The Twin Composite Higgs Scenario

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Introduction

“Leaving no stone unturned in the hunt for Naturalness”

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Naturalness

"Is m_H Unnatural?" $=$ "Is m_H Unpredictable?"

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$$\left(m_H^2\right)_{Phys.} = \int_0^{\infty} F_{true}(E;\, g_{true})$$
$$= \int_0^{\lesssim\, \Lambda_{\rm SM}} (\ldots) + \int_{\lesssim\, \Lambda_{\rm SM}}^{\infty} (\ldots)$$

Naturalness

"Is m_H Unnatural?" $=$ "Is m_H Unpredictable?"

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$$= \int_0^{\lesssim \Lambda_{\rm SM}} (\ldots) + \int_{\lesssim \Lambda_{\rm SM}}^{\infty} (\ldots)$$

UV Contribution

$$c\,{\Lambda_{\rm SM}}^2$$

SM Contribution

$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}{\Lambda_{\rm SM}}^2$$

Fine Tuning: $\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,\mathrm{GeV}}\right)^2$

Measures how much Unpredictable m_H is.

Naturalness

The usual argument:

$$\Delta \geq \left(\frac{\Lambda_{\mathrm{SM}}}{500\,\mathrm{GeV}}\right)^2 \quad \Rightarrow \quad \Lambda_{\mathrm{SM}} \leq 500\,\mathrm{GeV} \cdot \sqrt{\Delta}$$

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$$\Lambda_{\rm SM} = M_{\rm Partners} =$$ “Scale where m_H finds its physical origin ”

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Partners are SM charged:
- **SUSY:** Stops, Gluinos, …
- **CH:** Top Partners, EW partners…

Naturalness

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The usual **interpretation**:

$$\cancel{\Lambda_{\mathrm{SM}} \sim M_{\mathrm{Partners}}} =$$

"Scale where m_H finds its physical origin "

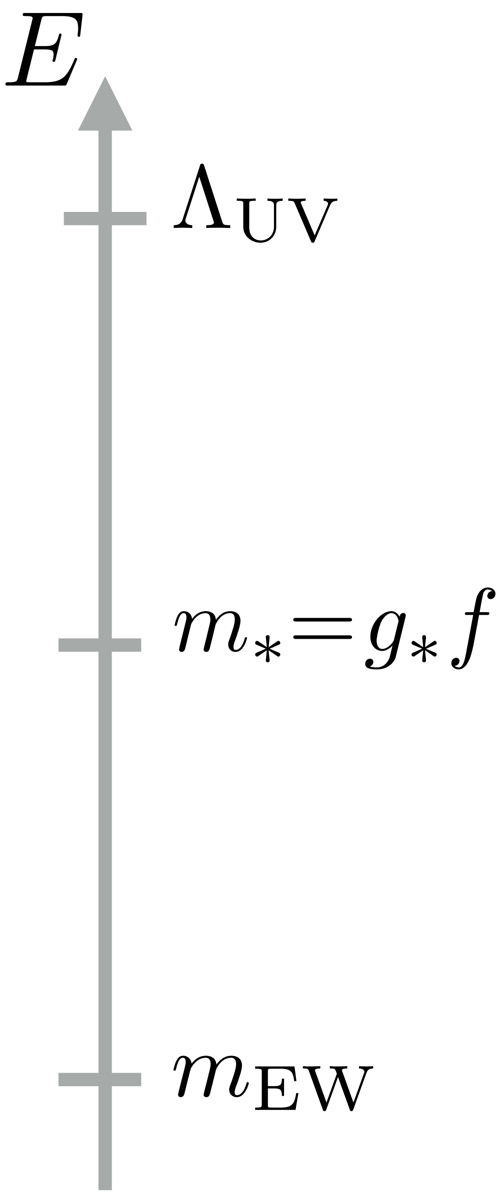
Y: Stops, Gluinos, …

Top Partners, EW partners…

The Twin Higgs Program:

- Keep tuning below ten
- Keep partners above few TeV
- Neutral particles at Λ_{SM} ("Twin" stuff)

Composite Higgs



Ingredients:

Composite Sector

Stable Λ_{UV}—m_* Hierarchy from slow running

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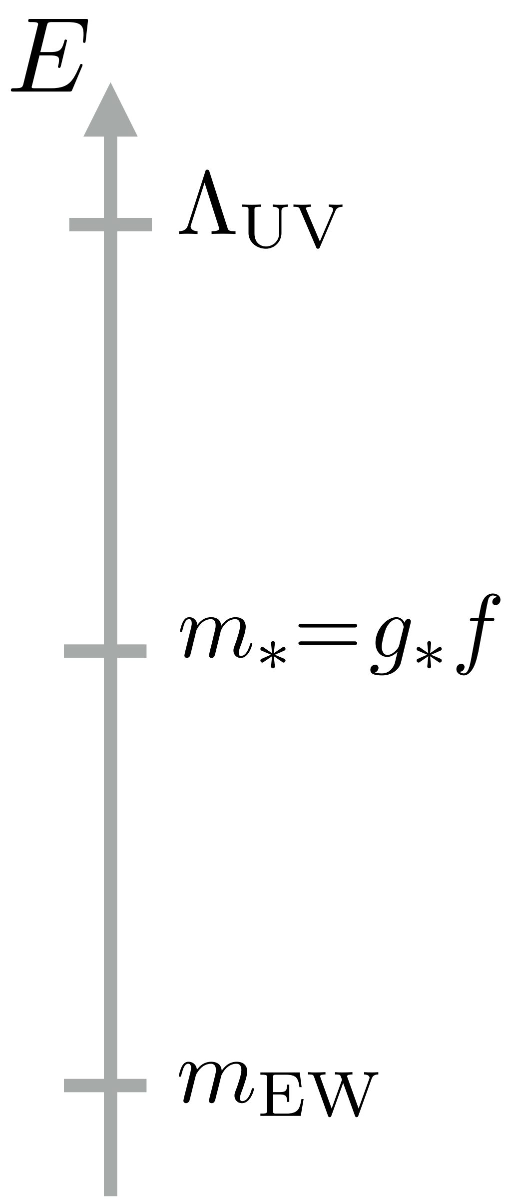

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CS parameters:

mass: m_*
coupling: g_*

CS symmetry:

$$\mathcal{G} \xrightarrow{f} \mathcal{H}$$

$$H \in \mathcal{G}/\mathcal{H}$$

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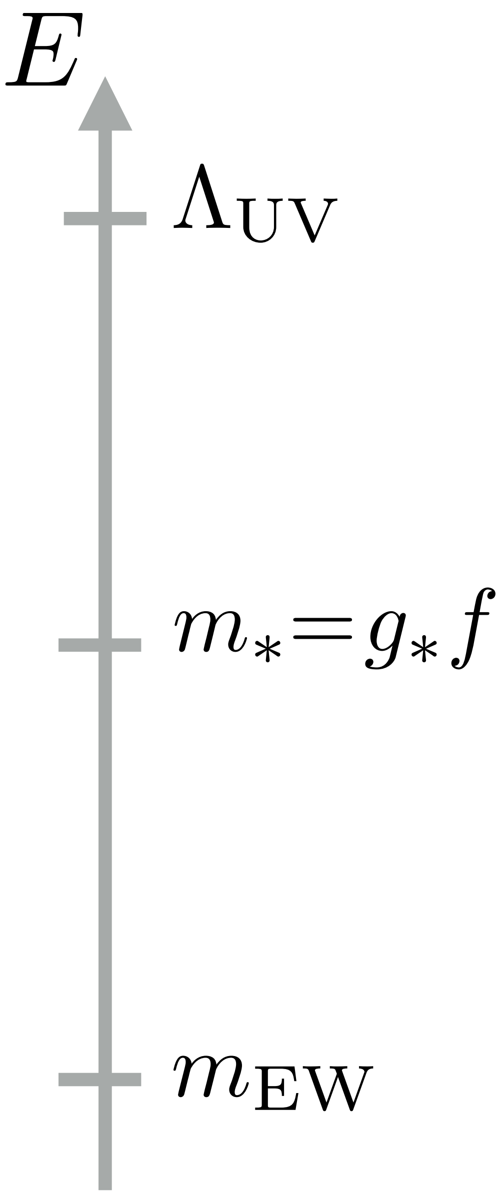

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Elementary Sector

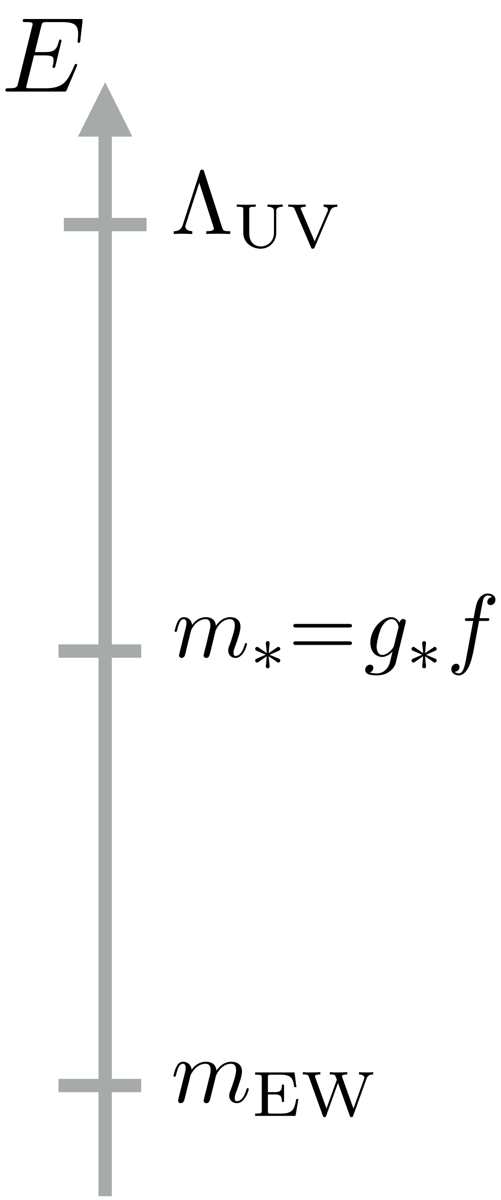
Contains other SM fields:

$$W_\mu^{1,2,3},\ B_\mu$$
$$f_L,\ f_R$$

Weakly Interacting:

$$g_{\mathrm{E}} < g_*$$

Composite Higgs



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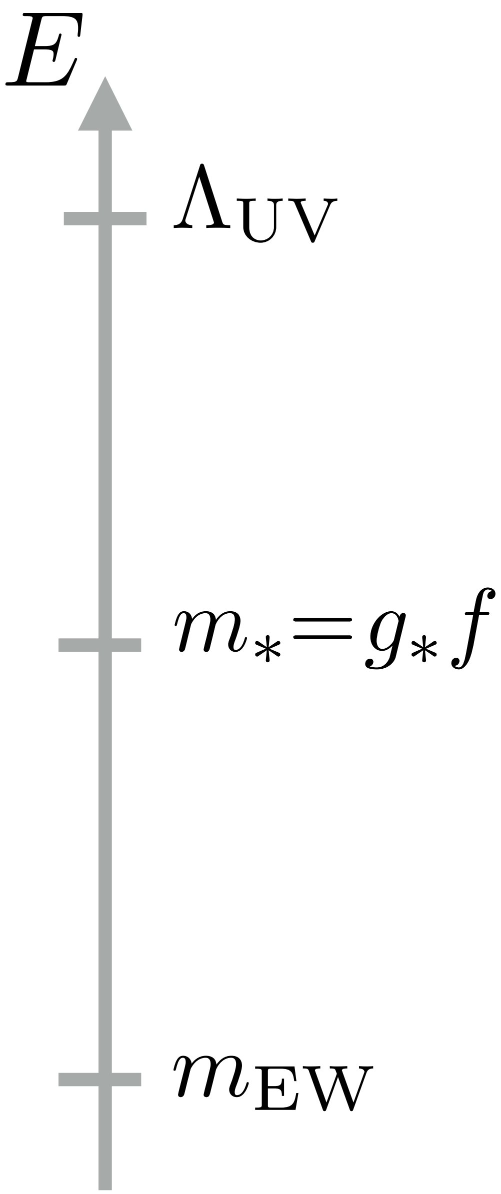

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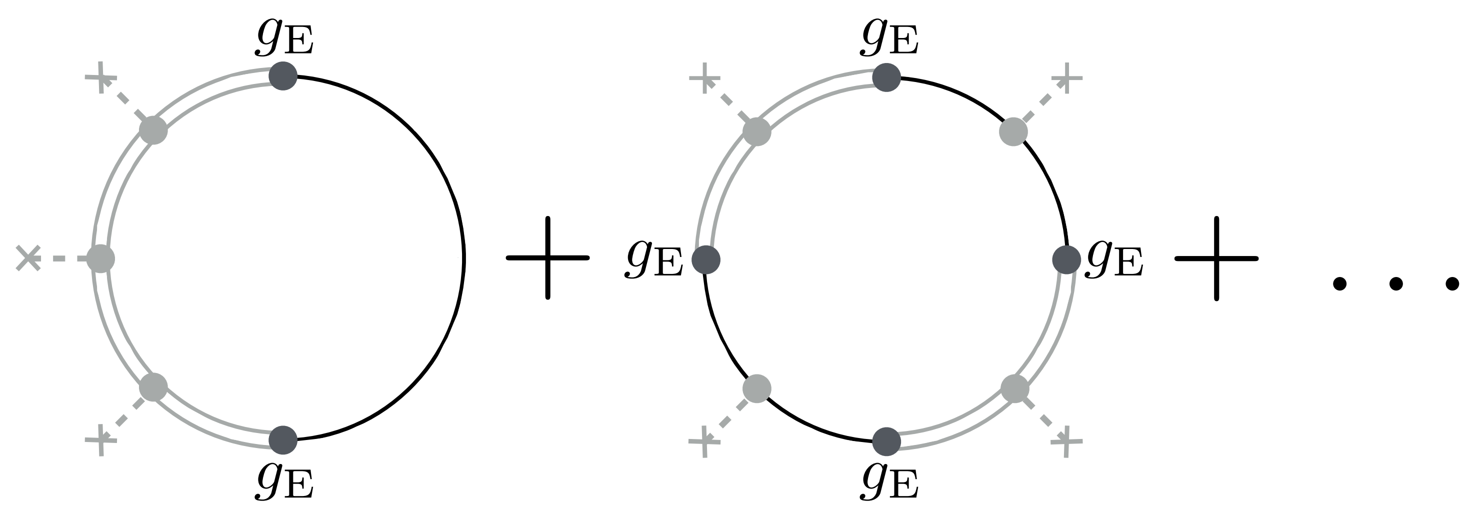
Minimal source of tuning: $\xi = \dfrac{v^2}{f^2} \ll 1$ (from EWPT&Higgs)

Composite Higgs

Potential from Elementary loops (Top dominates)



$$V = \frac{N_c m_*^4}{16\pi^2}\left[\left(\frac{g_{\rm E}}{g_*}\right)^2 \mathcal{V}_{(2)}[H/f] + \left(\frac{g_{\rm E}}{g_*}\right)^4 \mathcal{V}_{(4)}[H/f] + \dots\right]$$

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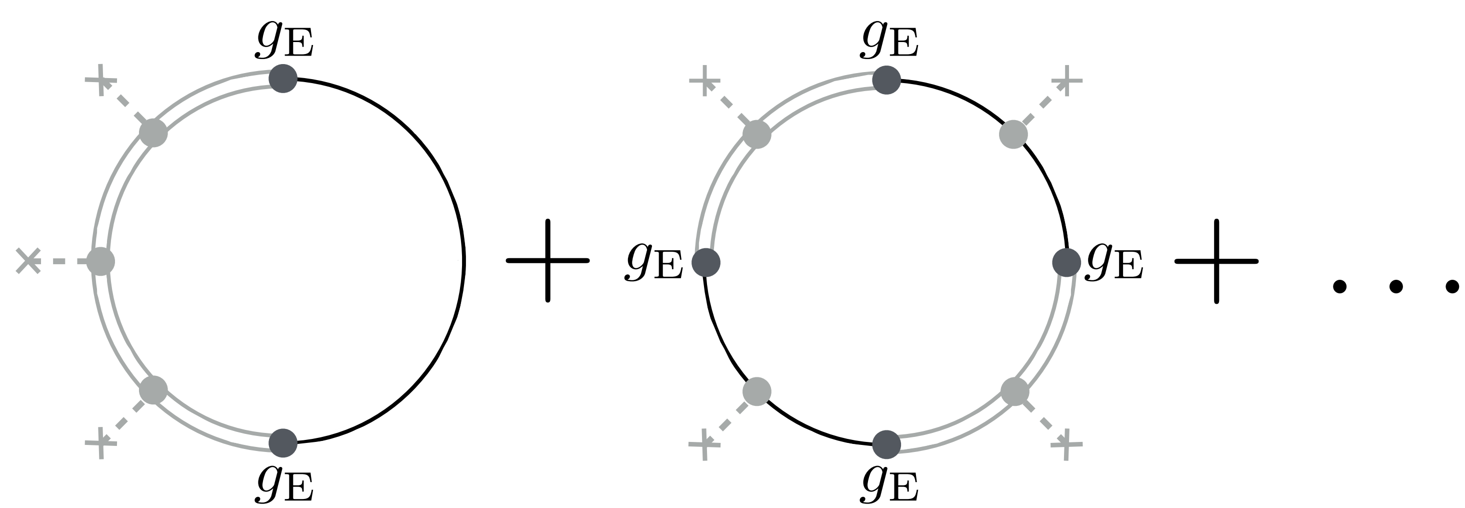

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$$\delta m_H^2 \sim \frac{N_c g_{\mathrm{E}}^2}{8\pi^2}\frac{m_*^4}{g_*^2 f^2} = \frac{N_c g_{\mathrm{E}}^2}{8\pi^2} m_*^2 = \frac{g_{\mathrm{E}}^2}{y_t^2}\left(\frac{m_*}{500\,\mathrm{GeV}}\right)^2 m_H^2$$

Res. scale = Tuning scale

Composite Higgs

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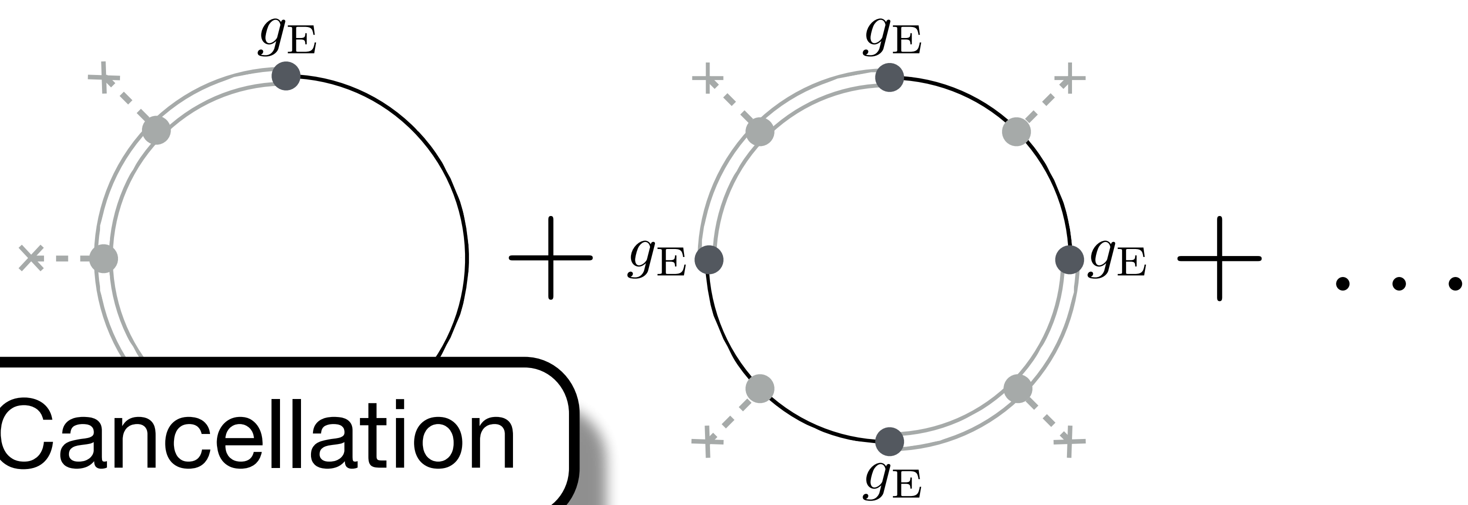

Twin Higgs Cancellation

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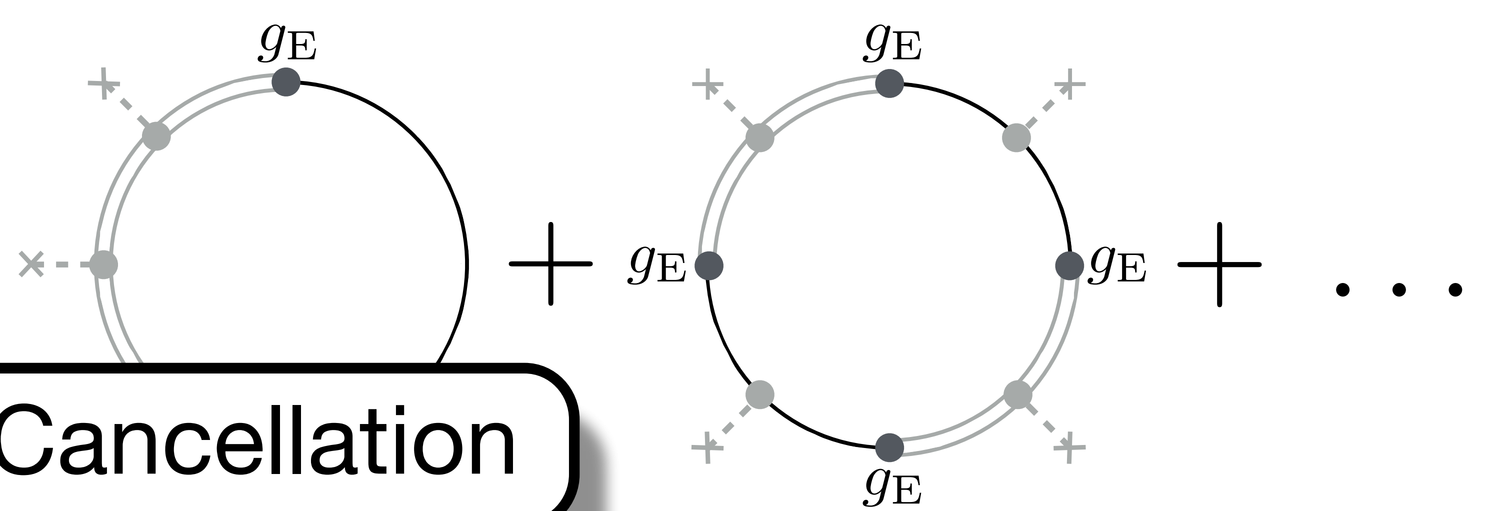

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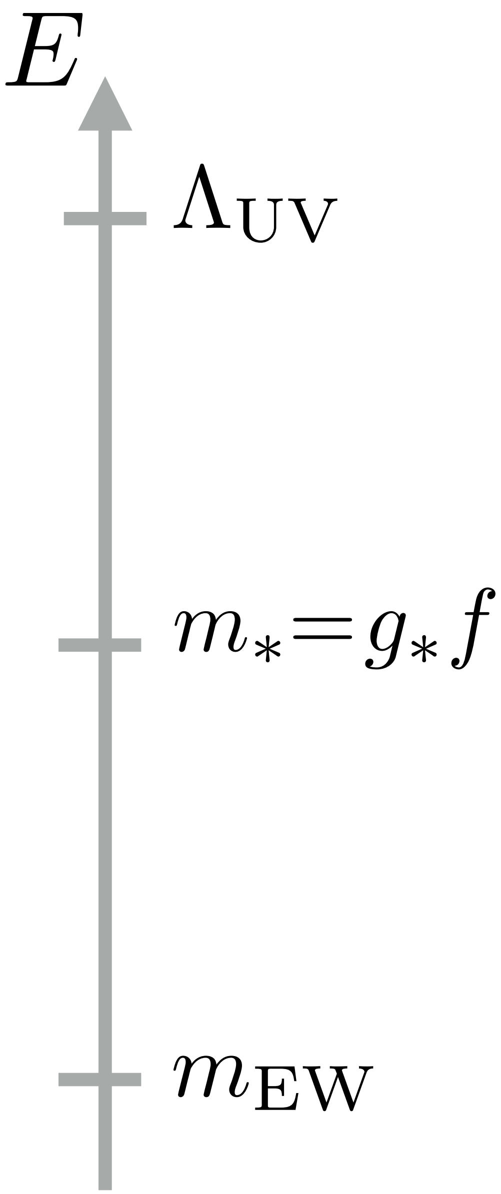
$$\delta m_H^2 \sim \cancel{\frac{N_c g_{\rm E}^2}{8\pi^2}\frac{m_*^4}{g_*^2 f^2} = \frac{N_c g_{\rm E}^2}{8\pi^2} m_*^2 \sim \frac{g_{\rm E}^2}{y_t^2}\left(\frac{m_*}{500\,{\rm GeV}}\right)^2} m_H^2$$ Res. scale = Tuning scale

$$\delta m_H^2 \sim \frac{N_c g_{\rm E}^4}{8\pi^2}\frac{m_*^4}{g_*^4 f^2} = \frac{N_c g_{\rm E}^4}{8\pi^2} f^2$$ Tuning scale disentangled from res.

Twin Composite Higgs



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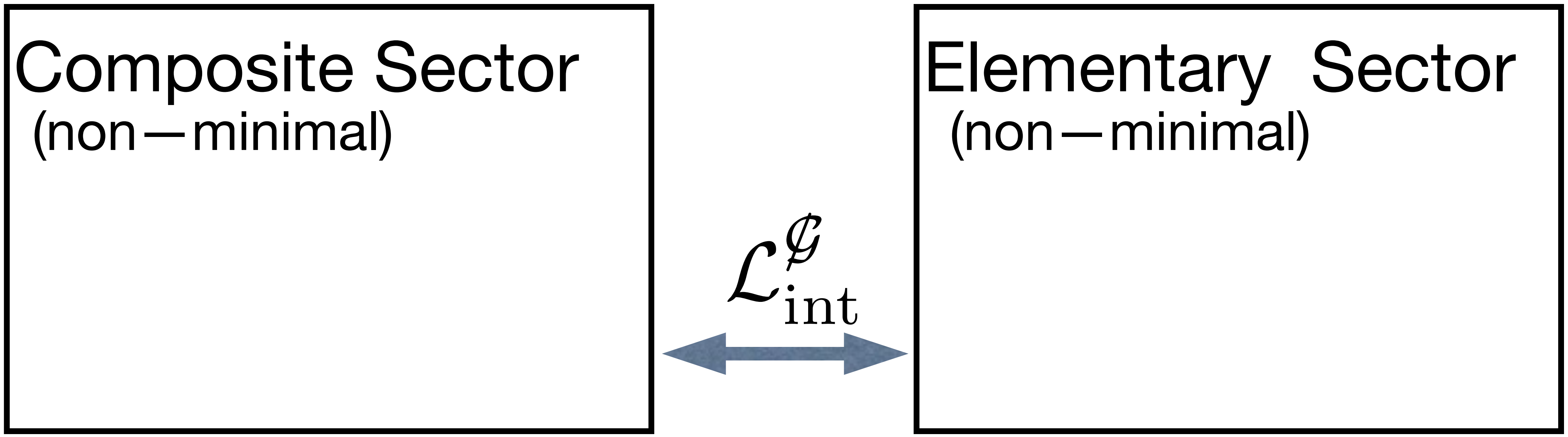

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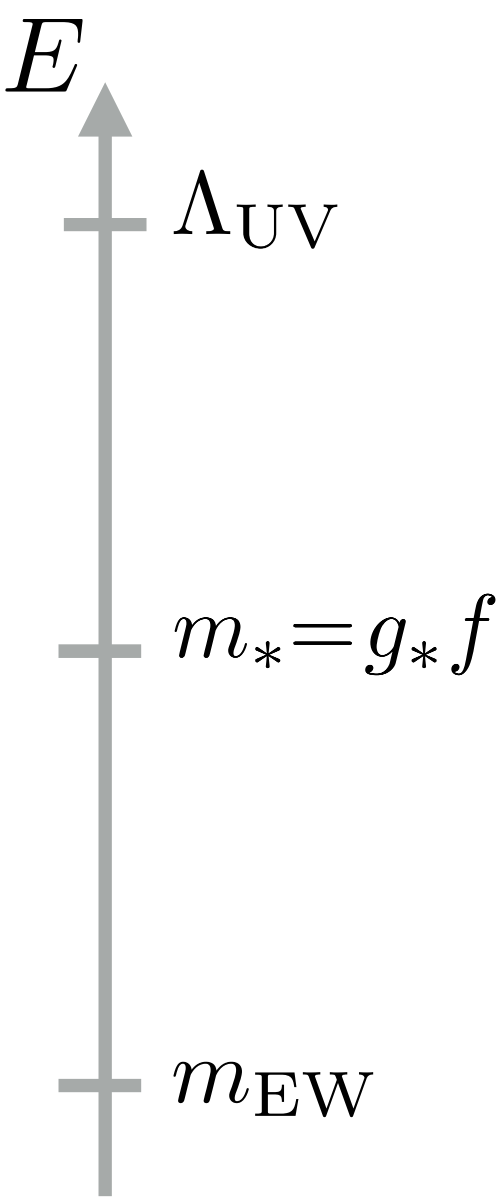

Ingredients:

Composite Sector
(non−minimal)

$$\mathrm{SO}(8) \to \mathrm{SO}(7)$$

$$\mathrm{SO}(8) \subset \mathrm{SO}(4) \times \widetilde{\mathrm{SO}}(4)$$

for custodial symmetry
[Geller, Telem, '14]

$\mathcal{L}_{\rm int}^{\not{\mathcal{G}}}$

Elementary Sector
(non−minimal)

Twin Composite Higgs

Ingredients:

E

Λ_{UV}

$m_* = g_* f$

m_{EW}

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7 NGB = Higgs + 3

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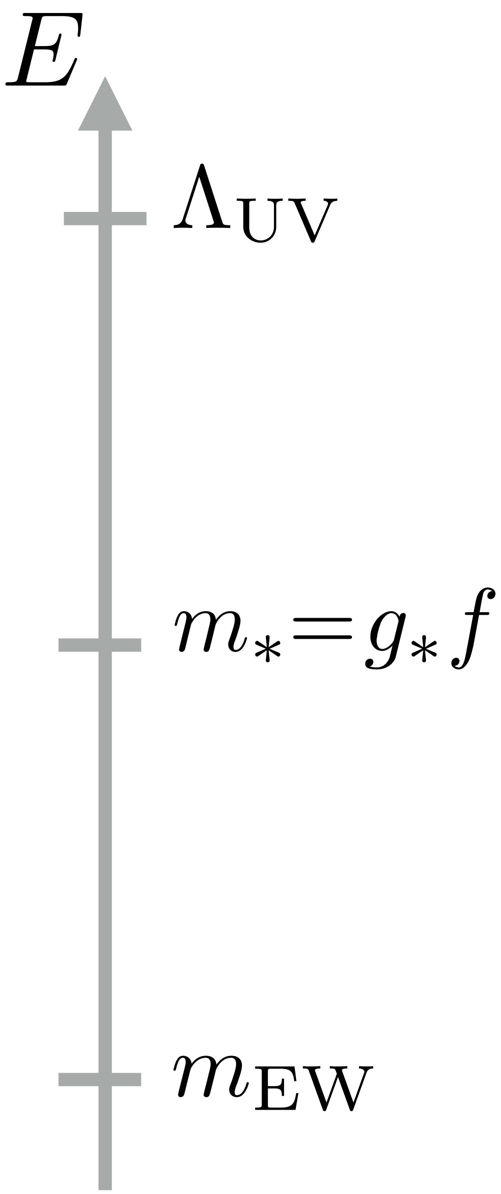

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Bosonic Spectrum:

EW bosons

$$M_W \sim g_2 f \sin\frac{\langle H \rangle}{f} = g_2 v$$

$$M_Z = M_W / \cos\theta_W \qquad M_\gamma = 0$$

Twin Composite Higgs

E

$\Lambda_{\rm UV}$

$m_* = g_* f$

$M_{\widetilde{W}}$

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Bosonic Spectrum:

EW bosons	Twin W's
$M_W \sim g_2 f \sin \frac{\langle H \rangle}{f} = g_2 v$	$M_{\widetilde{W}} \sim \widetilde{g}_2 f \cos \frac{\langle H \rangle}{f} \sim \widetilde{g}_2 f$
$M_Z = M_W / \cos\theta_W \qquad M_\gamma = 0$	No massless Twin Photon

Twin Composite Higgs

E

Λ_{UV}

$m_* = g_* f$

$M_{\widetilde{W}}$

m_{EW}

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(non—minimal)

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$\xleftrightarrow{\mathcal{L}_{\mathrm{int}}^{\not{G}}}$

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Twin W's

$$M_{\widetilde{W}} \sim \tilde{g}_2 f \cos \frac{\langle H \rangle}{f} \sim \tilde{g}_2 f$$

No massless Twin Photon

Plus resonances at m_*, like in ordinary CH, but heavier

Twin Composite Higgs

Gauge contribution to the potential, from a model

$$V_{g_2^2} = \frac{9 g_*^2 f^4}{512\pi^2}\left(g_2^2 \sin^2\frac{H}{f} + \widetilde{g}_2^2 \cos^2\frac{H}{f}\right)$$

Twin Higgs miracle: $g_2 = \widetilde{g}_2 \Rightarrow V_{g_2^2} = \text{const.}$

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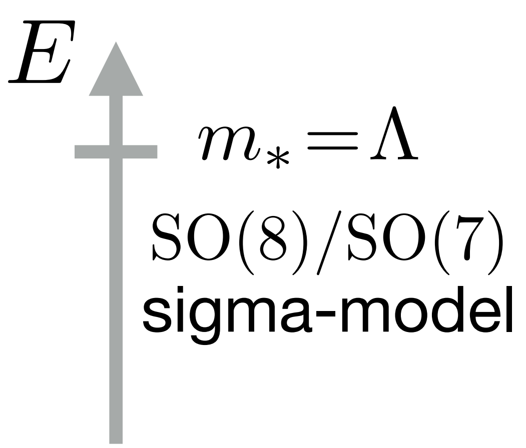
Guessing the cancellation: quadratic divergence



$$\vec{\Sigma} = \begin{bmatrix} \vec{\pi} \\ \vec{\widetilde{\pi}} \end{bmatrix} = U[H/f] \cdot \begin{bmatrix} \vec{0} \\ f \end{bmatrix} = \begin{bmatrix} \vec{0} \\ s_H f \\ \vec{0} \\ c_H f \end{bmatrix}$$

$$V^{\Lambda^2} = \frac{\Lambda^2}{16\pi^2}\left[g_2^2 |\vec{\pi}|^2 + \widetilde{g}_2^2 |\vec{\widetilde{\pi}}|^2\right] = \frac{\Lambda^2 f^2}{16\pi^2}\left[g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2\right]$$

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Guessing the cancellation: quadratic divergence

E

$m_* = \Lambda$

$\mathrm{SO}(8)/\mathrm{SO}(7)$

sigma-model

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$$V^{\Lambda^2} = \frac{\Lambda^2}{16\pi^2} [g_2^2 |\vec{\pi}|^2 + \widetilde{g}_2^2 |\vec{\widetilde{\pi}}|^2] = \frac{\Lambda^2 f^2}{16\pi^2} [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2]$$

But, in reality:

$$V = \int_0^\infty dE(\ldots) = \int_0^{<\Lambda} dE(\ldots) + \int_{<\Lambda}^\infty dE(\ldots)$$

what about this one?

Twin Composite Higgs

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Proving the cancellation: Spurion classification

$$\mathcal{L}_{\text{int}} = W_\mu^\alpha G_\alpha^A J_A^\mu + \widetilde{W}_\mu^\alpha \widetilde{G}_\alpha^A J_A^\mu \qquad G, \widetilde{G} \in \mathbf{28} = \mathbf{21} \oplus \mathbf{7}$$

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# of invariant operators = (# of H invariants) - (# of G invariants) = **2 - 1**

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$$I = \sum_{\alpha,\hat{a}} \left\{\mathrm{Tr}[T_{\mathbf{7}}^{\hat{a}} U^t G_\alpha U]\right\}^2 = \begin{cases} I = \frac{3}{4} g_2^2 \sin^2\frac{H}{f} \\ \widetilde{I} = \frac{3}{4}\widetilde{g}_2^2 \cos^2\frac{H}{f}\end{cases}$$

with same coefficient: Spurions are identical from CS viewpoint

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Having one invariant only, Λ^2 cancellation is sufficient

IF $V^{\Lambda^2} \propto [I + \widetilde{I}] \propto [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2]$

THEN $V \propto [I + \widetilde{I}] \propto [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2]$

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Disproving the cancellation: $\mathrm{SU}(4)/\mathrm{SU}(3)$ coset

$$G, \widetilde{G} \in \mathbf{15} = \ \mathbf{8} \oplus \mathbf{3} \oplus \mathbf{1}$$

# of invariant operators = (# of H invariants) - (# of G invariants) = **3 - 1**

$$I_1 = g_2^2 s_H^2 \qquad \widetilde{I}_1 = \widetilde{g}_2^2 c_H^2$$

$$I_2 = g_2^2 s_H^4 \qquad \widetilde{I}_2 = \widetilde{g}_2^2 c_H^4$$

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EVEN IF $V^{\Lambda^2} \propto [I_1 + \widetilde{I}_1] \propto [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2]$

STLL $V \propto [I_1 + \widetilde{I}_1 + c(I_2 + \widetilde{I}_2)] \propto [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2 + c(g_2^2 s_H^4 + \widetilde{g}_2^2 c_H^4)]$

Twin Composite Higgs

Gauge contribution to the potential, from a model

$$V_{g_2^2} = \frac{9 g_*^2 f^4}{512\pi^2}\left(g_2^2 \sin^2\frac{H}{f} + \widetilde{g}_2^2 \cos^2\frac{H}{f}\right)$$

Twin Higgs miracle: $g_2 = \widetilde{g}_2 \Rightarrow V_{g_2^2} = \text{const.}$

Enforcing the cancellation: Twin Parity

$$\mathcal{P}_{\rm Twin} = \begin{bmatrix} 0 & \mathbb{1}_4 \\ \mathbb{1}_4 & 0 \end{bmatrix} \in \mathrm{SO}(8)$$

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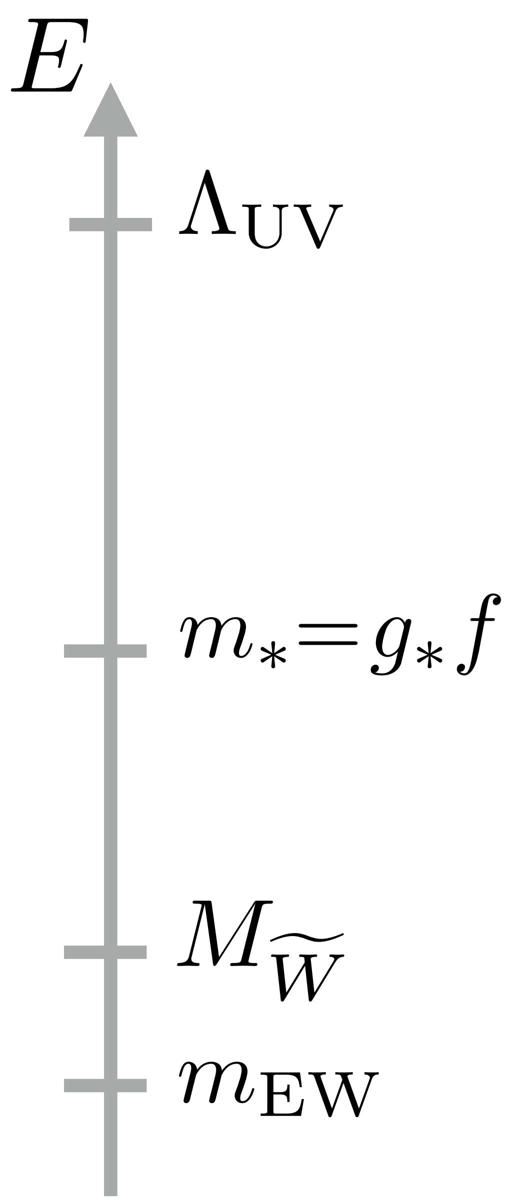
Broken by not gauging the Twin Hypercharge:

$$V_{g_1^2} = \frac{3g_*^2 f^4}{512\pi^2} g_1^2 \sin^2\frac{H}{f}$$

not canceled (not dangerous) quadratic contribution

Twin Composite Higgs



The Top quark sector:

Composite Sector

$$\mathrm{SO}(8) \to \mathrm{SO}(7)$$

times

$$\mathrm{U}(1)_X \times \widetilde{\mathrm{U}}(1)_X \times \mathrm{SU}(3) \times \widetilde{\mathrm{SU}}(3)$$

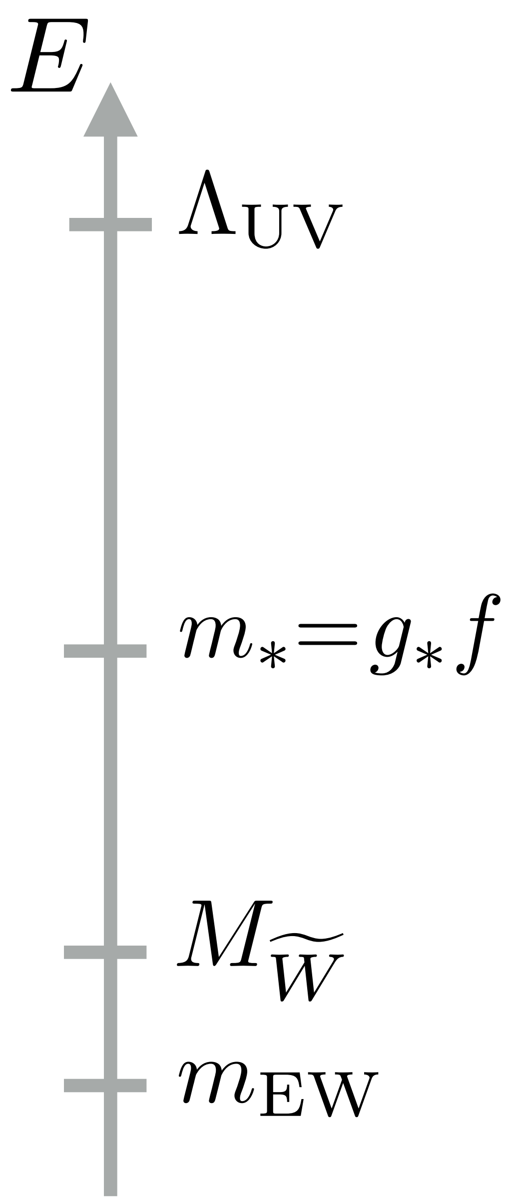
“times”

$$\mathcal{P}_{\rm twin}$$

$$\mathcal{L}_{\rm int}^{\not{\mathcal{G}}}$$

Elementary Sector

Twin Composite Higgs



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Twin Composite Higgs

E

$\Lambda_{\rm UV}$

$m_* = g_* f$

$m_{\widetilde{t}}$

$M_{\widetilde{W}}$

$m_{\rm EW}$

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SM top

$$m_t = \frac{y_t}{\sqrt{2}} \cdot v \sim \frac{y_L y_R}{g_*} \cdot v$$

Twin top

$$m_{\widetilde{t}} \sim \frac{\widetilde{y}_L \widetilde{y}_R}{g_*} \cdot f$$

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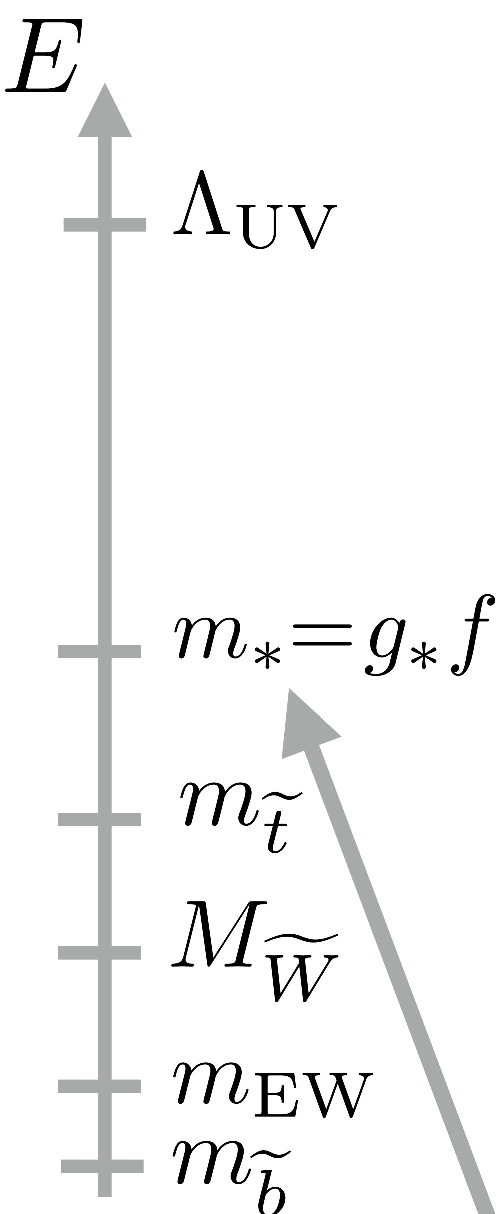
Still massless Twin Bottom

Twin Composite Higgs



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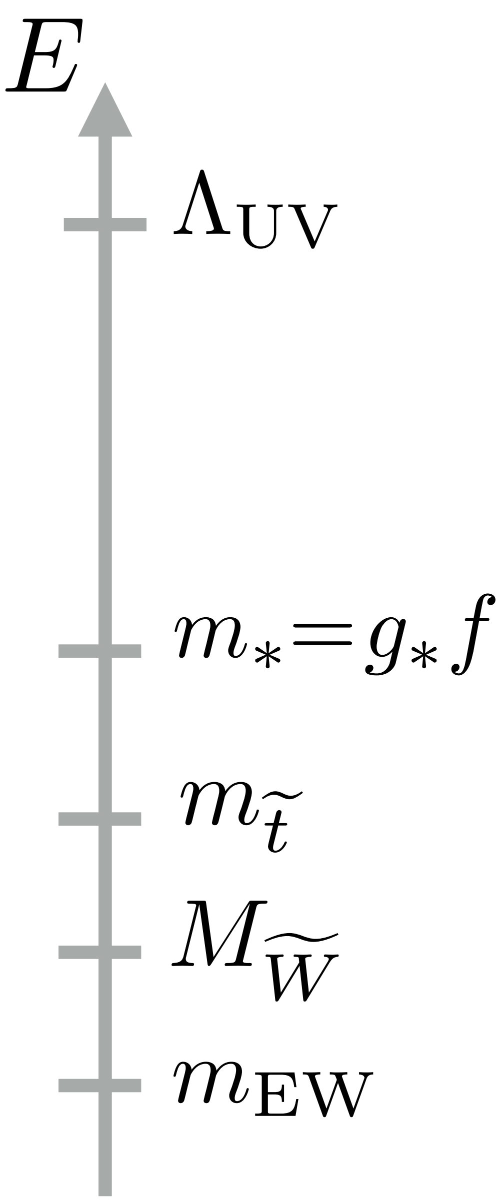
Still massless Twin Bottom

Plus resonances at m_*, like in ordinary CH, but heavier

Twin Composite Higgs



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Potential has cancellation ($\mathbf{8} = \mathbf{7} \oplus \mathbf{1} \Longrightarrow$ **1** operator)

$$V_{y^2} = \frac{N_c f^2 m_*^2}{32\pi^2}\left[y_L^2 s_H^2 + \widetilde{y}_L^2 c_H^2\right]$$

Twin Composite Higgs

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m_* $\quad y_L - \widetilde{y}_L = \dfrac{b g_1^2}{16\pi^2} y_L^2 \log \dfrac{\Lambda_{\rm UV}}{m_*}$

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4) From **IR running** $V_{IR}(H) = \frac{N_c}{16\pi^2} \left[m_t(H)^4 \log \frac{m_*^2}{m_t(H)^2} + m_{\widetilde{t}}(H)^4 \log \frac{m_*^2}{m_{\widetilde{t}}(H)^2} \right]$

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$$\frac{V(H)}{f^4} = \alpha s^2 + \beta \left(s^4 \log \frac{a}{s^2} + c^4 \log \frac{a}{c^2} \right)$$

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Naturally light Higgs:

$\log a \simeq 6 + \log \sqrt{\xi}$

OK for

- $g_* = 4\pi \Rightarrow m_* = 4\pi f \sim 9\mathrm{TeV}\sqrt{10\xi}$
- $y_L = y_t$: composite t_R
- Elementary t_R is disfavoured

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OK for $\begin{cases} g_* = 4\pi \Rightarrow m_* = 4\pi f \sim 9\text{TeV}\sqrt{10\xi} \\ y_L = y_t\text{: composite } t_R \\ \text{Elementary } t_R \text{ is disfavoured} \end{cases}$

Minimal VEV tuning ($1/\xi$) if: $\log \frac{\Lambda_{\rm UV}}{m_*} = \frac{80\pi^2}{bBg_1^2} \frac{y_t^2}{g_*^2} \geq \frac{50}{bB}$

large scale separation

Conclusions and Outlook

- Twin Higgs protects m_H from partner scale m_*
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    1. **Future** Top Partner bounds avoided (currently not an issue)
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- Two directions to work on:

PH/EXP

Could the Twin W, t (or b) be directly testable at the LHC?

TH/PH

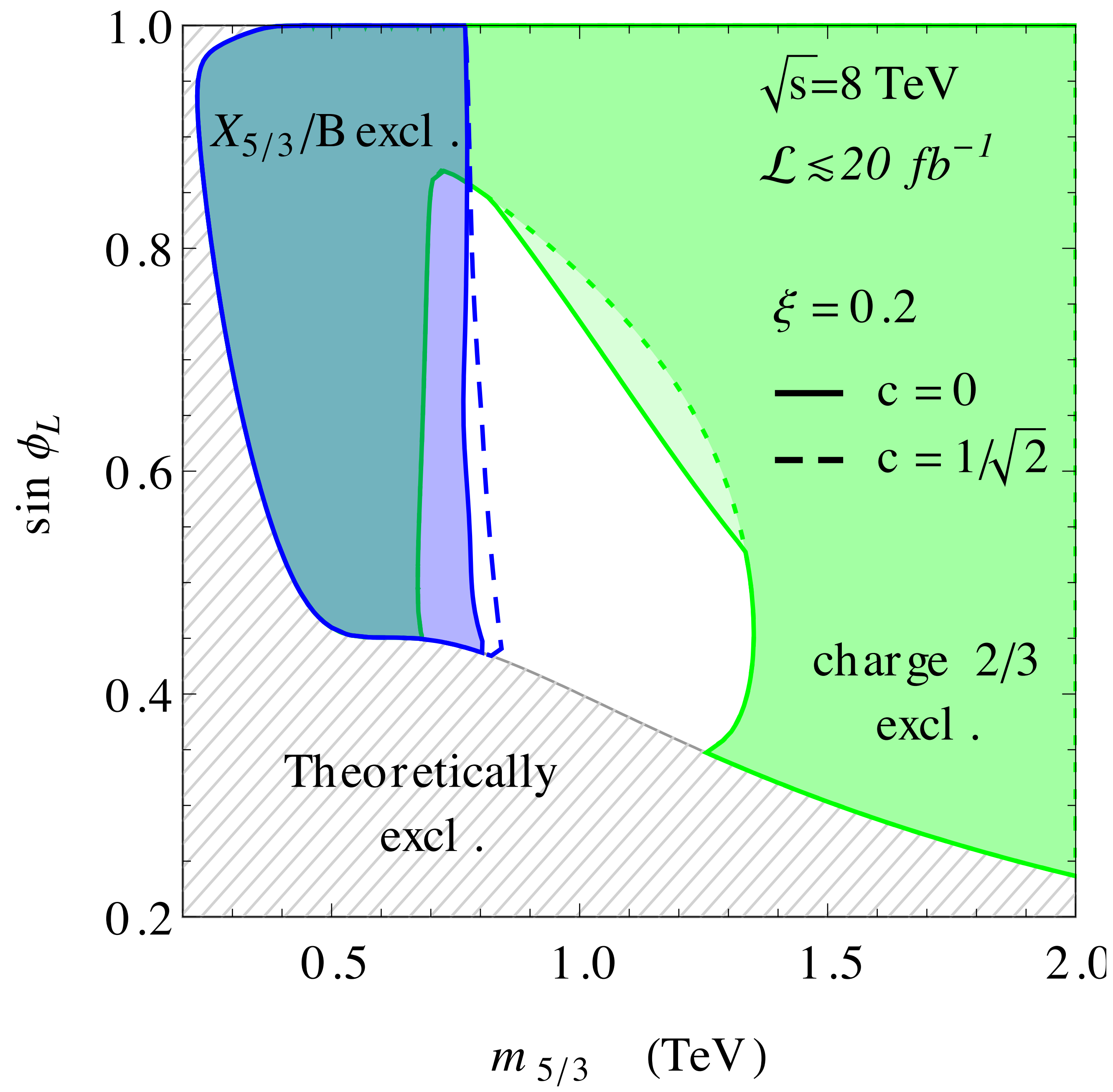
Alternative models?

Non—Twin implementations of Twin cancellation?

Top Partners

[Matsedonski, Panico, AW, to appear]

MCHM Models, simplified model approach:



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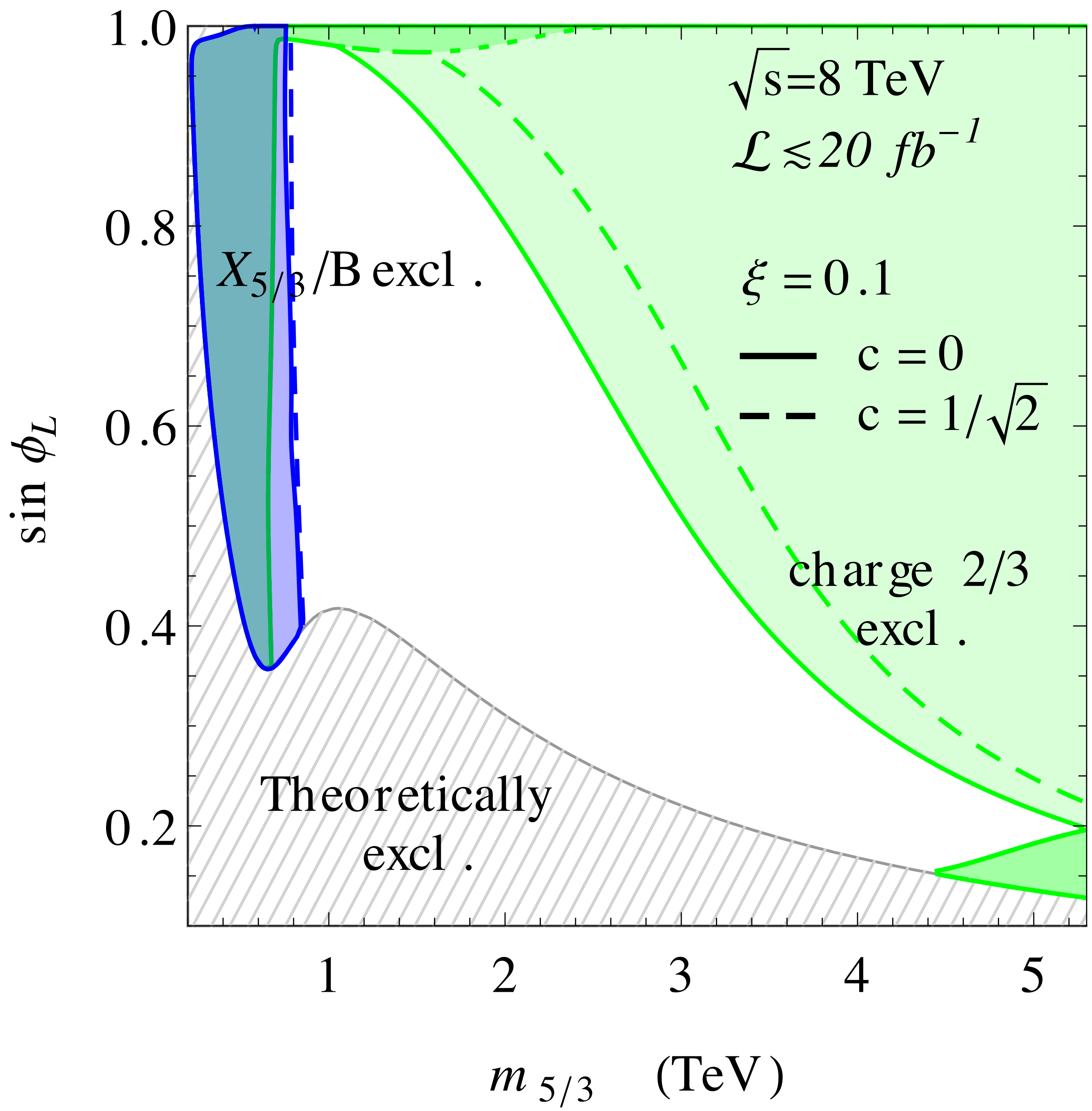

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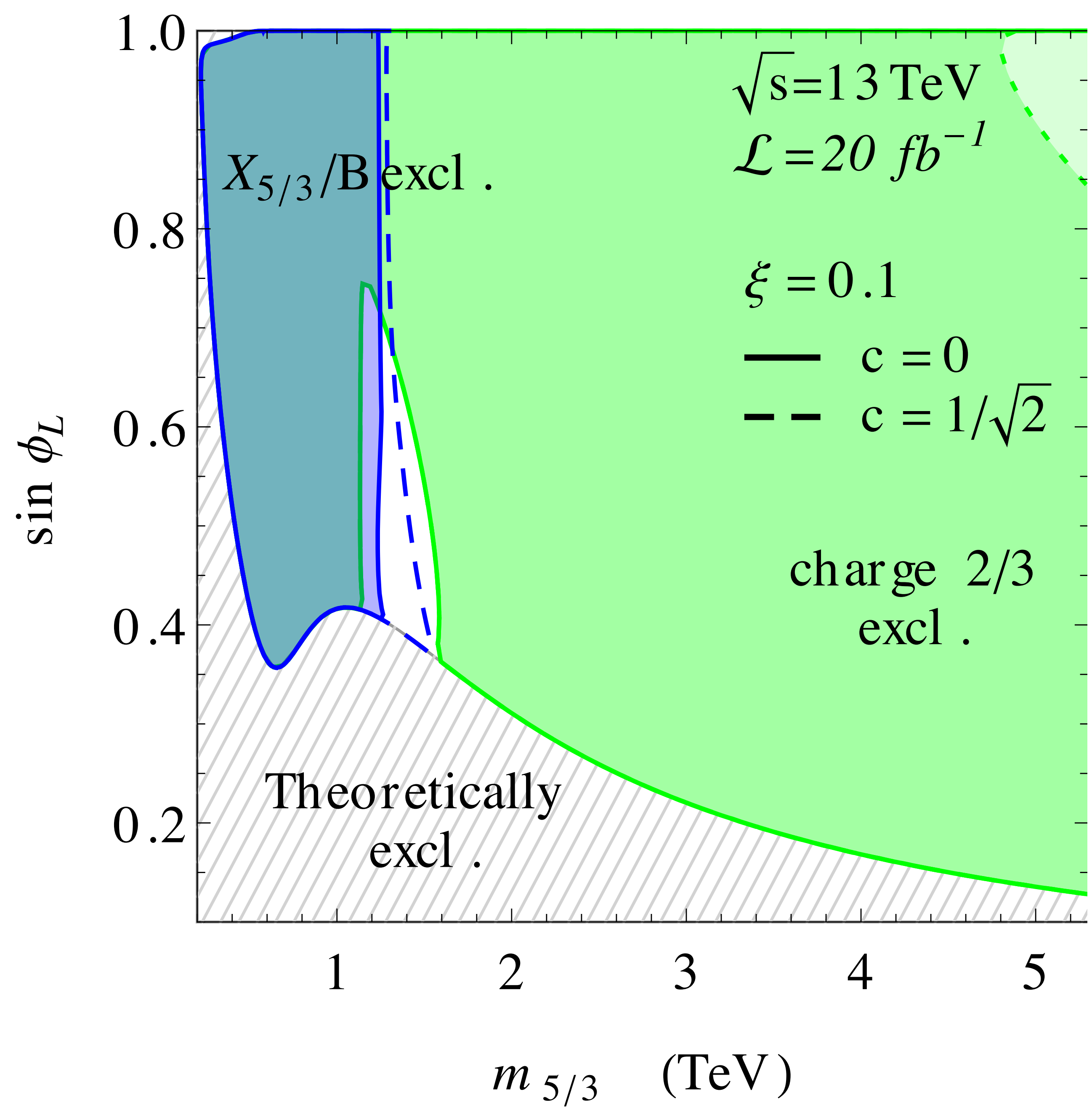
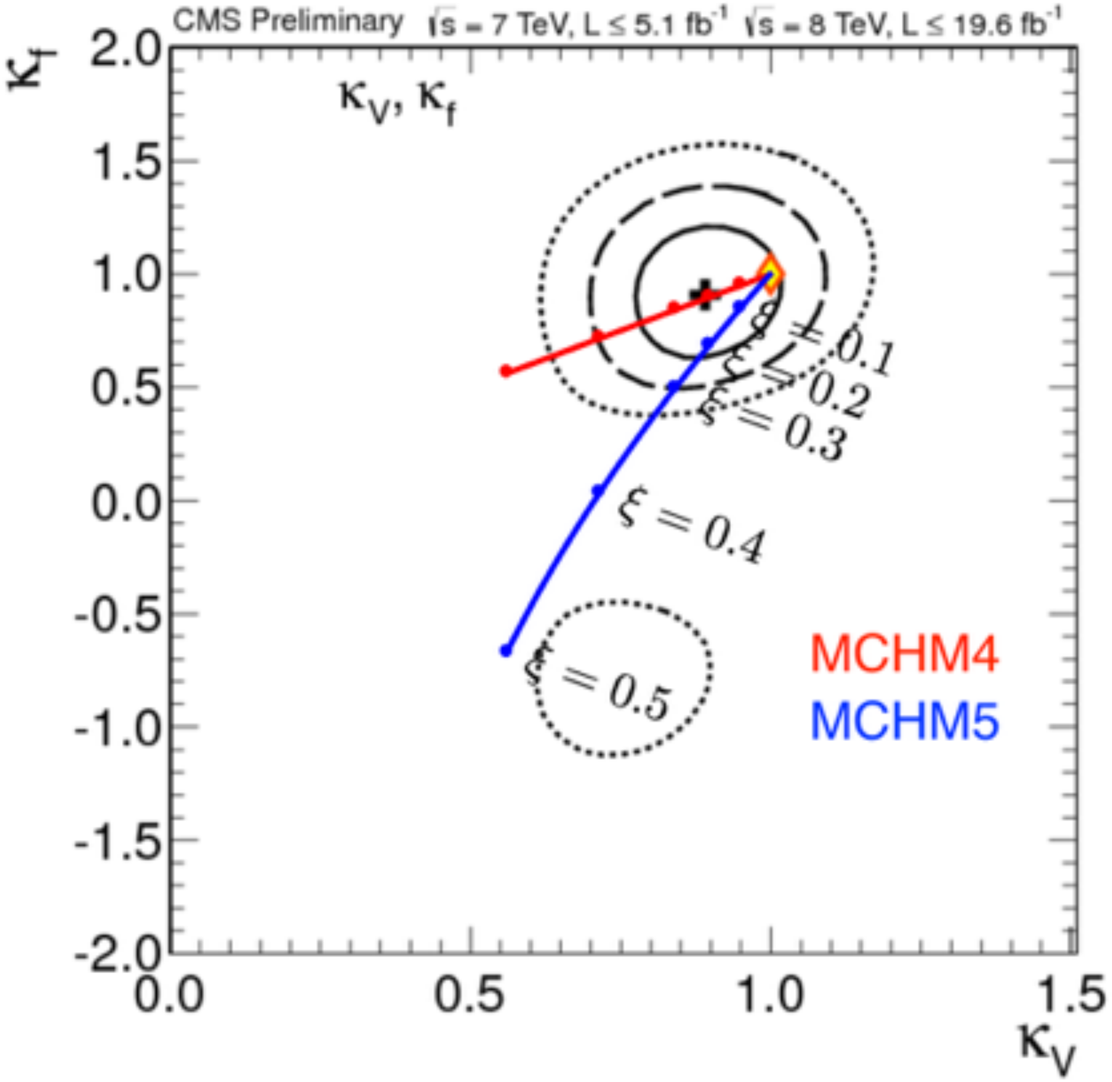
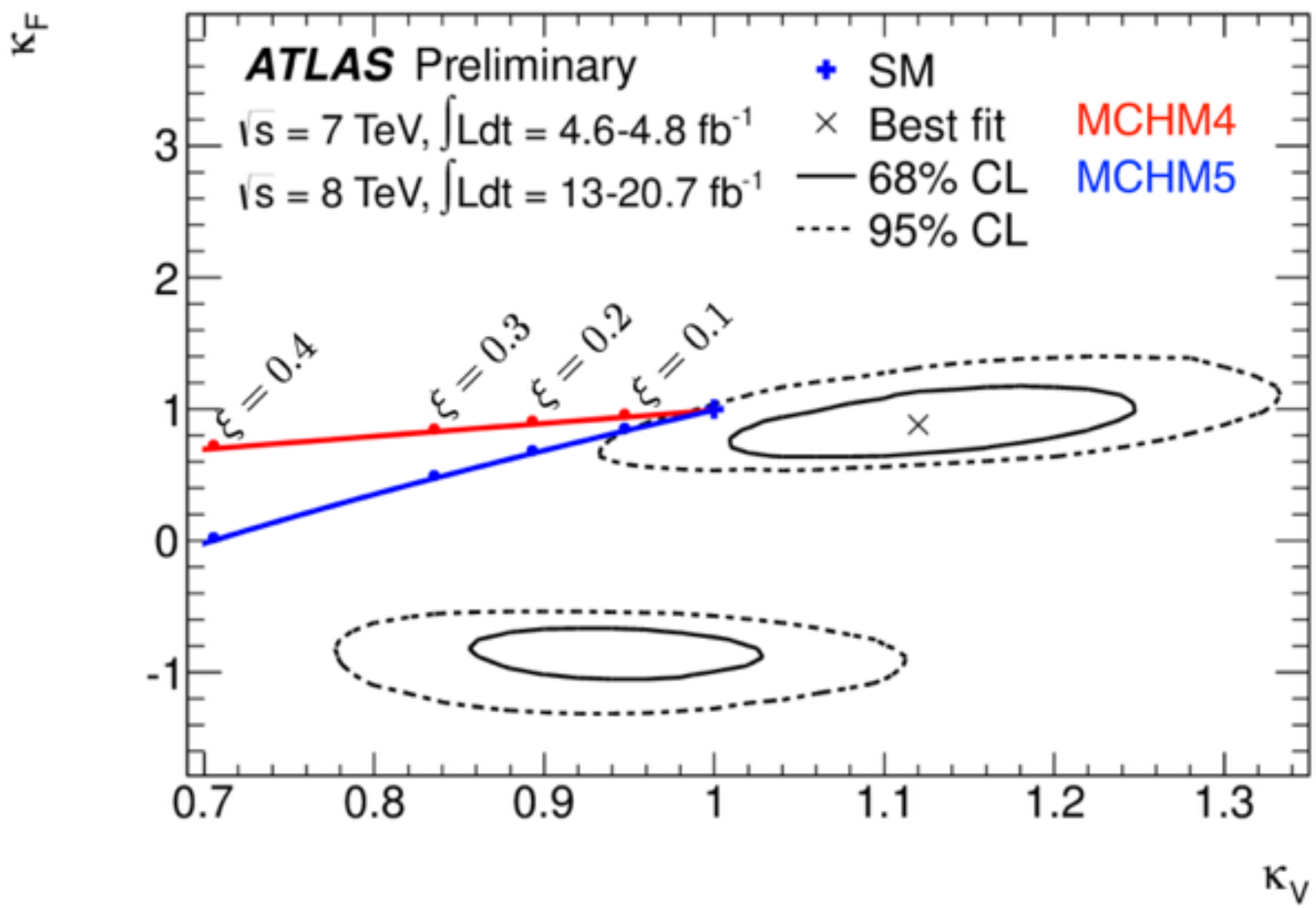


Higgs Couplings

A rough comparison with data:



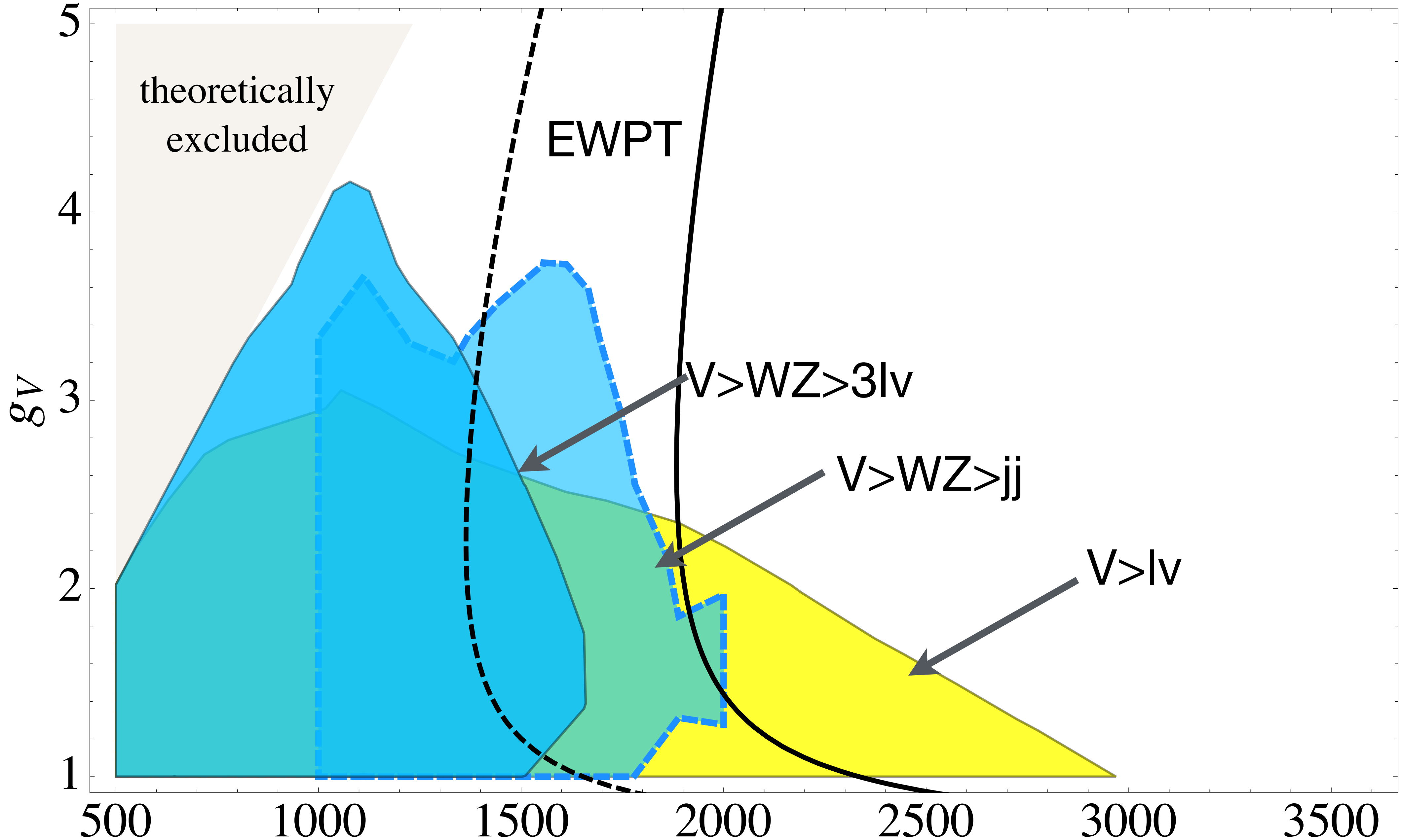


Expected Final LHC Reach: $\xi = 0.1$

Vector Resonances

[Pappadopulo, Torre, Thamm, AW, 2014]

Current Limits on W partners:



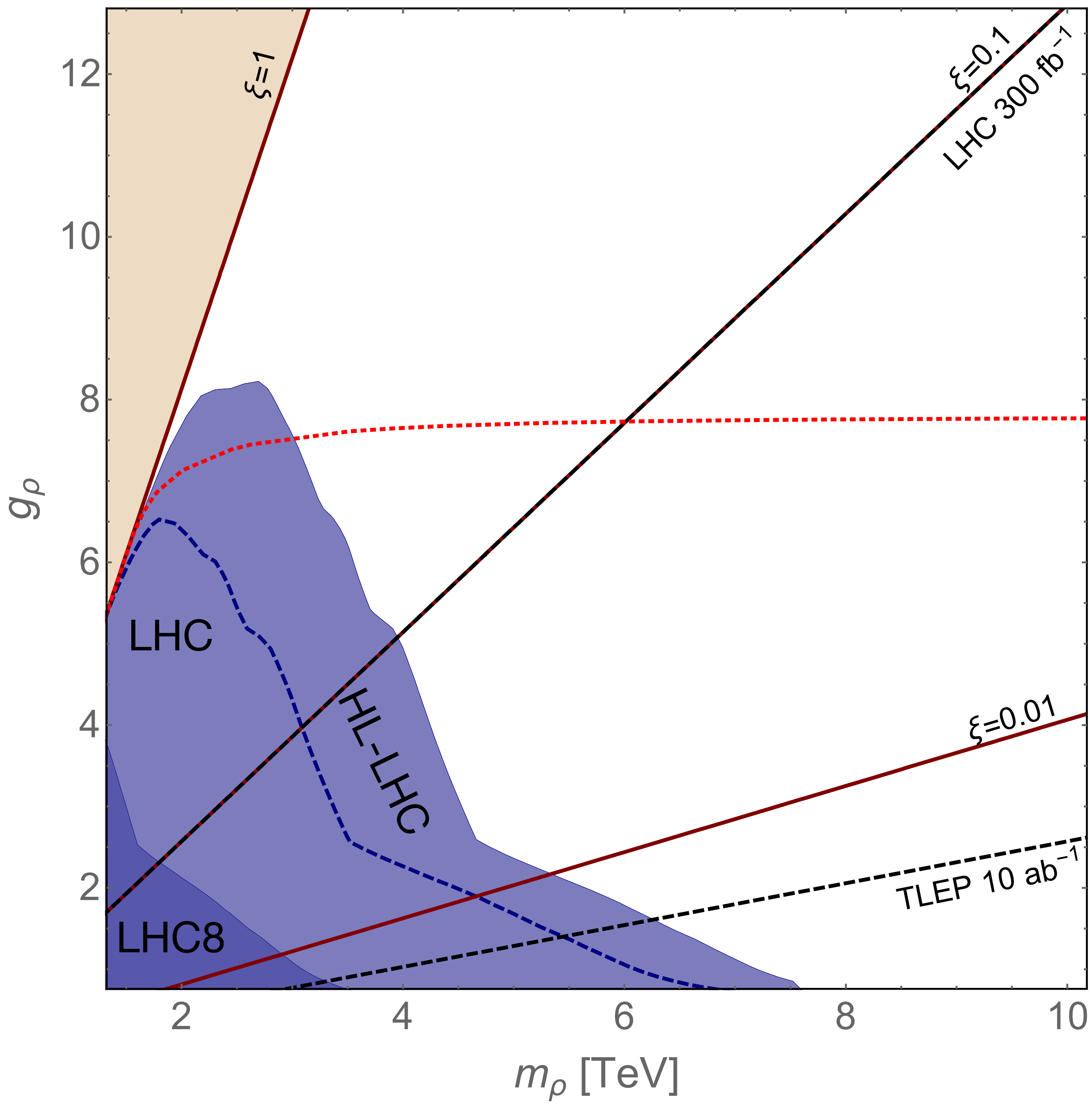
Even weaker if Top Partner decays open

[Contino et al. 2012; Greco et.al., 2013; Chala et al. 2014;]

Vector Resonances

[Torre, Thamm, AW, for FCC W.G.]

Direct versus Indirect @ LHC



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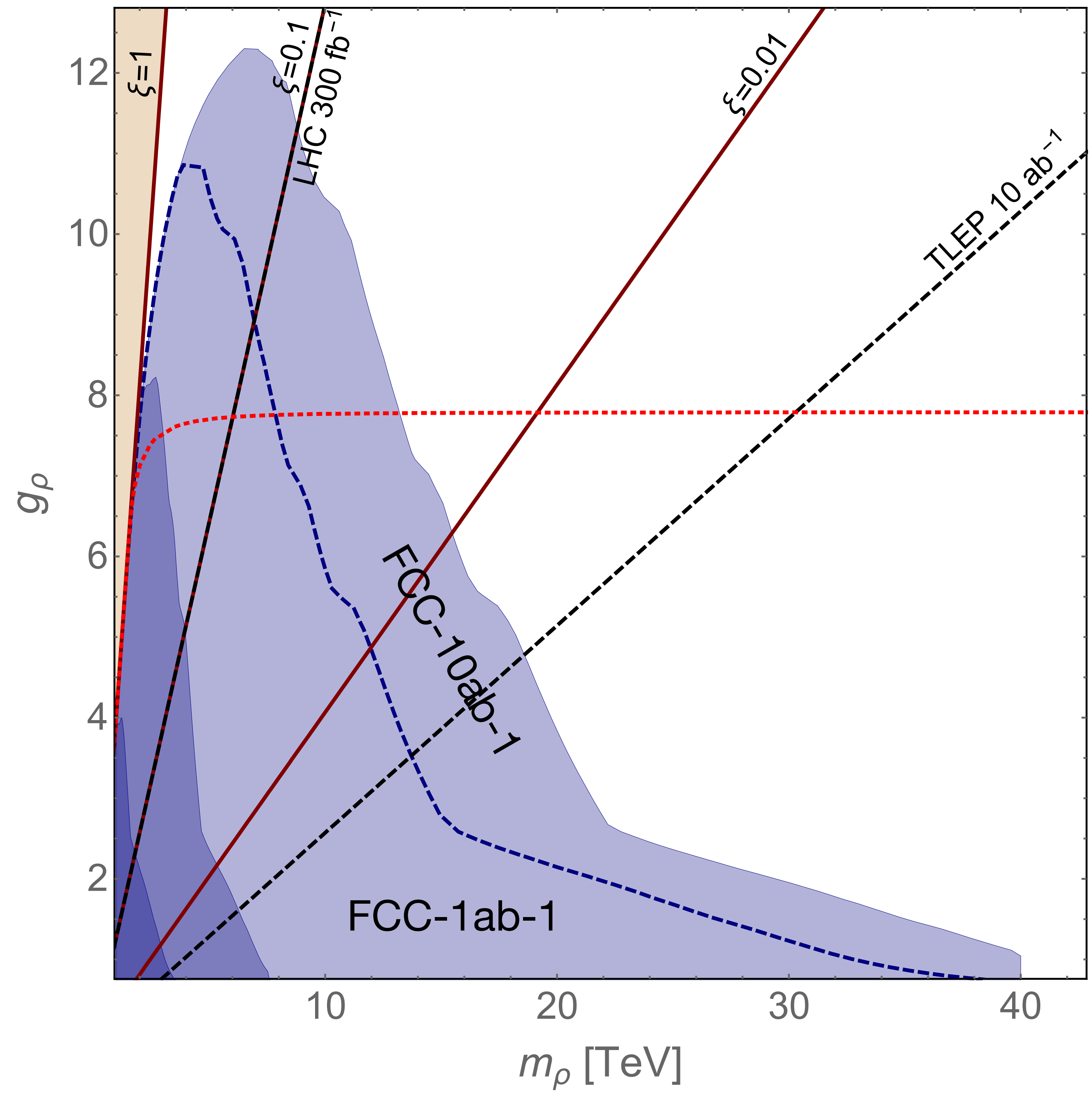
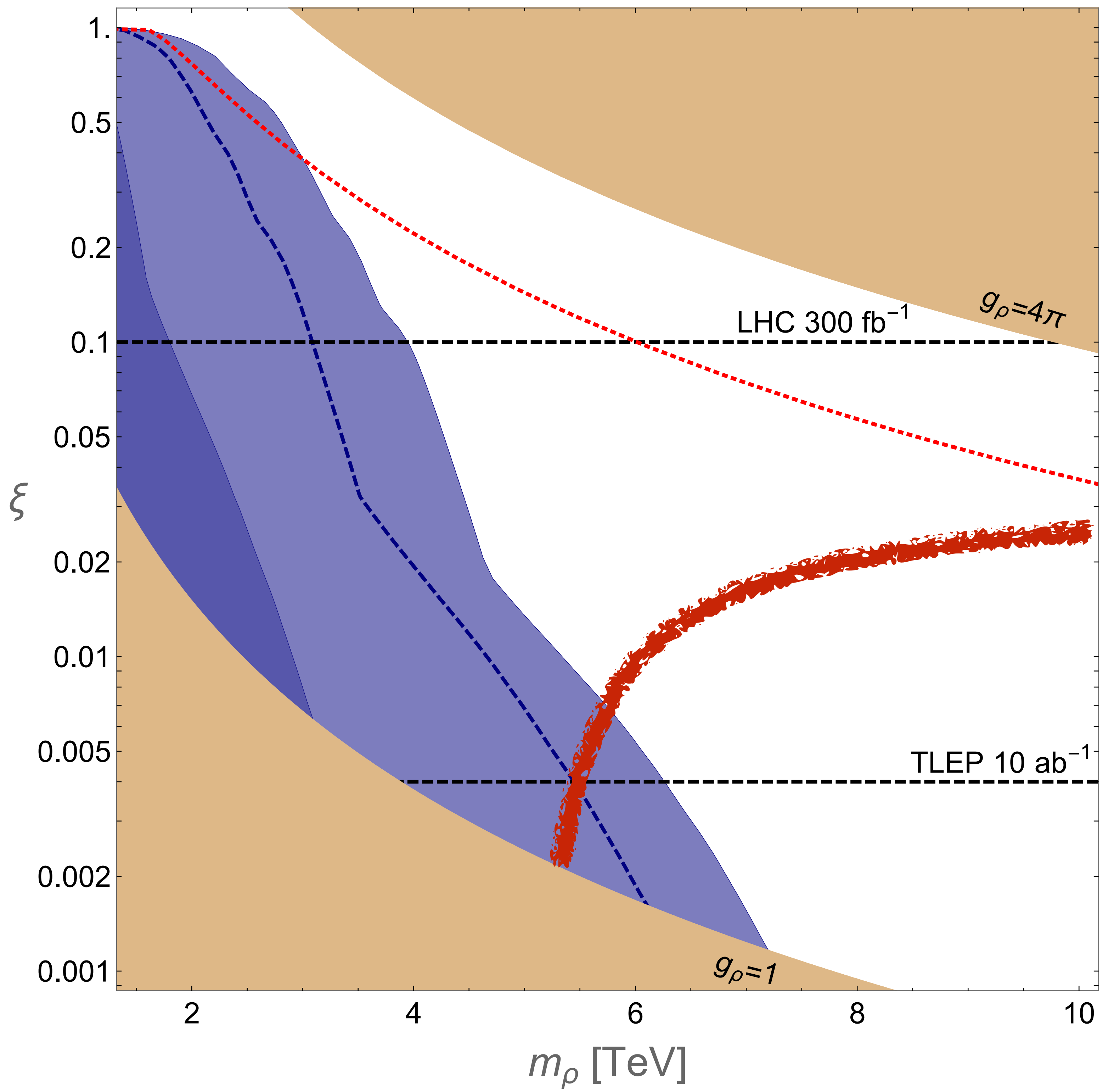


EWPT

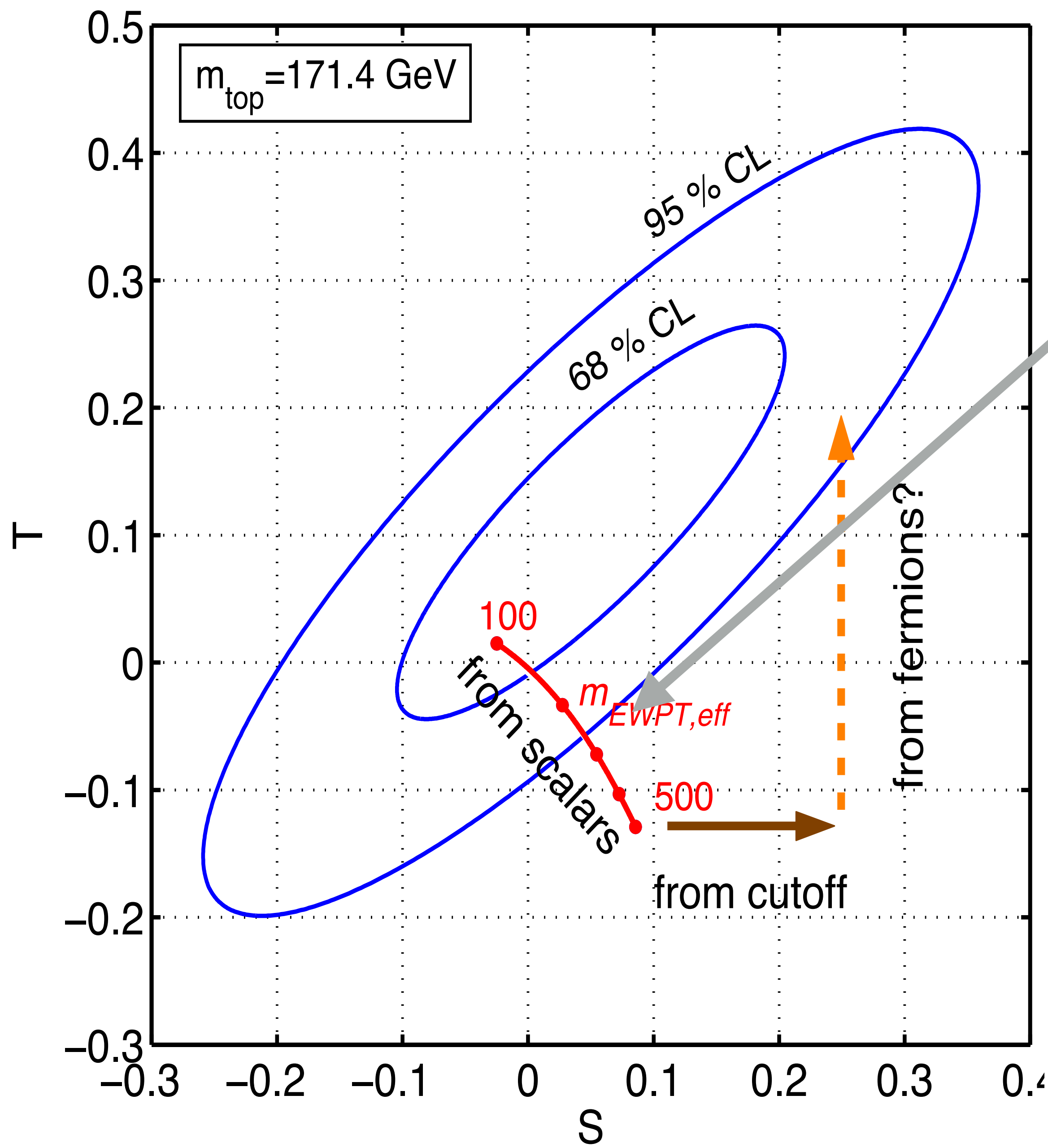
[Torre, Thamm, AW, for FCC W.G.]

Strict EWPT have a dramatic impact!



EWPT

However ...



[Barbieri, Bellazzini, Rychkov, Varagnolo, 2007]

$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

Modified Higgs couplings go in bad direction.

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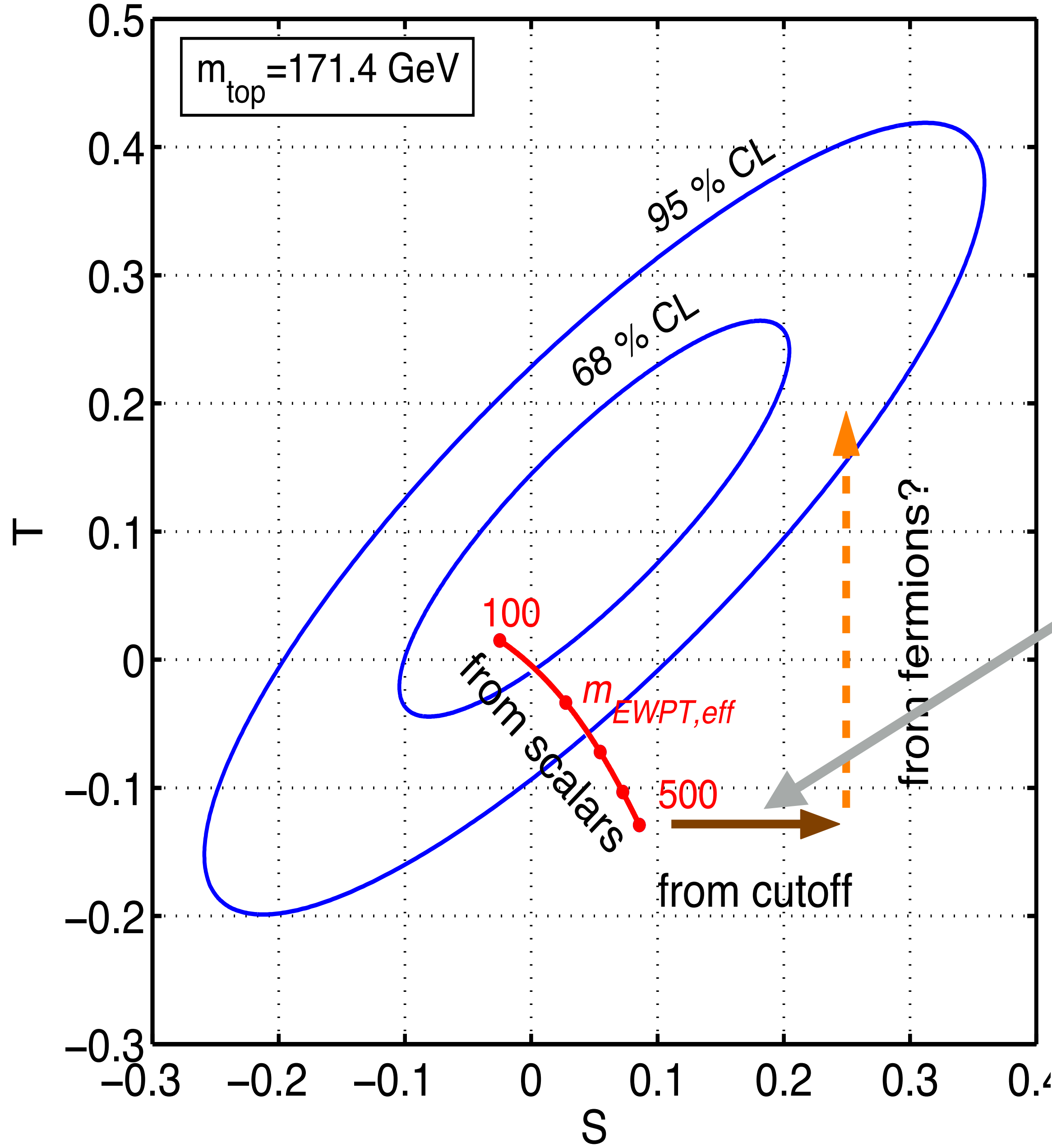

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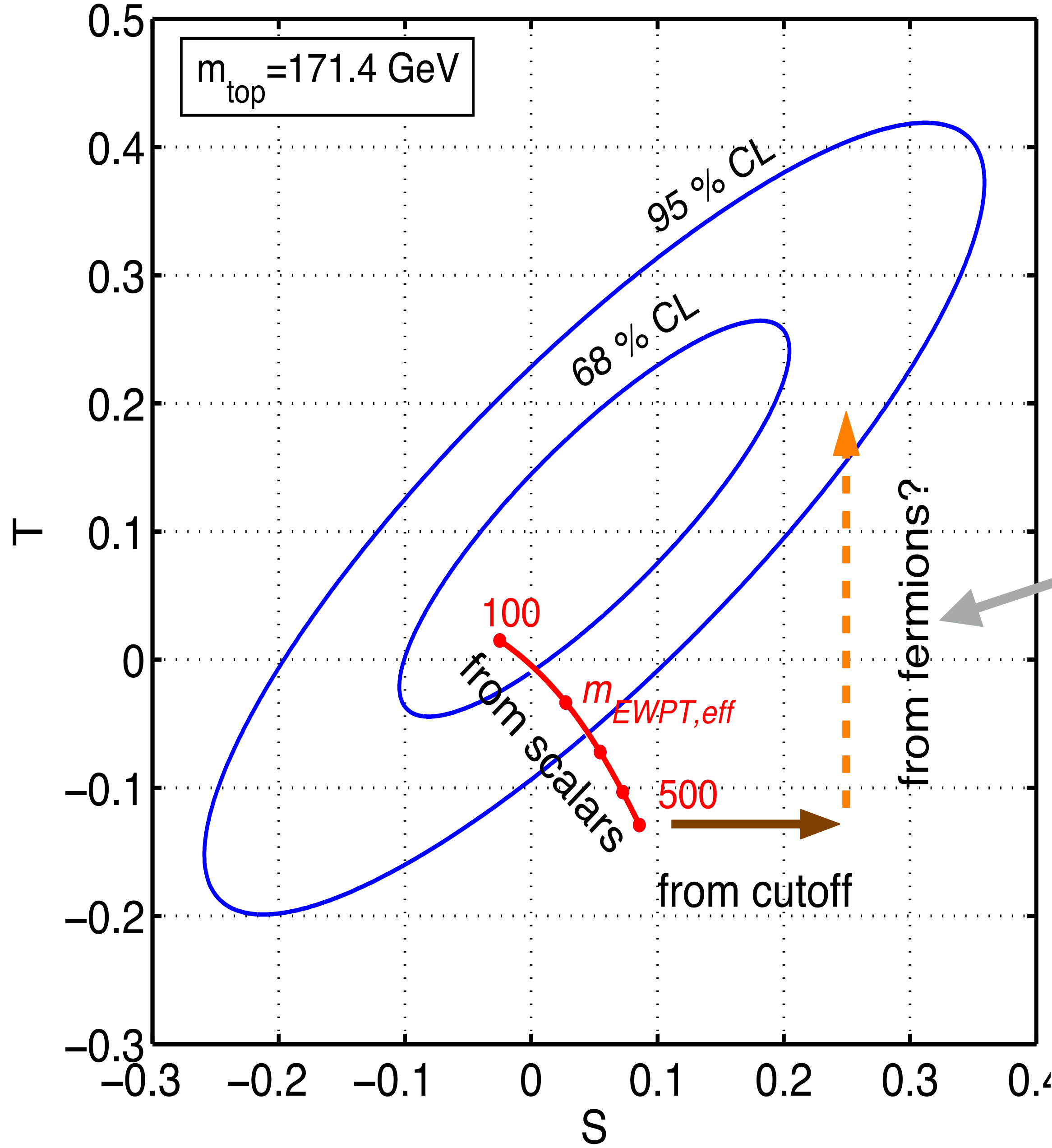

[Barbieri, Bellazzini, Rychkov, Varagnolo, 2007]

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$$\Delta \hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \beta \frac{3y_t}{16\pi^2}\xi\,,$$

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Light Top Partners come to rescue.

EWPT

[Torre, Thamm, AW, for FCC W.G.]

Allowing for a 1/5 cancellation