All about the Triplet

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- Introduction
- Increasing the Higgs mass w/o fine-tuning
- The Georgi-Machacek model, solving the T-parameter: susy breaking and dark matter.
- Conclusions

Introduction

- The run I of the LHC has discovered the last building block of the SM: The Higgs

- Its properties are compatible with the ones of the SM: minimal realization of the Higgs potential

- But an extended Higgs sector is not yet excluded and can have different and interesting signatures.

- One way of deviating from the minimal model is to include extra Higgses:
  - More doublets
  - singlets
  - Triplets
  - ……

- These extra fields could appear in a UV completion of the model and could remain light by the same mechanism as the SM Higgs
    - Pseudo-goldstone boson
    - Supersymmetry

- In this talk I am going to explore different aspects of an extended Higgs sector with triplets in a supersymmetric model.

- In general there are two possible triplets that could mix with the Higgs, Y=0 and Y=1.

- The kind of couplings are:

$$W = \lambda_0 H_u T_0 H_d + \lambda_{+1} H_d T_{+1} H_d + \lambda_{-1} H_u T_{-1} H_u$$

- In principle the triplet will get a vev once EWSB occurs and can lead to a dangerous contribution to the T-parameter

- I will either make sure that the vev of the triplet component is small or implement a symmetry to avoid contributions to the T-parameter.

Increasing the Higgs mass w/o fine tuning

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- One of the properties of adding an extended Higgs sector in supersymmetry is that one can deviate from the usual formula:

$$m_h^2 \leq m_z^2$$

- Unfortunately one has to pay a price in fine tuning, in order to maximize the new contribution one has to decoupled non-supersymmetricaly the new states.

- One way to avoid the fine-tuning is to double the fields, to couple one to the Higgs and decouple the other one:

$$W = \mu H_u \cdot H_d + \mu_\Sigma \mathrm{Tr}(\Sigma_1 \cdot \Sigma_2) + W_{H-\Sigma} + W_{\mathrm{Yukawa}}$$

- This trick was previously exploited for the case of singlets arXiv:1308.0792

- We will use triplets for a different dependence on tan β

- In the case of Y=0 the effect is similar than the singlet.
- On the other hand for the case of Y=1 the two fields are already needed to cancel anomalies
- I will couple one of the two triplets to the Higgses and the other one will be inert:

$$W_{H-\Sigma} = \lambda H_u \cdot \Sigma_1 H_u$$

- We can write the potential in the following way:

$$\Sigma_1 = \begin{pmatrix} T^-/\sqrt{2} & -T^0 \\ T^{--} & -T^-/\sqrt{2} \end{pmatrix}$$

$$\Sigma_2 = \begin{pmatrix} \chi^+/\sqrt{2} & -\chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V_{\text{neutral}} = {} & m_{H_u}^2 \left|H_u\right|^2 + m_{H_d}^2 \left|H_d\right|^2 + m_\chi^2 |\chi^0|^2 + m_T^2 |T^0|^2 \\ & + \left|2\lambda H_u^0 T^0 + \mu H_d^0\right|^2 + \left|\mu H_u^0\right|^2 + \left|\mu_\Sigma T^0\right|^2 + \left|\mu_\Sigma \chi^0 + \lambda H_u^0 H_u^0\right|^2 \\ & + \frac{g^2 + g'^{\,2}}{8} \left(H_d^0 H_d^{0*} - H_u^0 H_u^{0*} + 2T^0 T^{0*} - 2\chi^0 \chi^{0*}\right)^2 \\ & + \left(-\lambda A_\lambda H_u^0 H_u^0 T^0 - \mu B_\mu H_d^0 H_u^0 - \mu_\Sigma B_\Sigma T^0 \chi^0 + \text{h.c.}\right) \end{aligned}$$

- Upon integration of the triplets and going to the decoupling limit one gets the following mass for the Higgs (SM-like):

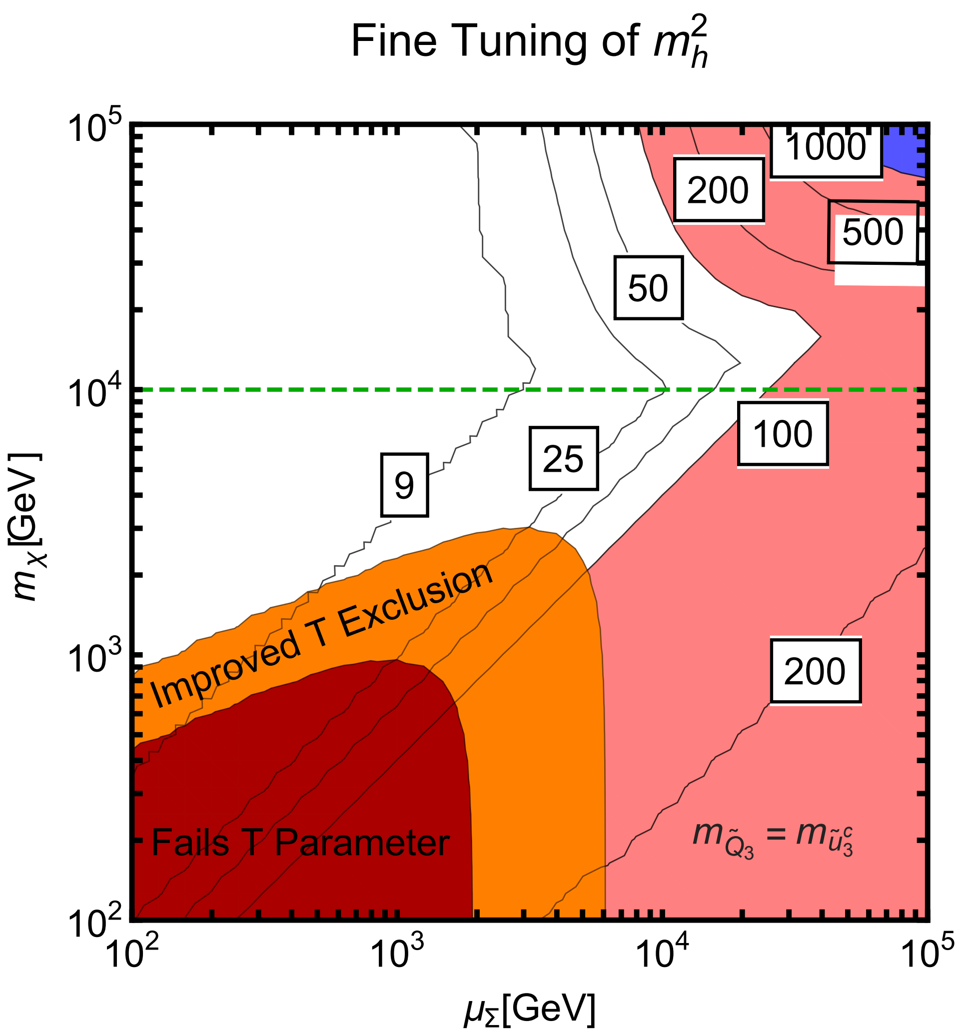
$$m_h^2 = m_Z^2 \cos^2(2\beta) + (\text{stop loops}) + 4v^2\lambda^2 \sin^4(\beta) \left(\frac{m_\chi^2}{\mu_\Sigma^2 + m_\chi^2} \right)$$
$$- \frac{v^2\lambda^2 \sin^2(2\beta)}{\mu_\Sigma^2 + m_T^2} \left| 2\mu^* - A_\lambda \tan(\beta) \right|^2 .$$

- Problems:
  - Fine-tuning:

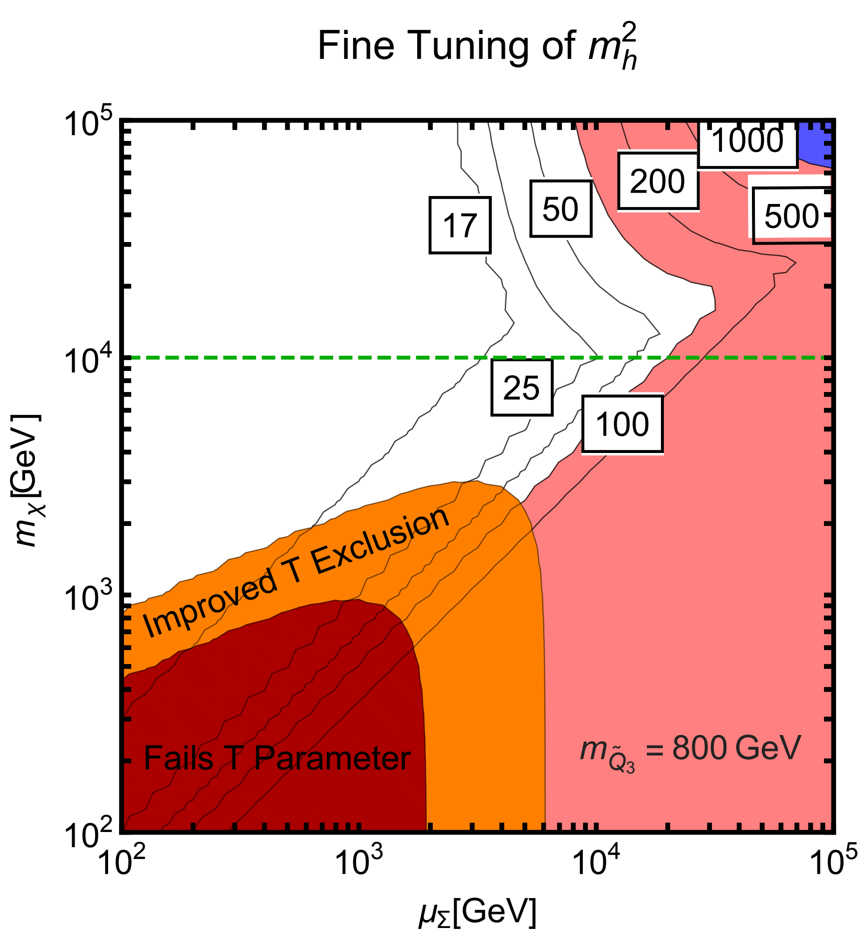
$$\Delta = \frac{2}{m_h^2}\max\left(m_{H_u}^2, m_{H_d}^2, \frac{dm_{H_u}^2}{d\log(u)}L, \frac{dm_{H_d}^2}{d\log(u)}L, \delta m_{H_u^0}^2, \mu B_{\mu,\mathrm{eff}}\right)$$

  - T-parameter:

$$\left\langle T^0\right\rangle_{Y=-1} \approx -\frac{v^2\lambda}{2}\frac{\sin(2\beta)\left(2\mu^* - A_\lambda\tan(\beta)\right)}{\mu_\Sigma^2 + m_T^2} \text{ and } \quad \left\langle \chi^0\right\rangle_{Y=1} \approx v^2\frac{-\lambda\mu_\Sigma\sin^2(\beta)}{\mu_\Sigma^2 + m_\chi^2}$$



$$m_T = 800 \text{ TeV} \quad \lambda = 0.25$$



- This model also changes the different decays channels since there are more states.
- Specially having more charginos can lead to distinct patterns of decays of stops
- The main drawback are the bounds that come from the T-parameter

The (SUSY)-Georgi-Machacek model: SUSY breaking and DM

- The GM model was proposed to ensure a custodial structure with triplets.
- It was supersymmetrized in arXiv:1308.4025

$$\bar{H} = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}, \quad \bar{\Delta} = \begin{pmatrix} -\frac{\Sigma_0}{\sqrt{2}} & -\Sigma_{-1} \\ -\Sigma_1 & \frac{\Sigma_0}{\sqrt{2}} \end{pmatrix}$$

$$W_0 = \lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{\lambda_3}{3} \operatorname{tr} \bar{\Delta}^3 + \frac{\mu}{2} \bar{H} \cdot \bar{H} + \frac{\mu_\Delta}{2} \operatorname{tr} \bar{\Delta}^2 + h_t \overline{Q}_L \cdot H_2 t_R + h_b \overline{Q}_L \cdot H_1 b_R$$

- RGE evolution, yukawa and U(1) break the custodial limit and generate a non-zero ρ so in general:

$$W = -\lambda_a H_1 \cdot \Sigma_1 H_1 + \lambda_b H_2 \cdot \Sigma_{-1} H_2 + \sqrt{2}\lambda_c H_1 \cdot \Sigma_0 H_2 + \sqrt{2}\lambda_3 \mathrm{tr}\, \Sigma_1 \Sigma_0 \Sigma_{-1}$$
$$- \mu H_1 \cdot H_2 + \frac{\mu_{\Delta_a}}{2} \mathrm{tr}\, \Sigma_0^2 + \mu_{\Delta_b} \mathrm{tr}\, \Sigma_1 \Sigma_{-1} + h_t\, \overline{Q}_L \cdot H_2 t_R + h_b\, \overline{Q}_L \cdot H_1 b_R$$

$$V_{\mathrm{SOFT}} = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + m_{\Sigma_0}^2 \Sigma_0^\dagger \Sigma_0 + m_{\Sigma_1}^2 \Sigma_1^\dagger \Sigma_1 + m_{\Sigma_{-1}}^2 \Sigma_{-1}^\dagger \Sigma_{-1} - m_3^2 H_1 \cdot H_2$$
$$+ \Big\{ \frac{B_{\Delta_a}}{2} \mathrm{tr}\Sigma_0^2 + B_{\Delta_b} \mathrm{tr}\Sigma_1 \Sigma_{-1} - A_{\lambda_a} H_1 \cdot \Sigma_1 H_1 + A_{\lambda_b} H_2 \cdot \Sigma_{-2} H_2$$
$$+ \sqrt{2} A_{\lambda_c} H_1 \cdot \Sigma_0 H_2 + \sqrt{2} A_{\lambda_3} \mathrm{tr}\, \Sigma_1 \Sigma_0 \Sigma_{-1} + a_t\, \tilde{Q}_L \cdot H_2 \tilde{t}_R + a_b\, \tilde{Q}_L \cdot H_1 \tilde{b}_R + h.c. \Big\}$$

- I am going to embed this model into a predictive scenario of SUSY breaking like GMSB to see the deviation from the custodial limit:

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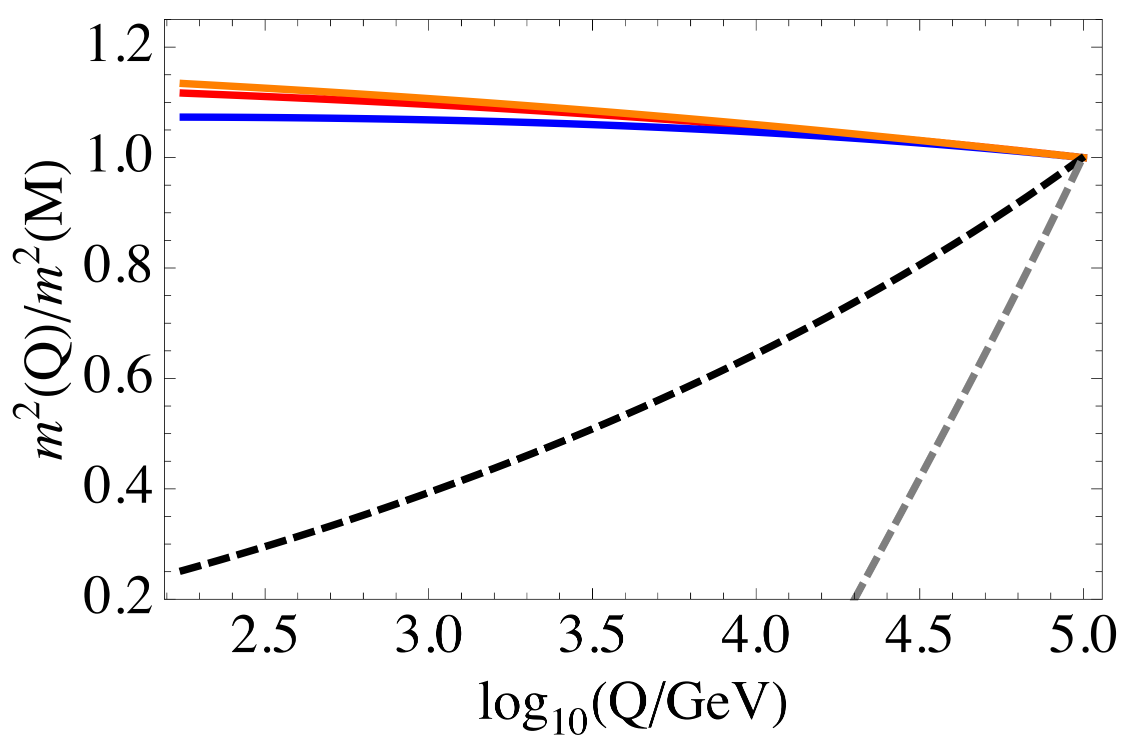
$$W=\left(\tilde\lambda_8^{ij}X+\mathcal{M}_8^{ij}\right)\Phi_{8i}\Phi_{8j}+\left(\tilde\lambda_3^{ij}X+\mathcal{M}_3^{ij}\right)\Phi_{3i}\Phi_{3j}+\left(\tilde\lambda_1^{ij}X+\mathcal{M}_1^{ij}\right)\bar\Phi_{1i}\Phi_{1j}$$

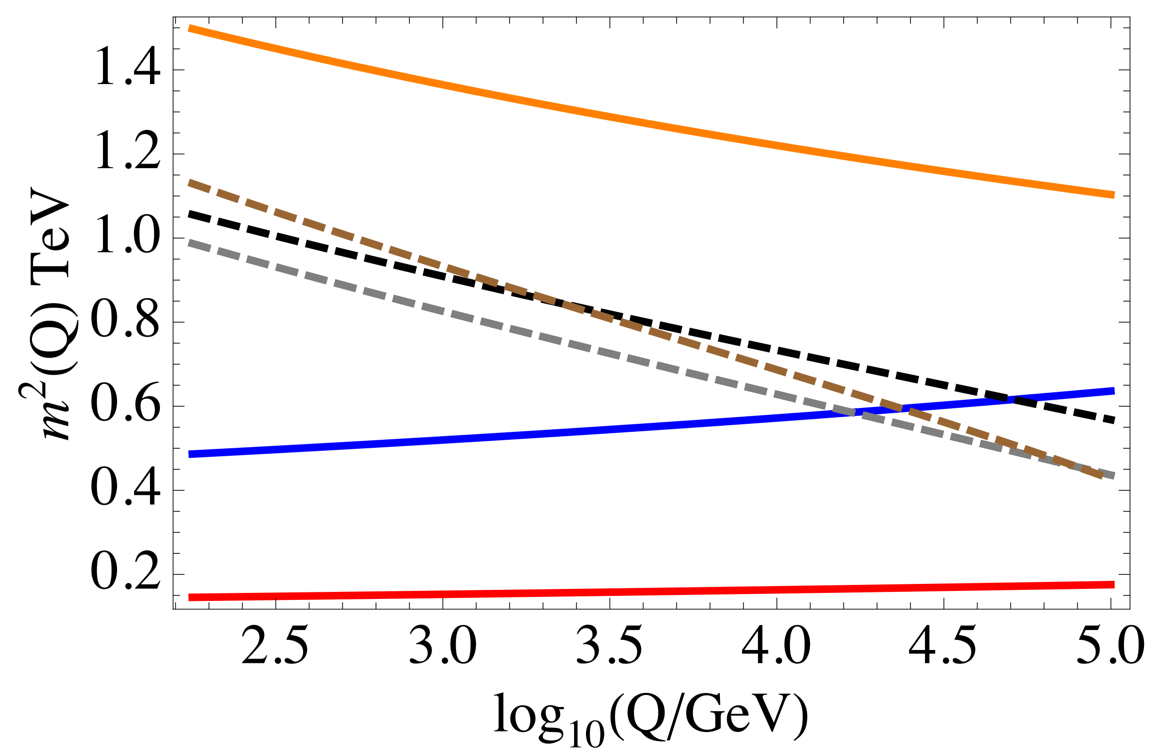
$$\begin{aligned} M_3 &= \frac{\alpha_3(\mathcal{M})}{4\pi}3n_8 g(\Lambda_8/\mathcal{M})\Lambda_8\,,\\ M_2 &= \frac{\alpha_2(\mathcal{M})}{4\pi}2n_3 g(\Lambda_3/\mathcal{M})\Lambda_3\,,\\ M_1 &= \frac{\alpha_1(\mathcal{M})}{4\pi}\frac{6}{5}n_1 g(\Lambda_1/\mathcal{M})\Lambda_1\,, \end{aligned}$$

$$\begin{aligned} m_{\tilde f}^2 = 2[C_3^f\left(\frac{\alpha_3(\mathcal{M})}{4\pi}\right)^2 3n_8 f(\Lambda_8/\mathcal{M})\Lambda_8^2 + C_2^f\left(\frac{\alpha_2(\mathcal{M})}{4\pi}\right)^2 2n_3 f(\Lambda_3/\mathcal{M})\Lambda_3^2\\ + C_1^f\left(\frac{\alpha_1(\mathcal{M})}{4\pi}\right)^2\frac{1}{2}\left(\frac{6}{5}\right)^2 n_1 f(\Lambda_1/\mathcal{M})\Lambda_1^2]\,. \end{aligned}$$

- The spectrum is generated at a high scale M
- Run down to the EW scale
- EWSB it is imposed
- m_h=125 GeV
- All experimental constrains (direct & indirect) are satisfied

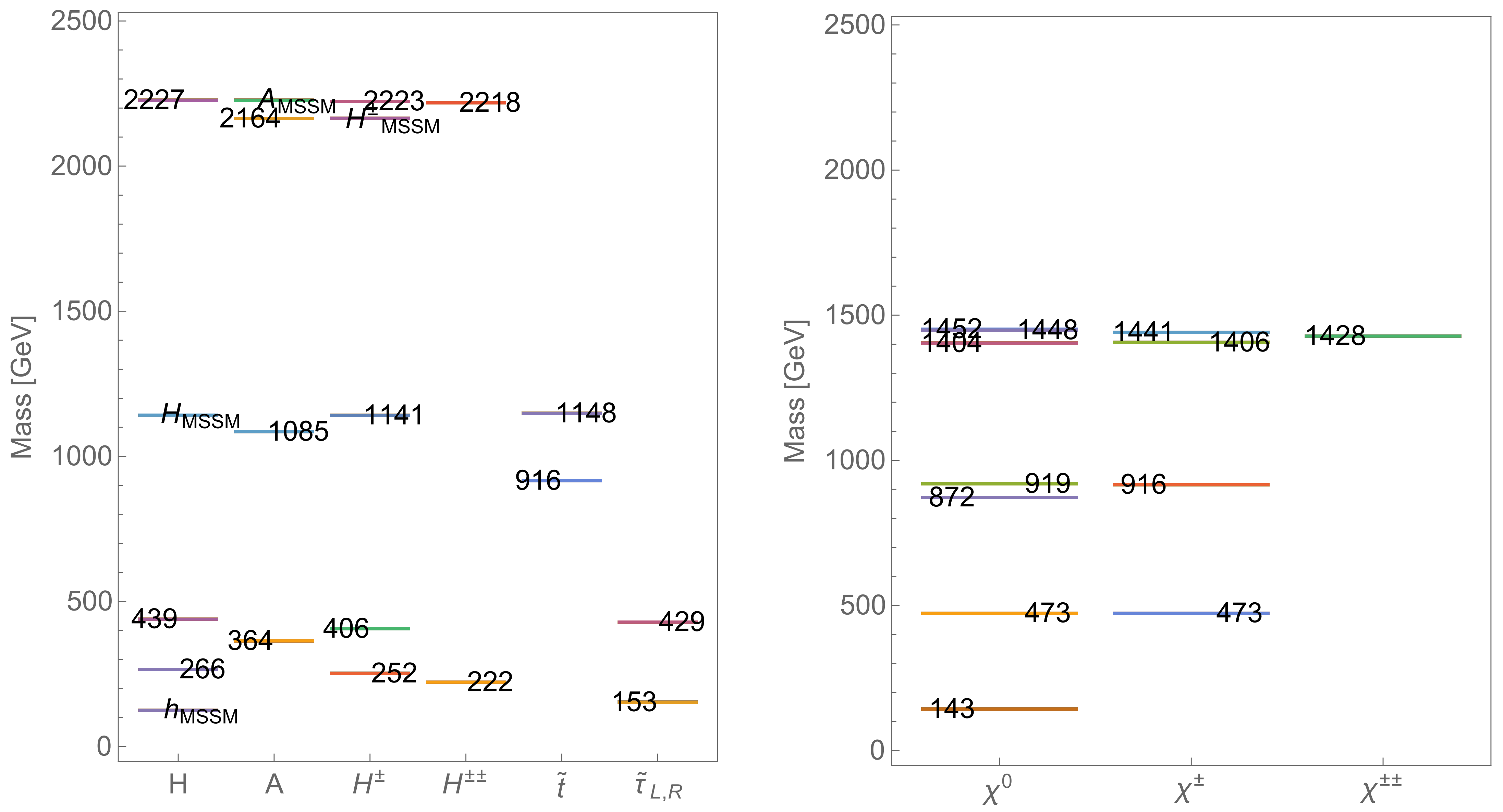
$$n_1 = 1,\ n_3 = 2,\ n_8 = 6 \quad \text{and} \quad \tilde{\lambda}_1 = 0.9,\ \tilde{\lambda}_3 = 0.5,\ \tilde{\lambda}_8 = 0.1\,.$$





Higgses

squarks & gauginos


Mass [GeV]
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2000
1500
1000
500
0
2227
A_{MSSM}
2223
2218
2164
$H^{\pm}_{\text{MSSM}}$
H_{MSSM}
1085
1141
1148
916
439
364
406
429
266
252
222
153
h_{MSSM}
H
A
$H^{\pm}$
$H^{\pm\pm}$
$\tilde{t}$
$\tilde{\tau}_{L,R}$
Mass [GeV]
2500
2000
1500
1000
500
0
1452
1448
1404
1441
1406
1428
919
916
872
473
473
143
χ^0
$\chi^{\pm}$
$\chi^{\pm\pm}$

tan β=1.38

- There are deviations on Higgs properties and exotic decays like:

$$H^\pm \to W^\pm Z$$

Scenario #1	WW	ZZ	$b\bar{b}$	$t\bar{t}$	$\gamma\gamma$
r_{hXX}	1.05	1.04	1.01	1.01	1.22
$\mu^{(gF)}_{hXX}, \mu^{(htt)}_{hXX}$	1.07	1.05	1	0.99	1.45
$\mu^{(WF)}_{hXX}, \mu^{(Wh)}_{hXX}$	1.16	1.14	1.08	1.07	1.58
$\mu^{(ZF)}_{hXX}, \mu^{(Zh)}_{hXX}$	1.14	1.11	1.06	1.05	1.54

How about DM?

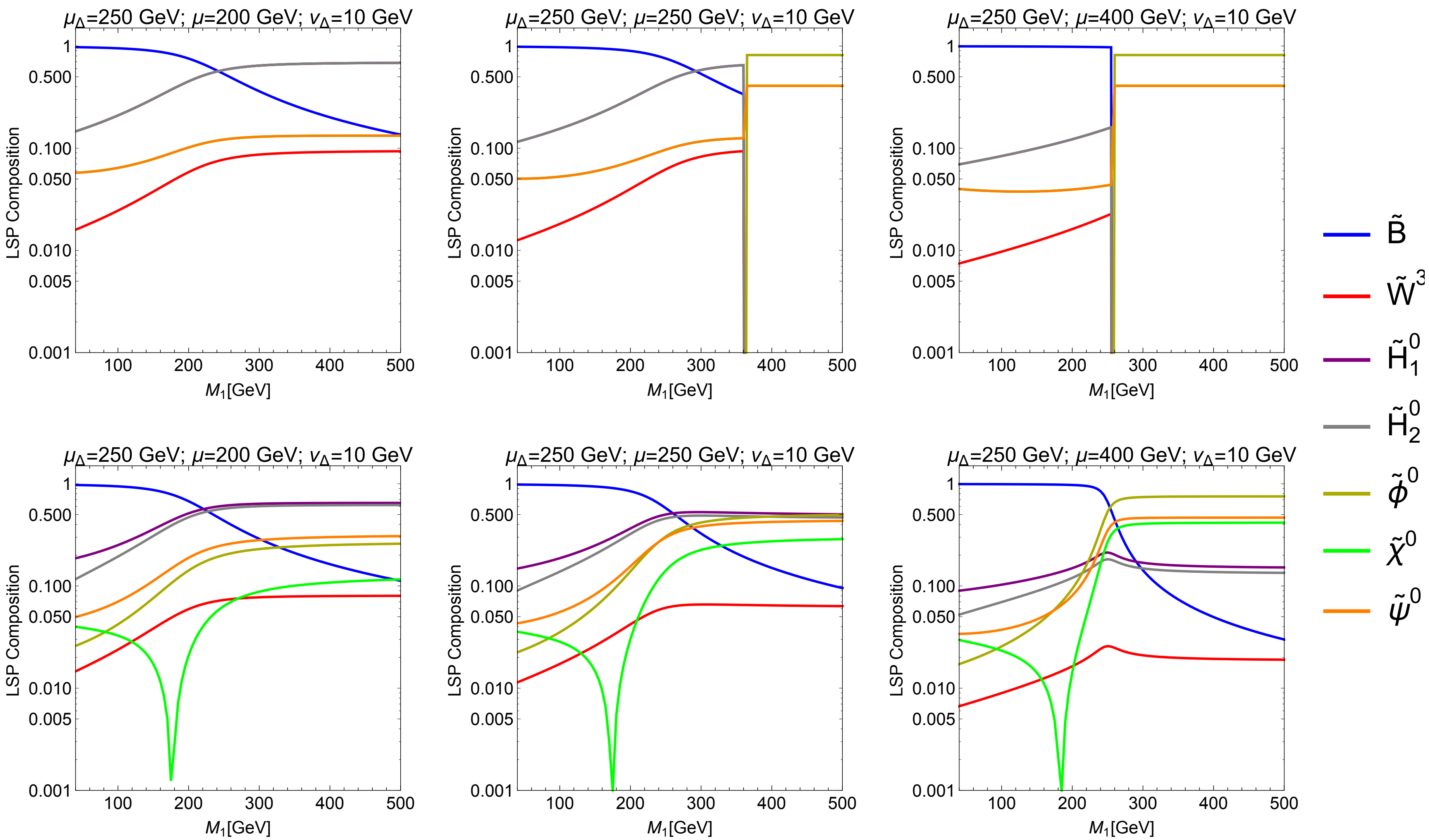
AD, M. García-Pepin, B. Ostdiek, M. Quirós

- Having extra fermionic states can have an impact in the composition and properties of the LSP
- I am going to present different cases where the relic abundance is obtained
- NB: I am deviating from GMSB. i e the gravitino is not the LSP!!!!!! (thanks to E. Pontón)

$$
\mathbf{M} = \begin{pmatrix}
M_1 & 0 & -\frac{1}{\sqrt{2}}g'c_\beta v_H & \frac{\sqrt{2}}{2}g's_\beta v_H & 0 & -g'v_\Delta & g'v_\Delta \\
0 & M_2 & \frac{\sqrt{2}}{2}g_2c_\beta v_H & -\frac{1}{\sqrt{2}}g_2s_\beta v_H & 0 & g_2v_\Delta & -g_2v_\Delta \\
-\frac{1}{\sqrt{2}}g'c_\beta v_H & \frac{1}{\sqrt{2}}g_2c_\beta v_H & -\sqrt{2}\lambda v_\Delta & -\frac{1}{\sqrt{2}}\lambda v_\Delta - \mu & -\lambda s_\beta v_H & 0 & -2\lambda c_\beta v_H \\
\frac{\sqrt{2}}{2}g's_\beta v_H & -\frac{1}{\sqrt{2}}g_2s_\beta v_H & -\frac{1}{\sqrt{2}}\lambda v_\Delta - \mu & -\sqrt{2}\lambda v_\Delta & -\lambda c_\beta v_H & -2\lambda s_\beta v_H & 0 \\
0 & 0 & -\lambda s_\beta v_H & \lambda c_\beta v_H & \mu_\Delta & -\frac{1}{\sqrt{2}}\lambda_3 v_\Delta & -\frac{1}{\sqrt{2}}\lambda_3 v_\Delta \\
g'v_\Delta & g_2v_\Delta & 0 & -2\lambda s_\beta v_H & -\frac{1}{\sqrt{2}}\lambda_3 v_\Delta & 0 & \mu_\Delta - \frac{1}{\sqrt{2}}\lambda v_\Delta \\
g'v_\Delta & -g_2v_\Delta & -2\lambda c_\beta v_H & 0 & -\frac{1}{\sqrt{2}}\lambda_3 v_\Delta & \mu_\Delta - \frac{1}{\sqrt{2}}\lambda_3 v_\Delta & 0
\end{pmatrix}
$$

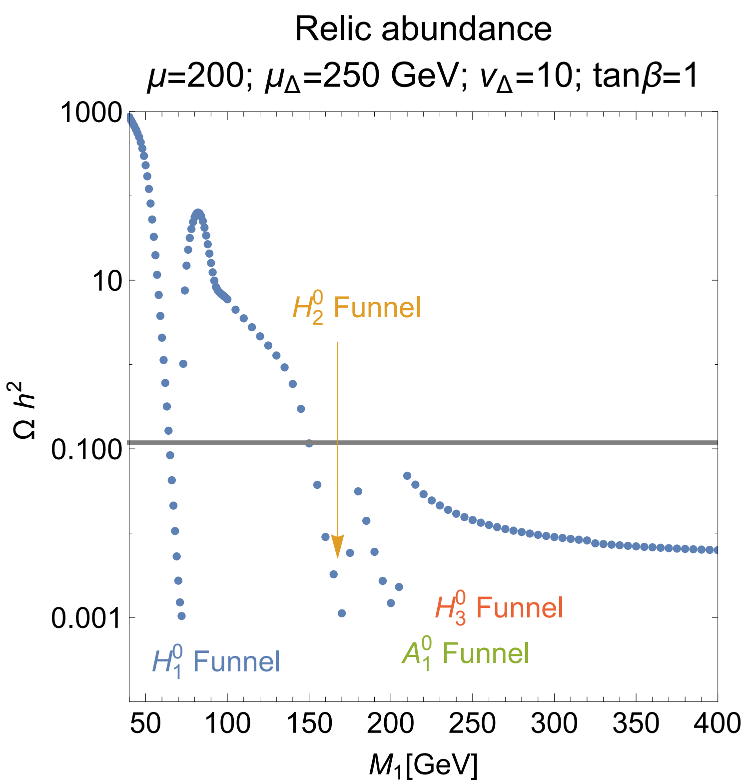
Neutralino Mass-Matrix

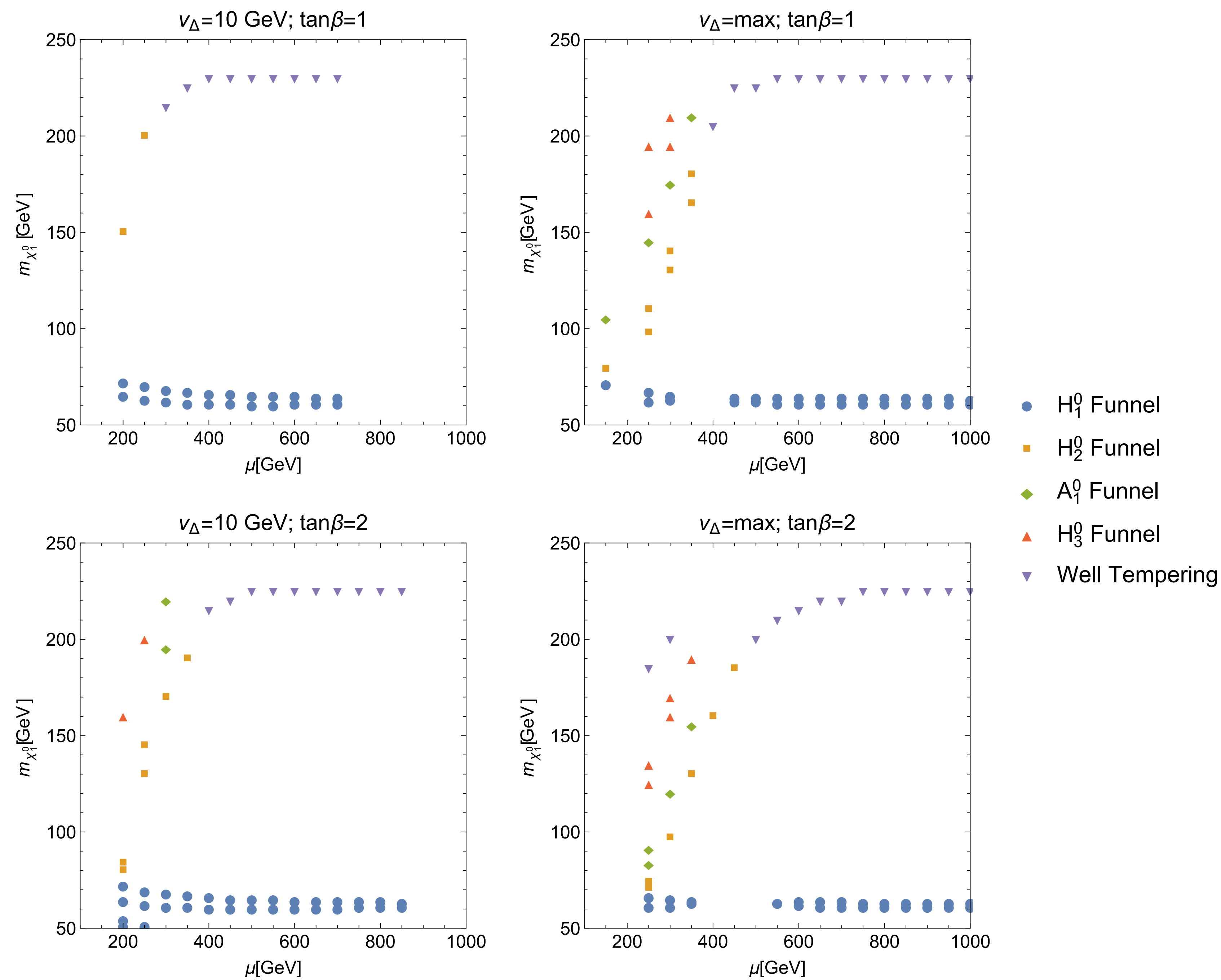
Composition of the LSP



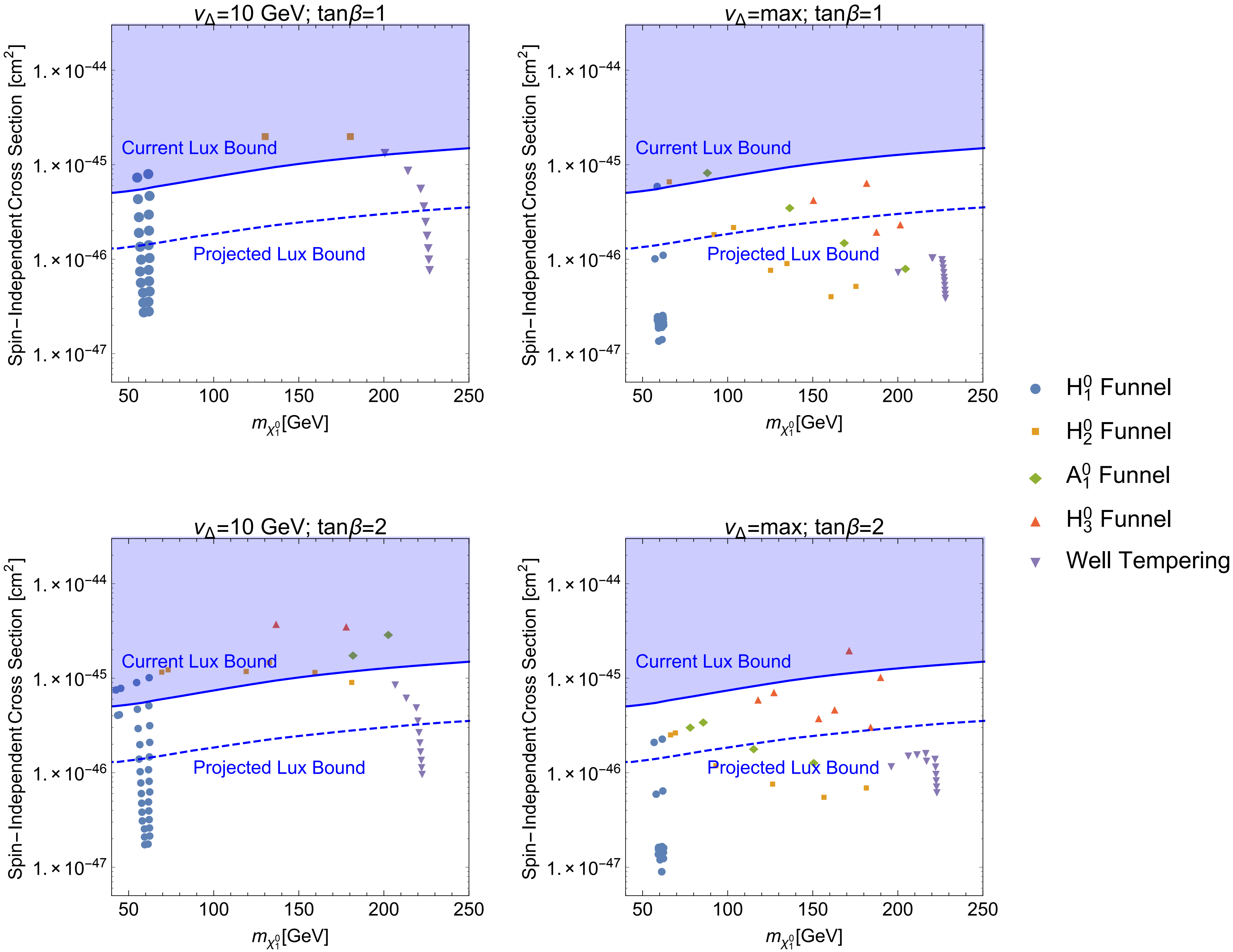
M_2=1 TeV

Relic Abudance

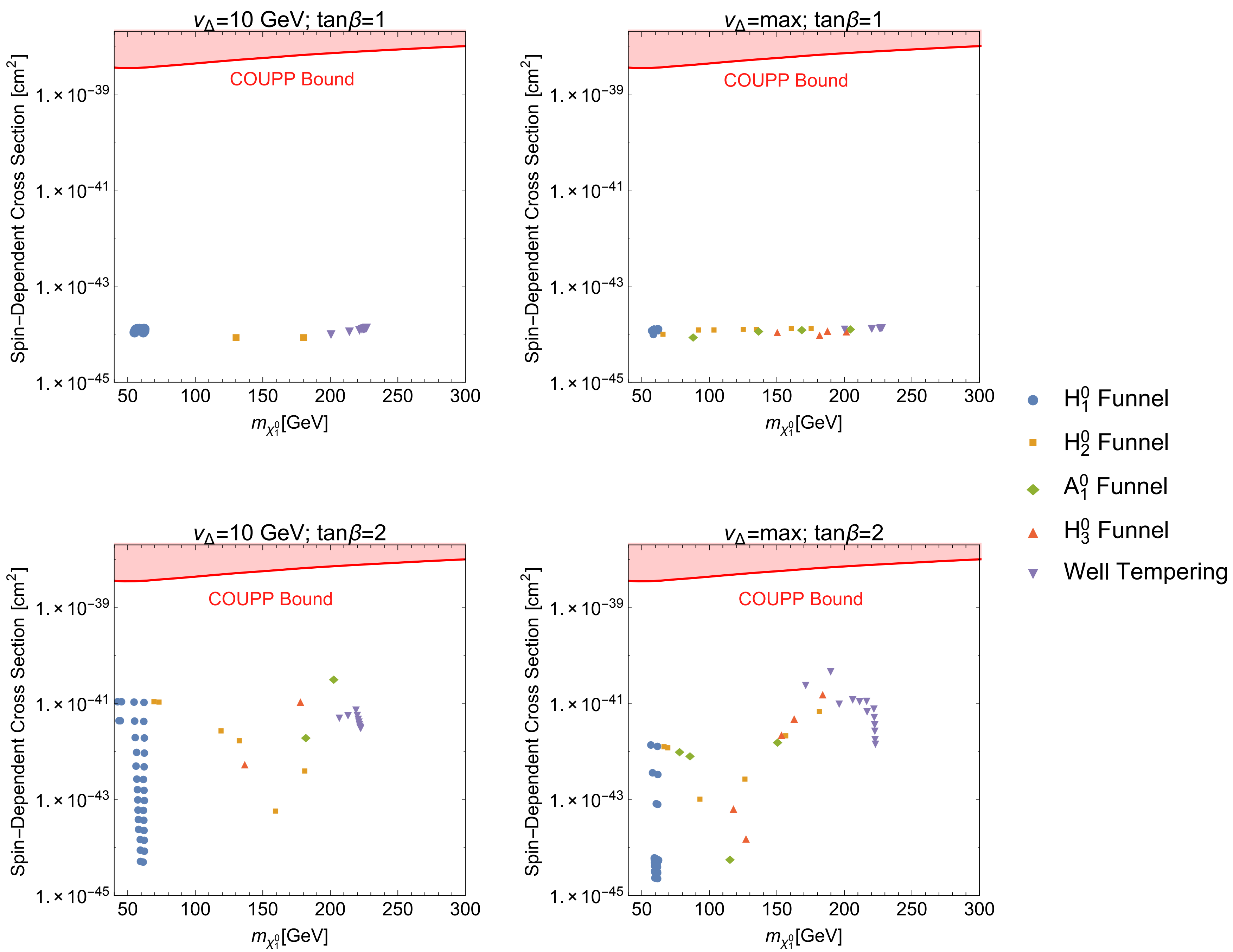




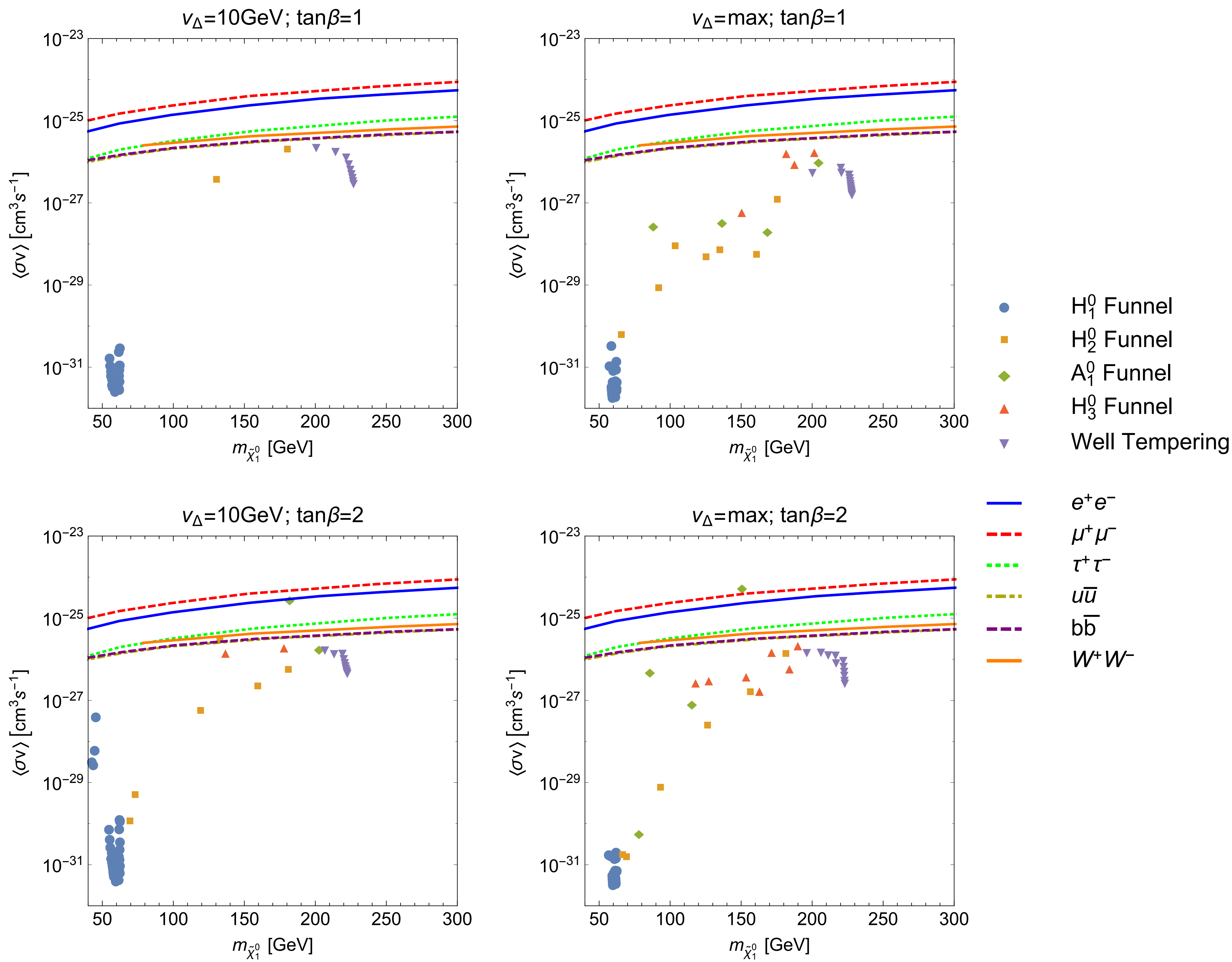
Spin independent xsec



Spin dependent xsec



Indirect detection



Conclusions

- One of the multiple possibilities for physics beyond the SM is an extended Higgs sector
- Extra scalars appear naturally in UV theories attempting to explain the Hierarchy problem
- In this talk I have supposed that supersymmetry is the explanation of the EW scale and moreover that there are triplets coupled to the usual Higgses.

- I have studied the reduction of fine tuning in the case where there is only a triplet of Y=1.

- Indeed one can find regions of the parameter space where there is sensibly much less tuning and the phenomenology of stops can be greatly changed.

- The main drawback is that one has to be careful about contributions to the T-parameter.

- One way to automatically have the T-parameter under control is the GM model.

- I have introduced the SCTM and study how can it be embedded into GMSB

- It naturally leads to a low messenger scale

- But one can successfully have a complete model with low tan β

- Finally I have analyzed the implications that having an extended sector of neutralinos on DM.

- New regions appear that can have very interesting implications for direct and indirect detection.

- The SCTM has very exotic decays for the Higgs sectors that I am currently studying.