PRECISION TESTS AND FINE TUNING IN TWIN HIGGS MODELS

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Based on: RC, D. Greco, R. Mahbubani, R. Rattazzi and R. Torre, arXiv:1702.00797

'DaMESyFla in the Higgs Era' - 15-17 March 2017, SISSA

Naturalness and the scale of New Physics

- When viewing the SM as an effective field theory, the Higgs mass is the observable most sensitive to the New Physics scale

$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_{g'}^2 - \frac{3\lambda_h}{8\pi^2}\Lambda_h^2 + \ldots$$

New physics expected at the scale

$$\Lambda^2 \sim \frac{4\pi^2}{3y_t^2} \times \frac{m_h^2}{\epsilon} \quad \Longrightarrow \quad \Lambda \sim 0.45\sqrt{\frac{1}{\epsilon}}\,\mathrm{TeV} \qquad \epsilon = \text{Fine Tuning}$$

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A lower value follows in models with RG evolution over a large energy window. For example, consider the MSSM with high-scale SUSY breaking:

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Soft Models

[R. Rattazzi, talk at "Neutral Naturalness", CERN 2015]

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Super-Soft Models

[Higgs mass fully generated at around the weak scale]

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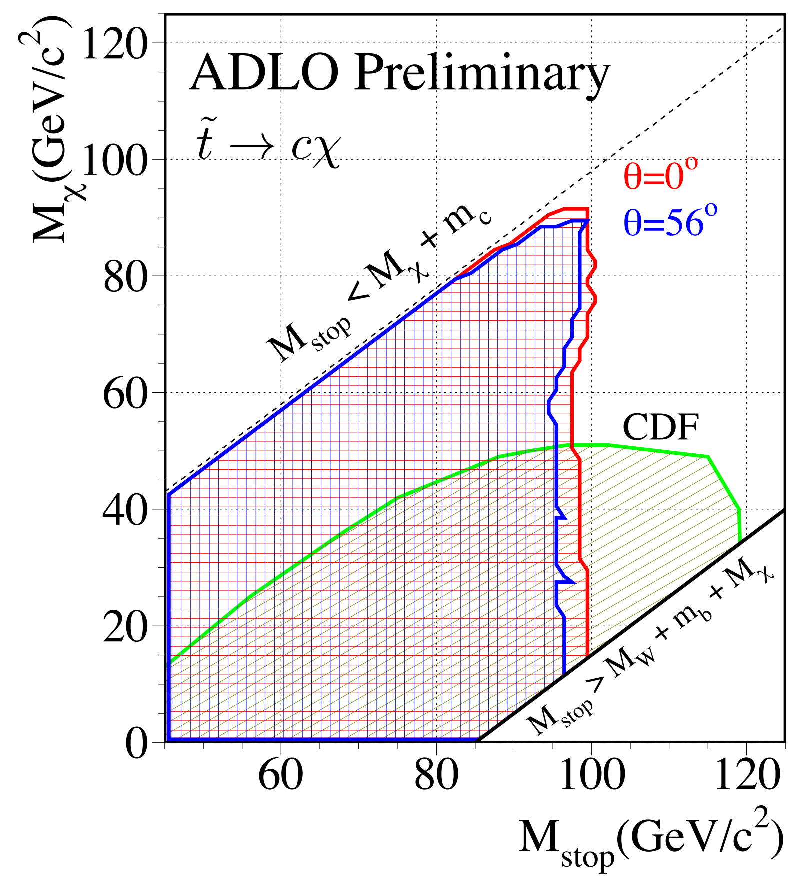
$$\Lambda \lesssim m_h, m_Z \qquad \textit{for } \Lambda_{UV} \gtrsim 100\,\mathrm{TeV} \textit{ and } \epsilon = 1$$



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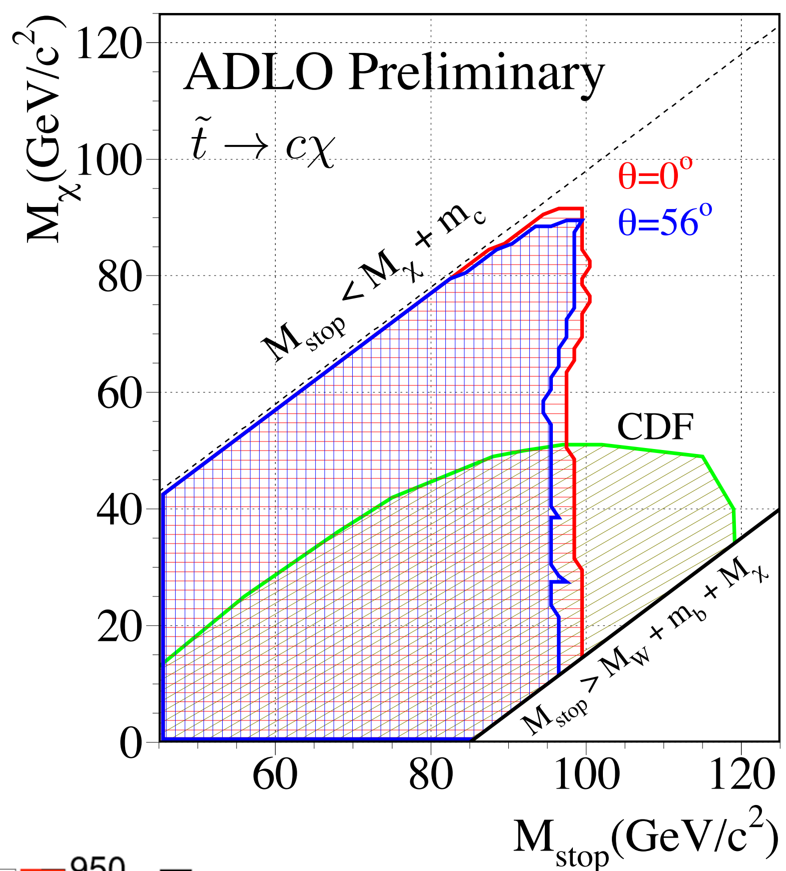
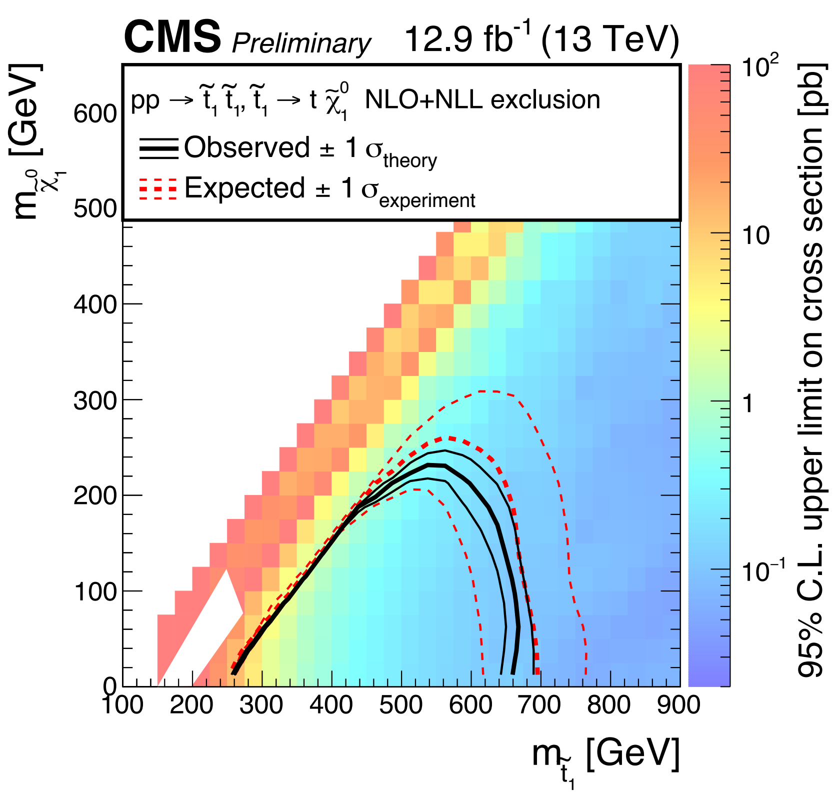
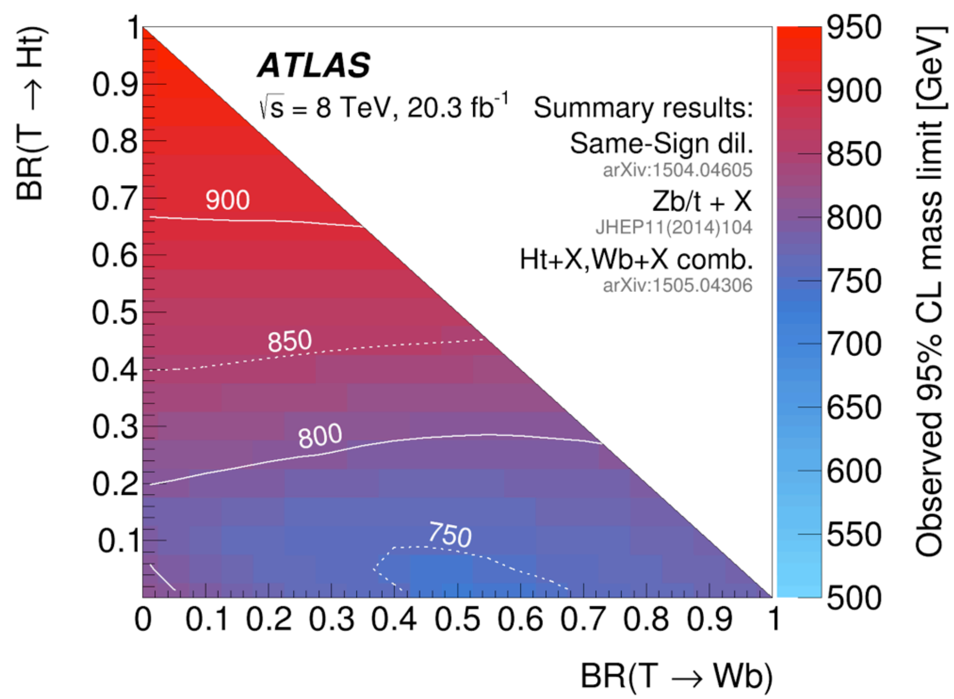


- Soft natural models are being probed now at the LHC





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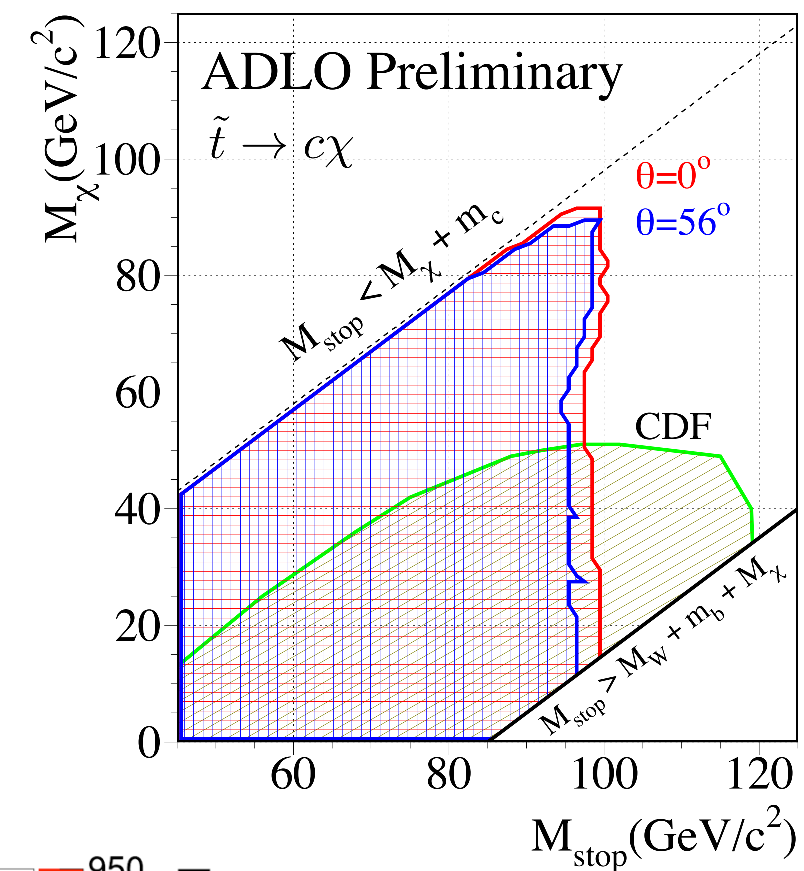

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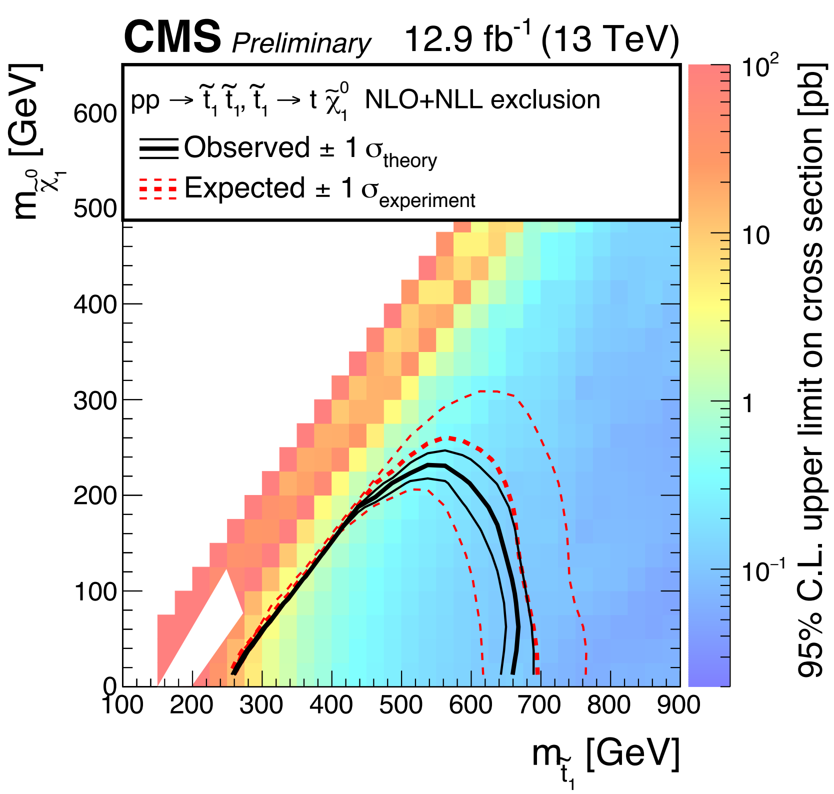
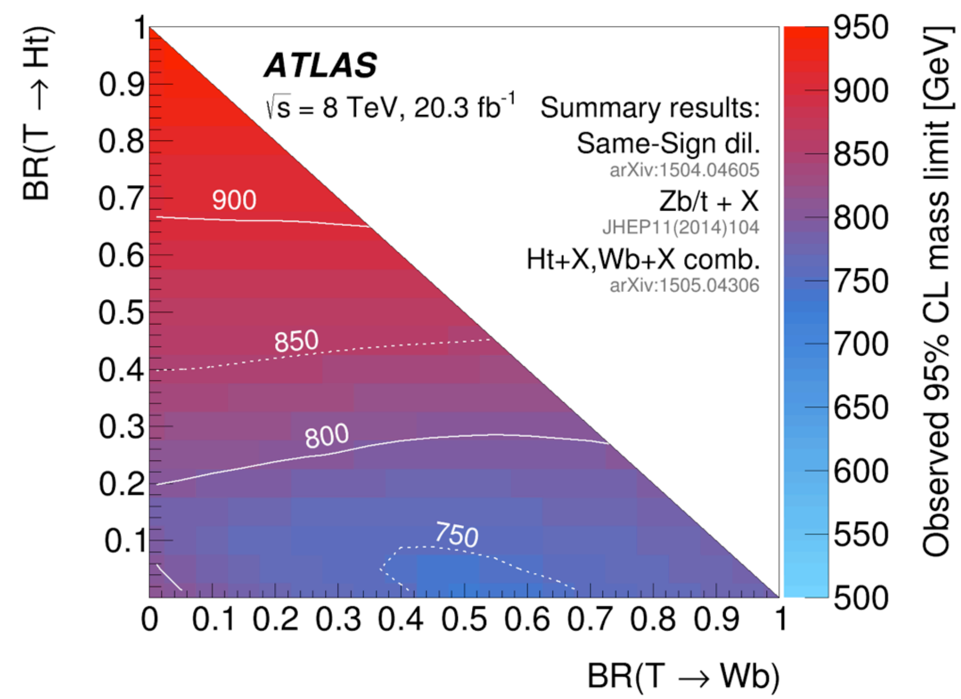


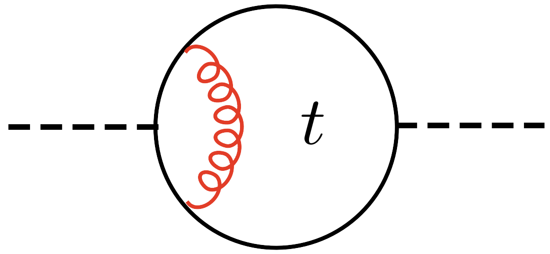


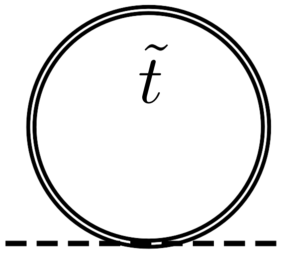
☞ *Both kind kind of theories are now confined into fine-tuned territory*

The Twin Higgs paradigm: *Higgs mass saturated by new states neutral under the SM gauge group*

Naive difficulty: *i) How to relate the coupling of the new states to* y_t*?*

ii) Make sure that 2-loop QCD corrections do not spoil the cancellation





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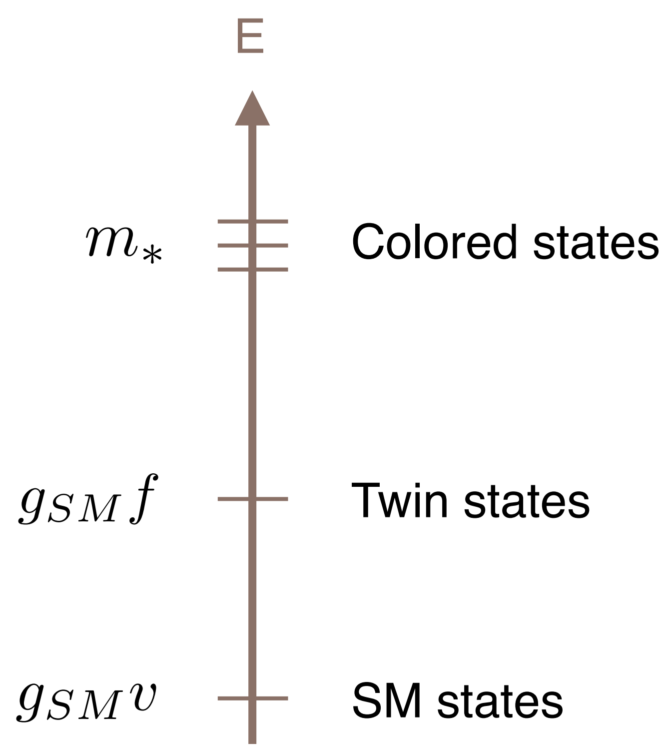
Twin Higgs idea: *the SM sector related to a copy through a* Z_2 *(Twin) parity*

[Chacko, Goh, Harnik, PRL 96 (2006) 231802]

SM sector	Twin parity ⟷	**Twin sector**
$SU(3)_c \times SU(2)_L \times U(1)_Y$		$\widetilde{SU}(3)_c \times \widetilde{SU}(2)_L \times \widetilde{U}(1)_Y$

Structure of Twin Higgs Theories



SM and Twin sectors extended to a more fundamental Z_2-invariant dynamics at this scale

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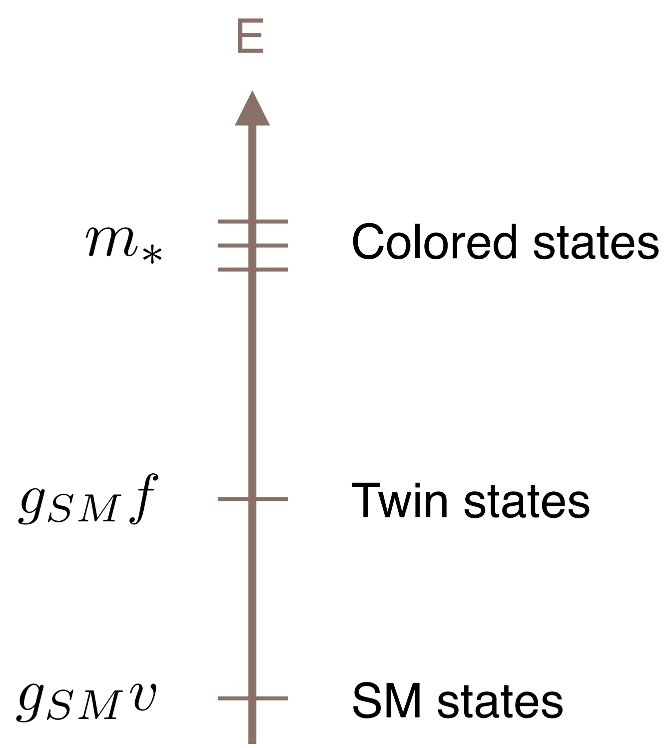

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Most general Z_2-invariant potential:

i) has $SO(4)\times\widetilde{SO}(4)$ accidental invariance

ii) mass term has larger $SO(8)$ invariance

$$V(H,\tilde{H}) = -m_\phi^2(|H|^2+|\widetilde{H}|^2) + \frac{\lambda_\phi}{2}(|H|^2+|\widetilde{H}|^2)^2 + \frac{\hat{\lambda}_h}{4}(|H|^4+|\widetilde{H}|^4)+\dots$$

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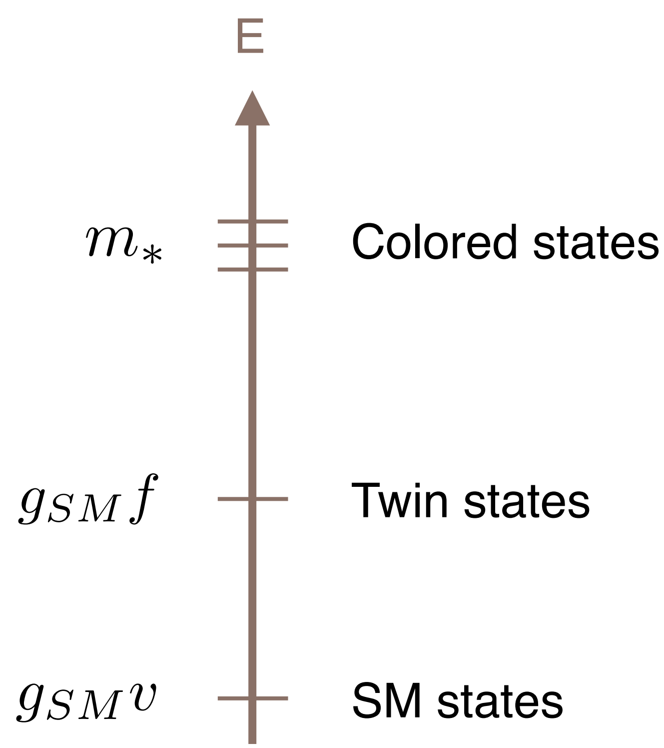

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☞ Consider scenarios where $SO(8)$-breaking terms are small, and let's analyze first the $SO(8)$-invariant limit

$$V(\phi) = -m_\phi^2|\phi|^2 + \frac{\lambda_\phi}{2}|\phi|^4$$

$$SO(8) \to SO(7) \supset SU(2)_L \times U(1)_Y$$

7 Nambu-Goldstone bosons

- *3 NGB eaten to give mass to* $\widetilde{W}$
- *Twin photon remains massless*
- *one massless SU(2) doublet* $\mathcal{H}$

$$\phi = \begin{pmatrix} H \\ \tilde{H} \end{pmatrix} \qquad \langle \phi \rangle = f = \frac{m_\phi}{\sqrt{\lambda_\phi}}$$

$$\phi = e^{i\pi/f} \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$$

In the unitary gauge:

$$H^\dagger H = f^2 \sin^2(h/f)$$

$$\tilde{H}^\dagger \tilde{H} = f^2 \cos^2(h/f)$$

$$\left(h^2 \equiv \mathcal{H}^\dagger \mathcal{H}\right)$$

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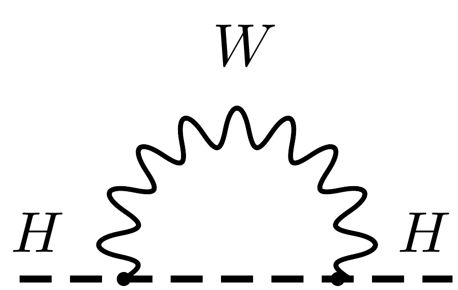
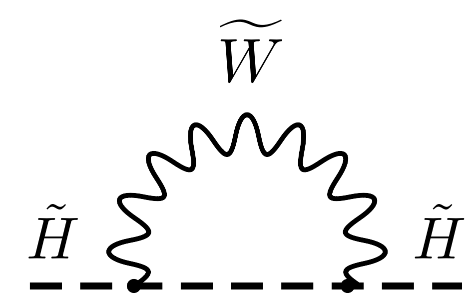
Cancellation in the mass term (due to accidental SO(8) from Z_2 invariance)

[Chacko, Goh, Harnik]



$\sin^2(h/f)$

+

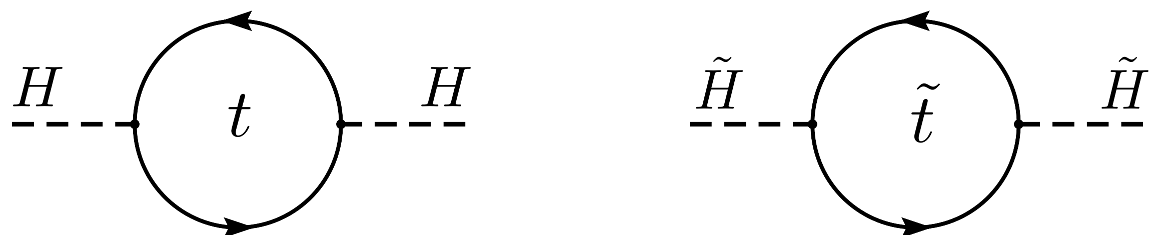


$\cos^2(h/f)$

$$\delta V \sim \frac{m_*^2}{16\pi^2}\left(g^2|H|^2 + \tilde{g}^2|\tilde{H}|^2\right) = \frac{m_*^2 f^2 g^2}{16\pi^2}\left(\sin^2\frac{h}{f} + \cos^2\frac{h}{f}\right) = const.$$

A similar cancellation occurs in the correction to the mass term from fermions:

$$\mathcal{L} \supset y_t\, \bar{q}_L H t_R + \tilde{y}_t\, \bar{\tilde{q}}_L \tilde{H} \tilde{t}_R + h.c. \qquad\qquad y_t = \tilde{y}_t$$



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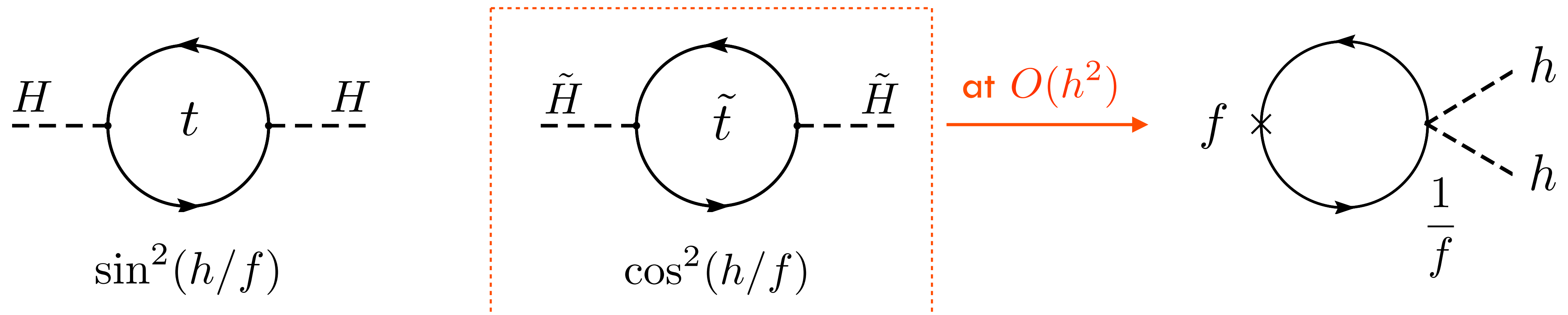

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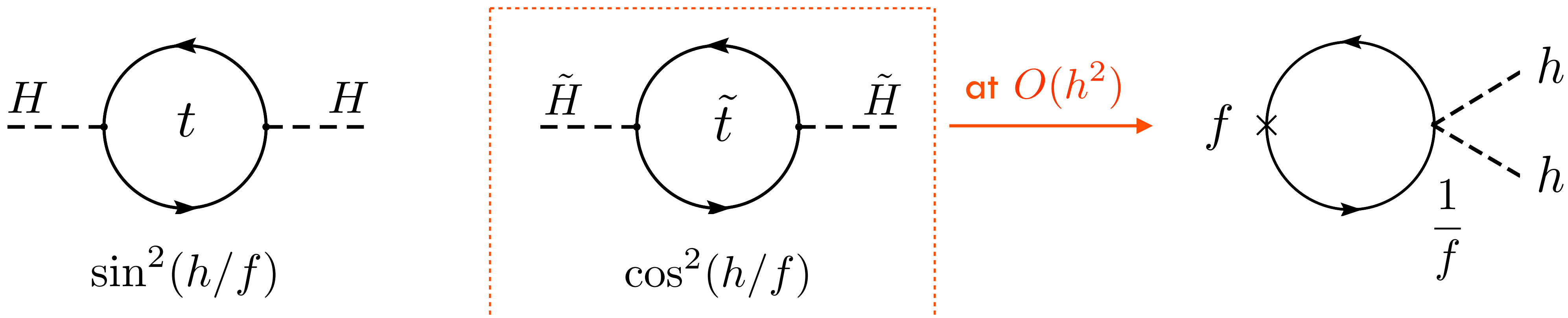
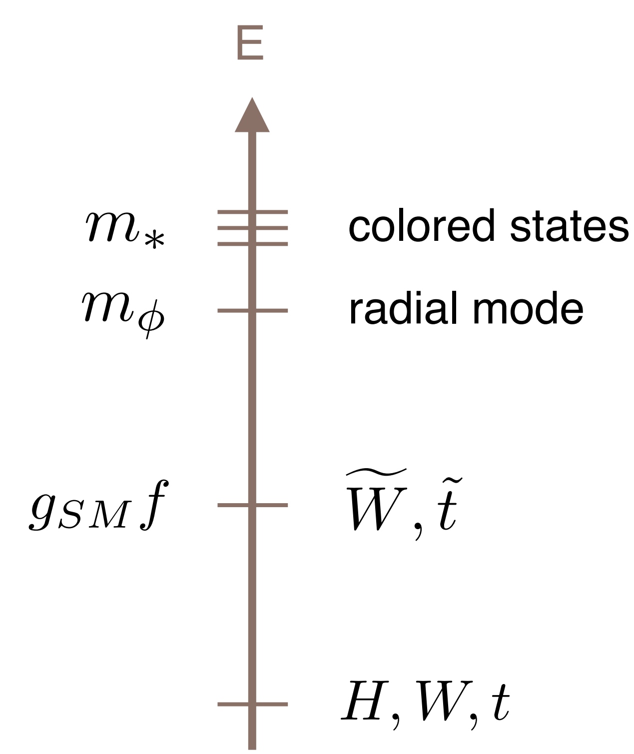


Mass of twin states: $m_{\widetilde{W}}^2 = \frac{1}{4} g^2 f^2$

$$m_{\tilde{t}} = \frac{y_t}{\sqrt{2}} f$$

Mass of radial mode: $m_\phi^2 = f^2 \lambda_\phi \lesssim m_*^2$

Massless twin photon can be removed by *not* gauging $\widetilde{U}(1)$ (small Z_2 breaking)



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$\tilde{H}^2 = f^2 - H^2$ at LO in $\hat{\lambda}_h/\lambda_\phi$

A non-vanishing SO(8)-breaking quartic gives the NGB a potential:

$$\lambda_h \simeq \hat{\lambda}_h$$

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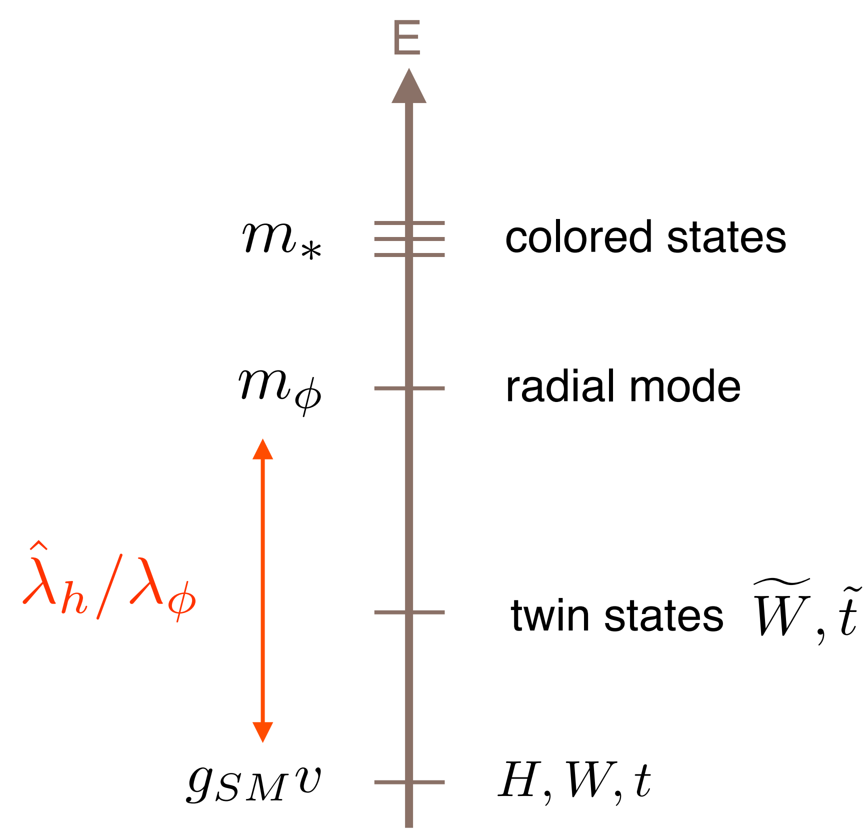

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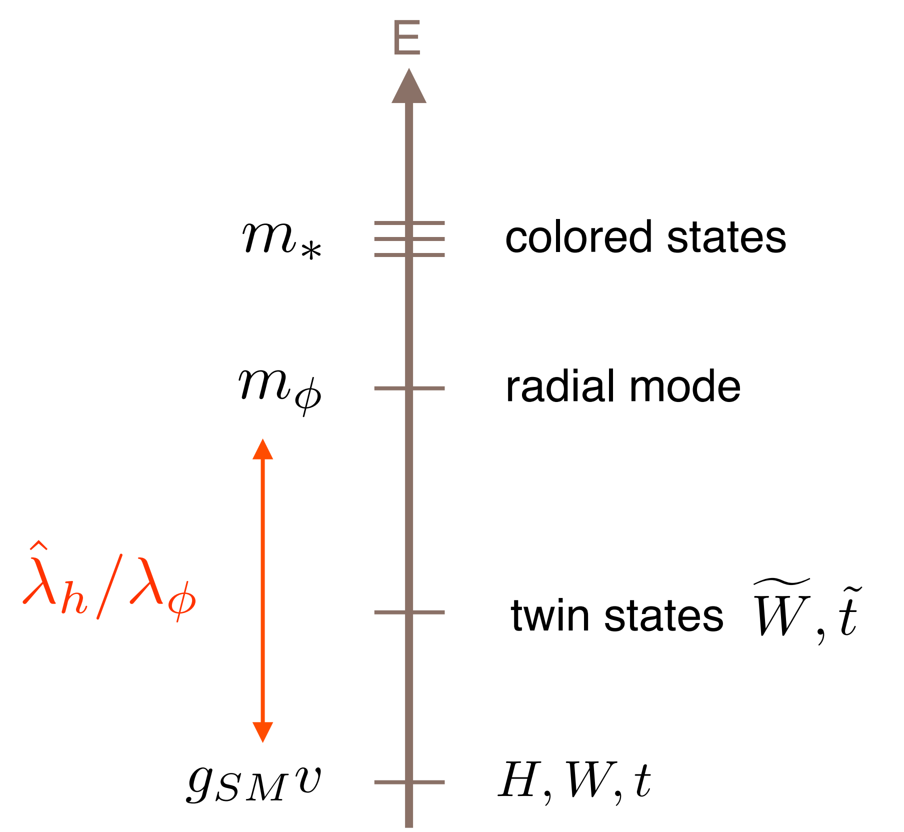
☞ Need to relate m_ϕ to m_*



Theories with $m_\phi \sim m_*$ (Sub-Hypersoft)

Consider the case in which $\quad m_\phi \sim m_*$

$$\lambda_\phi \equiv g_*^2$$

Then:

$$m_*^2 \sim \left(\frac{2g_*^2}{\lambda_h}\right)\frac{m_h^2}{\epsilon} \longrightarrow \lambda_h \sim \frac{3y_t^4}{4\pi^2}\log\frac{m_*^2}{m_t m_{\tilde{t}}} \Rightarrow m_*^2 \sim \frac{4\pi^2}{3y_t^2}\times\frac{m_h^2}{\epsilon}\times\frac{g_*^2}{y_t^2}\,\frac{1}{\log\dfrac{m_*^2}{m_t m_{\tilde{t}}}}$$

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☞ *To gain in FT, SO(8)-breaking terms must not be generated at* $O(g_{SM}^2)$

This can be ensured through symmetries and selection rules of the UV dynamics [Barbieri, Greco, Rattazzi, Wulzer, JHEP 1508 (2015) 161]

Fine Tuning and scales of New Physics

- Higgs mass term saturated by color-less twin tops

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$\Rightarrow$ FT minimized for maximal g_*
(i.e. when UV dynamics strongly coupled)

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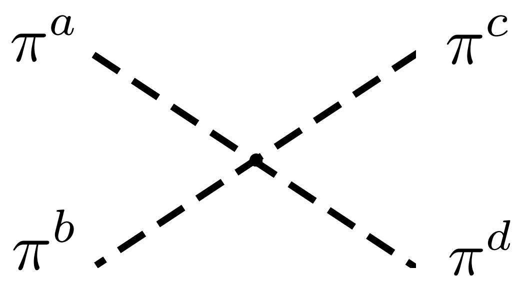
☞ Q: *How large g_* can be ?*

Estimating the strong coupling scale through the scattering of NGBs (low-energy viewpoint)



$$\mathcal{A}(\pi^a\pi^b \to \pi^c\pi^d) = \frac{s}{f^2}\delta^{ab}\delta^{cd} + \frac{t}{f^2}\delta^{ac}\delta^{bd} + \frac{u}{f^2}\delta^{ad}\delta^{bc}$$

$$\mathbf{7} \times \mathbf{7} = \mathbf{1} + \mathbf{21} + \mathbf{27}$$

Decomposing into partial wave amplitudes: $a^{\mathbf{1}}_{j=0} = \dfrac{N-2}{32\pi}\dfrac{s}{f^2}$ for $SO(N)/SO(N-1)$

Imposing an upper bound on the scattering phase: $|\delta| < \dfrac{\pi}{2}$

$$\boxed{g_* = \frac{m_*}{f} \leq \frac{\sqrt{s}}{f} \leq \frac{4\pi}{\sqrt{N-2}} \overset{N=8}{\simeq} 5}$$

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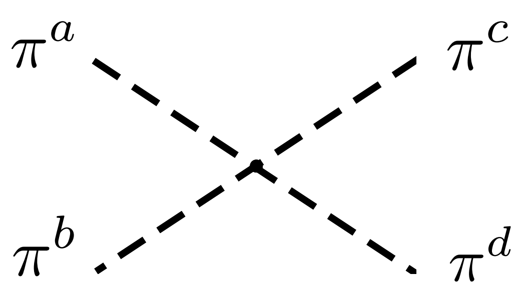

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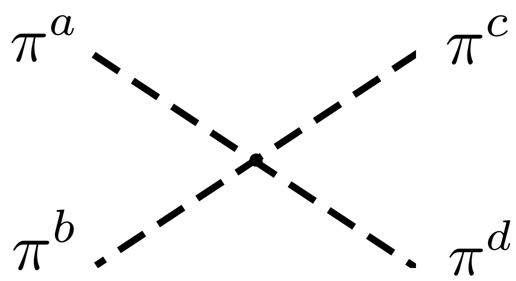
Decomposing into partial wave amplitudes: $$a^{\mathbf{1}}_{j=0} = \frac{N-2}{32\pi}\frac{s}{f^2} \qquad \text{for} \quad SO(N)/SO(N-1)$$

Imposing an upper bound on the scattering phase: $$|\delta| < \frac{\pi}{2}$$

$$\boxed{g_* = \frac{m_*}{f} \le \frac{\sqrt{s}}{f} \le \frac{4\pi}{\sqrt{N-2}} \overset{N=8}{\simeq} 5}$$

large size of multiplets lowers strong scale compared to naive expectation

Estimating the strong coupling scale through the scattering of NGBs (low-energy viewpoint)



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large size of multiplets lowers strong scale compared to naive expectation

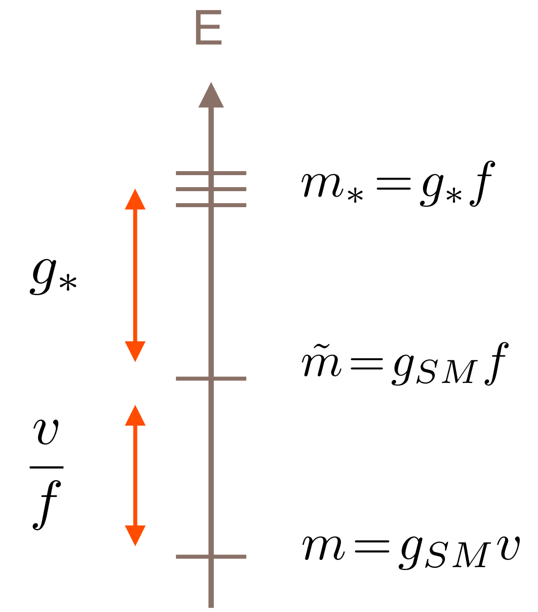
$$m_* \sim 0.45\,\text{TeV} \times \frac{g_*}{y_t} \times \frac{1}{\sqrt{\log \frac{m_*^2}{m_t m_{\tilde{t}}}}} \times \sqrt{\frac{1}{\epsilon}} \xrightarrow{g_* \lesssim 5} \boxed{m_* \lesssim (3-4)\,\text{TeV} \times \sqrt{\frac{0.1}{\epsilon}}}$$

... just beyond the LHC reach

EW and Higgs precision physics

Ratio of colored/twins obtained through a large g_* at fixed f

⇢ effects scaling with f do *not* decouple



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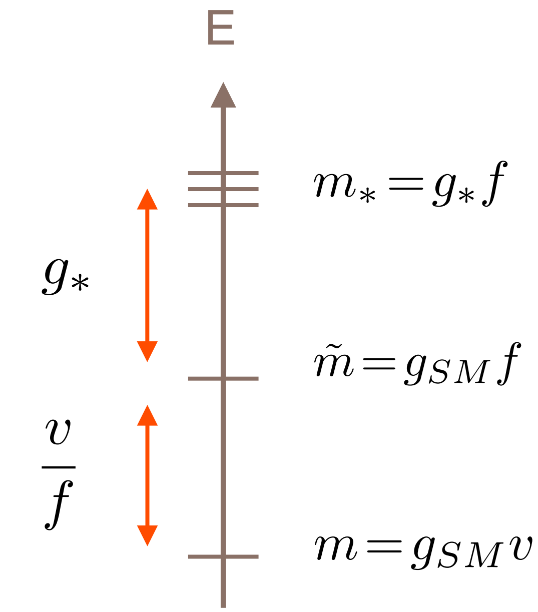

- Higgs couplings $\quad \frac{\delta c}{c} \sim \frac{v^2}{f^2} \longrightarrow \boxed{\xi \equiv \frac{v^2}{f^2} \lesssim 0.1 - 0.2}$

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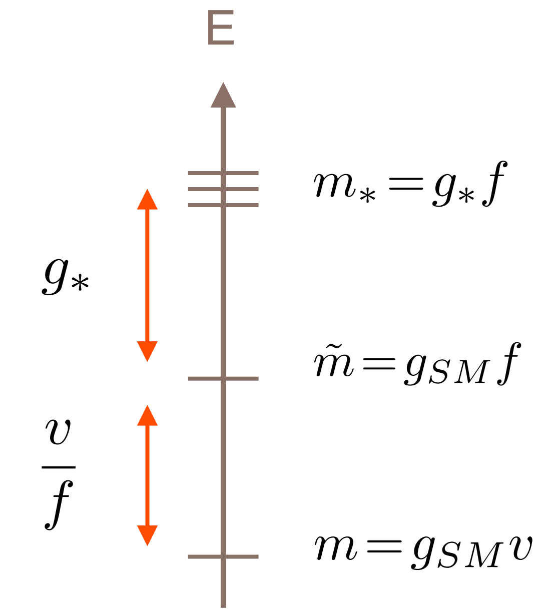

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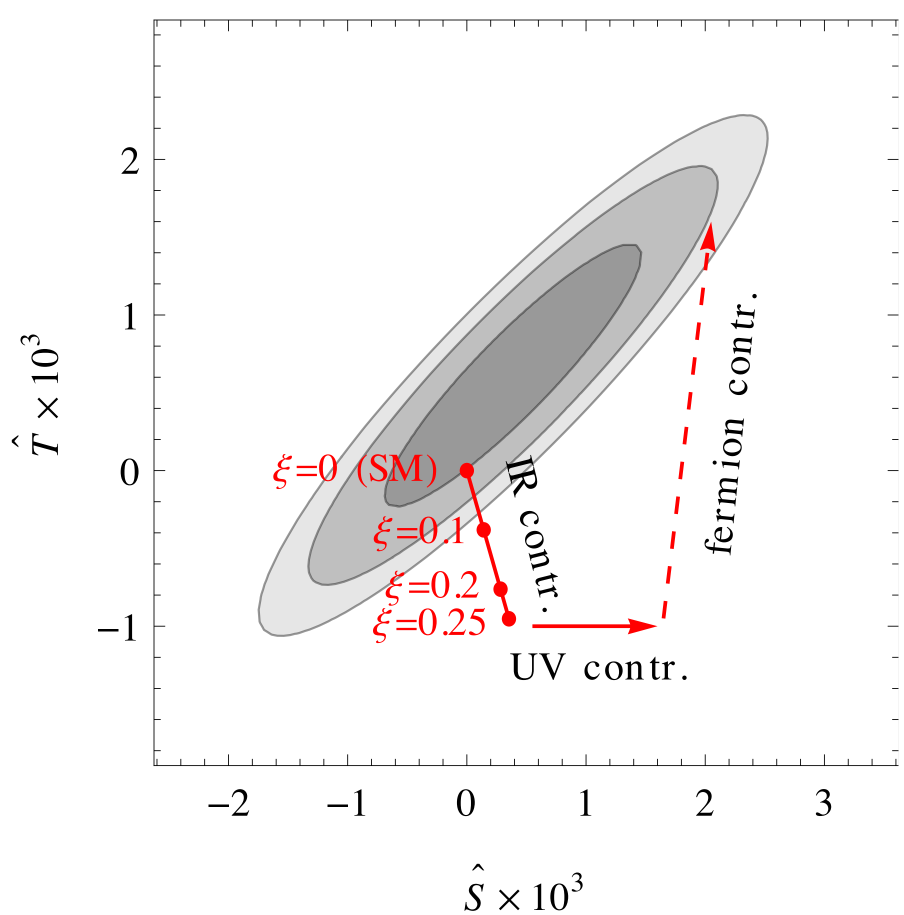
- EW precision observables

from arXiv:1306.4655



IR contribution from Higgs compositeness is a non-decoupling one

Fermion contribution

$$\Delta\hat{T}_\Psi \sim \frac{3y_t^2}{16\pi^2}\frac{y_t^2 v^2}{m_*^2}$$

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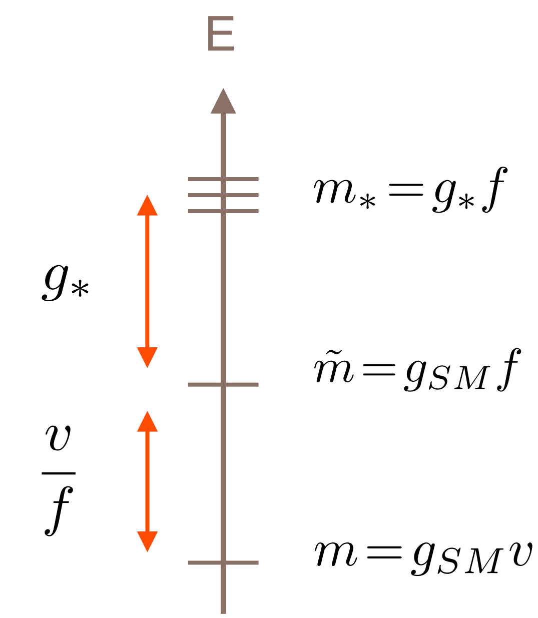

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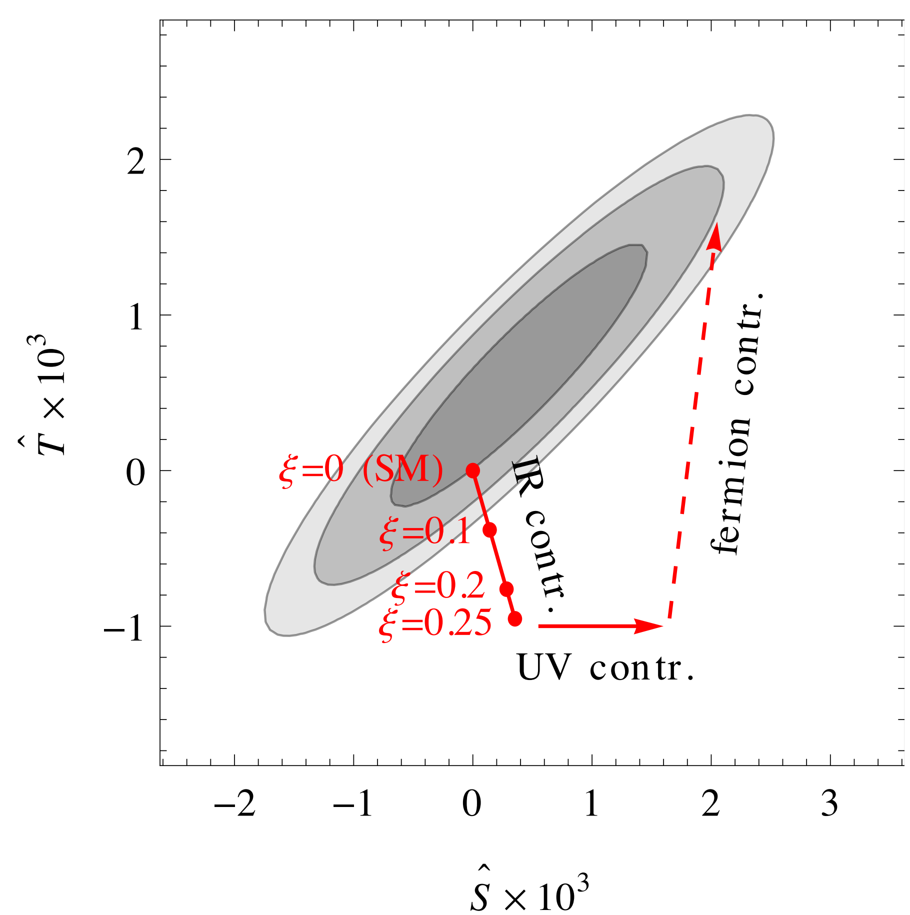

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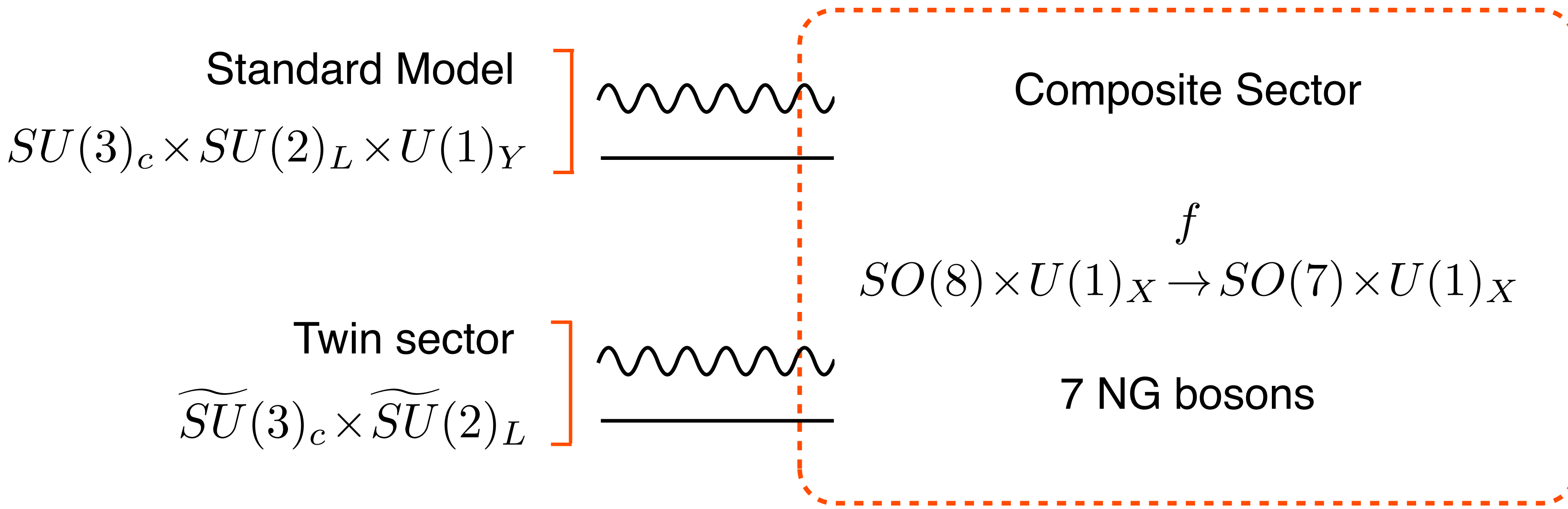
Can EWPT be satisfied in Composite TH theories ?

Phenomenology of an SO(8) Twin Higgs model

[R.C., D. Greco, R. Mahbubani, R. Rattazzi and R. Torre arXiv:1702.00797]



$$\mathcal{L}_{mix} = g\, W_\mu J^\mu + g'\, B_\mu J^\mu_B + \tilde{g}\, \widetilde{W}_\mu J^\mu$$
$$+\, y_L\, \bar{q}_L \mathcal{O}_q + y_R\, \bar{t}_R \mathcal{O}_t + \tilde{y}_L\, \bar{\tilde{q}}_L \widetilde{\mathcal{O}}_q + \tilde{y}_R\, \bar{\tilde{t}}_R \widetilde{\mathcal{O}}_t + h.c.$$

$$J^\mu_B = J^\mu_{3R} + J^\mu_X$$

Partial compositeness:

$$J^\mu, \longrightarrow \rho^\mu = \mathbf{28} \text{ of } SO(8)$$
$$J^\mu_X \longrightarrow \rho^\mu_X = \mathbf{1} \text{ of } SO(8)$$
$$\mathcal{O}_{q,t}, \widetilde{\mathcal{O}}_{q,t} \longrightarrow \Psi, \widetilde{\Psi} = \mathbf{8} \text{ of } SO(8)$$

Low, Tesi, Wang, Phys.Rev. D91 (2015) 095012
Barbieri, Greco, Rattazzi, Wulzer, JHEP 1508 (2015) 161

Higgs potential at NLO

- Higgs potential generated at the scale m_* by 1-loop threshold corrections

$$\delta V_B = \frac{3 g_\rho^2 g'^2}{512\pi^2} f^4 \sin^2(h/f)$$

(from Z_2 breaking)

$$\delta V_\Psi = \frac{N_c f^4}{128\pi^2} \left(y_L^4 F_1 + \tilde{y}_t^4 \widetilde{F}_1 \right) \left(\sin^4(h/f) + \cos^4(h/f) \right)$$

($F_1, \widetilde{F}_1$ are O(1) functions)

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By making the field redefinition $H \to H' = f \frac{H}{\sqrt{H^\dagger H}} \sin\left(\sqrt{H^\dagger H}/f\right)$

one gets the effective Lagrangian ($\tilde{y}_0 = \tilde{y}_2 = \tilde{y}_4 = y_1,\ \tilde{c}_2 = \tilde{c}_4 = 0$):

$$\mathcal{L}_H = |D_\mu H|^2 + \frac{1}{2f^2} [\partial_\mu (H^\dagger H)]^2 + \mu^2 H^\dagger H - \lambda_h (H^\dagger H)^2$$

$$\mathcal{L}_t = -y_1\, \bar{q}_L H^c t_R + h.c.$$

$$\mathcal{L}_{\tilde{t}} = -\frac{f}{\sqrt{2}} \left(\tilde{y}_0 - \frac{\tilde{y}_2}{2} \frac{H^\dagger H}{f^2} - \frac{\tilde{y}_4}{8} \frac{(H^\dagger H)^2}{f^4} + \dots \right) \bar{\tilde{t}}\tilde{t} + \bar{\tilde{t}}\, i \not{\partial}\, \tilde{t} \left(\tilde{c}_2 \frac{H^\dagger H}{f^2} + \frac{\tilde{c}_4}{6} \frac{(H^\dagger H)^2}{f^4} \right)$$

RG evolution from m_* down to $\mu \sim m_h, m_t$ encodes the bulk of radiative corrections:

$$\frac{m_t}{G_F^{-1/2}} = \frac{1}{\sqrt{2}} y_1(\mu) \qquad \frac{m_h^2}{G_F^{-1}} = 8\lambda_h(\mu)(1-\xi) \qquad \xi = \frac{v^2}{f^2}$$

$$\beta_{y_1} = \frac{1}{16\pi^2}\left(\frac{9}{4}y_1^3 - 4g_S^2 y_1\right)$$

$$\beta_{\lambda_h} = \frac{1}{16\pi^2}\left(6y_1^2\lambda_h - \frac{3}{4}y_1^4 - \frac{9}{8}\tilde{y}_0^2\tilde{y}_2^2 + \frac{3}{8}\tilde{y}_4\tilde{y}_0^3 - 3\tilde{y}_2\tilde{y}_0^3\tilde{c}_2 + \frac{3}{8}\tilde{y}_0^4\tilde{c}_4\right)$$

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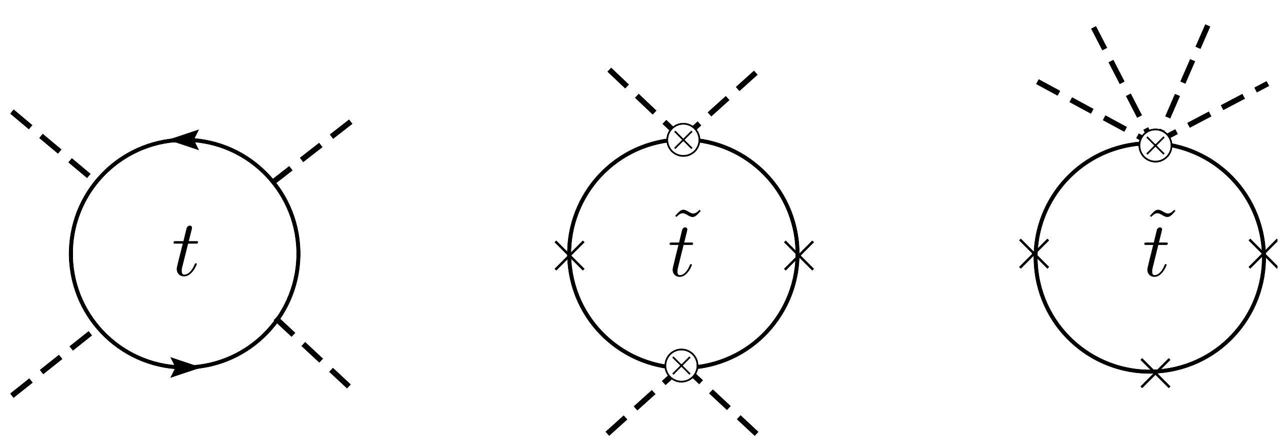

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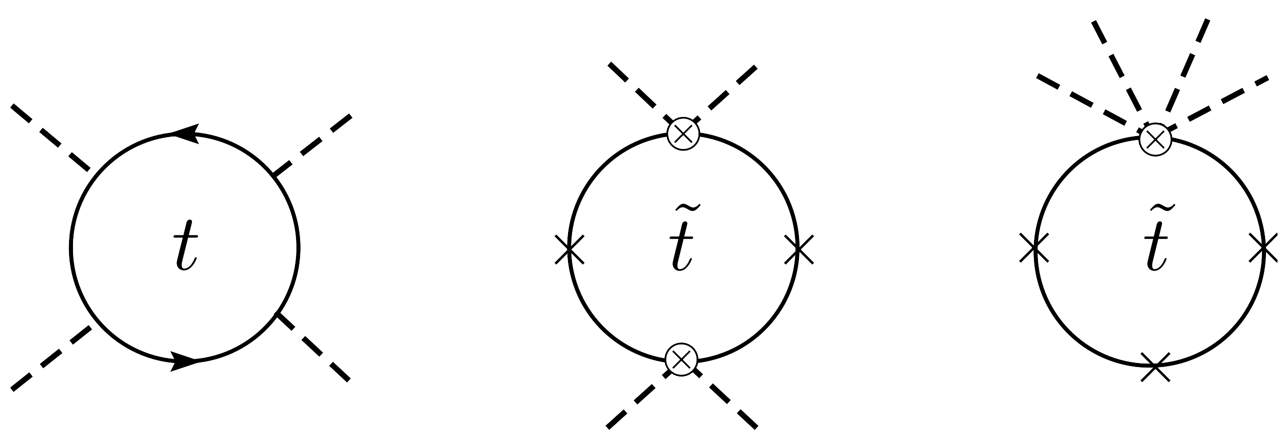
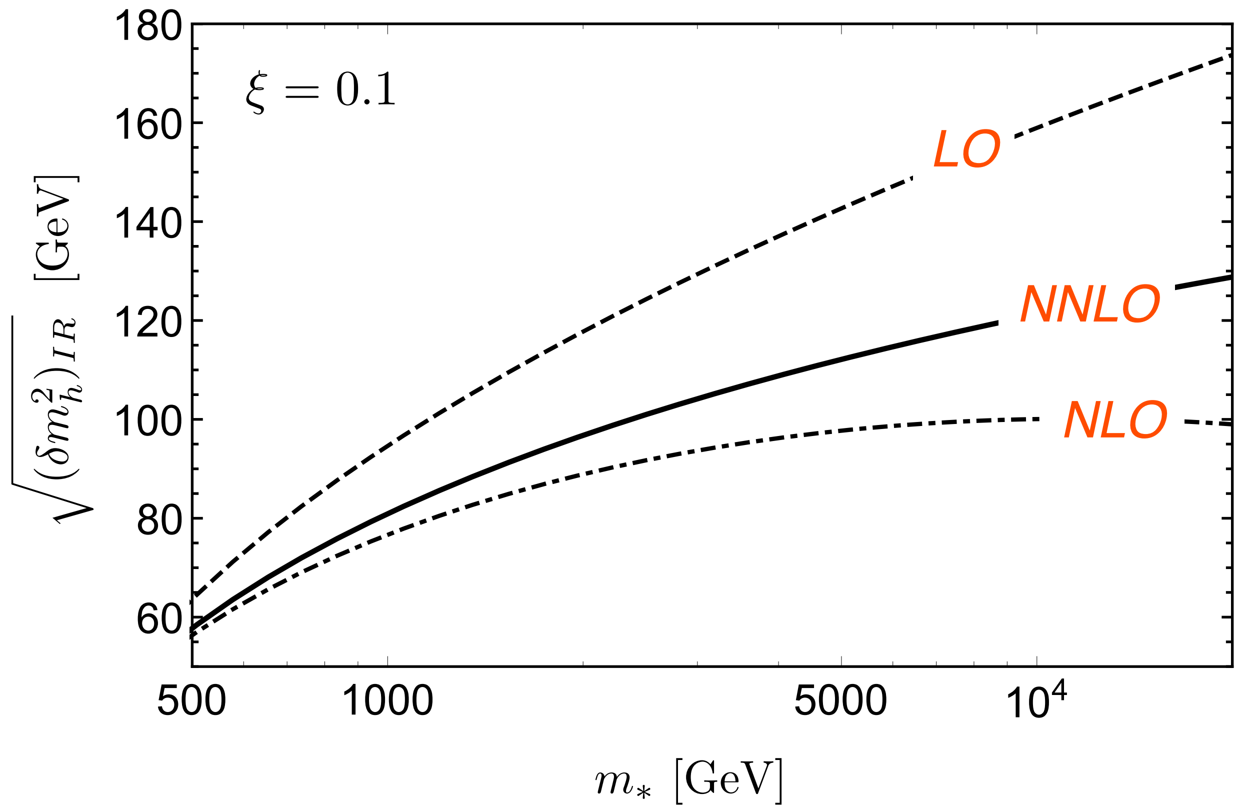


Twin top operators up to D=7 contribute and must be included

RG equations are solved at Next-to-Leading order in a combined perturbative expansion in $(\alpha \log)$ and ξ



Ex: for $m_* = 5\,\mathrm{TeV}$ and $\xi = 0.1$

NLO: -32%

NNLO: $+15\%$

NNLO curve taken from

Greco and Mimouni, arXiv:1609.05922

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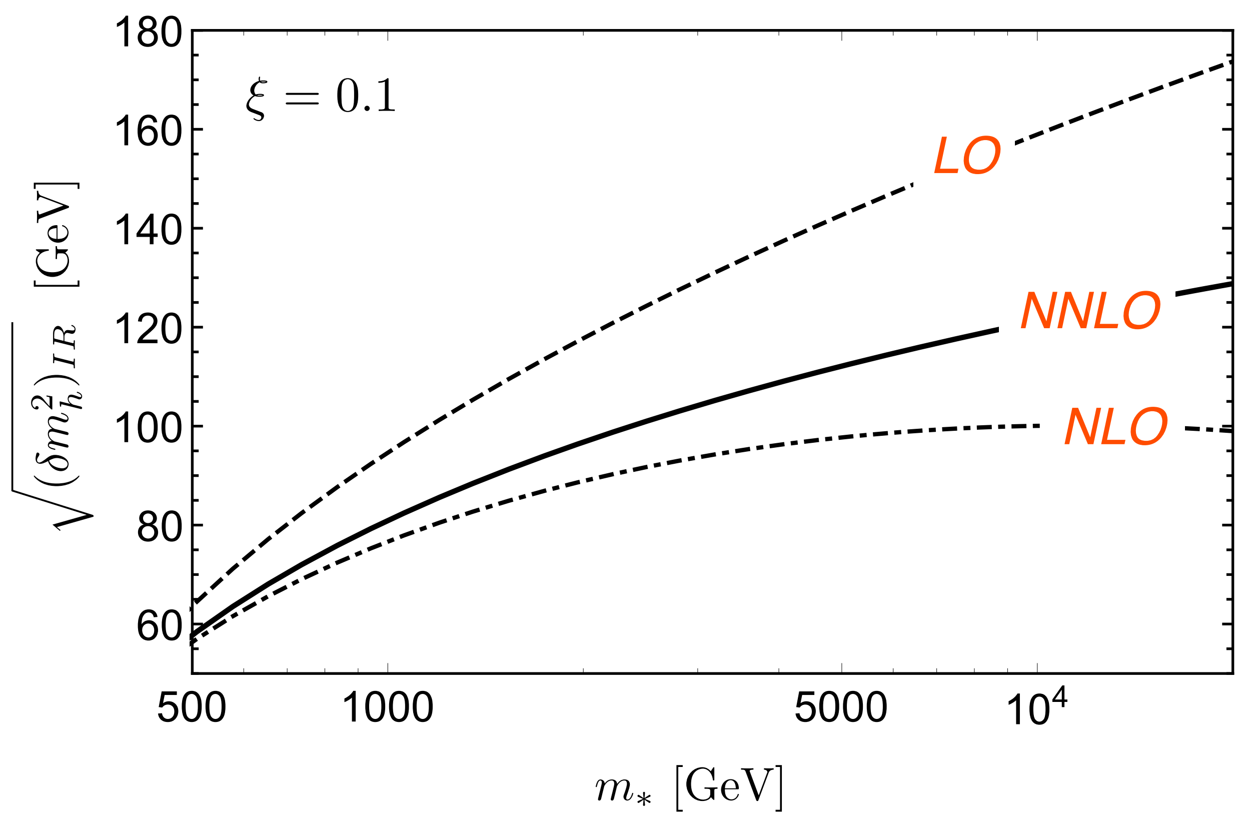

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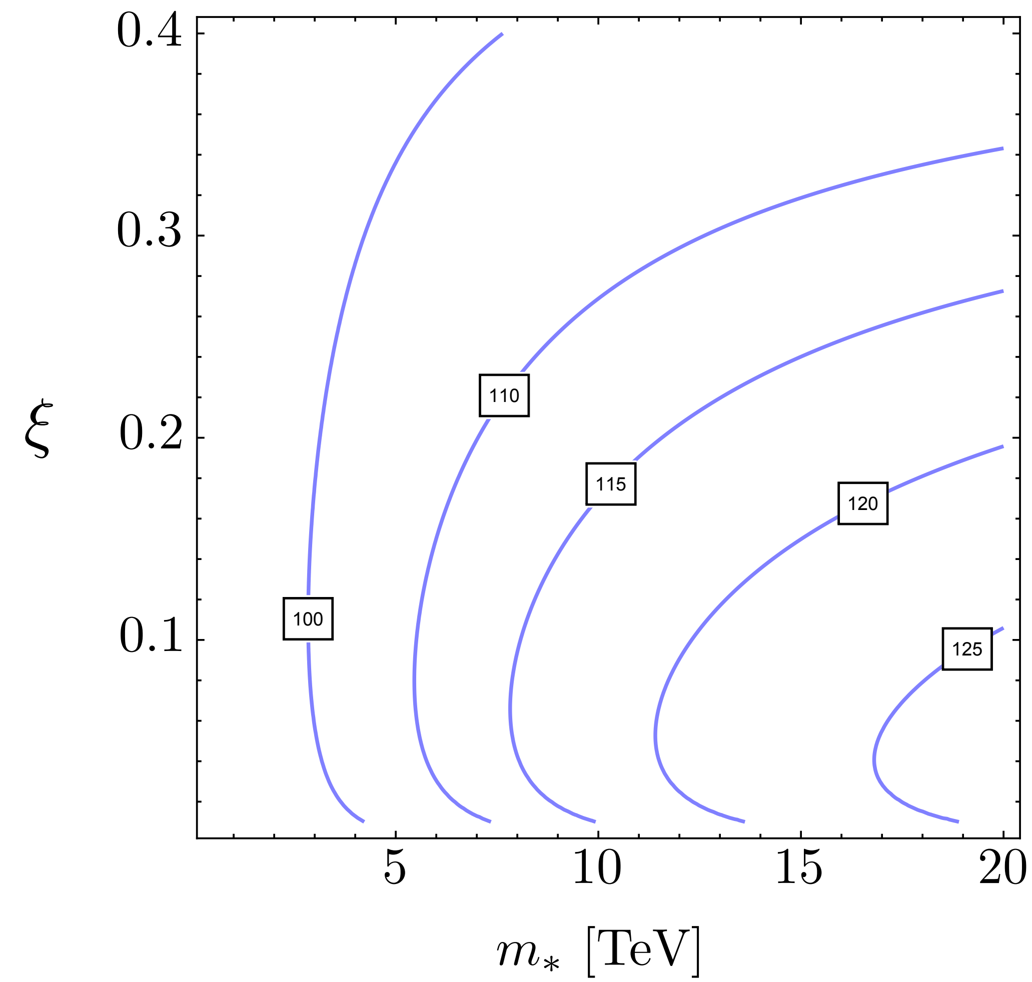

IR contribution almost accounts for the whole Higgs mass, UV threshold are sub-dominant

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IR = 74% (47% SM + 27% twin tops)

EW and Higgs precision physics

- 1-loop contributions to EWPO from Twin states are subleading
- Corrections parametrically the same as in CH models (with singlet t_R)

$$\Delta\hat{S} = \frac{g^2}{2g_\rho^2}\xi + \frac{g^2}{192\pi^2}\xi\log\frac{m_*^2}{m_h^2}$$

$$\Delta\widehat{T} = a_{UV}\frac{y_L^2}{16\pi^2}N_c\frac{y_L^2 v^2}{M_\Psi^2} + a_{IR}\frac{y_t^2}{16\pi^2}N_c\frac{y_L^2 v^2}{M_\Psi^2}\log\frac{M_\Psi^2}{m_t^2} - \frac{3g_1^2}{64\pi^2}\xi\log\frac{m_*^2}{m_h^2}$$

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$a_{UV}, a_{IR}, b_{UV}, b_{IR}$
coefficients of O(1)

For recent analyses of EWPT in CH models see:

C. Grojean, O. Matsedonskyi and G. Panico, JHEP 10 (2013) 160
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IR running down to EW scale

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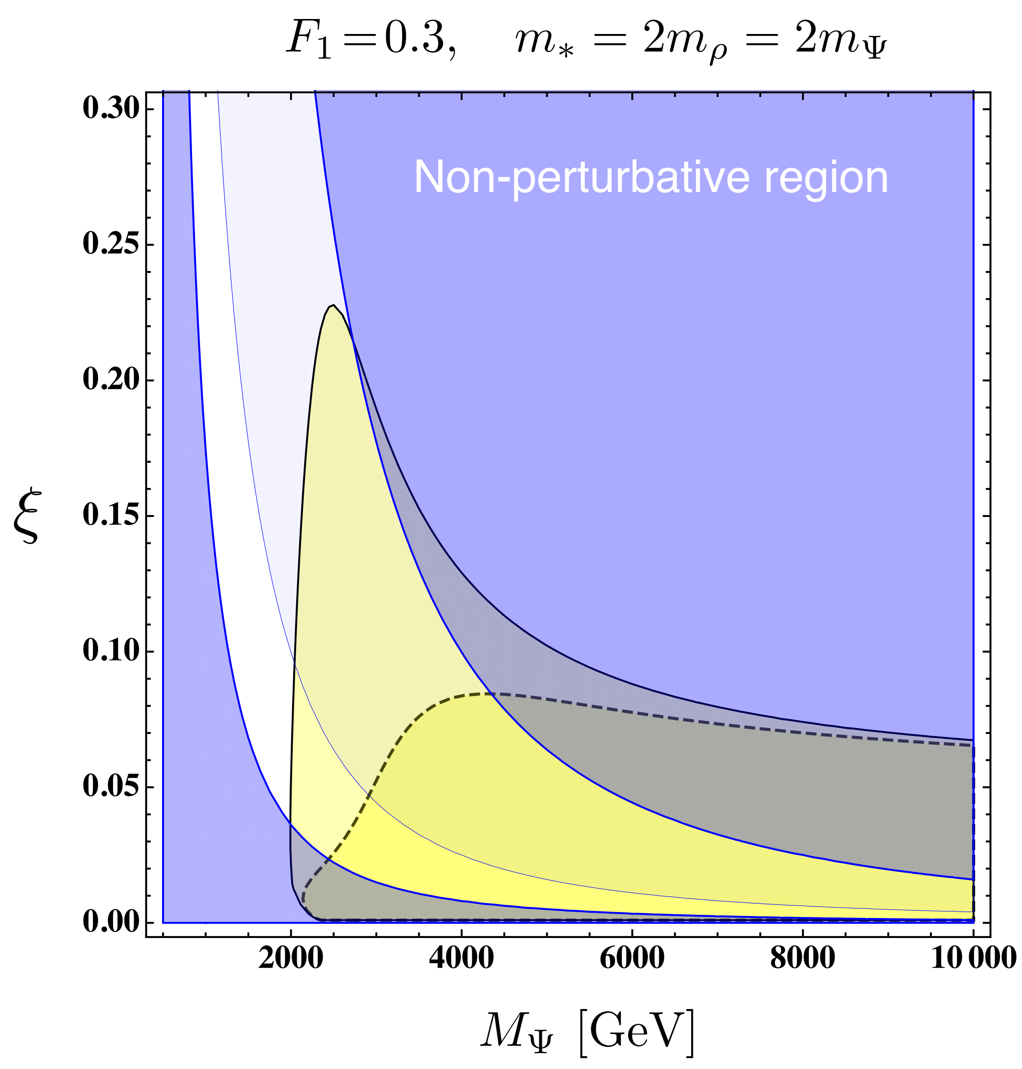
- Large ξ possible for $M_\Psi \lesssim 4\,\mathrm{TeV}$ and signs of $\Delta\hat{T}$, δg_{Lb} anti-correlated



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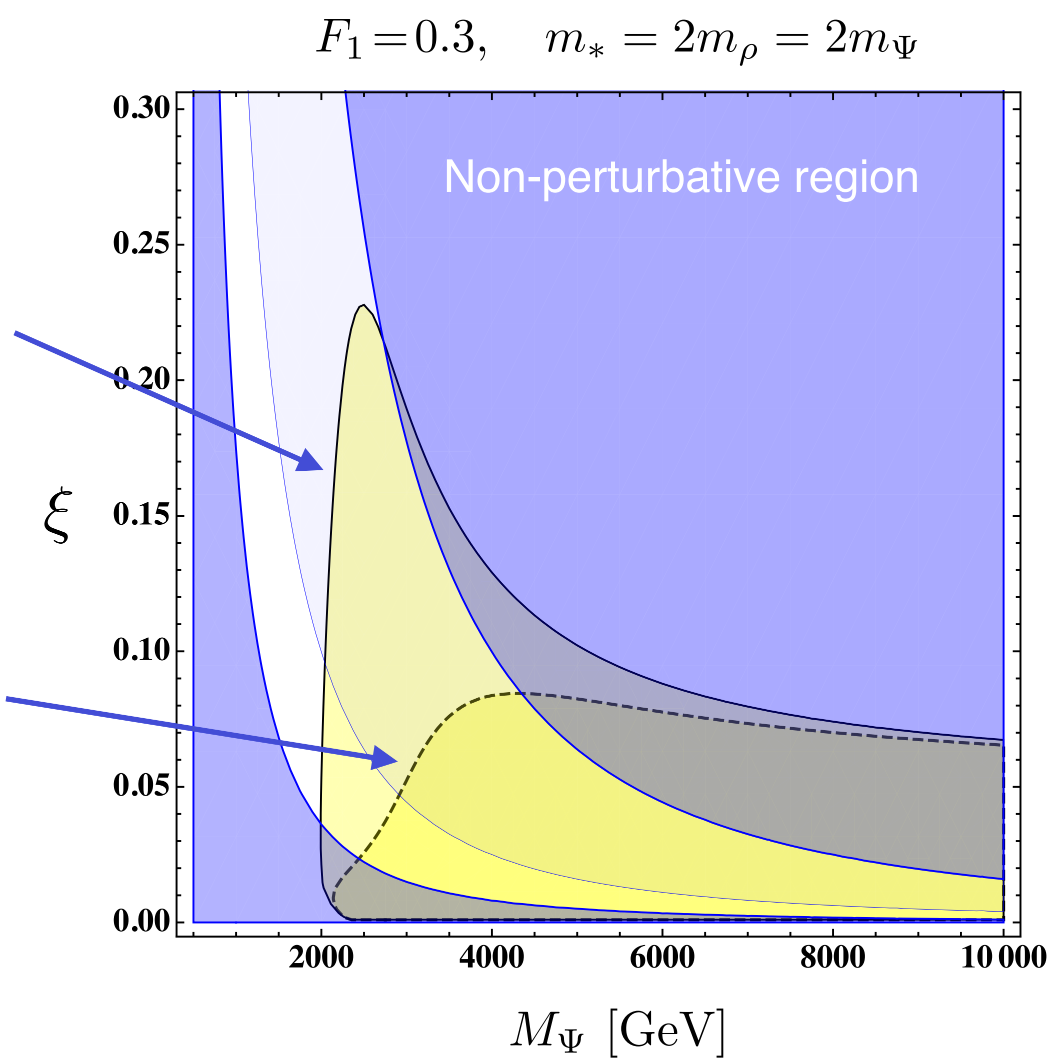

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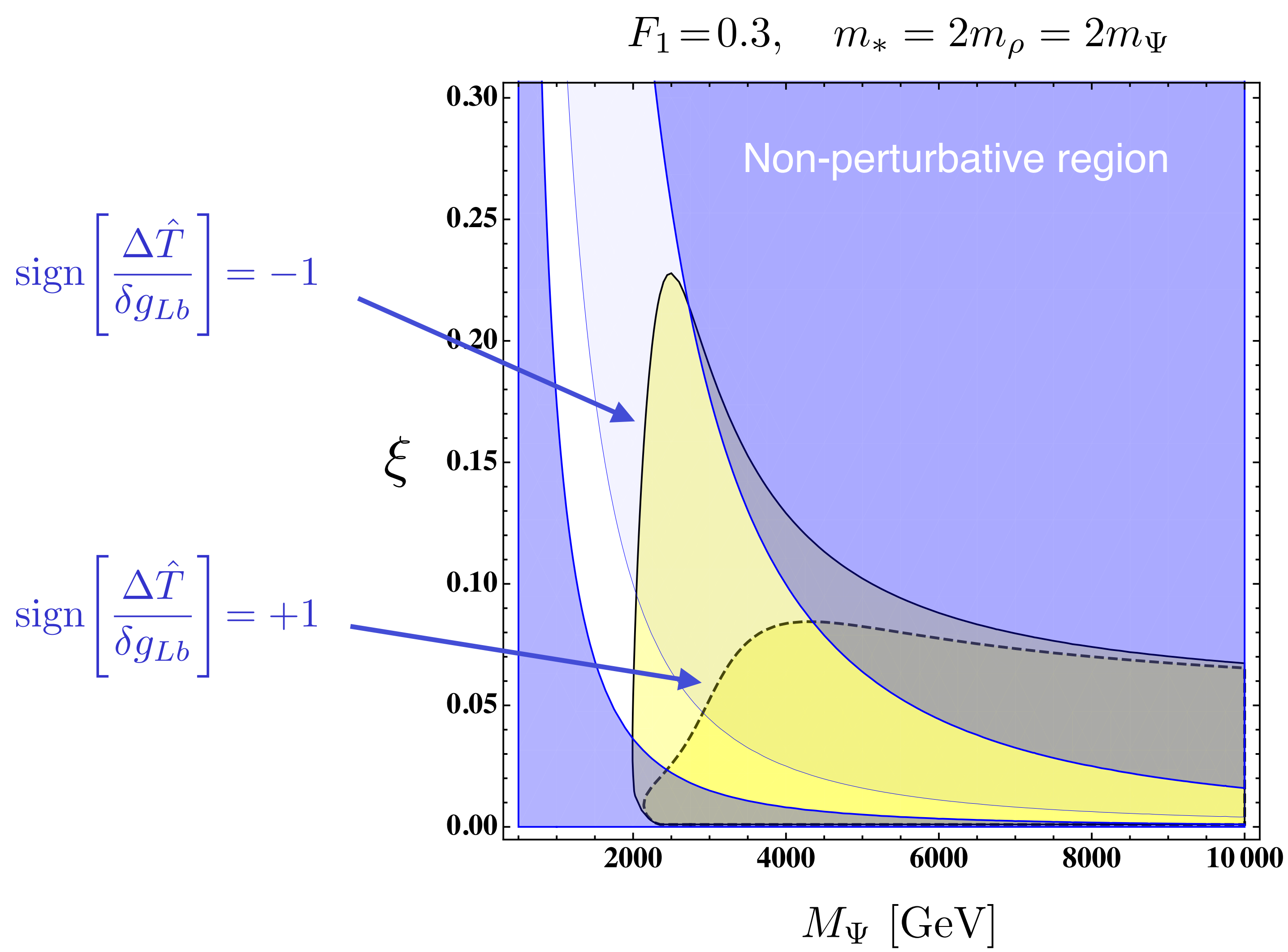

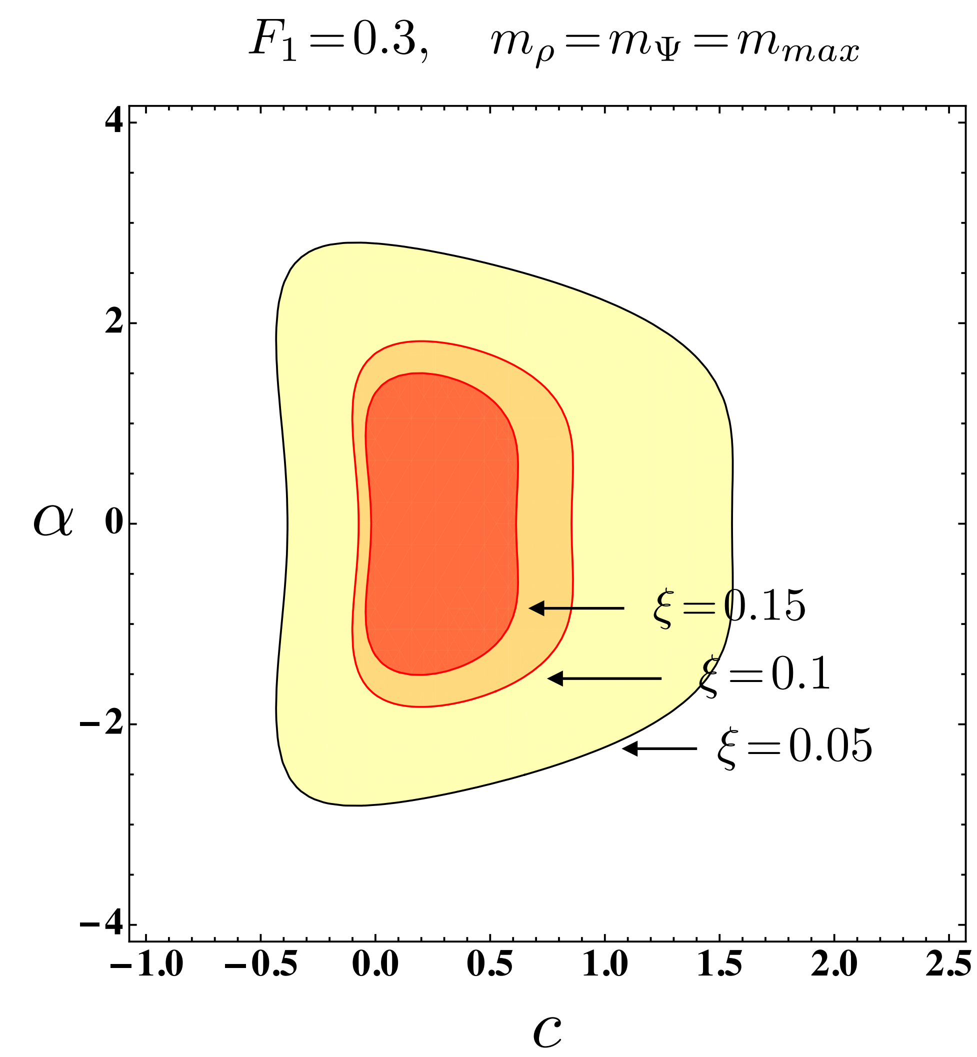

$$\mathcal{L} \supset \alpha\,\bar{\Psi}(\rho_\mu - E_\mu)\gamma^\mu\Psi + c\,\bar{\Psi}d_\mu\gamma^\mu\Psi$$

$$\alpha, c = O(1)$$

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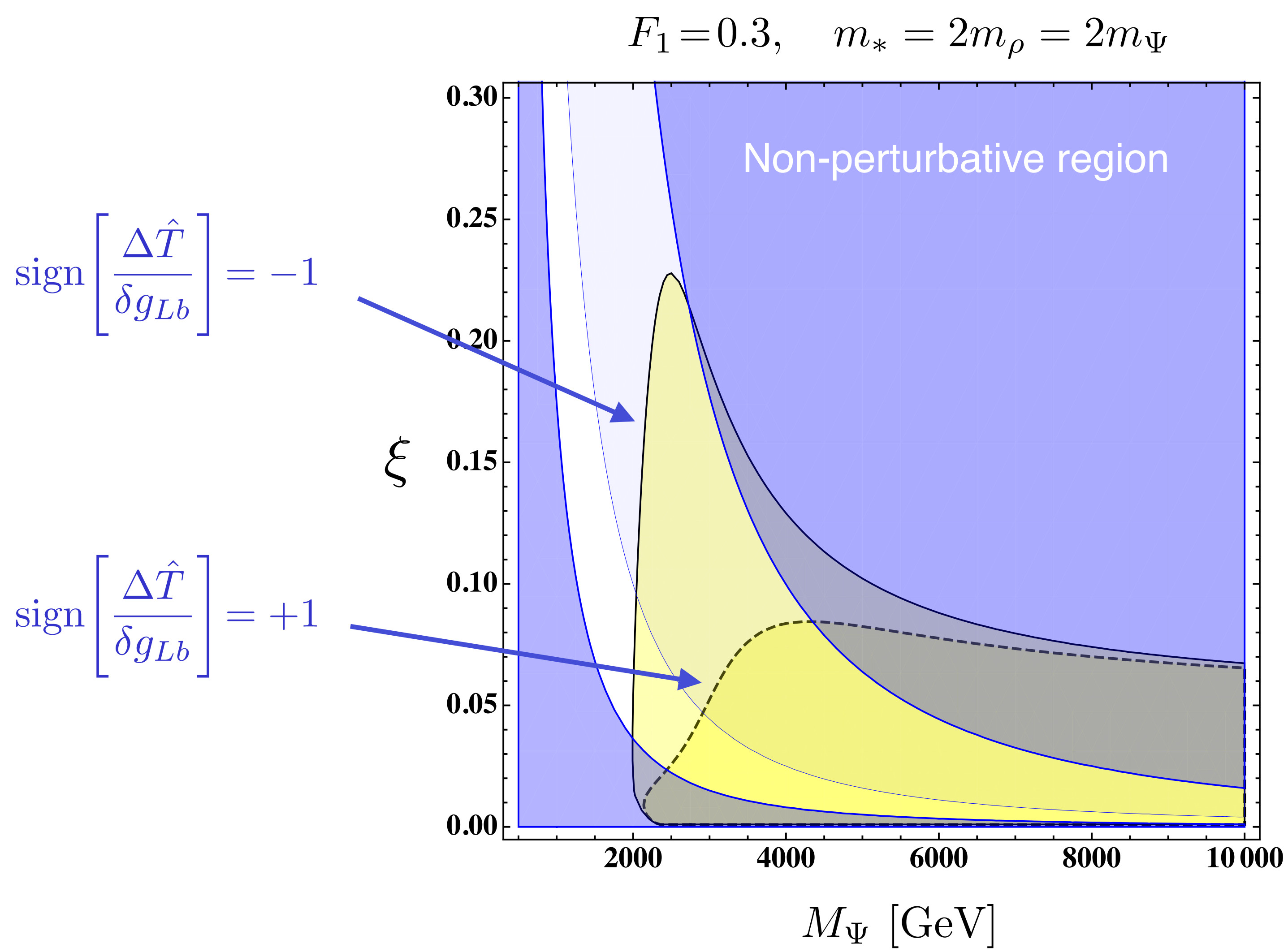

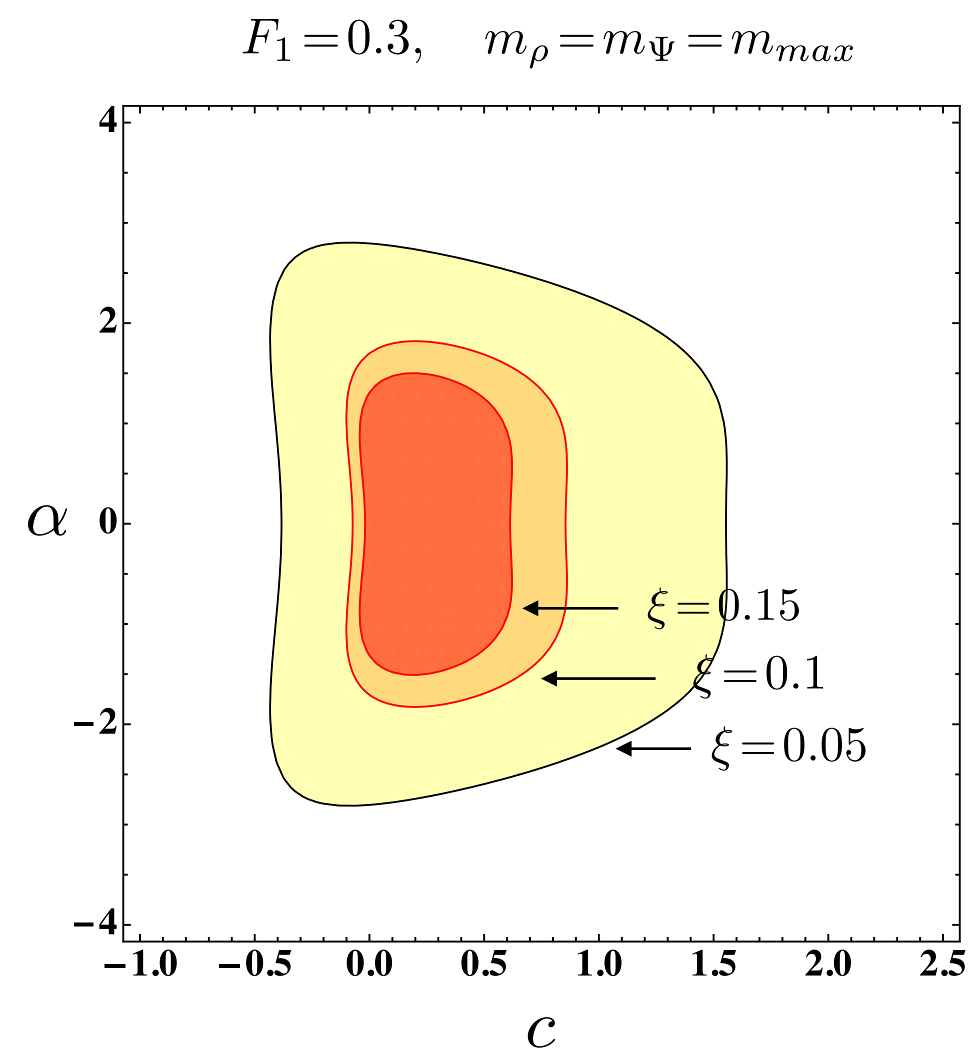

Moral: once the perturbative bound is satisfied, EWPT can be passed in a sizable portion of the parameter space

$$\mathcal{L} \supset \alpha\,\bar{\Psi}(\rho_\mu - E_\mu)\gamma^\mu\Psi + c\,\bar{\Psi}d_\mu\gamma^\mu\Psi$$

$$\alpha, c = O(1)$$

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  Condition on symmetries/selection rules of UV dynamics is required

  Ex: SO(8)/SO(7) works, SU(4)/SU(3) does not

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- Perturbativity bound on g_* made stringent by large multiplicity of states required for realistic models. Naive estimates give: $m_*/f \lesssim 3-5$

  This bound to be compared with $m_*/f \lesssim 1.5$ in CH models from Higgs mass

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  Higgs mass parametrically smaller than in CH models, experimental value easier to reproduce

- Naively, larger M_Ψ in tension with EWPT (because of too small $\Delta\hat{T}_\Psi$)

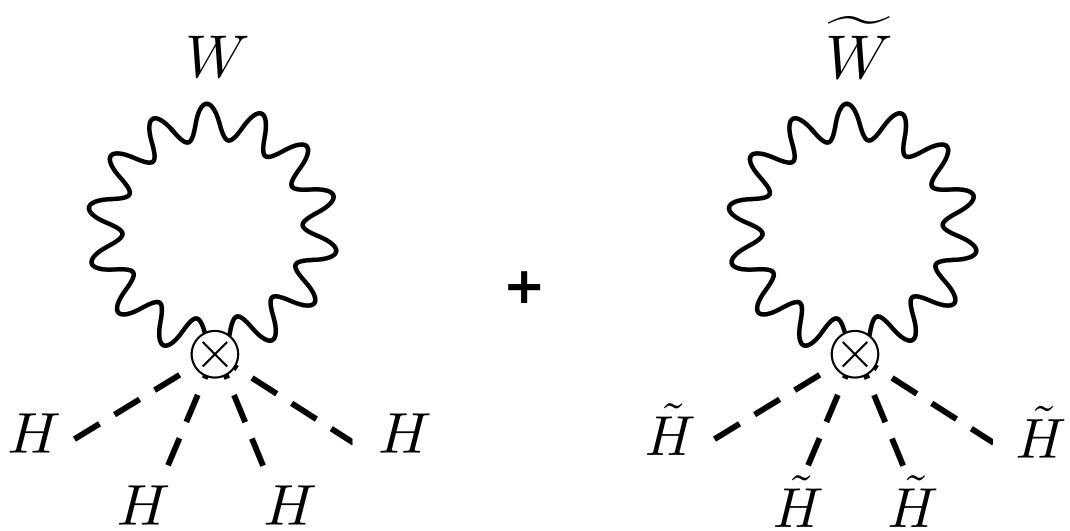
  In practice, $\xi \sim 0.2$ still allowed (though borderline) for $M_\Psi \lesssim 4\,\mathrm{TeV}$

Extra slides

On the size of SO(8)-breaking quartic term

In general, interactions of the type
$$\left(H^\dagger \overleftrightarrow{D_\mu} H\right)^2 + \left(\tilde{H}^\dagger \overleftrightarrow{D_\mu} \tilde{H}\right)^2$$
$$\left(H^\dagger \overleftrightarrow{D_\mu} H\right)\left(\tilde{H}^\dagger \overleftrightarrow{D_\mu} \tilde{H}\right)$$

are not SO(8) invariant and can generate a quartic at $O(g^2)$:



$$\sim \frac{m_*^2}{16\pi^2} \times \frac{g^2 g_*^2}{m_*^2}\left(|H|^4 + |\tilde{H}|^4\right)$$

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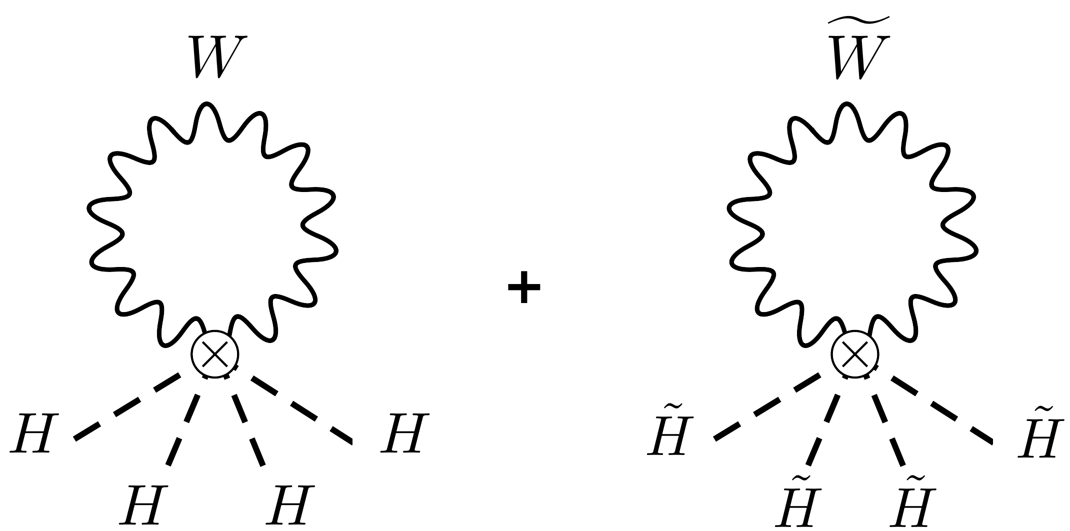

$$\sim \frac{m_*^2}{16\pi^2} \times \frac{g^2 g_*^2}{m_*^2} \left(|H|^4 + |\tilde{H}|^4\right)$$

☞ Symmetries and selection rules of the UV dynamics can forbid the SO(8)-breaking terms at $O(g_{SM}^2)$

- Whether or not SO(8)-breaking terms are generated at $O(g^2_{SM})$ can be determined solely based on *symmetries* and *spurion* quantum numbers

  [Barbieri, Greco, Rattazzi, Wulzer, JHEP 1508 (2015) 161]

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For example, consider the case:

- *SO(8)-invariant UV dynamics*
- *coset SO(8)/SO(7)*
- *gauge contribution to the potential*

spurion transforms as $\mathbf{28} = \mathbf{21} + \mathbf{7}$ of *SO(7)*

$$\mathcal{G}^a = U^\dagger(\pi) g T^a U(\pi)$$

$$\left.\begin{array}{l} \mathbf{21} \times \mathbf{21} \supset \mathbf{1} \\ \mathbf{7} \times \mathbf{7} \supset \mathbf{1} \end{array}\right] \rightarrow \textit{1 non-trivial invariant}$$

$$\left(\mathrm{Tr}[T^{\hat{a}}_{(\mathbf{7})} \mathcal{G}^a]\right)^2 + \left(\mathrm{Tr}[T^{\hat{a}}_{(\mathbf{7})} \tilde{\mathcal{G}}^a]\right)^2 = g^2 \sin^2(h/f) + \tilde{g}^2 \cos^2(h/f) \qquad ✔$$

- Whether or not SO(8)-breaking terms are generated at $O(g_{SM}^2)$ can be determined solely based on *symmetries* and *spurion* quantum numbers

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For example, consider the case:

- SU(4)-invariant UV dynamics

- coset SU(4)/SU(3)

- gauge contribution to the potential

spurion transforms as $\mathbf{15} = \mathbf{8} + (\mathbf{3} + \bar{\mathbf{3}}) + \mathbf{1}$ of *SU(3)*

$$\mathcal{G}^a = U^\dagger(\pi) g T^a U(\pi)$$

$$\left.\begin{array}{l} \mathbf{8} \times \mathbf{8} \supset \mathbf{1} \\ (\mathbf{3} + \bar{\mathbf{3}}) \times (\mathbf{3} + \bar{\mathbf{3}}) \supset \mathbf{1} \\ \mathbf{1} \times \mathbf{1} = \mathbf{1} \end{array}\right] \rightarrow$$ *2 non-trivial invariants*

$$\left(\mathrm{Tr}[T^{\hat{a}}_{(\mathbf{3}+\bar{\mathbf{3}})} \mathcal{G}^a]\right)^2 + \left(\mathrm{Tr}[T^{\hat{a}}_{(\mathbf{3}+\bar{\mathbf{3}})} \tilde{\mathcal{G}}^a]\right)^2 = g^2 \left(3 \sin^2(h/f) - \sin^4(h/f)\right) + \tilde{g}^2 \left(3 \cos^2(h/f) - \cos^4(h/f)\right)$$

$$\left(\mathrm{Tr}[T^{\hat{a}}_{(\mathbf{1})} \mathcal{G}^a]\right)^2 + \left(\mathrm{Tr}[T^{\hat{a}}_{(\mathbf{1})} \tilde{\mathcal{G}}^a]\right)^2 = g^2 \sin^4(h/f) + \tilde{g}^2 \cos^4(h/f)$$ ✘

Hypersoft Theories

Consider the case in which $m_\phi^2 \sim \text{loop} \times m_*^2$

Examples: 1) Theories where ϕ itself is a pNGB

2) SUSY with soft masses m_* generated at a scale $\sim m_*$ where ϕ is massless

Then:

$$m_h^2 \sim \frac{\lambda_h}{2\lambda_\phi}\frac{1}{\epsilon}\left(\frac{3y_t^2}{4\pi^2} + \frac{5\lambda_\phi}{16\pi^2}\right) m_*^2$$

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as in Technicolor

for $\lambda_\phi \gg y_t^2$

as naturally expected if

$SO(8)\text{-preserving} \gg SO(8)\text{-breaking}$

Super-Hypersoft Theories

Variant of the Hypersoft case where leading correction to m_ϕ comes from the top quark:

Example: Approximate SUSY in the scalar sector below m_*

gain in FT

$$m_h^2 \sim \frac{\lambda_h}{2\lambda_\phi}\frac{1}{\epsilon}\left(\frac{3y_t^2}{4\pi^2}+\cancel{\frac{5\lambda_\phi}{16\pi^2}}\right)m_*^2 \quad \Rightarrow \quad m_*^2 \sim \frac{4\pi^2}{3y_t^2}\times\frac{m_h^2}{\epsilon}\times\boxed{\frac{g_*^2}{\lambda_h}}$$

$$m_* \sim 1.4\,\mathrm{TeV}\,\frac{g_*}{\sqrt{2}y_t}\sqrt{\frac{1}{\epsilon}}$$