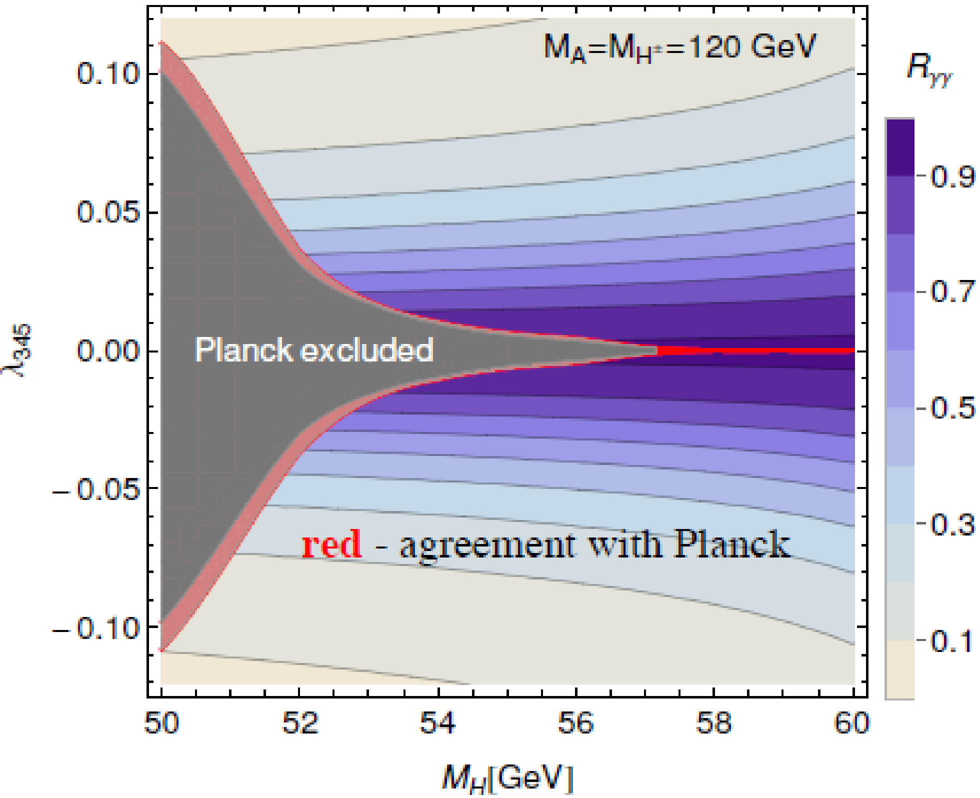
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$

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

New scan for IDM (2015)

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

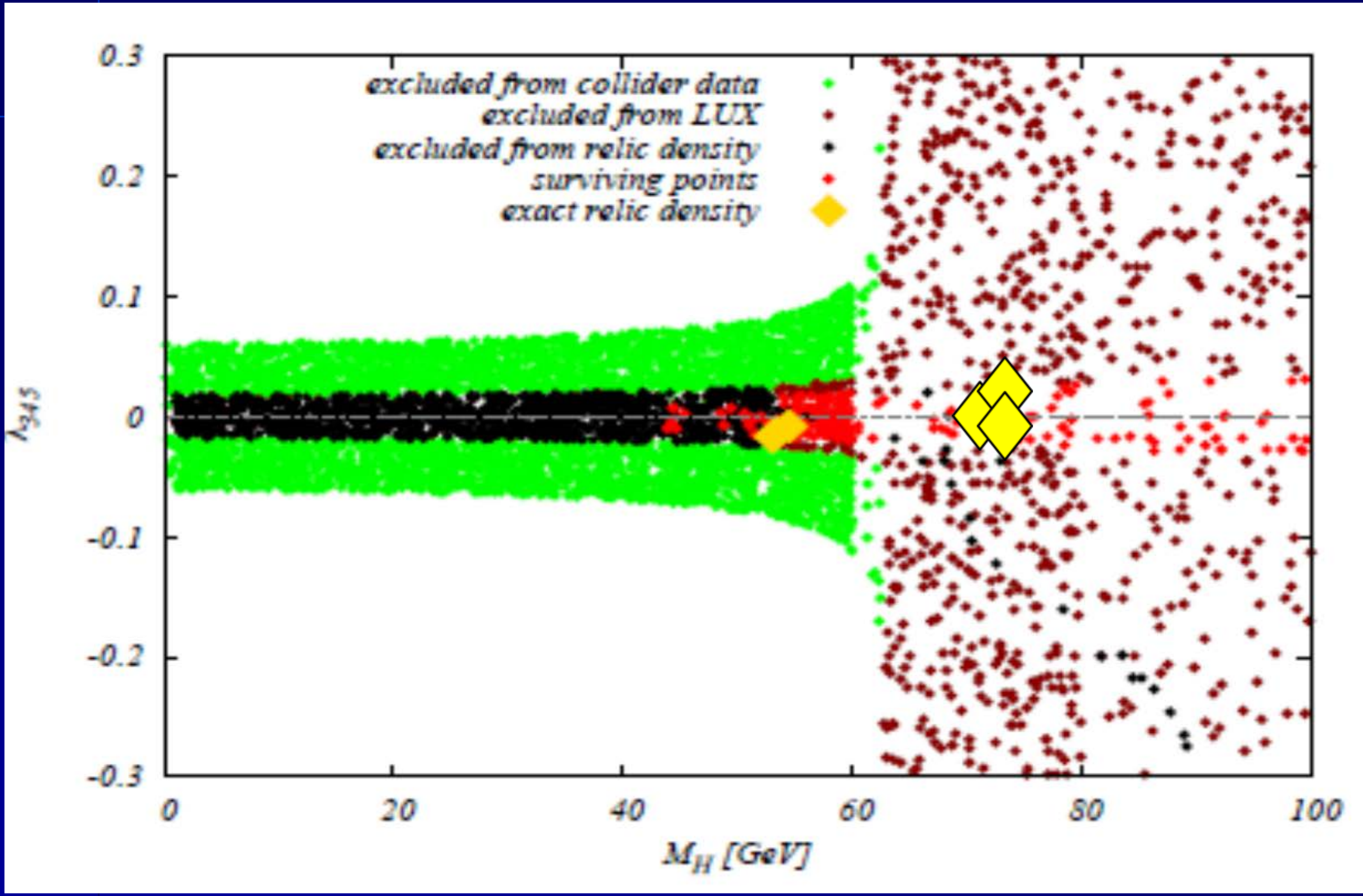
- Theor. constraints –
  stability of the potential (positivity), pert.unitarity, condition for the Inert vacuum
- STU (from 2014)
- Higgssignal/Higgs bounds
- Lifetime of H+ (< 10^{-7} s to decay inside detector)
- Relic density Planck Ω < 0.1241 (95% CL)
- Direct detection LUX
- --> scan over M_H up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

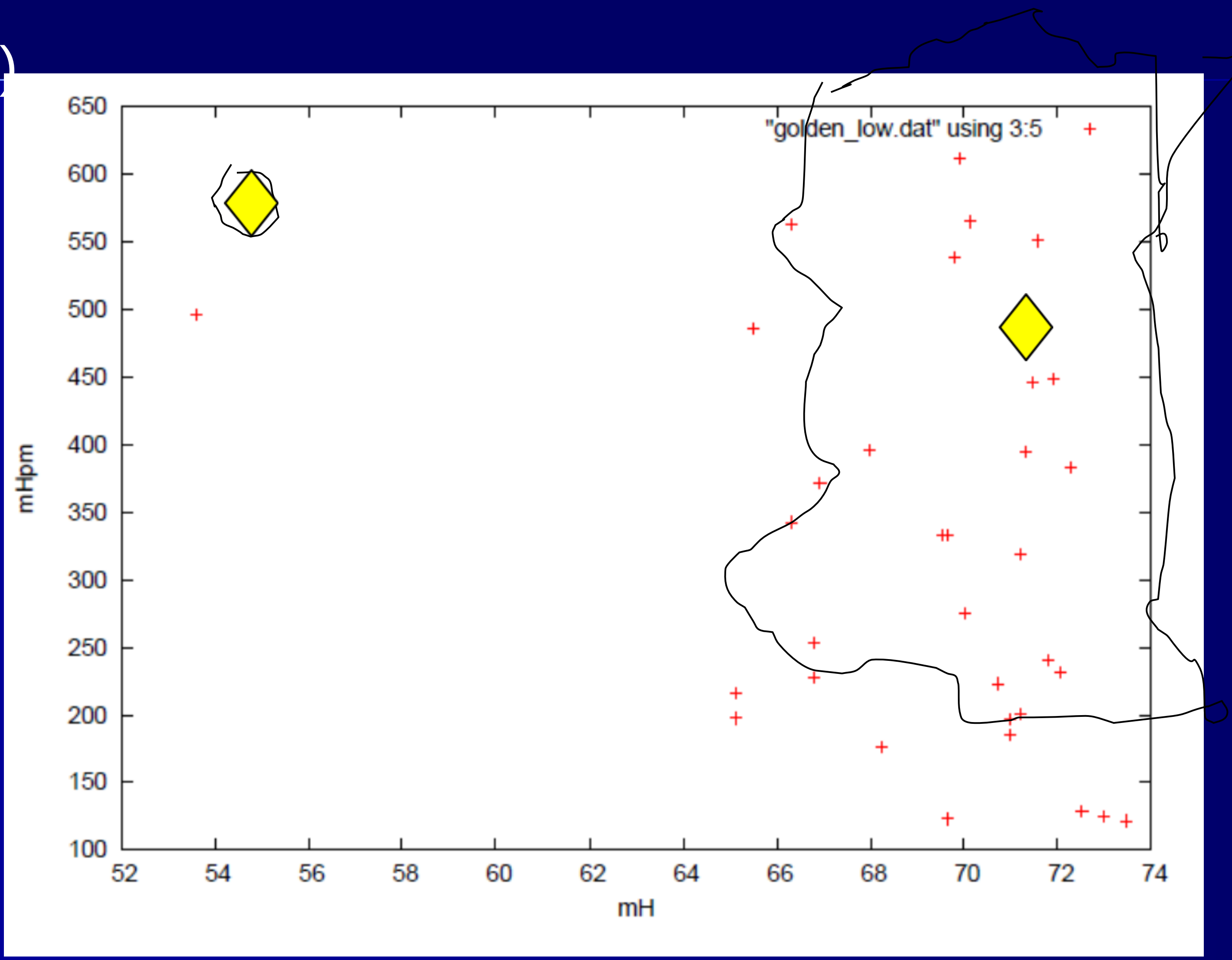


exact relic density

Limit on mass of DM: M_H> 45 GeV !

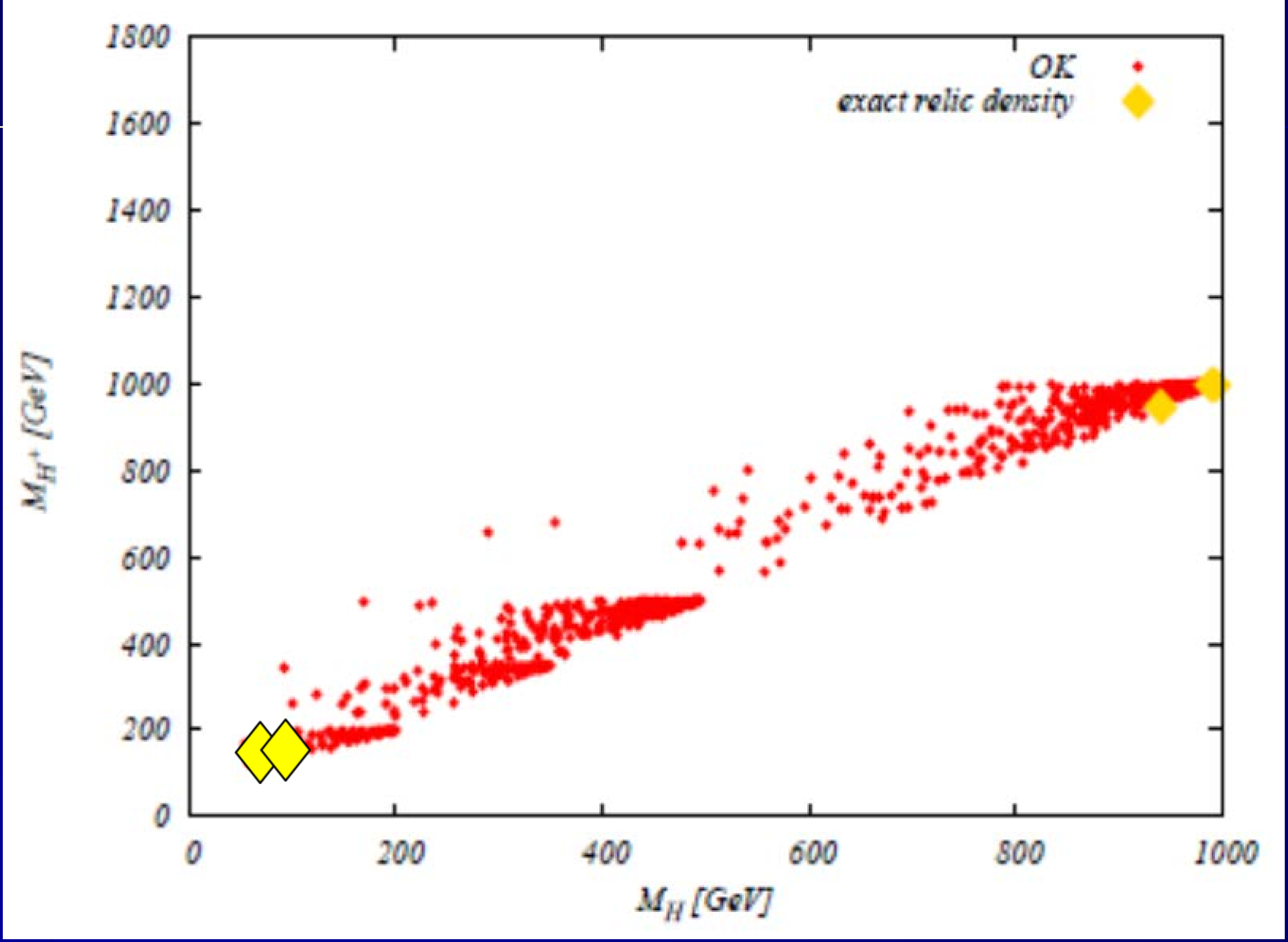
Exact relic density ♦ medium DM mass

MH+ (GeV)



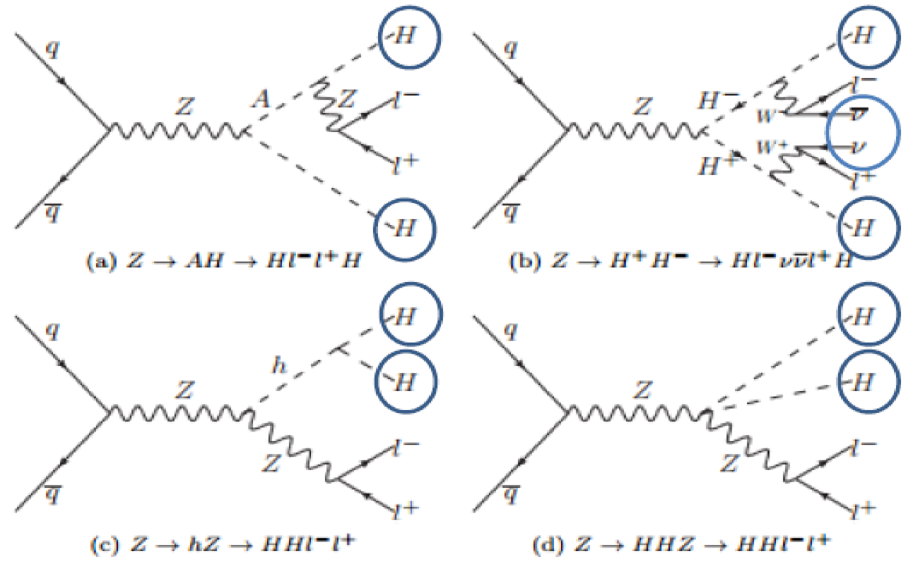
MH (GeV)

dark particles masses



LHC II – HA and H+H- production

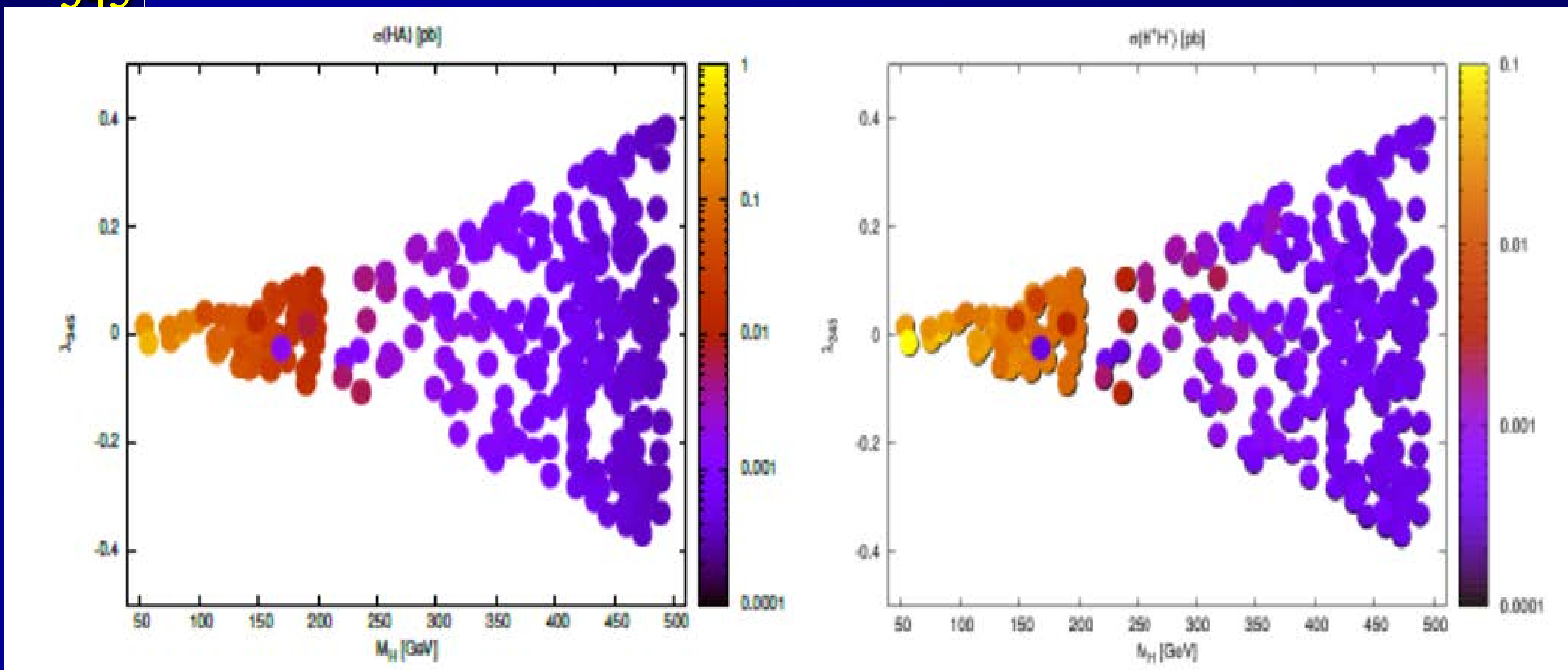
Our signal: 2l+MET



Benchmarks for LHC II

$$pp \to H\,A \;:\; \leq 0.03\,\mathrm{pb},$$
$$pp \to H^+H^- \;:\; \leq 0.01\,\mathrm{pb},$$
$$pp \to A\,A \;:\; \leq 0.0005\,\mathrm{pb},$$

λ_{345} **HA** **H+H-**



M_H

Cross section in pb, mass in GeV

Evolution of Universe to the Inert Phase

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

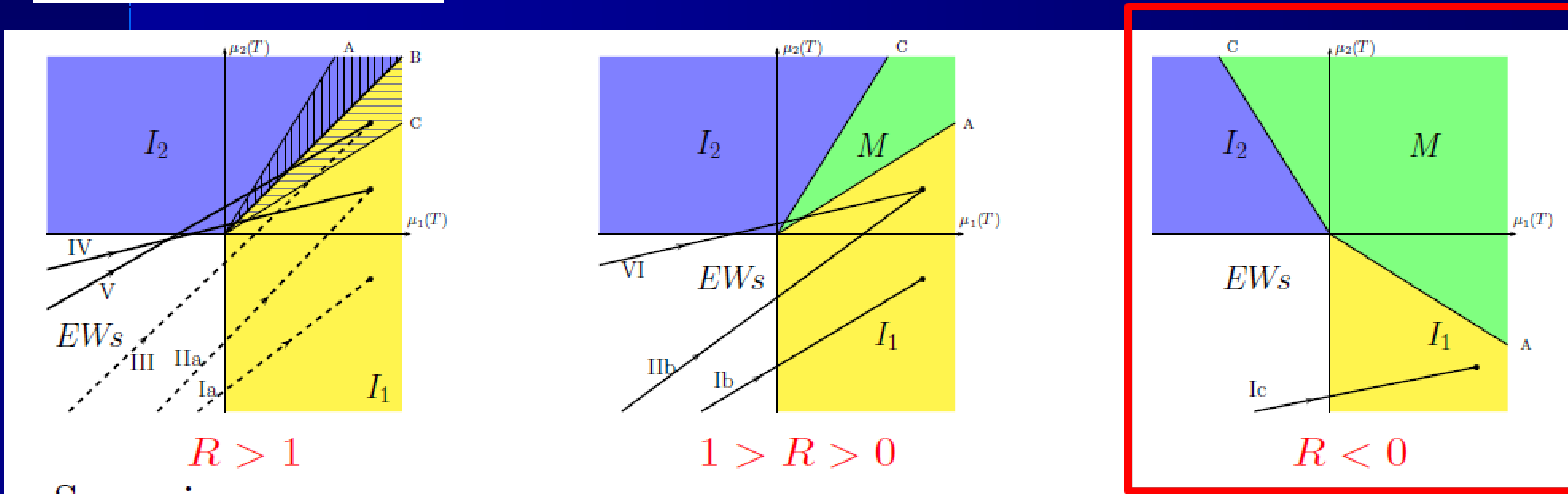
Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev,MK, Sokołowska PRD 2010,
Sokołowska 2011

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

$EWs \to I_2 \to I_1$



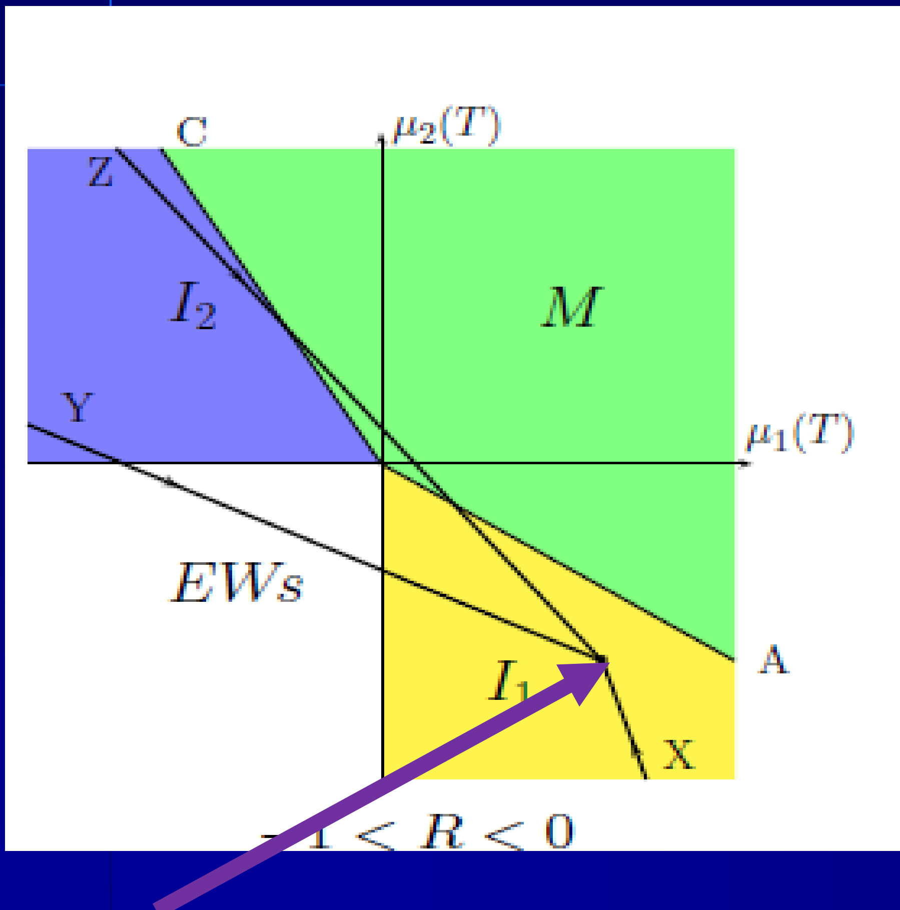
$EWs \to I_1$

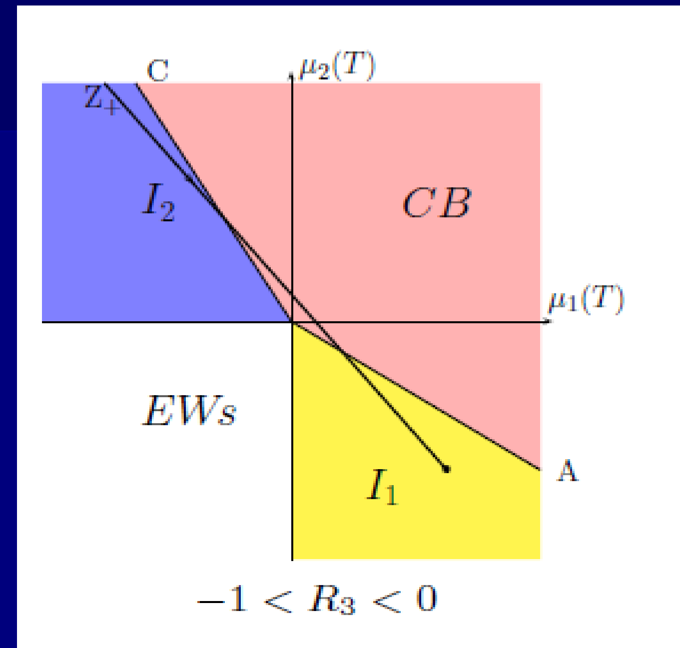
T^2 corrections

$\longrightarrow$ 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

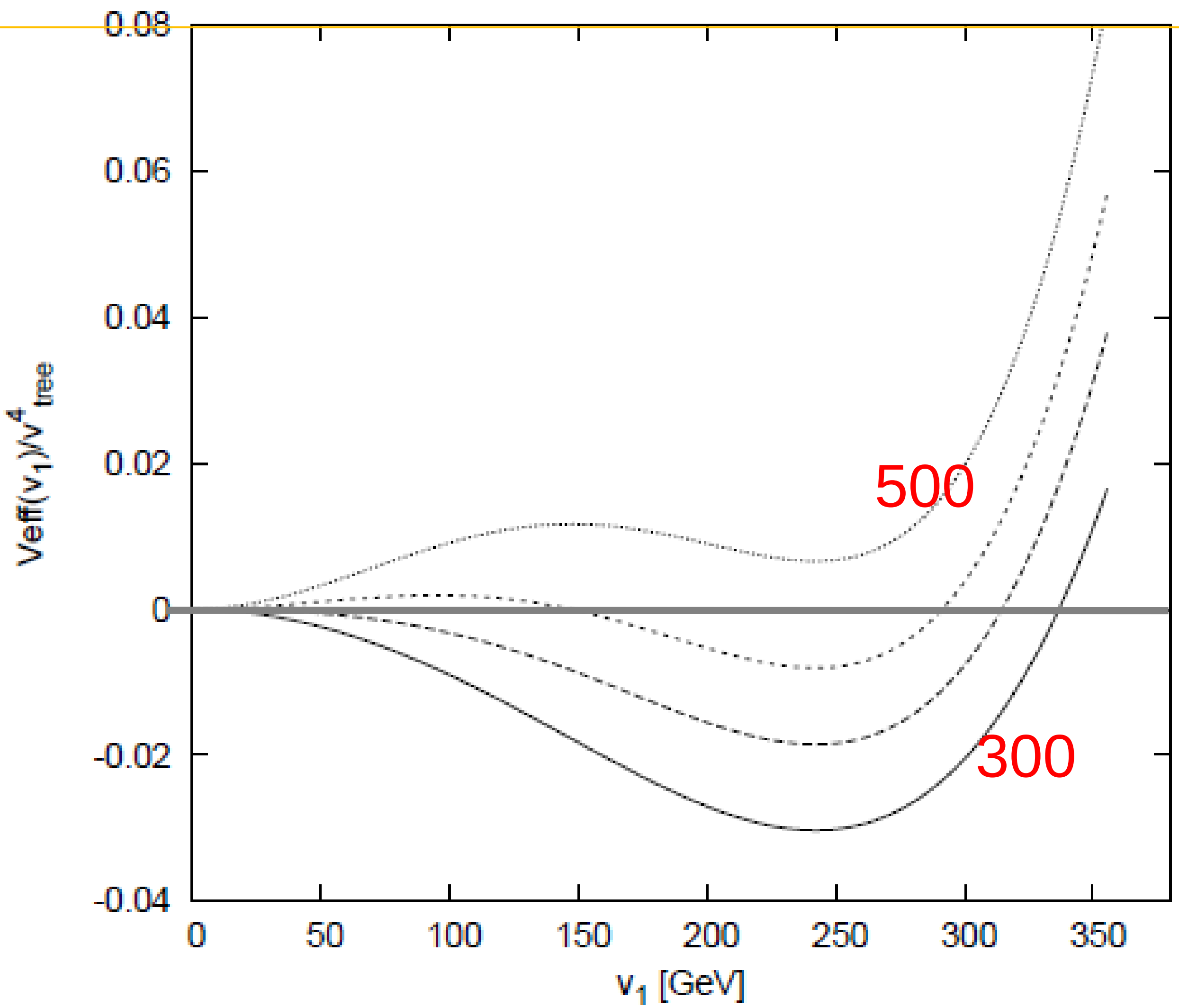
mass matrices

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

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

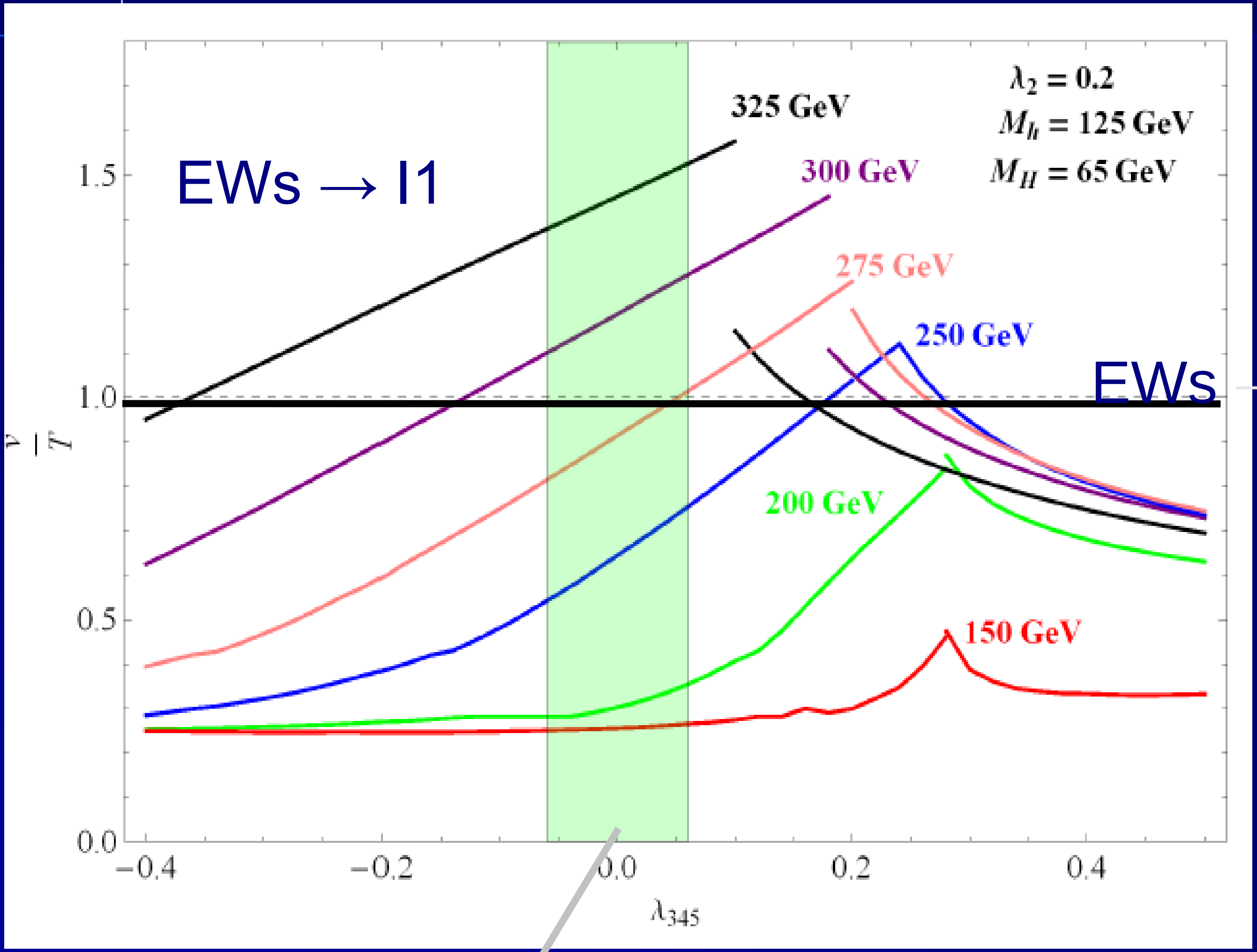
$v_{2(D)}$=0

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



EWs → I2 → I1

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

λ_{345}

R<0 Xenon100 bound R>0

Summary

- SM-like scenario – still valid (July 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

Higgs is a sensitive probe of DM !

Backup

Conclusion (beyond T^2)

Strong first order phase transition in IDM possible for realistic mass of Higgs boson (125 GeV) and DM (~65 GeV) for

1/ heavy (degenerate) H+ and A: mass 275-380 GeV
2/ low value of hHH coupling $|\lambda_{345}| < 0.1$
3/ Coleman-Weinberg term important

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

Vacuum metastability of IDM

- Extra scalars improved stability at large scales *Stal'2013*

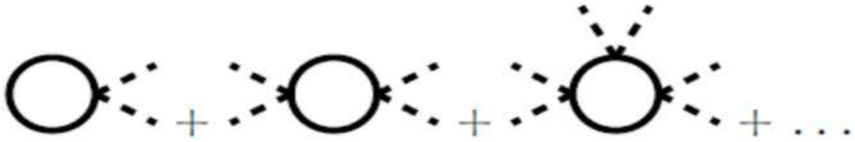
Effective potential

B. Świeżewska, JHEP 2015

[S. R. Coleman, E. J. Weinberg, PRD 7 (1973) 1888, G. Gil, P. Chankowski, and M. Krawczyk, PLB 717 (2012) 396]

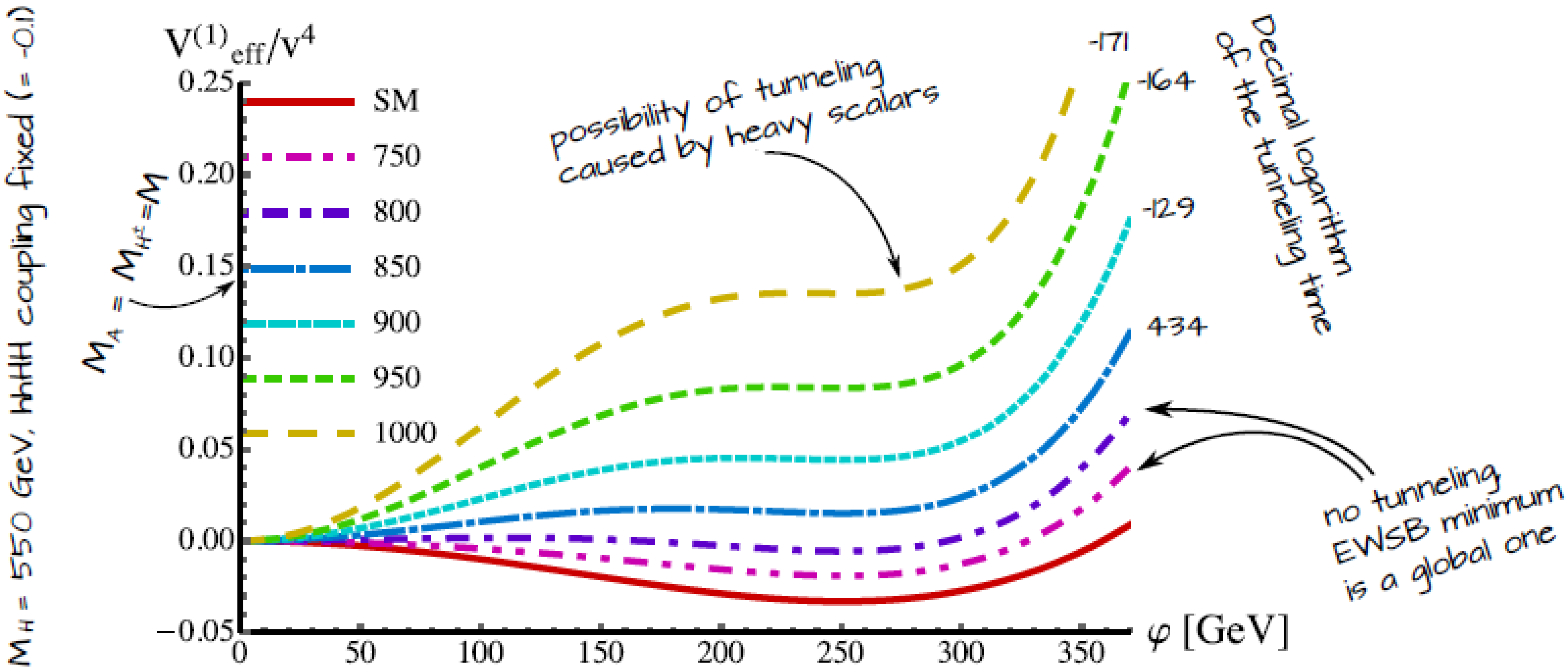
To take into account quantum corrections we analyse one-loop effective potential

$$V_{\text{eff}} = V^{(0)} + \delta V = V^{(0)} + \ldots$$



- in 2HDM – in principle all scalar fields allowed on external legs $\Rightarrow V_{\text{eff}}$ – multivariable function
- assumption: inert scalars are heavy, can be integrated out $\Rightarrow$ inert scalars allowed only in the loops, Higgs field on external legs
- on-shell (OS) renormalized potential

Vacuum stability with extra scalars



- quantum corrections from heavy scalar modify the potential around the EW scale
- maximum at $\varphi = 0$ becomes a minimum
- for heavy inert scalars – EWSB minimum is highly unstable

IDM safe

B. Świeżewska, JHEP 2015

IDM, if required to fulfill theoretical and experimental constraints, is safe from vacuum instability around the EW scale

For $M_A = M_{H^\pm} = M$

- meta/instability when relatively large splitting between M_H and M, $M^2 - M_H^2 \sim \lambda_{\text{scalar}} v^2$ $\Longrightarrow$ some scalar couplings large
- consistent with perturbative unitarity
- EWPT not constraining ($T = 0$)
- however, DM relic abundance requires small splittings, $\mathcal{O}(10\,\text{GeV})$ $\longrightarrow$ inconsistent with Planck measurements for heavy DM

IDM vs DATA

Many (scans) analyses of IDM…

theor. conditions (stability(positivity),pert.unitarity.
condition for Inert vacuum)

STU parameters (some LEP data)

LHC data:

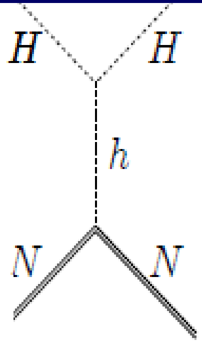
$R_{\gamma\gamma}$: sensitive to invisible decays (λ_{345}^2 and M_H)
H+ loop (λ_3 (sign !) ; if λ_3 <0 also λ_{345} <0)
enhancement only if λ_3 (λ_{345}) <0

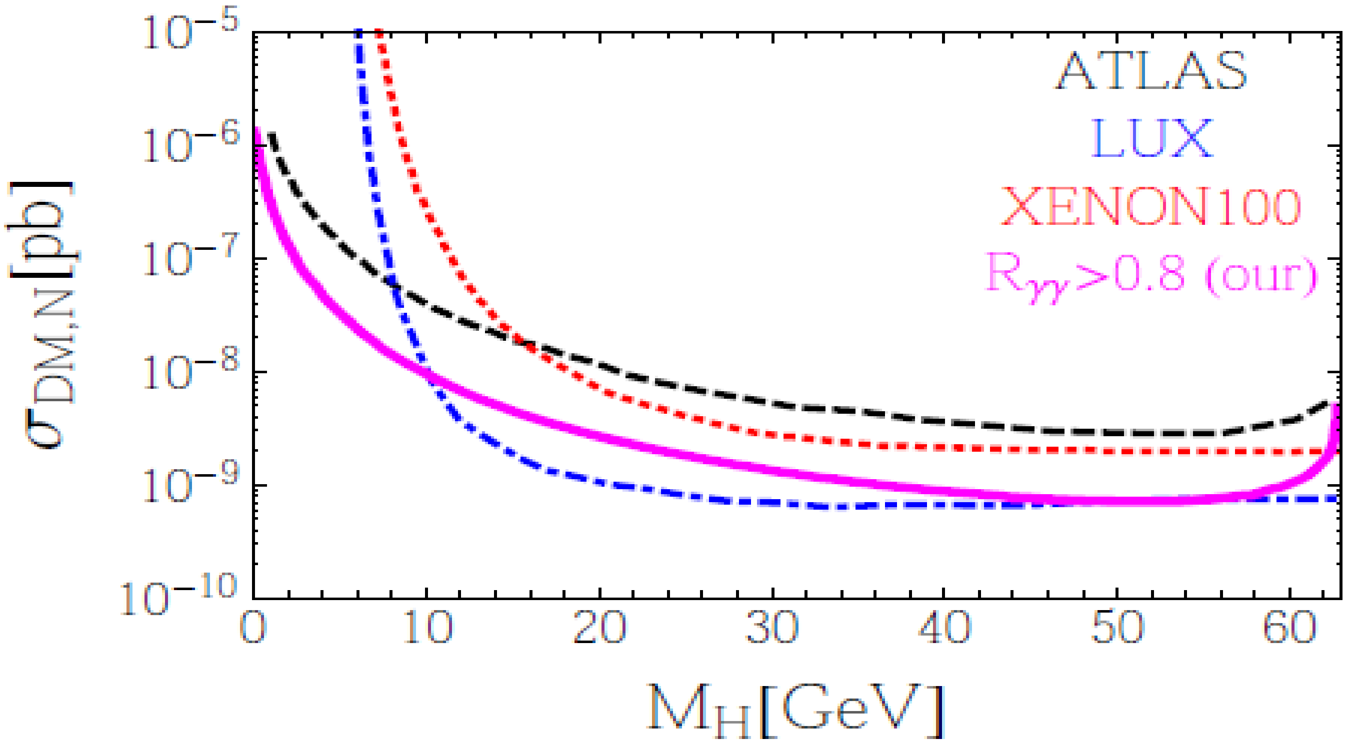
Br_{inv} < 20%; total Higgs h width < 22 MeV

Dark matter exp: relic density (WMAP, PLANCK)
direct detection (LUX)

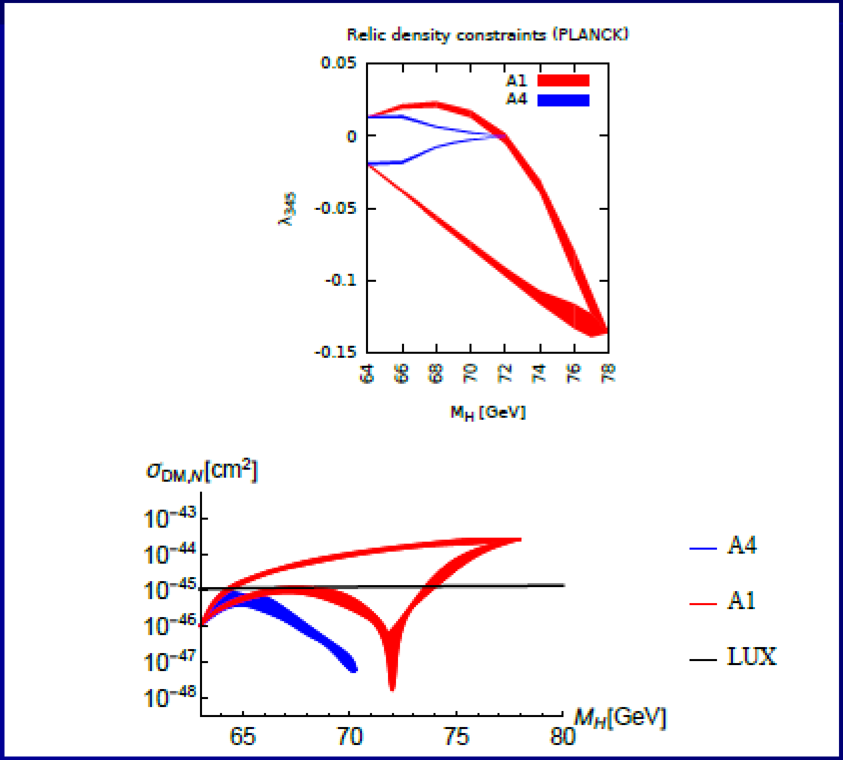
Direct detection – comparison with LHC, Xenon 100 and LUX

- DM-nucleon scattering cross section $\sigma_{\mathrm{DM,N}} \sim \lambda_{345}^2$
- $R_{\gamma\gamma}$ bounds on λ_{345} translated to $(M_H,\ \sigma_{\mathrm{DM},N})$ plane





... stronger than the dedicated DM experiments



Relic density constraints (PLANCK)
A1
A4
0.05
0
-0.05
-0.1
-0.15
λ_{345}
64
66
68
70
72
74
76
78
M_H [GeV]
$\sigma_{DM,N}$[cm^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
65
70
75
80
M_H[GeV]
A4
A1
LUX

Extrema → vacua (v = 246 GeV)

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

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

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

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

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

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

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

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

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

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