Sommerfeld Enhancement in the Inert Doublet Model

Camilo A. Garcia Cely

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In collaboration with Alejandro Ibarra and Michael Gustafsson

Outline

- Introduction
- Dark Matter as an Inert Scalar
- Gamma-ray spectral features: Annihilation into two photons
- Issues with Unitarity and the Sommerfeld enhancement
- Gamma-ray fluxes and H.E.S.S.
- Conclusions

SM doublet

$$\Phi = \begin{pmatrix} G^+ \\ \frac{v_h + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

Additional doublet

$$\Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}} \left(H^0 + iA^0\right) \end{pmatrix}$$

Dark Matter Stability

It is possible to postulate invariance under

$\Psi \to -\Psi \qquad \Phi \to \Phi$

$(Z_2 \; symmetry)$

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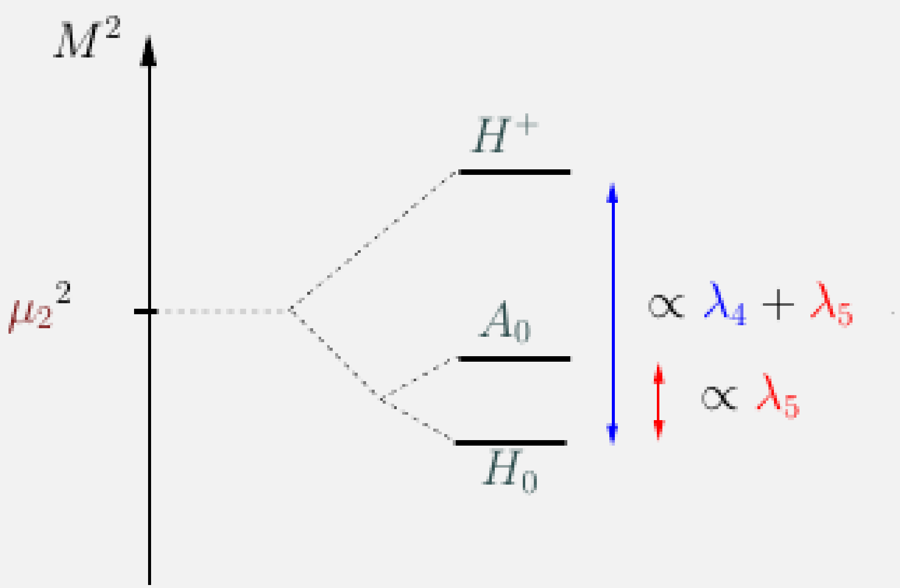
$(Z_2 \; symmetry)$

If the lightest particle that is charged under Z_2 is neutral : we have a **dark matter** candidate!!!

$$\mathcal{L}_{\Phi,\Psi} = \mathcal{L}_{\text{Yukawa}} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + (D_\mu\Psi)^\dagger(D^\mu\Psi) - m_1^2\Phi^\dagger\Phi - m_2^2\Psi^\dagger\Psi$$
$$-\lambda_1(\Phi^\dagger\Phi)^2 - \lambda_2(\Psi^\dagger\Psi)^2 - \lambda_3(\Phi^\dagger\Phi)(\Psi^\dagger\Psi) - \lambda_4(\Phi^\dagger\Psi)(\Psi^\dagger\Phi) - \frac{1}{2}\left(\lambda_5(\Phi^\dagger\Psi)(\Phi^\dagger\Psi) + \text{h.c.}\right)$$

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

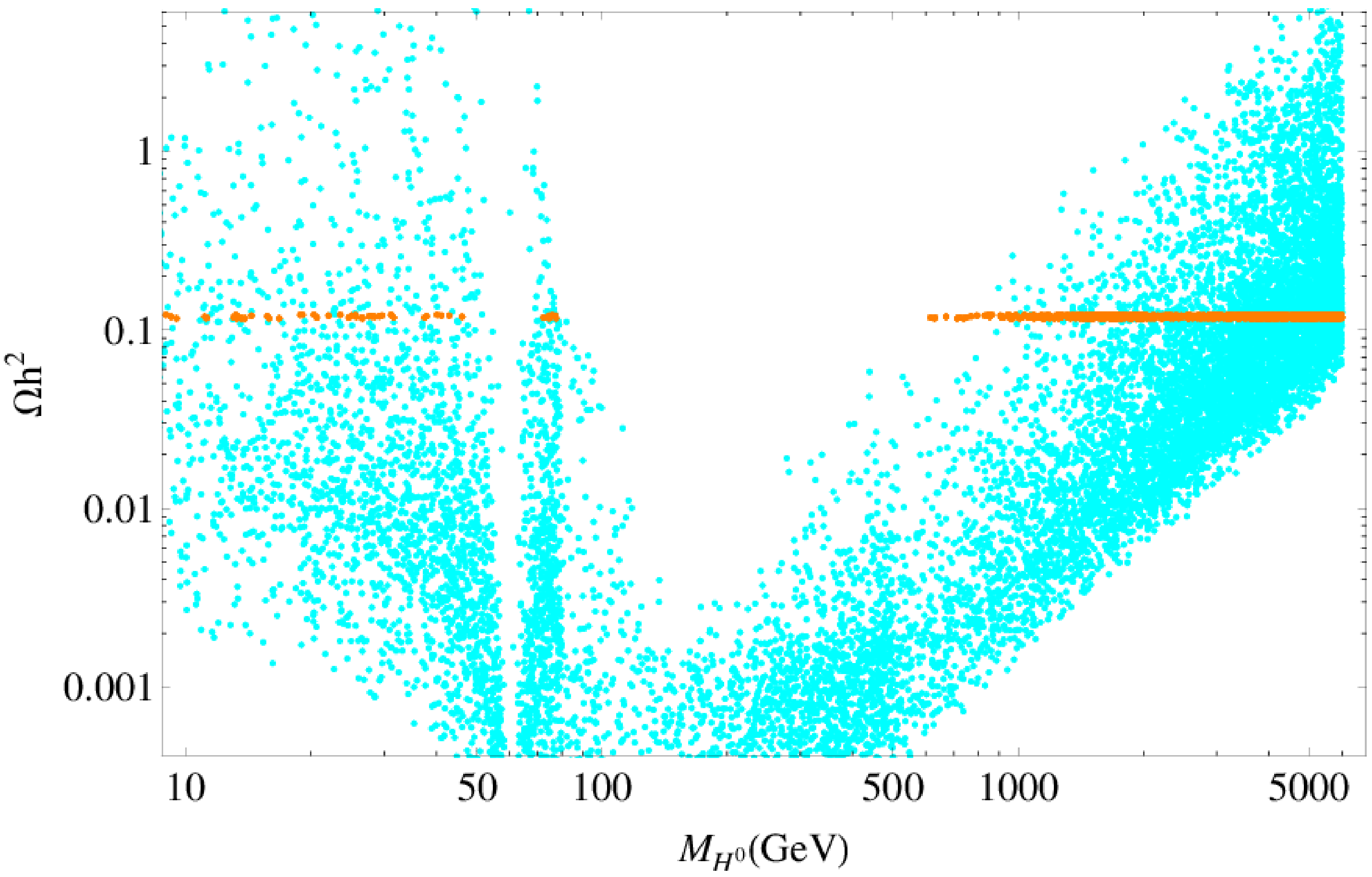


$$\lambda_{H_c} \equiv \lambda_3/2$$
$$\lambda_{H_0,A_0} \equiv (\lambda_3 + \lambda_4 \pm \lambda_5)/2$$

For a heavy dark matter candidate $(M_{H^0} \gg M_W)$ the splitting is relatively small and we expect the particles belonging to the extra doublet to have nearly degenerate masses .

Lopez-Honorez

Dark Matter Abundance

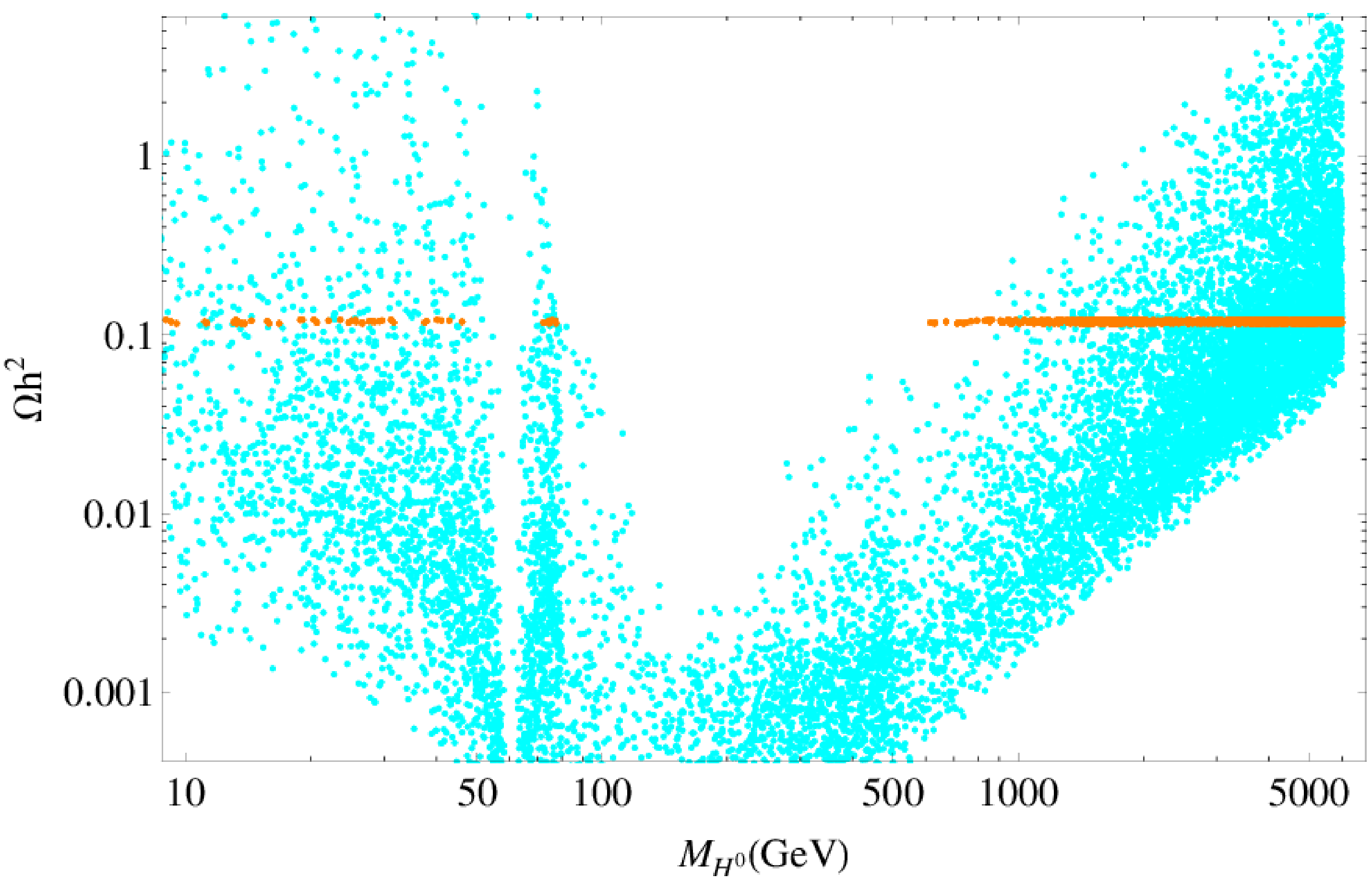


Dark Matter Abundance

$m_{H_0} \lesssim m_W$:   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,...



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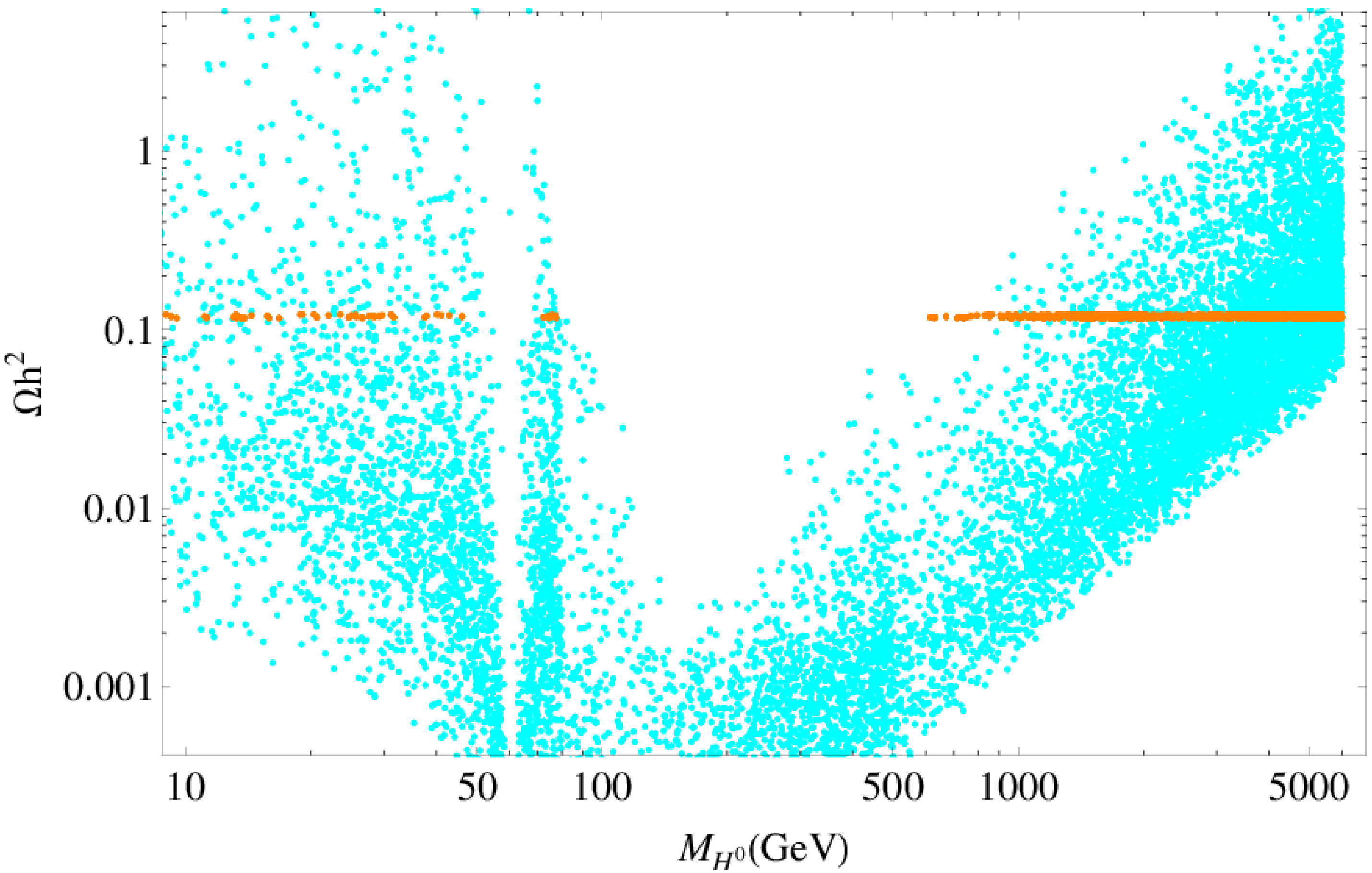
$m_{H_0} \gg m_W$:   TeV range

$H_0 H_0 \to ZZ, WW, hh$

Cirelli NPB06, Hambye JHEP09



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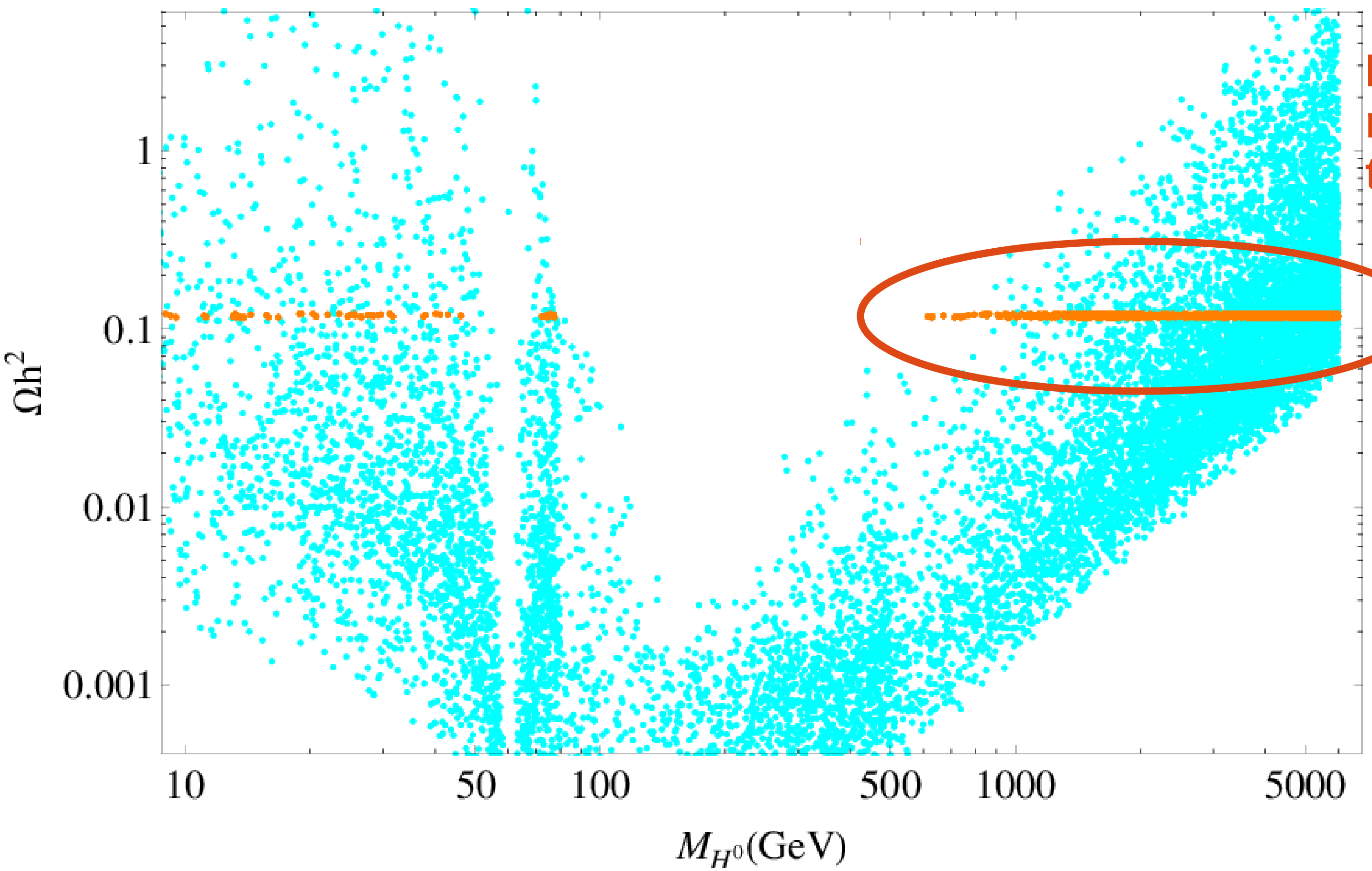
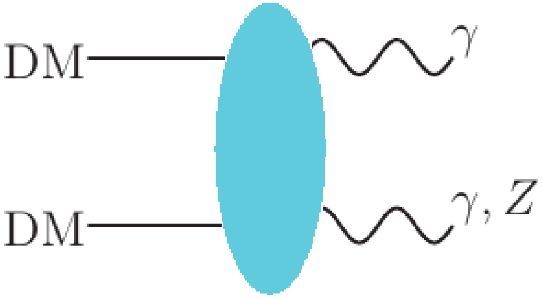


High-mass regime of the IDM

Gamma-ray spectral features

Smoking gun signature for dark matter : no astrophysical process is known to produce a sharp feature in the gamma-ray spectrum



Annihilation into Photons

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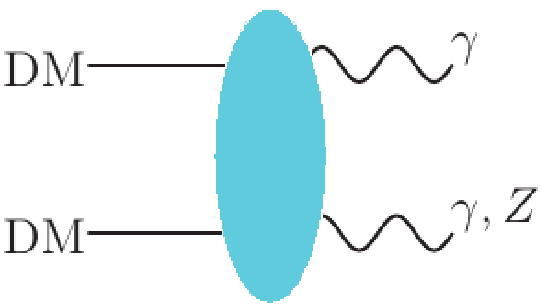

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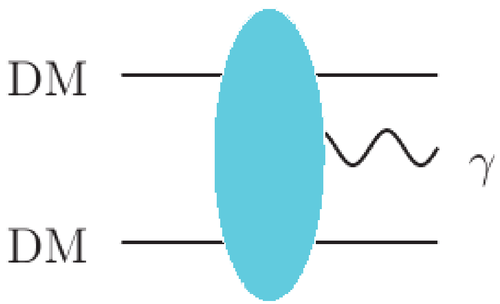

Virtual Internal Bremsstrahlung

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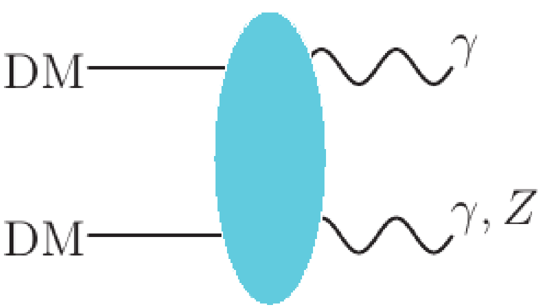

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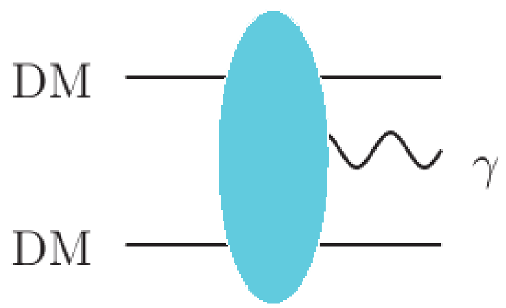

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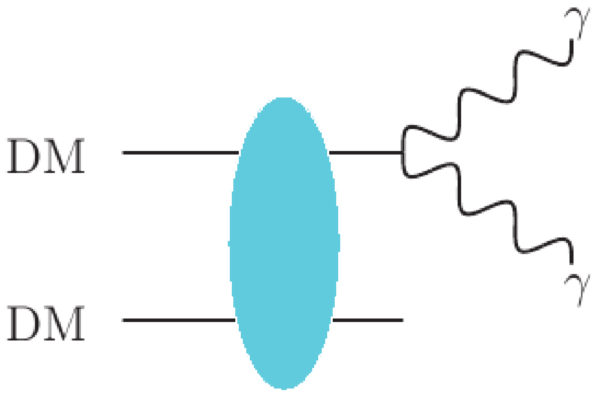

Box-shaped spectra

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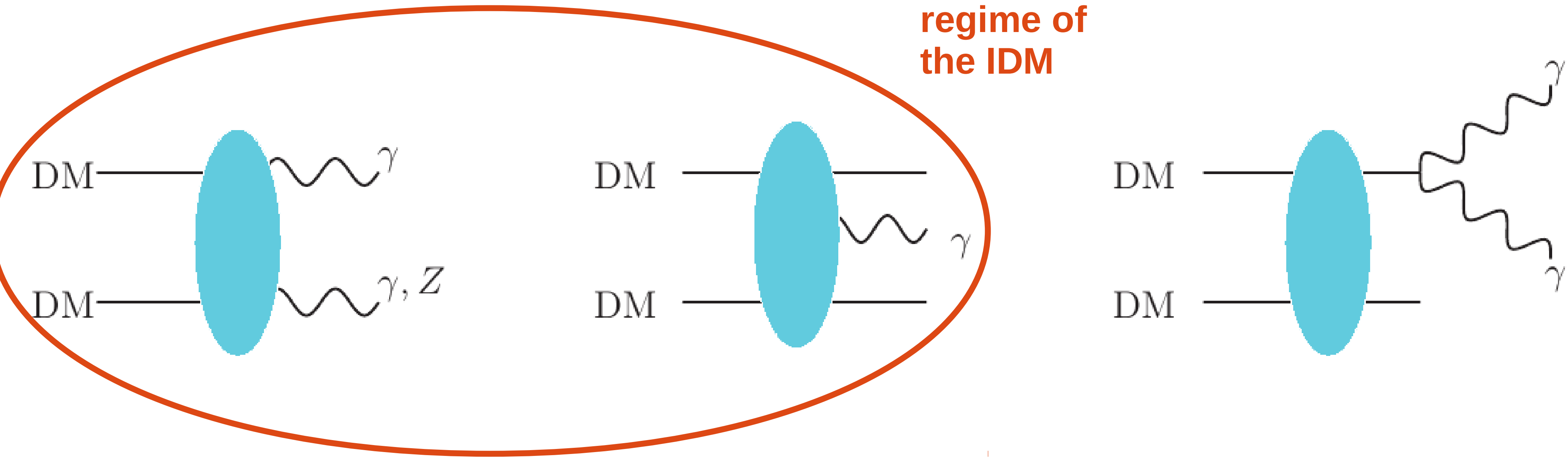
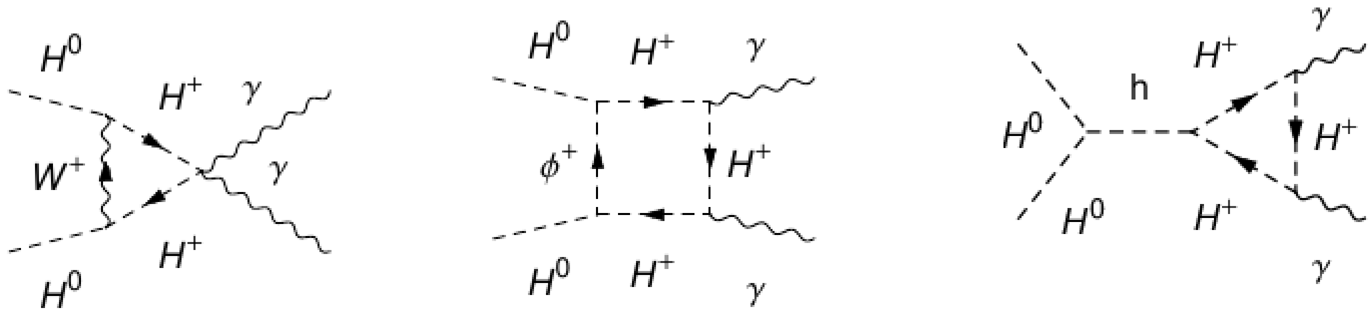


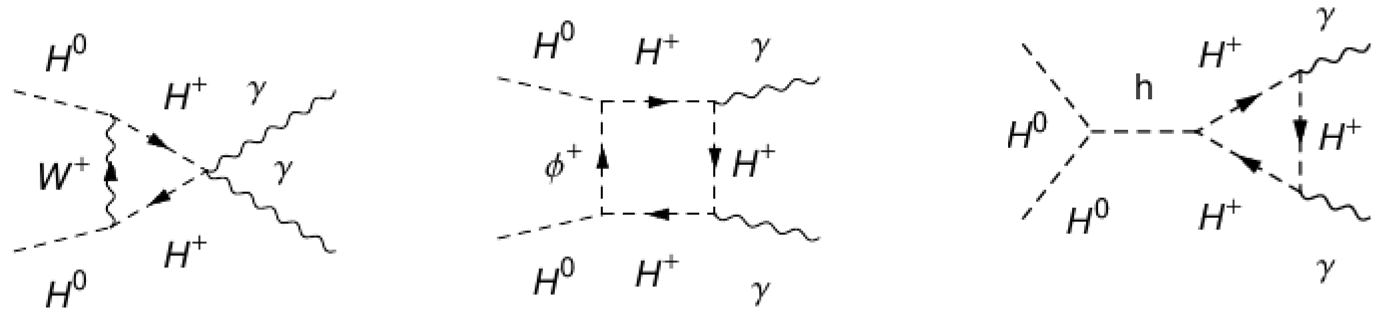
Annihilation into Photons | Virtual Internal Bremsstrahlung | Box-shaped spectra

One-loop annihilation into two photons



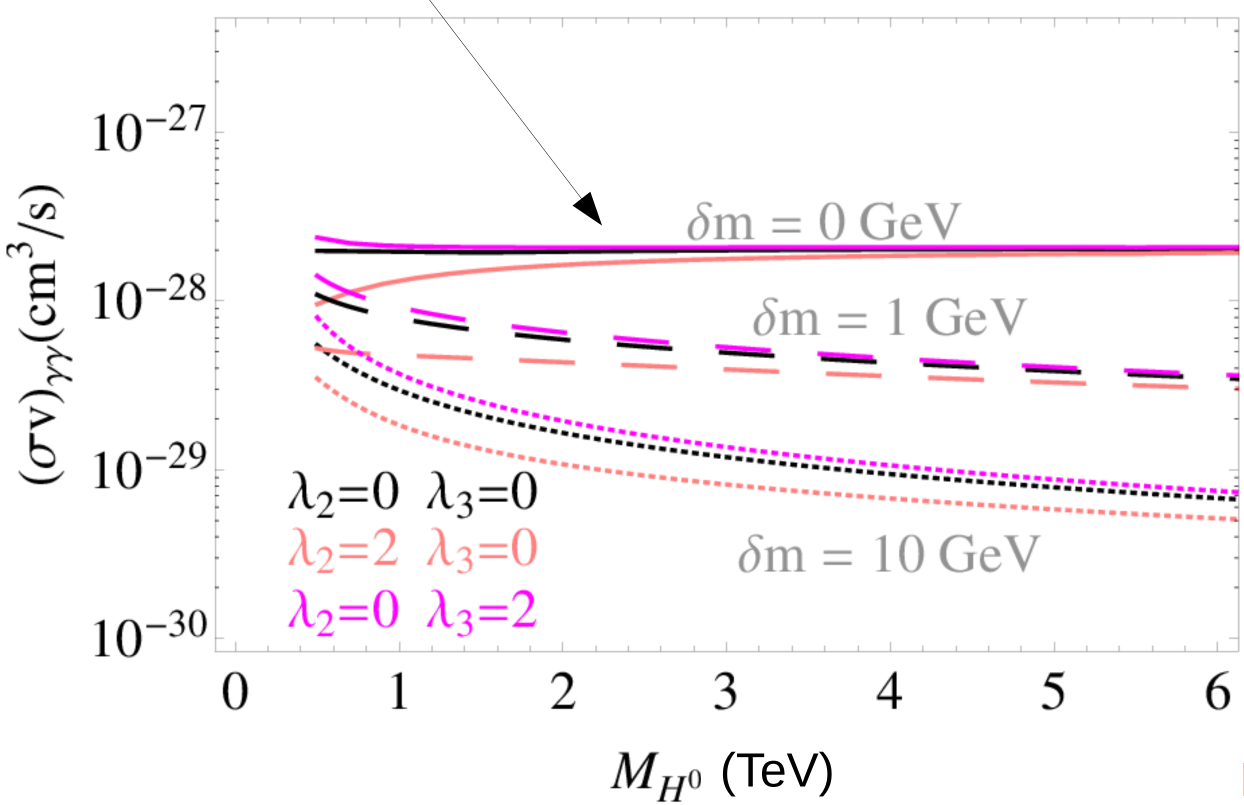
……...and many more

One-loop annihilation into two photons



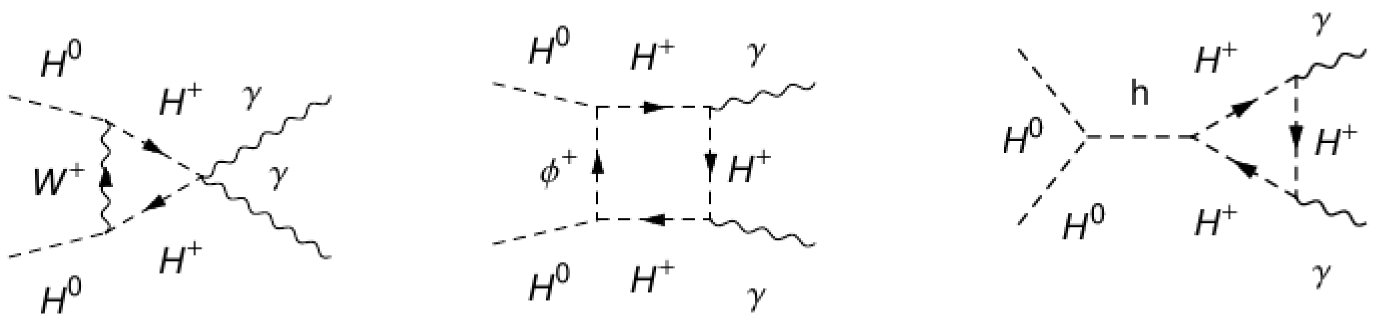
……..and many more

Something is wrong because the cross-section must be bounded from above by the unitarity limit



Preliminary

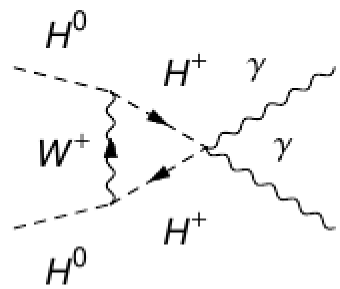
One-loop annihilation into two photons

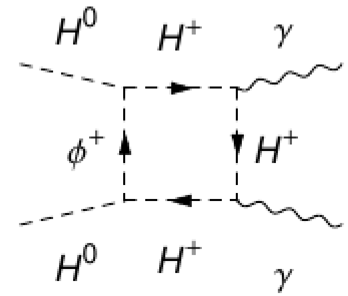


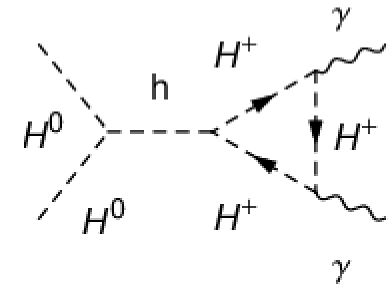
……..and many more

$$\mathcal{M}\left(H^0 H^0 \to \gamma\gamma\right)\Big|_{s-wave} = A\left(g^{\mu\nu} - \frac{p^{\mu}_{\gamma_2} p^{\nu}_{\gamma_1}}{2M^2_{H^0}}\right)\epsilon_\mu(p_{\gamma_1})\epsilon_\nu(p_{\gamma_2})$$

One-loop annihilation into two photons



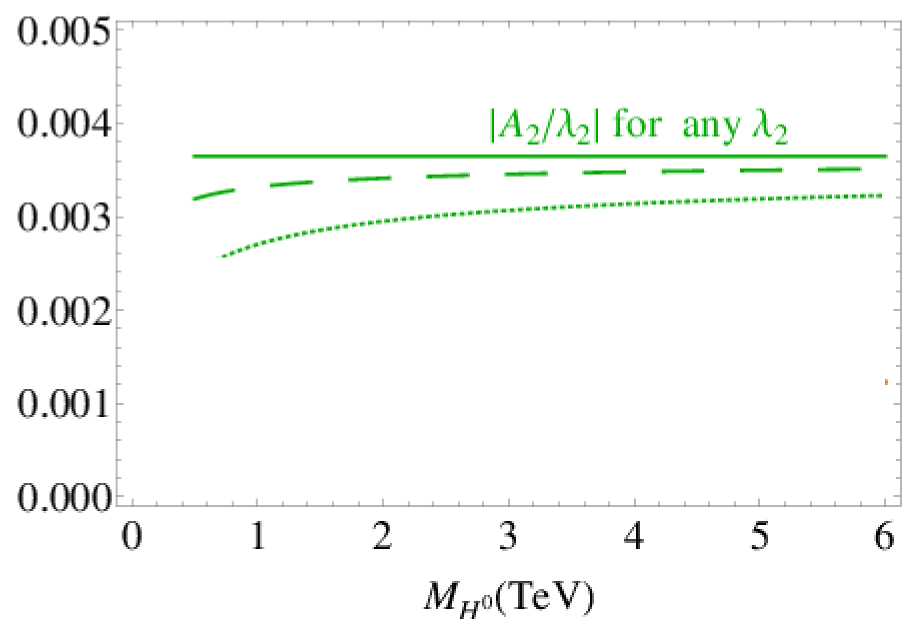




……..and many more

$$+ A_2(M_{H^0}, M_{H^+}, \lambda_2)$$

$$\mathcal{M}\left(H^0 H^0 \to \gamma\gamma\right)\Big|_{s-wave} = A\left(g^{\mu\nu} - \frac{p^{\mu}_{\gamma_2} p^{\nu}_{\gamma_1}}{2M^2_{H^0}}\right)\epsilon_\mu(p_{\gamma_1})\epsilon_\nu(p_{\gamma_2})$$



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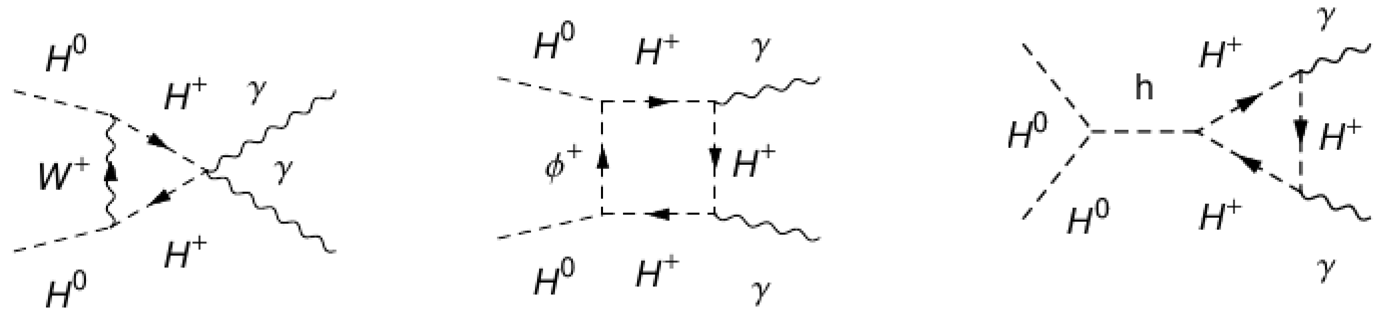

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$$+ A_2(M_{H^0}, M_{H^+}, \lambda_2) + A_3(M_{H^0}, M_{H^+}, \lambda_3)$$

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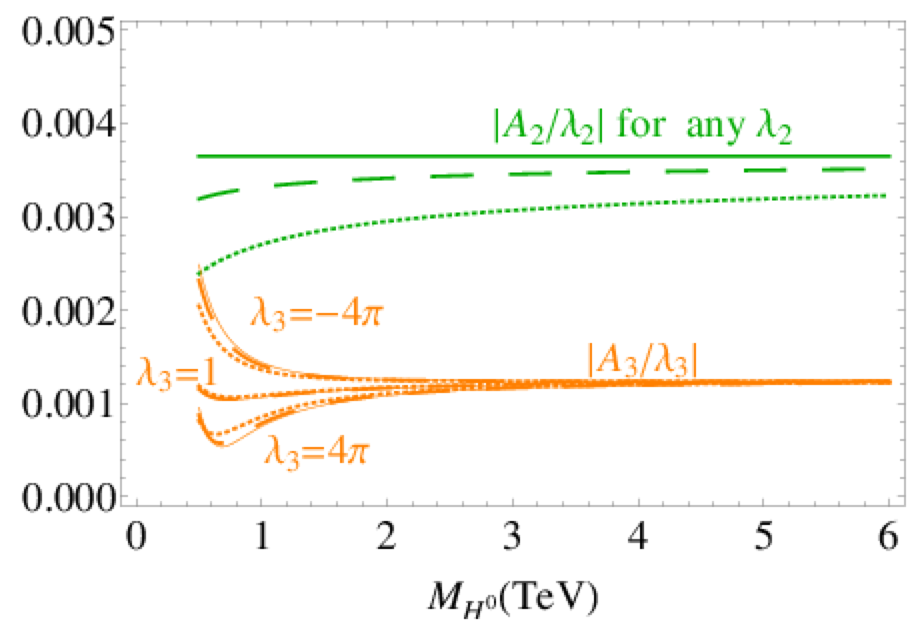

Preliminary

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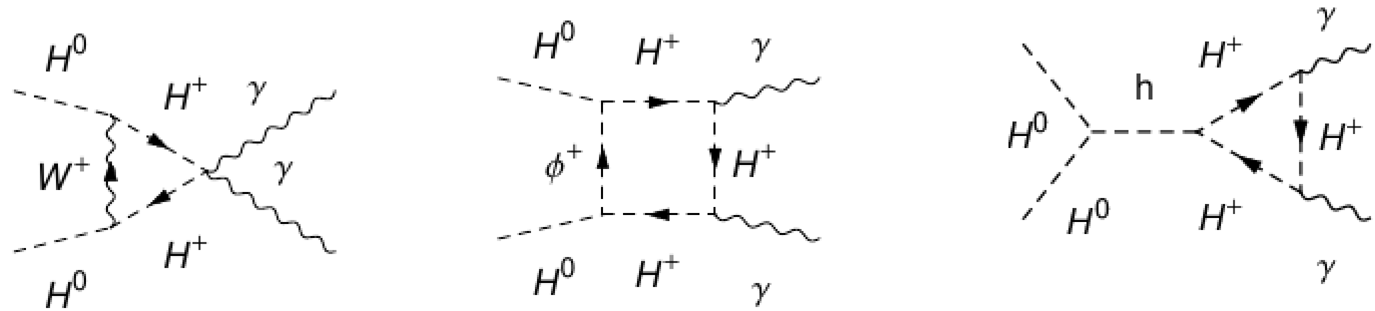

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$$A_0(M_{H^0}, M_{H^+}) + A_2(M_{H^0}, M_{H^+}, \lambda_2) + A_3(M_{H^0}, M_{H^+}, \lambda_3)$$

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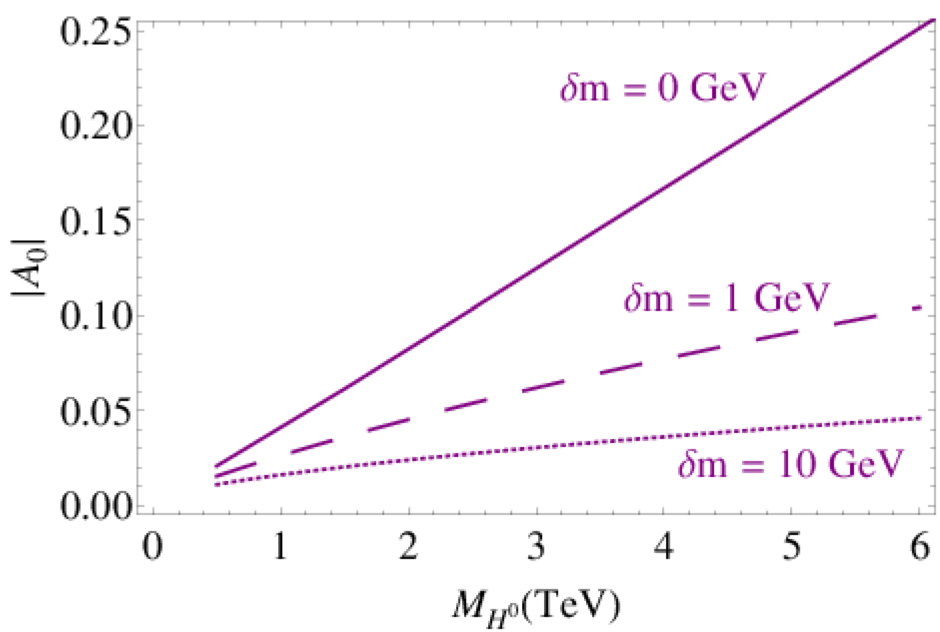

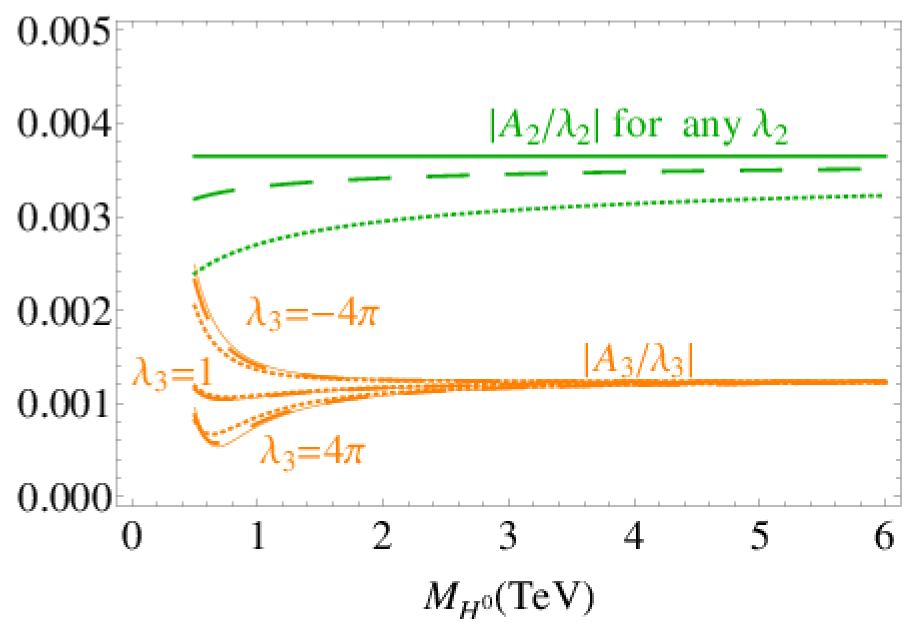

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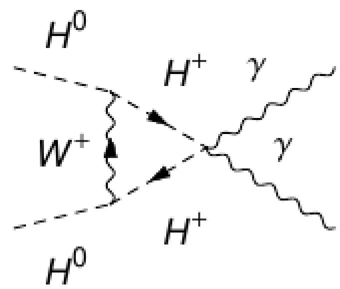
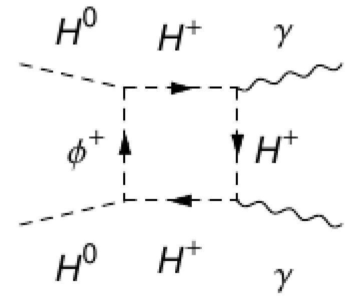
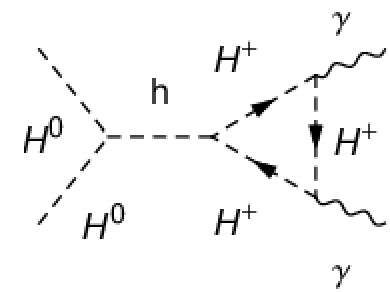


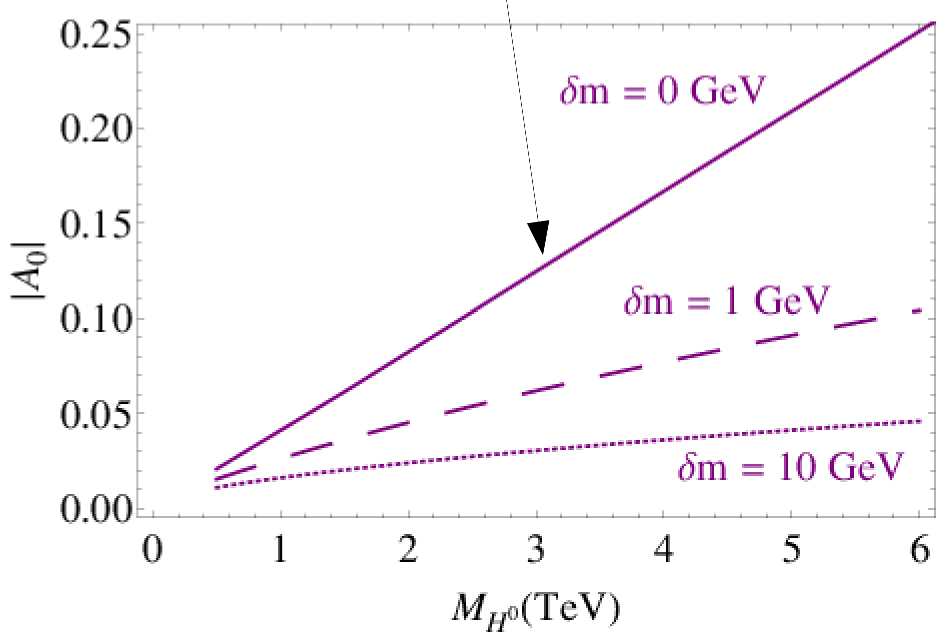


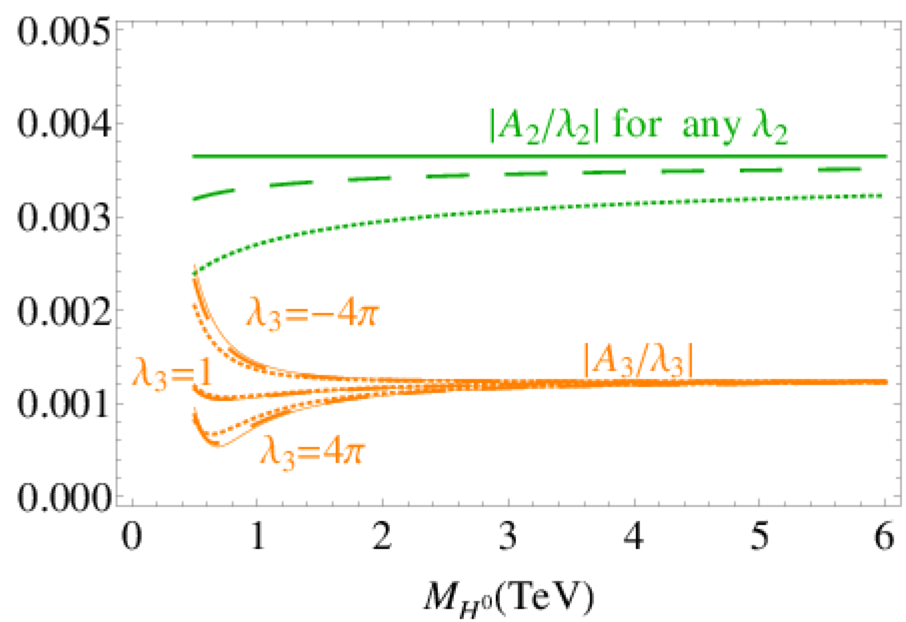


……..and many more

$$\sigma v \left(H^0 H^0 \to \gamma\gamma\right)\Big|_{s-wave} = \frac{|A|^2}{32\pi M_{H^0}^2}$$

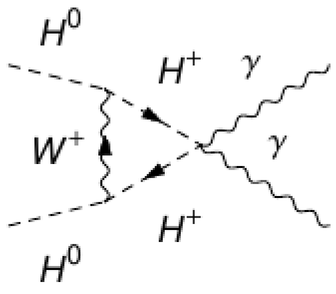
Something is wrong because





Preliminary

What is wrong?



$$A_0 \supset -\frac{4\alpha\alpha_2 M_{H^0}}{M_W}\int_0^1 dx \frac{1}{\sqrt{1-x}} \arctan\left(\frac{M_{H^0}}{M_W}\frac{x}{\sqrt{1-x}}\right).$$

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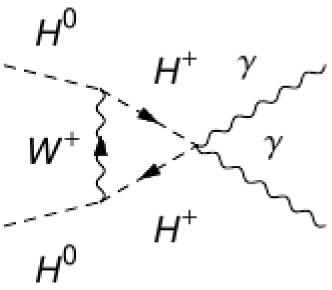

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- For each W boson that is exchanged in the initial state one gets a factor that goes like $\alpha_2 M_{H^0}/M_W$.

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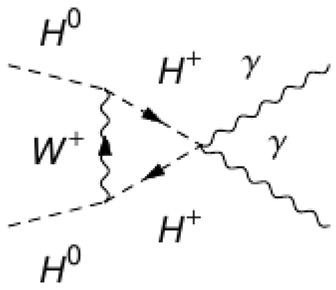

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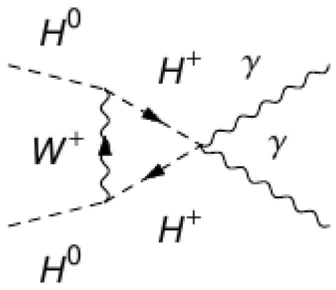

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- If $M_{H^0} \gtrsim M_W/\alpha_2 \approx 2\,\mathrm{TeV}$, the perturbative calculation breaks down because higher-order loop diagrams become more and more important.
- For these masses and in general in the high-mass regime of the IDM, the one-loop calculation is not reliable until these effects are taken into account.

Sommerfeld Enhancement!

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The exchange of W bosons - and in general of any boson- leads to a long range interaction that distorts the wave function of the annihilating particles

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Schrödinger equation accounting for that

$$g''(r) + M_{H^0}\left(\frac{1}{4}M_{H^0}v^2\mathbb{1} - V(r)\right)g(r) = 0$$

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$$\underbrace{\qquad\qquad}_{2\,\delta m}$$

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$V_{\text{Gauge}}(r) + V_{\text{Scalar}}(r)$: Yukawa Potentials

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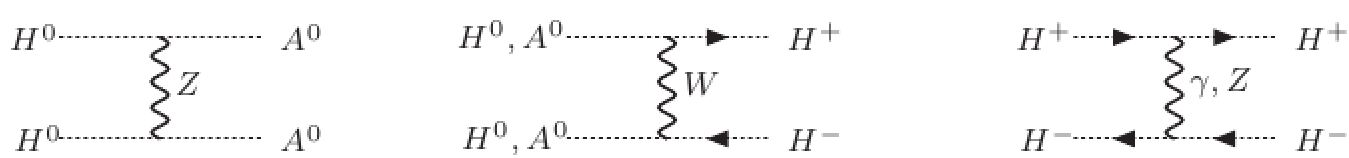

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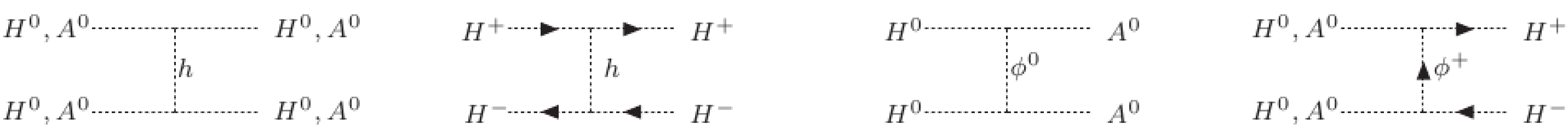

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Final State

$$\sigma v\left(H^0 H^0 \to f\right)\Big|_{s-wave} = \frac{1}{4M_{H^0}^2}\int\left(\prod_{a\in f}\frac{d^3 q_a}{(2\pi)^3 2E_a}\right)(2\pi)^4\delta^4\left(p_{H^0} + p'_{H^0} - \sum_{a\in f} q_a\right) \cdot\left|\mathcal{M}\left(H^0 H^0 \to f\right)\right|^2$$

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$$\cdot\left|d_{11}\,\mathcal{M}\left(H^0H^0 \to f\right) + \qquad\qquad\right|^2$$

Enhancement factors

Sommerfeld Enhancement

The exchange of W bosons - and in general of any boson- leads to a long range interaction that distorts the wave function of the annihilating particles

Schrödinger equation accounting for that $$g''(r) + M_{H^0}\left(\frac{1}{4}M_{H^0}v^2\mathbb{1} - V(r)\right)g(r) = 0$$

Final State

New annihilation channels open-up

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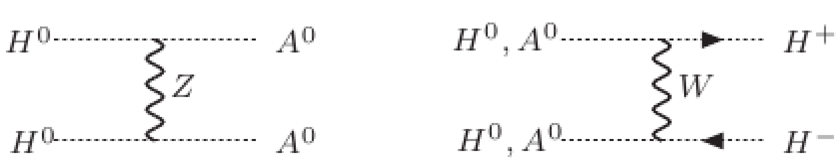
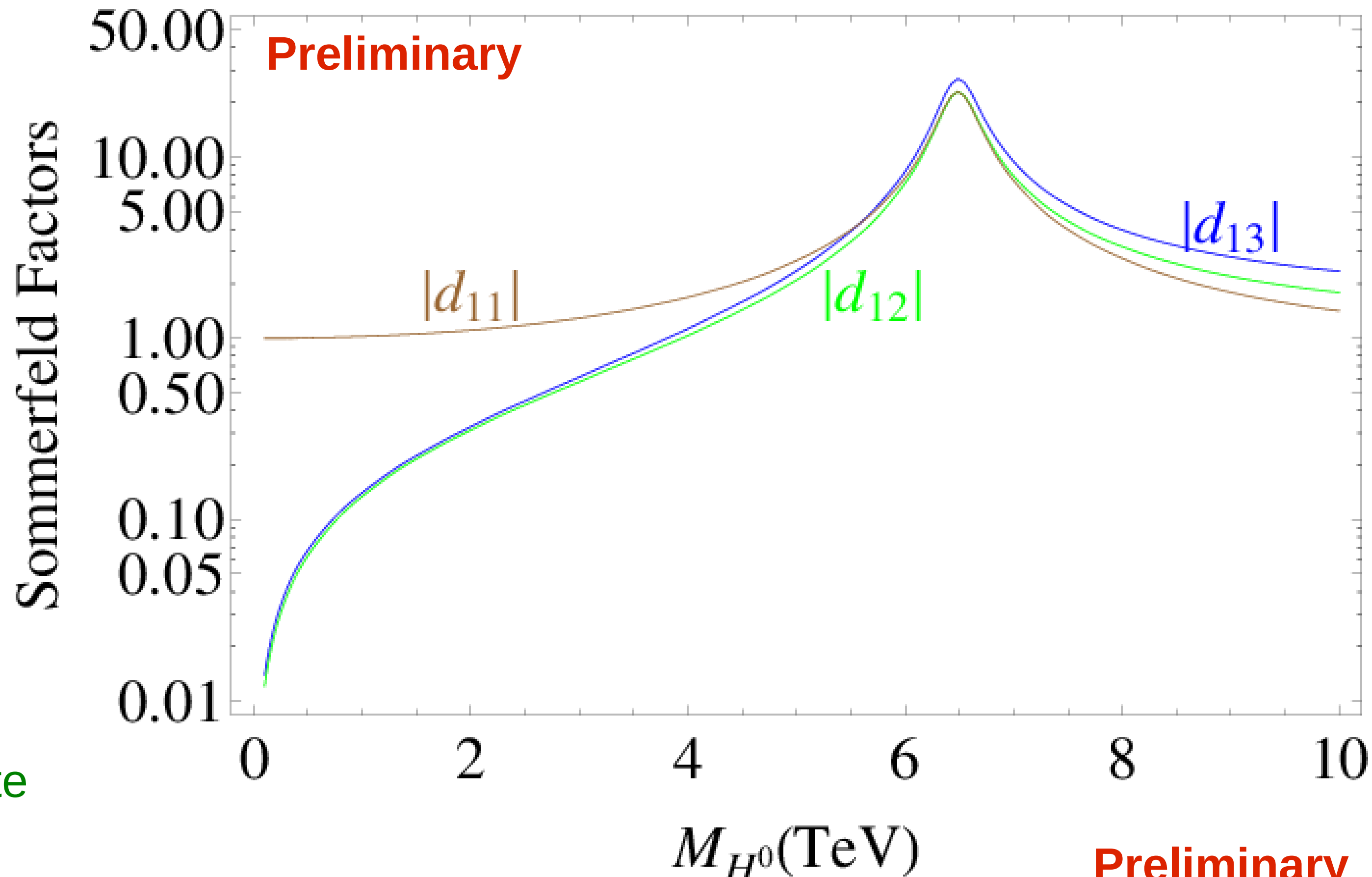
$$\cdot\left|d_{11}\,\mathcal{M}\left(H^0H^0 \to f\right) + d_{12}\,\mathcal{M}\left(A^0A^0 \to f\right) + \sqrt{2}d_{13}\,\mathcal{M}\left(H^+H^- \to f\right)\right|^2$$



Enhancement factors

Example: when all the quartic couplings vanish



Preliminary

Final State

$$\sigma v\left(H^0H^0\to f\right)\Big|_{s-wave} = \frac{1}{4M_{H^0}^2}\int\left(\prod_{a\in f}\frac{d^3q_a}{(2\pi)^3 2E_a}\right)(2\pi)^4\delta^4\left(p_{H^0}+p'_{H^0}-\textstyle\sum_{a\in f}q_a\right)$$

$$\cdot\left|d_{11}\,\mathcal{M}\left(H^0H^0\to f\right)+d_{12}\,\mathcal{M}\left(A^0A^0\to f\right)+\sqrt{2}d_{13}\,\mathcal{M}\left(H^+H^-\to f\right)\right|^2$$

Including this effect solves the problem with unitarity!!!

Hisano, Matsumoto, Nojiri,Saito PRD05

Including this effect solves the problem with unitarity!!!

Hisano, Matsumoto, Nojiri,Saito PRD05

$$\sigma v\left(H^0 H^0 \to \gamma\gamma\right)\Big|_{s-wave} = \frac{1}{4M_{H^0}^2}\int\left(\prod_{a\in f}\frac{d^3 q_a}{(2\pi)^3 2E_a}\right)(2\pi)^4\delta^4\left(p_{H^0}+p'_{H^0}-\sum_{a\in f} q_a\right)$$

$$\cdot\left|d_{11}\,\mathcal{M}\left(H^0 H^0 \to \gamma\gamma\right)+d_{12}\,\mathcal{M}\left(A^0 A^0 \to \gamma\gamma\right)+\sqrt{2}d_{13}\,\mathcal{M}\left(H^+ H^- \to \gamma\gamma\right)\right|^2$$

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$$\sigma v \left(H^0 H^0 \to \gamma\gamma\right)\Big|_{s-wave} = \frac{1}{4M_{H^0}^2}\int\left(\prod_{a\in f}\frac{d^3 q_a}{(2\pi)^3 2E_a}\right)(2\pi)^4\delta^4\left(p_{H^0}+p'_{H^0}-\sum_{a\in f} q_a\right)$$

$$\cdot\left| d_{11}\,\mathcal{M}\left(H^0 H^0 \to \gamma\gamma\right) + d_{12}\,\mathcal{M}\left(A^0 A^0 \to \gamma\gamma\right) + \sqrt{2} d_{13}\,\mathcal{M}\left(H^+ H^- \to \gamma\gamma\right)\right|^2$$

$\mathcal{M}\left(H^0 H^0 \to \gamma\gamma\right) \to 0$ $\qquad$ $\mathcal{M}\left(A^0 A^0 \to \gamma\gamma\right) \to 0$

Including this effect solves the problem with unitarity!!!

Hisano, Matsumoto, Nojiri, Saito PRD05

$$\sigma v\left(H^0H^0 \to \gamma\gamma\right)\Big|_{s-wave} = \frac{1}{4M_{H^0}^2}\int\left(\prod_{a\in f}\frac{d^3q_a}{(2\pi)^3 2E_a}\right)(2\pi)^4\delta^4\left(p_{H^0}+p'_{H^0}-\textstyle\sum_{a\in f}q_a\right)$$

$$\cdot\left|d_{11}\,\mathcal{M}\left(H^0H^0\to\gamma\gamma\right)+d_{12}\,\mathcal{M}\left(A^0A^0\to\gamma\gamma\right)+\sqrt{2}d_{13}\,\mathcal{M}\left(H^+H^-\to\gamma\gamma\right)\right|^2$$

0

0

A constant at tree-level

Including this effect solves the problem with unitarity!!!

Hisano, Matsumoto, Nojiri,Saito PRD05

$$\sigma v \left(H^0 H^0 \to \gamma\gamma\right)\Big|_{s-wave} = \frac{1}{4M_{H^0}^2}\int \left(\prod_{a\in f}\frac{d^3 q_a}{(2\pi)^3 2E_a}\right)(2\pi)^4\delta^4\left(p_{H^0}+p'_{H^0}-\Sigma_{a\in f}q_a\right)$$

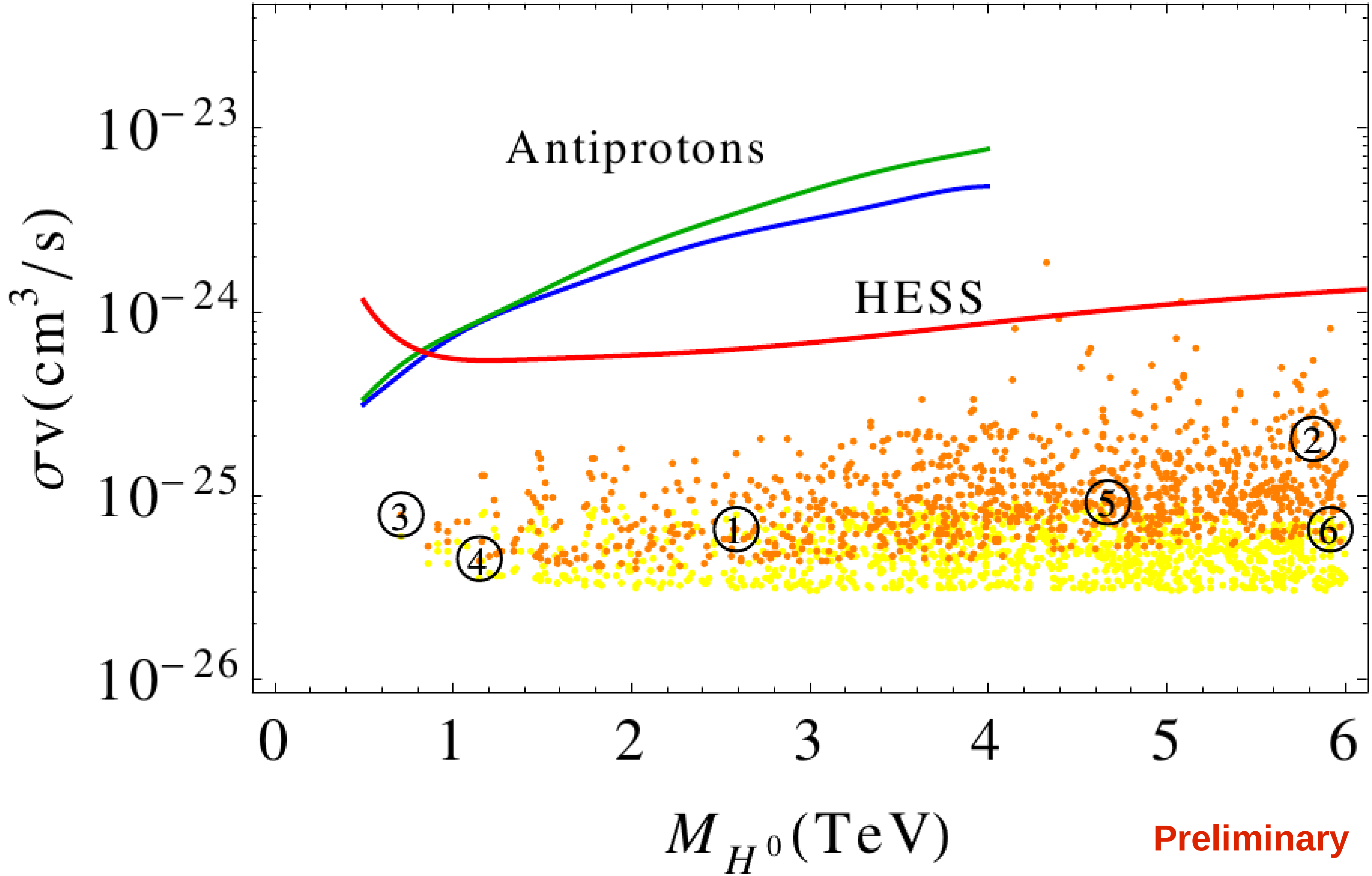
$$\cdot\left|d_{11}\,\mathcal{M}\left(H^0H^0\to\gamma\gamma\right)+d_{12}\,\mathcal{M}\left(A^0A^0\to\gamma\gamma\right)+\sqrt{2}d_{13}\,\mathcal{M}\left(H^+H^-\to\gamma\gamma\right)\right|^2$$

0

0

A constant at tree-level

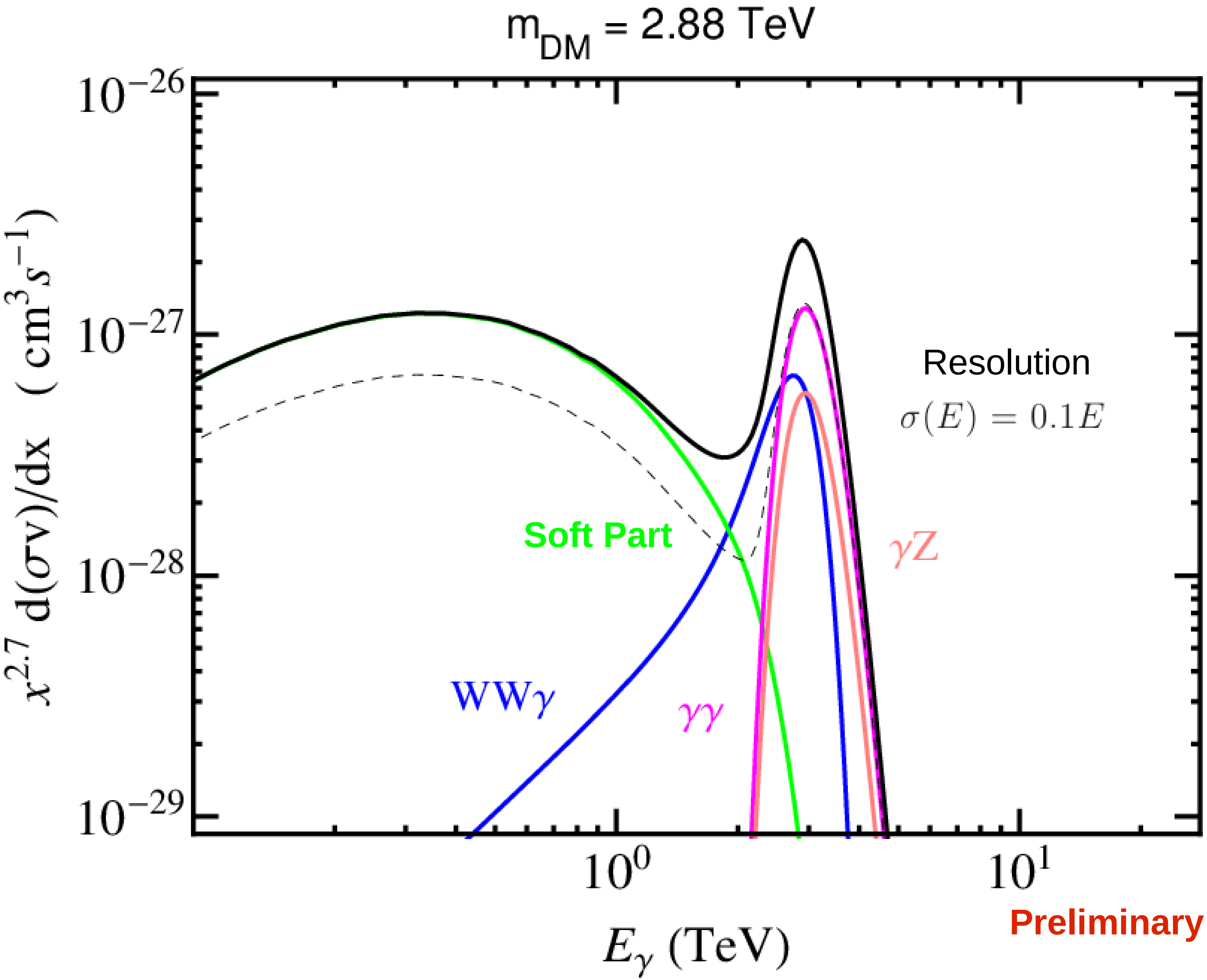
$$\sigma v\left(H^0H^0\to\gamma\gamma\right)=\frac{4\pi\alpha^2|d_{13}|^2}{M_{H^0}^2}$$



Antiprotons
HESS
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$\sigma v(cm^3/s)$
0
1
2
3
4
5
6
$M_{H^0}(TeV)$
Preliminary

One Benchmark

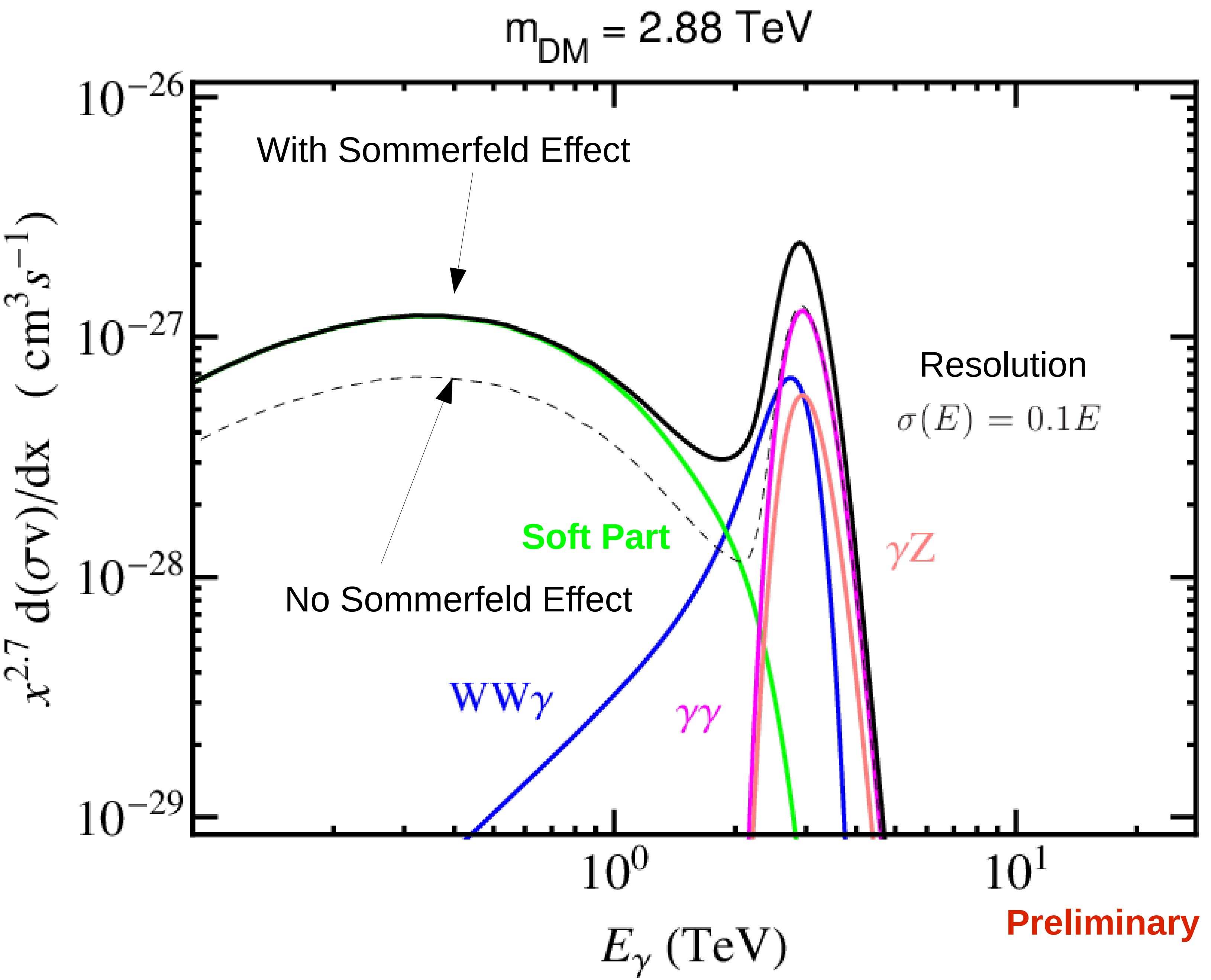
The lines dominate over IB



Preliminary

One Benchmark

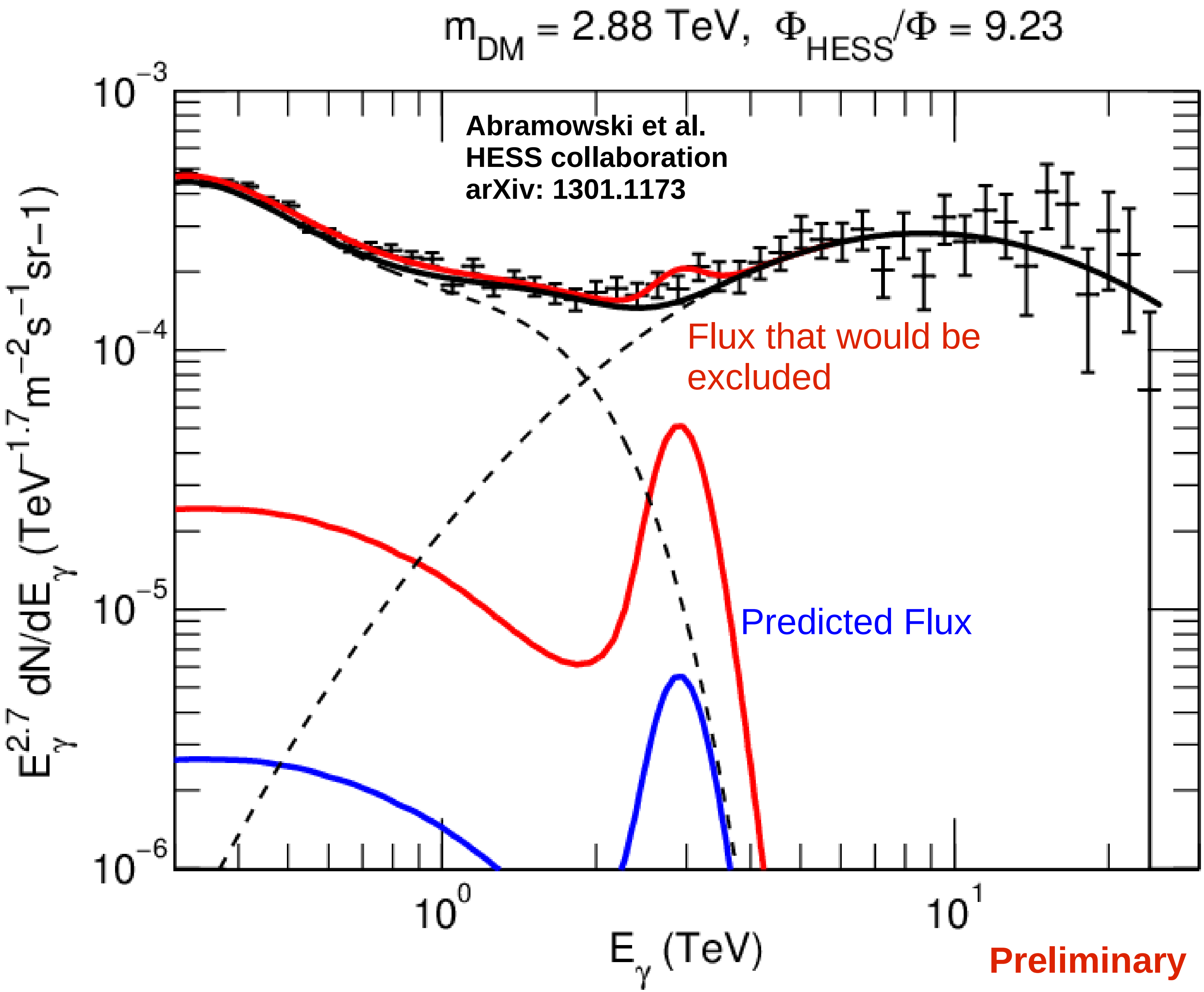
The lines dominate over IB



Preliminary

One Benchmark

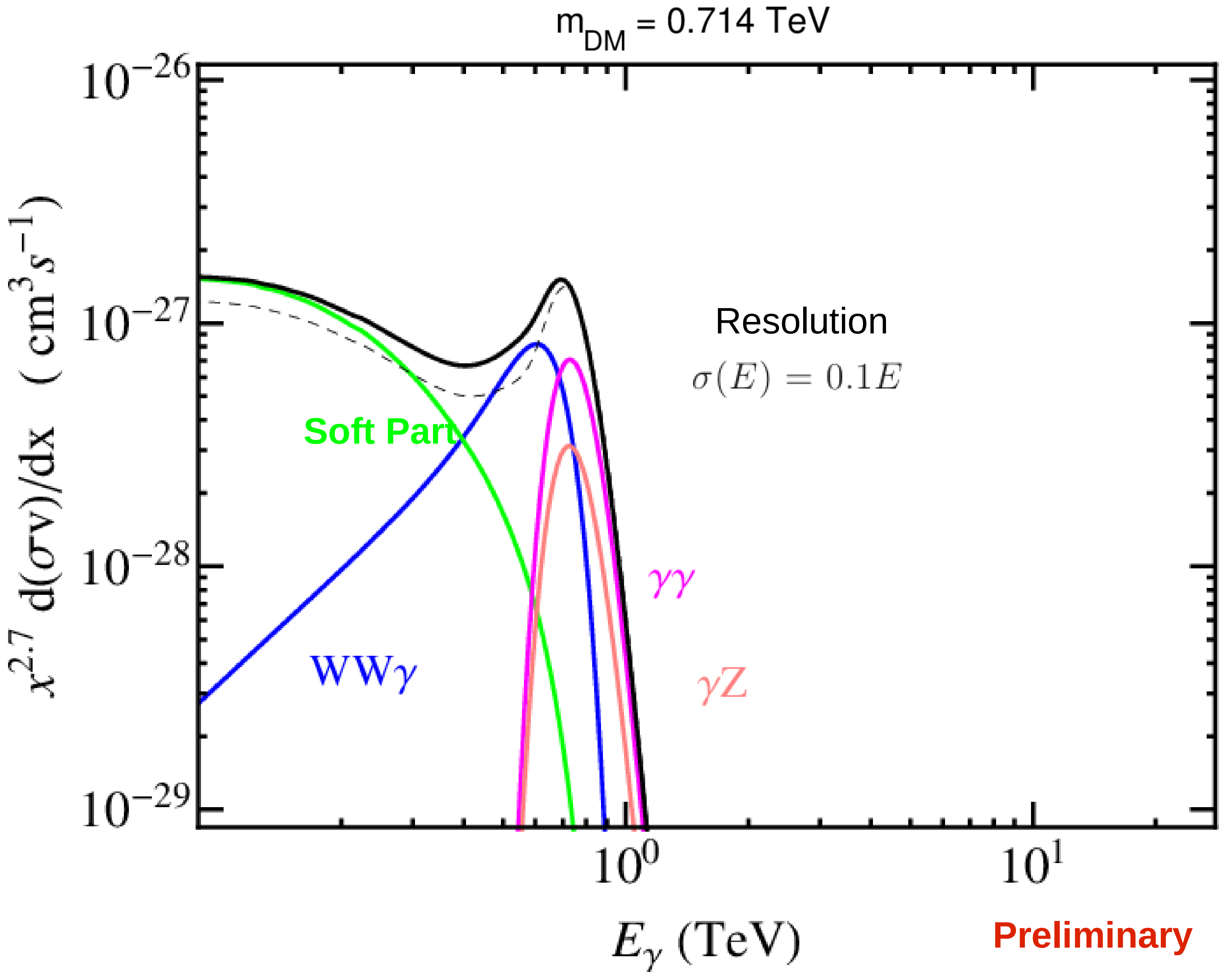
The lines dominate over IB



Preliminary

Another Benchmark

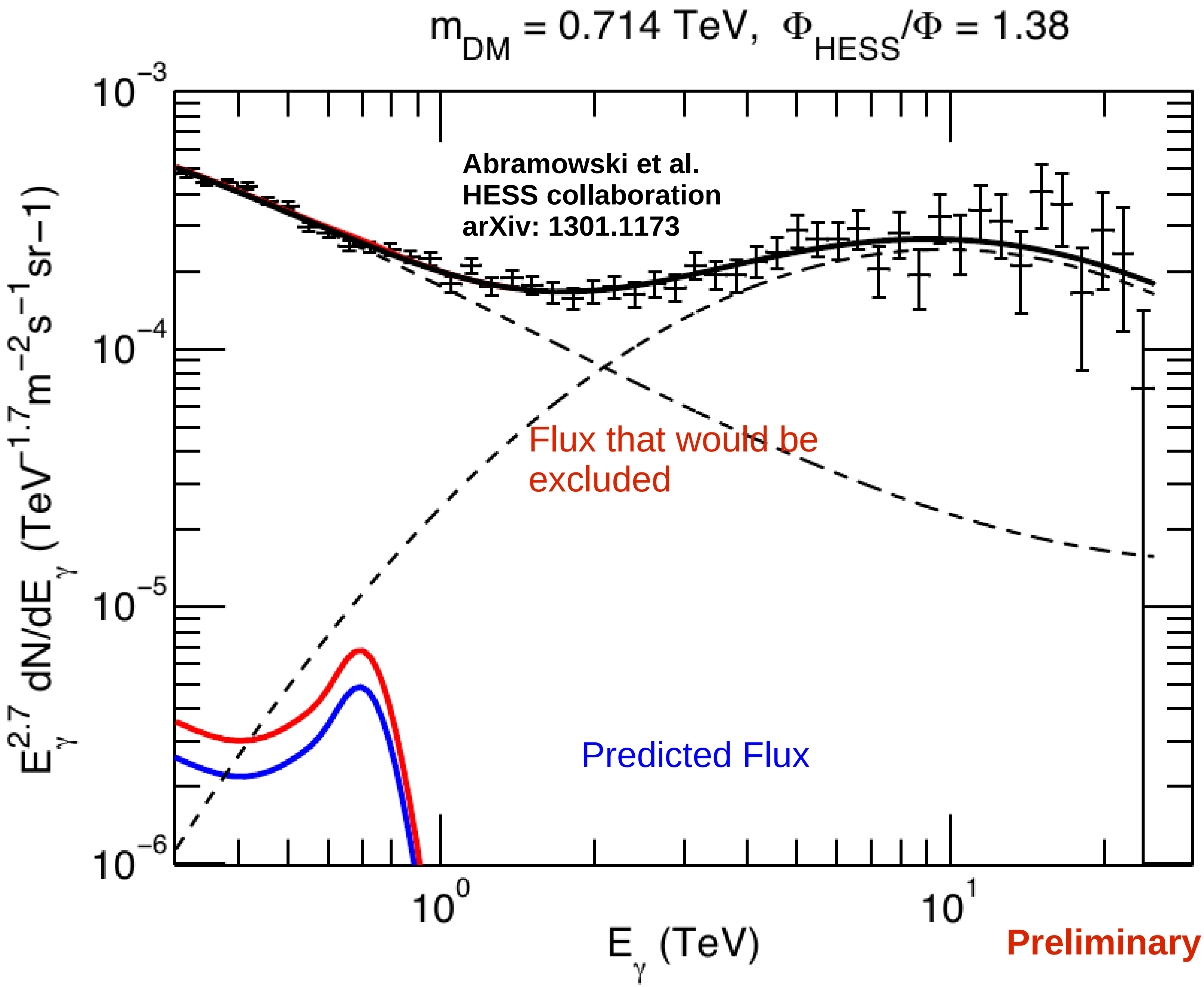
IB dominates over the lines



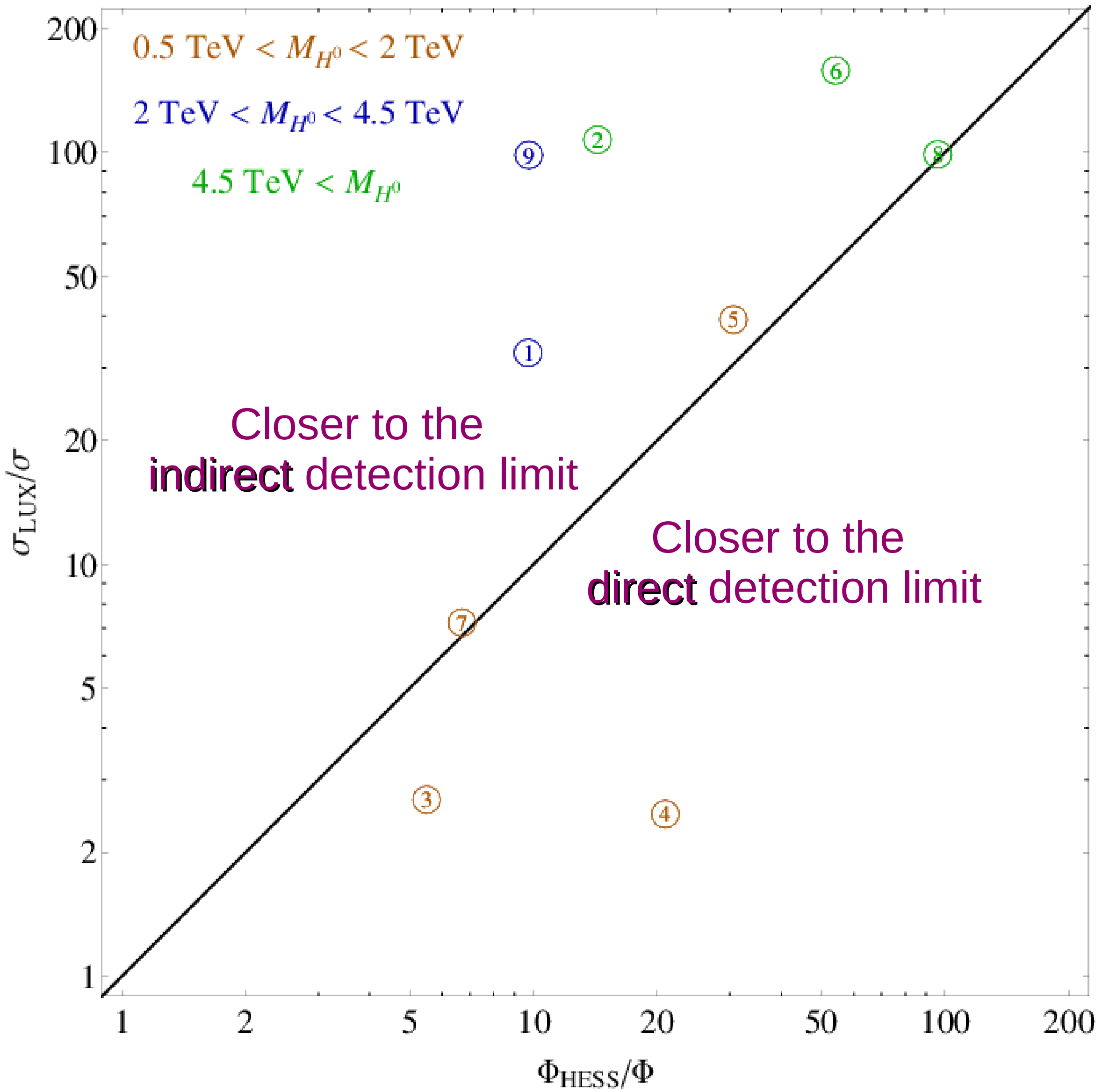
Preliminary

Another Benchmark

IB dominates over the lines

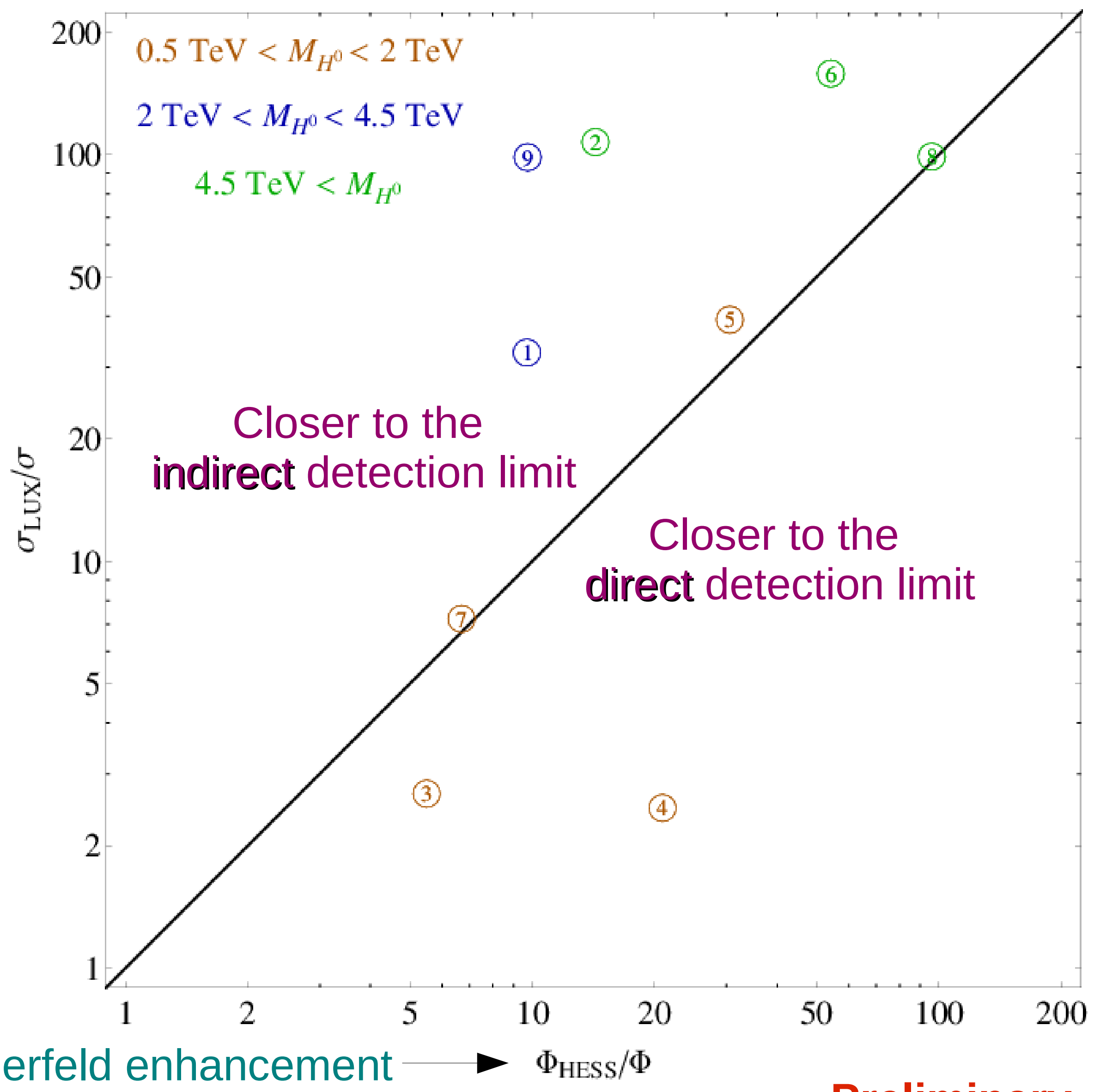


Direct Detection vs. Indirect Detection



Preliminary

Direct Detection vs. Indirect Detection



This includes Sommerfeld enhancement

Preliminary

Conclusions

- In the high mass regime of the inert doublet model, the internal bremsstrahlung process and annihilation into photons generate sharp gamma-ray spectral features.
- The Sommerfeld enhancement has to be taken into account in order to account for perturbative unitarity.
- These spectral features can be searched for with gamma-ray telescopes, and eventally found or excluded in the near future.