The Inert doublet model as a scalar WIMP model for dark matter

Laura Lopez Honorez

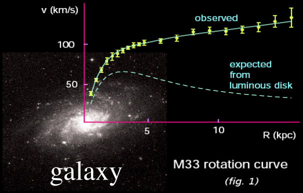
based on:

The Inert Doublet Model: An Archetype for Dark Matter:JCAP 0702:028
Scalar Multiplet Dark Matter: JHEP 0907:090
The inert doublet model of dark matter revisited:JHEP 1009:046
A new viable region of the inert doublet model: JCAP 1101:002

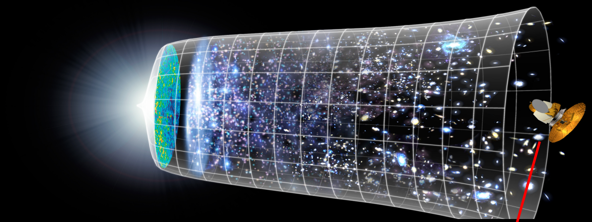
in collaboration with

T. Hambye, F. S. Ling, E. Nezri, J. Rocher, M. Tytgat, C. Yaguna

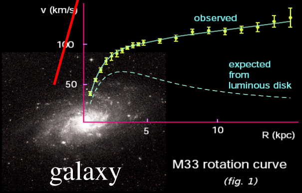
Particle and Astroparticle Theory Seminar -MPIK Heidelberg



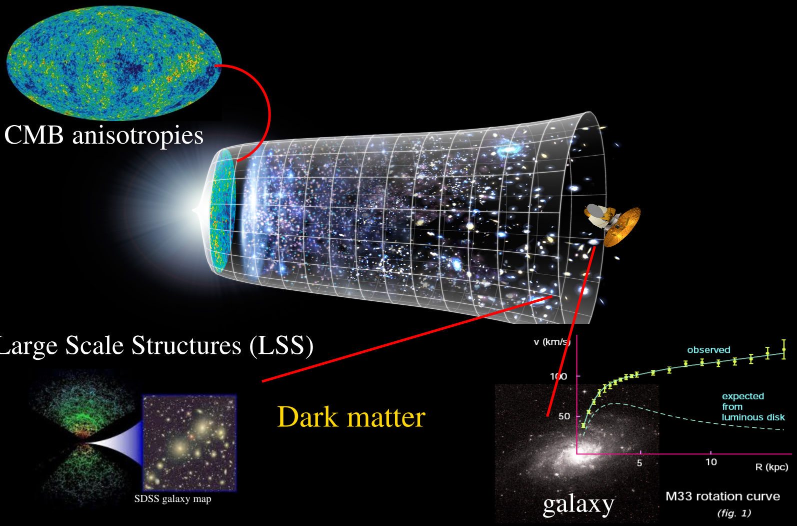
The Quest to determine the Composition of our Universe



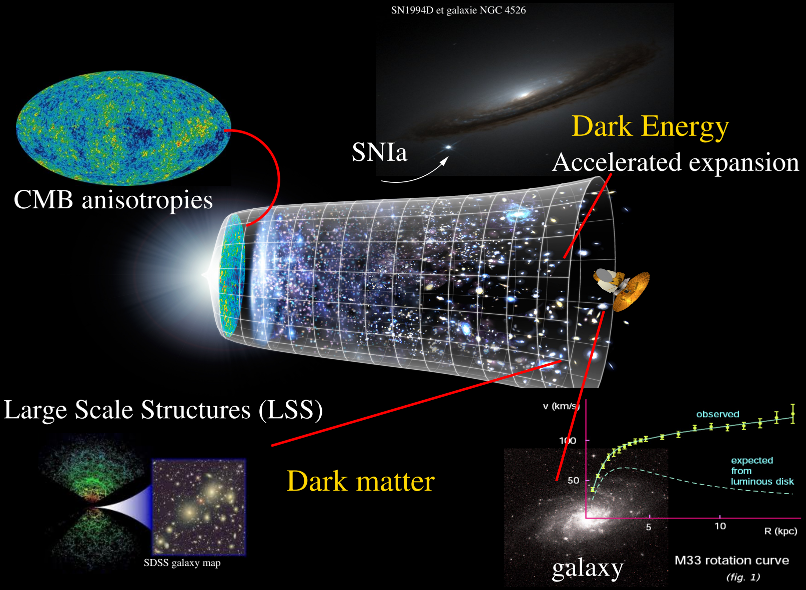
Dark matter



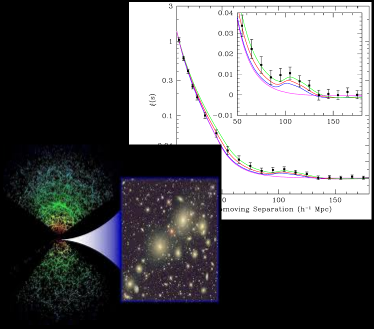
The Quest to determine the Composition of our Universe

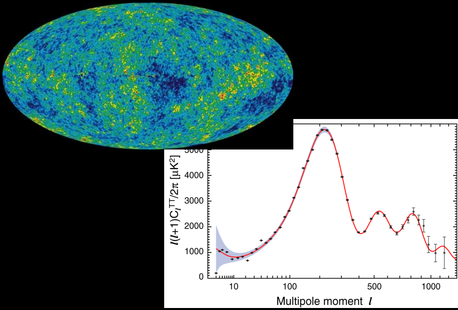


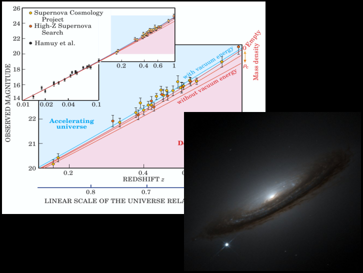
The Quest to determine the Composition of our Universe



The Quest to determine the Composition of our Universe

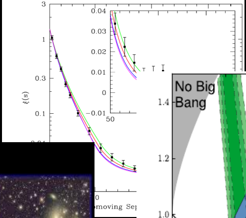

ξ(s)
moving Separation (h⁻¹ Mpc)

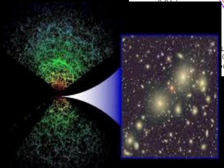

$l(l+1)C_l^{TT}/2\pi$ [μK²]
Multipole moment l

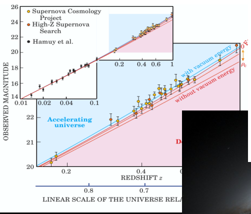

Supernova Cosmology Project
High-Z Supernova Search
Hamuy et al.
OBSERVED MAGNITUDE
with vacuum energy
without vacuum energy
Empty
Mass density
Accelerating universe
REDSHIFT z
LINEAR SCALE OF THE UNIVERSE REL

SDSS

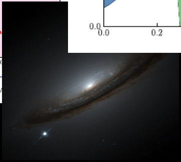
Eisenstein et al 2005

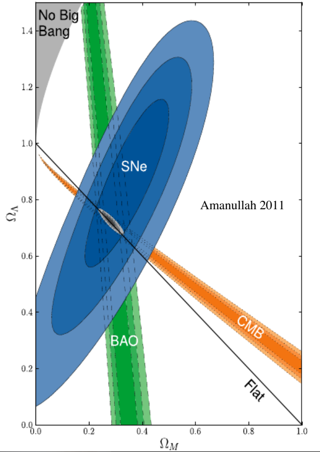


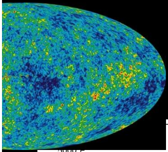


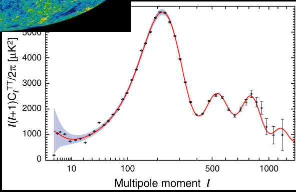


Pelmutter 2003







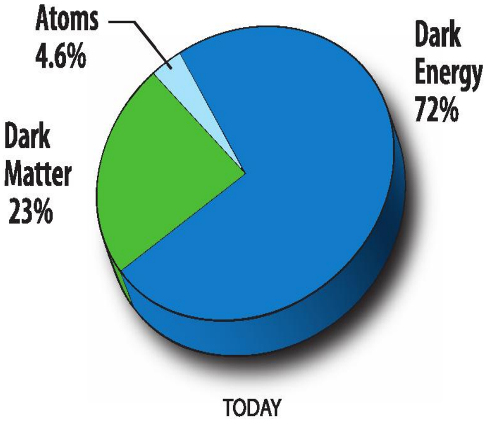


WMAP7, Larson et al 2010

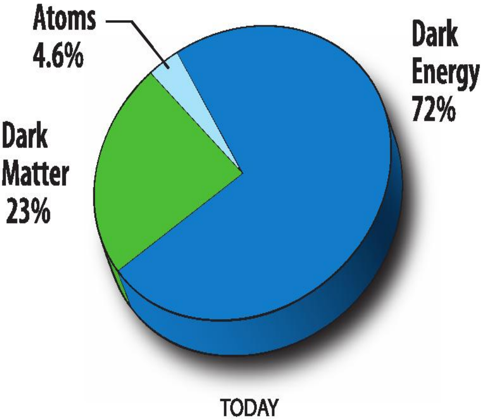
Concordance for a flat Universe today made of

~ 70% of dark energy as a Cosmo. Cst.

~ 30% of matter

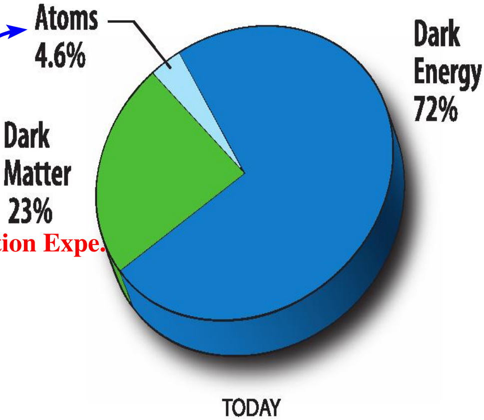

Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY

In other words $\Omega_{dm} h^2 = 0.1099$ (WMAP5)



In other words $\Omega_{dm} h^2 = 0.1099$ (WMAP5)

In this TALK! **Scalar DM Model** **Viable param. space**



+ Constraints from DM detection Expe.

WIMP as dark matter

Minimal DM spirit : SM + one $SU(2)_L$ n-uplet see Cirelli *et* all '05-'09

- DM = neutral member of the n-uplet
- stability $\rightsquigarrow$ usually extra Z_2 symmetry

WIMP as dark matter

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

- DM = neutral member of the n-uplet
- stability $\rightsquigarrow$ usually extra Z_2 symmetry

- Fermion multiplets : very predictive
  - all (co)annihilation are *known* gauge $\mathrm{SU}(2)_L \times \mathrm{U}(1)$ processes
  - *only one* free parameter m_{DM} to fix to match WMAP

WIMP as dark matter

Minimal DM spirit : SM + one $SU(2)_L$ n-uplet see Cirelli *et* all '05-'09

- DM = neutral member of the n-uplet
- stability $\rightsquigarrow$ usually extra Z_2 symmetry

- Fermion multiplets : very predictive
  - all (co)annihilation are *known* gauge $SU(2)_L \times U(1)$ processes
  - *only one* free parameter m_{DM} to fix to match WMAP

- Scalar multiplets H_n :
  - extra quartic coupling λ_i to Higgs H_1
  - a *range* free parameters : $\{m_{DM}, \lambda_i\}$ is compatible with Ω_{DM}^{WMAP}

Scalar DM model

- Extra n-uplet case ($n > 2$) :
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

Scalar DM model

- Extra n-uplet case ($n > 2$) :
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

$\rightsquigarrow$ multi-TeV range viable only

Scalar DM model

- Extra n-uplet case ($n > 2$) :
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

$\rightsquigarrow$ multi-TeV range viable only

- Particular case : $n = 2 \equiv$ IDM
  - three couplings to the Higgs.

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

  - non zero mass splittings :

$$H_2 = \begin{pmatrix} iH^+ \\ \frac{(H_0 - iA_0)}{\sqrt{2}} \end{pmatrix} \quad H_1 = \begin{pmatrix} 0 \\ \frac{(h + v_0)}{\sqrt{2}} \end{pmatrix}$$

Scalar DM model

- Extra n-uplet case ($n > 2$) :
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

$\rightsquigarrow$ multi-TeV range viable only

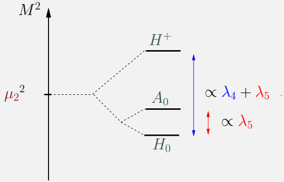
- Particular case : $n = 2 \equiv$ IDM
  - three couplings to the Higgs.

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

  - non zero mass splittings :

$$H_2 = \begin{pmatrix} iH^+ \\ \frac{(H_0 - iA_0)}{\sqrt{2}} \end{pmatrix} \quad H_1 = \begin{pmatrix} 0 \\ \frac{(h + v_0)}{\sqrt{2}} \end{pmatrix}$$

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



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

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

Scalar DM model

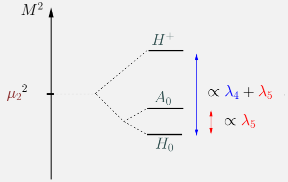
- Extra n-uplet case $(n > 2)$:
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

$\rightsquigarrow$ multi-TeV range viable only

- Particular case : $n = 2 \equiv$ IDM
  - three couplings to the Higgs.
    $\frac{1}{2}\left(\lambda_{H_0} H_0^2 + \lambda_{A_0} A_0^2 + 2\lambda_{H_c} H^+ H^-\right)\left(2v_0 h + h^2\right)$
  - non zero mass splittings :
    $$H_2 = \begin{pmatrix} iH^+ \\ \frac{(H_0 - iA_0)}{\sqrt{2}} \end{pmatrix} \quad H_1 = \begin{pmatrix} 0 \\ \frac{(h + v_0)}{\sqrt{2}} \end{pmatrix}$$

$\rightsquigarrow$ viable mass ranges $m_{H_0} \sim$ GeV-TeV range

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



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

We will refer to $H_0 - h$ coupling as $\lambda_{H_0} = \lambda_L$

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

More on the Inert doublet model

More on the Inert doublet model

- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle \sigma v_{eff} \rangle$
  Including $H_0 H_0 \to XX$ and $H_0 A_0, H_0 H^{\pm} \to XX$
  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...

More on the Inert doublet model

- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle \sigma v_{eff} \rangle$
  Including $H_0 H_0 \to XX$ and $H_0 A_0, H_0 H^\pm \to XX$
  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...
- Extra Constraints

More on the Inert doublet model

- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle\sigma v_{eff}\rangle$
  Including $H_0H_0 \to XX$ and $H_0A_0, H_0H^\pm \to XX$
  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...
- Extra Constraints
  - Vacuum stability : $\lambda_1, \lambda_2 > 0$ and $\lambda_L, \lambda_{H_c} > -\sqrt{\lambda_1\lambda_2}$
  - Inert Vacuum : $\mu_1^4/\lambda_1 < \mu_2^4/\lambda_2$ [Ginzburg et al PRD 82]
  - Perturbativity : strong couplings $|\lambda| > 4\pi$ are excluded

More on the Inert doublet model

- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle \sigma v_{eff} \rangle$
  Including $H_0 H_0 \to XX$ and $H_0 A_0, H_0 H^{\pm} \to XX$
  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...
- Extra Constraints
  - Vacuum stability : $\lambda_1, \lambda_2 > 0$ and $\lambda_L, \lambda_{H_c} > -\sqrt{\lambda_1 \lambda_2}$
  - Inert Vacuum : $\mu_1^4/\lambda_1 < \mu_2^4/\lambda_2$ [Ginzburg et al PRD 82]
  - Perturbativity : strong couplings $|\lambda| > 4\pi$ are excluded
  - No new contribution to the Z decay
  - No new low mass charged particles : $m_{H^\pm} > 90$ GeV see e.g. [Pierce & Thaler JHEP07]

More on the Inert doublet model

- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle \sigma v_{eff} \rangle$
  Including $H_0 H_0 \to XX$ and $H_0 A_0, H_0 H^\pm \to XX$
  using micrOMEGAs G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...

- Extra Constraints
  - Vacuum stability : $\lambda_1, \lambda_2 > 0$ and $\lambda_L, \lambda_{H_c} > -\sqrt{\lambda_1 \lambda_2}$
  - Inert Vacuum : $\mu_1^4/\lambda_1 < \mu_2^4/\lambda_2$ [Ginzburg et al PRD 82]
  - Perturbativity : strong couplings $|\lambda| > 4\pi$ are excluded
  - No new contribution to the Z decay
  - No new low mass charged particles : $m_{H^\pm} > 90$ GeV see e.g. [Pierce & Thaler JHEP07]
  - σ_{H_0-p} below the existing limits from direct detection searches
    $\rightsquigarrow$ Need a splitting $m_{A_0} - m_{H_0} \neq 0$

More on the Inert doublet model

- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle \sigma v_{eff} \rangle$
  Including $H_0 H_0 \to XX$ and $H_0 A_0, H_0 H^\pm \to XX$
  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...

- Extra Constraints
  - Vacuum stability : $\lambda_1, \lambda_2 > 0$ and $\lambda_L, \lambda_{H_c} > -\sqrt{\lambda_1 \lambda_2}$
  - Inert Vacuum : $\mu_1^4/\lambda_1 < \mu_2^4/\lambda_2$ [Ginzburg et al PRD 82]
  - Perturbativity : strong couplings $|\lambda| > 4\pi$ are excluded
  - No new contribution to the Z decay
  - No new low mass charged particles : $m_{H^\pm} > 90$ GeV see e.g. [Pierce & Thaler JHEP07]
  - σ_{H_0-p} below the existing limits from direct detection searches
    $\rightsquigarrow$ Need a splitting $m_{A_0} - m_{H_0} \neq 0$
  - EWPT measurements : heavy higgs allowed [Barbieri et al '06]
    $\rightsquigarrow$ need $m_{H_0} - m_{H^\pm} \neq 0$ and $m_{A_0} - m_{H^\pm} \neq 0$ with $m_{H^\pm} > m_{H_0}, m_{A_0}$

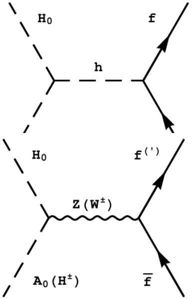
A first systematic study of the viable parameter space

based on LLH, Nezri, Oliver, Tytgat JCAP07

- $m_{H_0} \lesssim m_W$: GeV range

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

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



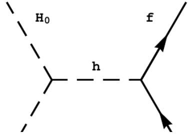
A first systematic study of the viable parameter space

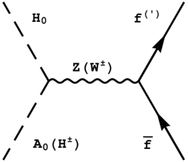
based on LLH, Nezri, Oliver, Tytgat JCAP07

- $m_{H_0} \lesssim m_W$: GeV range

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

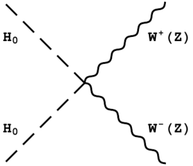
  Barbieri PRD06, LLH JCAP06,Gustafsson PRL07, Cao PRD07, Andreas JCAP08,...





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

  Cirelli NPB06, Hambye JHEP09



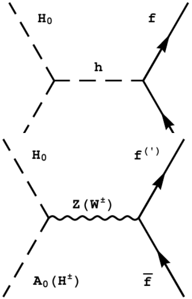
A first systematic study of the viable parameter space

based on LLH, Nezri, Oliver, Tytgat JCAP07

- $m_{H_0} \lesssim m_W$: GeV range

  $H_0H_0 \to h^* \to \bar{f}f$ and $H_0A_0 \to Z^* \to \bar{f}f$

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

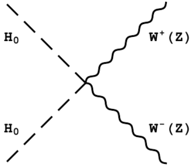


LARGE MASS GAP DUE TO EFFICIENT
WW AND *ZZ* ANNIHILATION

- $m_{H_0} \gg m_W$: TeV range

  $H_0H_0 \to ZZ, WW, hh$ and coannihil into bosons

  Cirelli NPB06, Hambye JHEP09



The High mass regime

based on: Scalar Multiplet Dark Matter
Hambye, Ling, LLH, J. Rocher

JHEP 09

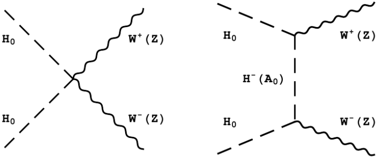
IDM in the High mass regime : Relic abundance

IDM in the High mass regime : Relic abundance

Quartic couplings OFF : pure gauge

$$m_{H_0} = m_{A_0} = m_{H_c} \gg m_{W,Z}, m_h$$

e.g. contribution to σ_g^{00} : $H_0 H_0 \to XX$

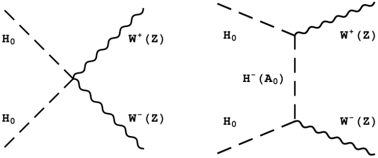


IDM in the High mass regime : Relic abundance

Quartic couplings OFF : pure gauge

$$m_{H_0} = m_{A_0} = m_{H_c} \gg m_{W,Z}, m_h$$

e.g. contribution to σ_g^{00} : $H_0 H_0 \to XX$



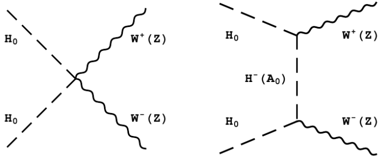
$$\sigma_{\rm eff} = \sum_{ij} \sigma_g^{ij} \propto \frac{g^4}{m_{H_0}^2}$$

IDM in the High mass regime : Relic abundance

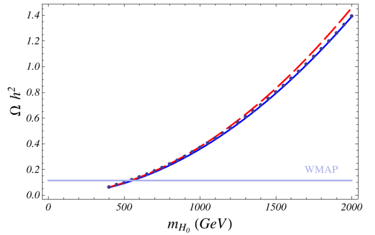
Quartic couplings OFF : pure gauge

$$m_{H_0} = m_{A_0} = m_{H_c} \gg m_{W,Z}, m_h$$

e.g. contribution to σ_g^{00} : $H_0 H_0 \to XX$



$$\sigma_{\text{eff}} = \sum_{ij} \sigma_g^{ij} \propto \frac{g^4}{m_{H_0}^2}$$



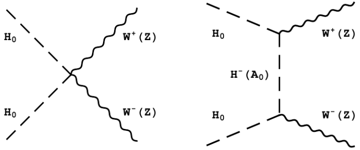
$\rightsquigarrow$ Only $m_{H_0} = m^* \sim 534$ GeV satisfy WMAP

in agreement with Cirelli *et* all '05

IDM in the High mass regime : Relic abundance

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

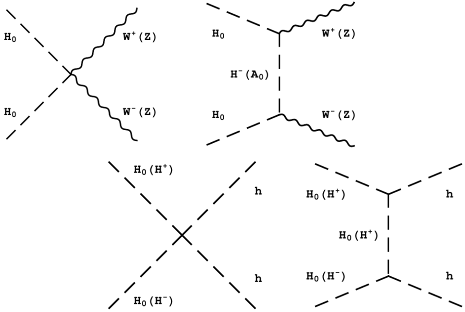
for *e.g.* $H_0 H_0 \to XX$



IDM in the High mass regime : Relic abundance

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

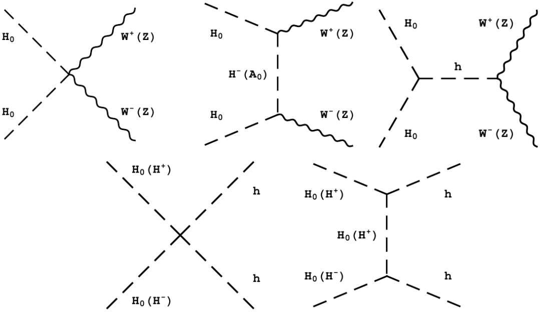
for *e.g.* $H_0 H_0 \to XX$



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.* $H_0 H_0 \to XX$



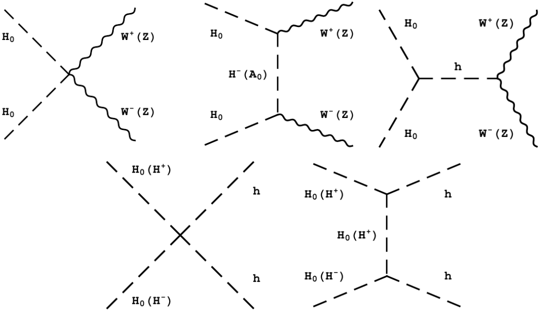
IDM in the High mass regime : Relic abundance

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

$$\sigma_{\rm eff} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij}\right) \propto \frac{1}{m_{H_0}^2}$$

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

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



IDM in the High mass regime : Relic abundance

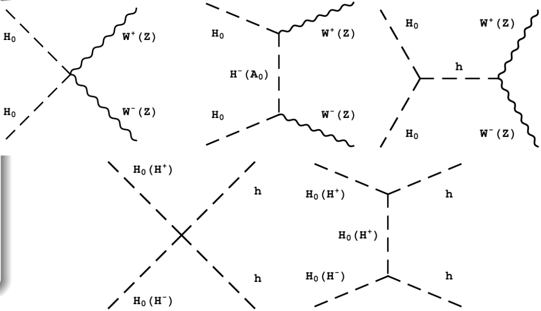
Quartic couplings ON : extra Higgs processes and $m_{H_0} \neq m_{A_0} \neq m_{H_c}$

$$\sigma_{\rm eff} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij} \right) \propto \frac{1}{m_{H_0}^2}$$

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

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

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



IDM in the High mass regime : Relic abundance

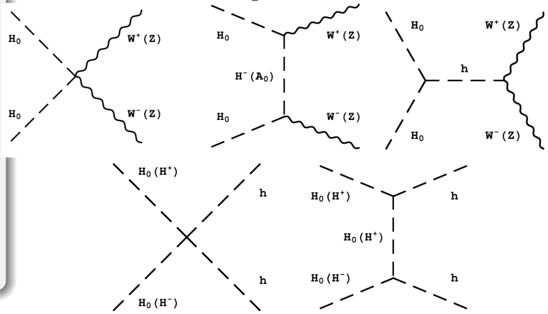
Quartic couplings ON : extra Higgs processes and $m_{H_0} \neq m_{A_0} \neq m_{H_c}$

$$\sigma_{\text{eff}} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij} \right) \propto \frac{1}{m_{H_0}^2}$$

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

- $m^* \sim 534$ GeV is minimal to satisfy WMAP
- the expression of $\Lambda \rightsquigarrow \lambda_i^{max}$ with at large mass $\lambda_i^{max} \propto m_{H_0}$

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



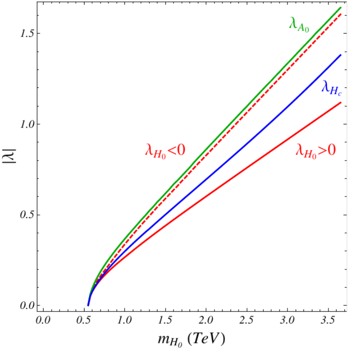
IDM in the High mass regime : Relic abundance

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

$$\sigma_{\rm eff} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij}\right) \propto \frac{1}{m_{H_0}^2}$$

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

- $m^* \sim 534$ GeV is minimal to satisfy WMAP
- the expression of $\Lambda \rightsquigarrow \lambda_i^{max}$ with at large mass $\lambda_i^{max} \propto m_{H_0}$



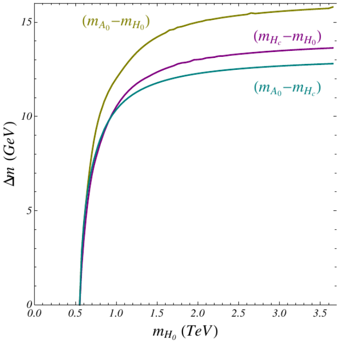
IDM in the High mass regime : Relic abundance

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

$$\sigma_{\rm eff} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij} \right) \propto \frac{1}{m_{H_0}^2}$$

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

- $m^* \sim 534$ GeV is minimal to satisfy WMAP
- the expression of $\Lambda \rightsquigarrow \lambda_i^{max}$ with at large mass $\lambda_i^{max} \propto m_{H_0}$
- mass splittings are bounded as $m_i - m_j \propto (\lambda_i - \lambda_j)/m_{H_0}$ $\rightsquigarrow$ no heavy higgs



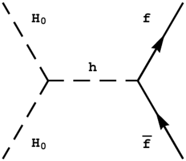
Cancellations above W threshold

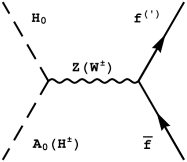
based on:

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

LLH & Yaguna

Inert doublet model viable parameter space



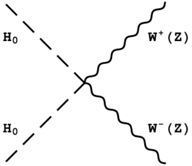


- $m_{H_0} \lesssim m_W$: GeV range

  $H_0 H_0 \to h^* \to \bar{f} f$ 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

  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

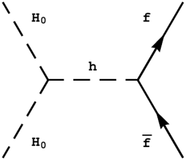
  Cirelli NPB06, Hambye JHEP09

Inert doublet model viable parameter space

- $m_{H_0} \lesssim m_W$: GeV range

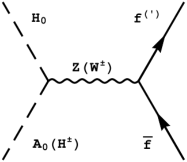
  $H_0 H_0 \to h^* \to \bar{f}f$ and $H_0 A_0 \to Z^* \to \bar{f}f$

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



- 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

- $m_{H_0} \gg m_W$: TeV range

  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

  Cirelli NPB06, Hambye JHEP09

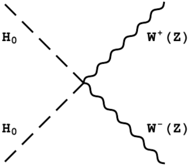


Illustration of cancellation in 2 body processes

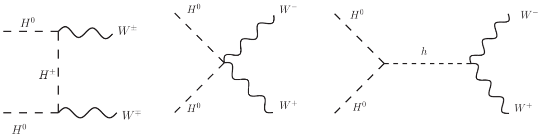


Illustration of cancellation in 2 body processes

Destructive interf. possible for :

$$\lambda_L \simeq \frac{-2(m_{H^0}^2 - (M_h/2)^2)}{v^2}$$

- $\lambda_L < 0$ for $m_{H^0} > M_h/2$
- $\lambda_L > 0$ for $m_{H^0} < M_h/2$

always need : $m_{H^0} < M_h, m_t$

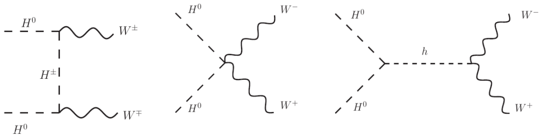


Illustration of cancellation in 2 body processes

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

Destructive interf. possible for :

$$\lambda_L \simeq \frac{-2(m_{H^0}^2 - (M_h/2)^2)}{v^2}$$

- $\lambda_L < 0$ for $m_{H^0} > M_h/2$
- $\lambda_L > 0$ for $m_{H^0} < M_h/2$

always need : $m_{H^0} < M_h, m_t$

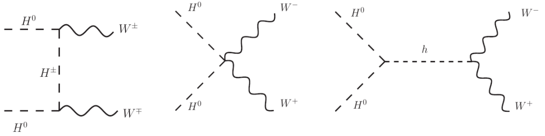


Illustration of cancellation in 2 body processes

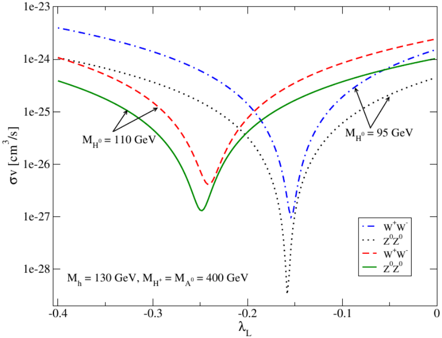
Above W threshold, for fixed parameters, one can obtain $\Omega_{H_0} = \Omega_{dm}^{WMAP}$

Destructive interf. possible for :

$$\lambda_L \simeq \frac{-2(m_{H^0}^2 - (M_h/2)^2)}{v^2}$$

- $\lambda_L < 0$ for $m_{H^0} > M_h/2$
- $\lambda_L > 0$ for $m_{H^0} < M_h/2$

always need : $m_{H^0} < M_h, m_t$



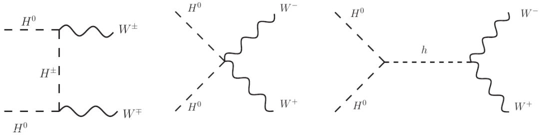


Illustration of cancellation in 2 body processes

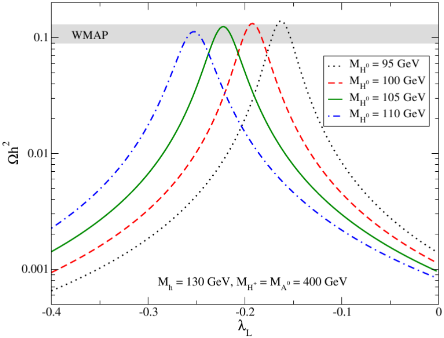
Above W threshold, for fixed parameters, one can obtain $\Omega_{H_0} = \Omega_{dm}^{WMAP}$

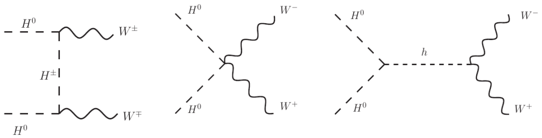
Destructive interf. possible for :

$$\lambda_L \simeq \frac{-2(m_{H^0}^2 - (M_h/2)^2)}{v^2}$$

- $\lambda_L < 0$ for $m_{H^0} > M_h/2$
- $\lambda_L > 0$ for $m_{H^0} < M_h/2$

always need : $m_{H^0} < M_h, m_t$





Viable parameter space thanks to cancellations above m_W

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

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

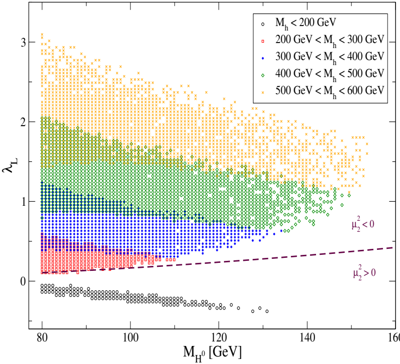
200 GeV < M_h < 600 GeV

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



Viable parameter space thanks to cancellations above m_W

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

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

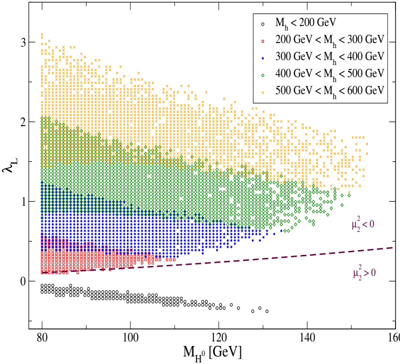
200 GeV < M_h < 600 GeV

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 $m_{H^+} > m_{A_0}, m_{H^0}$

Extra contributions from 3 body annihilations

based on:

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

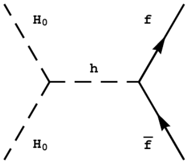
LLH & Yaguna

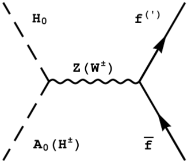
Inert doublet model viable parameter space

- $m_{H_0} \lesssim m_W$: GeV range

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

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

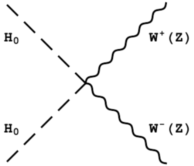




- Above W-threshold : cancellations

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

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



- $m_{H_0} \gg m_W$: TeV range

  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

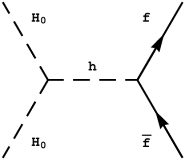
  Cirelli NPB06, Hambye JHEP09

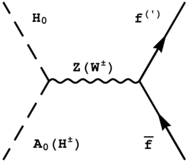
Inert doublet model viable parameter space

- $m_{H_0} \lesssim m_W$: GeV range

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

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

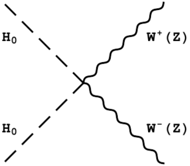




- Above W-threshold : cancellations

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

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



- $m_{H_0} \gg m_W$: TeV range

  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

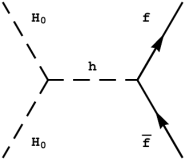
  Cirelli NPB06, Hambye JHEP09

Inert doublet model viable parameter space

- $m_{H_0} \lesssim m_W$: GeV range

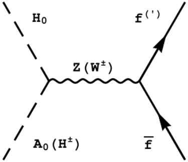
$$H_0 H_0 \to h^* \to \bar{f} f \text{ and } H_0 A_0 \to Z^* \to \bar{f} f$$

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



Significantly affected by 3bdy annihilation :

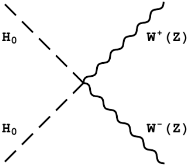
$$H_0 H_0 \to W W^* \to W \bar{f} f'$$



- Above W-threshold : cancellations

$$H_0 H_0 \to WW \text{ vs } H_0 H_0 \to h \to WW$$

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



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

Cirelli NPB06, Hambye JHEP09

Importance of 3-body processes : Is that so surprising ?

3-body processes can take over 2-body processes

3-body ≡ real + virtual massive particle

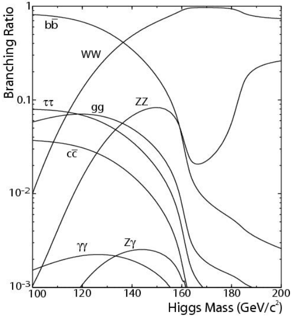
e.g. $WW^* \to W\bar{f}f'$

Importance of 3-body processes : Is that so surprising ?

3-body processes can take over 2-body processes

3-body ≡ real + virtual massive particle
e.g. $WW^* \to W\bar{f}f'$

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

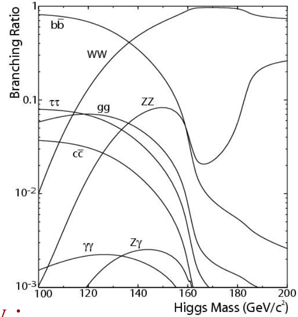


Importance of 3-body processes : Is that so surprising ?

3-body processes can take over 2-body processes

3-body $\equiv$ real + virtual massive particle
e.g. $WW^* \to Wf\bar{f}'$

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



3-body processes can enhance DM annihilation/decay :

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

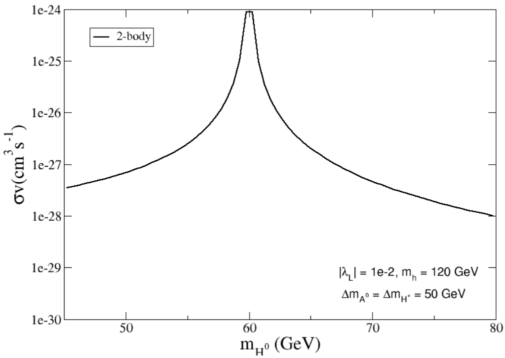
$\rightsquigarrow$ Significant effect on : neutralino LSP [Chen & Kamionkowski JHEP '98, Yaguna PRD'10],
gravitino LSP [Choi & Yaguna '1003,& all '1007],
Higgs DM [Hosotani, Ko & Tanaka PLB'09], singlet scalar DM [Yaguna PRD'10],
Inert Doublet Model [LLH & Yaguna JHEP'10]

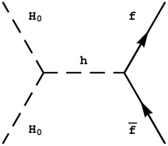
Extra contributions from 3 body annihilations

Analysis for fixed parameters

2-3 body annihilation cross section near m_W threshold

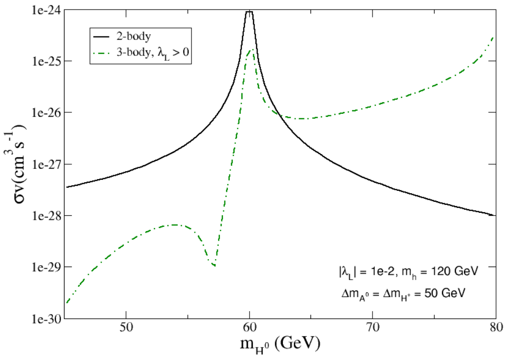
- σv_{2bdy} : higgs mediated,
  $\rightsquigarrow$ suppressed by Yukawa, m_h

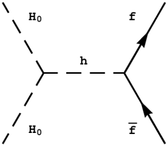


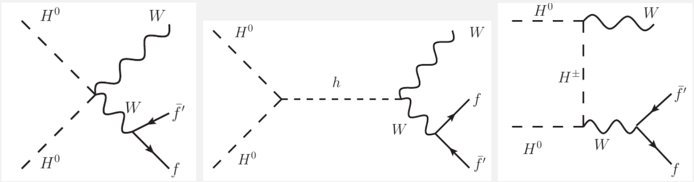


2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
  ⇝ suppressed by Yukawa, m_h
- $\sigma v_{3bdy} = \sigma v(WW^*)$
  ⇝ high multiplicity
  ⇝ gauge unsuppressed



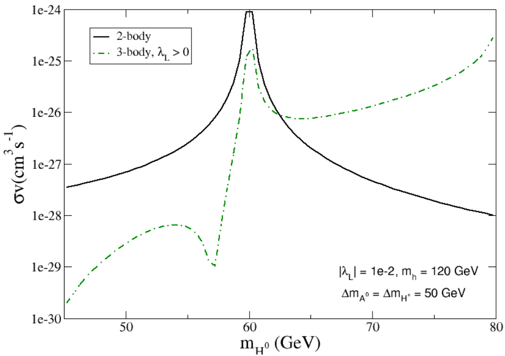


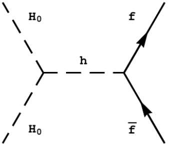


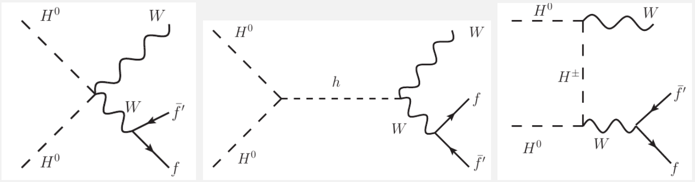
2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
  $\rightsquigarrow$ suppressed by Yukawa, m_h
- $\sigma v_{3bdy} = \sigma v(WW^*)$
  $\rightsquigarrow$ high multiplicity
  $\rightsquigarrow$ gauge unsuppressed

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



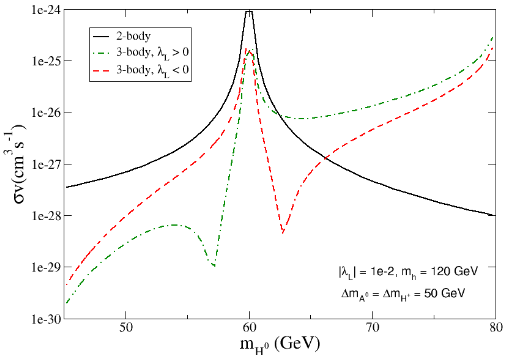


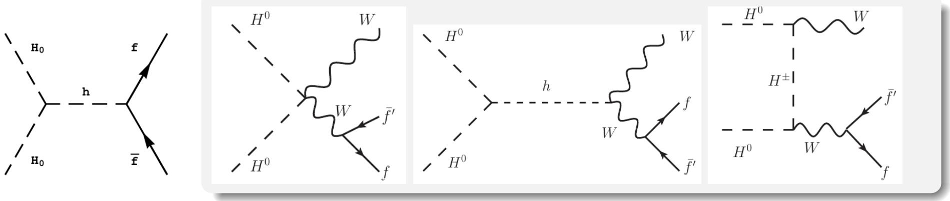


2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
  $\rightsquigarrow$ suppressed by Yukawa, m_h
- $\sigma v_{3bdy} = \sigma v(WW^*)$
  $\rightsquigarrow$ high multiplicity
  $\rightsquigarrow$ gauge unsuppressed

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

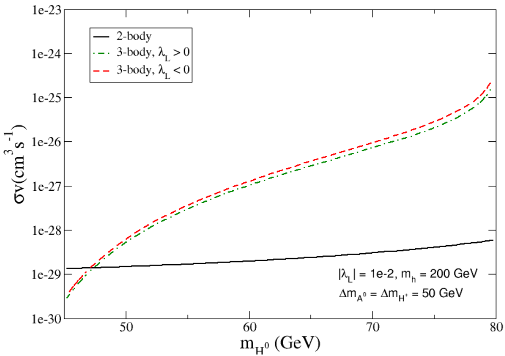


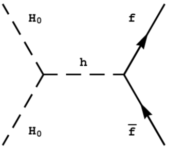


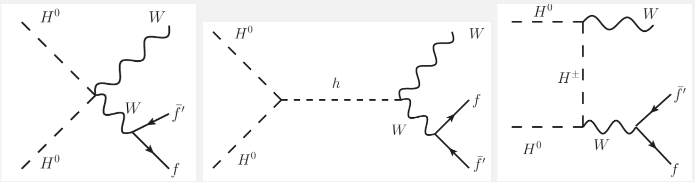
2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
  $\rightsquigarrow$ suppressed by Yukawa, m_h
- $\sigma v_{3bdy} = \sigma v(WW^*)$
  $\rightsquigarrow$ high multiplicity
  $\rightsquigarrow$ gauge unsuppressed

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







Comparing 2-3 body relic density

For what concerns the relic density :

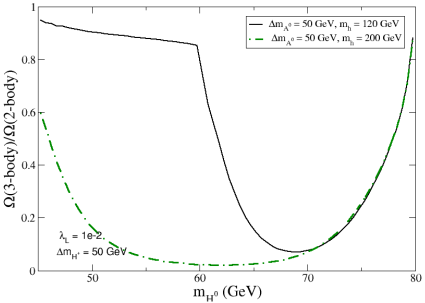
- roughly $\Omega_{dm} \propto 1/\langle \sigma v \rangle$ with
$\langle \sigma v \rangle = \langle \sigma v(\text{ 2-body}) \rangle + \langle \sigma v(WW^*) \rangle$
- We expect
$\Omega_{dm}(\text{3-body}) \lesssim \Omega_{dm}(\text{2-body})$

Comparing 2-3 body relic density

For what concerns the relic density :

- roughly $\Omega_{dm} \propto 1/\langle\sigma v\rangle$ with $\langle\sigma v\rangle = \langle\sigma v(\text{ 2-body})\rangle + \langle\sigma v(WW^*)\rangle$
- We expect $\Omega_{dm}(\text{3-body}) \lesssim \Omega_{dm}(\text{2-body})$

$\rightsquigarrow$ confirmed numerically using modified micrOMEGAs

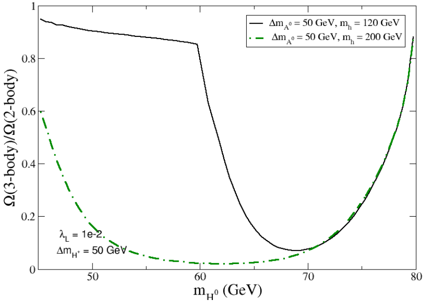


Comparing 2-3 body relic density

For what concerns the relic density :

- roughly $\Omega_{dm} \propto 1/\langle\sigma v\rangle$ with $\langle\sigma v\rangle = \langle\sigma v(\text{ 2-body})\rangle + \langle\sigma v(WW^*)\rangle$
- We expect $\Omega_{dm}(\text{3-body}) \lesssim \Omega_{dm}(\text{2-body})$

$\rightsquigarrow$ confirmed numerically using modified micrOMEGAs



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

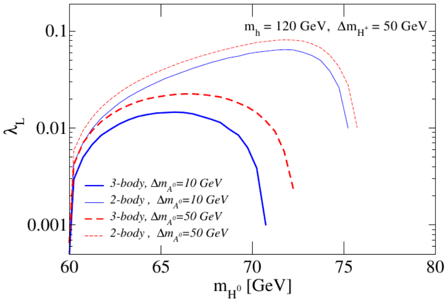
Extra contributions from 3 body annihilations

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

Viable parameter space

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

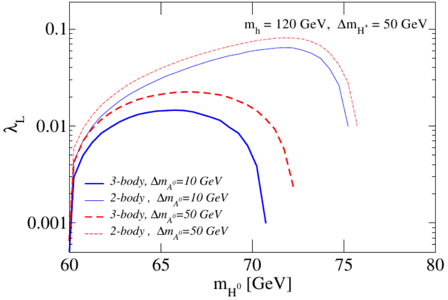
Going from 2bdy only to 2+3bdy with or without coannihilations :



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 :

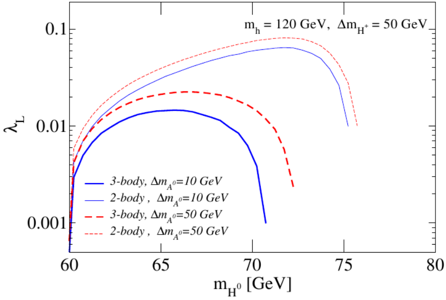


- correct $|\lambda_L|$ is reduced up to $\sim \mathcal{O}(10)$.
- $|\lambda_L| = 0$ at lower m_{H^0}
  - 2bdy settled by the onset of W^+W^- annihilations
  - 2+3bdy depends on WW^* annihilations

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 :



- correct $|\lambda_L|$ is reduced up to $\sim \mathcal{O}(10)$.
- $|\lambda_L| = 0$ at lower m_{H^0}
  - 2bdy settled by the onset of W^+W^- annihilations
  - 2+3bdy depends on WW^* annihilations

rather generic feature of the Inert doublet model independently of m_h

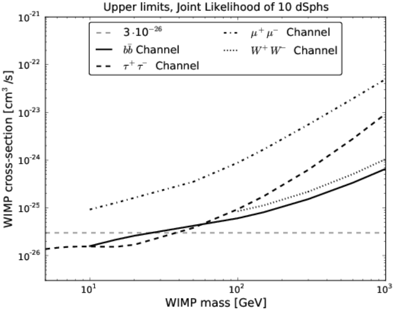
$\rightsquigarrow$ modify prospects for DM detection

Constraints from direct and indirect detection searches

Indirect Detection

Indirect detection searches are becoming a serious treat for low mass WIMP DM.
Typically $\langle \sigma v \rangle \sim 10^{-26} \mathrm{cm}^3/\mathrm{s}$

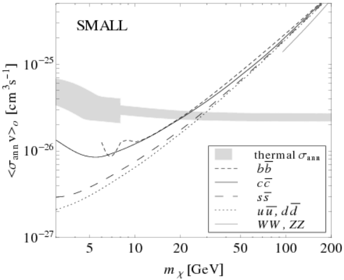
First this year, using gamma rays :



From the analysis of 10 dSphs with the Fermi-LAT.

[Llena Garde, Conrad, Cohen-Tanugi et all '11]

Recently, using anti-proton flux :

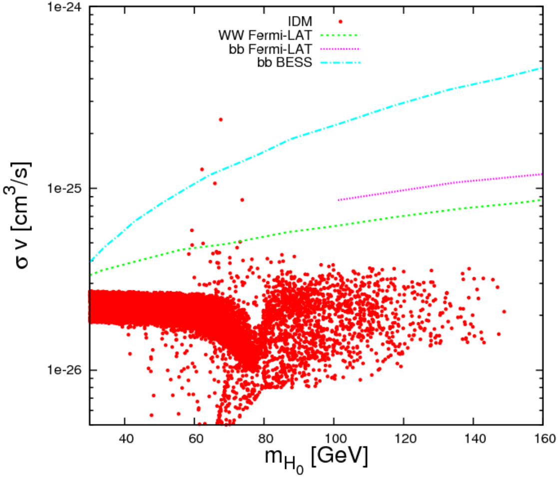


From new analysis of BESS-Polar II

[Kappl & Winkler '11]

$\rightsquigarrow$ rule out low mass WIMP

Indirect Detection in the IDM



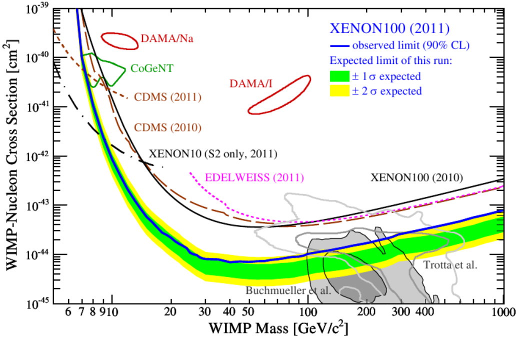
result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$

A part from the low mass regime the IDM is still quite safe from the point of view of indirect detection searches

BUT....

Direct detection

... a serious treat for the IDM

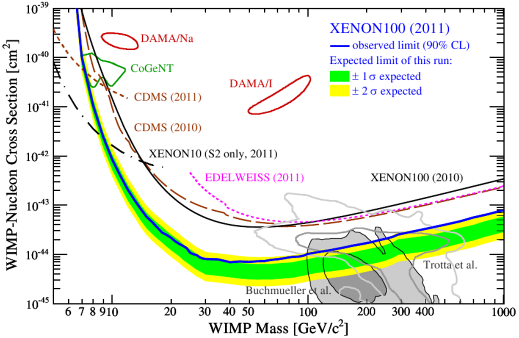


Results from 100 Live Days of XENON100 Data

E. Aprile et al PRD '11

Direct detection

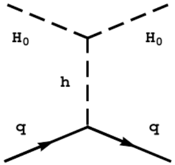
... a serious treat for the IDM



Results from 100 Live Days of XENON100 Data

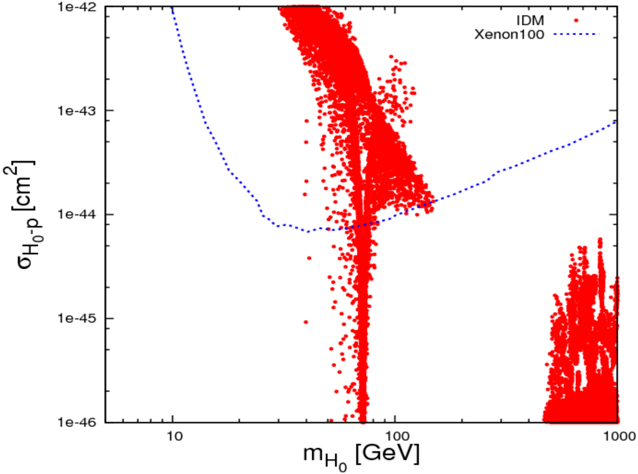
E. Aprile et al PRD '11

Relevant process for elastic scattering in the IDM :

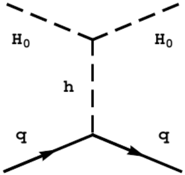


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

Direct detection in the IDM

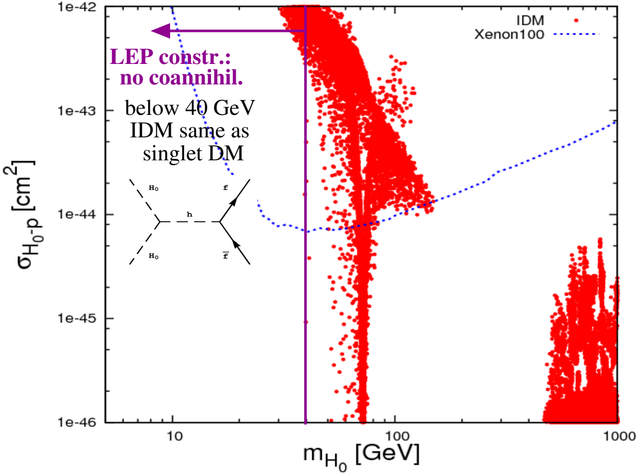


result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$

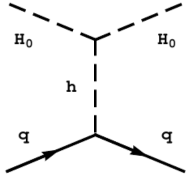


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2} \right)^2$$

Direct detection in the IDM

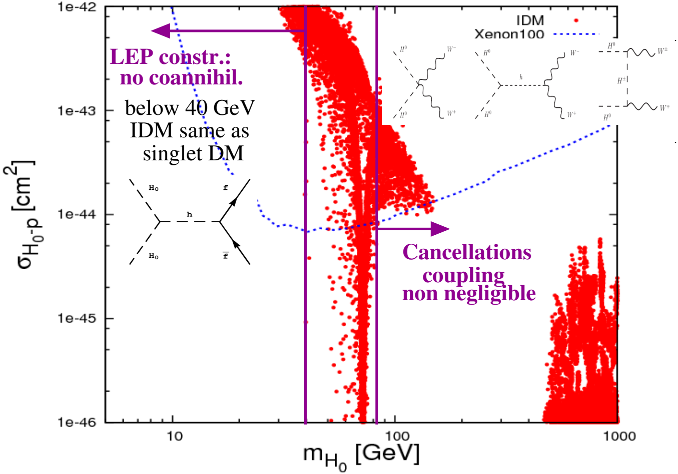


result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$

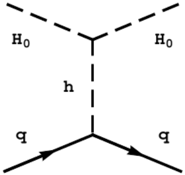


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2} \right)^2$$

Direct detection in the IDM

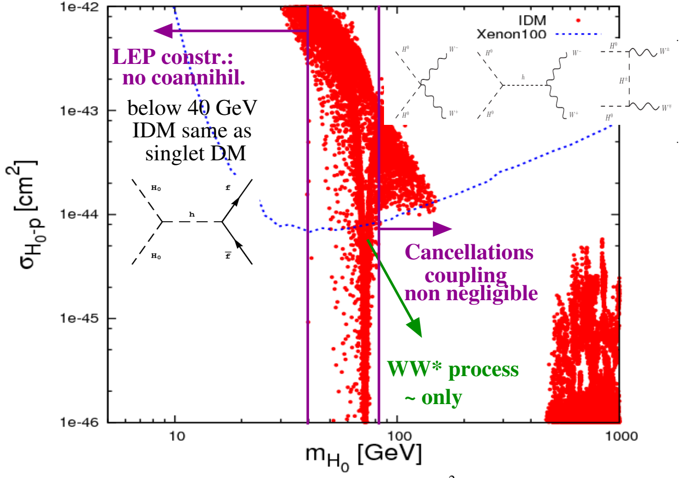


result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$

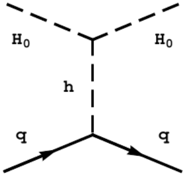


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2} \right)^2$$

Direct detection in the IDM

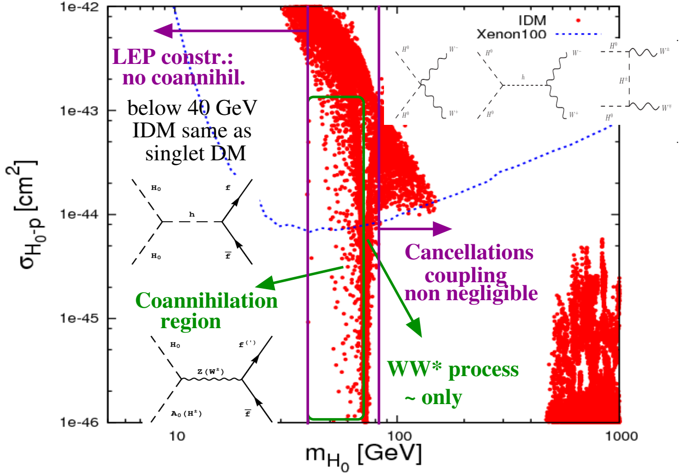


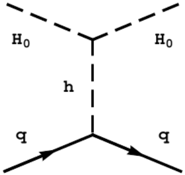
result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$



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

Direct detection in the IDM

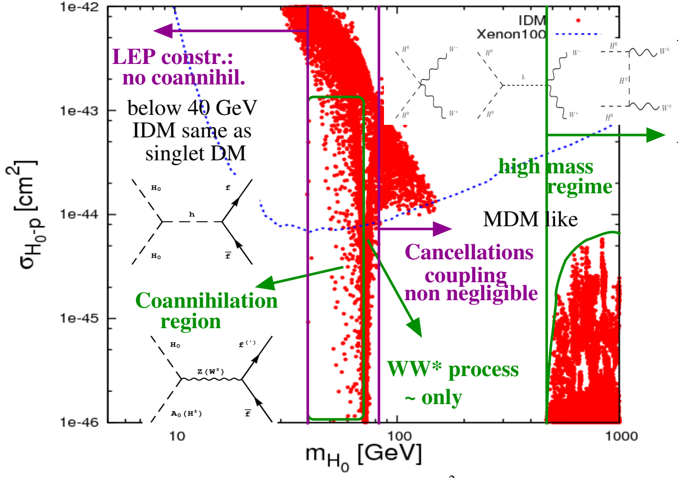


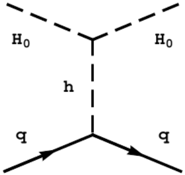


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$

Direct detection in the IDM





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

result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$

$\rightsquigarrow$ only the $40 - 100$ GeV range and $\gg m_W$ are still viable

Conclusion

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

- Parameter space with correct Ω_{dm}
  - GeV range up to $m_{H^0} \sim 130$ (160) GeV for M_h <200 GeV (600 GeV)
  - large mass gap due to efficient annihilations into $H_0 H_0 \to WW, ZZ, \bar{t}t, hh$
  - TeV range for $m_{H_0} > 530$ GeV

  with scalar and gauge (very well known ! !) interactions.

- Surviving parameter space after Xenon100
  - GeV range for $m_{H^0} \sim 40$ GeV- 100 GeV mainly thanks to coannihilation, 3 bdy-processes
  - full TeV range driven by gauge interactions

This is the End

Thank you for your attention ! !

Backup

IDM : Constraints from accelerators 1

Constraints from LEPII Lundstrom, Gustafsson & Edsjo PRD '09

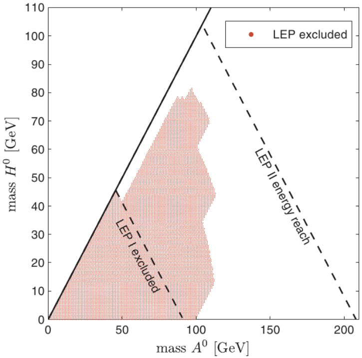
Exclusion plot from LEPII analysis derived from on neutralino searches :

$$e^+e^- \to \chi_1^0\chi_2^0 \to \chi_1^0\chi_1^0 f\bar{f}$$

to be compared with :

$$e^+e^- \to A^0H^0 \to H^0H^0 f\bar{f}$$

taking into account different spin and different decay processes for the NLSP



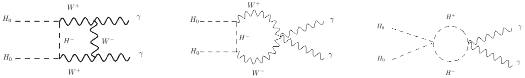
IDM : Constraints from accelerators 2

- at LHc
  - dilepton signal Dole et al PRD '10 : $l^+ l^- +$ missing E.
    Dominant signal : $pp \to H^0 A^0 \to H^0 H^0 l^+ l^-$
    bgd : production of hZ with $h \to H^0 H^0$ as long as $m_h > 2m_{H^0}$
  - trilepton signal Dole et al PRD '10 : $l^+ l^- + l$ missing E.
    Dominant signal : $pp \to H^\pm A^0 \to H^0 W^* H^0 Z^* \to H^0 H^0 l^+ l^- l\nu$
    $pp \to H^\pm H^0 \to A^0 W^* H^0 \to H^0 H^0 l^+ l^- l\nu$
    bgd : WZ production

  signal could be resolved for ~ 40 GeV H^0 (already ruled out by DD)

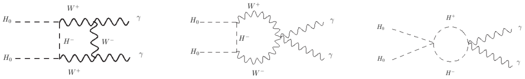
Indirect detection : Gamma ray lines [Gustafsson *et al* '07]

Gamma Ray lines come from loop level contributions to $\Phi_\gamma^{GC} \rightsquigarrow$ negligible



Indirect detection : Gamma ray lines [Gustafsson *et al* '07]

Gamma Ray lines come from loop level contributions to $\Phi_\gamma^{GC} \rightsquigarrow$ negligible



However for Heavy Higgs (low M_{H_0} only)

- Contributions from $H_0 H_0 \xrightarrow{h} f\bar{f}$ to $\langle\sigma_A v\rangle$ and Φ_γ^{GC} are suppressed
- Relic density from coannihilations

TABLE I: *IDM benchmark models. (In units of GeV.)*

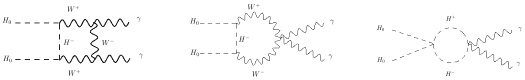
Model	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2	$\lambda_2 \times 1$ GeV
I	500	70	76	190	120	0.1
II	500	50	58.5	170	120	0.1
III	200	70	80	120	125	0.1
IV	120	70	80	120	95	0.1

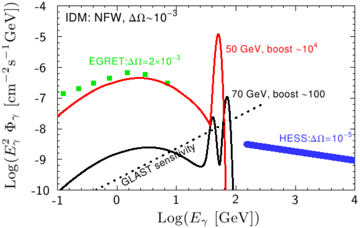
TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$	Branching ratios [%]:					$\Omega_{\rm DM}h^2$
	[cm^{3}s^{-1}]	$\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Indirect detection : Gamma ray lines [Gustafsson *et al* '07]

Gamma Ray lines come from loop level contributions to $\Phi_\gamma^{GC} \rightsquigarrow$ negligible





However for Heavy Higgs (low M_{H_0} only)

- Contributions from $H_0 H_0 \xrightarrow{h} f\bar{f}$ to $\langle\sigma_A v\rangle$ and Φ_γ^{GC} are suppressed
- Relic density from coannihilations
- Gamma line signal can become the main feature of the gamma ray spectrum

TABLE I: *IDM benchmark models. (In units of GeV.)*

Model	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2	$\lambda_2 \times 1$ GeV
I	500	70	76	190	120	0.1
II	500	50	58.5	170	120	0.1
III	200	70	80	120	125	0.1
IV	120	70	80	120	95	0.1

TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$	Branching ratios [%]:					$\Omega_{\rm DM}h^2$
	$[{\rm cm}^3{\rm s}^{-1}]$	$\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Indirect detection : Gamma ray lines [Gustafsson *et al* '07]

Interest : signal from $H_0 H_0 \to \gamma\gamma$ or $H_0 H_0 \to Z\gamma$ appear at energies characteristics of M_{H_0}

Problem : For significant gamma ray lines need large boost factors

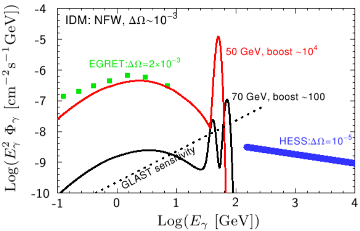


TABLE I: *IDM benchmark models. (In units of GeV.)*

Model	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2	$\lambda_2 \times 1$ GeV
I	500	70	76	190	120	0.1
II	500	50	58.5	170	120	0.1
III	200	70	80	120	125	0.1
IV	120	70	80	120	95	0.1

TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$ [cm^{3}s^{-1}]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{DM}h^2$
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

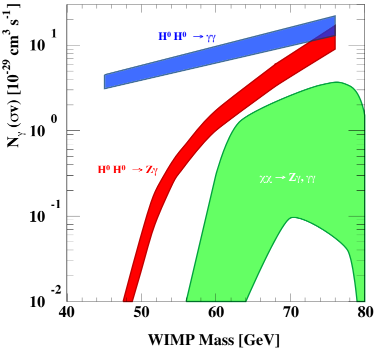
Indirect detection : Gamma ray lines [Gustafsson *et al* '07]

Interest : signal from $H_0H_0 \to \gamma\gamma$ or $H_0H_0 \to Z\gamma$ appear at energies characteristics of M_{H_0}

Problem : For significant gamma ray lines need large boost factors

General feature : stronger line signals in the IDM than in the MSSM

Annihilation rate into γ lines



$M_h = 500$ GeV, $M_{H^\pm} = M_{H_0} + 120$ GeV, $\lambda_2 = 0.1$

Comparing 2-3 body relic density

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

Including coannihilations

:

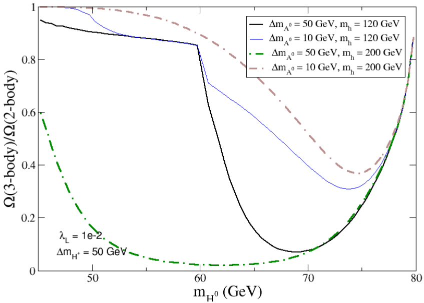
- coannihilations $\equiv$ 2-bdy pure gauge process $H_0 A_0 \to Z \to \bar{f}f$
- Including coannihilations can change the impact of the 3-bdy processes

Comparing 2-3 body relic density

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

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

- coannihilations $\equiv$ 2-bdy pure gauge process $H_0 A_0 \to Z \to \bar{f}f$
- Including coannihilations can change the impact of the 3-bdy processes

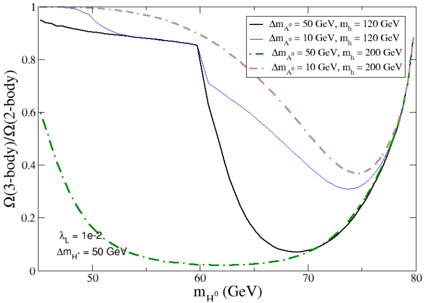


Comparing 2-3 body relic density

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

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

- coannihilations $\equiv$ 2-bdy pure gauge process $H_0 A_0 \to Z \to \bar{f} f$
- Including coannihilations can change the impact of the 3-bdy processes

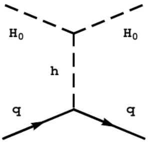


$\rightsquigarrow$ still 3-body final states significantly affect predictions for Ω_{dm}

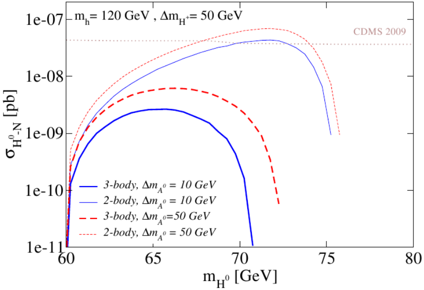
Implications for Direct Detection

Direct detection through Elastic Scattering

Prospects along the viable parameter space :



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



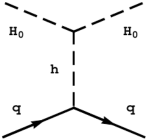
$\rightsquigarrow$predictions for σ_{H_0-N} reduced up to $\sim \mathcal{O}(100)$

$\rightsquigarrow$ better compatibility with present bounds

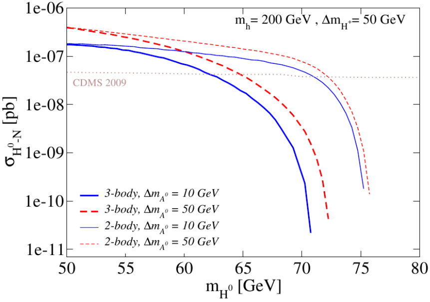
Implications for Direct Detection

Direct detection through Elastic Scattering

Prospects along the viable parameter space :



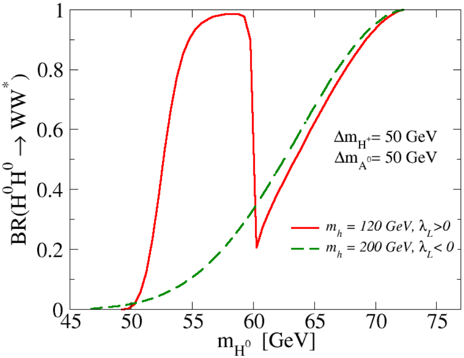
$$\sigma_{H_0-N} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$



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

$\rightsquigarrow$ better compatibility with present bounds

For Indirect Detection including 3bdy

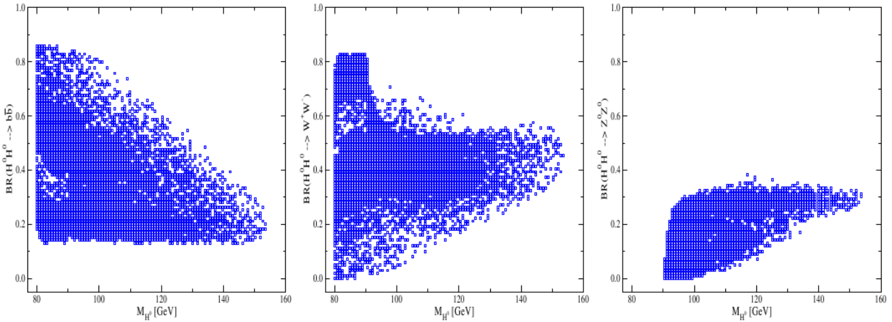


annihilations no more $\bar{b}b$ dominated

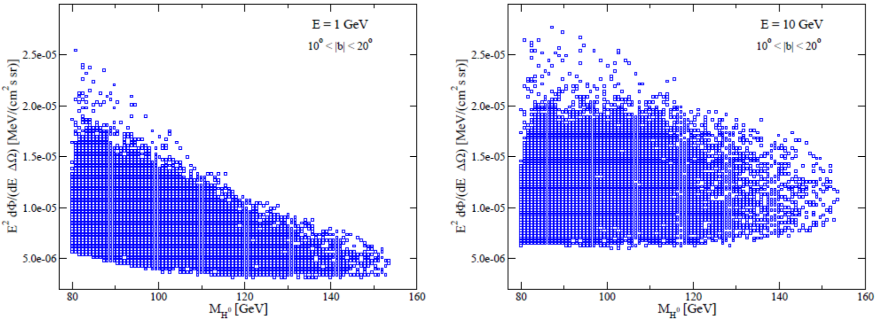
$\rightsquigarrow$BR($H_0 H_0 \to WW^*$) ~ 1
for m_{H^0} near W threshold

work in progress...

Indirect Detection in the cancellation regime



Differential gamma ray flux



$\frac{d\Phi_{\rm halo}}{dE} = \frac{1}{2}\frac{\sigma v}{4\pi} r_\odot \frac{\rho_\odot^2}{m_{\rm DM}{}^2} \bar{J}\Delta\Omega \frac{dN}{dE}$, where $r_\odot = 8.5$ kpc, $\rho_\odot = 0.39\ \mathrm{GeV/cm^3}$ is the local Catena '09 $\bar{J}\Delta\Omega = \int_{\Delta\Omega} d\Omega(b,l) \int_{\rm los} \frac{ds}{r_\odot}\left(\frac{\rho_{\rm halo}(r(s,\psi))}{\rho_\odot}\right)^2$., we use NFW profile.

These fluxes are much smaller than those measured by FERMI Abdo '10 which are $\mathcal{O}(10^{-3})$ MeV/(cm^2 s sr) at those energies

It is thus not possible to obtain any constraints from this data.

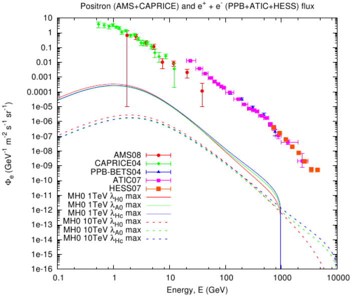
IDM large mass : Indirect detection prospects

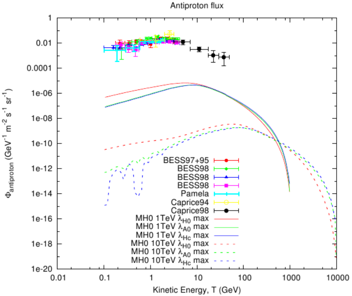
γ and ν signals : $\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{\rm DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\, \rho_0^2\, R_0}{4\pi} \bar{J}(\Delta\Omega)$, below the sensitivity of current experiments

Charged antimatter cosmic ray signals

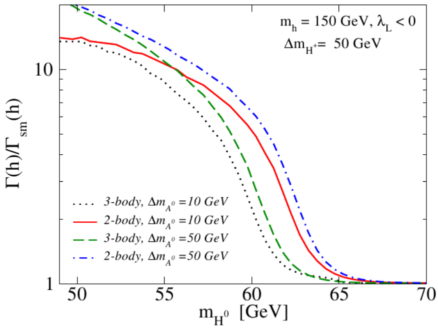
$$\vec{\nabla}\left[K(E,\vec{x})\vec{\nabla}\mathcal{N}_{\rm cr} - \vec{V}_{\rm conv}\mathcal{N}_{\rm cr}\right] + \frac{\partial}{\partial E}\left[b(E)\mathcal{N}_{\rm cr} + K_{EE}\frac{\partial}{\partial E}\mathcal{N}_{\rm cr}\right] + \Gamma(E)\mathcal{N}_{\rm cr} + \mathcal{Q}\,, = 0$$

$$\mathcal{Q} = BF\frac{\langle\sigma v\rangle\rho^2}{2m_{DM}^2} \times \sum_i \frac{{\rm d}n_{cr}^i}{{\rm d}E} BR_i\,.$$





$m_{H_0} < m_W$: Detection at colliders

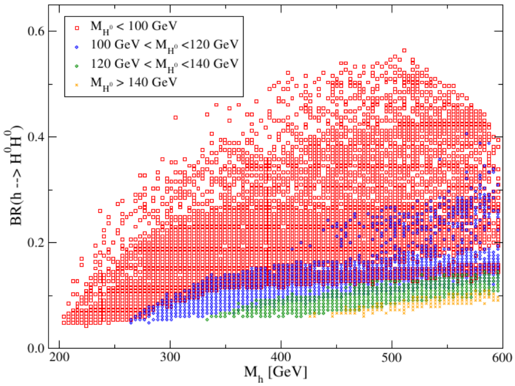


through extra contributions to $\Gamma(h)$ due to

$h \to A_0 A_0, H_0 H_0$ [Cao PRD07]

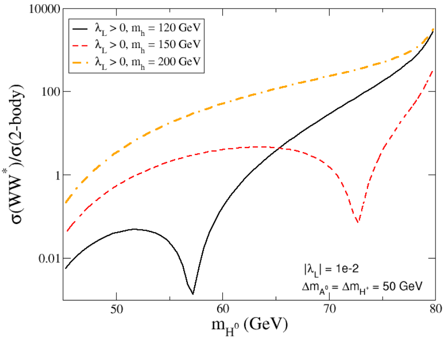
$\rightsquigarrow$ The new parameter space slightly change the prospects

Cancellations : contribution to Higgs decay width



Comparing 2-3 body annihilation cross section

3bdy annihilation dominates over 2 bdy on

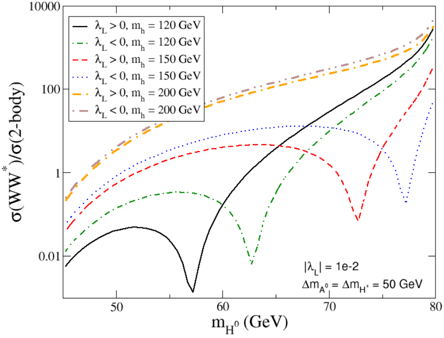


- $\lambda_L = 10^{-2}$

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

Comparing 2-3 body annihilation cross section

3bdy annihilation dominates over 2 bdy on

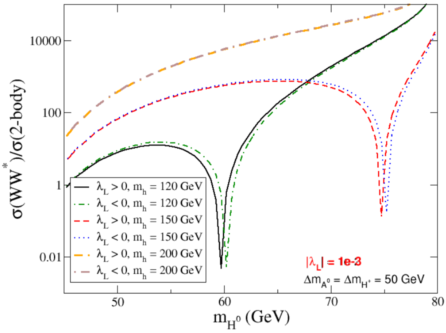


- $\lambda_L = 10^{-2}$

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

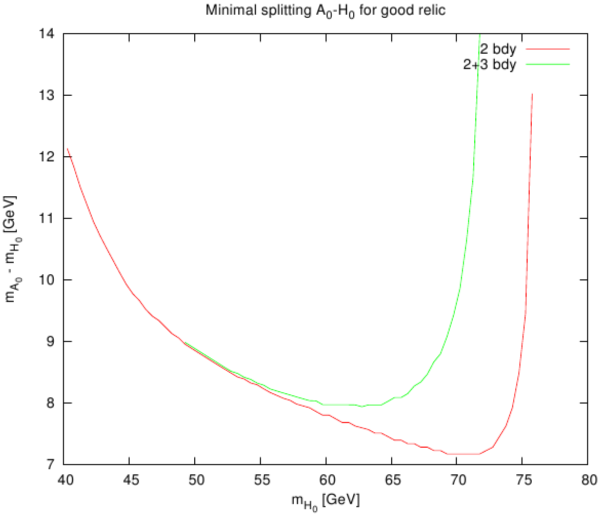
Comparing 2-3 body annihilation cross section

3bdy annihilation dominates over 2 bdy on



- $\lambda_L = 10^{-2}$
  ... a significant range of the parameter space, depend on m_h
- $\lambda_L = 10^{-3}$
  ... the entire mass range independently of m_h
  but not representative for $H_0 \equiv$ DM

Coannihilation



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

n-uplets : Potential - constraints

- Full Potential

$$V(H_n,H_1) = V_1(H_1) + \mu^2 H_n^\dagger H_n + \frac{\lambda_2}{2}\left(H_n^\dagger H_n\right)^2 + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_n^\dagger H_n\right) + \frac{\lambda_4}{2}\left(H_n^\dagger \tau_a^{(n)} H_n\right)^2 + \lambda_5 \left(H_1^\dagger \tau_a^{(2)} H_1\right)\left(H_n^\dagger \tau_a^{(n)} H_n\right) ,$$

- Dark scalars couplings to Higgs and masses :

$\frac{\lambda_3}{2}\left(\frac{1}{2}\Delta^{(0)\,2} + \sum_{0<Q\leq j_n} \Delta^{(Q)}\Delta^{(-Q)}\right)(2v_0 h + h^2)$

mass of all components : $m_0^2 = \mu^2 + \frac{\lambda_3 v_0^2}{2}$

at one-loop (Cirelli'05) : $m\left(\Delta^{(Q)}\right) - m\left(\Delta^{(0)}\right) = Q^2 \Delta M_g$

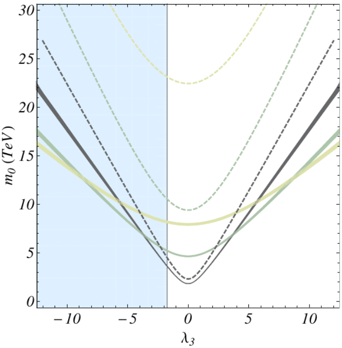
with $\Delta M_g = g M_W \sin^2\frac{\theta_W}{2} \simeq (166 \pm 1)$ MeV

- Stability constraint

$$\lambda_{1,2} > 0 \quad ,$$
$$\lambda_3 > -\sqrt{2\lambda_1\lambda_2} \quad .$$

Multiplets : Relic density detection

Models	$\lambda_3 = 0$	$\lambda_3 = 2\pi$	$\lambda_3 = 4\pi$	$\lambda_3 = 0$ (SE)	$\lambda_3 = 4\pi$ (SE)
Real Triplet	1.826 ± 0.028	11.1	21.9	2.3	28.1
Real Quintuplet	4.642 ± 0.072	9.6	17.4	9.4	35.7
Real Septuplet	7.935 ± 0.12	10.6	16.1	22.4	46.3



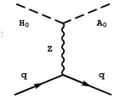
MDM

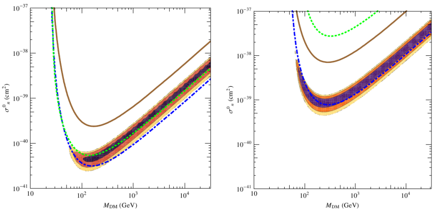
Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV
2	1/2	0	EL	0.54 ± 0.01
2	1/2	1/2	EH	1.1 ± 0.03
3	0	0	HH^*	2.0 ± 0.05
3	0	1/2	LH	2.4 ± 0.06
3	1	0	HH, LL	1.6 ± 0.04
3	1	1/2	LH	1.8 ± 0.05
4	1/2	0	HHH^*	2.4 ± 0.06
4	1/2	1/2	(LHH^*)	2.4 ± 0.06
4	3/2	0	HHH	2.9 ± 0.07
4	3/2	1/2	(LHH)	2.6 ± 0.07
5	0	0	(HHH^*H^*)	5.0 ± 0.1
5	0	1/2	–	4.4 ± 0.1
7	0	0	–	8.5 ± 0.2

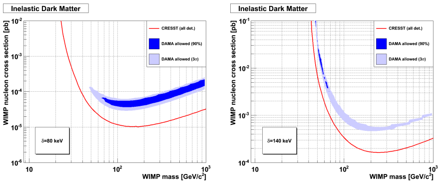
from Cirelli et al NPB 753

Inelastic Scattering (Arina *et* all '09) - new exclusion CRESST

$$m_{A_0} - m_{H_0} = \delta$$



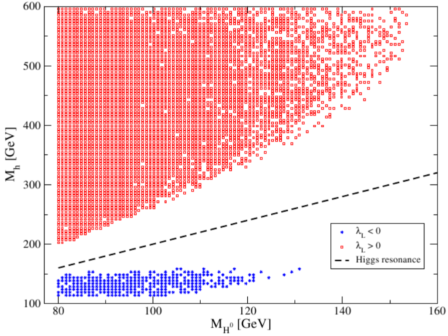


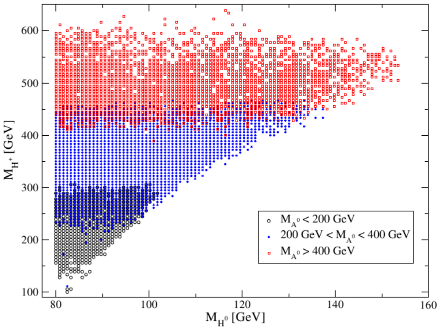


Left : allowed region consitent with DAMA @ 90, 99, 99.9 % CL for inert doublet for $\delta = 80, 150$ keV (green Xenon10, blue CRESST II 99%CL, $v_0 = 220$ km/s, $v_{esc} = 650$ km/s.

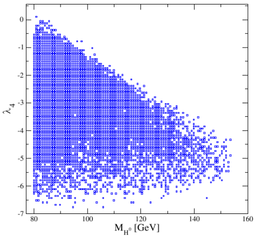
Right : new limits (july 2010 from CRESST, Seidel IDM2010), 1 pb= 10^{-36}cm^2

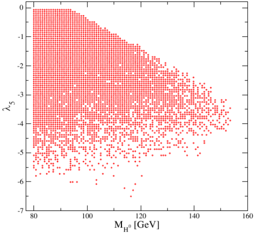
Cancellations require increasing M_h, m_{H^+}, m_{A_0}

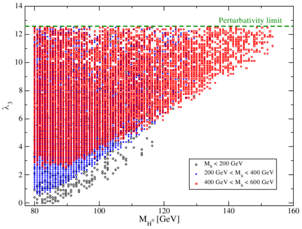




Cancellations : Couplings







IDM : Mass Ranges

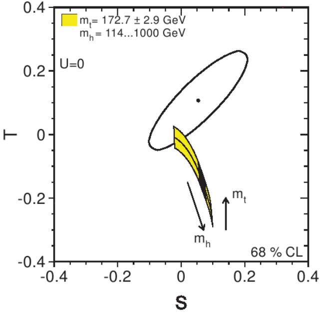
Mass Ranges	main contributions to σ_{eff}	mass splittings	main Refs
$m_{H_0} \ll m_W(\mathcal{O}(GeV))$	$H_0H_0 \to h^* \to \bar{f}f$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \sim 90$ GeV	Andreas *et* all '08
$m_{H_0} \lesssim m_W$	$H_0H_0 \to h^* \to \bar{f}f$ $H_0A_0(H^+) \to Z^*(W^*) \to \bar{f}f^{(')}$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \gtrsim 7$ 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 : $\Delta T \approx \frac{1}{24\pi^2\alpha v^2}(M_{H^+}-M_{A_0})(M_{H^+}-M_{H_0})$

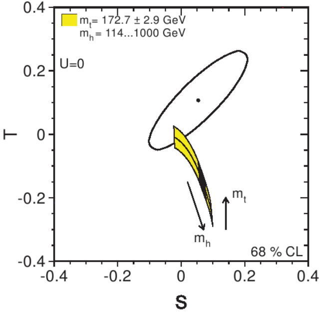


How to conciliate Heavy Higgs and EWPT measurements ?

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 : $\Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(M_{H^+} - M_{A_0})(M_{H^+} - M_{H_0})$



$\rightsquigarrow$ 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 :

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

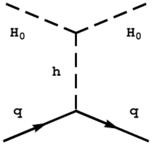
- Stability constraint

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

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

Prospects for Direct and Indirect detection

Direct detection through Elastic Scattering ($m_{A_0} - m_{H_0} >$150 keV)

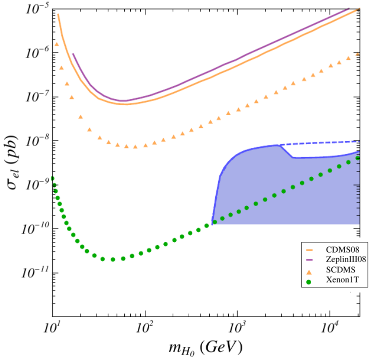


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

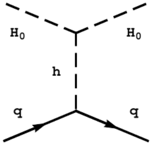
$M_{H_0} \propto \lambda_{H_0} \rightsquigarrow \sigma_{el} < 9.4 10^{-9}$ pb
bounded $\lambda_{H_0} \rightsquigarrow$ absolute upper bound

Prospects for Direct and Indirect detection

Direct detection through Elastic Scattering ($m_{A_0} - m_{H_0}$ >150 keV)



$m_h = 120$ GeV for illustration



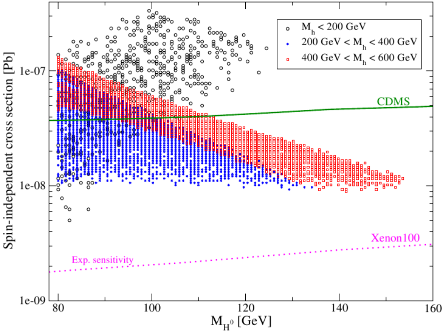
$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

$M_{H_0} \propto \lambda_{H_0} \rightsquigarrow \sigma_{el} < 9.410^{-9}$ pb

bounded $\lambda_{H_0} \rightsquigarrow$ absolute upper bound

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

$\rightsquigarrow$ 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