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Evolution of the Universe to the present Inert Phase (Dark)

2HDMs

Today: Intert Model

In the Past?

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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.
See eg. CP Study and the Nonstandard Higgs Workshop 2002-2006
(CERN Report hep-ph/0608079)

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 ($\rho = 1$) , no mass for photon

Fermion masses via Yukawa interaction

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

mass ↔ selfinteraction unknown

couplings to WW/ZZ, Yukawa couplings to fermions

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 (ρ =1), no mass for photon?

Fermion masses via Yukawa interaction –

various models – Model I, II, III, IV...

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,Weinberg,Branco,Rebelo,Lavoura,Ferreira,Barroso, Santos,Silva,Diaz-Cruz,Grimus, Ecker, Ivanov,Ginzburg, Osland, Nishi, Nachtamnn, 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: $\Phi_1 \to \Phi_1$ $\Phi_2 \to -\Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term

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→
  no CP violation in the scalar sector *Branco, Rebelo*
- Softly broken → *Weinberg,Paschos*
  CP violation possible, tree-level FCNC absent
- Hard breaking →
  CP violation possible, even without CP mixing (*)
  tree-level FCNC danger

Ma'78

Today

Z_2 symmetry both <u>in L and in vacuum</u> – Inert Model

doublet Φ_1 as in SM, with Higgs boson h SM-like,

4 scalars from Φ_2 with Z_2-odd parity (dark scalars)

The lightest dark scalar candidate for a dark matter

Possible vacuum states

(parameters in V- real)

The most general vacuum state

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

with v_1, v_2, u , ξ - real, positive

For the Inert vacuum $u = v_2 = 0$, $v = v_1$

For the CP conserving CPc $u = \xi = 0$

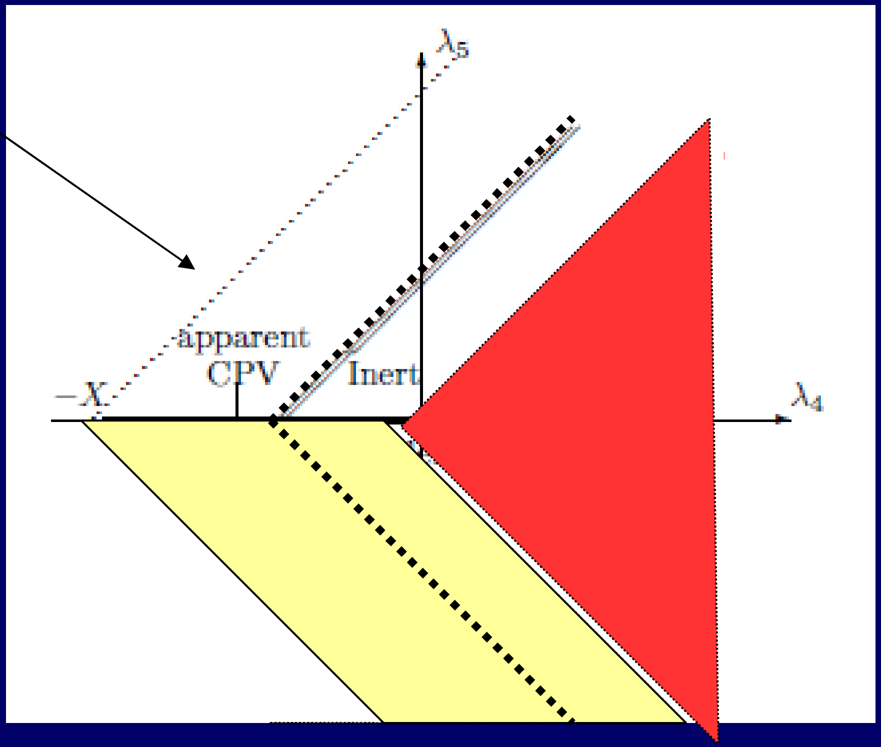
For the Charge Breaking ChB $v_2 = \xi = 0$

Various vacua on λ_5 x λ_4 plane for V with an explicit Z_2 symmetry

Positivity constrains on V:

$X=\sqrt{\lambda_1\lambda_2}+\lambda_3>0$

$\lambda_4 \pm \lambda_5 > -X$

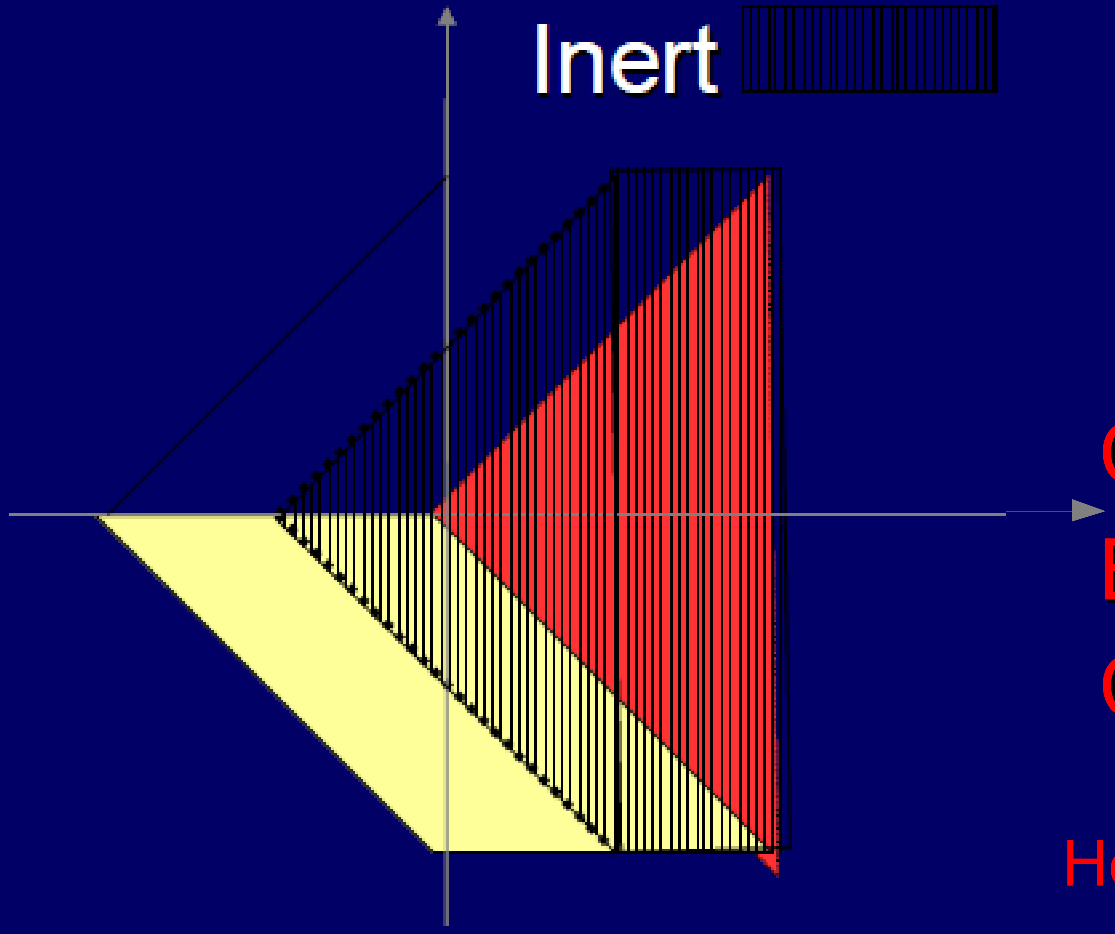


Charge Breaking

ChB

CP conserving – CPc

Various vacua on $\lambda_5 \times \lambda_4$ plane



Inert ▥

Charge Breaking

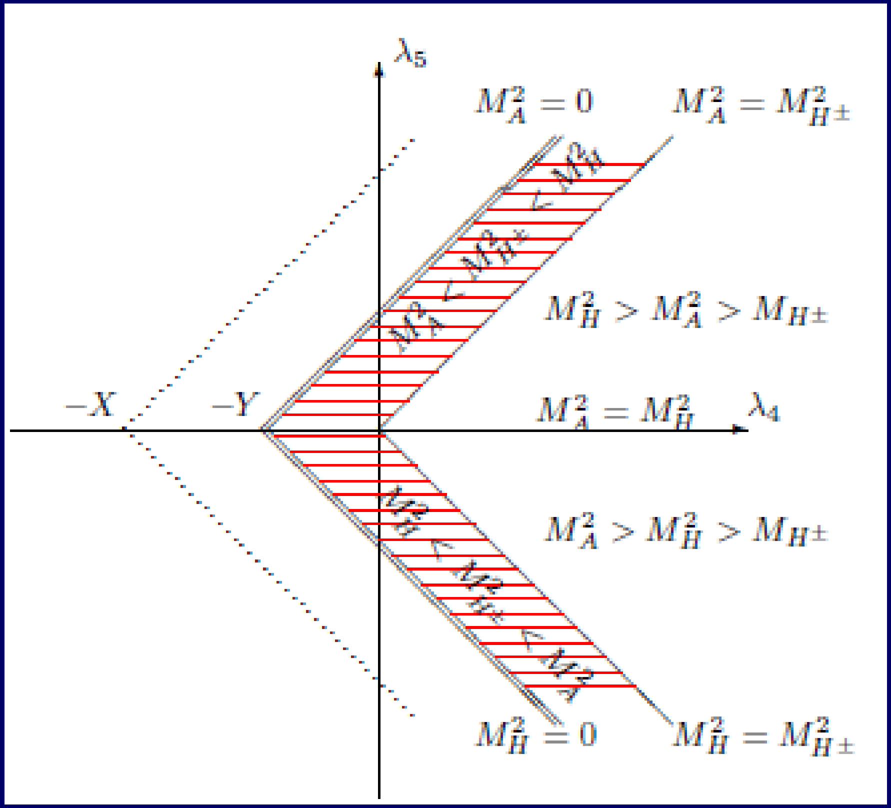
ChB

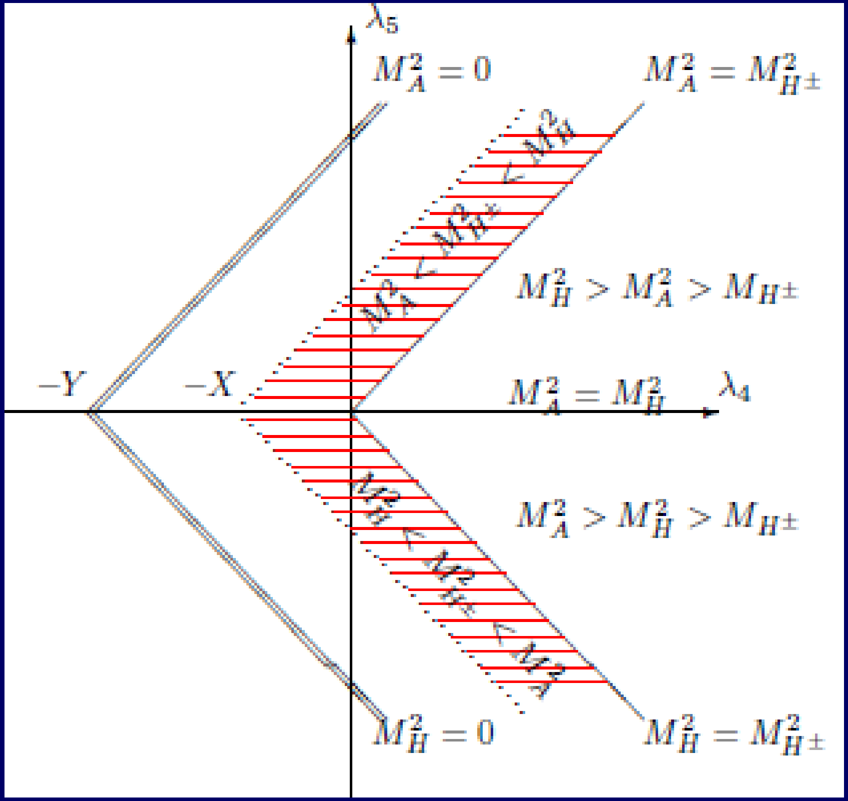
Here $\sqrt{\lambda_1 \lambda_2} - \lambda_3 > 0$

CP conserving – CPc

Intert Model – dark scalar masses

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





If H is the dark matter candidate

$$\rightarrow \lambda_5 < 0$$

Inert Model (Dark 2HDM) vs data

Ma..' 78, Barbieri.. ' 2006

Exact Z_2 symmetry in L and in vacuum →

Z_2 parity: odd is only Φ_2

Φ_1

- Nonzero vev only doublet Φ_1 (Higgs doublet) only it couples to fermions (Model I)
- Higgs boson h SM-like: $M^2_h = m_{11}^2 = \lambda_1 v^2$

Φ_2

- Zero vev for Φ_2 (scalar doublet) and no Yukawa int. i
- Four scalars with Z_2 - odd parity (dark scalars D)
- The lightest dark scalar -a candidate for dark matter

Dark scalars

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

Testing Inert Model

- Since only dark scalars have odd Z_2-parity

  -they can be produced only in pairs

  -the lightest dark particle – a suitable DM

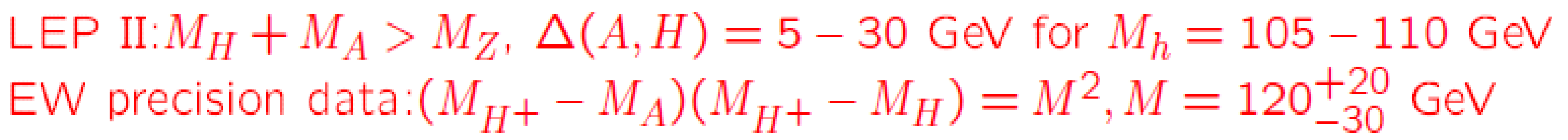
- The strategy to test such model for <u>light h</u>

  (Barbieri et al '2006 heavy h)

  -consider properties of SM-like h and look for deviations

  -consider properties of dark scalars, especially DM candidate

- Cao, Ma, Rajasekaren' 2007: colliders signal/constraints

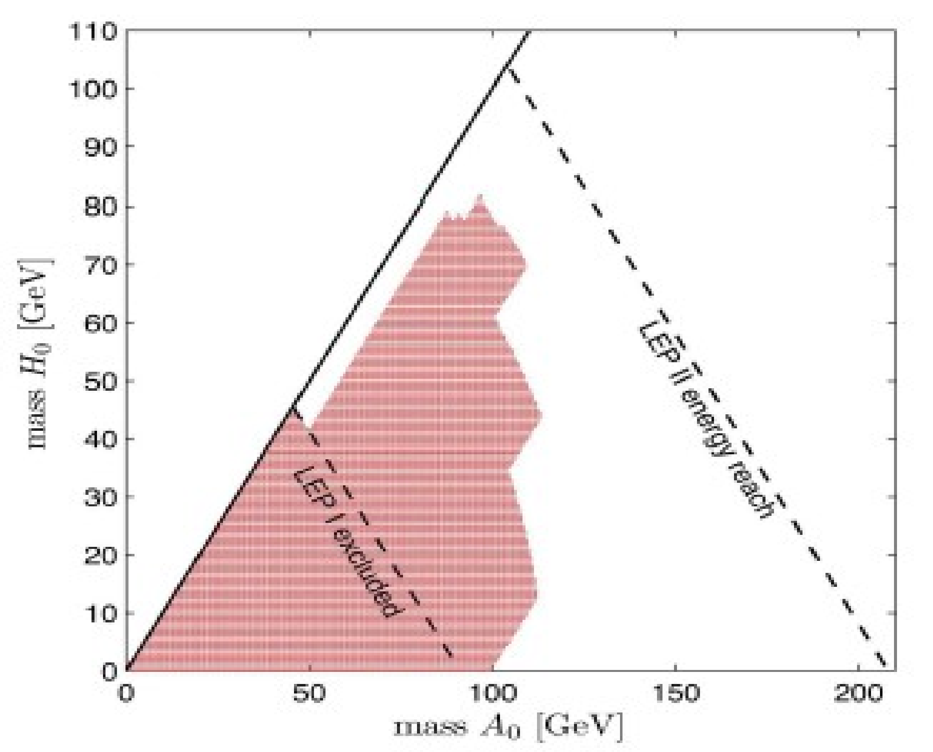


LEP II: $M_H + M_A > M_Z$, $\Delta(A,H) = 5 - 30$ GeV for $M_h = 105 - 110$ GeV

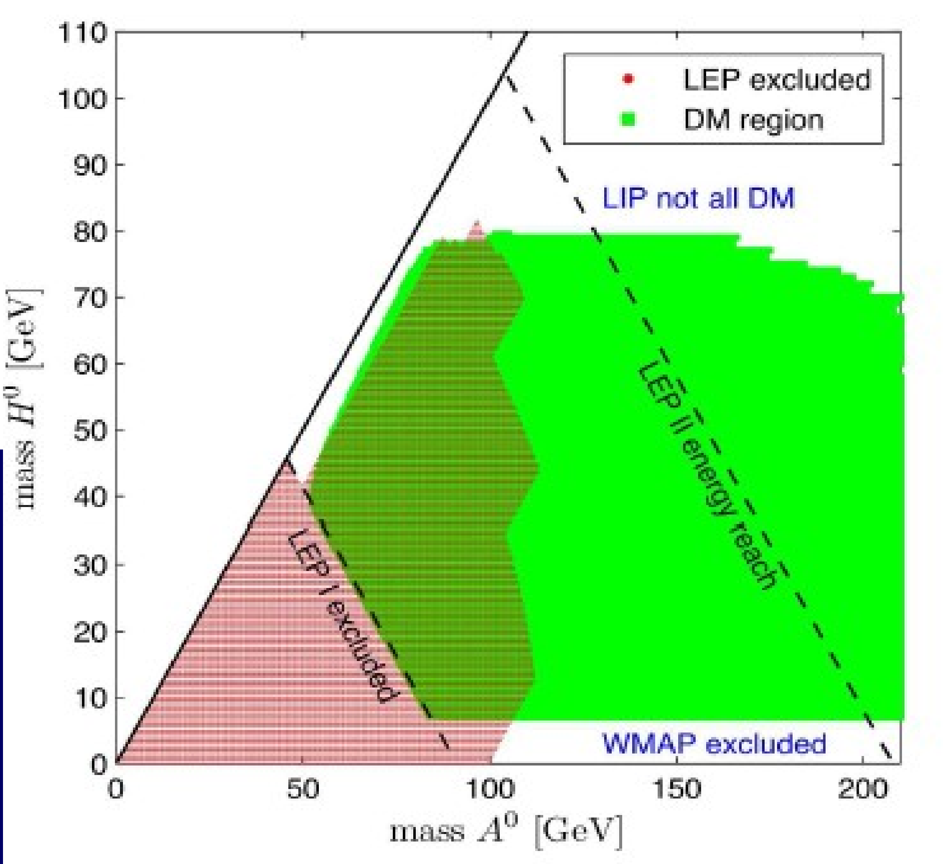
EW precision data: $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

Dark 2HDM: LEP II exclusion

Lundstrom et al 0810.3924



$M_A - M_H = 8$ GeV



LEP II + WIMP

$M_h = 200$ GeV

Evolution of Universe – different vacua in the past ?

We consider 2HDM with an explicit Z_2 symmetry

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:

ChB

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

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

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(CPc)

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

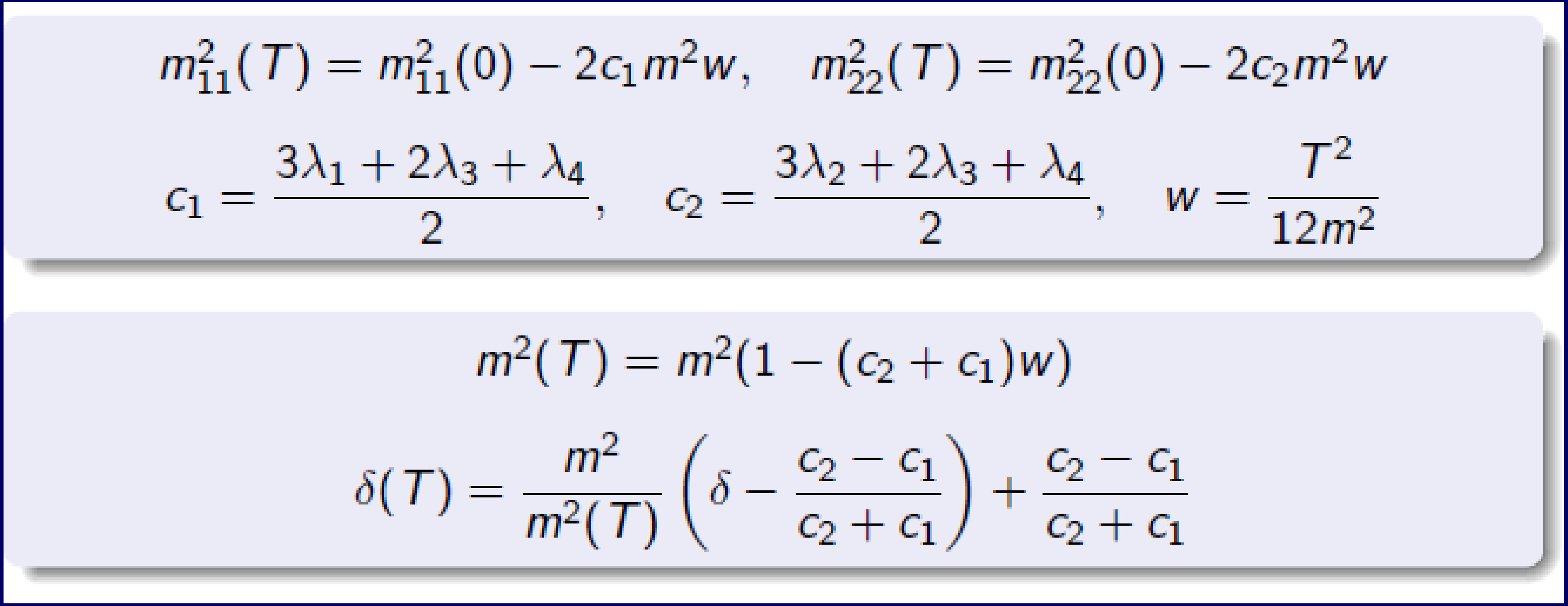
$$\mathcal{E}_C = -\frac{k^2m^4}{4}\left(\frac{1}{\Lambda_{345+}} + \frac{\delta^2}{\Lambda_{345-}}\right)$$

Depending on value of δ → a true vacuum, ie. the one with the minimal energy

Termal evolution of parameters

Matsubara method (T>> m^2) –

only quadratic parameters change with T



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

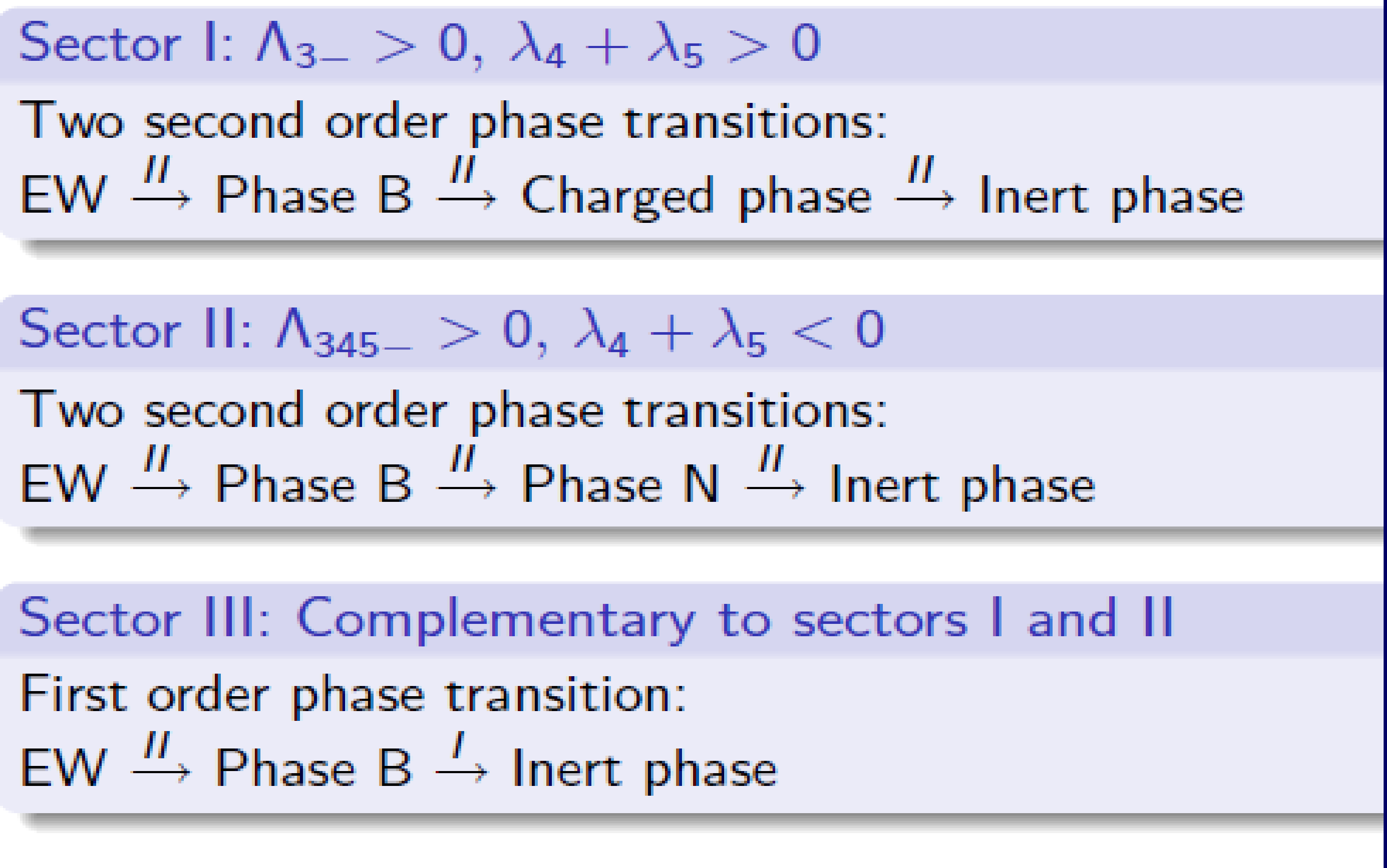
$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{2}, \quad c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{2}, \quad w = \frac{T^2}{12m^2}$$

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

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

δ evolves possibly passing diffrent phases

Phase transitions from the EW phase



Sector I: $\Lambda_{3-} > 0,\ \lambda_4 + \lambda_5 > 0$

Two second order phase transitions:

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

Sector II: $\Lambda_{345-} > 0,\ \lambda_4 + \lambda_5 < 0$

Two second order phase transitions:

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

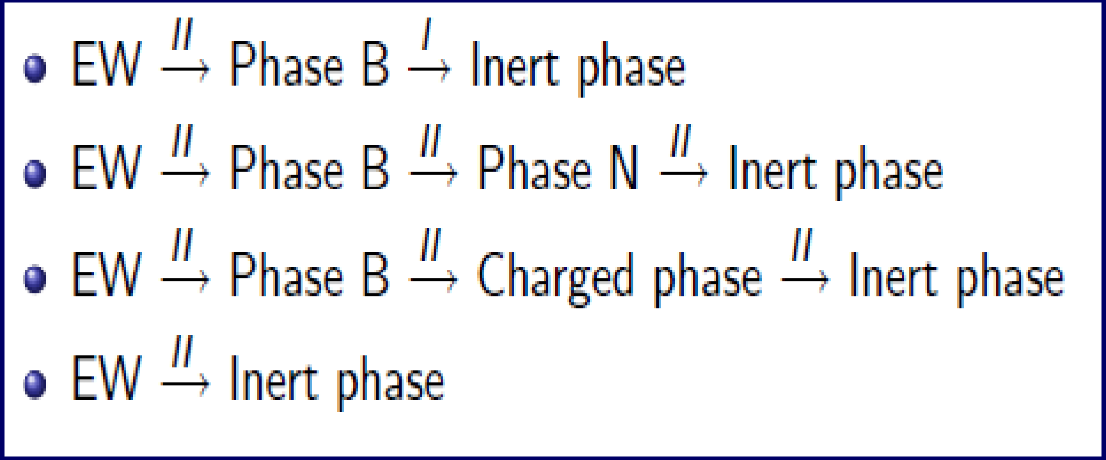
Sector III: Complementary to sectors I and II

First order phase transition:

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

Conclusions

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

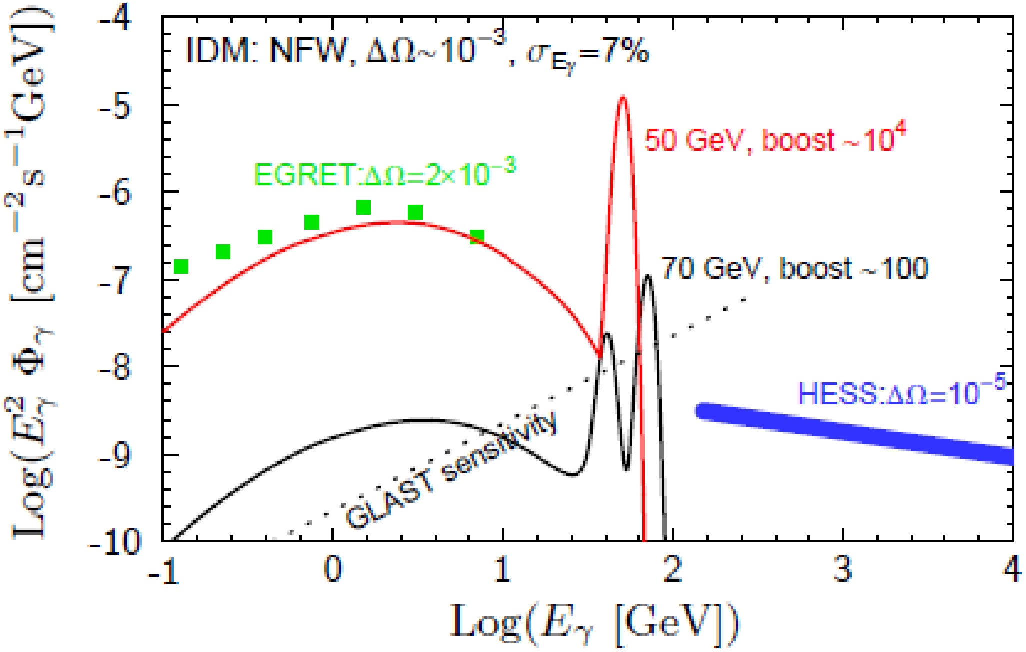


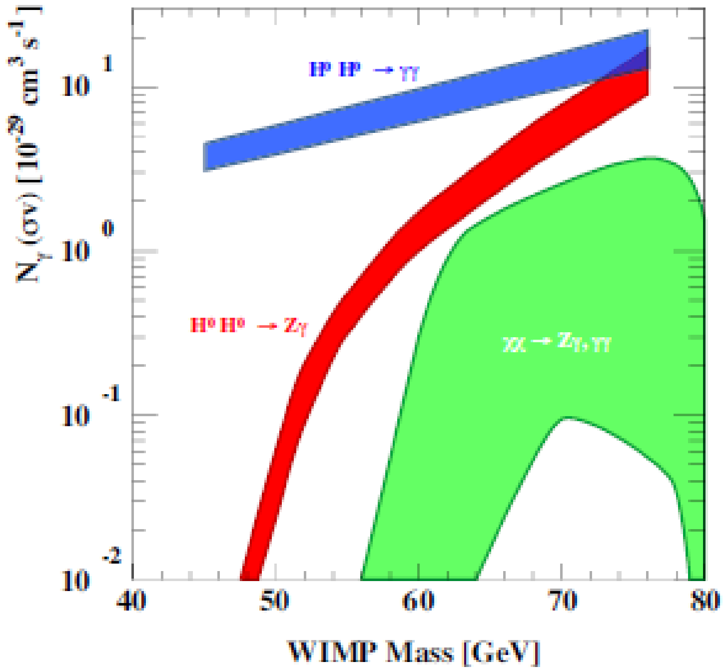
- EW $\xrightarrow{II}$ Phase B $\xrightarrow{I}$ Inert phase
- EW $\xrightarrow{II}$ Phase B $\xrightarrow{II}$ Phase N $\xrightarrow{II}$ Inert phase
- EW $\xrightarrow{II}$ Phase B $\xrightarrow{II}$ Charged phase $\xrightarrow{II}$ Inert phase
- EW $\xrightarrow{II}$ Inert phase

- Various scenarios
- Can we find clear signals ?

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,

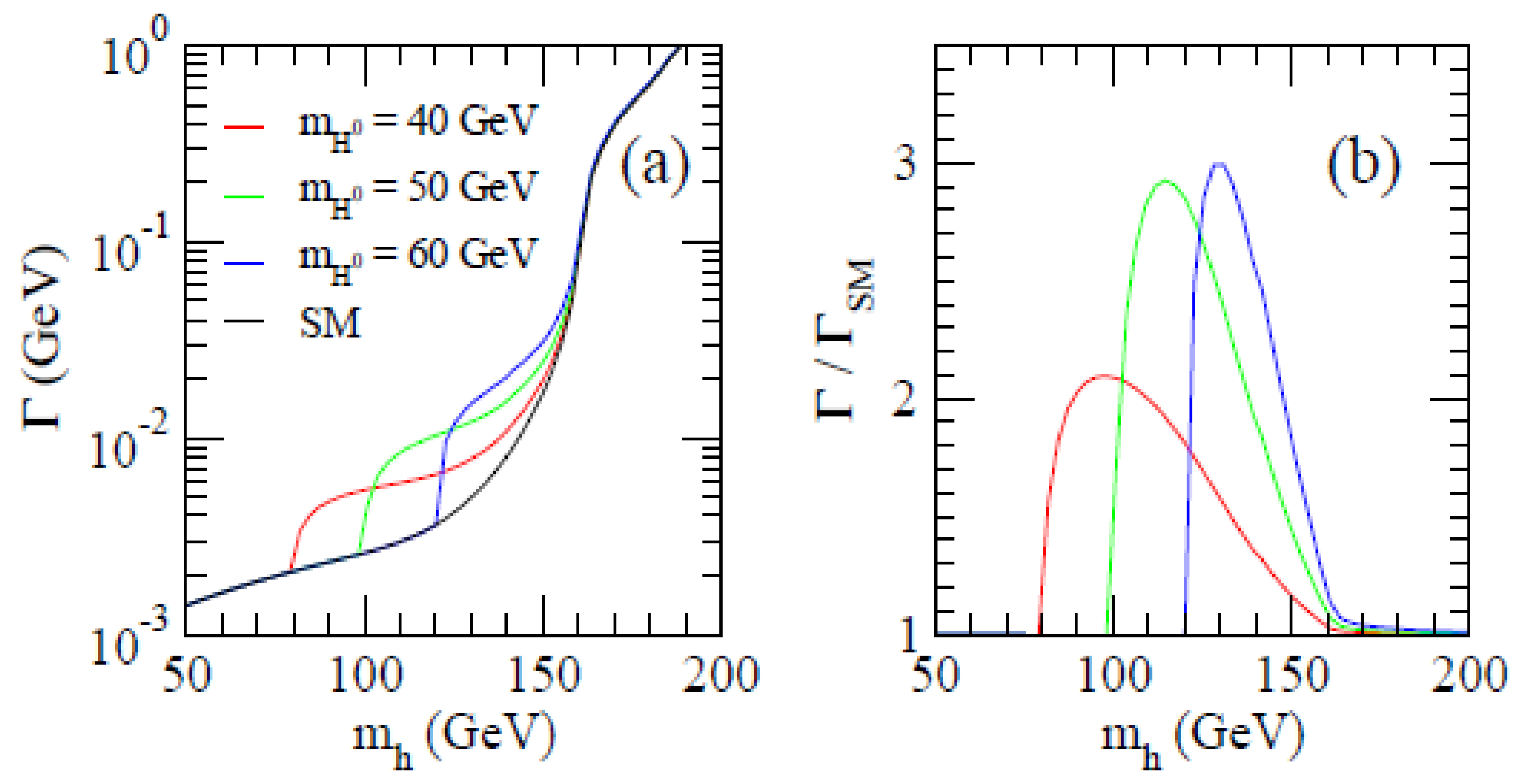
  A = 50-70 GeV, h = 500 and 120 GeV

- Honorez, Nezri, Oliver, Tytgat 2006-7:

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

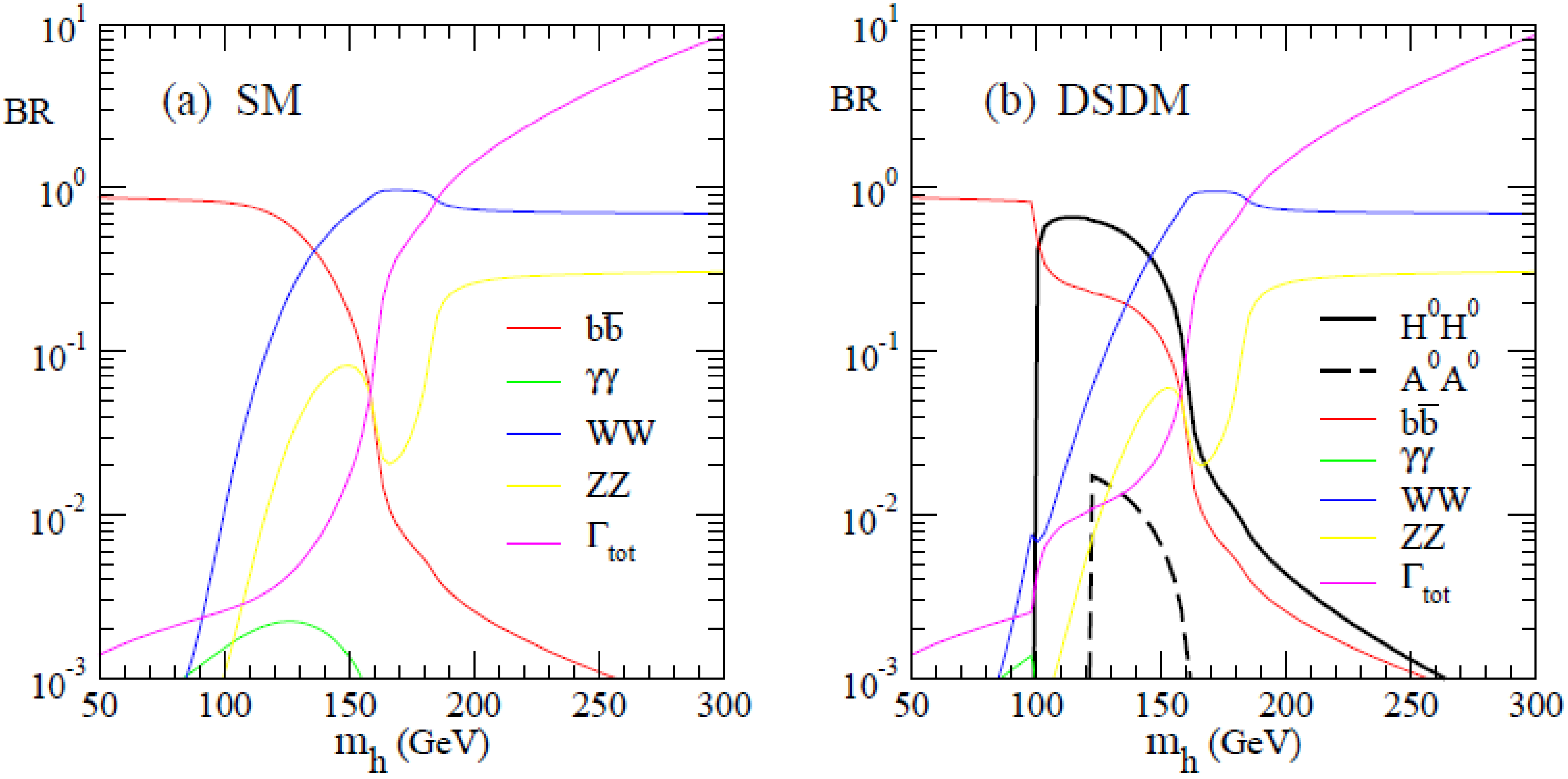
  Here mass of h = 120 GeV, large mass H+ close to A = 400 - 550 GeV

Dark 2HDM – total width of h



Dark 2HDM – additional decays for h

Ma' 2007



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

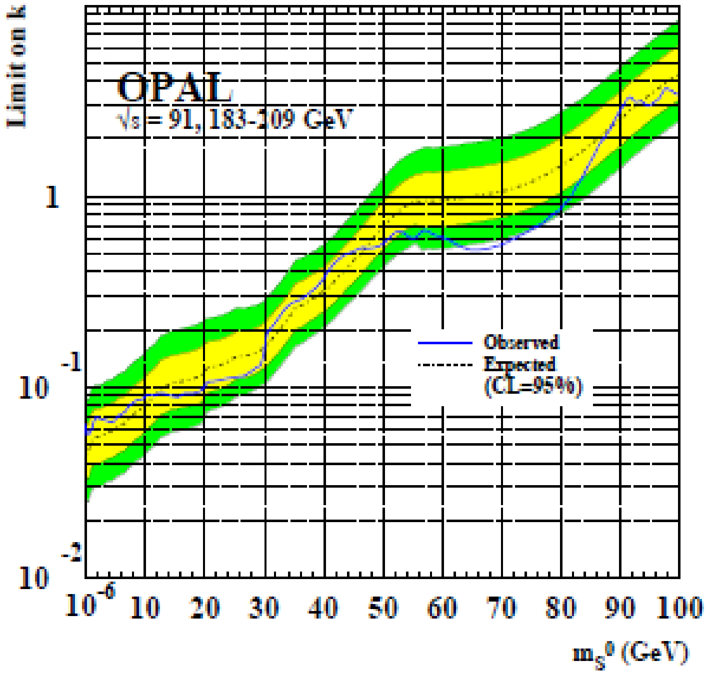
Backup slides

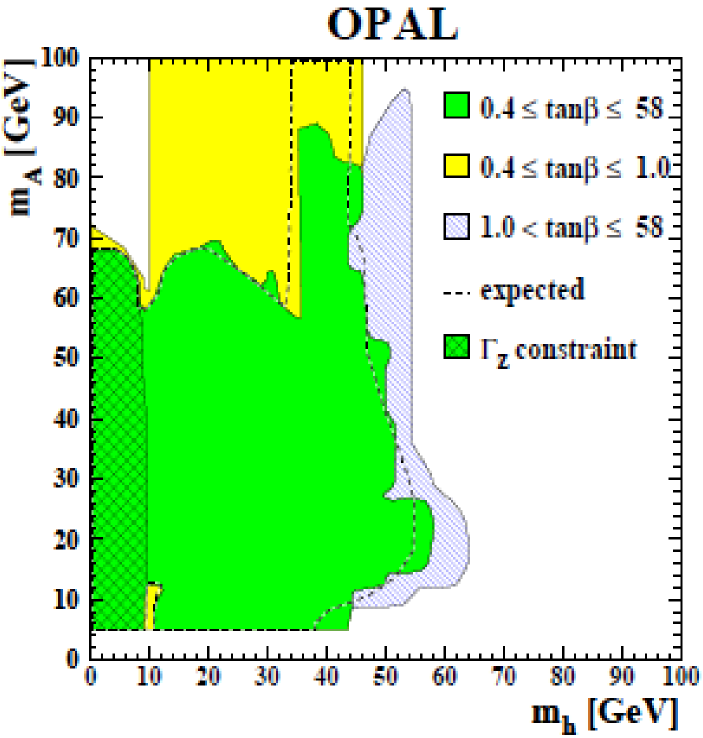
Neutral Higgs bosons - couplings to gauge boson, and mass exclusion

LEP: 2HDM with Z2 symmetry

Light h OR light A in agreement with current data

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





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

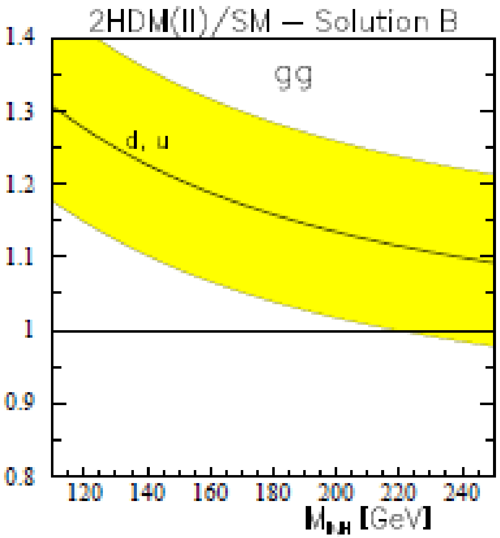
Loop couplings ggh, γγh in 2HDM

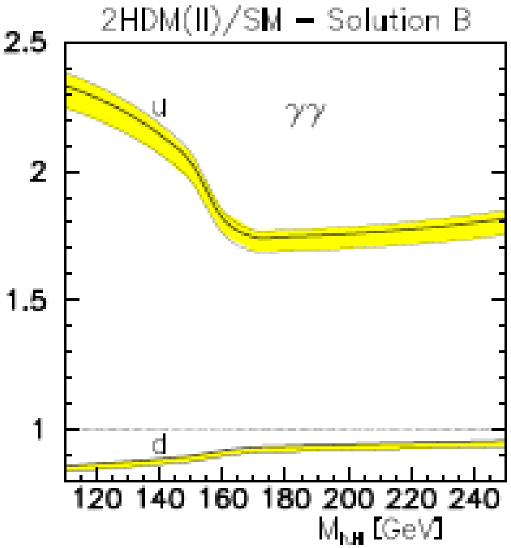
The coupling between neutral and charged Higgs bosons: $h_i H^+ H^-$

γγh

$$\chi_{H^\pm}^{(i)} = \left(1 - \frac{M_i^2}{2M_{H^\pm}^2}\right)\chi_V^{(i)} + \frac{M_i^2 - \nu v^2}{2M_{H^\pm}^2}\mathrm{Re}(\chi_u^{(i)} + \chi_d^{(i)}).$$

For small m_{12}^2...even for χ_V, χ_u, χ_d equal 1, (SM-like scenario A) → large non-decoupling effects due to heavy $H^\pm$. 600 GeV


2HDM(II)/SM – Solution B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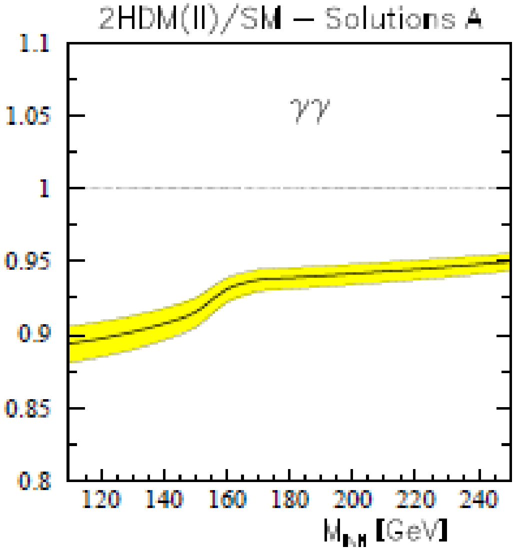
2HDM(II)/SM – Solutions A

ggh - solution B „wrong" signs of fermion couplings

Dark 2HDM: $\gamma\gamma h$