Constraining the Inert Doublet Model

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In this talk:

- Basics of the Two-Higgs-Doublet Model (2HDM)
- Role of Z_2 symmetry
- Constraints on CP conserving 2HDM (II)

- Exact Z_2 symmetry and Inert (Dark) Doublet Model
- Inert Doublet Model: standard Higgs boson and dark scalars
- The lightest dark scalar is stable → a candidate for dark matter
- Constraints - colliders and DM

In collaboration with D. Sokołowska and K. Kanishev

Symmetries of the Two-Higgs-Doublet Model

Two SU(2) doublets of scalar fields, ϕ_1 and ϕ_2, both with $Y = +1$.
Potential:

$$\begin{aligned} V_{2HDM} \quad &= \tfrac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \tfrac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \\ &+\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \tfrac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\ &+\left[(\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2))(\phi_1^\dagger\phi_2) + \text{h.c.}\right]_{hard} \\ &-\tfrac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right]_{soft} + m_{22}^2(\phi_2^\dagger\phi_2)\right\} \end{aligned}$$

In general 14 parameters: (λ_{5-7}, m_{12}^2 complex)
⟶ only **11** independent due to reparametrization freedom

Z_2 transformation $\phi_1 \to -\phi_1$, $\phi_2 \to \phi_2$ ($1 \leftrightarrow 2$);

- Exact Z_2-symmetry in V if $\lambda_6 = \lambda_7 = m_{12}^2 = 0$
- Soft Z_2 breaking is governed by a single parameter Re m_{12}^2

5 physical scalar Higgs particles are expected - 2 charged $H^\pm$

Lee, Veltman,Weinberg, Glashow, Diaz-Cruz, Mendez, Haber, Pomarol, Barroso, Santos, Hollik, Pokorski, Rosiek, Djouadi, Illiana, Branco, Rebelo, Zerwas, Gunion, Grzadkowski, Kalinowski, Akeroyd, Arhrib, Dubnin, Froggatt, Sher, Pilaftsis, Kanemura, Okada, Carena, Davidson, Ginzburg, Osland, Kanishev, Ivanov, Nachtmann, Nishi,...

Symmetries of Two-Higgs-Doublet Model

•2HDM allows for CP violation Lee' 73 and the tree-level flavour-changing-neutral-currents (FCNC)

•CP violation and FCNC can be naturally suppressed by imposing in Lagrangian a Z_2 symmetry, that is the invariance of L under

$$(\phi_1 \to \phi_1, \phi_2 \to -\phi_2) \quad \text{or} \quad (\phi_1 \to -\phi_1, \phi_2 \to \phi_2).$$

In Yukawa int.:eg. $d_R \to -d_R, u_R \to u_R$ and each right-handed fermion couples to only one doublet (Model II) Glashow and Weinberg'77

•Exact Z_2 symmetry - no CP violation, no FCNC at the tree level
Soft Z_2 violation - CP violation possible, no FCNC at the tree level

•2HDM contains two fields, ϕ_1 and ϕ_2, with identical quantum numbers, so global transformations which mix these fields and change the relative phases are allowed without changing physical picture. (However, as a result there may appear *apparent* hard Z_2 violation, *apparent* CP violation, change of $\tan\beta$ ..)

Basis independent analysis by using invariants (Haber et al.) or group theoretical methods (Ivanov, Nishi, Nachtmann)

Vacuum states

- The most general VEV can be reduced to the form

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

with v_1, v_2, u, ξ real, $v_1 > 0$. Z_2 is spontaneously broken if v_2 or $u \neq 0$

- $u \neq 0$ corresponds to *a charged vacuum*, with a heavy photon, charge nonconservation, etc

Diaz-Cruz, Mendez'1992, and Barroso, Ferreira, Santos..'94;

- Veltman' 97 - "..introducing more than one scalar doublet has the obvious disadvantage that in general no zero mass vector boson survives. In other words, the observed zero photon mass is then *accident*".

- Big progress: Barroso, Ferreira, Santos '04,'05, Ginzburg'05, Ginzburg, Kanishev 07, Sokołowska MK, 07, Ivanov, Nishi, Nachtman, Ginzburg, Kanishev, Ivanov 2008

Extremum conditions

Vanishing of the first derivatives of V

$$\left.\frac{\partial V}{\partial \phi_1}\right|_{\substack{\phi_1=\langle\phi_1\rangle,\\ \phi_2=\langle\phi_2\rangle}} = 0, \qquad \left.\frac{\partial V}{\partial \phi_2}\right|_{\substack{\phi_1=\langle\phi_1\rangle,\\ \phi_2=\langle\phi_2\rangle}} = 0$$

lead to following set of conditions:

- $[(\lambda_4+\lambda_5)v_1v_2\cos\xi - m_{12}^2]\, u = 0$
- $[(\lambda_5-\lambda_4)v_1v_2\sin\xi]\, u = 0$
- $[2\lambda_5 v_1 v_2\cos\xi - m_{12}^2]\, v_2\sin\xi = 0$ etc.

To fulfill them: [..]=0, and/or $u=0$, $\sin\xi=0$, $v_2=0$ → different extrema

- To get minimum → eigenvalues of the squared mass matrix (second derivatives) should be positive (minimum constraint)
- in addition positivity (vacuum stability) constraints
- (and tree-level unitarity and perturbativity constraints)

Existing constraints for 2HDM (II) with CP conservation

CP conserving 2HDM(II) with Z_2 symmetry spontaneously broken
$(\lambda_{6,7} = m_{12}^2 = 0; u = \xi = 0)$
five Higgs bosons: h,H- CP even, A- CP odd,$H^\pm$
$\Rightarrow$ 7 parameters: $M_h, M_H, M_A, M_{H^\pm},\ \alpha, \tan\beta = v_2/v_1$

MODEL II (as in MSSM)

Couplings (relative to SM):	h	A
to W/Z:	$\chi_V = \sin(\beta-\alpha)$	0
to down quarks/leptons:	$\chi_d = \chi_V - \sqrt{1-\chi_V^2}\tan\beta$	$-i\gamma_5 \tan\beta$
to up quarks:	$\chi_u = \chi_V + \sqrt{1-\chi_V^2}/\tan\beta$	$-i\gamma_5/\tan\beta$

- For H couplings like for h with:
$\sin(\beta-\alpha) \leftrightarrow \cos(\beta-\alpha)$ and $\tan\beta \to -\tan\beta$.

- For large $\tan\beta$ → enhanced couplings to $d-$type fermions (and τ, μ, e)!

- $\chi_{VH+}^h = \cos(\beta-\alpha)$ - complementarity to hVV!

DATA

LEP • direct:(h) Bjorken process $Z \to Zh$, $\to$ sin$(\beta-\alpha)$
(hA) pair prod. $e^+e^- \to hA$, $\to$ cos$(\beta-\alpha)$
(h/A) Yukawa process $e^+e^- \to bbh/A$, $\tau\tau h/A$, $\to$ tan β
$(H^\pm)$ $e^+e^- \to H^+H^-$ above 80 GeV
via loop:$(h/A$, and $H^\pm)$ $Z \to h/A\gamma$ $\to$ large and small tan β

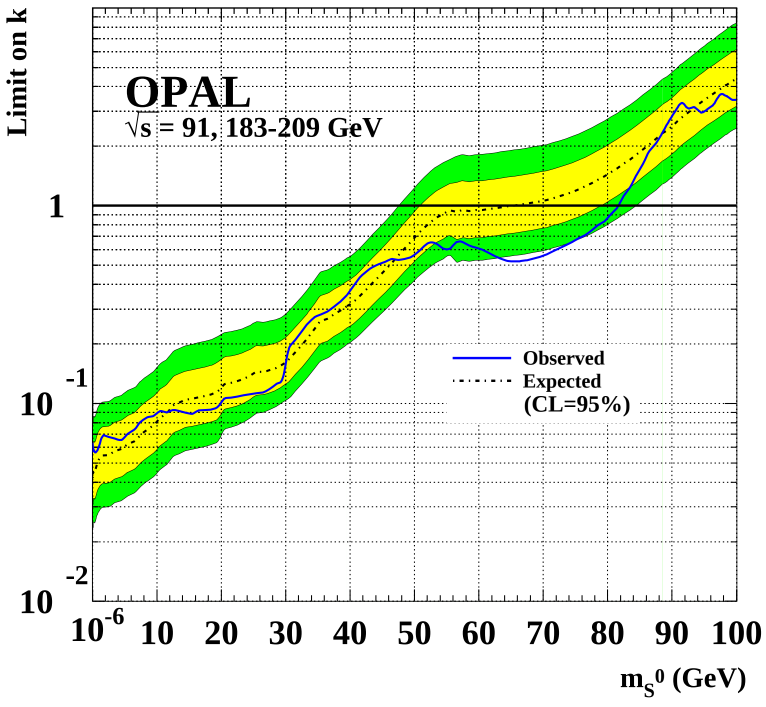
Others exp. • via loop:(h/A) $\Upsilon \to h/A\gamma$ $\to$ upper limits for χ_d
loop: $(H^\pm)$ $b \to s\gamma$, $\to$ lower limit for $M_{H^\pm}$ Model II 300 GeV
leptonic tau decay $\to$ $\to$ lower & upper limit for $M_{H^\pm}$
g-2 data , $\to$ allowed bound for χ_d - very light h excluded
B $\to \tau\nu$ $\to$ exclusion M_{H^+} vs tan β

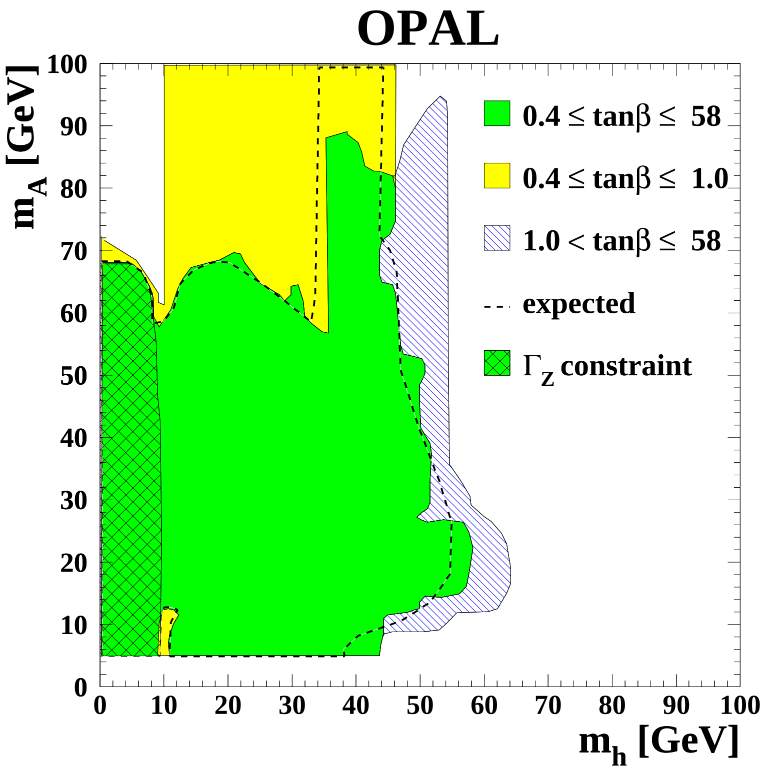
Global fit (2HDM) • (all Higgses)
Chankowski at al.,'99 (EPJC 11,661;PL B496,195)
Cheung and Kong '03, Osland 2007

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: $cos(\beta-\alpha)$

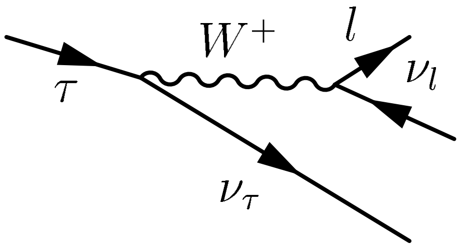


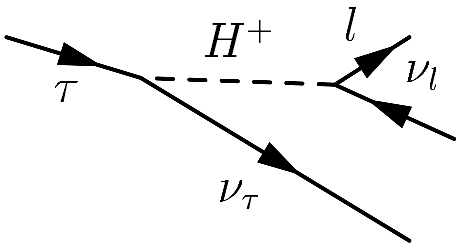


Light scalar h → small $k = sin^2(\beta-\alpha)$!

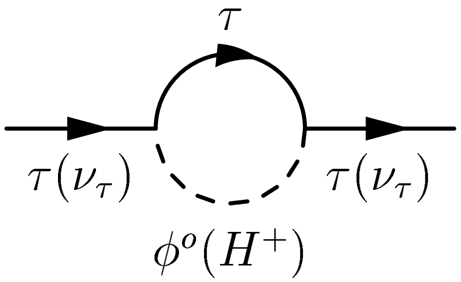
Leptonic tau decays

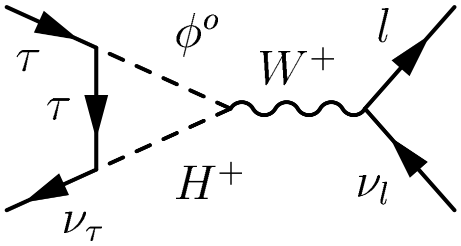
In SM - tree-level W exchange,   in 2HDM: tree-level charged Higgs





In 2HDM loop corrections involve also neutral Higgs bosons → dominant contributions at large $\tan\beta$ $(\phi^0 = h, H, A)$





with D. Temes, EPJC 44, 435 (2005)

We derived 95% C.L. bounds on Δ^l, for the electron muon Br
→ a lower and UPPER limits on mass of H^+

Partial widths or leptonic τ decays: SM vs 2HDM

SM at tree-level = the $W^{\pm}$ exchange (with leading order corrections to the W propagator, and dominant QED one-loop contributions)

2HDM extra tree contribution due to the exchange of H^{+}

$$\Gamma^{H^{\pm}}_{tree} = \Gamma_0 \left[\frac{m_\tau^2 m_l^2 \tan^4\beta}{4 M^4_{H^{\pm}}} - 2 \frac{m_l m_\tau \tan^2\beta}{M^2_{H^{\pm}}} \frac{m_l}{m_\tau} \kappa\left(\frac{m_l^2}{m_\tau^2}\right)\right],$$

where $\kappa(x) = \frac{g(x)}{f(x)}$, $g(x) = 1 + 9x - 9x^2 - x^3 + 6x(1+x)\ln(x)$.

The second term - from the interference with the SM - much more important. It gives negative contribution to Br:

$$-m_l^2/M^2_{H^{\pm}} \tan\beta^2$$

One loop contribution for large $\tan\beta$

$$\Delta_{oneloop} \approx \frac{G_F m_\tau^2}{8\sqrt{2}\pi^2} \tan^2\beta\,\tilde{\Delta}$$

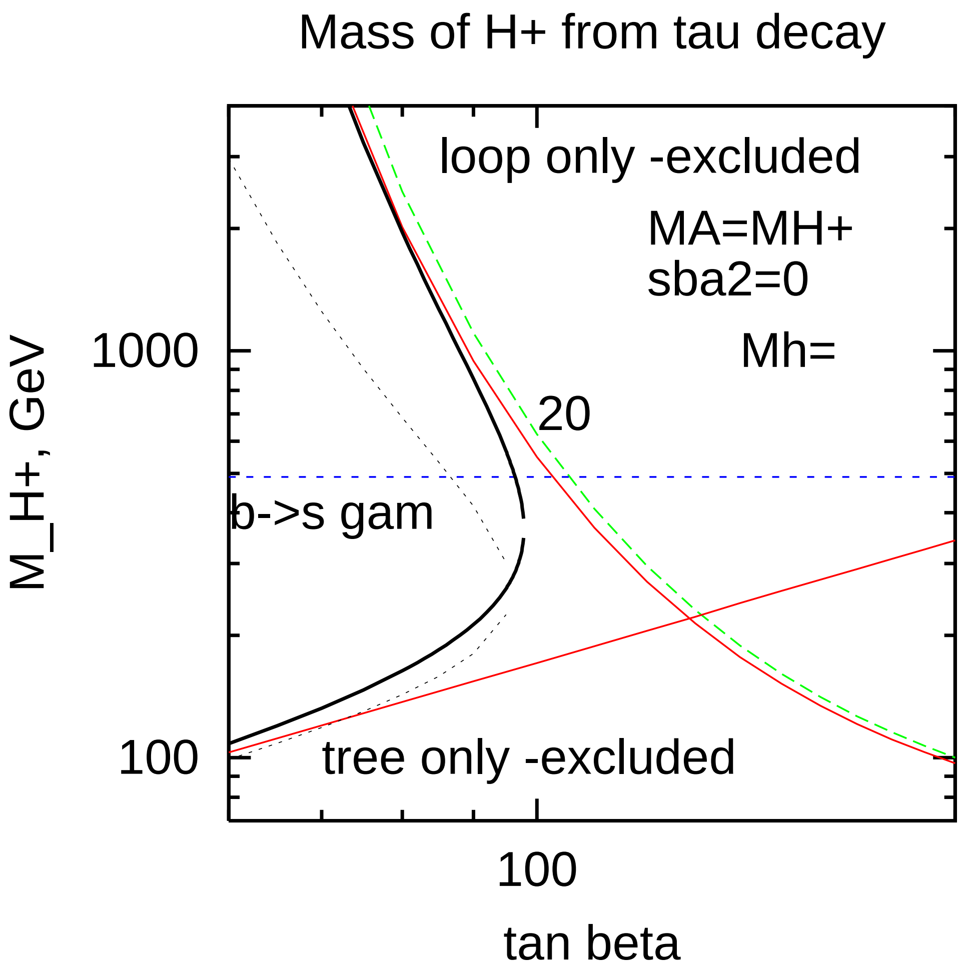
$$\begin{aligned}\tilde{\Delta} = \quad & \Bigg[-\left(\ln\left(\frac{M_{H+}^2}{m_\tau^2}\right) + F(R_{H^\pm})\right) \\ & + \frac{1}{2}\left(\ln\left(\frac{M_A^2}{m_\tau^2}\right) + F(R_A)\right) \\ & + \frac{1}{2}\cos^2(\beta-\alpha)\left(\ln\left(\frac{M_h^2}{m_\tau^2}\right) + F(R_h)\right) \\ & + \frac{1}{2}\sin^2(\beta-\alpha)\left(\ln\left(\frac{M_H^2}{m_\tau^2}\right) + F(R_H)\right)\Bigg], \qquad (1)\end{aligned}$$

where $R_\phi \equiv M_\phi / M_{H^\pm}$ and $F(R) = -1 + 2\,R^2 \ln R^2/(1-R^2)$

NOTE, $\tilde{\Delta}$ does not depend on m_τ!

Loop corrections are the same for e and μ channels

95% CL Limits for mass of H^+: One-loop and tree contr.



dotted: $M_A = 100$ GeV; μ (red), e (green) (old $b \to s\gamma$)

Inert Doublet Model (Dark 2HDM)

- Here the Z_2-symmetry conservation is assumed both explicit and spontaneous. Z_2 transformation:

$$(\phi_1 \to \phi_1, \phi_2 \to -\phi_2)$$

- Scalar 2HDM potential with $\lambda_{6,7} = m_{12}^2 = 0$ and real λ_5.

Vacuum: $< \phi_1 >= v$ and $< \phi_2 >= 0$.
Z_2-parity is odd for ϕ_2, even Z_2-parity for: ϕ_1 and for all other fields (gauge fields, fermions) (Deshpande, Ma '1978).

- Only the first doublet has a nonzero vev and Yukawa interaction with fermions → ϕ_1 is like a standard Higgs doublet, with one physical Higgs boson h with the coupling to gauge bosons and fermions as in SM (at the tree level) and mass

$$M_h^2 = m_{11}^2 = \lambda_1 v^2$$

Dark scalars

- The second (dark) doublet ϕ_2 describes 4 physical spin-0 particles $H^{\pm}, H, A$ - dark scalars D with odd Z_2-parity:

$$
\begin{aligned}
M^2_{H+} &= -\frac{m^2_{22}}{2} + \frac{\lambda_3}{2} v^2 \\
M^2_{H} &= -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2} v^2 \\
M^2_{A} &= -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2} v^2
\end{aligned} \qquad (2)
$$

- Selfcouplings of 4 D particles are proportional to λ_2,

- Couplings between Higgs boson h and dark scalars D are proportional to $M^2_D + m^2_{22}/2$,

- D couple to W/Z (eg. $H^{\pm}W^{\mp}H,\ H^{\pm}W^{\mp}A,\ AZH$)

- Positivity conditions read $\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > -\sqrt{\lambda_1\lambda_2}$

$$\lambda_3 + \lambda_4 \pm |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$$

Testing model

Since only dark scalars have odd Z_2-parity

- they can be produced only in pairs
- the lightest dark scalar can be a suitable DM candidate

The strategy to test such model:

(I will not discuss Barbieri at al. '2006 approach with a heavy Higgs boson h)

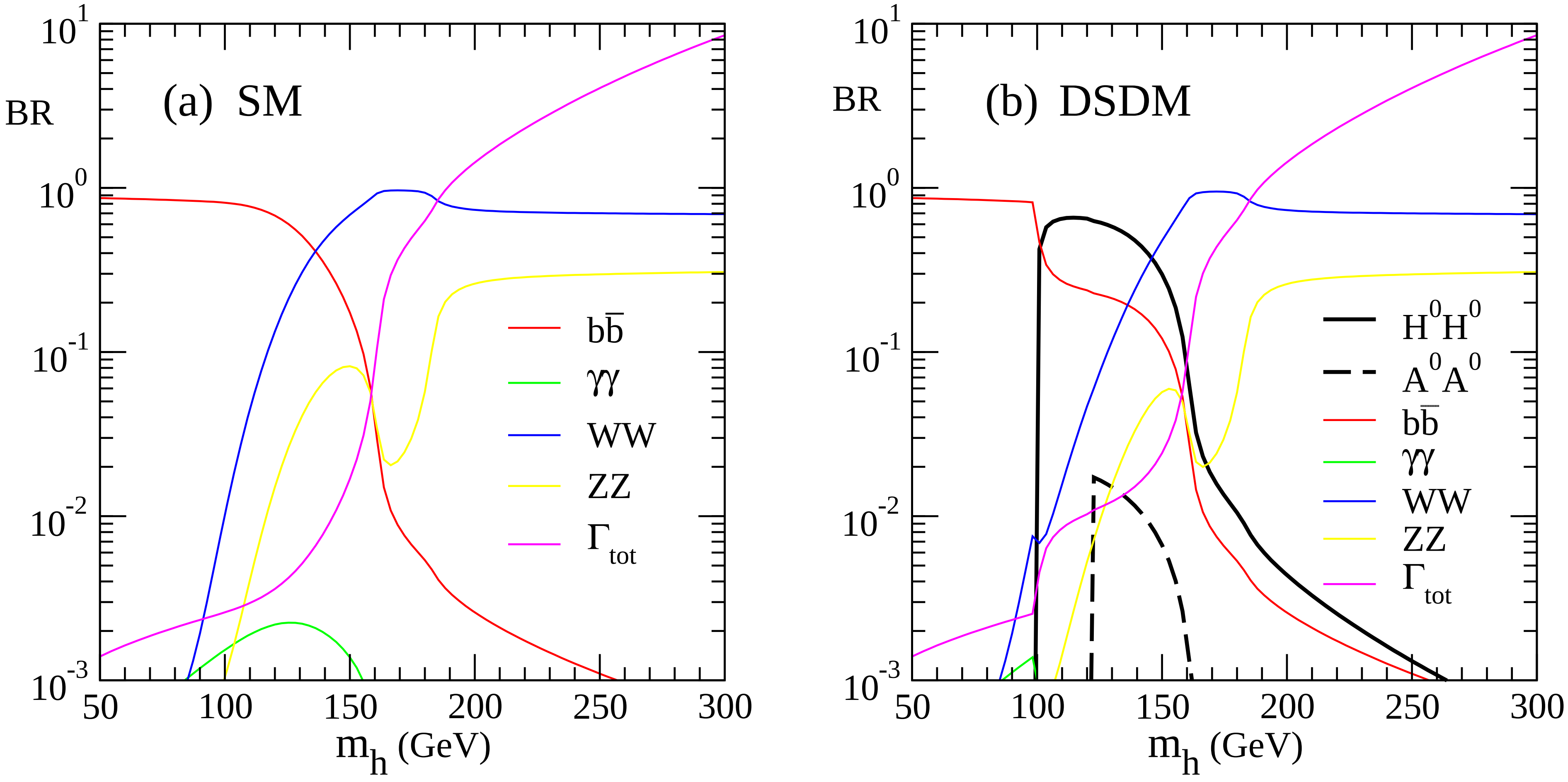
- to consider properties of Higgs boson h, which is very much SM-like. Some deviation from the SM decay rates may appear if dark scalars are relatively light due additional decays $h \to$ DD

- to consider properties of dark scalars, especially the DM candidate.

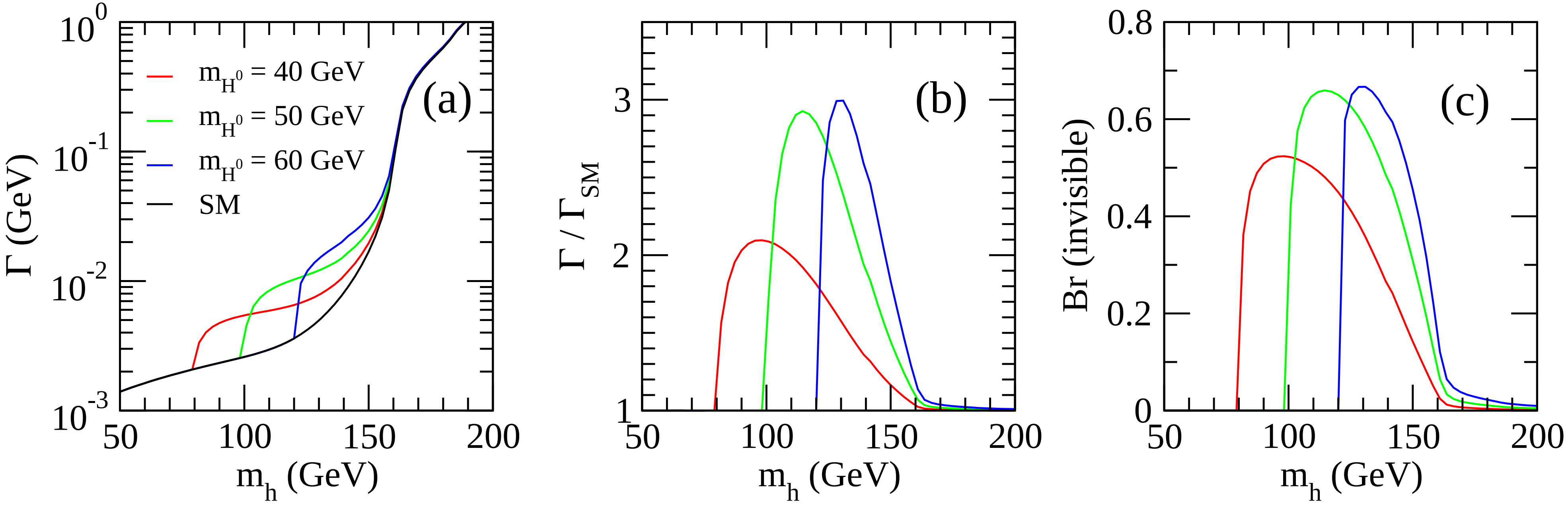
Cao,Ma,Rajasekaren- 2007: colliders signal/constraints for Dark 2HDM in the case $M_{H}+ > M_A > M_H$, with stable H

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



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



Modification of the total width due to additional (dark) decay channels.

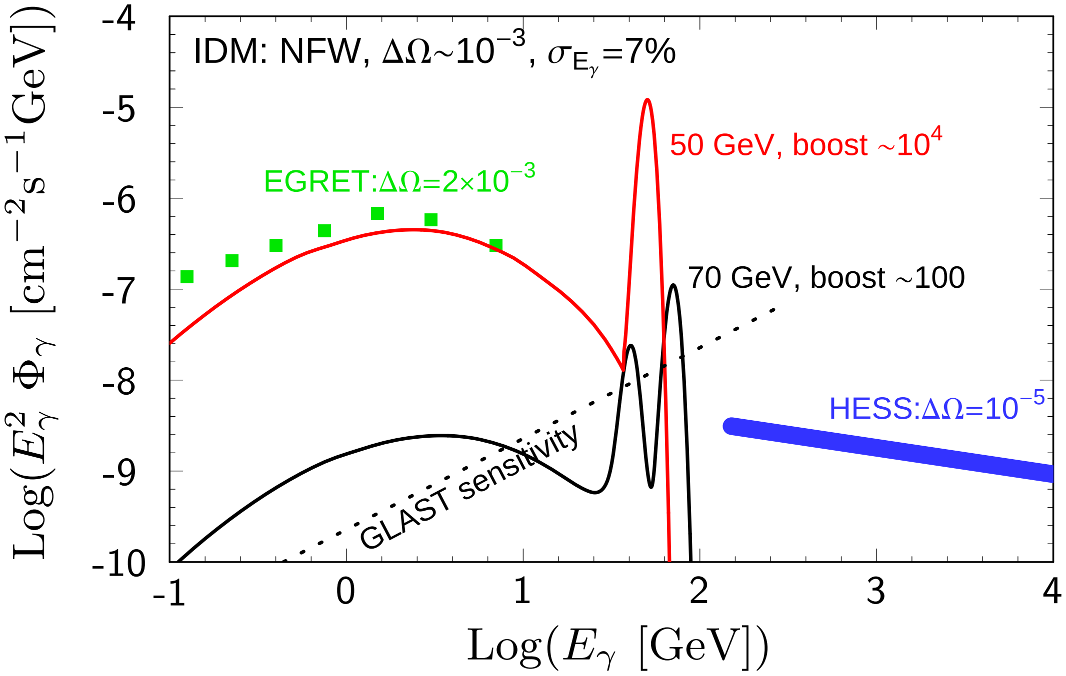
Conclusion on colliders signals

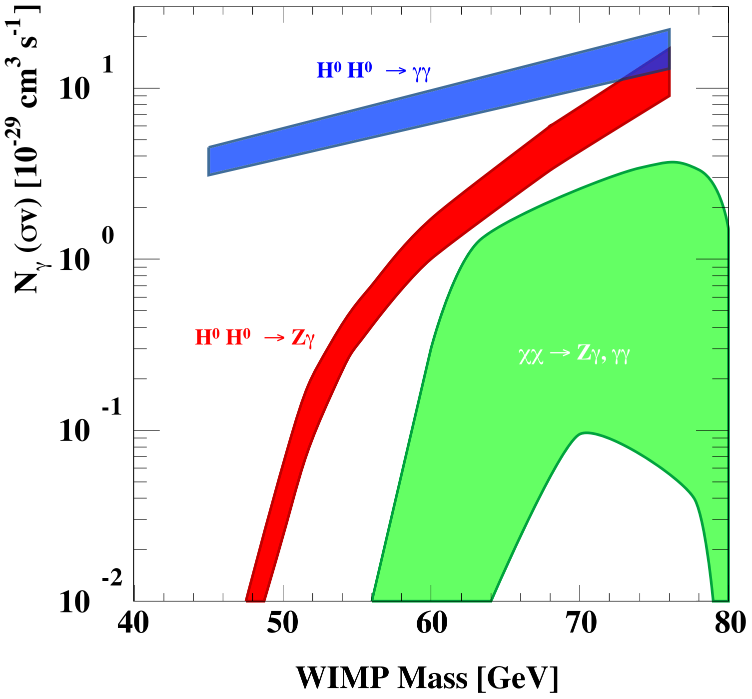
- dramatic change of Br for mass of h 100-150 GeV, due to decay to dark scalars HH. Br for "standard" channels to $bb/WW/ZZ/\gamma\gamma$ highly suppressed (factor 2)

- LHC discovery potential (best AH production) studied. Promising for mass M_H around 50 GeV.

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).





Conclussion on gamma lines

●Gustafsson et al : Striking DM line signal are promising features to search for with GLAST satelite...
M_H between 40-80 GeV, mass of H^+ =170 GeV, A =50 -70 GeV, M_h=500 GeV (and also for M_h=120 GeV)

●Honorez, Nezri, Oliver,Tytgat - 2006-7: H as a perfect example or archetype of WIMP - within reach of GLAST ...

Here also M_h =120 GeV, M_{H+} large (close to M_A) 400 -550 GeV

●GLAST (now FERMI) launched on 11 June 2008

Conclusion

- 2HDM is a great laboratory of the physics beyond SM

- Z_2 symmetry - accidental or real?

- If real and respected exactly → the Inert Doublet Model

- One doublet as in SM, with SM-like Higgs h. Other - inert or dark - no direct interaction with fermions, not involved in the mass generation. Physical states - spin-0 particles (no Higgs particles!) - dark or inert particles $D = H^{\pm},\ A,\ H$.

- The lightest (neutral) D is a good candidate for DM