Signatures of the Inert Doublet Dark Matter Model

Alejandro Ibarra

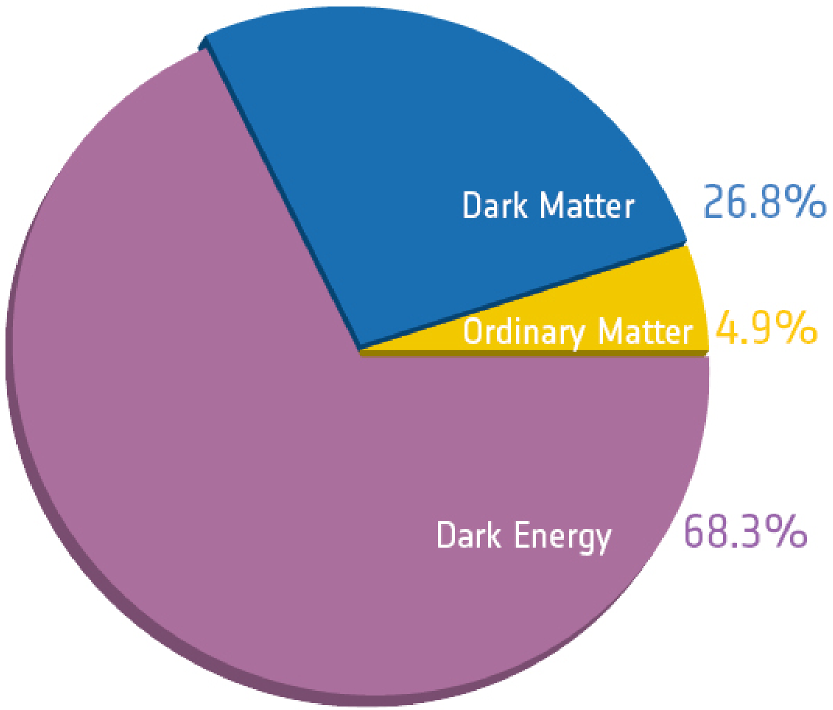
Technische Universität München

Based on works with

Camilo Garcia-Cely, JCAP 1309 (2013) 025.
Camilo Garcia-Cely, Michael Gustafsson, in preparation

Capri
25 May 2014

Composition of the Universe after Planck



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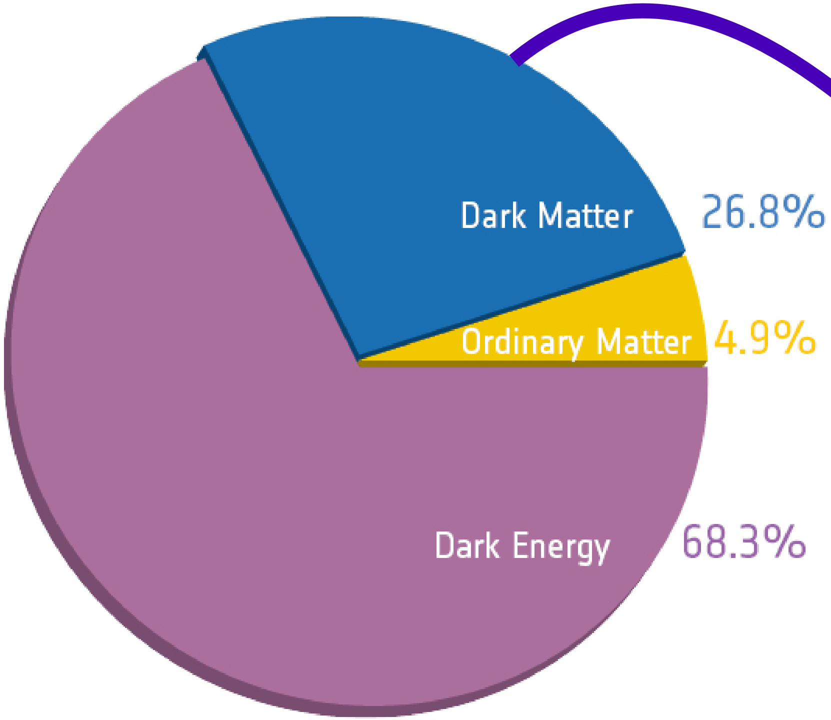

Could be composed by scalar doublets

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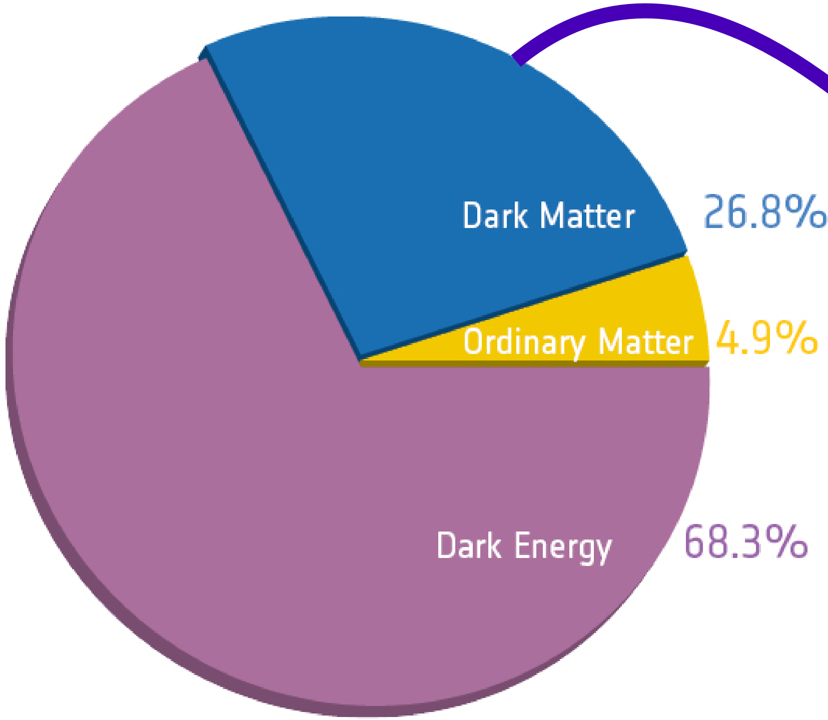
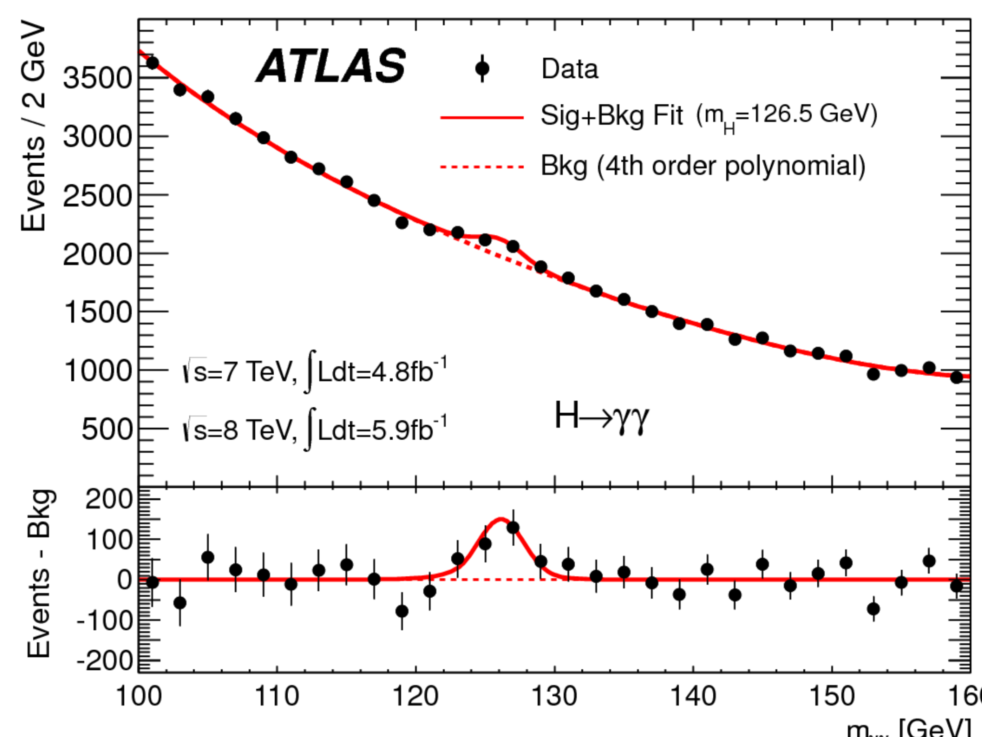


Could be composed by scalar doublets

At least one scalar doublet exists in Nature! (although unstable)



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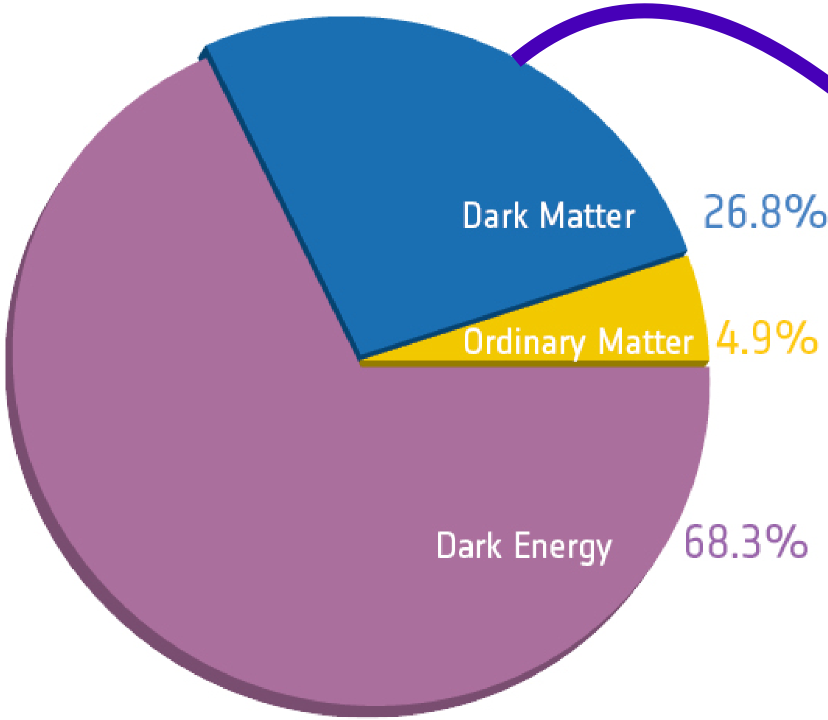

Could be composed by scalar doublets

The Inert Doublet Model

Deshpande, Ma '78

Barbieri, Hall, Rychkov '06
Lopez Honorez, Nezri, Oliver, Tytgat '06
Cirelli, Fornengo, Strumia '06
Majumdar, Ghosal '06
Gustafsson, Lundström, Bergström, Edsjö '07
Agrawal, Dolle, Krenke '08
Andreas, Tytgat, Swillens '09
Nezri, Tytgat, Vertongen '09
Arina, Ling, Tytgat '09
Hambye, Ling, Lopez Honorez, Rocher '09
Lopez Honorez, Yaguna '10
Klasen, Yaguna, Ruiz-Alvarez '13
AI, Garcia Cely '13
...

The Inert Doublet Model

Simple extension of the Standard Model accounting for the dark matter of the Universe.

Assumptions:

1) Introduce a scalar field, η, with identical gauge quantum numbers as the Standard Model Higgs boson.
2) Postulate that the vacuum possess an exact $\mathbb{Z}_2$ symmetry, under which η is odd, while all the Standard Model particles are even: $\begin{array}{ccc} \eta & \to & -\eta \\ \mathrm{SM} & \to & \mathrm{SM} \end{array}$

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Implications

1) The $\mathbb{Z}_2$ symmetry ensures that η contains an absolutely stable particle
   $\rightarrow$ dark matter candidate.
2) The exotic doublet η does not interacts at tree level with any of the Standard Model fermions. The doublet η is "inert".
3) The inert doublet η, communicates with the observable sector via gauge interactions and via the Higgs portal, e.g. $(\Phi^\dagger\Phi)\,(\eta^\dagger\eta)$
   $\rightarrow$ thermal dark matter production possible

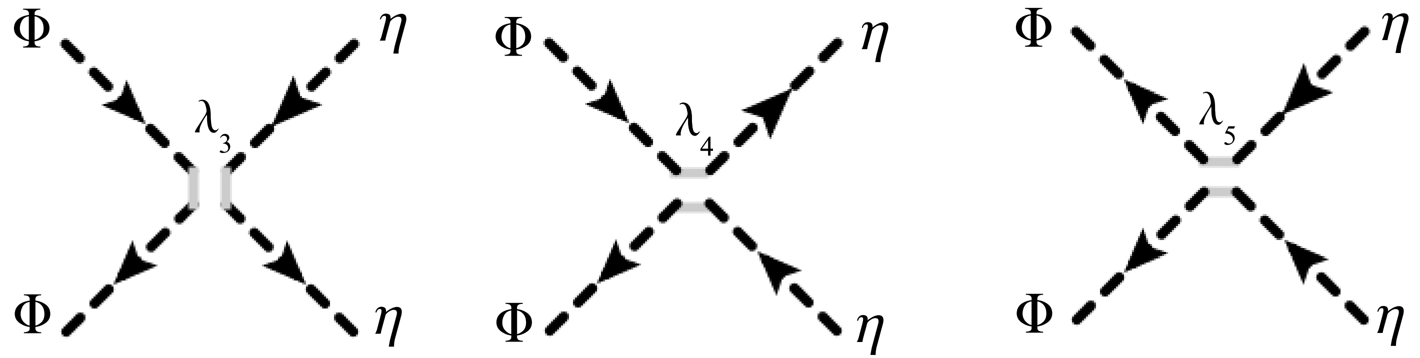
The Inert Doublet Model

Lagrangian of the scalar sector $\mathcal{L} = \mathcal{L}_\Phi + \mathcal{L}_\eta - V_{\text{int}}$

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - m_\Phi^2 (\Phi^\dagger \Phi) - \lambda_1 (\Phi^\dagger \Phi)^2$$

$$\mathcal{L}_\eta = (D_\mu \eta)^\dagger (D^\mu \eta) - m_\eta^2 (\eta^\dagger \eta) - \lambda_2 (\eta^\dagger \eta)^2$$

$$V_{\text{int}} = \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \frac{1}{2}\Big(\lambda_5 (\Phi^\dagger \eta)(\Phi^\dagger \eta) + \text{h.c.}\Big)$$



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After the electroweak symmetry breaking

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \langle \Phi^0 \rangle \end{pmatrix} , \qquad \langle \eta \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$\mathbb{Z}_2$ symmetry preserved

Physical scalar fields: h, H^0, A^0, $H^\pm$:

$$\Phi = \begin{pmatrix} 0 \\ \langle \Phi^0 \rangle + h \end{pmatrix} , \qquad \eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}} (H^0 + i A^0) \end{pmatrix}$$

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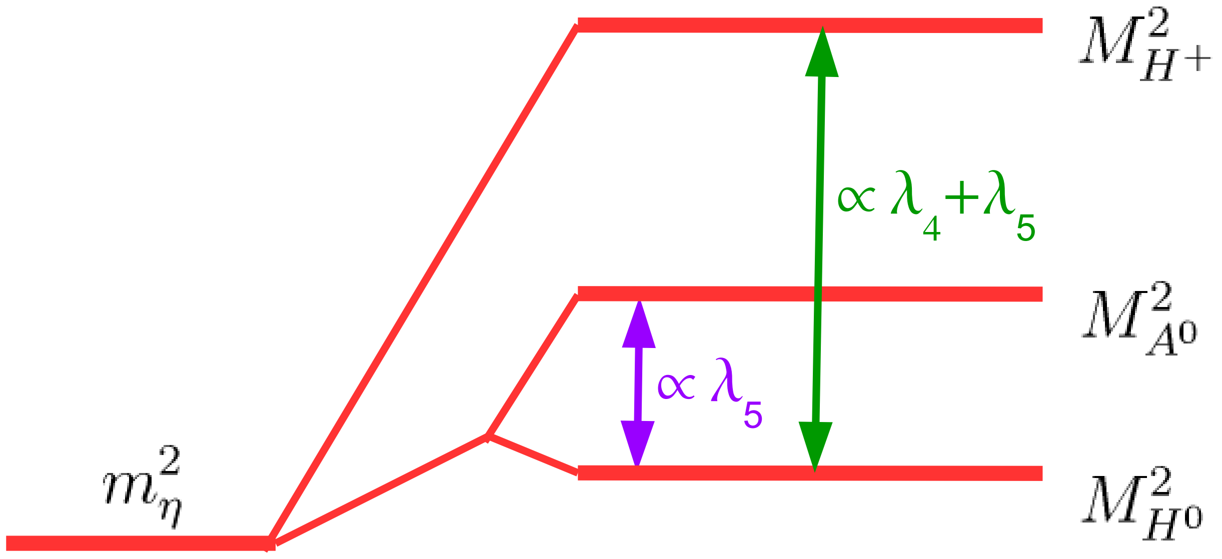
Mass splittings between the exotic scalars and their interactions with h determined by the quartic couplings λ_3, λ_4, λ_5.

The Inert Doublet Model

Mass splittings

$$M_{H^+}^2 - M_{H^0}^2 \propto (\lambda_4 + \lambda_5) \qquad M_{A^0}^2 - M_{H^0}^2 \propto \lambda_5$$



The Inert Doublet Model

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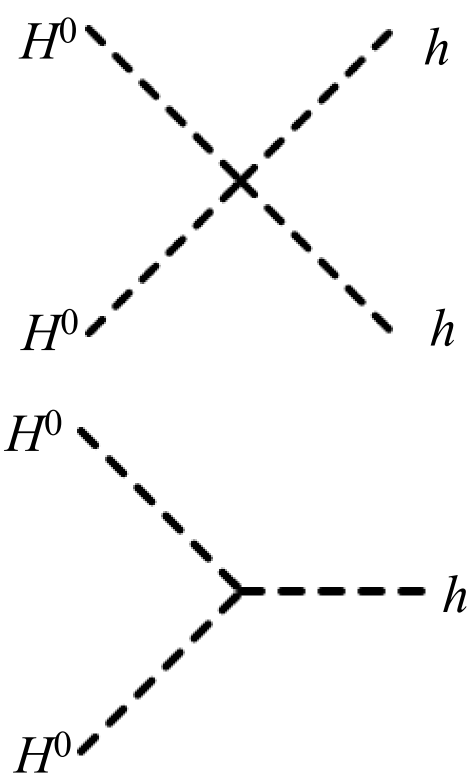
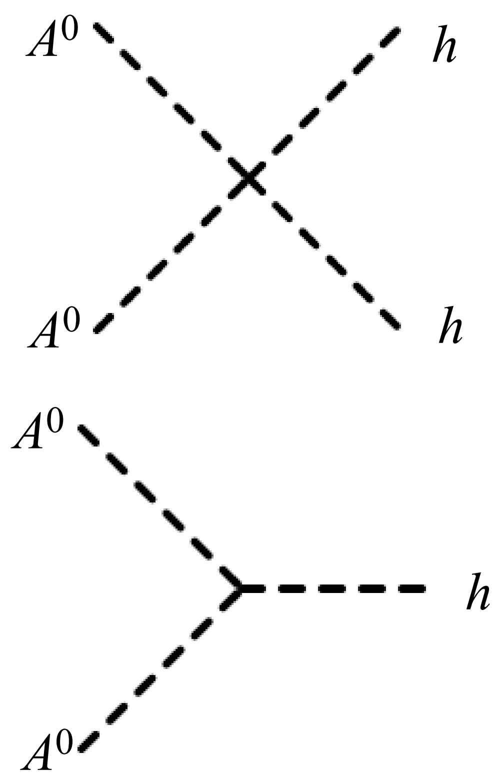
$$M^2_{H^+} - M^2_{H^0} \propto (\lambda_4 + \lambda_5) \qquad M^2_{A^0} - M^2_{H^0} \propto \lambda_5$$

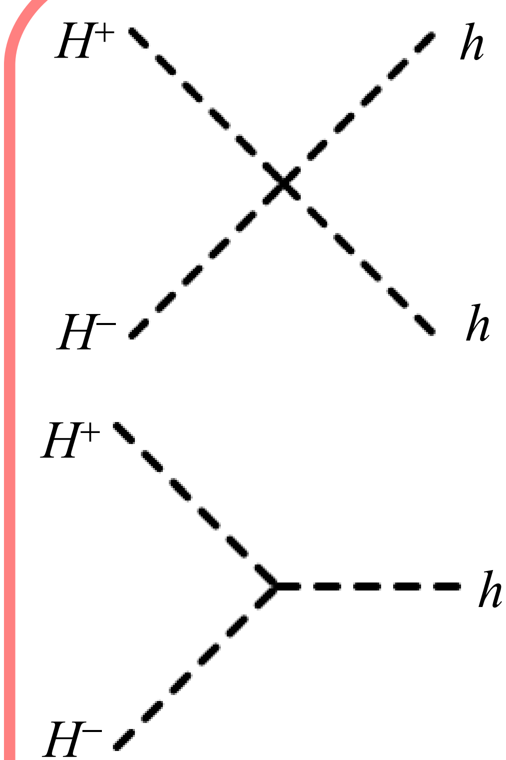
Interactions



$\propto (\lambda_3 + \lambda_4 + \lambda_5)$



$\propto (\lambda_3 + \lambda_4 - \lambda_5)$



$\propto \lambda_3$

The Inert Doublet Model

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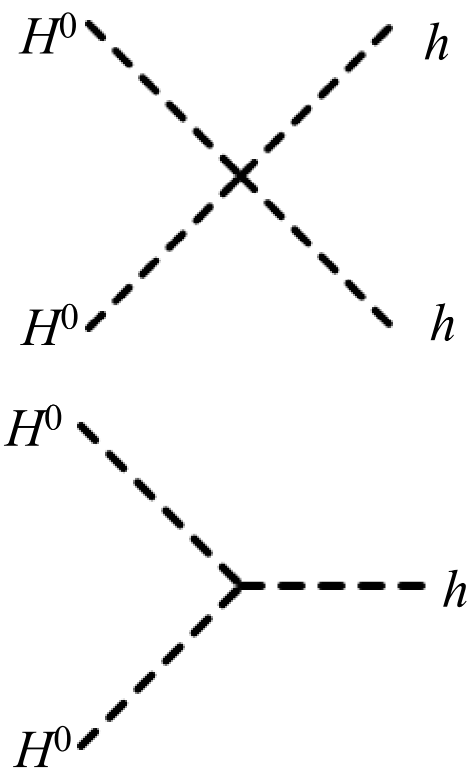
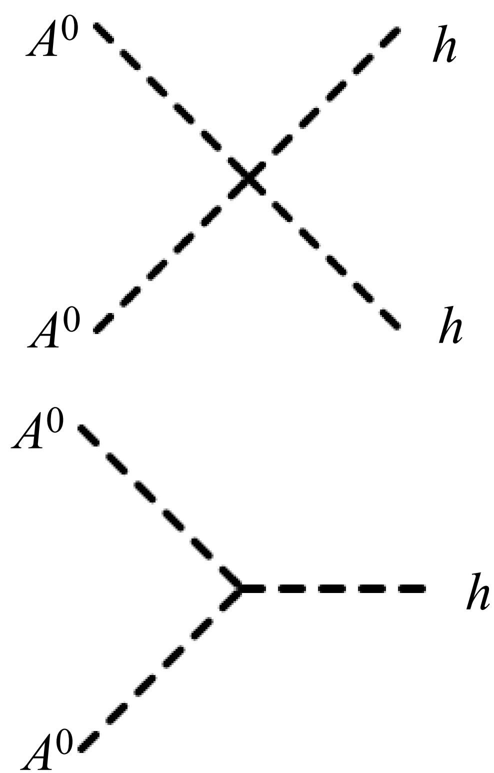
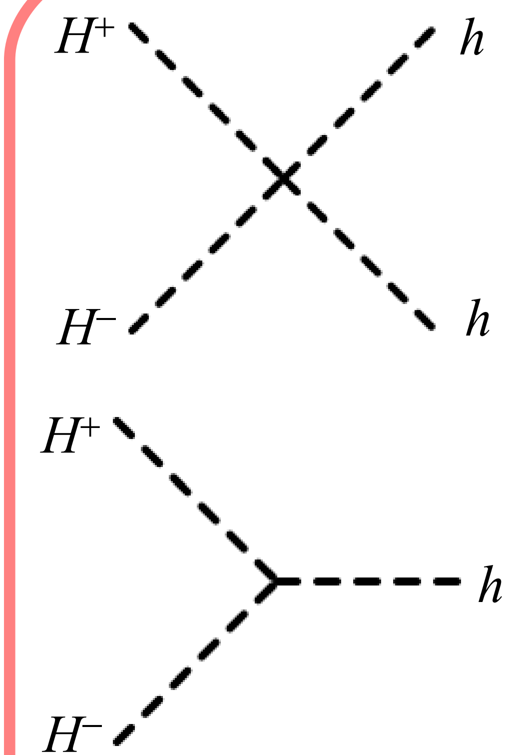


$$\propto \frac{1}{2}\left(\lambda_3 + \frac{M_{H^0}^2 - M_{H^+}^2}{\langle \Phi^0 \rangle^2}\right)$$



$$\propto \frac{1}{2}\left(\lambda_3 + \frac{M_{A^0}^2 - M_{H^+}^2}{\langle \Phi^0 \rangle^2}\right)$$



$$\propto \lambda_3$$

The Inert Doublet Model

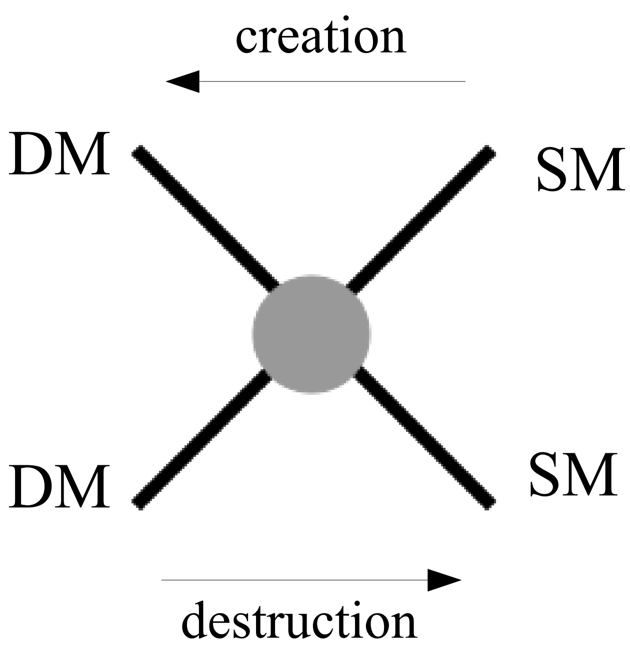
Rich phenomenology. Parameter space constrained by

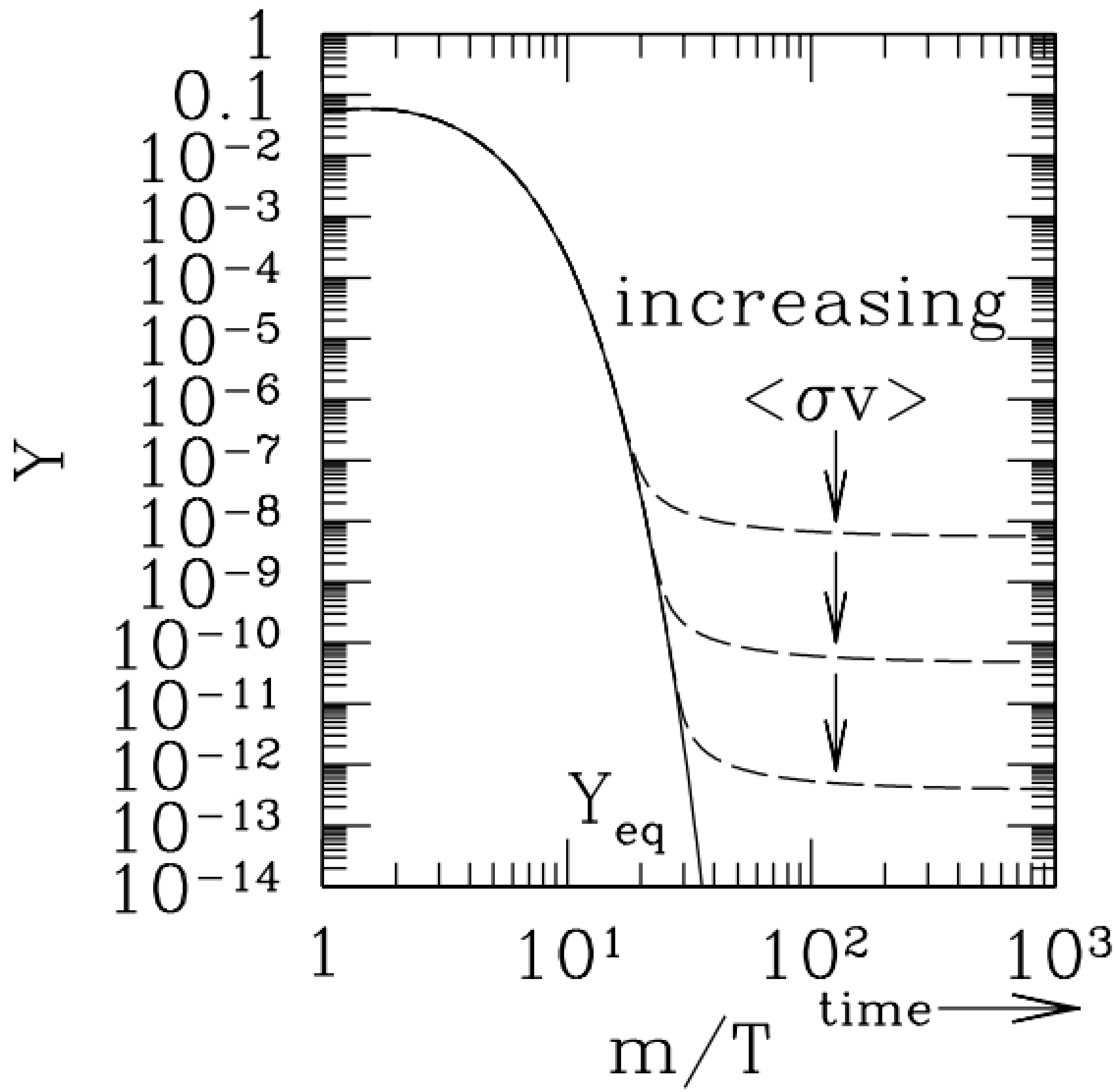
- Perturbativity
- Vacuum stability
- Collider searches
- Electroweak precision tests
- Relic dark matter abundance
- Direct dark matter searches
- Indirect dark matter searches

This talk

Relic abundance

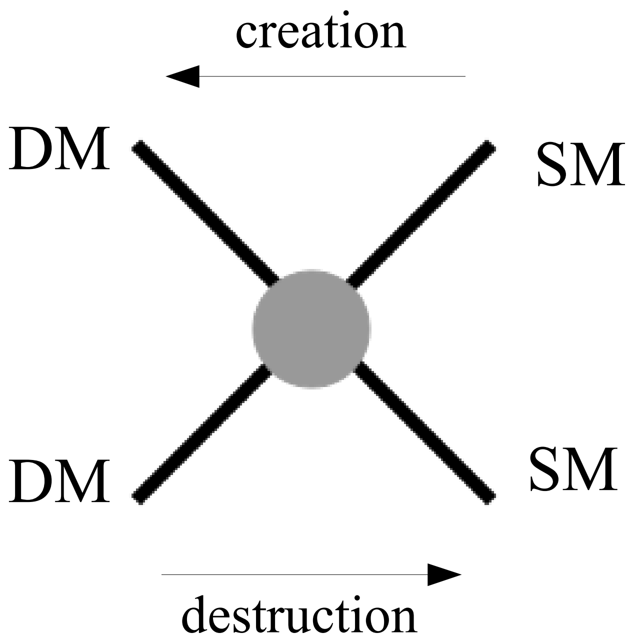
WIMP dark matter production





Relic abundance

WIMP dark matter production



Relic abundance of DM particles

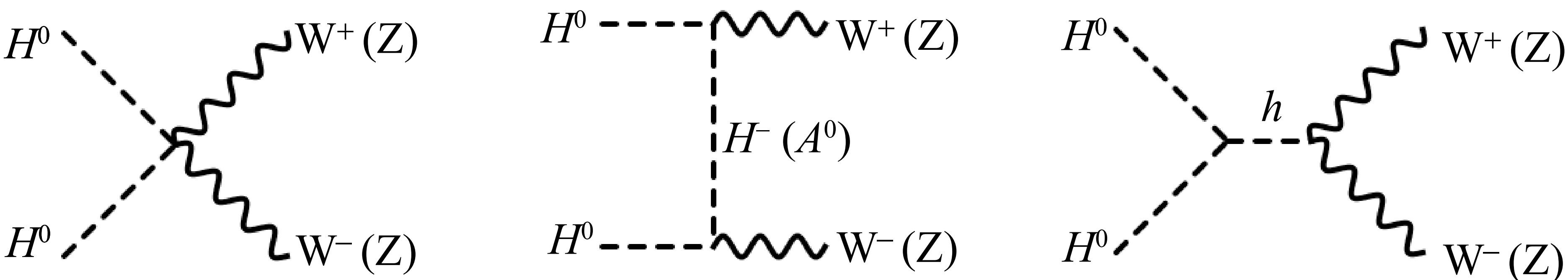
$$\boxed{\Omega h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}}$$

Correct relic density, $\Omega h^2 = 0.1$, if

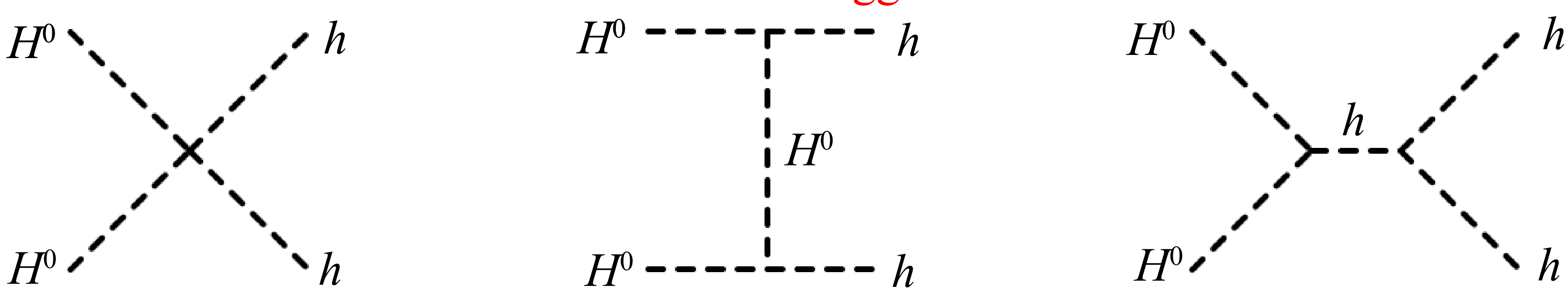
$$\boxed{\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}$$

Relic abundance

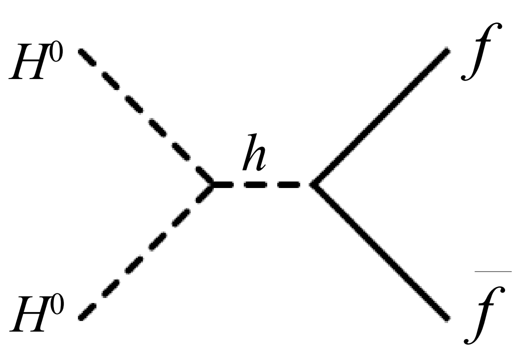
Annihilations into gauge bosons



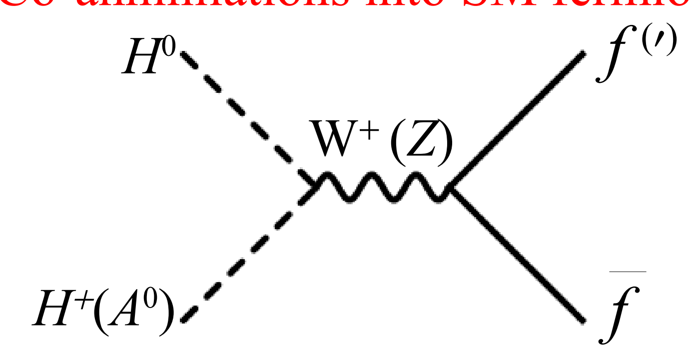
Annihilations into Higgs bosons



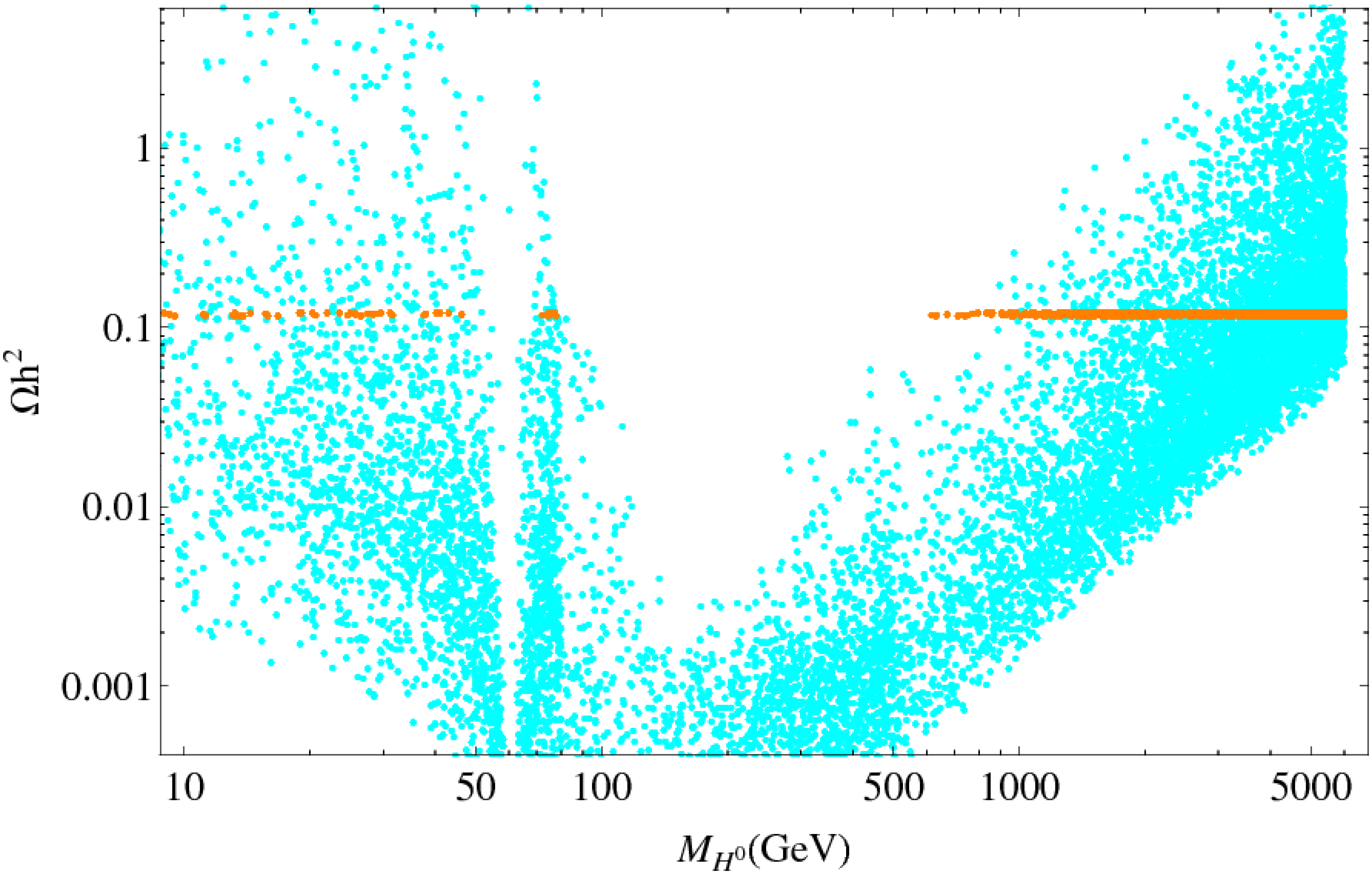
Annihilations into SM fermions



Co-annihilations into SM fermions



Relic abundance



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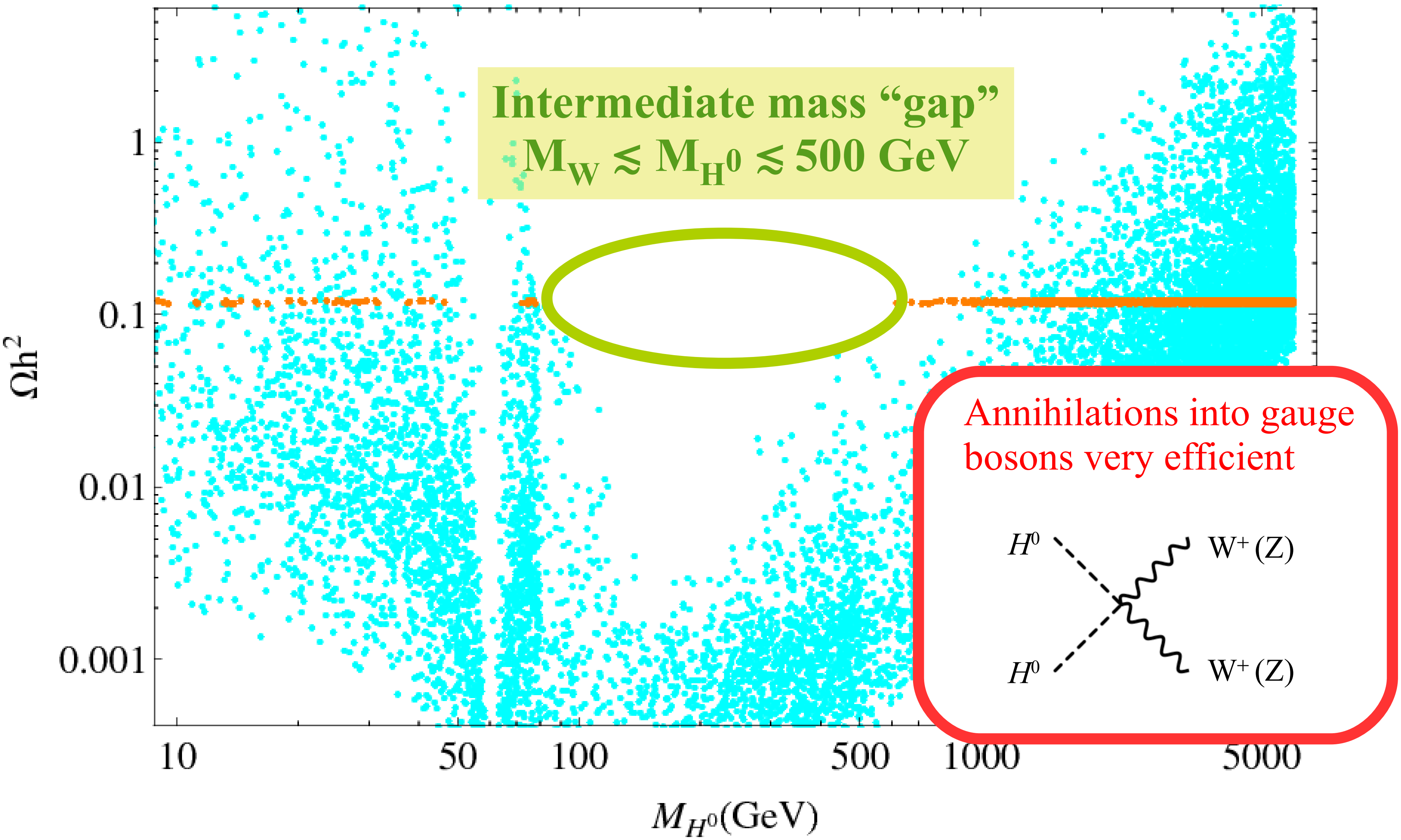

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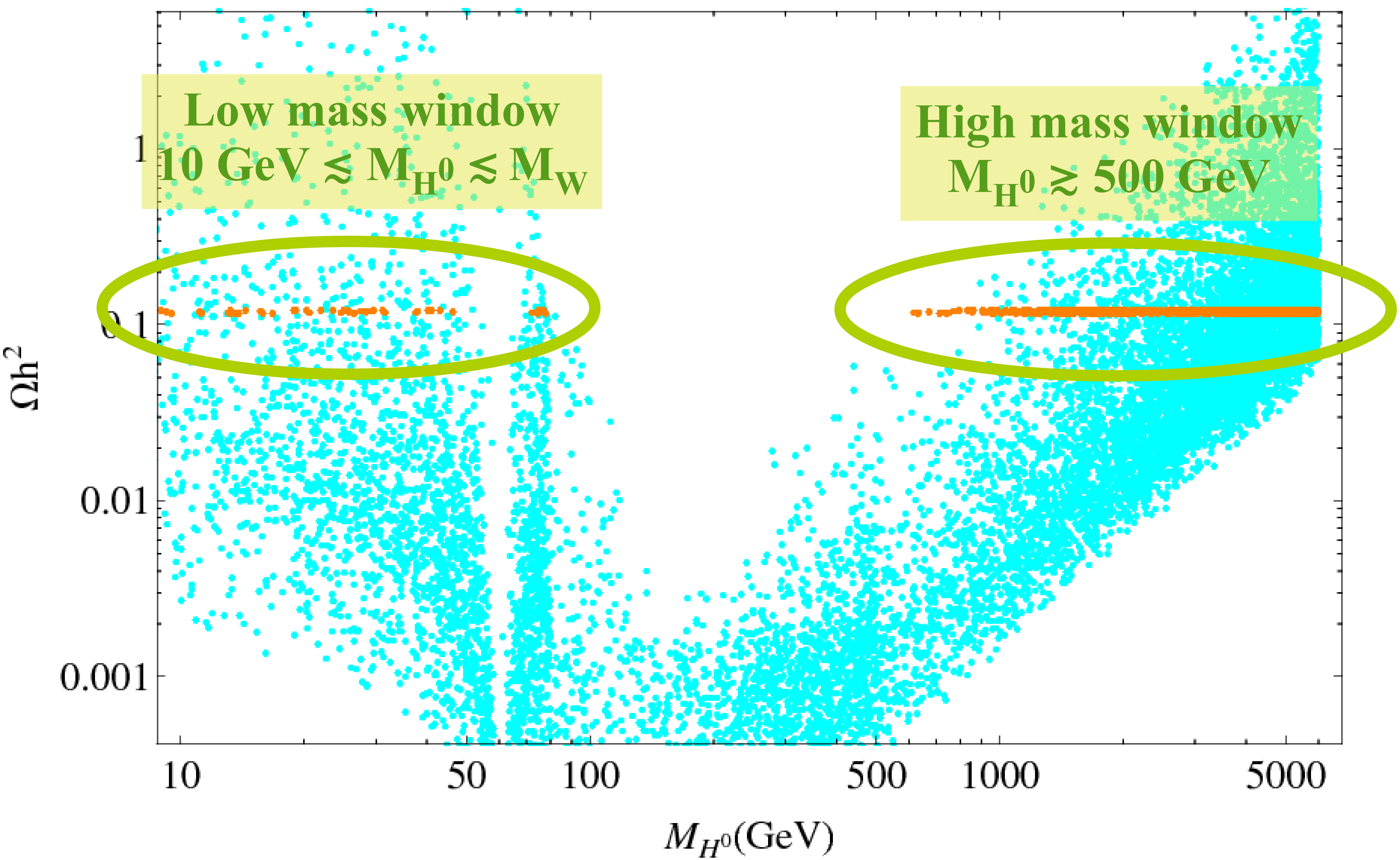

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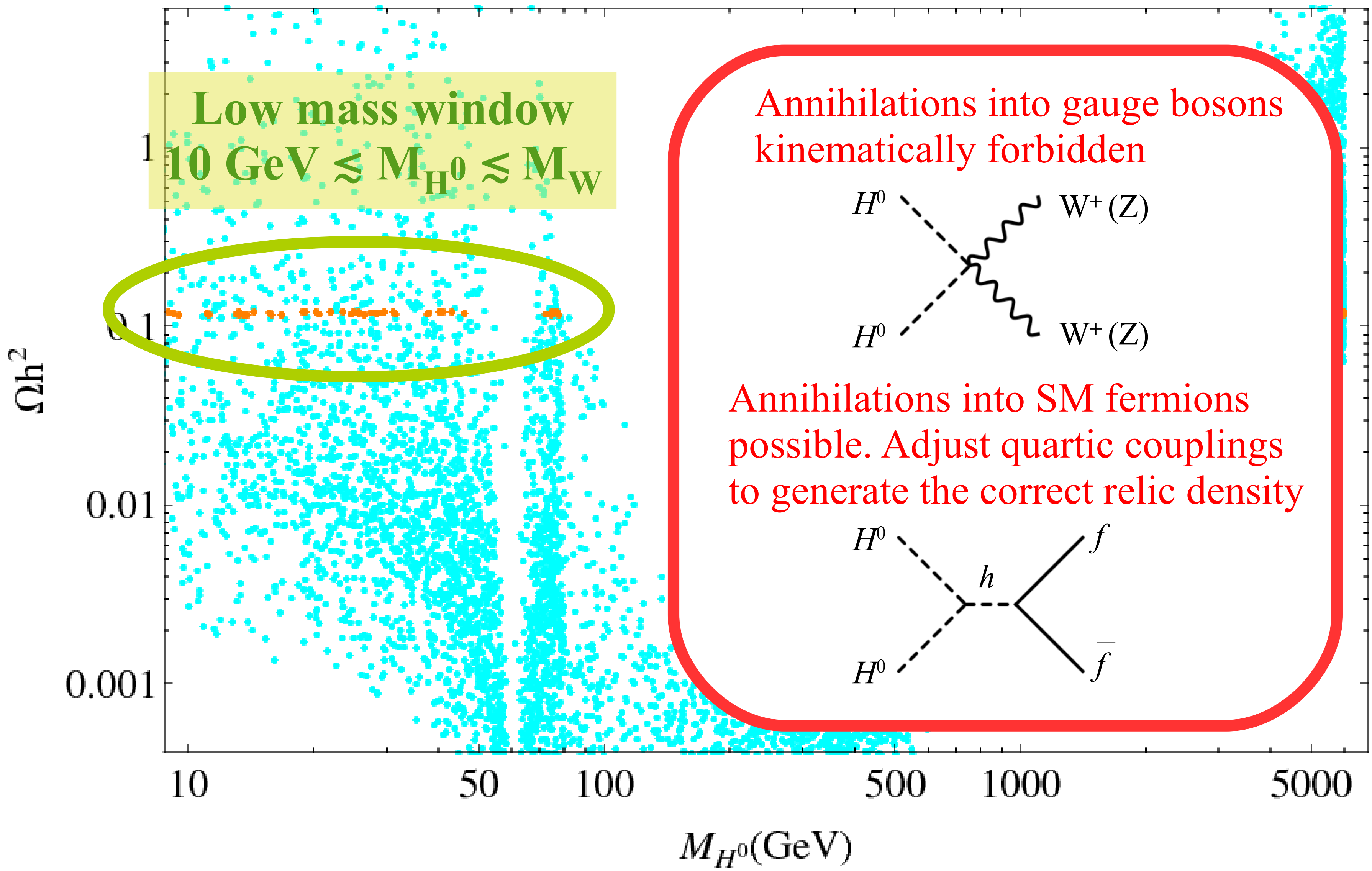

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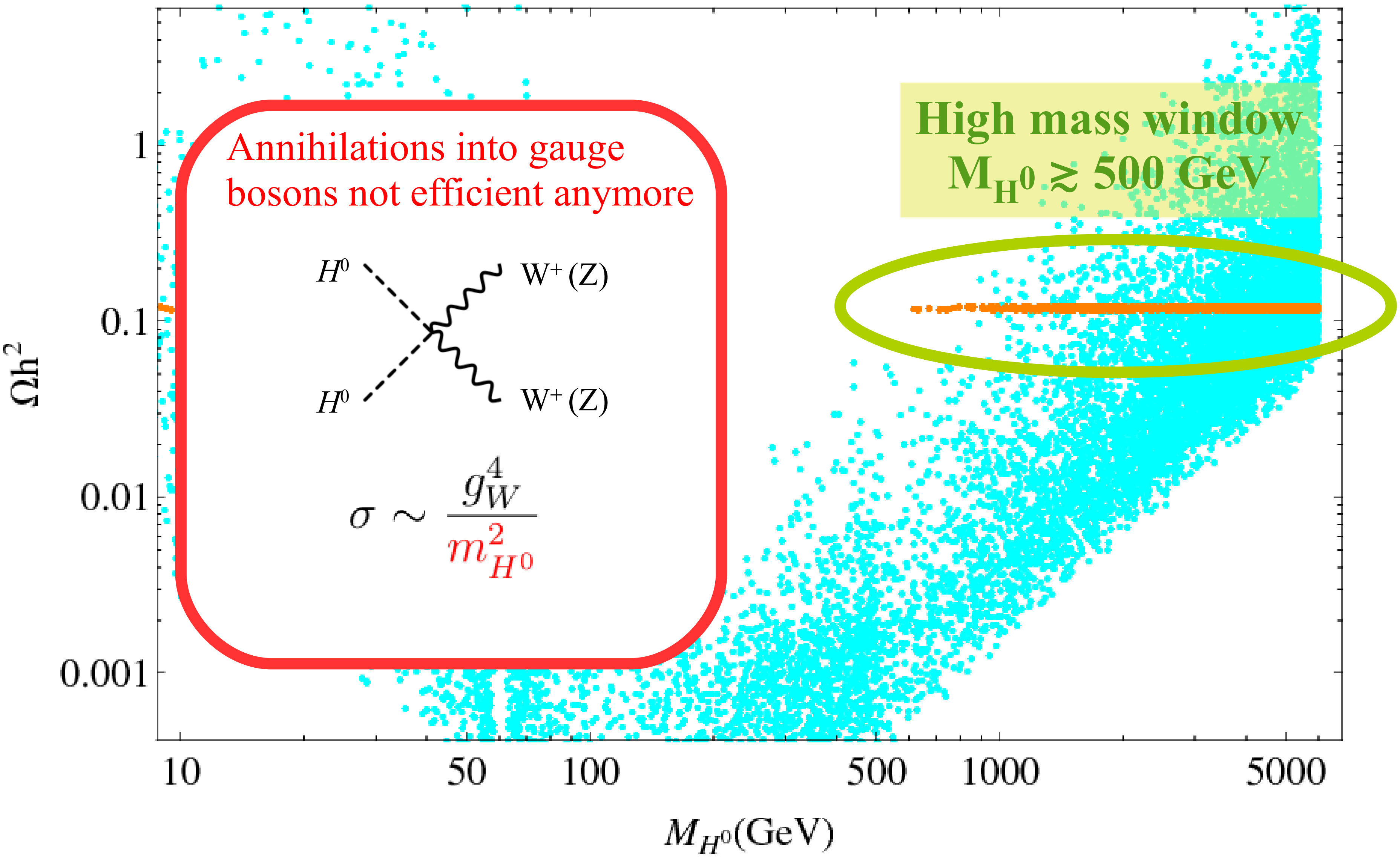

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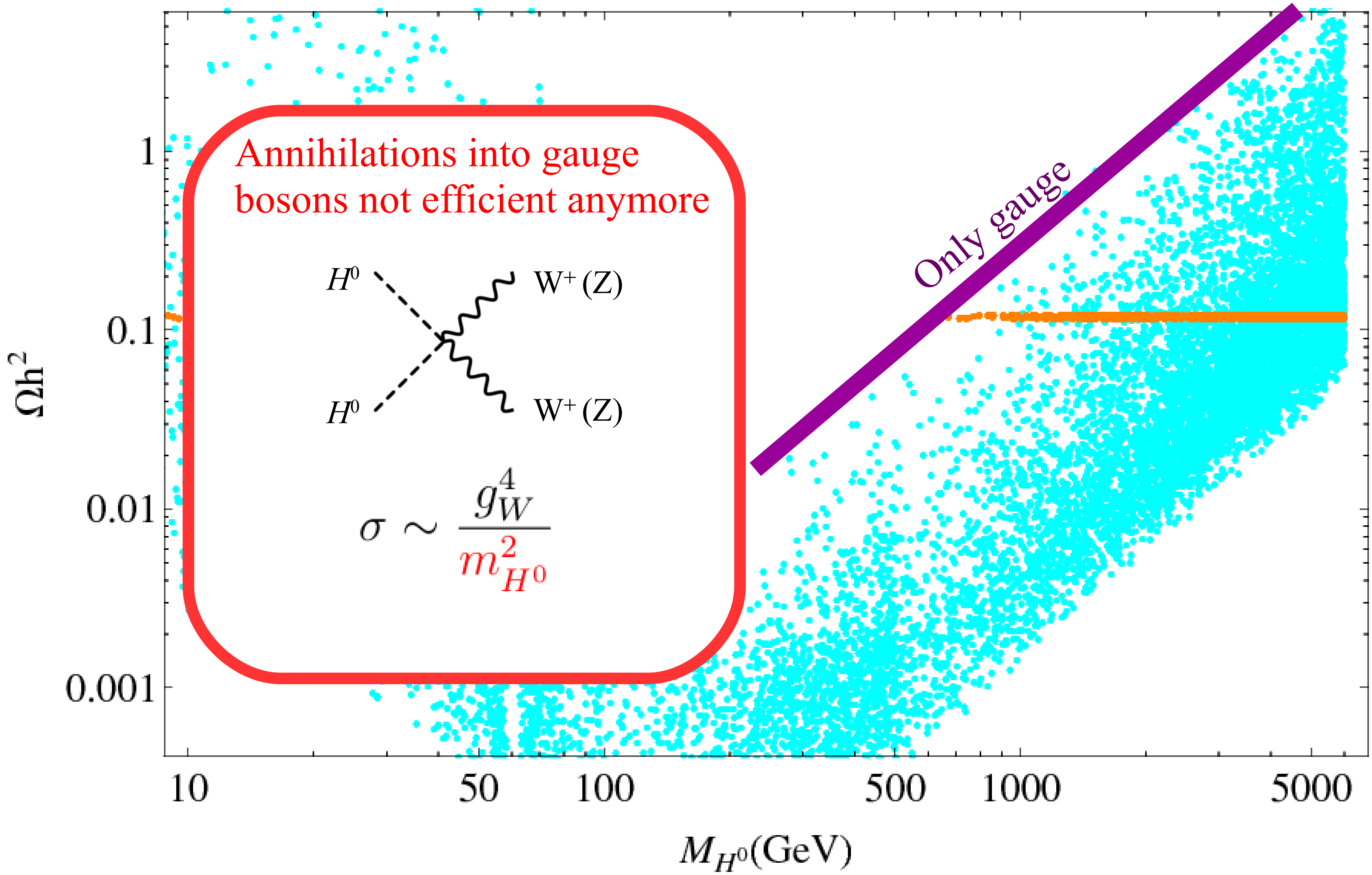

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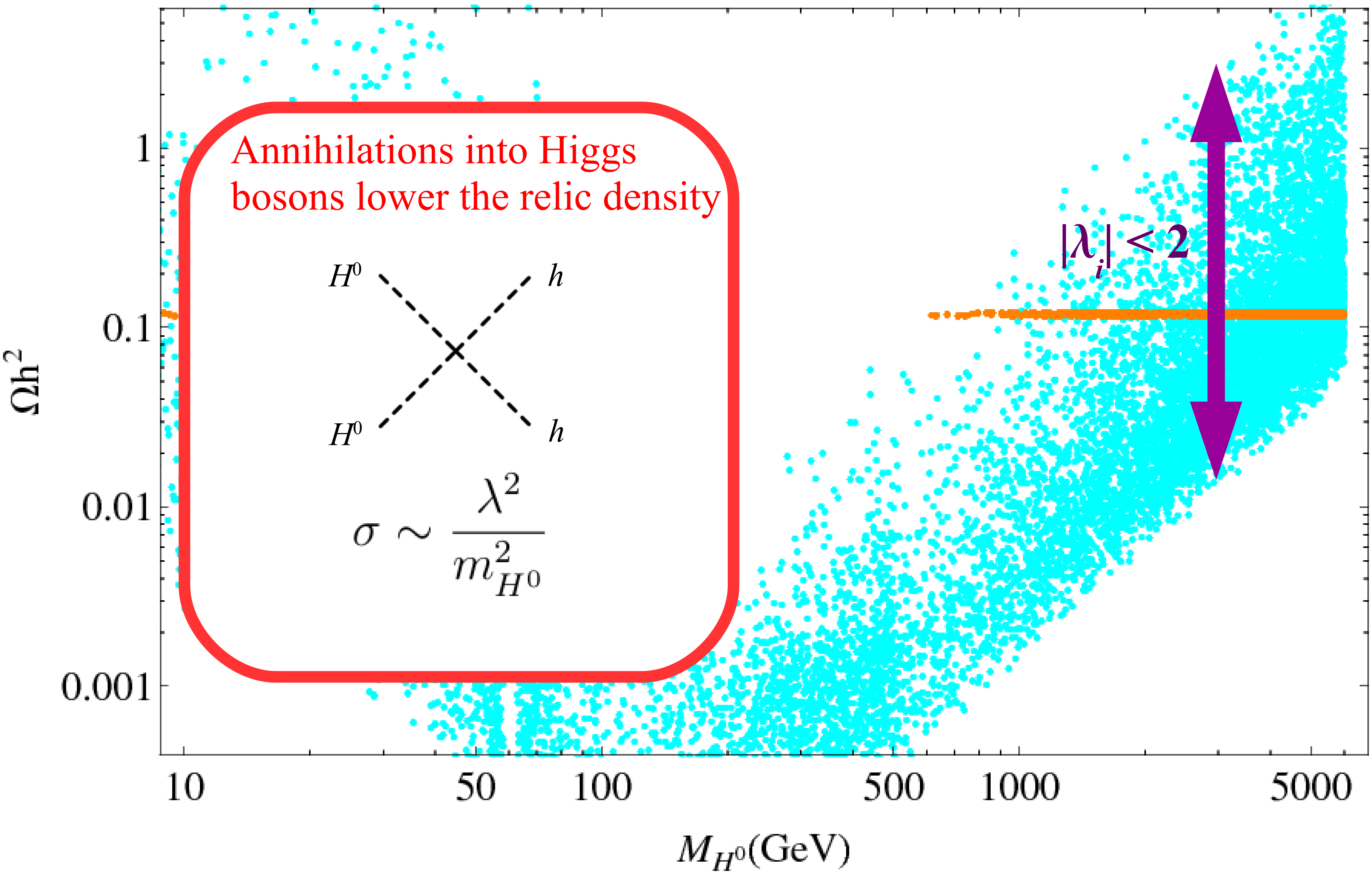
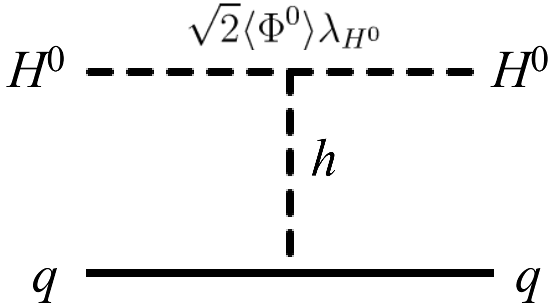
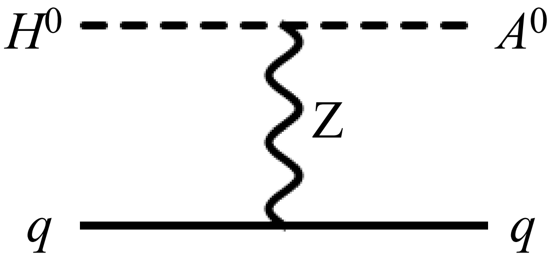


Direct detection





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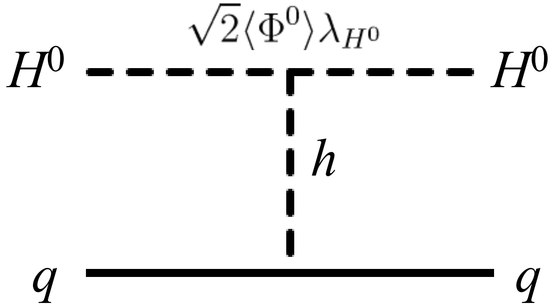
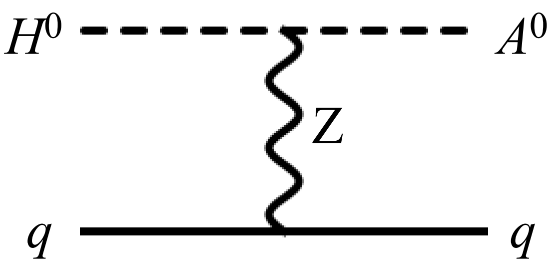
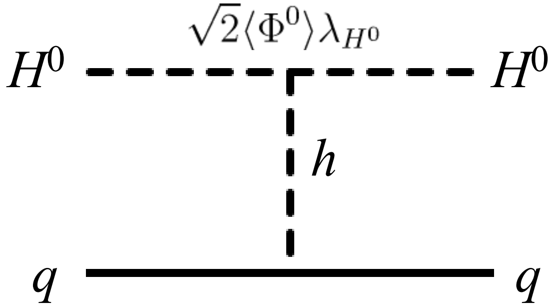




Irrelevant if $m_{A^0} - m_{H^0} \gtrsim 100$ keV

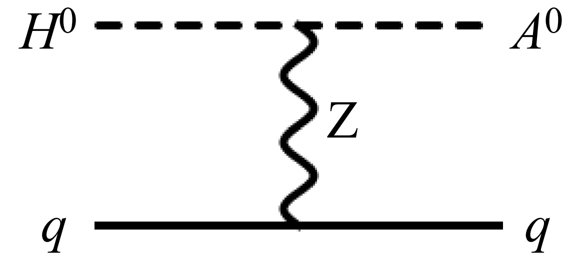
If allowed, typically leads to a too large scattering rate.

Direct detection



Most important channel

$$\boxed{\sigma(H^0 p) \simeq 4 \times 10^{-44} \lambda^2_{H^0} \left(\frac{1\,\mathrm{TeV}}{M_{H^0}}\right)^2 \mathrm{cm}^2}$$



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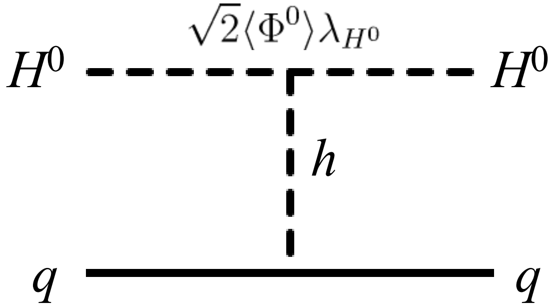

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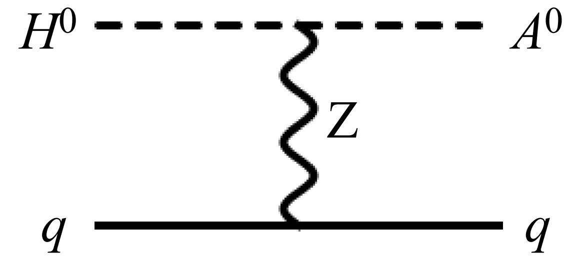

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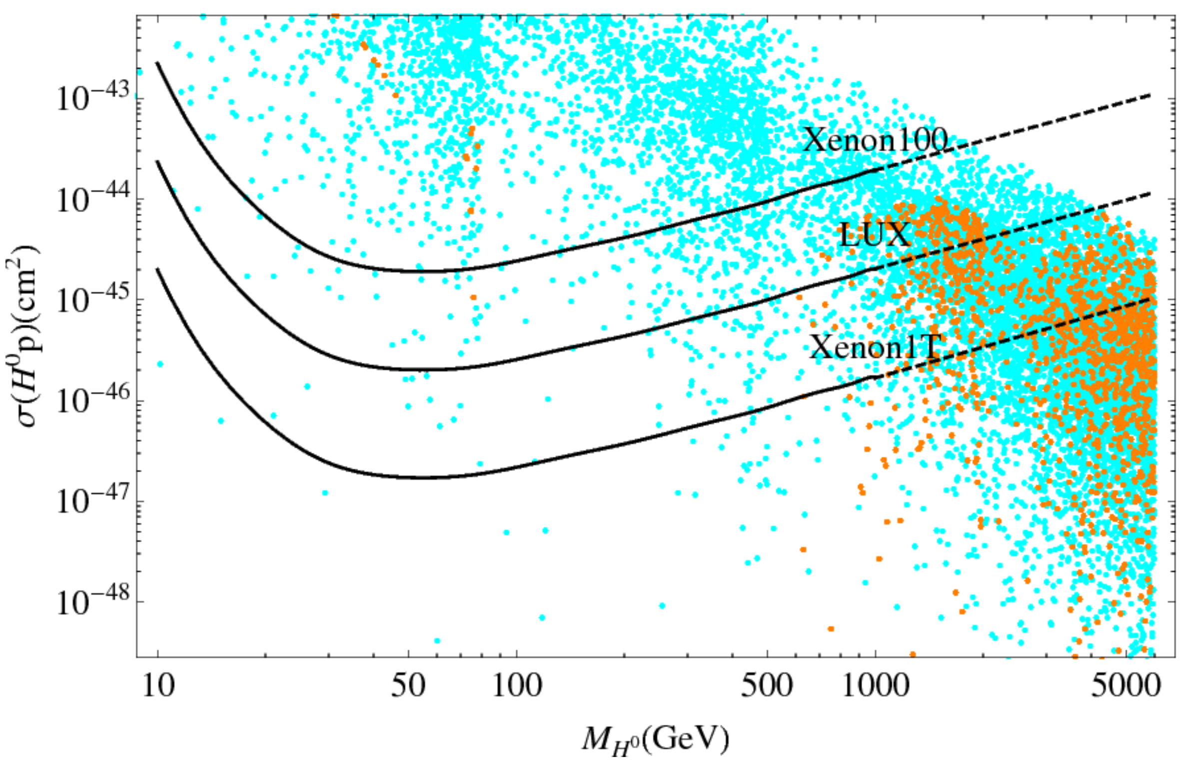

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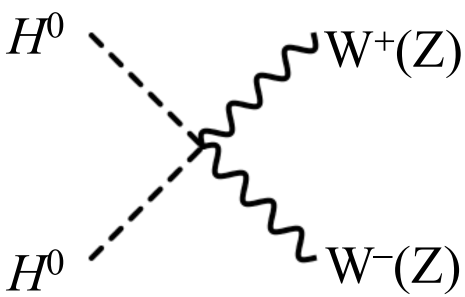
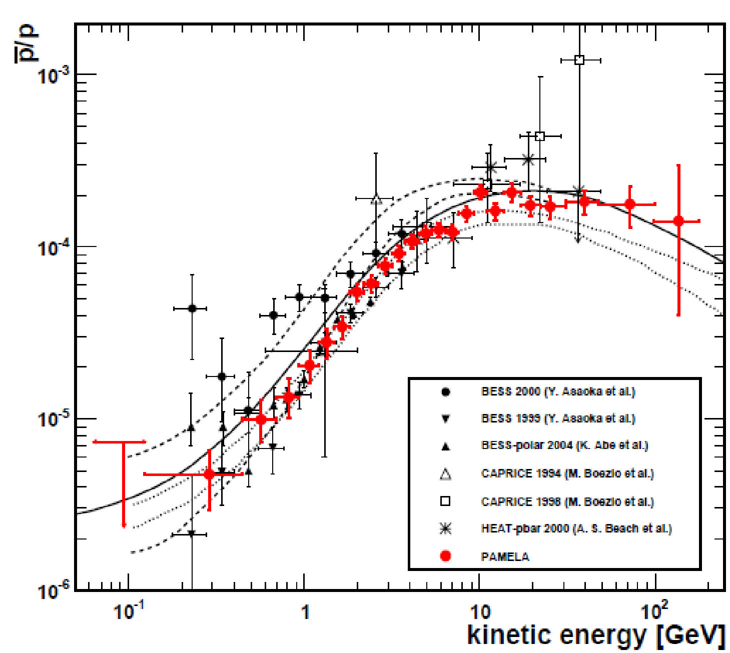


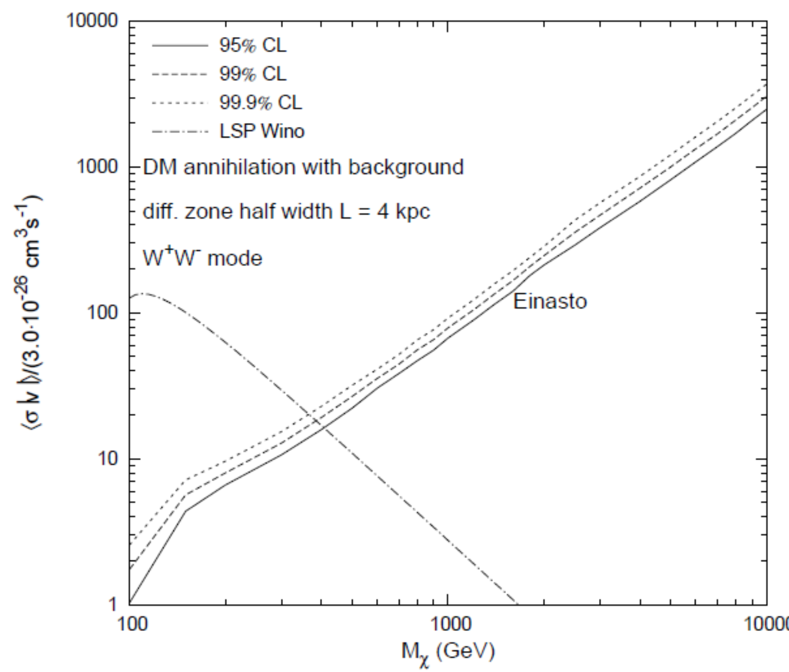
$+ \ldots$

The decays of the W, Z and Higgs bosons produce a flux of antiprotons, electrons/positrons, neutrinos and gamma-rays that could be detected at the Earth.

Antiprotons

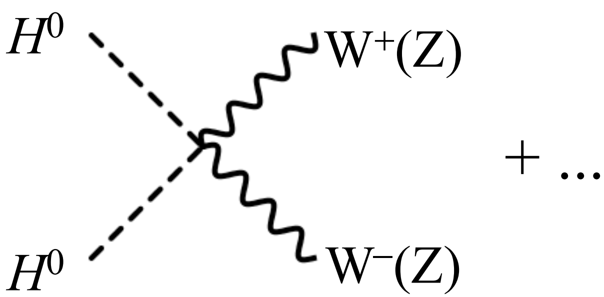


Adriani et al., PAMELA coll arXiv:1007.0821



Cholis, arXiv:1007.1160

Indirect detection



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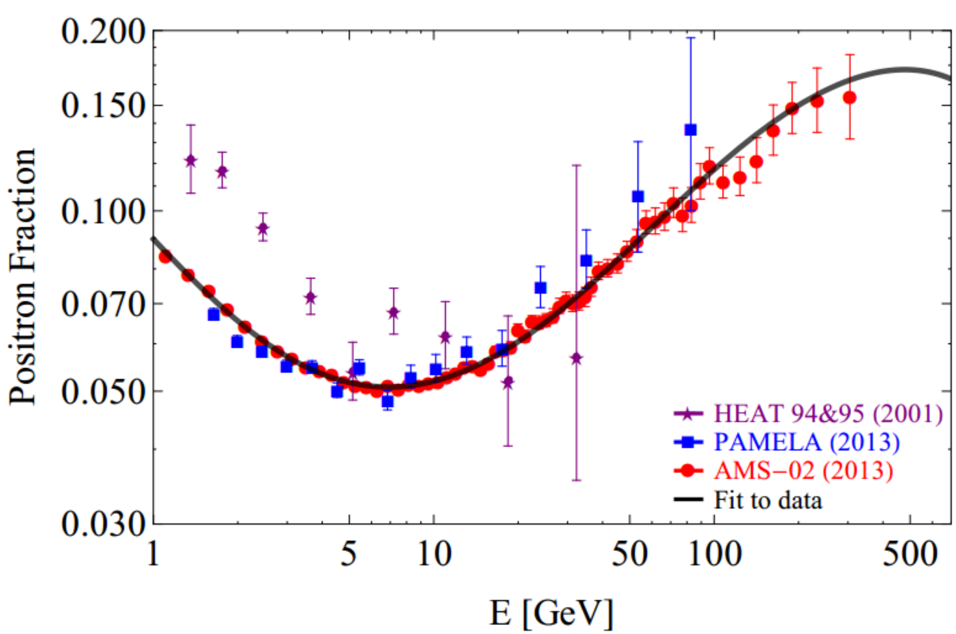
Positrons



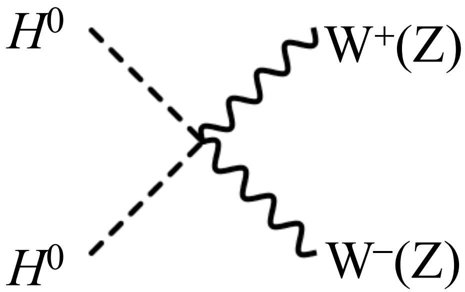
Positron fraction well fitted by:

$$\Phi^{\rm IS}_{e^+}(E) = \underbrace{C_{e^+} E^{-\gamma_{e^+}}}_{\text{Secondary production}} + \underbrace{C_s E^{-\gamma_s} \exp(-E/E_s)}_{\text{Sources}}$$

and corrected for solar modulation effects.

$\longrightarrow$ Limits on dark matter properties

Indirect detection



+ …

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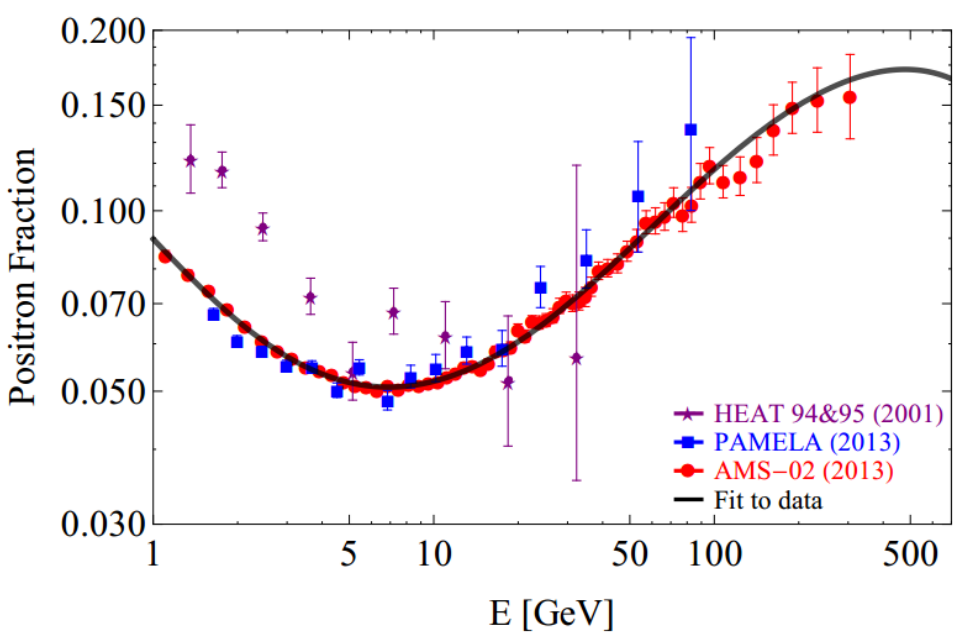
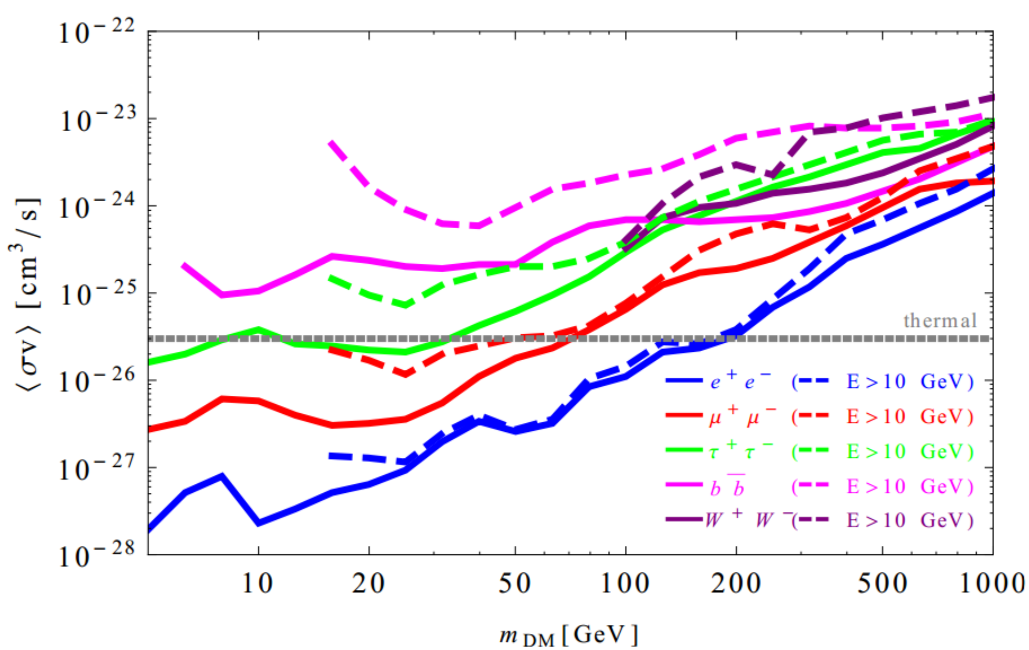
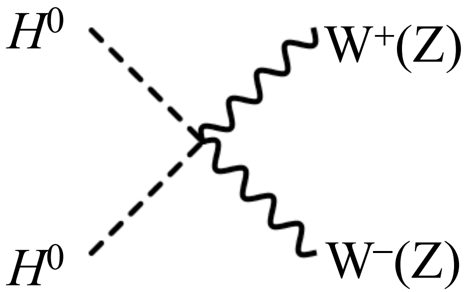




AI, Lamperstofer, Silk, arXiv:1309.2570

Indirect detection



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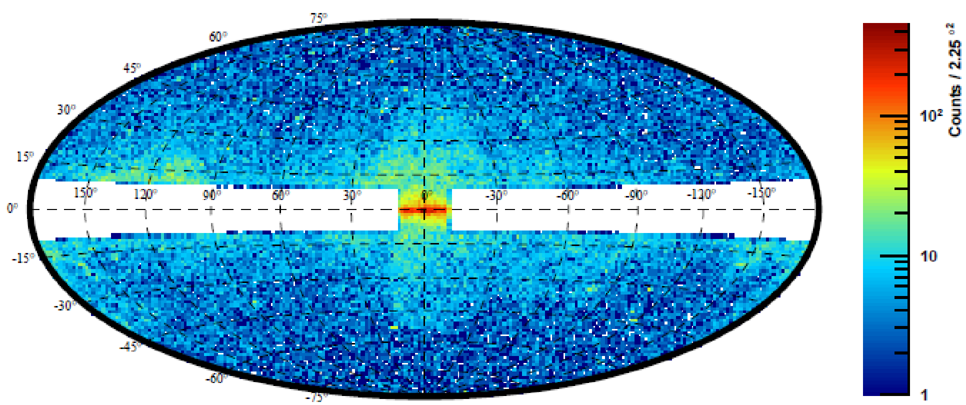
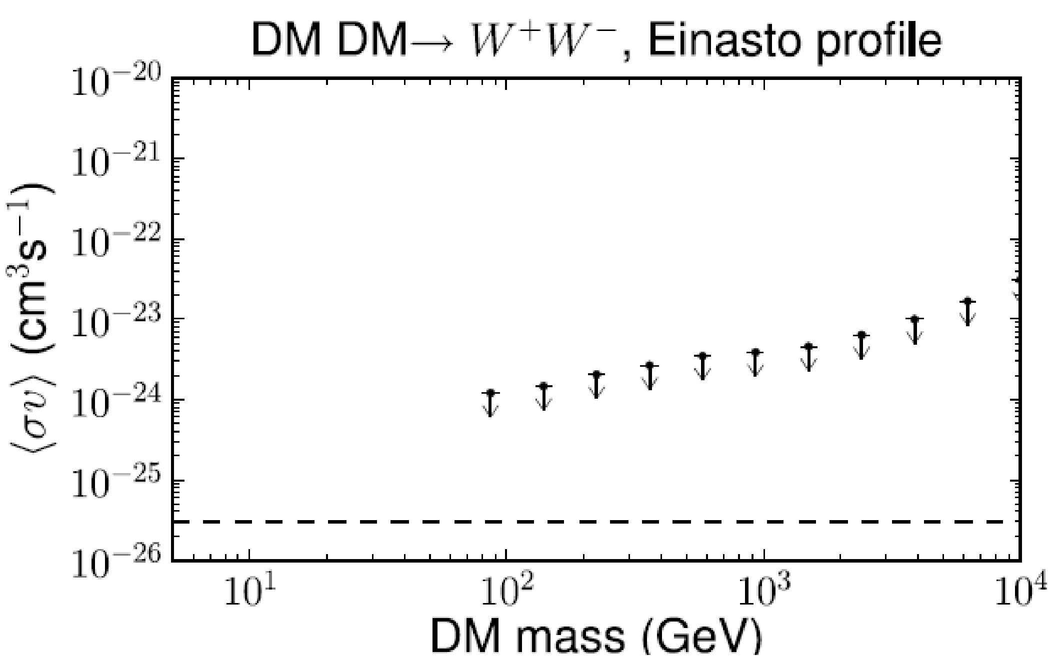
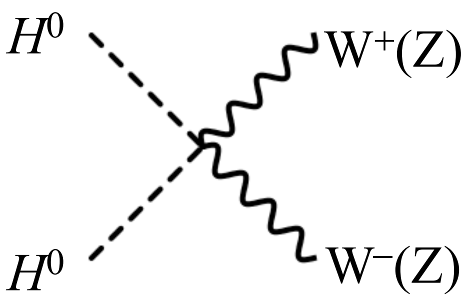
Gamma rays: diffuse flux





Ackermann et al., Fermi Coll.
arXiv:1205.2739

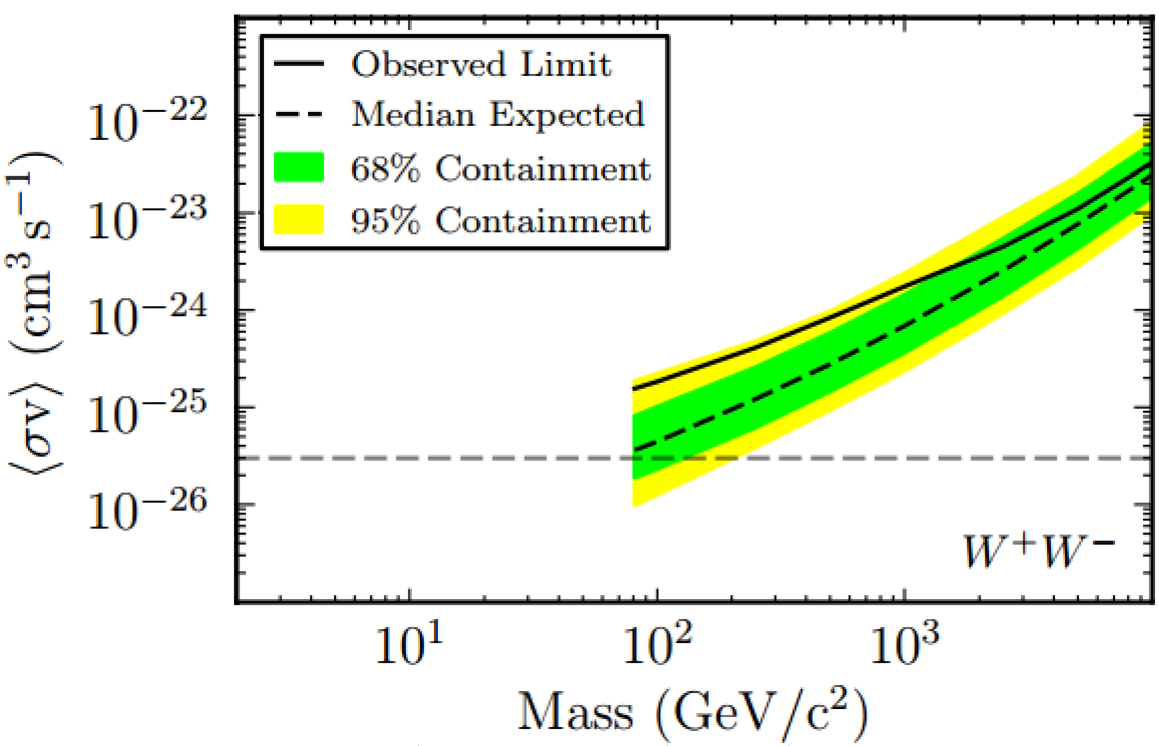
Indirect detection



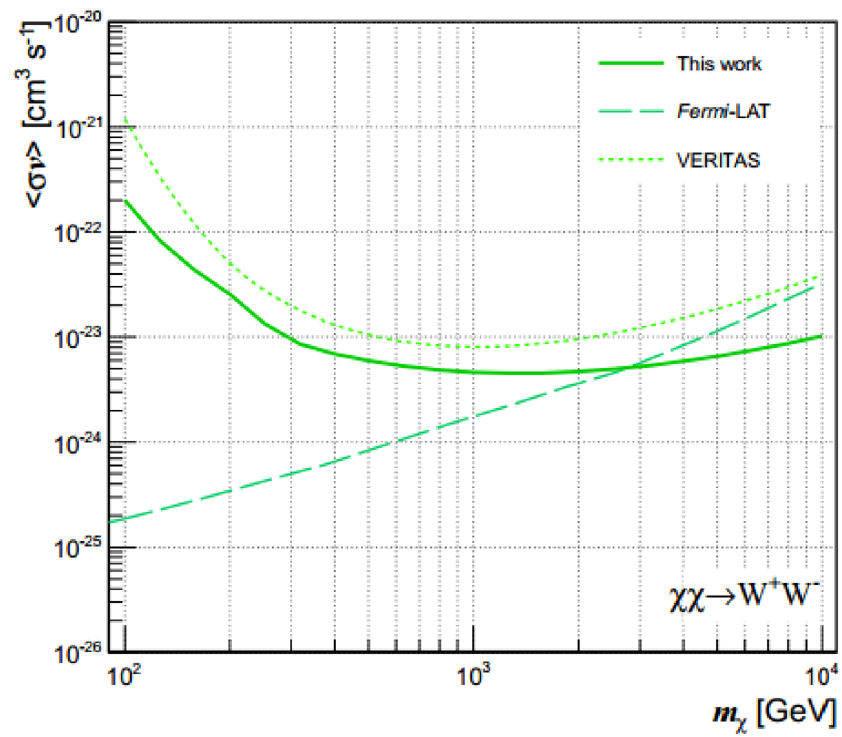
$+ \ldots$

The decays of the W, Z and Higgs bosons produce a flux of antiprotons, electrons/positrons, neutrinos and gamma-rays that could be detected at the Earth.

Gamma rays: dwarf galaxies

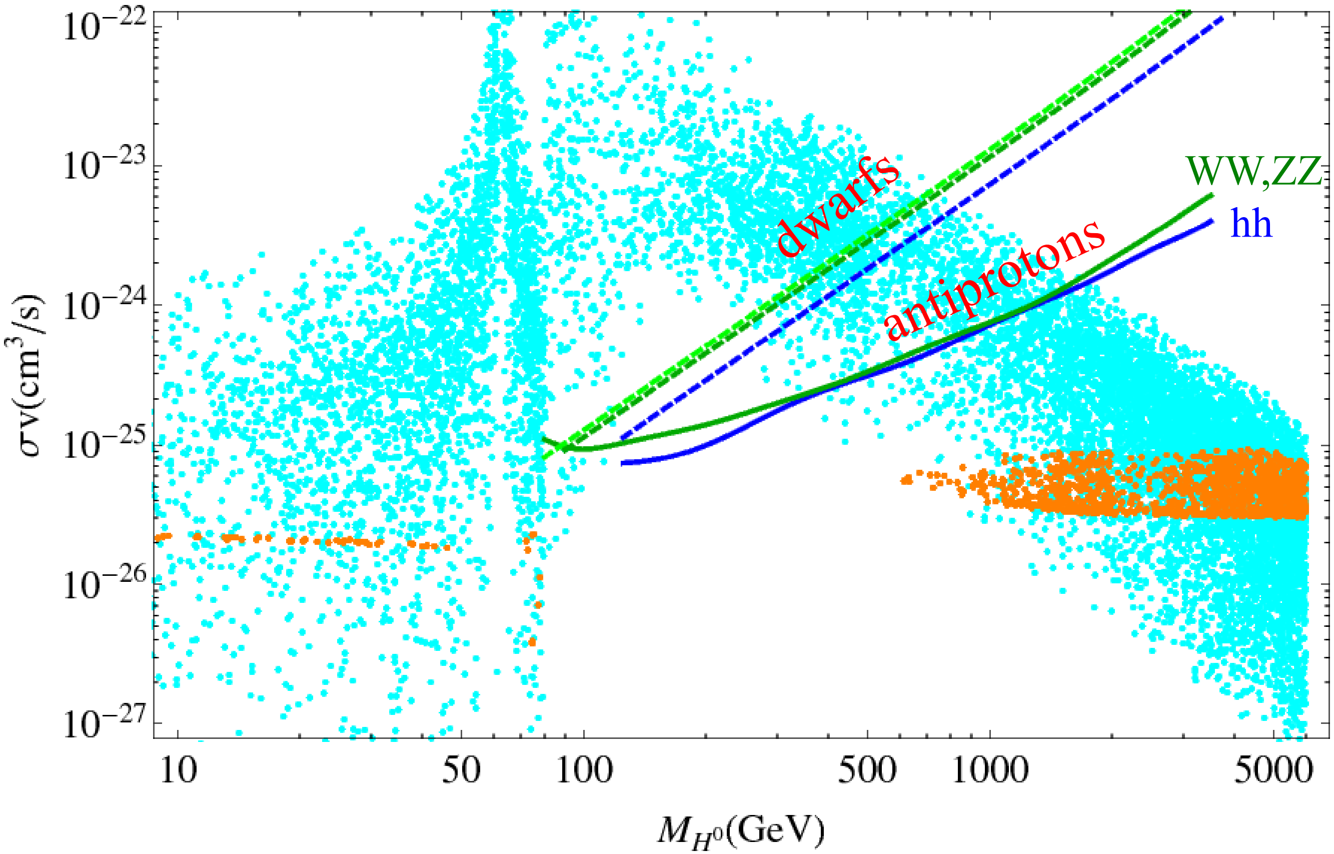


Ackermann et al., arXiv:1310.0828

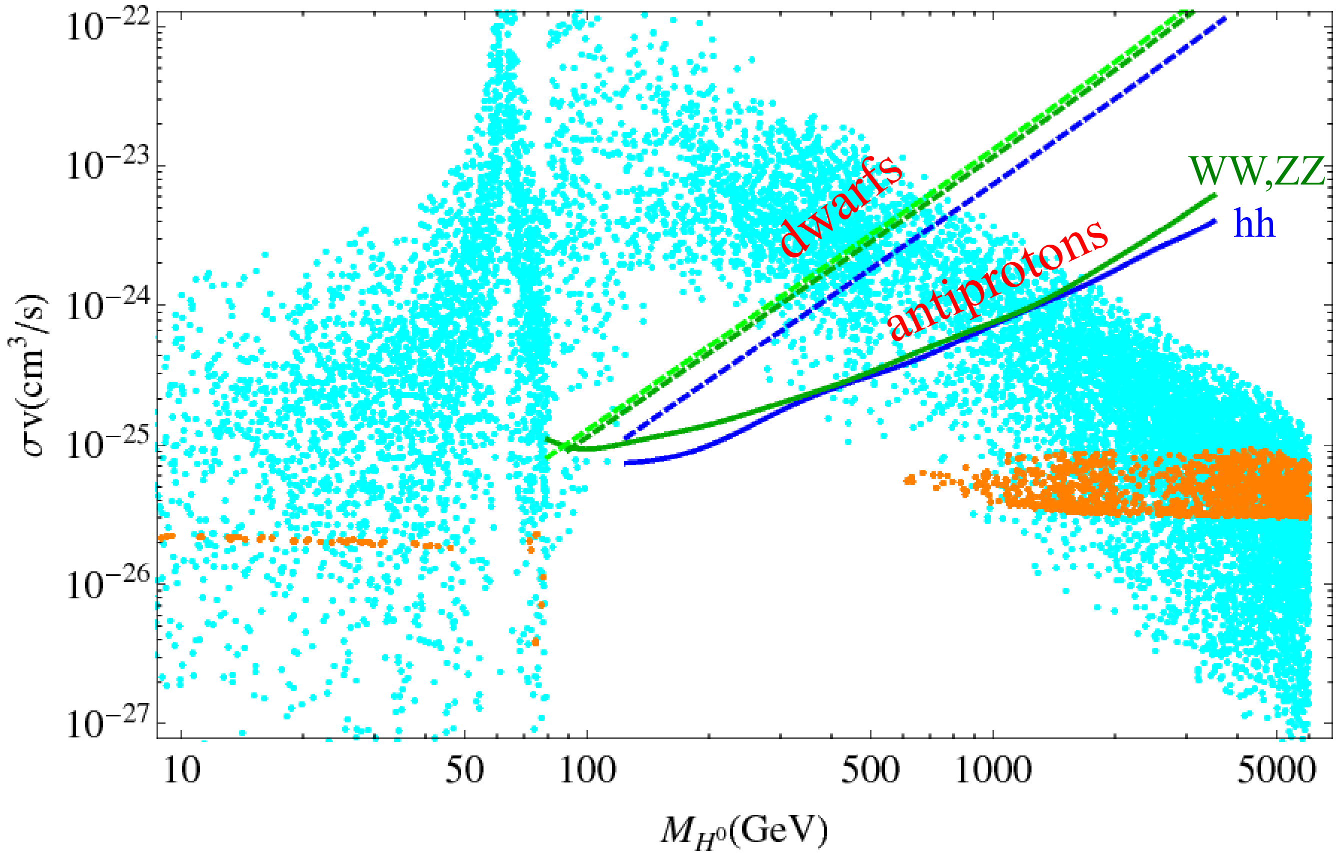


Aleksić et al., arXiv:1312.1535

Indirect detection



Indirect detection



Closing in!

However, astrophysical processes could produce an antiproton flux or a featureless gamma-ray flux that could mimic the annihilations $H^0\ H^0 \to W^+\ W^-$

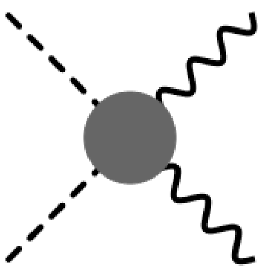
How to discover dark matter in indirect dark matter searches?

Indirect detection: Gamma-ray spectral features

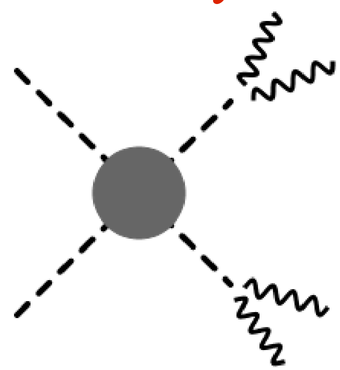
Smoking gun for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

Three gamma-ray spectral features have been identified:

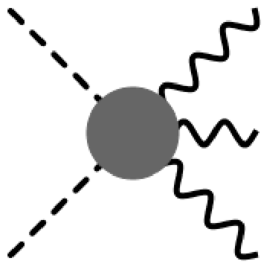
Gamma ray line

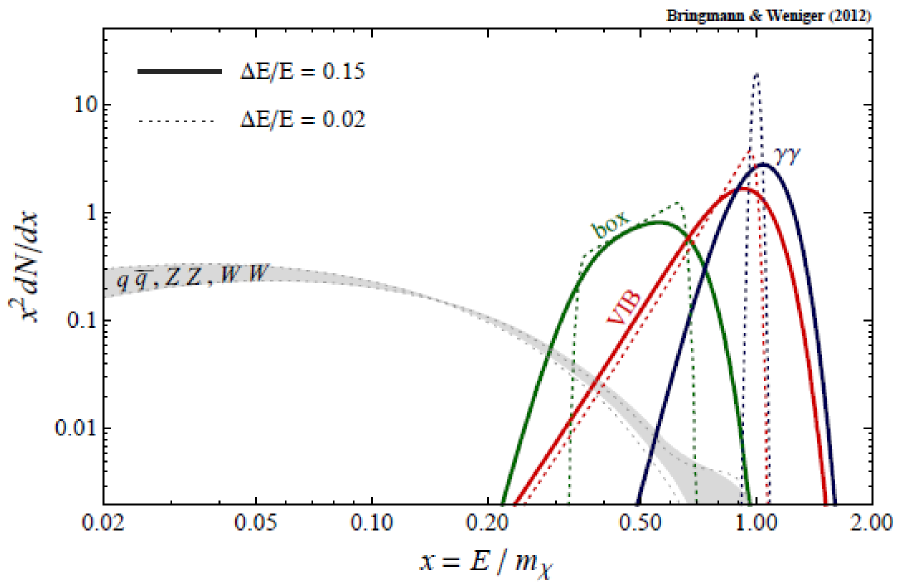


Gamma ray box



Internal bremsstrahlung





Indirect detection: Gamma-ray spectral features

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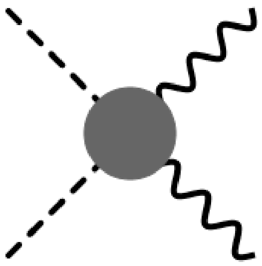
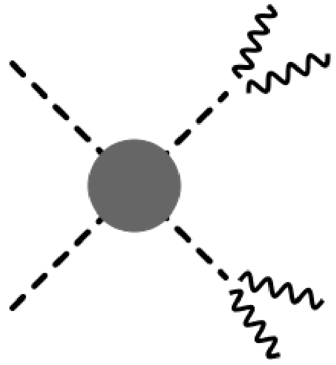
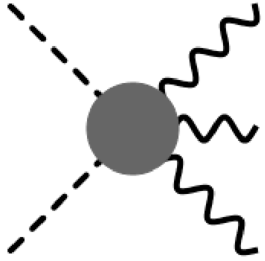


Gamma ray box



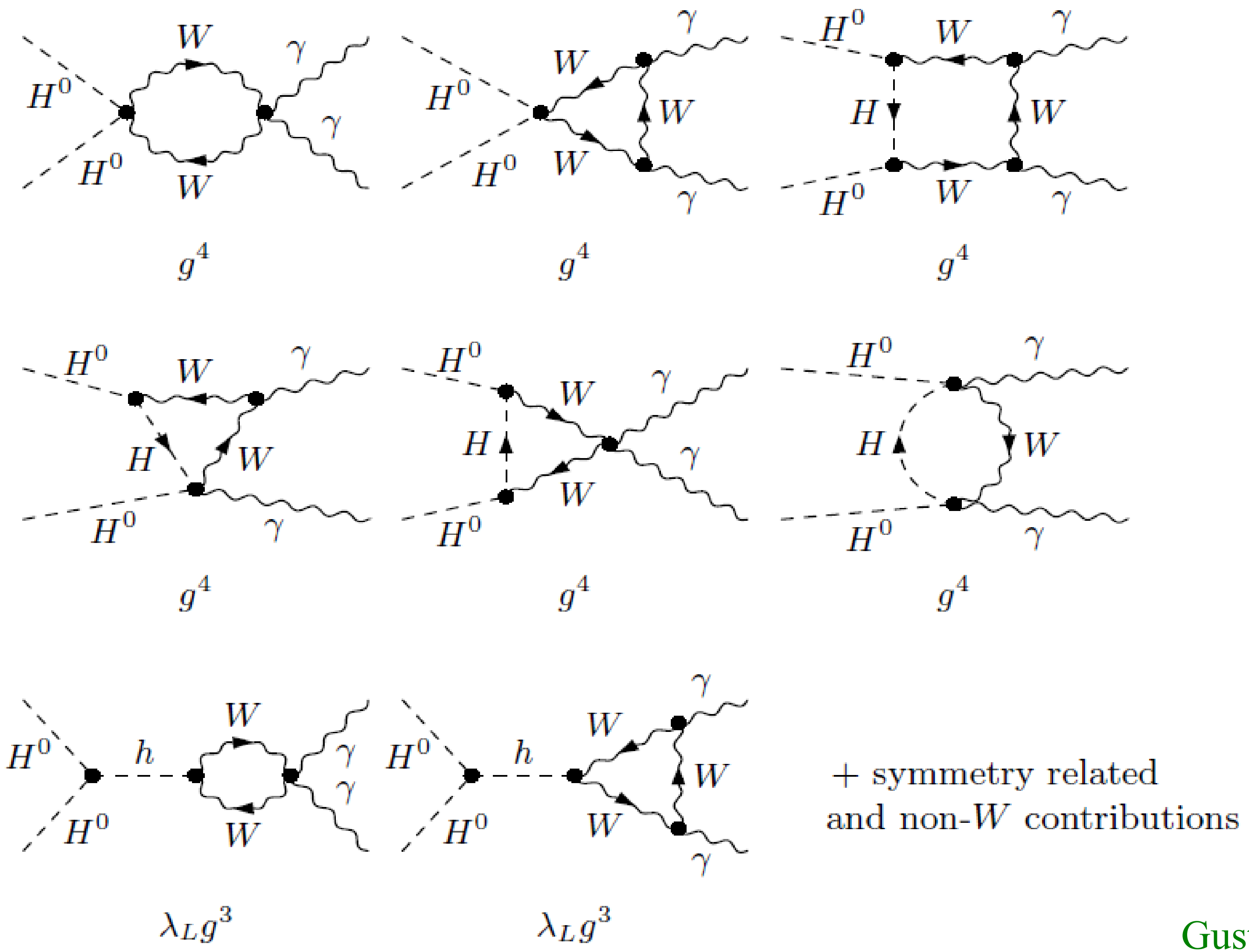
Internal bremsstrahlung



The three of them arise in the inert doublet model!

Indirect detection: Gamma-ray spectral features

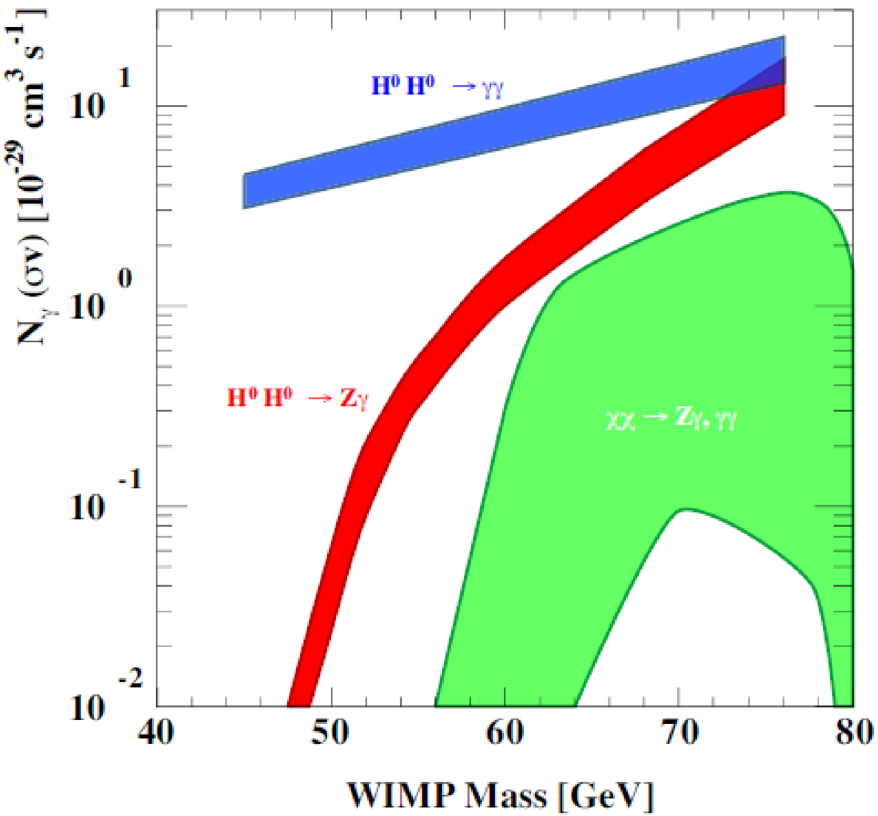
Gamma-ray lines



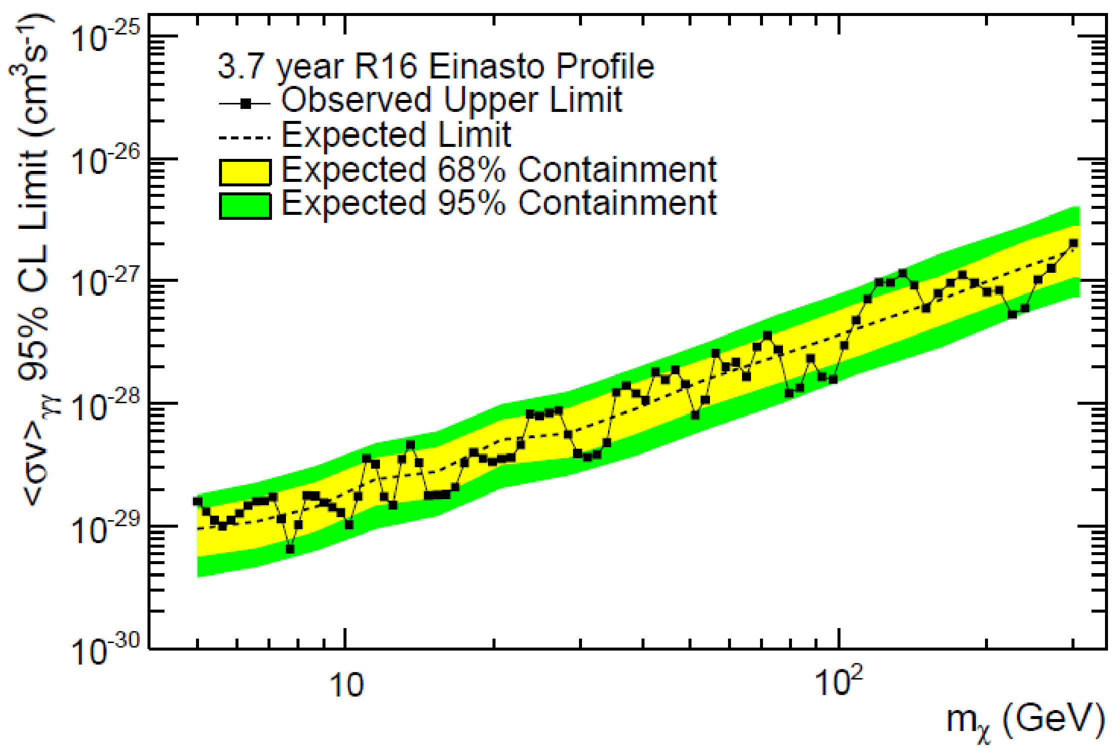
Gustafsson

Indirect detection: Gamma-ray spectral features

Gamma-ray lines



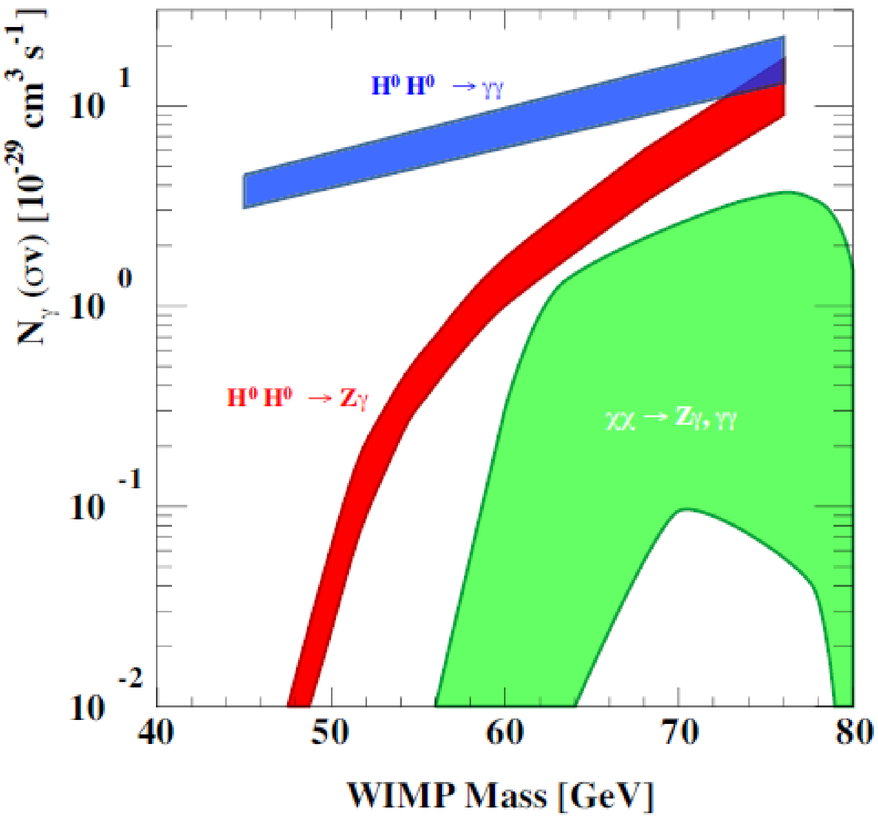
Gustafsson, Lundström, Bergström, Edsjö
astro-ph/0703512



Ackermann et al., Fermi Coll.
arXiv:1305.5597

Indirect detection: Gamma-ray spectral features

Gamma-ray lines



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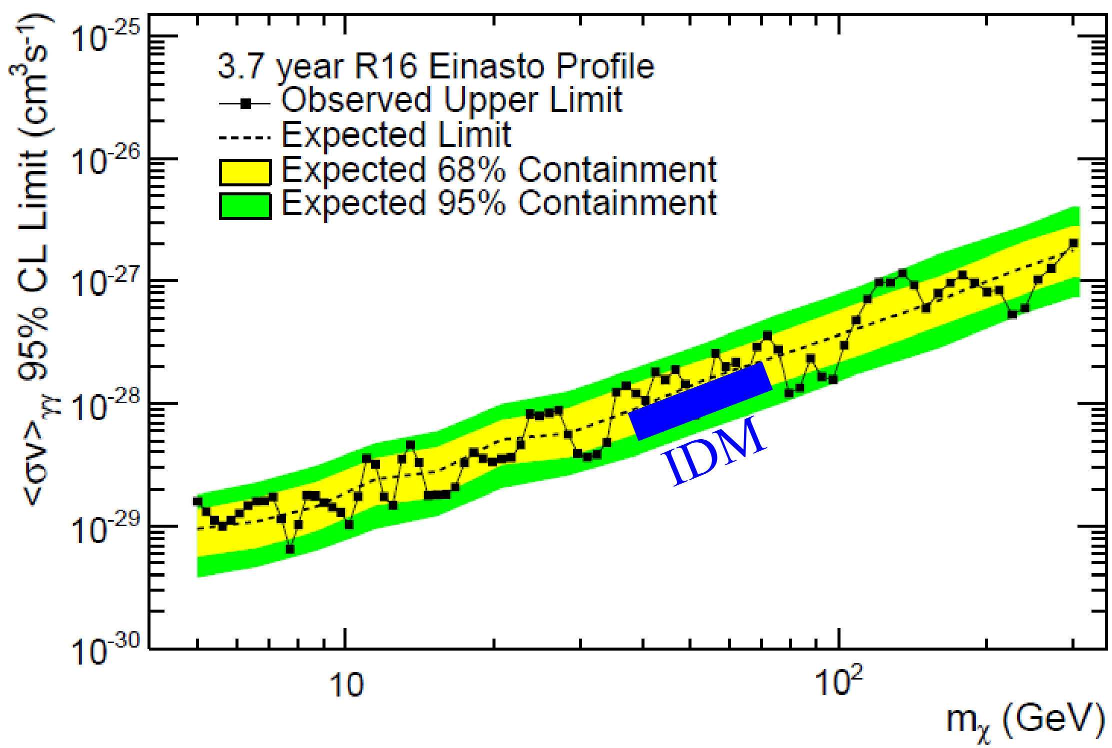

Ackermann et al., Fermi Coll.
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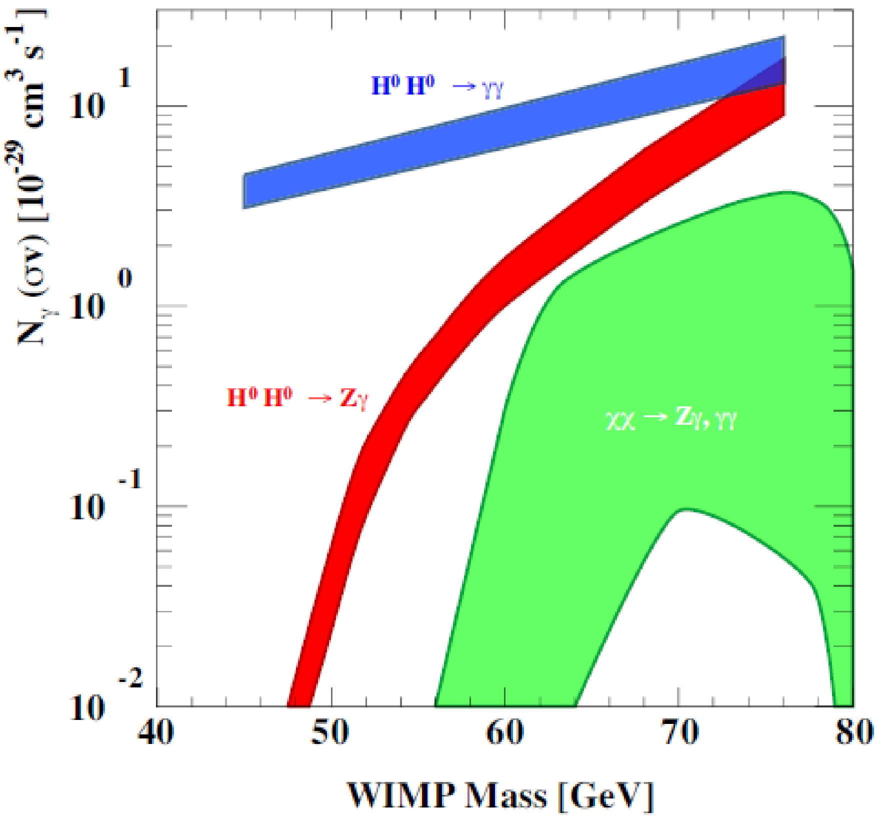
Indirect detection: Gamma-ray spectral features

Gamma-ray lines



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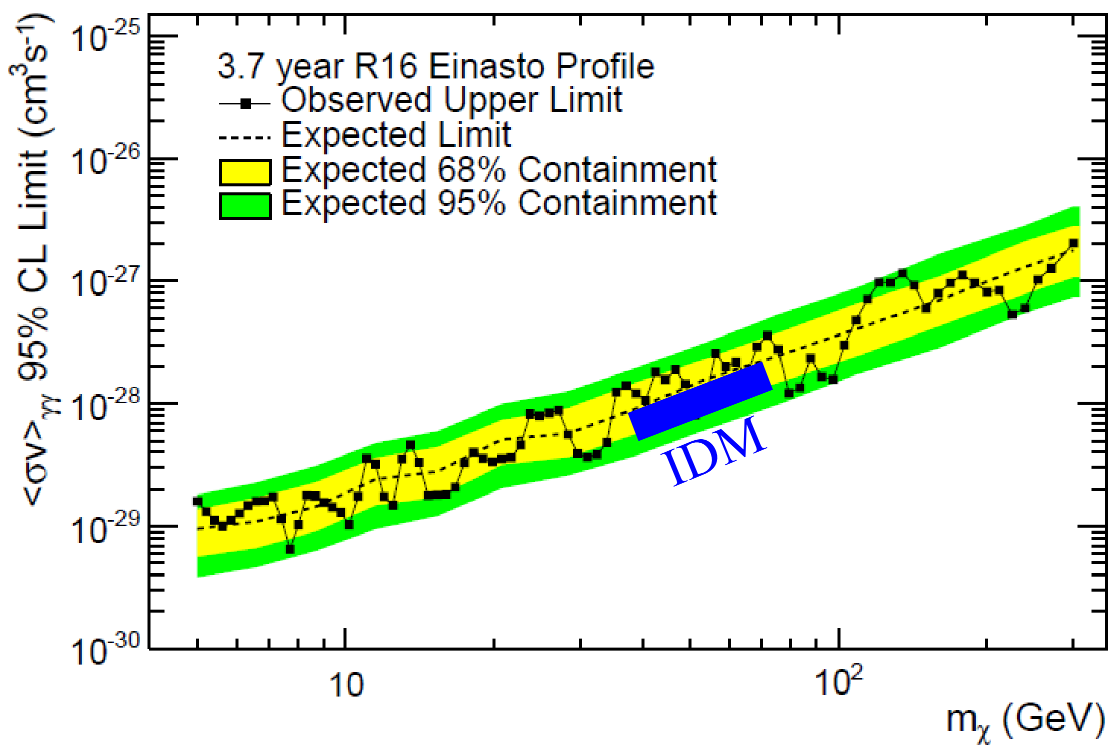


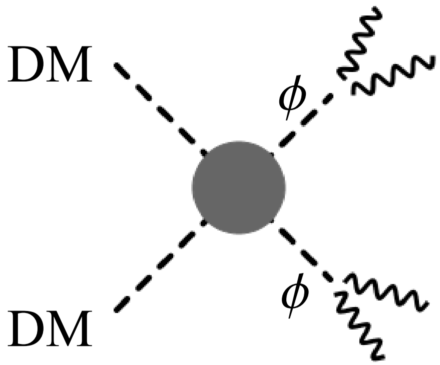
Ackermann et al., Fermi Coll.
arXiv:1305.5597

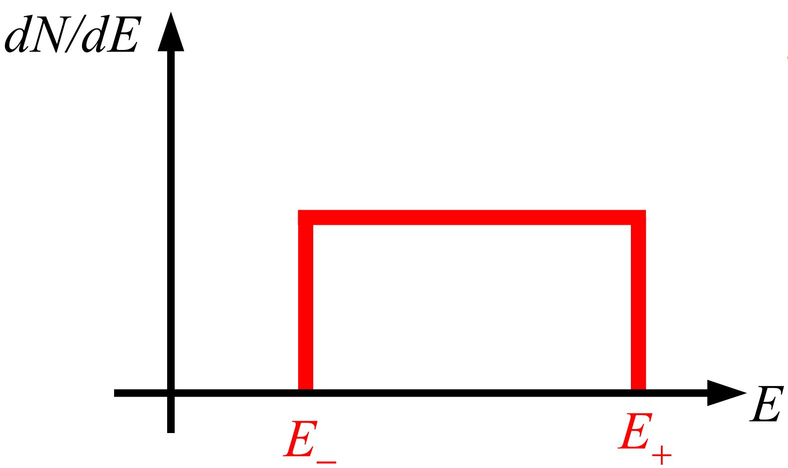
Gamma lines in the high-mass regime? In progress...

AI, Garcia-Cely, Gustafsson

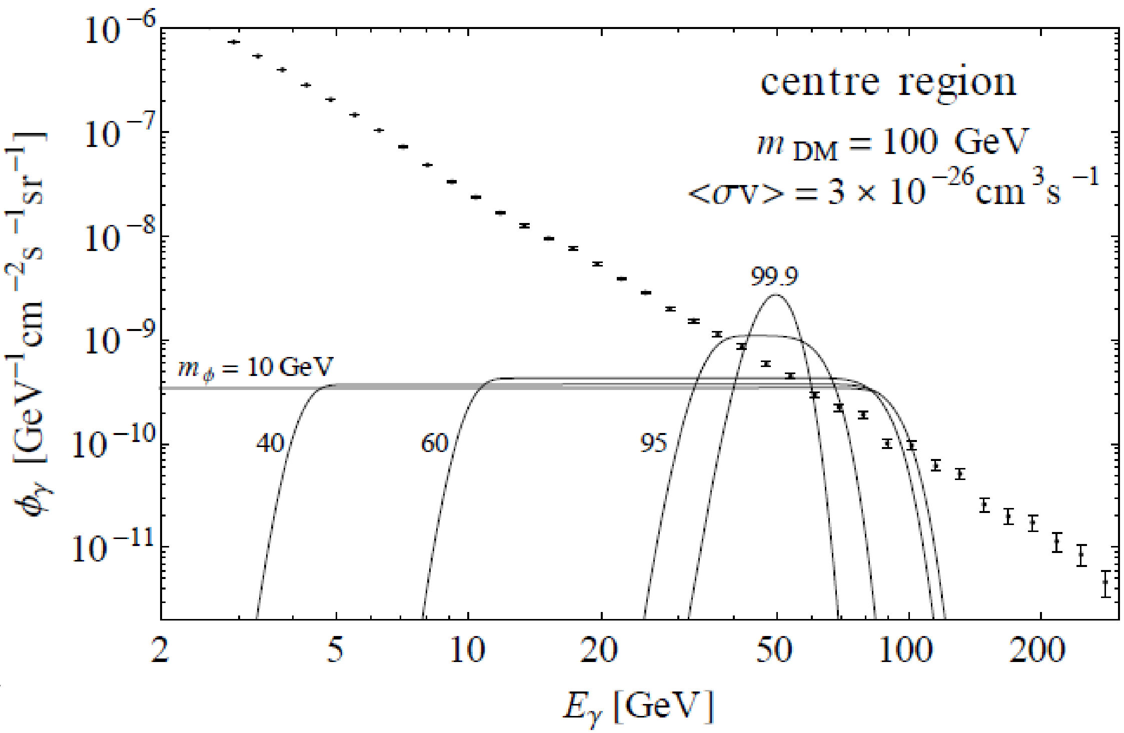
Indirect detection: Gamma-ray spectral features

Gamma-ray boxes





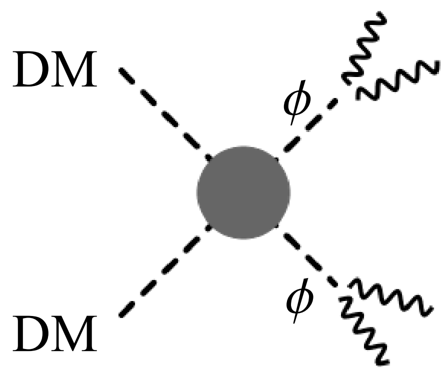
$$E_\pm = \frac{m_{\rm DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_\phi^2}{m_{\rm DM}^2}}\right)$$

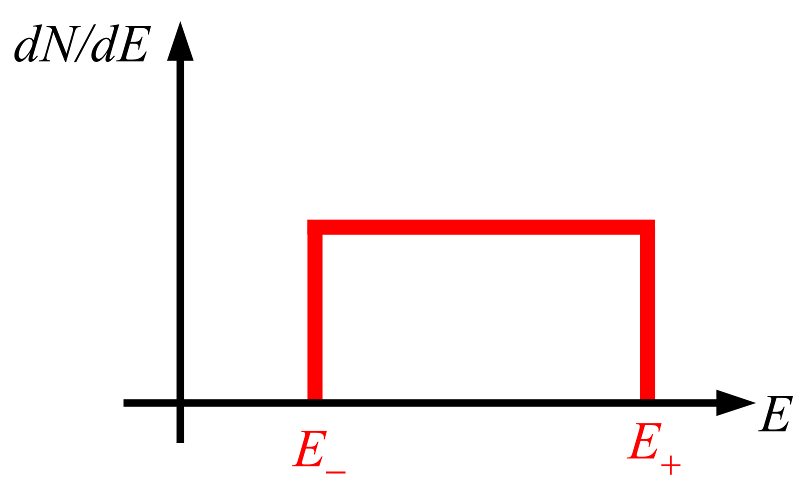


AI, Lopez Gehler, Pato
arXiv:1205.0007

Indirect detection: Gamma-ray spectral features

Gamma-ray boxes





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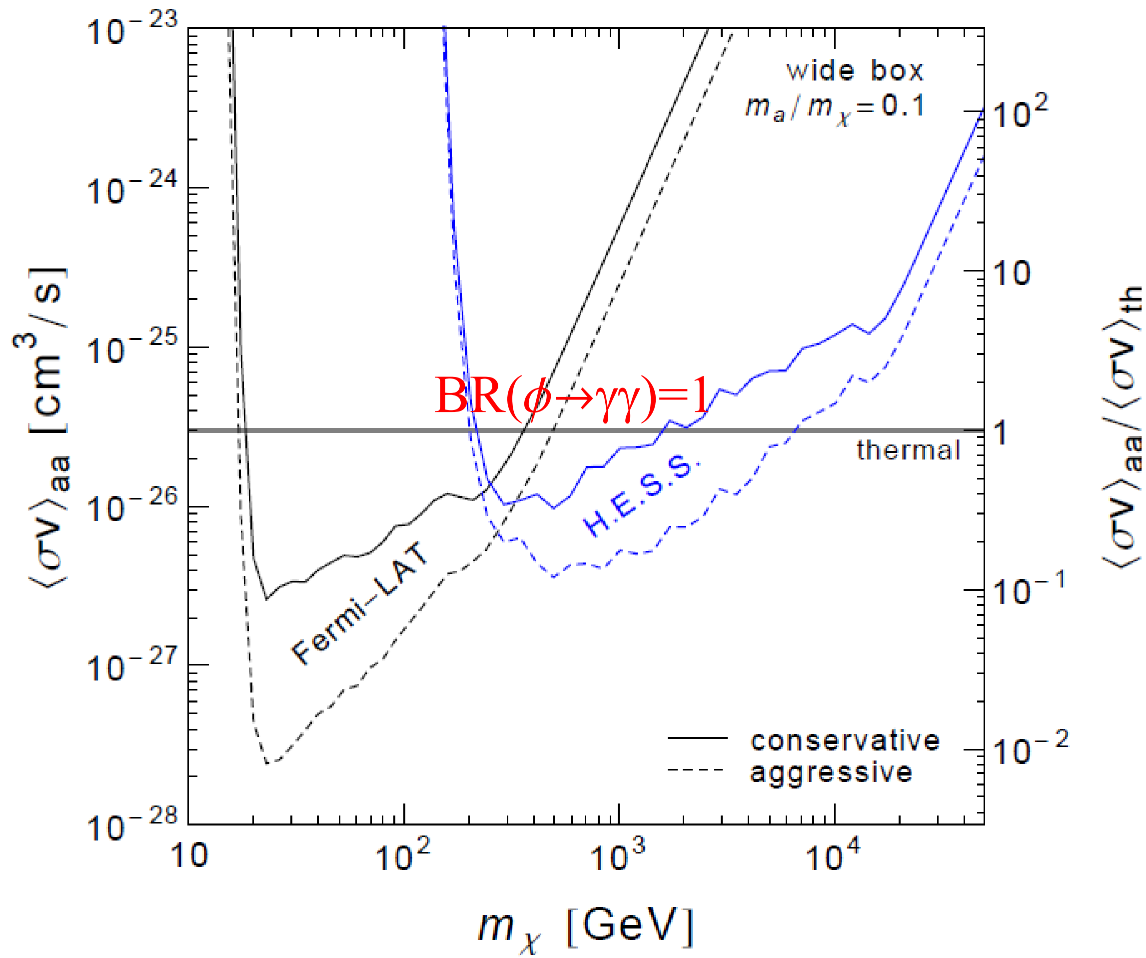
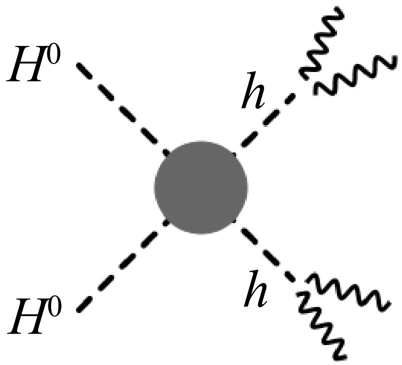
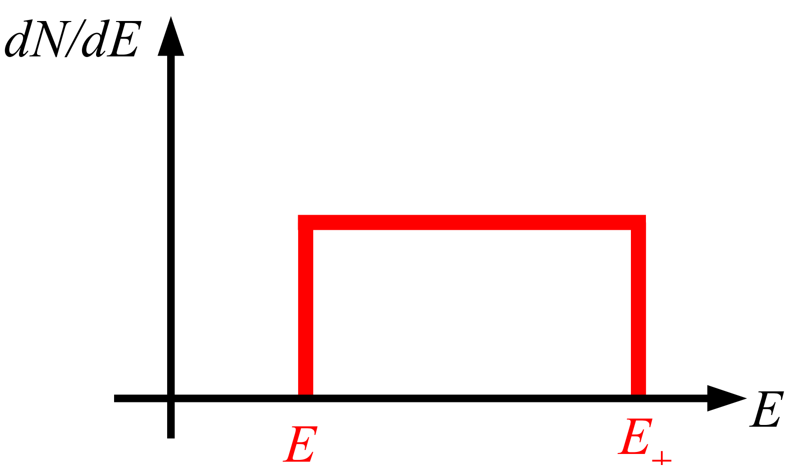


AI, Lee, Lopez Gehler, Park, Pato
arXiv:1303.6632

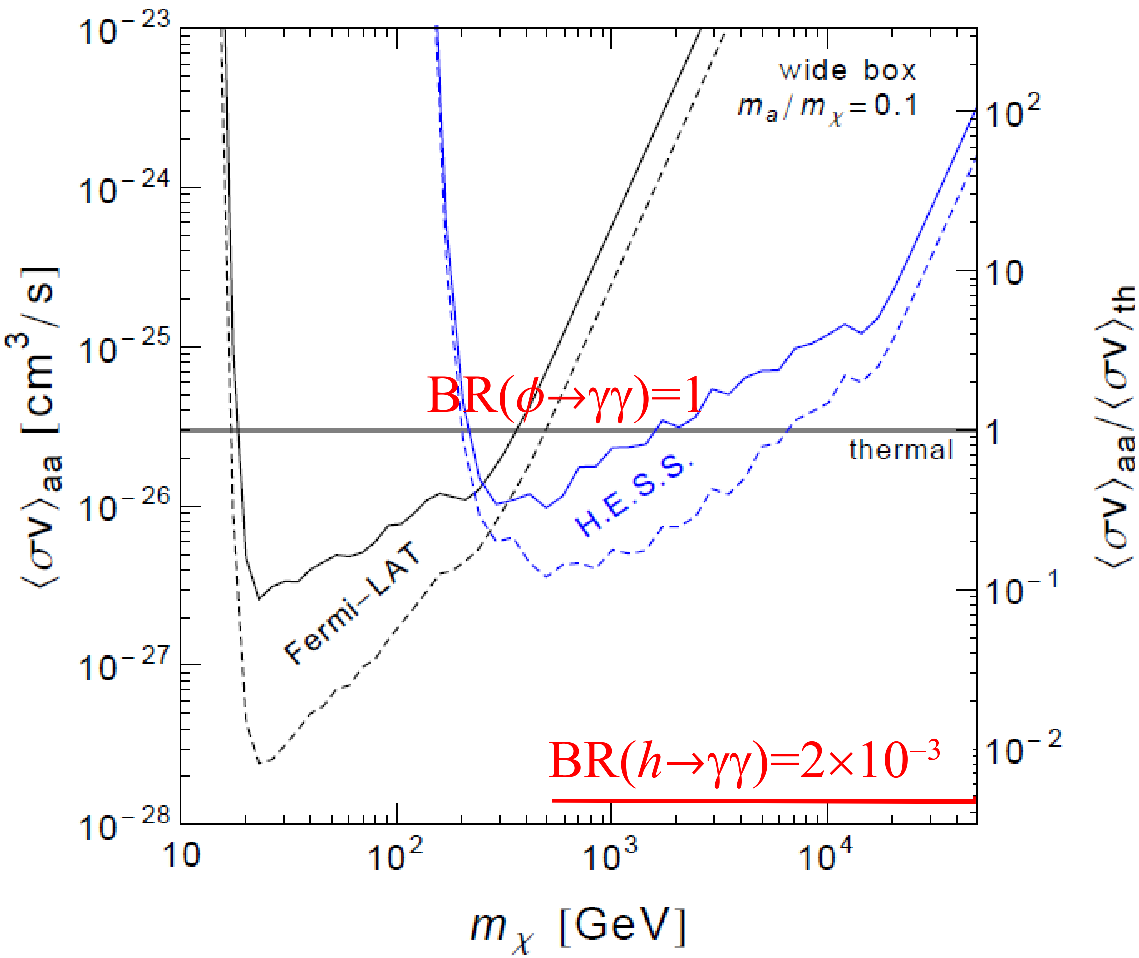
Indirect detection: Gamma-ray spectral features

Gamma-ray boxes





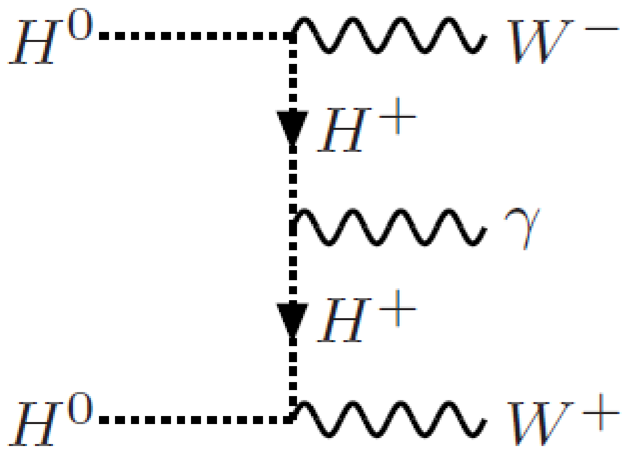
$$E_\pm = \frac{M_{H^0}}{2}\left(1 \pm \sqrt{1 - \frac{m_h^2}{M_{H^0}^2}}\right)$$



AI, Lee, Lopez Gehler, Park, Pato
arXiv:1303.6632

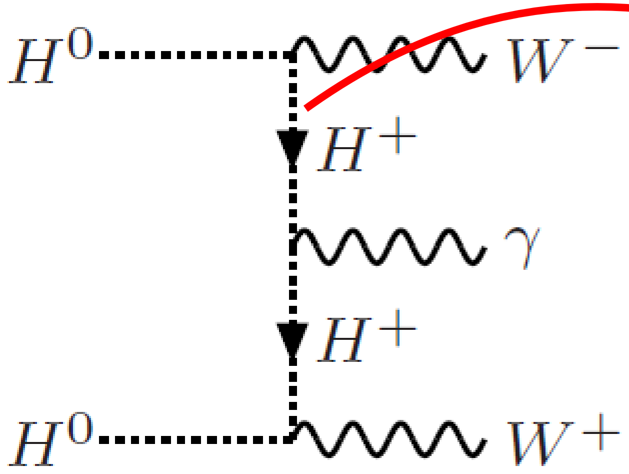
Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung



Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung



$$\boxed{\begin{aligned}\Delta(p) &\propto \left((p_{H^0} - p_W)^2 - M_{H^+}^2\right)^{-1} \\ &\approx (M_{H^0}^2 + M_W^2 - M_{H^+}^2 - 2M_{H^0}E_W)^{-1}\end{aligned}}$$

In the case $M_{H^0} \approx M_{H^+} \gg M_W$ the scalar propagator gets enhanced when E_{W} is small.

Indirect detection: Gamma-ray spectral features

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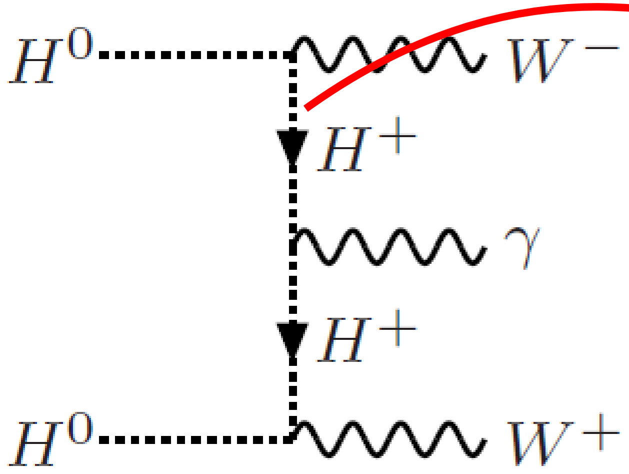

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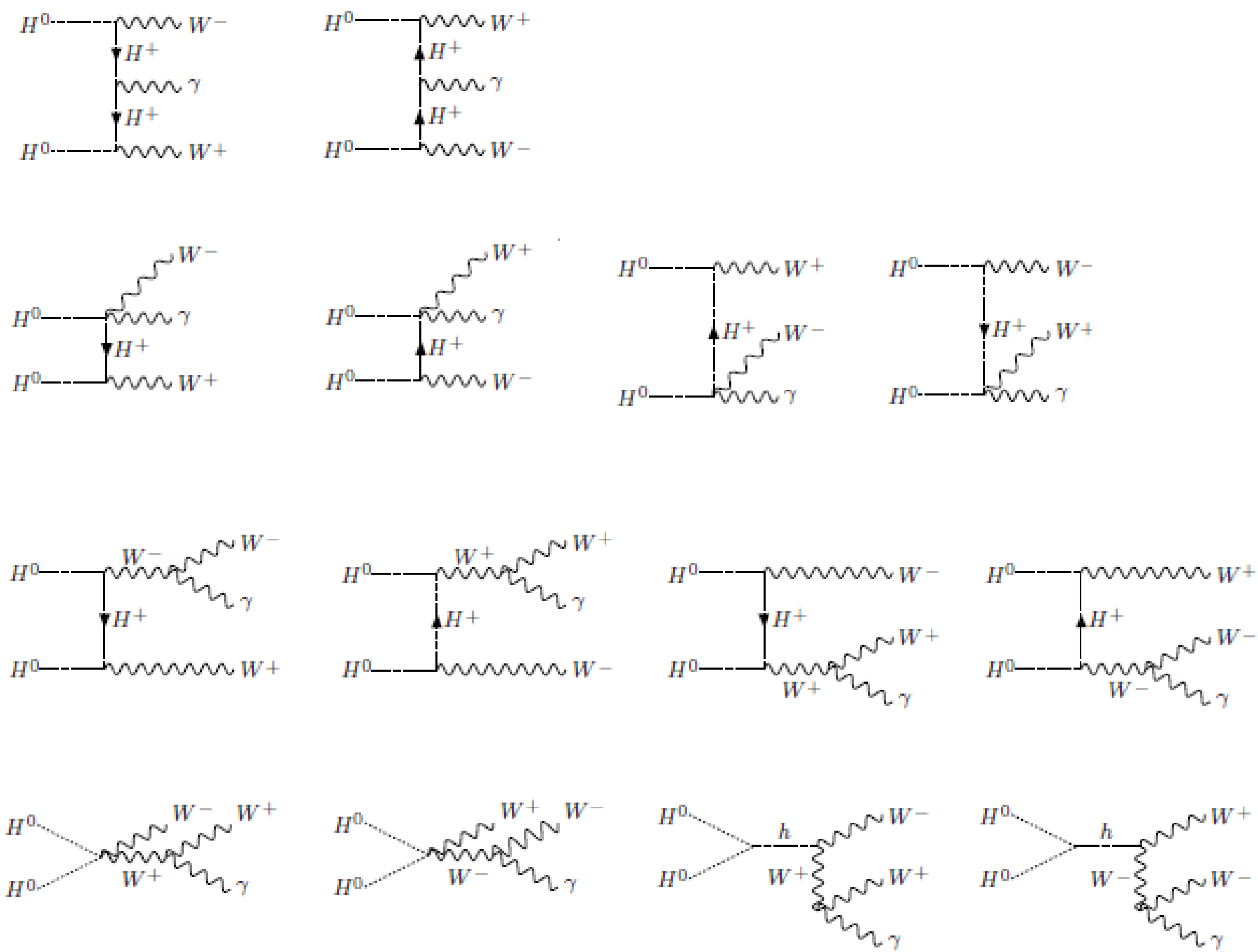
In the case $M_{H^0} \approx M_{H^+} \gg M_W$ the scalar propagator gets enhanced when E_W is small.

The condition $M_{H^0} \approx M_{H^+} \gg M_W$ is automatically fulfilled in the high mass window of the inert doublet dark matter model.

Enhancement of the amplitude (and the rate) when E_γ is close to the kinematic end-point.

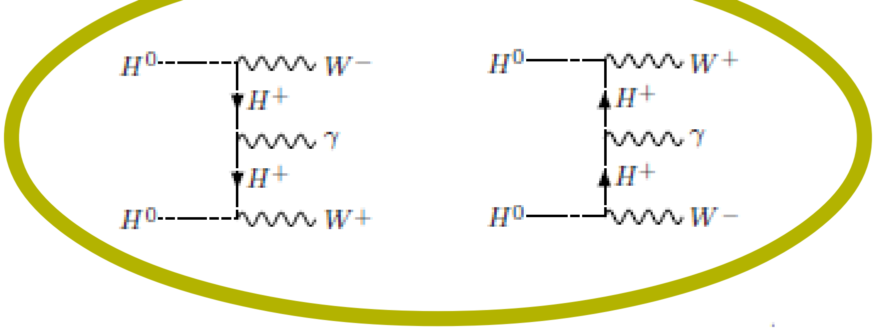
Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung

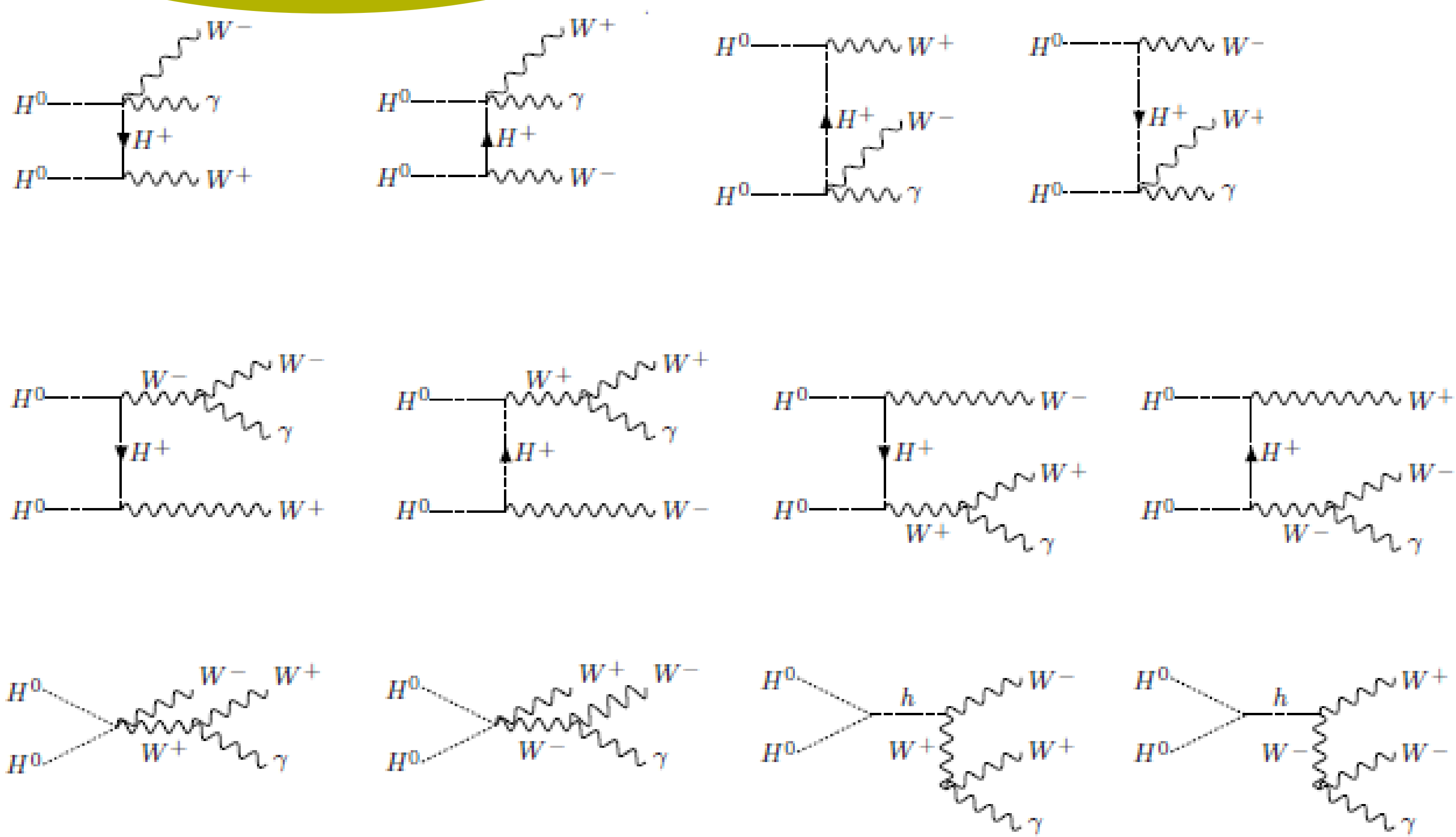


Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung

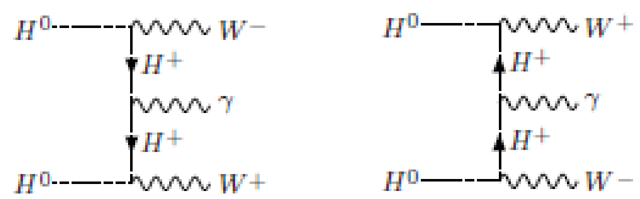


Photons emitted from the internal lines

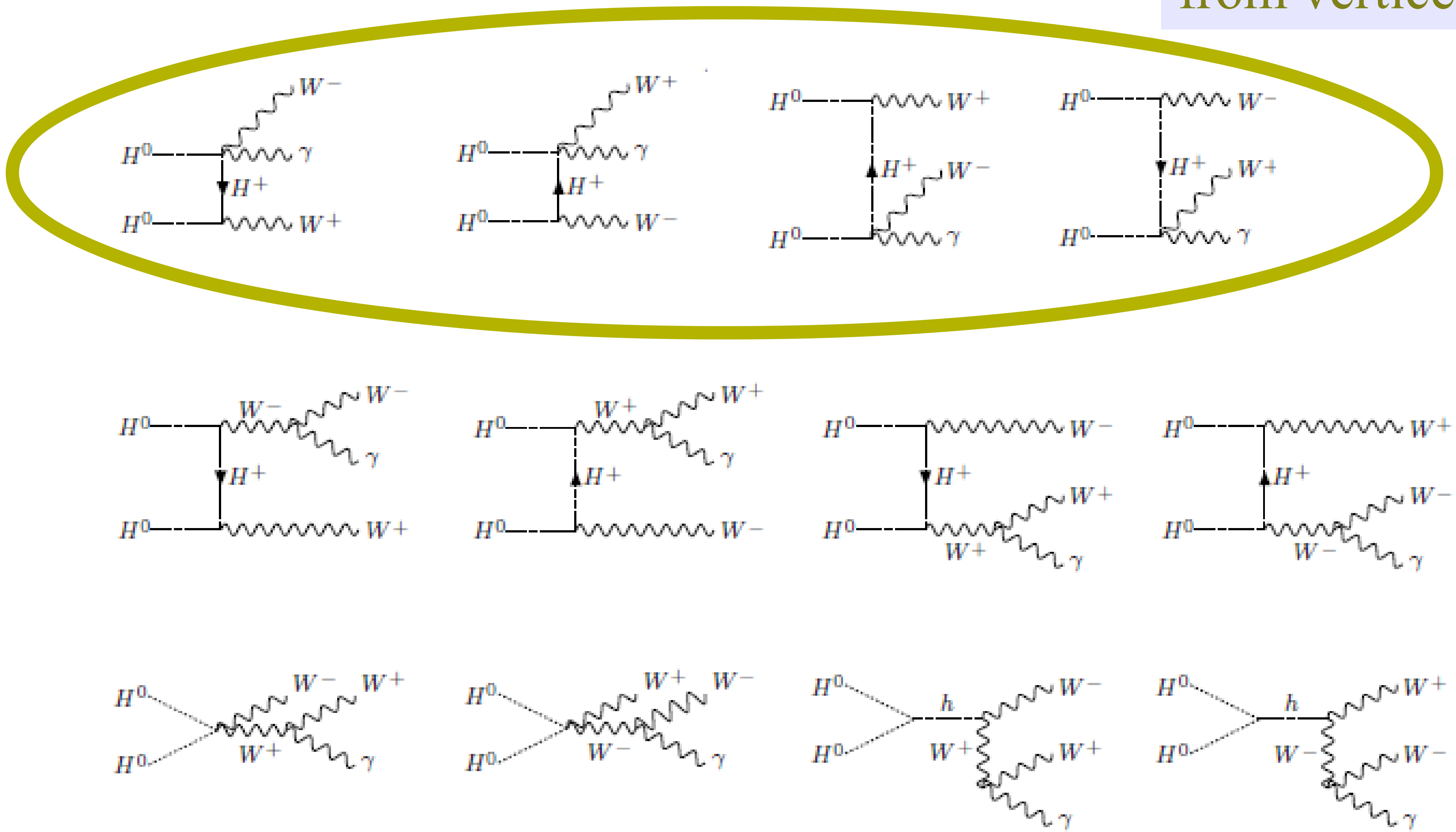


Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung



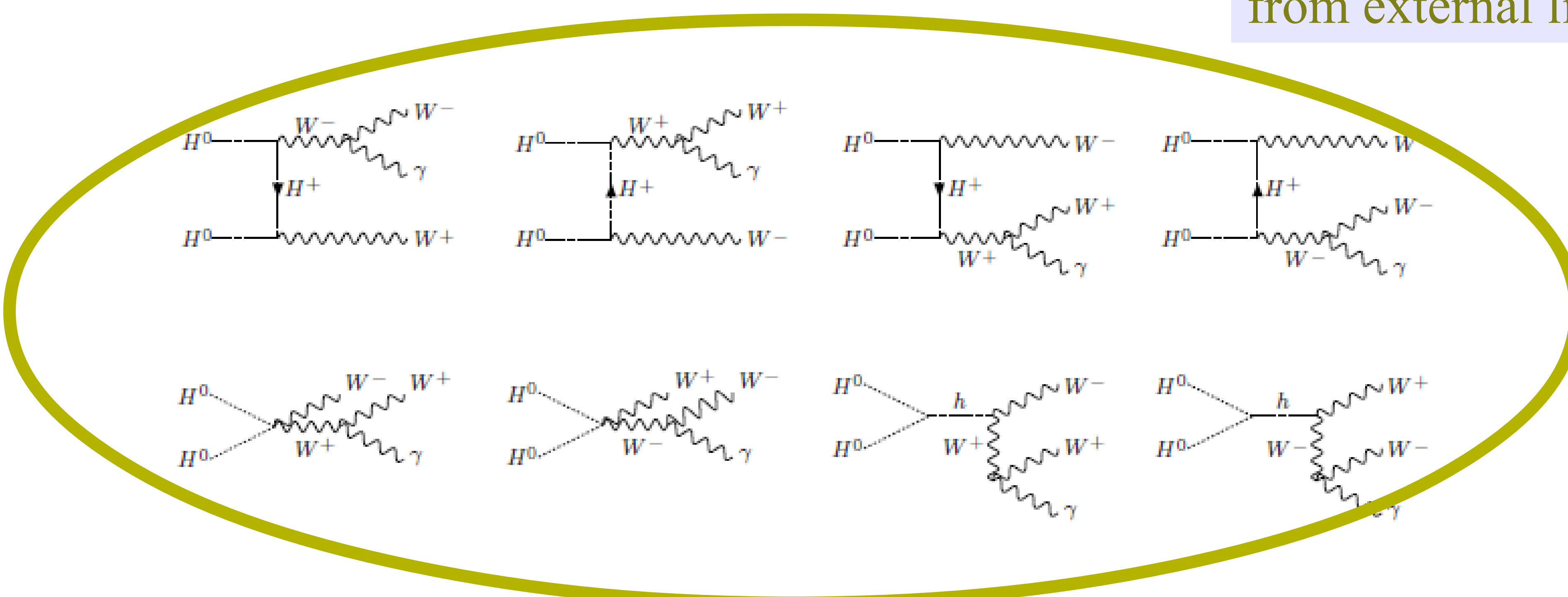
Photons emitted from vertices

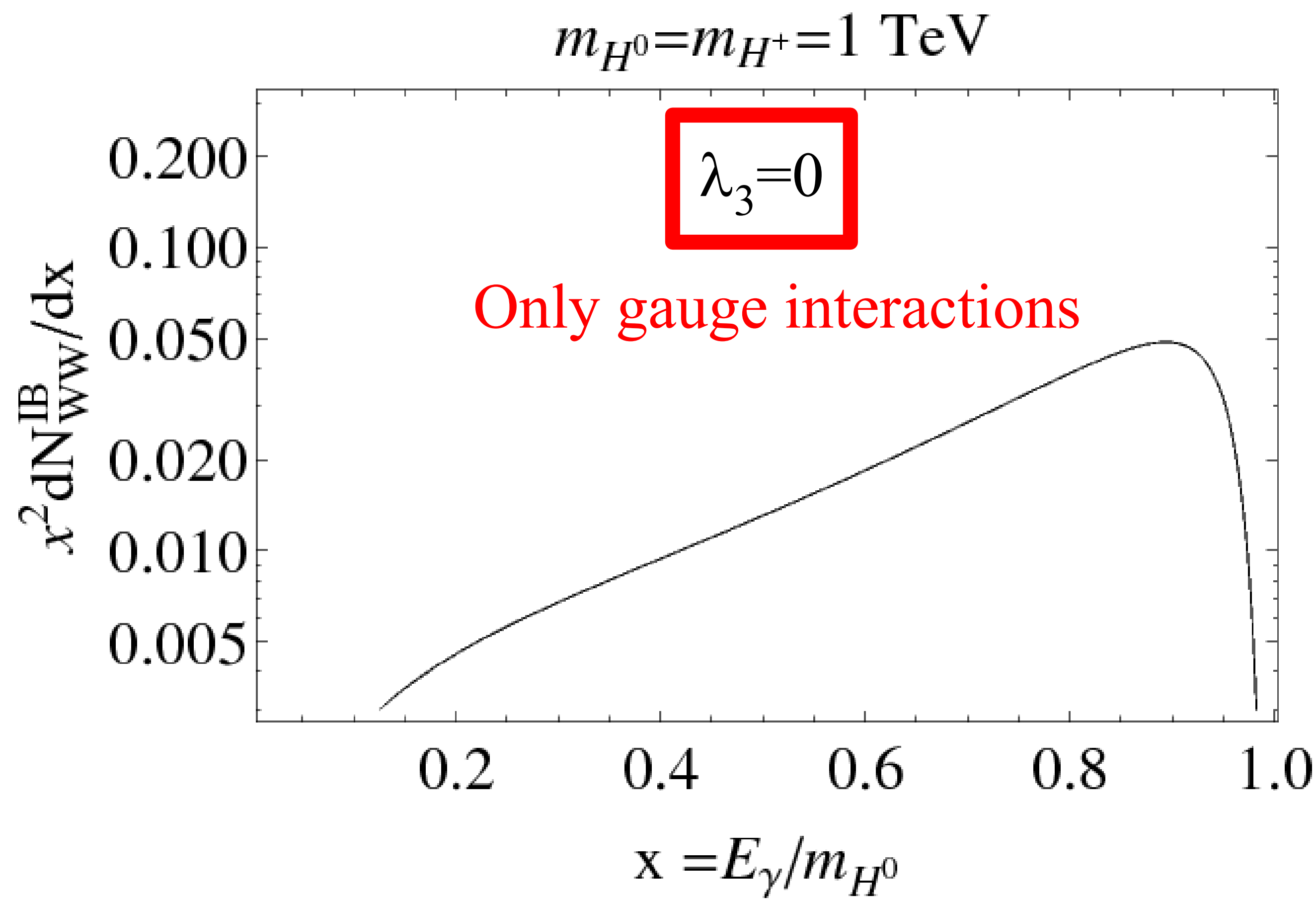


Indirect detection: Gamma-ray spectral features

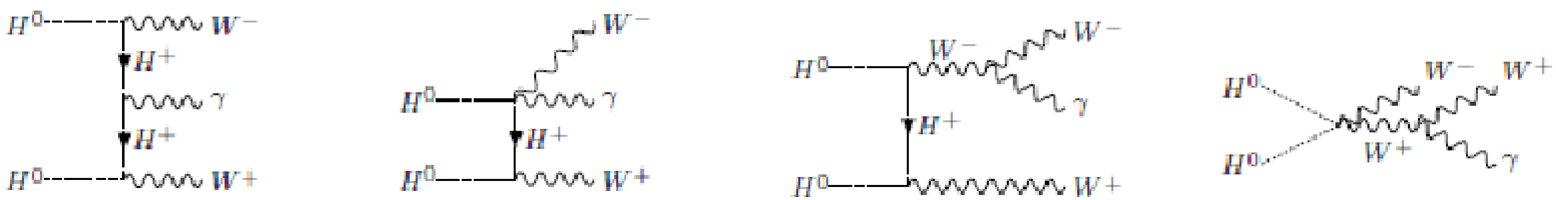
Internal Bremsstrahlung

Photons emitted from external lines

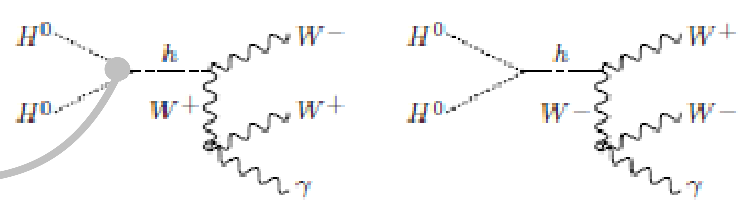




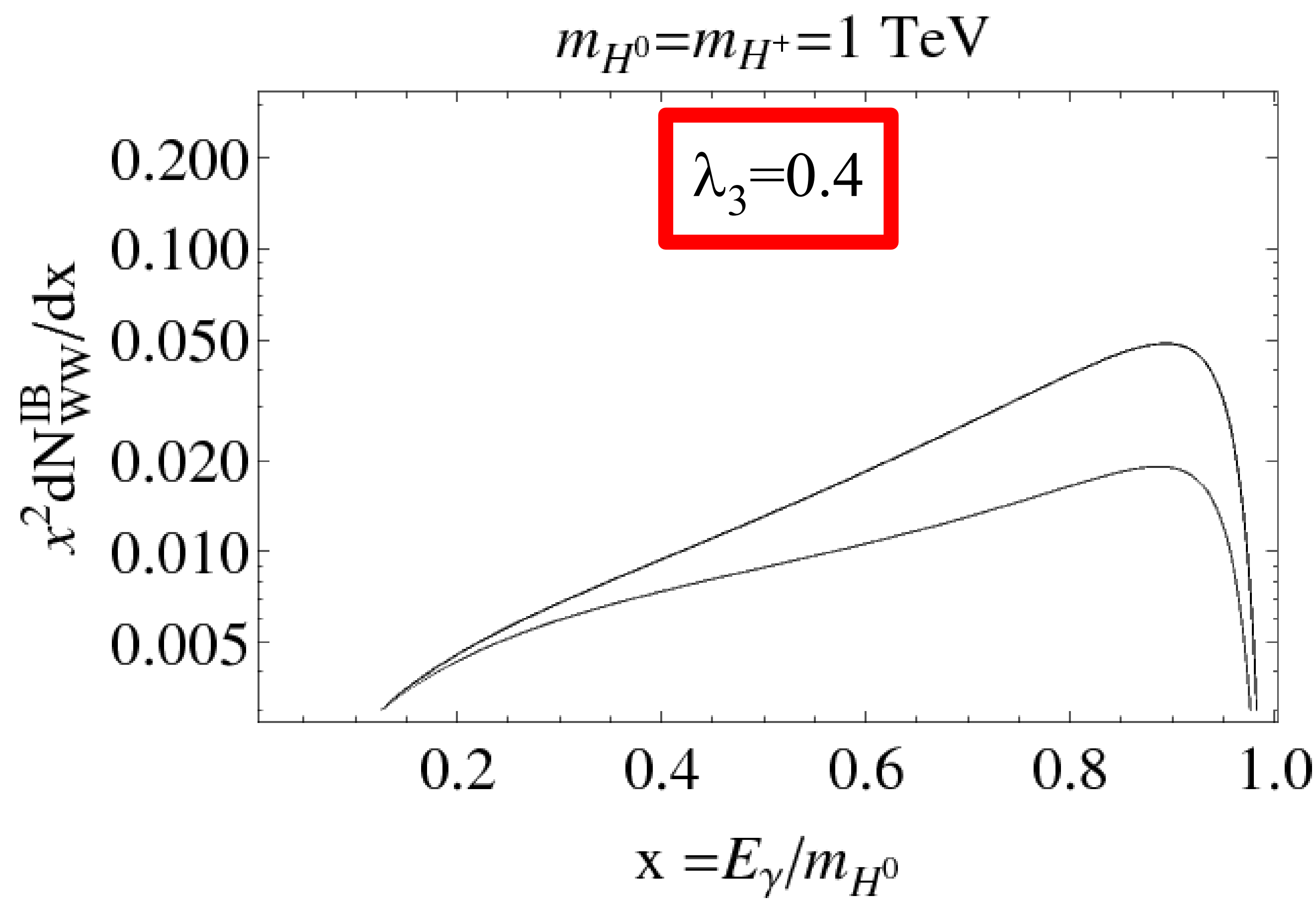
AI, Garcia Cely
arXiv:1306.4681



+ ...



$$\propto \frac{1}{2}\left(\lambda_3 + \frac{M^2_{H^0} - M^2_{H^+}}{\langle \Phi^0 \rangle^2}\right)$$



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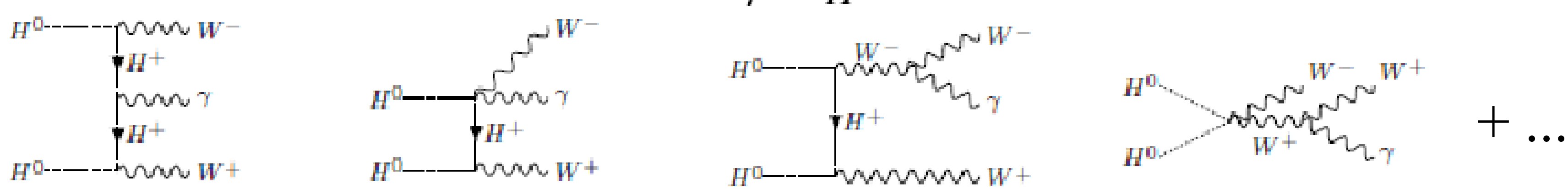
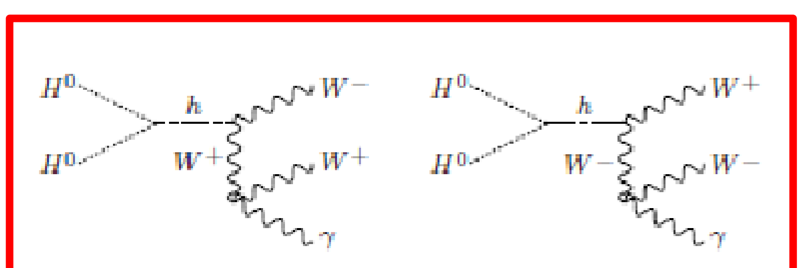
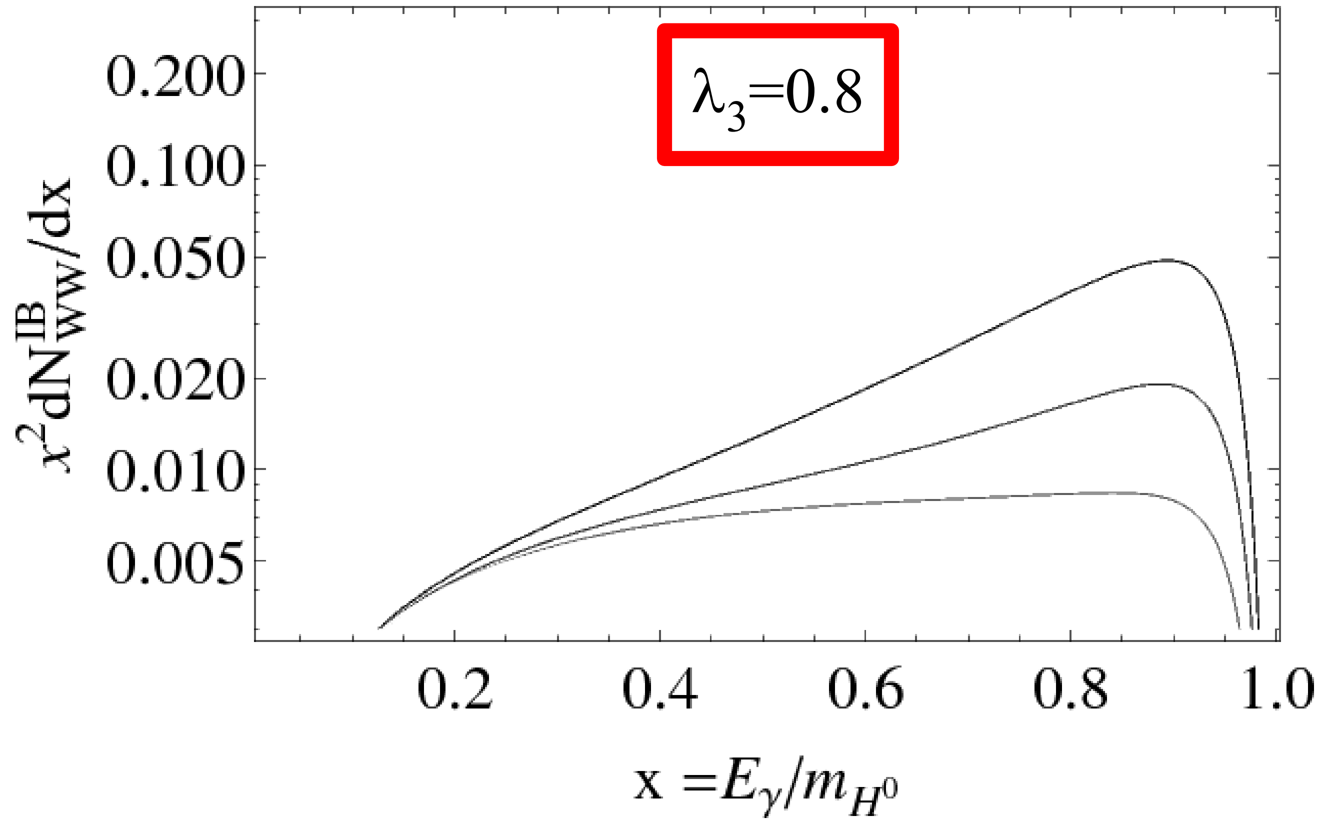
arXiv:1306.4681





$m_{H^0}=m_{H^+}=1$ TeV



AI, Garcia Cely
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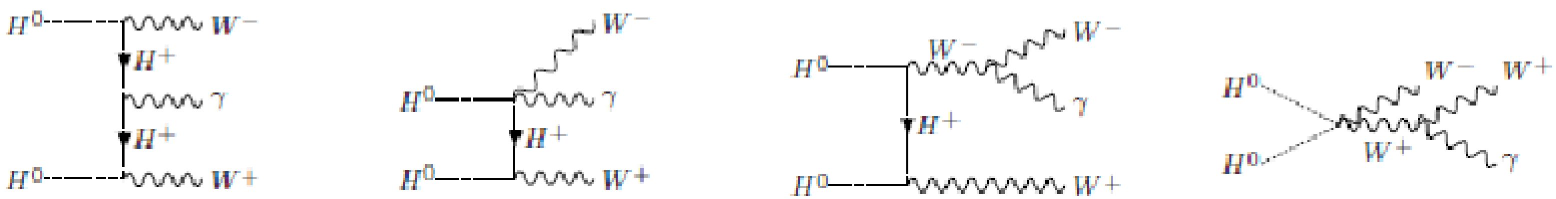
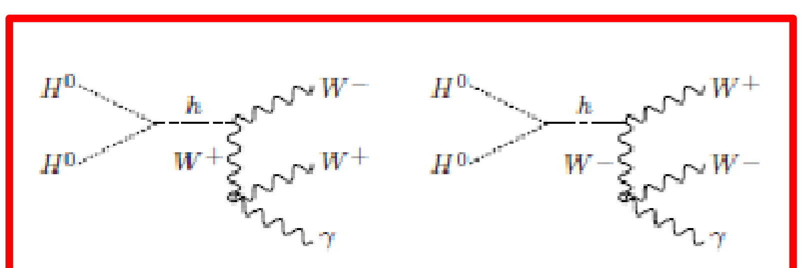
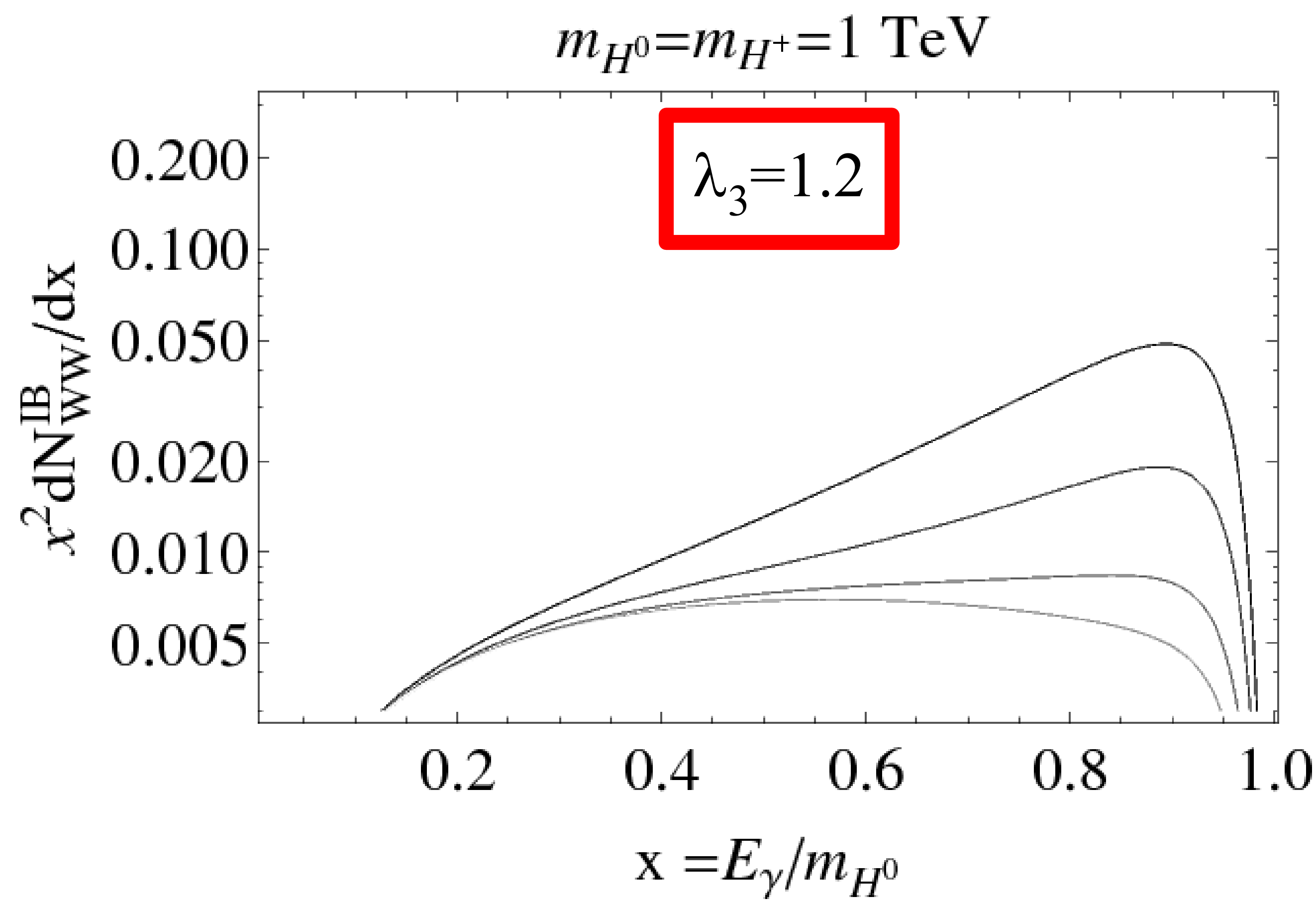


$+ \ldots$





AI, Garcia Cely
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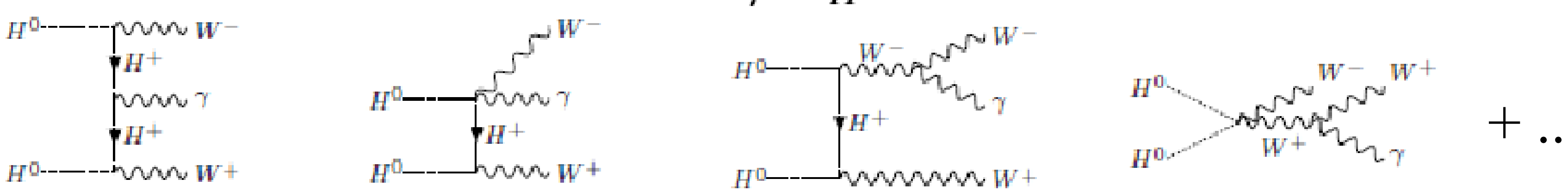

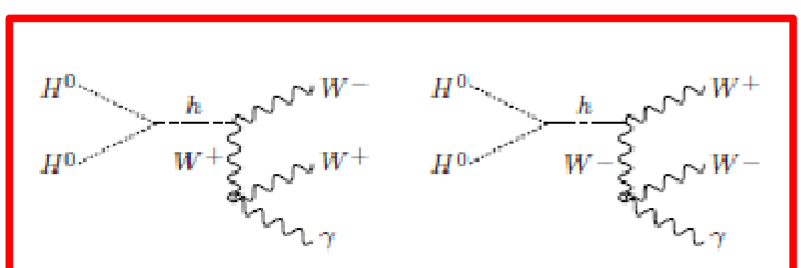

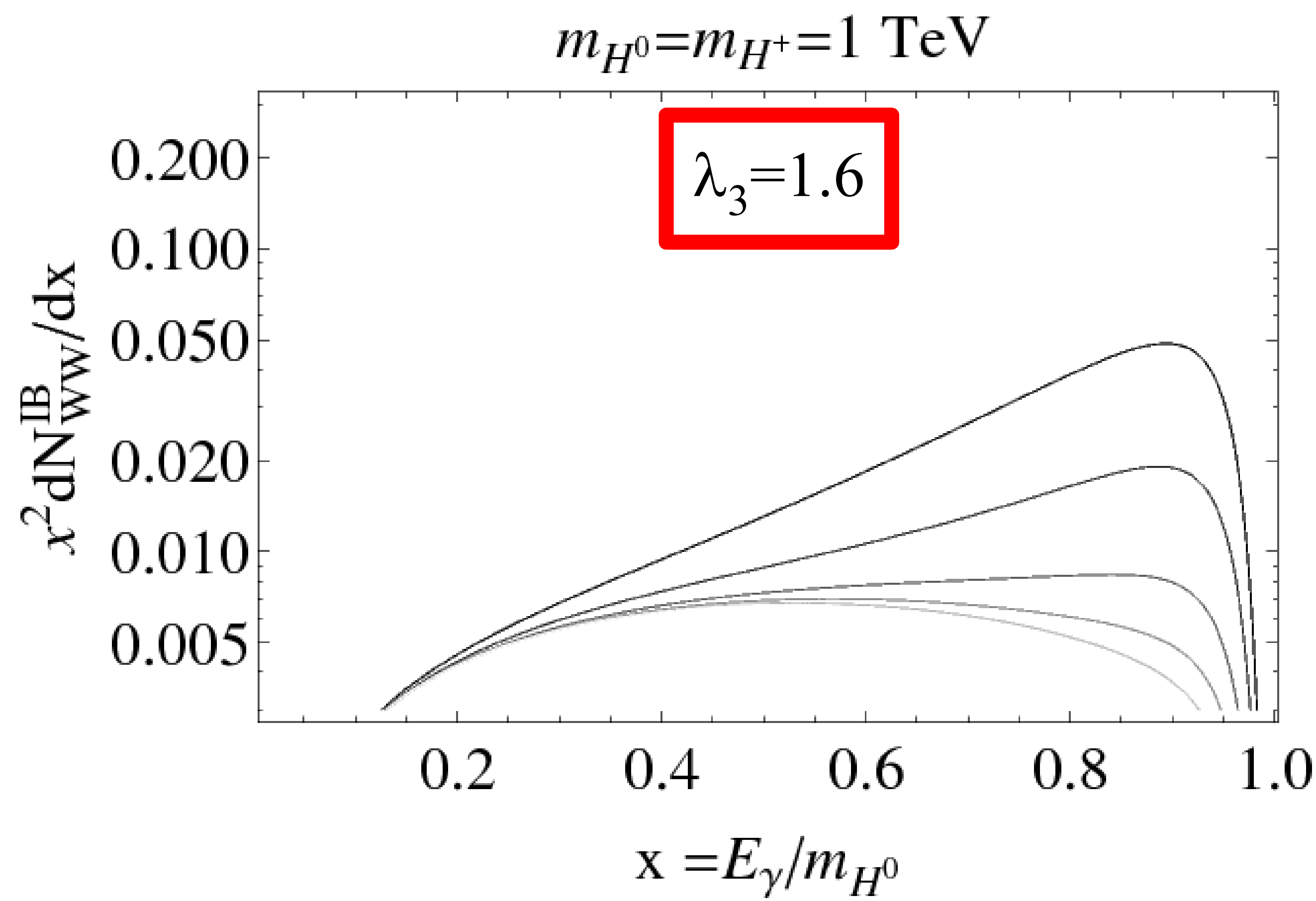

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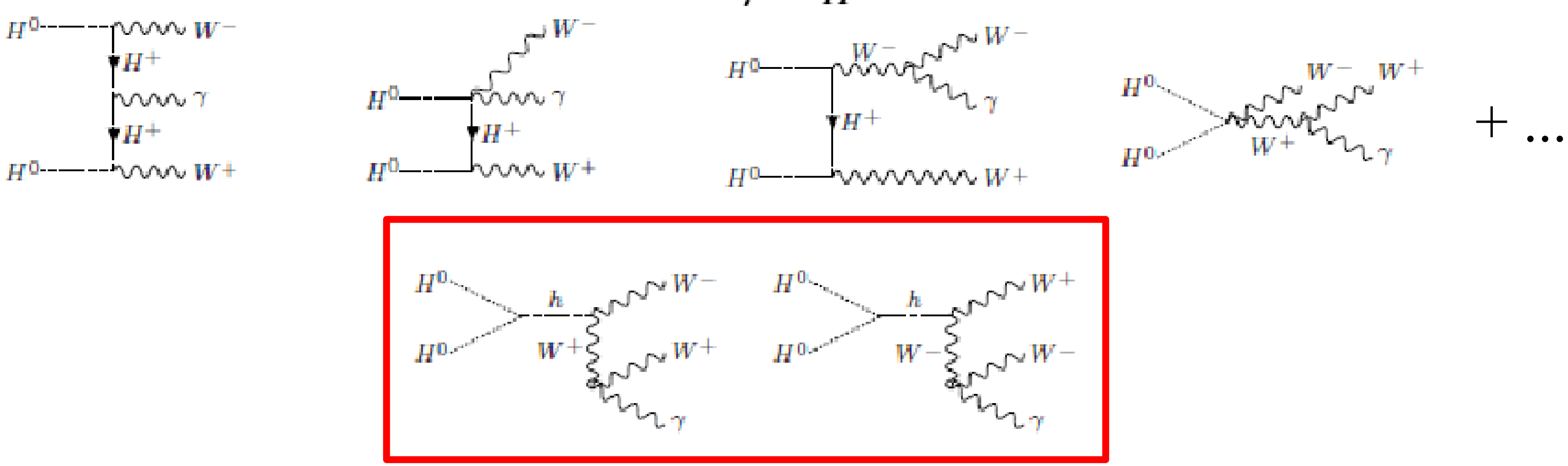

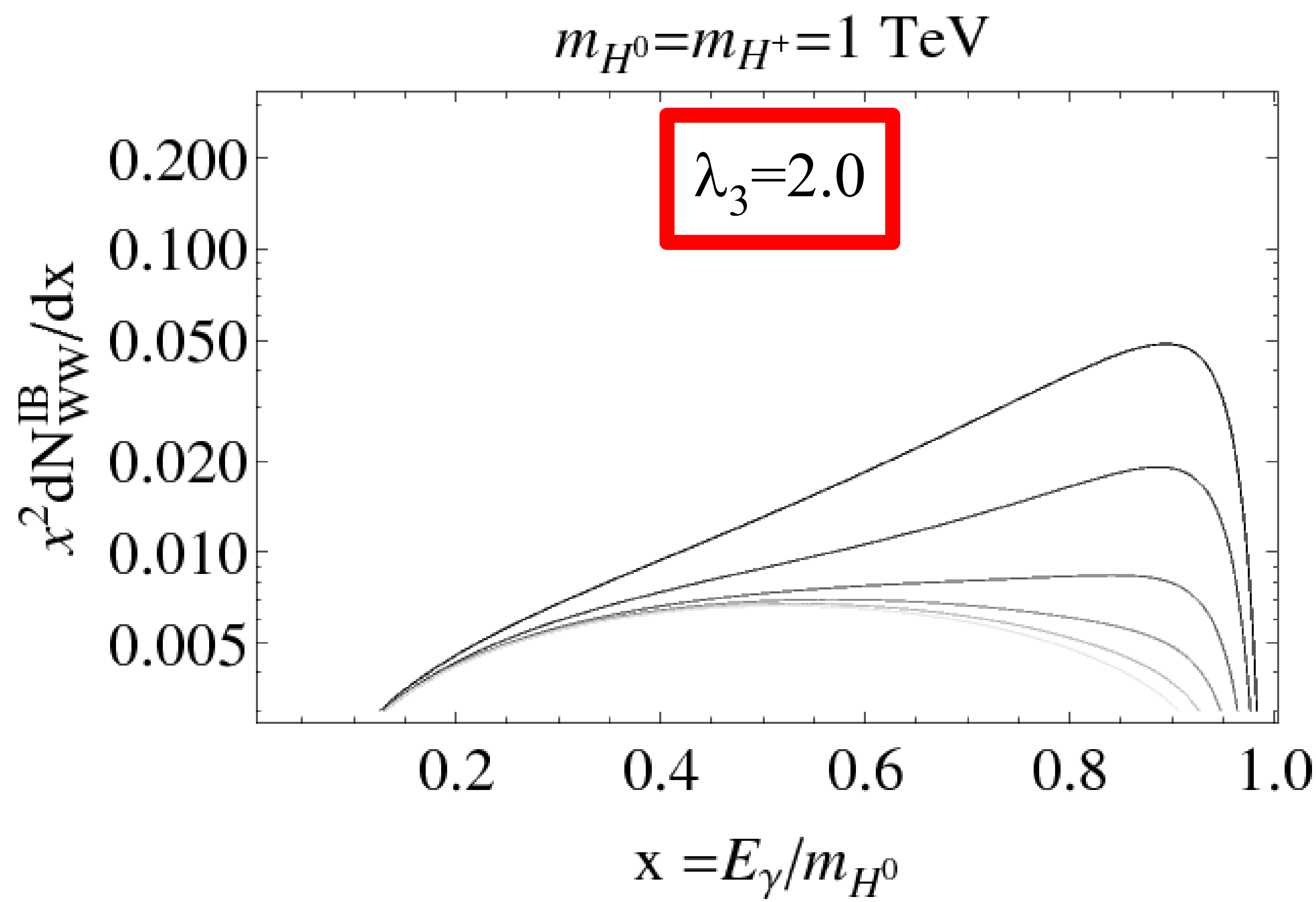

AI, Garcia Cely
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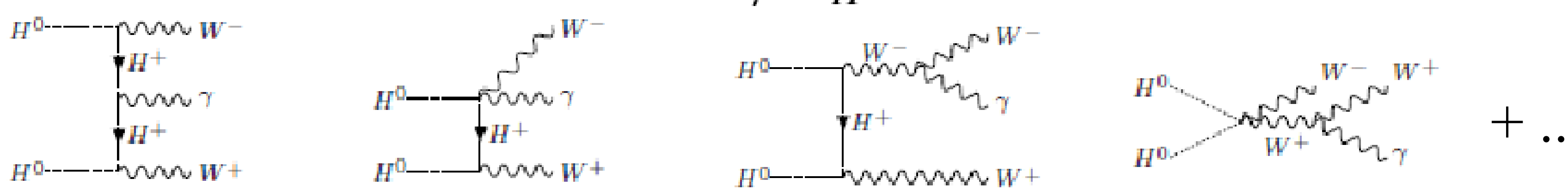
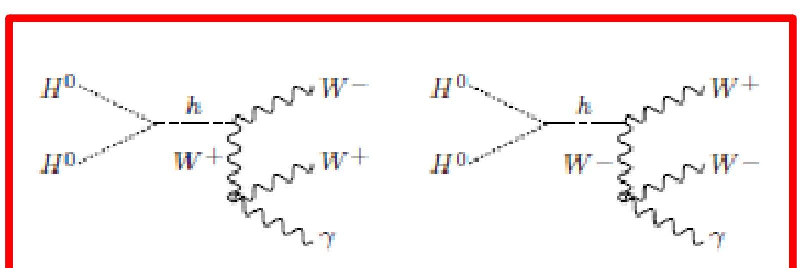
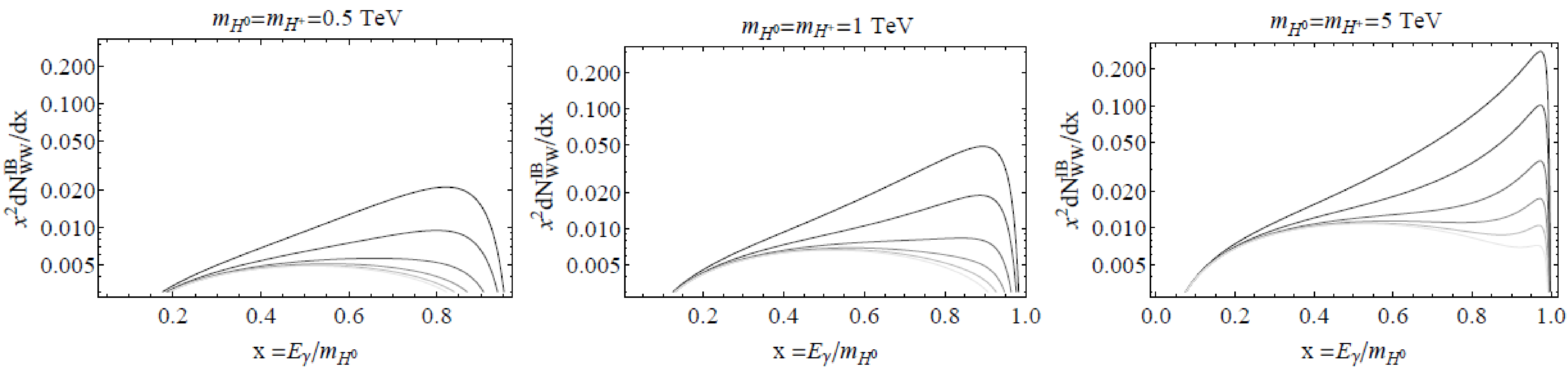




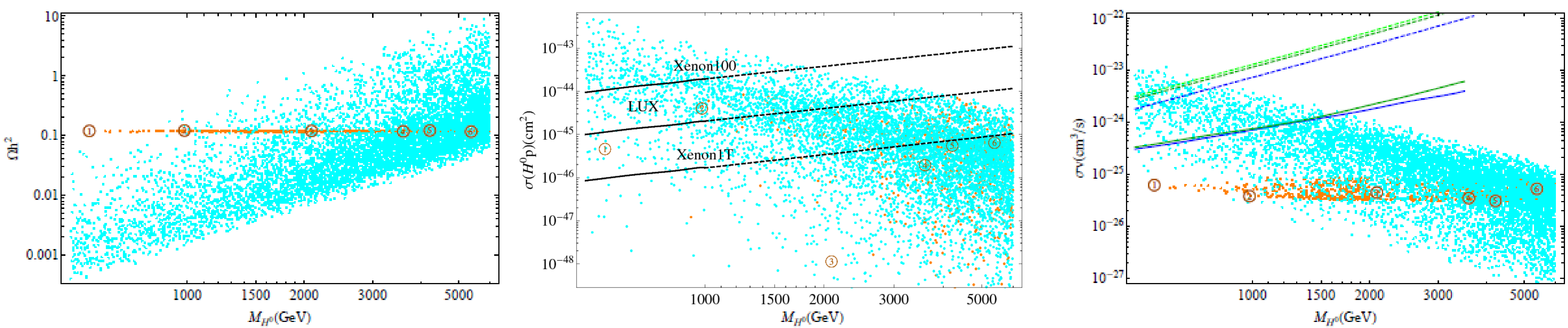


Especially for large dark matter masses and λ_3 small, the spectral feature is very prominent.

Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung: benchmark points

BMP	M_{H^0}(GeV)	M_{H^+}(GeV)	M_{A^0}(GeV)	λ_3	λ_4	λ_5	λ_{H^0}	λ_{A^0}
1	559.99	561.85	560.67	-0.02	-0.06	-0.01	-0.05	-0.03
2	983.75	993.60	991.79	0.17	-0.38	-0.26	-0.23	0.03
3	2088.3	2090.99	2100.26	0.39	0.46	-0.83	0.01	0.83
4	3596.67	3597.99	3609.7	-0.07	1.24	-1.55	-0.19	1.36
5	4212.49	4213.09	4225.29	-0.58	1.61	-1.78	-0.37	1.41
6	5382.08	5382.21	5392.59	1.08	1.82	-1.87	0.51	2.38



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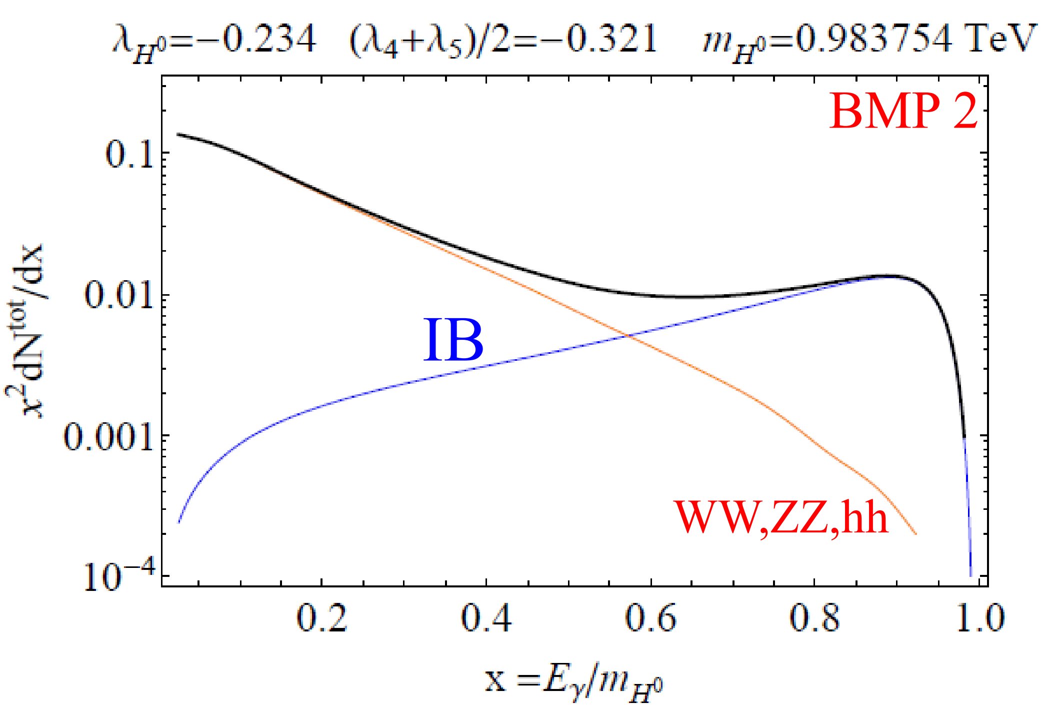
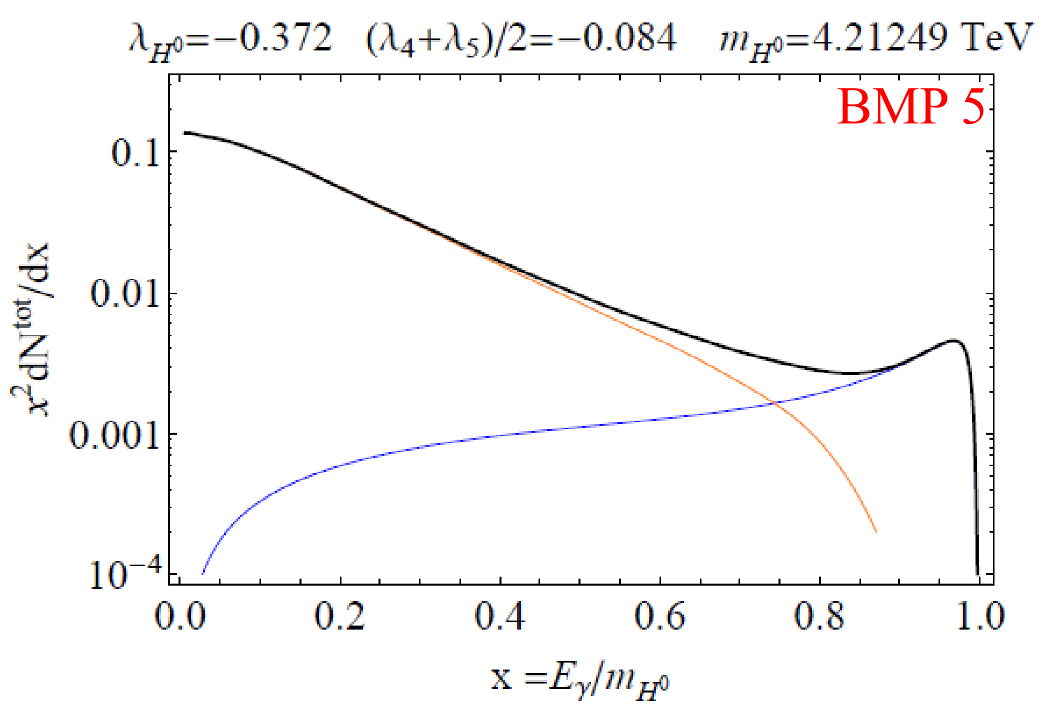
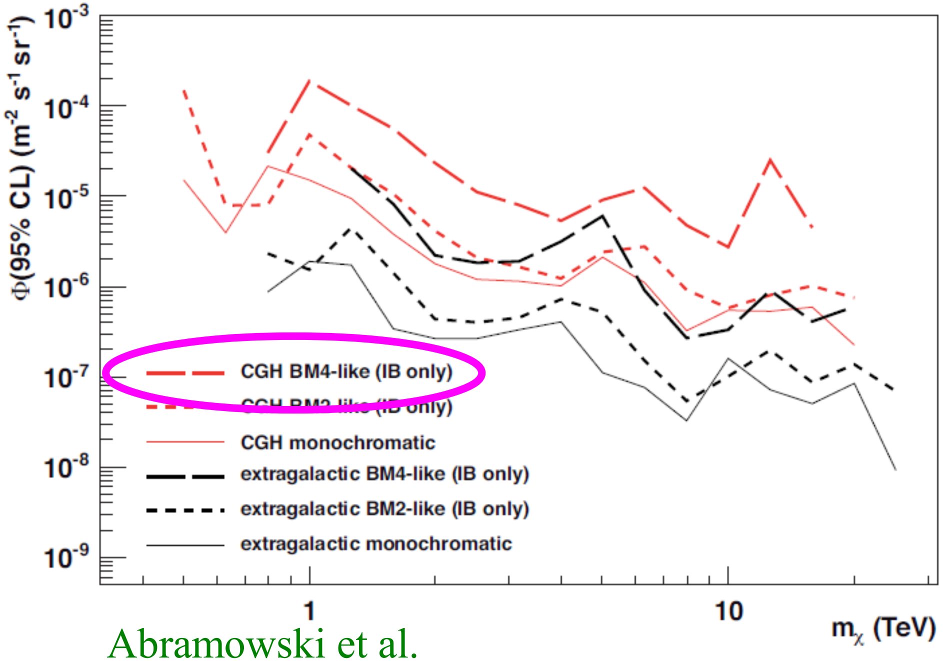
5	4212.49	4213.09	4225.29	-0.58	1.61	-1.78	-0.37	1.41
6	5382.08	5382.21	5392.59	1.08	1.82	-1.87	0.51	2.38





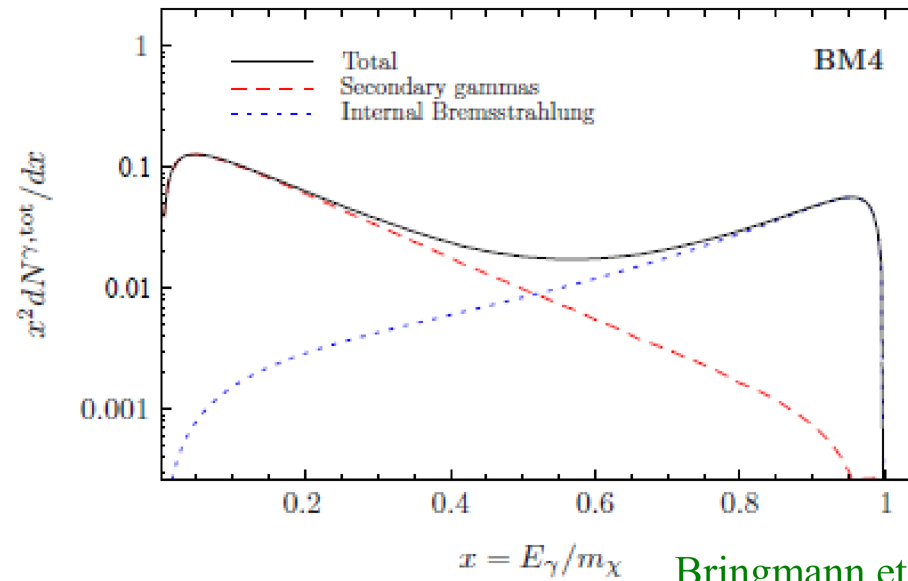
Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung: H.E.S.S. limits

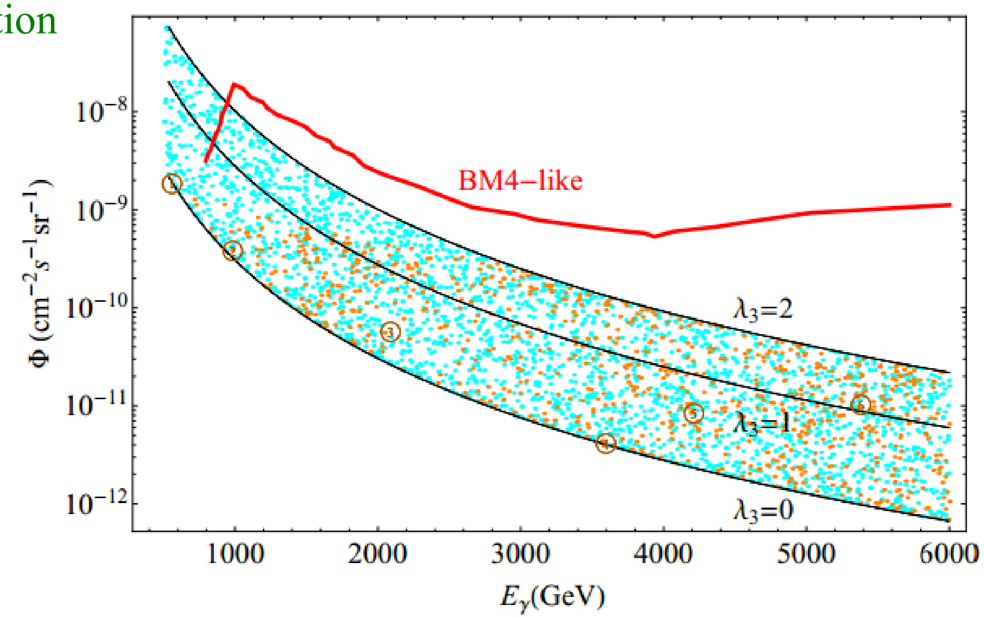


Abramowski et al.
H.E.S.S. collaboration
arXiv:1301.1173

$\chi\,\chi \to W^+\,W^-\,\gamma$



Bringmann et al.
arXiv:0710.3169



AI, Garcia Cely
arXiv:1306.4681

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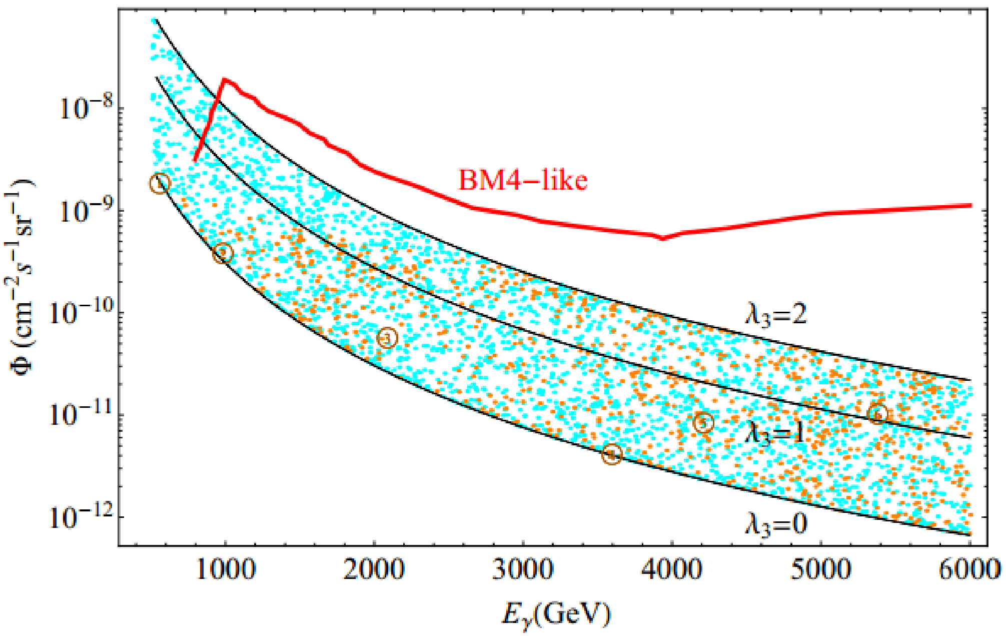
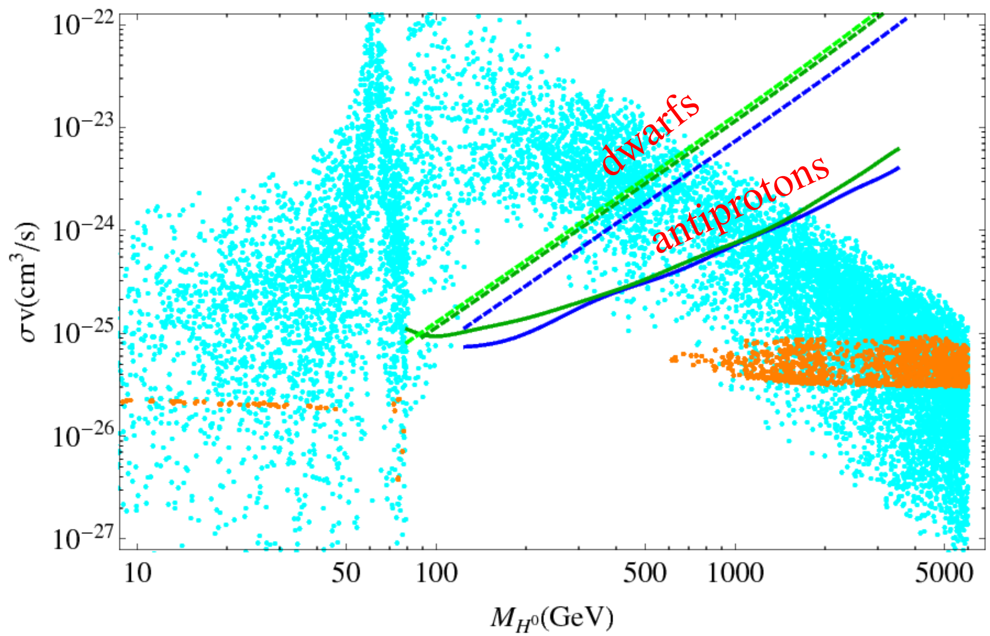




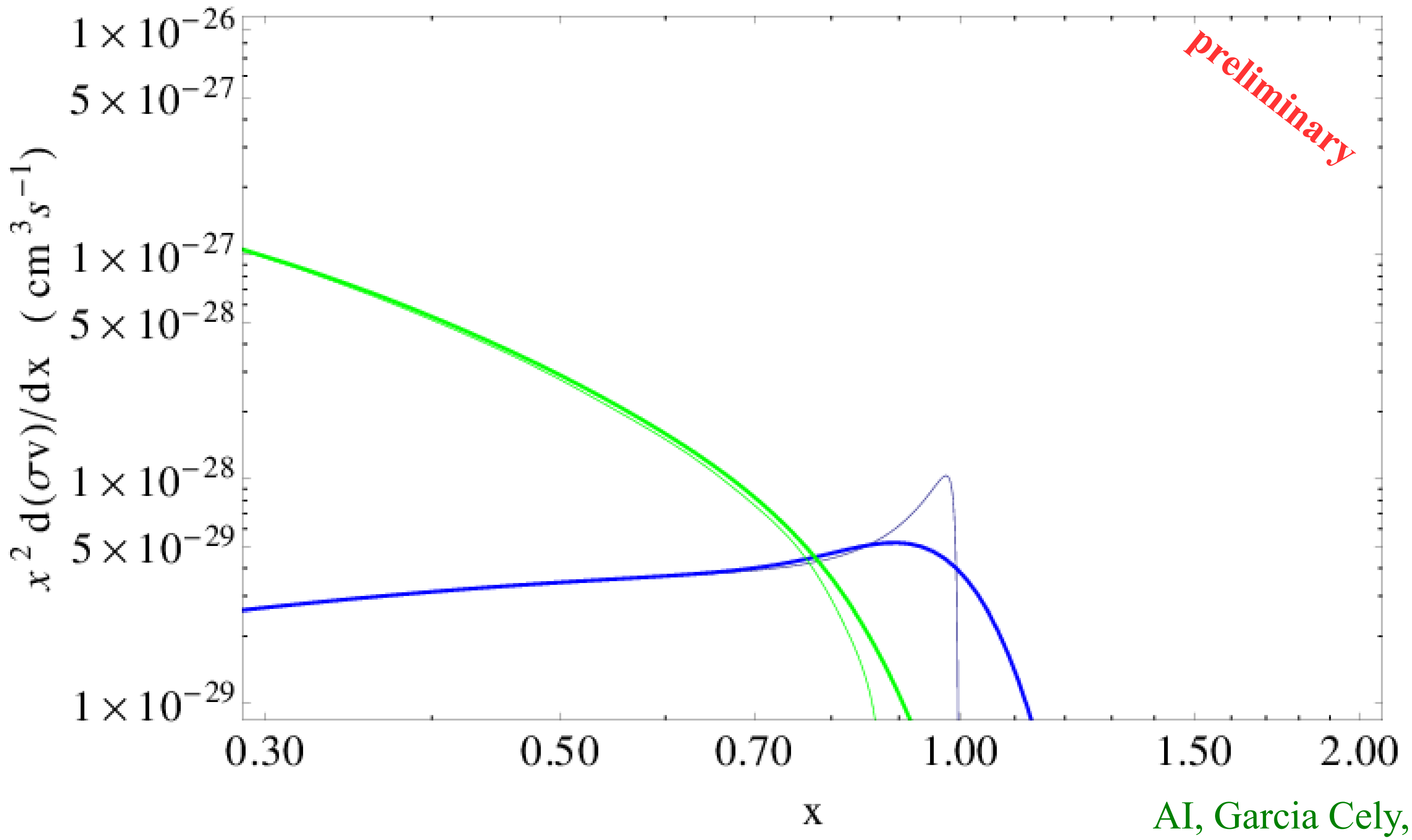
Future gamma-ray telescopes might explore the region where spectral features could be observed.

Indirect detection: Gamma-ray spectral features

Internal Bremsstrahlung + lines

So far, we have considered separately the different spectral features. For a given set of model parameters, all of them appear.

$M_{H^0} = 5836\,\mathrm{GeV},\ (\lambda_4 + \lambda_5) = -0.01,\ \lambda_3 = -0.86$



AI, Garcia Cely, Gustafsson
In preparation

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Internal Bremsstrahlung + lines

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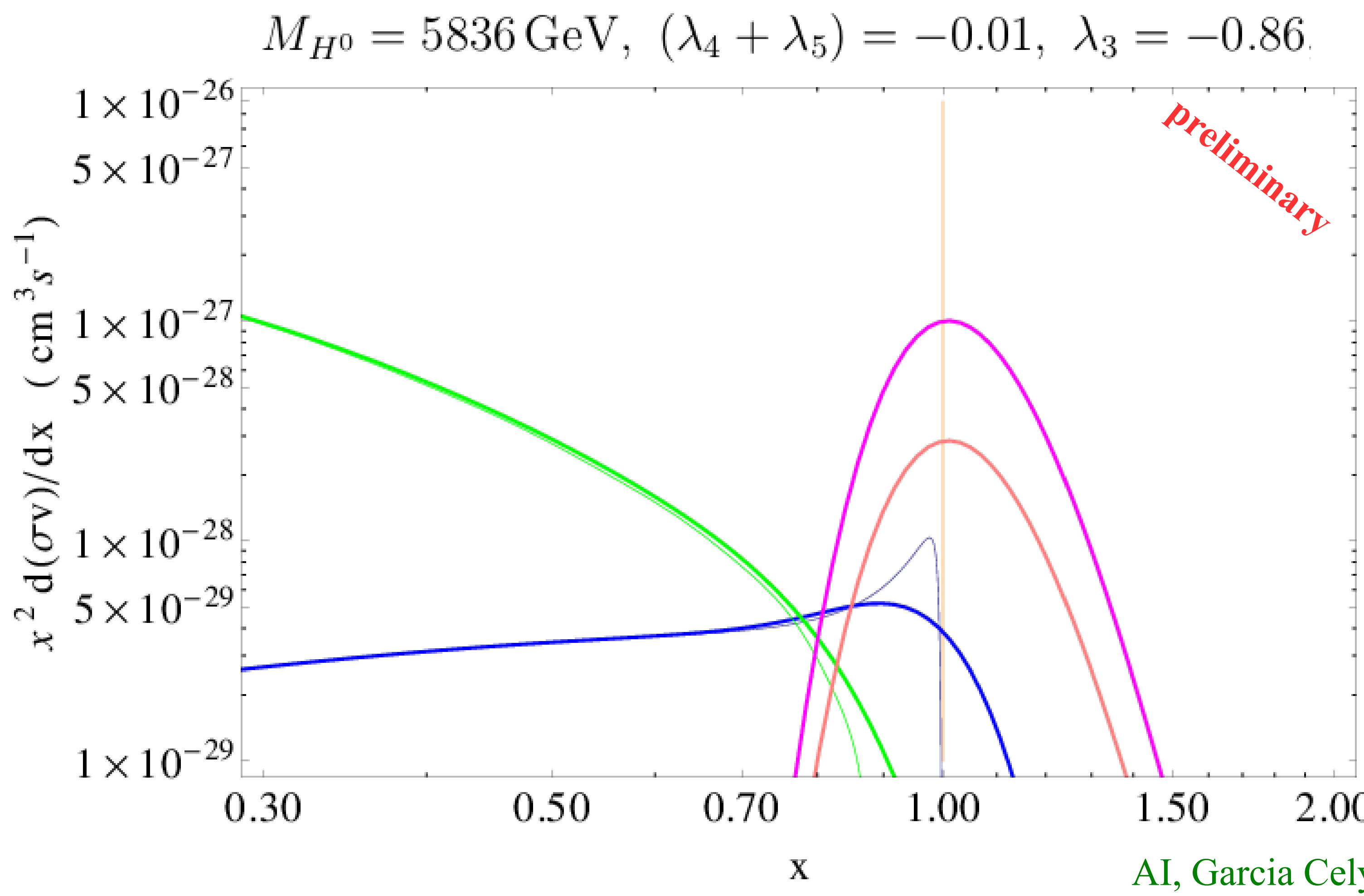

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In preparation

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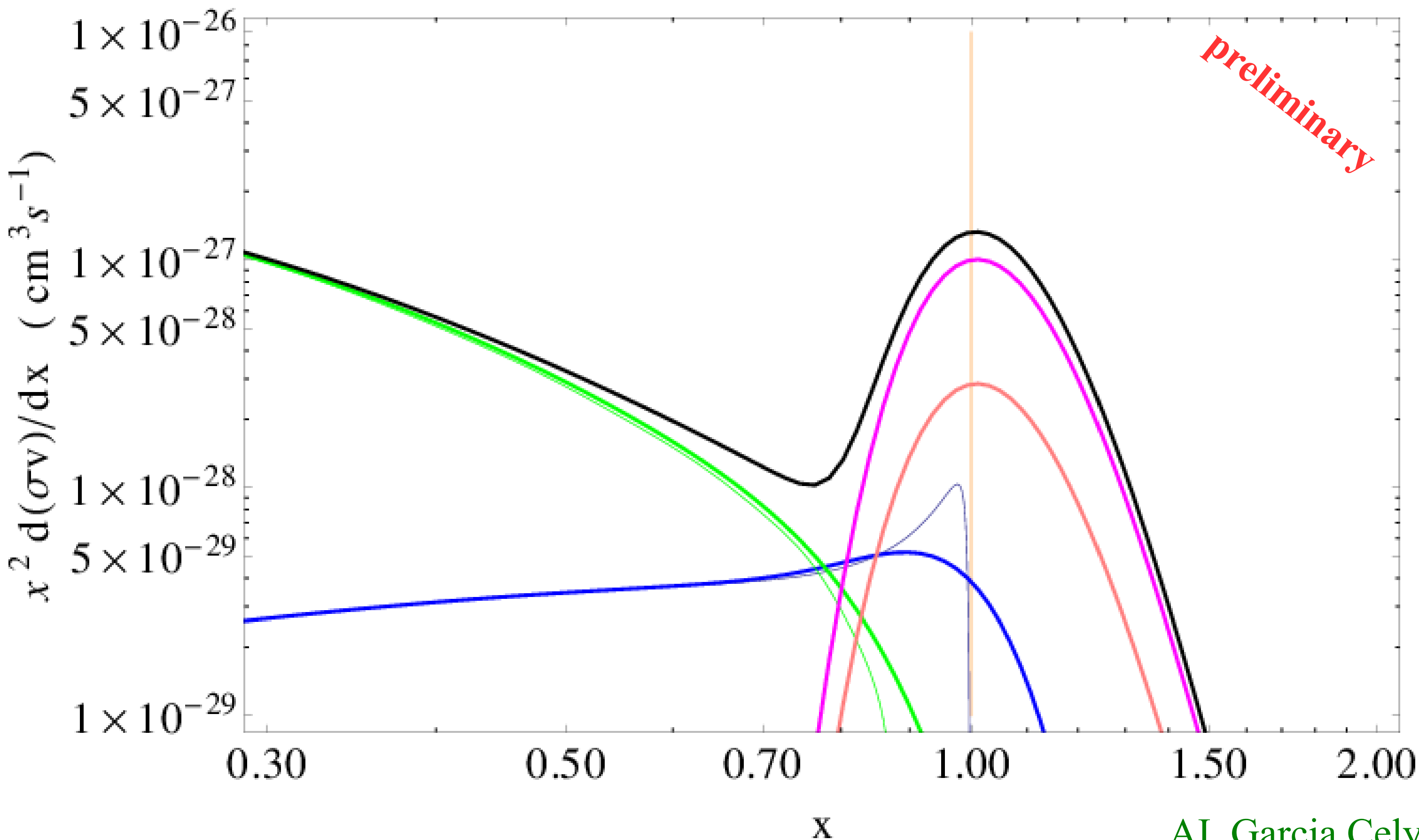

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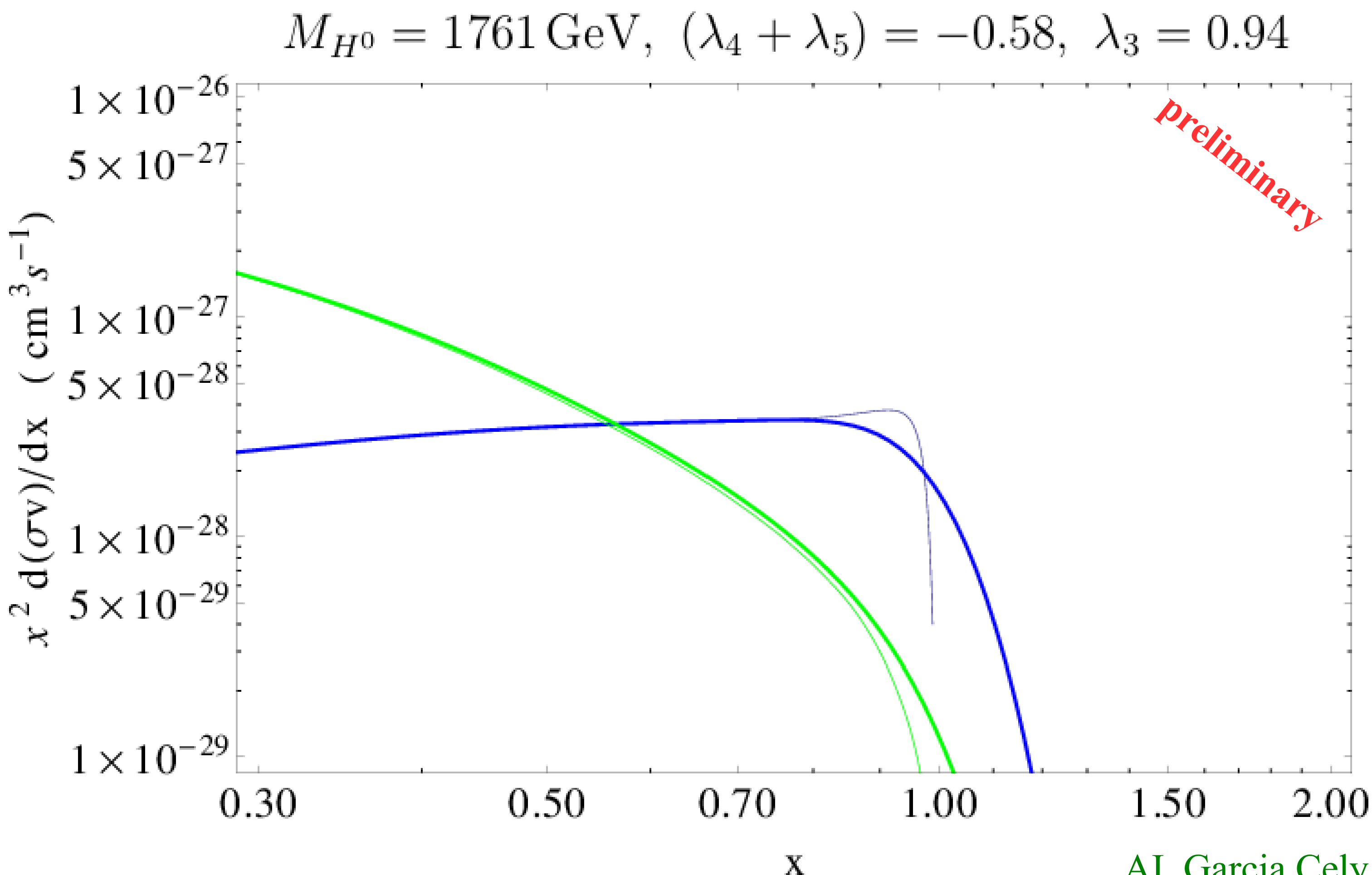

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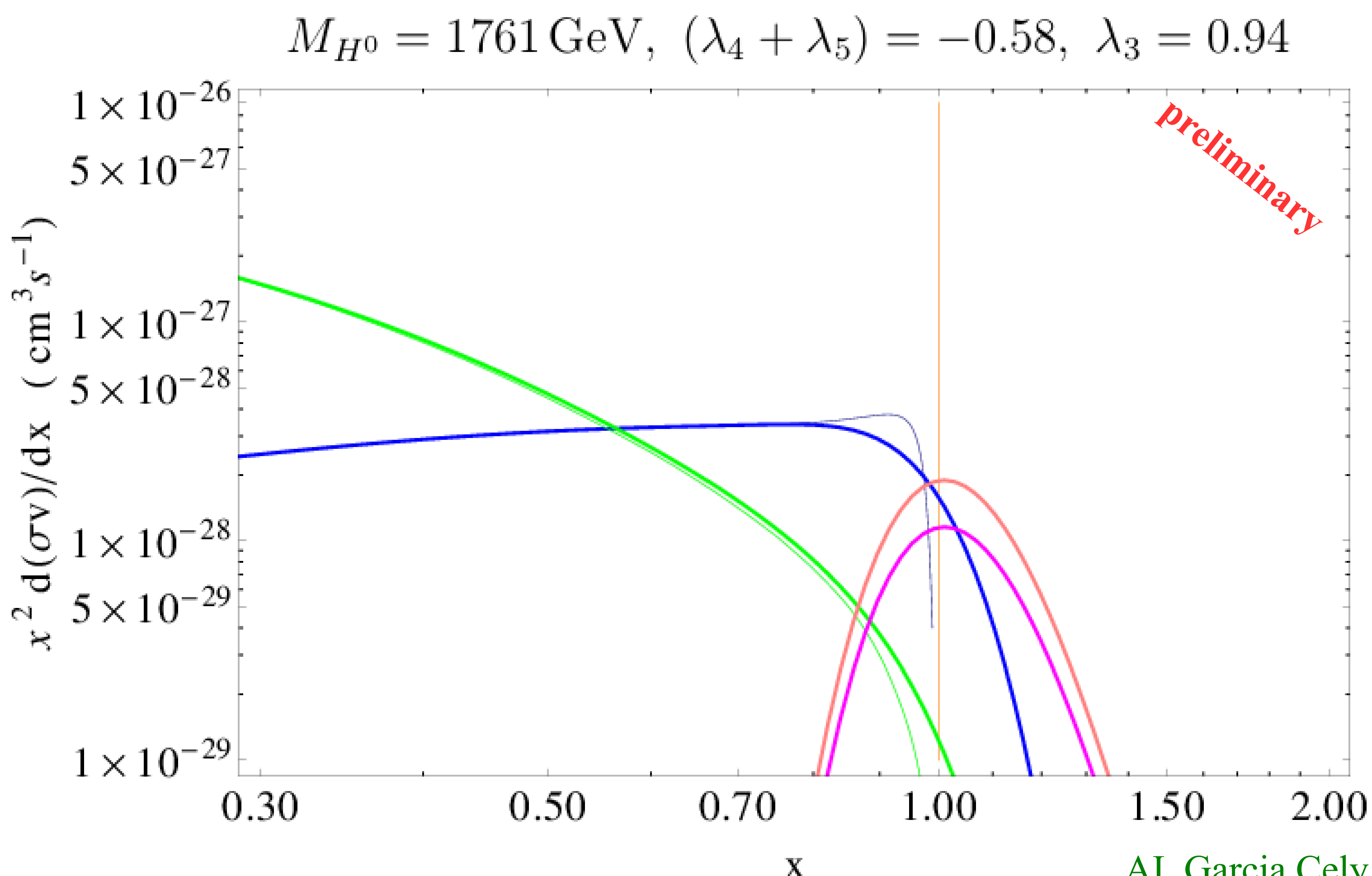

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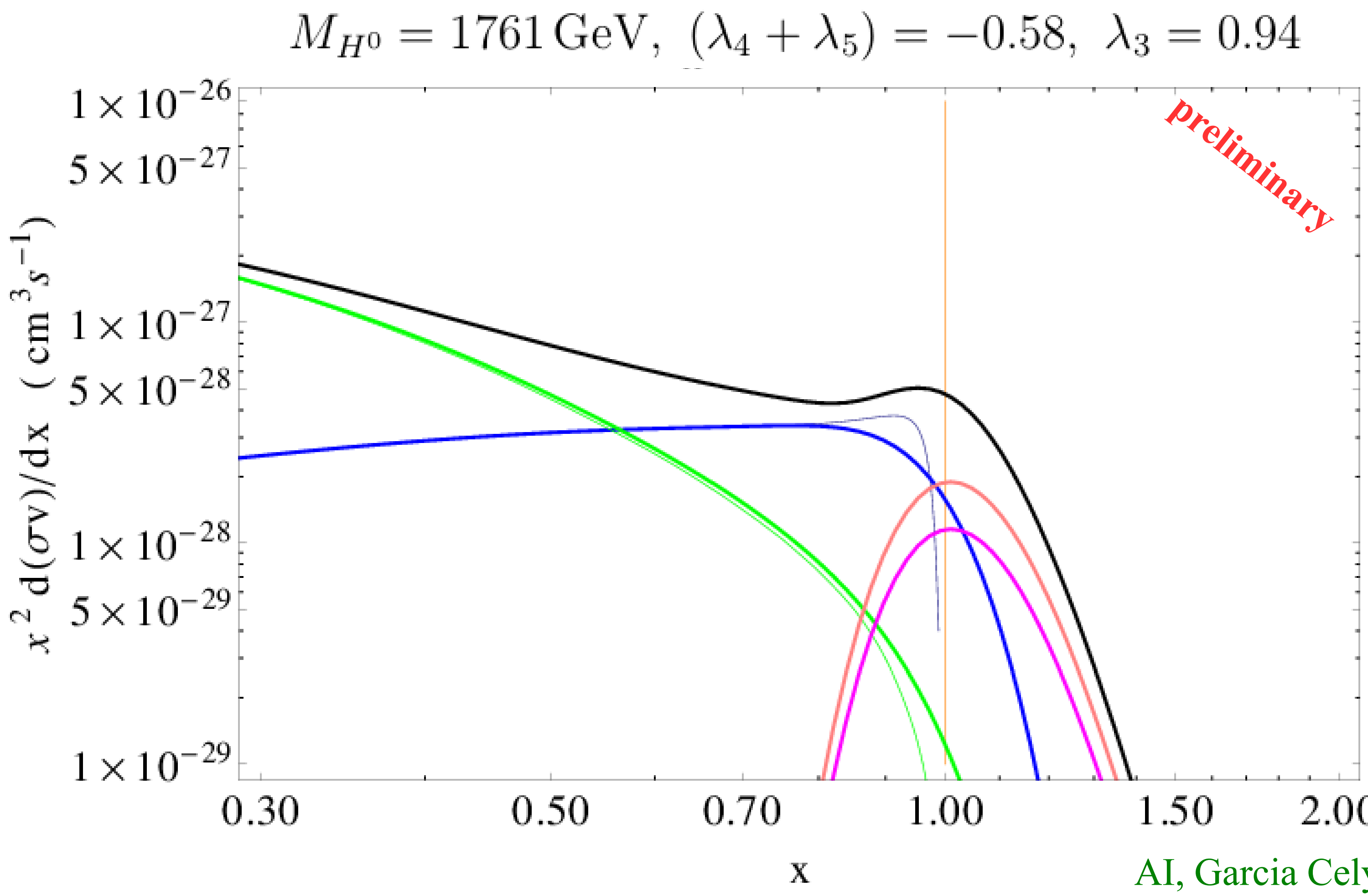

AI, Garcia Cely, Gustafsson
In preparation

Conclusions

The inert doublet model is a simple extension of the Standard Model which accounts for the dark matter of the Universe.

It offers a rich phenomenology and predicts potentially observable effects in direct and indirect dark matter searches, collider searches and electroweak precision tests.

Large portions of the parameter space will be explored in the near future by direct dark matter search experiments (LUX, XENON1T).

It generically predicts gamma-ray spectral features which, if observed, would constitute a strong hint for dark matter annihilations in the Milky Way center.