Study of the Internal Bremsstrahlung in the Inert Doublet Model

Camilo A. Garcia Cely
Technische Universität München

Mainz Institute for Theoretical Physics
Workshop “Cosmic Rays and Photons from Dark Matter Annihilation: Theoretical Issues”

29 June 2013

Based on arXiv:1306.4681, in collaboration with Pr. Alejandro Ibarra

Outline

- Inert doublet model and dark matter
- Indirect searches and spectral features
- Benchmark points and effect of the model parameters on the internal Bremsstrahlung
- H.E.S.S. Upper limits
- Conclusions

The inert doublet model

Let $\eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$ be an extra doublet, and Φ the SM doublet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\eta \qquad \mathcal{L}_{\rm SM} \supset -\mu_1^2 \Phi^\dagger \Phi - \lambda_1 (\Phi^\dagger \Phi)^2$$

$$\mathcal{L}_\eta = (D_\mu \eta)^\dagger (D^\mu \eta) - \mu_2^2 \eta^\dagger \eta - \lambda_2 (\eta^\dagger \eta)^2 - \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta)$$
$$-\lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) - \frac{1}{2}\left(\lambda_5 (\Phi^\dagger \eta)(\Phi^\dagger \eta) + \text{h.c.}\right) .$$

Invariant under

$$\eta \to -\eta \qquad \Phi \to \Phi$$

$$(Z_2 \ symmetry)$$

Electroweak symmetry breaking

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} , \qquad \langle \eta \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Z_2 is not spontaneously broken

The inert doublet model

Let $\eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$ be an extra doublet, and Φ the SM doublet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\eta \qquad \mathcal{L}_{\rm SM} \supset -\mu_1^2 \Phi^\dagger\Phi - \lambda_1 (\Phi^\dagger\Phi)^2$$

$$\mathcal{L}_\eta = (D_\mu \eta)^\dagger (D^\mu \eta) - \mu_2^2 \eta^\dagger\eta - \lambda_2 (\eta^\dagger\eta)^2 - \lambda_3 (\Phi^\dagger\Phi)(\eta^\dagger\eta)$$
$$-\lambda_4 (\Phi^\dagger\eta)(\eta^\dagger\Phi) - \frac{1}{2}\left(\lambda_5 (\Phi^\dagger\eta)(\Phi^\dagger\eta) + \text{h.c.}\right) .$$

Invariant under

$\eta \to -\eta \qquad \Phi \to \Phi$

$(Z_2 \; symmetry)$

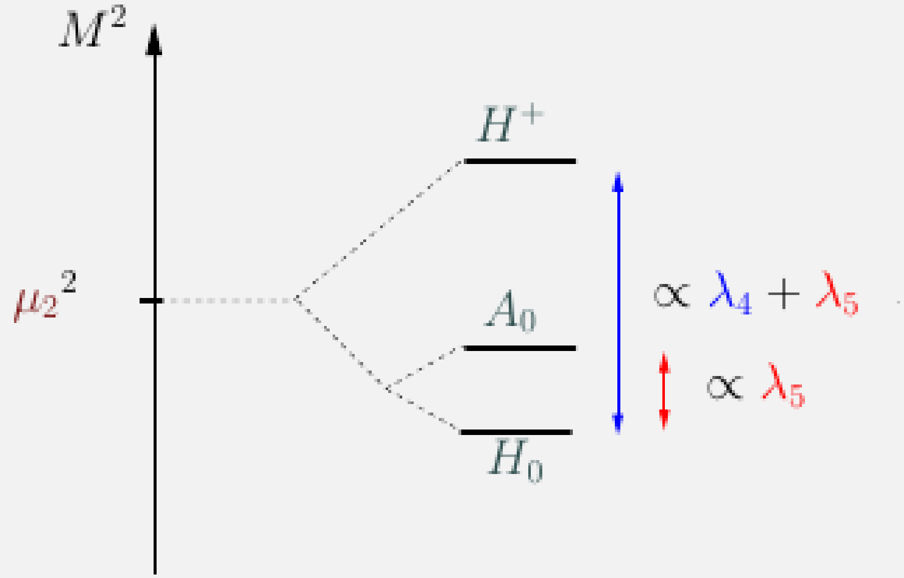
Electroweak symmetry breaking

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} , \qquad \langle\eta\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Z_2 is not spontaneously broken

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

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

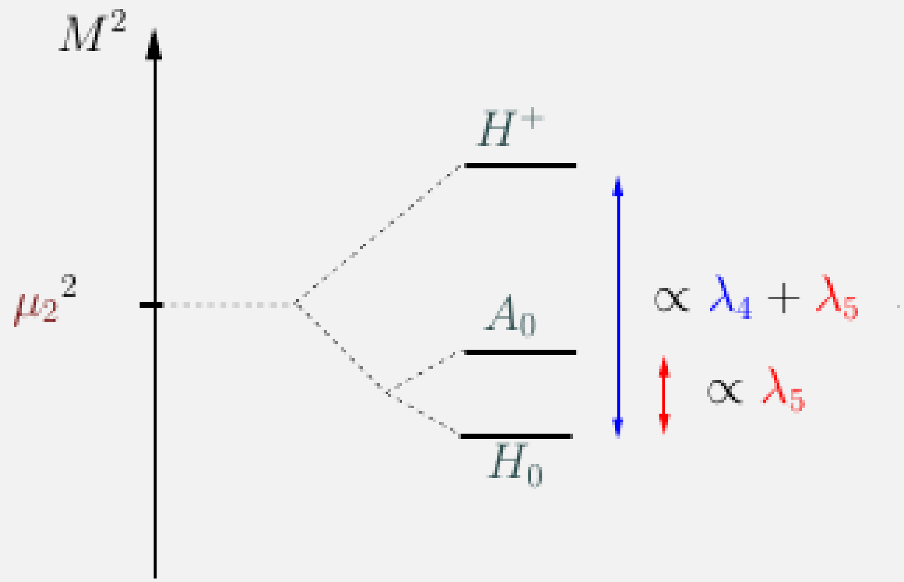


$$\lambda_{H_c} \equiv \lambda_3/2$$

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

Lopez-Honorez

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



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

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

Lopez-Honorez

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 .

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,...

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,...

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

$$H_0 H_0 \to ZZ, WW, hh$$

Cirelli NPB06, Hambye JHEP09

Dark Matter Abundance

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

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

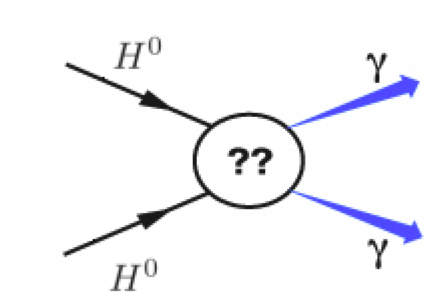
Barbieri PRD06, LLH JCAP06,Gustafsson PRL07, Cao PRD07, Andreas JCAP08,...

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

$$H_0 H_0 \to ZZ, WW, hh$$

Cirelli NPB06, Hambye JHEP09

Indirect Searches



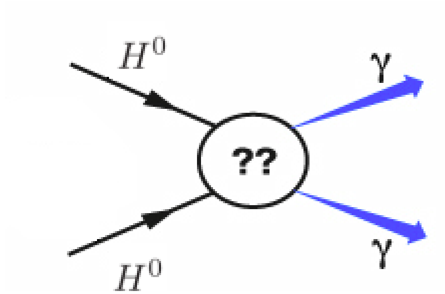
No astrophysical uncertainties

“Smoking gun”

Potentially low statistics.

Gustafsson et al. 2007

Indirect Searches



No astrophysical uncertainties

"Smoking gun"

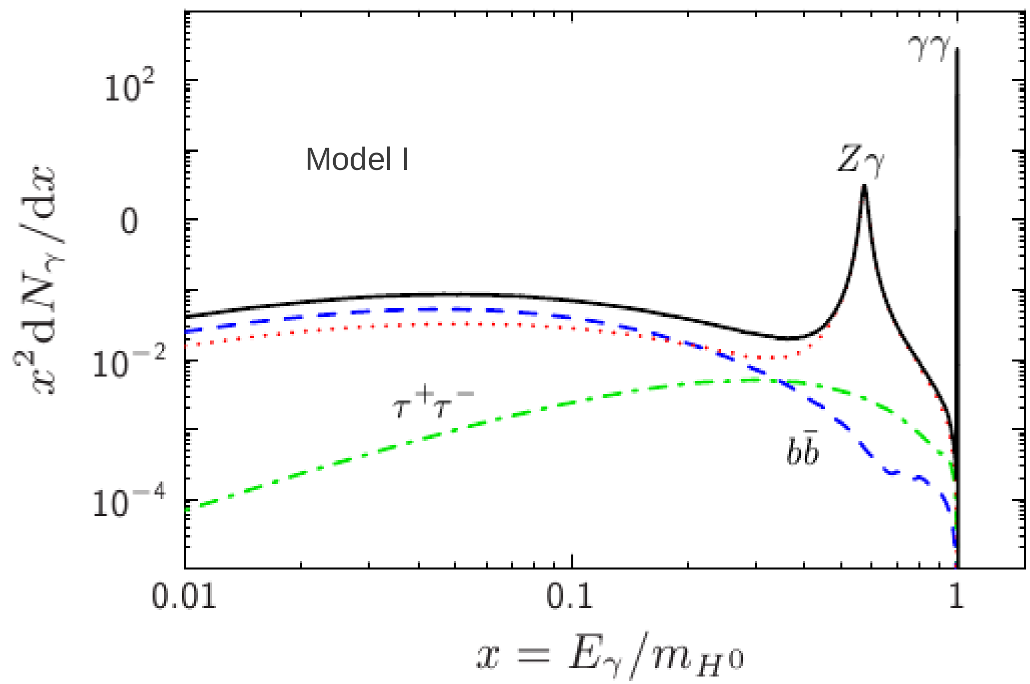
Potentially low statistics.

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

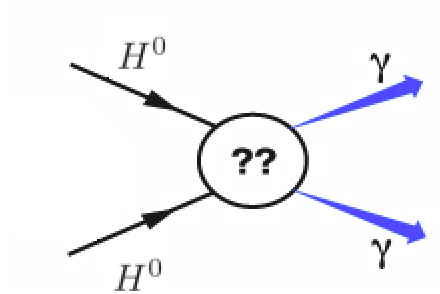
TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$ [cm^{3}s^{-1}]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\rm CDM}h^2$
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



Gustafsson et al. 2007

Indirect Searches



No astrophysical uncertainties

"Smoking gun"

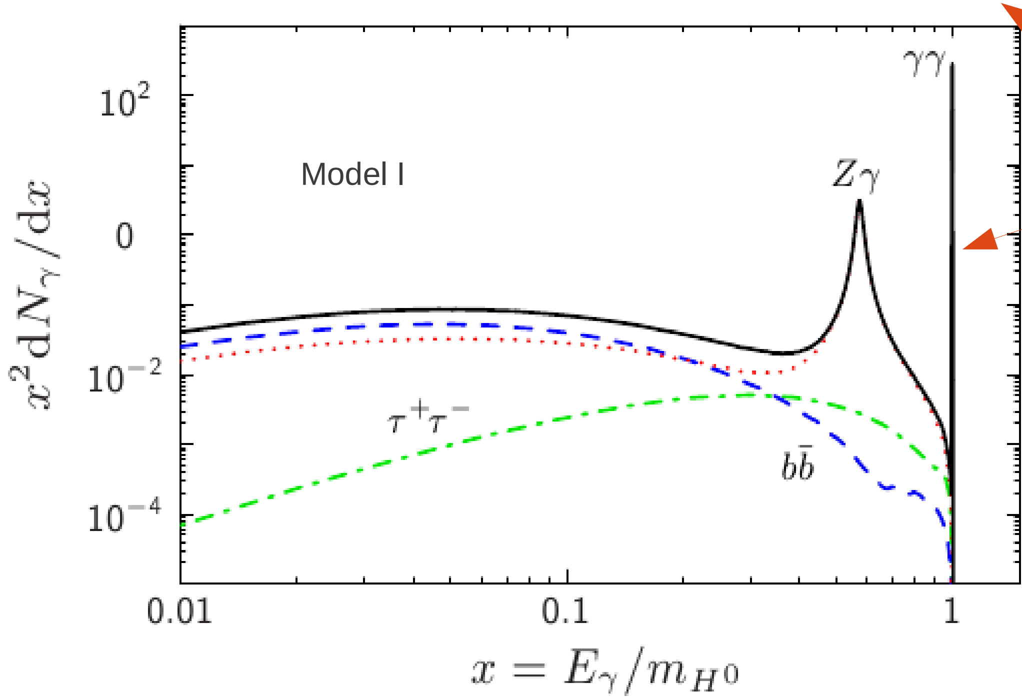
Potentially low statistics.

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 [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\mathrm{CDM}}h^2$
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



Very prominent spectral features, small cross sections (loop suppressed) though!

Gustafsson et al. 2007

How else can we get spectral features?

How else can we get spectral features?

Let us consider annhilation into a final state $X\bar{X}\gamma$.

No loop suppression, but 3-body phase
space suppression!

How else can we get spectral features?

Let us consider annhilation into a final state $X\bar{X}\gamma$.

No loop suppression, but 3-body phase space suppression!

In general, one can single out two situations where photons emitted from virtual charged particles may give an even more important contribution to the total IB spectrum than FSR: i) the three-body final state $X\bar{X}\gamma$ satisfies a symmetry of the initial state that cannot be satisfied by the two-body final state $X\bar{X}$ or ii) X is a boson and the annihilation into $X\bar{X}$ is dominated by t-channel diagrams.

T. Bringmann et al. 2008

How else can we get spectral features?

Let us consider annhilation into a final state $X\bar{X}\gamma$.

No loop suppression, but 3-body phase space suppression!

In general, one can single out two situations where photons emitted from virtual charged particles may give an even more important contribution to the total IB spectrum than FSR: i) the three-body final state $X\bar{X}\gamma$ satisfies a symmetry of the initial state that cannot be satisfied by the two-body final state $X\bar{X}$ or ii) X is a boson and the annihilation into $X\bar{X}$ is dominated by t-channel diagrams.

T. Bringmann et al. 2008

How else can we get spectral features?

Let us consider annhilation into a final state $X\bar{X}\gamma$.

No loop suppression, but 3-body phase space suppression!

In general, one can single out two situations where photons emitted from virtual charged particles may give an even more important contribution to the total IB spectrum than FSR: i) the three-body final state $X\bar{X}\gamma$ satisfies a symmetry of the initial state that cannot be satisfied by the two-body final state $X\bar{X}$ or ii) X is a boson and the annihilation into $X\bar{X}$ is dominated by t-channel diagrams.

T. Bringmann et al. 2008

How else can we get spectral features?

Let us consider annhilation into a final state $X\bar{X}\gamma$.

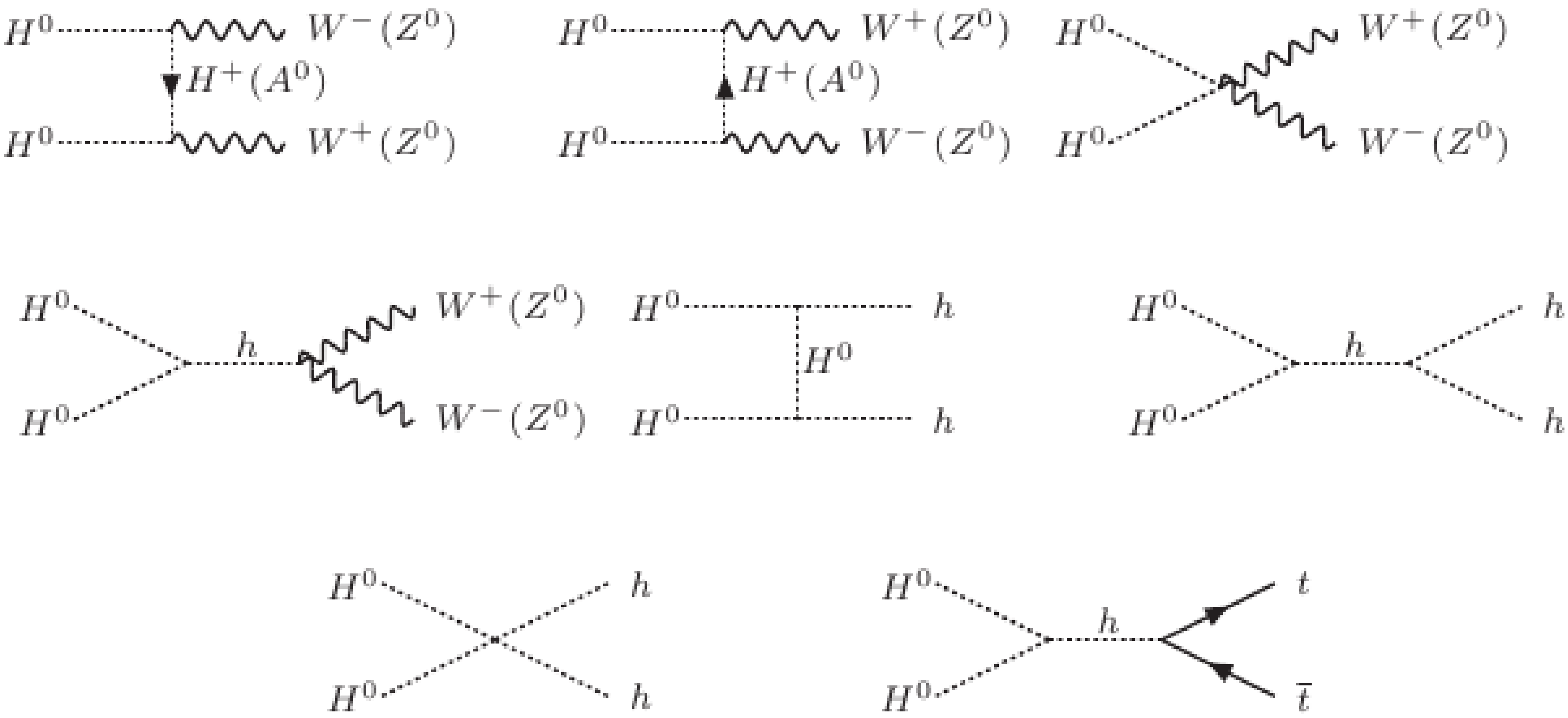
No loop suppression, but 3-body phase space suppression!

In general, one can single out two situations where photons emitted from virtual charged particles may give an even more important contribution to the total IB spectrum than FSR: i) the three-body final state $X\bar{X}\gamma$ satisfies a symmetry of the initial state that cannot be satisfied by the two-body final state $X\bar{X}$ or ii) X is a boson and the annihilation into $X\bar{X}$ is dominated by t-channel diagrams.

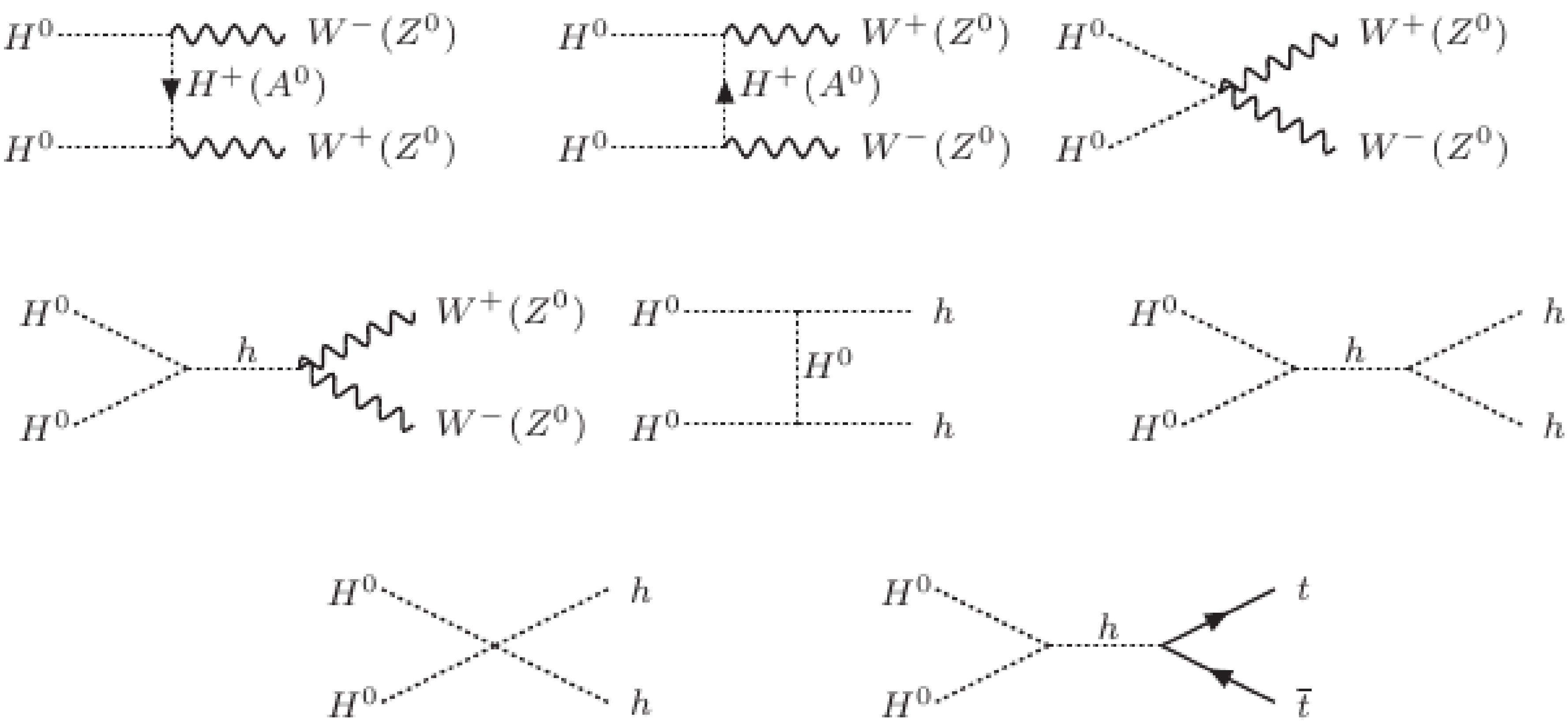
T. Bringmann et al. 2008

That is the case for the inert doublet model in the high mass regime if X is a W boson!

Annihilation diagrams



Annihilation diagrams

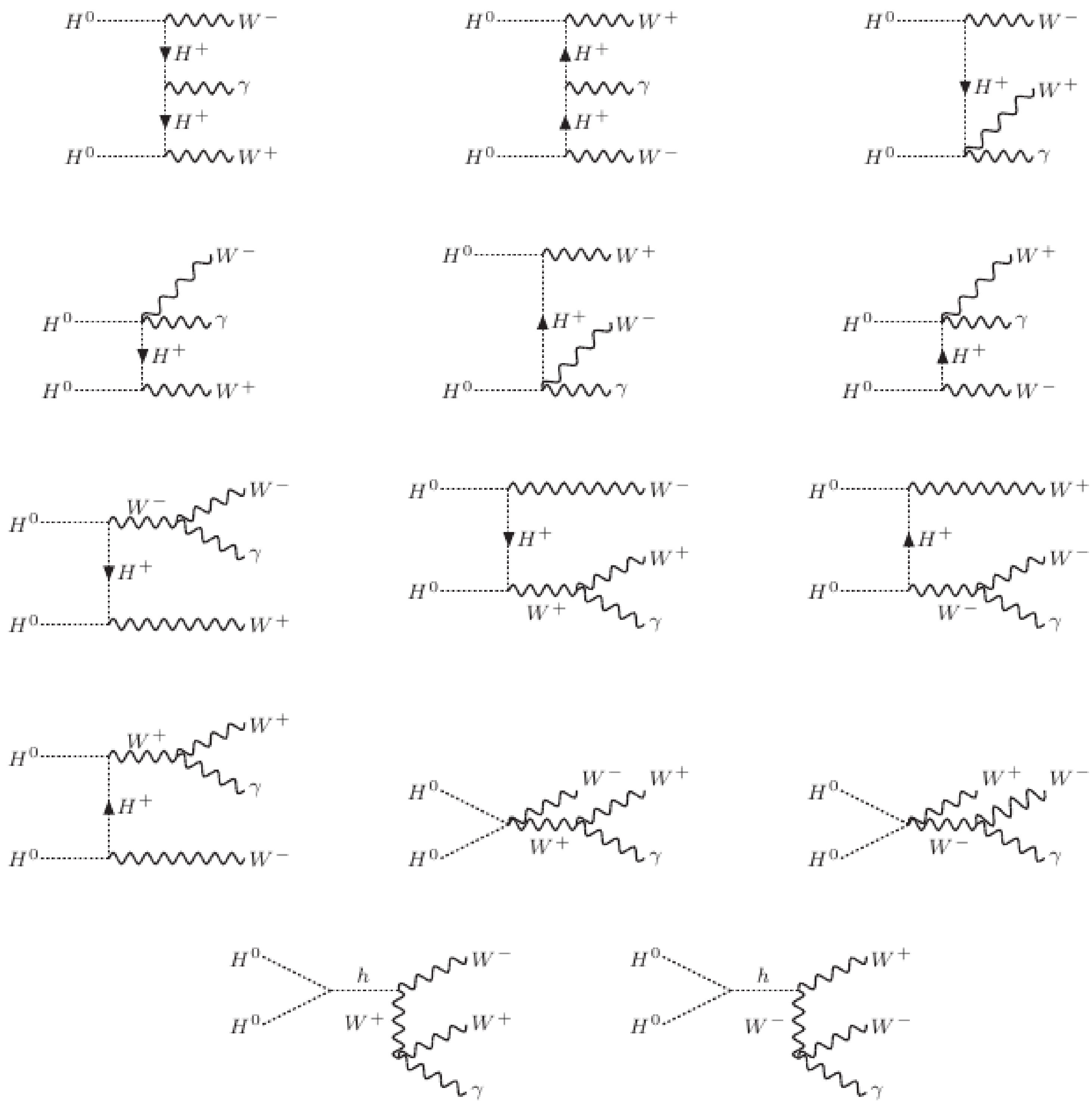


Why the t-channel?

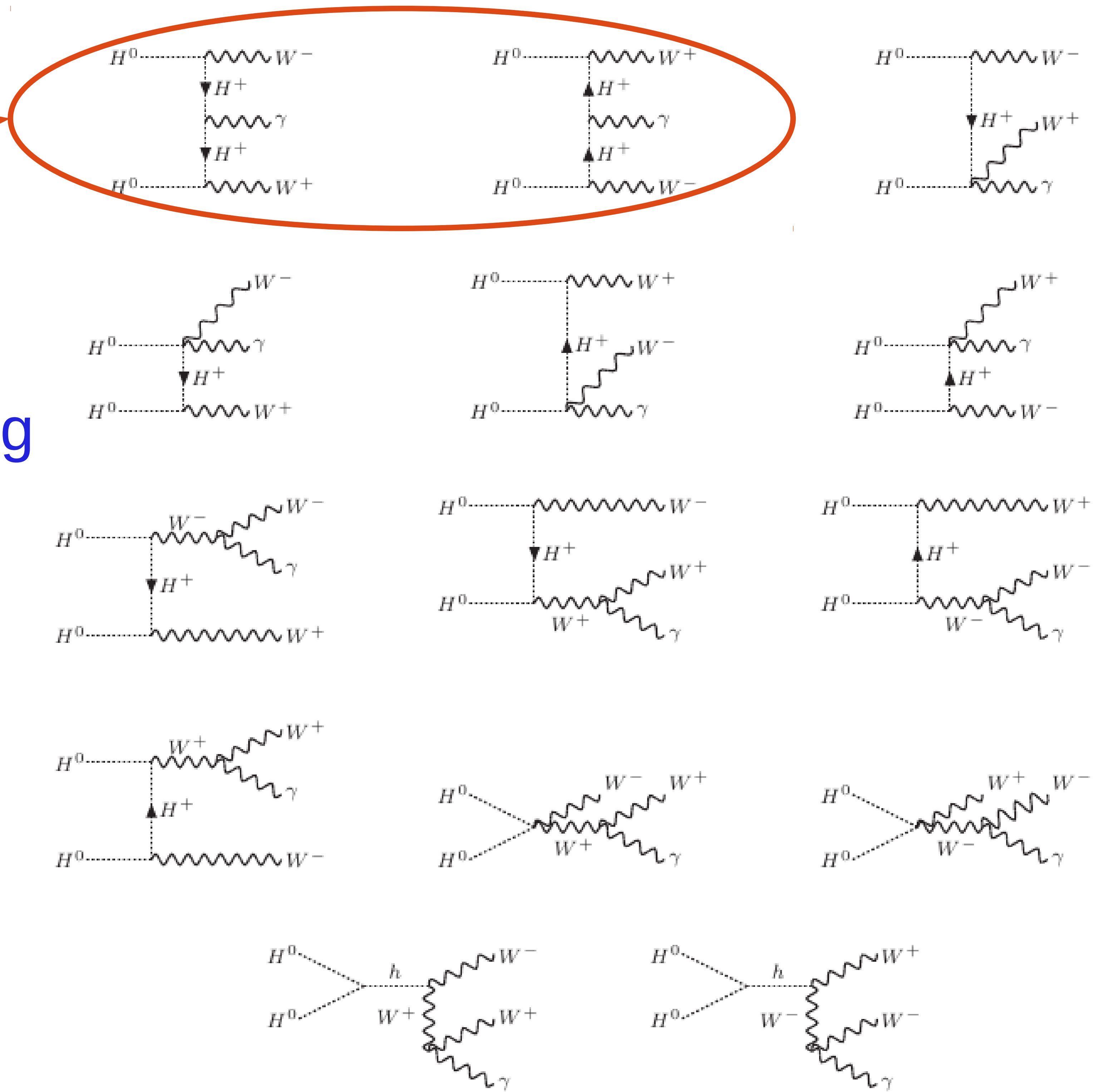
$$D_t(p_W) \propto \left((p_{H^0} - p_W)^2 - M_{H^+}^2\right)^{-1}$$
$$\approx \left(M_{H^0}^2 + M_W^2 - M_{H^+}^2 - 2M_{H^0}E_W\right)^{-1}$$

If H^0 and H^+ are almost degenerate in mass, one thus finds an enhancement for small E_W.

Bremsstrahlung diagrams



Photons emitted from internal lines

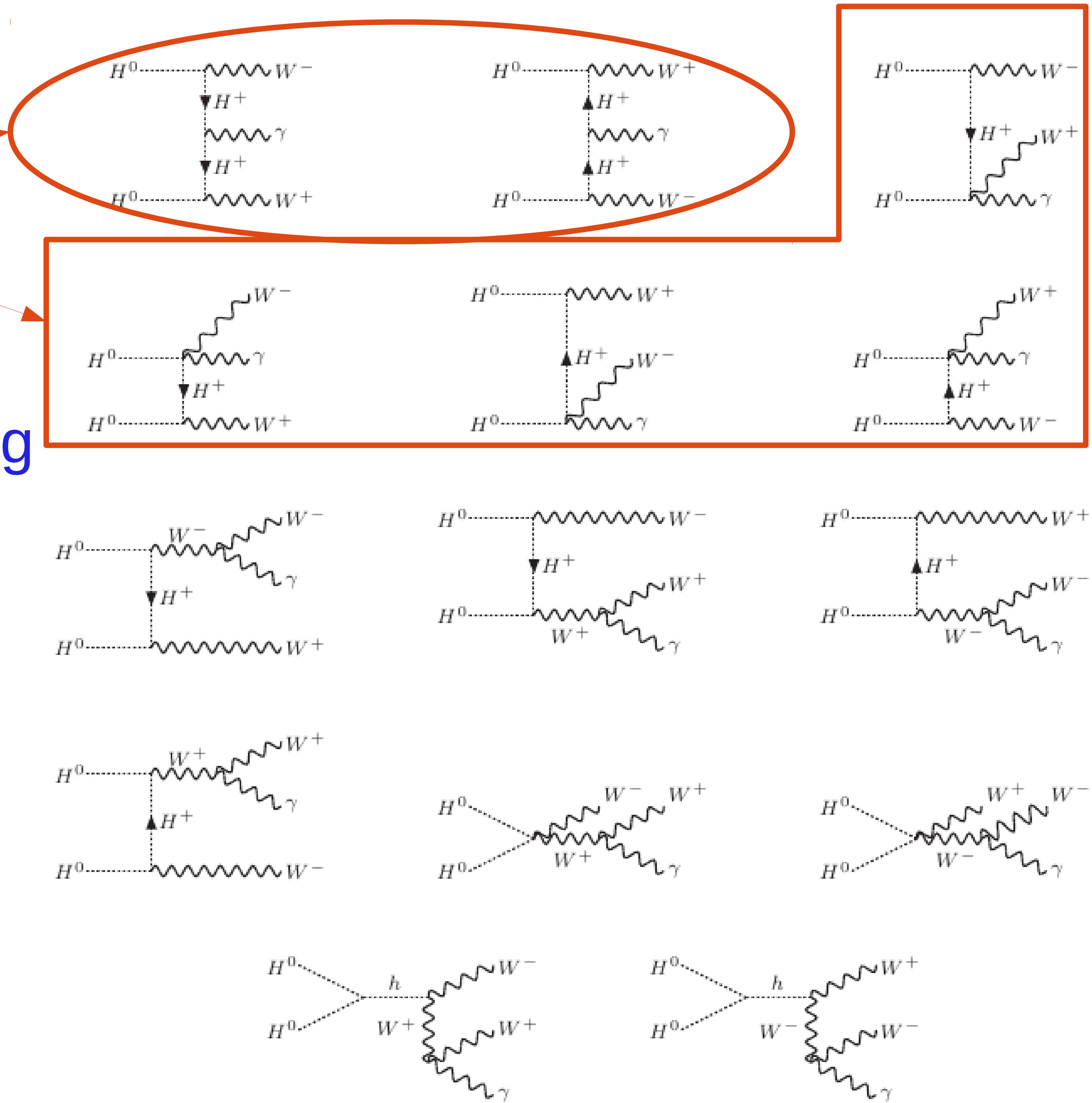


Bremsstrahlung diagrams

Photons
emitted from
internal lines

Photons
emitted from
vertices

Bremsstrahlung diagrams

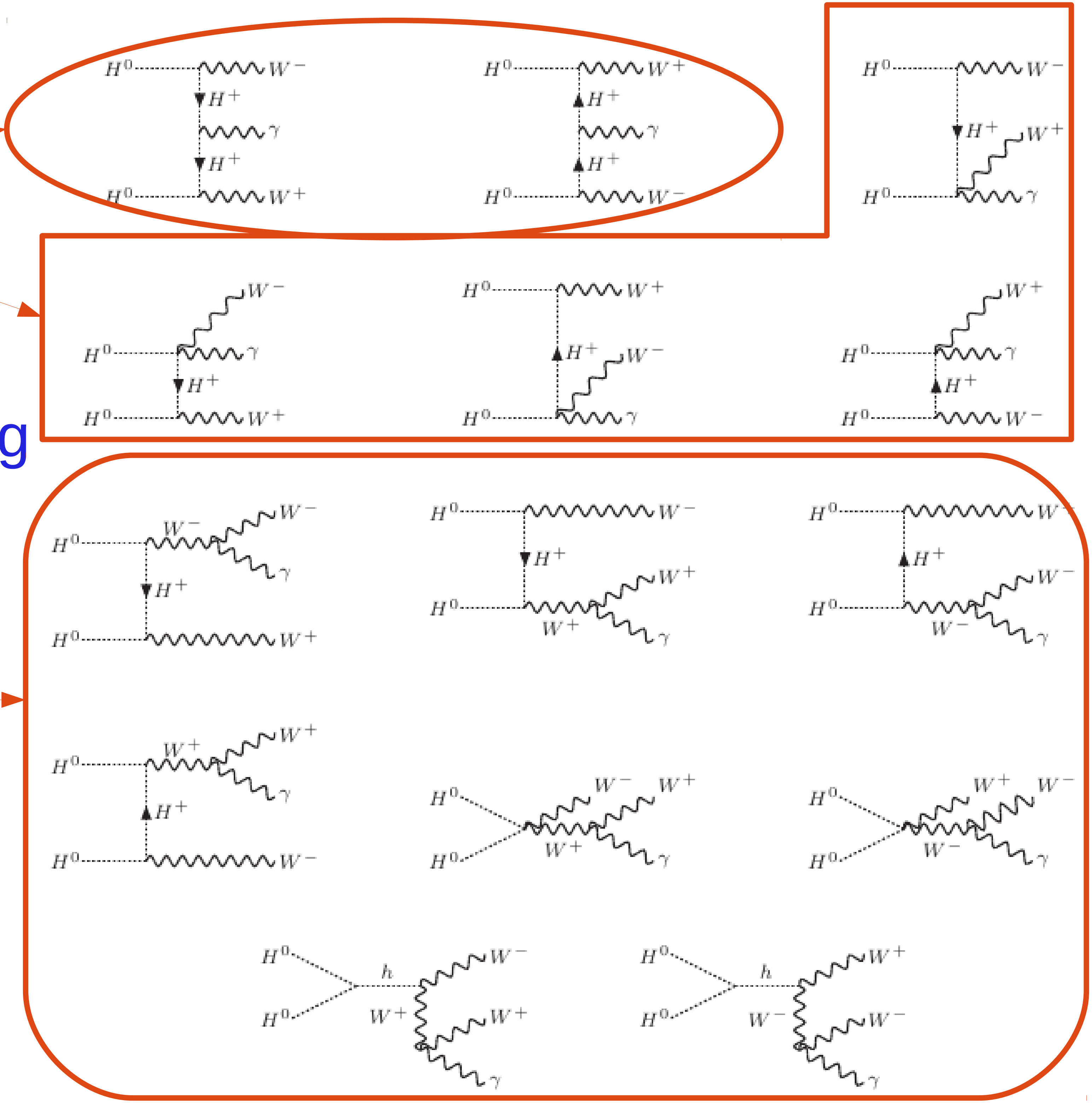


Bremsstrahlung diagrams

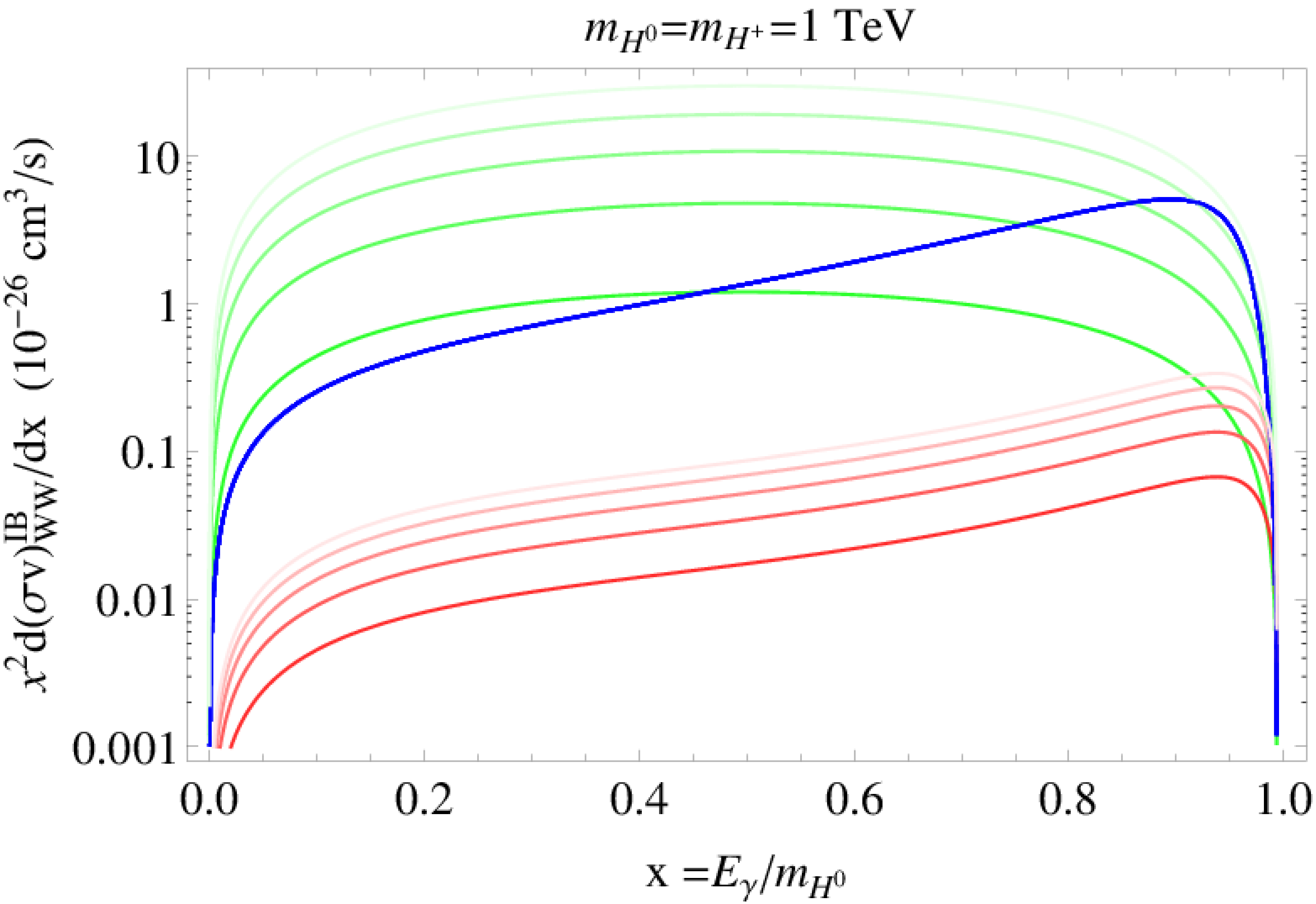
Photons emitted from internal lines

Photons emitted from vertices

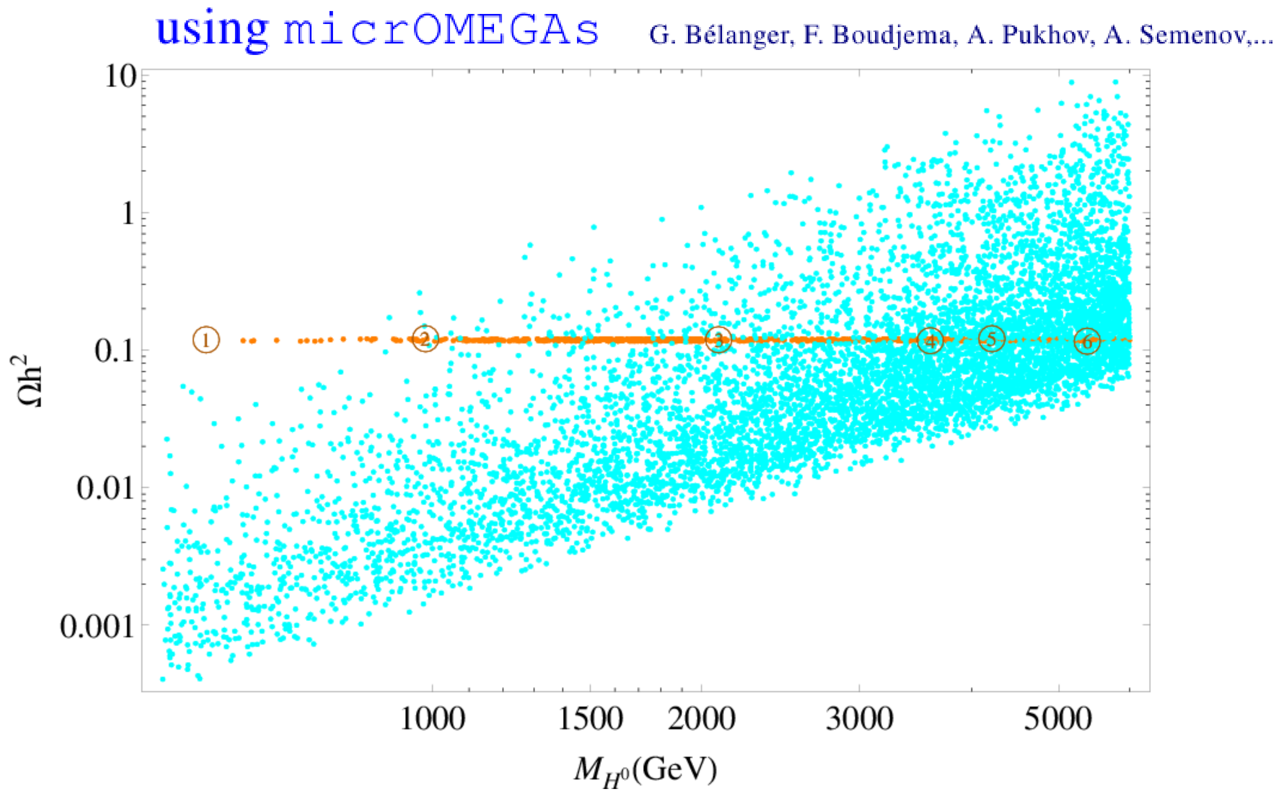
Photons emitted from external lines



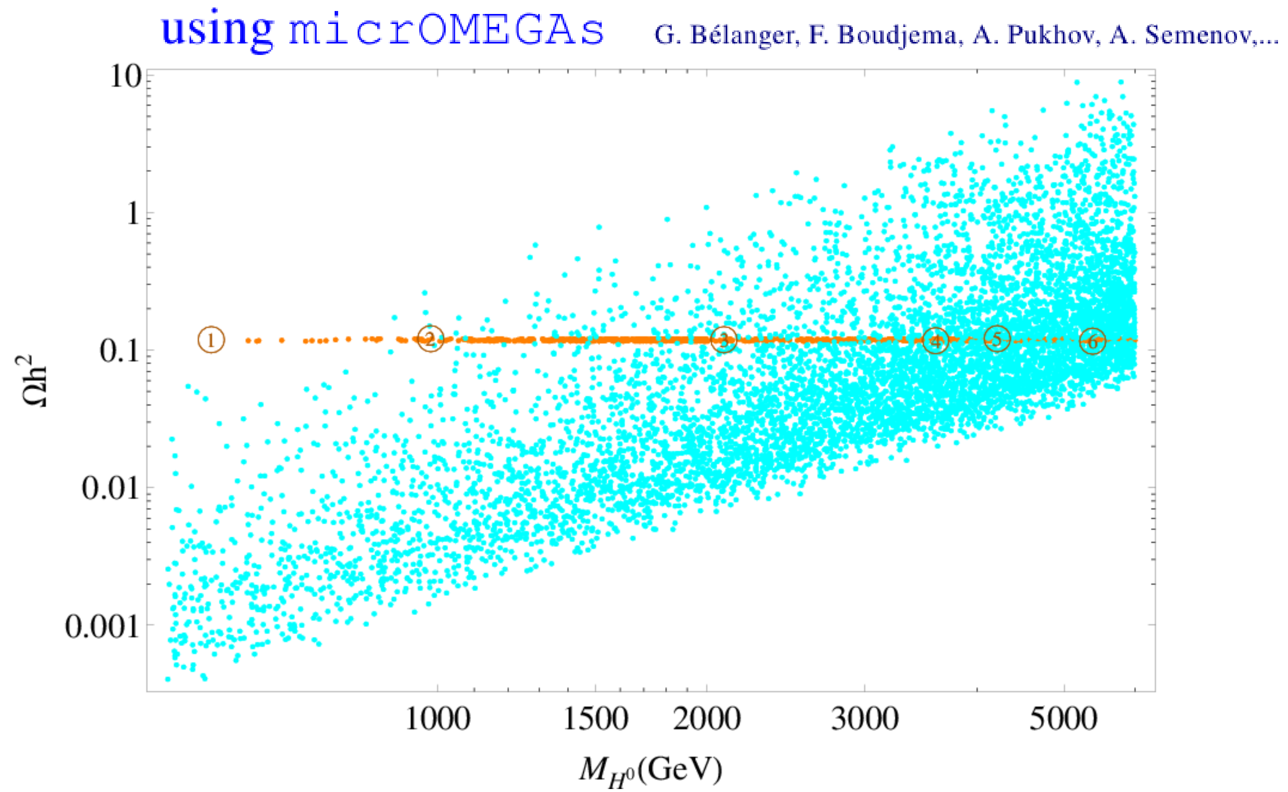
$$\frac{d(\sigma v)_{W^+W^-\gamma}}{dx} = \left.\frac{d(\sigma v)}{dx}\right|_{\text{Gauge}} + \left.\frac{d(\sigma v)}{dx}\right|_{\text{Quartic}} + \left.\frac{d(\sigma v)}{dx}\right|_{\text{Interference}} ,$$



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



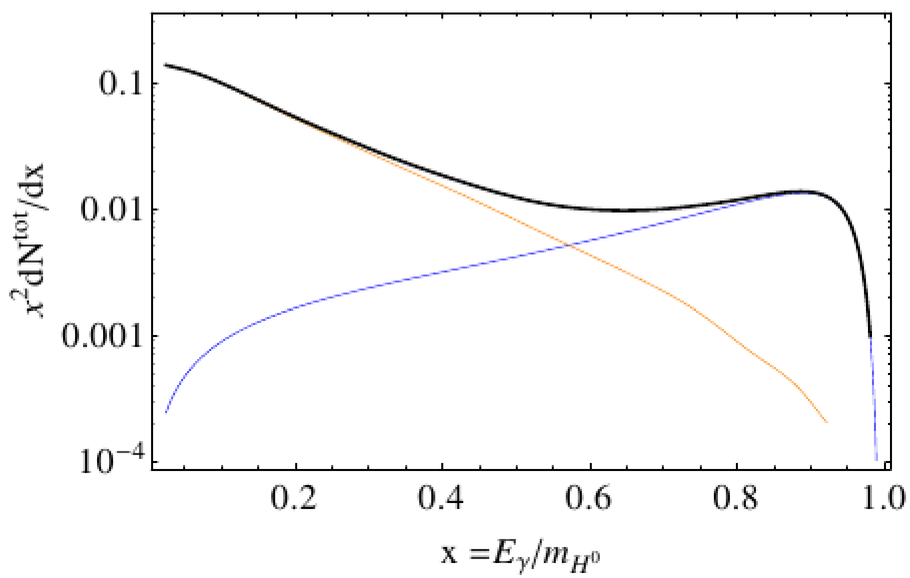
Benchmark points

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

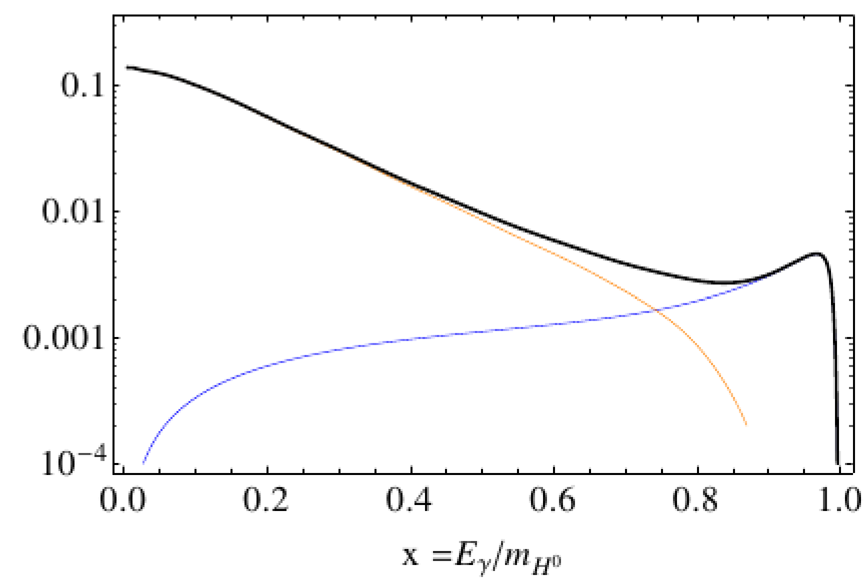
Cross Sections and Spectra

BMP	$\sigma v (10^{-26}\mathrm{cm}^3/\mathrm{s})$	BR(%)					Ωh^2
		W^+W^-	ZZ	hh	$t\bar{t}$	$W^+W^-\gamma$	
1	6.42	50.25	43.54	2.57	0.60	3.03	0.119
2	3.95	34.91	22.87	36.02	3.03	3.17	0.121
3	4.58	13.80	84.35	0.01	0.00	1.84	0.119
4	3.52	2.36	95.29	1.83	0.01	0.51	0.117
5	3.14	8.75	83.82	5.80	0.03	1.60	0.121
6	5.38	9.29	84.92	3.92	0.01	1.86	0.116

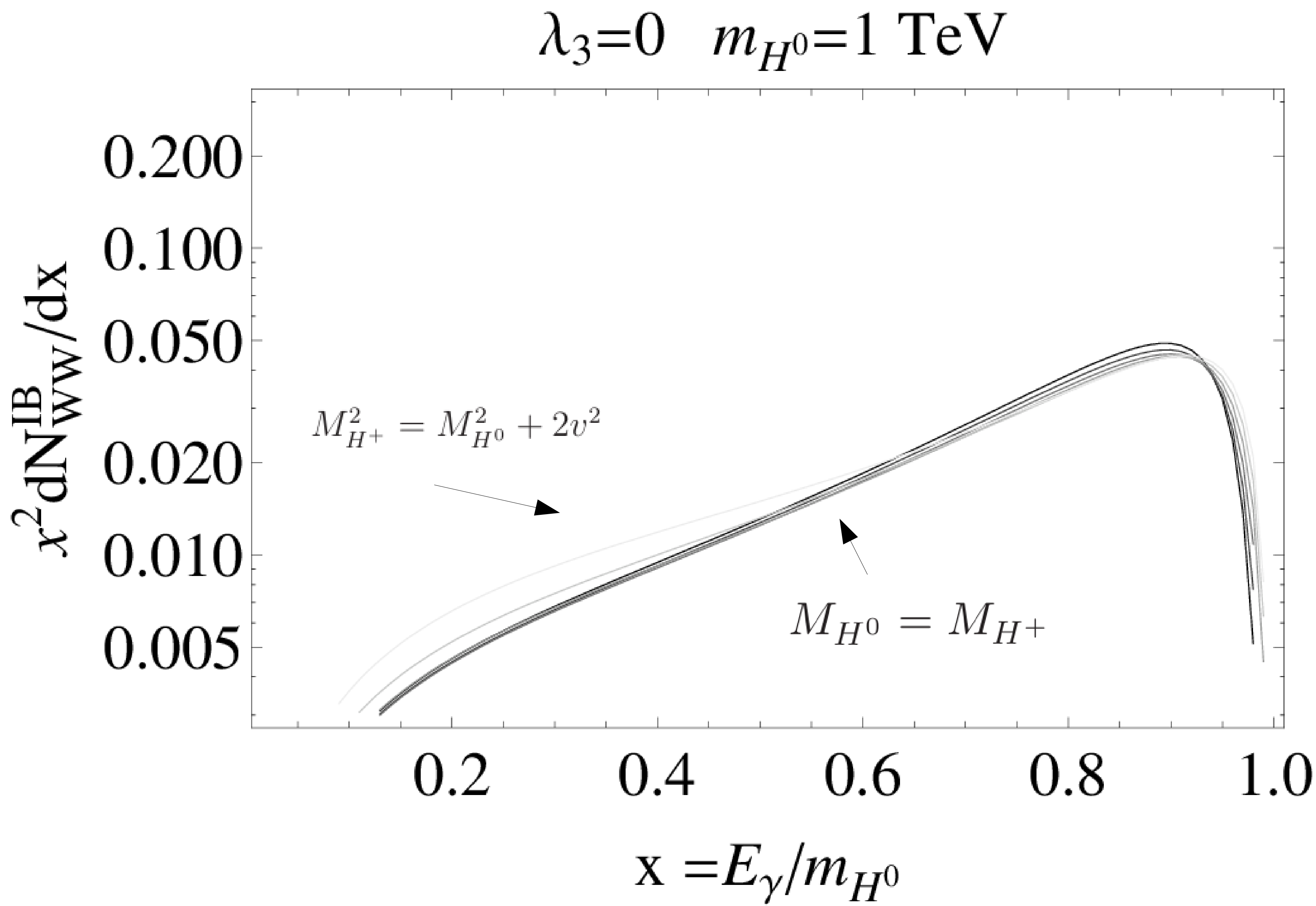
BMP 2



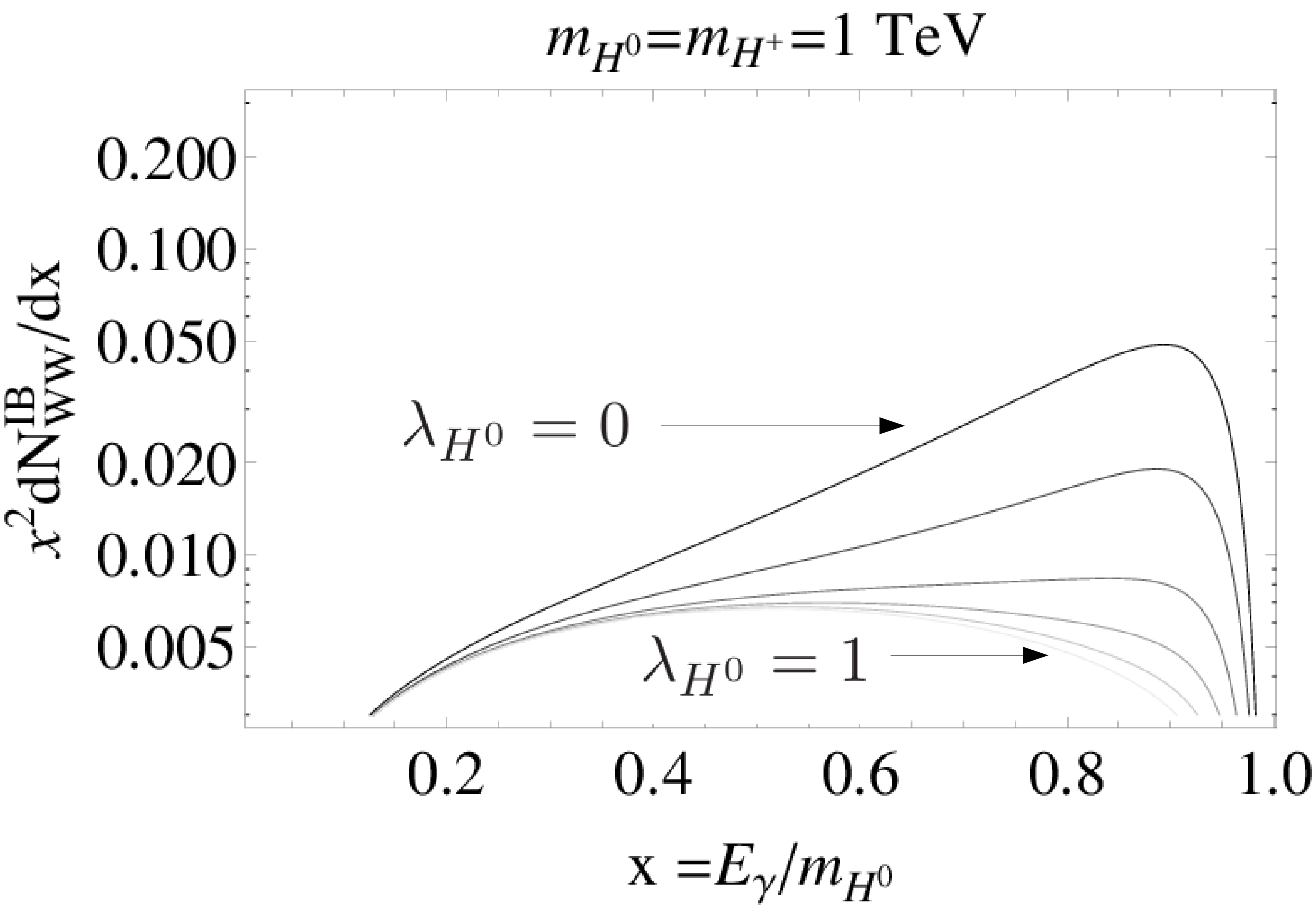
BMP 5



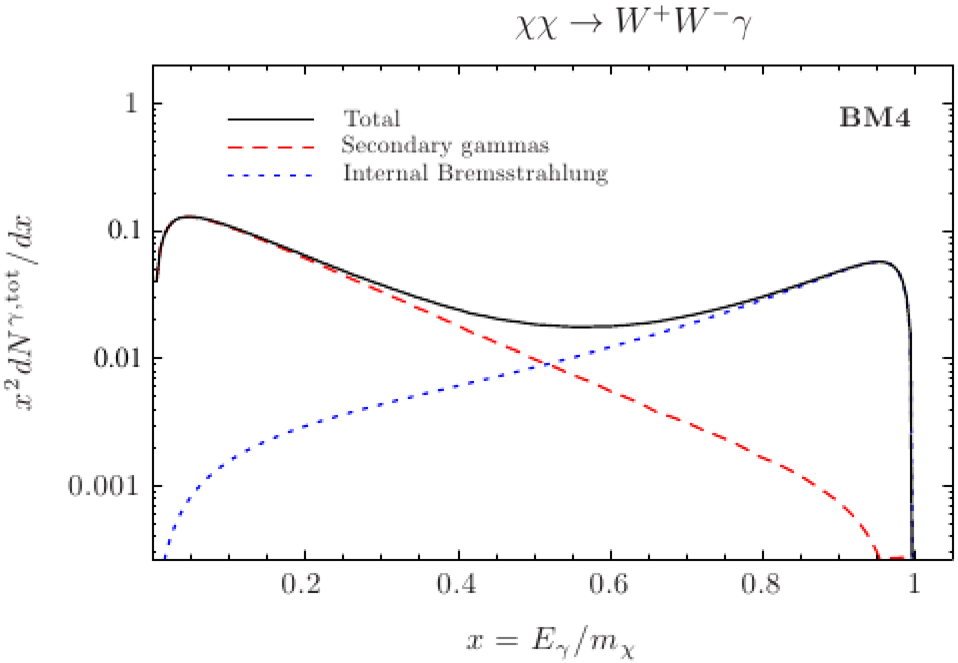
Effect of the mass splitting ($\lambda_4 + \lambda_5$)



Effect of λ_{H^0}

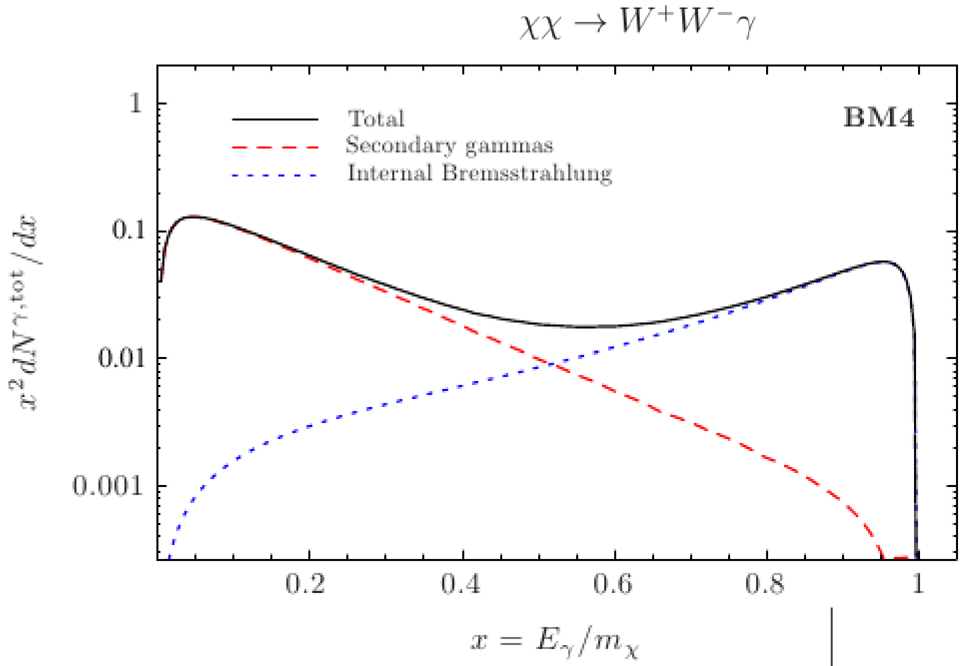


H.E.S.S. searches for photon-like signatures



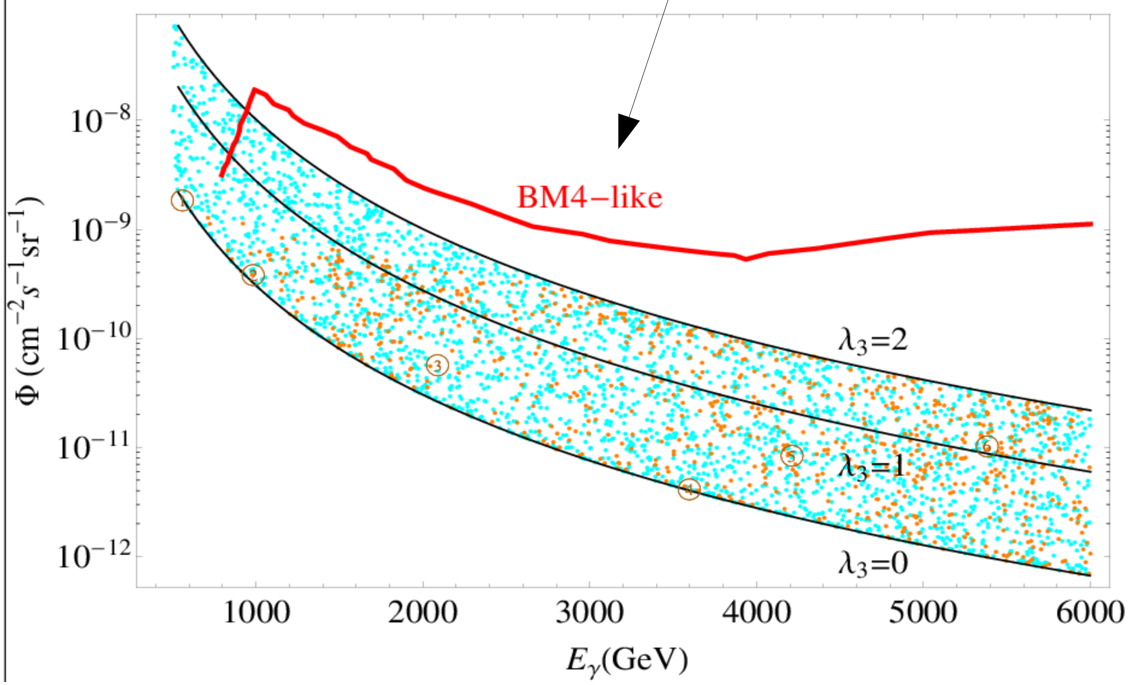
T. Bringmann et al. 2008

H.E.S.S. searches for photon-like signatures



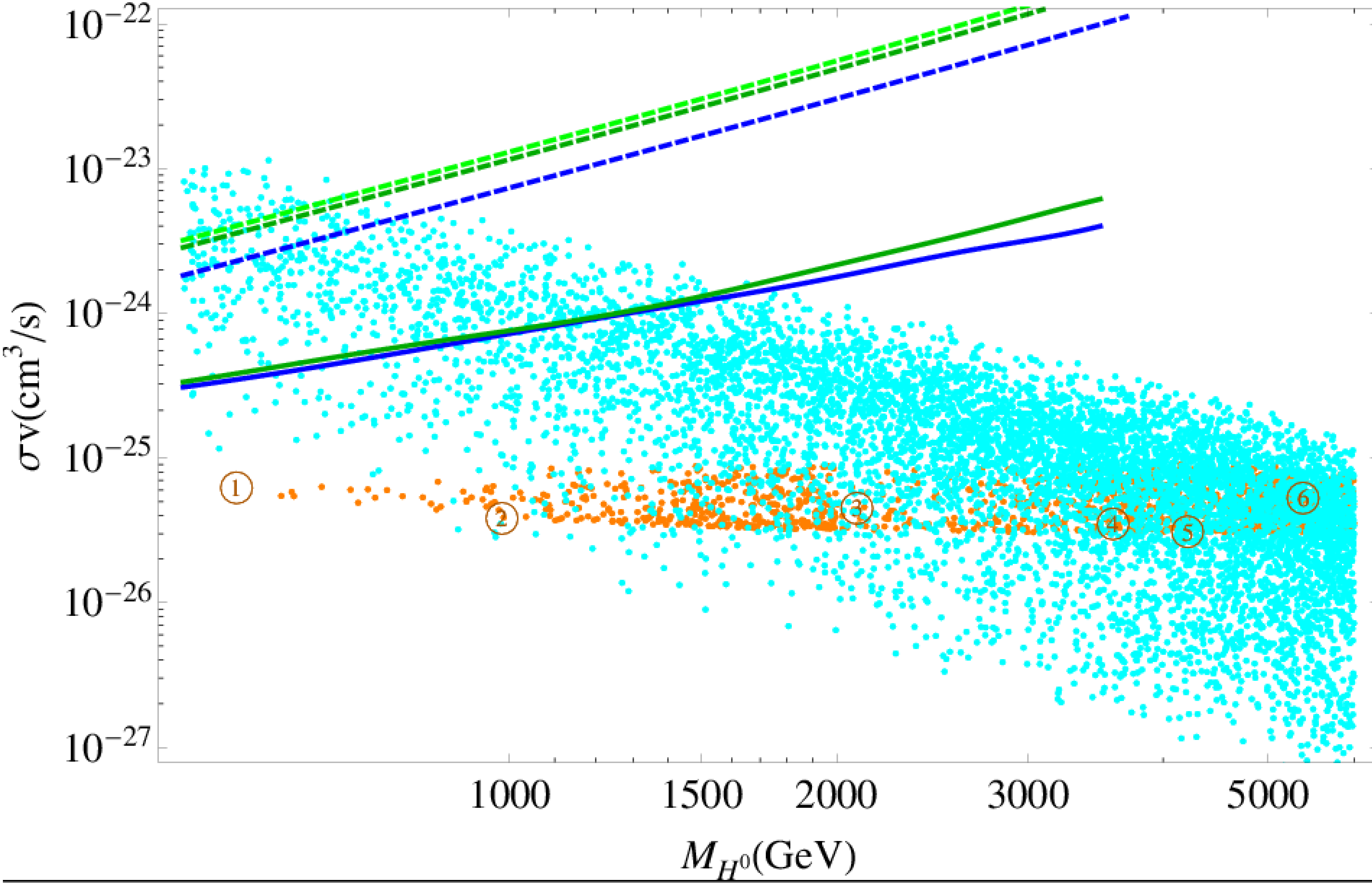
T. Bringmann et al. 2008

Flux upper limits on spectral features (BM4-like IB-only), derived from the central galactic halo region (CGH)

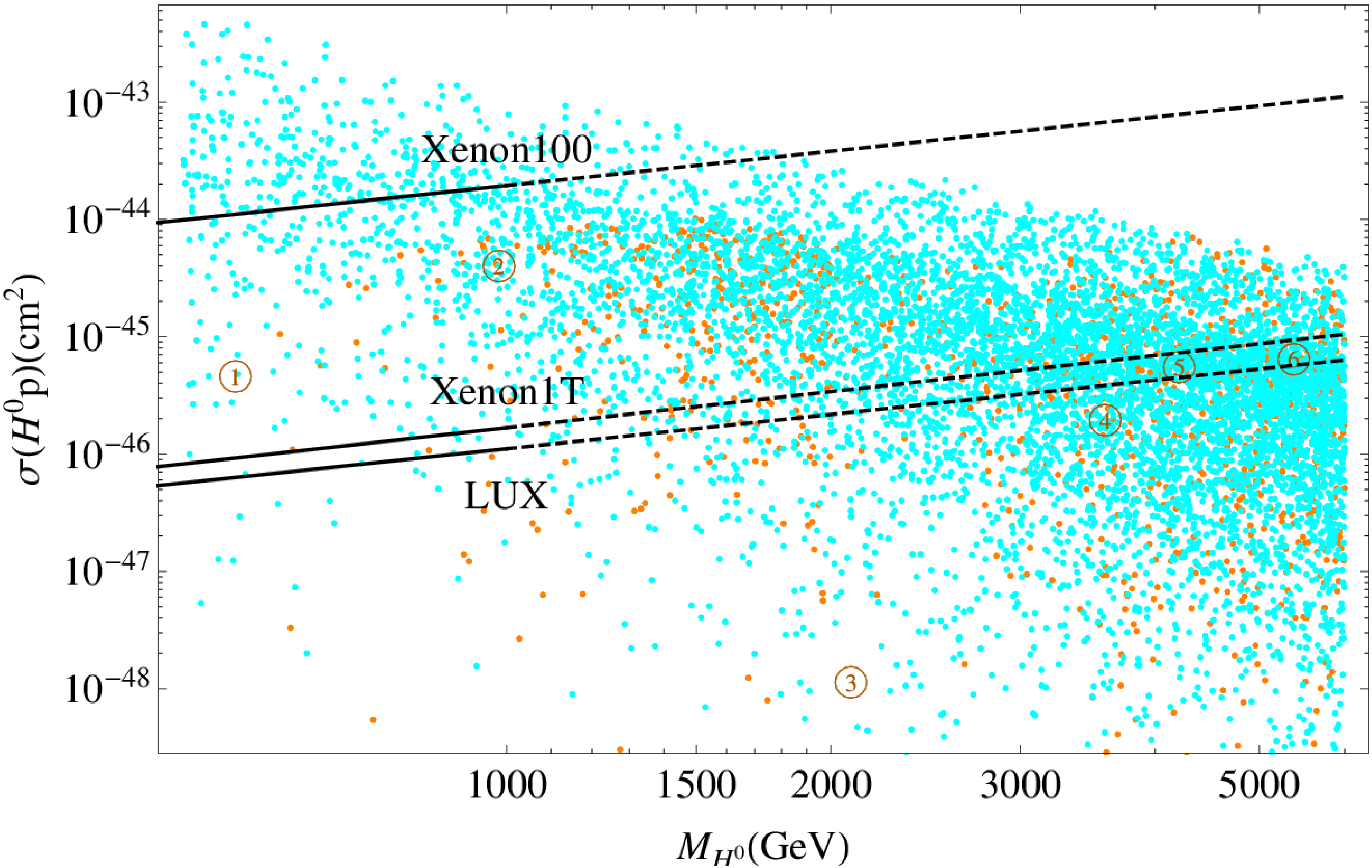


Conclusions

- Internal Bremsstrahlung signatures are present in the high-mass regime of the inert doublet model.
- In the case of small quartic couplings the feature is more prominent.
- In the high mass regime of the inert doublet model, the internal bremsstrahlung can lead to observable signatures in gamma-ray telescopes



10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\sigma v(\mathrm{cm}^3/\mathrm{s})$
1000
1500
2000
3000
5000
$M_{H^0}(\mathrm{GeV})$
1
2
3
4
5
6



10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
$\sigma(H^0\text{p})(\text{cm}^2)$
Xenon100
Xenon1T
LUX
1
2
3
4
5
6
1000
1500
2000
3000
5000
$M_{H^0}(\text{GeV})$