SUSY 2024

Theory meets Experiment

Dark Particles at the LHC:

LHC-Friendly Dark Matter Characterization via Non-Linear EFT

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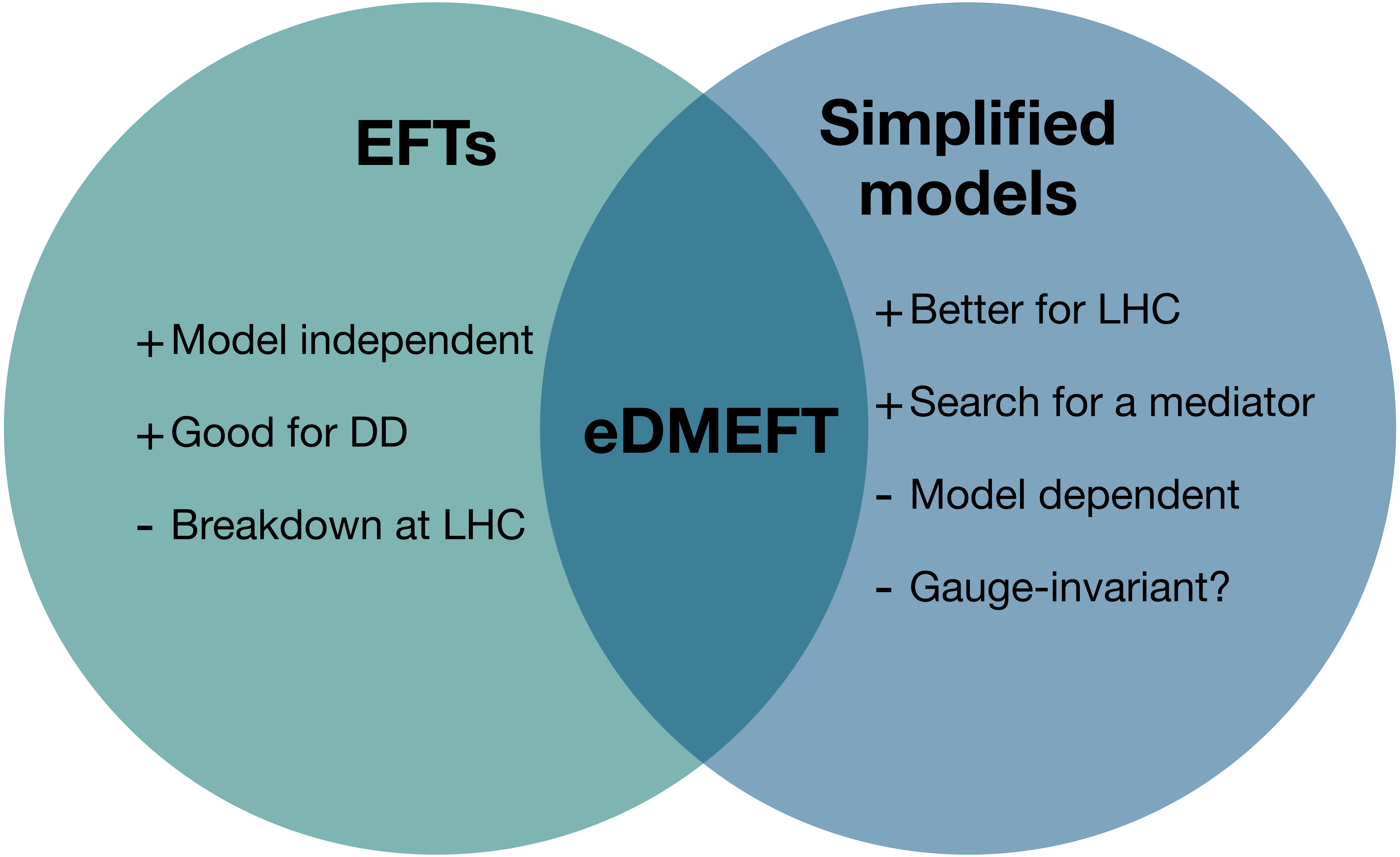
EFT & Simplified Models



Non-linear Approach

- **To solve the dichotomy, recently the 'extended Dark Matter Effective Field Theory' (eDMeft) framework was proposed** (see T.Alanne et al. Eur. Phys. J. C, 80(5):446, 2020 & T.Alanne et al. JHEP, 10:172, 2020)
- **Extended the formalism to two scalar mediators.**
- **With non-linear formalism more representation of scalar mediator can be cover**

Goldstone Matrix

$$\Sigma(x) = e^{i\sigma^a \phi^a(x)/v}$$

$SU(2)_L \times U(1)_Y$

$$\Sigma \to e^{i\varphi_L^a(x)\sigma^a/2}\Sigma e^{-i\varphi_Y(x)\sigma^3/2}$$

$$D_\mu \Sigma = \partial_\mu \Sigma - ig\frac{\sigma^a}{2}W_\mu^a \Sigma + ig'\Sigma\frac{\sigma^3}{2}B_\mu$$

We work adding under this formalism 3 new fields

$$\chi, \quad S_1, \quad S_2$$

eDMEFT

$$\mathcal{O}_d^C\left(h, \mathcal{S}_1, \mathcal{S}_2\right) \equiv \sum_{k=0}^{d} \sum_{j=0}^{d-k} \sum_{i=0}^{j} C_{i,j-i}^{(k)} h^k \mathcal{S}_1^i \mathcal{S}_2^{j-i}$$

$$\mathcal{L} = \mathcal{L}_{\text{gauge-ferm}}^{\text{SM}} + \bar{\chi} i \not{\partial} \chi - \mathcal{O}_2^y(h, \mathcal{S}_1, \mathcal{S}_2) \bar{\chi}_L \chi_R + \text{h.c.}$$ → **DM coupling to scalars**

$$+\mathcal{O}_5^\lambda(h, \mathcal{S}_1, \mathcal{S}_2)$$ → **All Scalar interactions**

$$+\frac{v^2}{4} \text{Tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] \mathcal{O}_3^\kappa(h, \mathcal{S}_1, \mathcal{S}_2)$$ → $W^+W^-\phi\,, ZZ\phi\ldots$

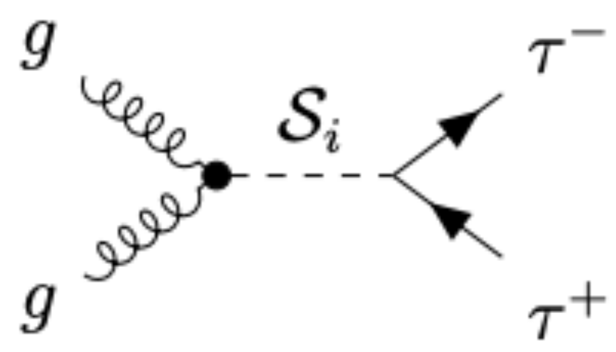
$$+i\frac{v^2}{4} \text{Tr}\left[\Sigma^\dagger (D^\mu \Sigma) \sigma^3\right] \left(\partial_\mu h\, \mathcal{O}_2^s(h, \mathcal{S}_1, \mathcal{S}_2) + \partial_\mu \mathcal{S}_1\, \mathcal{O}_2^{s1}(h, \mathcal{S}_1, \mathcal{S}_2) + \partial_\mu \mathcal{S}_2\, \mathcal{O}_2^{s2}(h, \mathcal{S}_1, \mathcal{S}_2)\right)$$ → $Z\phi_1\phi_2\ldots\phi_m$

$$-\sum_\phi \frac{\phi}{16\pi^2}\left[g'^2 c_B^\phi B^{\mu\nu} B_{\mu\nu} + g^2 c_W^\phi W^{I\mu\nu} W_{\mu\nu}^I + g_s^2 c_G^\phi G^{a\mu\nu} G_{\mu\nu}^a\right]$$ → $GG\phi, W^+W^-\phi$

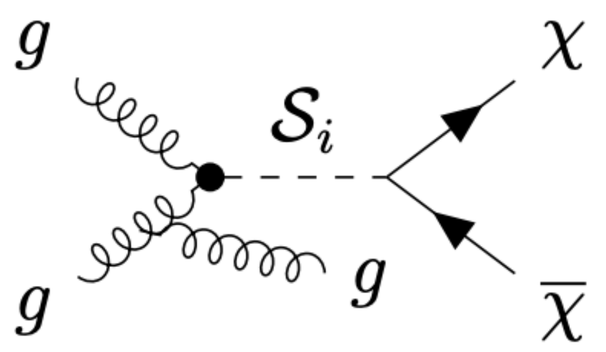
$$-\frac{v}{\sqrt{2}}\left(\left(\bar{u}_L^{(i)} \quad \bar{d}_L^{(i)}\right) \Sigma \begin{pmatrix} Y_{ij}^u u_R^{(j)} \\ Y_{ij}^d d_R^{(j)} \end{pmatrix} \mathcal{O}_2^{c_q}\left(h, \mathcal{S}_1, \mathcal{S}_2\right) + \bar{\ell}_L^{(i)} \Sigma Y_{ij}^\ell \ell_R^{(j)} \mathcal{O}_2^{c_\ell}\left(h, \mathcal{S}_1, \mathcal{S}_2\right) + \text{h.c.}\right)$$ → $\bar{f}f\phi$

Possible signatures

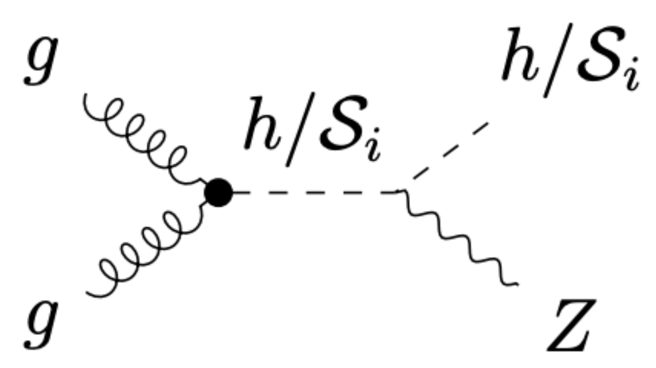
Collider Signatures



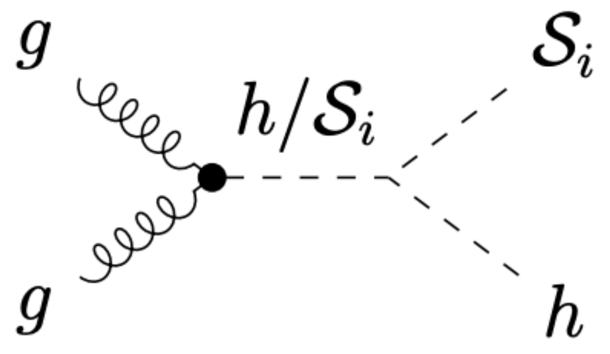
τ **Pair production**



Mono-jet

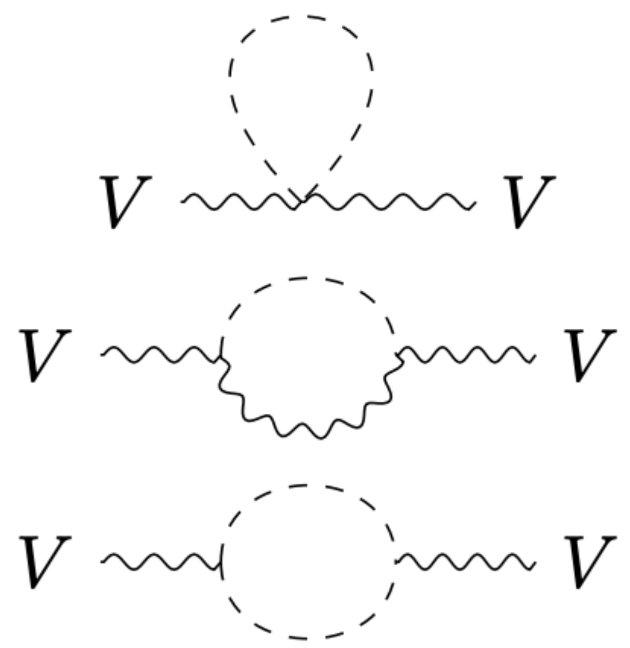


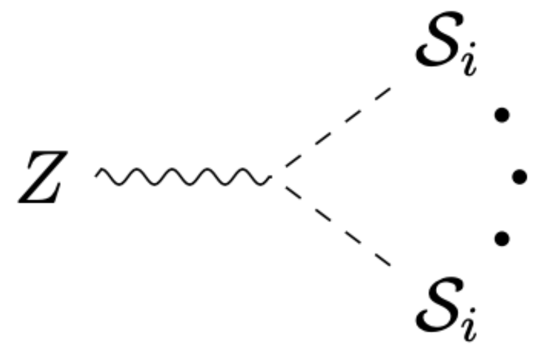
Mono-Z



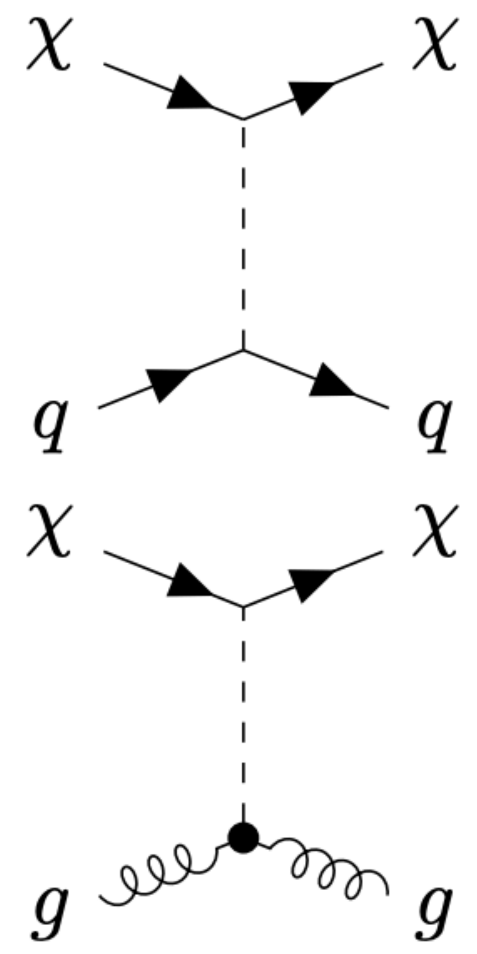
Mono-h

EWPO

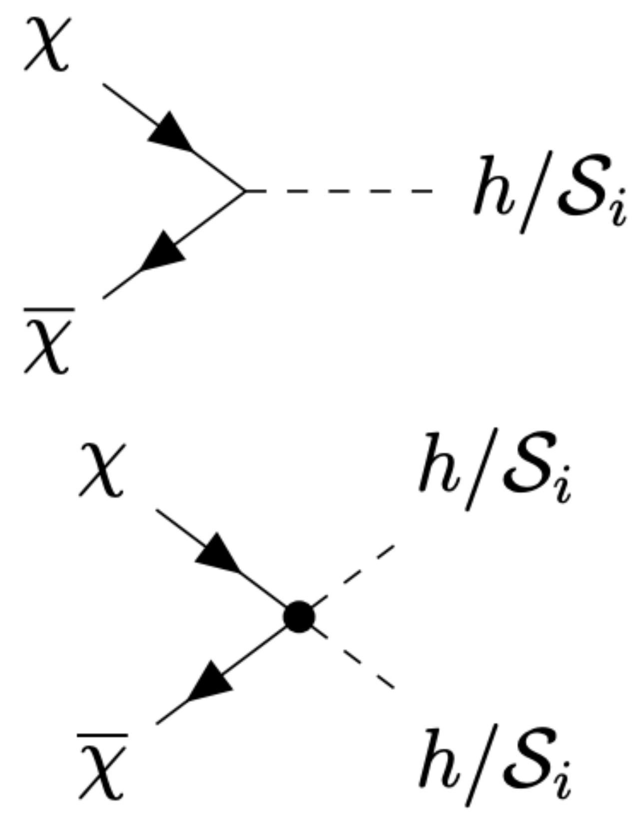




Direct Detection



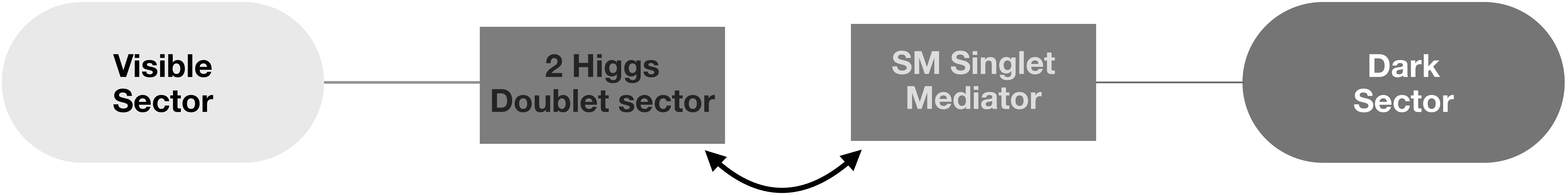
Relic Density



A simplified model

2HDM+Pseudoscalar

- **Good compromise between theoretical consistency and predictivity (still limited number of free parameters);**
- **Benchmark for a large variety of collider studies;**
- **Interesting Dark Matter phenomenology.**



Mass Mixing

LHC Dark Matter Working Group: Phys. Dark. Univ. 27 (2020) 100351

(see also e.g. M. Bauer et al. JHEP 05 (2017) 138, T. Robens Symmetry 13 (2021) 12, 2341)

2HDM+P

Z_2 symmetry for 2HDM potential

$$V_{2HDM} = m_1^2\phi_1^\dagger\phi_1 + m_2^2 m_1^2\phi_2^\dagger\phi_2 - m_3^2\left(\phi_1^\dagger\phi_2 + h.c.\right) + \frac{1}{2}\lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\phi_2^\dagger\phi_2\right)^2 + \frac{1}{2}\lambda_5\left(\left(\phi_1^\dagger\phi_2\right)^2 + h.c.\right)$$
$$+\lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right)$$

$$V\left(\Phi_1, \Phi_2, a_0\right) = V_{2HDM}\left(\phi_1, \phi_2\right) + V_{self}\left(a_0\right) + V_{a_0,2HDM}\left(\phi_1, \phi_2, a_0\right)$$

$$V_{self}\left(a_0\right) = \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{1}{4}\lambda_a a_0^4$$

$$\Phi_j = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\hat{\phi}_j^+ \\ v_j + \hat{\rho}_j + i\hat{\eta}_j\end{pmatrix} \quad \text{with } j = 1,2$$

$$V_{a_0,2HDM}\left(\phi_1, \phi_2, a_0\right) = \kappa\left(ia_0\phi_1^\dagger\phi_2 + h.c.\right) + \lambda_{1P}a_0^2\phi_1^\dagger\phi_1 + \lambda_{2P}a_0^2\phi_2^\dagger\phi_2$$

Mixing and EW Symmetry Breaking

$$\langle \phi_1 \rangle = v_1$$

$$\frac{v_2}{v_1} = \tan\beta$$

$$\langle \phi_2 \rangle = v_2$$

$$(\phi_1, \phi_2, a_0) \longrightarrow (h, a, H, A, H^{\pm})$$

Mixing and Yukawa sector

$$\begin{pmatrix} A^0 \\ a^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix} \longrightarrow L_{Yuk} = \sum_f \frac{m_f}{v} \left[g_{Hff} H\bar{f}f + g_{hff} h\bar{f}f - i g_{aff} a\bar{f}\gamma_5 f - i g_{Aff} A\bar{f}\gamma_5 f \right]$$

	Type I	Type II	Type X	Type Y
g_{htt}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{hbb}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$
$g_{h\tau\tau}$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{Htt}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{Hbb}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$
$g_{H\tau\tau}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{A^0tt}	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$
g_{A^0bb}	$-\frac{1}{\tan\beta}$	$\tan\beta$	$-\frac{1}{\tan\beta}$	$\tan\beta$
$g_{A^0\tau\tau}$	$-\frac{1}{\tan\beta}$	$\tan\beta$	$\tan\beta$	$-\frac{1}{\tan\beta}$

Alignment limit $\longrightarrow$

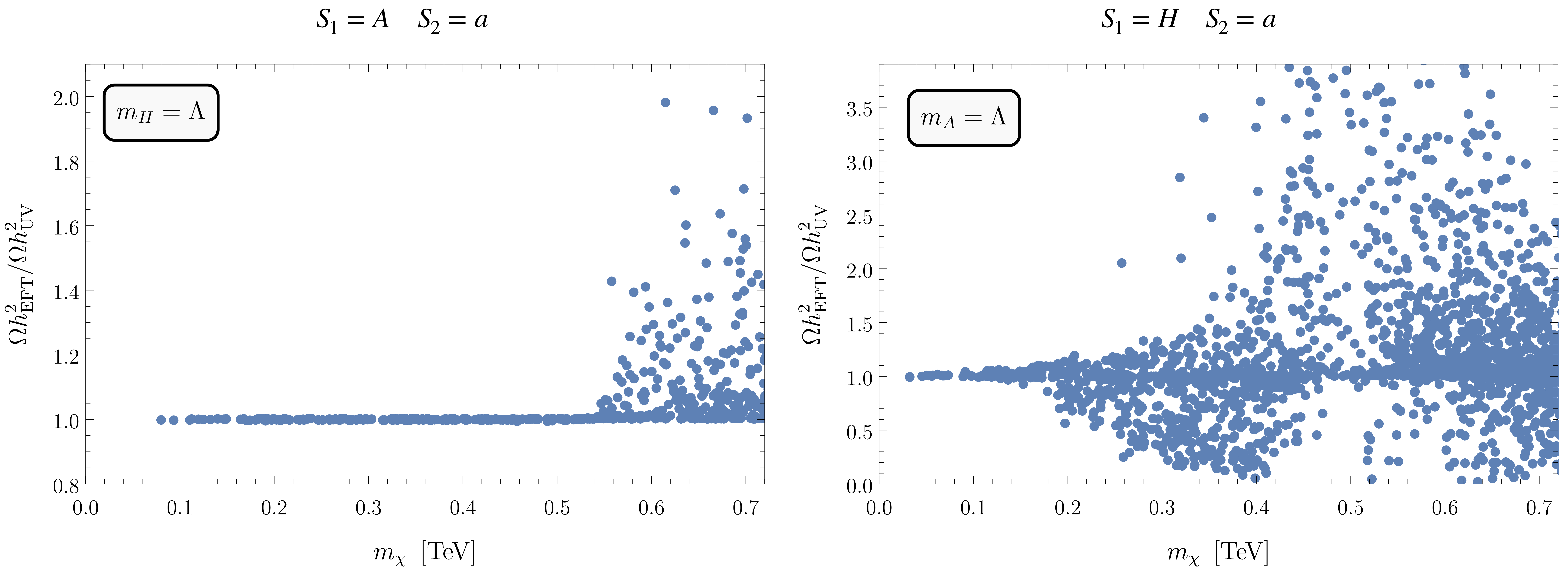
$$g_{hff} \to 1$$

$$g_{Aff} = \cos\theta g_{A^0ff}$$

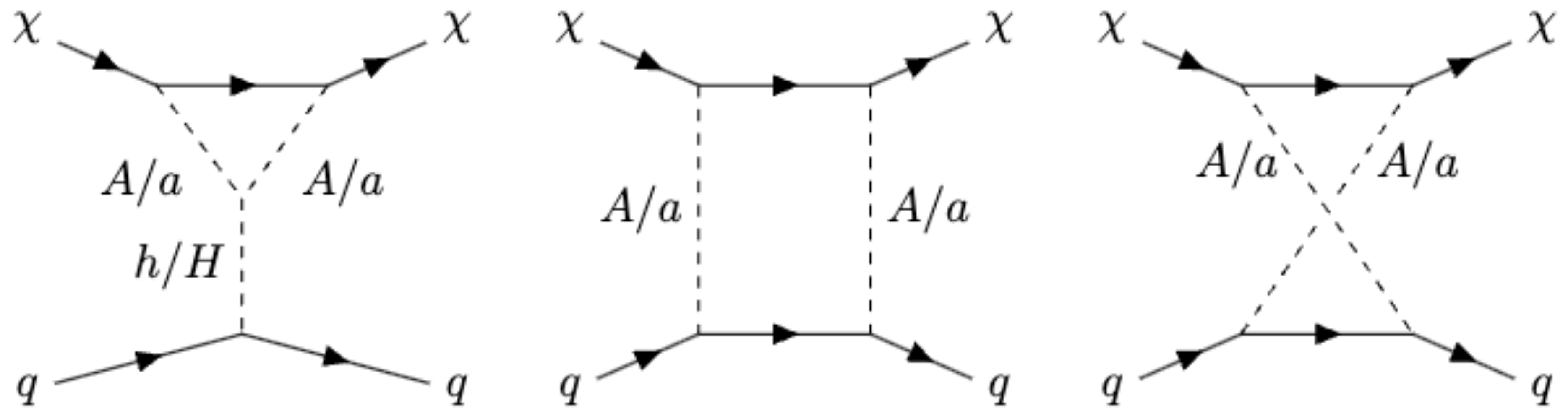
$$g_{aff} = \sin\theta g_{A^0ff}$$

Relic Density

Better results for double pseudoscalar setup

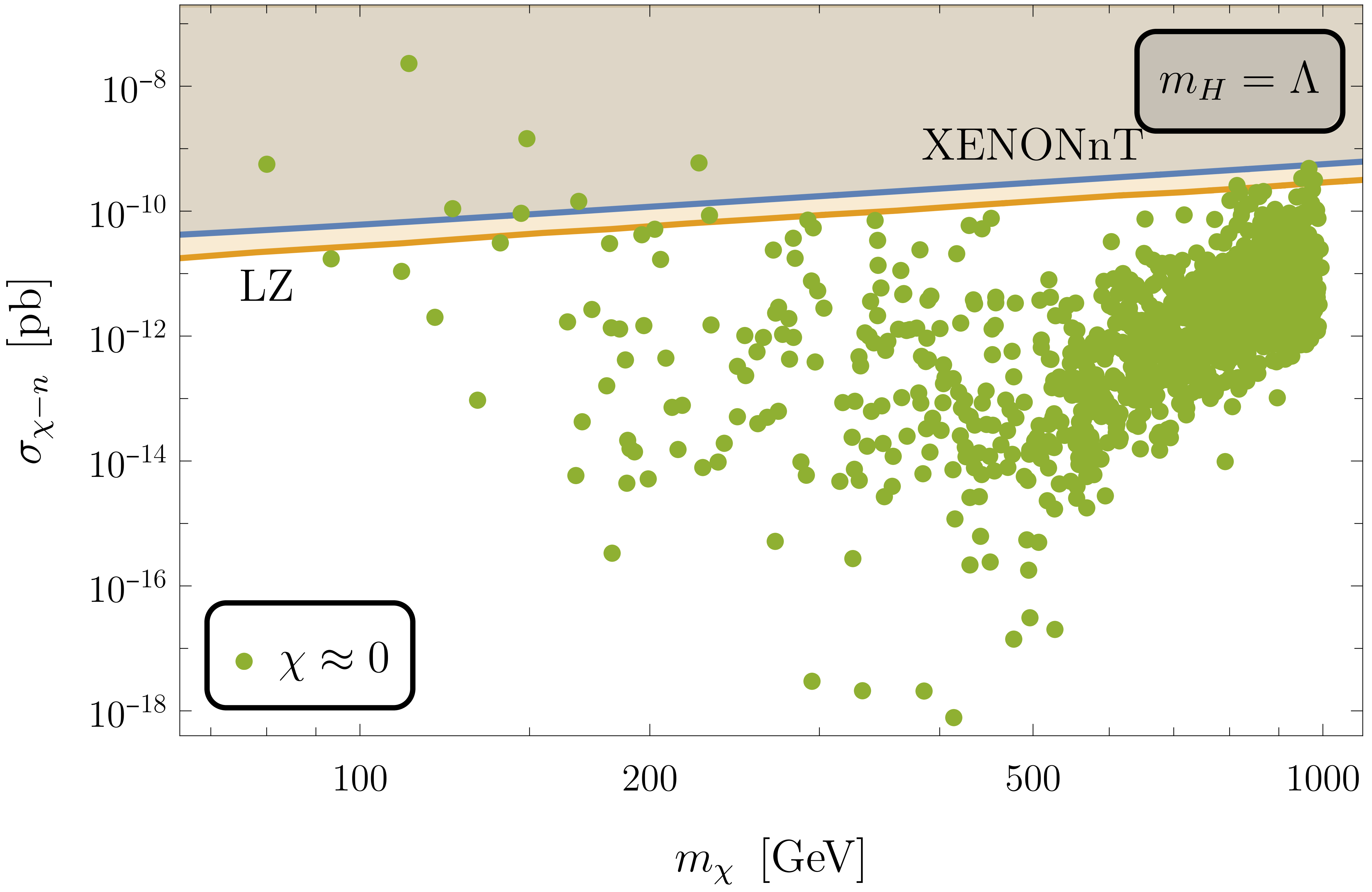


Direct Detection

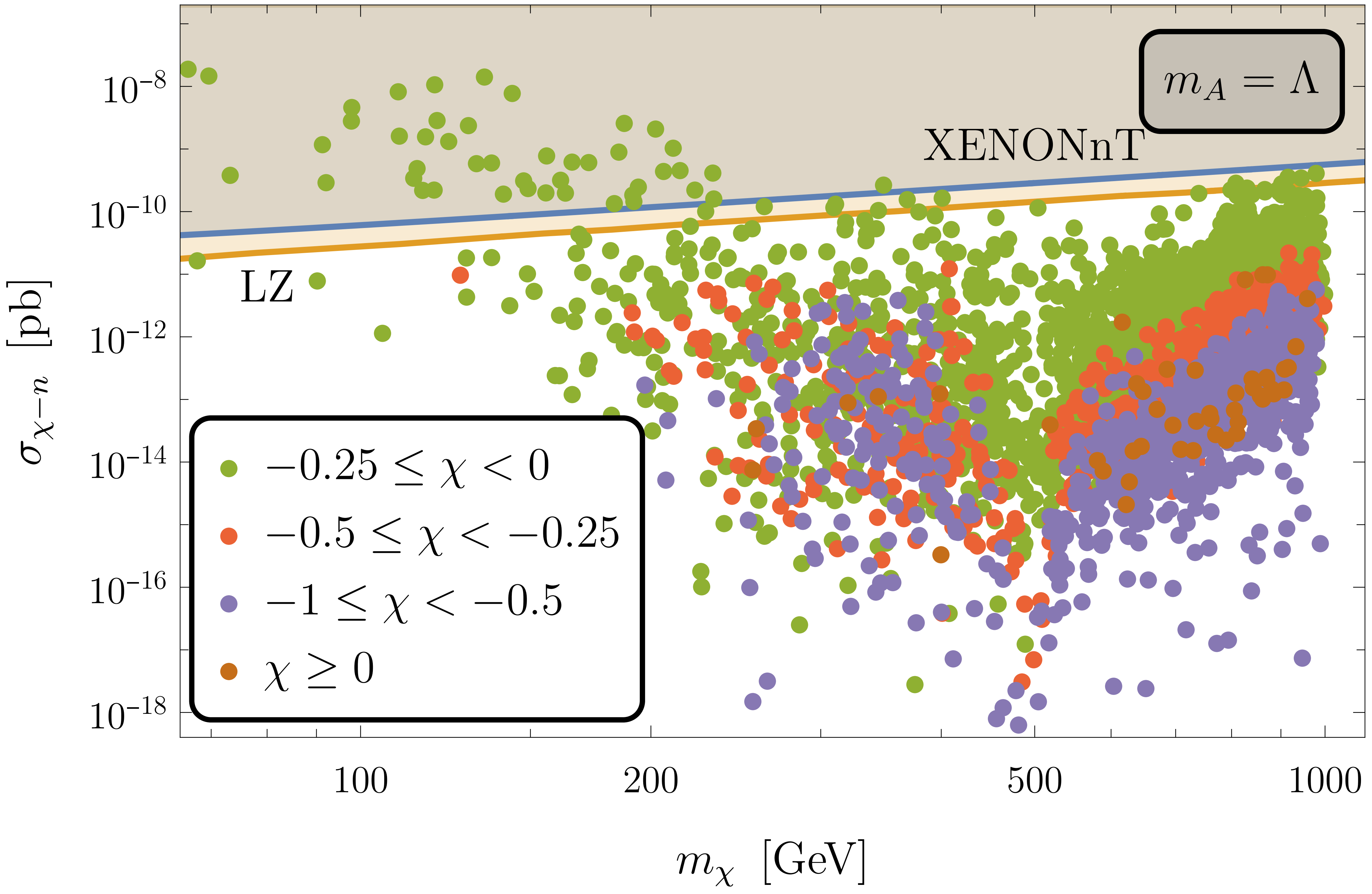


$$\chi \equiv \left(\sigma^{\rm EFT}_{\chi-n} - \sigma^{\rm UV}_{\chi-n}\right)/\sigma^{\rm UV}_{\chi-n}$$

$S_1 = A \quad S_2 = a$



$S_1 = H \quad S_2 = a$



Maximum Gap

EWPO

$$\Delta\rho = \frac{\alpha_{\rm QED}\left(m_Z^2\right)}{16\pi^2 m_W^2\left(1-m_W^2/m_Z^2\right)}\left[f\left(m_{H^\pm}^2, m_H^2\right) + c_\theta^2\left(f\left(m_{H^\pm}^2, m_A^2\right) - f\left(m_A^2, m_H^2\right)\right) + s_\theta^2\left(f\left(m_{H^\pm}^2, m_P^2\right) - f\left(m_P^2, m_H^2\right)\right)\right]$$

+

Invisible Higgs

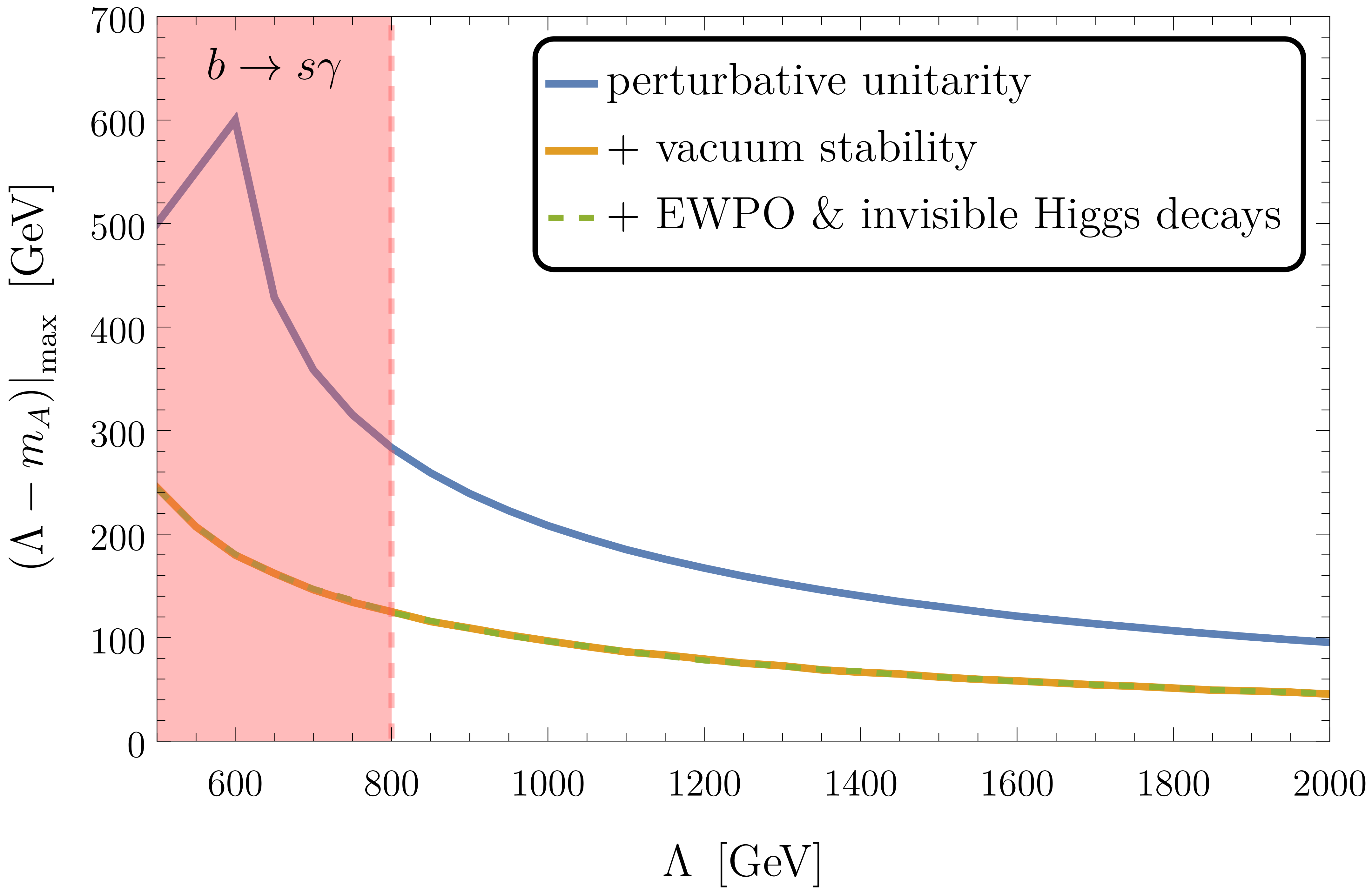
$$\Gamma_h^{\rm BSM} = \sum_{\phi_1,\phi_2}\Gamma\left(h\to\phi_1\phi_2\right)$$

+

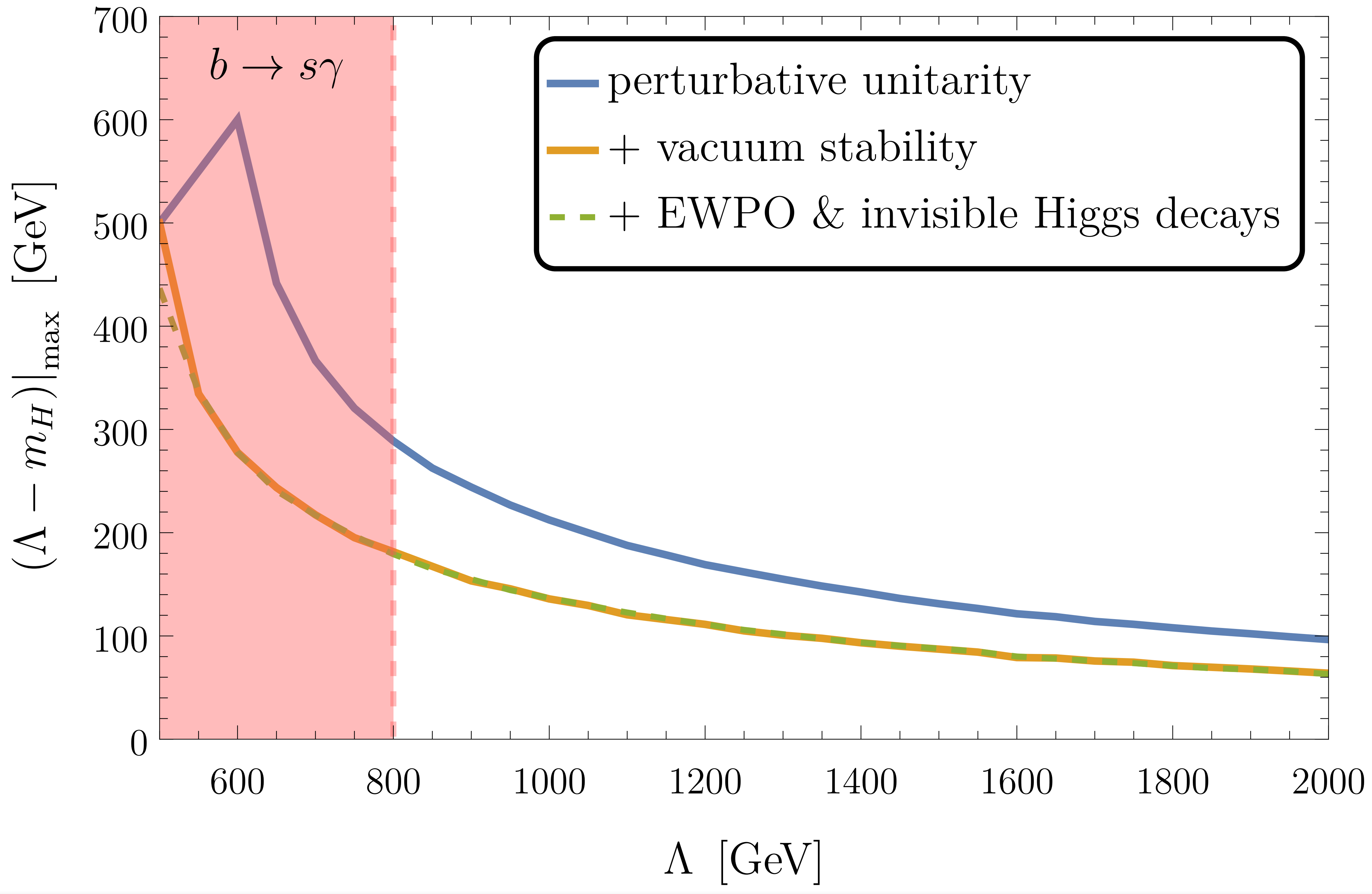
Perturbative unitarity & Vacuum stability

See e.g. G. Arcadi et al. Phys. Rev. D, 108(5):055010, 2023 for more detail

$S_1 = A \quad S_2 = a$

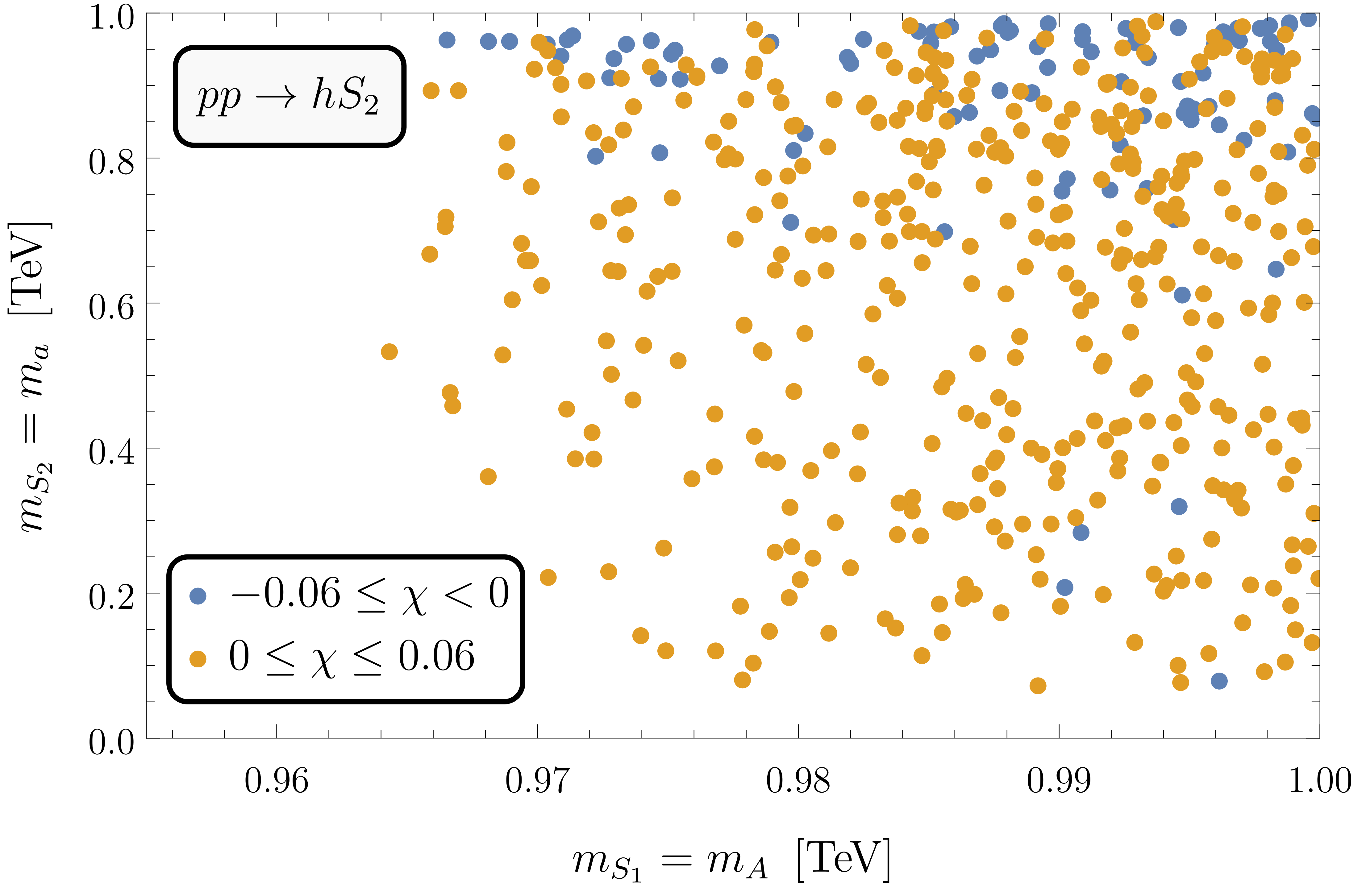


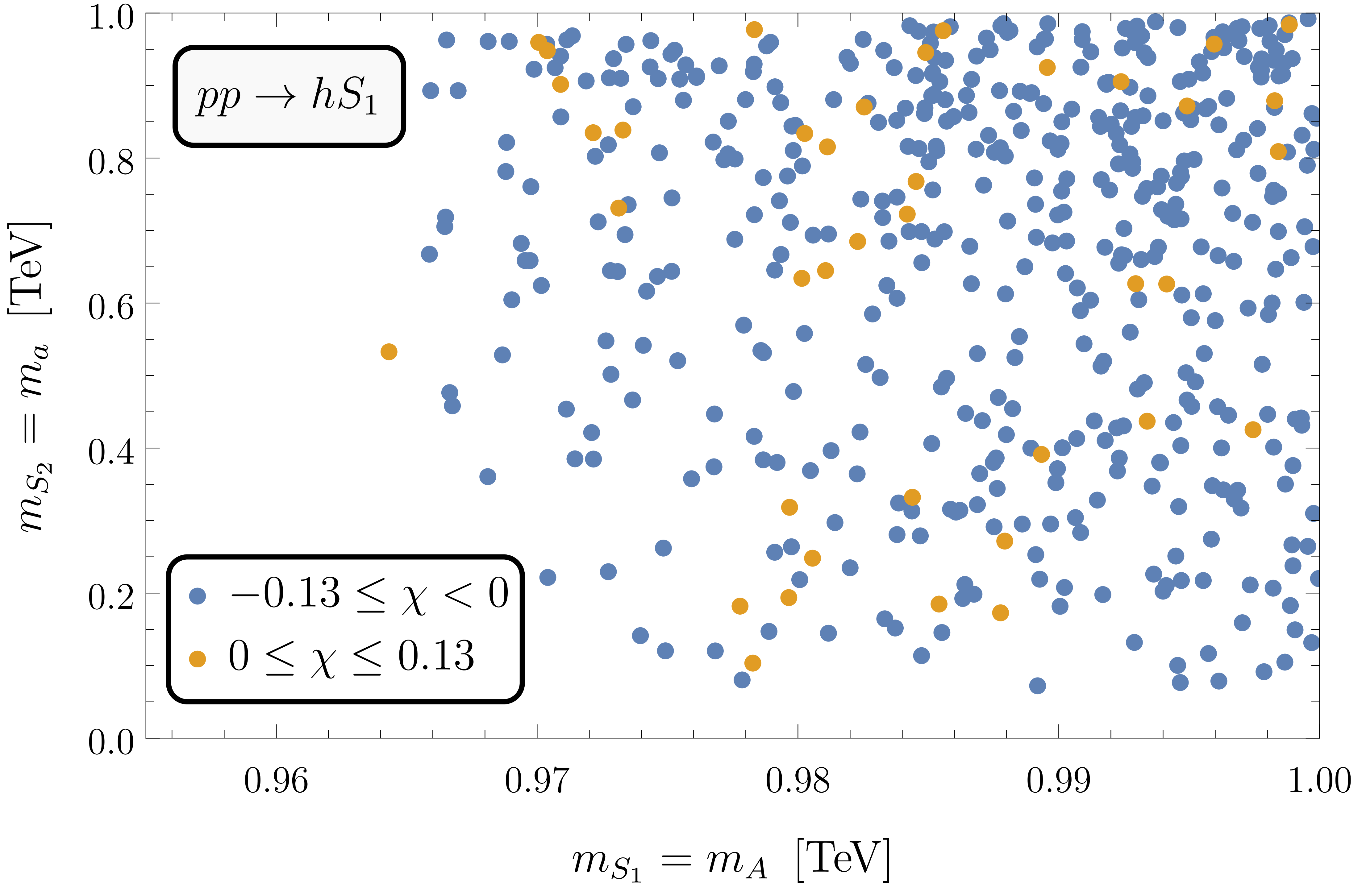
$S_1 = H \quad S_2 = a$



Mono-Higgs

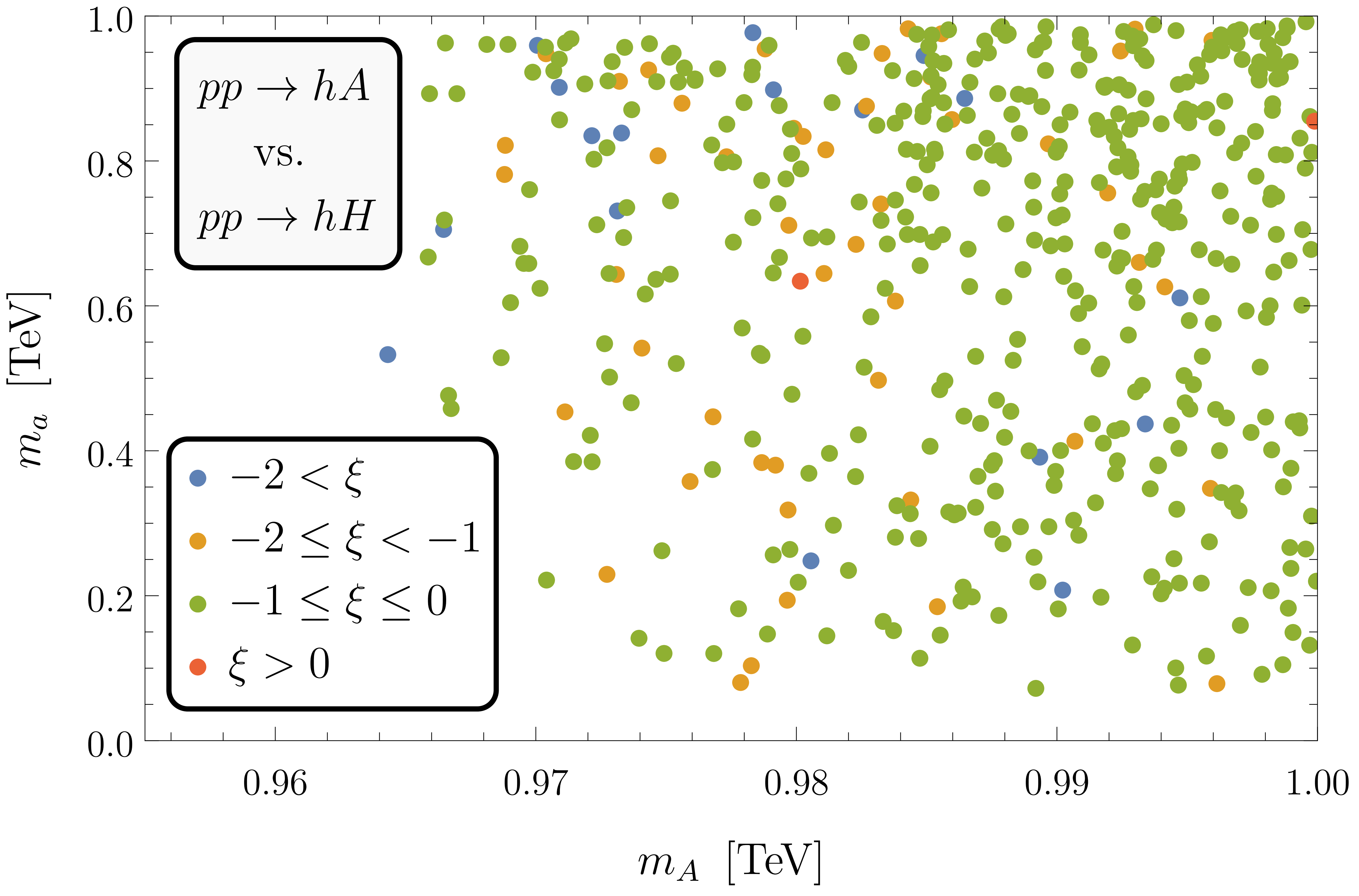
$$\chi \equiv \left(\sigma_{pp}^{\rm EFT} - \sigma_{pp}^{\rm UV}\right)/\sigma_{pp}^{\rm UV}$$

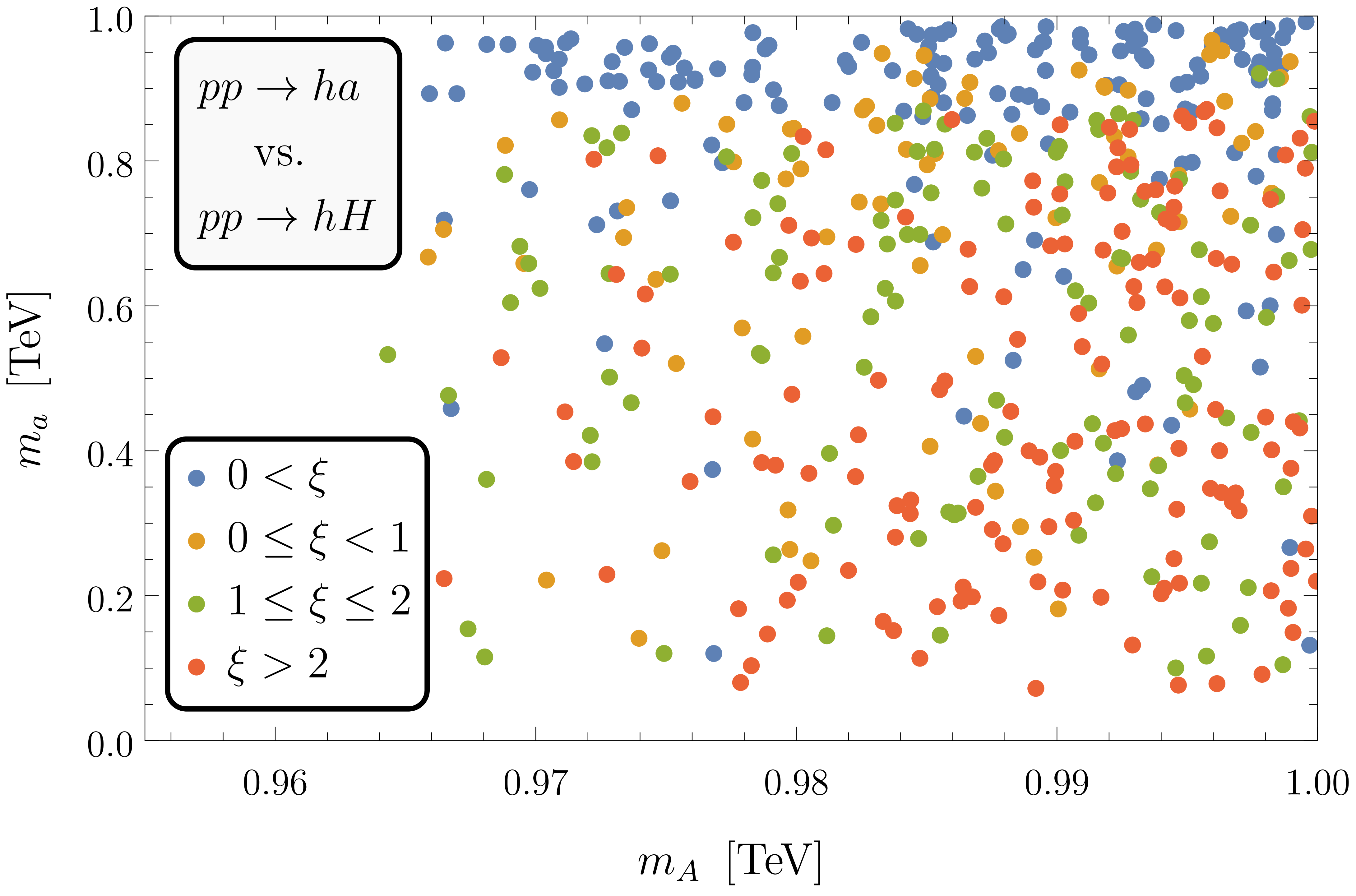




Mono-Higgs

$$\xi \equiv \log_{10}\left(\sigma^{\text{UV}}_{pp\to h\phi}/\sigma^{\text{UV}}_{pp\to hH}\right)$$





Conclusions

- **We extend eDMEFT to capture more LHC signatures**
- **We compare eDMEFT with simplified models to show the validity**
- **Final Steps:**
  - Extended comparison to other models
  - Can we detect if our singlets come from a multiplet or not?

Back Up

Mono-Z

$pp \to ZS_1$
$\chi < 7$
$7 \leq \chi < 8.5$
$8.5 \leq \chi \leq 10$
$\chi > 10$
$m_{S_1} = m_A$ [TeV]
$m_{S_2} = m_a$ [TeV]
0.96
0.97
0.98
0.99
1.00
0.0
0.2
0.4
0.6
0.8
1.0
$pp \to ZS_2$
$\chi < -0.99$
$-0.99 \leq \chi < 0$
$0 \leq \chi \leq 0.99$
$\chi > 0.99$

Mono-Z

$pp \to ZA$
vs.
$pp \to ZH$
$-0.1 < \xi$
$-0.1 \leq \xi < 0$
$0 \leq \xi \leq 0.1$
$\xi > 0.1$
m_a [TeV]
m_A [TeV]
1.0
0.8
0.6
0.4
0.2
0.0
0.96
0.97
0.98
0.99
1.00
$pp \to Za$
vs.
$pp \to ZH$
$0 < \xi$
$0 \leq \xi < 1$
$1 \leq \xi \leq 2$
$\xi > 2$

Toy Model

$$-\mathscr{L} \supset \mu_\Phi^2 \; \Phi \;^2 + \lambda_\Phi \; \Phi \;^4 + \mu_S^2 \; S \;^2 + \lambda_S \; S \;^4 + \lambda_{\Phi S} \; \Phi \;^2 \; S \;^2 + \mu_a^2 a^2$$

$$-\mathscr{L} \supset y_{\chi S} \overline{\chi_L} S \chi_R + \sum_O y_{\mathcal{Q} S} \overline{\mathcal{Q}_L} S \mathcal{Q}_R + h.c.$$

With heavy chiral quarks $\mathcal{Q} = \mathscr{B}, \mathscr{T}$

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	global $U(1)$
S	$\mathbf{1}$	$\mathbf{1}$	0	+1
$\mathcal{T}_L$	$\mathbf{3}$	$\mathbf{1}$	4/3	+1/2
$\mathcal{T}_R$	$\mathbf{3}$	$\mathbf{1}$	4/3	−1/2
$\mathcal{B}_L$	$\mathbf{3}$	$\mathbf{1}$	4/3	+1/2
$\mathcal{B}_R$	$\mathbf{3}$	$\mathbf{1}$	4/3	−1/2
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	+1/2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	−1/2

$$\Phi = \begin{pmatrix} G^+ \\ \left(v_h + h + iG^0\right)/\sqrt{2} \end{pmatrix} \quad , \quad S = \frac{1}{\sqrt{2}}\left(v_s + s + ia\right)$$