On the composite Higgs

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Outline

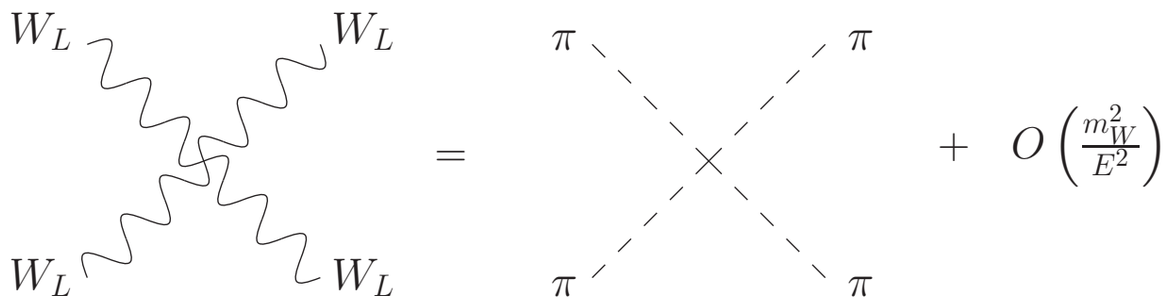
- ✦ The Higgs & Naturalness
- ✦ The composite-pNGB Higgs
  1. Generic features
  2. Potentials
  3. Models
  4. Top-partners
- ✦ Non-standard phenomenology?
  1. Extra NGB's
  2. NMCHM
  3. Top-partners decays

PRELIMINARY PRELIMINARY PRELIMINARY

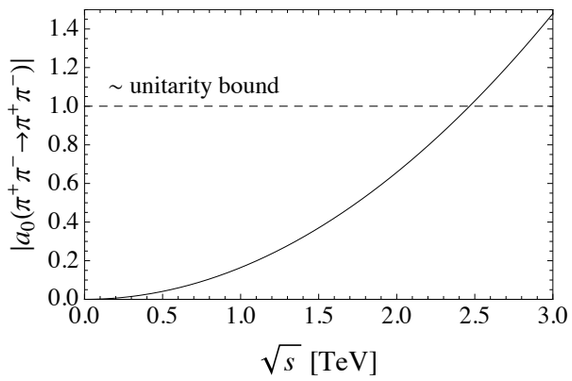
The Higgs & Naturalness

The Higgs & Naturalness

Without the Higgs:



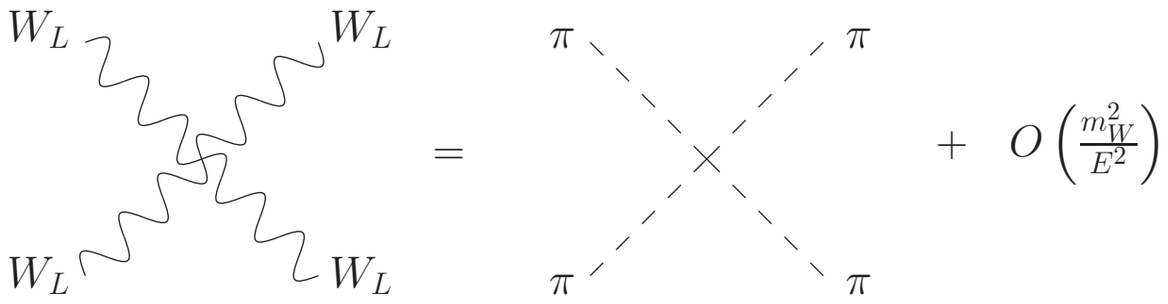
$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{E^2}{v^2}$$



We knew what to look for

The Higgs & Naturalness

Without the Higgs:



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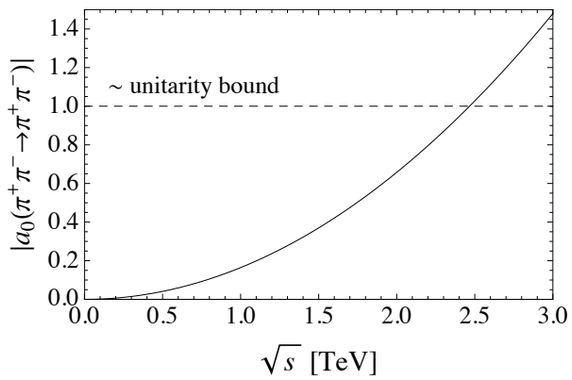
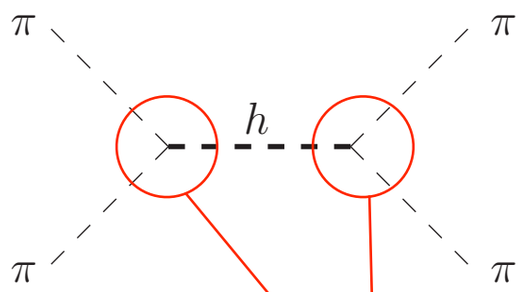


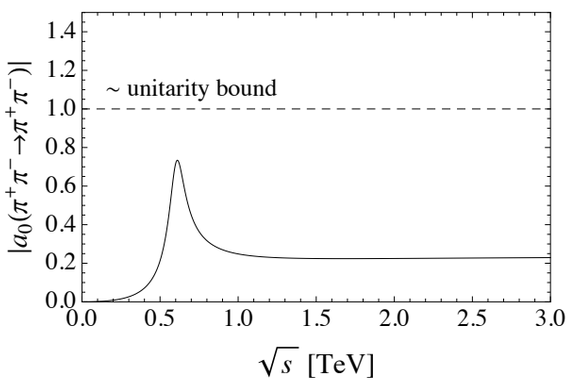
We knew what to look for

With the Higgs:



$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{E^2}{v^2}\left(1 - c_V^2\right) + O\left(\frac{m_h^2}{v^2}\right)$$

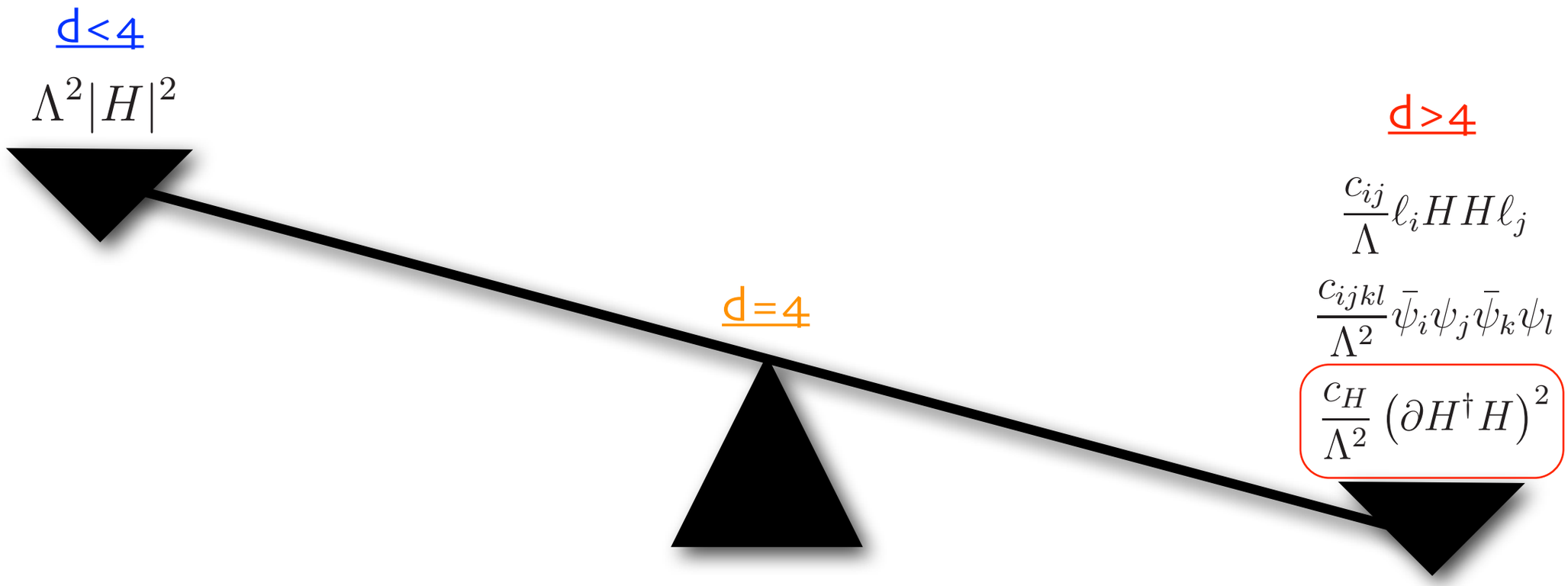
SM elementary Higgs: $c_V = 1$



The SM can be extended to arbitrarily high energies*

neutrino masses, dark matter, (extra) CP-violation, (quantum) gravity

$$\Lambda \gg v$$



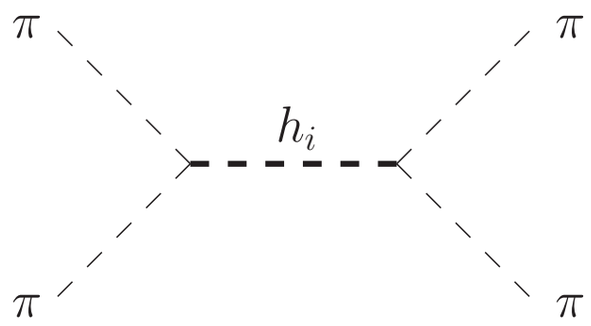
The SM is generically fine-tuned

Naturalness is (for me) the best guide to BSM

$$\Lambda \longrightarrow v$$

Supersymmetry

weak coupling



$$\mathcal{A} \sim \frac{E^2}{v^2}\left(1 - \sum_i c_{V\,i}^2\right) + O\left(\frac{m_{h_i}^2}{v^2}\right)$$

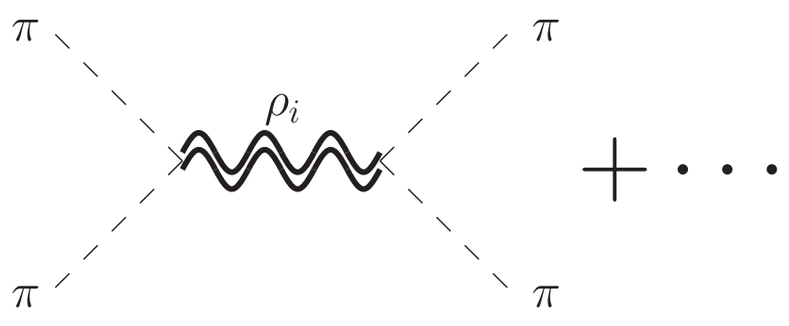
$$\sum_i c_{V\,i}^2 = 1$$

new states at

$$gv \sim 100\,\mathrm{GeV}$$

Compositeness

strong coupling



$$\mathcal{A} \sim \frac{E^2}{v^2}\left(1 - \sum_i c_{V\,i}^2\right) + O\left(\frac{m_{\rho_i}^2}{v^2}\right) + O\left(\frac{E^4}{v^4}\right)$$

$$\sum_i c_{V\,i}^2 \neq 1$$

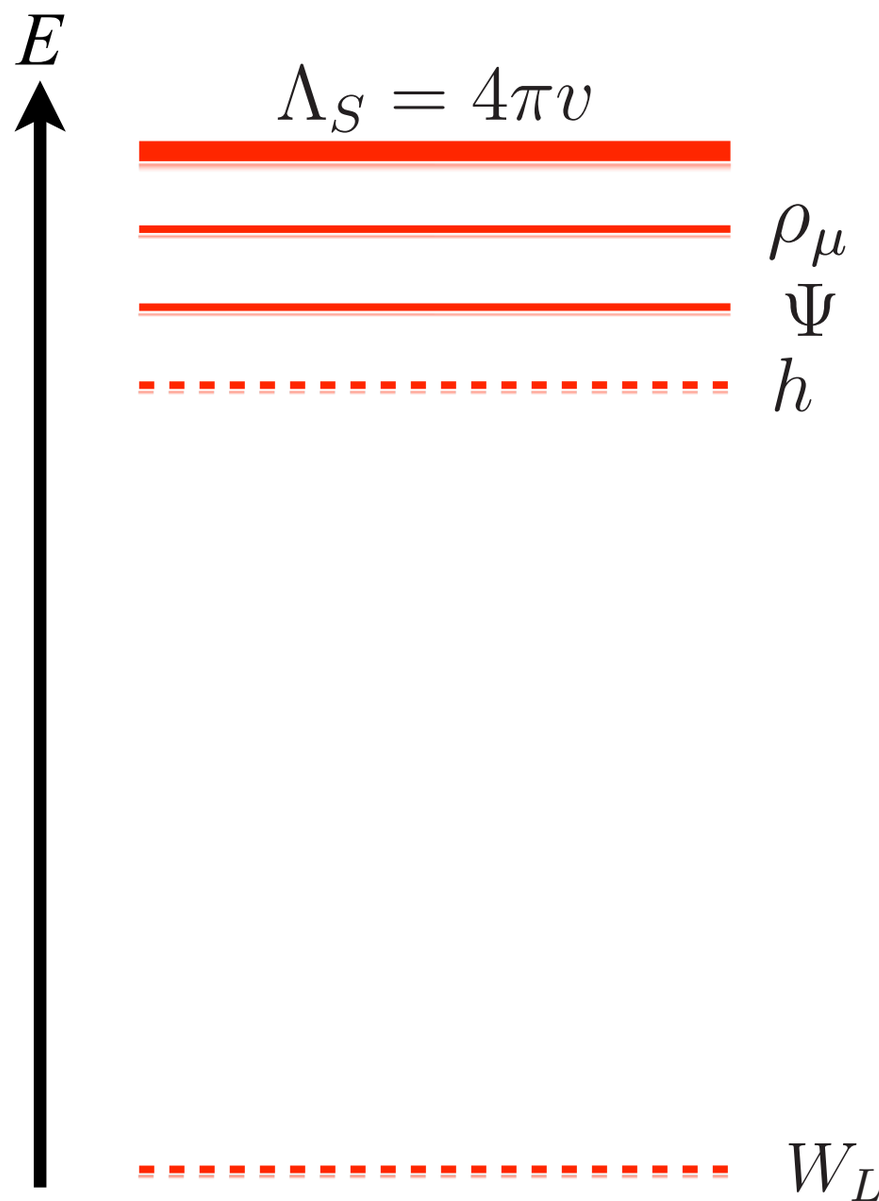
new states at

$$4\pi v \sim 2\,\mathrm{TeV}$$

The composite-pNGB Higgs

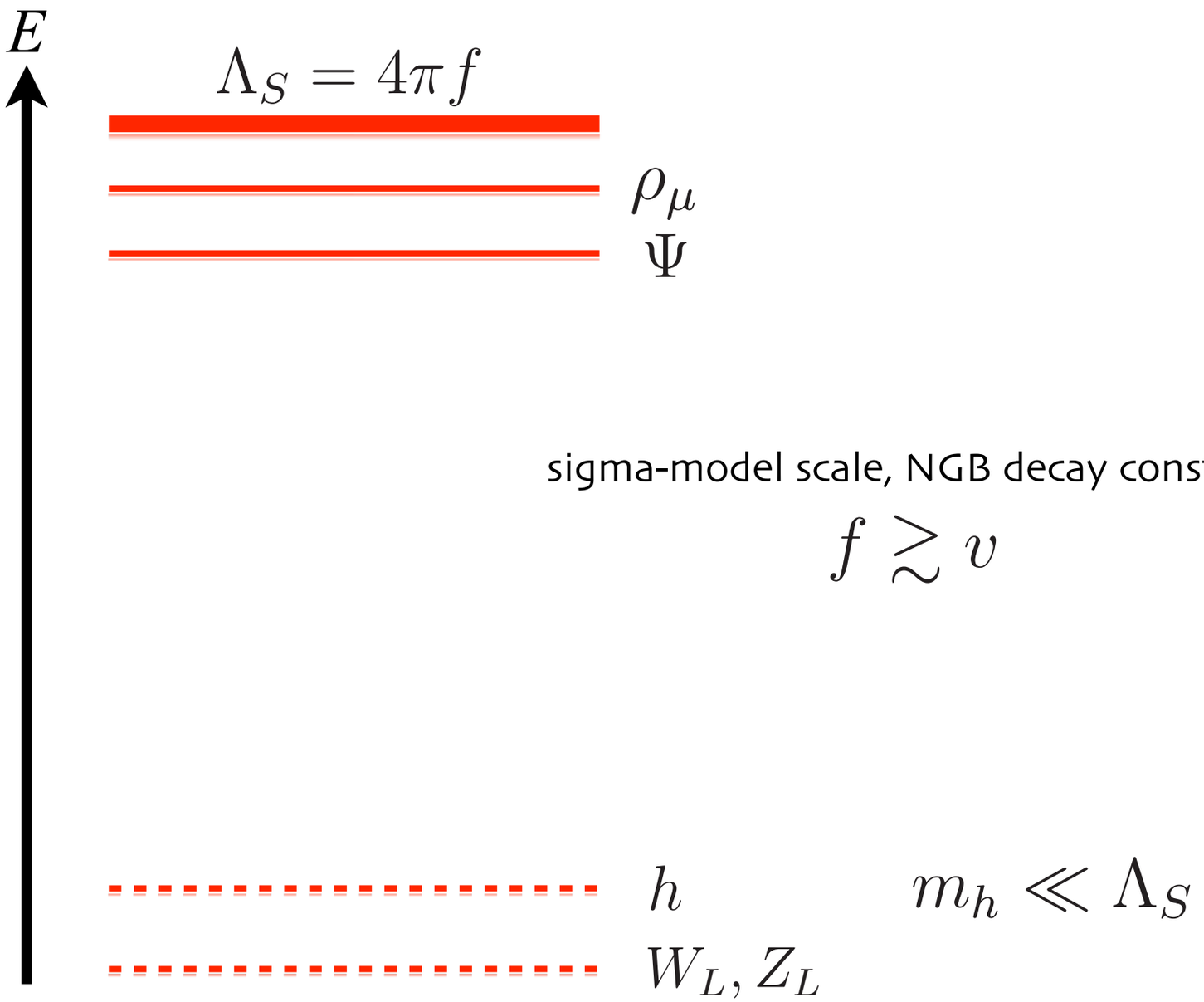
The composite-pNGB Higgs

Weinberg, Susskind '79



The composite-pNGB Higgs

Georgi, Kaplan '84



sigma-model scale, NGB decay constant

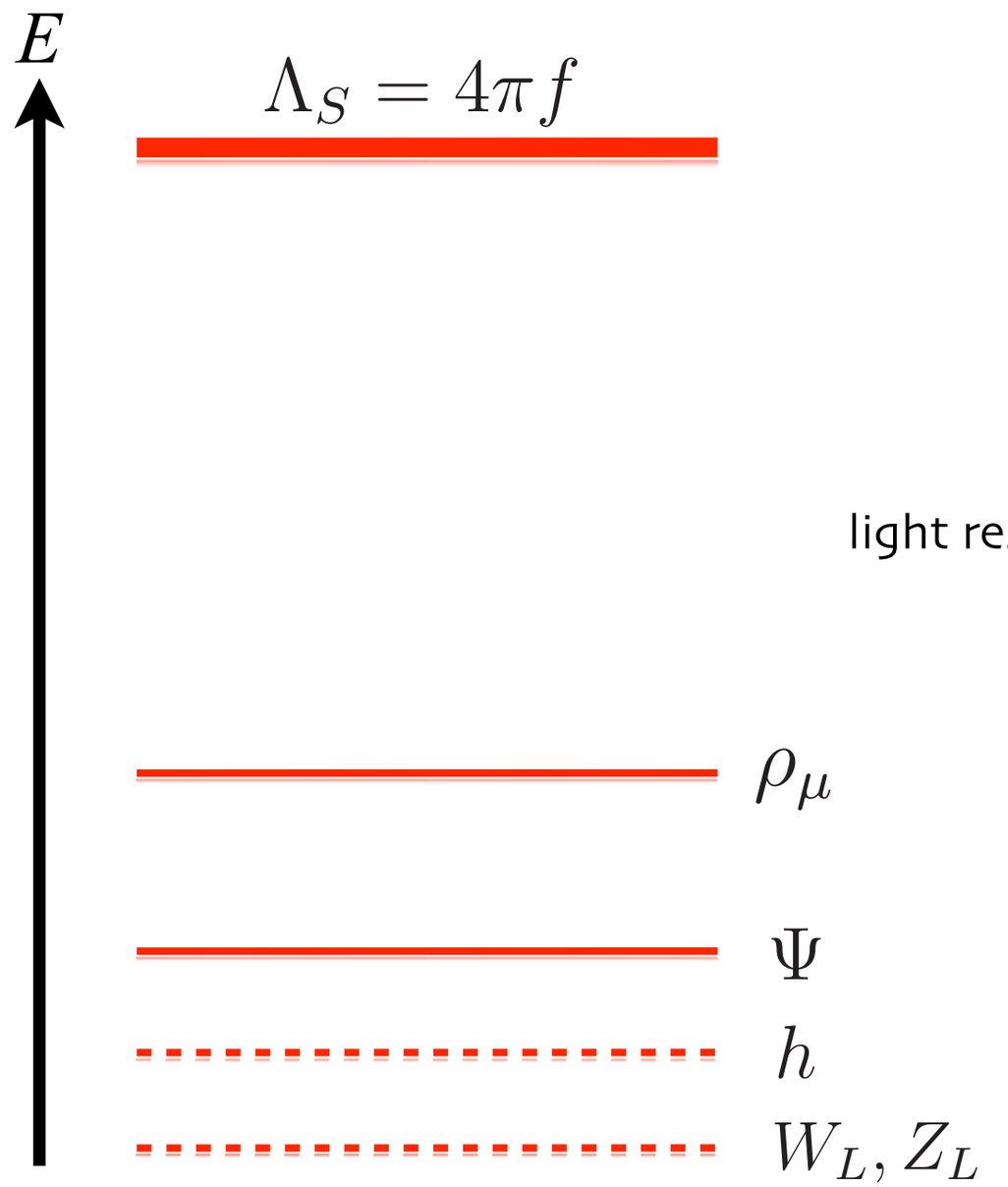
$$f \gtrsim v$$

The Higgs should be a (pseudo-)Goldstone boson of the strong dynamics

The composite-pNGB Higgs

Arkani-Hamed, Cohen, Katz, Nelson '02

Contino, Nomura, Pomarol '04



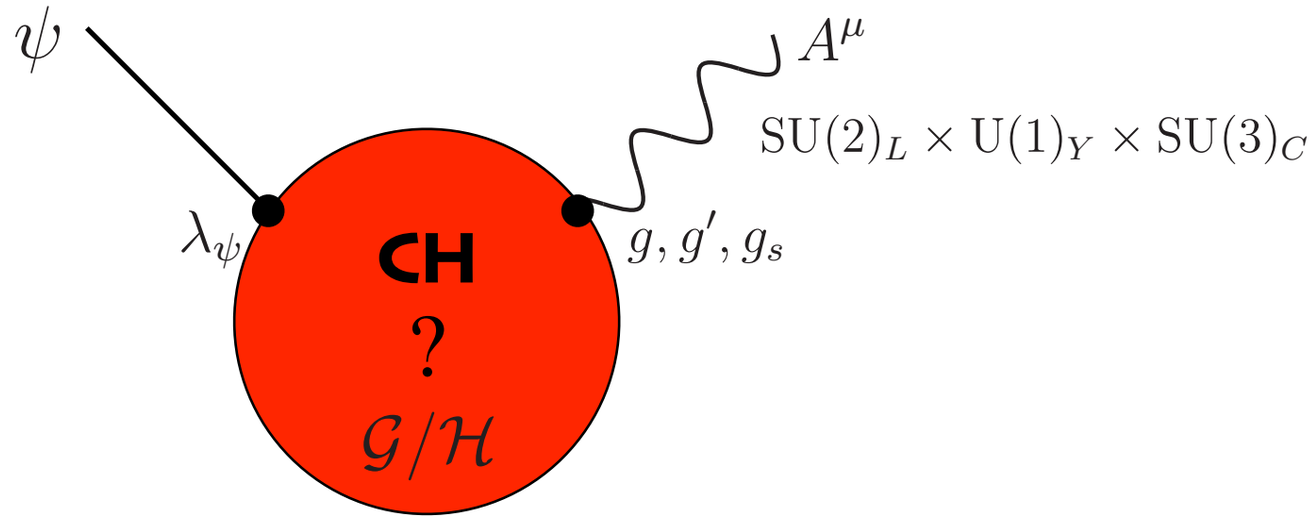
$$f \gtrsim v$$

light resonances masses and couplings

$$m_{*=\Psi,\rho,\sigma} < \Lambda_S$$

Some (fermionic and vector) resonances should be light & weakly coupled

Generic features



$$U = e^{ih_{\hat{a}}T^{\hat{a}}}$$

Spontaneous Symmetry Breaking

$\mathcal{G} \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ weakly gauged

$\mathcal{H} \supset \mathrm{SO}(4) \cong \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ custodial

$\mathcal{G}/\mathcal{H} \supset \mathbf{4} = (\mathbf{2},\mathbf{2})$ Higgs

Operators

$\mathcal{J}_\mu \longrightarrow \rho_\mu$

$\mathcal{O}_\psi \longrightarrow \Psi$

?

Explicit Symmetry Breaking

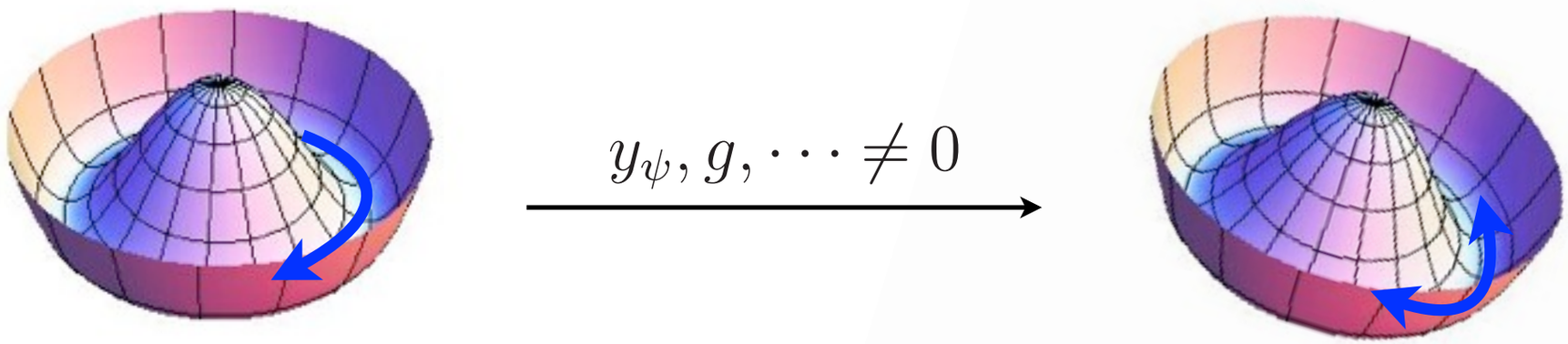
$$\mathcal{L} \supset g A^\mu \mathcal{J}_\mu$$

$$\mathcal{L} \supset \lambda_\psi \bar{\psi} \mathcal{O}_\psi \qquad \left(\mathcal{L} \supset y_\psi \bar{\psi}_L \psi_R \mathcal{O}_H\right)$$

?

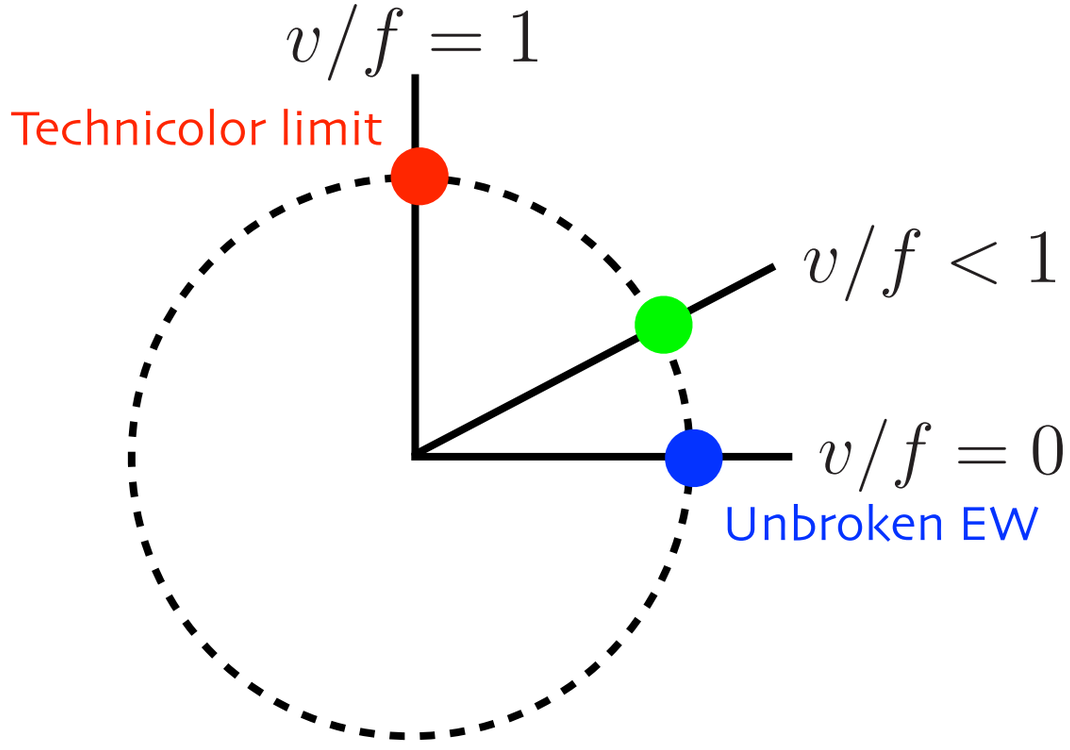
Generic features

$V(H) = 0$ $\qquad$ $V(H) \neq 0$



$$\langle H \rangle = \frac{v}{\sqrt{2}}$$

Misalignment of the electroweak vacuum



v << f allows to comply with EW precision tests & Higgs couplings

Potentials

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

$$\mu^2_{exp} \approx (90\,\mathrm{GeV})^2 \quad \& \quad \lambda_{exp} \approx 0.13$$

Does a composite Higgs reproduce this?

$$\Delta V(h) = \frac{g^2_{SM} g^2_* f^2}{16\pi^2}\left(-ah^2 + b\frac{h^4}{2f^2}\right)$$

Explicit Symmetry Breaking

$$g_{SM} = \lambda_L, \lambda_R, g, \cdots$$

?

L and R top couplings

$$y_t \sim \frac{\lambda_L \lambda_R}{g_\Psi}$$

gauge couplings

leptons, DM,
constituent masses,...

SM-partners masses

$$m_* \sim g_* f$$

Model-dependent coefficients

LO: $a, b \sim 1$

NLO: $a, b \sim \frac{g^2_{SM}}{g^2_*}$ $a, b \sim \frac{g^2_*}{16\pi^2}$

Potentials

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i) **The Higgs mass parameter is tuned**:

$$\Delta_{\mu^2} = \frac{\delta\mu^2}{\mu^2_{exp}} \sim \frac{a g^2_{SM} m^2_*}{(800\,\mathrm{GeV})^2} \sim (10\%)^{-1}\left(\frac{a}{1}\right)\left(\frac{g^2_{SM}}{N_c y_t^2}\right)\left(\frac{m_*}{800\,\mathrm{GeV}}\right)^2$$

ii) **The Higgs quartic is 1-loop size**:

$$\Delta_\lambda = \frac{\delta\lambda}{\lambda_{exp}} \sim \frac{b g^2_{SM} g^2_*}{3^2} \sim 1\left(\frac{b}{1}\right)\left(\frac{g^2_{SM}}{N_c y_t^2}\right)\left(\frac{g_*}{2}\right)^2$$

Models

'Holographic': $a, b \sim 1 \qquad g_* = g_\Psi, g_\rho \ll 4\pi$

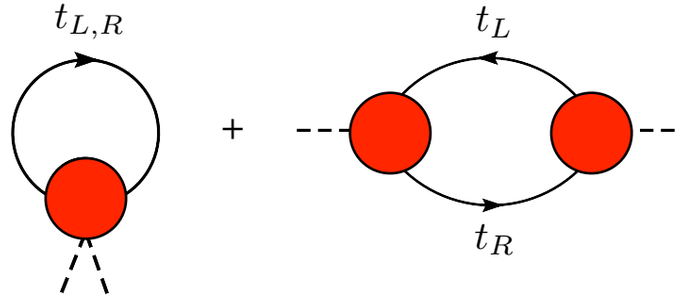
$$\Delta = \Delta_{\mu^2} \times \Delta_\lambda \sim (5\%)^{-1} \left(\frac{f}{1\,\mathrm{TeV}}\right)^2 \left(\frac{g_*}{2}\right)^4$$

$g^2_{SM} \sim N_c y_t^2$

Different realizations depending on quantum numbers of top under G, e.g. $\mathrm{SO}(5)/\mathrm{SO}(4)$

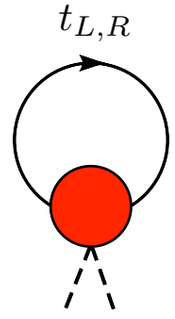
- V(h) at $O(\lambda^2_{L,R}, \lambda^4_{L,R})$ $\qquad q_L \in \mathbf{5}\,, t_R \in \mathbf{5}$

  MCHM5



$$\mu^2 \sim \frac{2N_c\lambda^2_{L,R}m^2_\Psi}{16\pi^2} \quad \& \quad \lambda \sim \frac{2N_c\lambda^4_{L,R}}{16\pi^2} \longrightarrow \lambda_L \sim \lambda_R \sim \sqrt{g_\Psi y_t} \qquad \Delta \sim (1\%)^{-1}\left(\frac{f}{1\,\mathrm{TeV}}\right)^2\left(\frac{g_\Psi}{2}\right)^5$$

- V(h) at $O(\lambda^2_{L,R})$ $\qquad q_L \in \mathbf{14}\,, t_R \in \mathbf{14}$



Tuning as expected (above)

$\lambda_L \sim \lambda_R \sim \sqrt{g_\Psi y_t}$

Models

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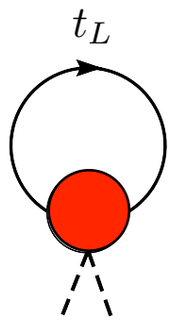
$$\Delta = \Delta_{\mu^2} \times \Delta_\lambda \sim (5\%)^{-1} \left(\frac{f}{1\,\mathrm{TeV}}\right)^2 \left(\frac{g_*}{2}\right)^4 \qquad g_{SM}^2 \sim N_c y_t^2$$

Different realizations depending on quantum numbers of top under G, e.g. $\mathrm{SO}(5)/\mathrm{SO}(4)$

- V(h) at $O(\lambda_{L,R}^2)$ $\quad q_L \in \mathbf{5}\,, t_R \in \mathbf{1}$



top R fully composite

$\lambda_L \sim y_t$

$\mu^2 \sim \frac{2N_c y_t^2 m_\Psi^2}{16\pi^2}$ & $\lambda \sim \frac{2N_c y_t^4}{16\pi^2}$ $\longrightarrow$ Extra source of quartic needed

Leptons, DM, ?

Models

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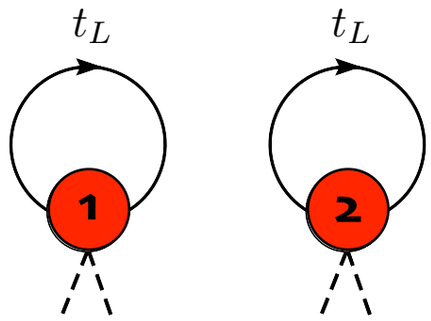

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Similar to Little Higgs (next)

However, light resonances are more difficult to obtain in explicit models (extra-d)

Models

'Little': $a \sim 1\,, b \sim 16\pi^2/g_*^2 \qquad g_* = g_\Psi, g_\rho \ll 4\pi$

$$\Delta = \Delta_{\mu^2} \times \Delta_\lambda \sim (5\%)^{-1} \left(\frac{f}{1\,\mathrm{TeV}}\right)^2 \left(\frac{g_*}{2}\right)^2$$

Same tuning as in 'holographic', different scaling with g_*

Trick: Free (collective) quartic without mass term from Higgs partners = extra NGBs

$$V(h,\phi) = \lambda_1 f \left|\phi + \frac{h^2}{f} + \cdots\right|^2 + \lambda_2 f \left|\phi - \frac{h^2}{f} + \cdots\right|^2 \longrightarrow \lambda = \frac{\lambda_1 \lambda_2}{\lambda_1 + \lambda_2}$$

$\phi = \mathbf{3}, \mathbf{1}_A, \mathbf{3}_S \quad \mathrm{SU}(2)_L$

Schmaltz, Thaler '08

Models

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Schmaltz, Thaler '08

SUMMARY

Most natural EWSB requires light and weakly coupled SM partners (& maybe extra NGBs)

Top-partners

(i) Fixed quantum numbers under unbroken group H = SO(4).

(ii) Representations related to top Yukawa, to cut-off Higgs potential.

SO(4) SU(2)$_L$ x SU(2)$_R$ U(1)$_X$

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

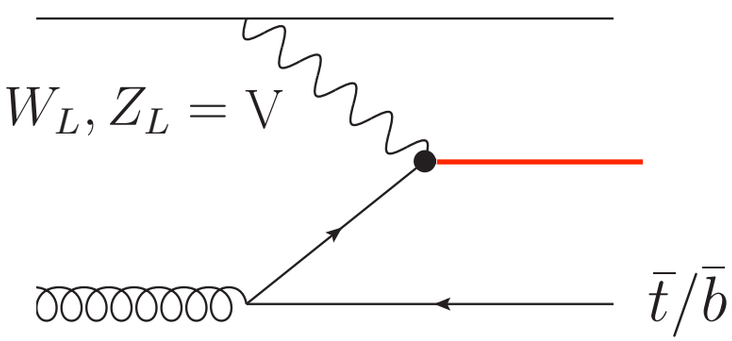
$$\mathbf{4}_{2/3} = (\mathbf{2},\mathbf{2})_{2/3} \to q = 5/3, \cdots$$

$$\mathbf{6}_{2/3} = (\mathbf{3},\mathbf{1})_{2/3} + (\mathbf{1},\mathbf{3})_{2/3}$$

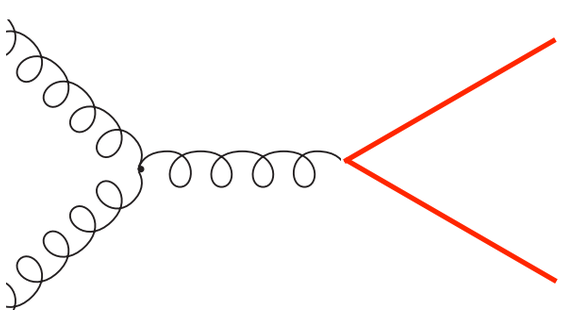
$$\mathbf{9}_{2/3} = (\mathbf{3},\mathbf{3})_{2/3} \to q = 8/3, \cdots$$

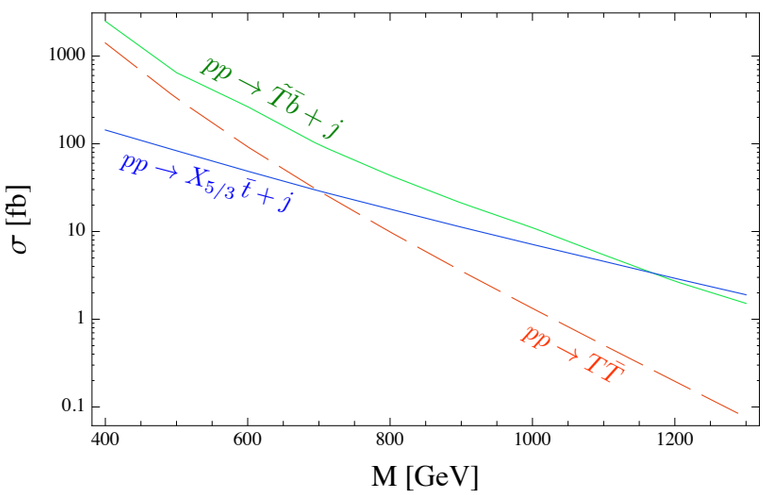
Production

single



pair





De Simone, Matsedonskyi, Rattazzi, Wulzer '13

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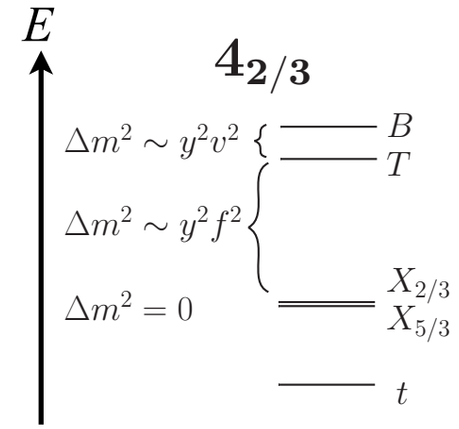
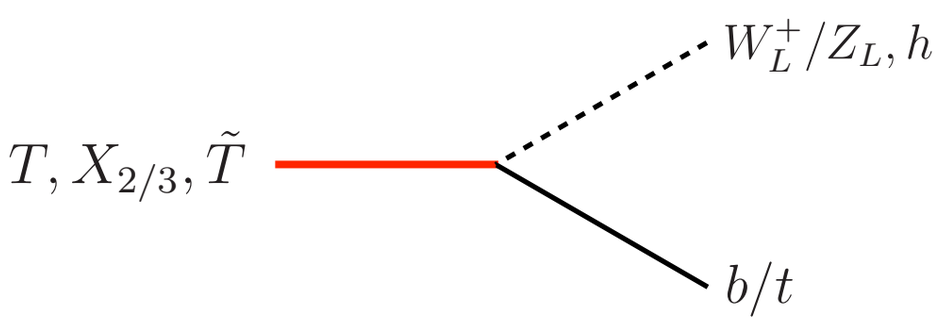
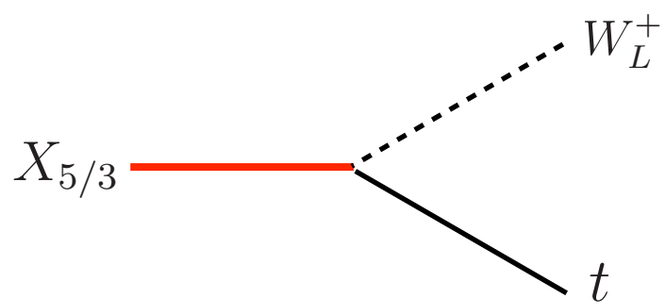


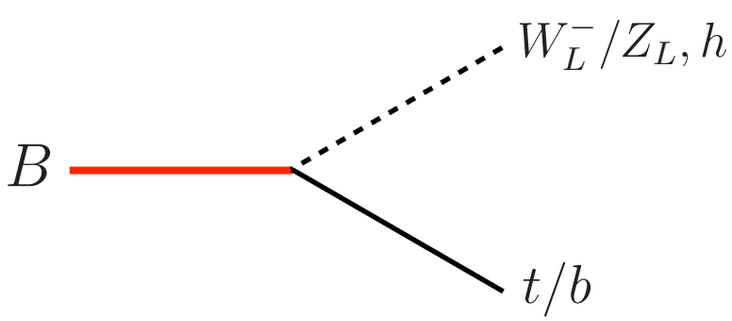
Decay

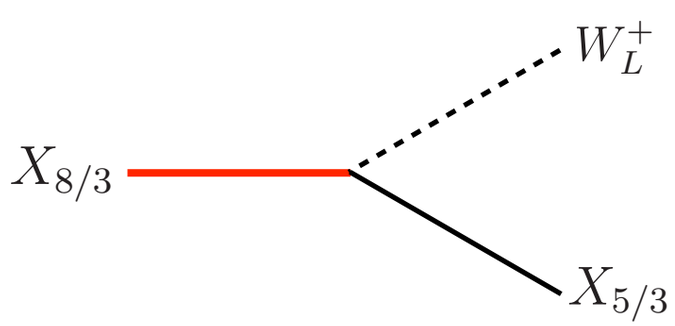
dominated by top/bottom and Higgs





T H t connection

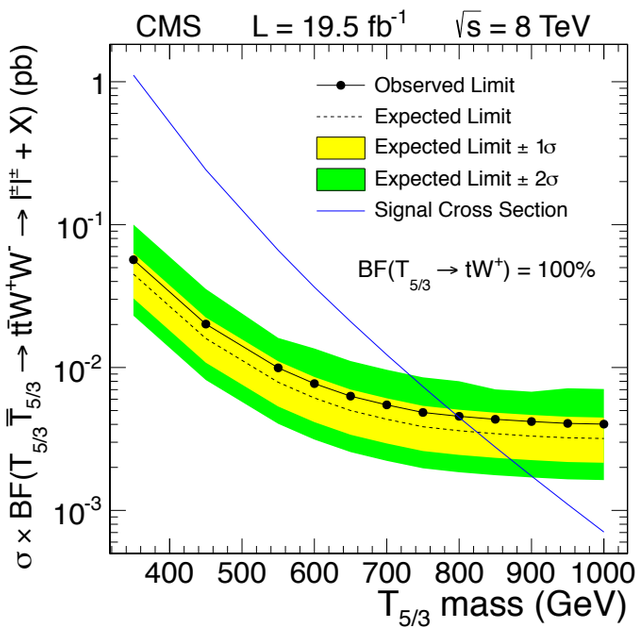


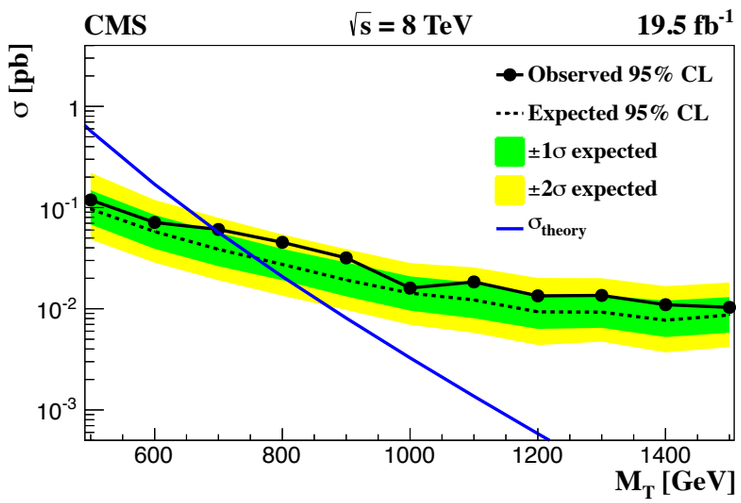


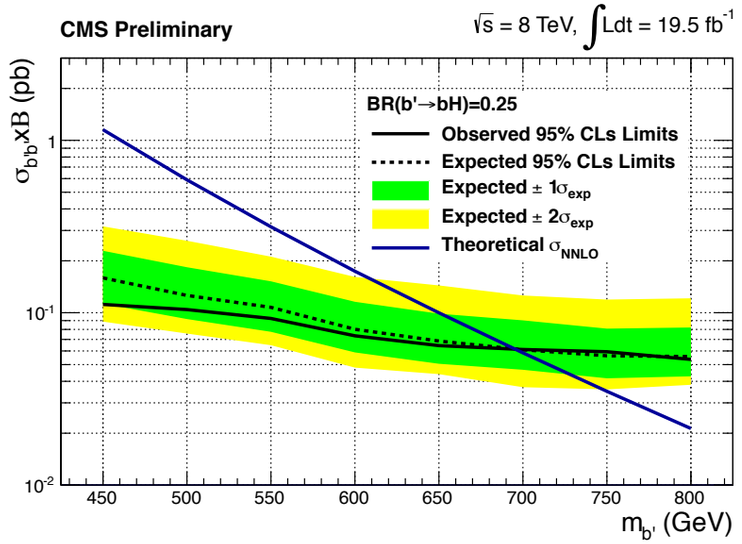
Top-partners

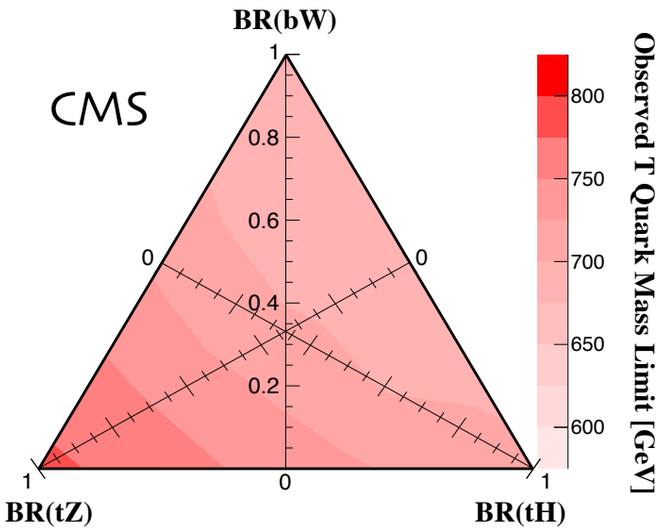
Searches

(pair production)



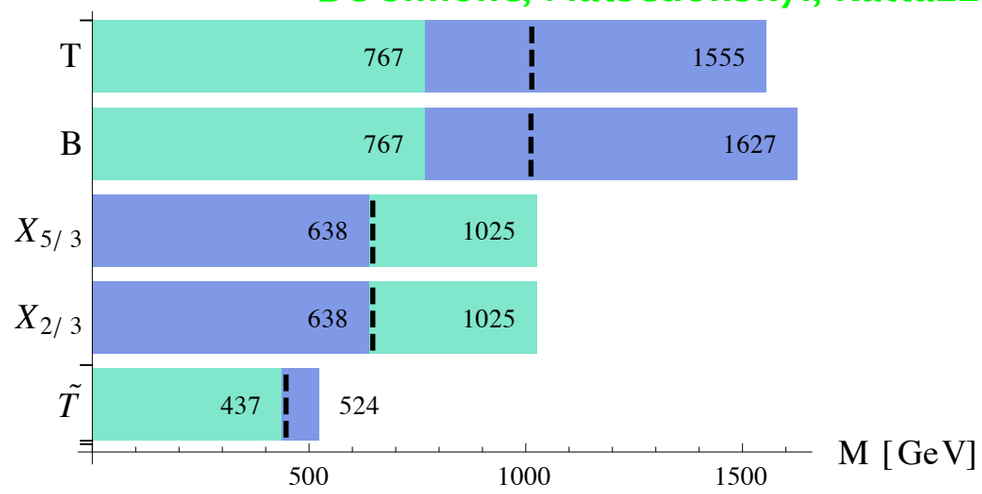






theoretical analysis combination

De Simone, Matsedonskyi, Rattazzi, Wulzer '13



bounds reaching 1 TeV = fine-tuning increasing

Non-standard phenomenology?

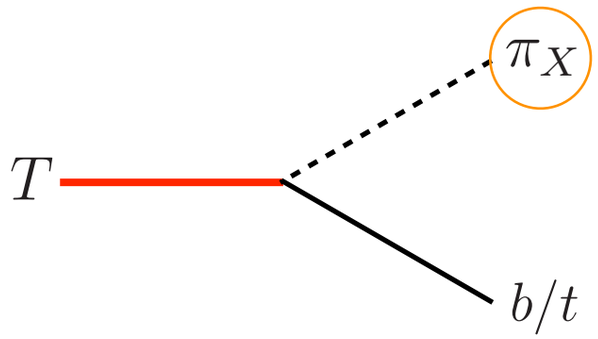
PRELIMINARY

Extra NGB's

If top-partners are colored: QCD pair production

Could there be any other decays?

Only likely extra light states = NGB's



$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_\mathcal{H} = \mathbf{r}_{\mathrm{SU}(2)\times\mathrm{SU}(2)}\,(\mathbf{r}_{\mathrm{SU}(2)\times\mathrm{U}(1)})$
$\mathrm{SO}(5)$	$\mathrm{SO}(4)$	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
$\mathrm{SU}(3)\times\mathrm{U}(1)$	$\mathrm{SU}(2)\times\mathrm{U}(1)$		5	$\mathbf{2}_{\pm\mathbf{1/2}} + \mathbf{1_0}$
$\mathrm{SU}(4)$	$\mathrm{Sp}(4)$	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SU}(4)$	$[\mathrm{SU}(2)]^2\times\mathrm{U}(1)$	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm\mathbf{2}} = 2\cdot(\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	$\mathrm{SO}(6)$	✓	6	$\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	$\mathrm{SO}(5)\times\mathrm{U}(1)$	✓*	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	$[\mathrm{SU}(2)]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$
$\mathrm{Sp}(6)$	$\mathrm{Sp}(4)\times\mathrm{SU}(2)$	✓	8	$(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$
$\mathrm{SU}(5)$	$\mathrm{SU}(4)\times\mathrm{U}(1)$	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\cdot(\mathbf{2},\mathbf{2})$
$\mathrm{SU}(5)$	$\mathrm{SO}(5)$	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$
$\mathrm{SO}(8)$	$\mathrm{SO}(7)$	✓	7	$\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(9)$	$\mathrm{SO}(8)$	✓	8	$\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$
$\mathrm{SO}(9)$	$\mathrm{SO}(5)\times\mathrm{SO}(4)$	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$
$[\mathrm{SU}(3)]^2$	$\mathrm{SU}(3)$		8	$\mathbf{8} = \mathbf{1_0} + \mathbf{2}_{\pm\mathbf{1/2}} + \mathbf{3_0}$
$[\mathrm{SO}(5)]^2$	$\mathrm{SO}(5)$	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SU}(4)\times\mathrm{U}(1)$	$\mathrm{SU}(3)\times\mathrm{U}(1)$		7	$\mathbf{3}_{-\mathbf{1/3}} + \bar{\mathbf{3}}_{+\mathbf{1/3}} + \mathbf{1_0} = 3\cdot\mathbf{1_0} + \mathbf{2}_{\pm\mathbf{1/2}}$
$\mathrm{SU}(6)$	$\mathrm{Sp}(6)$	✓*	14	$\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$
$[\mathrm{SO}(6)]^2$	$\mathrm{SO}(6)$	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$

Bellazzini, Csaki, JS '14

simplest non-minimal model

The Next to Minimal Composite Higgs Model

SO(6)/SO(5) = SU(4)/Sp(4)

SO(5) SU(2)$_L$ x SU(2)$_R$

NGB's: $\mathbf{5} = (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

H η

$$U = e^{i\pi^i T^i} = \begin{pmatrix} \mathbf{1}_{3\times 3} & 0 & 0 & 0 \\ 0 & 1-\frac{h^2}{1+\sqrt{1-h^2-\eta^2}} & -\frac{h\eta}{1+\sqrt{1-h^2-\eta^2}} & h \\ 0 & -\frac{h\eta}{1+\sqrt{1-h^2-\eta^2}} & 1-\frac{\eta^2}{1+\sqrt{1-h^2-\eta^2}} & \eta \\ 0 & -h & -\eta & \sqrt{1-h^2-\eta^2} \end{pmatrix}$$

d and e symbols: $-iU^\dagger D_\mu U = d_\mu^i T^i + e_\mu^a T^a$

kinetic term: $$\frac{f^2}{4} d_\mu^i d_i^\mu = \frac{f^2}{2}(D_\mu h)^2 + \frac{f^2}{2}(\partial_\mu \eta)^2 + \frac{f^2}{2}\frac{(hD_\mu h + \eta\partial_\mu\eta)^2}{1-h^2-\eta^2}$$

singlet mass

Assumption about explicit breaking: $t_R = \mathbf{1}$ $q_L = (t_L, b_L) \in Q_L = \mathbf{6}$ SO(6)

$$Q_L = \frac{1}{\sqrt{2}} \begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ 0 \\ 0 \end{pmatrix}$$

$$-y_t f \left[\bar{Q}_L U\right]_6 t_R = y_t f \bar{t}_L h t_R$$

U(1)-eta unbroken!

no mass/decay from top for singlet

singlet mass

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U(1)-eta unbroken!

no mass/decay from top for singlet

$\tau_R = \mathbf{6}$ $\ell_L = (\nu_{\tau L}, \tau_L) \in L_L = \mathbf{6}$ SO(6)

$$L_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i\alpha \\ \beta \end{pmatrix} \tau_R$$

$$-y_\tau f \left[\bar{L}_L U\right]_6 \left[U^\dagger \bar{L}_R\right]_6 = y_\tau f \bar{\tau}_L h \tau_R \left(\beta\sqrt{1-h^2-\eta^2} + i\alpha\eta\right)$$

$$m_\eta^2 \sim \frac{m_\tau M_\tau^3}{16\pi^2 v f} \simeq (50\,\mathrm{GeV})^2 \left(\frac{M_\tau}{4\,\mathrm{TeV}}\right)^3 \left(\frac{1\,\mathrm{TeV}}{f}\right)$$

singlet mass

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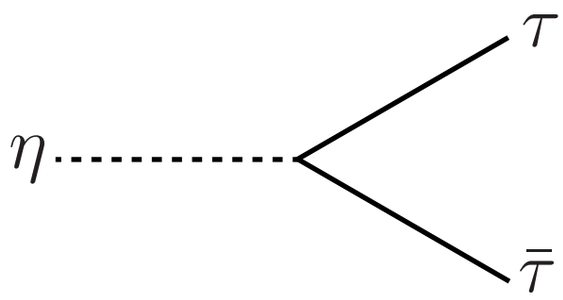
Even if top contributes to eta mass: $m_\eta \sim \frac{N_c y_t M_T}{4\pi} < M_T$

Kinematics allows top-partners to decay to singlet (plus tops)

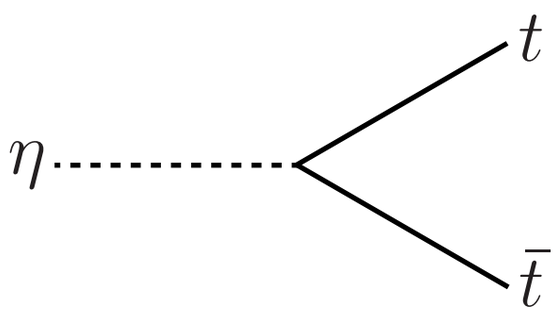
not an accident, symmetries

singlet decays

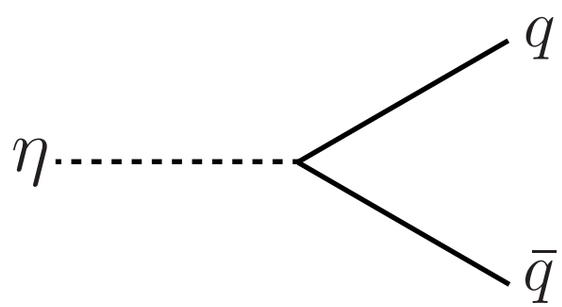
If light as before:



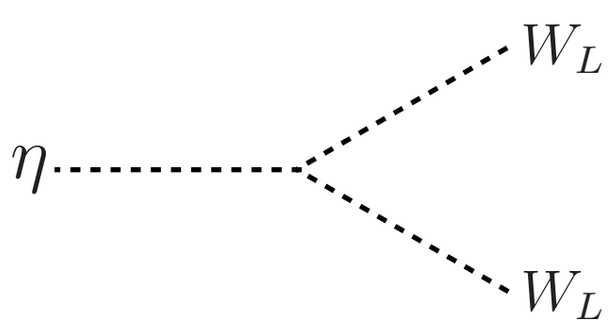
If heavy from tops:



Also possible:

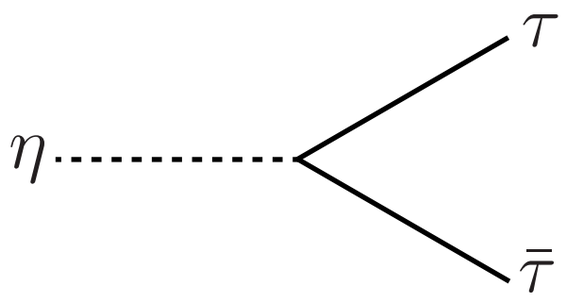


Not possible*:

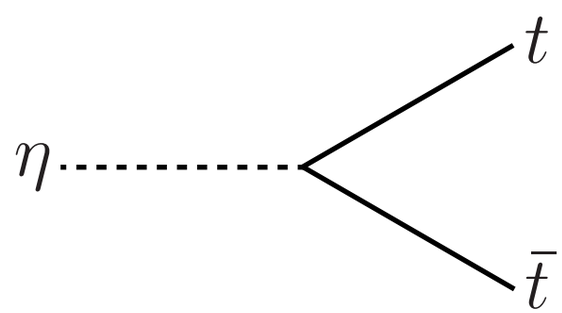


singlet decays

If light as before:



If heavy from tops:



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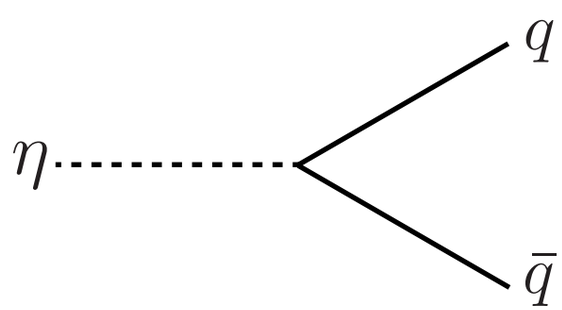

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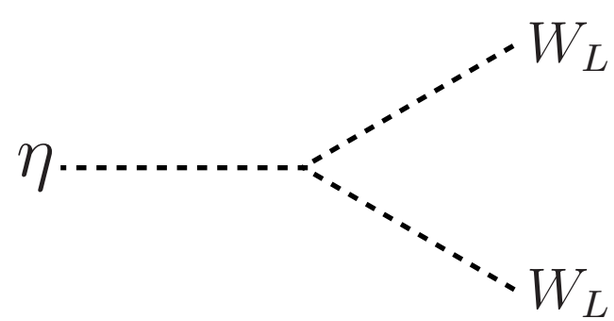

Model dependent
keep an open mind

Summary

A pseudo-Goldstone boson Higgs is a viable candidate for the EW scale

and...

It requires light & weakly coupled top-partners

but...

It is tuned at < 10% due to experimental bounds:

top-partner searches

so...

we should make sure we do not miss e.g. important decays

Thank you for your attention