CORFU2010

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The inert Model and Evolution of the Universe

2HDMs

Z_2 symmetry

The Inert Model

Various vacua

Today= Inert phase

Thermal evolutions

Maria Krawczyk
University of Warsaw
I. Ginzburg, K. Kanishev
(Novosibirsk University),
D.Sokołowska, G. Gil, B. Gorczyca
(University of Warsaw)

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

mass $\leftrightarrow$ selfinteraction unknown

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

SU(2) x U(1) → ?

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 (relative couplings to SM χ)

2HDM Potential

Lee'73, Haber, Gunion, Glashow, Weinberg, Paschos, Despande, Ma, Wudka, Branco, Rebelo, Lavoura, Ferreira, Barroso, Santos, Bottela, Silva, Diaz-Cruz, Grimus, Ecker, Ivanov, Ginzburg, Krawczyk, Osland, Nishi, Nachtmann, Akeroyd, Kanemura, Kalinowski, Grządkowski ,Hollik, Rosiek..

$$V = \lambda_1(\Phi_1^\dagger\Phi_1)^2+\lambda_2(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

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

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

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

Z_2 symmetry transformations:

$\Phi_1\to\Phi_1 \quad \Phi_2\to -\ \Phi_2$ $\qquad\qquad$ $\Phi_1\to-\Phi_1 \quad \Phi_2\to\ \Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

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

Explicit Z_2 symmetry in V: λ_6, λ_7, $m^2{}_{12}=0$

Inert Model or Dark 2HDM

Ma'78
Barbieri'06

Z_2 symmetry under $\Phi_1 \to \Phi_1 \quad \Phi_2 \to - \Phi_2$

both in L and in vacuum → Inert Model

Today

$<\Phi_1> = v \qquad <\Phi_2> = 0$

→ Φ_1 as in SM (BEH), with Higgs boson h (SM-like)

→ Φ_2 - no vev, with 4 scalars (no Higgs bosons!)
no interaction with fermions (inert doublet)

Conservation of the Z_2 symmetry; only Φ_2 has odd Z_2-parity

→ The lightest scalar – a candidate for dark matter
(Φ_2 dark doublet with dark scalars) .

We are in the Inert phase

$\Phi_1 \rightarrow \Phi_S$ Higgs doublet S

$\Phi_2 \rightarrow \Phi_D$ Dark doublet D

Two Z_2 transformations:

S: $\Phi_S \rightarrow -\Phi_S$ $\Phi_D \rightarrow \Phi_D$ SM $\rightarrow$ SM

D: $\Phi_S \rightarrow \Phi_S$ $\Phi_D \rightarrow -\Phi_D$ SM $\rightarrow$ SM

Other vacua?

Where we were before?

Lagrangian

$$\mathcal{L} = \mathcal{L}_{gf}^{SM} + \mathcal{L}_H + \mathcal{L}_Y(\psi_f, \phi_S) ; \quad \mathcal{L}_H = T - V .$$

$$V = -\frac{1}{2}\left(m_{11}^2(\phi_S^\dagger \phi_S) + m_{22}^2(\phi_D^\dagger \phi_D)\right) + \frac{1}{2}\left(\lambda_1(\phi_S^\dagger \phi_S)^2 + \lambda_2(\phi_D^\dagger \phi_D)^2\right) + \lambda_3(\phi_S^\dagger \phi_S)(\phi_D^\dagger \phi_D) + \lambda_4(\phi_S^\dagger \phi_D)(\phi_D^\dagger \phi_S) + \frac{\lambda_5}{2}\left((\phi_S^\dagger \phi_D)^2 + (\phi_D^\dagger \phi_S)^2\right)$$

$$\lambda_5 < 0 .$$

Vacua for the potential with explicit Z_2 symmetry and real parameters

Ginzburg, Kanishev, MK, Sokołowska'09

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

Finding minima → global minimum = vacuum

Positivity (stability) constraints

$$\left[\ \lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R + 1 > 0. \ \right]$$

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

Extremum fulfilling the positivity constraints with the lowest energy = vacuum

Possible vacuum states

(V with explicit Z_2)

The most general vacuum state

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

v_S, v_D, u , -

real, ≥ 0

$v^2 = v_1^{\;2} + v_2^{\;2} + u^2$
$= (246\ \mathrm{GeV})^2$

EWs	EWs	$u = v_D = v_S = 0$
Inert	I_1	$u = v_D = 0$
Inert-like	I_2	$u = v_S = 0$
Mixed	M	$u = 0$
Charge Breaking	Ch	$u \neq 0 \quad v_D = 0$

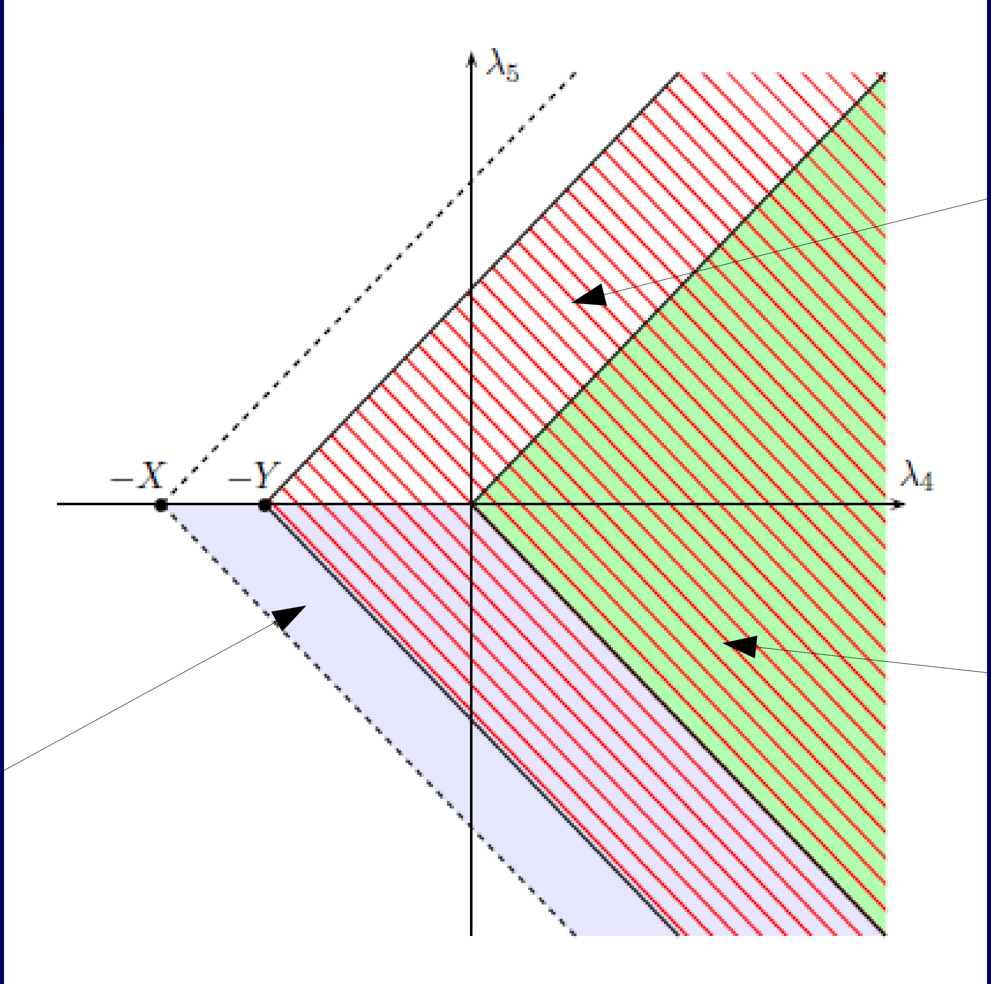
Various vacua on (λ_4, λ_5) plane

Positivity constrains on V: $X = \sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0$

$\lambda_4 \pm \lambda_5 > -X$

Inert and Inert-like

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



Charge Breaking

Ch

Mixed

Note the overlap of the Inert with M and Ch !

TODAY

2HDM with explicit S (Z_2) symmetry

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

Model I (Yukawa int.)

- Charged breaking phase ?
  photon is massive, el.charge is not conserved...
  → no
- Neutral phases:
  Mixed M ok, many data, but no DM
  Inert I1 OK! there are some data
  Inert-like I2 no, all fermions massless, no DM

Inert Model (Dark 2HDM) vs data

Ma..' 78, Barbieri.. ' 2006

Exact (D)Z_2 symmetry in L <u>and</u> in vacuum →

D-parity: odd is only Φ_D

Φ_S

- Nonzero vev has only doublet Φ_S (Higgs doublet)

only it couples to fermions (Model I)

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

Φ_D

- Zero vev for ΦD (scalar doublet) and no Yukawa int.
- Four scalars with odd Z_2-parity (dark scalars D)
- The lightest dark scalar - stable

Dark scalars D = H+,H-,H,A

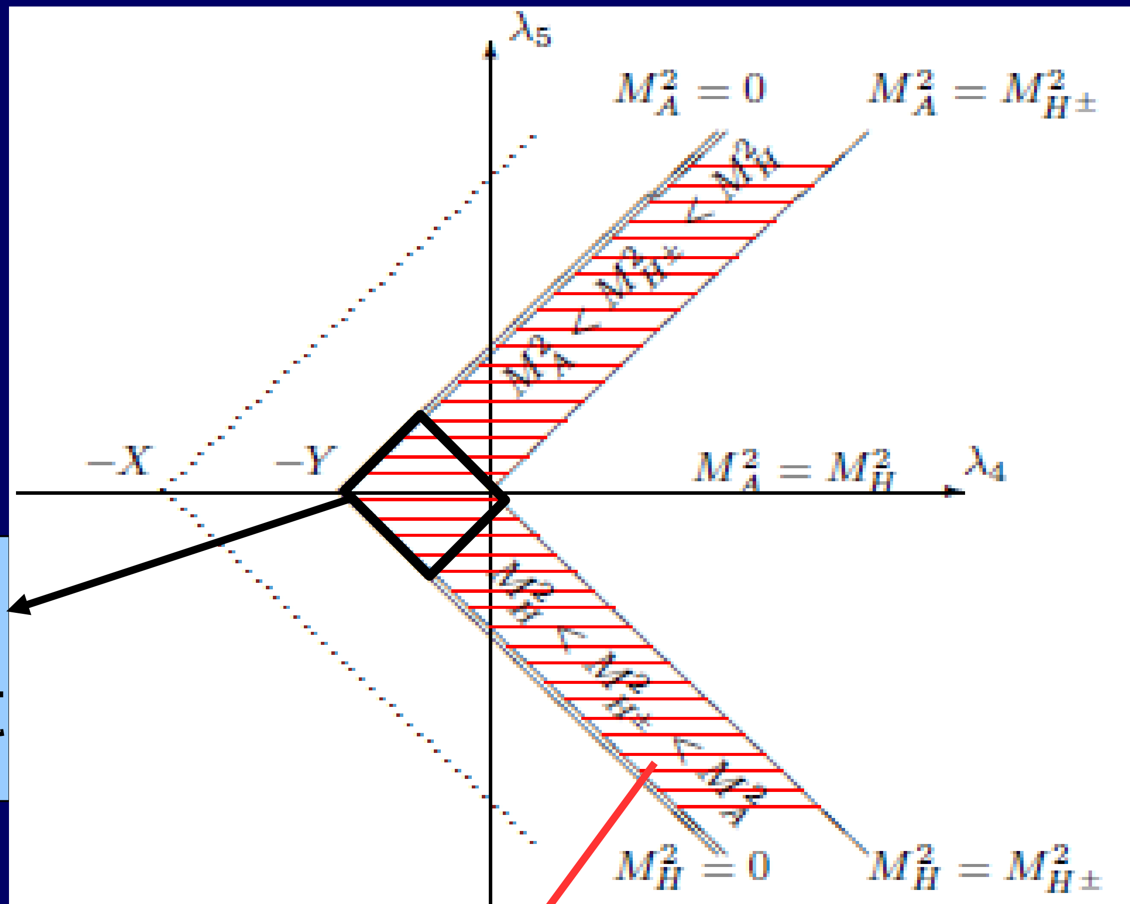
- Masses

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

- D couple to V = W/Z (eg. AZH, $H^- W^+ H$), not to DV V!
- Selfcouplings DDDD proportional to λ_2
- Couplings between Higgs boson h and D proportional to $M^2_D + m_{22}^2/2$

Intert Model – dark scalar masses

using X (positivity) and $Y = M_{H+}^2\, 2/v^2$



here H+
the heaviest

here H is the dark matter candidate ($\lambda_5 < 0$)

Testing Inert Model

- To consider

  properties of SM-like h (light and heavy)

  properties of dark scalars

  (produced only in pairs!)

  DM candidate

- Colliders signal/constraints

Barbieri et al '2006 for heavy h

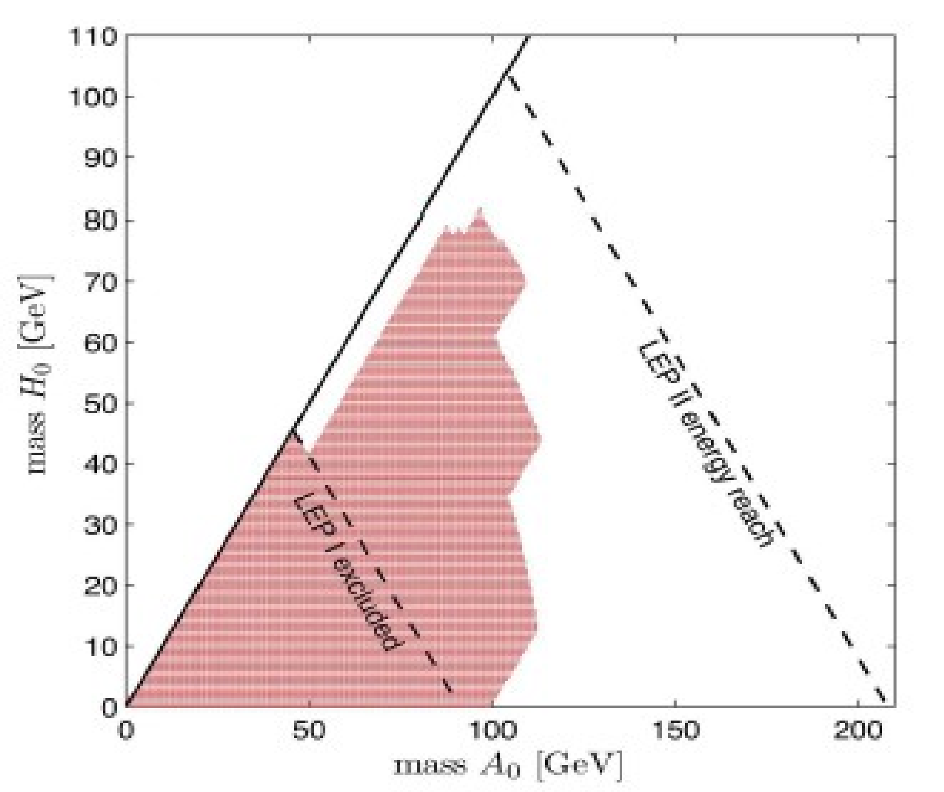
Cao, Ma, Rajasekaren' 2007 for a light h

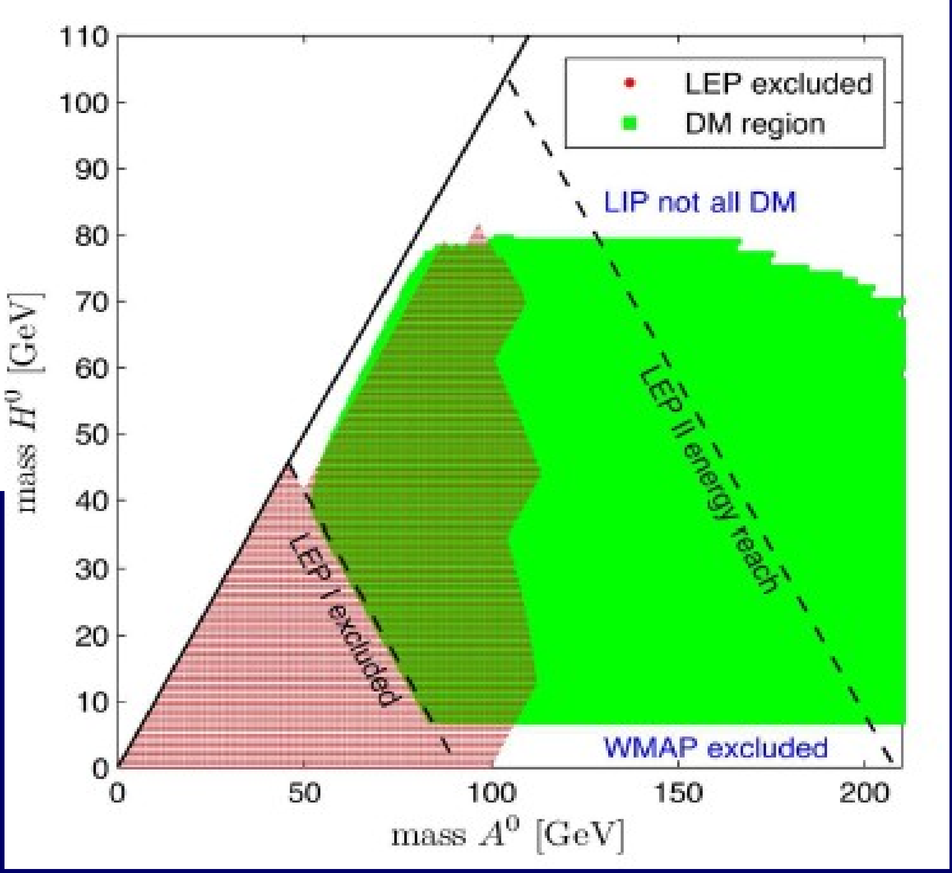
LEP II: $M_H + M_A > M_Z$, $\Delta(A,H) = 5 - 30$ GeV for $M_h = 105 - 110$ GeV

EW precision data: $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

Dark 2HDM: LEP II exclusion: H vs A

Lundstrom et al 0810.3924





LEP II + WIMP

M_h = 200 GeV

$M_A - M_H > 8$ GeV

Inert Model: constraints LEP+DM → LHC

E. Dolle, S. Su, 0906.1609 [hep-ph]

LEP (exclusion and EW precision data)

\+ relic density using MicroOMEGA/CalCHEP

$\delta_1 = m_{H\pm} - m_S$ $\delta_2 = m_A - m_S$

Viable region for relic density

S=H

	DM	SM h	m_S	δ_1, δ_2	λ_L
(I)	low m_S	low m_h	30 – 60 GeV	50 - 90 GeV	-0.2 to 0
(II)			60 – 80 GeV	at least one is large	-0.2 to 0.2
(III)		high m_h	50 – 75 GeV	large δ_1 $\delta_2 < 8$ GeV	-1 to 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 to 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 to 0.3

Other analysis (IDM)

Gustafsson et al.2007: *striking DM line signals -promising features to search with GLAST*

Mass of: H = 40-80 GeV, H+ = 170 GeV,

A = 50-70 GeV, h = 500 and 120 GeV

Honorez, Nezri, Oliver, Tytgat 2006-7

H as a perfect example or arcgetype of WIMP – within reach of GLAST (FERMI)

Here mass of h = 120 GeV, mass H+ close to A = 400-550 GeV

C. Arina, F-S Ling, M. Tytgat 2009

IDM&iDM or the inert doublet Model and inelastic dark matter

Mass H=10 GeV and 535 GeV – 50 TeV ! (DAMA data)

Evolution of the Universe – different vacua in the past

Ginzburg, Ivanov,Kanishev 2009
Ginzburg, Krawczyk, Sokołowska 2010

We consider 2HDM with an explicit Z_2 symmetry assuming that today the Inert Model is realized.

Yukawa interaction – Model I →
all fermions couple only to Φ_S

Possible neutral extrema (u=0):

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

$$m_{11}^2 < 0, \quad m_{22}^2 < 0.$$

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

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

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

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

a true vacuum → with the minimal energy

Energy difference

I_1-I_2 :

$$\mathcal{E}_{I_1} = -\frac{m_{11}^4}{8\lambda_1};\qquad \mathcal{E}_{I_2} = -\frac{m_{22}^4}{8\lambda_2};$$

I_1-M

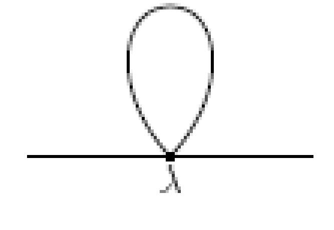
$$\mathcal{E}_{I_1} - \mathcal{E}_M = \frac{\left(m_{11}^2\lambda_{345} - m_{22}^2\lambda_1\right)^2}{8\lambda_1^2\lambda_2(1-R^2)};$$

I_2-M

$$\mathcal{E}_{I_2} - \mathcal{E}_M = \frac{\left(m_{22}^2\lambda_{345} - m_{11}^2\lambda_2\right)^2}{8\lambda_1\lambda_2^2(1-R^2)}.$$

For M vacuum to exist:
(1-R)(1+R)>0
$\rightarrow$ 1-R>0

Thermal corrections of V



Matsubara method (temperature T>> m²) –

-only quadratic (mass) parameters change with T

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

$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{12} + \frac{3g^2 + g'^2}{32} + \frac{g_t^2 + g_b^2}{8}\,,$$

$$c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{12} + \frac{3g^2 + g'^2}{32}\,.$$

Positivity condition:

$$c_2 + c_1 > 0,$$

g and g' EW coupling constant

with T → different phases possible

Phase transitions from the EW symmetric phase

The phase diagram $(\mu_1(T),\ \mu_2(T))$

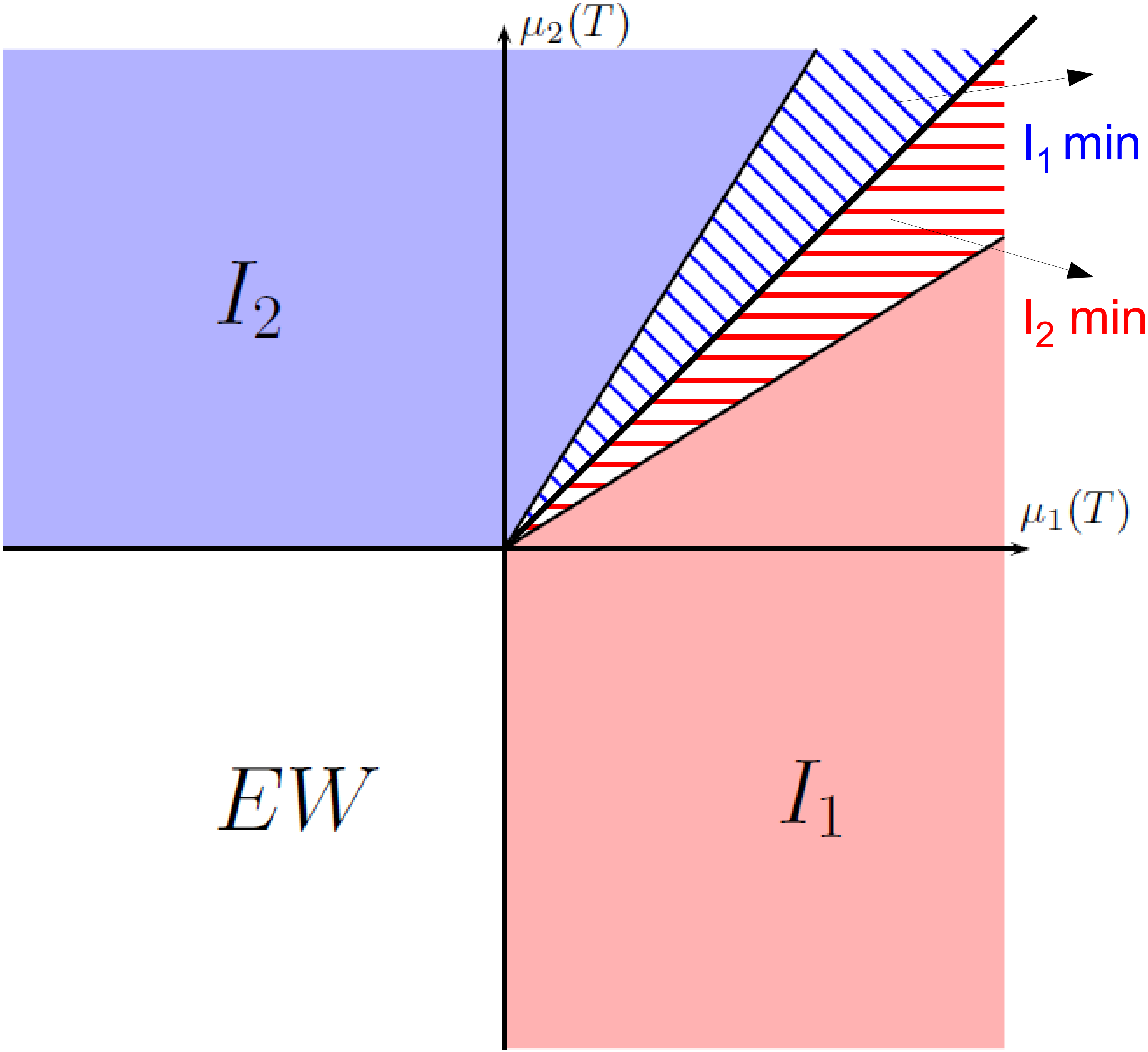
$$\mu_1(T) = m_{11}^2(T)/\sqrt{\lambda_1}, \qquad \mu_2(T) = m_{22}^2(T)/\sqrt{\lambda_2}\ .$$

The evolution parameters

$$\widetilde{c}_1 = c_1/\sqrt{\lambda_1}, \qquad \widetilde{c}_2 = c_2/\sqrt{\lambda_2}, \qquad \widetilde{c} = \widetilde{c}_2/\widetilde{c}_1 .$$

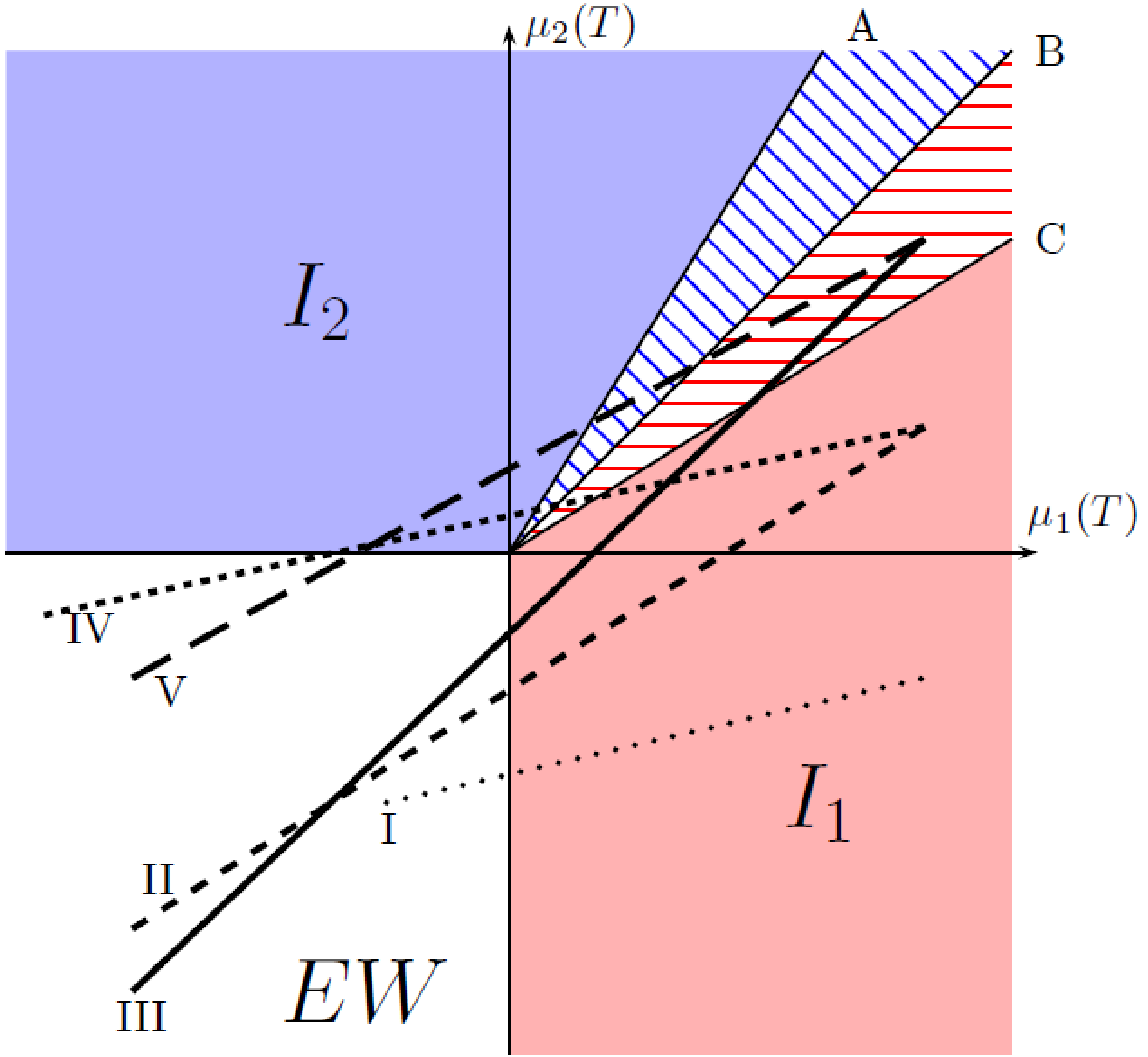
to the present INERT phase $\mu_1 > 0$

vacua



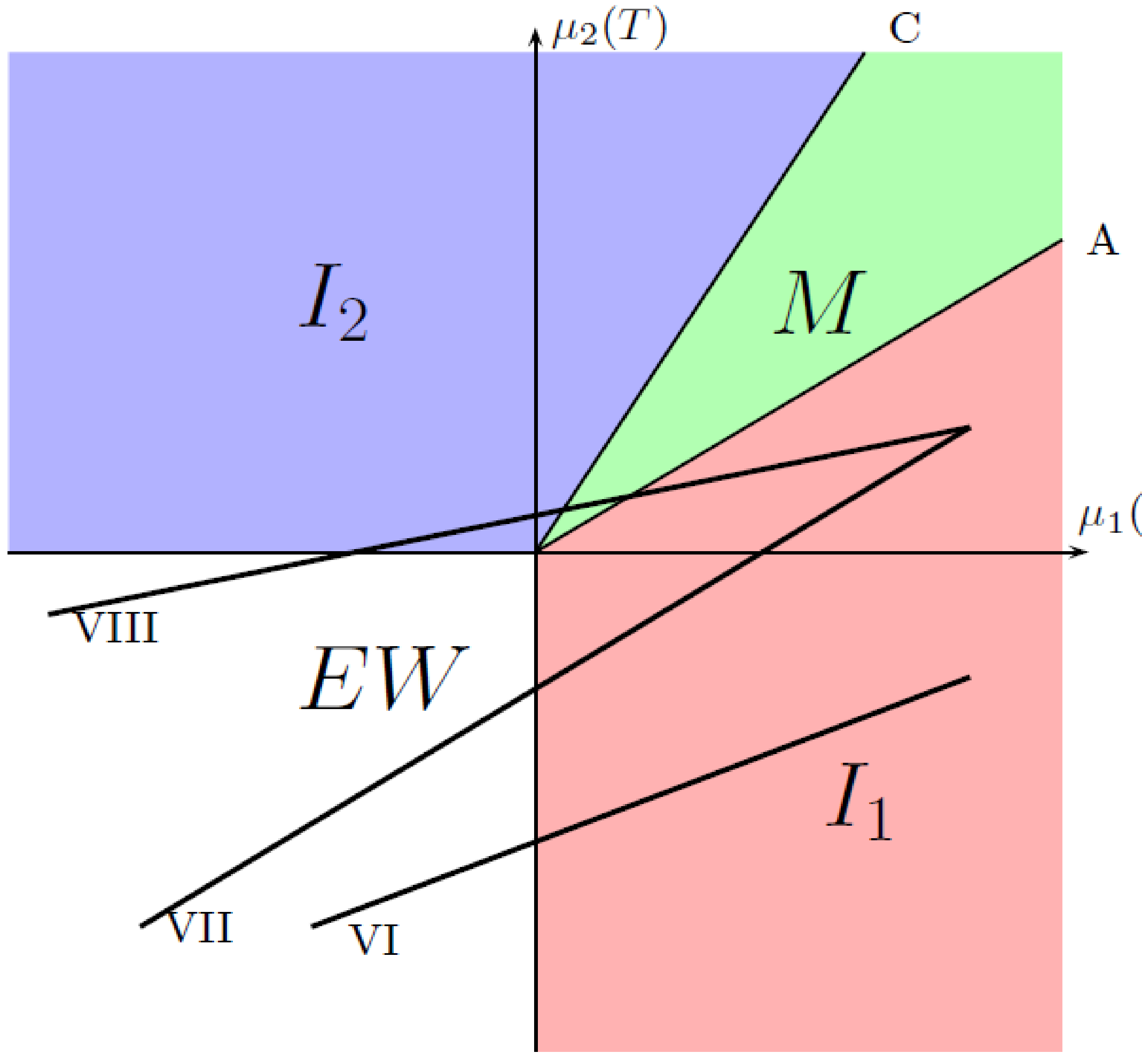
R>1

Mixed vacuum impossible



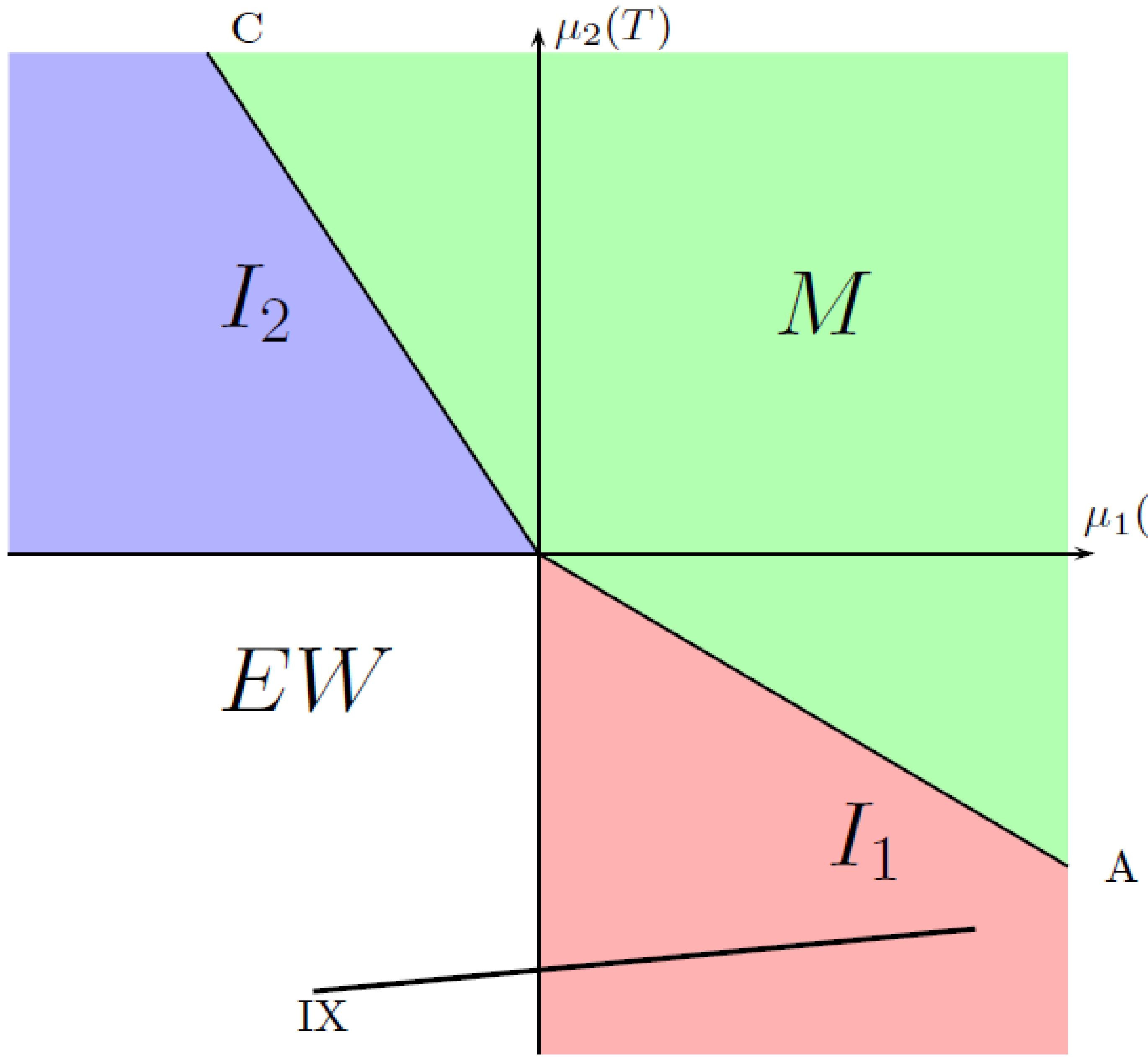
0<R<1

$0 < R\mu_1 < \mu_2 < \mu_1/R.$



$\mu_2 > \mu_1/R, \quad \mu_2 > \mu_1 R$

-1<R<0



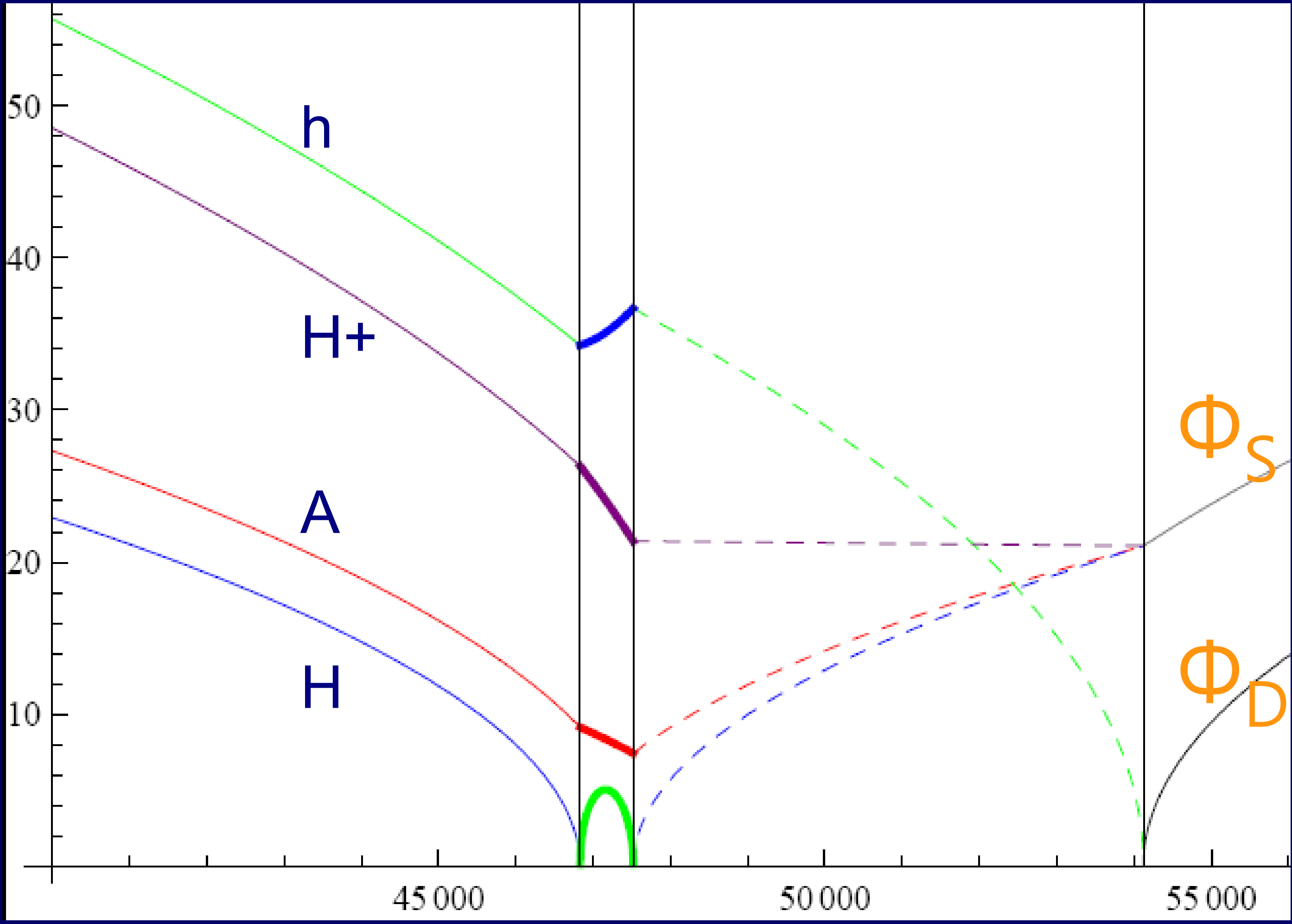
Masses of scalars vs T2 Mh=120 GeV

M_{H+}=110

M_A=68

M_H=60

ray VIII



Inert M Inert-like EWs

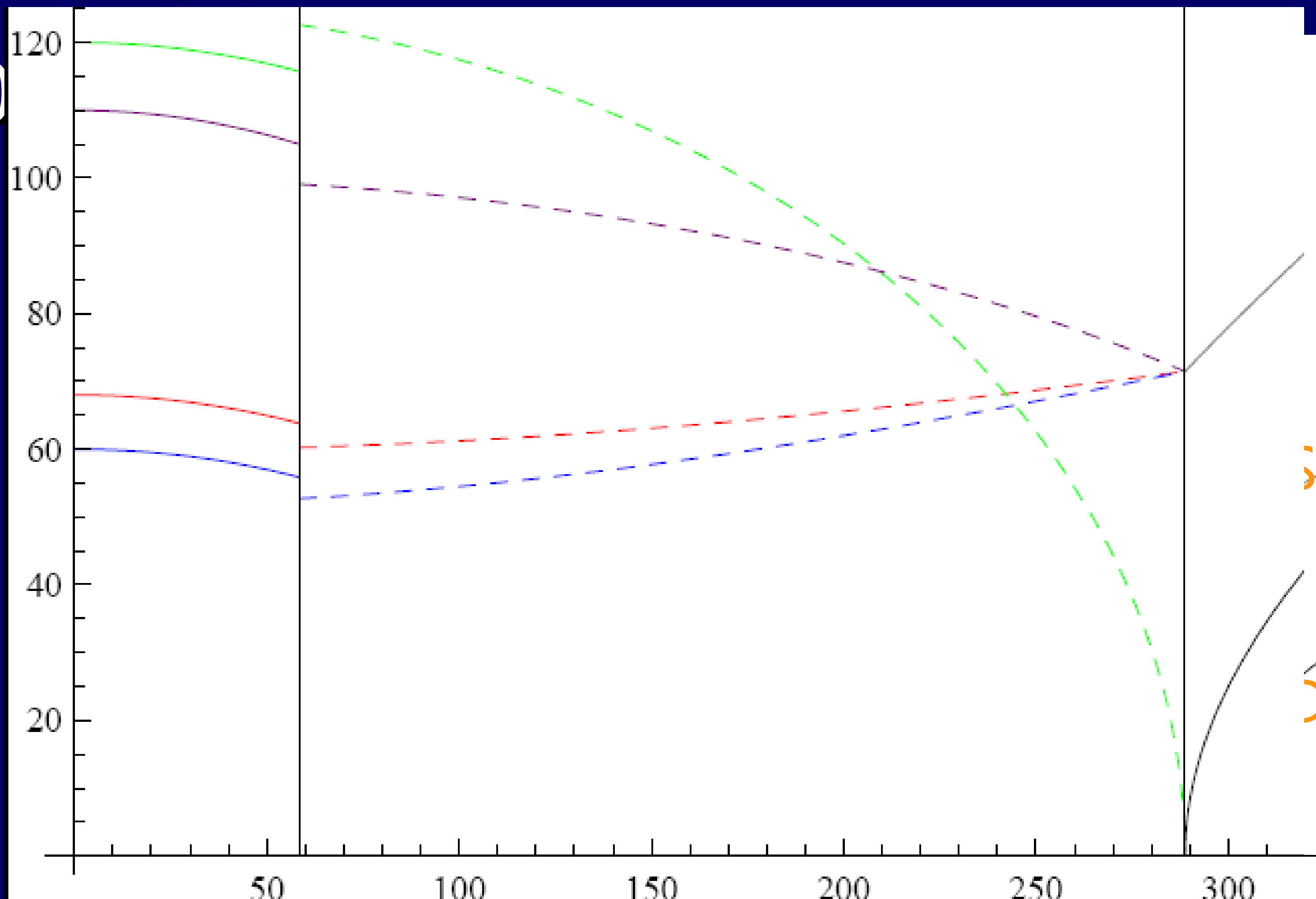
Masses of scalars vs T
Mh=120 GeV

M_{H+}=110

M_A=68

M_H=60

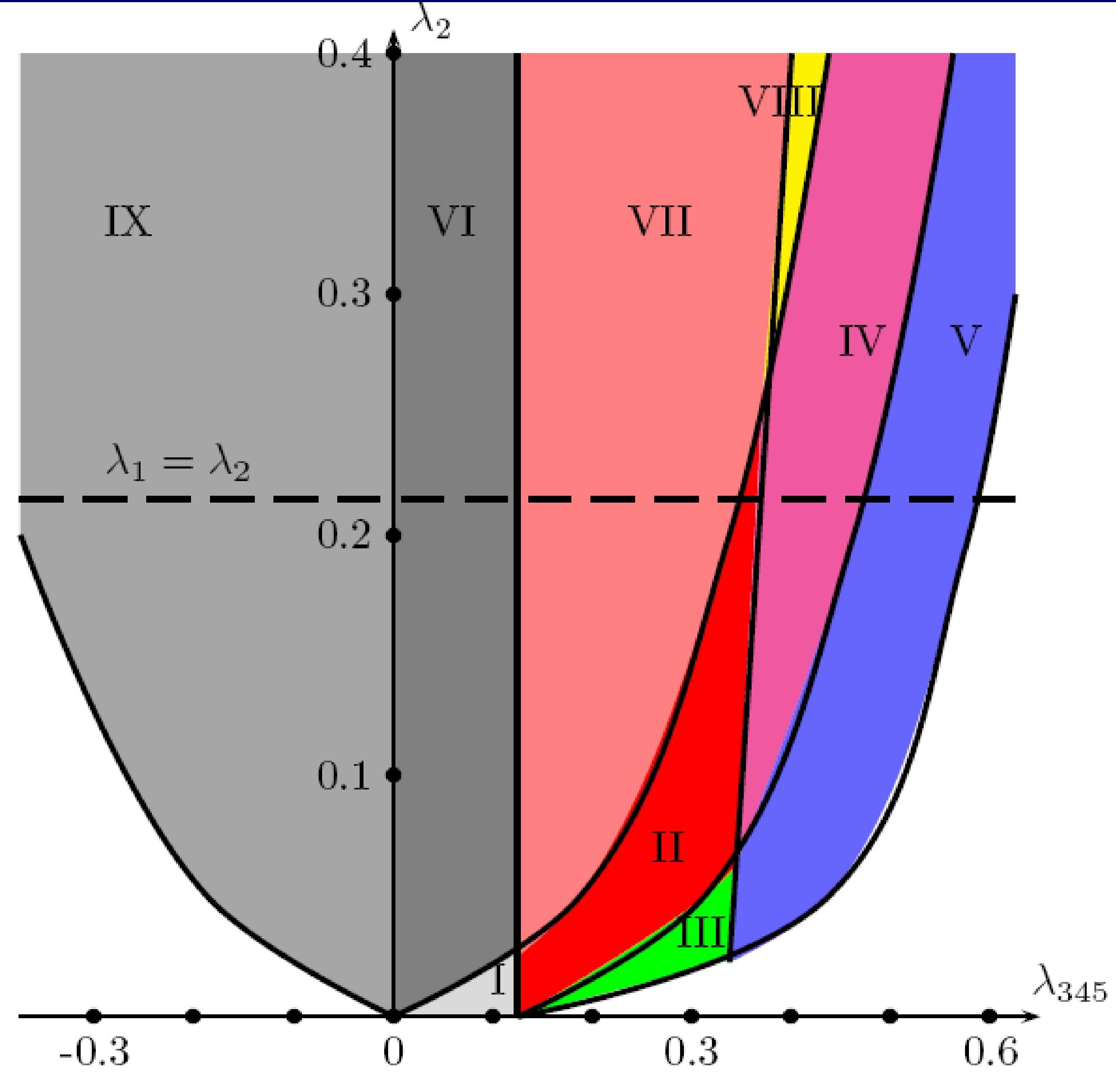
ray V



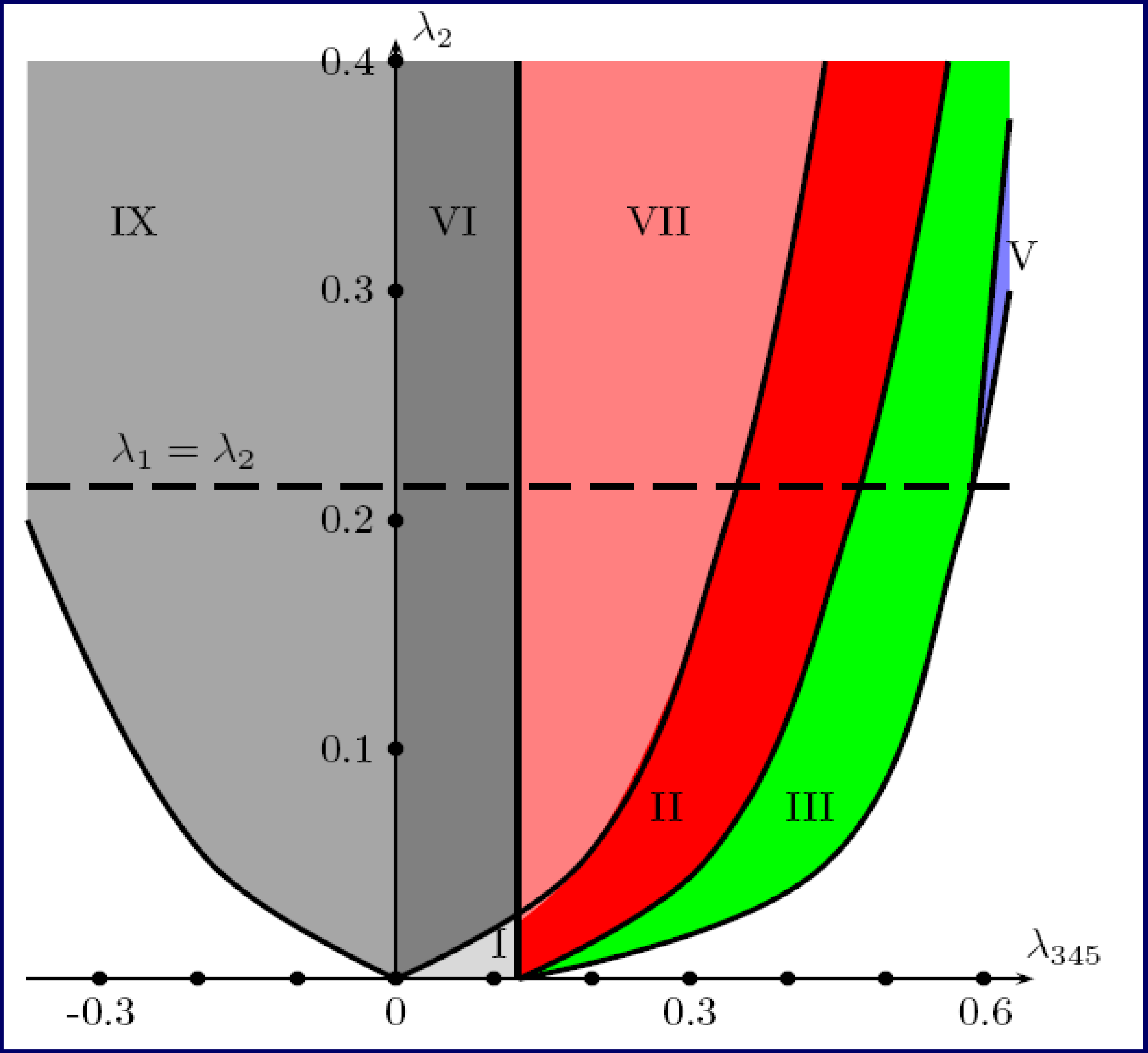
Inert

Inert-like

EWs



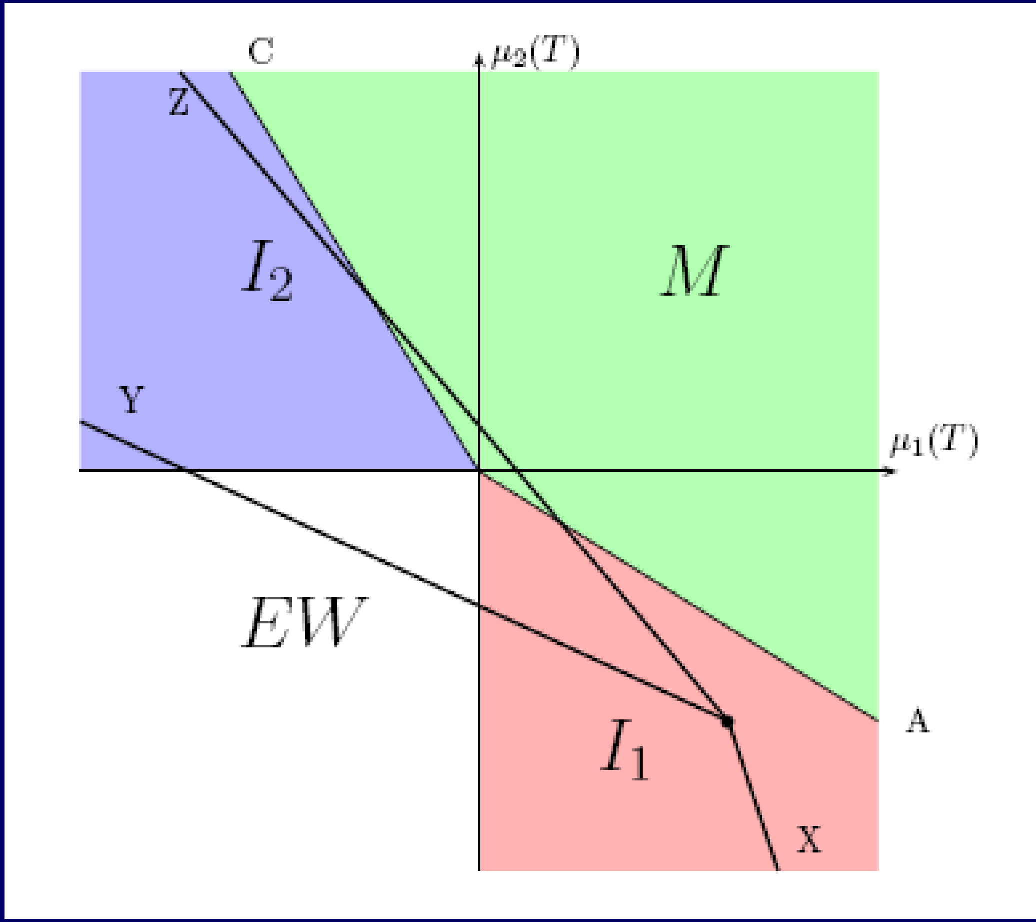
λ_2
0.4
0.3
0.2
0.1
IX
VI
VII
VIII
IV
V
II
III
I
$\lambda_1 = \lambda_2$
λ_{345}
-0.3
0
0.3
0.6



Without fermions in evolution parameter c_1

Non-restoration of EW symmetry

c_1 or $c_2 < 0$



Conclusions

- Intert Model in agreement with present data – soon tests at FERMI and LHC
- What was in the Past?

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

$$EWv: \quad \begin{array}{l} I_2 \xrightarrow{II} \begin{cases} EWs \xrightarrow{II} I_1 \\ M \xrightarrow{II} I_1 \end{cases} \\ I_1 \to I_1 \end{array} ,$$

neutral !

DM matter may appear later..