Higgs Workshop

Toyama 13.02.2013

Inert Doublet Model with 125 GeV Higgs

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THE THEORY OF MATTER and STANDARD MODEL(S)

F. Wilczek, LEPFest, Nov.2000 (hep-ph/0101187)

Theory of Matter = $SU(2)_{I\ weak} \times U(1)_{Y\ weak} \times SU(3)_{color}$

Theory of Matter refers to the core concepts:
- quantum field theory
- gauge symmetry
- spontaneous symmetry breaking
- asymptotic freedom
- the assignments of the lightest quarks and leptons

Standard Models: Choose the number of Higgs (scalar) doublets
SM=1HDM, 2HDM (MSSM,IDM), 3HDM ...
Note, that the lightest scalar is often SM-like

NonStandard Models are based on more radical assumptions.

Plan

- Higgs at LHC 2012
- SM-like Higgs scenarios
- Two Higgs Doublet Models – 2HDM

- Z2 symmetry in 2HDM

  → Normal (Mixed) Model (as MSSM)

  → Dark 2HDM = 2HDM with Dark Matter
  called Inert Doublet Model (IDM)

- Enhancement in $\gamma\gamma$ Higgs final states

- Evolution of the Universe (T^2 and beyond) in IDM

LHC

Higgs-like particle with mass~125-126 GeV observed at 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)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

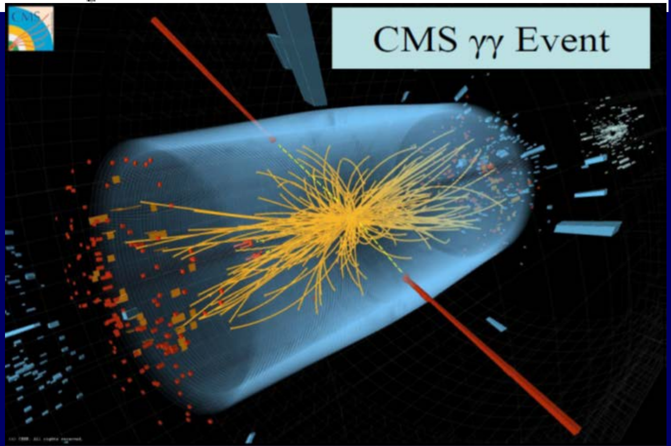
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

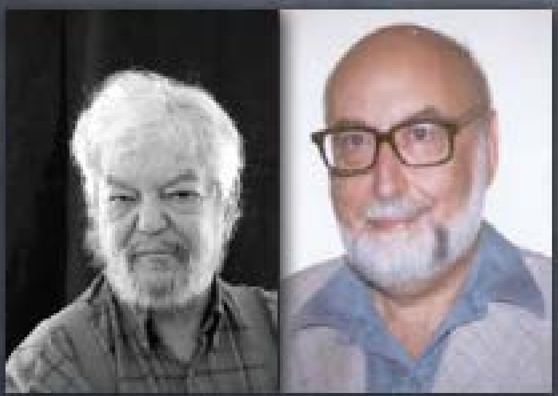
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



Important loop couplings ggH,γγH

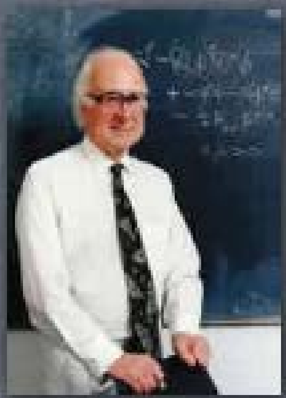
2010 Sakurai Prize

... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."



Brout Englert

PRL 13, 321-323 (1964)



Higgs

PRL 13, 508-509 (1964)

Hagen Guralnik Kibble

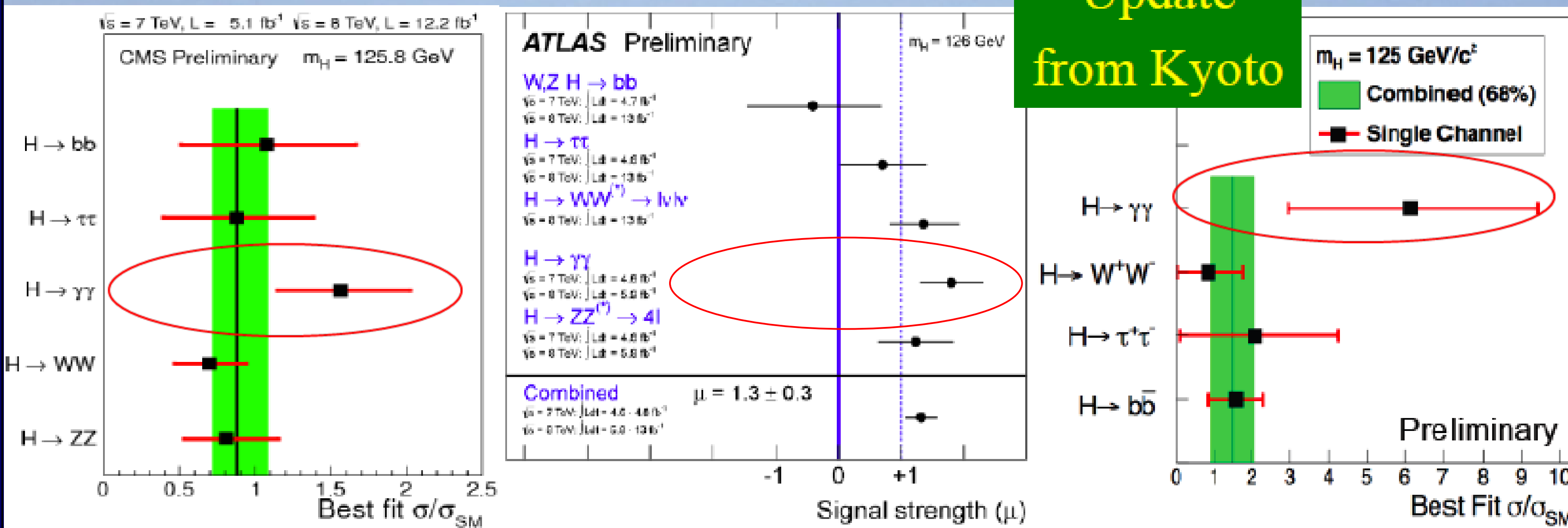
PRL 13, 585-587 (1964)

Nambu, Nobel 2008
SSB to particle physics

J. Ellis, 20.11.2012

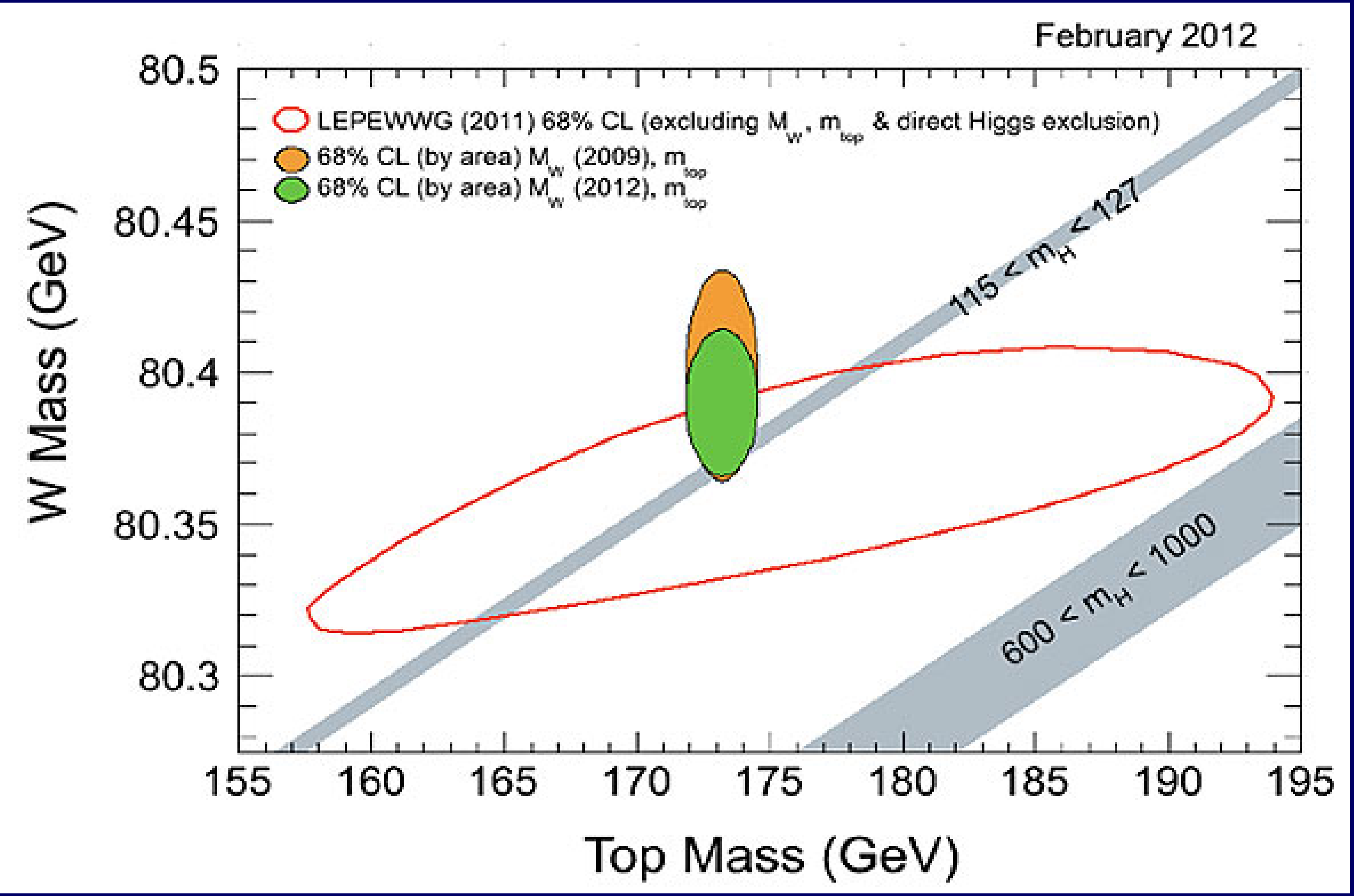
Summary of the Story so far

Update from Kyoto



Signals compatible (so far) with the Standard Model

Tevatron



February 2012
LEPEWWG (2011) 68% CL (excluding M_W, m_{top} & direct Higgs exclusion)
68% CL (by area) M_W (2009), m_{top}
68% CL (by area) M_W (2012), m_{top}
$115 < m_H < 127$
$600 < m_H < 1000$
80.5
80.45
80.4
80.35
80.3
W Mass (GeV)
155
160
165
170
175
180
185
190
195
Top Mass (GeV)

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow U(1)_{QED}$

Standard Model

Doublet of SU(2): $\Phi = (\varphi^{+}, v + H + i\zeta)^{T}$

Masses for $W^{+/-}$, Z (tree $\rho = 1$) , no mass for the photon

Fermion masses via Yukawa interaction

Higgs particle H_{SM} - spin 0, neutral, CP even

couplings to WW/ZZ, Yukawa couplings to fermions

unknown mass $\leftrightarrow$ selfinteraction

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

SU(2) x U(1) → ?

T.D. Lee 1973

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: H+ and H- and neutrals:

- CP conservation: CP-even h, H & CP-odd A
- CP violation: h_1,h_2,h_3 with undefinite CP parity*

Sum rules hold (for relative couplings to SM χ)

SM-like scenarios

- In many models SM-like scenarios are possible

Our definition of SM-like scenario (2012):

Higgs h with mass ~ 125 GeV, SM tree-level couplings*
within exp. accuracy *(* up to sign)*

No other new particles seen …
(too heavy or too weakly interacting)

Note: Loops ggh, $\gamma\gamma$h, γZh may differ from the SM case

- In models with two SU(2) doublets:
  - MSSM with decoupling of heavy Higgses
  - 2HDM (Mixed), where *both h or H can be SM-like*
  - Inert Doublet Model, only *one SM-like Higgs h*

2HDM's

Branco,Rebelo,Ferreira
Silva,Lavoura,Sher '12
Haber, Gunion
Ginzburg, MK, Ivanov
Nachtmann, Maniatis,
Pilaftsis,…

SYMMETRIES!!!

Potential

Yukawa

Vacuum

2HDM Lagrangian $L=L_{SM}+L_H+L_Y$

Potential

with $L_H=T-V$

$$V = \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2+\tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

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

$$+\ [(\lambda_6(\Phi_1^\dagger\,\Phi_1)+\lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2)+h.c]$$

$$-\ \tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1)-\ \tfrac{1}{2}m^2_{22}(\Phi^\dagger\Phi_2)-\ \tfrac{1}{2}[m^2_{12}(\Phi_1^\dagger\Phi_2)+h.c.]$$

Z_2 symmetry transformation: $\Phi_1\to\Phi_1\ \ \Phi_2\to -\Phi_2$

(or vice versa)

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12}=\mu^2$)

Explicit Z_2 symmetry in V: λ_6, λ_7, $m^2_{12}=0$ (NO CP violation)

Various models of Yukawa inter.

typically with some Z2 type symmetry to avoid FCNC

Model I - only one doublet interacts with fermions

Model II – one doublet with down-type fermions d , l

other with up-type fermions u

Model III - both doublets interact with fermions

Model IV (X) - leptons interacts with one doublet, quarks with the other

Model Y - one doublet with down-type quarks d

other with up-type quarks u and leptons

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

+ Extra dim 2HDM models + others

Extrema of the 2HDM potential with explicit Z_2 symmetry

Ginzburg, Kanishev, MK, Sokołowska'09

Finding extrema: $\partial V / \partial \Phi|_{\Phi = \langle\Phi\rangle} = 0$

Finding minima → global minimum = vacuum

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

Possible extrema (vacuua)

for V with Z_2 symmetry $\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$ (D symmetry)

The most general extremum state $\Phi_1 \to \Phi_S$ $\Phi_2 \to \Phi_D$

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

v_S, v_D, u - real

v_S, $u \geq 0$

$v^2 = v_S^2 + v_D^2 + u^2$

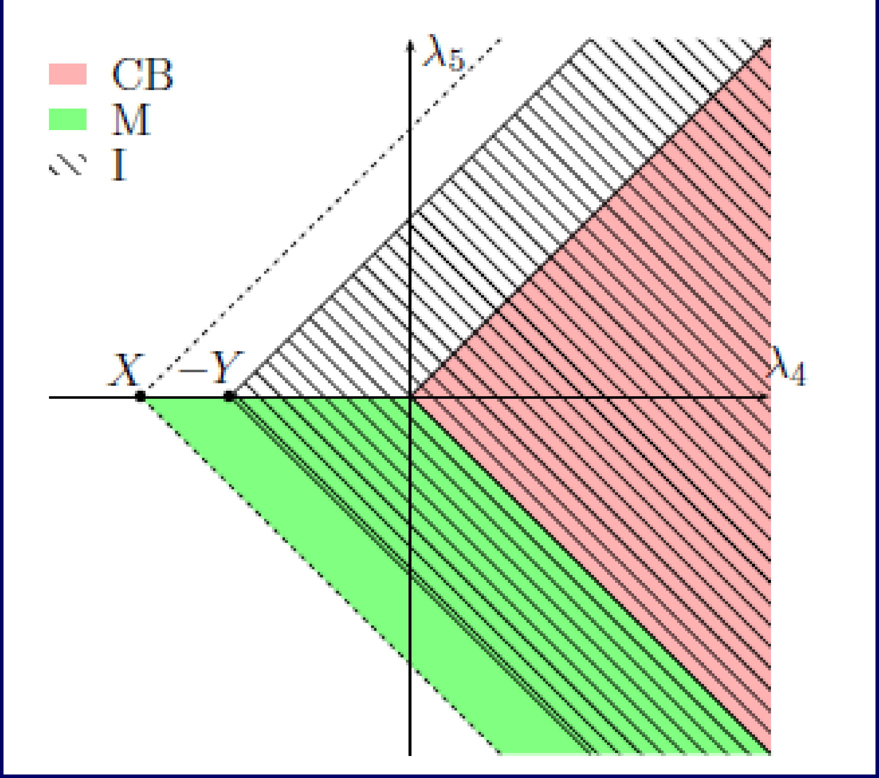
EWs	EWs	$u = v_D = v_S = 0$
Inert	I_1	$u = v_D = 0$
Inert-like	I_2	$u = v_S = 0$
Mixed (Normal, MSSM like)	M	$u = 0$
Charge Breaking	Ch	$u \neq 0$ $v_D = 0$

D-symmetric potential - vacua

Stable vacuum (positivity) $\lambda_4 \pm \lambda_5 > -X$, $X = \sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0$

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

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



$Y = M_{H+}^2\, 2/v^2|_{\text{Inert}}$

Neutral vacua

- Mixed M [v1, v2 ≠ 0]
- Inert I1 (I2) [v1(v2) ≠ 0]

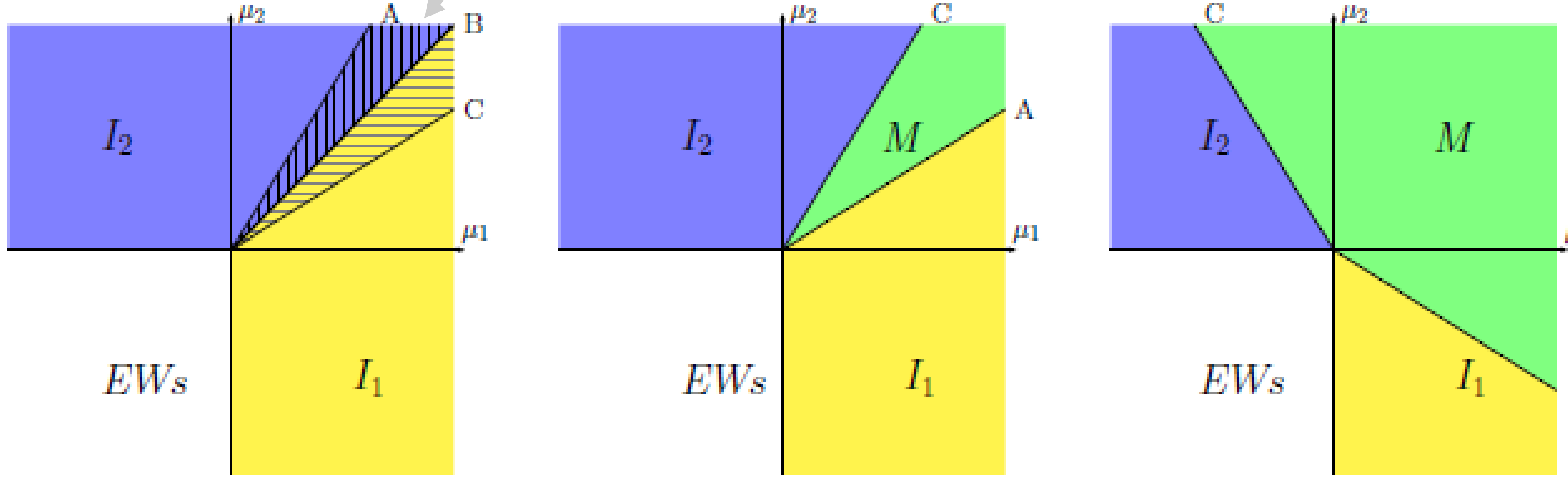
- Charged breaking vacuum CB

Inert overlaps both with Mixed and CB !

Phase diagrams for D-sym. V

coexistence
of minima

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



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

Inert (I1) vacuum
for Mh=125 GeV →

$$\mu_1 = \frac{m_{11}^2}{\sqrt{\lambda_1}},$$

Phase for TODAY (incl. LHC data..)

2HDM with <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...
  $\to$ No
- Neutral phases:
  <u>Mixed M</u> in agreement with data
  here Model 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

  Inert 2 ? NO (fermions massless)

Inert Doublet Model

Ma,…'78
Barbieri..'06

Symmetry under Z_2 transf. $\Phi_S \to \Phi_S$ $\Phi_D \to - \Phi_D$
both in L (V and Yukawa interaction = Model I only Φ_S)
and in the vacuum:

Today

$<\Phi_S> = v$ $<\Phi_D> = 0$ Inert vacuum I_1

Φ_S as in SM (BEH), with Higgs boson h (SM-like)
Φ_D has no vev, with 4 scalars (no Higgs bosons!)
no interaction with fermions (inert doublet)

Here Z_2 symmetry exact $\to Z_2$ parity, only Φ_D has odd Z_2-parity
$\to$ The lightest scalar stable -a dark matter candidate
(Φ_D dark doublet with dark scalars) .

$\Phi_1 \to \Phi_S$ Higgs doublet S $\Phi_2 \to \Phi_D$ Dark doublet D

The Inert Doublet Model: An Archetype for Dark Matter, Lopez Honorez,..Tytgat ..07

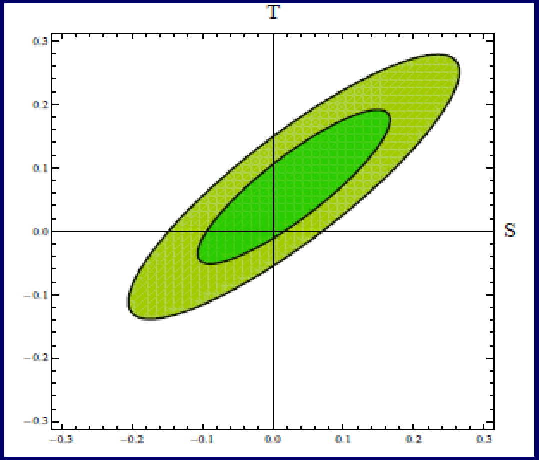
Confronting with data

Ma,..2006,..
**B. Gorczyca(Świeżewska), Thesis2011, 1112.4356, 1112.5086 ,*
Posch..2011, Dolle, Su…
Arhrib..2012, Chang…2012

Constraints:
vacuum stability,
perturbative unitarity
condition for a specific vacuum

Data:
EWPT (S and T)
LEP, LHC and DM data

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



Inert Doublet Model: it's a SM-like scenario for h; H=DM

In contrast Mixed Model (II) with 5 Higgses
sum rules for relative couplings eg. $(\chi^h{}_V)^2 + (\chi^H{}_V)^2 = 1$
can have SM-like h or H (with χ_V=1) V=W/Z

Unitarity constraints on parameters of V (D symmetry)

B. Gorczyca (Świeżewska), MSc Thesis, July 2011

Full scattering matrix macierz 25x25 for scalars (including Goldstone's)

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_1 & & & & & \\ & \mathcal{M}_2 & & & & \\ & & \mathcal{M}_3 & & & \\ & & & \mathcal{M}_4 & & \\ & & & & \mathcal{M}_5 & \\ & & & & & \mathcal{M}_6 \end{pmatrix}.$$

in high energy limit

Block-diagonal form due electric charge and CP conservation

M1: G+H-, G-H+, hA, GA, GH, hH
M2: G+G-, H+H-, GG, HH, AA, hh
M3: Gh, AH
M4: G+G, G+H, G+A, G+h, GH+, HH+,AH+,hH+
M5: G+G+, H+H+
M6: G+H+

Unitarity constraints
→ |eigenvalues|< 8 π

Kanemura et al. 93; 2001
Akeroyd,Arhrib,Naimi, 2000….

Pert. unitarity constraints on lambda's

B. Gorczyca, MSc Thesis, July 2011

$$
\begin{aligned}
0 &\leqslant \lambda_1 \leqslant 8.38,\\
0 &\leqslant \lambda_2 \leqslant 8.38,\\
-6.05 &\leqslant \lambda_3 \leqslant 16.44,\\
-15.98 &\leqslant \lambda_4 \leqslant 5.93,\\
-8.34 &\leqslant \lambda_5 \leqslant 0.
\end{aligned}
$$

(hold for Mixed as well)

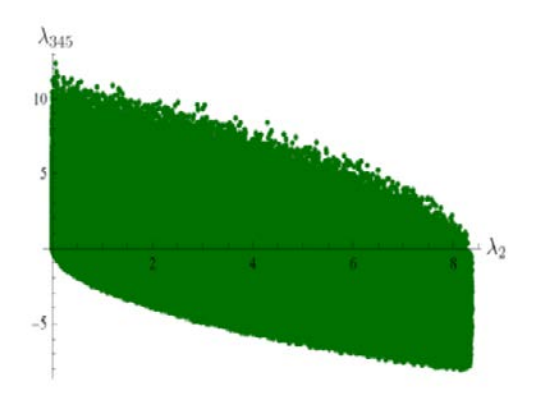
and for combinations

Couplings for dark particles in IDM

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

$\lambda_{45}=\lambda_4+\lambda_5$

$$
\begin{aligned}
-8.10 &\leqslant \lambda_{345} \leqslant 12.38,\\
-7.76 &\leqslant \bar{\lambda}_{345} \leqslant 16.45,\\
-8.28 &\leqslant \tfrac{1}{2}\lambda_{45} \leqslant 0,\\
-7.97 &\leqslant \tfrac{1}{2}\bar{\lambda}_{45} \leqslant 6.08,
\end{aligned}
$$



Condition for the Inert vacuum

IDM:

- $\langle \phi_S \rangle = \frac{v}{\sqrt{2}}, \langle \phi_D \rangle = 0$
- 5 physical scalars: $h, H, A, H^{\pm}$ (h - the Higgs boson)
- The Inert vacuum can be realized only if:

$$m_{11}^2 > 0, \quad \lambda_1 > 0, \quad \lambda_3 v^2 \geqslant m_{22}^2,$$

$$(\lambda_3 + \lambda_4 \pm \lambda_5) v^2 \geqslant m_{22}^2, \quad \frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}$$

For 125 GeV h: $M^2_h = m_{11}{}^2 = \lambda_1 v^2$ and max λ_2 value

upper limit: $m_{22}{}^2 < 9.\ 10$^4 GeV^2

Testing Inert Doublet Model

Ma'2006,.Barbieri 2006, Dolle,Su, Gorczyca(Świeżewska), MSc T2011, 1112.4356, 1112.5086, Posch, 2011, Arhrib..2012

Using properties of

- the SM-like h, $M^2_h = m_{11}^2 = \lambda_1 v^2$

Using properties of dark scalars

- masses depend on m_{22}^2
- the dark scalars D interact always in pairs!

$$M_{H^+}^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3}{2} v^2$$

$$M_H^2 = -\frac{m_{22}^2}{2} + \underbrace{\frac{\lambda_3+\lambda_4+\lambda_5}{2}}_{\lambda_{345}} v^2$$

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

D couple to V = W/Z (eg. AZH, $H^- W^+ H$), not DVV!

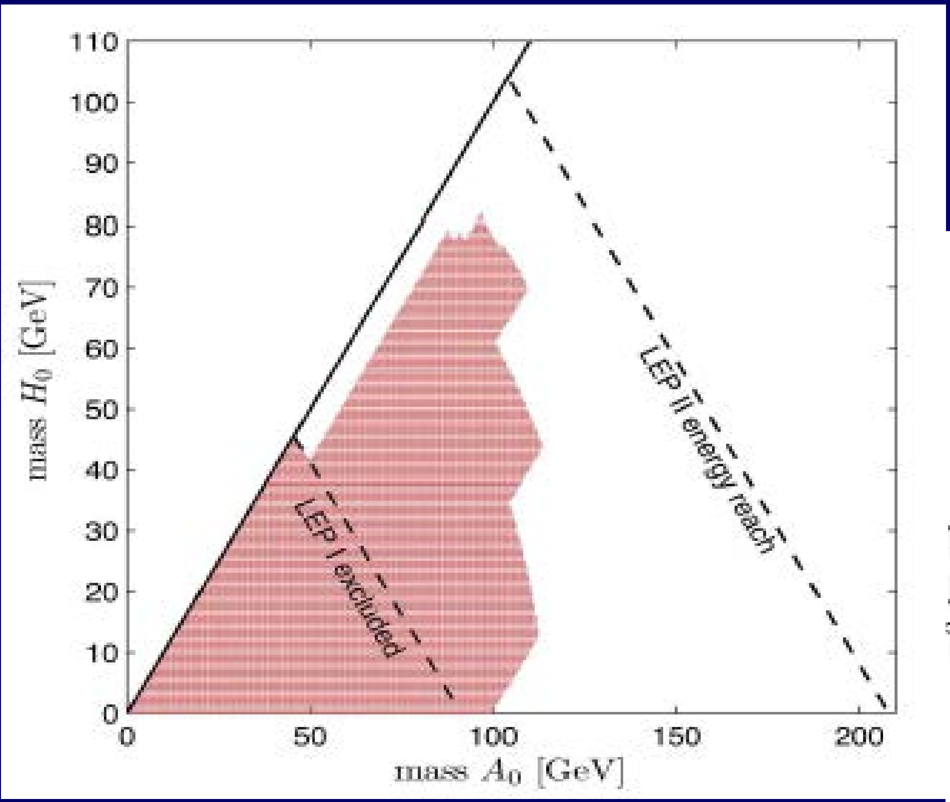
Quartic selfcouplings D^4 proportional to λ_2

hopeless to be measured at colliders! *(→ DM D. Sokołowska)*

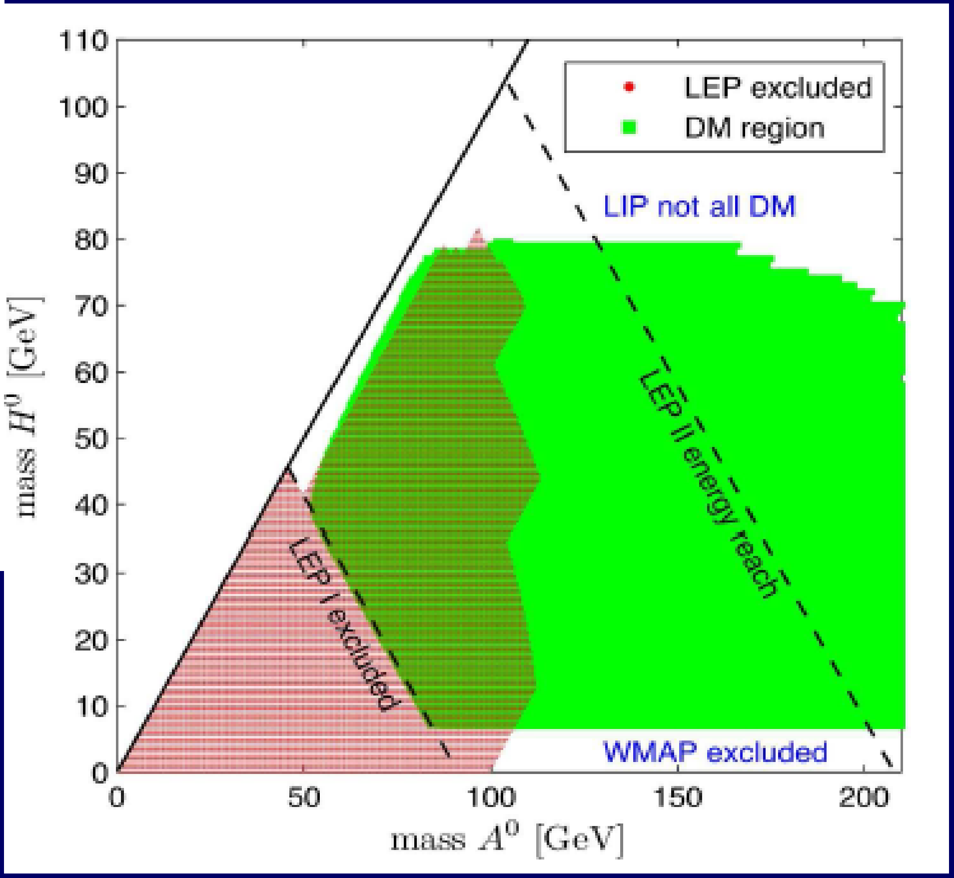
Couplings with Higgs: hHH ~ λ_{345} h H+H- ~ λ_3

IDM: LEP II exclusion (masses H vs A)

Lundstrom... hep-ph/0810.3924



DM=H



LEP II + WIMAP

IDM constraints: LEP + S,T,U + DM relic density

constraints for masses and $D_H D_H h_S$, $D_H D_H h_S h_S$ couplings

D. Sokołowska 2010
using MicroOmega's

Dark scalars:

- **low DM mass** $M_{D_H} \lesssim 10$ GeV,
  large mass splittings: $\Delta(D_A, D_H)$ and $\Delta(D^{\pm}, D_H)$
- **medium DM mass** $M_{D_H} \approx (40 - 160)$ GeV,
  large $\Delta(D^{\pm}, D_H)$, small or large $\Delta(D_A, D_H)$
- **high DM mass** $M_H \approx (500 - 1000)$ GeV,
  small $\Delta(D_A, D_H)$ and $\Delta(D^{\pm}, D_H)$

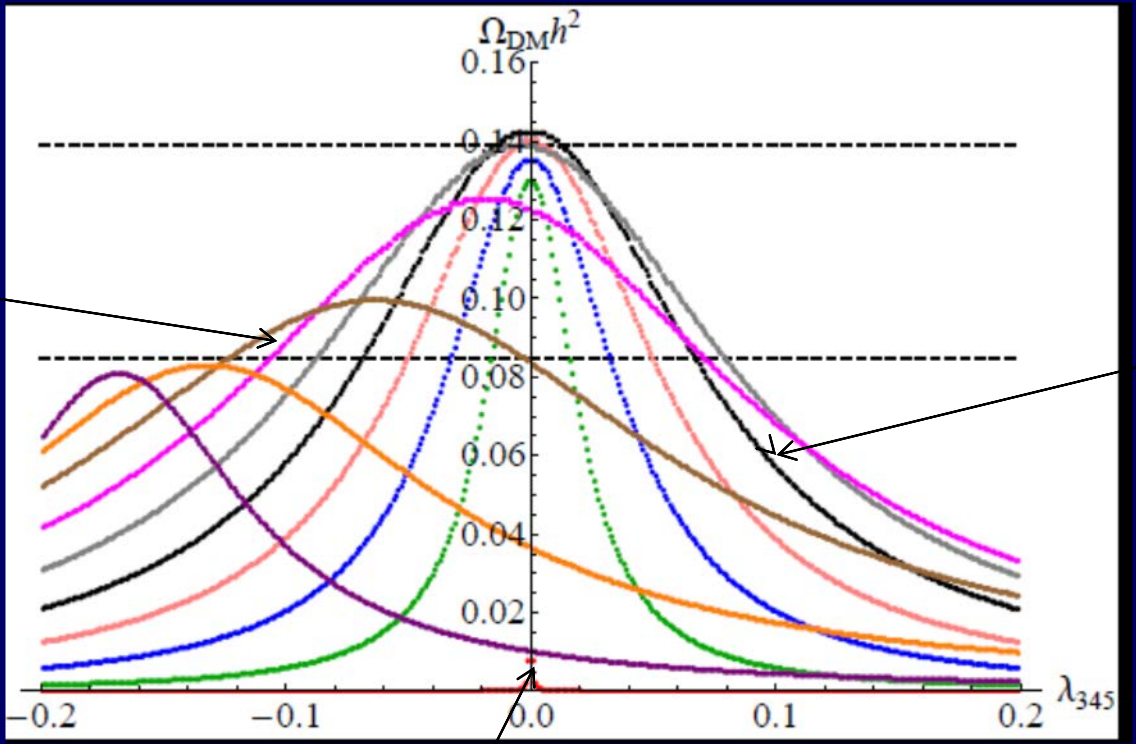
Lopez Honorez et al. '07, Hambye et al. '08,'09, Agrawal et al. '09, Dolle et al. '09, Arina et al. '09, ...

Higgs boson:

- both light and heavy Higgs boson possible in IDM
- LHC 2012 $\Rightarrow M_{h_S} \approx 125$ GeV – SM-like Higgs in IDM

ATLAS & CMS Collaborations: 1207.7214, 1207.7235 [hep-ex]

Relict density for DM with mass 62,64,…,80 GeV



76

HA coannihilation
Δ [50,8]

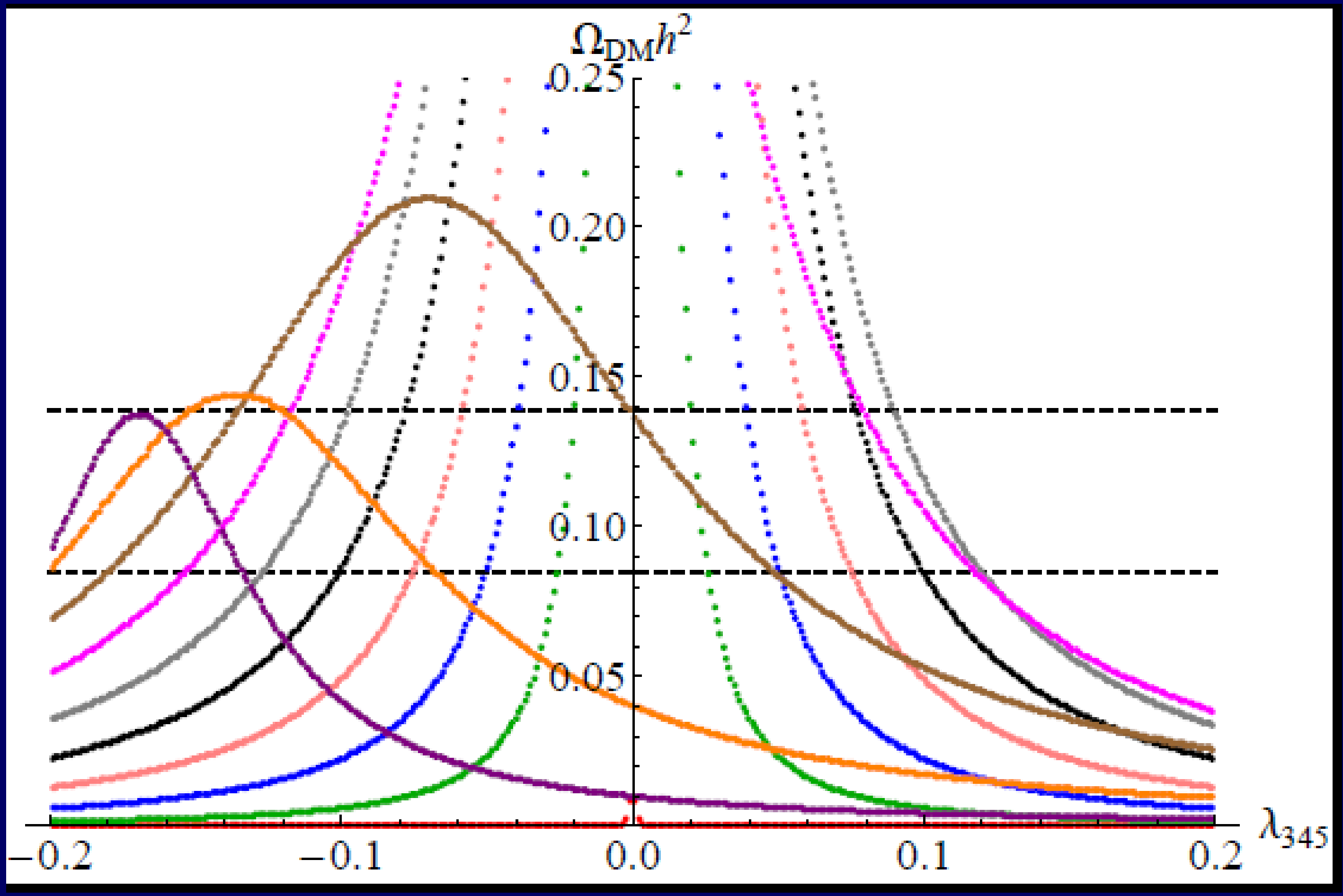
70 GeV

62 GeV

above 76 GeV asymmetry due to annihilation to gauge bosons

D. Sokołowska, 2013

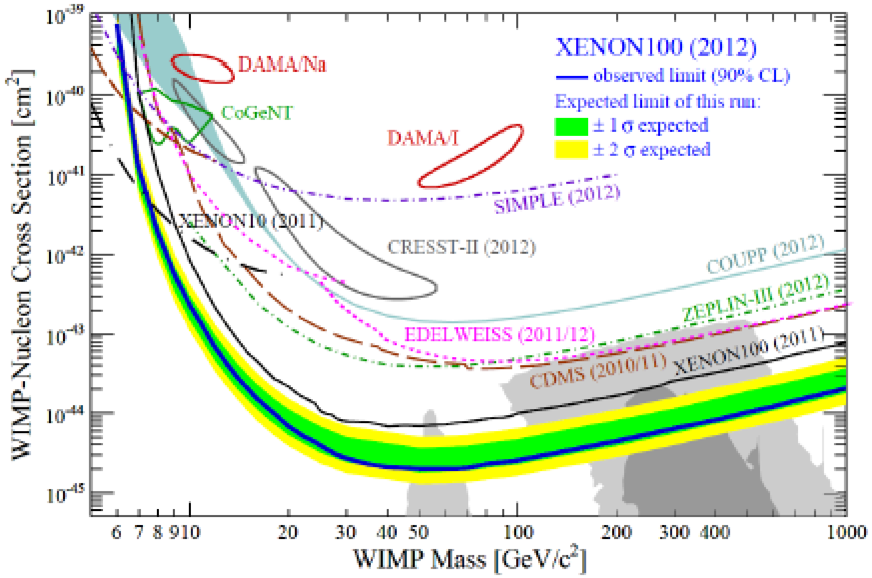
Relict density for DM with mass 62,64,…,80 GeV



no HA coannihilation
Δ= [50,50]

IDM constraints: Direct detection experiments

dark matter – nucleon stattering → DM-quark interactions



detection signals (DAMA, CoGeNT, CRESST-II) point to the light DM

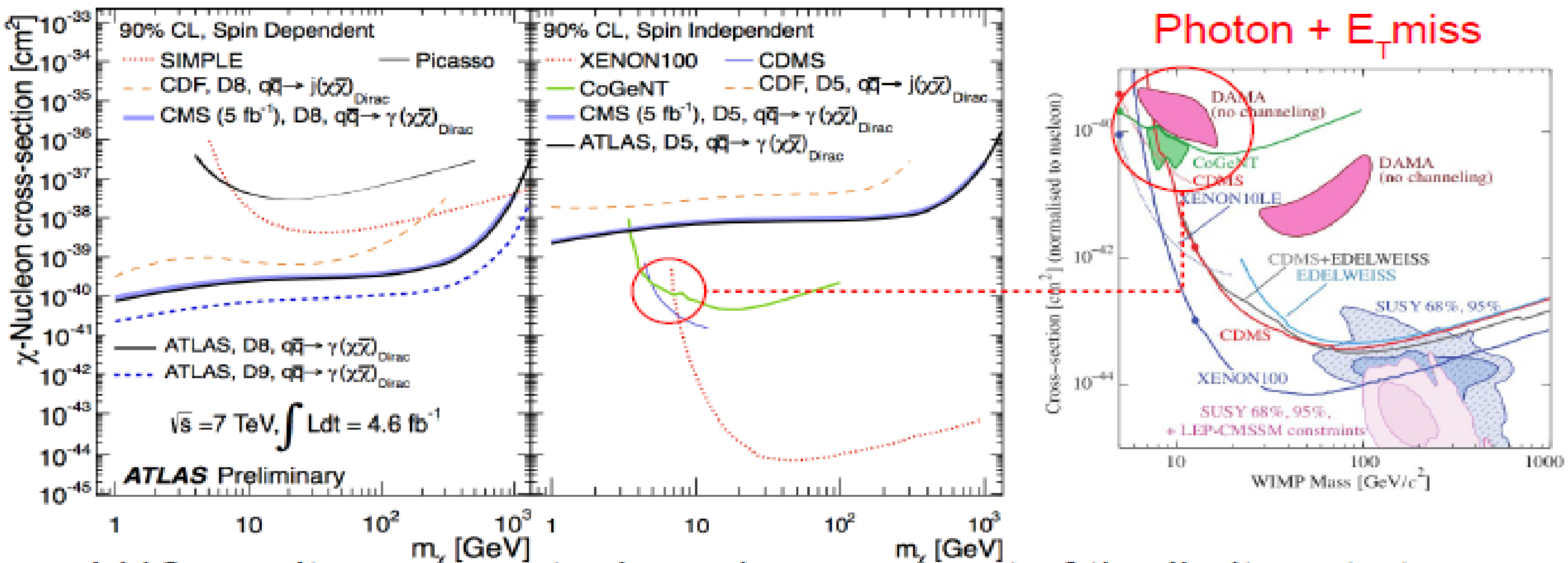
but there is no agreement with

exclusion limits (XENON100, CDMS-II)

arXiv:1109.0702,1207.5988[astro-ph]

DM - LHC

WIMP search



- LHC results represent a large improvement of the limits set at Tevatron
- Limits on scattering σ : ~10^{-40}-10^{-41} cm^2 (SD) and ~10^{-38} cm^2 (SI) for m_χ<100 GeV
- Not enough sensitivity yet to exclude/confirm CoGeNT/DAMA excess at ~10 GeV in case of D1/D5 models

IDM – scan (B. Świeżewska 2012)

Constraints: M_h=125 GeV (λ_1=0.25)
pert. vacuum stability,
conditions for Inert I1 vacuum:
perturbative unitarity condition
EWPT
Relic density, LEP+LHC

H = dark matter
0 > $\lambda_{45}=\lambda_4+\lambda_5$

$$\begin{aligned} M_h &= 125\,\mathrm{GeV}, \\ 70\,\mathrm{GeV} \leqslant M_{H^\pm} &\leqslant 800\,\mathrm{GeV}\,(1400\,\mathrm{GeV}), \\ 0 < M_A &\leqslant 800\,\mathrm{GeV}\,(1400\,\mathrm{GeV}), \\ 5 \leqslant M_H &< M_A, M_{H^\pm}, \\ -25\cdot 10^4\,\mathrm{GeV}^2\,(-2\cdot 10^6\,\mathrm{GeV}^2) \leqslant m_{22}^2 &\leqslant \sqrt{\lambda_2} M_h v \lesssim 9\cdot 10^4\,\mathrm{GeV}^2. \\ 0 < \lambda_2 &\leqslant 10. \end{aligned}$$

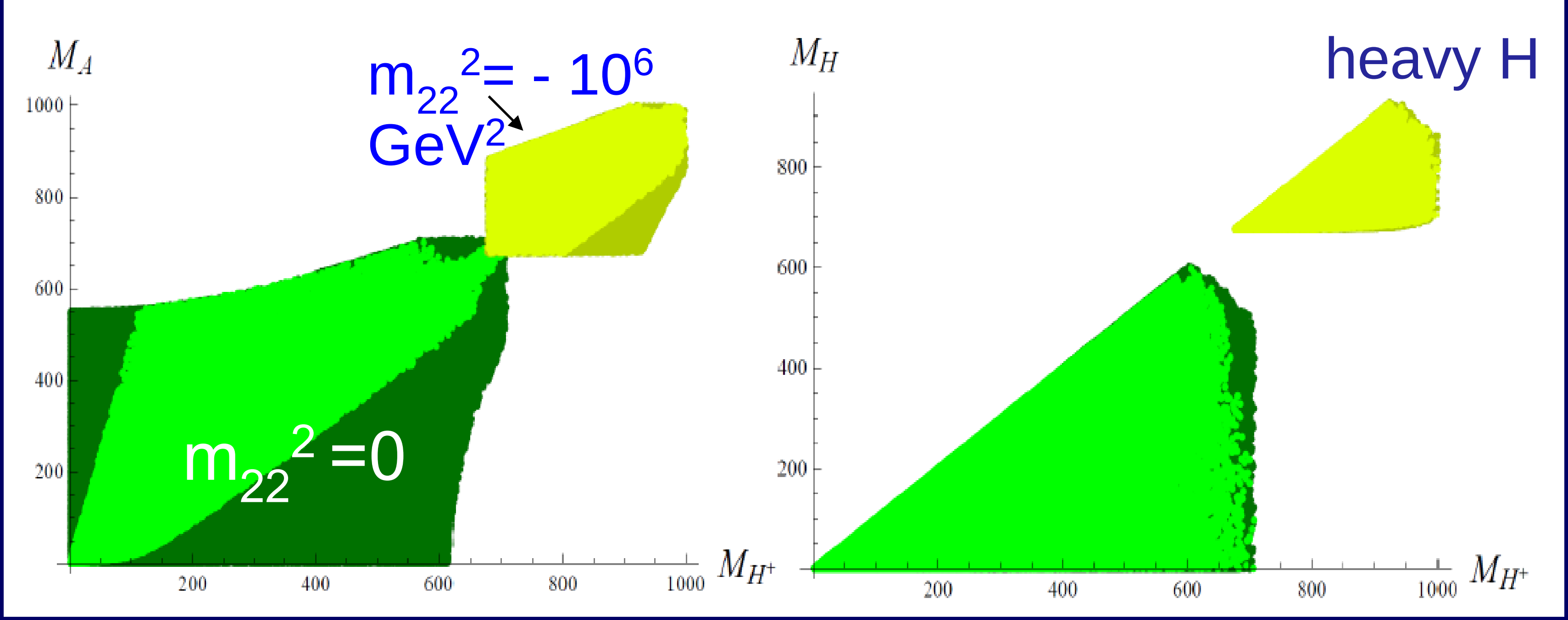
narrow (wide) range

condition for I_1

Inert Doublet Model with Mh=125 GeV

$m_{22}^2 = 0$

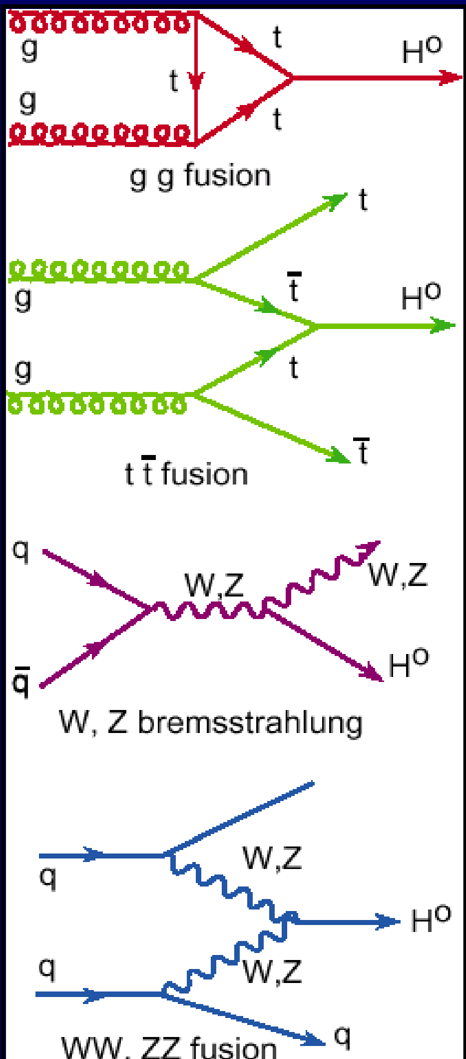
$$M_H \leqslant 602\,\mathrm{GeV},$$
$$M_{H^\pm} \leqslant 708\,\mathrm{GeV},$$
$$M_A \leqslant 708\,\mathrm{GeV}.$$



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

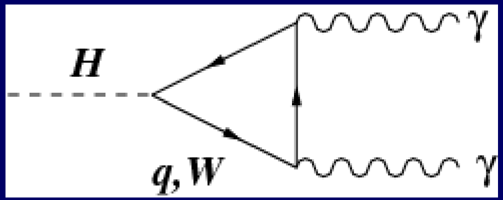
EWPT (pale regions)

LHC: loop couplings hgg, hγγ (hZγ)



for hgg - b and t important

for h $\gamma\gamma$



- t and b, W, (H+ in 2HDM)

In SM W and t interfer destructively

so if coupling of t may change

sign an enhancement possible

2HDM (Mixed) Ginzburg, MK, Osland,2001;

Carmi et al.,,,, in 2011,12

In IDM only hγγ may differ from SM

$h \to \gamma\gamma$

Świeżewska, MK (Dec. 2012)

[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)], P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021]

$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} = \frac{\left(\sigma(gg \to h)\mathrm{Br}(h \to \gamma\gamma)\right)^{IDM}}{\left(\sigma(gg \to h)\mathrm{Br}(h \to \gamma\gamma)\right)^{SM}} = \frac{\mathrm{Br}(h \to \gamma\gamma)^{IDM}}{\mathrm{Br}(h \to \gamma\gamma)^{SM}}$$

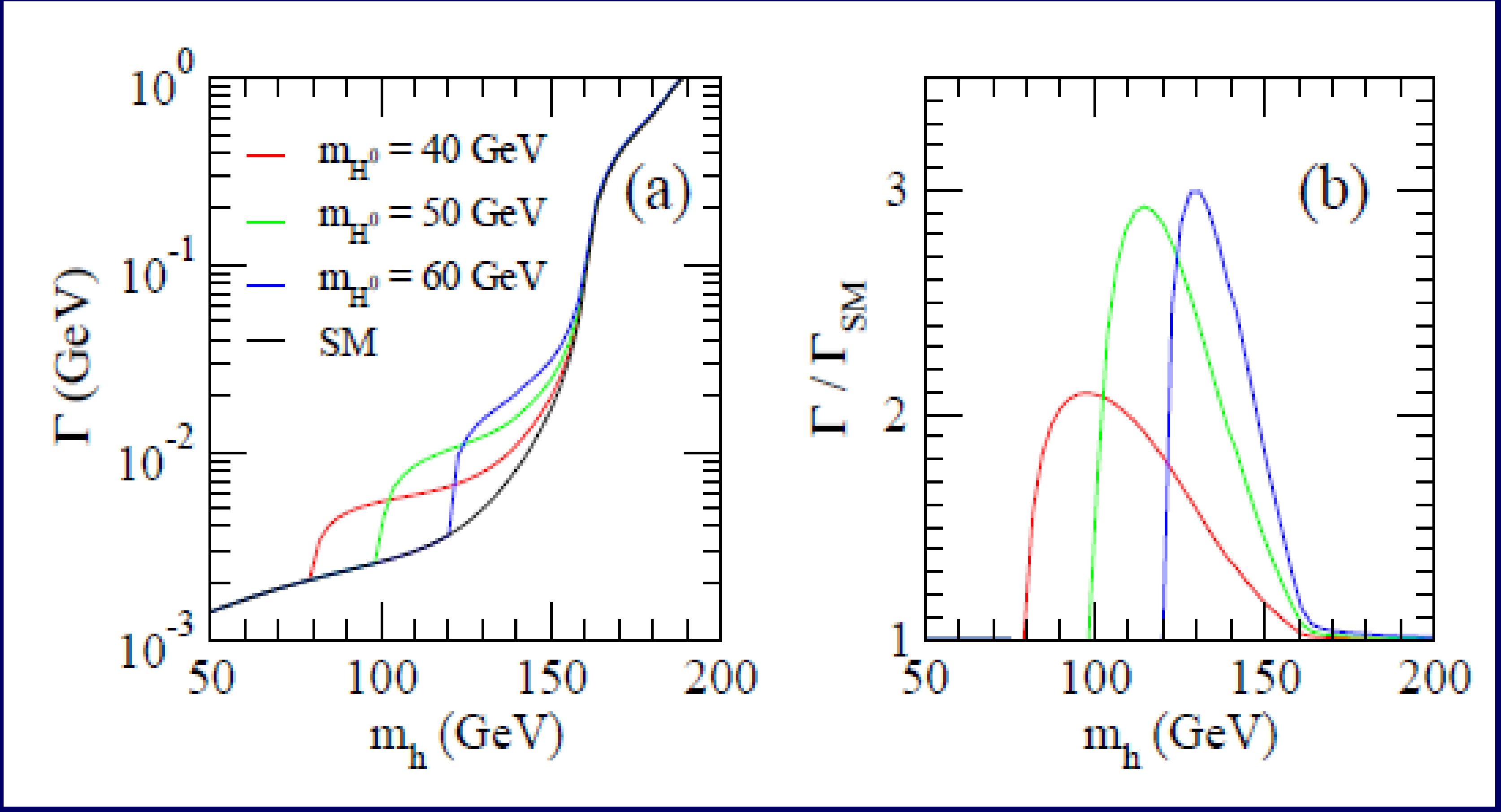
- Narrow width approximation
- Largest contribution to the production is from gg fusion
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$

Two sources of possible enhancement:

modification of the partial ($h \to \gamma\gamma$) or the total decay width ($h \to X$)

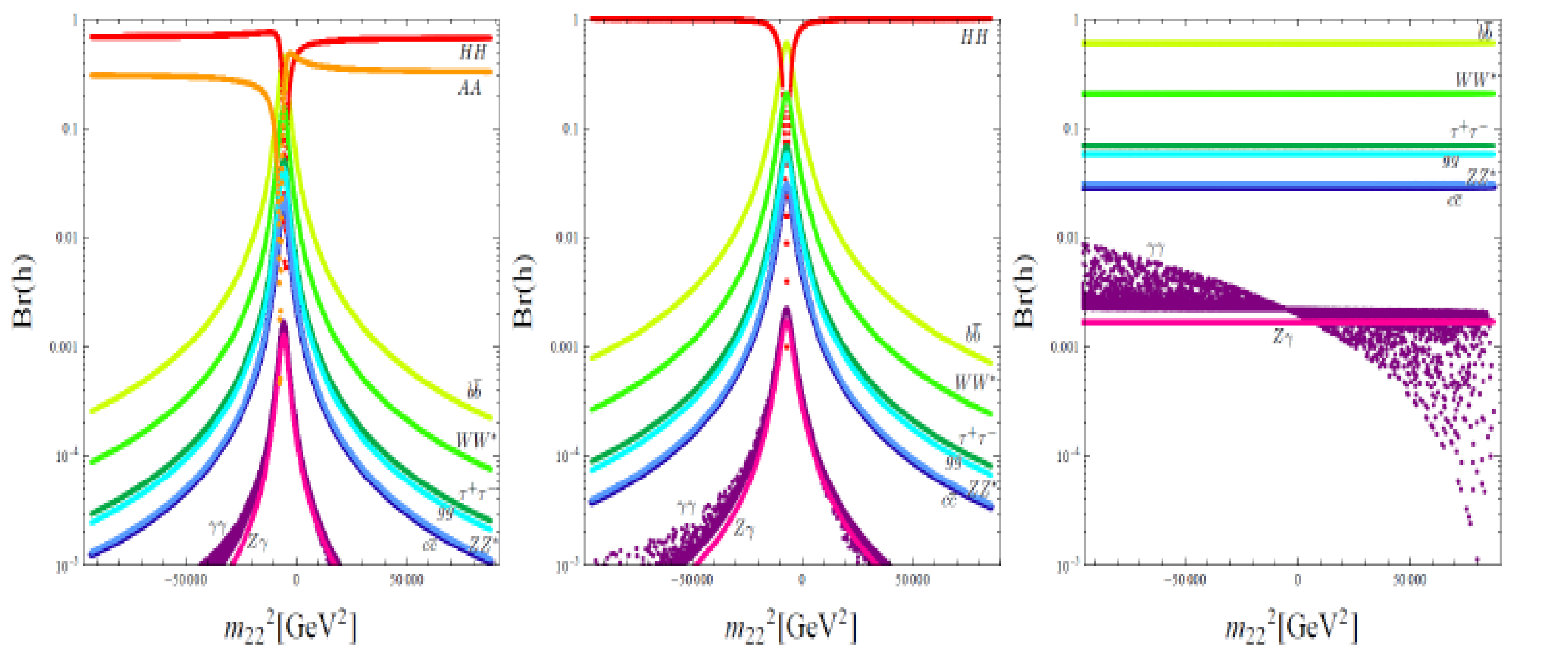
IDM – total width of h

Cao, Ma, Rajasekaren' 2007



Br of Higgs boson (125 GeV)
HH and AA channels open or closed

for positive and negative m_{22}^2 *for positive as Arhrib..'12*



H(50 GeV),A(60 GeV) both open

H open H(60 GeV),A(>63 GeV)

H(75 GeV),A(>63 GeV) both closed

Sources of modifications to $R_{\gamma\gamma}$ - charged scalar loop

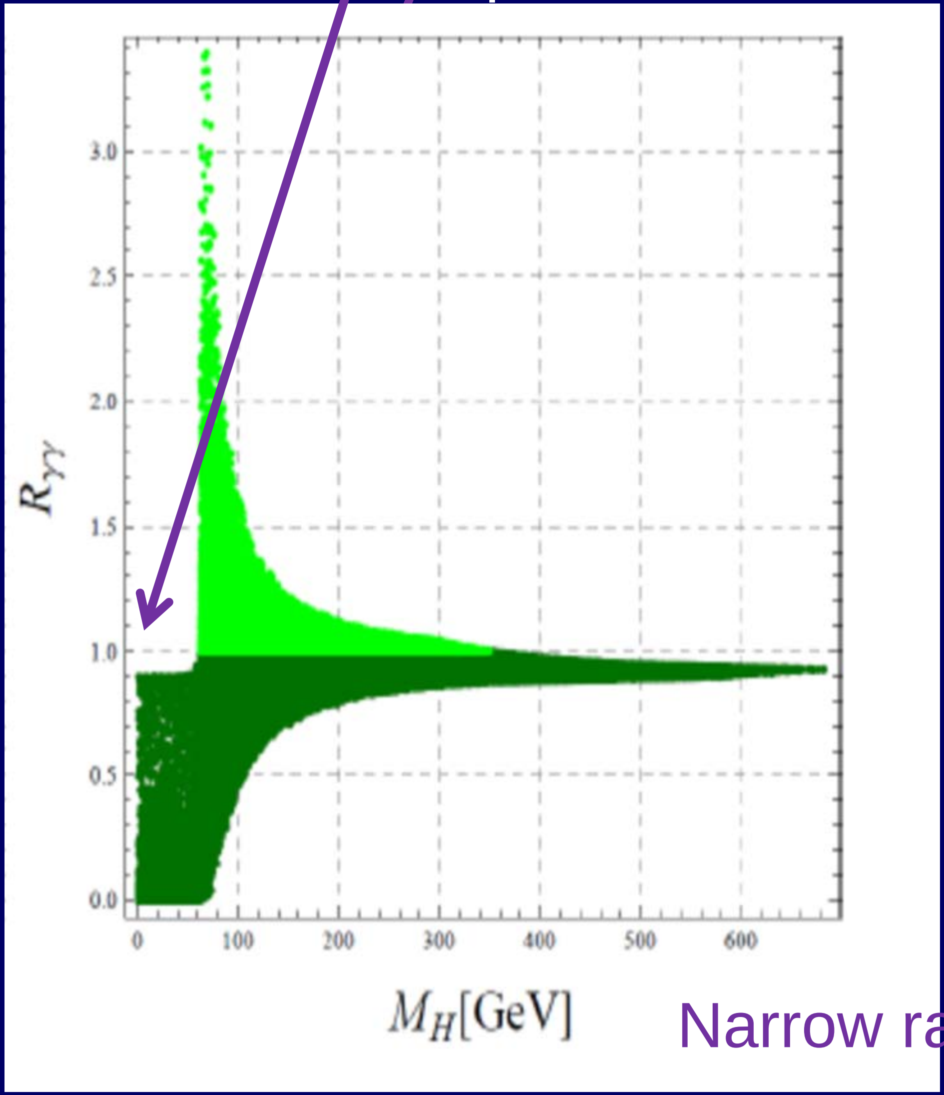
$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \frac{4}{3} g_t A_{1/2}\left(\frac{4M_t^2}{M_h^2}\right) + g_W A_1\left(\frac{4M_W^2}{M_h^2}\right) + \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

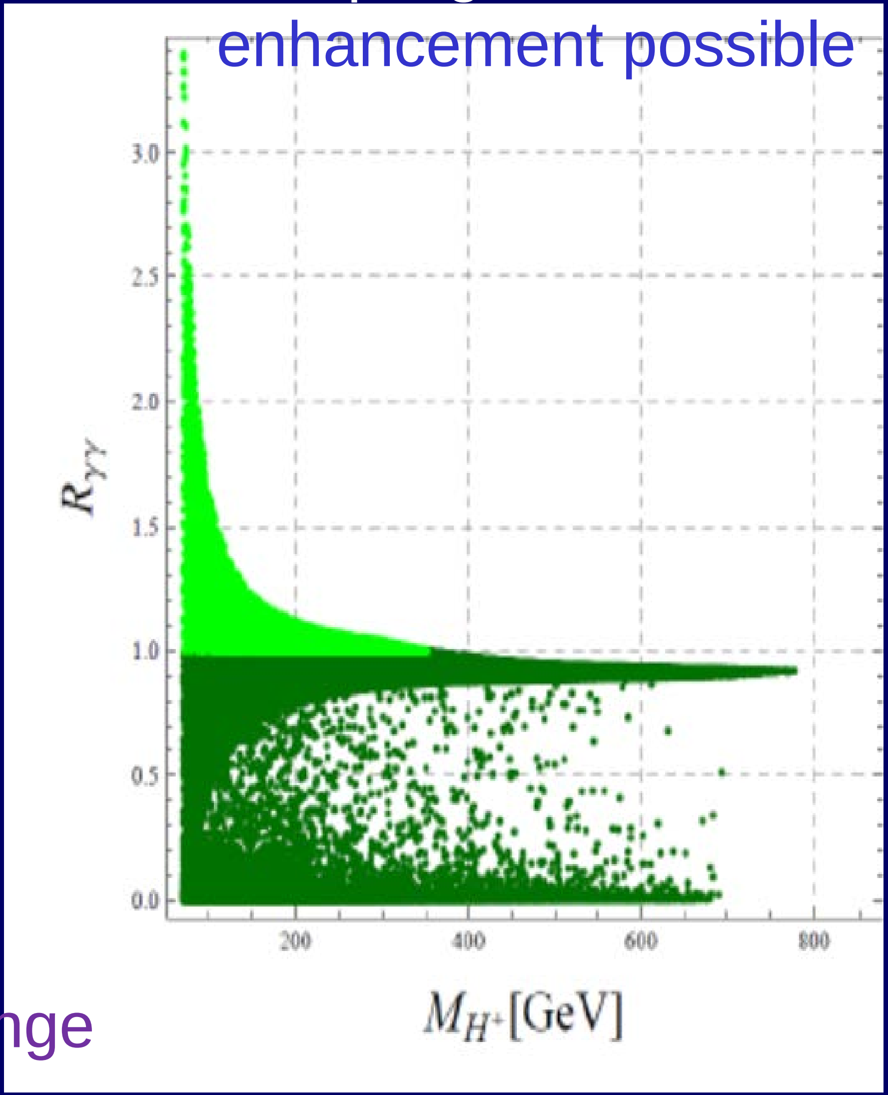
- If $h \to HH$ kinematically closed, $R_{\gamma\gamma} = \Gamma(h \to \gamma\gamma)^{IDM} / \Gamma(h \to \gamma\gamma)^{SM}$.
- $g_t, g_W = 1 \Rightarrow R_{\gamma\gamma}$ depends only on two of the parameters $M_{H^\pm}, \lambda_3, m_{22}^2$ $\left(M_{H^\pm}^2 = \frac{1}{2}(-m_{22}^2 + \lambda_3 v^2)\right)$
- $R_{\gamma\gamma} > 1$ can be solved analytically -> formula
- enhancement in $h \to \gamma\gamma$ only possible for $m_{22}^2 < -9800\ \mathrm{GeV}^2$ $(\lambda_3 < 0)$

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

Invisible decays makes enhancement impossible

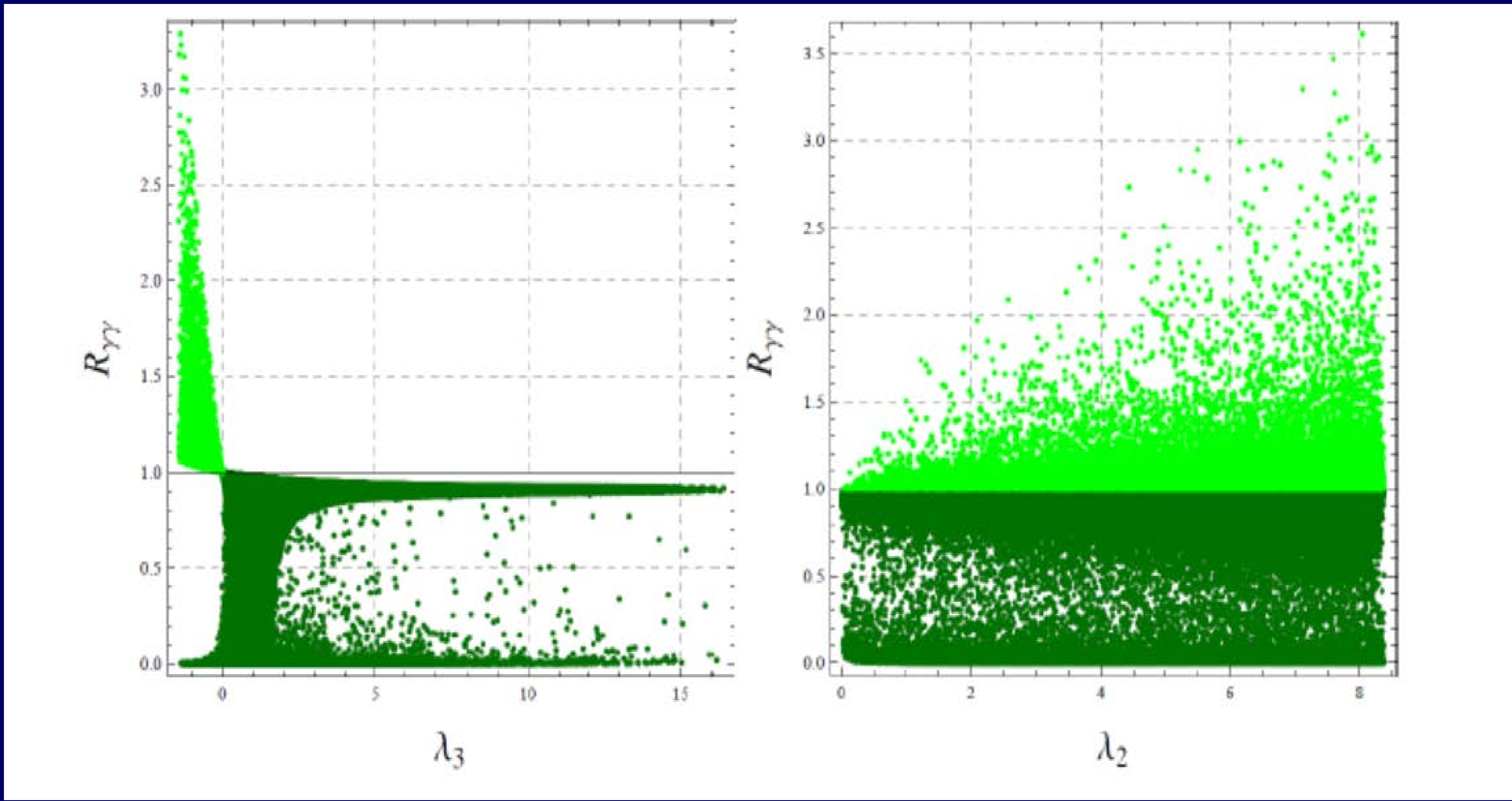
Light H+ with proper sign of hH+H- coupling makes enhancement possible





Narrow range

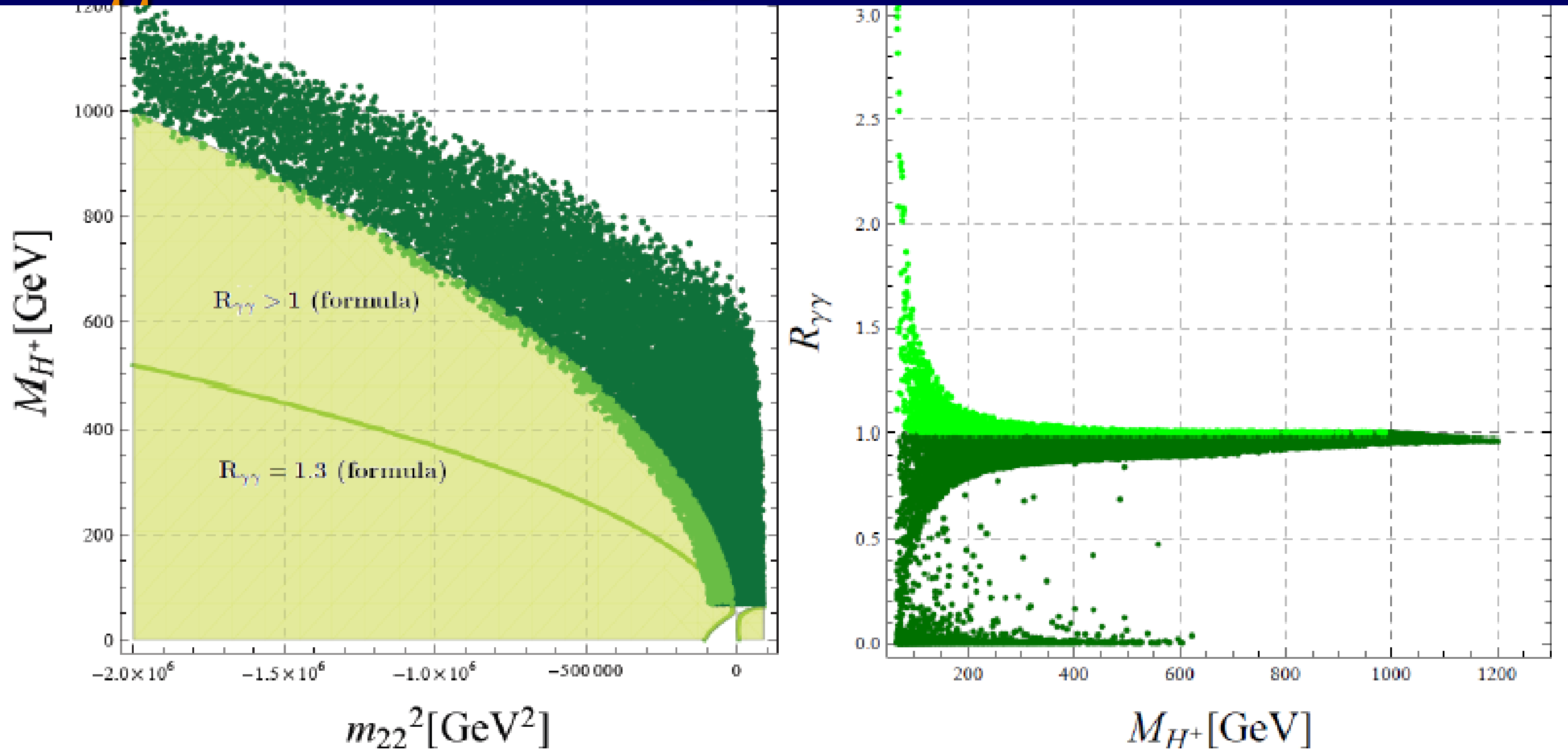
$R_{\gamma\gamma}$ as a function of λ_3 and λ_2



similar result
Arhrib at al

enhancement for negative λ_3

$R_{\gamma\gamma}$ - wide range of m_{22}^2



similar result
Arhrib at al

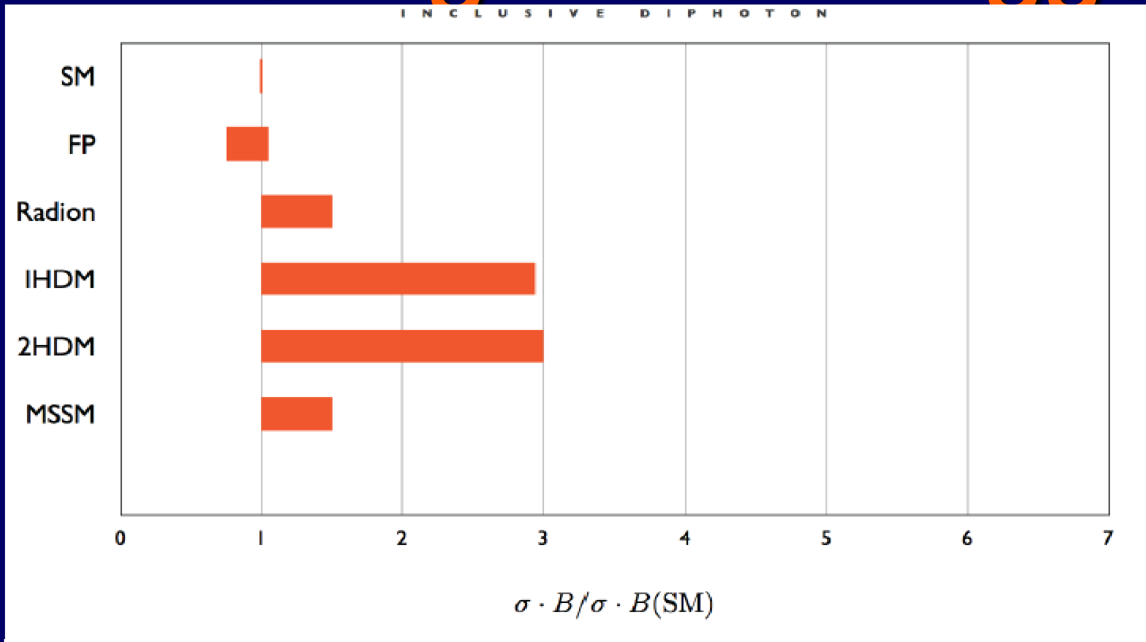
- $R_{\gamma\gamma} \geqslant 1$ also for big $M_{H^\pm}$, e.g. $M_{H^\pm} = 1$ TeV
- Substantial enhancement, $R_{\gamma\gamma} \geqslant 1.3$, only for $M_{H^\pm} \lesssim 130$ GeV

Mimicking the SM Higgs boson-Chang..

1211.6823(29.11.2012)

inclusive

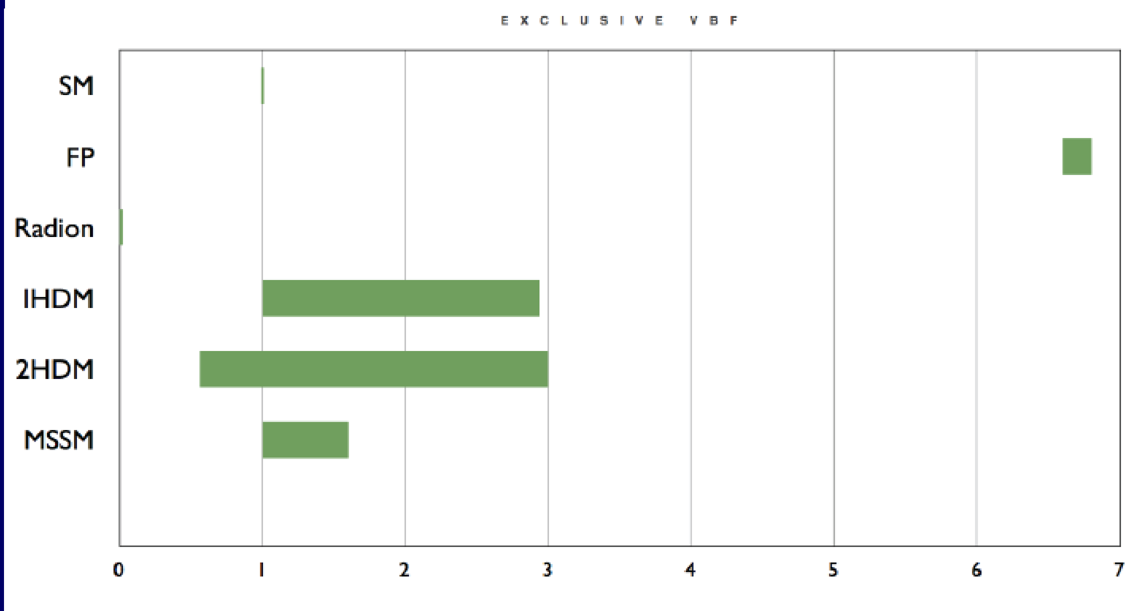
$$\frac{\sigma(X)\times B(X\to\gamma\gamma)}{\sigma(h_{\rm SM})\times B(h_{\rm SM}\to\gamma\gamma)}$$



2HDM(II), IHDM=IDM

Only taking ratio >1

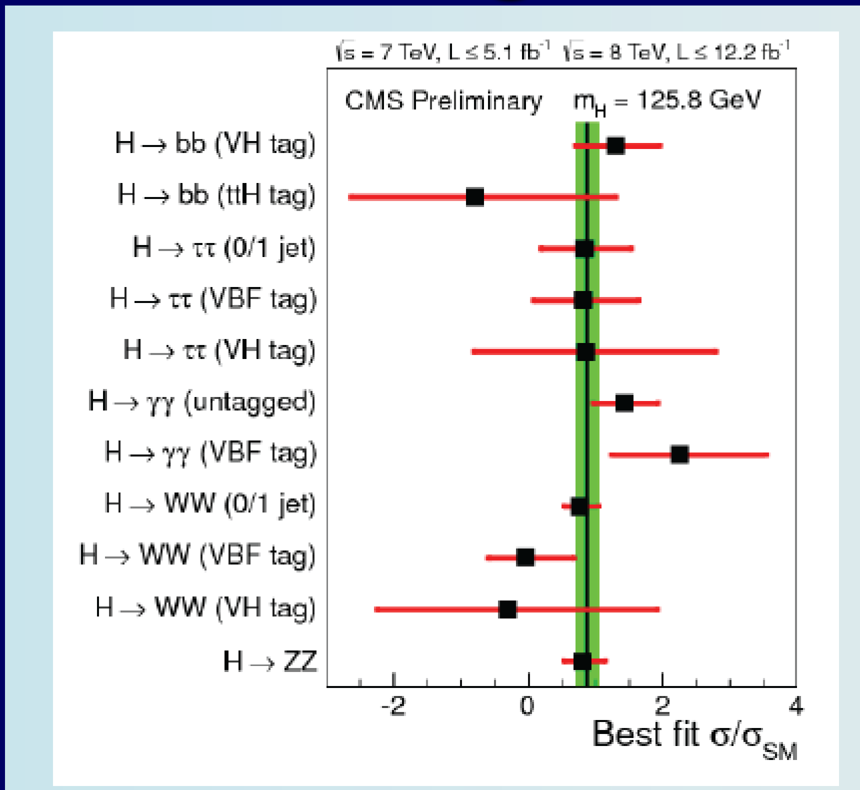
(except fermiophobic)



exclusive (VBF)

$$\frac{\sigma(pp\to jjX)\times B(X\to\gamma\gamma)}{\sigma(pp\to jjh_{\rm SM})\times B(h_{\rm SM}\to\gamma\gamma)}$$

Gamma-gamma enhancement



Mimicking the SM Higgs boson-Chang..

If moderate excess is seen in both inclusive production and exclusive VBF production, it could be the Higgs boson of the IHDM, 2HDM, or the MSSM. However, if the excess is over 60% it will pose severe challenge to the MSSM.

I agree

Conclusions I

- SM-like scenarios in 2HDM

- 2HDM (Mixed) where *both h or H can be SM-like*

- Inert Doublet Model: h is *SM-like* and H=DM
mass of H+ below 135 GeV if $R\gamma\gamma$ >1.3
(H+ has no Yukawa couplings)

If $R\gamma\gamma$ >1 H mass >62.5 GeV
and <135 GeV, if $R\gamma\gamma$ > 1.3

If $R\gamma\gamma$ >1.3 $-1.46 < \lambda_3 , \lambda_{345} < -0.24$

IDM and evolution of the Universe

- Inert Doublet Model (IDM) provides DM and it is in agreement with present astrophysical and collider data including the 125 GeV Higgs boson
- If today (T=0) Universe in the Inert phase what was in the past ?
- We have studied temperature dependent Z2 sym. 2HDM potential → evolution of the Inert vacuum and sequences of different vacua in the past (one, two and three phase transitions)

- with leading T2 corrections (only m^2_{ii} (T^2))

(*PRD 82(2010) Ginzburg, Kanishev, MK, D. Sokołowska)*

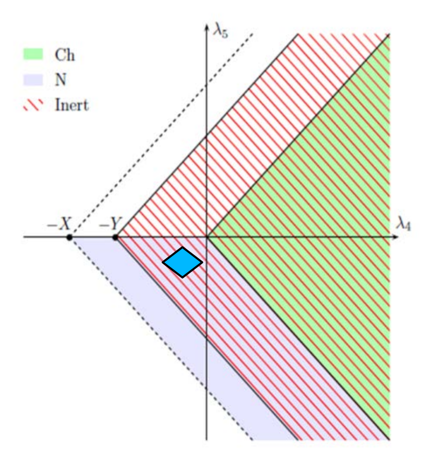
- beyond T2 corrections (to find strong enough first-order phase transition needed for baryogenesis)

(G. Gil Thesis'2011, G.Gil, P. Chankowski, MK Phys. Lett. B 2012

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

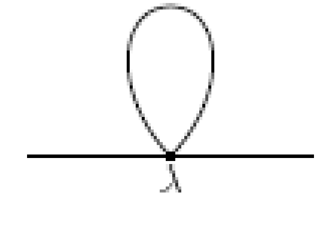
Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev,MK, Sokołowska PRD 2010,
Sokołowska 2011

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 type phase transitions...

Termal corrections of parameters



Evolution of the Universe

Scalar, bosonic and fermionic contributions to $\Delta V \to m_{ii}^2(T)$:

$$m_{11}^2(T) = m_{11}^2 - c_1 T^2 \,, \quad m_{22}^2(T) = m_{22}^2 - c_2 T^2$$

$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{6} + \frac{3g^2 + g'^2}{8} + \frac{g_t^2 + g_b^2}{2}, \quad c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{6} + \frac{3g^2 + g'^2}{8}$$

- fermionic contribution in c_1 (Model I)
- $c_1 + c_2 > 0$ from positivity constrains
- c_1 and c_2 positive to restore EW symmetry in the past

For a given T we determine:

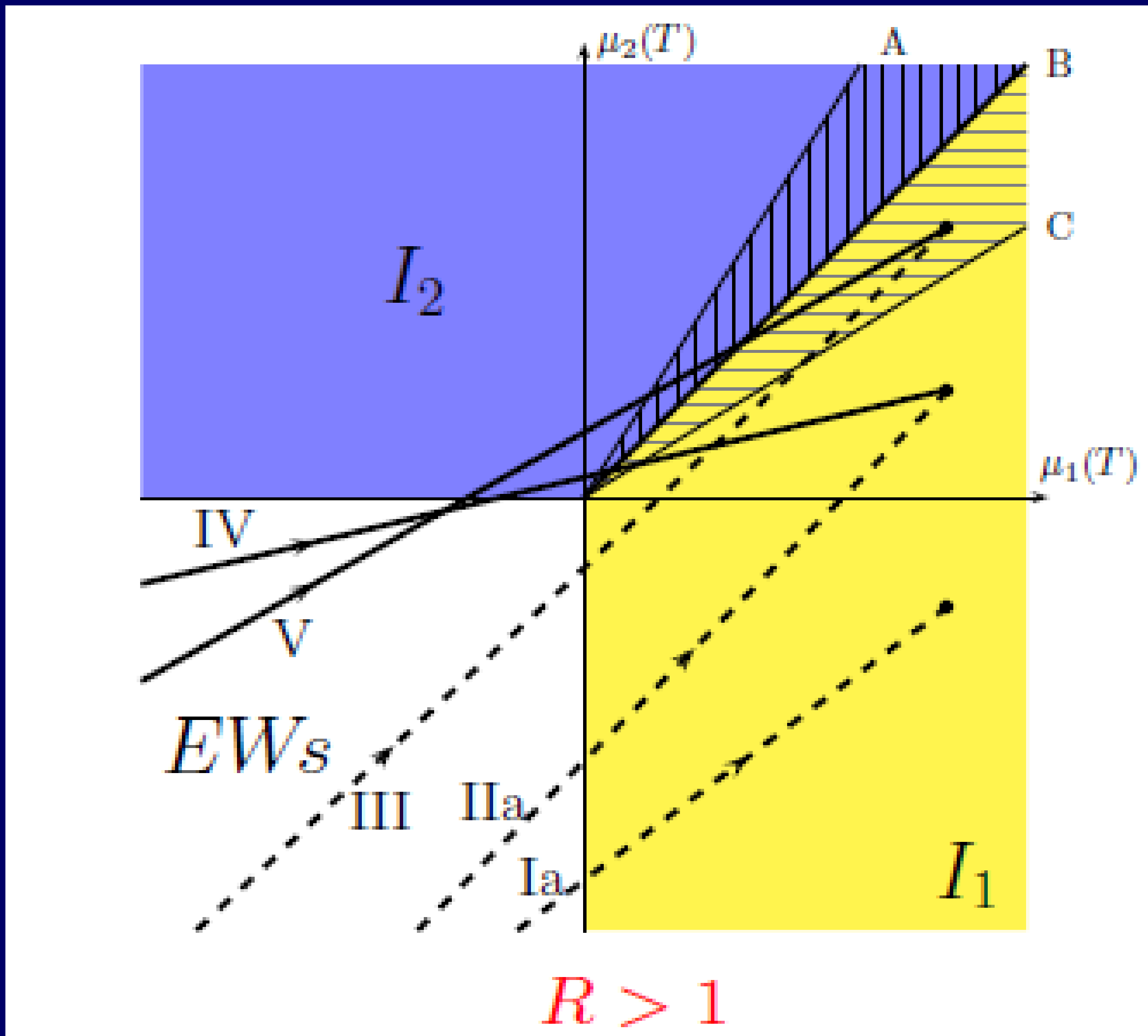
- sign of $v_i^2\big|_{I_1, I_2, M}(T) \to$ possible existence of a given extremum
- values of λ_i (fixed) $\to$ existence of a local minimum
- value of extremum energy $\to$ global minimum

$\Rightarrow$ **sequences of possible phase transitions**

For $u = 0$ (neutral extrema) three separate cases of $EWs \to ... \to I_1$:

$$R = \lambda_{345}/\sqrt{\lambda_1 \lambda_2} : \quad R > 1, \quad 1 > R > 0, \quad 0 > R > -1$$

Phase diagram (μ_1,μ_2)



$\mu_i = m_{ii}^2/\sqrt{\lambda_i}$

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

Stability condition

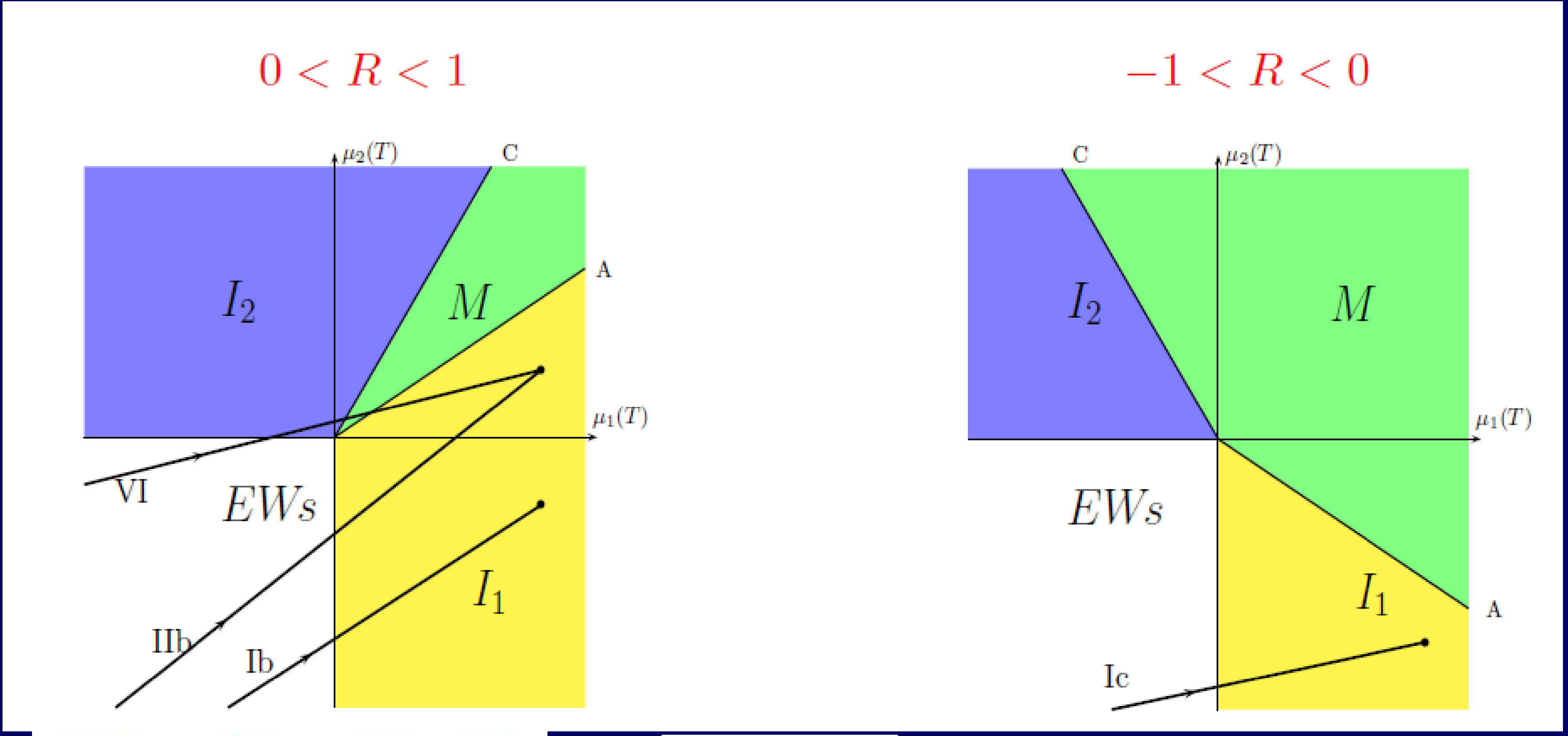
$EWs \rightarrow I_1$

$EWs \rightarrow I_2 \rightarrow I_1$

T^2 corrections → rays from EWs to the Inert phase

unique possibility: 1st order phase transition $I_2 \rightarrow I_1$

Phase diagrams

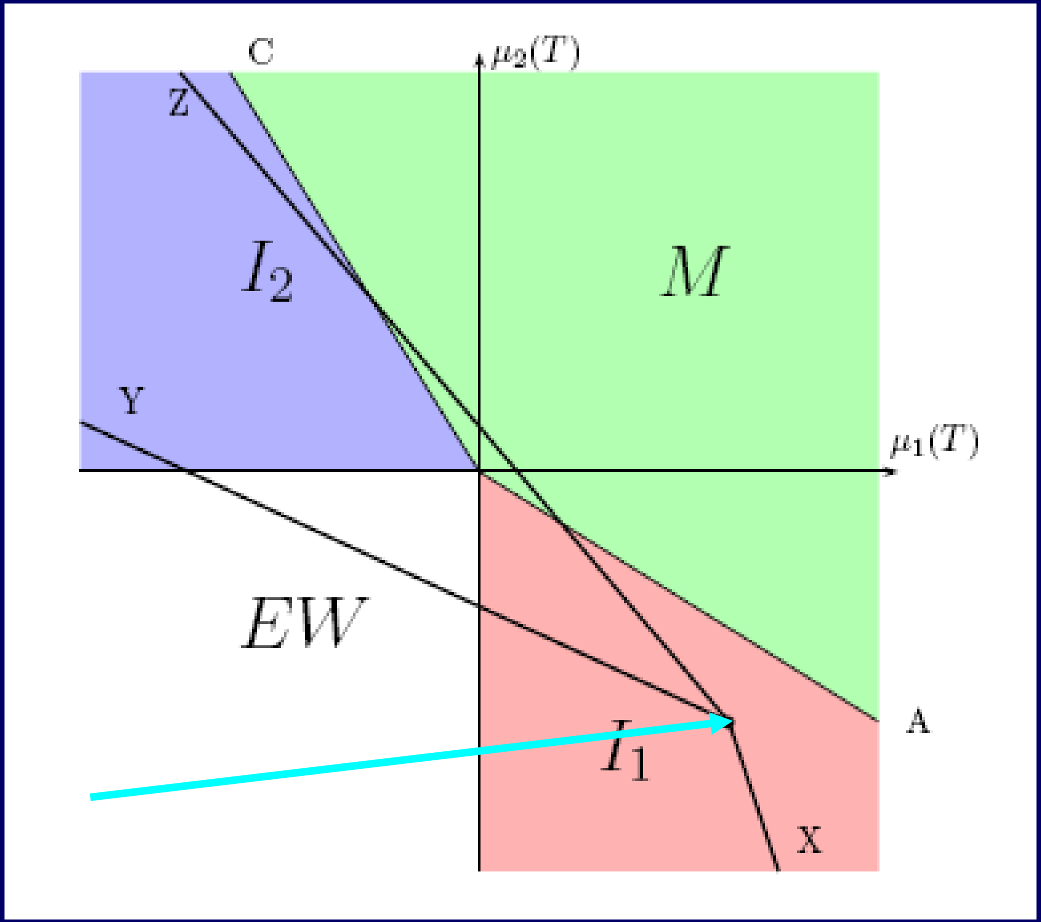


$EWs \to I_2 \to M \to I_1$

$EWs \to I_1$

Non-restoration of EW symmetry R <0 possible

c_1 or $c_2 < 0$



There is only one evolution with EW restoration in the past

- in one step and with $R_{\gamma\gamma} > 1$!

Sokołowska PhD,Thesis 2012

Sensitivity to HHHH coupling λ_2 medium DM mass - example

Medium DM mass: example

- fixed values of scalars' masses $\rightarrow (\lambda_{345}, \lambda_2)$ phase space:

$$M_{D_H} = 50 \text{ GeV}, \; M_{D_A} = 120 \text{ GeV}, \; M_{D^\pm} = 120 \text{ GeV}, \; M_{h_S} = 120 \text{ GeV}$$

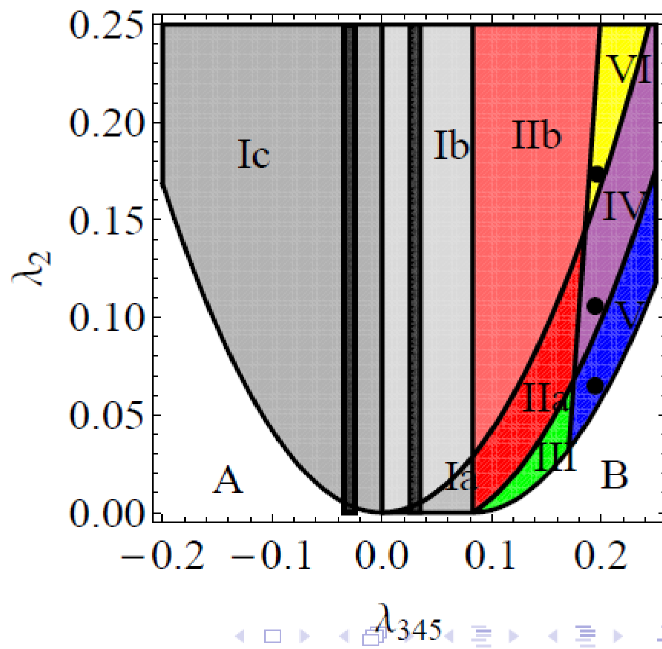
- fixed value of λ_{345}:

$$\lambda_{345} = 0.1945$$

- **rays may differ only by value of λ_2**

vertical bounds – WMAP-allowed region

Ray no.	λ_2
$EWs \rightarrow I_2 \rightarrow I_1$	
IV	$\lambda_2 = 0.1031$
V	$\lambda_2 = 0.0684$
$EWs \rightarrow I_2 \rightarrow M \rightarrow I_1$	
VI	$\lambda_2 = 0.1672$



limits on λ_2
- positivity
- Inert vacuum

Conclusions II

- Intert Doublet Model in agreement with data
- Inert phase today - what was in the Past ?
- Various evolution scenarios :

$$EWs \xrightarrow{II} \begin{cases} I_1 \\ I_2 & \begin{cases} \xrightarrow{II} M \qquad \xrightarrow{II} I_1 \\ \xrightarrow{I} I_1 \end{cases} \end{cases}$$

- Can we find clear signals ?

  - Ch breaking in the past?-excluded if DM neutral
  - DM matter may appear later
  - Inert phase today and $R_{\gamma\gamma}$ >1 for 125 GeV Higgs EW symmetry breaking in one step

Beyond T2 corrections – strong 1st order phase transition in IDM? EW bariogenesis?

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

mass matrices

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

number of states

counter terms →

Fixing counterterms

We require that v1=v1(tree)

and that h field propagator has a pole for tree-level mass-squared M_h^2

Then we put conditions on λ_{345} (hHH), λ_2(HHHH)

On the other hand λ_2 cannot be directly measured in the foreseeable future[6] so its precise definition at the loop-level is not important. Here for simplicity we choose to subtract the divergences of $V_{\rm eff}^{(1L)}$ proportional to v_2^4 and $v_1^2 v_2^2$ using the $\overline{\rm MS}$ scheme. This fixes the combinations $\delta\lambda_2+2\lambda_2\delta Z_2$ and $\delta\lambda_{345}+\lambda_{345}(\delta Z_1+\delta Z_2)$. Once the latter counterterm is fixed the last necessary combination $\delta m_{22}^2 + m_{22}^2\delta Z_2$ is determined by renormalizing the H^0 propagator on-shell. The counterterms $\delta\lambda_3$ and $\delta\lambda_5$ can be then used to enforce that the tree-level masses M_{A^0} and $M_{H^\pm}$ remain unchanged by one-loop corrections (they do not need to be determined explicitly).

One-loop temperature dependent effective potential

$$\Delta^{(1L)}V_{T\neq 0} = \frac{T^4}{2\pi^2}\sum_{\text{fields}} C_s \int_0^\infty dx\, x^2 \ln\left[1-(-1)^{2s}\exp\left(-\sqrt{x^2+\mathcal{M}_s^2/T^2}\right)\right].$$

For $T^2 \gg \mathcal{M}_s^2$ the contribution of $\mathcal{M}_s^2$ to (12) can be expanded:

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_B = |C_s|\left\{-\frac{\pi^2}{90}T^4 + \frac{1}{24}T^2\mathcal{M}_s^2 - \frac{T}{12\pi}|\mathcal{M}_s^3| - \frac{\mathcal{M}_s^4}{64\pi^2}\left(\ln\frac{\mathcal{M}_s^2}{T^2} - C_B\right)\right.$$

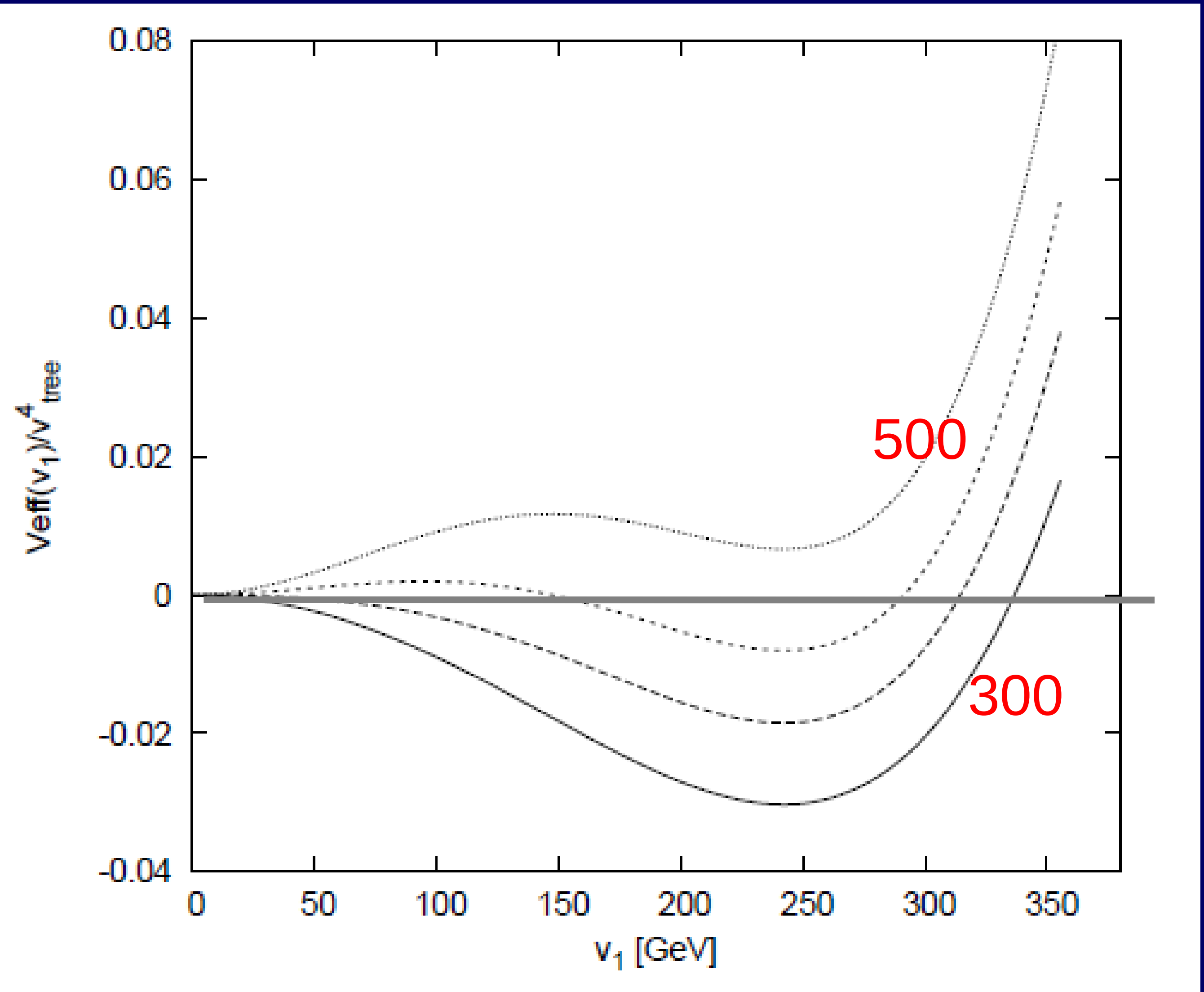
$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_F = |C_s|\left\{-\frac{7\pi^2}{720}T^4 + \frac{1}{48}T^2\mathcal{M}_s^2 + \frac{\mathcal{M}_s^4}{64\pi^2}\left(\ln\frac{\mathcal{M}_s^2}{T^2} - C_F\right)\right\}$$

($C_B = 5.40762$, $C_F = 2.63503$). In the opposite limit $T^2 \ll \mathcal{M}_s^2$ one has

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_s = -|C_s|\,T^4\left(\frac{|\mathcal{M}_s|}{2\pi T}\right)^{3/2}\left(1+\frac{15}{8}\frac{T}{|\mathcal{M}_s|}+\ldots\right)\exp\left(-\frac{|\mathcal{M}_s|}{T}\right),$$

both for B and F

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

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

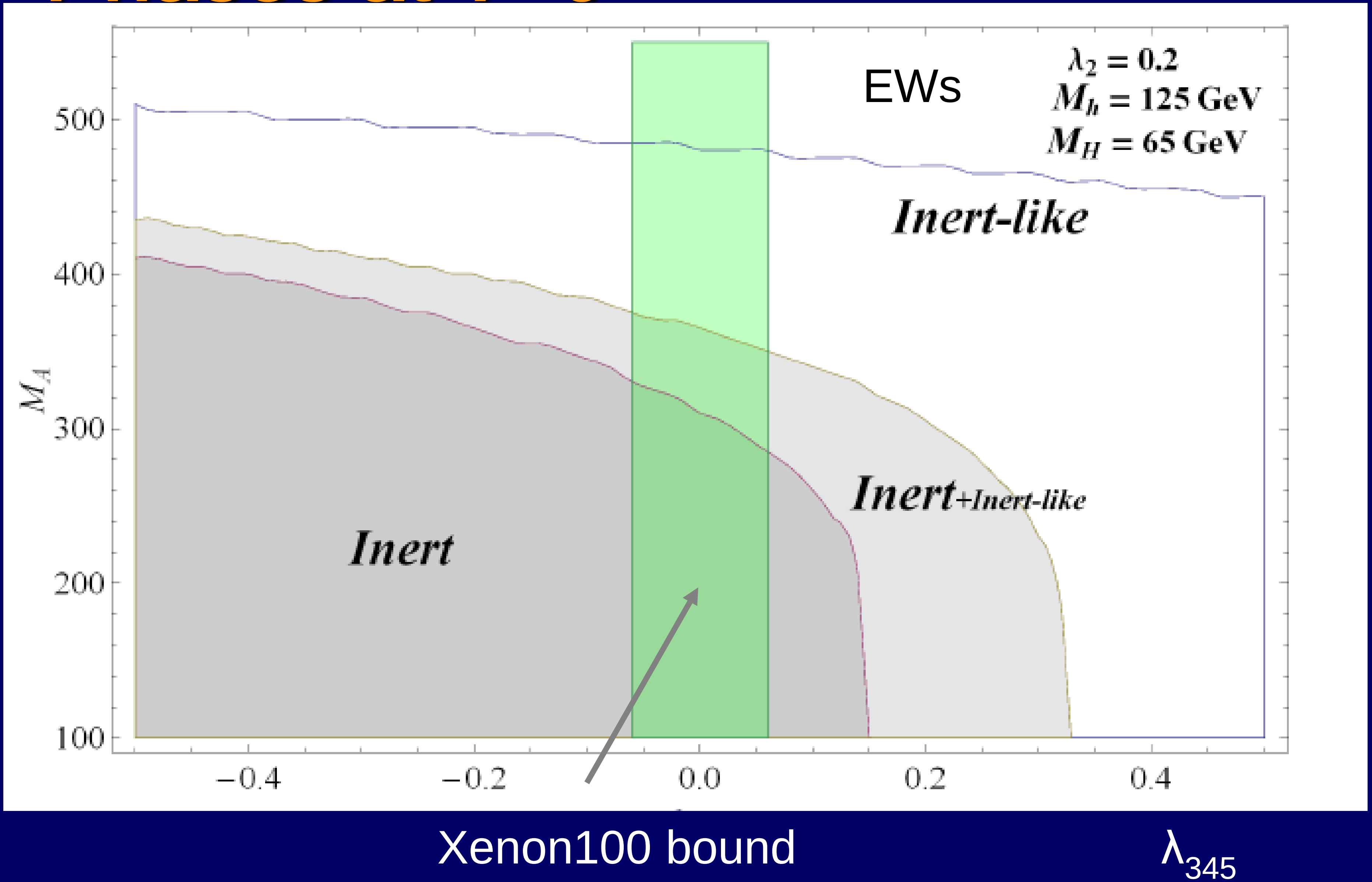
We are looking for parameter space of IDM which allows for a strong first order phase transition

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

being in agreement with collider and astro physical data

We focus on medium DM, with $M_H \ll v$, heavy degenerated A and H+ and M_h=125 GeV

Phases at T=0

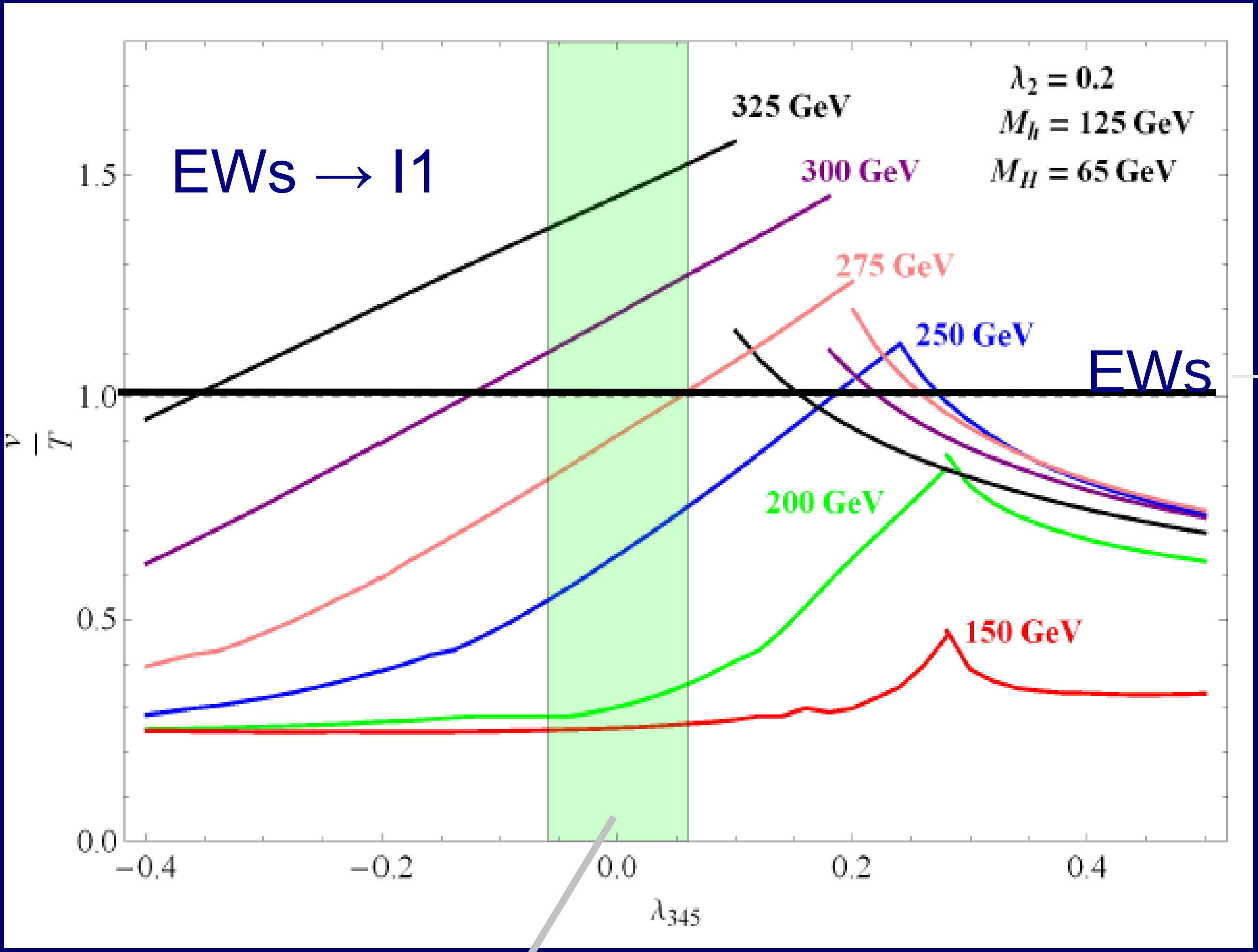


EWs
$\lambda_2 = 0.2$
$M_h = 125$ GeV
$M_H = 65$ GeV
Inert-like
Inert+Inert-like
Inert
M_A
500
400
300
200
100
−0.4
−0.2
0.0
0.2
0.4
Xenon100 bound
λ_{345}

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

Mh=125 GeV, MH=65 GeV, λ2=0.2

strong 1st order phase transition if ratio > 1



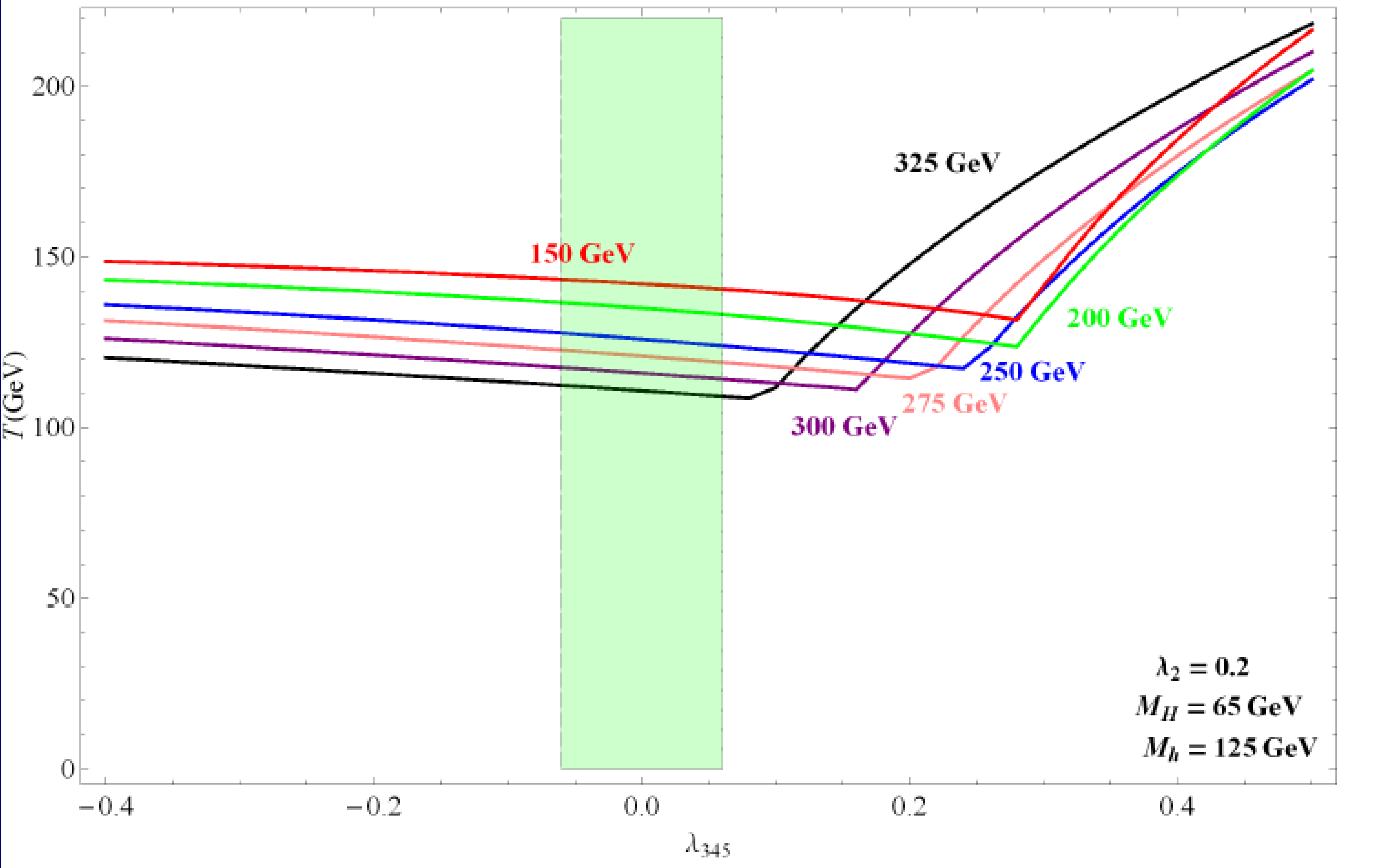
→ I2 → I1

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

λ_{345}

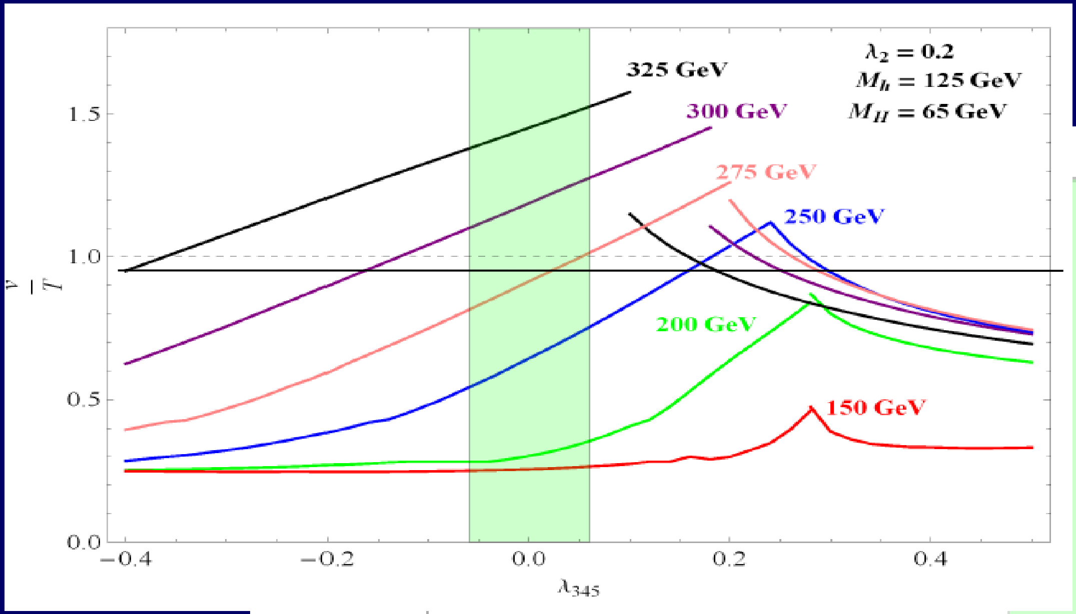
R<0 Xenon100 bound R>0

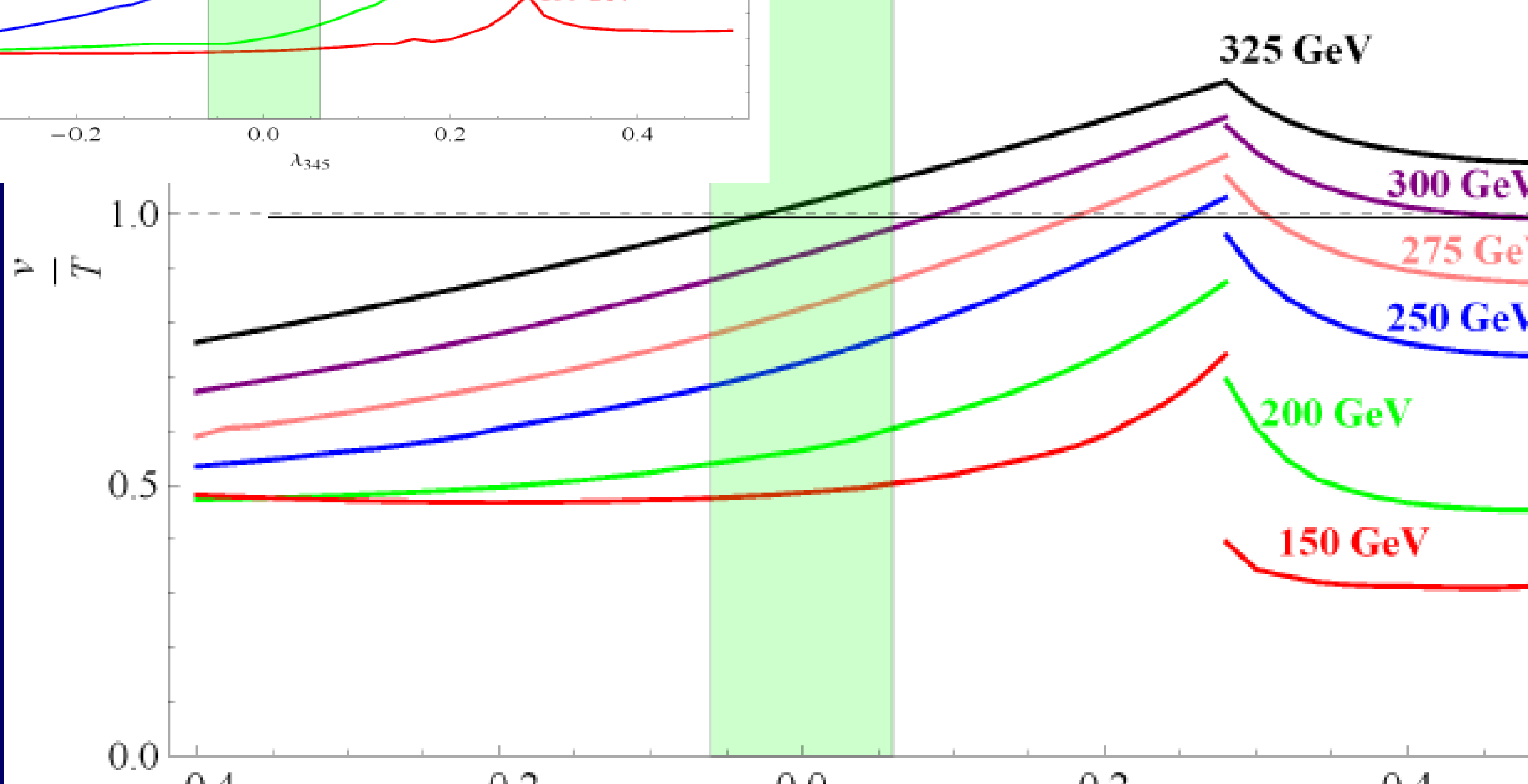
T_{EW} as a function of λ_{345}



Role of Coleman-Weinberg term

with and without CW term





Conclusion III

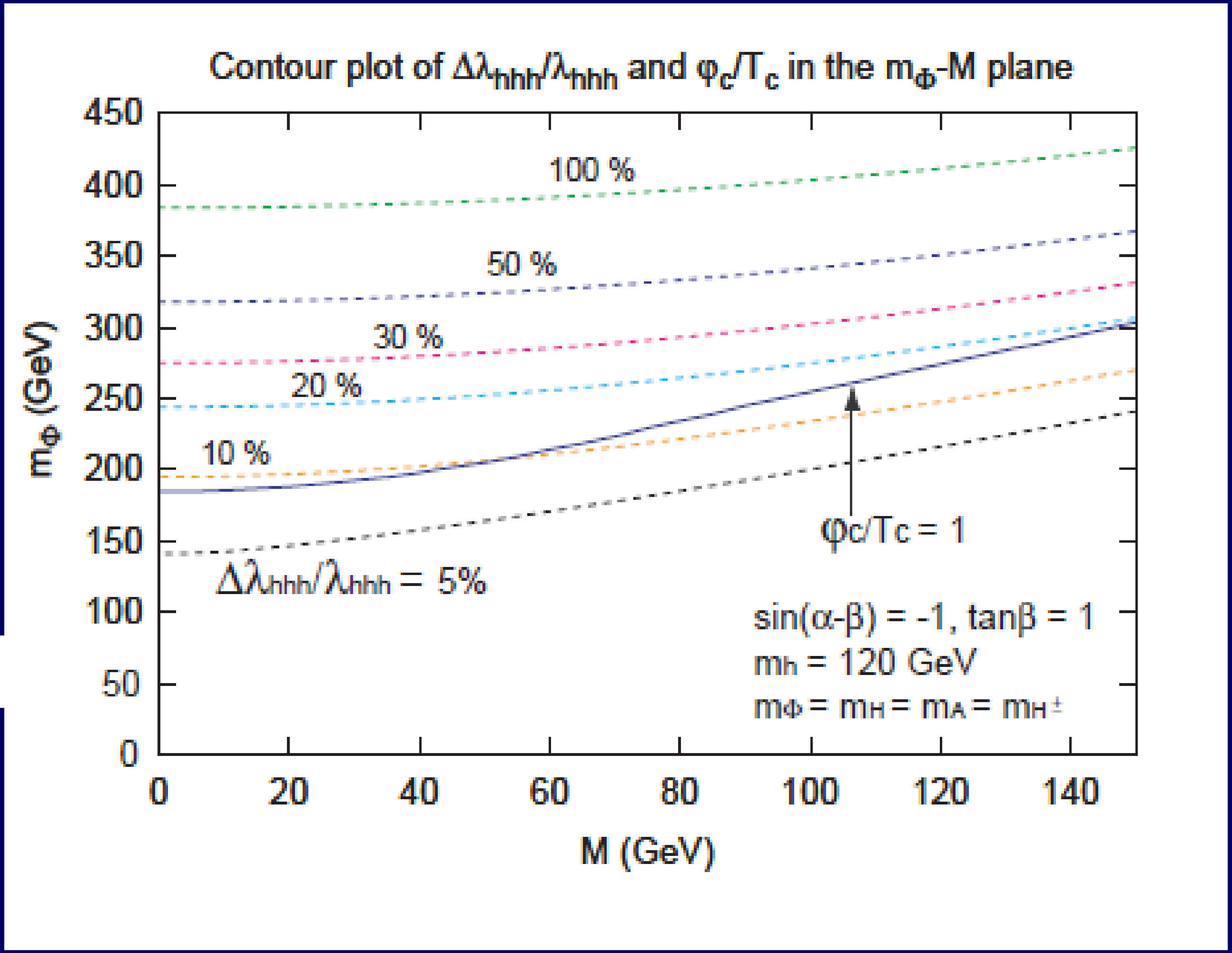
Strong first order phase transition in IDM possible
for realistic mass of Higgs boson (125 GeV)
and DM (~65 GeV) for

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)

Electroweak baryogenesis and quantum corrections to the triple Higgs boson coupling ’2004

Shinya Kanemuraa, Yasuhiro Okada, Eibun Senahab



$m_H = m_A = m_{H^\pm} (\equiv m_\Phi)$

$M^2 \ (= m_3^2/\sin\beta\cos\beta),$

2HDM – a great laboratory of BSM

In particular

IDM with SM-like Higgs sector and DM

At LHC – SM-like signal with possible enhancement in gamma-gamma channel → strong constraints on masses of DM and H+, as well as DM couplings

Evolution of Universe in only one step?

PLC

$\Gamma\,(h \to \gamma\,\gamma) \sim 3\ \%$

$$\gamma\gamma \to h \to b\bar{b}$$

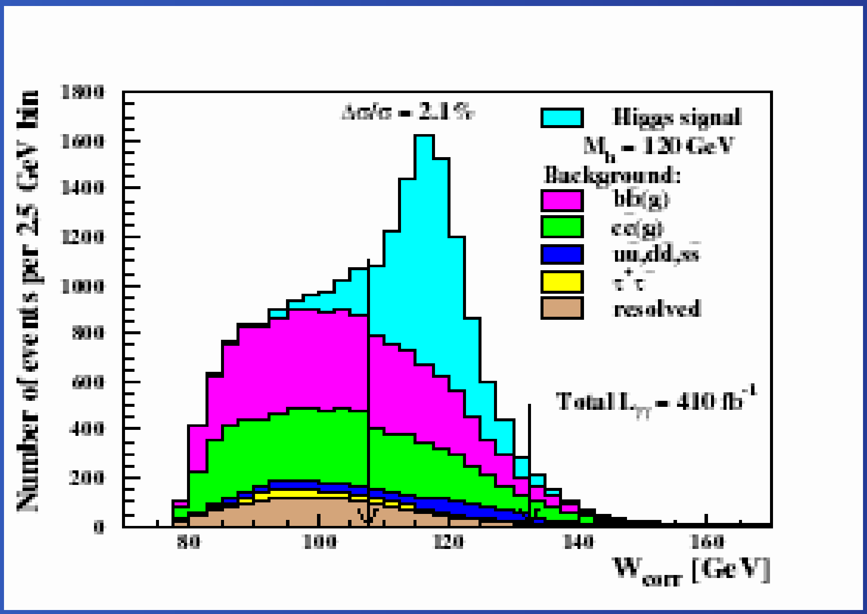
NŻK

SM summary

Niezurawski et al.,

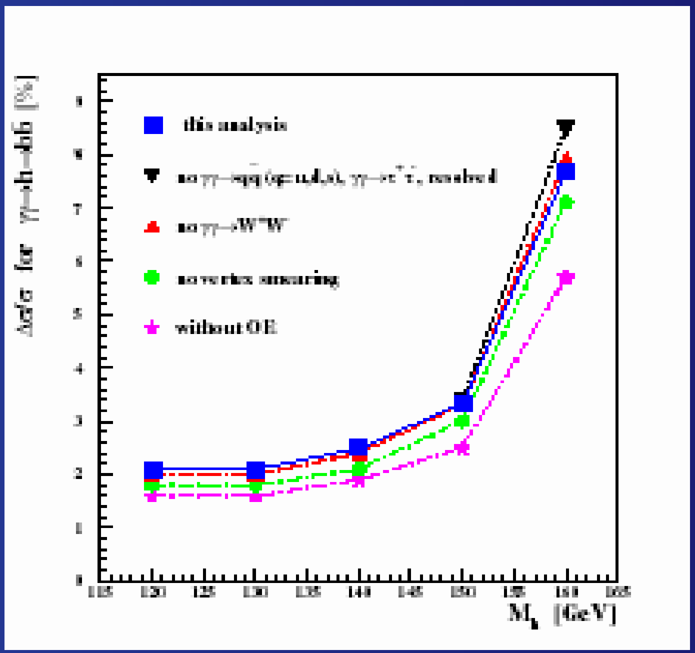
Monig, Rosca

Results for $M_h = 120$ GeV



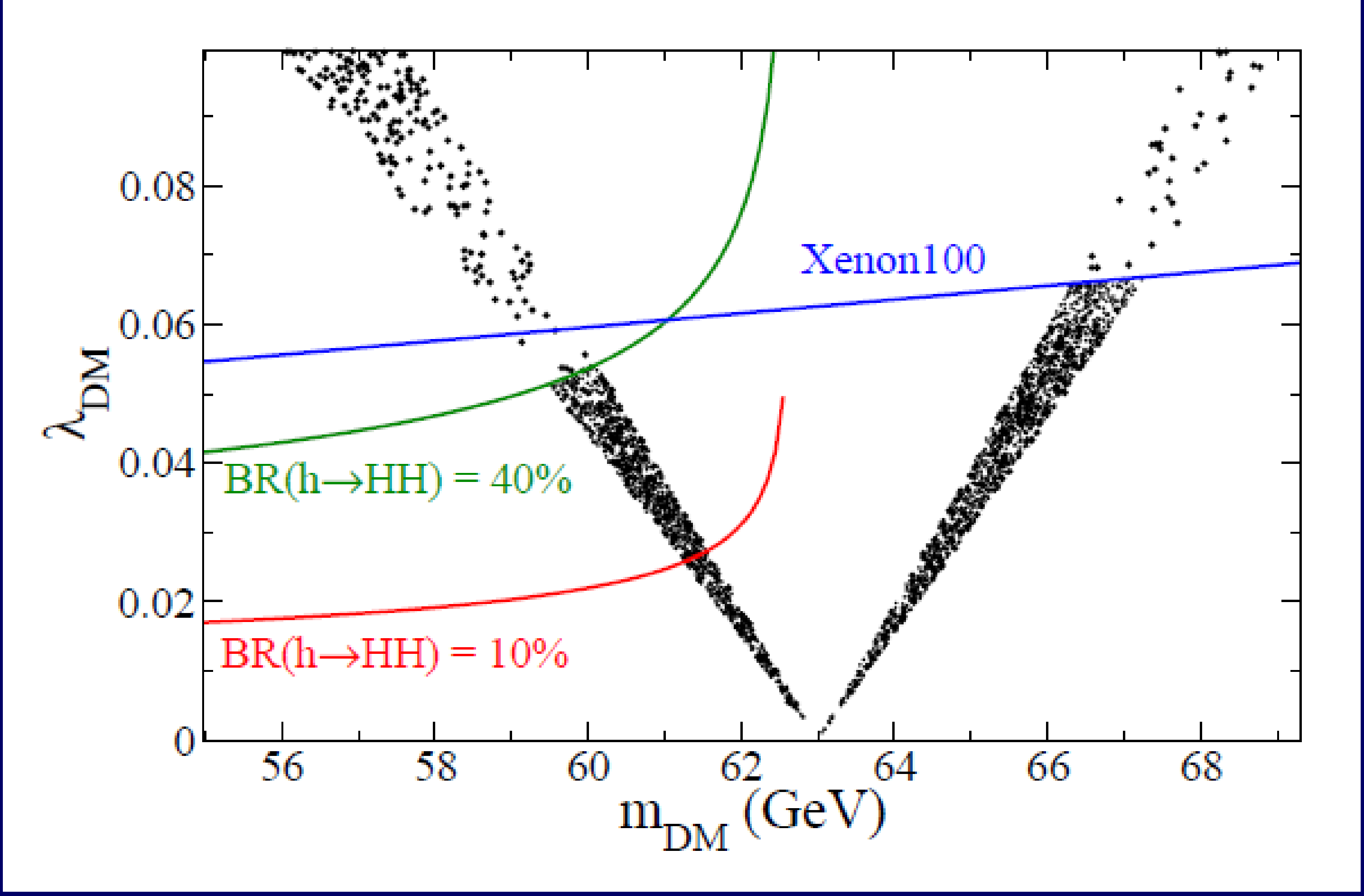
Corrected invariant mass distributions for signal and background events

Results for $M_h = 120\text{-}160$ GeV



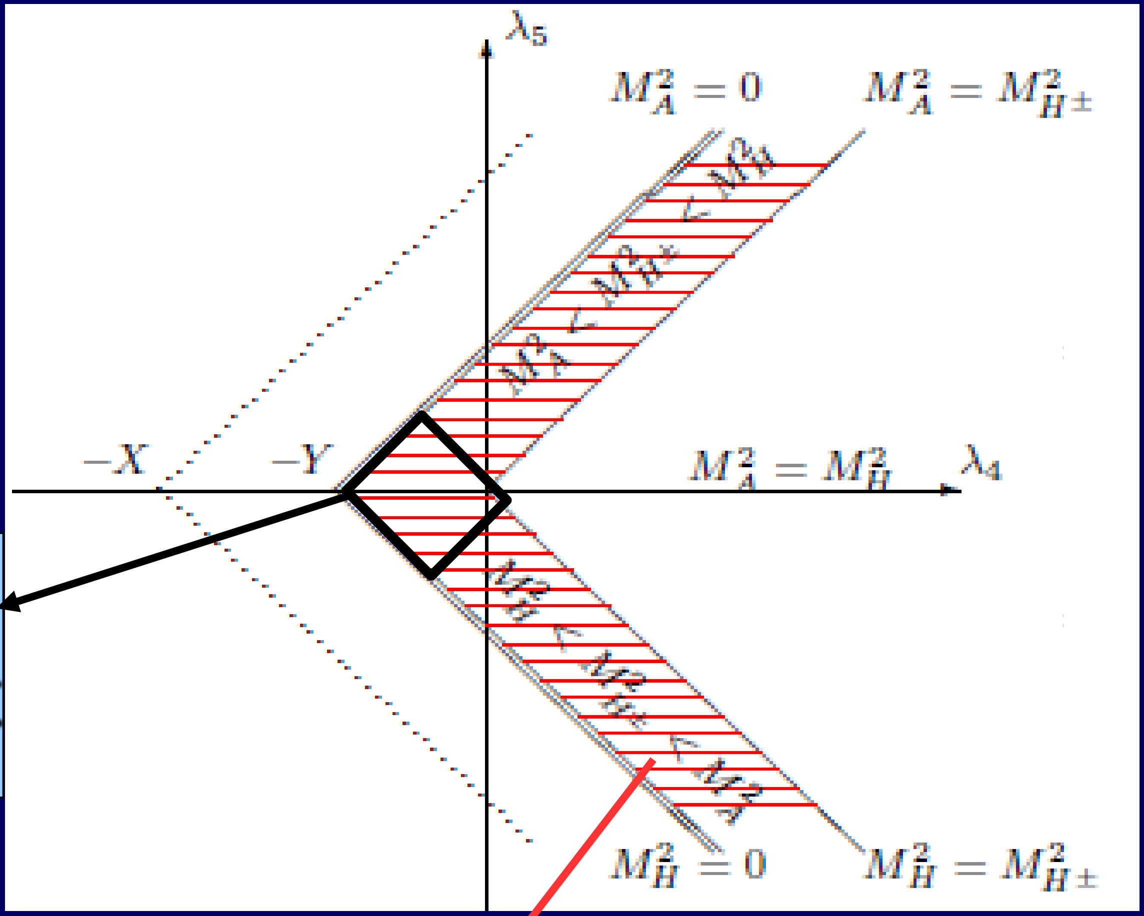
For $M_h = 150$, 160 GeV additional cuts to reduce $\gamma\gamma \to W^+W^-$

D. Borach, J. Cline
Inert Doublet DM with Strong EW phase transition 1204.4722[hep-ph]



Dark scalar masses

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



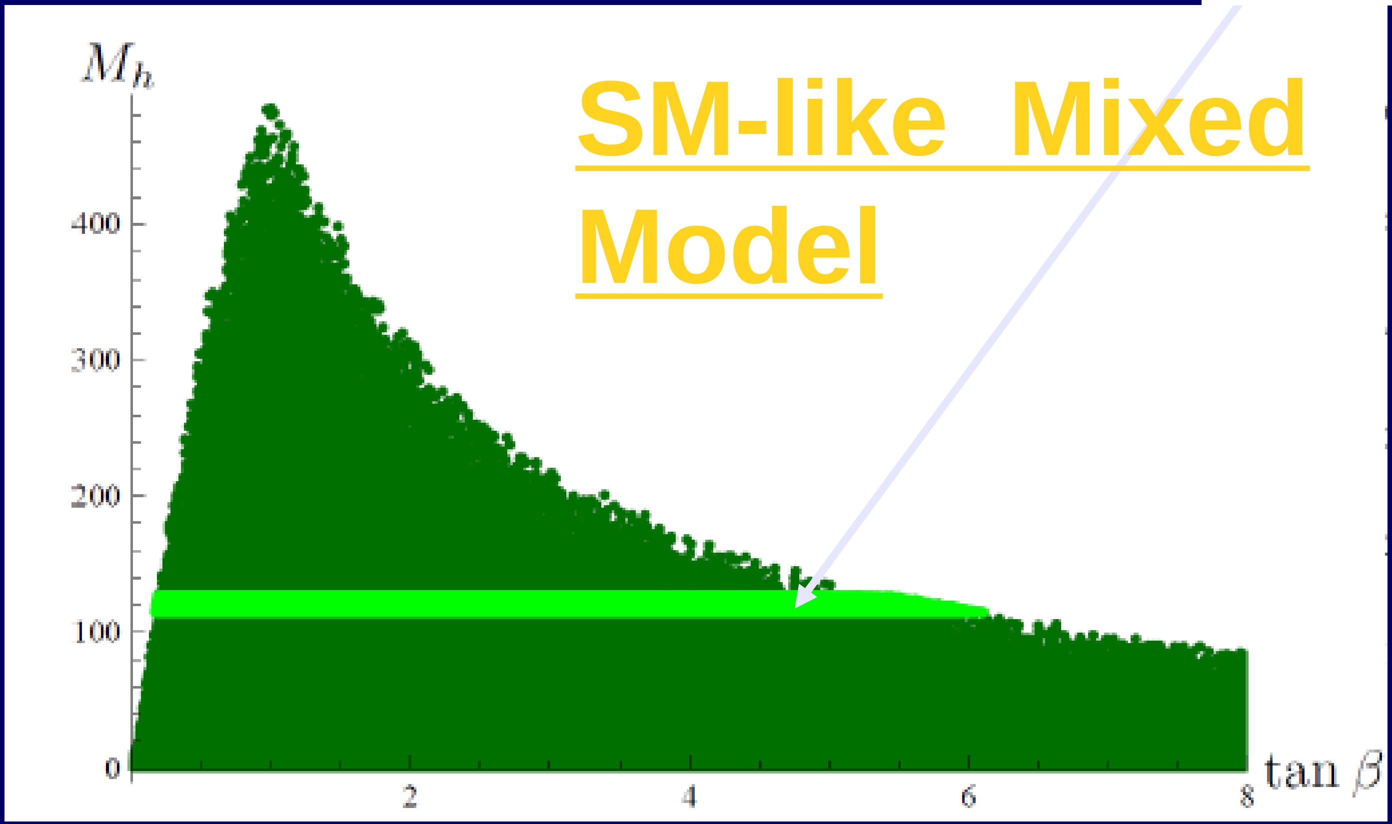
here H+
the heaviest

here H is the lightest ($\lambda_5 < 0$) – our DM

M_h vs tan β

For h mass =125 GeV

$0.18 \lesssim \tan\beta \lesssim 5.59$



SM-like Mixed Model

B.Gorczyca, MK

1112.5086v2 [hep-ph]

tan β

constrained by mass not Yukawa!