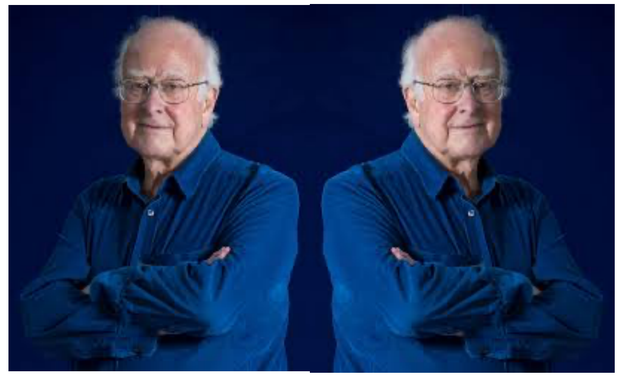
The Twin Higgs



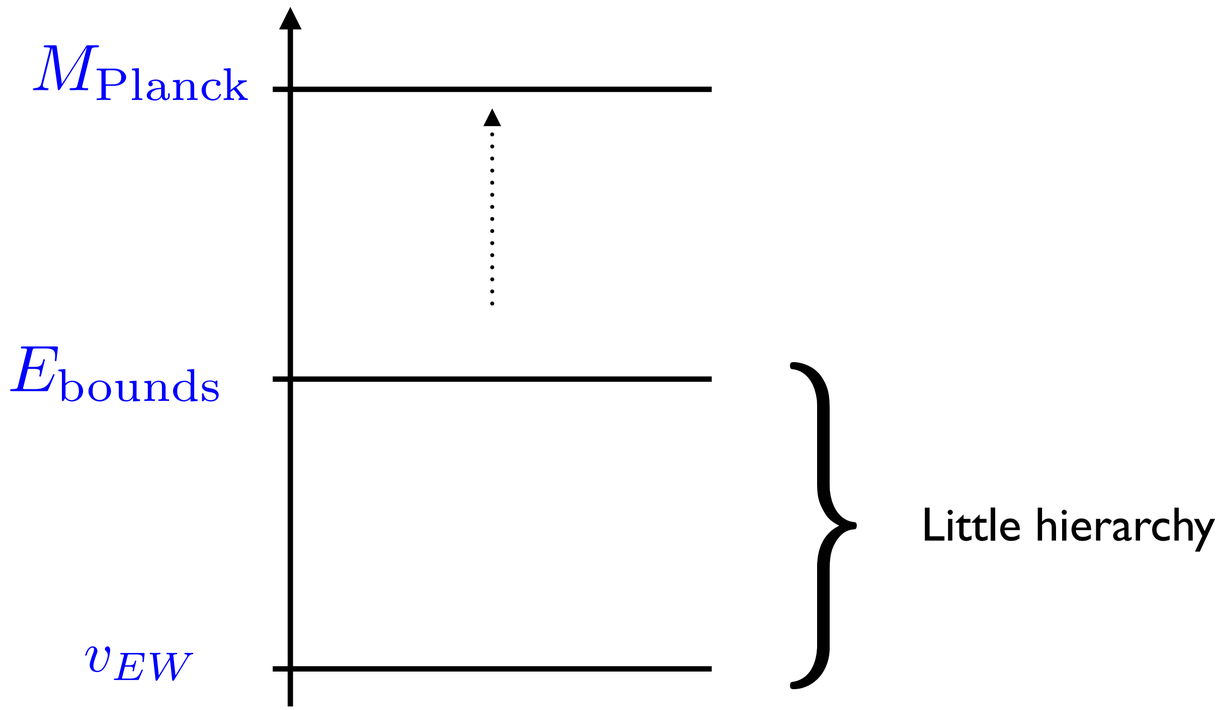
Gustavo Burdman

University of São Paulo

Higgs@Capri2025

Naturalness and the LHC

Is the electroweak scale natural ? Can we explain $m_h \ll \Lambda_{\rm SM} \simeq$ few TeV ?



Naturalness and the LHC

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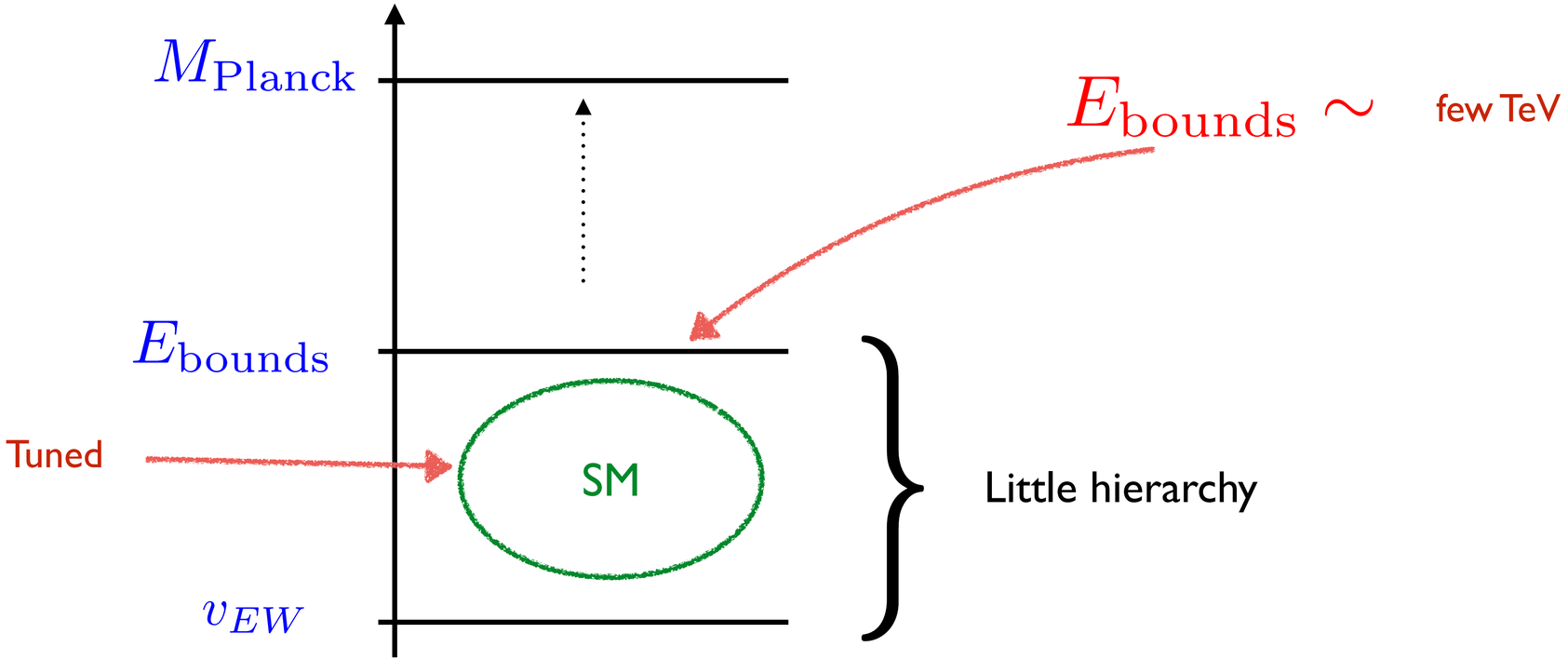
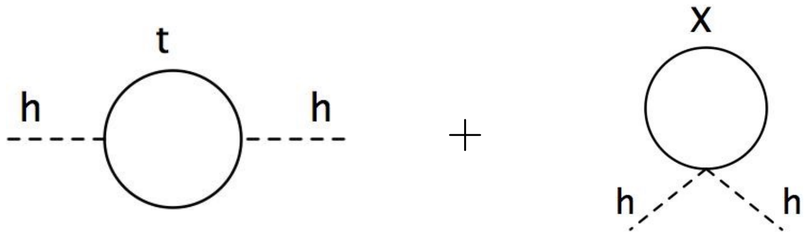


Neutral Naturalness and the LHC

UV sensitivity of m_h^2 is dominated by top quark

E.g.:



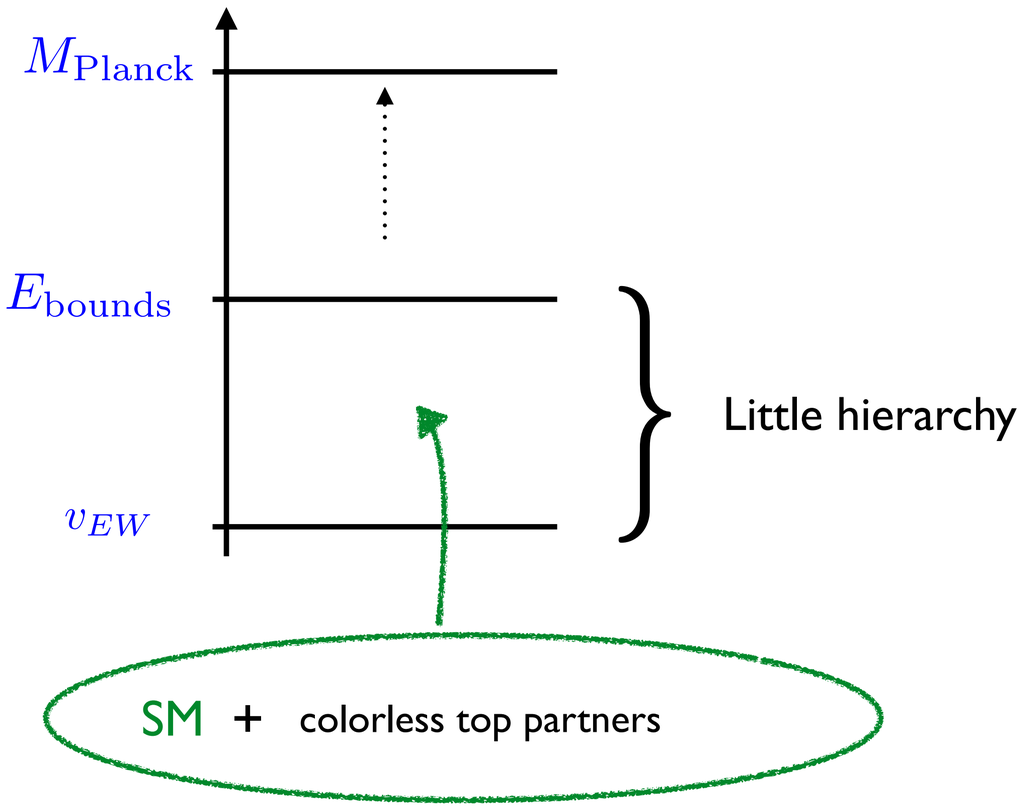
Top partners X carry color ⇒ they are easily produced at the LHC

But, <u>top partners need not carry color!</u> If the symmetry protecting m_h^2 does not commute with $SU(3)_c$

E.g. if it exchanges $SU(3)_c \to SU(3)'$ $\Rightarrow$ X does not carry $SU(3)_c$ color but $SU(3)'$

Neutral Naturalness

Neutral Naturalness Models



<u>The Twin Higgs</u>

Higgs is a pNGB

Chacko, Goh, Harnik, 0506256

<u>Folded Supersymmetry</u>

Higgs protected by SUSY

GB, Chacko, Goh, Harnik,0609152

The Twin Higgs

- The Higgs is a pNGB from a spontaneously broken global symmetry at some scale f:

$$SU(4) \to SU(3) \qquad \Rightarrow \text{7 NGBs. 4 of them will be the Higgs doublet } \begin{pmatrix} \phi_3 + i\phi_4 \\ \phi_1 + i\phi_2 \end{pmatrix}$$

- We gauge an $SU(2)_A \times SU(2)_B$ subgroup of $SU(4)$ such that the $\mathbf{4}$ of $SU(4)$ splits as

$$\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad \text{choosing } \langle \mathcal{H} \rangle \text{ so that } H_A \text{ is (approximately) the SM Higgs doublet.}$$

- But the *partial* gauging of $SU(4)$ breaks it *explicitly.* This generates a UV sensitive $V(\mathcal{H})$ through gauge loops

$$\frac{9}{64\pi^2}\left(g_A^2 H_A^\dagger H_A \Lambda_A^2 + g_B^2 H_B^\dagger H_B \Lambda_B^2\right)$$

- If we impose a Z_2 exchange symmetry to force $g_A = g_B = g$ and $\Lambda_A = \Lambda_B = \Lambda$ we obtain

$$\frac{9\, g^2}{64\pi^2}\left(\mathcal{H}^\dagger \mathcal{H}\right)\ \Lambda^2 \qquad \text{which is } SU(4) \text{ symmetric so it doesn't contribute to } m_h^2$$

The Twin Higgs

Mirror Twin Higgs: duplicate all the SM interactions as in $SM_A \times SM_B \times Z_2$

$$SU(3)_A \times SU(2)_A \times U(1)_A \times SU(3)_B \times SU(2)_B \times U(1)_B \times Z_2$$

For every SM interaction there is a twin particle with the analogous twin quantum numbers

In the non-linear representation we have $\mathcal{H} = e^{i\pi^{\hat{a}}(x)t^{\hat{a}}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f + \frac{\sigma(x)}{\sqrt{2}} \end{pmatrix}$ where the $t^{\hat{a}}$ are the 7 broken generators

Once 3 of the NGBs are “eaten" by $W_B^{\pm}, Z_B$ the remaining 4 are the SM-like doublet H_A.

In terms of them $\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = \begin{pmatrix} \frac{H}{\sqrt{H^\dagger H}} \sin\left(\frac{\sqrt{H^\dagger H}}{f}\right) \\ f \cos\left(\frac{\sqrt{H^\dagger H}}{f}\right) \end{pmatrix}$ with $H = \begin{pmatrix} \phi_3 + i\phi_4 \\ \phi_1 + i\phi_2 \end{pmatrix}$ the SM Higgs doublet

The Twin Higgs

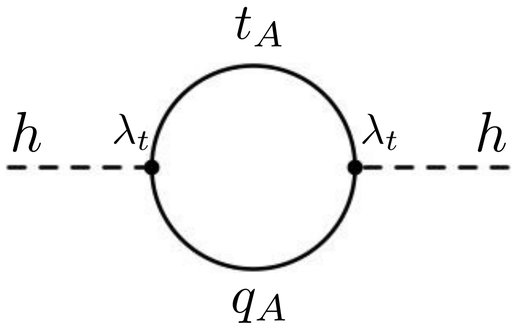
Top quark: $\lambda_{t_A} H_A\, q_A\, t_A + \lambda_{t_B} H_B\, q_B\, t_B$ also results in UV sensitive contributions to $V(\mathcal{H})$

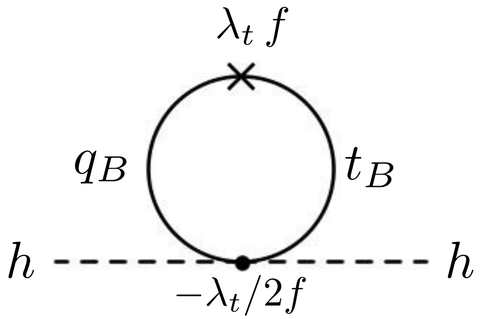
$$-\frac{N_c}{8\pi}\left(\lambda_{t_A}^2 H_A^\dagger H_A \Lambda_A^2 + \lambda_{t_B}^2 H_B^\dagger H_B \Lambda_B^2\right) \xrightarrow{Z_2} -\frac{N_c}{8\pi}\,\lambda_t^2\,\mathcal{H}^\dagger\mathcal{H}\,\Lambda^2$$

We can see the cancellation by expanding $\mathcal{H}$ in terms of the Higgs doublet h

$$\lambda_t\, h\, q_A\; t_A + \lambda_t\left(f - \frac{1}{2f}\, h^\dagger h\right) q_B\, t_B$$

$\Rightarrow$





quadratic divergence in m_h^2 cancelled

Twin Higgs Phenomenology: Higgs Physics

The physical electroweak scale is $v_{\rm EW} = \sqrt{2} f \sin\left(\frac{v}{\sqrt{2} f}\right) = 246\ \text{GeV}$

The minimization of the Z_2 symmetric $V(\mathcal{H})$ requires $v_{\rm EW} = f$

- Higgs invisible decays:

$\text{Br}(h \to B) < 50\,\%$ $\Rightarrow$ $f > v_{\rm EW}$ $\Rightarrow$ Introduce a *soft* Z_2 breaking.

But *dimensionless* couplings still Z_2 symmetric E.g. Yukawas: $\lambda_t = \lambda_{\tilde{t}}$

Measurements of Higgs couplings will be more constraining on $\frac{f}{v_{\rm EW}}$ than invisible decays

Twin Higgs Phenomenology: Higgs Physics

- Higgs couplings to SM particles:

Couplings of the Higgs to SM particles are suppressed by a universal factor

$$\cos\theta = \cos\left(\frac{v}{\sqrt{2}f}\right)$$

$$\sigma(pp \to h) = \cos^2\theta\ \sigma_{\rm SM}(pp \to h) \qquad \Gamma(h \to SM_i) = \cos^2\theta\ \Gamma_{\rm SM}(h \to SM_i)$$

Invisible Higgs width: decays to the twin sector

$$\Gamma(h \to B) = \sin^2\theta\ \Gamma_{\rm SM}(h)\ \delta$$

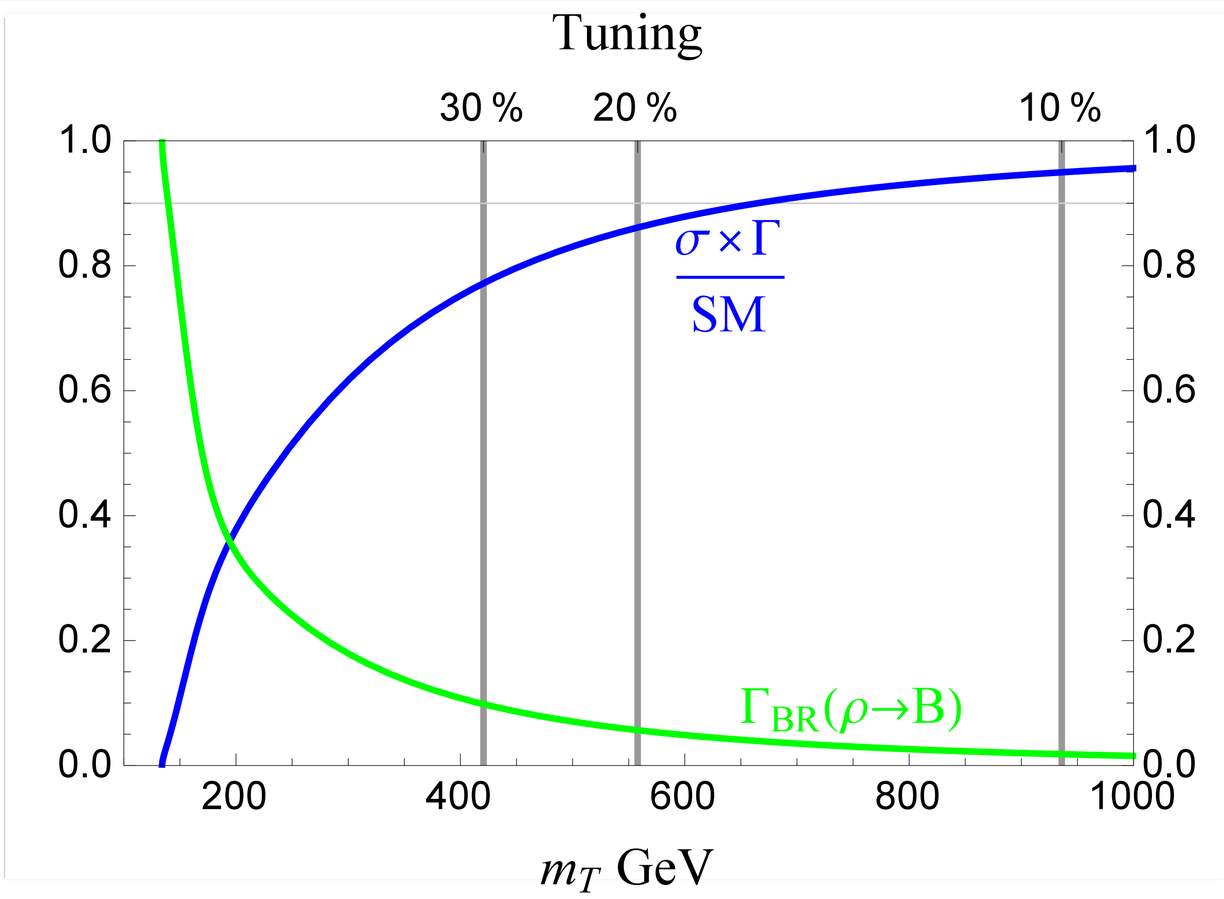
With $\delta < 1$ a kinematic suppression for $v_{\rm EW} < f$

Twin Higgs Phenomenology: Higgs Physics

Experimental bounds on suppression wrt to the SM of $\sigma \times \Gamma$ result in bounds on f (blue line)

Here $m_T = \lambda_t \, f \cos\theta$ is the twin top mass

$$m_T \simeq \lambda_t \, f \left(1 - \frac{v^2}{2\sqrt{2} f^2}\right) \simeq f$$



Allowing for up to a $10\,\%$ deviation from the SM

$$m_T \gtrsim 650 \text{ GeV}$$

From GB, Chacko, Harnik, Lima, Verhaaren,1411.3310

Twin Higgs Phenomenology: Cosmology (Bad)

- In the Mirror Twin Higgs there is an entire twin SM

$\Rightarrow$ 3 Twin neutrinos + 1 massless Twin photon $\rightarrow N_{\text{eff.}}$ distaster $\rightarrow \Delta N_{\text{eff.}} = 0.7$

Ruled out by data: $N_{\text{eff.}}^{\text{exp.}} = 3.10 \pm 0.17$ CMB (Planck), BAO (DESI)

- Solutions

- Make the $\tilde{\nu}'s$ heavy: *Bittar, GB, Costa, 2404.11651*

E.g. spontaneous breaking of Z_2 $\quad m_{\tilde{\nu}} \simeq f$

SM neutrino masses from Type II see-saw $\Rightarrow$ Scalar Triplets at the TeV scale

$\Delta N_{\text{eff.}} = 0.17$

-Fraternal Twin Higgs: *Craig, Katz, Strassler, Sundrum, 1501.05310*

Only 3rd generation in the twin sector. No gauging of $\tilde{U}(1)_Y$.
Lightest hadrons: 0^{++} glueballs. Mixes with Higgs. Interesting DV signals at the LHC.

- Asymmetric reheating: *Chacko, Craig, Fox, Harnik, 1611.07975*

SM reheats at much higher T than the Twin Sector. Dilutes the Twin energy density

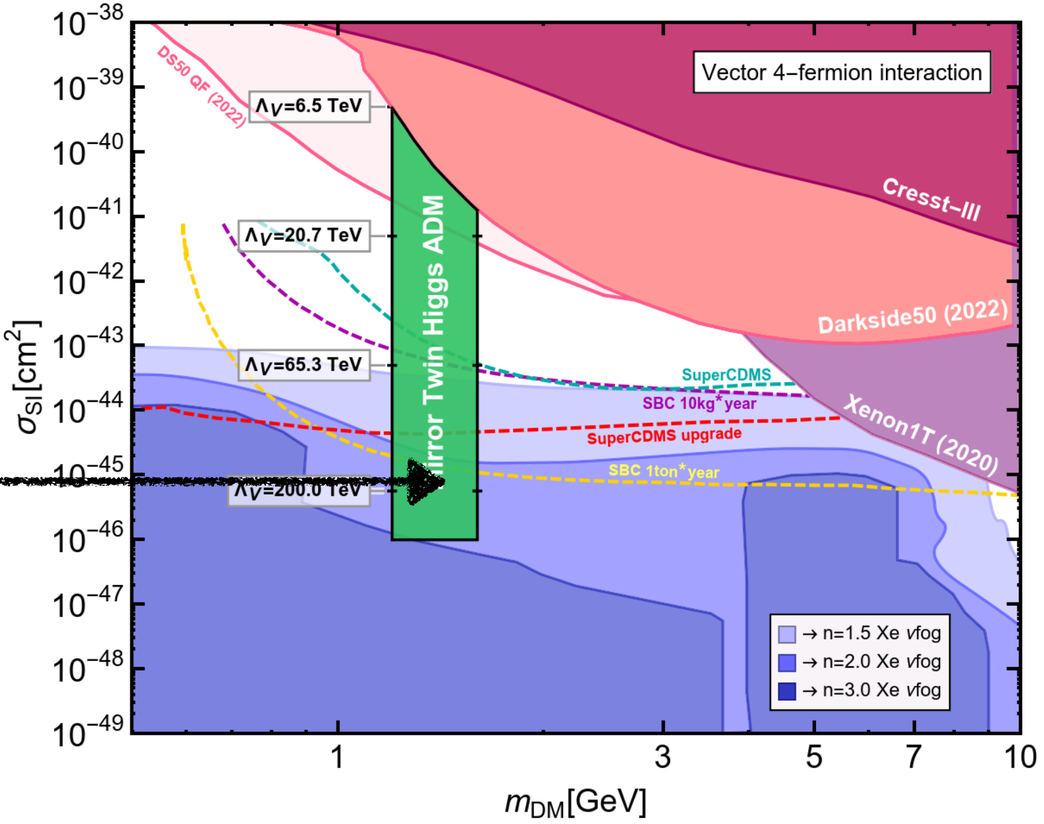
Twin Higgs Phenomenology: Cosmology (good)

The Twin sector provides a playing ground for models of dark matter and baryogenesis

- WIMP DM in the fraternal TH: $\tilde{\tau}$ *Garcia-Garcia, Lasenby, March-Russel 1505.07109, Craig, Katz 1505.07113*
- Asymmetric Dark Matter in the Mirror Twin Higgs: $\tilde{n}$ *Farina, 1506.03520*
- Baryogenesis and ADM *Bittar, GB, Kiriliuk, 2307.04662*

Direct detection of the $\tilde{n}$ in the ADM model in the Mirror Twin Higgs

$m_{\tilde{n}} \simeq 1.4$ GeV



The Radial Excitation in Twin Higgs Models

The radial excitation $\sigma(x)$ *is* the Twin Higgs

$$\mathcal{H} = e^{i\pi^{\hat{a}}(x)t^{\hat{a}}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f + \frac{\sigma(x)}{\sqrt{2}} \end{pmatrix}$$

Parametrizing the Z_2 and $SU(4)$ explicit breaking in $V(\mathcal{H}) \longrightarrow$ h and σ mix with a small angle α

So now the suppression angle of the $h \to SM$ couplings is given by $\theta' = \theta - \alpha$

$$g(h \to SM) = \cos\theta' \; g_{\rm SM}(h \to SM)$$

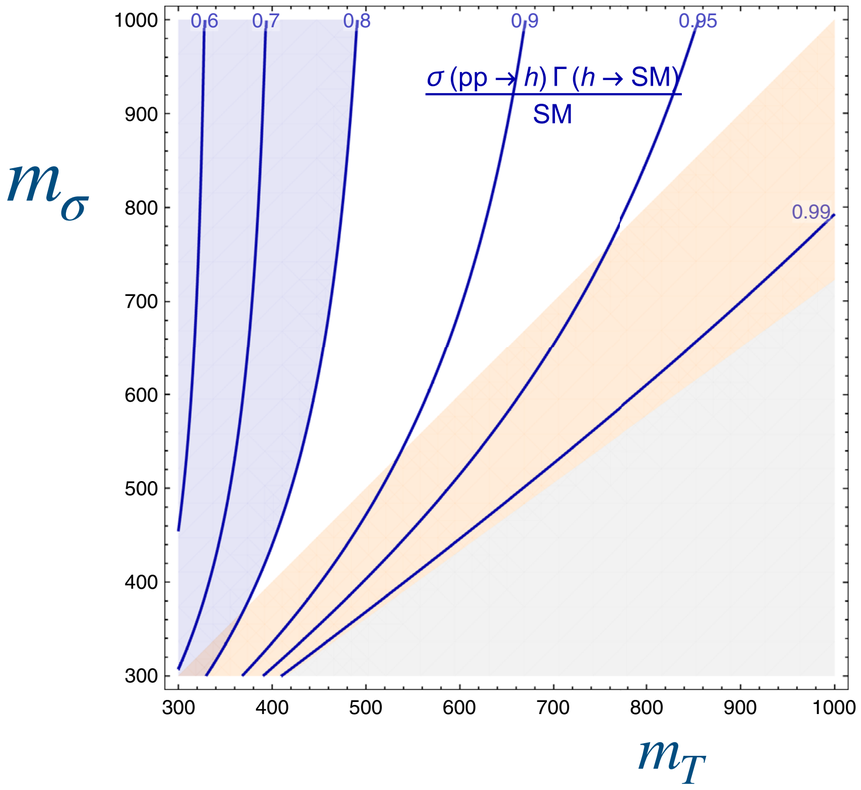
But for the σ we have

$$g(\sigma \to {\rm SM}) = \sin\theta' \; g_{\rm SM}(h \to {\rm SM})$$

The only unsuppressed σ coupling is $\sigma \to hh$

The Radial Excitation in Twin Higgs Models

From *Chacko et al., 1711.05300*



$$\Rightarrow \; m_\sigma \gtrsim 600 \text{ GeV}$$

Production suppressed by $\sin^2\theta'$ $\begin{cases} \sigma \to ZZ, t\bar{t} & \text{suppressed by } \sin^2\theta' \\ \sigma \to h\,h & \text{unsuppressed} \end{cases}$

Important invisible width of σ $\quad \Gamma(\sigma \to \text{inv.})$ only suppressed by $\cos^2\theta'$

Detailed predictions
for Run 3 and HL-LHC

Janini, Martins, Pereira, GB, in progress

Summary

- The Twin Higgs is a solution to the hierarchy problem that remains natural

- It predicts very specific signals at the (HL-)LHC:
  - Observable and universal suppression of Higgs couplings to SM states
  - An observable $\Gamma_{\text{inv.}}(h)$
  - A new, heavy CP even scalar with $m_\sigma > 650\ \text{GeV}$

- It has a dark sector amenable to build Dark Matter and Baryogenesis scenarios
  - WIMP miracle is back at Fraternal Twin Higgs. Twin tau is the DM.
    Lightest scalar is twin glueball that mixes with Higgs. Interesting DV signals at the LHC.
  - Asymmetric Dark Matter naturally realized with a $O(1)\ \text{GeV}$ twin neutron.