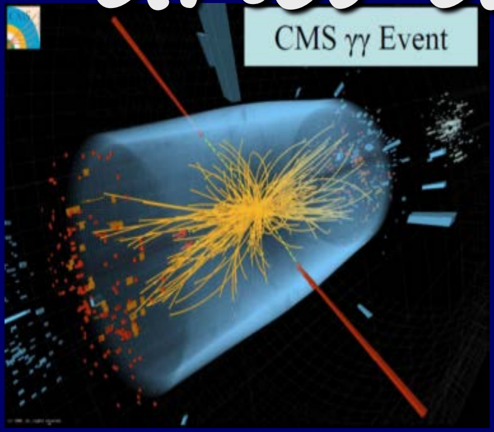
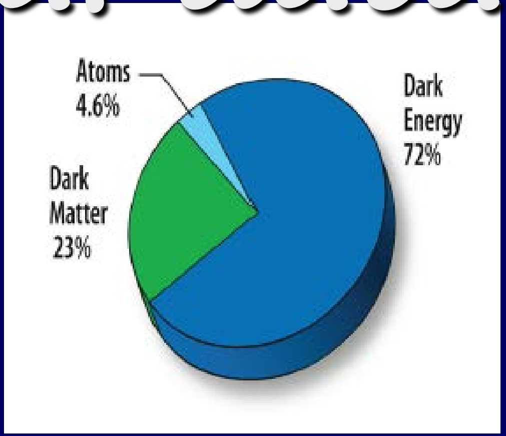
Ustroń, 15.9. 2015

The Inert Doublet Model in light of LHC and astrophysical data

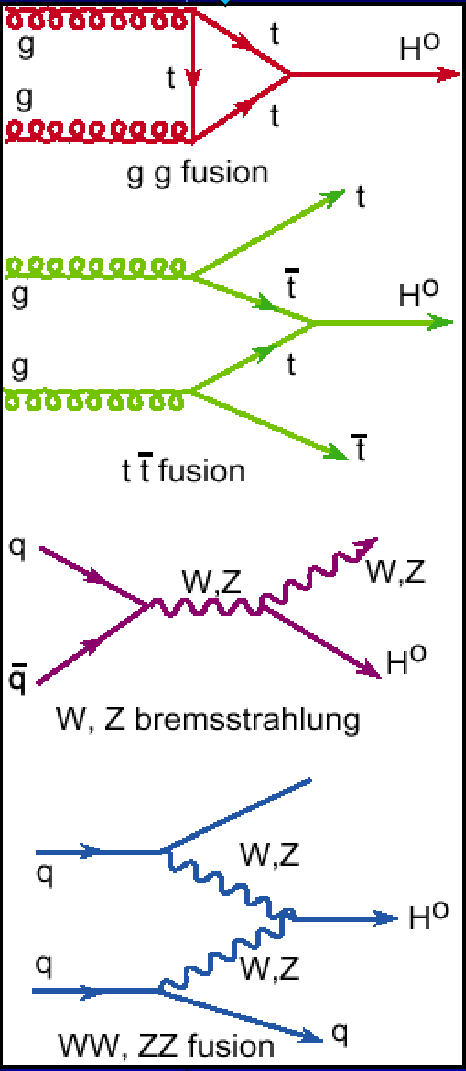


Maria Krawczyk
University of Warsaw



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

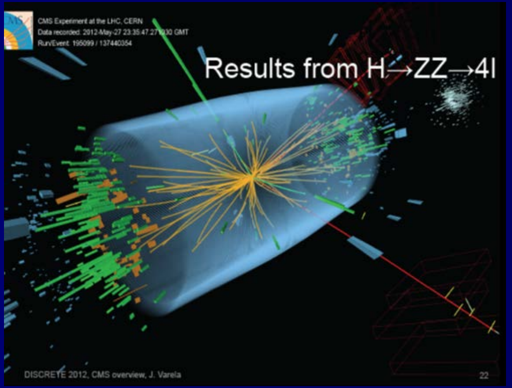
Production and decay of Higgs particle at LHC ~ SM

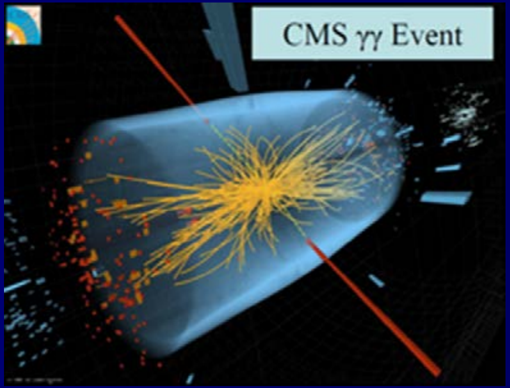


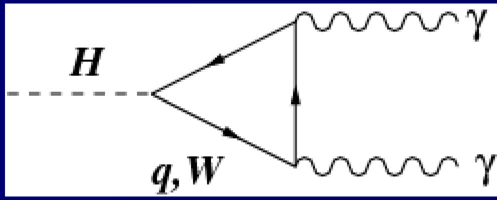
main decays

1) $H \to \gamma\gamma$
2) $H \to$ tau tau
3) $H \to bb$
4) $H \to WW \to l\nu l\nu$
5) $H \to ZZ \to 4l$

decay to $\gamma\gamma$
t,b,W... loop







SM-like Higgs

- Mass 125.09 ± 0.24 GeV   ZZ → 4 l, γ γ
- Total width < 23 MeV (95%CL); SM ~4 MeV
- Signal strenghts   (CMS)

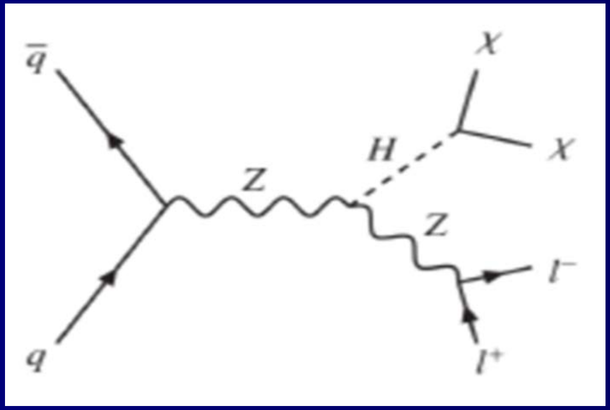
  → ZZ 1.09 ± 0.29

  γγ   1.12 ± 0.24

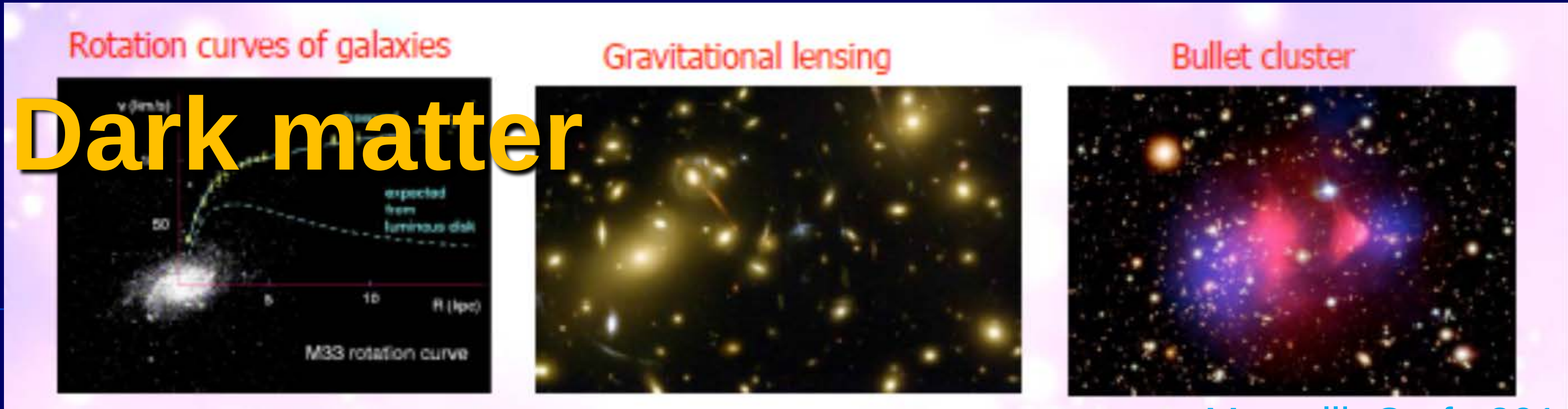
  tot   1.00 ± 0.14
- Invisible decay

  ATLAS BR < 0.27 (95% CL)

  CMS   BR < 0.32 (95% CL)



Dark matter



Morsolli, Corfu 2014

Relic density

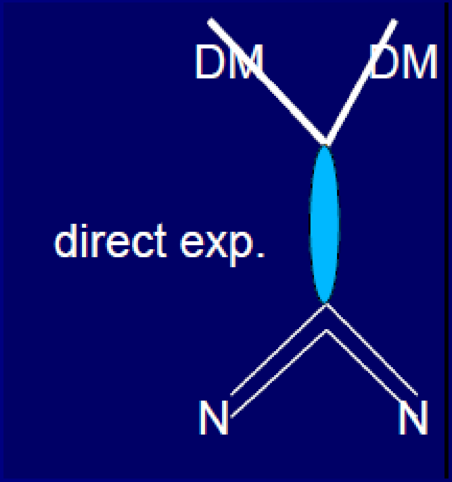
WMAP $$0.1018 < \Omega_{DM} h^2 < 0.1234$$

3 sigma:

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

Direct detection

DM N → DM N

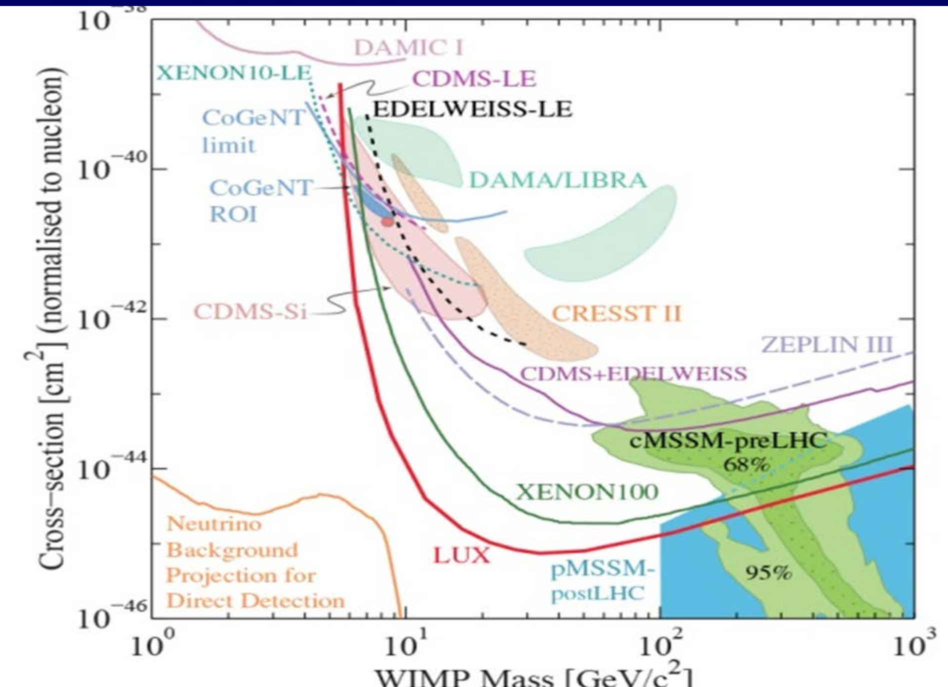


confusing data…

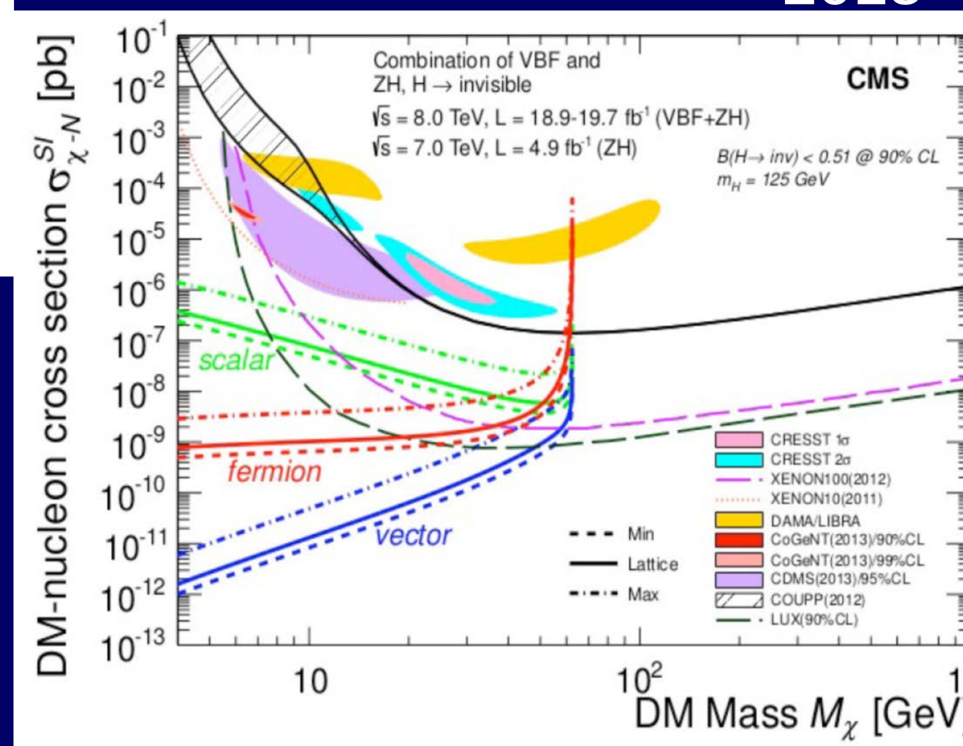
DM DATA?

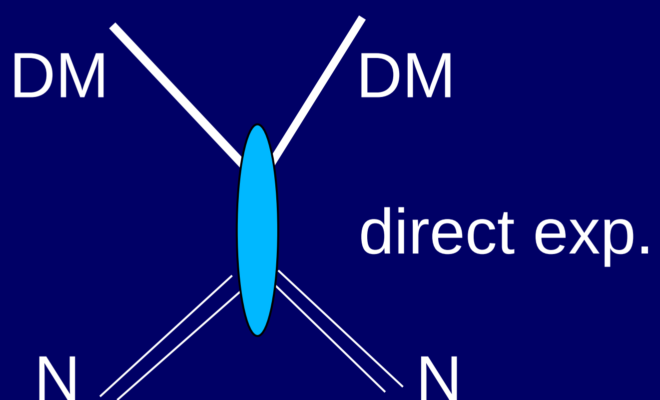
"One should be aware, however, that this area of investigation is at present beset with large controversies, and one should allow the dust to settle before drawing strong conclusions in either directions."

Lars Bergstrom, *Dark Matter Evidence, Particle Physics Candidates and Detection Methods*, arXiv:1205.4882 [astro-ph.HE]



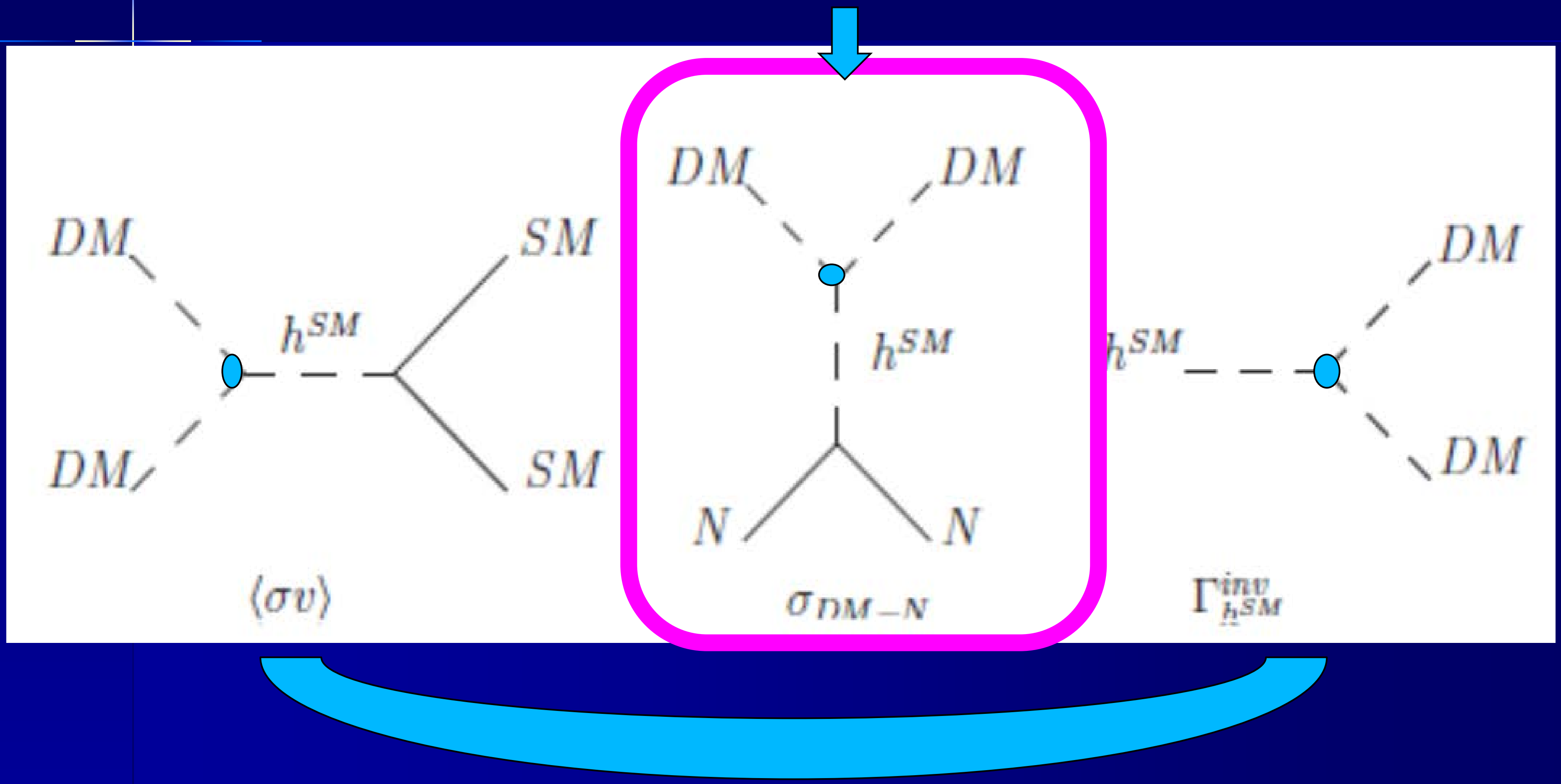
2015



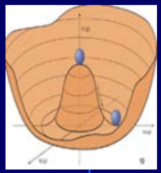


Higgs portal with the SM-like h

direct detection



T.D. Lee 1973



2HDM's

SYMMETRIES!!!

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

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 two charged

Inert Doublet Model (IDM)

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

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

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

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

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

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

Inert Doublet Model (IDM)

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

Today

Higgs and Dark Matter sectors in agreement with data

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≠0 ------------------------------------

Charge Breaking	CB	$v_D = 0$

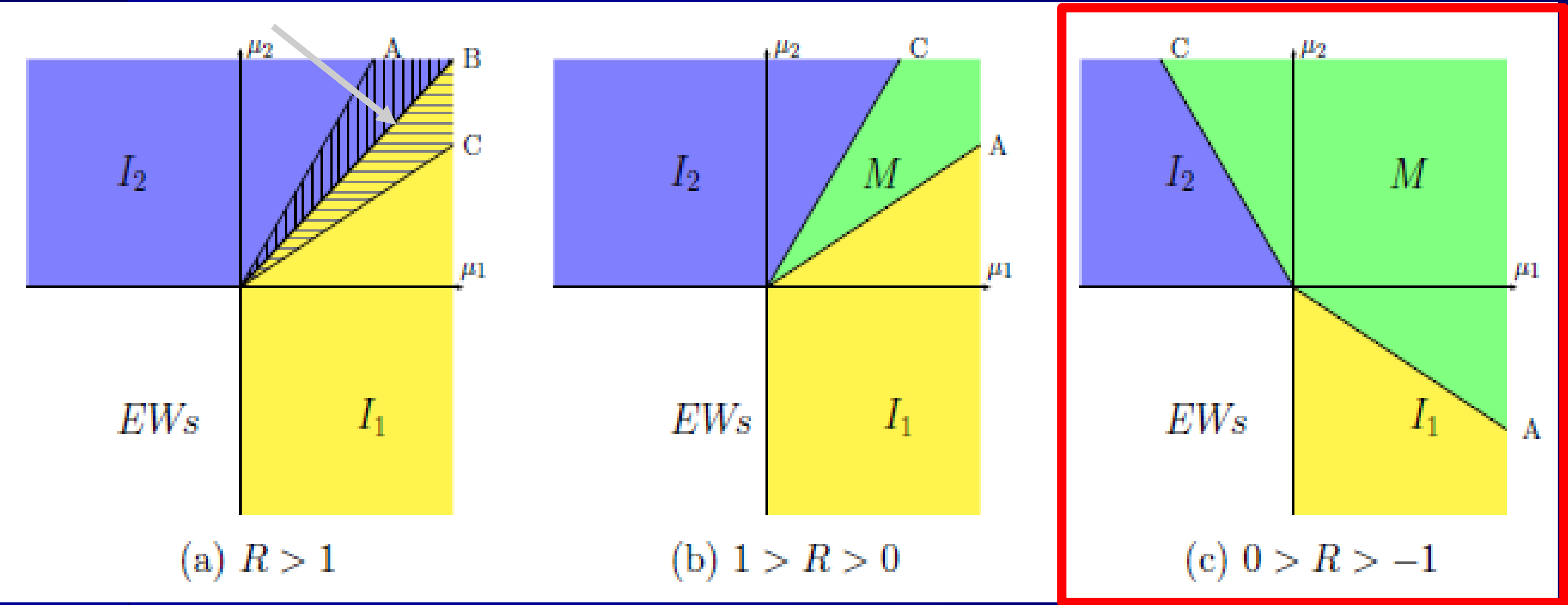
Phase diagrams for D-sym. V

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

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

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

coexistence of
I_1 and I_2 minima



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

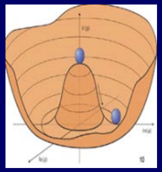
here $\lambda_{345} < 0$!

Inert Doublet Model

Ma,…'78
Barbieri..'06

Φ_S as in SM (BEH)

Φ_D – no vev



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

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

(no Higgses!)

Higgs boson h (SM-like)

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

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

positivity

$\lambda_4 \pm \lambda_5 > -X = \sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0$

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

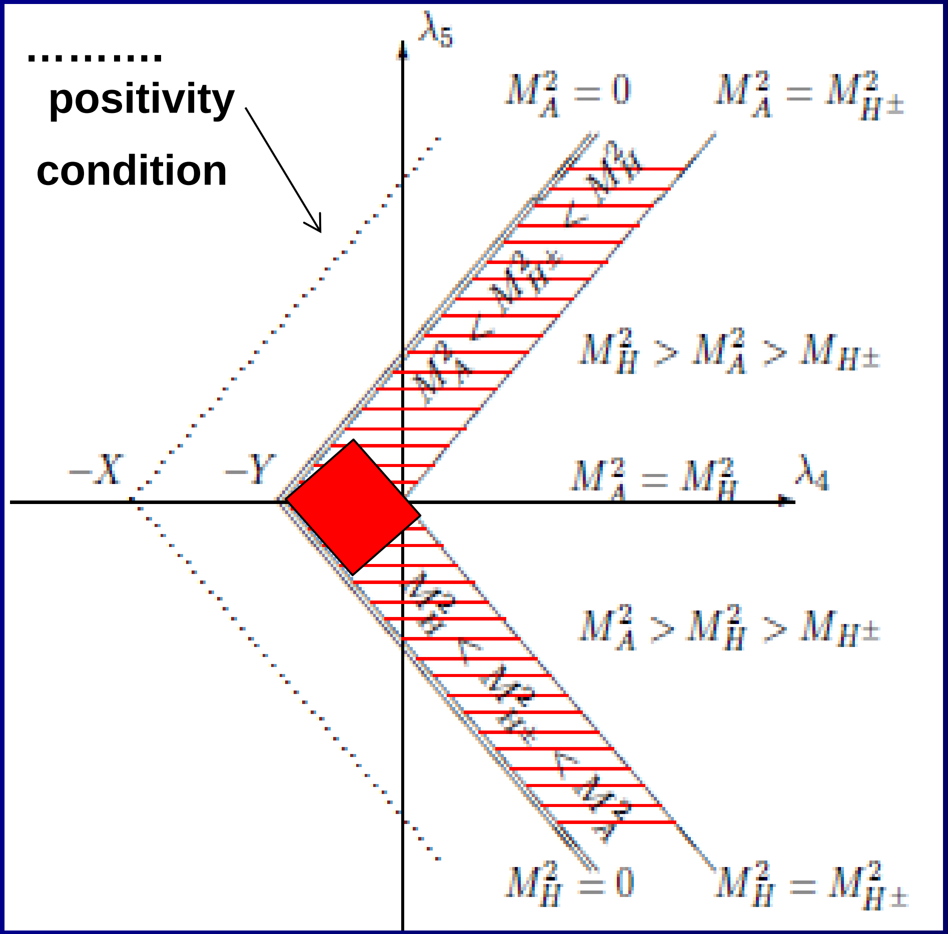
- Dark particles D

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

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

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

λ_{345}



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

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

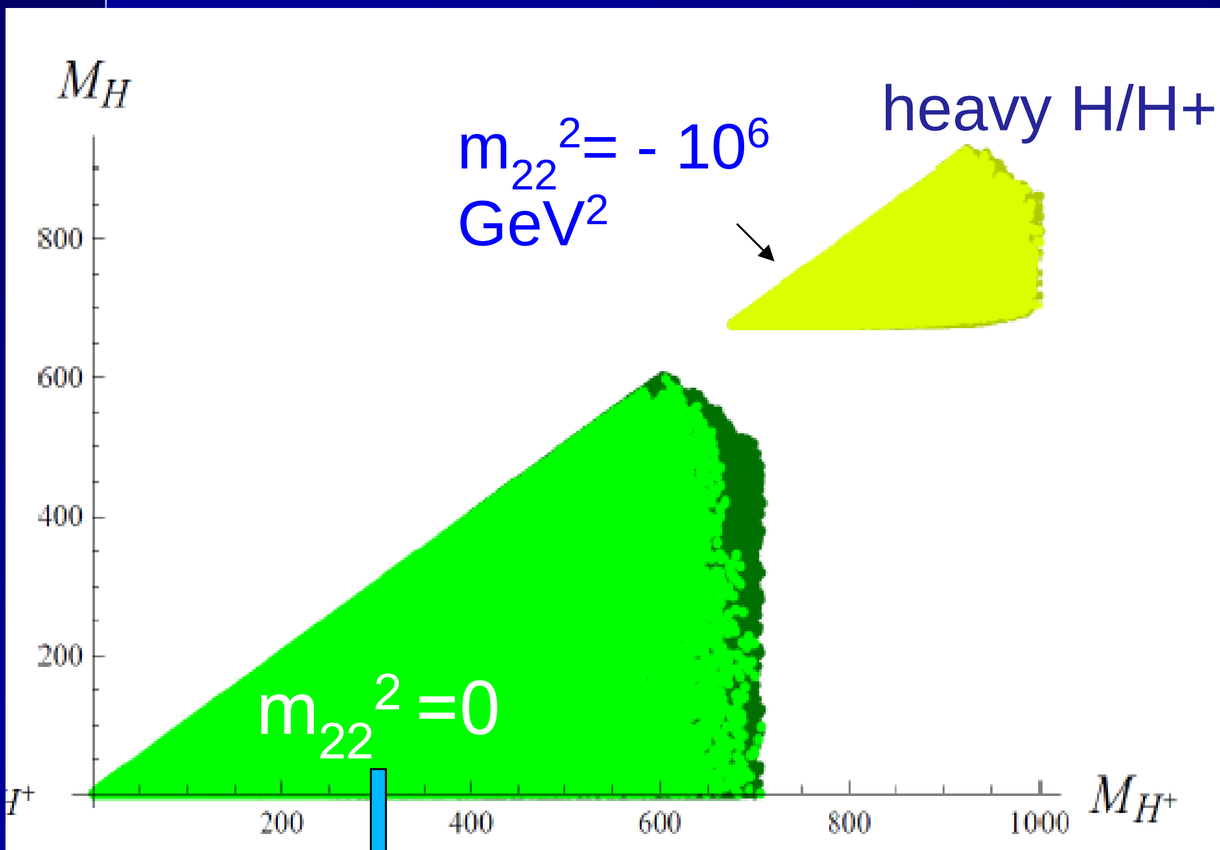
Couplings with Higgs: hHH ~ λ_{345} h H+H- ~ λ_3

Inert Doublet Model with M_h=125 GeV

Świeżewska 2011

$m_{22}^2 = 0$

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



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

Data:

EWPT (S and T)

$$S = 0.03 \pm 0.09$$
$$T = 0.07 \pm 0.08$$
$$\rho = 87\%$$

LEP, no LHC yet

EWPT (pale regions)

$\gamma\gamma$ 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]

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

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

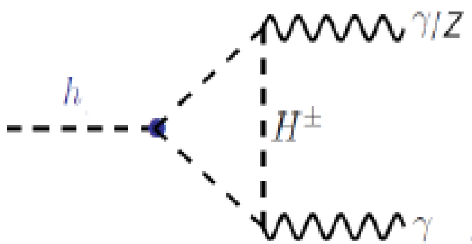
$R_{Z\gamma}$ – treated analogously

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



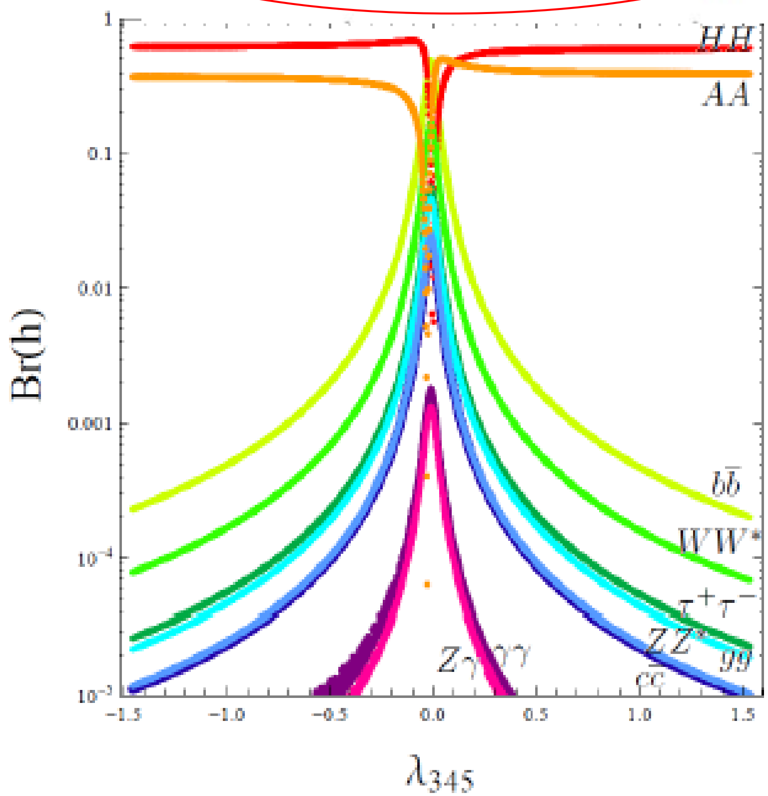
Invisible decays

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



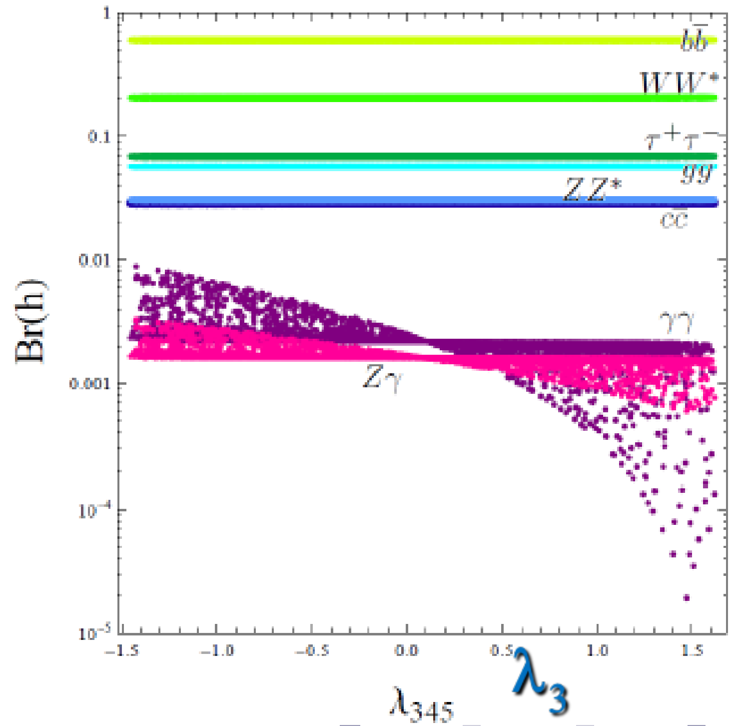
Charged scalar $H^{\pm}$ loop

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)]

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

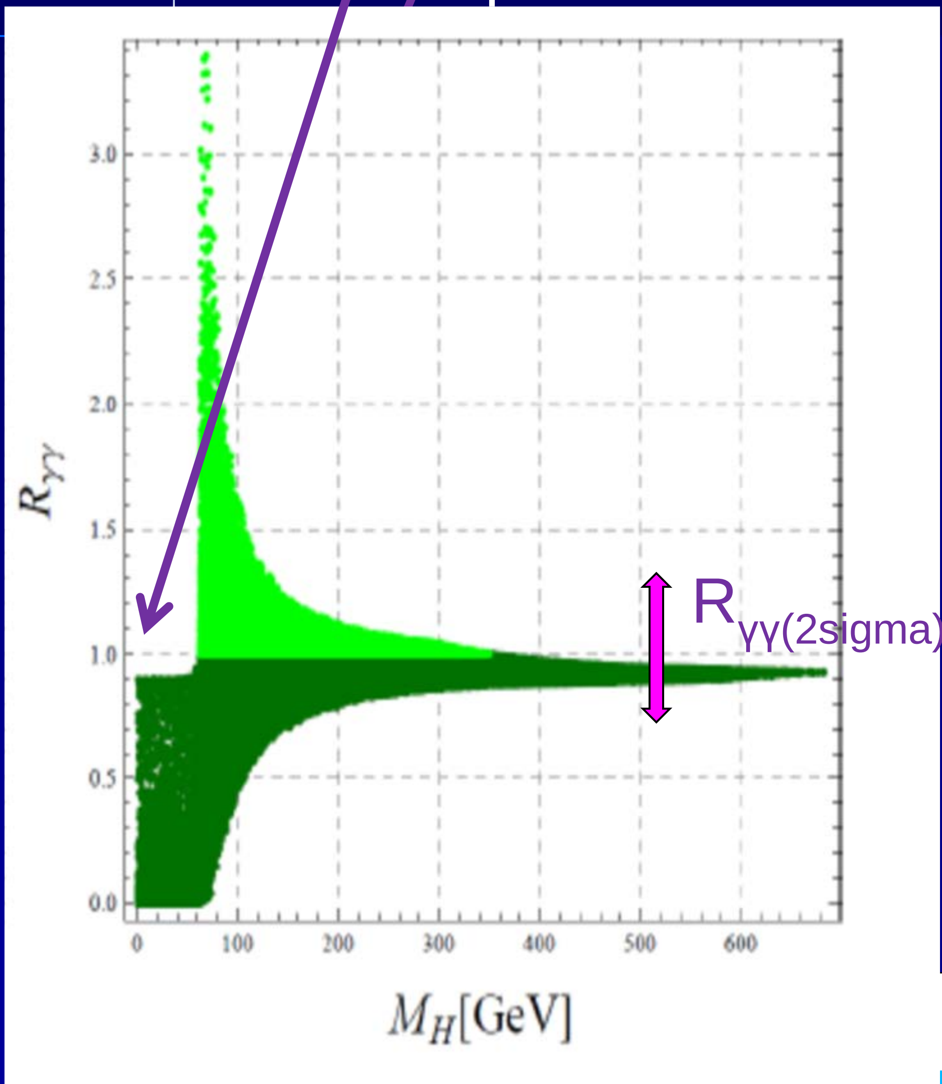
- Constructive or destructive interference between SM and $H^{\pm}$ contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- Invisible channels closed $\Rightarrow H^{\pm}$ contribution visible

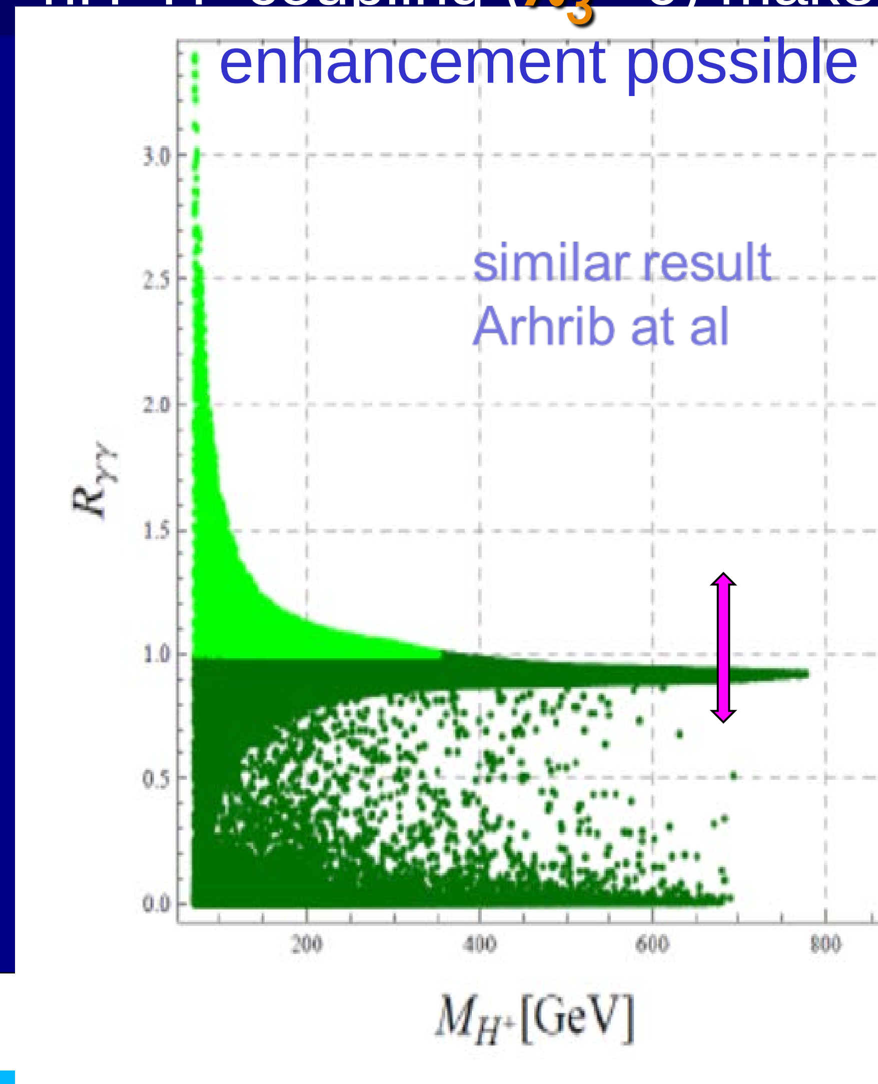


$R_{\gamma\gamma}$ as a function of mass H, H +

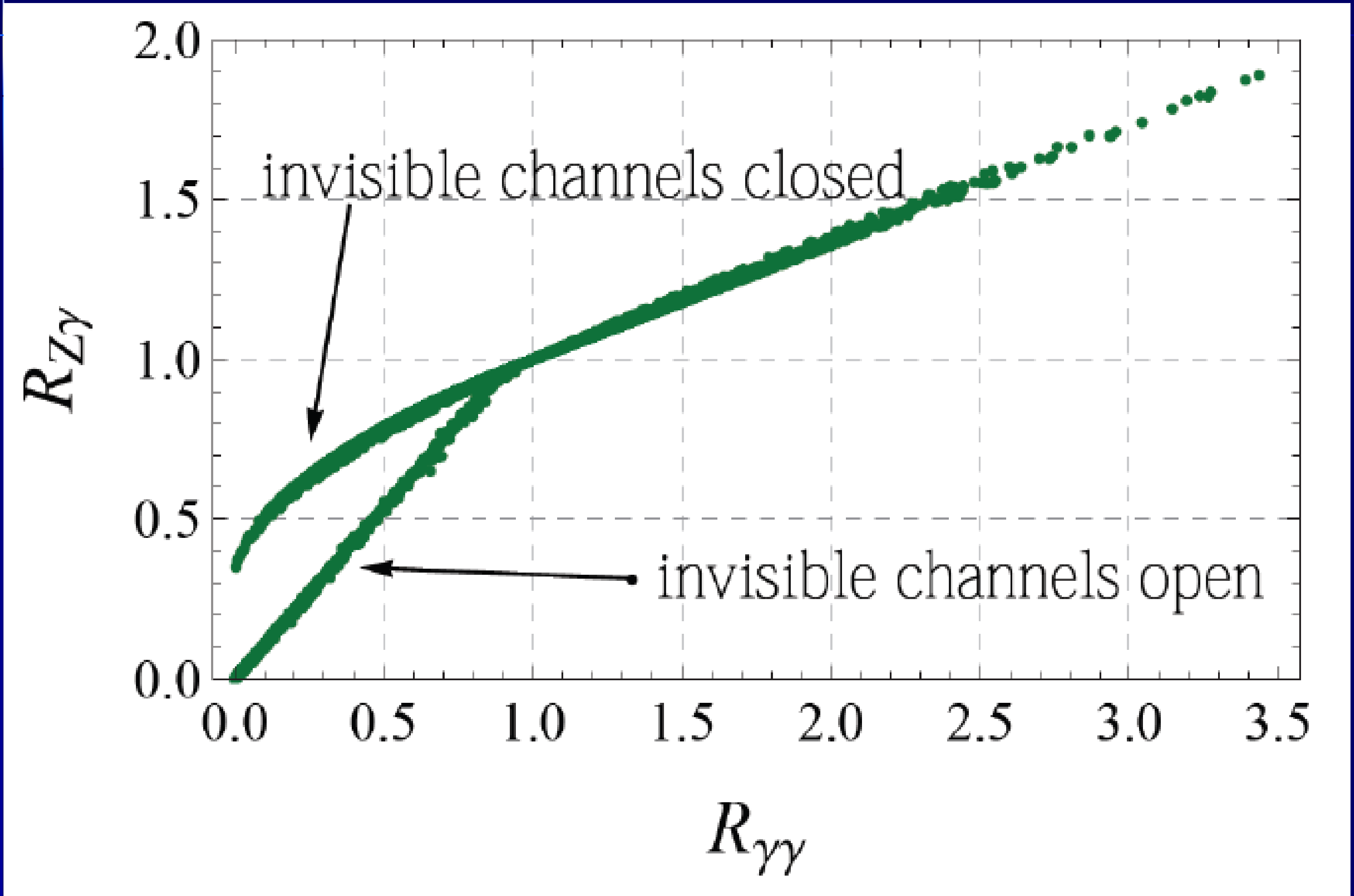
Invisible decays makes enhancement impossible

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



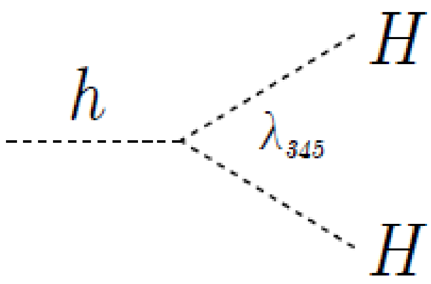


γγ versus Zγ in IDM



Invisible h decay →coupling hHH

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

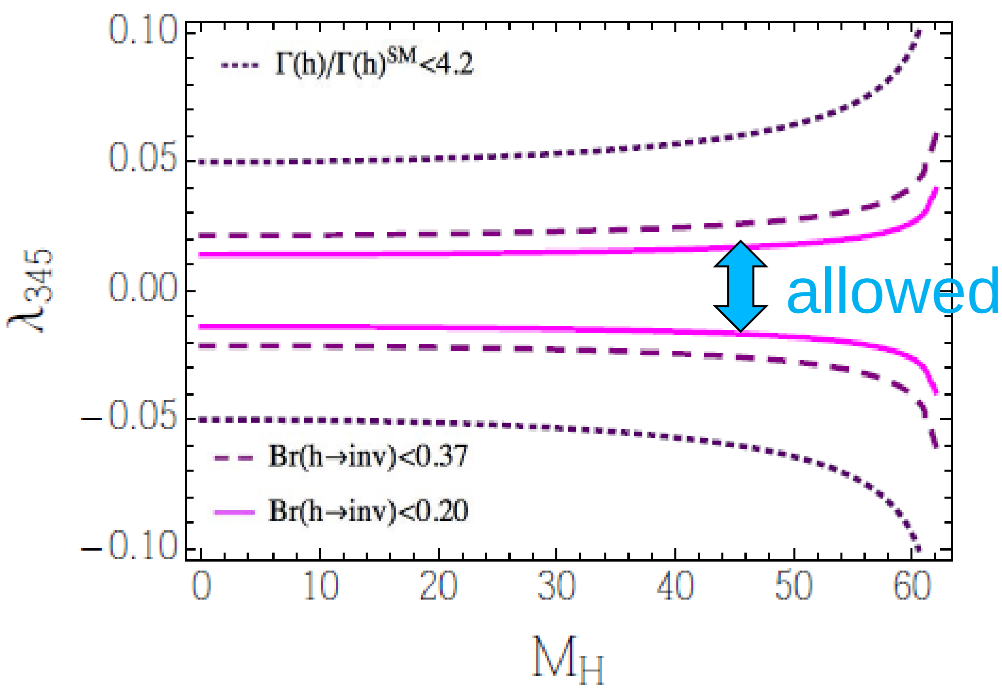


LHC:

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

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]

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

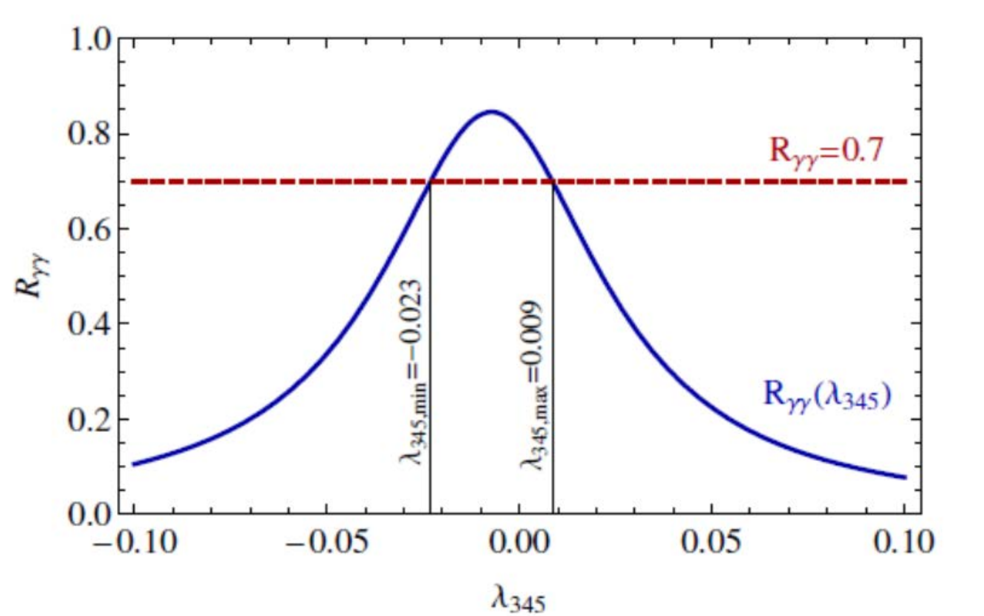
$$\text{ATLAS} : R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$$
$$\text{CMS} : R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$$

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

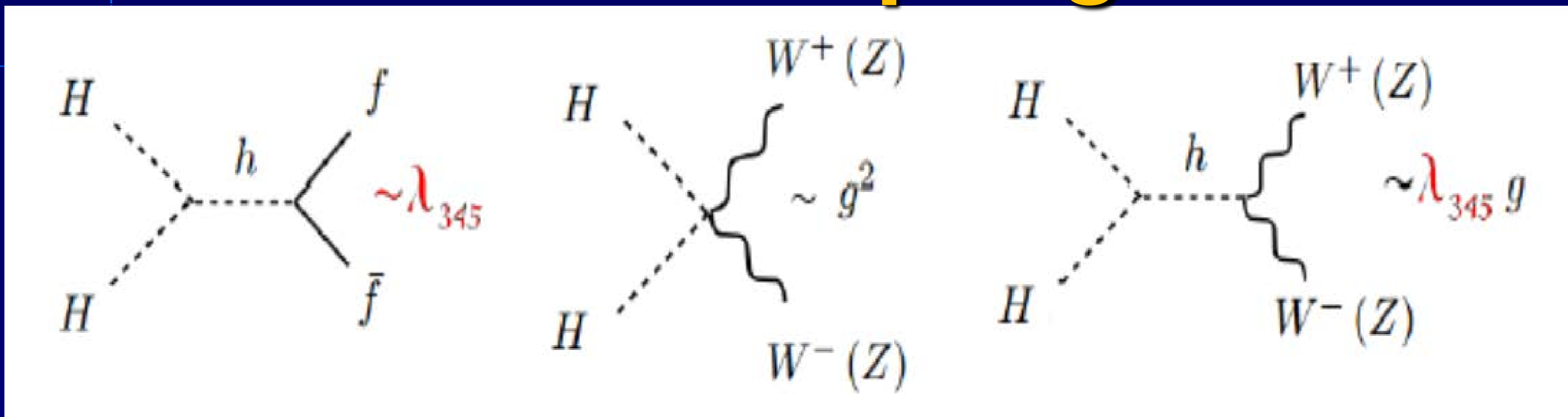
1.12 ± 0.24

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

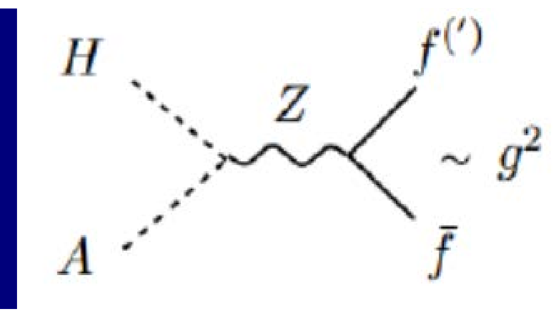
DM mass below 62.5 GeV allowed only if
$R_{\gamma\gamma} < 1$



Relic density constraints on masses and couplings of DM

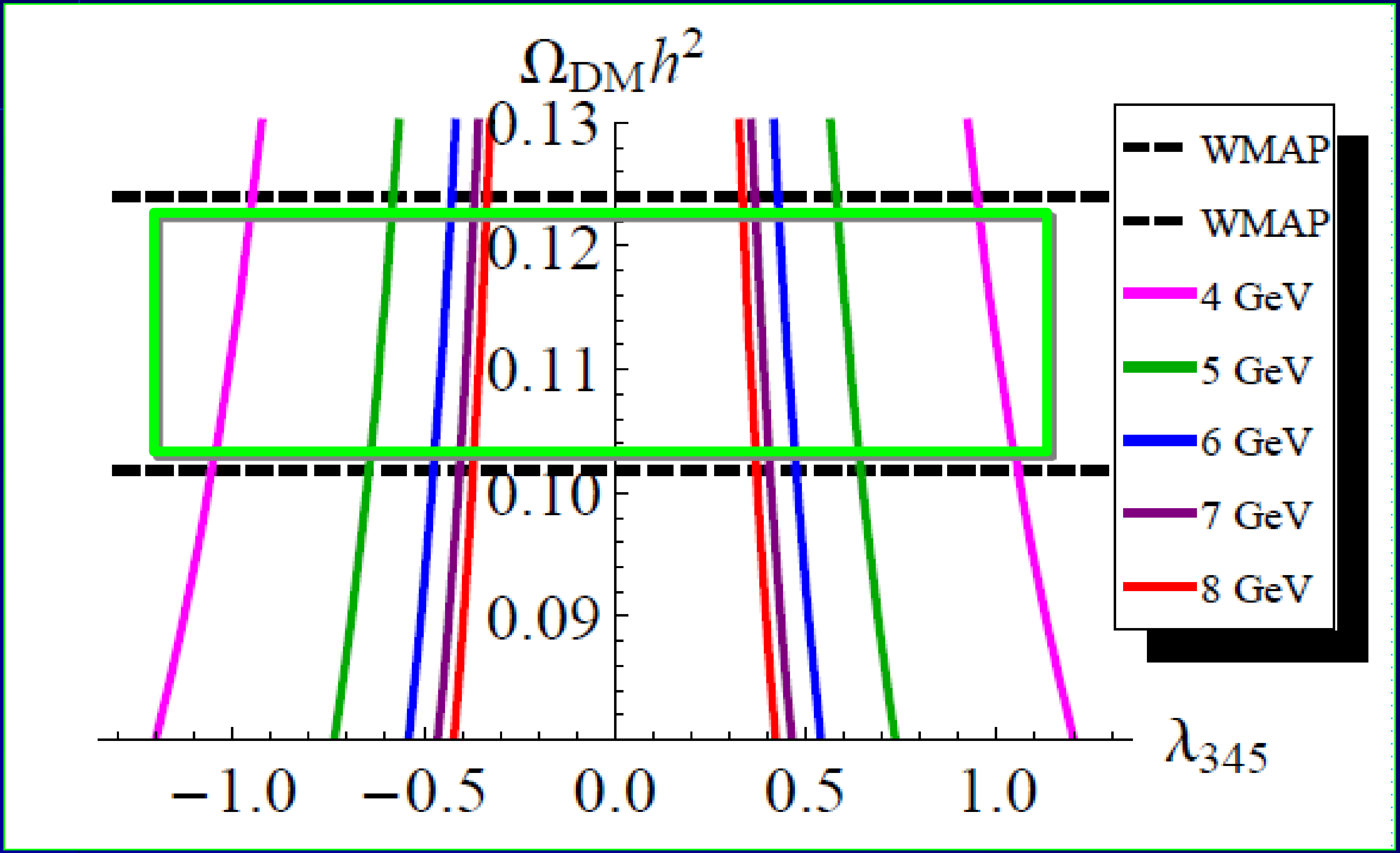


Coannihilation possible
for small (AH) mass splitting



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

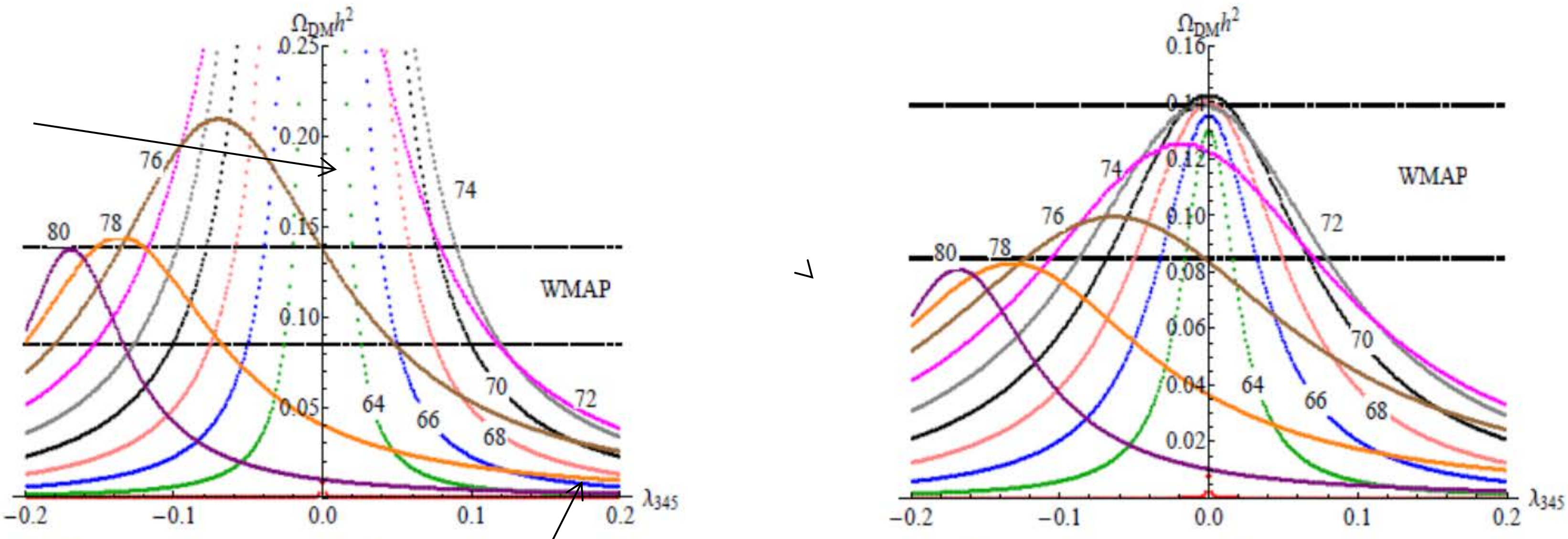
WMAP window for light H (DM)



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

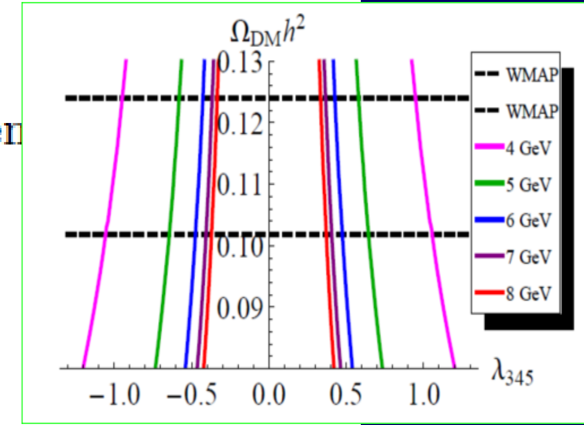
Low mass H – excluded by LHC!

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

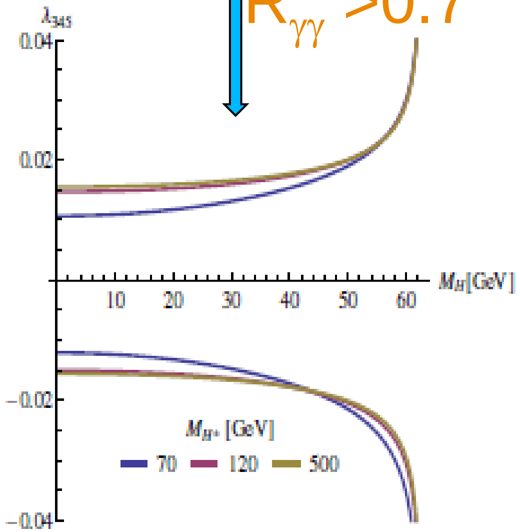
[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

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

$h \to AA$ 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:

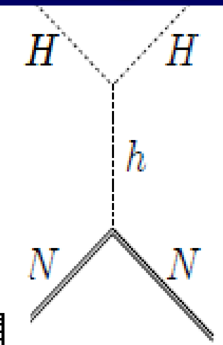
  $M_H = 8.6\text{ GeV} \Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$

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

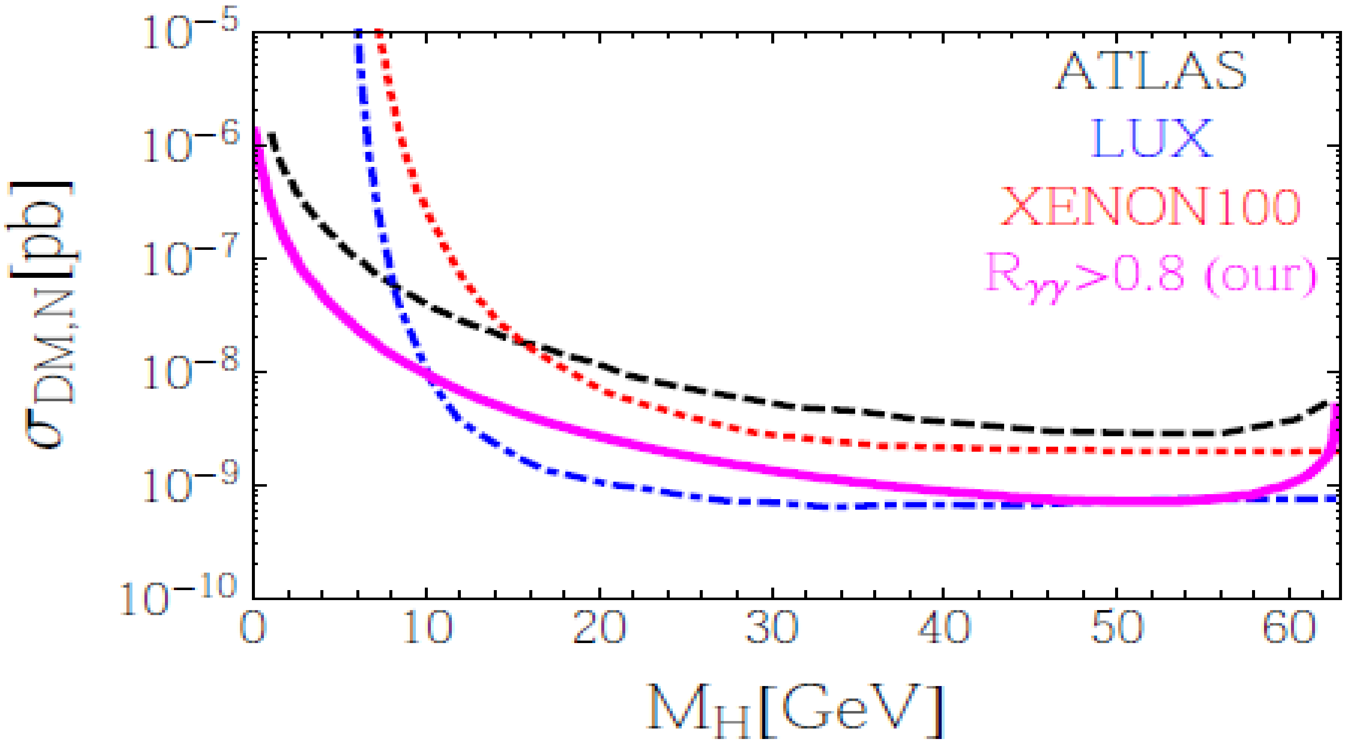
Low DM mass excluded

Sokołowska/Świeżewska

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

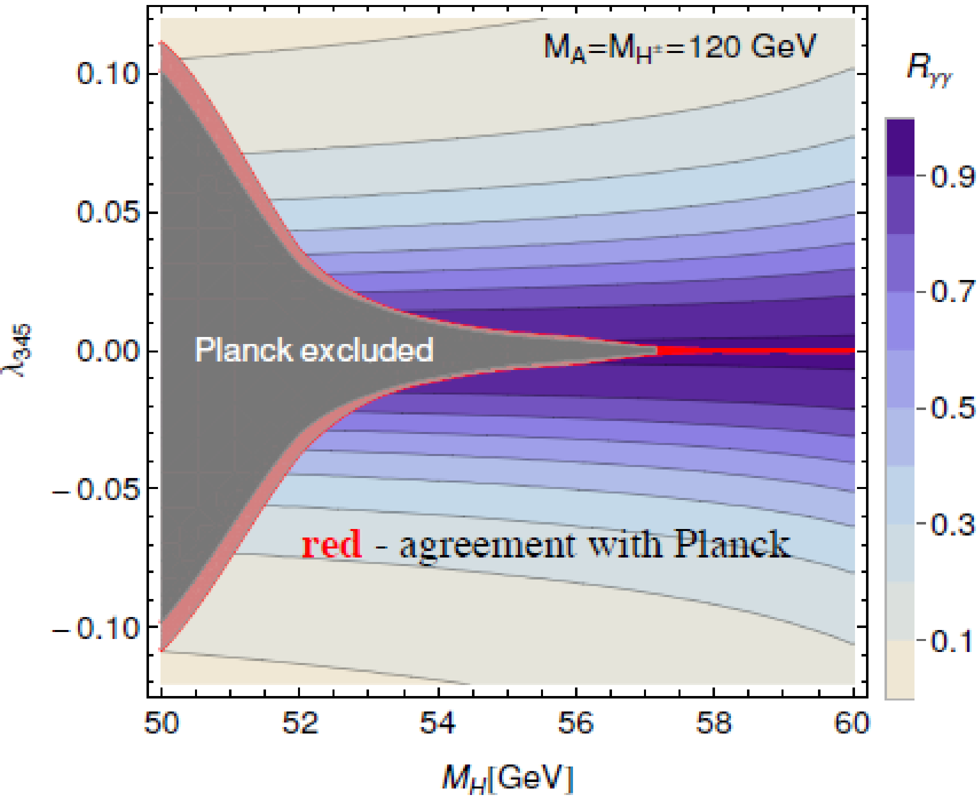


... stronger than the dedicated DM experiments

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

New scan for IDM (2015)

A. Ilnicka, T. Robens, MK

- 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 to1 TeV

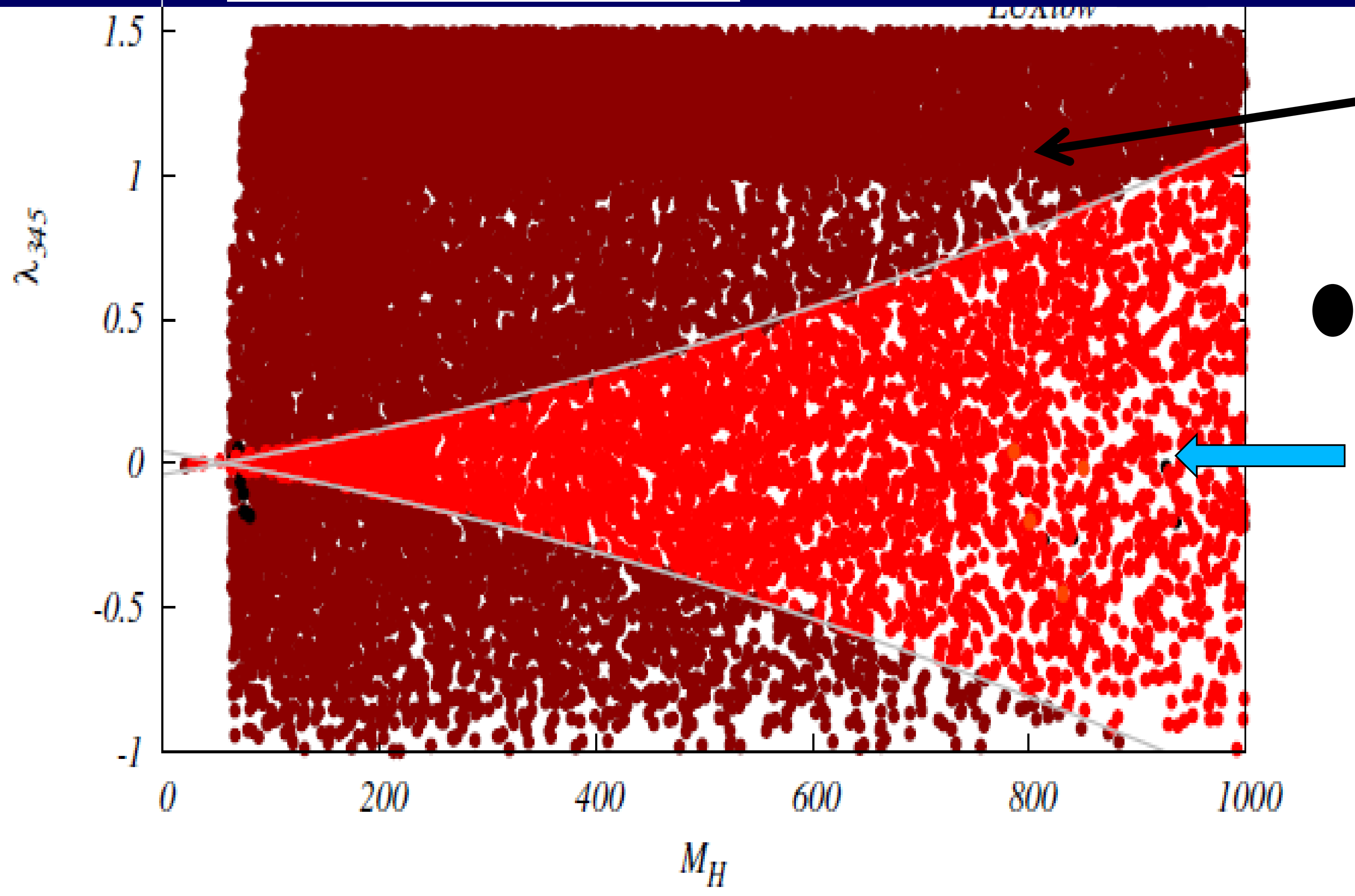
+LEP constraints
H total width
W/Z total width

New scan

A.Ilnicka, T. Robens, MK

$M_H, M_A, M_{H\pm}, \lambda_2, \lambda_{345}.$

1505.04734,1508.01671

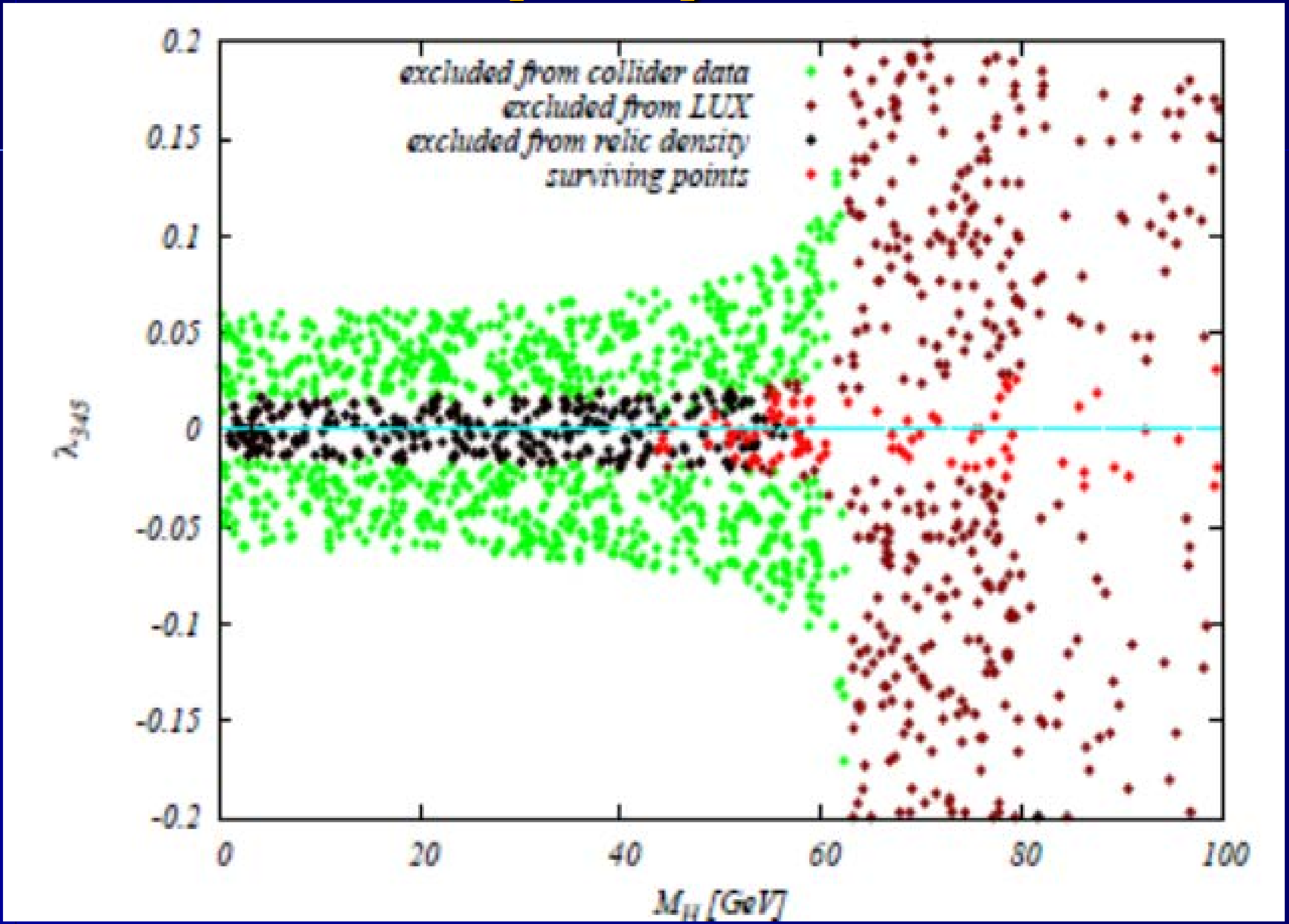


LUX excluded

Planck excluded

OK

Low mass H (DM)

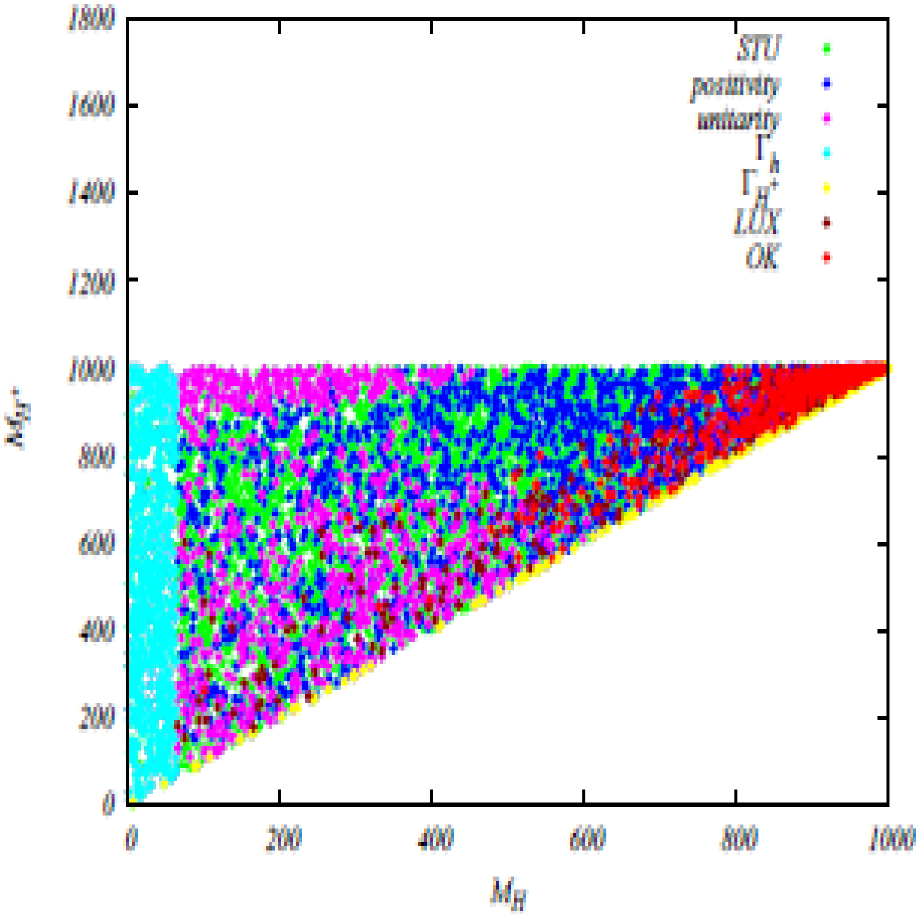


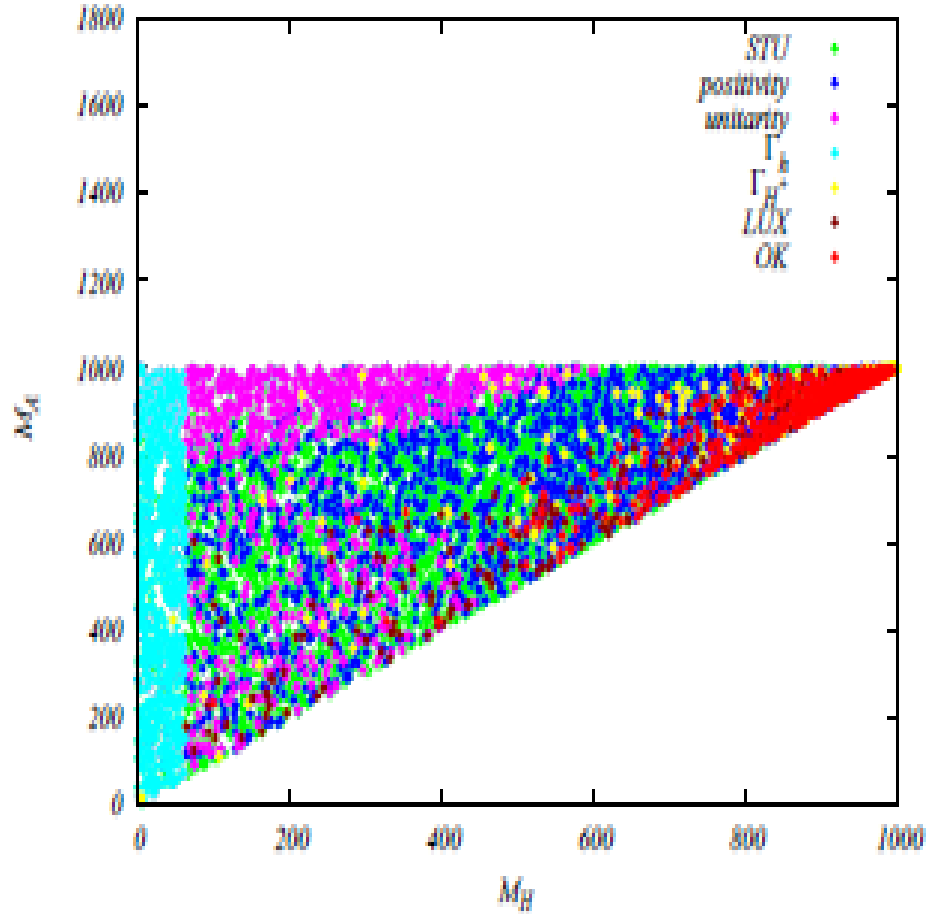
Limit on mass of DM: M_H> 45 GeV !

New scan: dark particles masses

MH vs MH+

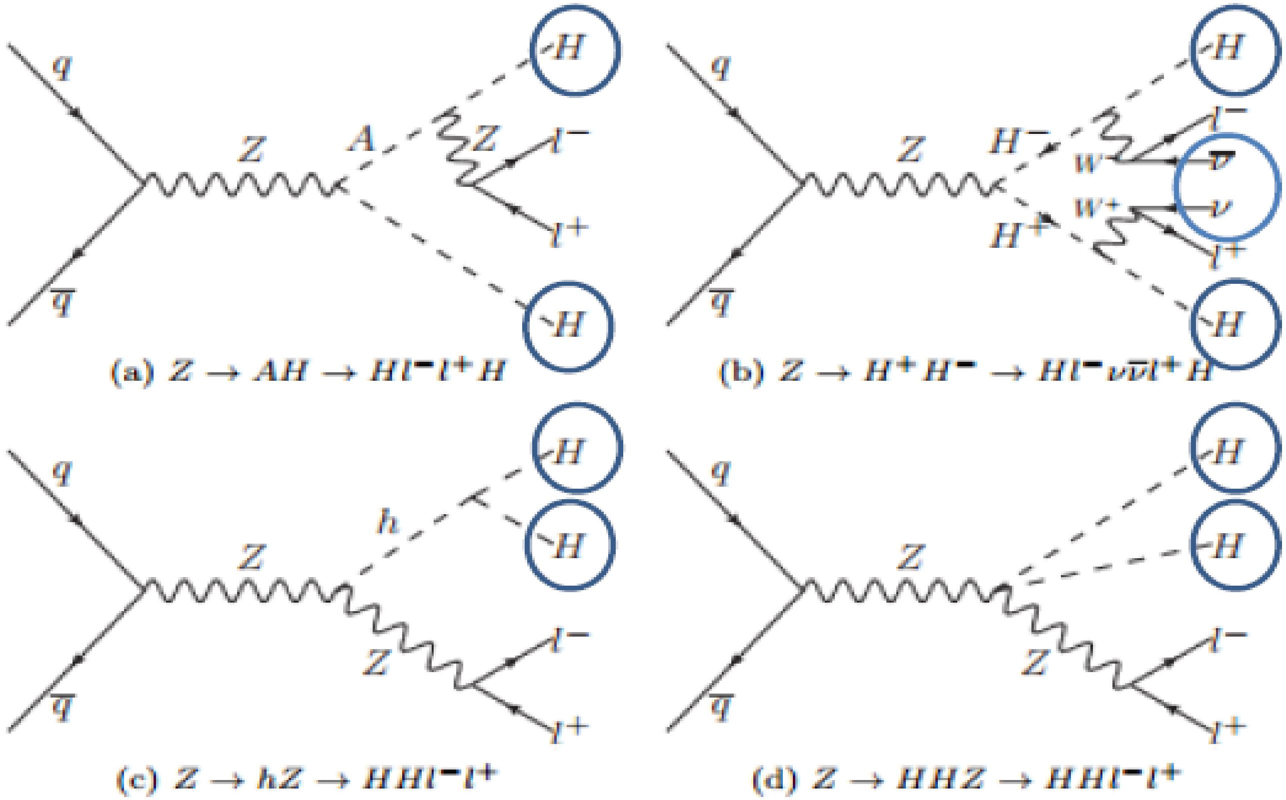
MH vs MA





LHC II – HA and H+H- production

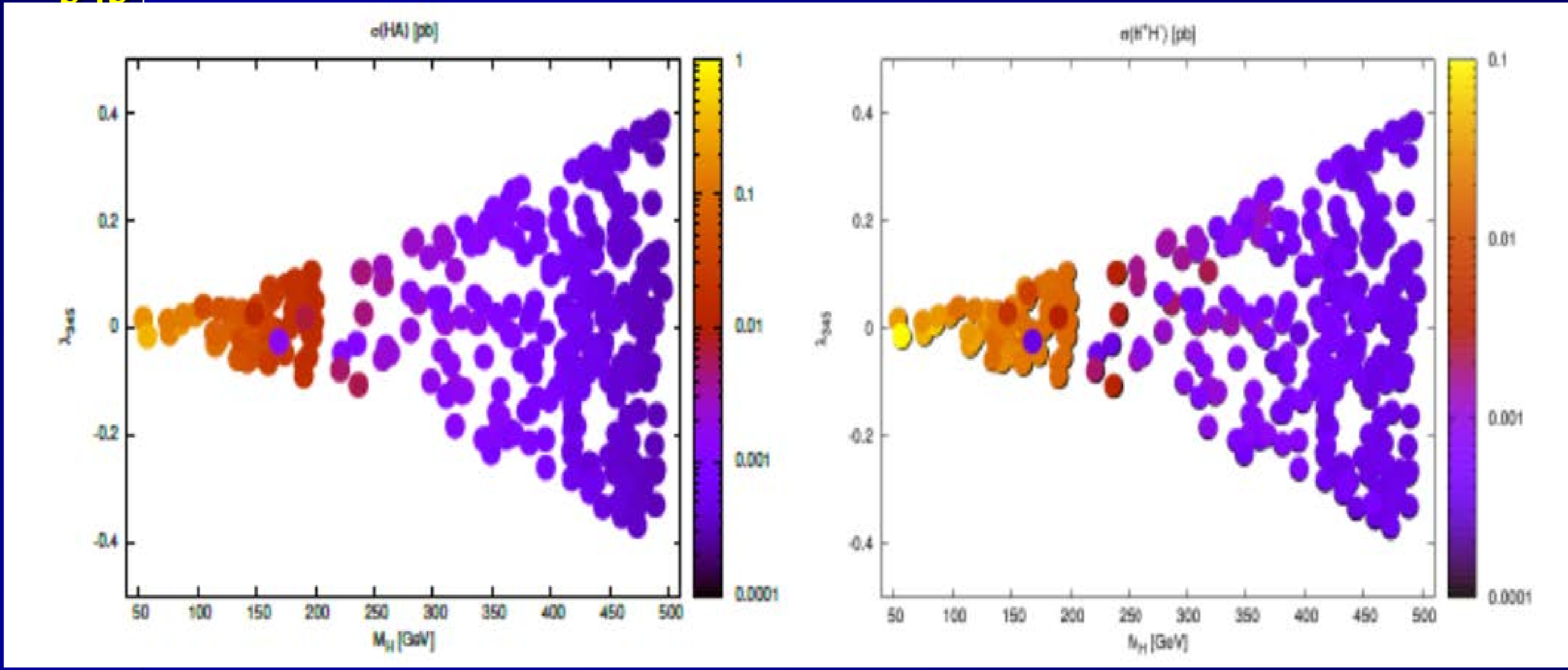
Our signal: 2l+MET



Benchmarks for LHC II

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

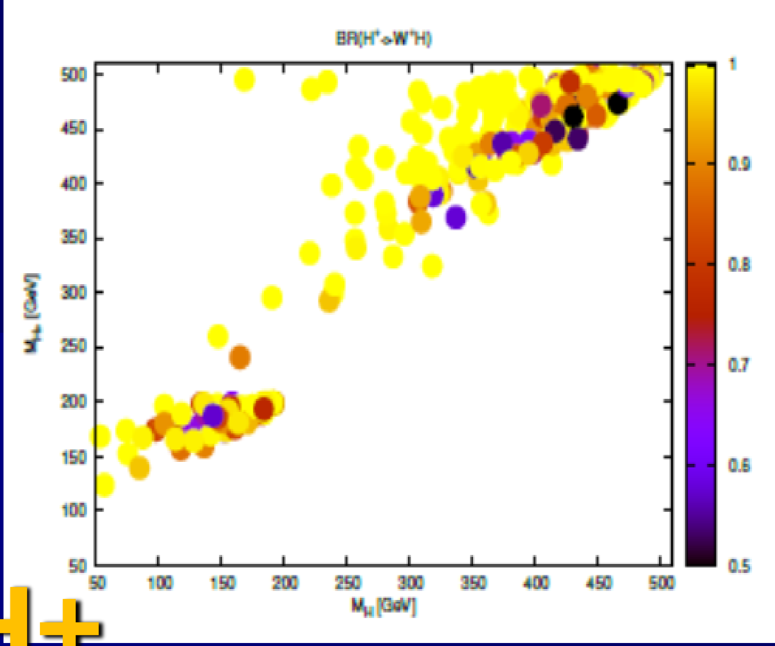
λ_{345} **HA** **H+H-**



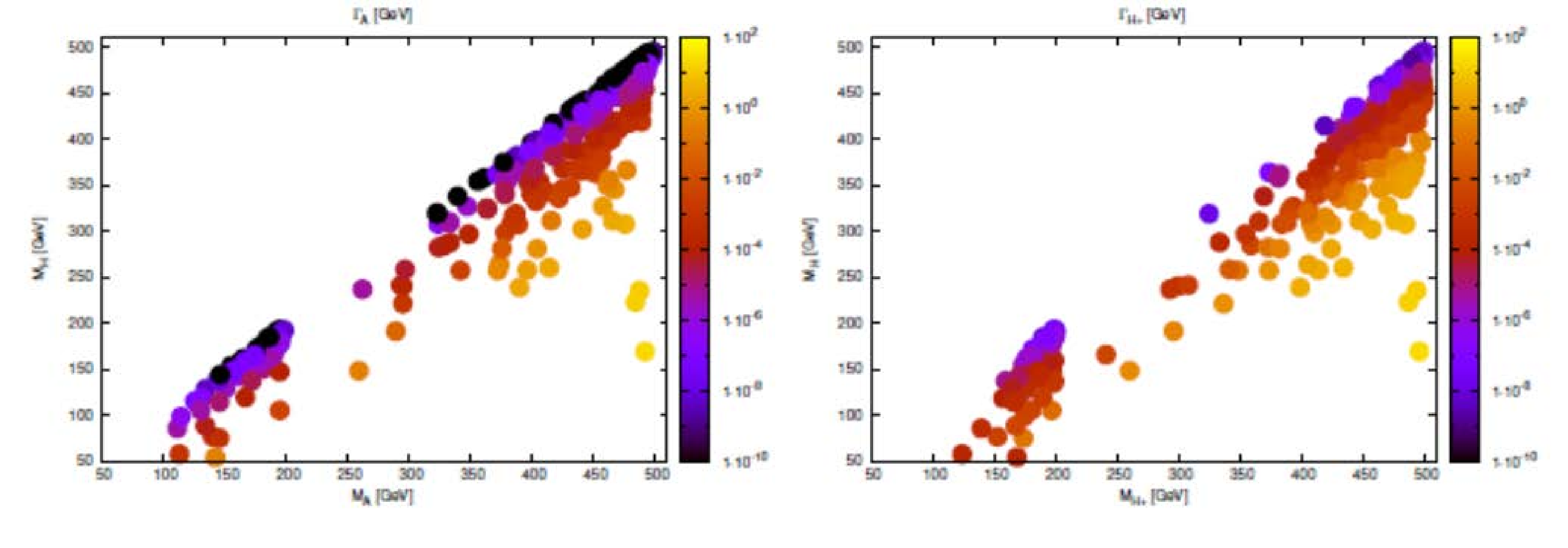
M_H

Cross section in pb, mass in GeV

Br (H+ → W+ H)



Total width for A, H+



For all points, $\Gamma/M \sim 0.05$,

Summary

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

  SM doublet → one Higgs SM-like h

  Dark doublet → 4 scalars (two charged)

  one stable (H=DM)

- IDM in agreement with LHC data and relic density + direct detection LUX data, $M_H > 45$ GeV

Higgs is a sensitive probe of DM !

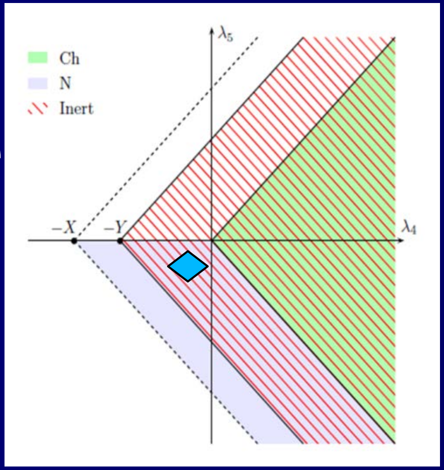
Evolution of Universe to the Inert Phase

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

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

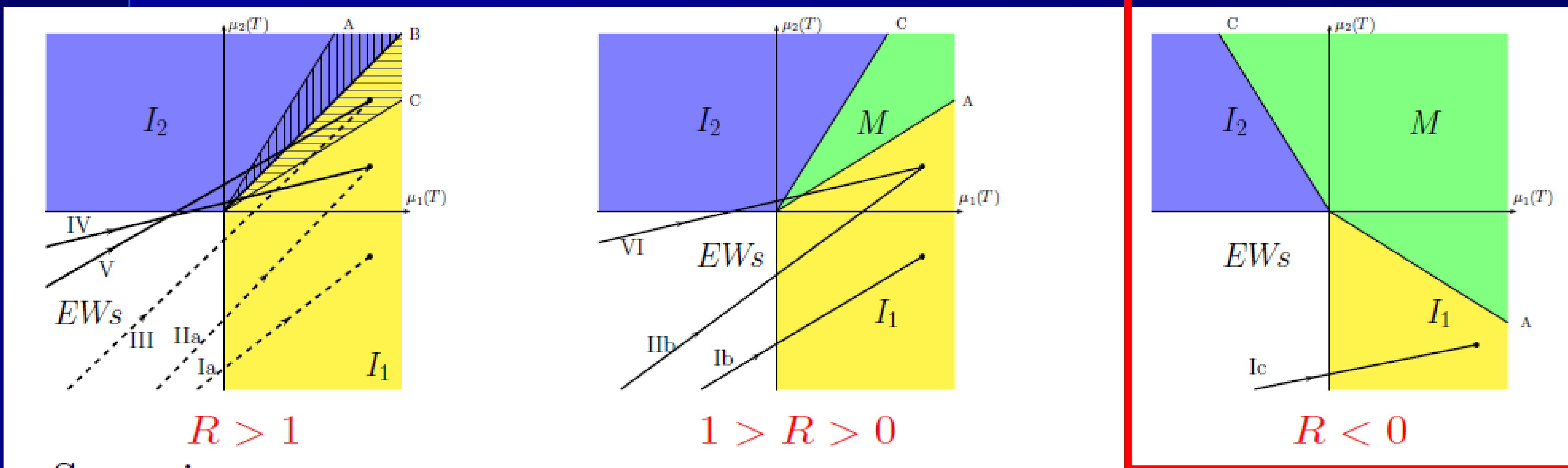
We consider 2HDM with an explicit D symmetry assuming that today the Inert Doublet Model describes reality. In the simplest approximation only *mass terms* in V vary with temperature like T^2, while λ*'s* are fixed

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

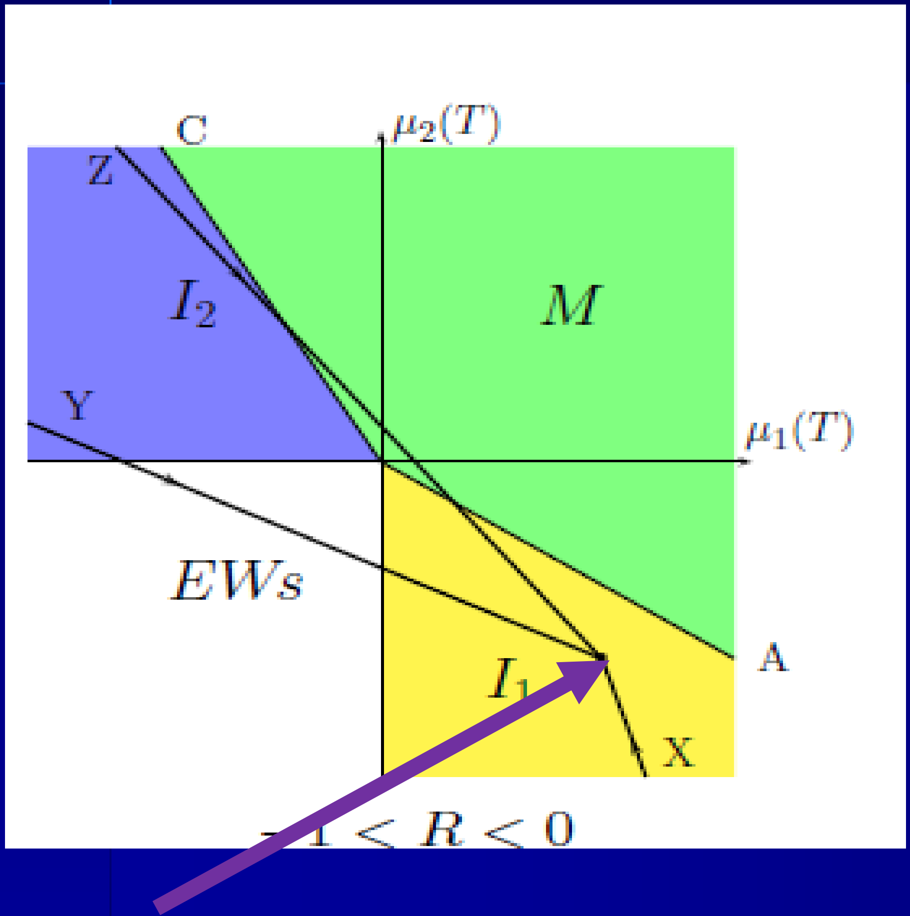
$\to$ rays from EWs phase to Inert phase

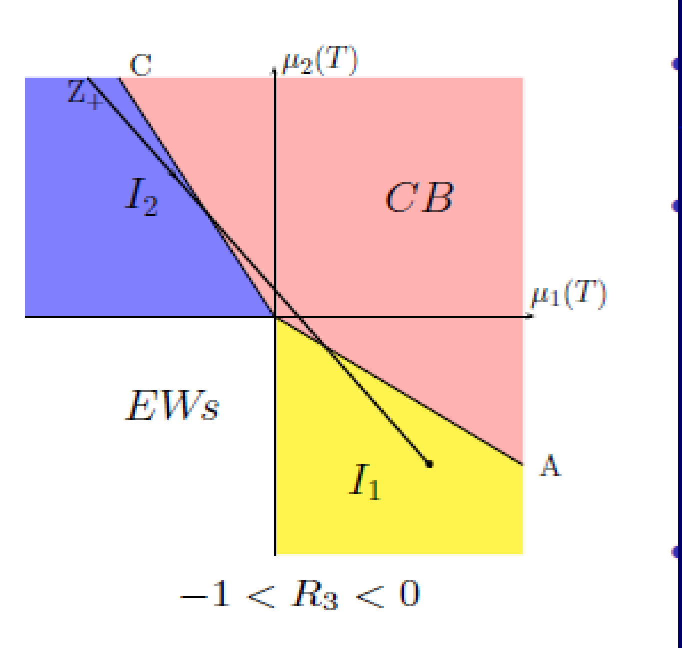
one, two or three stages of Universe

(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

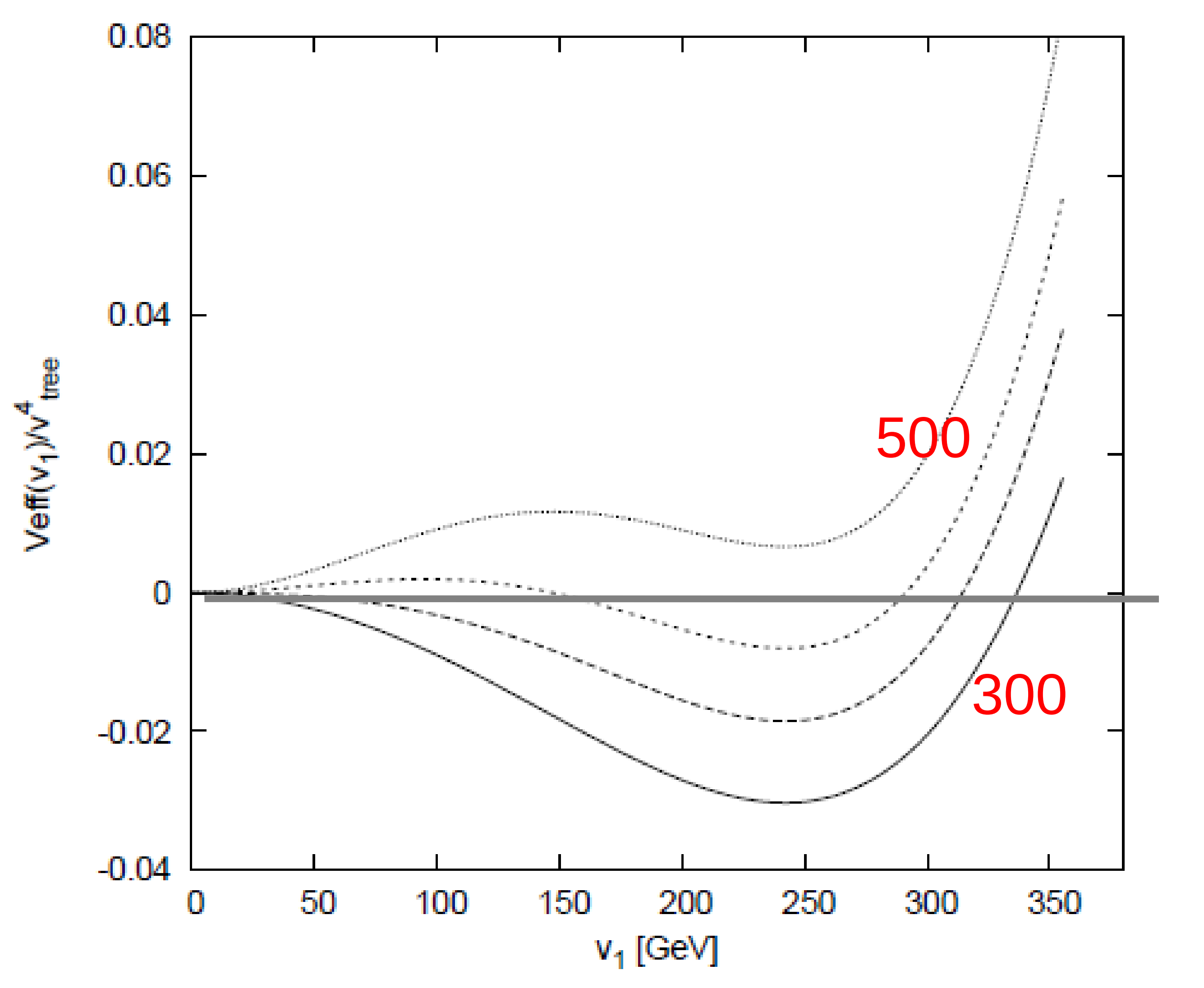
mass matrices

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

number of states

counter terms →

Effective T=0 potential



Mh=125 GeV

MH=65 GeV

MH+=MA=
500,450,400,300
GeVṼ

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)

Strength of the phase transition

$v(T_{EW})/T_{EW}$

We are looking for parameter space of IDM which allows for a strong first order phase transition

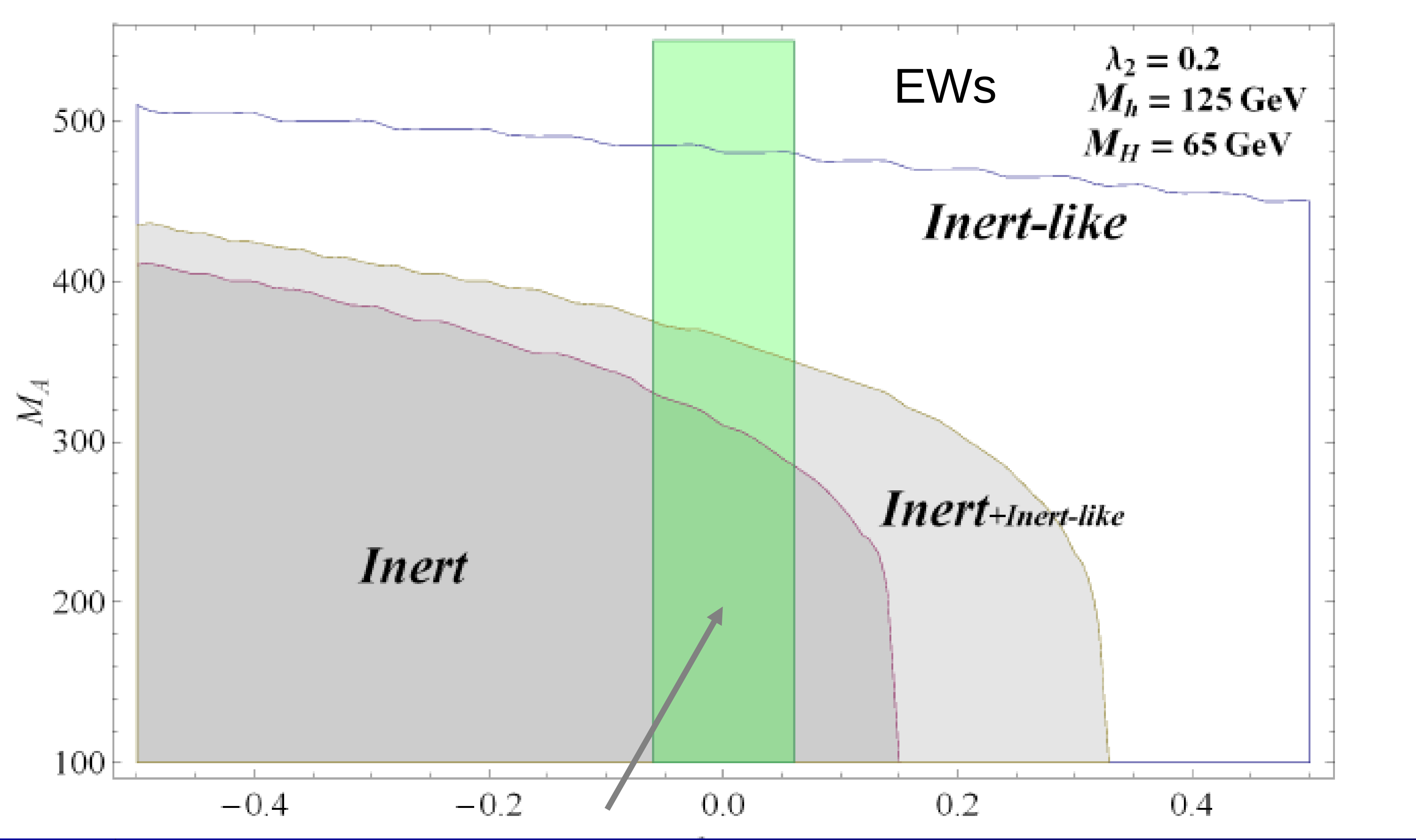
$v(T_{EW})/T_{EW} > 1$

being in agreement with collider and astrophys. data

We focus on medium DM, with M_H « v,

heavy degenerated A and H+ and M_h=125 GeV

Phases at T=0



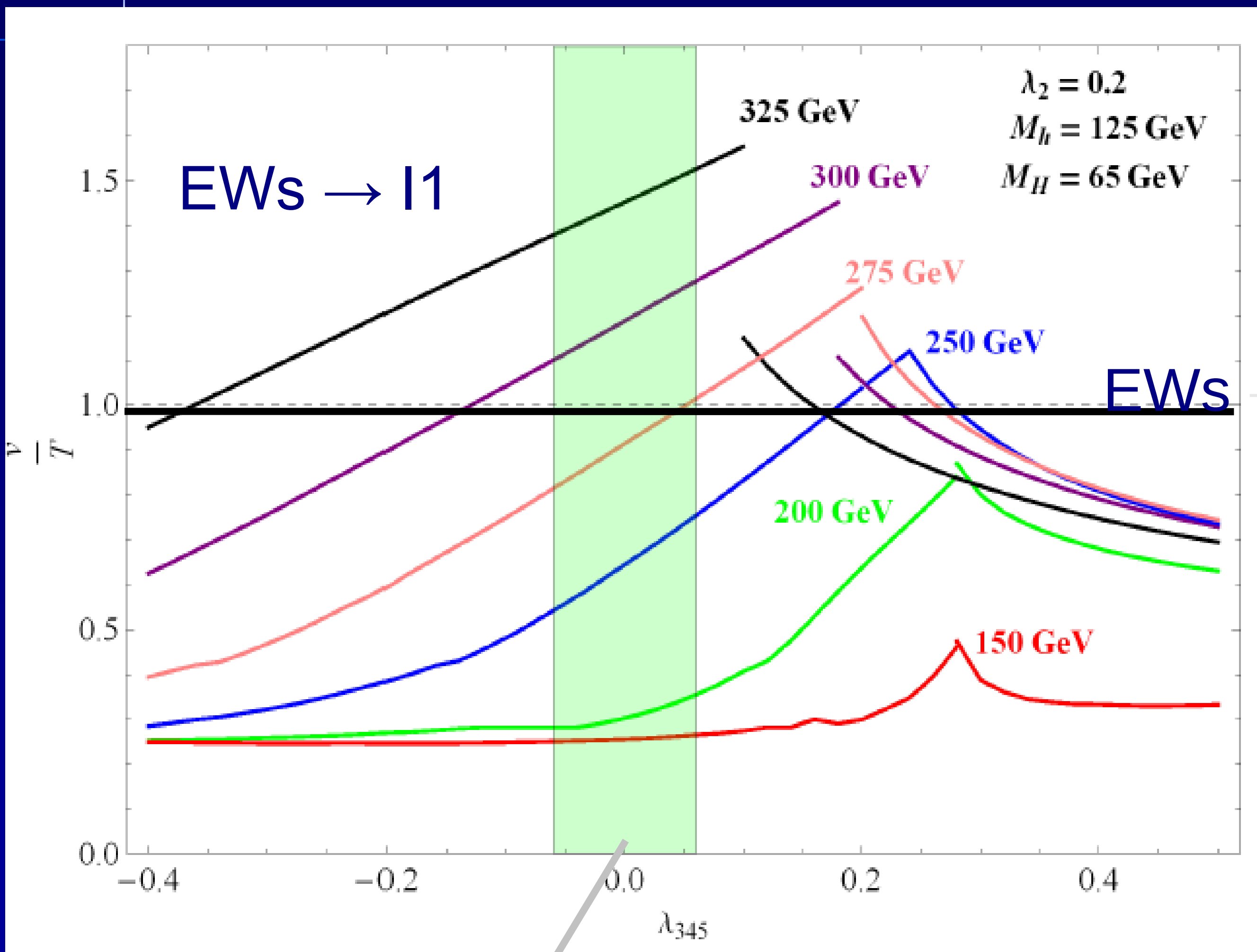
Xenon100 bound

λ_{345}

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

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

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*

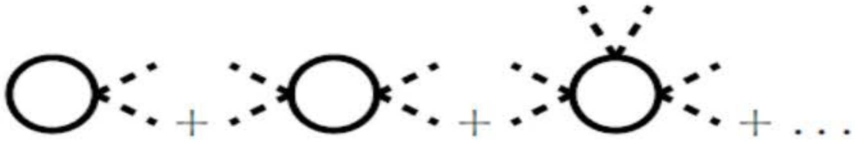
Effective potential

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]

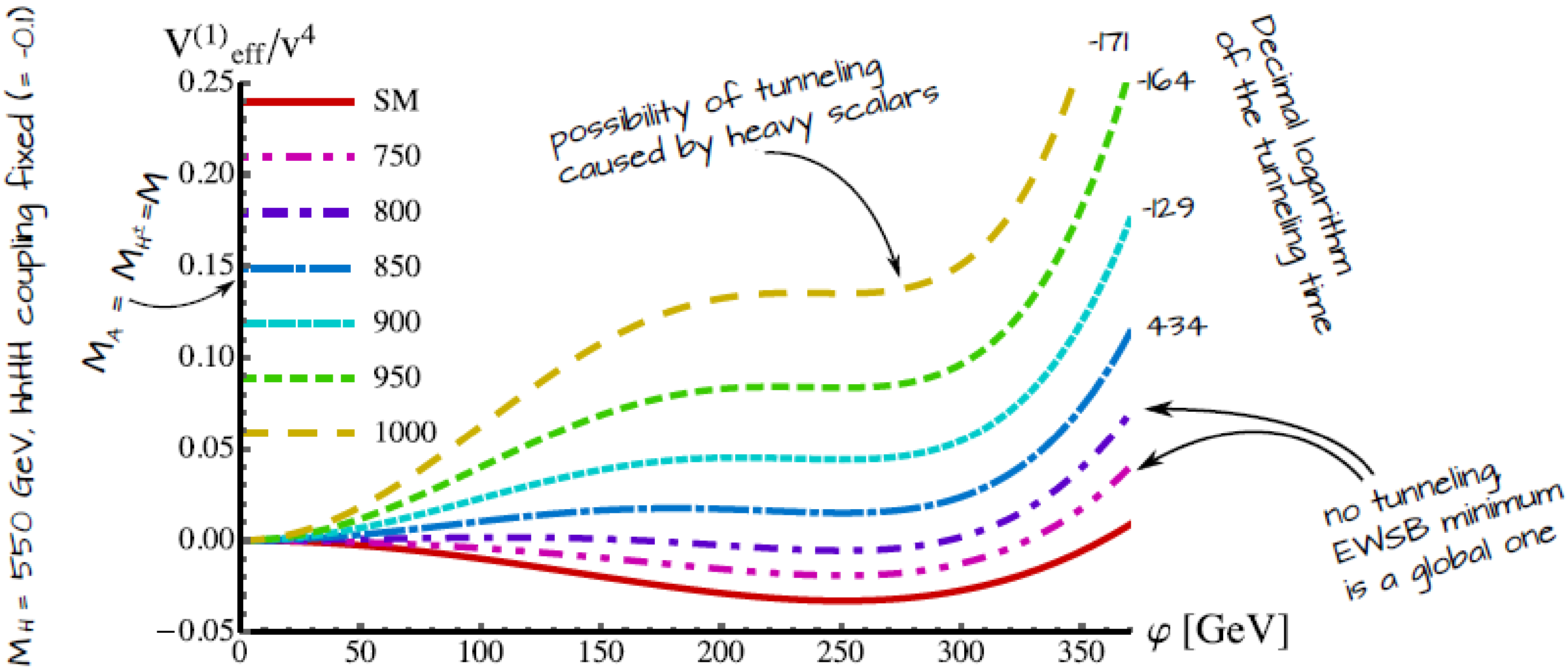
To take into account quantum corrections we analyse one-loop effective potential

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



- 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

Summary III

IDM in agreement with Higgs and DM data

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 $\lambda_3 <0$ also $\lambda_{345} <0$)
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)

4.07.2012

Higgs-like particle with mass125 -126 GeV observed by ATLAS+CMS (+Tevatron)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

26.06.1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

27.07.1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

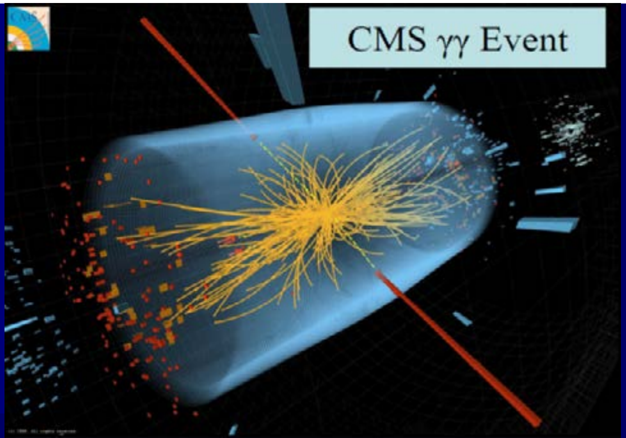
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

12.10.1964



Extrema → vacua (v = 246 GeV)

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

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

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

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

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

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

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

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

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

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

Phase for TODAY

2HDM with an <u>explicit</u> D symmetry (ie. in Lagrangian L)

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

- Charge breaking phase Ch?

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

- Neutral phases:

<u>Mixed M</u> in agreement with data

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

D spont. broken

<u>Inert I1</u> OK! In agreement with accelerator

and astrophysical data (neutral DM)

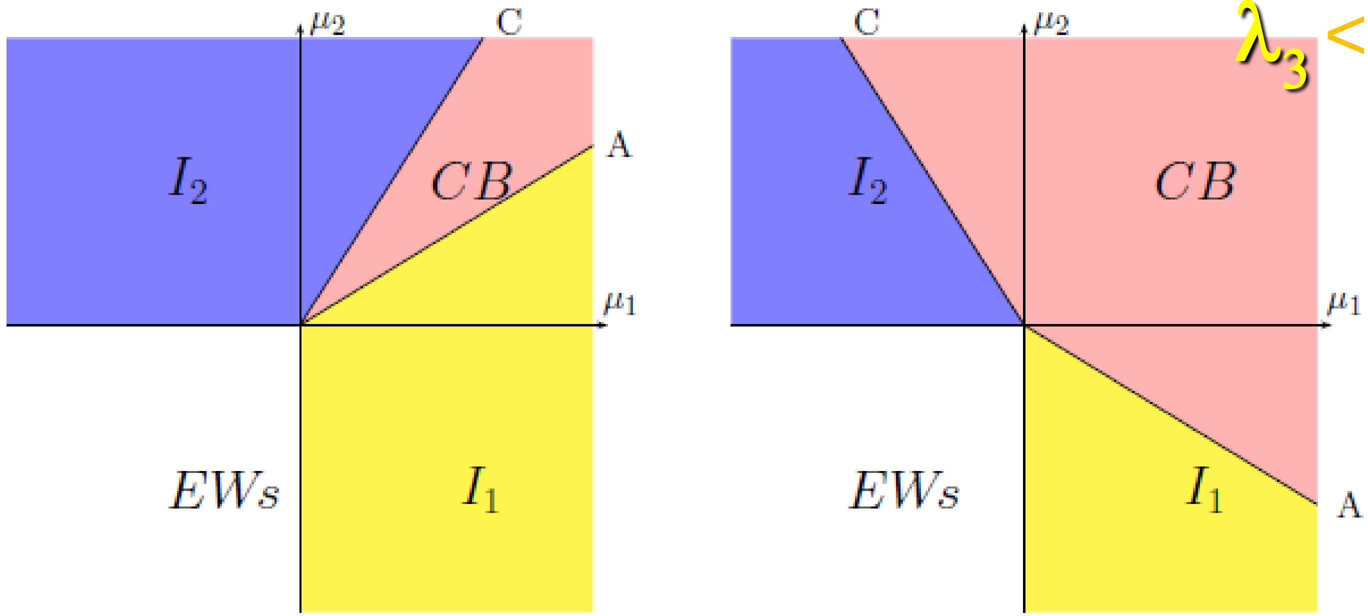
(Model I - only Φ_S interacts with fermions)

D symmetry exact

<u>Inert-like I2</u> NO (fermions massless !)

Phase diagrams for D-sym. V
Charged Breaking phase

$\lambda_3 < 0$

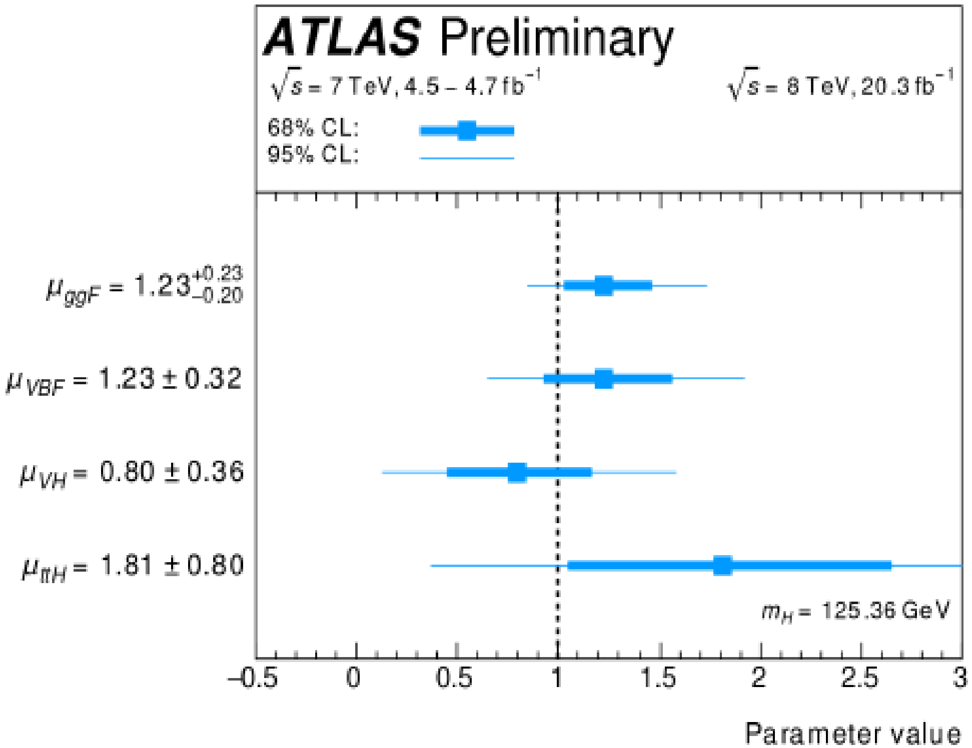


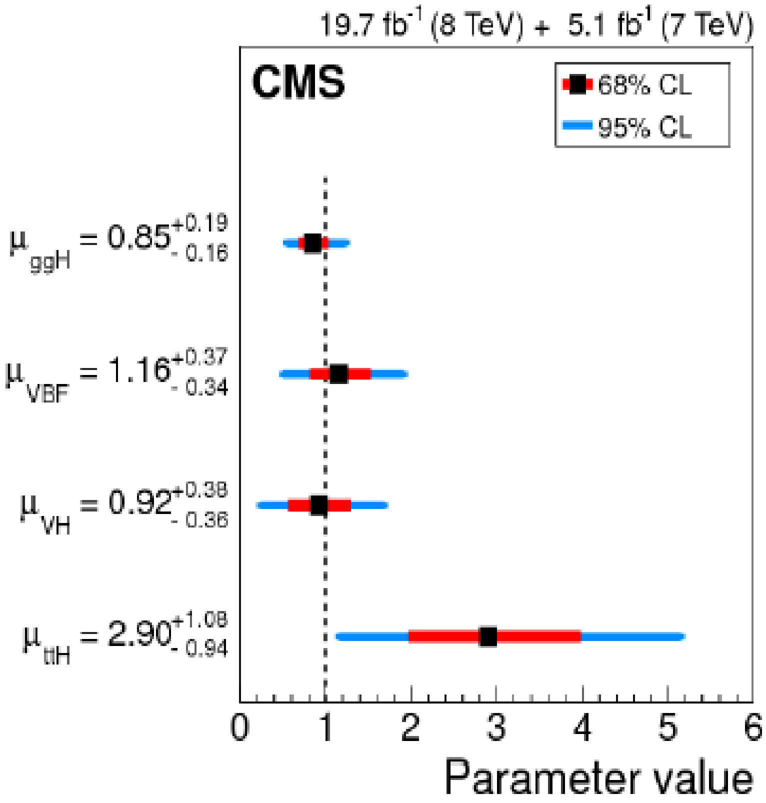
(a) $1 > R_3 > 0$ (b) $0 > R_3 > -1$

$$R_3 + 1 > 0$$

$$R_3 = \lambda_3 / \sqrt{\lambda_1 \lambda_2}.$$

Signal strength – grouped by production mode

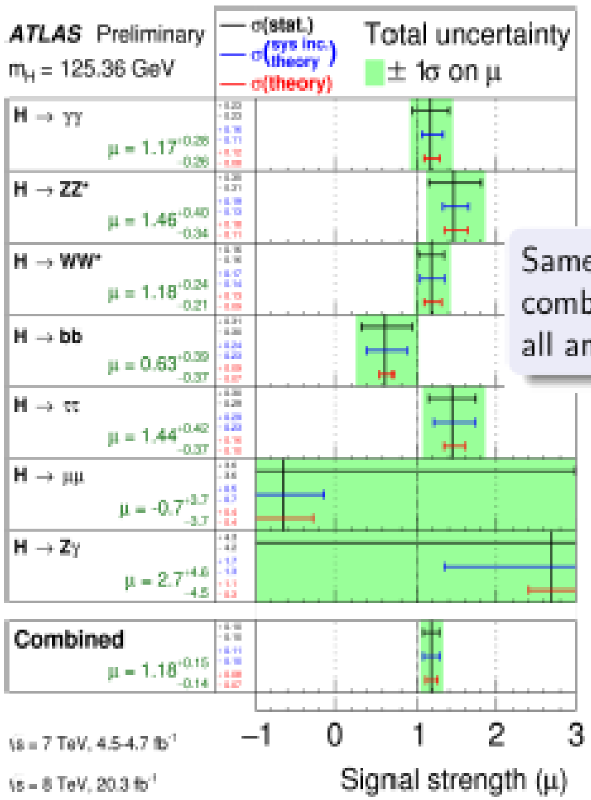




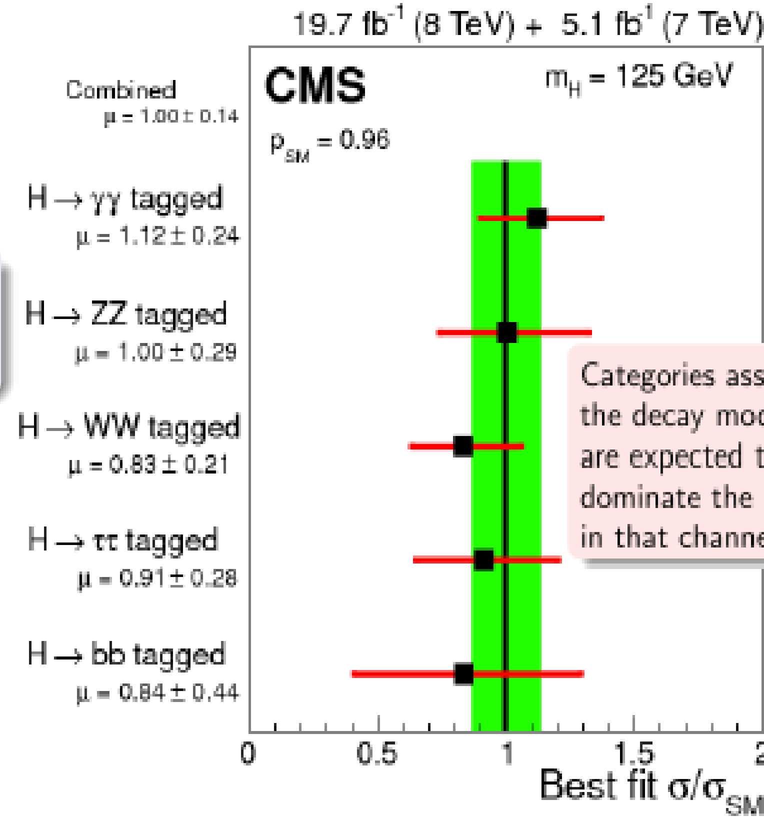
Production mode groups

- Assumed SM branching fractions to factor out the signal strengths from production modes
- Excess 2σ in ttH — interesting

Signal strength – grouped by decay mode



Same decay channel combined together for all analyses



Categories assigned to the decay mode group are expected to dominate the sensitivity in that channel for SM

Decay mode groups

Plestina

- Assumed SM fractions of production cross sections
- Overall signal strength ATLAS: $1.18 \pm 0.10(stat.)^{+0.08}_{-0.07}(theo.) \pm 0.07(syst.)$
- Overall signal strength CMS: $1.00 \pm 0.09(stat.)^{+0.08}_{-0.07}(theo.) \pm 0.07(syst.)$
- *Theoretical* uncertainty includes QCD scales, PDF+α_S, UEPS, and BR

Extrema of the Z_2 symmetric potential

Ginzburg, Kanishev, MK, Sokołowska'09

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

Finding minima → global minimum (vacum)

Positivity (stability) constraints (V with real parameters)

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

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

Extremum fulfilling the positivity constraints with the lowest energy = vacuum