Scalar Dark Matter: A revision of the inert doublet model

Laura Lopez Honorez

Service de Physique Théorique - Université Libre de Bruxelles

based on:

A new viable region of the inert doublet model: JCAP 1101:002
The inert doublet model of dark matter revisited:JHEP 1009:046

in collaboration with C. Yaguna

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile 2011 - Italy

Scalar WIMP as dark matter

Minimal DM spirit : SM + extra $SU(2)_L$ 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 $\rightarrow$ SM, $H_1 \rightarrow H_1$ and $H_2 \rightarrow -H_2$

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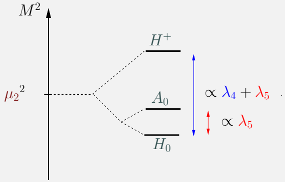
$$\frac{1}{2}\left(\lambda_{H_0} H_0^2 + \lambda_{A_0} A_0^2 + 2\lambda_{H_c} H^+ H^-\right)\left(2v_0 h + h^2\right)$$

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



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

$$\lambda_{H_0,A_0} \equiv (\lambda_3 + \lambda_4 \pm \lambda_5)/2$$

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Here we take H_0 as the LZ_2P and $\lambda_L \equiv \lambda_{H_0}$

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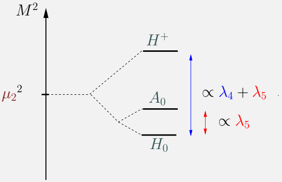

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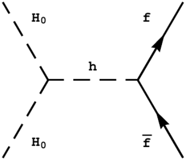
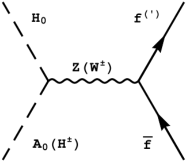
Inert doublet model parameter space

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

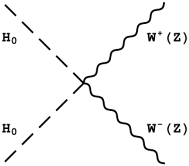
  $H_0 H_0 \to h^* \to \bar{f} f$ and $H_0 A_0 \to Z^* \to \bar{f} f$

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





LARGE MASS GAP DUE TO EFFICIENT
WW AND *ZZ* ANNIHILATION



- $m_{H_0} \gg m_W$: TeV range ($\gtrsim 530$ GeV) :
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  Cirelli NPB06, Hambye JHEP09

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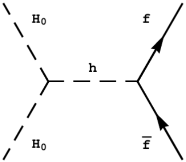
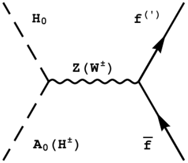


Significantly affected by 3bdy annihilation :

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



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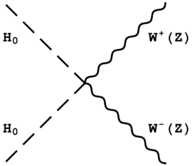

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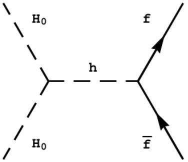

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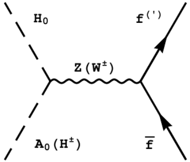
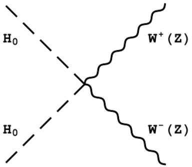


- Above W-threshold : cancellations

  $H_0 H_0 \to WW$ vs $H_0 H_0 \to h \to WW$

LARGE MASS GAP DUE TO EFFICIENT
WW AND ZZ ANNIHILATION



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Extra contributions from 3 body annihilations

Analysis for fixed parameters

based on:

A new viable region of the inert doublet model: JHEP 1009:046

2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
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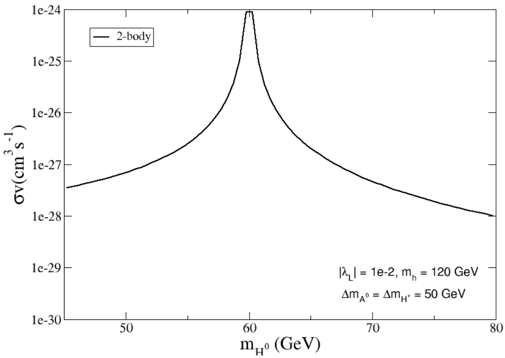

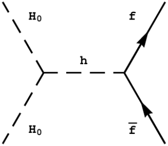

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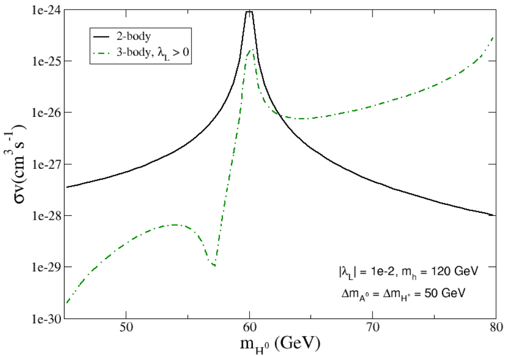

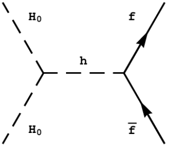

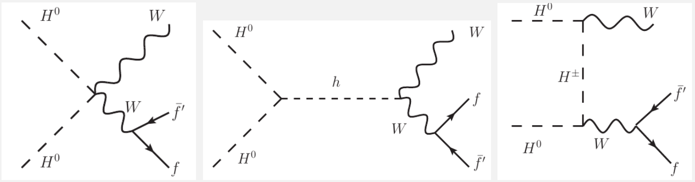

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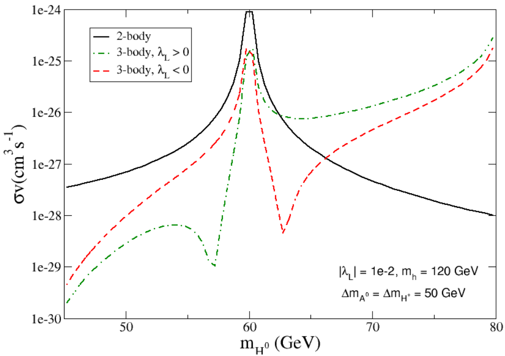

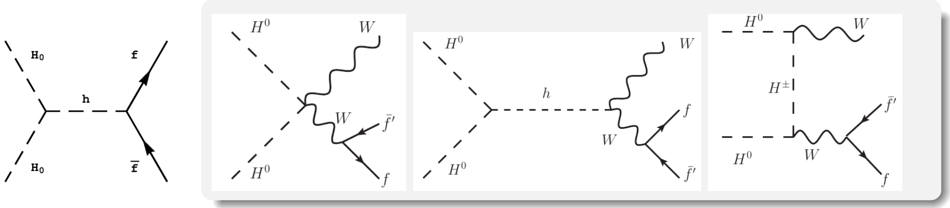

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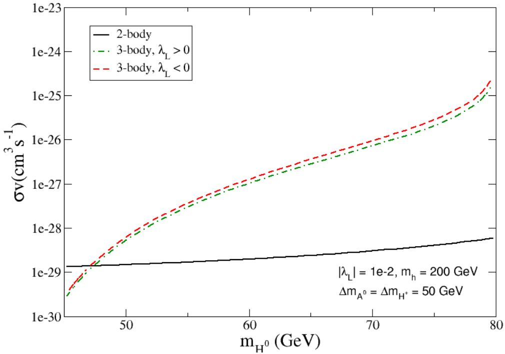

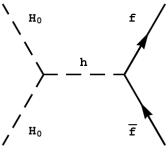

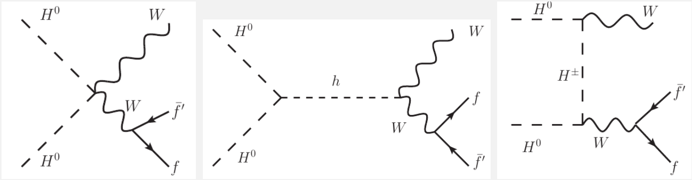

Comparing 2-3 body relic density

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

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

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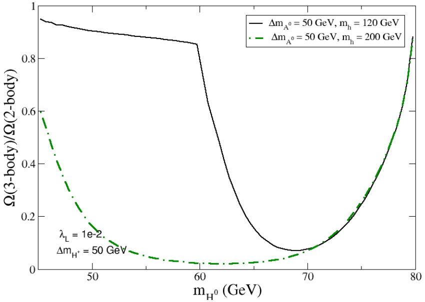
$\rightsquigarrow$ confirmed numerically using modified micrOMEGAs



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

Extra contributions from 3 body annihilations

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

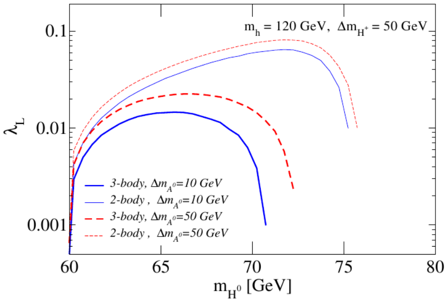
based on:

A new viable region of the inert doublet model: JHEP 1009:046

Viable parameter space

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

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



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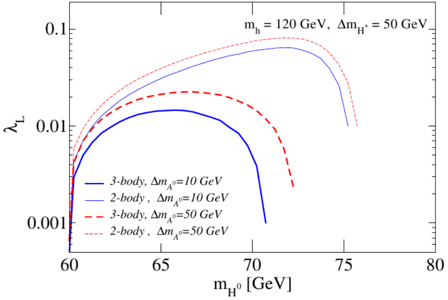

- correct $|\lambda_L|$ is reduced up to $\sim \mathcal{O}(10)$.
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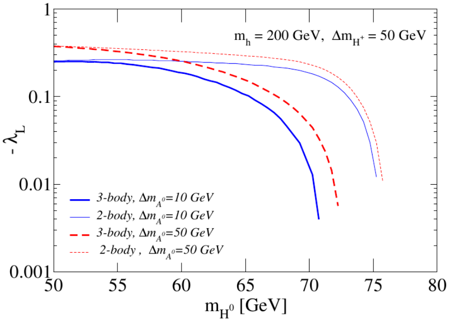

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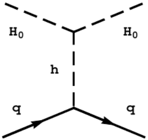
$\rightsquigarrow$ rather generic feature of the Inert doublet model independently of m_h

$\rightsquigarrow$ modify prospects for DM detection

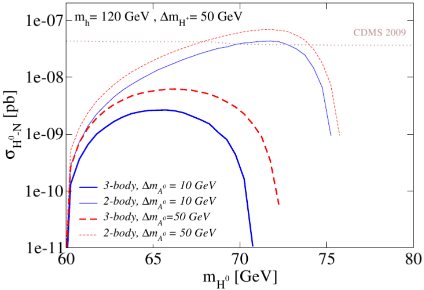
Implications for Direct Detection

Direct detection through Elastic Scattering

Prospects along the viable parameter space :



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



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

⇝ better compatibility with present bounds

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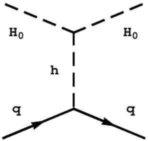

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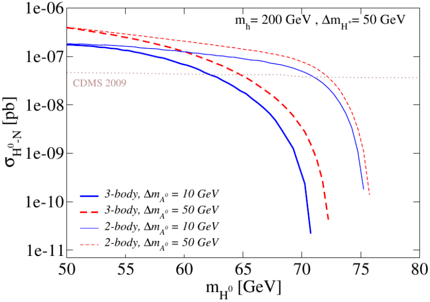

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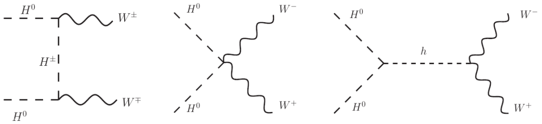
Cancellations above W threshold

based on:

A new viable region of the inert doublet model: JCAP 1101:002

Illustration of cancellation in 2 body processes

Above W threshold, for fixed parameters, one obtains $\Omega_{H_0} = \Omega_{dm}^{WMAP}$



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- for $m_{H^0} \gg m_W, M_h$ (Hambye '09)
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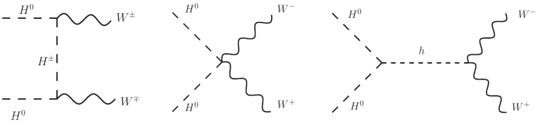

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i.e.
- $\lambda_L < 0$ for $m_{H^0} > M_h/2$
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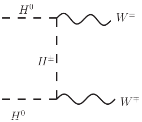
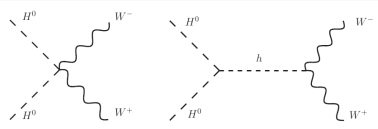
- always need : $m_{H^0} < M_h, m_t$





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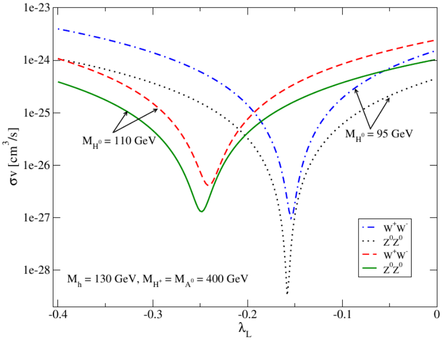

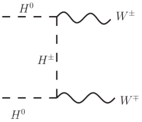

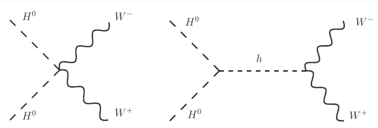

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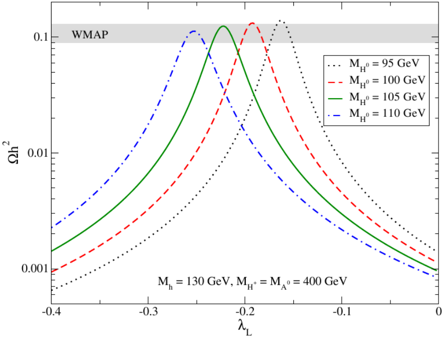
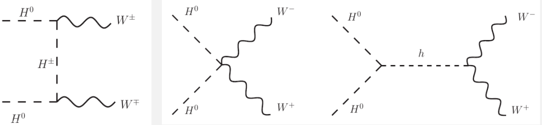




New viable parameter space thanks to cancellations

Result of a scan for $m_{H^0} > m_W$ and $\Omega_{H_0} = \Omega_{WMAP}$

$\lambda_L > 0$ $M_{Ho} < M_h/2$

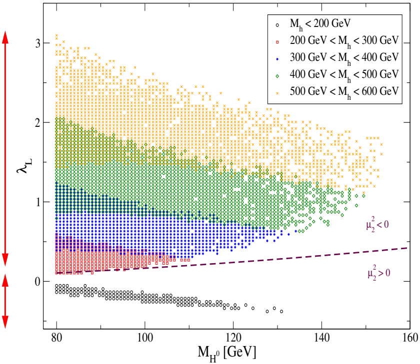
200 GeV < M_h < 600 GeV

up to M_{Ho} ~ 160 GeV

$\lambda_L < 0$ $M_{Ho} > M_h/2$

for M_h < 200 GeV

up to M_{Ho}=130 GeV



New viable parameter space thanks to cancellations

Result of a scan for $m_{H^0} > m_W$ and $\Omega_{H_0} = \Omega_{WMAP}$

$\lambda_L > 0$ $M_{Ho} < M_h/2$

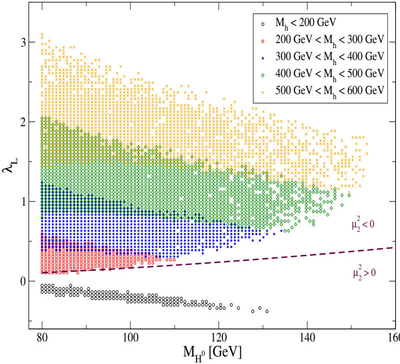
200 GeV < M_h < 600 GeV

up to M_{Ho} ~ 160 GeV

$\lambda_L < 0$ $M_{Ho} > M_h/2$

for M_h < 200 GeV

up to M_{Ho}=130 GeV

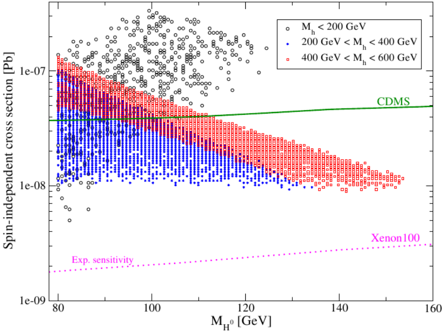


NB : IDM can comply with EWPT measurements for large M_h as Barbieri '06 :

$\Delta T_{H_0,H^+,A_0}$ can compensate negative T_h for $m_{H^+} > m_{A_0}, m_{H^0}$

Direct Detection searches

... A very efficient probe of the $m_{H^0} > m_W$ parameter space :



Remember :

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

and for cancellations,

λ_L is necessarily non zero

⇝ a large fraction of the parameter space is already ruled out by CDMS Ahmed '10

the remaining viable param. space is within the reach of Xenon 100 Aprile '10

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
- Cancellations between diagrams contributing to $H_0 H_0 \to ZZ, WW$ $\rightsquigarrow$ new viable region from W-threshold up to $m_{H^0} \sim 130$ (160) GeV for M_h <200 GeV (600 GeV)
- The genuine DM viable parameter space next to W threshold was derived
  - below W-threshold : λ_L is reduced up to $\mathcal{O}\,(10)$
  - above W-threshold : $\lambda_L > 0\,(< 0)$ for $m_{H^0} < M_h/2$ ($m_{H^0} > M_h/2$)
- Prospects for DM detection are modified
  - Direct detection :
    below W-threshold σ_{H_0-N} decreases by a factor $\mathcal{O}\,(100)$
    above W-threshold within the reach of Xenon 100

This is the End

Thank you for your attention ! !

Backup

Important 3-body processes : Is that so surprising ?

3-body processes can take over 2-body processes

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

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

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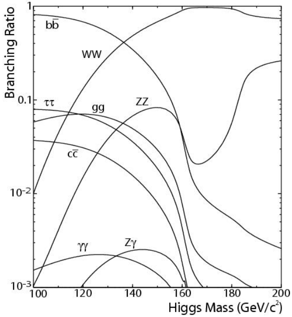
Well known example : higgs decay
$\mathrm{BR}(h \to WW^*) \gg \mathrm{BR}(h \to \bar{b}b)$ for $m_h \lesssim 2M_W$



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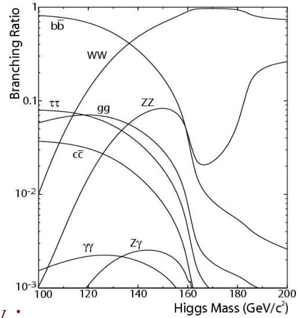
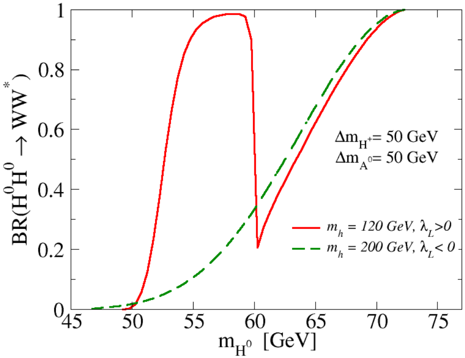


3-body processes can enhance DM annihilation/decay :

$\rightsquigarrow$ 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],
Higgs DM [Hosotani, Ko & Tanaka PLB'09], singlet scalar DM [Yaguna PRD'10],
Inert Doublet Model [LLH & Yaguna JHEP'10]

For Indirect Detection



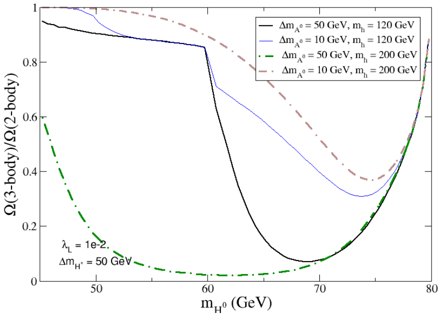
annihilations no more $\bar{b}b$ dominated

$\rightsquigarrow$ BR$(H_0 H_0 \to WW^*) \sim 1$

for m_{H^0} near W threshold

work in progress...

Coannihilation-fixed parameter

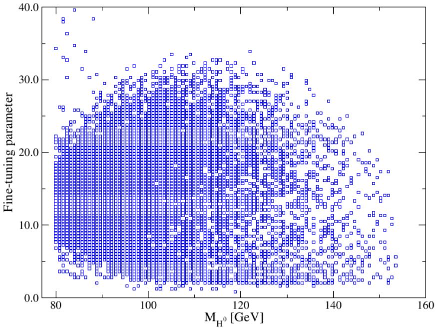


Above W threshold - fine tuning ?

a_i ($i = 1, ..., n$) are free parameters of a given dark matter model, the fine-tuning parameter

$$\Delta_{\Omega h^2, a_i} \equiv \frac{\partial \log \Omega h^2}{\partial \log a_i} .$$

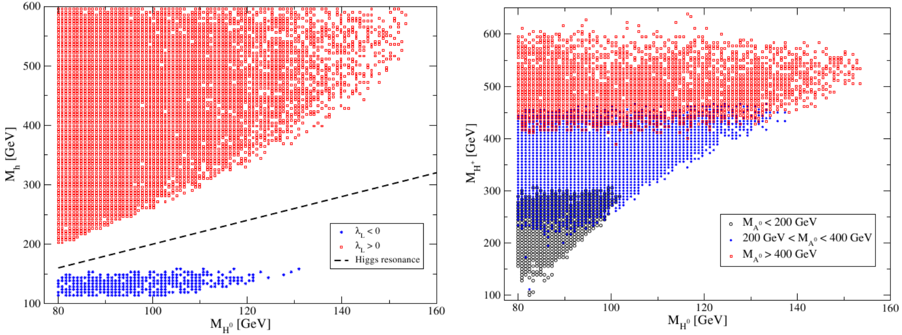
And the total fine-tuning, $\Delta_{\Omega h^2,\text{total}}$, is obtained by summing in quadrature the contributions of the different parameters of the model



$$\Delta_{\Omega h^2,\text{total}} = \sqrt{\Delta^2_{\Omega h^2, m_{H0}} + \Delta^2_{\Omega h^2, m_{H+}} + \Delta^2_{\Omega h^2, m_{A_0}} + \Delta^2_{\Omega h^2, \lambda_L} + \Delta_{\Omega h^2, M_h}^2} .$$

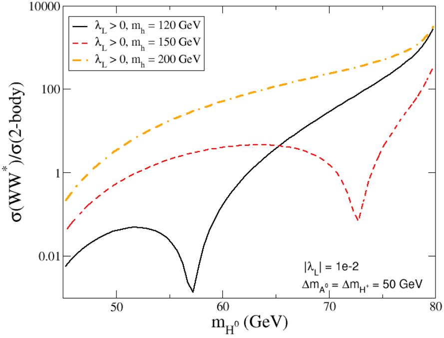
The fine-tuning parameter is large if a small variation in the parameters of the models leads to a large modification of the relic density. If, for instance, $\Delta_{\Omega h^2,\text{total}} \lesssim 10$, a measurement of the parameters of the model at the 10% level will enable to compute Ωh^2 to within a factor $\mathcal{O}(2)$. As a rule of thumb, one can say that the fine-tuning is small if $\Delta_{\Omega h^2,\text{total}} \lesssim 10$.

Cancellations require increasing M_h, m_{H^+}, m_{A_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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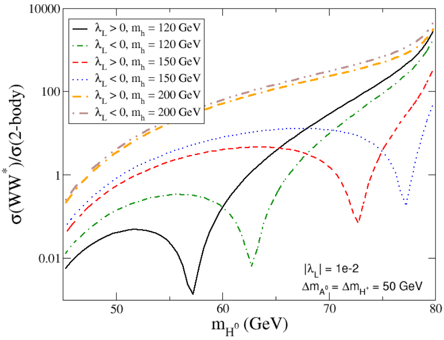

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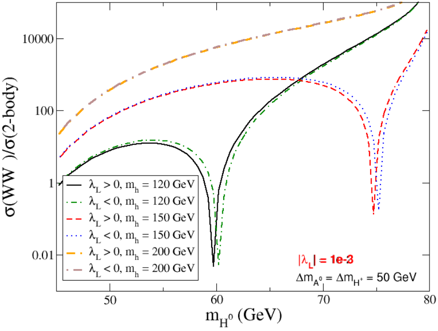


- $\lambda_L = 10^{-2}$

  ... 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

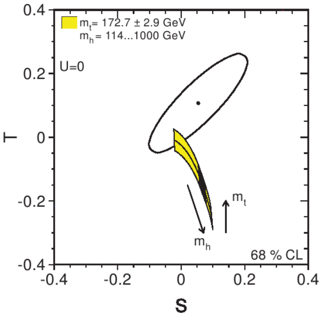
Mass Ranges	main contributions to σ_{eff}	mass splittings	main Refs
$m_{H_0} \ll m_W (\mathcal{O}(GeV))$	$H_0H_0 \to h^* \to \bar{f}f$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \sim 90$ GeV	Andreas *et* all '08
$m_{H_0} \lesssim m_W$	$H_0H_0 \to h^* \to \bar{f}f$ $H_0A_0(H^+) \to Z^*(W^*) \to \bar{f}f^{(')}$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \gtrsim 7$ GeV	Barbieri *et* all '06 LLH *et* all '06
$m_{H_0} \gg m_W (\mathcal{O}(TeV))$	$H_0H_0 \to ZZ, WW, hh$ coannihil into bosons	$\Delta m_{ij} \lesssim 17.6$ GeV	Hambye *et* all '09

How to conciliate Heavy Higgs and EWPT measurements ?

New physics affect EW observables

Contributions to EWPT measurement variable T from :

- Higgs : $T(M_h) = -\frac{3}{8\pi \cos^2\theta_W} \ln \frac{M_h}{M_Z}$.
- H_2 scalars : $\Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(M_{H^+} - M_{A_0})(M_{H^+} - M_{H_0})$



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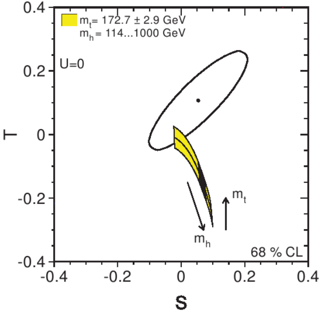


$\rightsquigarrow$ When $M_{H^+} > M_{A_0}, M_{H_0}$ positive contributions from ΔT can compensate the too large negative contributions from $T(M_h)$ due to heavy Higgs.

$\rightsquigarrow$ With H_2 new physics one may push M_h up to 500-600 GeV [Barbieri *et al* '06]

IDM : Potential - constraints

- Full Potential

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

- 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

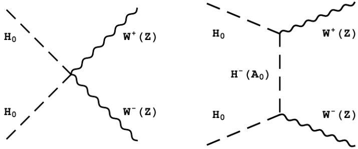
$$\lambda_{1,2} > 0\ ,$$
$$\lambda_{H0}\ ,\quad \lambda_{A_0}\ ,\quad \lambda_{H_c} > -\sqrt{\lambda_1\lambda_2}\ .$$

- 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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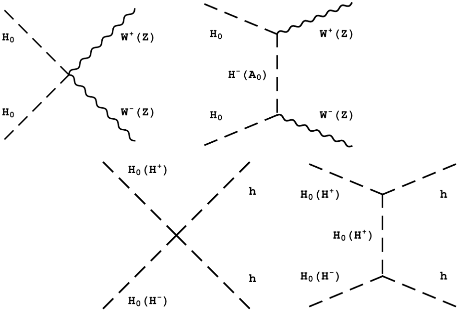

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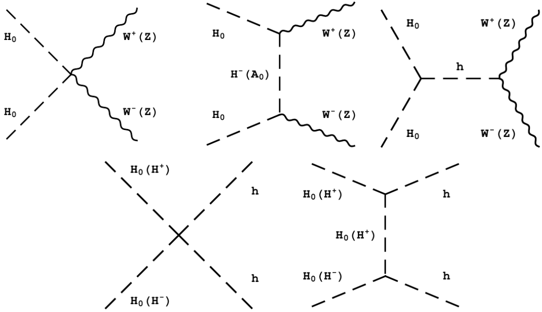

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where $\sigma_\lambda^{ij} = \frac{\Lambda^{ij}}{m_{H_0}^2}$ with $\Lambda^{ij} \propto \lambda * \lambda$ and $\Lambda^{ij} > 0$

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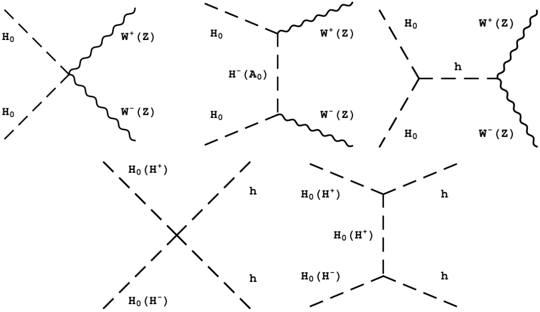

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- $m^* \sim 534$ GeV is minimal to satisfy WMAP

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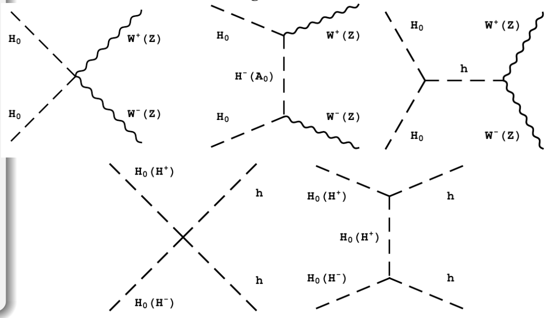

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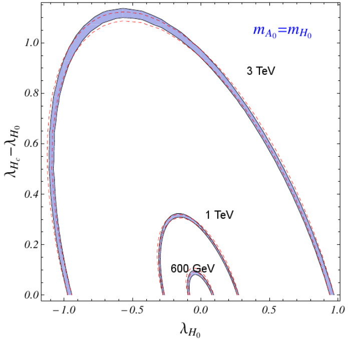
- for fixed m_{H_0} and $\sigma_{\rm eff}$ λ_i lie on ellipsoid surface



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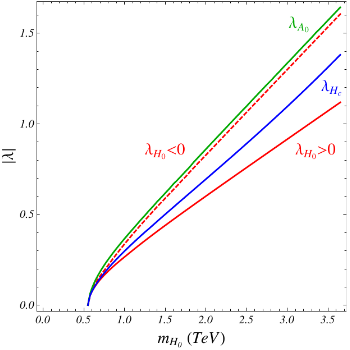

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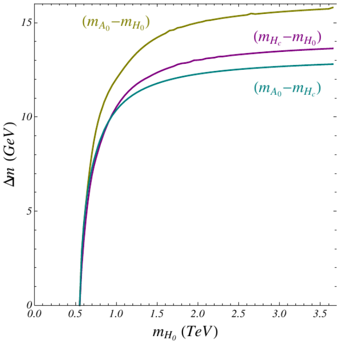
- $m^* \sim 534$ GeV is minimal to satisfy WMAP
- for fixed m_{H_0} and $\sigma_{\rm eff}$ λ_i lie on ellipsoid surface
  $\rightsquigarrow \lambda_i$ are bounded, $\lambda_i^{max} \propto m_{H_0}$ at high mass.
- mass splittings are also bounded as $m_i - m_j \propto (\lambda_i - \lambda_j)/m_{H_0}$



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