A new vision of the inert doublet model of dark matter

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Universidad Autónoma de Madrid

based on *The inert doublet model of dark matter revisited.*
arXiv:1003.3125

in collaboration with C. Yaguna

IDM 2010 - Montpellier

Why revisiting the Inert doublet model ?

3-body processes can take over 2-body processes

3-body $\equiv$ real + virtual massive particle

e.g. $WW^* \to W\bar{f}f'$

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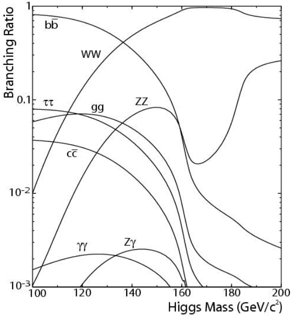
$\mathrm{BR}(h \to WW^*) \gg \mathrm{BR}(h \to \bar{b}b)$ for $m_h \lesssim 2M_W$



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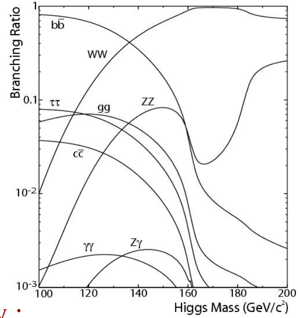

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⇝ Affect relic abundance, viable parameter space, detection

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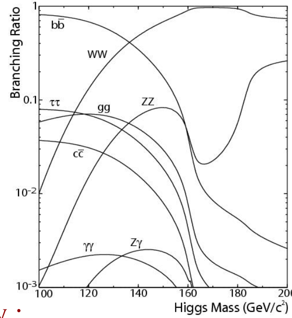

3-body processes can enhance DM annihilation/decay :

$\rightsquigarrow$ Affect relic abundance, viable parameter space, detection

$\rightsquigarrow$ Significant effect on : neutralino LSP [Chen & Kamionkowski JHEP '98, Yaguna PRD'10], gravitino LSP [Choi & Yaguna '1003,& all '1007] (see Yaguna talk ! !), Higgs DM [Hosotani, Ko & Tanaka PLB'09], singlet scalar DM [Yaguna PRD'10]

$\rightsquigarrow$ In this talk : 3bdy annihilation in the Inert doublet model

Scalar WIMP as dark matter

Minimal DM spirit : SM + extra $\mathrm{SU}(2)_L$ doublet see Cirelli *et* all '05-'09

- DM = neutral member of the extra doublet
  Higgs : $H_1 \rightsquigarrow h$ and DM : $H_2 \rightsquigarrow H_0, A_0, H^\pm$
- stability $\rightsquigarrow$ extra Z_2 symmetry
  SM $\to$ SM, $H_1 \to H_1$ and $H_2 \to -H_2$

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Possible Interactions

- (co)annihilation through *known* $\mathrm{SU}(2)_L \times \mathrm{U}(1)$ gauge bosons exchange
- quartic coupling λ_i to Higgs H_1

$$\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

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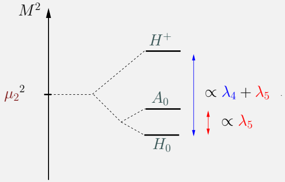
$$\frac{1}{2}\left(\lambda_{H_0} H_0^2 + \lambda_{A_0} A_0^2 + 2\lambda_{H_c} H^+ H^-\right)\left(2v_0 h + h^2\right)$$

$${m_\chi}^2 = \mu_2^2 + \lambda_\chi v_0^2$$



$$\lambda_{H_c} \equiv \lambda_3/2$$

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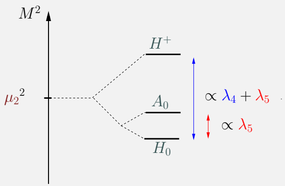

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Here we take H_0 as the LZ$_2$P and $\lambda_L \equiv \lambda_{H_0}$

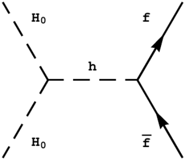
Inert doublet model parameter space

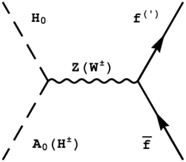
free parameters : $m_{H_0}, m_h, \lambda_L, \Delta m_{A^0}, \Delta m_{H^+}$

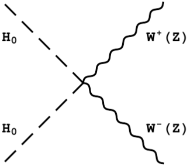
- $m_{H_0} \lesssim m_W$: GeV range ($\sim 10 - 80$ GeV) :

  $$H_0 H_0 \to h^* \to \bar{f} f \text{ and } H_0 A_0 \to Z^* \to \bar{f} f$$

  Barbieri PRD06, LLH JCAP06,Gustafsson PRL07, Cao PRD07, Andreas JCAP08,...







- $m_{H_0} \gg m_W$: TeV range ($\gtrsim 530$ GeV) :
  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

  Cirelli NPB06, Hambye JHEP09

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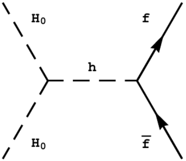

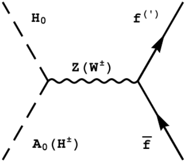

LARGE MASS GAP DUE TO EFFICIENT
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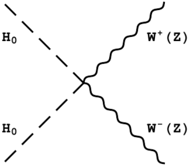

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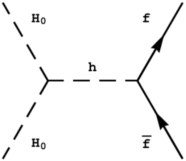
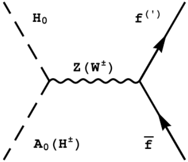
  $\rightsquigarrow$ Significantly affected by 3bdy annihilation :

  $H_0 H_0 \to W W^* \to W \bar{f} f'$





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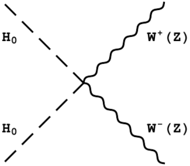

Analysis for fixed parameters

2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
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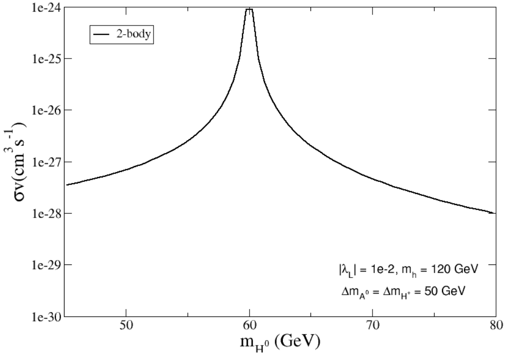

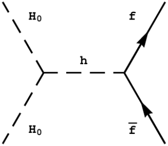

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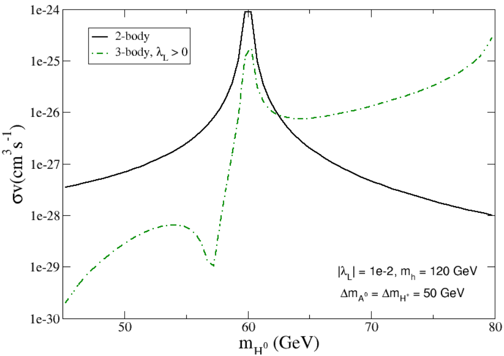

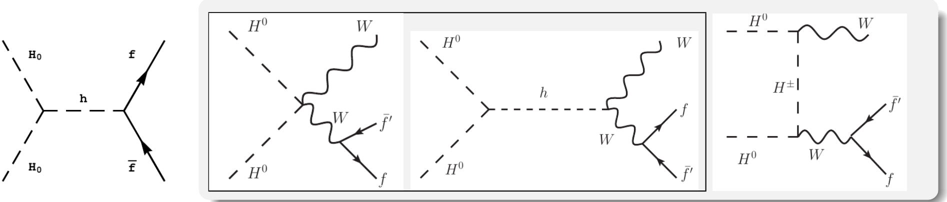

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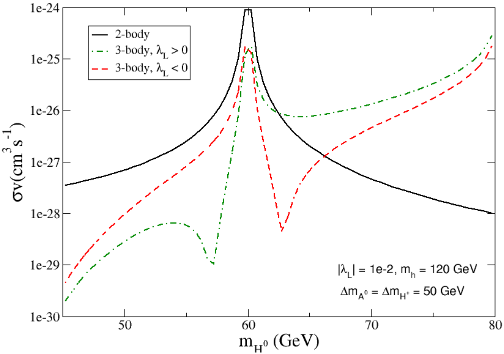

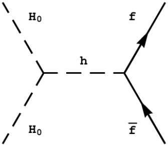

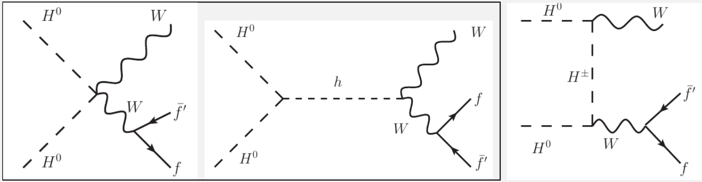

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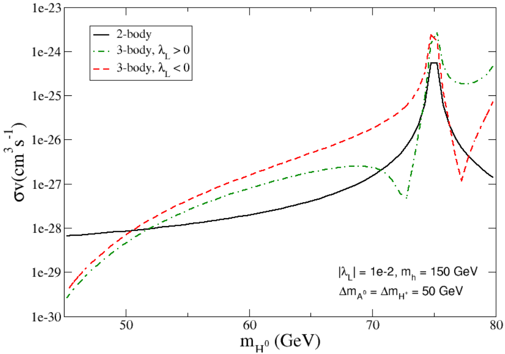

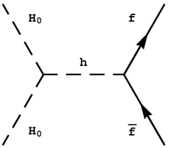

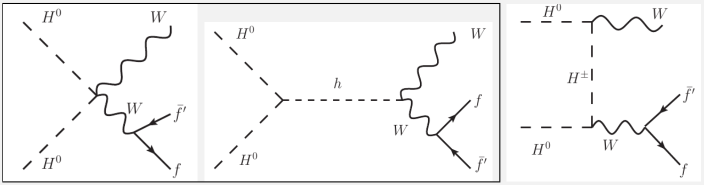

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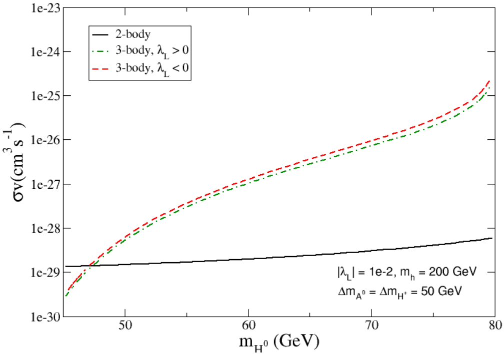
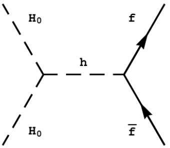
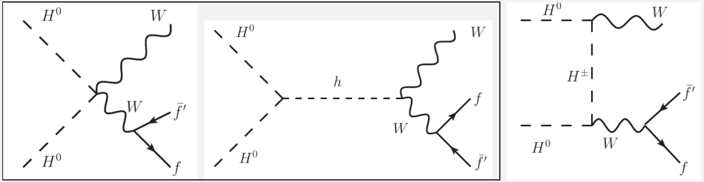
$\rightsquigarrow$ σv_{2bdy} vs σv_{3bdy} depends on m_{H^0}, m_h, λ_L sign and amplitude







Comparing 2-3 body relic density

Ω_{dm} is Δm dependent $\leftrightarrow$ allows coannihilations

In the absence of coannihilations :

- roughly $\Omega_{dm} \propto 1/\langle\sigma \mathrm{v}\rangle$ with

$\langle\sigma \mathrm{v}\rangle = \langle\sigma \mathrm{v}(\text{ 2-body})\rangle + \langle\sigma \mathrm{v}(WW^*)\rangle$

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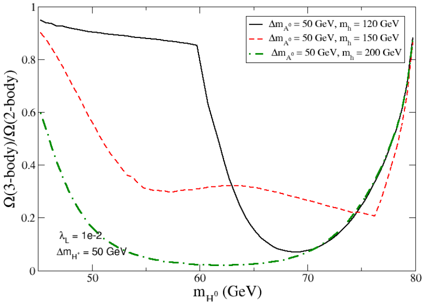

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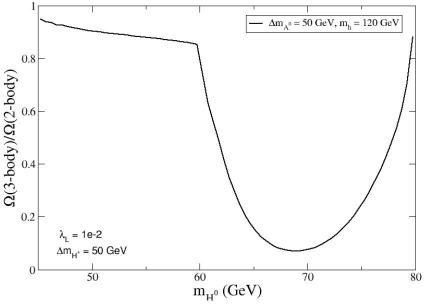

Including coannihilations ($\Delta m_{A^0} = 10, \Delta m_{H^+} = 50$ GeV) :

- coannihilations $\equiv$ 2-bdy pure gauge process $H_0 A_0 \to Z \to \bar{f} f$
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- near h resonance H_0 annihilation enhanced $\rightsquigarrow$ coannihilation negligible

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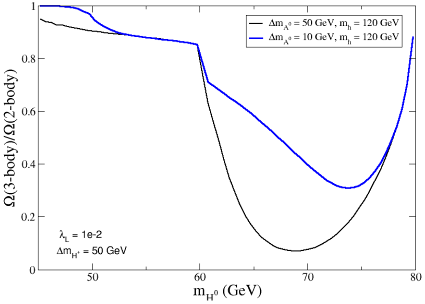

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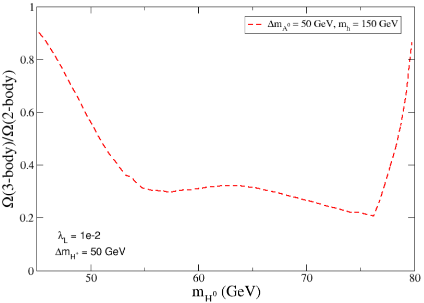

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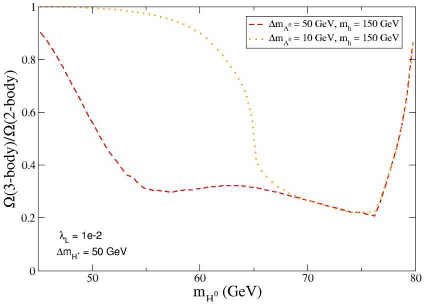

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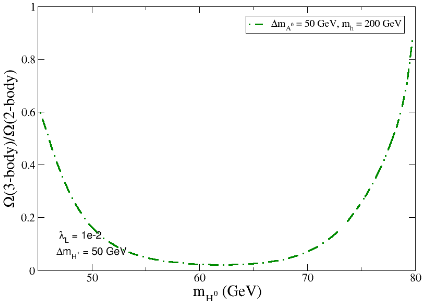

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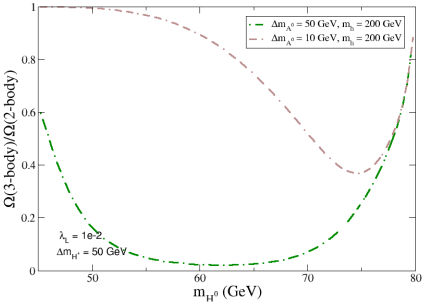

Including coannihilations ($\Delta m_{A^0} = 10, \Delta m_{H^+} = 50$ GeV) :

- coannihilations $\equiv$ 2-bdy pure gauge process $H_0 A_0 \to Z \to \bar{f}f$
  $\rightsquigarrow$ can weaken the 3-bdy domination
- near h resonance H_0 annihilation enhanced $\rightsquigarrow$ coannihilation negligible

$\rightsquigarrow$ still 3-body final states significantly affect predictions for Ω_{dm}

Parameters for $\Omega_{H_0} = \Omega_{dm}^{WMAP}$

Viable parameter space

Derive the $\lambda_L - m_{H^0}$ compatible with $\Omega_{dm}^{WMAP} h^2 = 0.11$

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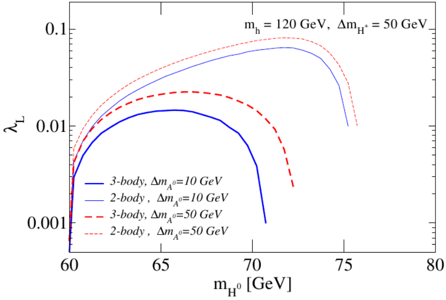
Going from 2bdy only to 2+3bdy with or without coannihilations :



- correct λ_L is reduced up to $\sim \mathcal{O}(10)$.
- viable m_{H^0} range shrinks
  - 2bdy settled by the onset of W^+W^- annihilations
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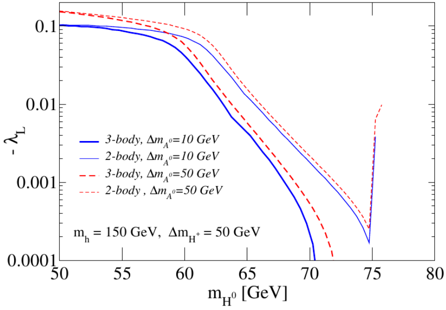

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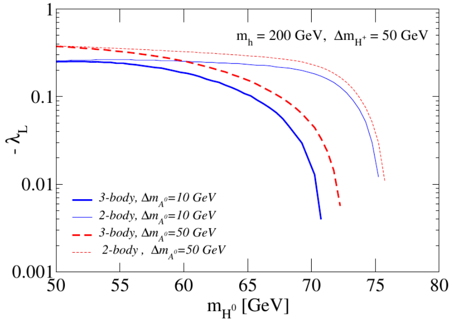

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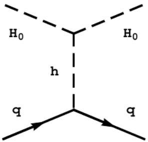
$\rightsquigarrow$ rather generic feature of the Inert doublet model independently of m_h

$\rightsquigarrow$ modify prospects for DM detection

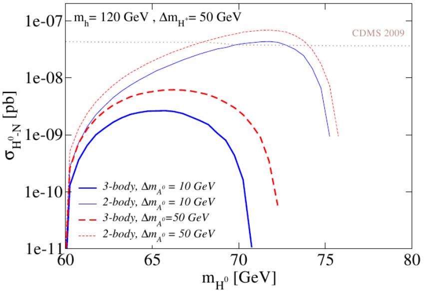
Implications for Direct Detection

Direct detection through Elastic Scattering

Prospects along the viable parameter space :



$$\sigma_{H_0-N} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$



$\rightsquigarrow$predictions for σ_{H_0-N} reduced up to $\sim \mathcal{O}(100)$

$\rightsquigarrow$ better compatibility with present bounds

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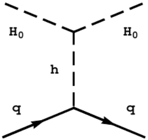

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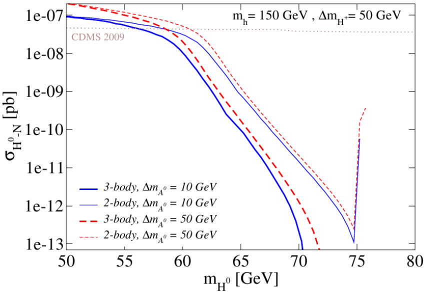

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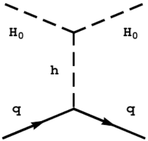

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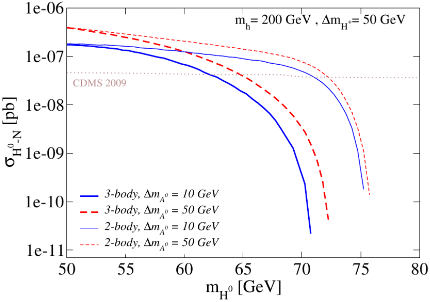
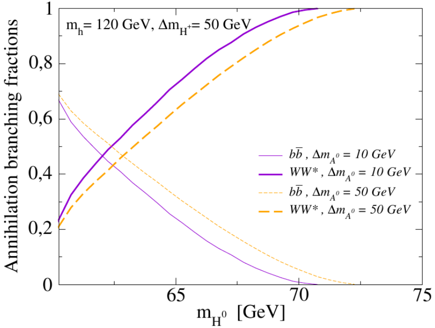


⇝predictions for σ_{H_0-N} reduced up to $\sim \mathcal{O}(100)$

⇝ better compatibility with present bounds

More Implications

For Indirect Detection



- new parameter space
- annihilations no more $\bar{b}b$ dominated

$\rightsquigarrow$R($H_0 H_0 \to WW^*$) ~ 1
for m_{H^0} near W threshold

More Implications

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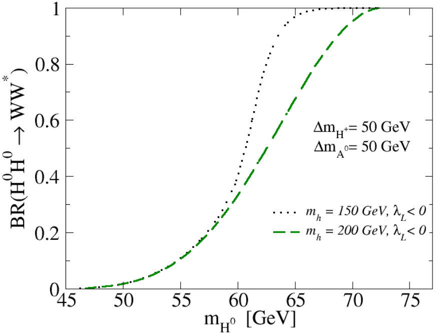

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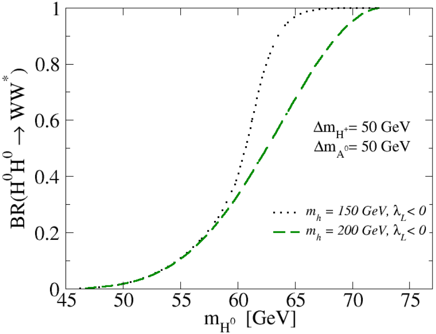

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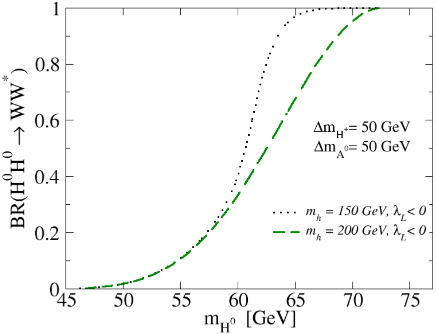

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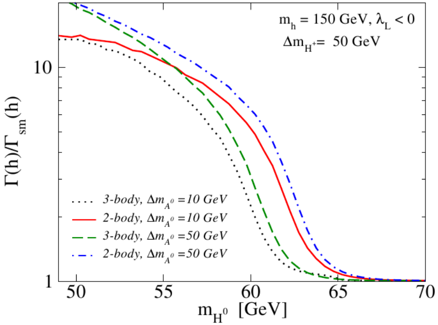
Detection at colliders



through extra contributions to $\Gamma(h)$ due to

$h \rightarrow A_0A_0, H_0H_0$ [Cao PRD07]

$\rightsquigarrow$ The new parameter space slightly change the prospects

Conclusion

The Inert Doublet is a WIMP with a rich Scalar DM phenomenology

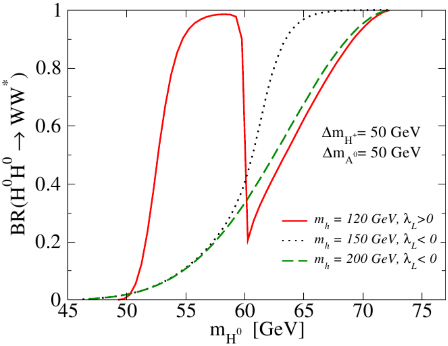
- We have shown that for $m_{H_0} \lesssim m_W$, annihilation into 3 bdy final states (WW^*) MUST be taken into account
- The genuine DM viable parameter space next to W threshold was derived
  - relevant coupling to higgs λ_L is reduced up to $\mathcal{O}(10)$
  - the viable range in m_{H^0} shrinks by several GeVs
- Prospects for DM detection are modified
  - Direct detection : σ_{H_0-N} decreases by a factor $\mathcal{O}(100)$
  - DM annihilation is no more $\bar{b}b$ dominated, BR(WW*) ~ 1 for $m_{H_0} \lesssim 60$ GeV

This is the End

Thank you for your attention ! !

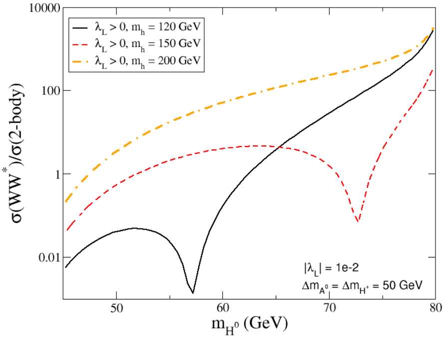
Backup

branchings


1
0.8
0.6
0.4
0.2
0
45
50
55
60
65
70
75
$BR(H^0H^0 \to WW^*)$
m_{H^0} [GeV]
Δm_{H^+}= 50 GeV
Δm_{A^0}= 50 GeV
m_h = 120 GeV, λ_L>0
m_h = 150 GeV, λ_L< 0
m_h = 200 GeV, λ_L< 0

Comparing 2-3 body annihilation cross section

3bdy annihilation dominates over 2 bdy on



- $\lambda_L = 10^{-2}$

... a significant range of the parameter space, depend on m_h

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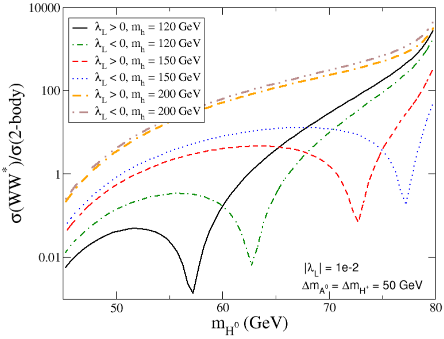

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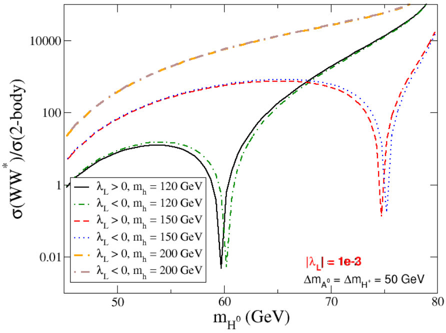


- $\lambda_L = 10^{-2}$

  ... a significant range of the parameter space, depend on m_h
- $\lambda_L = 10^{-3}$

  ... the entire mass range independently of m_h

  but not representative for $H_0 \equiv$ DM

IDM : Mass Ranges

Mass Ranges	main contributions to σ_{eff}	mass splittings	main Refs
$m_{H_0} \ll m_W (\mathcal{O}(GeV))$	$H_0 H_0 \to h^* \to \bar{f} f$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \sim 90$ GeV	Andreas *et* all '08
$m_{H_0} \lesssim m_W$	$H_0 H_0 \to h^* \to \bar{f} f$ $H_0 A_0 (H^+) \to Z^*(W^*) \to \bar{f} f^{(')}$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \gtrsim 7$ GeV	Barbieri *et* all '06 LLH *et* all '06
$m_{H_0} \gg m_W (\mathcal{O}(TeV))$	$H_0 H_0 \to ZZ, WW, hh$ coannihil into bosons	$\Delta m_{ij} \lesssim 17.6$ GeV	Hambye *et* all '09

IDM : Potential - constraints

- Full Potential

$$\begin{aligned} V(H_1,H_2) &= \mu_1^2|H_1|^2+\mu_2^2|H_2|^2+\lambda_1|H_1|^4+\lambda_2|H_2|^4 \\ &+\lambda_3|H_1|^2|H_2|^2+\lambda_4|H_1^\dagger H_2|^2+\frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2+h.c.\right] \end{aligned}$$

- Dark scalars couplings to Higgs and masses :

$$\frac{1}{2}\left(\lambda_{H_0}H_0^2+\lambda_{A_0}A_0^2+2\lambda_{H_c}H^+H^-\right)\left(2v_0h+h^2\right)$$
$$m_h^2=2\lambda_1 v_0^2\ , \quad m_i^2=\mu_2^2+\lambda_i v_0^2.$$

- Stability constraint

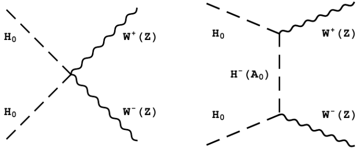
$$\begin{aligned} \lambda_{1,2} &> 0 \quad , \\ \lambda_{H0}\ , \quad \lambda_{A_0}\ , \quad \lambda_{H_c} &> -\sqrt{\lambda_1\lambda_2}\ . \end{aligned}$$

- EWPT measurements : $\Delta T \approx \frac{1}{12\pi^2\alpha v^2}(m_{H^+}-m_{A_0})(m_{H^+}-m_{H_0})$

IDM in the High mass regime : Relic abundance

Quartic couplings ON : extra Higgs processes and $m_{H_0} \neq m_{A_0} \neq m_{H_c}$

for *e.g.* $H_0 H_0 \to XX$



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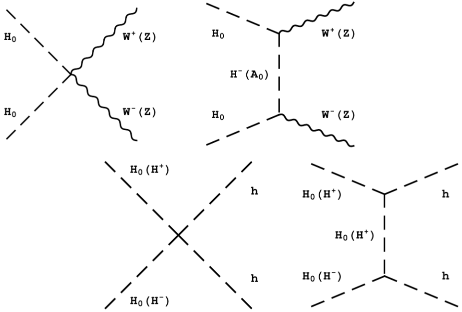

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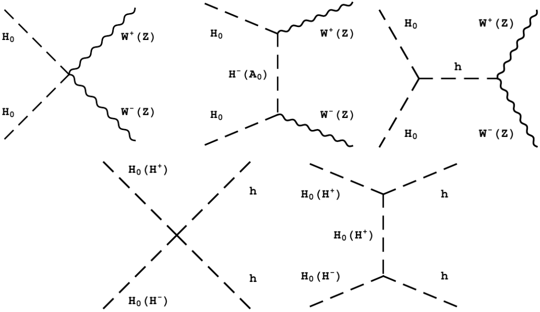

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where $\sigma_\lambda^{ij} = \frac{\Lambda^{ij}}{m_{H_0}^2}$ with $\Lambda^{ij} \propto \lambda * \lambda$ and $\Lambda^{ij} > 0$

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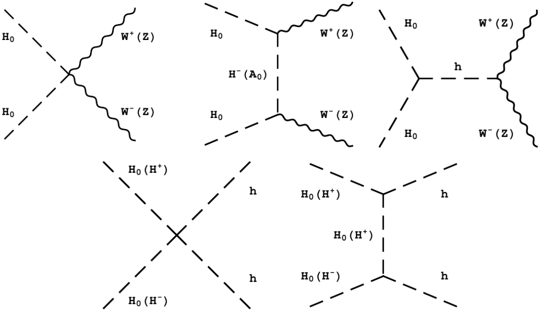

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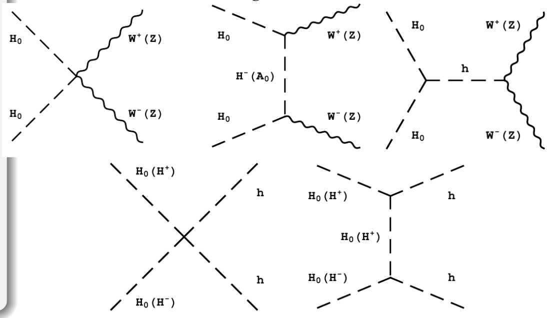

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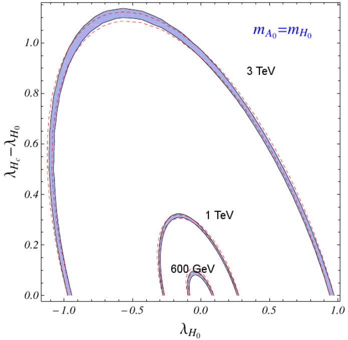

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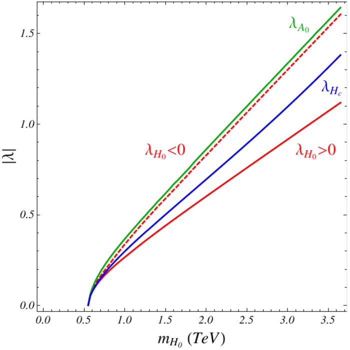

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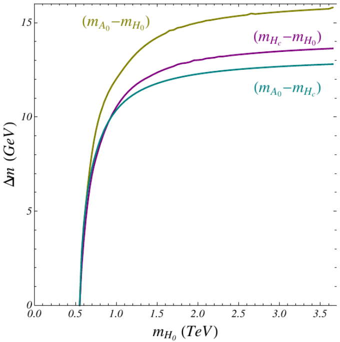
- mass splittings are also bounded as $m_i - m_j \propto (\lambda_i - \lambda_j)/m_{H_0}$



3bdy effect on DM ?

3-body processes can enhance DM annihilation :

- supersymmetric dark matter :
  - neutralino LSP : Chen & Kamionkowski JHEP '98 study $\sigma v_{v \to 0}$ and impact on ν detection from annihilation in the Earth bellow WW and $\bar{t}t$ mass threshold
    Yaguna PRD'10 demonstrate up to 10% effect on Ωh^2_χ for bino-like χ including $\bar{t}t*$ (usually 2-bdy $\bar{b}b$ dom)
  - gravitino LSP : Choi & Yaguna '1003 $W^* l$ and $Z^* \nu$ give significant (up to 90%) to $\tilde{G}$ decay (usually 2-bdy $\gamma\nu$ dom)
    Choi, Restrepo, Yaguna & Zapata '1007 gamma+antimatter signal [see Yaguna talk ! !]
- scalar DM
  - Higgs DM : Hosotani, Ko & Tanaka PLB'09 (gauge-Higgs unification)
    $\Omega_{DM} \rightsquigarrow m_{DM} = 75$ GeV (2bdy only) $\Rightarrow m_{DM} =70$ GeV (including 3bdy)
  - singlet scalar DM : Yaguna PRD'10, $SS \to h \to WW^*$ enhance $\sigma v_{v \to 0}$ and reduce Ω_{DM} independently of S-higgs coupling

This is the End