Study of the Internal Bremsstrahlung in the Inert Doublet Model

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Technische Universität München

Particle Physics School Colloquium
April 12th, 2013

Based on work in progress done under the advice of Pr. Alejandro Ibarra

Motivation

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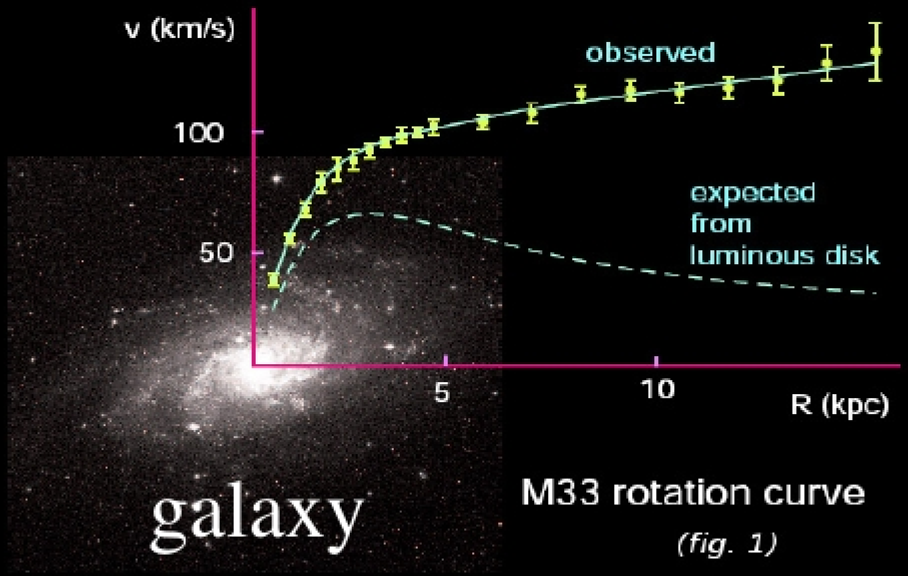

(fig. 1)

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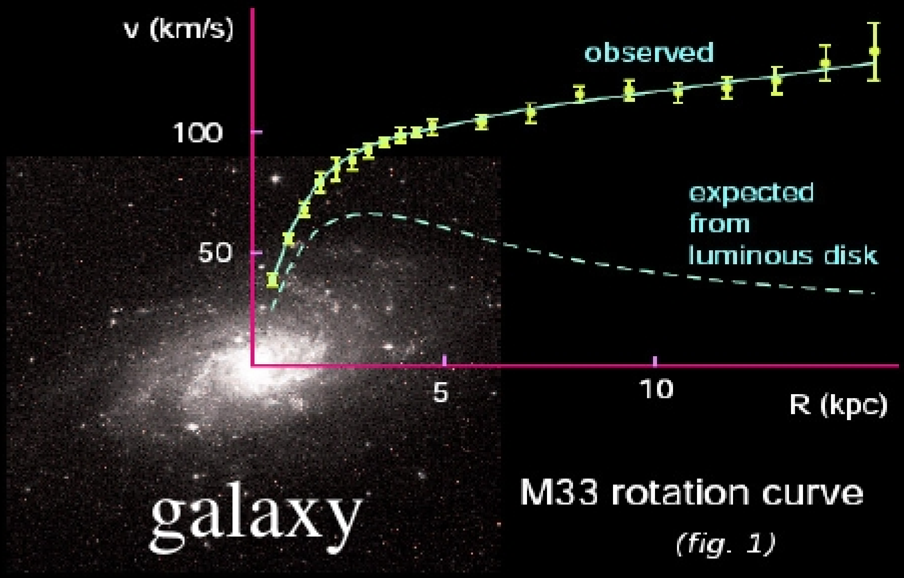
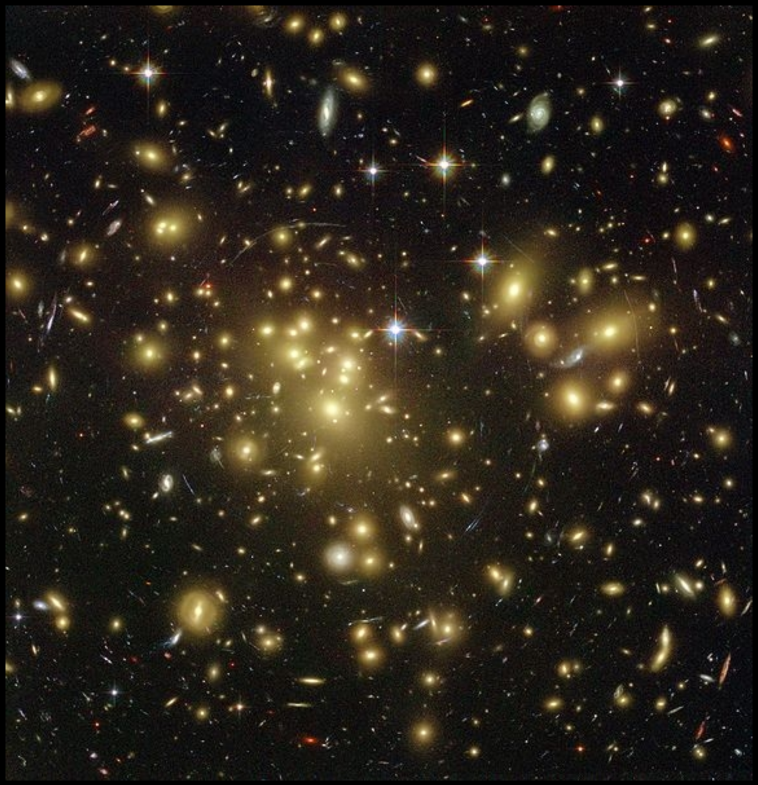


M33 rotation curve
(fig. 1)



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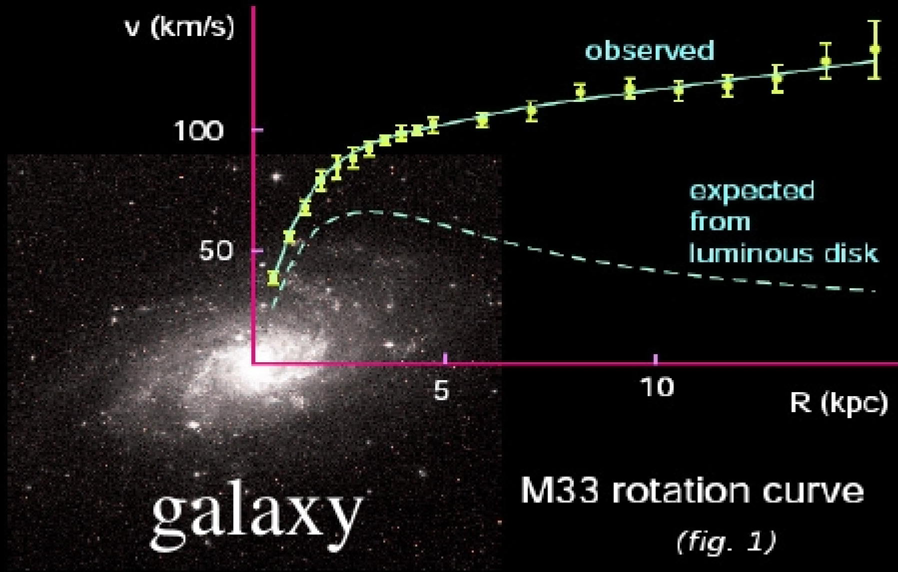
v (km/s)
observed
100
50
expected
from
luminous disk
5
10
R (kpc)
galaxy
M33 rotation curve
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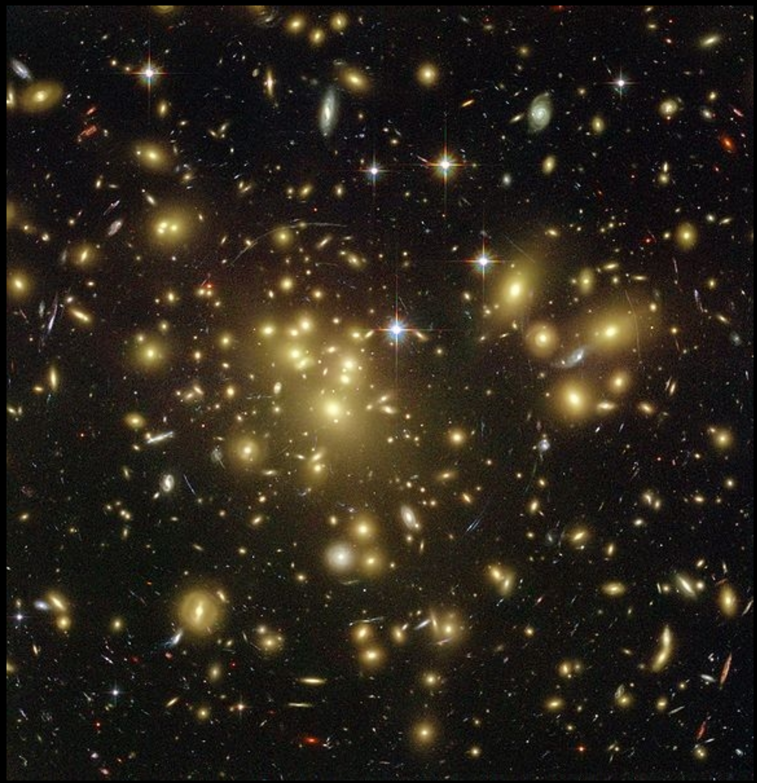

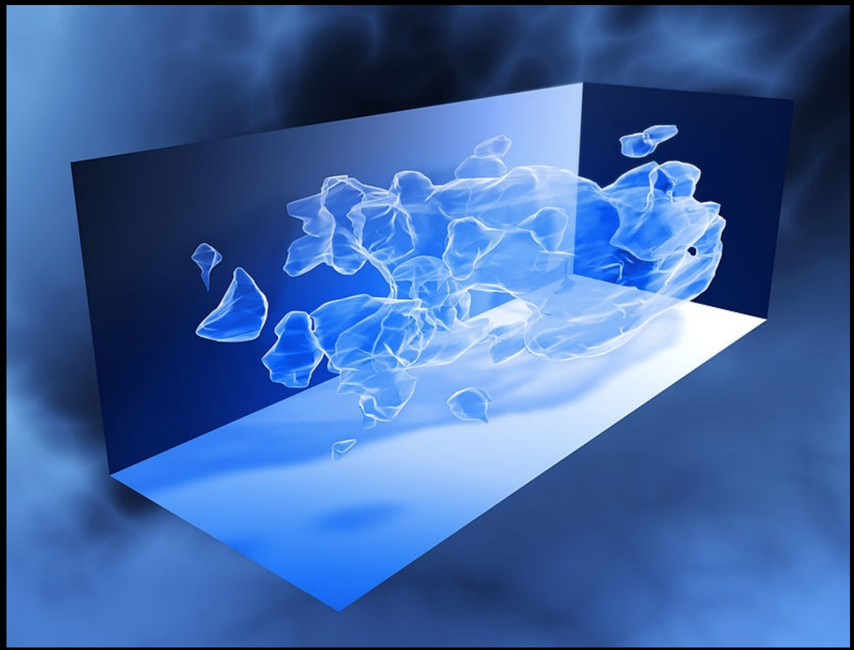

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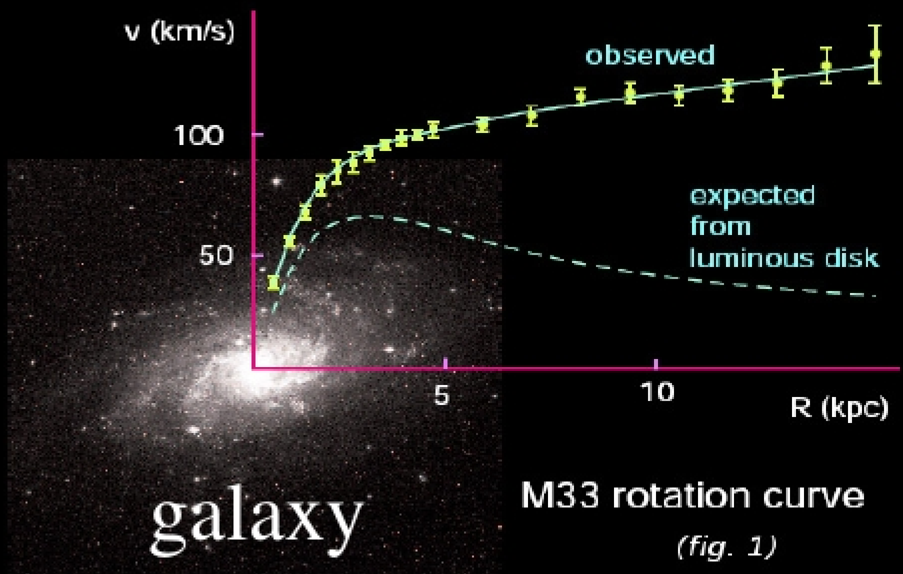
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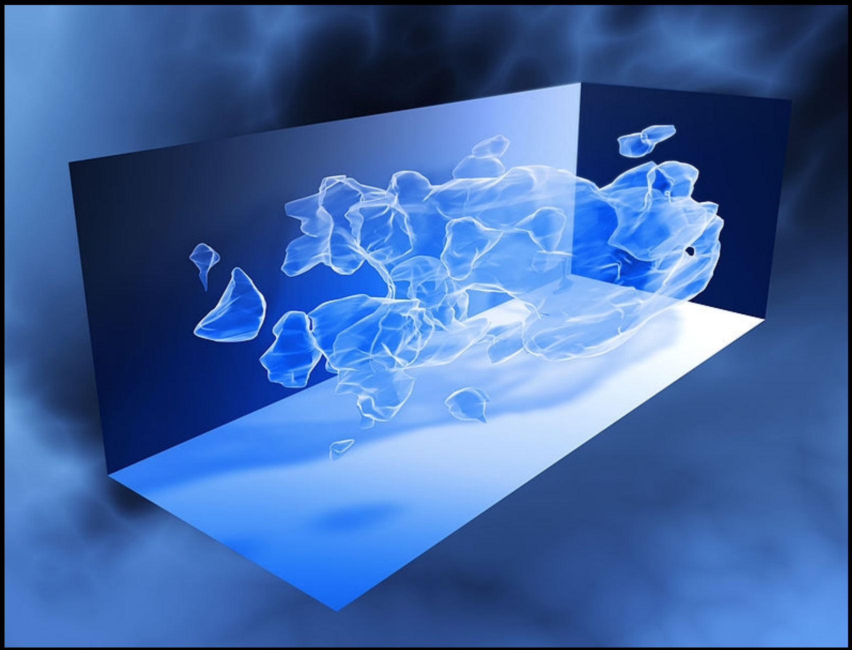
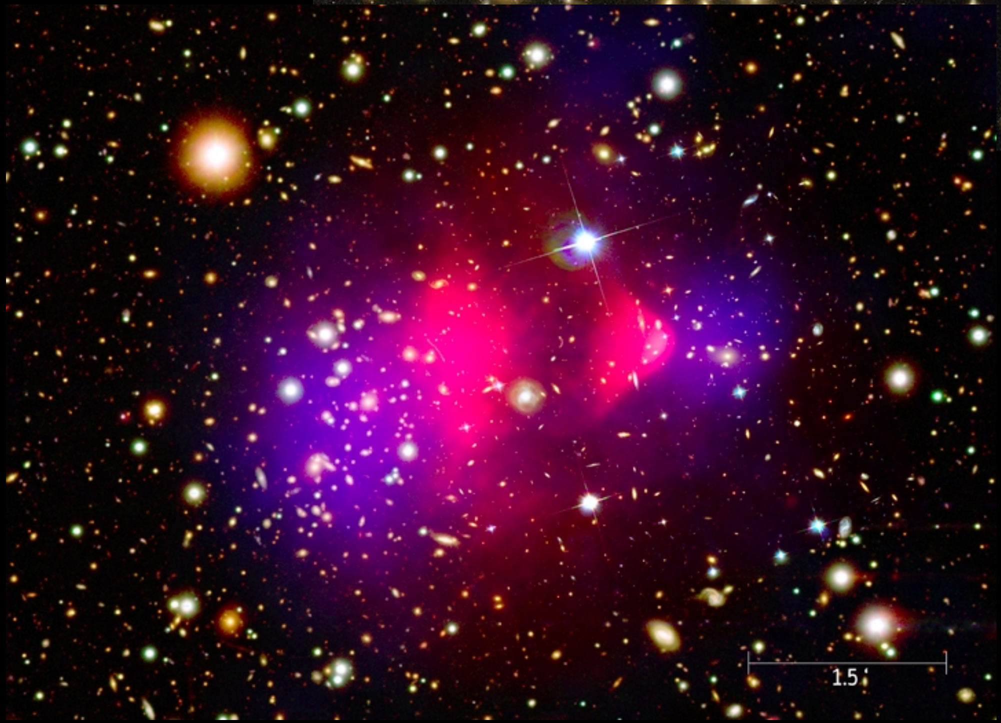
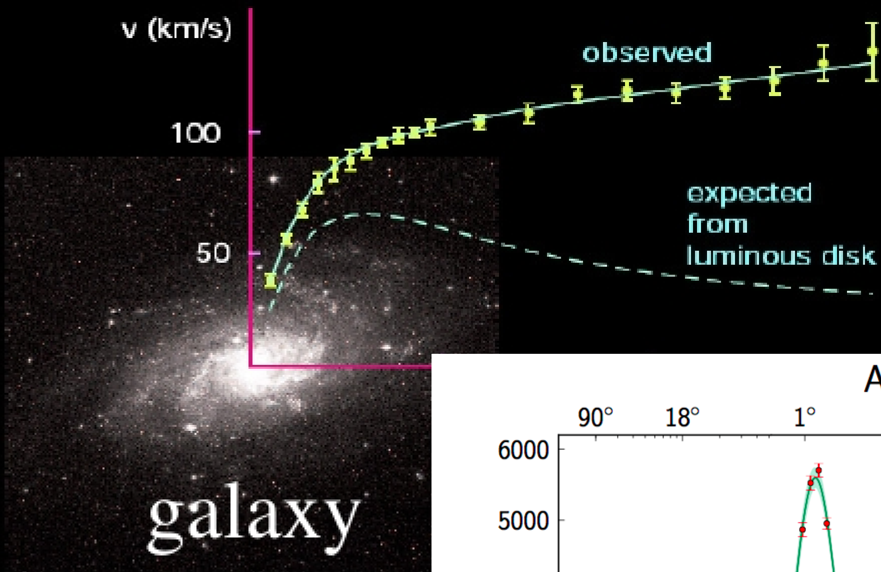



1.5

Motivation



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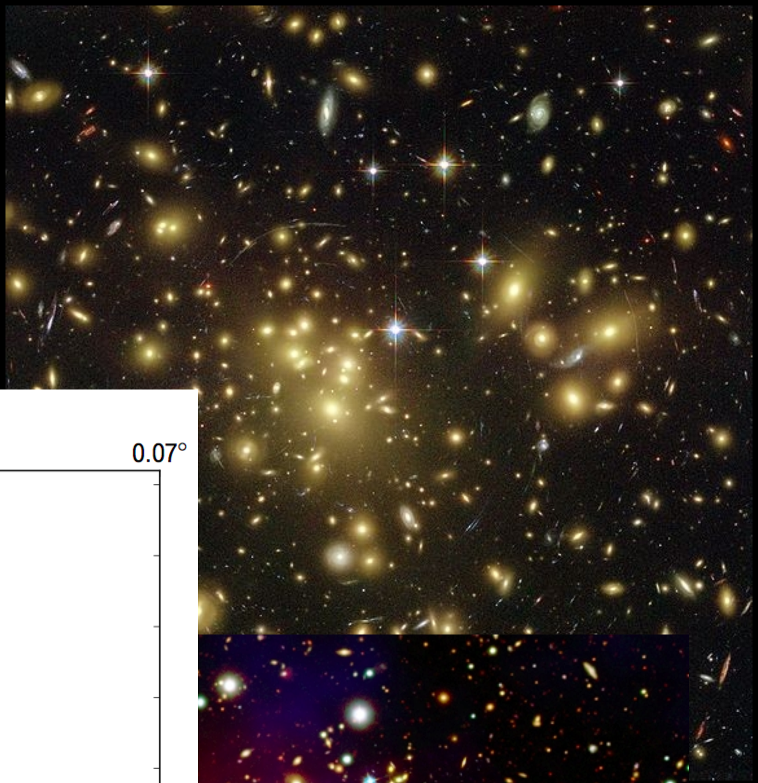
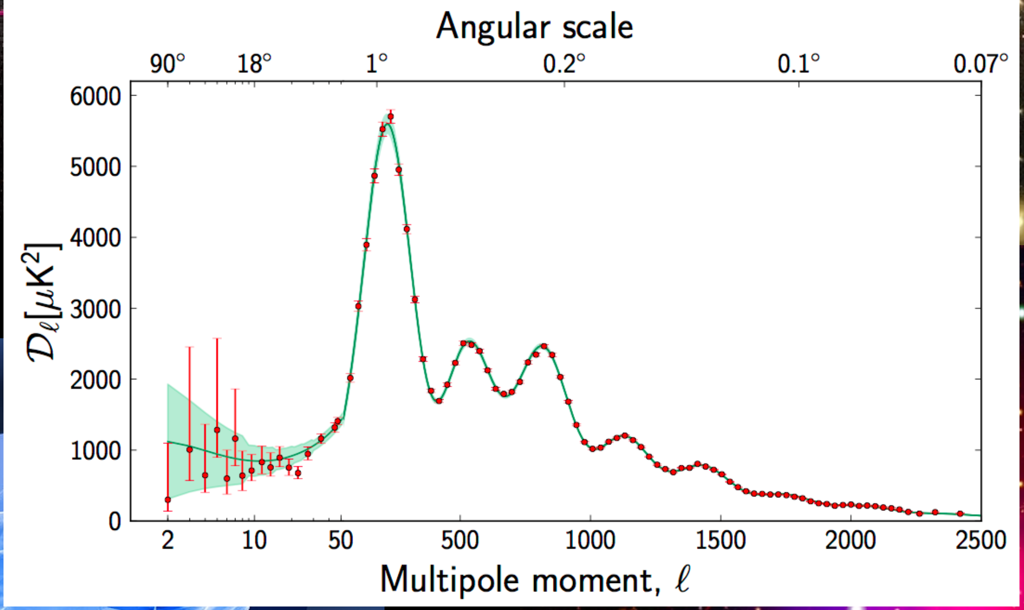
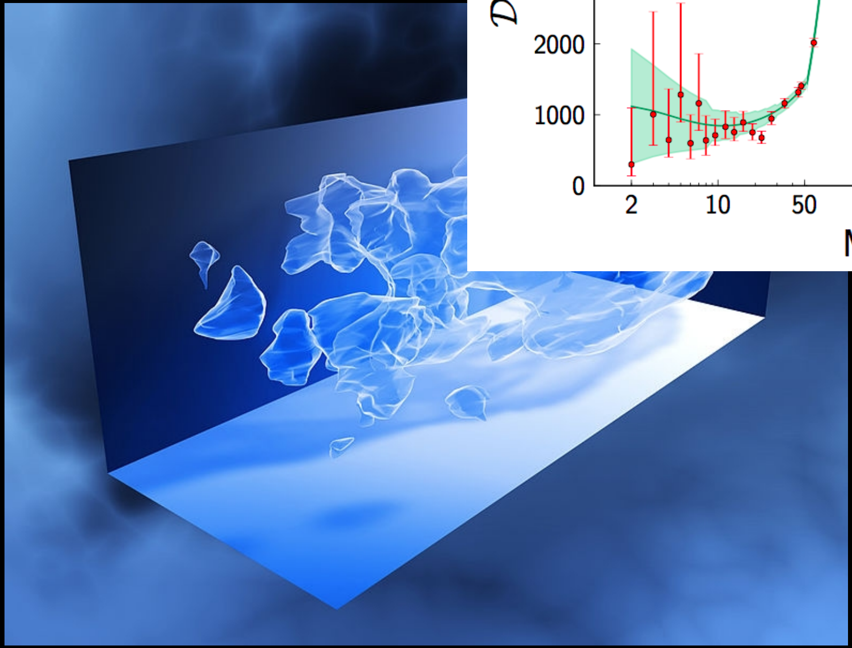
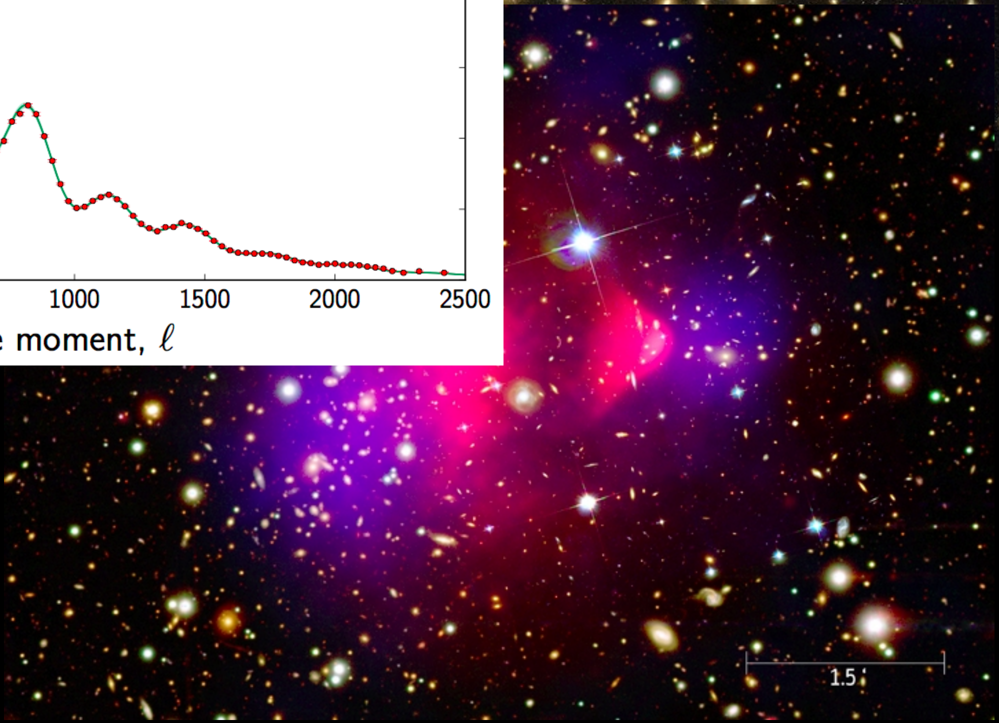




Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ





1.5'

Study of SM plus extra scalar doublets, with a Z_2 symmetry to avoid FCNC.

Weinberg and Glashow. '76
Deshpande and E. Ma '77

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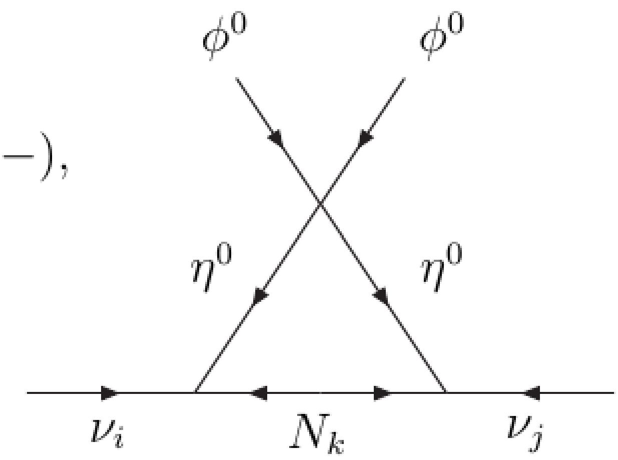
One Extra Scalar Doublet + Right-Handed Neutrinos

E. Ma. '98

$$(\nu_i, l_i) \sim (2, -1/2; +), \quad l_i^c \sim (1, 1; +), \quad N_i \sim (1, 0; -),$$

$$(\phi^+, \phi^0) \sim (2, 1/2; +), \quad (\eta^+, \eta^0) \sim (2, 1/2; -).$$



- The dark matter candidate is one the neutral components of the doublet
- The stability of the dark matter is ensured by means of a Z_2 symmetry
- The corresponding canonical see-saw scale of 10^9 GeV can be reduced to 1 TeV

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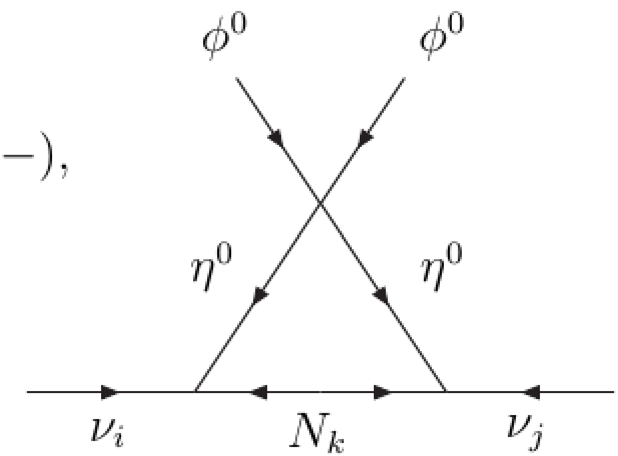

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Phenomenology of Inert Doublet Model

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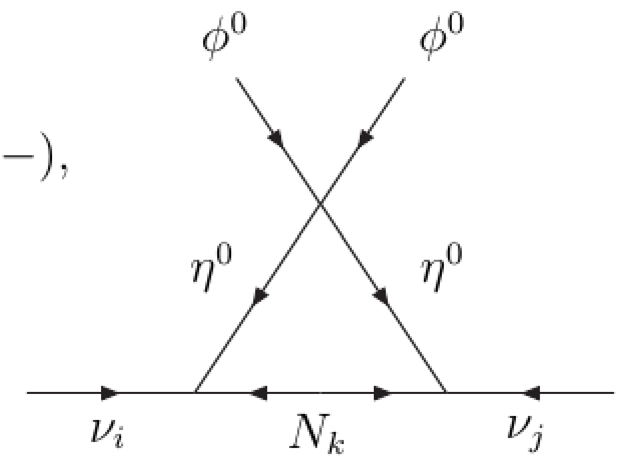

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Lagrangian of the inert doublet model

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

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_\eta$$

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$$-\lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) - \frac{1}{2}\left(\lambda_5 (\Phi^\dagger \eta)(\Phi^\dagger \eta) + \text{h.c.}\right) .$$

← Invariant under $\eta \to -\eta \qquad \Phi \to \Phi$

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After 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

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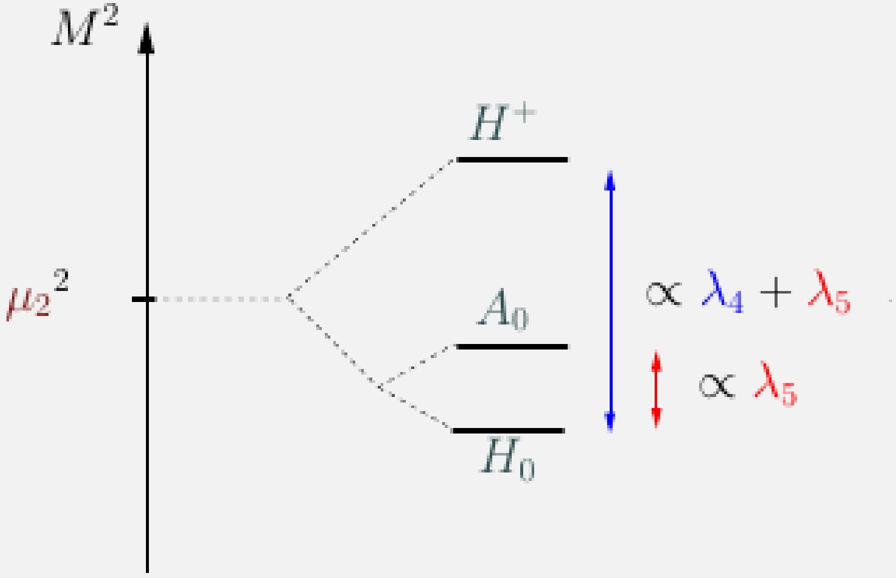
$$V_{Scalar} = \frac{1}{2}(M_h^2 h^2 + M_{H^0}^2 H^2 + M_{A^0}^2 A^2) + M_{H^+}^2 H^+ H^- + \lambda_1 \left(\frac{1}{4} h^4 + v h^3\right)$$
$$+ \lambda_2 \left(\frac{1}{2} A^2 + \frac{1}{2} H^2 + H^+ H^-\right)^2 + \left(\frac{1}{2} h^2 + v h\right)(\lambda_{A^0} A^2 + \lambda_{H^0} H^2 + \lambda_3 H^+ H^-)$$

$$M_h^2 = -2\mu_1^2 \,, \qquad M_{H^0}^2 = \mu_2^2 + \lambda_{H^0} v^2 \,, \qquad M_{A^0}^2 = \mu_2^2 + \lambda_{A^0} v^2 \,, \qquad M_{H^+}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$$\lambda_{H^0} = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) \,, \qquad \lambda_{A^0} = \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5) \,.$$

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



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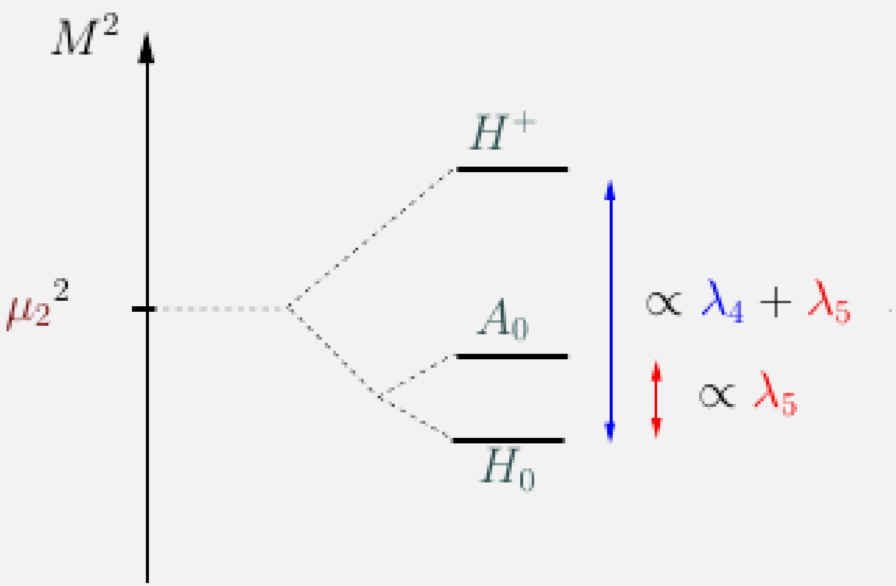

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There are five independent parameters, we take them as

M_{H^0} λ_2, λ_3, λ_4 and λ_5.

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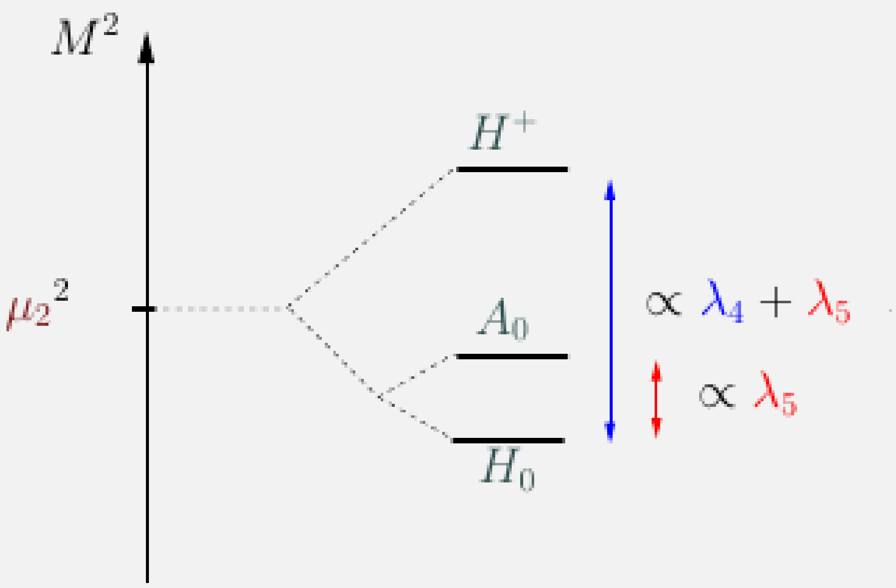

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For a heavy dark matter candidate $(M_{H^0} \gg M_W)$the splitting is relatively small and we expect the particles belonging to the extra doublet to have nearly degenerate masses .

Conditions on the couplings

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Vacuum Stability

$$\lambda_1 > 0\,, \qquad \lambda_2 > 0\,, \qquad \lambda_3 > -2(\lambda_1\lambda_2)^{\frac{1}{2}}\,,$$

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Perturbativity

$$\lambda_i \lesssim 1.$$

Dark Matter Abundance

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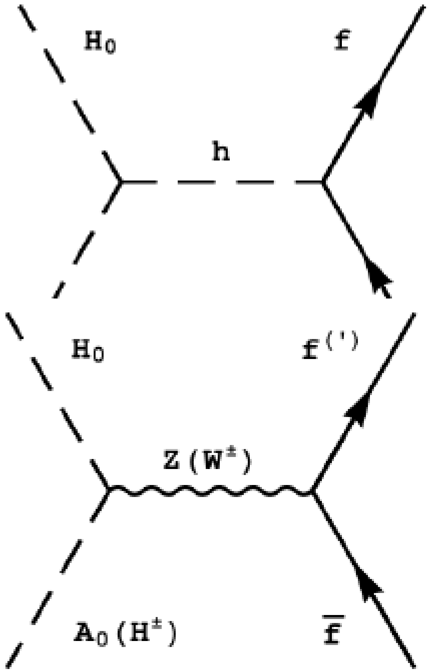
$m_{H_0} \lesssim m_W$: GeV range

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

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



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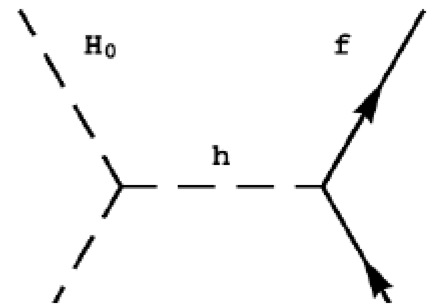

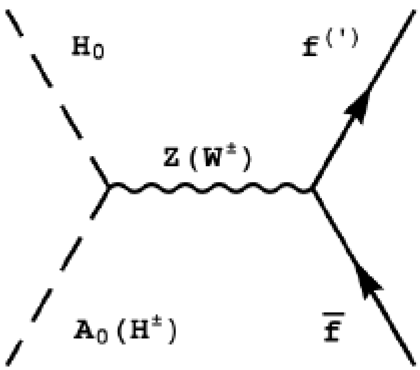

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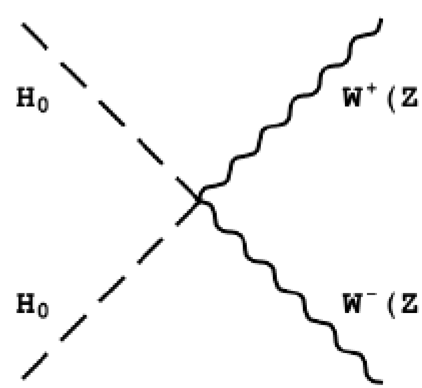
Cirelli NPB06, Hambye JHEP09



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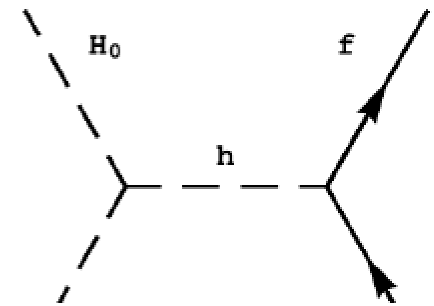

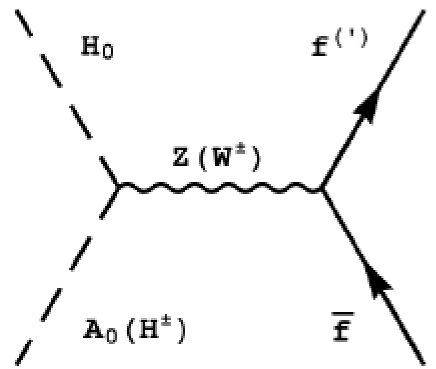

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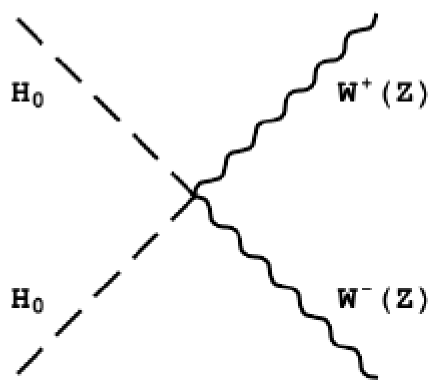
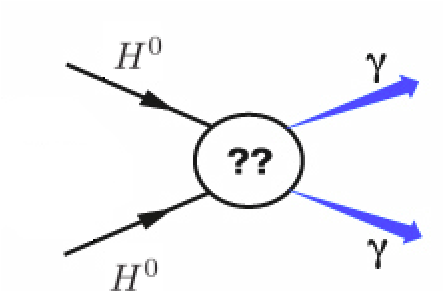


Indirect Searches



No astrophysical uncertainties

"Smoking gun"

Potentially low statistics.

Gustaffson et al. 2007

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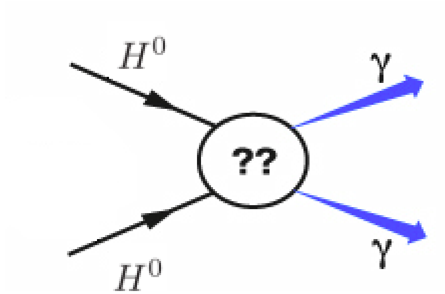

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TABLE I: *IDM benchmark models. (In units of GeV.)*

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	$v\sigma_{tot}^{v\to 0}$ [$\mathrm{cm^3 s^{-1}}$]	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
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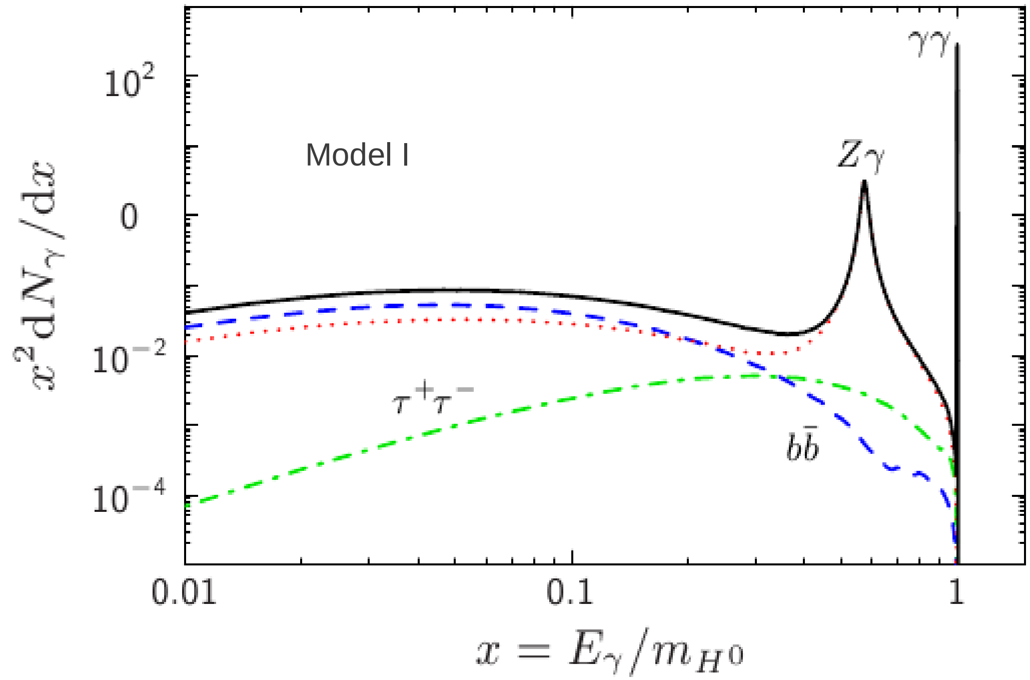

Gustaffson et al. 2007

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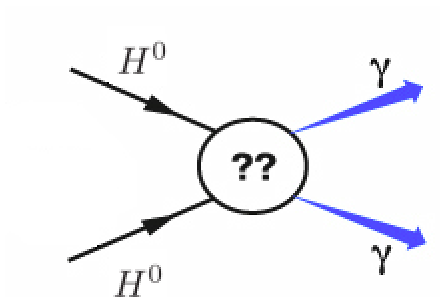

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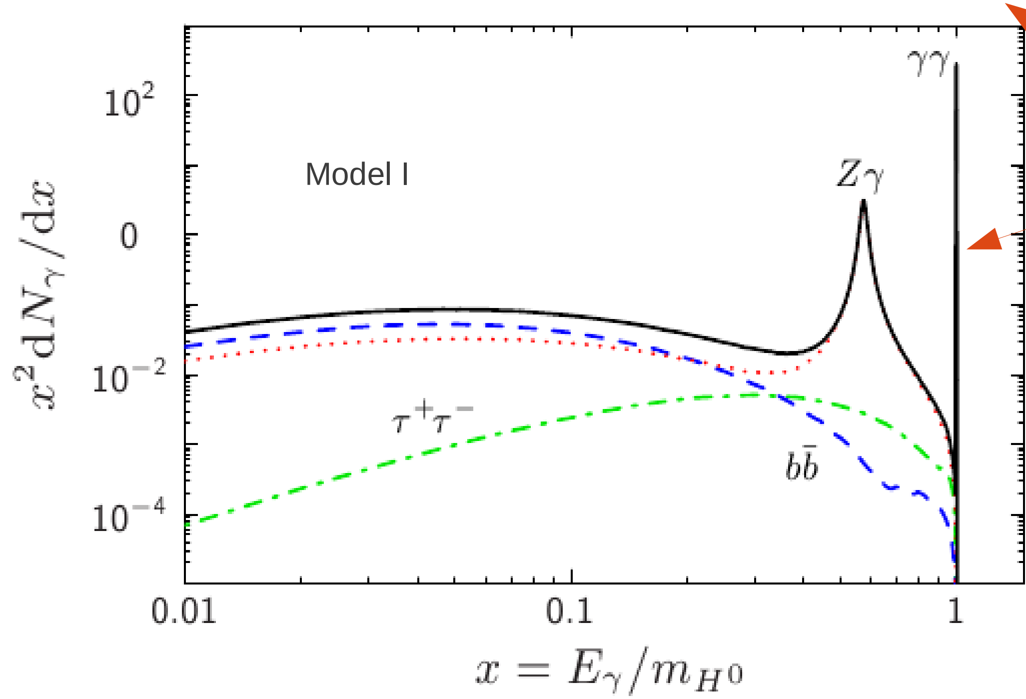

Very prominent spectral features, but very small cross sections (loop suppressed)

Gustaffson et al. 2007

How else can we get spectral features?

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

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

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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

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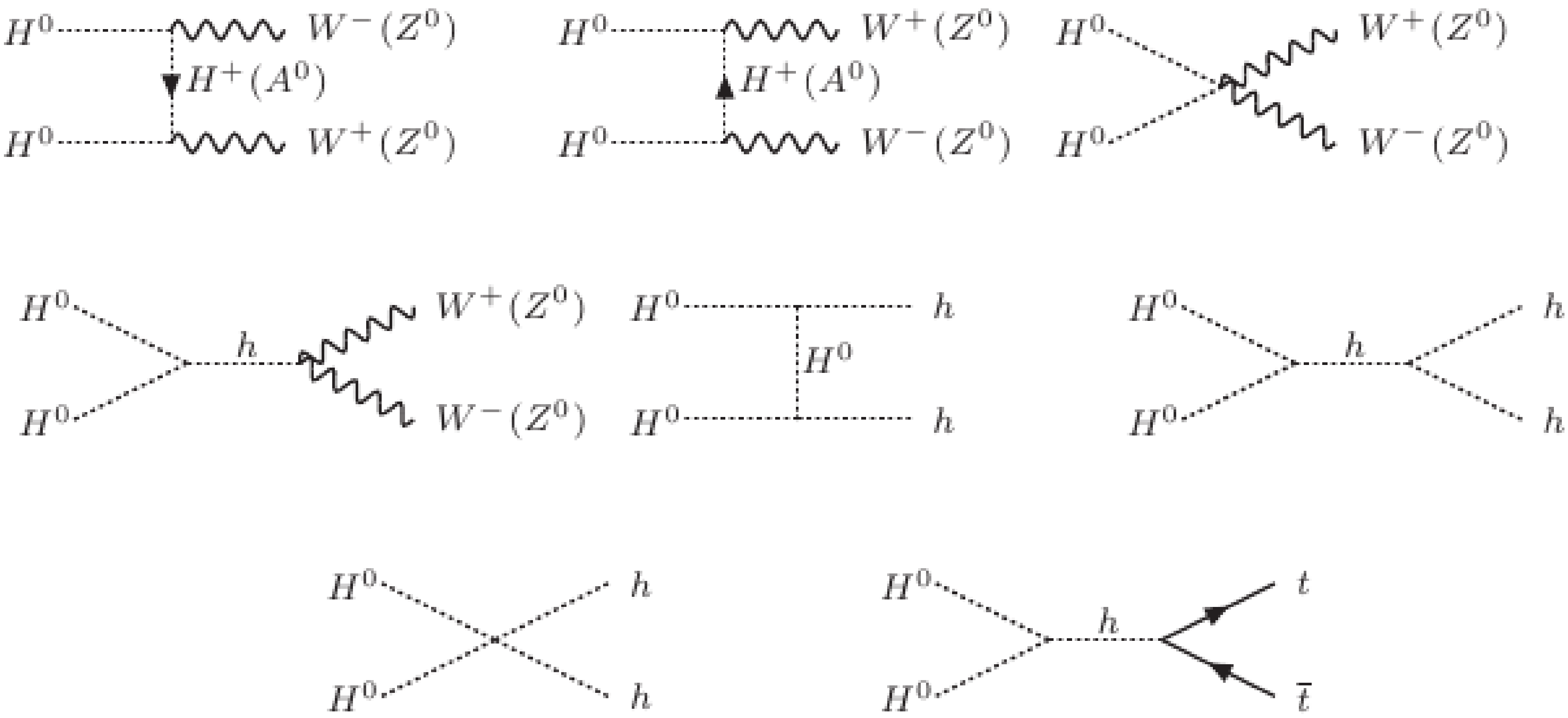
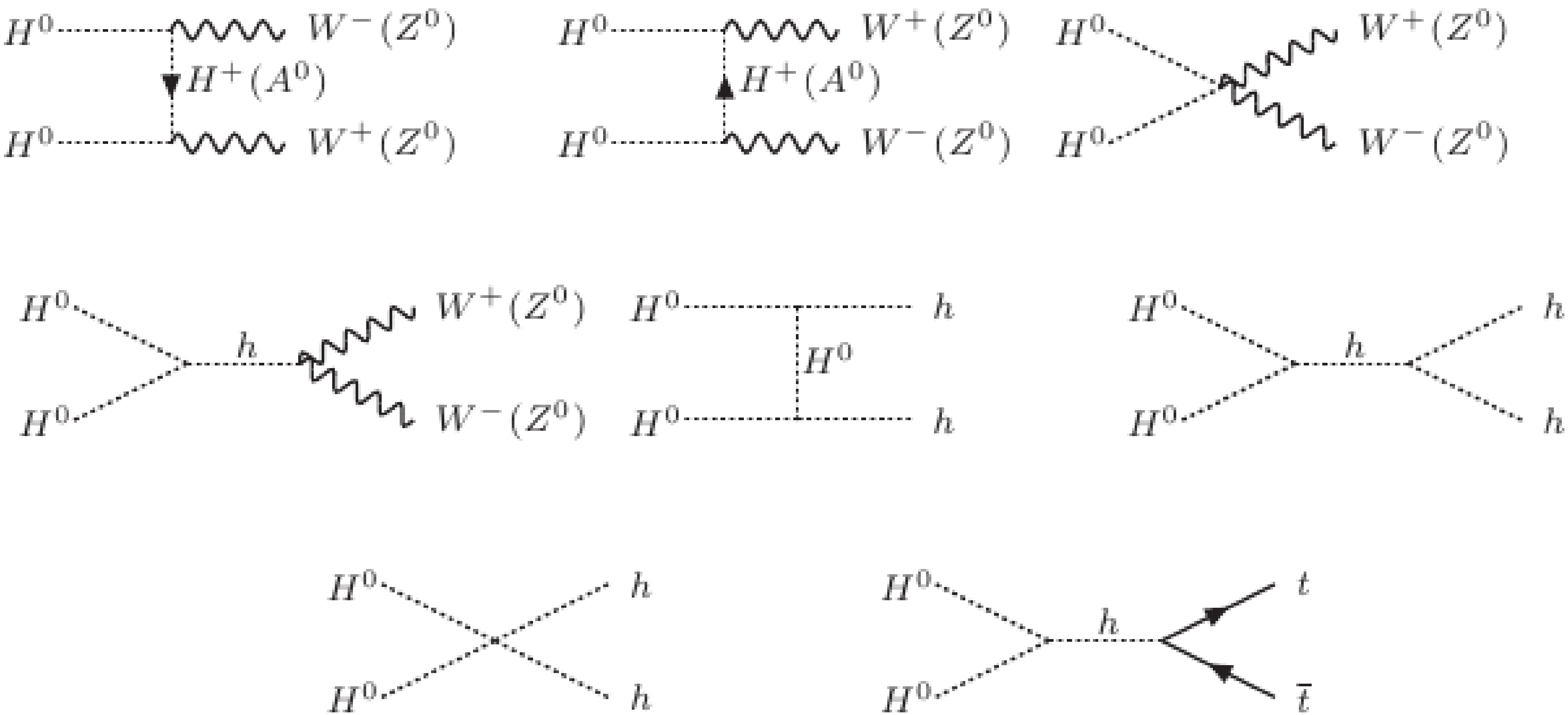
That is the case for the inert doublet model in
the high mass regime if X is a W boson!

Annihilation diagrams



Annihilation diagrams



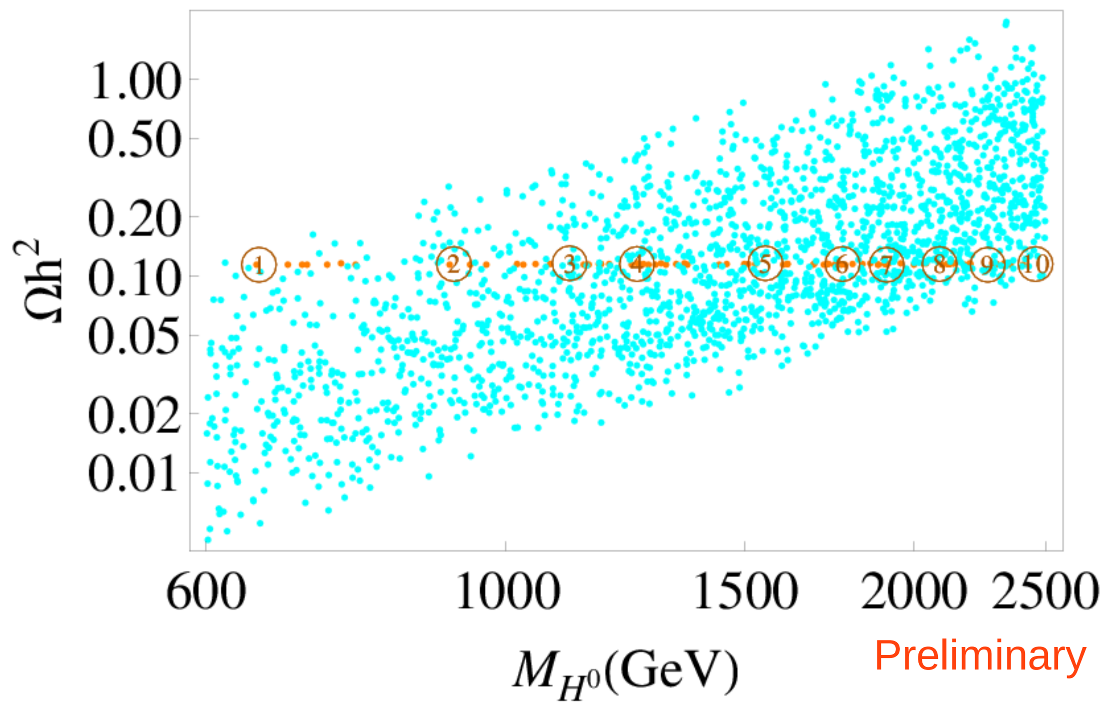
Why the t-channel?

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

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

using micrOMEGAs G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...

Benchmark points



BMP	λ_2	λ_3	λ_4	λ_5	M_{H^0}(GeV)	M_{H^+}(GeV)	M_{A^0}(GeV)	Br(WW)	Br(ZZ)	Br(hh)	Br($t\bar{t}$)
1	0.32	0.02	-0.21	-0.04	657.	663.	659.	42.	41.	14.	2.
2	0.47	-0.48	0.08	-0.09	915.	915.	918.	55.	21.	23.	2.
3	0.23	0.14	0.06	-0.46	1114.	1119.	1126.	25.	67.	8.	0.
4	0.85	-0.44	0.26	-0.46	1249.	1251.	1260.	45.	18.	35.	2.
5	0.52	0.03	0.21	-0.71	1554.	1559.	1568.	12.	71.	16.	0.
6	0.93	0.91	-1.20	-0.13	1771.	1782.	1773.	85.	8.	7.	0.
7	0.68	0.84	-0.53	-0.68	1909.	1919.	1920.	55.	40.	5.	0.
8	0.19	0.18	0.49	-0.90	2089.	2092.	2102.	8.	90.	2.	0.
9	0.90	0.78	0.39	-0.74	2267.	2269.	2277.	26.	71.	3.	0.
10	0.93	0.61	0.43	-0.97	2459.	2462.	2471.	18.	82.	0.	0.

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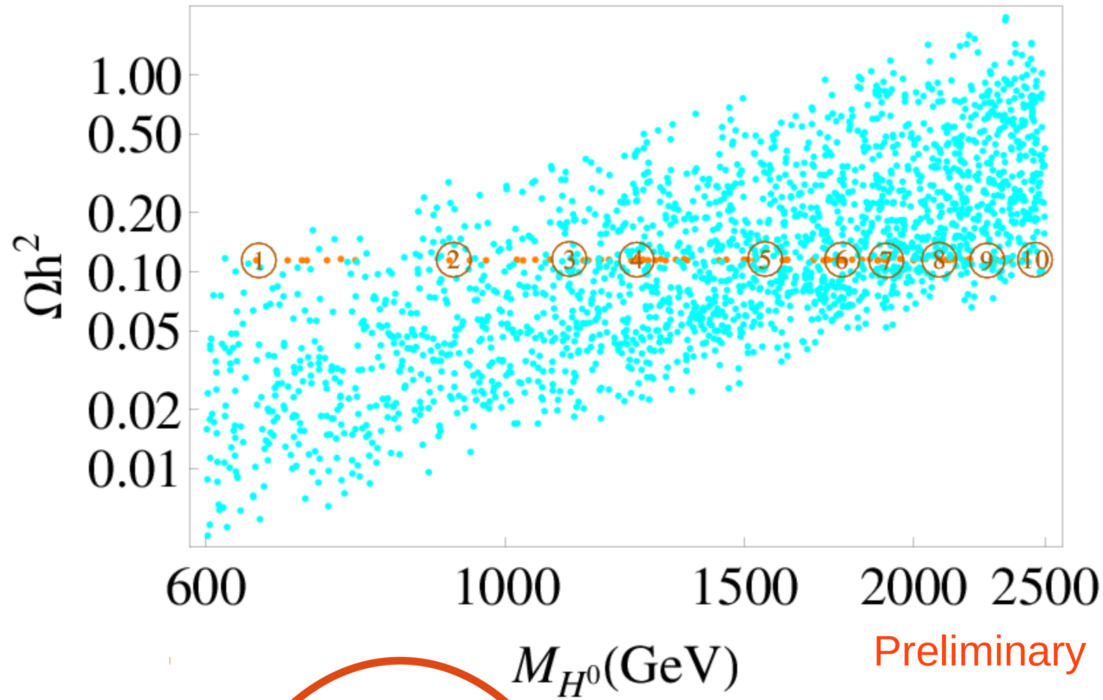

Preliminary

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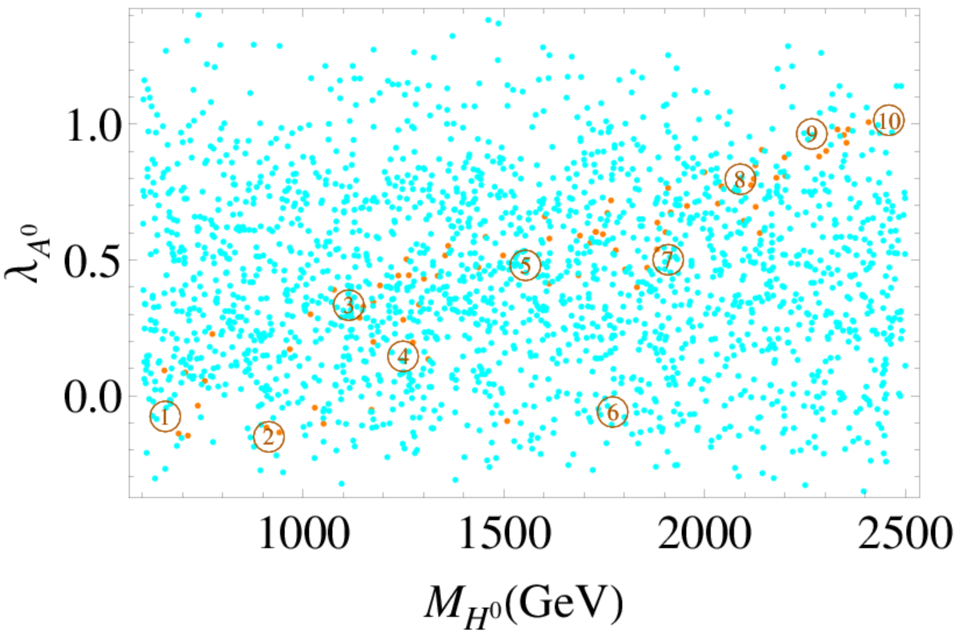

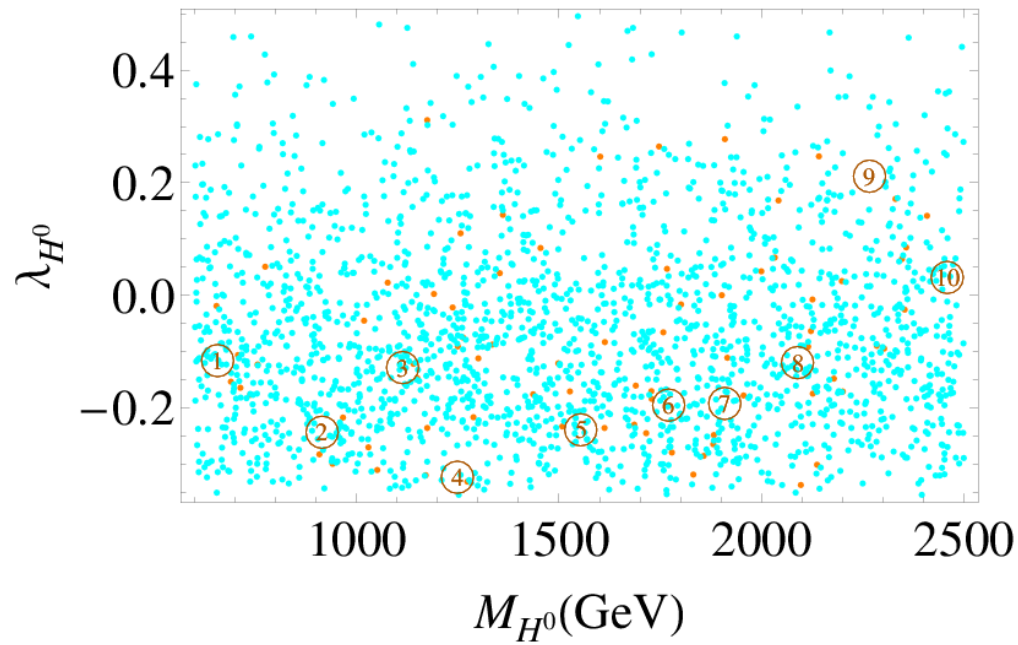

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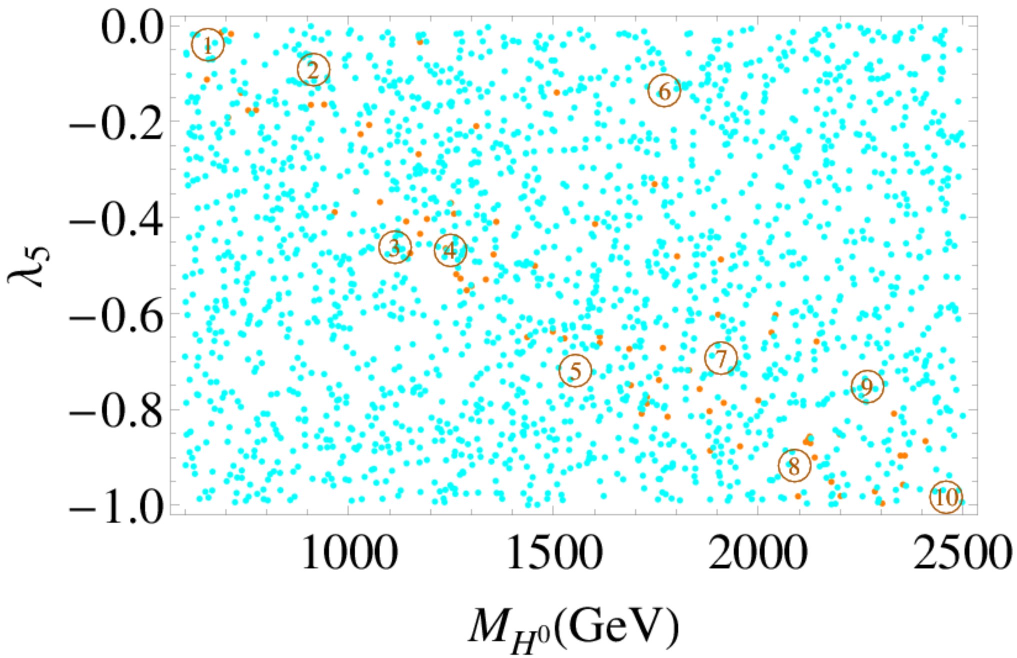
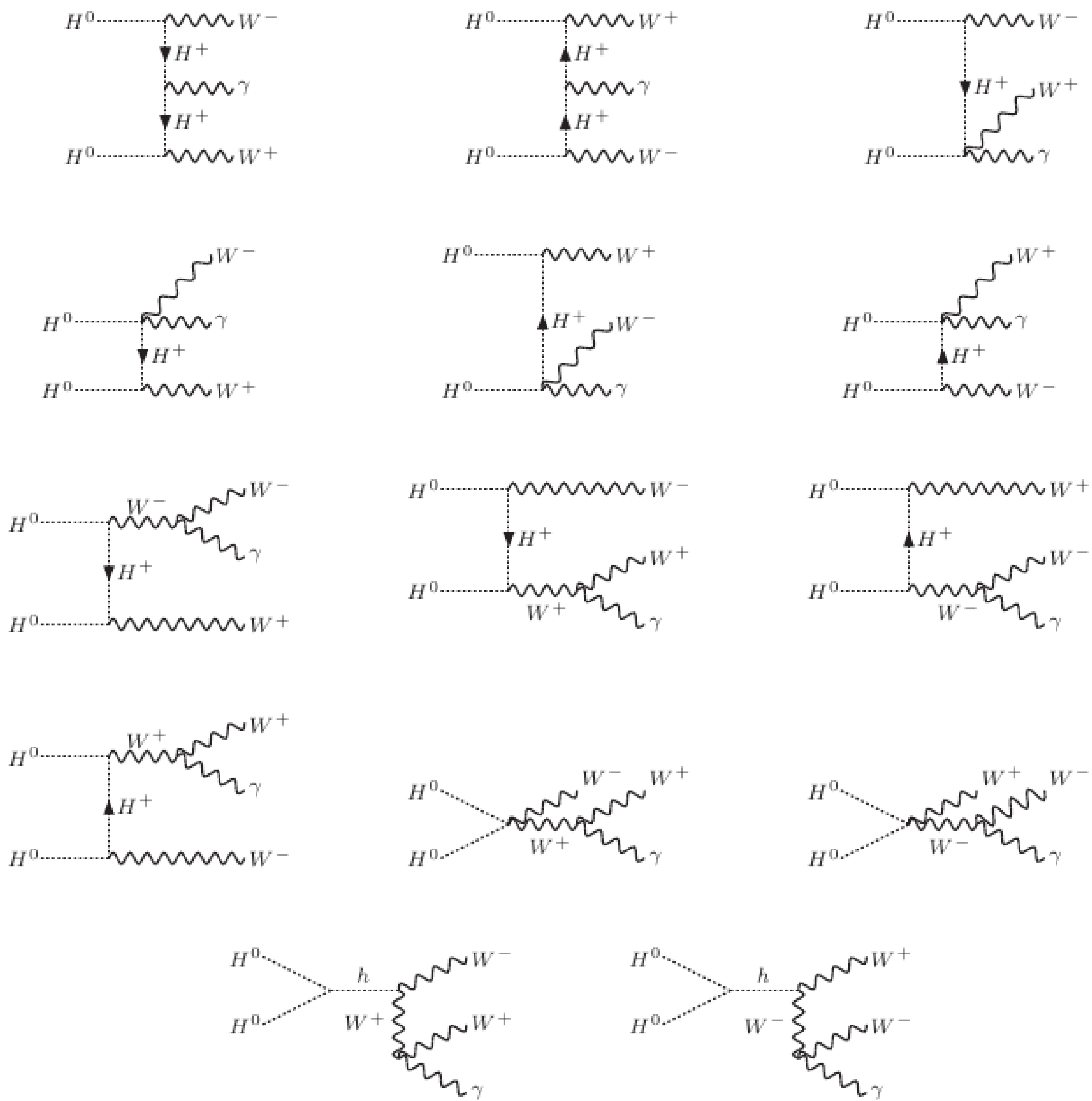
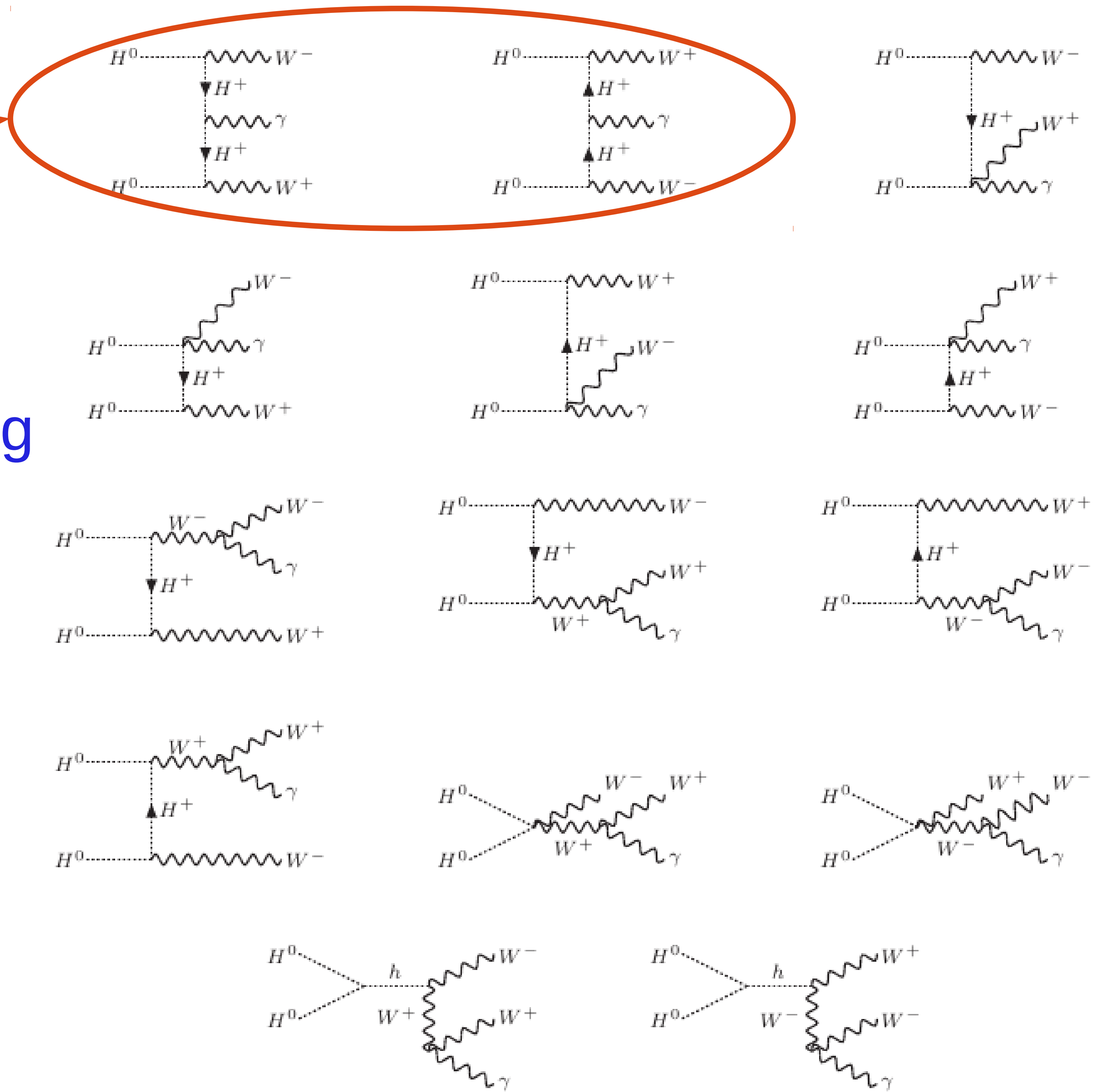


Bremsstrahlung diagrams



Photons emitted from internal lines

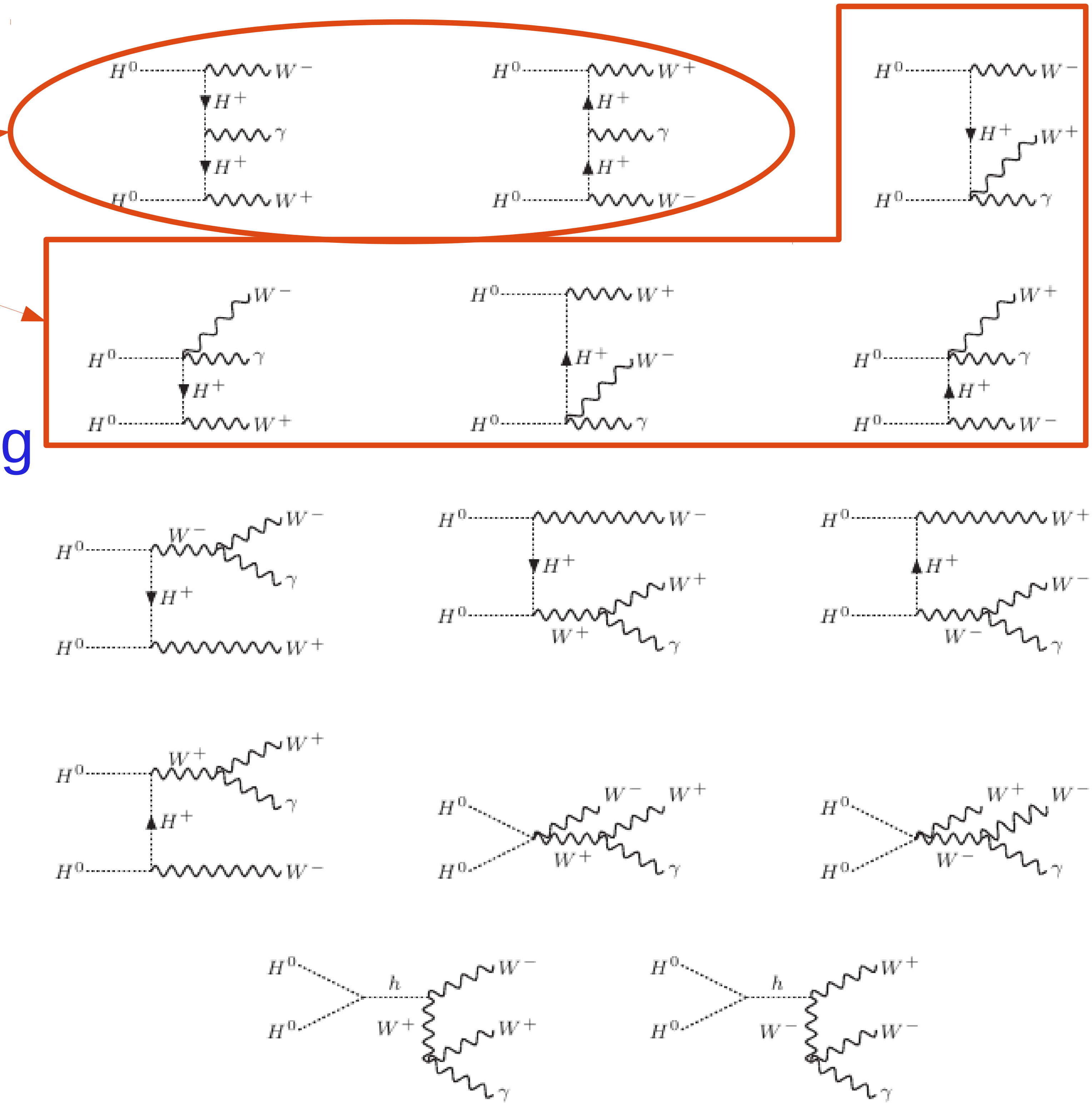
Bremsstrahlung diagrams



Photons emitted from internal lines

Photons emitted from vertices

Bremsstrahlung diagrams



Bremsstrahlung diagrams

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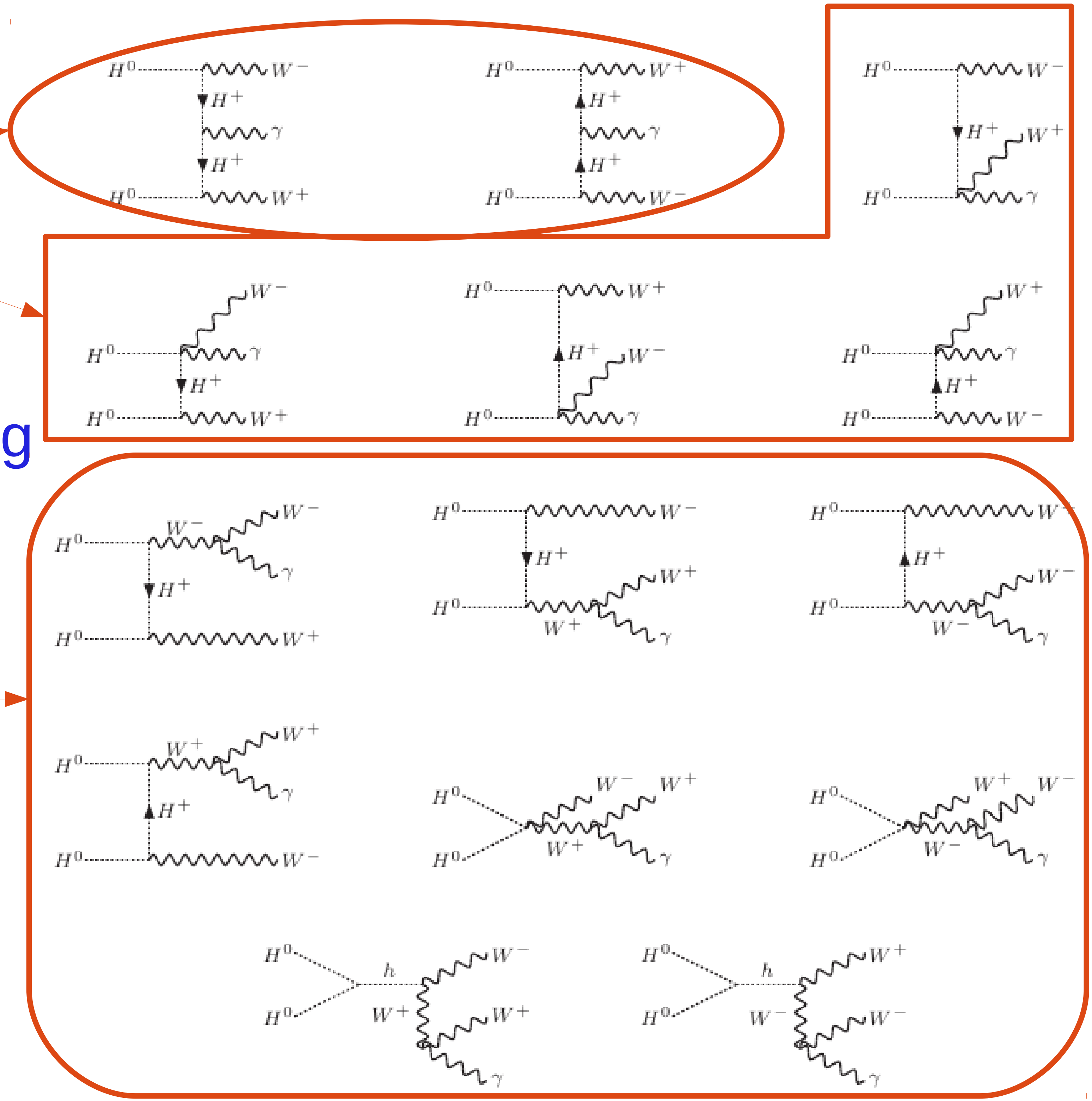
Photons emitted from vertices

Photons emitted from external lines



Cross Sections and Spectra

BMP	$\sigma v (10^{-27} cm^3/s)$
1	1.62
2	3.20
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4	1.97
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6	3.63
7	2.86
8	0.47
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Not so small

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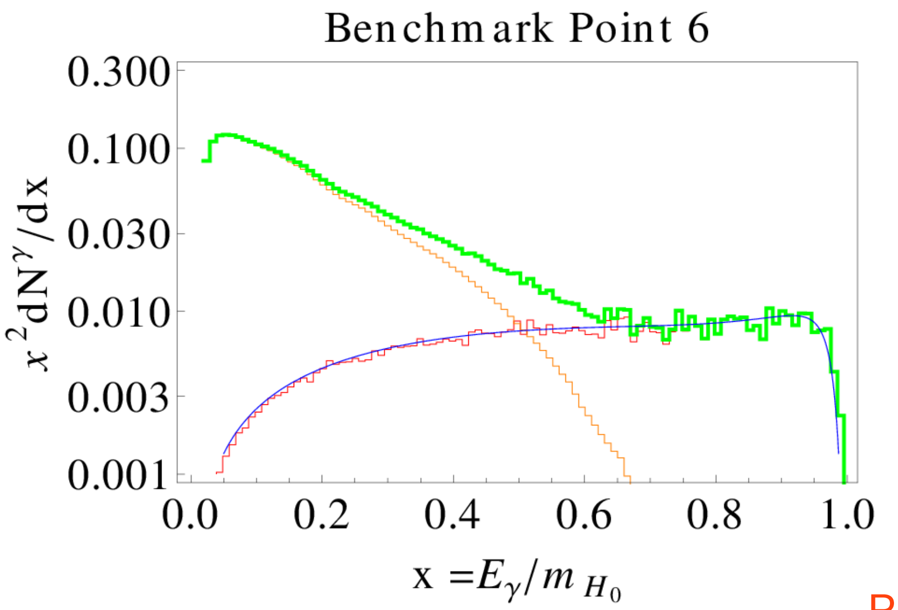

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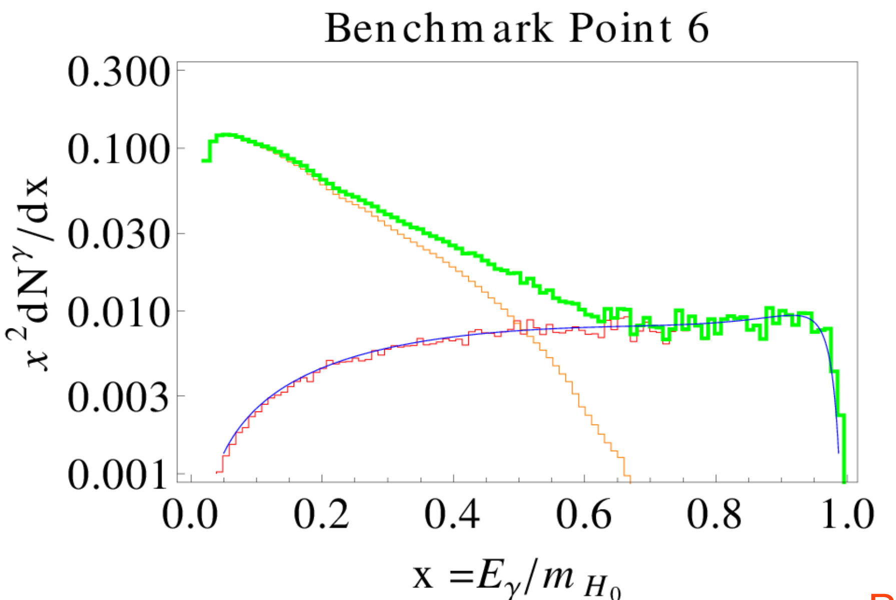

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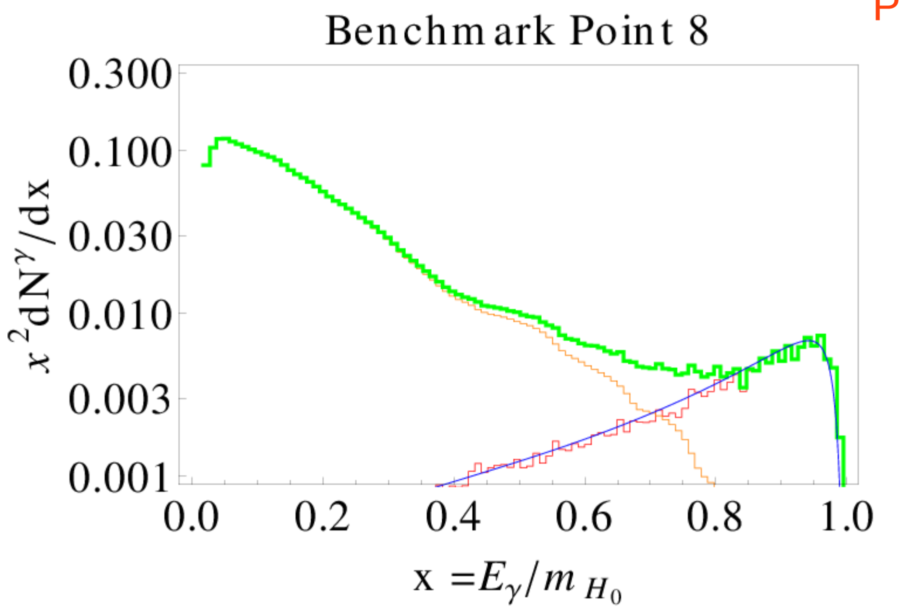
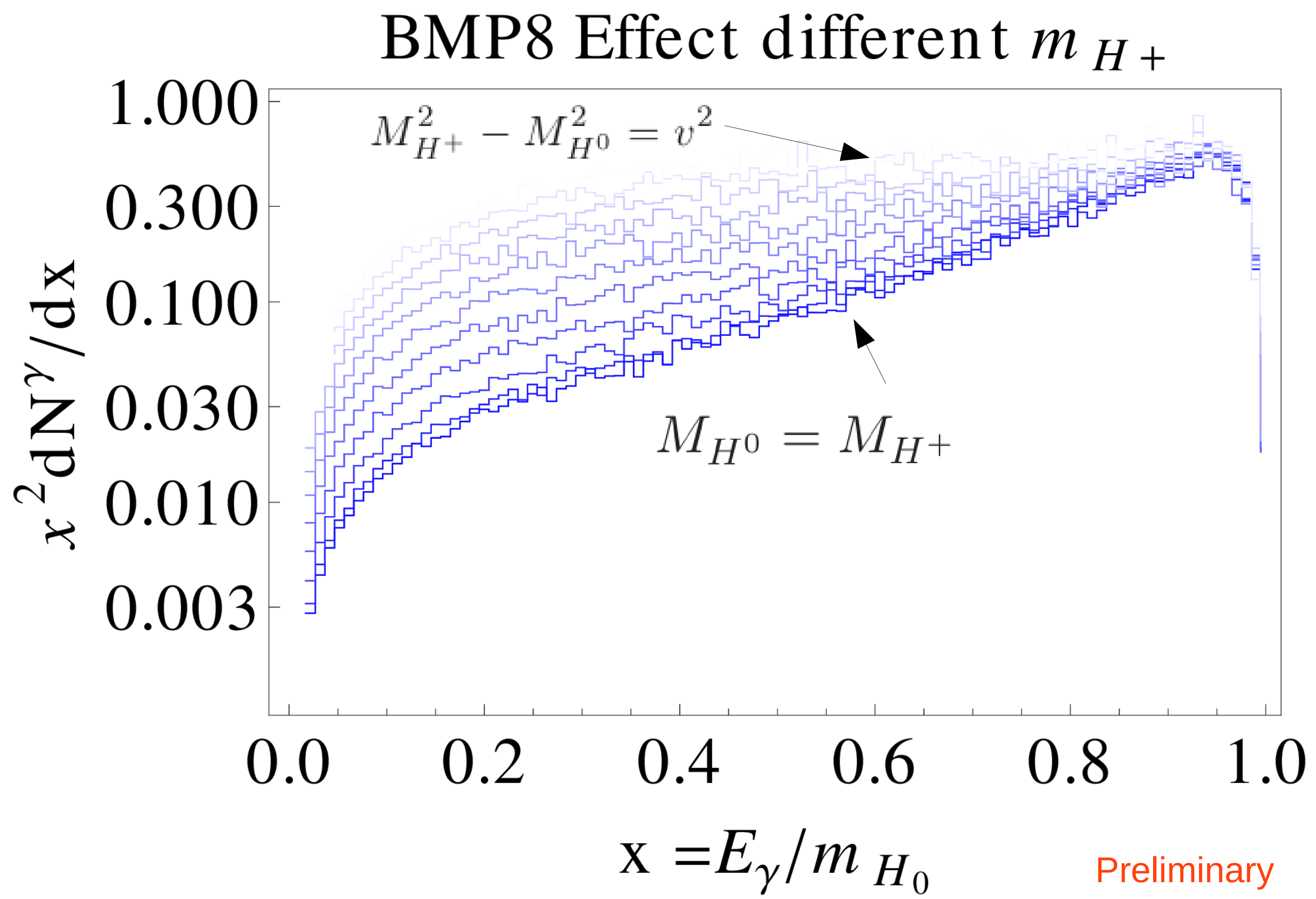


Effect of the mass splitting ($\lambda_4 + \lambda_5$)



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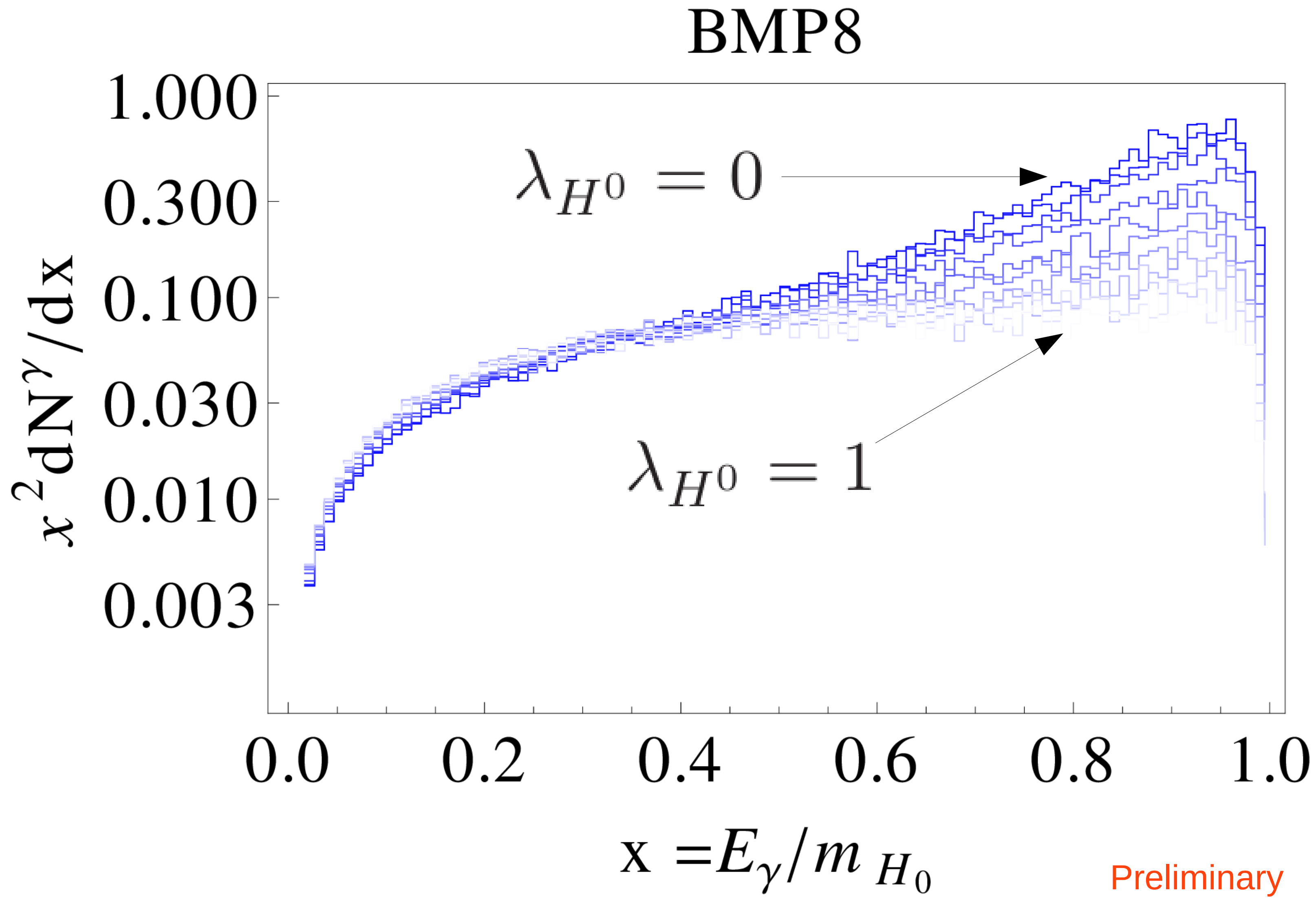
Effect of λ_{H^0}



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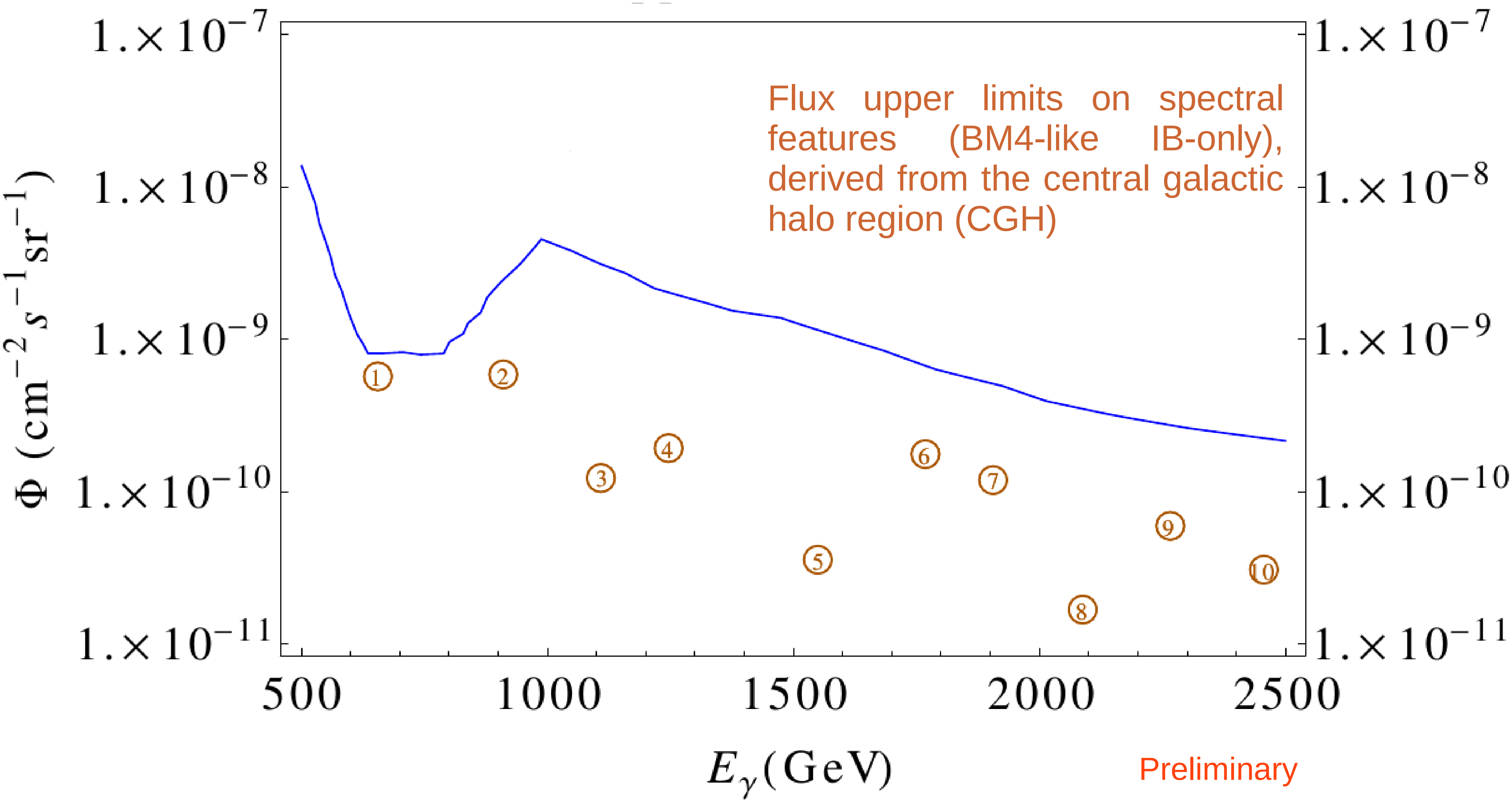
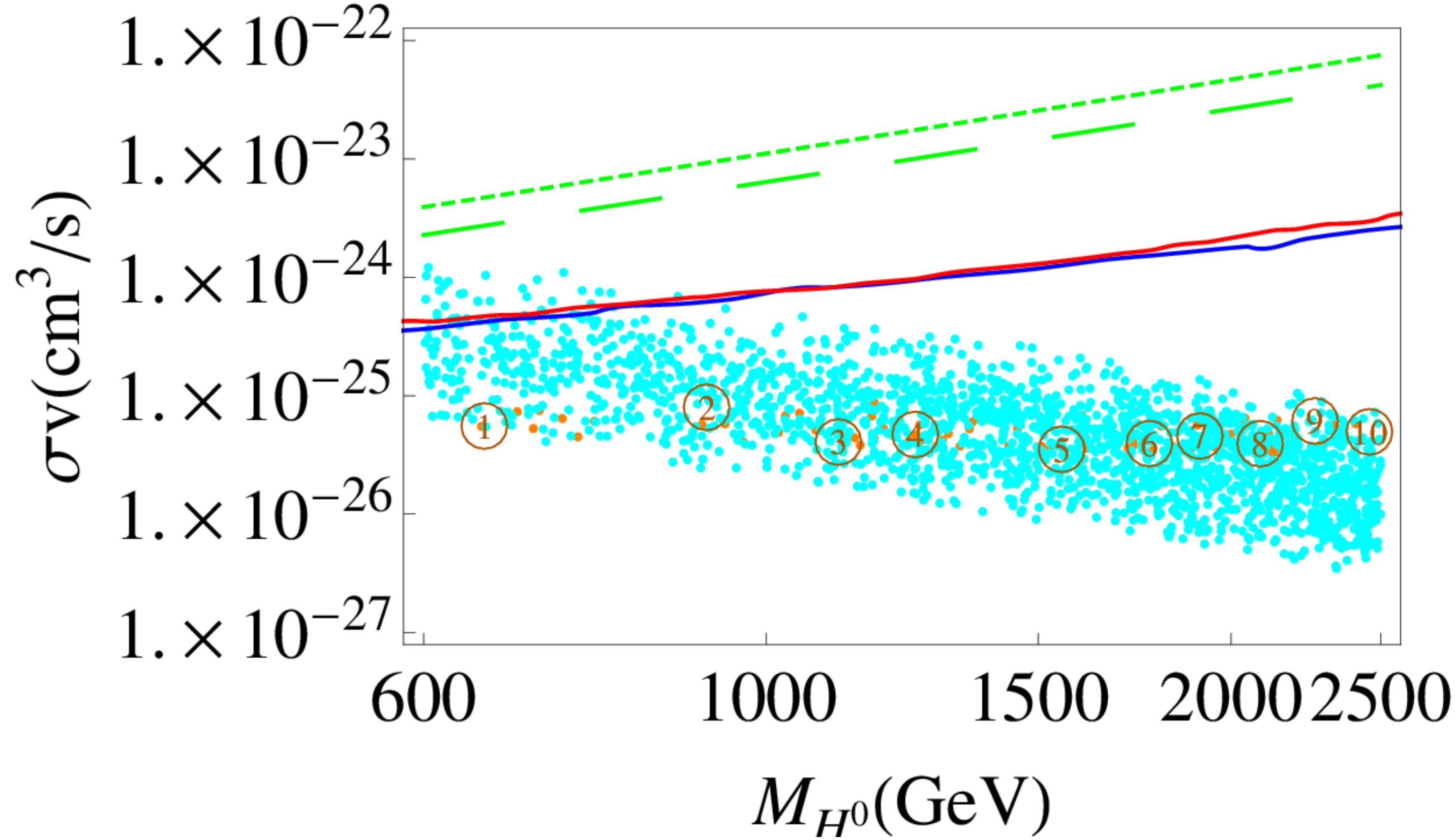
H.E.S.S. searches for photon-like signatures



Conclusions

- Internal Bremsstrahlung signatures are present in the high-mass regime of the inert doublet model.
- In the case of small quartic couplings -or near degeneracy of the exotic scalar bosons- the feature is more prominent.
- For heavy inert dark matter, internal bremsstrahlung signatures might be more relevant than mono-energetic photons in indirect searches.



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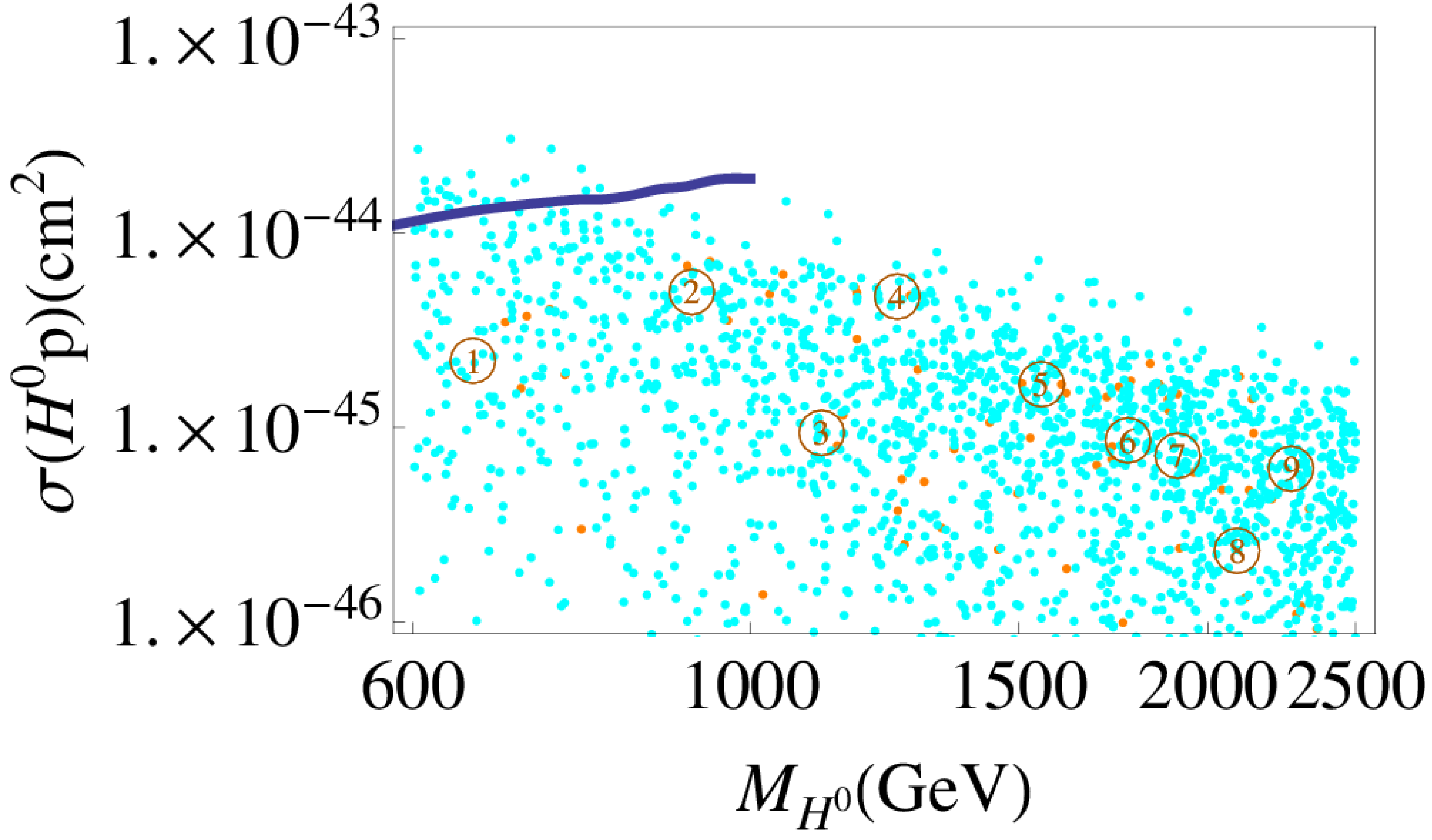

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