LC09

Perugia, 22.09.2009

Evolution of the Universe to the present Inert phase

2HDMs

Z_2 symmetry

The Inert Model

Various vacua

Today = Inert phase

Thermal evolutions

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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), 3HDM ...
Note, that the lightest scalar is often SM-like

NonStandard Models are based on more radical assumptions.

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

$SU(2) \times U(1) \rightarrow$?

Two Higgs Doublet Models

Two doublets of SU(2) ($Y=1$, $\rho=1$) - 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, Botella, Silva, Diaz-Cruz, Grimus, Ecker, Ivanov, Ginzburg, Krawczyk, Osland, Nishi, Nachtmann, Maniatis, Manteuffel, 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 transformation: $\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

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

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12}=0$

Z_2 symmetry: $\Phi_1 \rightarrow \Phi_1 \quad \Phi_2 \rightarrow -\Phi_2$

- If Z_2 symmetry holds in the Lagrangian L
  no CP violation in the scalar sector

Lee' 73

Glashow, Weinberg'77, Paschos '77

Despande, Ma' 78

- Softly broken $Z_2 \rightarrow$ *Branco, Rebelo '85*
  CP violation possible, tree-level FCNC absent,
  Decoupling and non-decoupling possible *Haber'95*

- Hard breaking $Z_2 \rightarrow$
  CP violation possible [* even without CP mixing]
  Lavoura, Silva' 94 ; Kanishev, MK, Sokołowska' 2008
  tree-level FCNC

Yukawa interactions

(with or without Z_2 symmetry)

Model I - only Φ_1 interacts with fermions

Model II – Φ_1 with down-type fermions d , l

Φ_2 with up-type fermions u

Model III - both doublets interact with fermions

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

Model Y - Φ_1 with down-type quarks d

Φ_2 with up-type quarks u and leptons

Top 2HDM – top with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

+ Extra dim 2HDM models ….

Inert or Dark 2HDM

Deshpande, Ma'78
Barbieri, Hall, Rychkov'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

$<\Phi_1^T>= (0,v) \qquad <\Phi_2^T>= (0,0)$

→ Φ_1 as in SM, 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) .

Possible vacuum states (for real V)

A. Barroso, P.M. Ferreira, R. Santos, J.P. Silva, hep-ph/0507329,

The most general vacuum state

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}v_1 \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} u \\ \frac{1}{\sqrt{2}}v_2 e^{i\xi} \end{pmatrix}$$

v_1, v_2, u , ξ - real, ≥ 0

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

Inert	I	$u = v_2 = 0$
Normal (CP conserving)	N	$u = \xi = 0$
Charge Breaking	Ch	$u \neq 0 \quad v_2 = 0$
Vacuum	B	$u = v_1 = 0$
CP violating	CP	$u = 0\ \xi \neq 0$

Vacua for the potential with explicit Z_2 symmetry and real parameters

Ginzburg, Kanishev, MK, Sokołowska'09

Finding extrema: $\partial V / \partial \Phi_1|_{\Phi_1 = \langle\Phi_1\rangle} = 0$ and $(\Phi_1 \to \Phi_2)$

Finding minima → global minimum = vacuum

Positivity (stability) constraints (for $\lambda_6, \lambda_7, m^2_{12}=0$)

$$\lambda_1 > 0, \quad \lambda_2 > 0, \; \Lambda_{3+} > 0, \; \Lambda_{345+} > 0, \; \tilde{\Lambda}_{345+} > 0.$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad \tilde{\lambda}_{345} = \lambda_3 + \lambda_4 - \lambda_5.$$

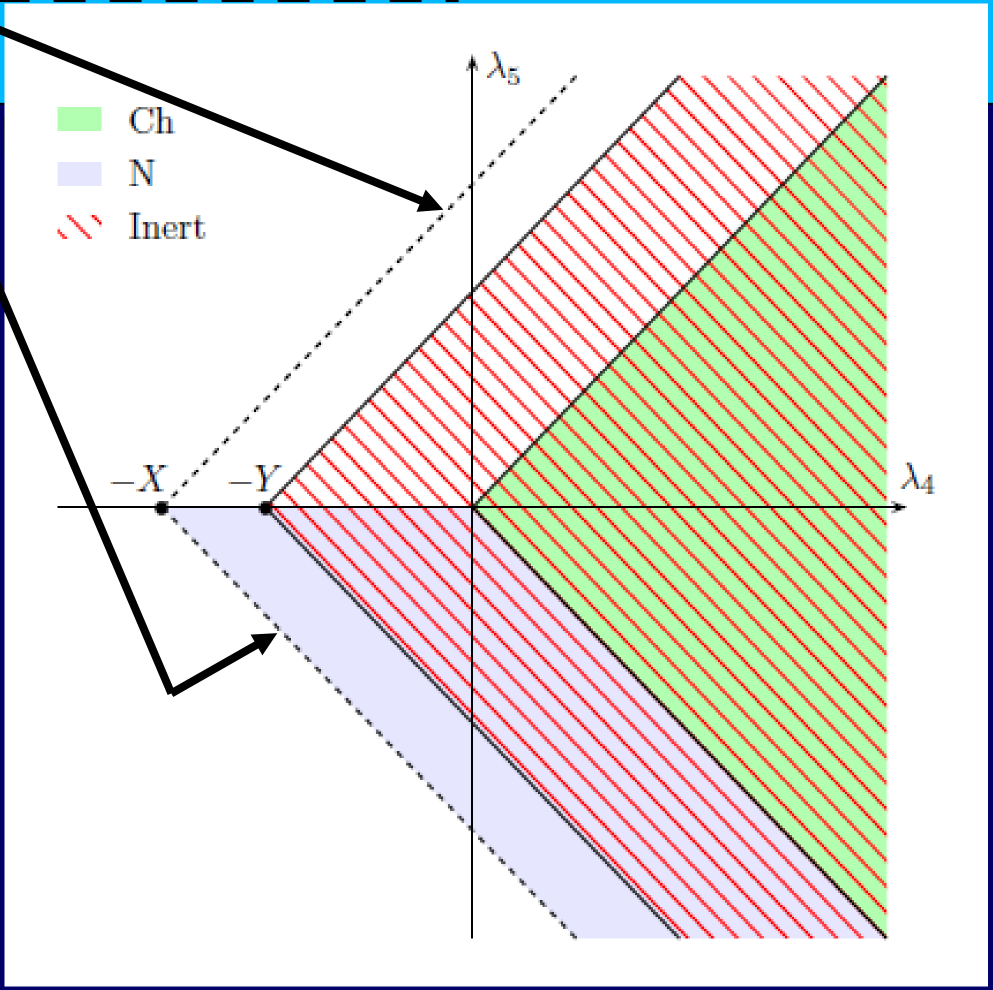
$$\Lambda_{345\pm} = \sqrt{\lambda_1\lambda_2} \pm \lambda_{345}, \quad \tilde{\Lambda}_{345\pm} = \sqrt{\lambda_1\lambda_2} \pm \tilde{\lambda}_{345}, \quad \Lambda_{3\pm} = \sqrt{\lambda_1\lambda_2} \pm \lambda_3.$$

Extremum fulfilling the positivity constraints with the lowest energy = vacuum

Various extrema on (λ_4 , λ_5) plane (Z_2 sym)

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

$\lambda_4 \pm \lambda_5 > -X$



Inert (or B)

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

Charge breaking Ch

Normal

Note the overlap of the Inert with N and Ch !

TODAY

2HDM with explicit Z_2 symmetry

$\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$ with Model I (Yukawa int.)

Which extremum is a vacuum?

- Charged breaking ?

  massive photon, el.charge is not conserved

  $\to$ No

- Neutral :

  Normal ok, many data, but no DM

  Inert OK! there are some data

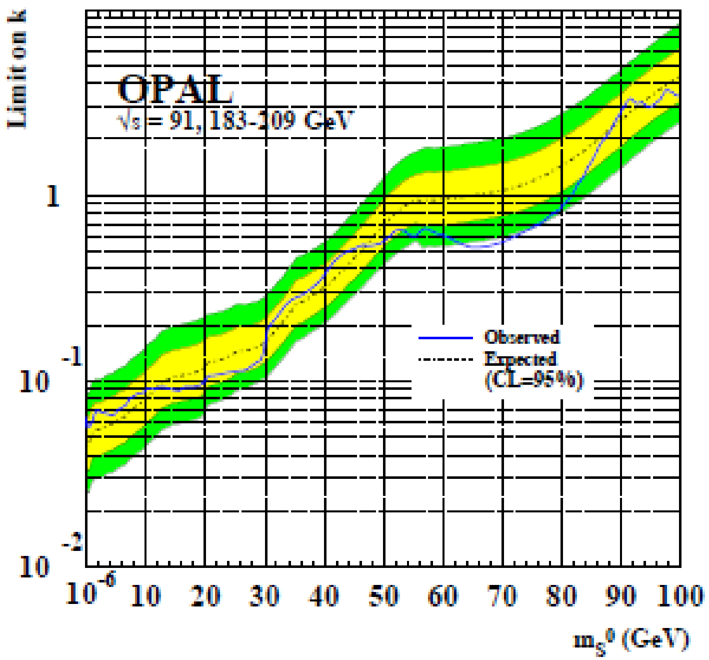
  B no, all fermions massless, no DM

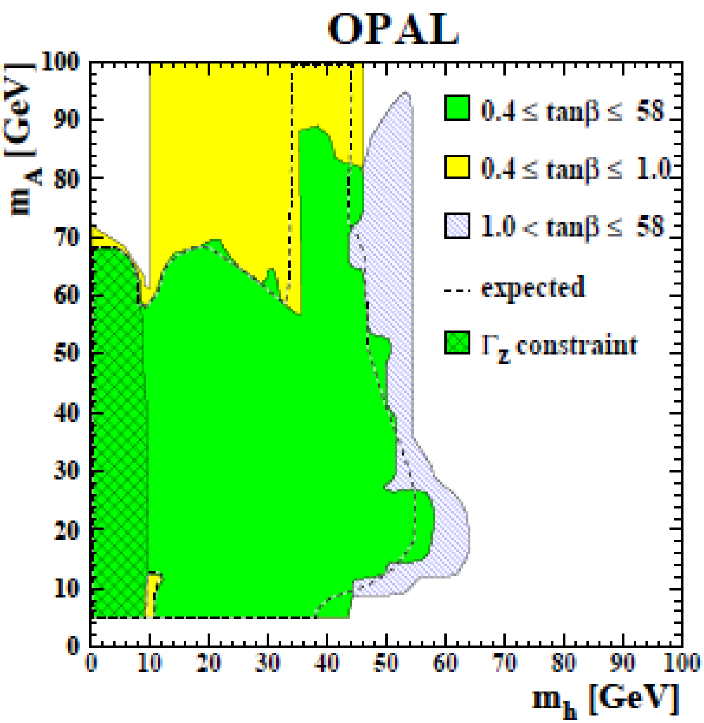
LEP: 2HDM (N vacuum) v_1, v_2 (tanβ);Model I,II..

Neutral Higgs bosons - couplings to gauge boson, and mass exclusion

Light h OR light A in agreement with current data

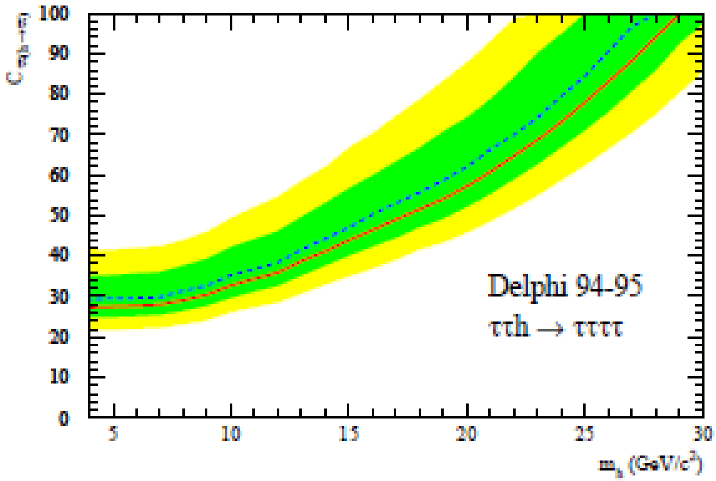
hZZ: $sin(\beta - \alpha)$ and hAZ: $cos(\beta - \alpha)$

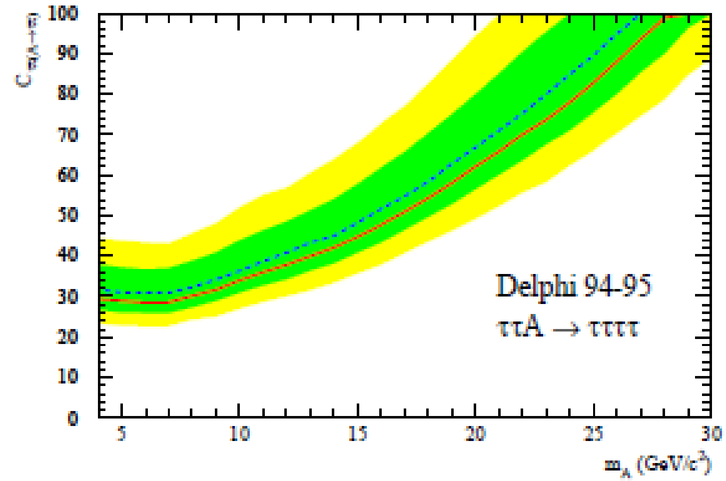




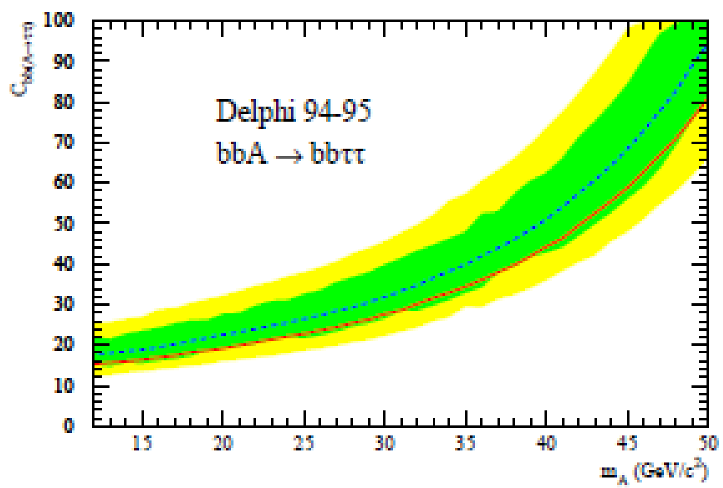
Light scalar h → small $k = sin^2(\beta - \alpha)$!

Upper (95%) limits for Yukawa couplings χ_d ($\tan\beta$) in 2HDM (II)





Yukawa coupling ($\tan\beta$) up to 20 allowed mass larger than 35 GeV!



Inert Model (Dark 2HDM) vs data

Ma..1978,2007, Barbieri.. 2006

Exact Z_2 symmetry in L and in vacuum →

Z_2-parity: odd is only Φ_2

Φ_1

- Nonzero vev has only doublet Φ_1 (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_2

- Zero vev for Φ_2 (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

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

- D couple to V = W/Z (eg. AZH, $H^- W^+ H$),

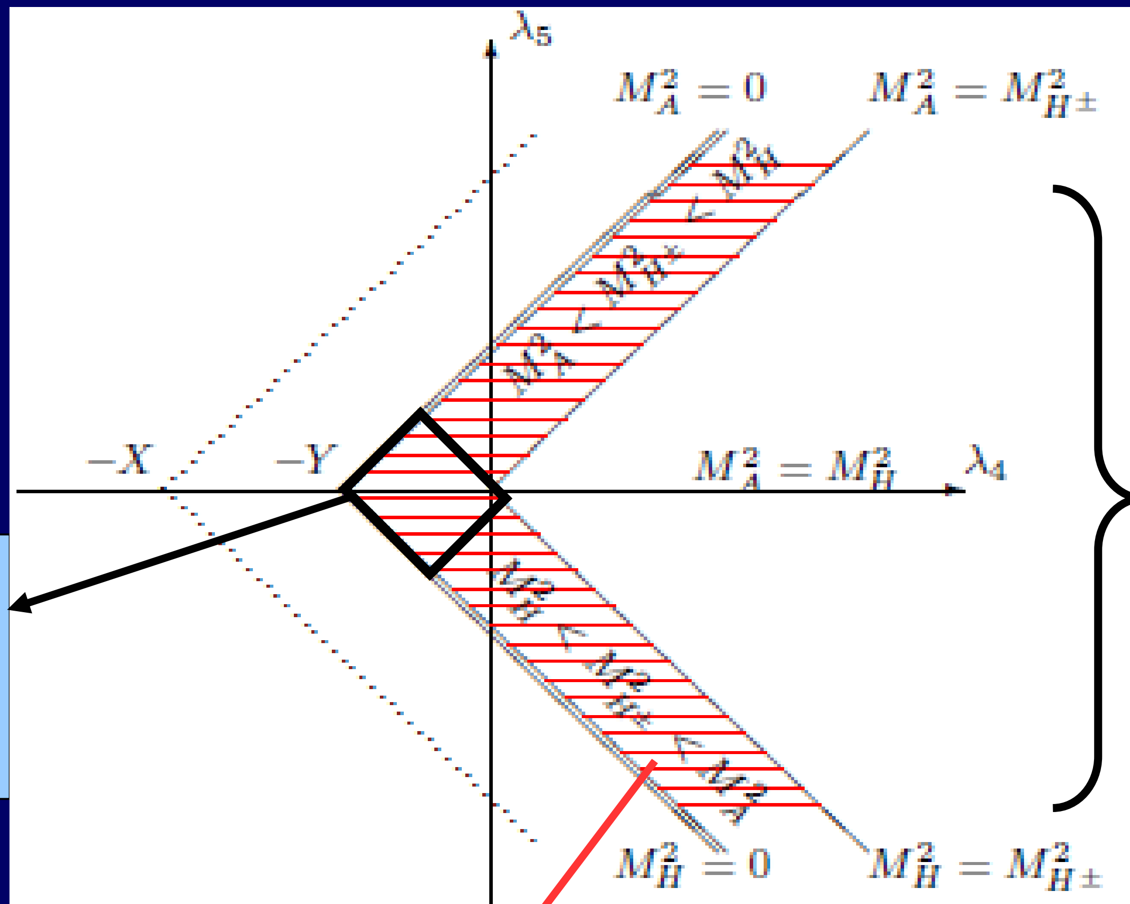
  no DV V !

- 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+ is the lightest

here H+ is 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

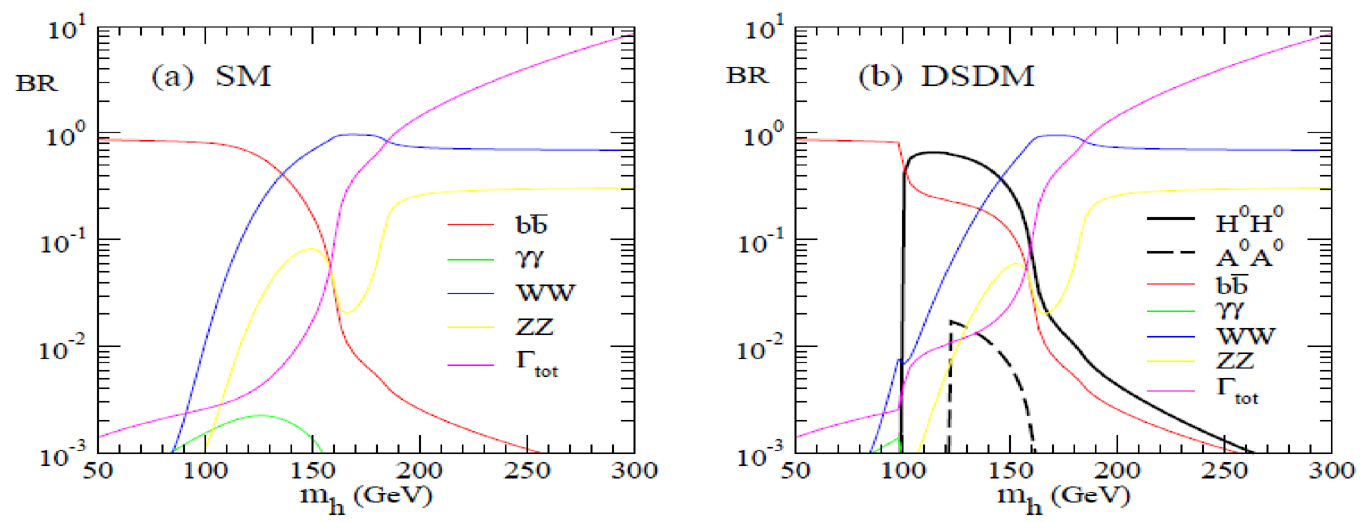
Cao, Ma, Rajasekaren' 2007 for a light h

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

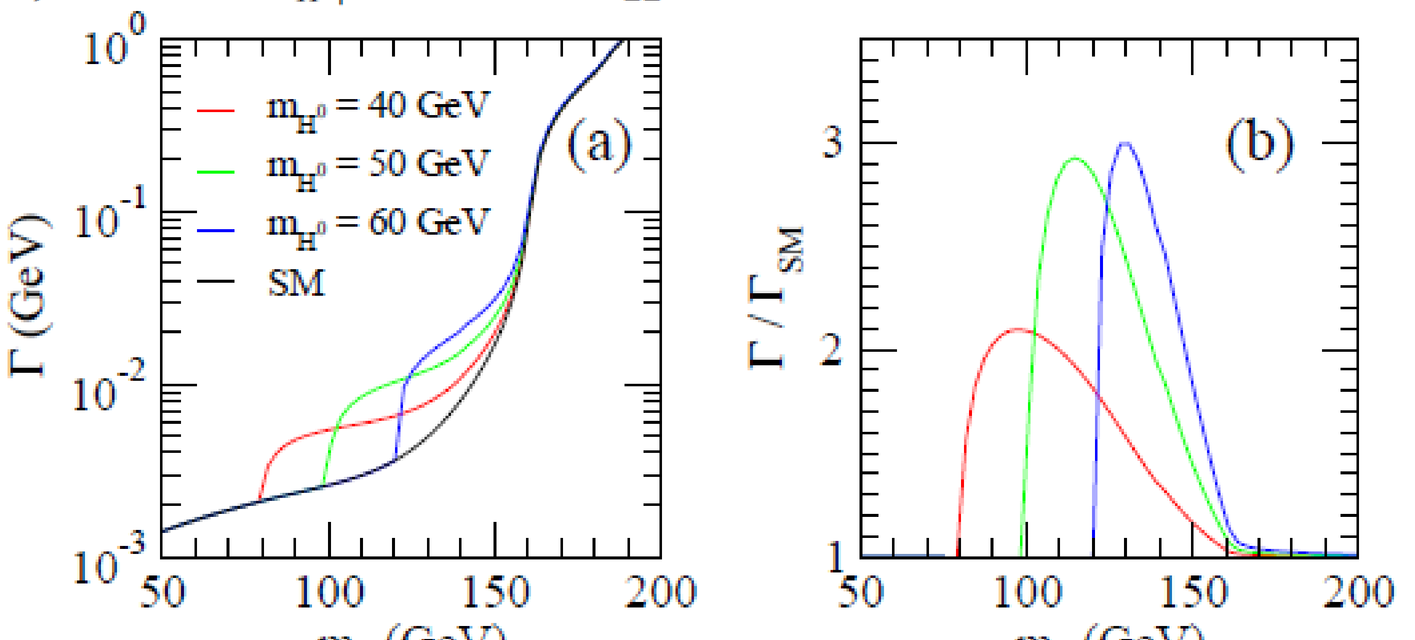
EW precision data: $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

Dark 2HDM – additional decays of h

Ma..‘ 2007

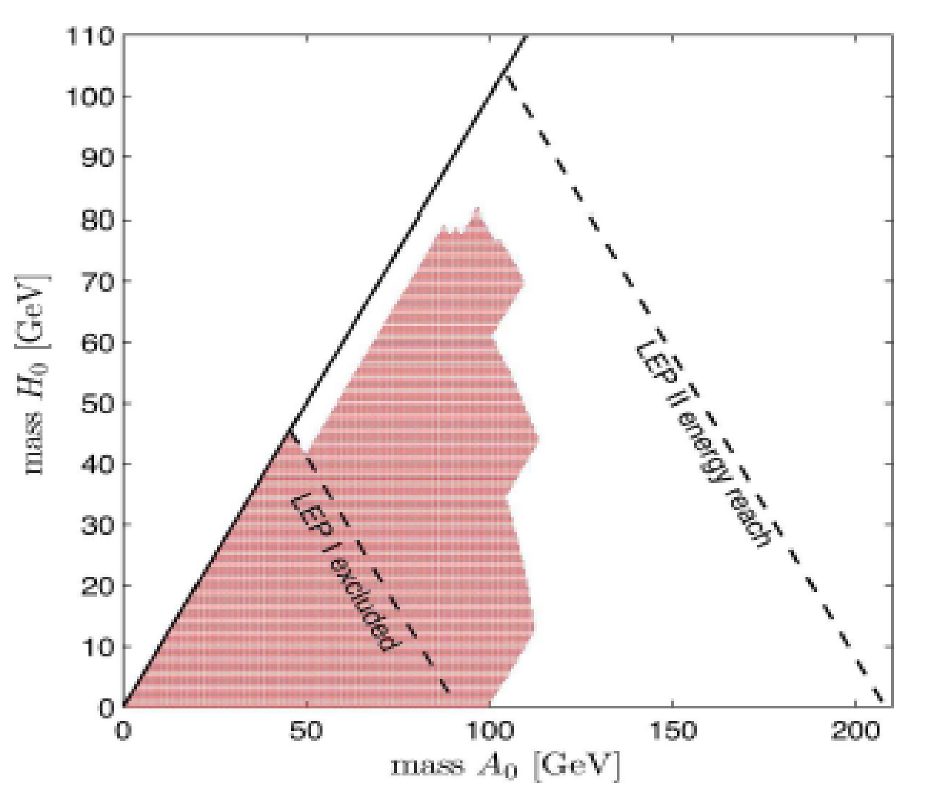


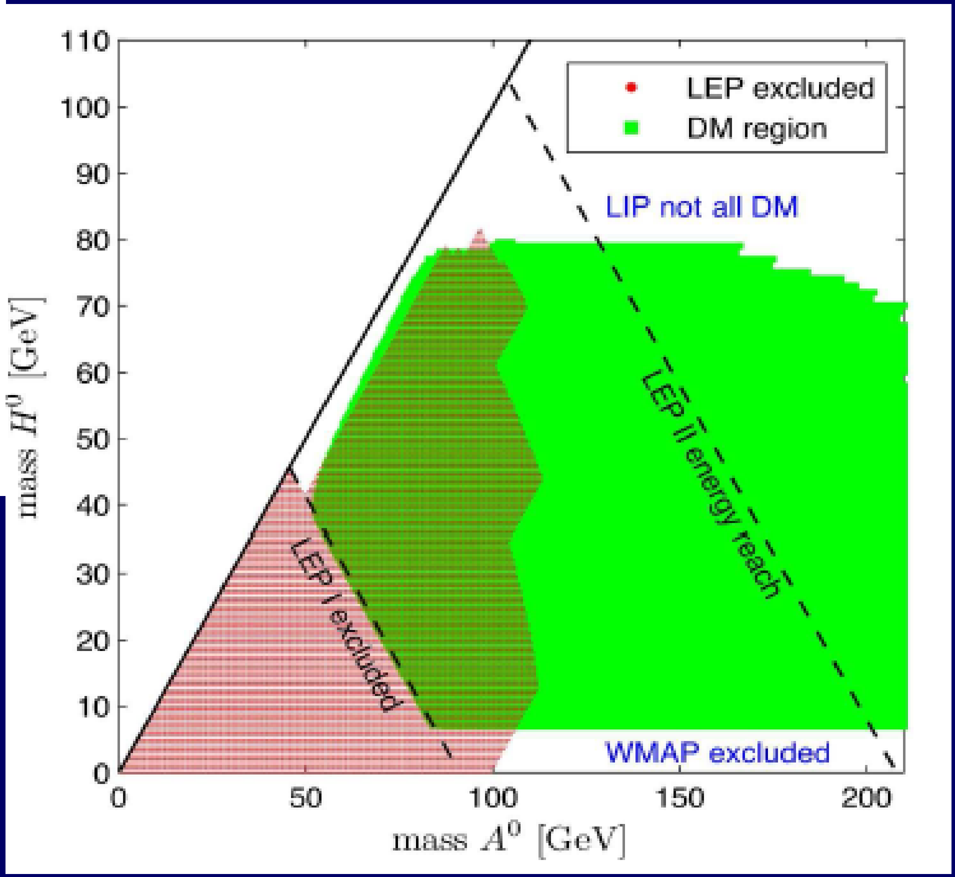
For $M_H = 50$ GeV, $\Delta(A,H)$=10 GeV, M_{H+}=170 GeV, m_{22}=20 GeV



Dark 2HDM: LEP II exclusion

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

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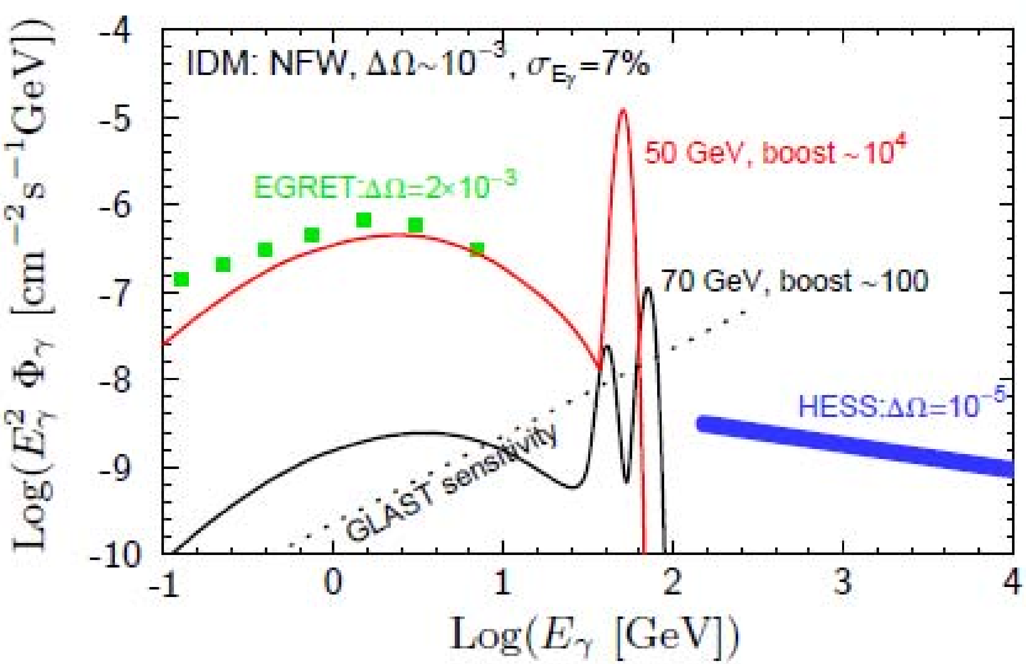
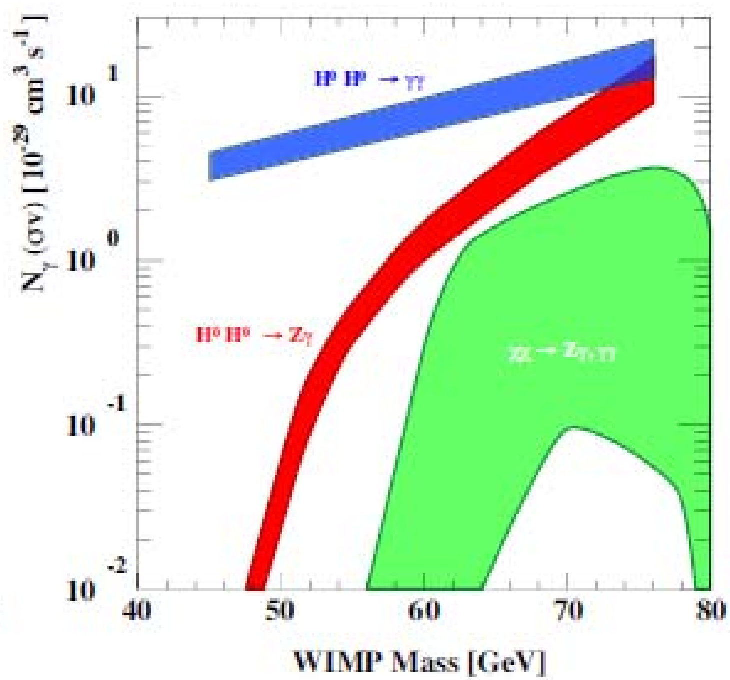
Significant Gamma Lines from Inert Doublet Model

Gustafsson,Lundstrom,Bergstrom,Edsjo' 2007 studied direct annihilation of HH into $\gamma\gamma$ and $Z\gamma$ for M_H between 40-80 GeV (loop process, energy below WW threshold).





Conclusion on gamma lines

- 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 archetype of WIMP – within reach of GLAST*

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

- September 2009 → waiting on FERMI results

Evolution of the Universe – different vacua in the past ?

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

Useful parametrization with k and δ

$$\lambda_2/\lambda_1 = k^4, \quad m_{11}^2 = m^2(1-\delta), \quad m_{22}^2 = k^2 m^2(1+\delta)$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad \tilde{\lambda}_{345} = \lambda_3 + \lambda_4 - \lambda_5.$$

$$\Lambda_{345\pm} = \sqrt{\lambda_1\lambda_2} \pm \lambda_{345}, \quad \tilde{\Lambda}_{345\pm} = \sqrt{\lambda_1\lambda_2} \pm \tilde{\lambda}_{345}, \quad \Lambda_{3\pm} = \sqrt{\lambda_1\lambda_2} \pm \lambda_3.$$

Yukawa interaction – Model I →

all fermions couple only to Φ_1

Possible vacua:

Ch } u≠0

$$v_1^2 = \frac{m^2 k^2}{2}\left(\frac{1}{\Lambda_{3+}} - \frac{\delta}{\lambda_{3-}}\right), \; v_2 = 0, \quad u^2 = \frac{m^2}{2}\left(\frac{1}{\Lambda_{3+}} + \frac{\delta}{\lambda_{3-}}\right)$$

$$\mathcal{E}_{ch} = -\frac{m^4 k^2}{8}\left(\frac{1}{\Lambda_{3+}} + \frac{\delta^2}{\Lambda_{3-}}\right)$$

Inert, B, N } u=0

Inert:

$$v_2 = 0, \; v^2 = v_1^2 = \frac{m^2(1-\delta)}{\lambda_1}, \quad \mathcal{E}_A = -\frac{m^4(1-\delta)^2}{8\lambda_1}$$

B:

$$v_1 = 0, \; v^2 = v_2^2 = \frac{m^2(1+\delta)}{k^2\lambda_1}, \quad \mathcal{E}_B = -\frac{m^4(1+\delta)^2}{8\lambda_1}$$

N:

$$v_1^2 = \frac{m^2 k^2}{2}\left(\frac{1}{\Lambda_{345+}} - \frac{\delta}{\Lambda_{345-}}\right), \; v_2^2 = \frac{m^2}{2}\left(\frac{1}{\Lambda_{345+}} + \frac{\delta}{\Lambda_{345-}}\right),$$

$$\mathcal{E}_C = -\frac{k^2 m^4}{4}\left(\frac{1}{\Lambda_{345+}} + \frac{\delta^2}{\Lambda_{345-}}\right)$$

Depending on value of δ →

a true vacuum (with the minimal energy)

Depending on δ → a true vacuum

$$\mathcal{E}_I - \mathcal{E}_N = \frac{m^4}{8}\,\frac{(\Lambda_{345-} + \delta\Lambda_{345+})^2}{\lambda_1 \Lambda_{345-}\Lambda_{345+}}, \quad \mathcal{E}_I - \mathcal{E}_{Ch} = \frac{m^4}{8}\,\frac{(\Lambda_{3-} + \delta\Lambda_{3+})^2}{\lambda_1 \Lambda_{3-}\Lambda_{3+}}$$

$$\mathcal{E}_N - \mathcal{E}_{Ch} = \frac{k^2 m^2}{4}\lambda_{45}\left[\frac{1}{\Lambda_{3+}\Lambda_{345+}} - \frac{\delta^2}{\Lambda_{3-}\Lambda_{345-}}\right], \quad \mathcal{E}_I - \mathcal{E}_B = \frac{m^4\delta}{2\lambda_1}.$$

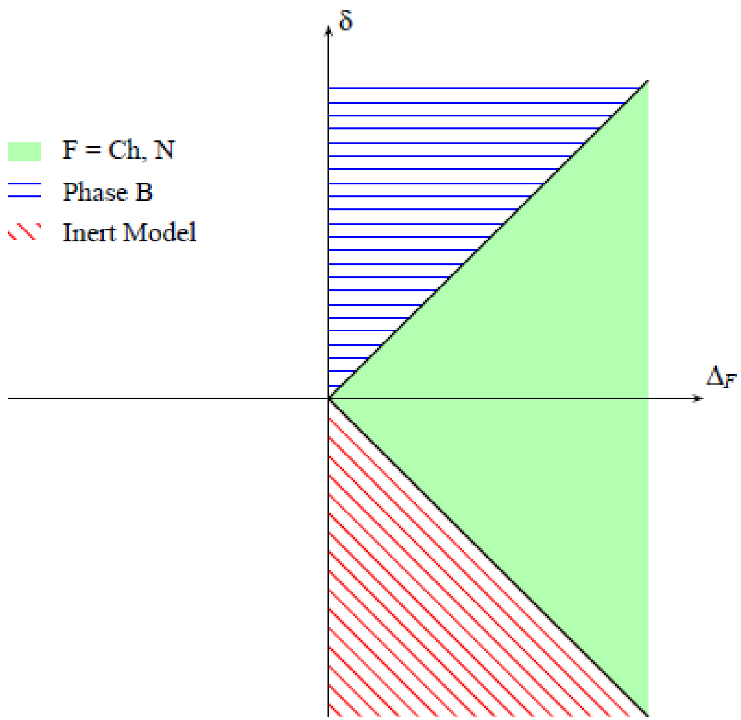
For Ch

$$\Delta_{Ch} = \Lambda_{3-}/\Lambda_{3+} > 0$$

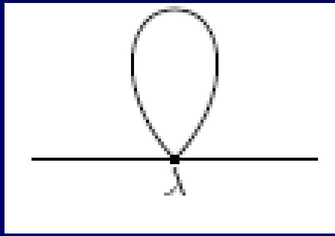
For N

$$\Delta_N = \Lambda_{345-}/\Lambda_{345+} > 0$$

So, if δ change with time?



Termal corrections of parameters



Matsubara method (temperature T>> m^2) –

-only quadratic (mass) parameters change with T

$$m_{11}^2(T) = m_{11}^2(0) - 2c_1 m^2 w, \quad m_{22}^2(T) = m_{22}^2(0) - 2c_2 m^2 w$$

$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{2}, \quad c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{2}, \quad w = \frac{T^2}{12m^2}$$

$$c_1, c_2 > 0$$

$$m(T=0) \equiv m, \delta(0) \equiv \delta$$

$$m^2(T) = m^2(1 - (c_2 + c_1)w)$$

$$\delta(T) = \frac{m^2}{m^2(T)}\left(\delta - \frac{c_2 - c_1}{c_2 + c_1}\right) + \frac{c_2 - c_1}{c_2 + c_1}$$

$m_{11}^2(T)$, $m_{22}^2(T)$ ↓ with T ↓ → different phases

Extrema:

- In the EW symmetry vacuum, both m^2_{11} (T) , m^2_{22}(T)<0

  Both mass parameter grow with time t

- In the Inert extremum condition: $m^2_{11} = \lambda_1 v^2$, so $m^2_{11} > 0$

- B extremum condition: $m^2_{22} = \lambda_2 v^2 > 0$, so $m^2_{22} > 0$

Since m^2_{11} (T), m^2_{22}(T) are monotonic functions of T (T^2)

→ if Inert (or B) was an extremum in the past then m^2_{11} (T) (or m^2_{22}(T)) positive for the rest of the evolution

- What happened next, depends on other parameters

Phase transitions from the EW symmetric phase

[redacted] $\Lambda_{3-} > 0,\ \lambda_4 + \lambda_5 > 0$ $\delta(T_{Ch\pm}) = \pm\Delta_{Ch}$

Two second order phase transitions:

$\text{EW} \xrightarrow{II} \text{Phase B} \xrightarrow{II} \text{Charged phase} \xrightarrow{II} \text{Inert phase}$

[redacted] $\Lambda_{345-} > 0,\ \lambda_4 + \lambda_5 < 0$ $\delta(T_{N\pm}) = \pm\Delta_N$

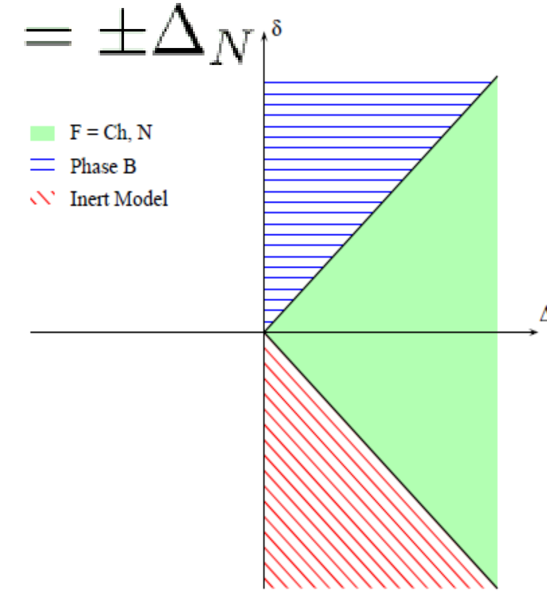
Two second order phase transitions:

$\text{EW} \xrightarrow{II} \text{Phase B} \xrightarrow{II} \text{Phase N} \xrightarrow{II} \text{Inert phase}$

[redacted]

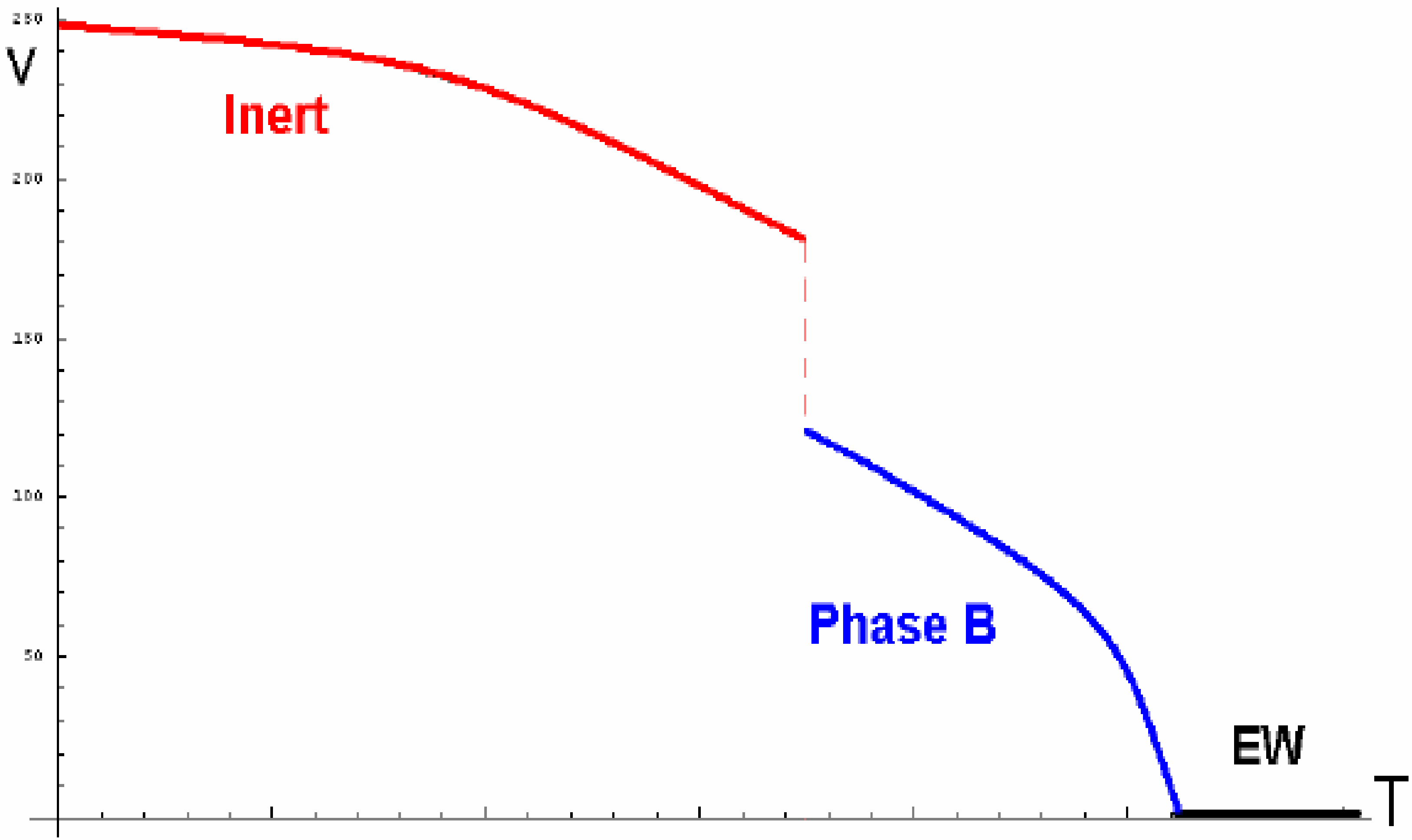
First order phase transition:

$\text{EW} \xrightarrow{II} \text{Phase B} \xrightarrow{I} \text{Inert phase}$



to the present INERT phase

EW – B – I: an example



Conclusions

- Rich content of 2HDMs
- Intert Model in agreement with present data – soon tests at FERMI and LHC
- What was in the Past?

  - EW $\xrightarrow{II}$ Phase B $\xrightarrow{I}$ Inert phase
  - EW $\xrightarrow{II}$ Phase B $\xrightarrow{II}$ Phase N $\xrightarrow{II}$ Inert phase
  - EW $\xrightarrow{II}$ Phase B $\xrightarrow{II}$ Charged phase $\xrightarrow{II}$ Inert phase
  - EW $\xrightarrow{II}$ Inert phase

excluded if DM neutral !

- Various scenarios
- Can we find clear signals ?

B-Inert is the 1st order phase transition –discontinuities

It is possible not to have DM at high temperature

Model I for N, Inert, B phase

- For the N Phase (α – mixing angle, χ – relative coupling)
  - Interaction with fermions:

$$\chi_t^{H^0} \; : \; \frac{\sin\alpha}{\sin\beta} \; ; \; \chi_b^{H^0} \; : \; \frac{\sin\alpha}{\sin\beta} \; ; \; \chi_t^{h^0} \; : \; \frac{\cos\alpha}{\sin\beta} \; ; \; \chi_b^{h^0} \; : \; \frac{\cos\alpha}{\sin\beta}$$

$$\chi_t^{A^0} \; : \; -i\gamma_5 \cot\beta \; ; \; \chi_b^{A^0} : i\gamma_5 \cot\beta$$

  - Interaction with gauge bosons

$$\chi_h^V = \cos\alpha, \qquad \chi_H^V = \sin\alpha, \qquad \chi_A^V = 0.$$

- For the Inert Model:
  - Dark scalars from φ_2 do not interact with fermions
  - They have no triple interactions with gauge bosons $H_i V_1 V_2$, but there are vertices $H_i H_j V$ and $H_i H_j V_1 V_2$
  - h from φ_1 interacts with fermions and gauge bosons like SM Higgs boson

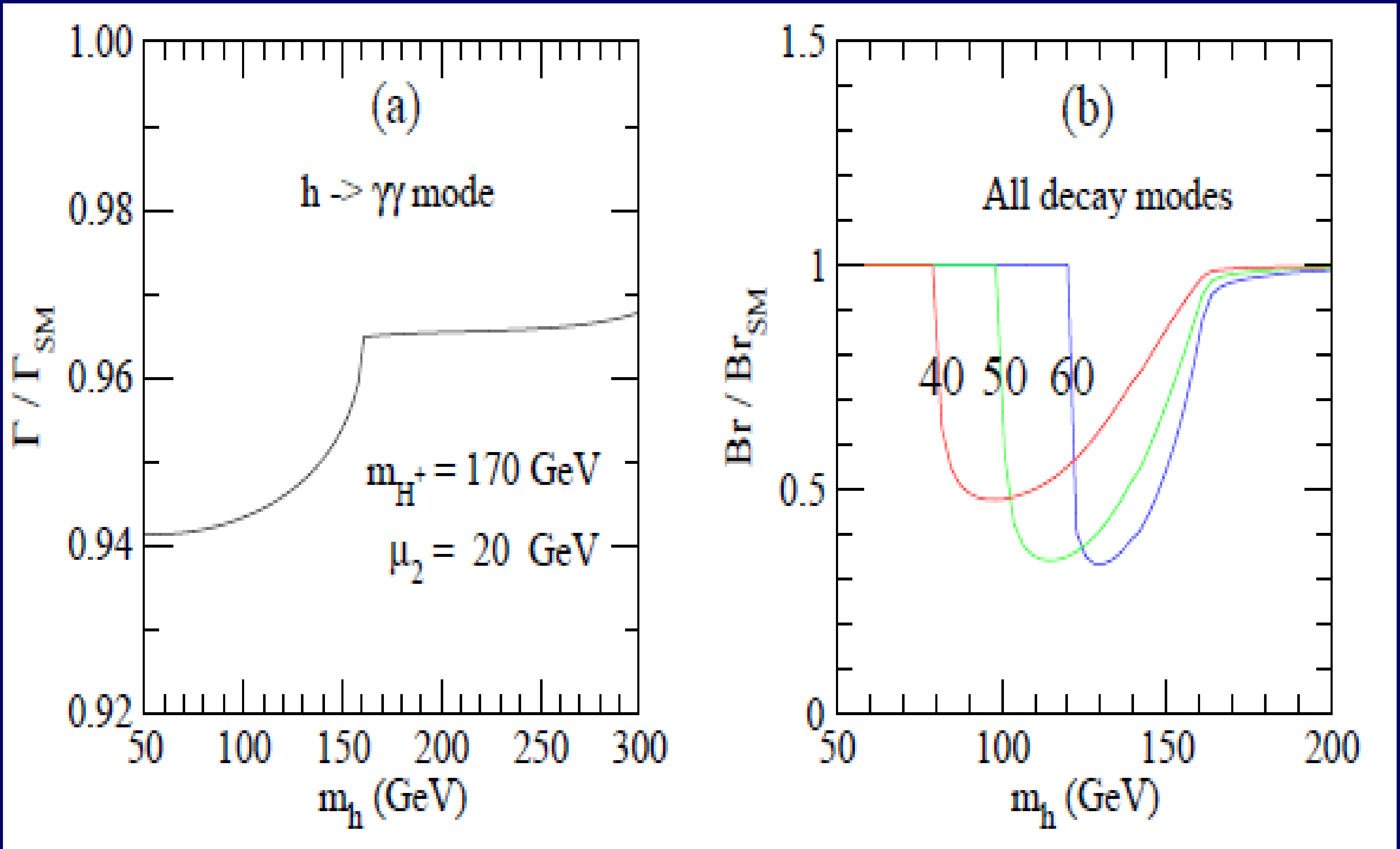
Collider reach @ LHC

S = H (DM)

$pp \to SA \to SSZ^{(*)} \to SSl^+l^-$

	m_S	(δ_1, δ_2)	S	B	S/B	S/√(B)
	GeV	GeV	fb	fb	L=100 fb^{-1}	
LH1	40	(100,100)	3.68	102.18	0.04	3.64
LH2	40	(70,70)	0.97	0.88	1.11	10.37
LH3	82	(50,50)	0.19	0.47	0.40	2.75
LH4	73	(10,50)	0.22	0.47	0.47	3.23
LH5	79	(50,10)	0.33	0.30	0.09	0.52
HH1	76	(250,100)	0.69	27.17	0.03	1.33
HH2	76	(200,30)	1.22	27.65	0.04	2.32

Dark 2HDM: $\gamma\gamma$h



2HDM: old idea and recent progress

- T.D. Lee 1973 – mainly for spontaneous CP violation
- Rich phenomenology ....
- 2004-2009: deeper understanding of V using symmetry (reparametrization freedom or is tan β a physical parameter?, condition for CP conservation, vacuum states)- *Haber, Gunion; Ginzburg, MK; Nishi, Nachtmann, Maniatis, Manteiffel, Ivanov, Kanishev, Sokołowska, Barroso, Santos, Ferreira, Silva, Botella, Lavoura, Branco, Rebelo, Grimus, Osland, Vives...*
- *2006-9* Dark matter: *Ma, Barbieri;*
  Evolution of the Universe: *Ginzburg, Ivanov, Kanishev, MK, Sokołowska*

New analyses for LHC, ILC, PLC
Constraints from Flavour data
Generators for 2HDM