Top partners: alternative scenarios

Javi Serra

Technische Universität München

Strong Dynamics at the Electroweak Scale
Montpellier, 7 December 2017

The uses or abuses of symmetries

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SM & hierarchy problems

d=0	d=2	d=4	d>4
$\Lambda_{\rm UV}^4\sqrt{g}$	$c\Lambda_{\rm UV}^2\|H\|^2$	$\mathcal{L}_{\rm kin\ +\ gauge}$	$\frac{\lambda_M^{ij}}{\Lambda_{\rm UV}}\ell_i H H \ell_j$
		$Y_i^j\bar{\psi}_L^i H\psi_{Rj}$	$\frac{\lambda_B}{\Lambda_{\rm UV}^2}qqq\ell$
		$\lambda\|H\|^4$	$\frac{e\hat{Y}_i^j}{\Lambda_{\rm UV}^2}\bar{\psi}_L^i H\sigma^{\mu\nu}\psi_{Rj}F_{\mu\nu}$
		$\theta\widetilde{G}_{\mu\nu}\widetilde{G}^{\mu\nu}$	$\frac{gg'}{\Lambda_{\rm UV}^2}H^\dagger W_{\mu\nu}HB^{\mu\nu}$

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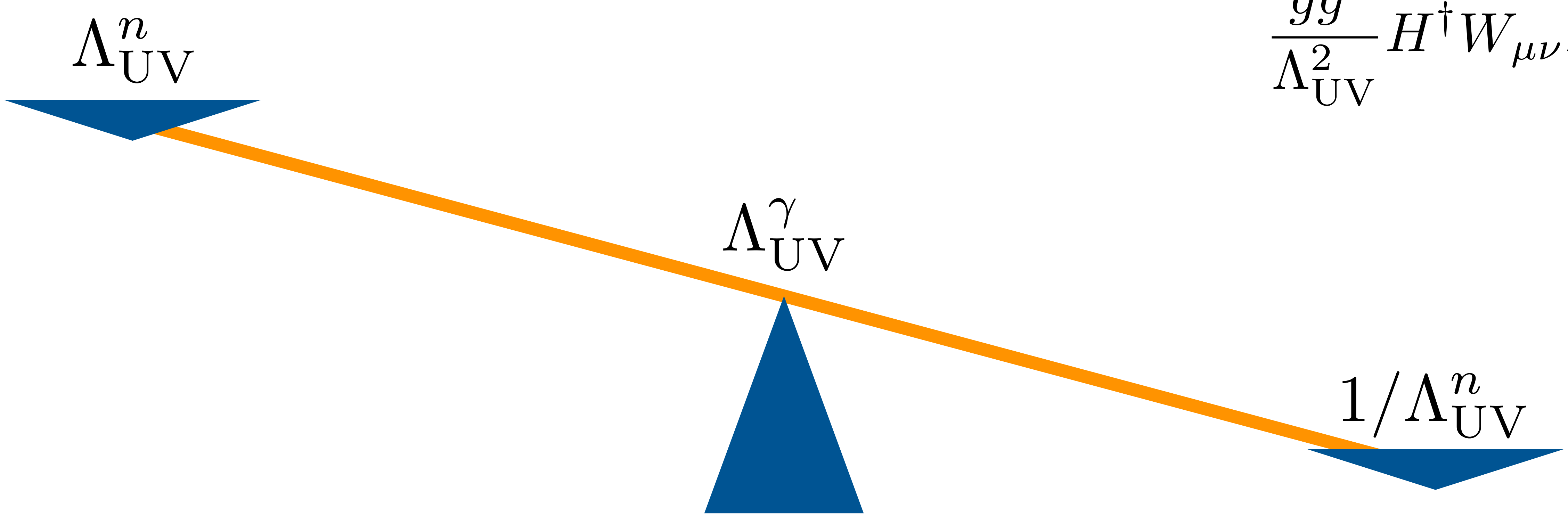

Natural expectation gives rise to known hierarchy problems.

SM & hierarchy problems

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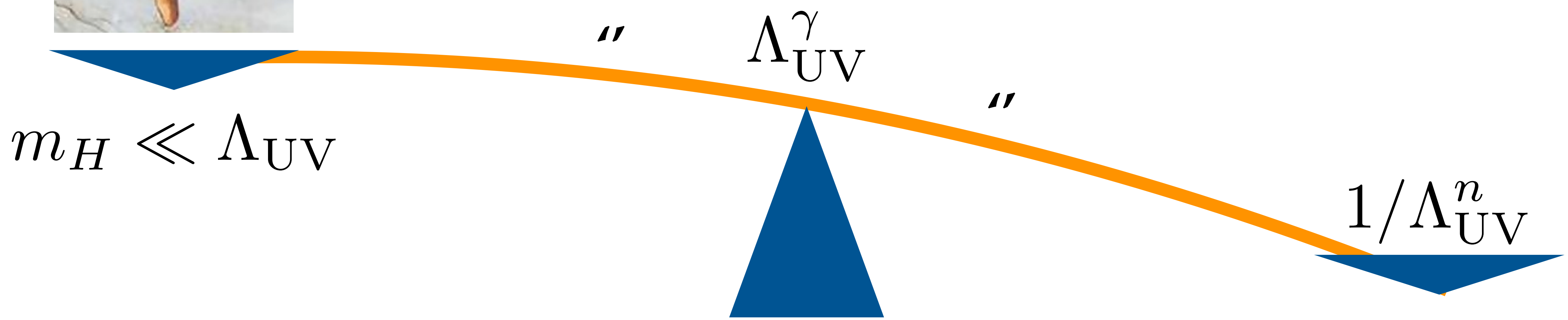
tuning



Gauge principle + (unnatural) separation of scales describes observations.

SM accidental symmetries

$\Lambda_{\rm UV} \gg {\rm TeV}$, decoupling, explains a lot

	symmetry	spurion
B, L numbers	$U(1)_{B,L_e,L_\mu,L_\tau}$	"exact"
Flavor	$SU(3)_{q,u,d,\ell,e}$ $SU(2)^3_{\rm quarks}$	$Y \to 0$ $y_t \neq 0$
CP	$\psi \to \psi^*$	$\delta \to 0$
Custodial	$SO(4)_C \cong SU(2)_L \times SU(2)_R$	$y_t, g' \to 0$
Unification	$SU(5)$	"remnant" $\bar{\mathbf{5}} + \mathbf{10}$

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hints of high UV scales

Gauge principle + (unnatural) decoupling has been "corroborated":

neutrino masses?

$$m_\nu \approx 0.05\text{eV} \longleftrightarrow \frac{\lambda_M}{\Lambda_{\text{UV}}} \sim (10^{15}\text{GeV})^{-1}$$

$\Lambda_{\text{UV}} \lesssim 10^7\text{GeV}$

type I

strong CP problem?

$$\theta \ll 1 \longleftrightarrow \frac{a}{f_a}\widetilde{G}_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$\Lambda_{\text{UV}} \lesssim 4\pi f_a\,,\, f_a \gtrsim 10^9\text{GeV}$

$\Lambda_{\text{UV}} \lesssim 10\text{TeV}$

KSVZ

dark matter?

$$(-1)^{3B+L+2s} = -1 \longleftrightarrow \text{ "stability"}$$

Suggests the characteristic scale of ***some*** phenomena is high.

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We are not content with unnatural separation of scales:

$$\Lambda_{\mathrm{UV}} \sim \mathrm{TeV}$$

If no separation of scales, SM symmetries (successes) are generically lost.

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No BSM physics discovered yet.

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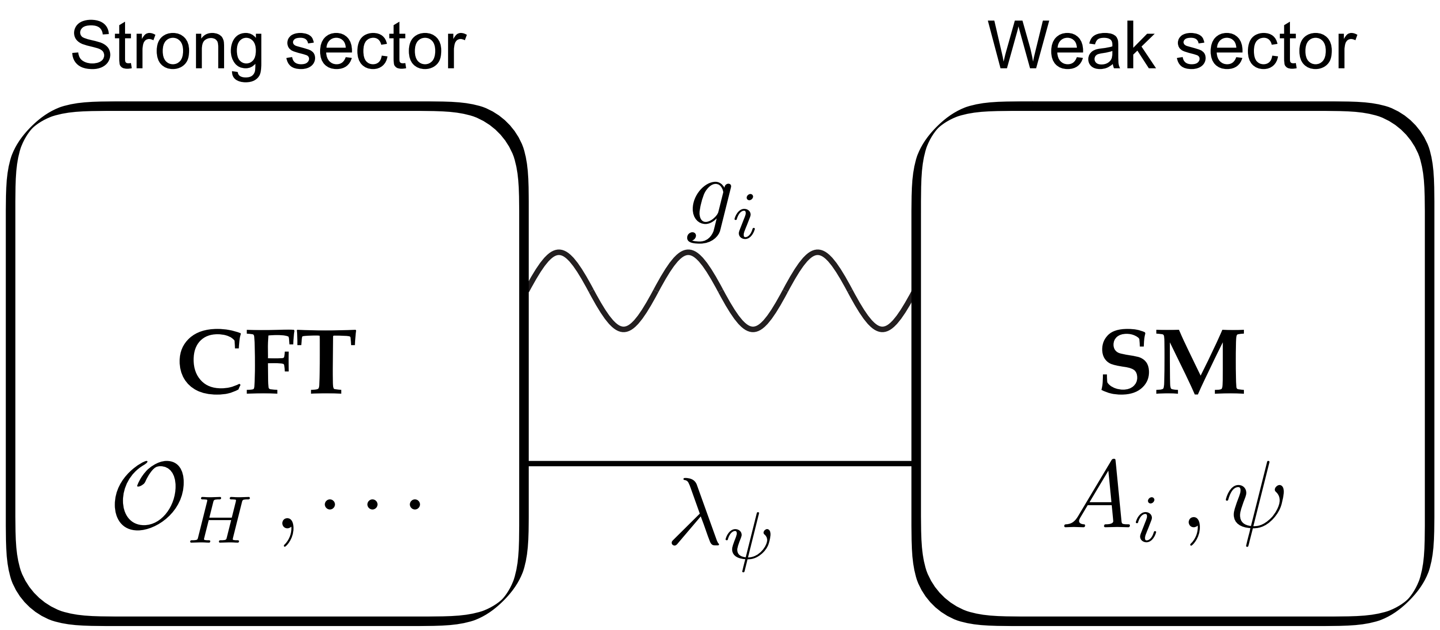
Higgs (of course) and **top** are singled out:

$$\Lambda^{H}_{\mathrm{UV}} \sim \Lambda^{t}_{\mathrm{UV}} \sim \mathrm{TeV}$$

modern Composite Higgs models

$$\Lambda'_{\rm UV} \equiv \Lambda_{\not B}\,, \Lambda_{\not L}\,, \Lambda_{Fl\not a vor}\,, \Lambda_{S\not U(5)} \;\; ?$$



$d(\mathcal{O}_{|H|^2}) \gtrsim 4$ *no more EW hierarchy problem*

$\Lambda^H_{\rm UV} \equiv m_*$

Energy

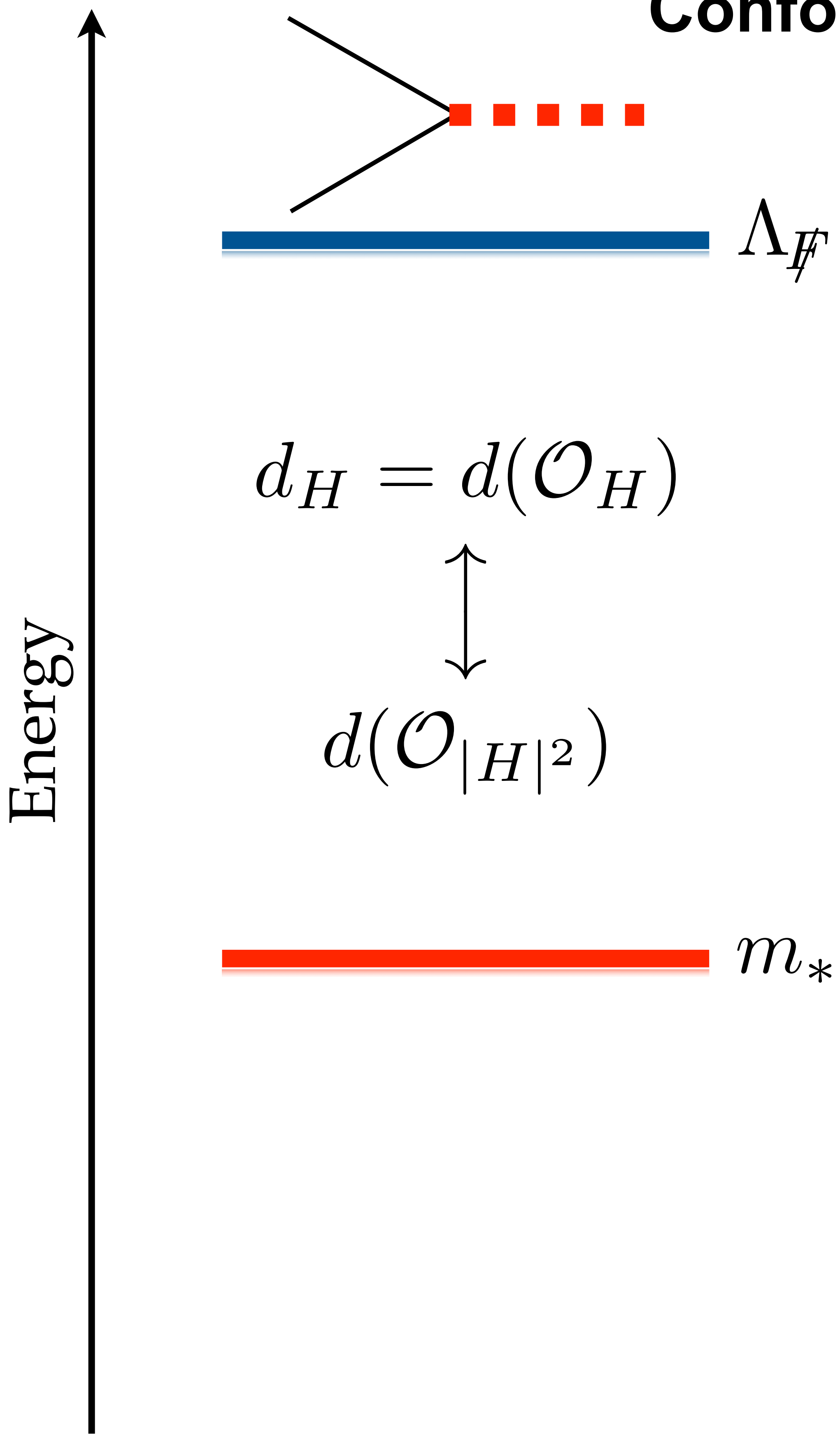
g_* = Higgs coupling $\quad g_* \gtrsim g_i\,, \lambda_\psi$

f = Higgs scale

$m_* \sim g_* f$ = Composites' mass

$$\epsilon_{g_i} \equiv g_i/g_* \qquad \epsilon_\psi \equiv \lambda_\psi/g_*$$

Conformal Technicolor (CTC)



$$\frac{Y_i^j}{\Lambda_{\not{F}}^{d_H-1}}\bar{\psi}_L^i \mathcal{O}_H \psi_{Rj} + \frac{1}{\Lambda_{\not{F}}^2}\bar{\psi}^i\bar{\psi}^j\psi_k\psi_l$$

Decoupling: $d_H \to 1\,,\, \Lambda_{\not{F}} \to \infty$

1 flavor spurion (SM):

$$Y(m_*) \sim Y(\Lambda_{\not{F}})\left(\frac{m_*}{\Lambda_{\not{F}}}\right)^{d_H-1}$$

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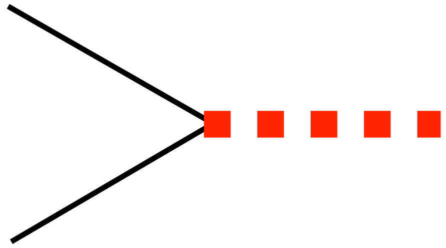

$\Lambda_{\not F}$

$$\frac{Y_i^j}{\Lambda_{\not F}^{d_H-1}} \bar{\psi}_L^i \mathcal{O}_H \psi_{Rj} + \frac{1}{\Lambda_{\not F}^2} \bar{\psi}^i \bar{\psi}^j \psi_k \psi_l$$

$$d_H = d(\mathcal{O}_H)$$

$\updownarrow$

$$d(\mathcal{O}_{|H|^2})$$

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m_*

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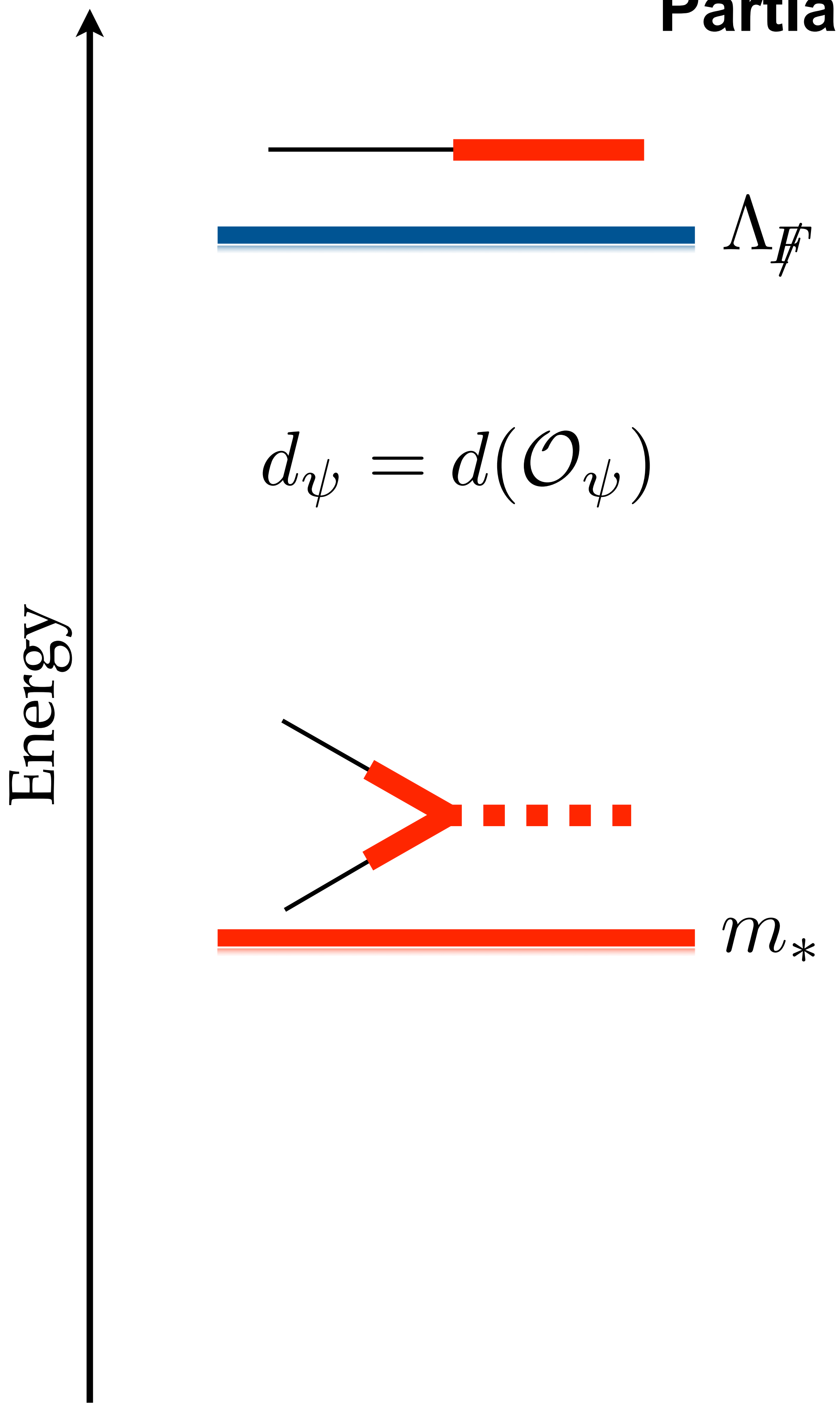
top

$$y_t \sim 1 \longrightarrow \begin{matrix} d_H \gtrsim 1.5 \\ \text{bootstrap} \\ d(\mathcal{O}_{|H|^2}) \gtrsim 4 \end{matrix} \longrightarrow \Lambda^t_{\rm UV} \lesssim O(10) m_*$$

flavor generation & the top

Partial Compositeness (PC)



$$\frac{g_* \epsilon_{\psi i}}{\Lambda_{\not F}^{d_\psi - 5/2}} \bar{\psi}^i \mathcal{O}_\psi + \frac{1}{\Lambda_{\not F}^2} \bar{\psi}^i \bar{\psi}^j \psi_k \psi_l$$

$$d_\psi = d(\mathcal{O}_\psi)$$

Decoupling: $d_\psi \to 5/2 \, , \Lambda_{\not F} \to \infty$

2 flavor spurions:

$$\epsilon_{\psi_{L,R}}(m_*) \sim \epsilon_{\psi_{L,R}}(\Lambda_{\not F}) \left(\frac{m_*}{\Lambda_{\not F}} \right)^{d_{\psi_{L,R}} - 5/2}$$

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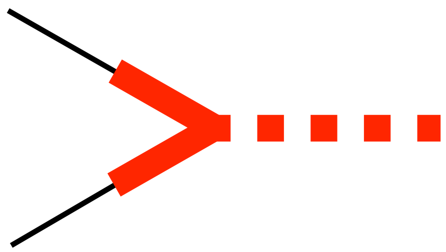

m_*

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top

$$y_t \sim \epsilon_q \epsilon_t g_* \sim 1 \longrightarrow \quad \epsilon_{q,t} \in (y_t/g_*, 1) \quad \longrightarrow \Lambda^t_{\rm UV} \sim m_*$$

BSM (approximate) symmetries

B, L numbers $U(1)_{B,L_e,L_\mu,L_\tau}$

e.g. neutrino masses

CTC

$m_* = 3\text{TeV}\,, g_* = \pi$

$$m_\tau \sim \frac{g_* v}{\sqrt{2}} \left(\frac{m_*}{\Lambda_{\not{F}}}\right)^{d_H - 1} \longrightarrow \quad d_H \approx 2\,, \Lambda_{\not{F}} \approx 10^6 \text{GeV}$$

$$m_\nu \sim \frac{(g_* v)^2}{2 m_*} \left(\frac{m_*}{\Lambda_{\not{F}}}\right)^{2d_H - 1} \approx 10^5 (\Delta m)_{\text{atm}}$$

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We must require *L number* at $\Lambda_{\not F}$

use or abuse ? 🤔

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Note that in PC X *number* must exist such that: $Y = T_R^3 + X$

$$X = \alpha L = \beta B$$

BSM (approximate) symmetries

Flavor & CP $SU(3)_{q,u,d,\ell,e}$ $\psi \to \psi^*$

EDMs, $\mu \to e\gamma$, ϵ_K

PC

$$\frac{g_*^2}{(4\pi)^2}\frac{e g_* v}{m_*^2\sqrt{2}}\epsilon_{\psi i}\epsilon_\psi^j \bar{\psi}^i \sigma^{\mu\nu}\psi_j F_{\mu\nu} \qquad \frac{g_*^2}{m_*^2}\epsilon_{\psi i}\epsilon_{\psi j}\epsilon_\psi^k \epsilon_\psi^l \bar{\psi}^i \bar{\psi}^j \psi^k \psi_l$$

$g_* = \pi$

$$m_*^{\text{quarks}} \gtrsim 10\text{TeV} \qquad m_*^{\text{leptons}} \gtrsim 100\text{TeV}$$

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1 flavor spurion (SM): $\epsilon_{\psi_L} \sim Y$

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Note dynamics (PC + CTC) can eliminate the need for accidental symmetries at m_*

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Custodial $SO(4)_C \cong SU(2)_L \times SU(2)_R$

T-parameter

$$\frac{1}{f^2}|H^\dagger D_\mu H|^2 \qquad \hat{T} \sim \frac{v^2}{f^2} \lesssim 10^{-3} \qquad f \gtrsim 5\text{TeV}$$

use or abuse ? 🤔

Unavoidable *Custodial* symmetry at m_*

1-loop generated

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Custodial parity $P_{LR} : T^3_R(b_L) = T^3_L(b_L)$

Zb_Lb_L coupling

$$\frac{\epsilon_q^2}{f^2} H^\dagger D_\mu H \bar{q}\gamma^\mu q \qquad \delta g_b \sim \epsilon_q^2 \frac{v^2}{f^2} \lesssim 10^{-3} \qquad m_* \gtrsim 4\text{TeV}$$

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1-loop generated

Note most CH models easily incorporate these symmetries; see next.

BSM (approximate) symmetries

Some effects cannot be suppressed by symmetries…

S-parameter

$$\frac{gg'}{m_*^2} H^\dagger W_{\mu\nu} H B^{\mu\nu} \qquad \widehat{S} \sim \epsilon_g^2 \frac{v^2}{f^2} \lesssim 10^{-3} \qquad m_* \gtrsim 2.5\text{TeV}$$

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$$m_H \ll m_*$$

requires dynamics

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$$m_H \ll m_*$$

requires dynamics & symmetry

Higgs as a (pseudo-)NGB, $H \to H + f\,\theta$

use or abuse ?

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$$m_H \ll m_*$$

requires dynamics & symmetry

Higgs as a (pseudo-)NGB, $H \to H + f\,\theta$

use or abuse ? 🤔

“Simple” extension of Technicolor idea:

e.g. $SO(5)/SO(4)$

with *SO(4)* symmetry + P_{LR} automatic at LO in derivatives!

Higgs potential & top partners

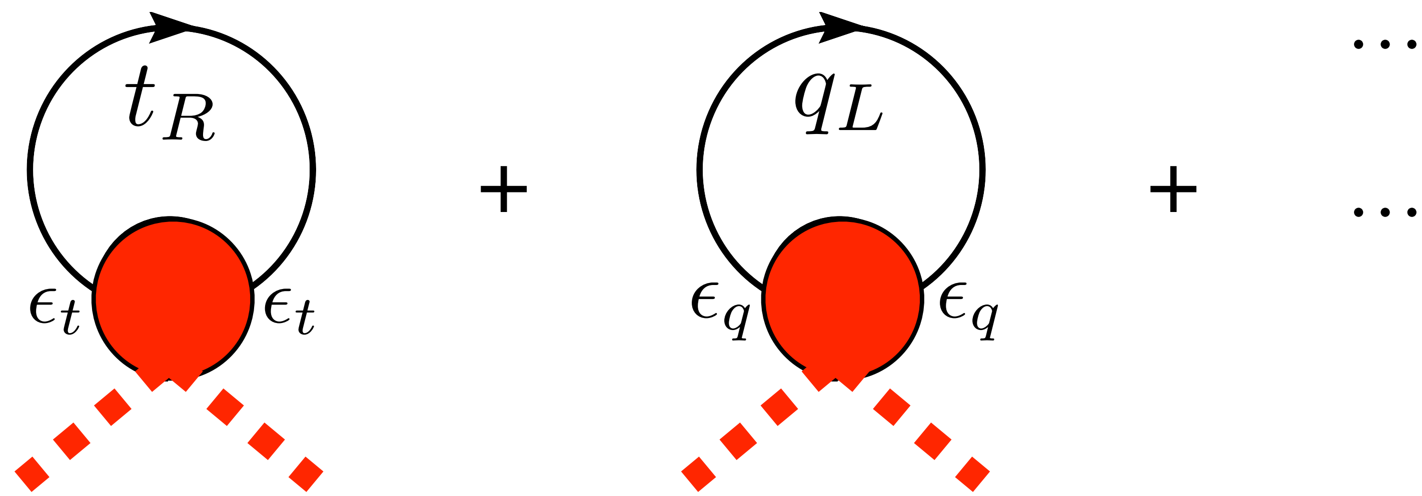
$$V(H/f) = \epsilon_{\rm SM}^2 \frac{m_*^4}{(4\pi)^2}\left(a\frac{|H|^2}{f^2} + \frac{b}{2}\frac{|H|^4}{f^4}\right)$$

radiatively generated potential

<u>spurions</u>

$$\epsilon_t = \lambda_t/g_*$$
$$\epsilon_q = \lambda_q/g_*$$
$$\epsilon_g = g/g_*$$
$$\cdots$$

$$O(\epsilon^2): \quad V =$$



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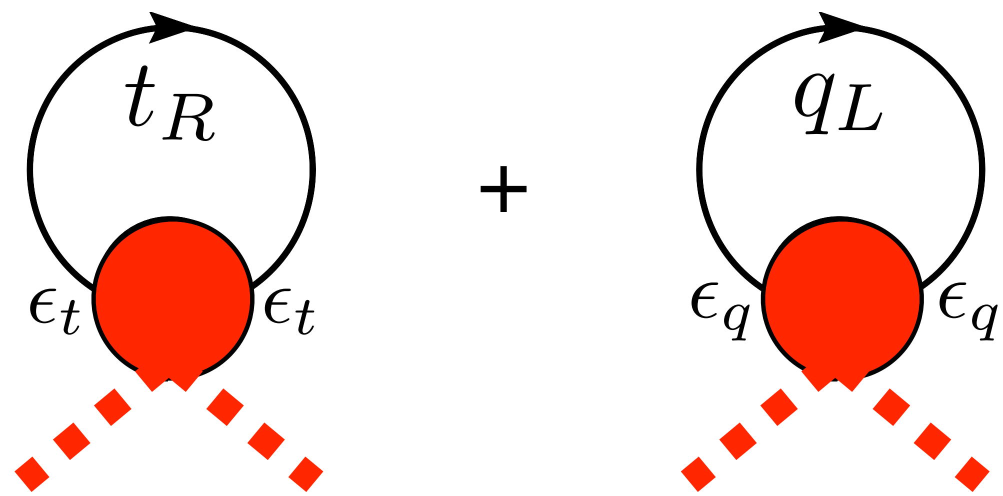
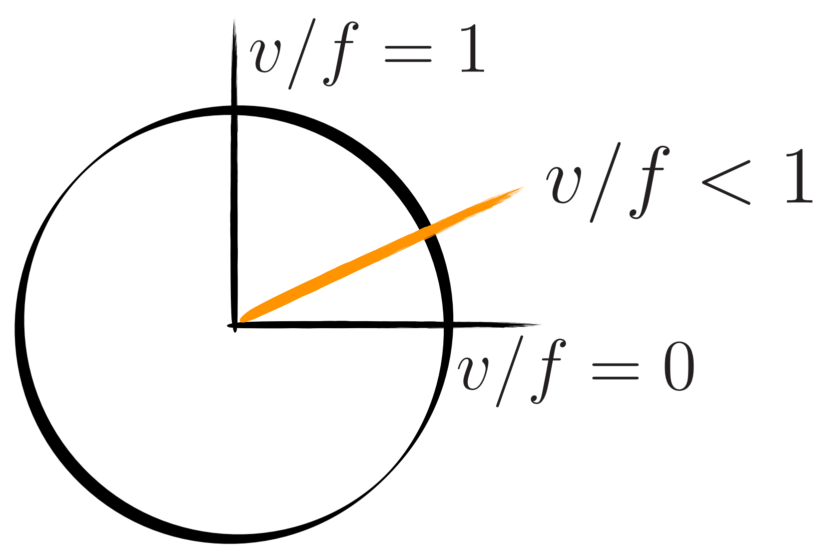


$+ \quad \cdots$

Misalignment:

$$\frac{\langle H \rangle = v}{f} = \sqrt{\frac{a}{b}}$$



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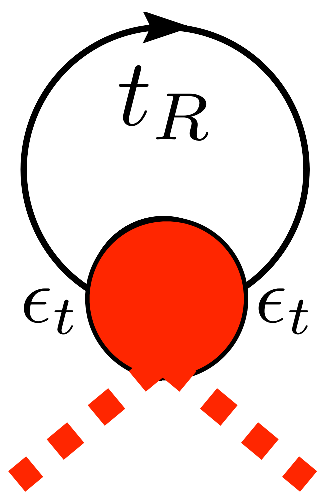

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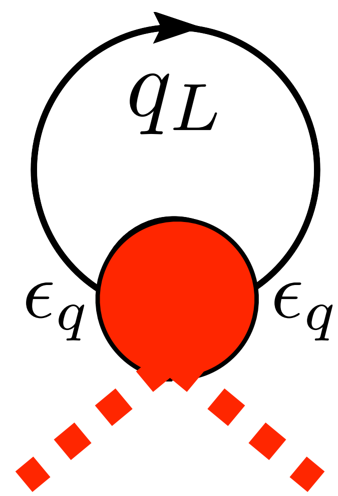

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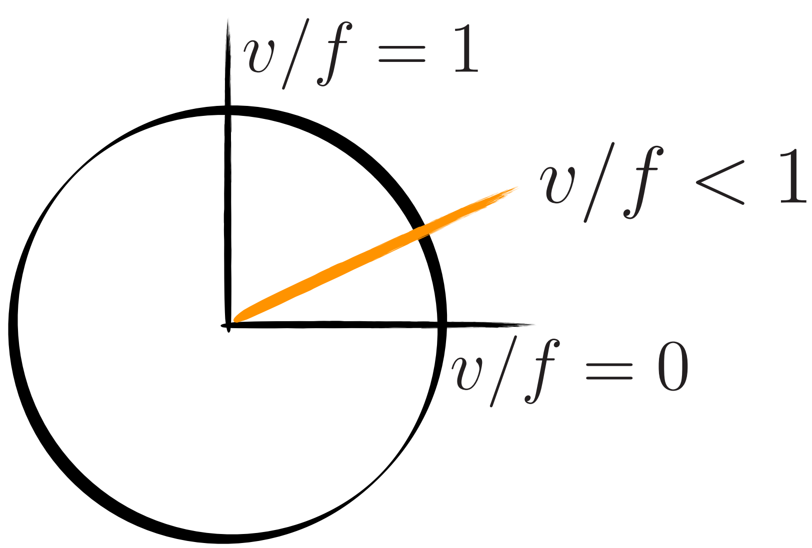

Overall size:

$\epsilon_{q,t} \in (y_t/g_*, 1)$ largest spurion

$$V \sim \epsilon_{q,t}^2 \frac{m_T^4}{(4\pi^2)}$$

$m_* \rightarrow$ top partner's mass

Higgs potential & top partners

Top partners control the Higgs potential.

$$V_{\text{exp}} \approx -\frac{m_h^2}{2}|H|^2 + \frac{m_h^2}{2v^2}|H|^4$$

$m_h \approx 125\text{GeV}$
$v \approx 246\text{GeV}$

reproduced only if **light & weakly coupled top partners**:

$$\Delta_{\mu^2} \sim (0.1)^{-1}\left(\frac{\lambda_{q,t}^2}{3y_t^2}\right)\left(\frac{m_T}{1\text{TeV}}\right)^2 \qquad \Delta_\lambda \sim (1)^{-1}\left(\frac{\lambda_{q,t}^2}{3y_t^2}\right)\left(\frac{g_T}{2}\right)^2$$

$$g_T = m_T/f$$

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$g_T = m_T/f$

and a *mild* **tuning**.

Higgs couplings

$$\frac{1}{f^2}(\partial_\mu |H|^2)^2 \qquad \delta g_h \sim \frac{v^2}{f^2} \lesssim 0.1 \qquad f \gtrsim 750\text{GeV}$$

Phenomenology dictated by **quantum numbers**:

$$SU(3)_C \times [SO(5)/SU(2)_L \times SU(2)_R] \times U(1)_X$$

$$\mathbf{5} = (\mathbf{1}, \mathbf{1}) \oplus (\mathbf{2}, \mathbf{2})$$

$$\Psi_{\mathbf{1}} = (\mathbf{3}, \mathbf{1}, \mathbf{1})_{2/3}$$

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$$p(g)p(g) \to \Psi\bar{\Psi}$$

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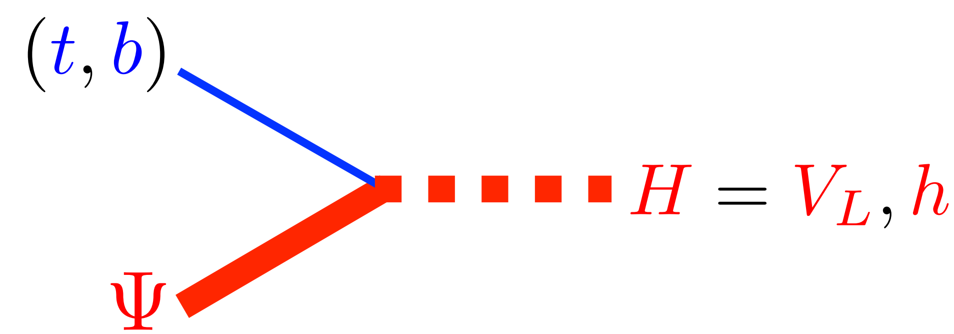

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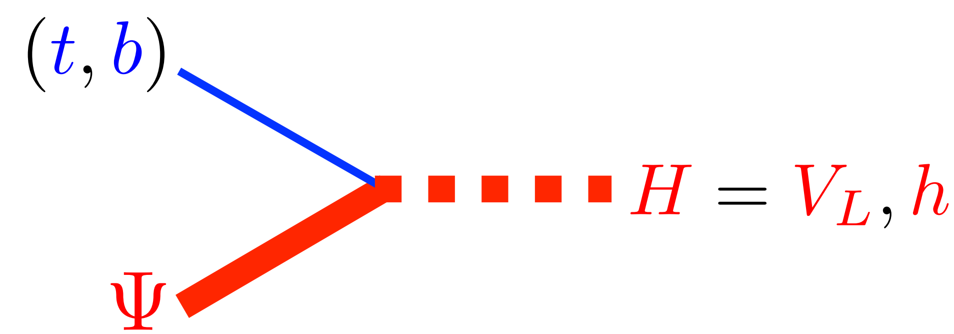

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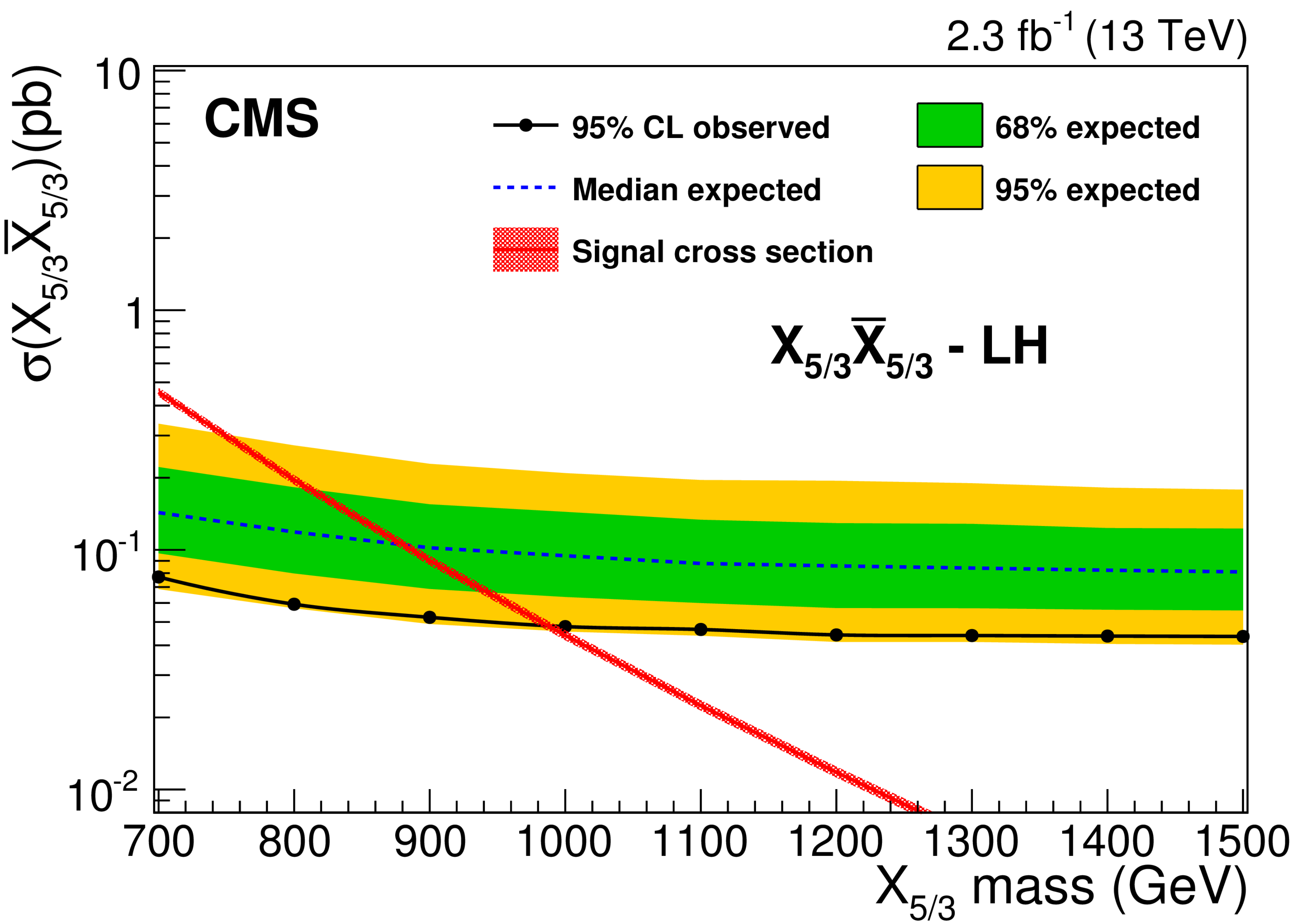
Branching ratios:

$$\Psi_1 \to (h, Z_L)\, t\,, W_L^+ b$$

$$T \to (h, Z_L)\, t$$

$$X_{5/3} \to W_L^+\, t$$

LHC 13TeV data



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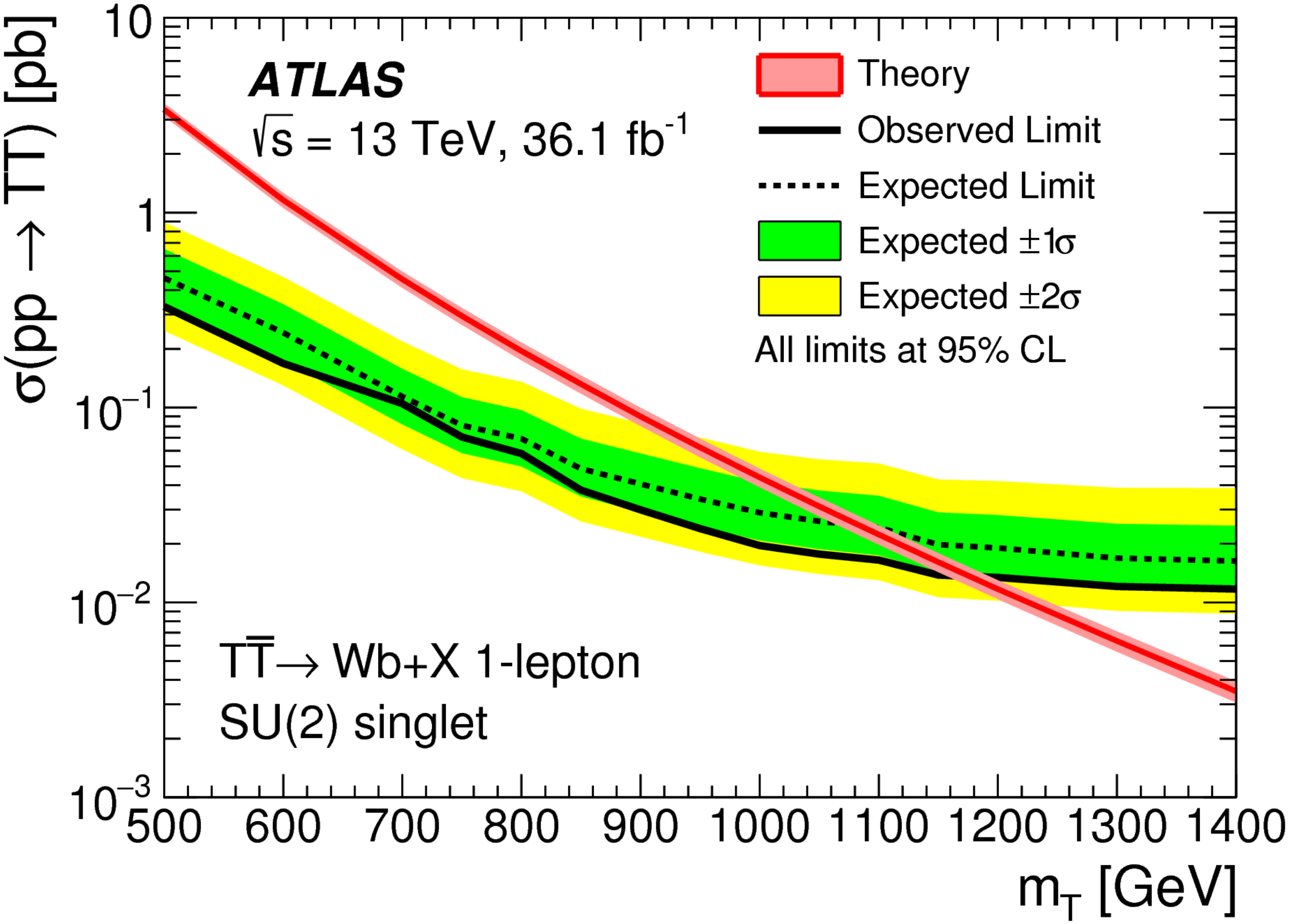

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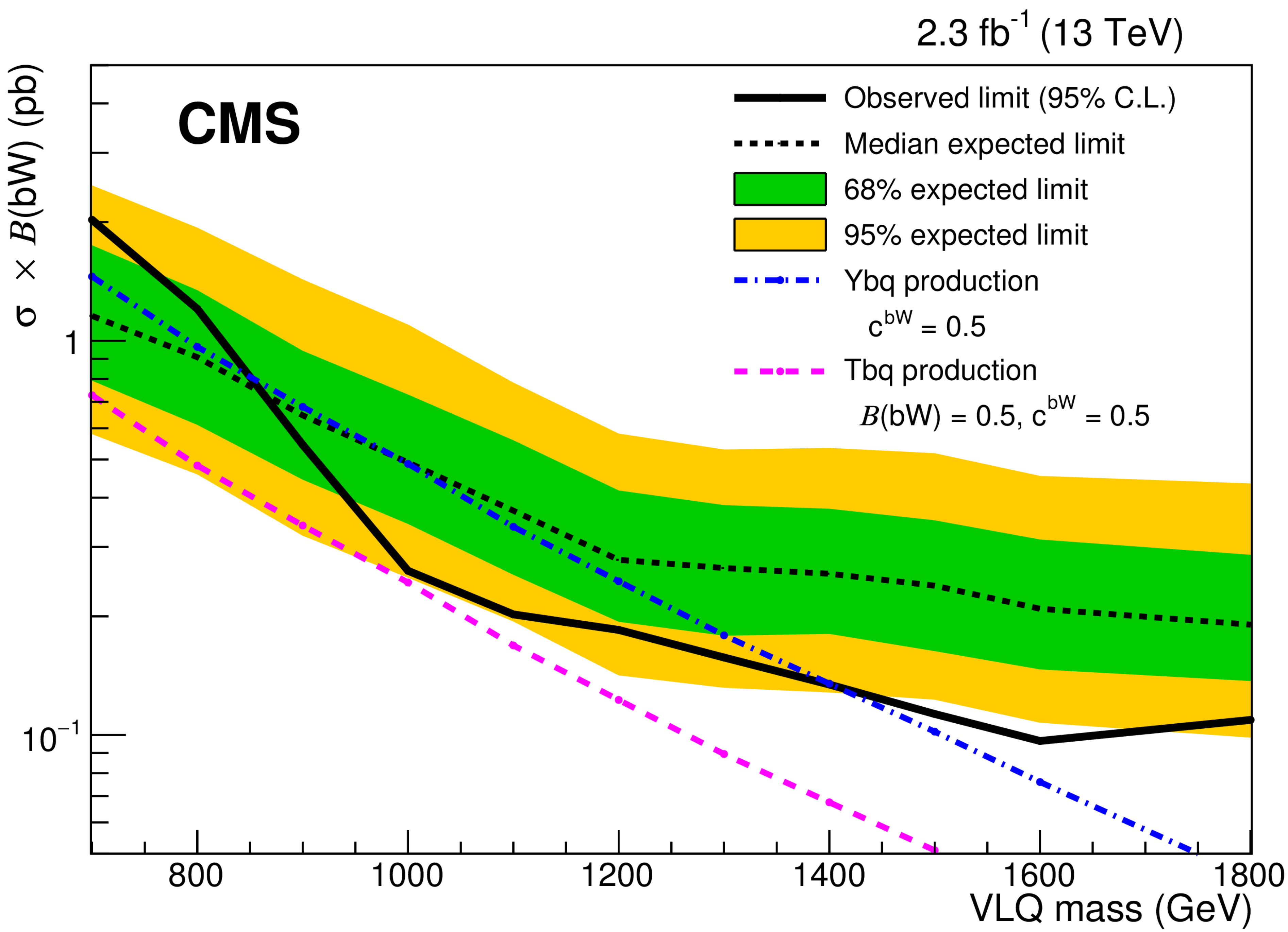

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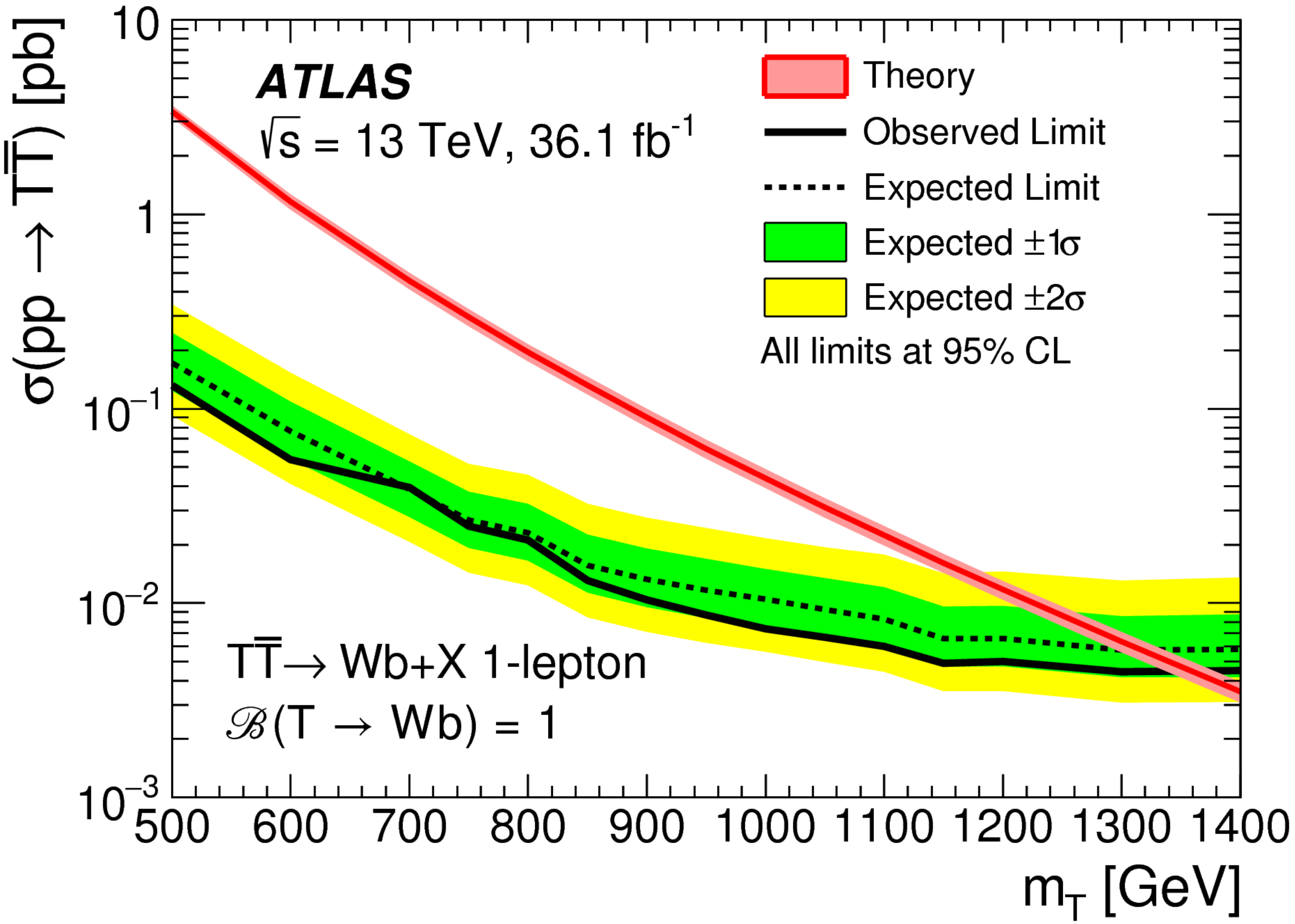

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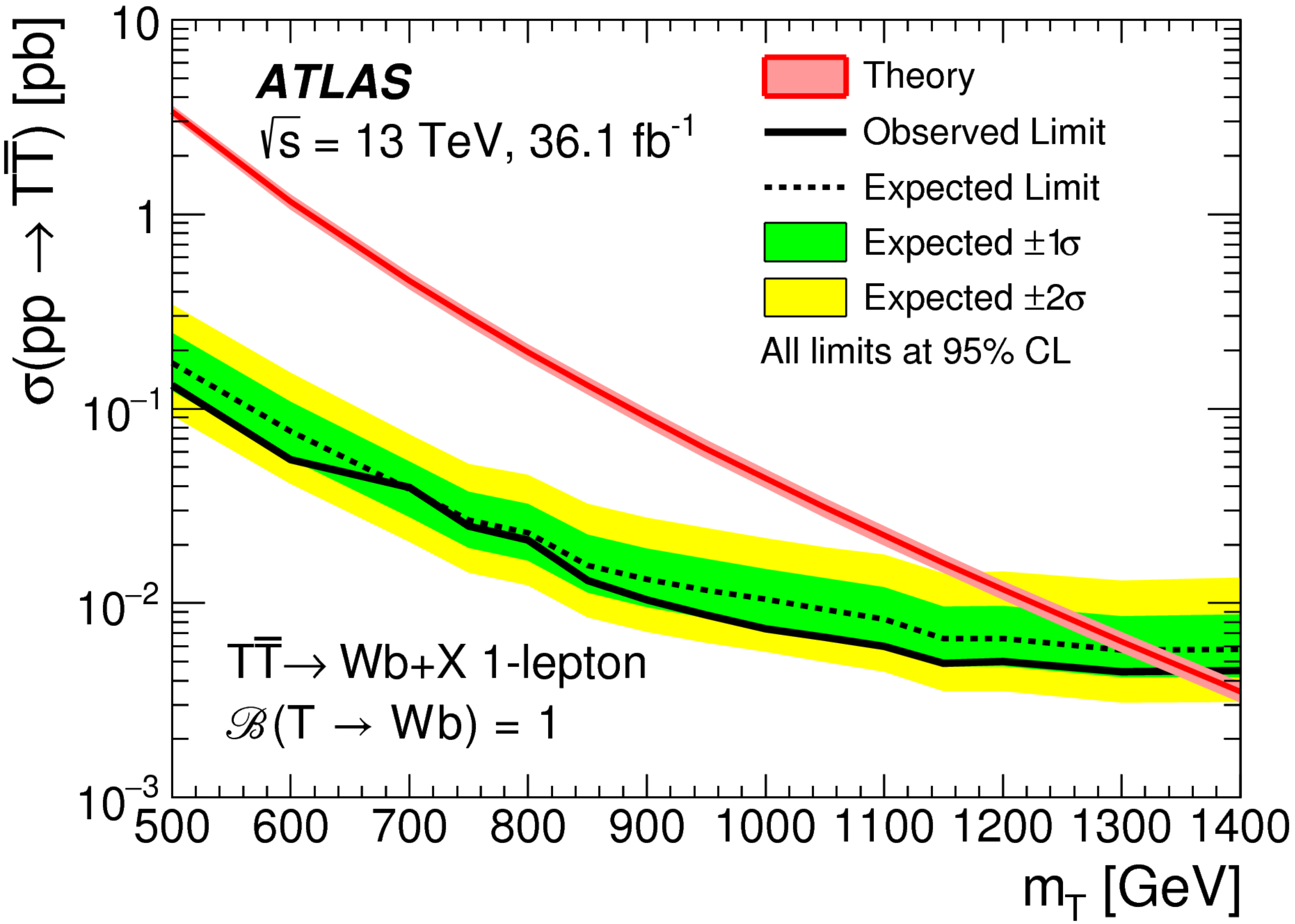


$$m_T \gtrsim 1.35\text{TeV} \quad \longrightarrow \quad \Delta \sim (0.05)^{-1}$$

Increased tuning from LHC searches.

more BSM (approximate) symmetries

What if there are **non-standard** top-partner **decays**.

e.g. $SO(6)/SO(5)$

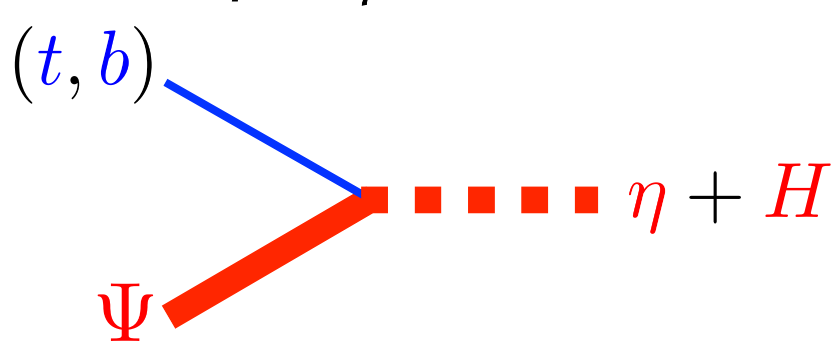
One extra singlet NGB beyond the Higgs:

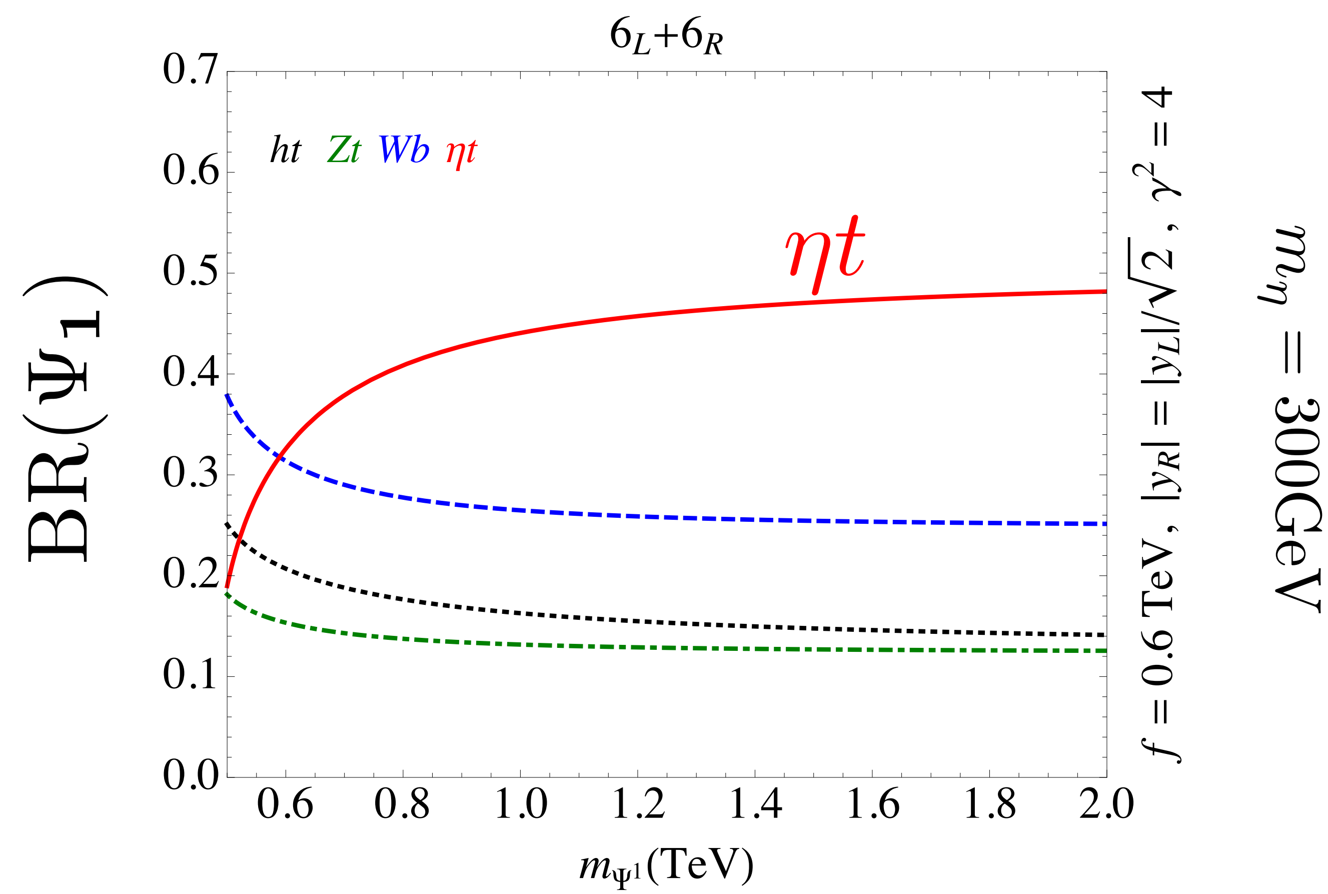
$$\mathbf{5} = \eta + H = (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2})_{SU(2)_L \times SU(2)_R}$$

η naturally light:

$$m_\eta \sim \epsilon_{q,t} \frac{g_T}{4\pi} m_T < m_T$$

η coupled to Ψ:





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use or abuse ?

Note this is the minimal CH model with $SO(4)_C$ realizable à la QCD (technifermions).

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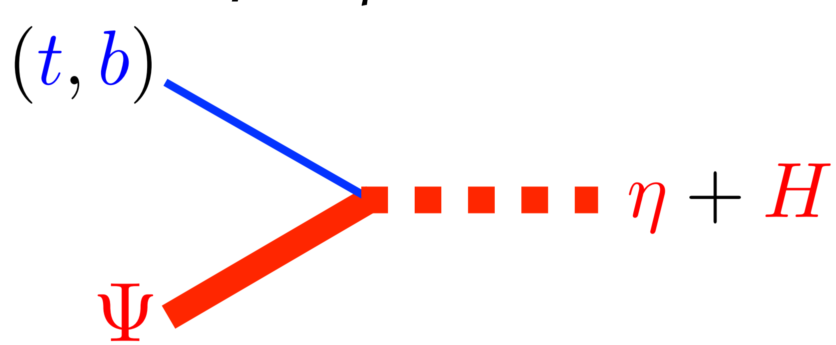
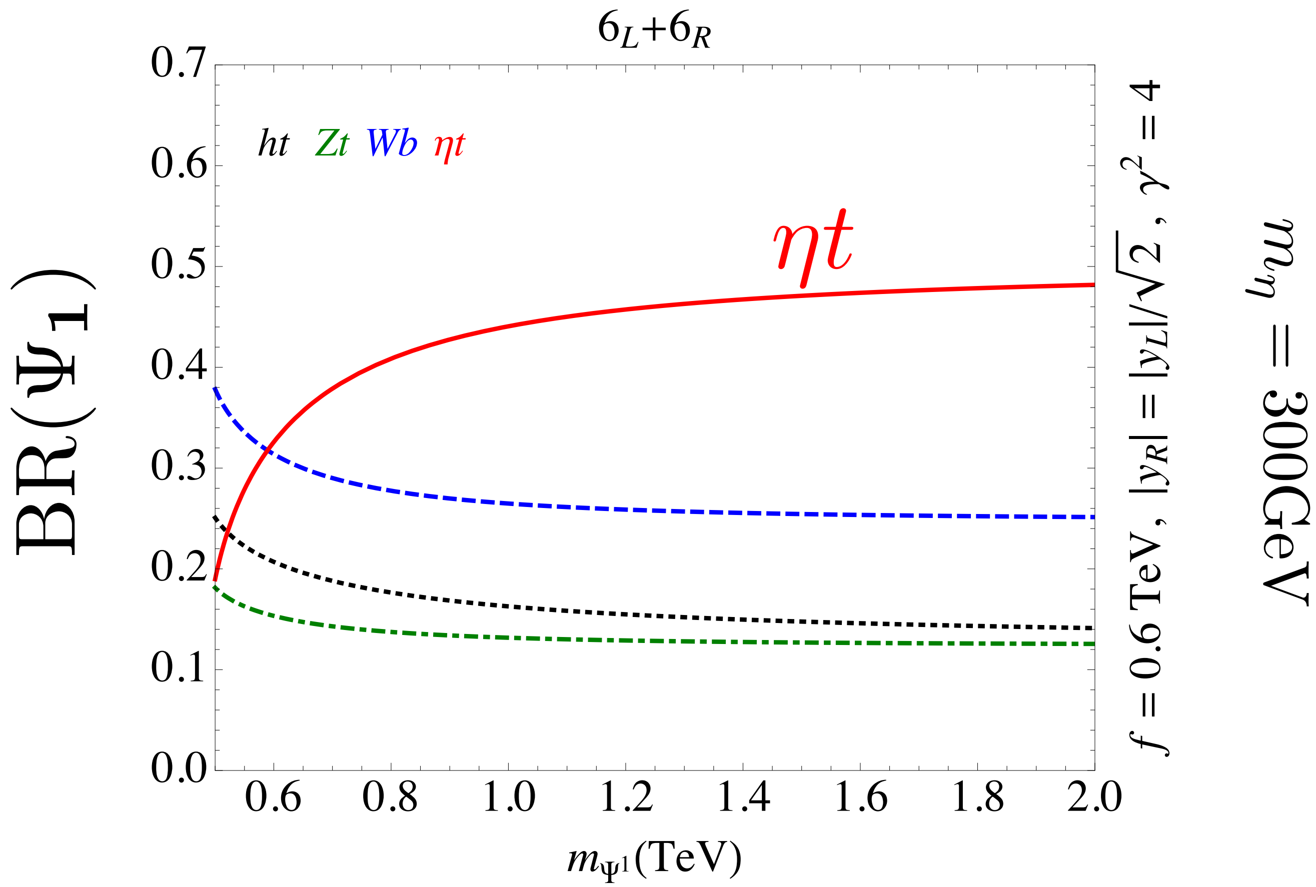
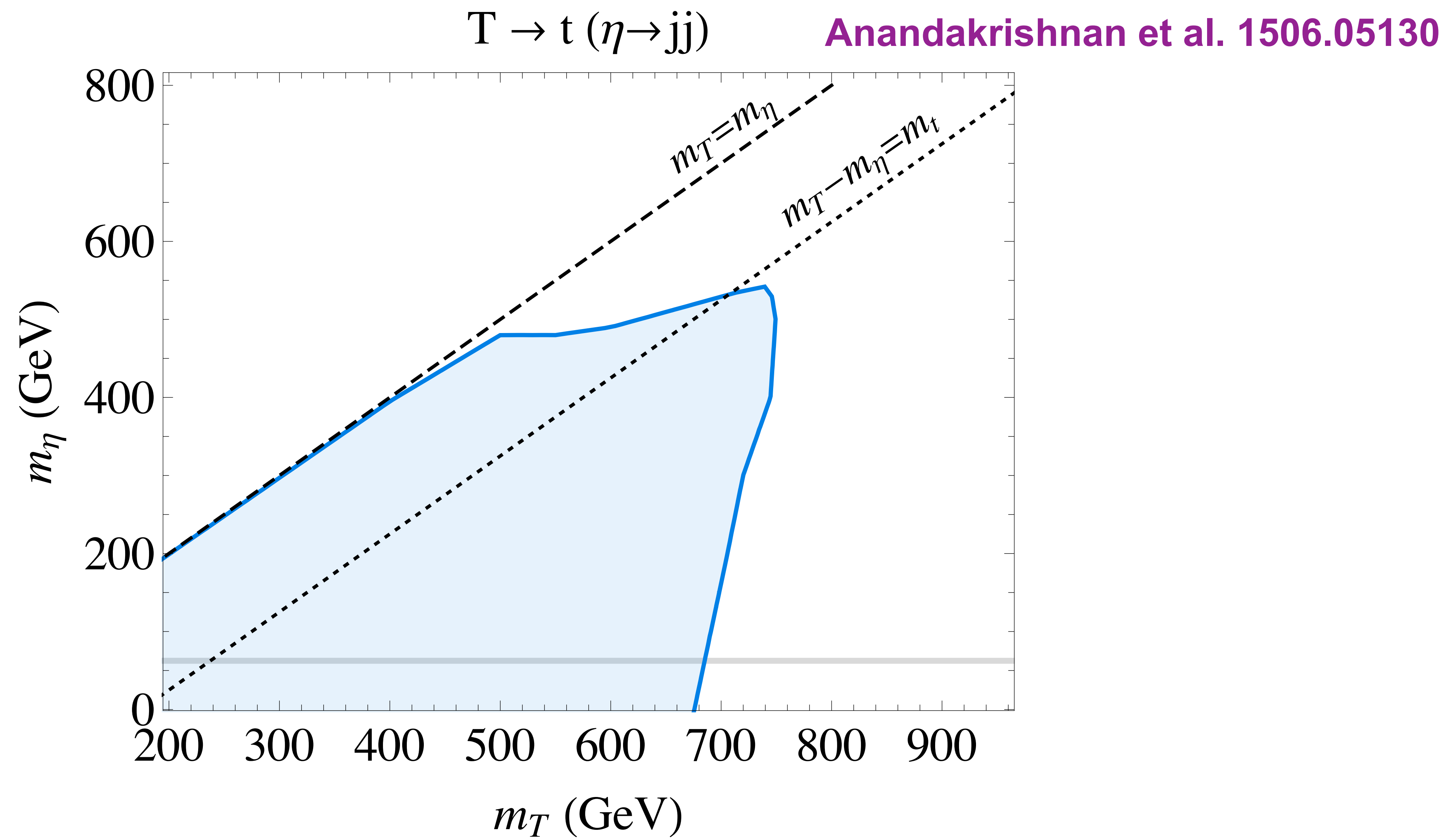




more BSM (approximate) symmetries

$$\mathrm{BR}(\eta \to gg) \approx 1 \quad \text{if} \quad m_\eta \lesssim 2m_t$$

(recast of) LHC 8TeV data



The bounds, thus tuning, are *mildly* weaker.

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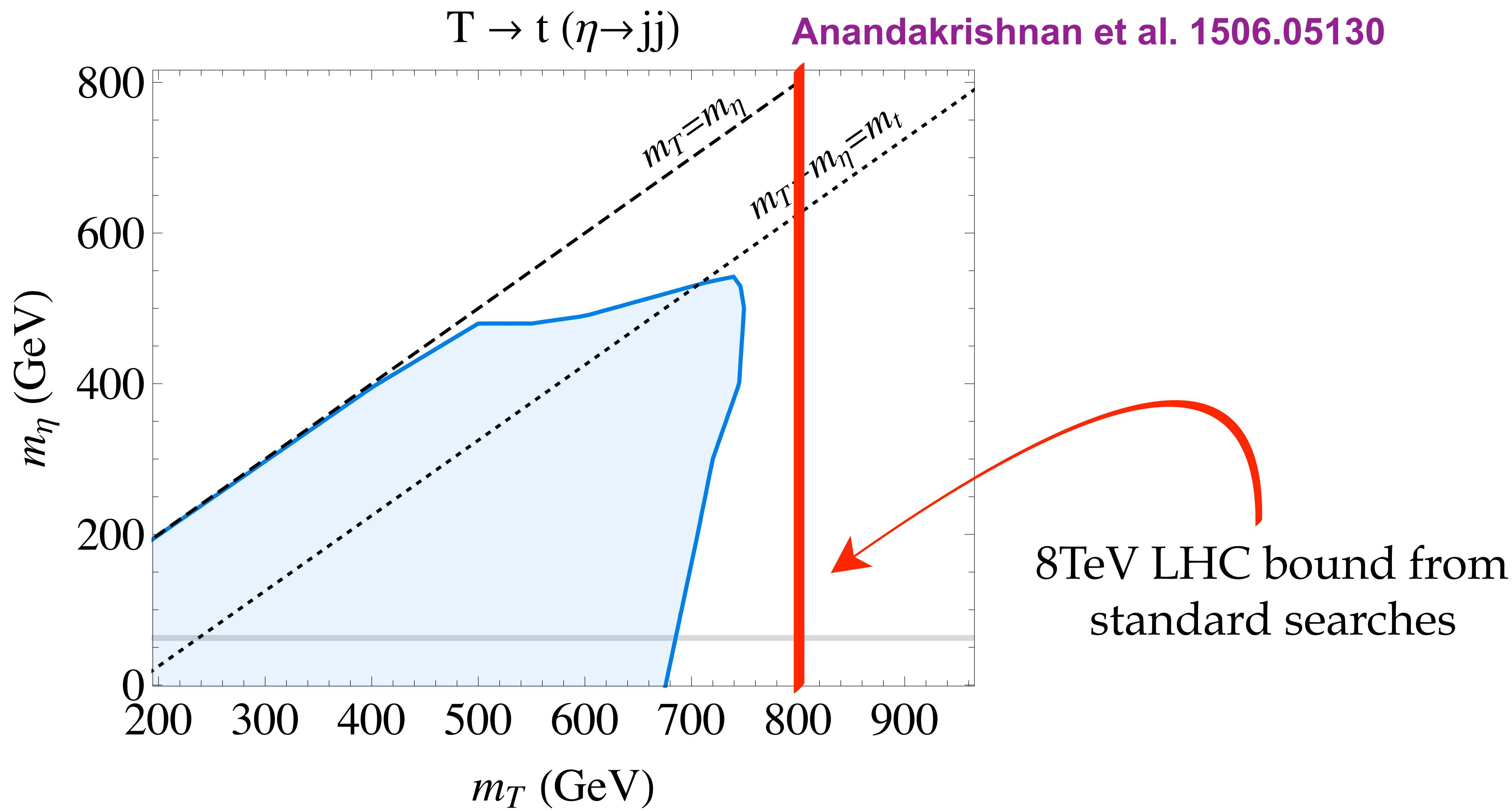

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the last epicycle on BSM (approximate) symmetries

Are *colored* top partners really needed?

Twin Higgs mechanism

SM

gauged
$SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\overset{Z_2}{\longleftrightarrow}$$

$\widetilde{\mathbf{SM}}$

gauged
$\widetilde{SU(3)}_C \times \widetilde{SU(2)}_L \times \widetilde{U(1)}_Y$

$$V(H,\widetilde{H}) = -\mu^2\left(|H|^2 + |\widetilde{H}|^2\right) + \frac{\lambda}{4}\left(|H|^2 + |\widetilde{H}|^2\right)^2 + \qquad \dots$$

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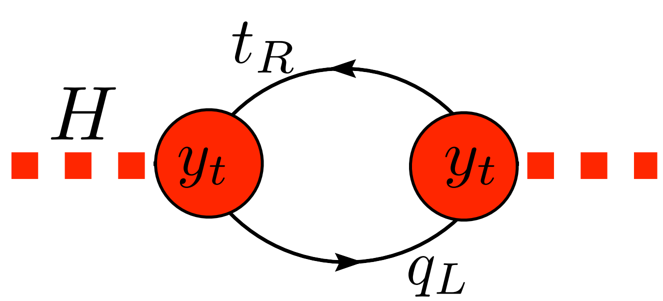

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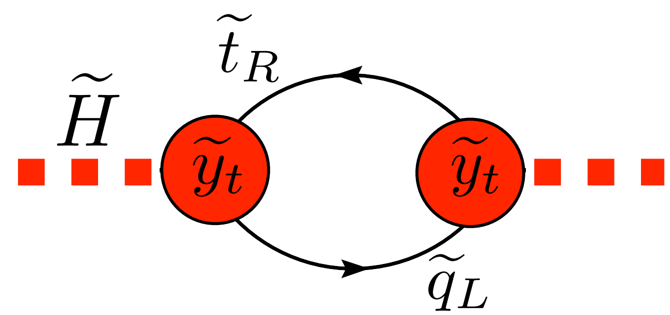

$y_t = \widetilde{y}_t$

the last epicycle on BSM (approximate) symmetries

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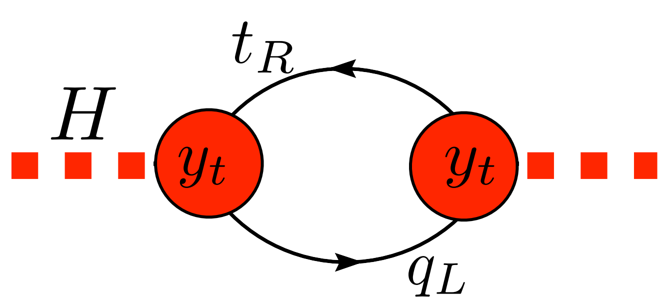
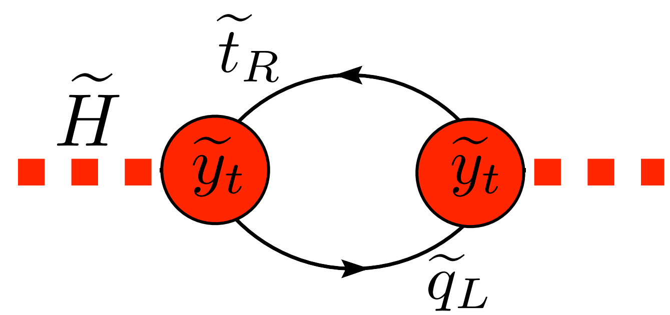
$V_{LO} =$  +  $y_t = \widetilde{y}_t$

$$\langle H \rangle = 0\,,\, \langle \widetilde{H} \rangle = f/\sqrt{2} \;\downarrow$$

$$SO(8)/SO(7)$$

The Higgs is an exact NGB, even after radiative corrections!

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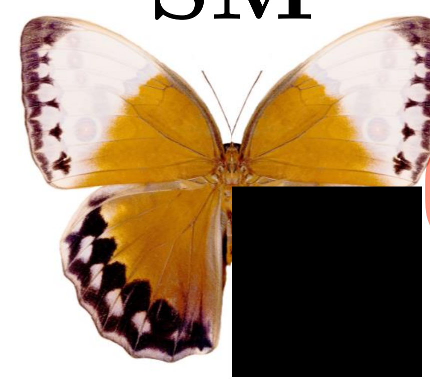

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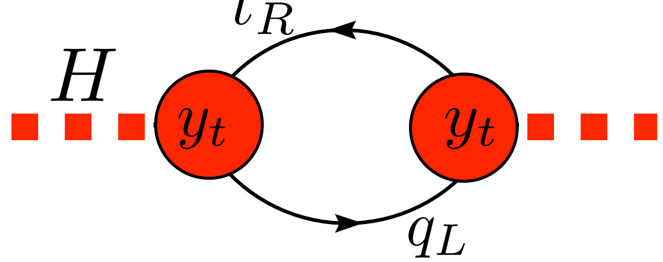

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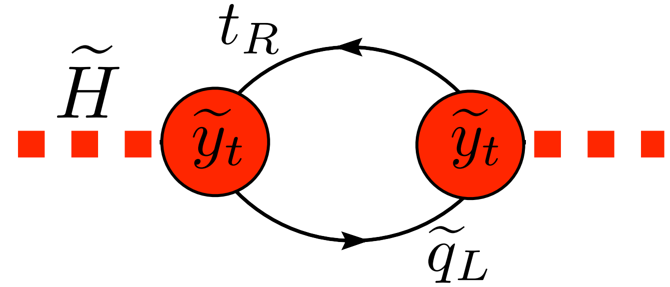

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twin Higgs

How do we get the Higgs VEV & mass?

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$SO(4)\times\widetilde{SO(4)}$

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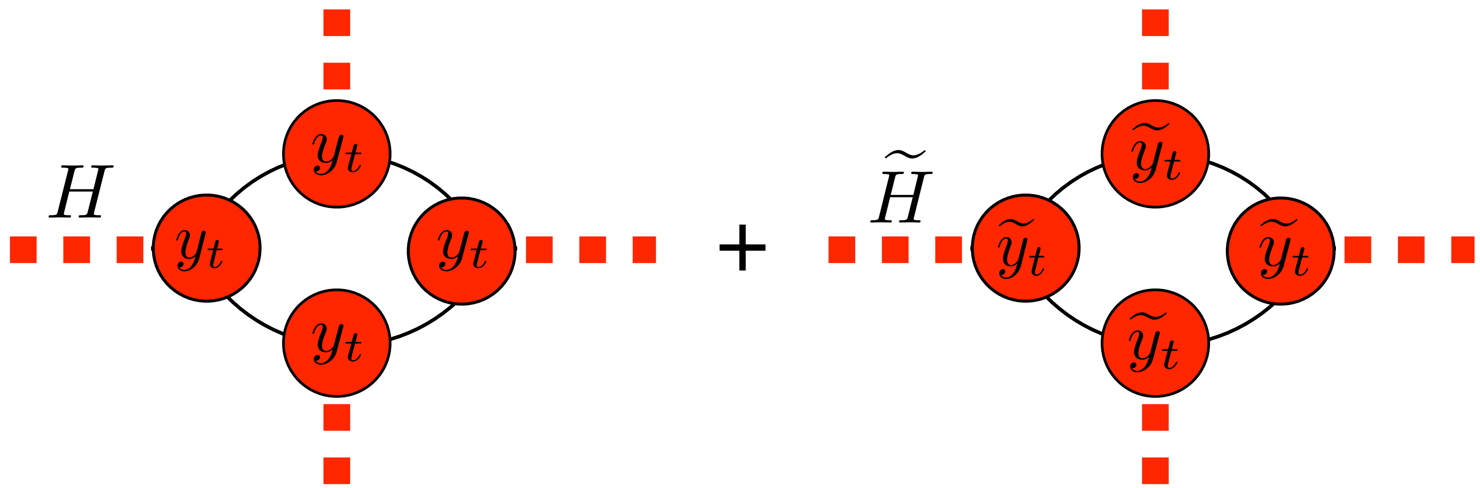

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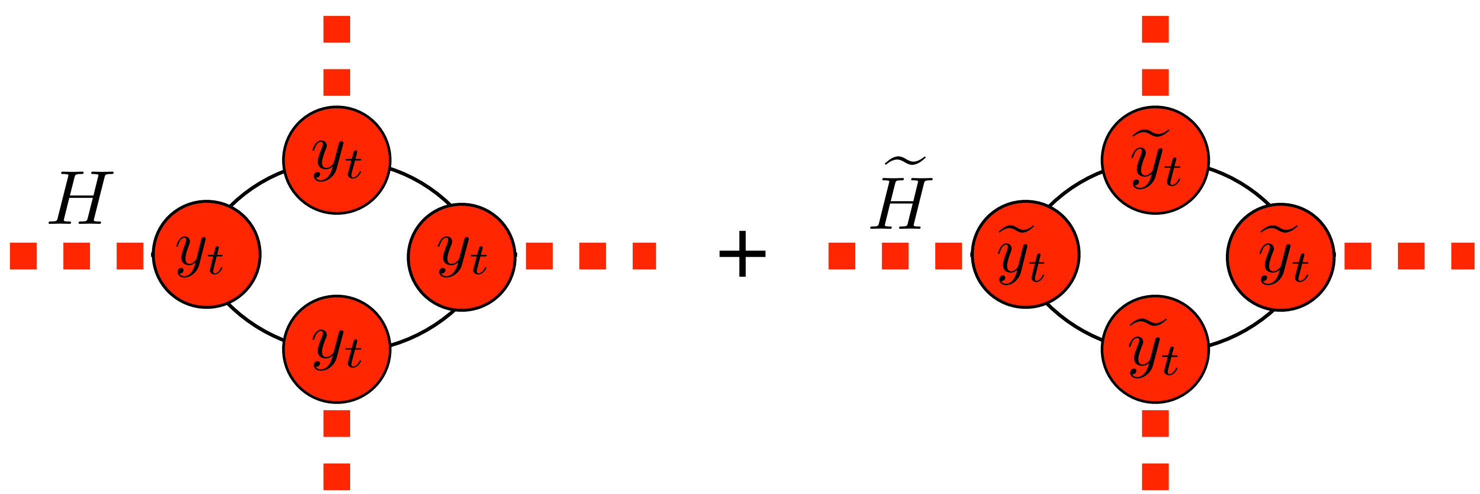

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$SO(8)/SO(7)$ $\downarrow$

$$\Sigma = \Big(\overbrace{\pi_1\,\pi_2\,\pi_3\,h}^{H}\;\overbrace{\widetilde{\pi}_1\,\widetilde{\pi}_2\,\widetilde{\pi}_3\,\sqrt{1-\pi_i^2+\widetilde{\pi}_i^2-h^2}}^{\widetilde{H}}\Big)$$

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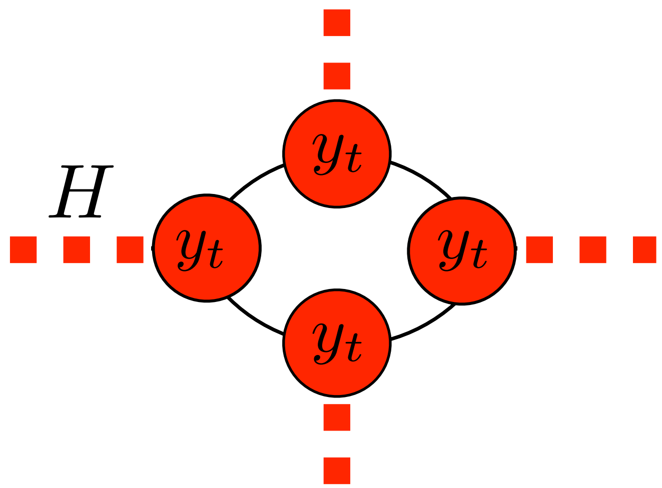
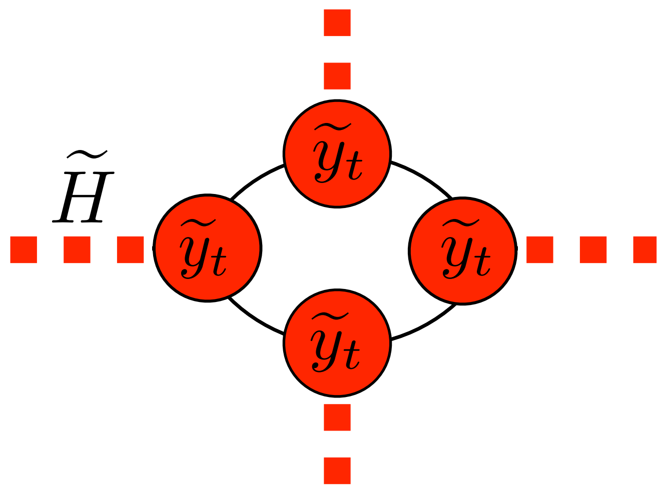
$V_{NLO} =$ 

$+$ 

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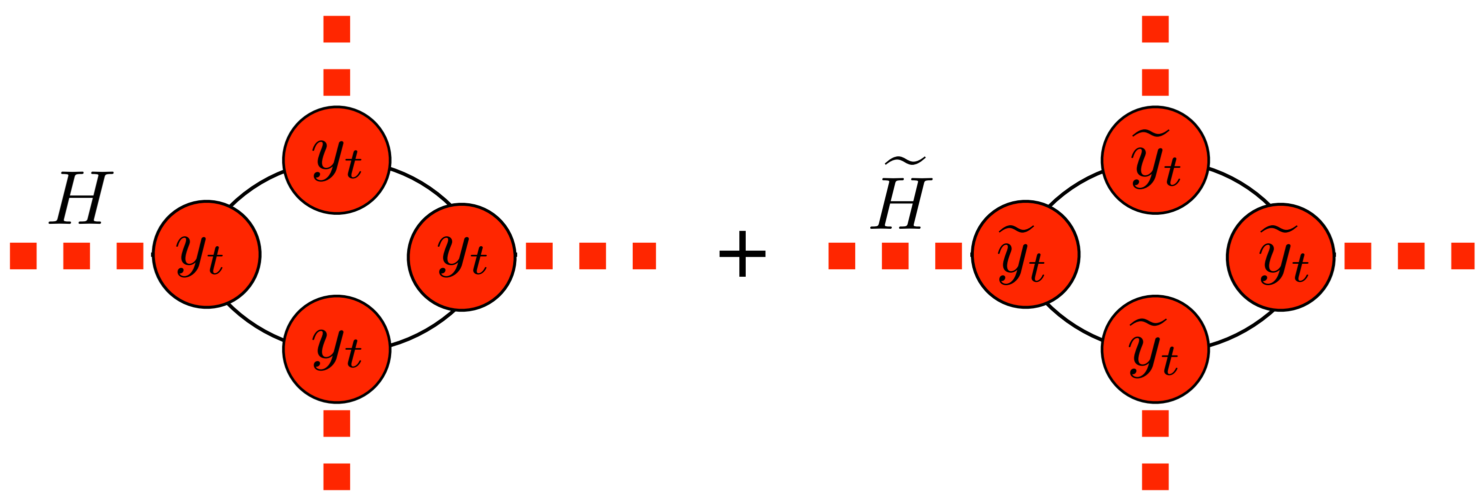

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$SO(4)\times\widetilde{SO(4)}$

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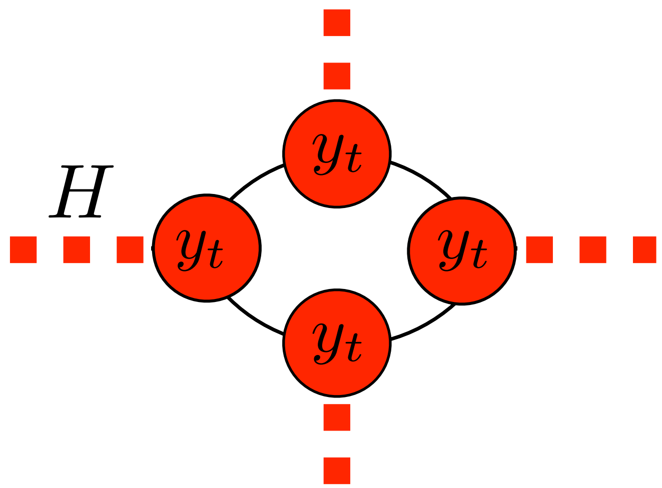

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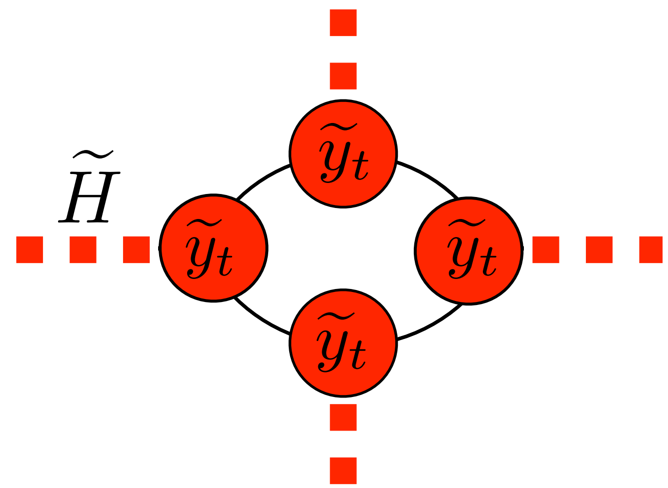


$y_t = \widetilde{y}_t$

$SO(8)/SO(7)$ $\downarrow$

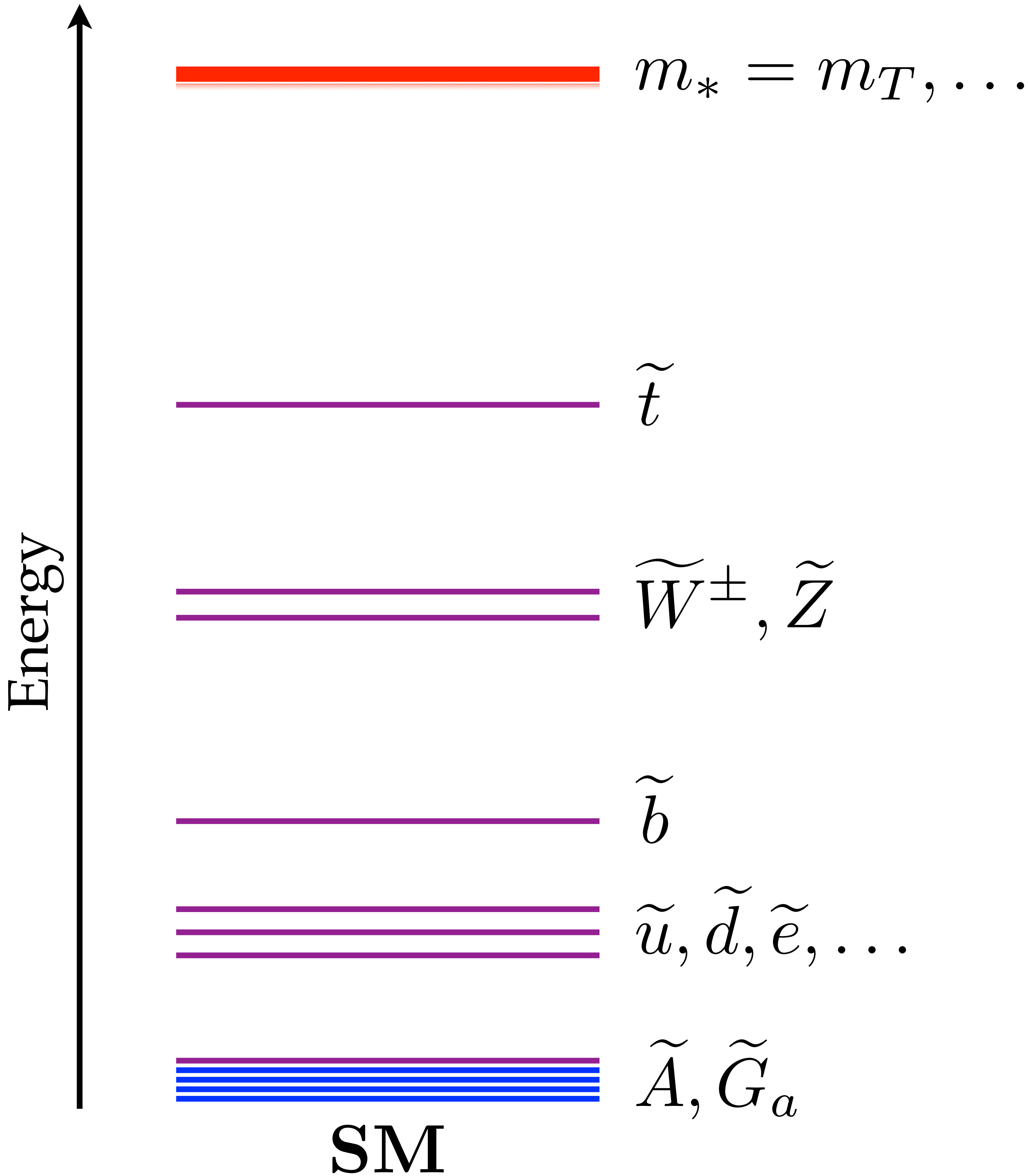
$$\Sigma = \Big(\underbrace{\pi_1\ \pi_2\ \pi_3\ h}_{H}\ \underbrace{\widetilde{\pi}_1\ \widetilde{\pi}_2\ \widetilde{\pi}_3\ \sqrt{1-\pi_i^2+\widetilde{\pi}_i^2-h^2}}_{\widetilde{H}}\Big)$$

$$V(H) = \frac{3f^4}{64\pi^2}\left[y_t^4|H|^2+\widetilde{y}_t^4(1-|H|^2)^2\right]\log \qquad y_t=\widetilde{y}_t$$

The Higgs potential is not sensitive to (colored) top partner mass.
There is no tension (tuning) coming from LHC searches.

twin Higgs

$\langle H \rangle = 0$

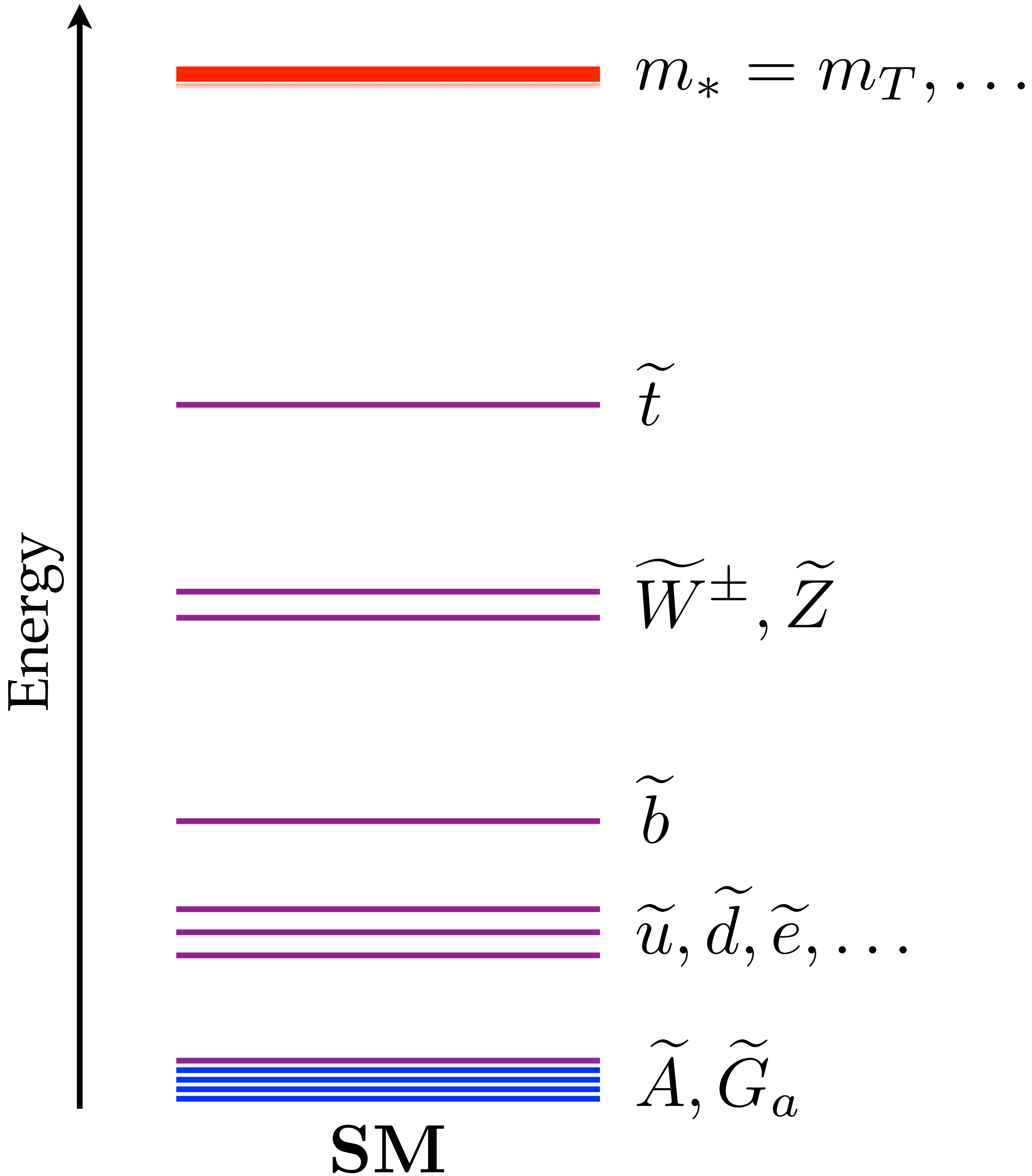


$$m_{\widetilde{\psi}} = \frac{y_\psi f}{\sqrt{2}}$$

$$m_{\widetilde{W}} = \frac{g f}{2}$$

twin Higgs

$\langle H \rangle = 0$



$$m_{\widetilde{\psi}} = \frac{y_\psi f}{\sqrt{2}}$$

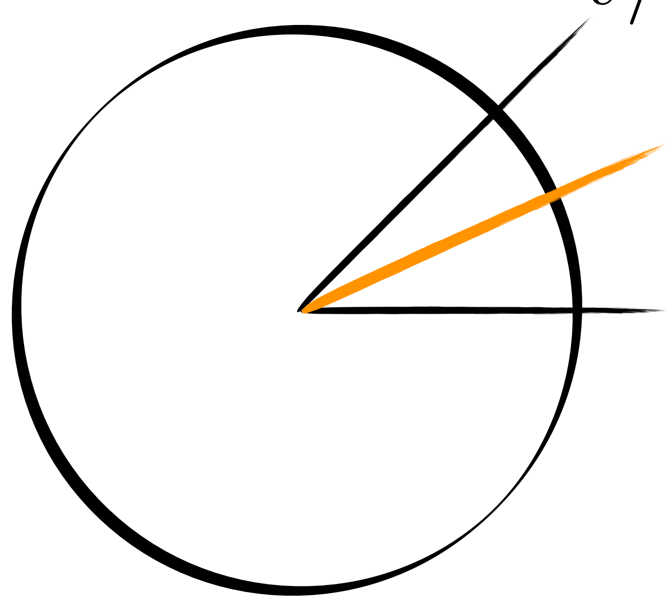
$$m_{\widetilde{W}} = \frac{g f}{2}$$

All twin states are SM-neutral.

twin Higgs

$$V(H) = \frac{3f^4}{64\pi^2}\left[y_t^4|H|^2 + \widetilde{y}_t^4(1-|H|^2)^2\right]\log \qquad y_t = \widetilde{y}_t$$

Misalignment:



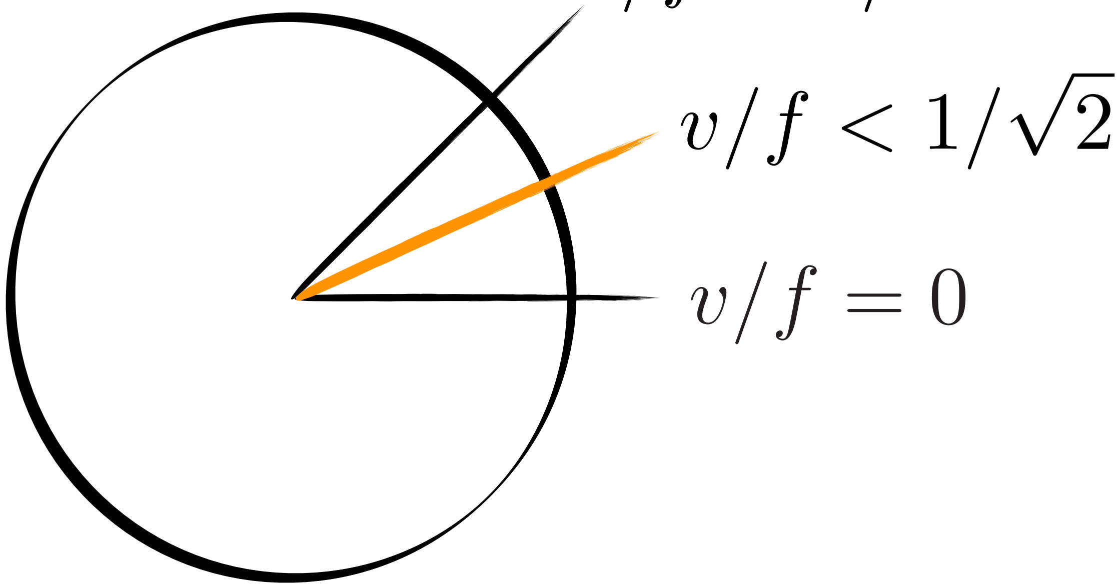
twin Higgs

$$V(H) = \frac{3f^4}{64\pi^2}\left[y_t^4|H|^2 + \widetilde{y}_t^4(1-|H|^2)^2\right]\log \qquad y_t = \widetilde{y}_t$$

Minimal **tuning**:

$$\Delta_v^{-1} = 2\frac{v^2}{f^2}$$

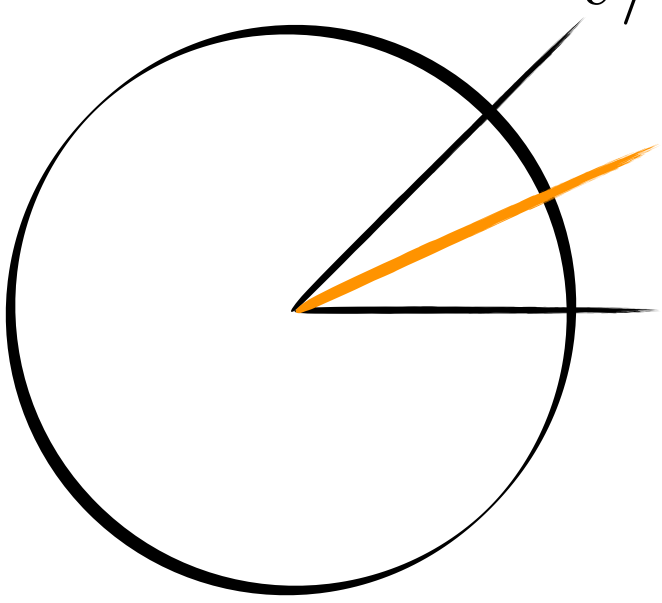
Misalignment:



twin Higgs

$$V(H) = \frac{3f^4}{64\pi^2}\left[y_t^4|H|^2 + \tilde{y}_t^4(1-|H|^2)^2\right]\log \qquad y_t = \tilde{y}_t$$

Misalignment:



Minimal **tuning**:

$$\Delta_v^{-1} = 2\frac{v^2}{f^2}$$

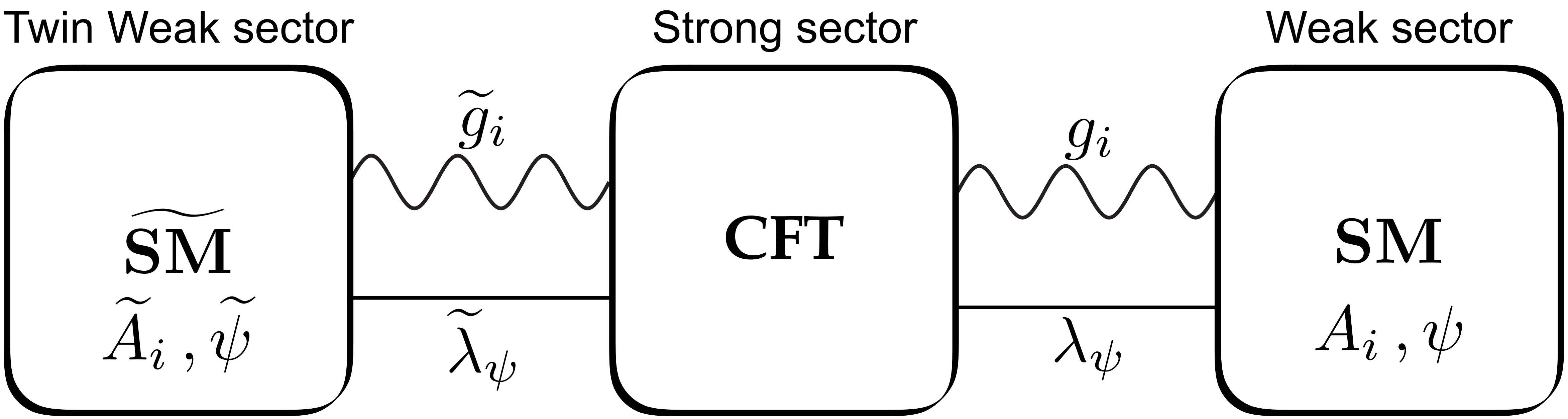
Explicit ***Z*₂ breaking** is required to misalign the Higgs VEV, e.g.:

- Twin $U(1)_Y$ is not gauged.
- Only 3rd generations fermions have twins (*fraternal Higgs*).
- Only the top has a twin (*brother Higgs*); see next.

…

composite twin Higgs

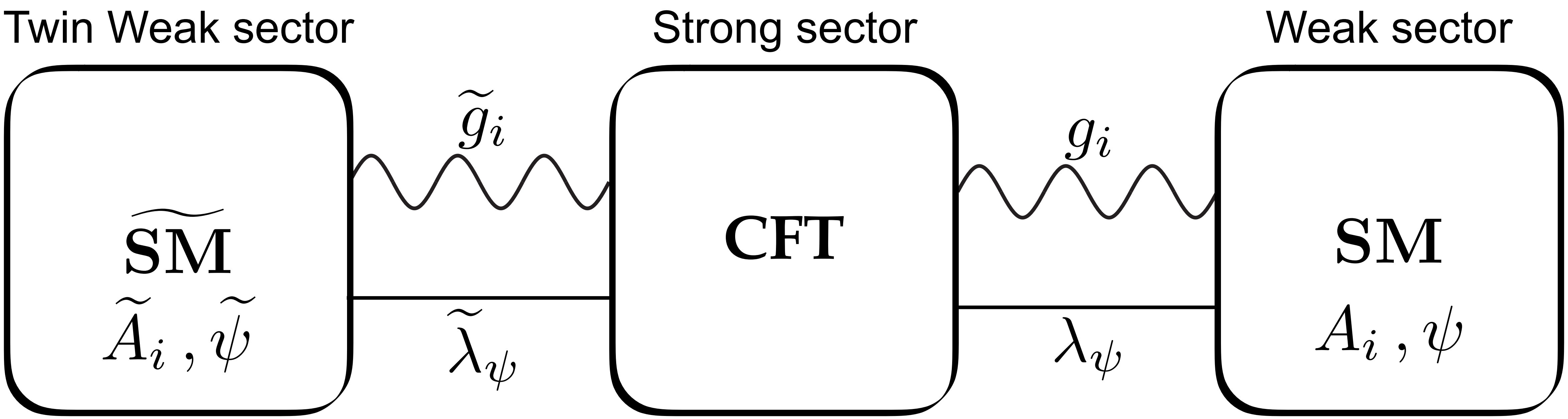
Replace the linear σ-model by strong sector and follow through.



$$[SO(8)/SO(7)] \times SU(3)_C \times \widetilde{SU(3)}_C \times U(1)_X \times \widetilde{U(1)}_X \times Z_2$$

composite twin Higgs

Replace the linear σ-model by strong sector and follow through.



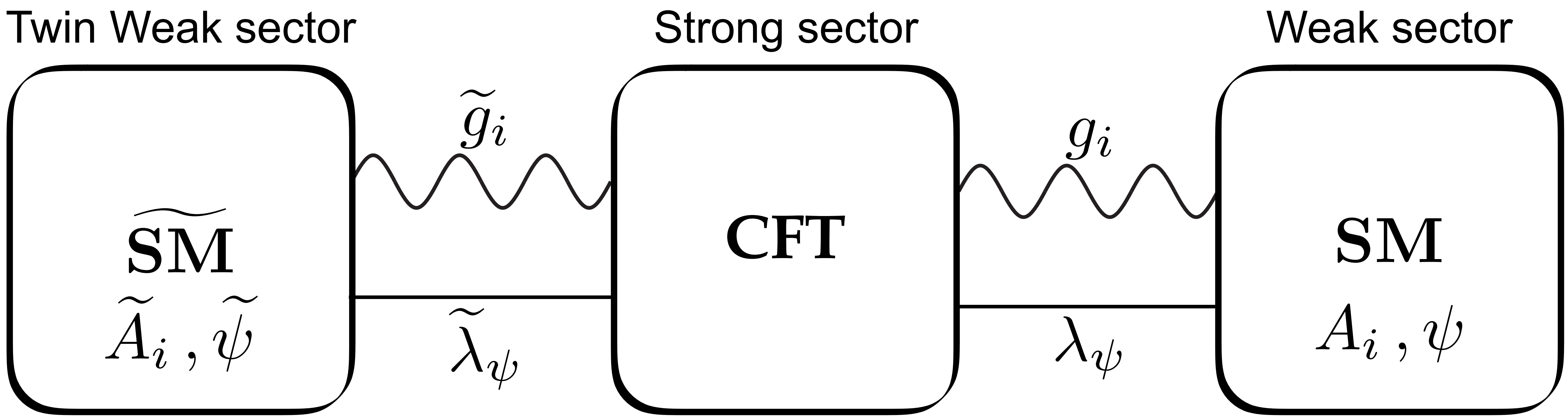
$$[SO(8)/SO(7)] \times SU(3)_C \times \widetilde{SU(3)}_C \times U(1)_X \times \widetilde{U(1)}_X \times Z_2$$

PC

$$Z_2 : \widetilde{A}_i \leftrightarrow A_i \longleftrightarrow \widetilde{g}_i = g_i$$

composite twin Higgs

Replace the linear σ-model by strong sector and follow through.



$$[SO(8)/SO(7)] \times SU(3)_C \times \widetilde{SU(3)}_C \times U(1)_X \times \widetilde{U(1)}_X \times Z_2$$

PC

$$Z_2 : \; \widetilde{A}_i \leftrightarrow A_i \longleftrightarrow \widetilde{g}_i = g_i$$

$$\lambda_q q_L \mathcal{O}_q + \lambda_t t_R \mathcal{O}_t \qquad \mathcal{O}_q = (\mathbf{8},\mathbf{3},\mathbf{1})_{2/3,0} \quad \mathcal{O}_t = (\mathbf{1},\mathbf{3},\mathbf{1})_{0,2/3}$$

$$\widetilde{\lambda}_q \widetilde{q}_L \widetilde{\mathcal{O}}_q + \widetilde{\lambda}_t \widetilde{t}_R \widetilde{\mathcal{O}}_t \qquad \widetilde{\mathcal{O}}_q = (\mathbf{8},\mathbf{1},\mathbf{3})_{0,2/3} \quad \widetilde{\mathcal{O}}_t = (\mathbf{1},\mathbf{1},\mathbf{3})_{0,2/3}$$

$$Z_2 : \quad \widetilde{\psi} \leftrightarrow \psi \longleftrightarrow \widetilde{\lambda}_\psi = \lambda_\psi$$

twin Higgs phenomenology

- The Higgs remains a pseudo-NGB:

Higgs couplings

$$\frac{1}{f^2}(\partial_\mu |H|^2)^2 \qquad \delta g_h \sim \frac{v^2}{f^2} \lesssim 0.1 \qquad f \gtrsim 750\text{GeV}$$

- The strong sector has a mass gap naturally high*: $m_* \approx 5\text{TeV}$

e.g. S-parameter

$$\widehat{S} \sim \frac{m_W^2}{m_*^2} \lesssim 10^{-3}$$

- No production of heavy resonances at the LHC.

- Higgs portal type of collider phenomenology.

summary

Symmetries have shaped the way we address the limitations of the SM.

One may argue that we have taken this philosophy to the extreme,
for a good purpose, the *electroweak hierarchy problem*.

Variants of the standard solutions based on symmetries, such as Composite Higgs models, **no** longer require light **colored top partners**.

Searches for these theories are on its way.

DON'T PANIC

try to ACT NATURAL

Thank you!

light & weakly coupled top partners

$$m_T < m_* \approx 2.5\text{TeV}$$

S-parameter bound

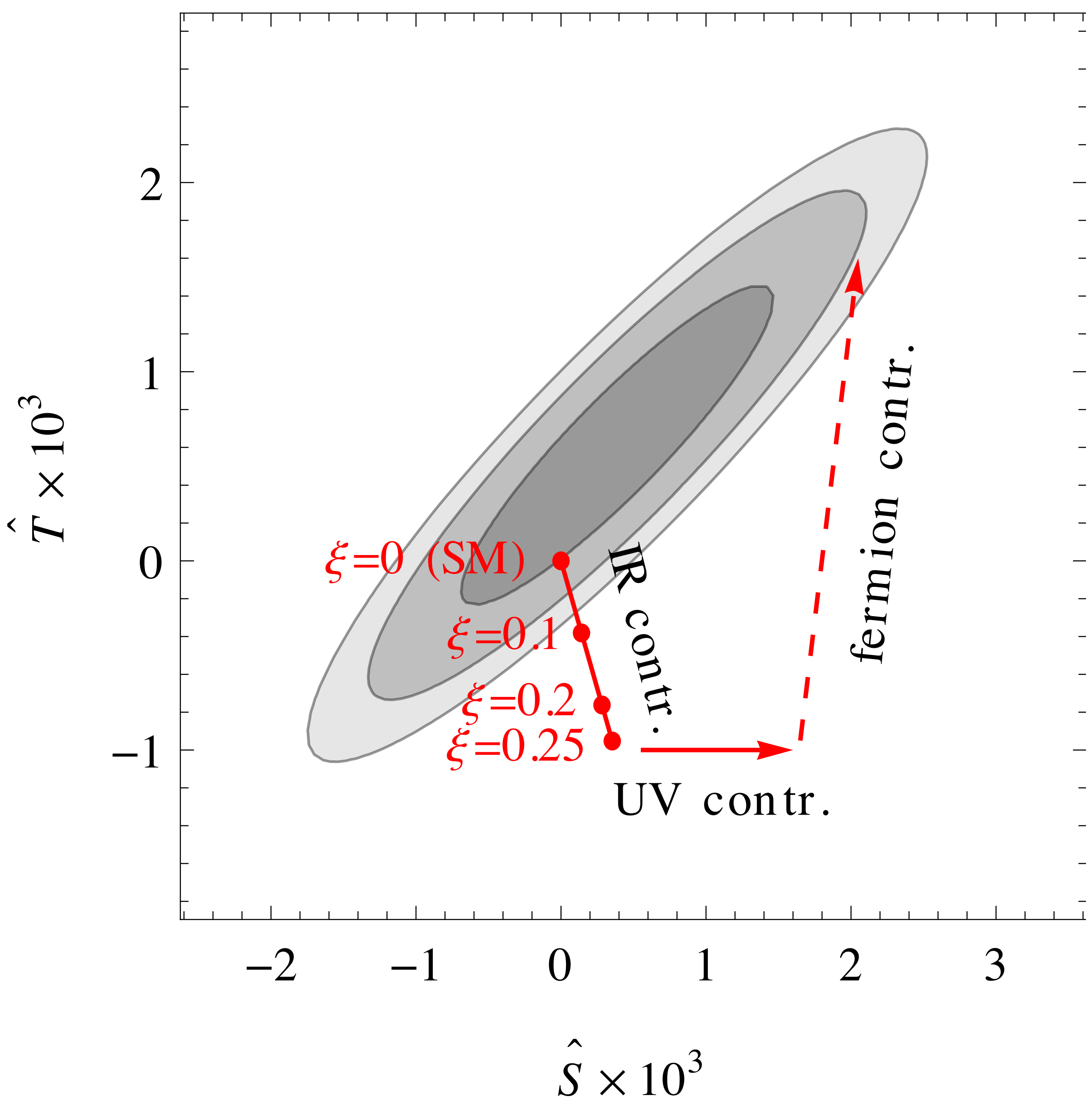
There might be several reasons, e.g.:

- $\epsilon_{q,t} \to 1 \quad \longleftrightarrow \quad d(\mathcal{O}_{q,t}) \to 3/2$ = free field dimension

- Accidental Ψ chiral symmetry.

- Large N counting.

EWPT & top partners



$$\Delta\widehat{T} \sim \frac{3y_L^2}{16\pi^2}\frac{y_L^2 v^2}{m_*^2}$$

Another way to understand twin Higgs:

brother Higgs