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School on Strongly Coupled Physics Beyond the Standard Model

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Little Higgs Models - Lecture 2

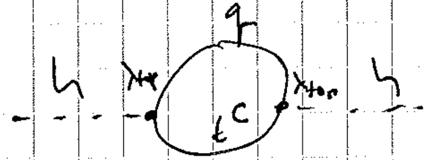
J. Thaler
MIT
U.S.A.

Lecture 2: Collective Yukawas & Gauge Couplings

Little Higgs $\Longrightarrow$ Composite Higgs Model w/ collective quartic

$v_{EW} \ll f_\pi$

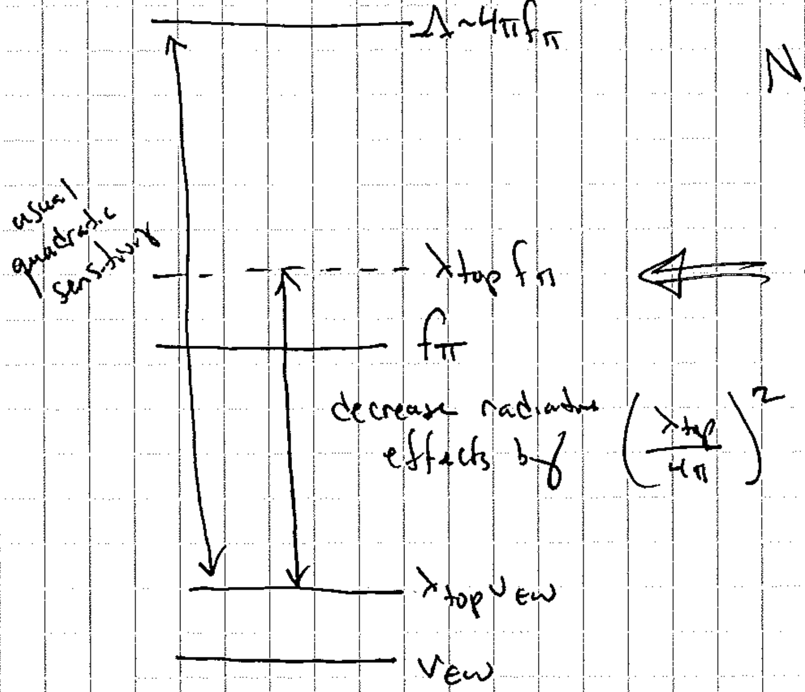
Generic Radiative Corrections ($\Lambda \sim 4\pi f_\pi$)



$$\Rightarrow \quad V \sim \lambda_{top}^2 f^4 \sin^2\left(\frac{h}{f_\pi}\right)$$

Destroys collective quartic structure!

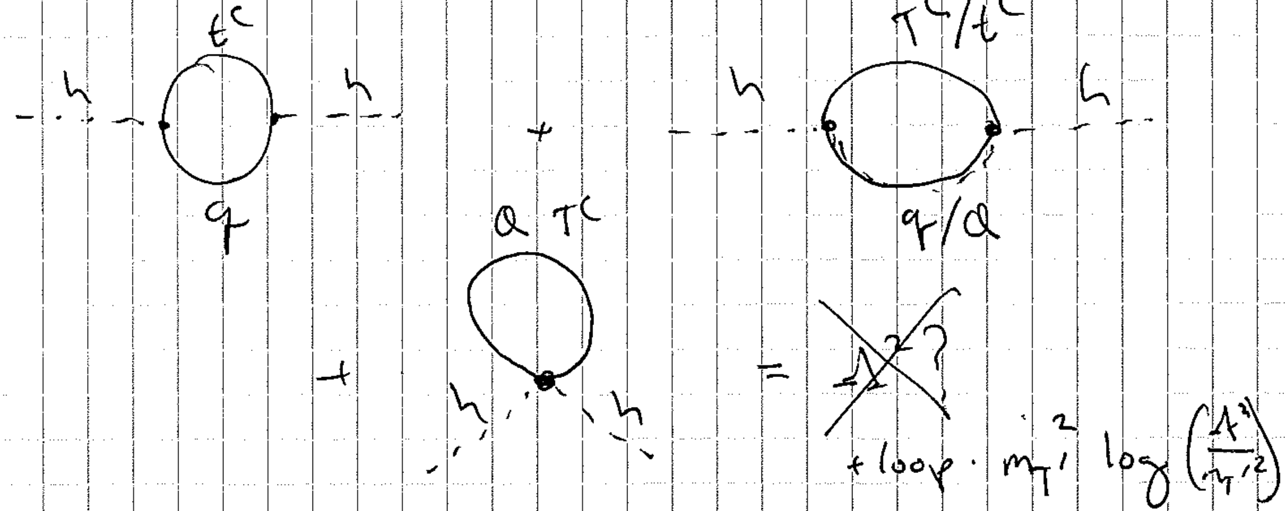
Need reason for radiative corrections to be small.



$\Longleftarrow$ top Partners!

(and same with gauge interactions)

Partner particles



Require special relationship between masses & couplings...

Seems difficult! Actually trivial-ish.

Toy Model from yesterday

NLΣM :
$SO(6) \times SO(6) / SO(6)$

$$\Sigma = e^{\frac{i}{f}\left(\begin{array}{c|c|c} Q\ \ b_{extra} & h_1 & h_2 \\ \hline & Q & \bar{q} \\ \hline & & \bar{Q} \end{array}\right)}$$

(Perhaps more familiar (no custodial $SU(2)_c$)

NLΣM
$SU(4) \times SU(4) / SU(4)$

$$\Sigma = \exp\left[\frac{i}{f}\left(\begin{array}{c|c|c} & h_1 & h_2 \\ \hline h_1^\dagger & & \phi \\ h_2^\dagger & & \end{array}\right)\right]$$

complex singlet)

Want to augment

$$\lambda_{top}\, q\, h\, t^c$$

such that approximate shift symmetry persists

Easiest method for fermions;

Assume all couplings to Σ are <u>fully</u> symmetric, then add soft breaking!

Back to the moose:

$$Q = \begin{pmatrix} Q_a \\ Q_b \\ Q_5 \leftrightarrow U_5' \\ Q_6 \end{pmatrix} \qquad \underset{SO(6)_L}{\bigcirc} \cdots\cdots \Sigma \cdots\cdots \underset{SO(6)_R}{\bigcirc} \qquad U^c = \begin{pmatrix} U_a^c \leftrightarrow Q_a' \\ U_b^c \\ U_5^c \\ U_6^c \end{pmatrix}$$

Everyone gets mass from $\langle\Sigma\rangle = \mathbb{1}$. Add back in "prime" fields for SM states.

$$\mathcal{L} = \lambda_1 f\, Q_i \Sigma_{ij} U_j^c + \lambda_2 f\, Q_a' U_a^c + \lambda_3 f\, Q_5 U_5'^c$$

full 6 of SO(6) — break $SO(6)_R$ — break $SO(6)_L$

Need <u>all</u> of λ_1 λ_2 λ_3 to break $h \to h + \epsilon$ shift symmetry!

SM Couplings after diagonalization

q_{SM} = linear combination of Q_a / Q_a'

t^c_{SM} = linear combination of $U_5^c / U_5'^c$

$\lambda_{eff}\, q_{SM} h_1 t^c_{SM}$ $\qquad \lambda_{eff} = \dfrac{\lambda_1 \lambda_2 \lambda_3}{\sqrt{\lambda_1^2 + \lambda_2^2}\sqrt{\lambda_1^2 + \lambda_3^2}}$

Automatically get top partners!

T_a	$(3, 2, 1/6)$	$m_a = \sqrt{\lambda_1^2 + \lambda_2^2}\, f$
T_b	$(3, 2, 7/6)$	$m_b = \lambda_1 f$
T_5	$(3, 1, 2/3)$	$m_5 = \sqrt{\lambda_1^2 + \lambda_3^2}\, f$
T_6	$(3, 1, 2/3)$	$m_6 = \lambda_1 f$

Radiative Higgs mass is finite @ 1-loop!

$$\Delta m^2 = -\frac{3}{8\pi^2} \lambda_{eff}^2 \frac{m_a^2 m_5^2}{m_a^2 - m_5^2} \log\left(\frac{m_a^2}{m_5^2}\right)$$

(Log divergences @ 2 loop)

Bottom Line for Yukawas

G/H Σ model

Couple Fermions to Σ in complete multiplets of G, then add soft breakings to generate SM Yukawa couplings

Key Assumption: Breaking of G is really soft. G is a good symmetry and only breaking appears as small mass terms.

(Some claims in literature of hidden fine tuning. Equivalent to saying G is not even a good symmetry.)

Ok, Fermions are boring. Much more fun with gauge groups.

Collective Gauge Couplings.

Today: One example for how it works.

Tomorrow: General techniques for gauge partners.

Same principle of collective symmetry breaking. Introduce gauge couplings in such a way that no single gauge coupling breaks all of the shift symmetries acting on H.

Easiest example: Two site models

Global: $SO(6)_L$ Σ $SO(6)_R$

$\Sigma \to L \Sigma R^{\dagger}$

$[SU(2)\times U(1)]_L$ $[SU(2)\times U(1)]_R$

L or R alone is enough to forbid Higgs potential!

g_L alone preserves $SO(6)_R$

g_R alone preserves $SO(6)_L$

Because $\langle \Sigma \rangle = \mathbb{1}$, only low energy gauge group is $[SU(2)\times U(1)]$ ✓

In equations:

$$\mathcal{L} = \frac{f^2}{4} \operatorname{tr} \left| D_\mu \Sigma \right|^2$$

$$D_\mu \Sigma = \partial_\mu \Sigma + i g_L L_\mu \Sigma - i g_R \Sigma R_\mu$$

$\langle \Sigma \rangle = 1 \Rightarrow$ One linear combination of L and R is massless

$$\frac{1}{g_{SM}^2} = \frac{1}{g_L^2} + \frac{1}{g_R^2}$$

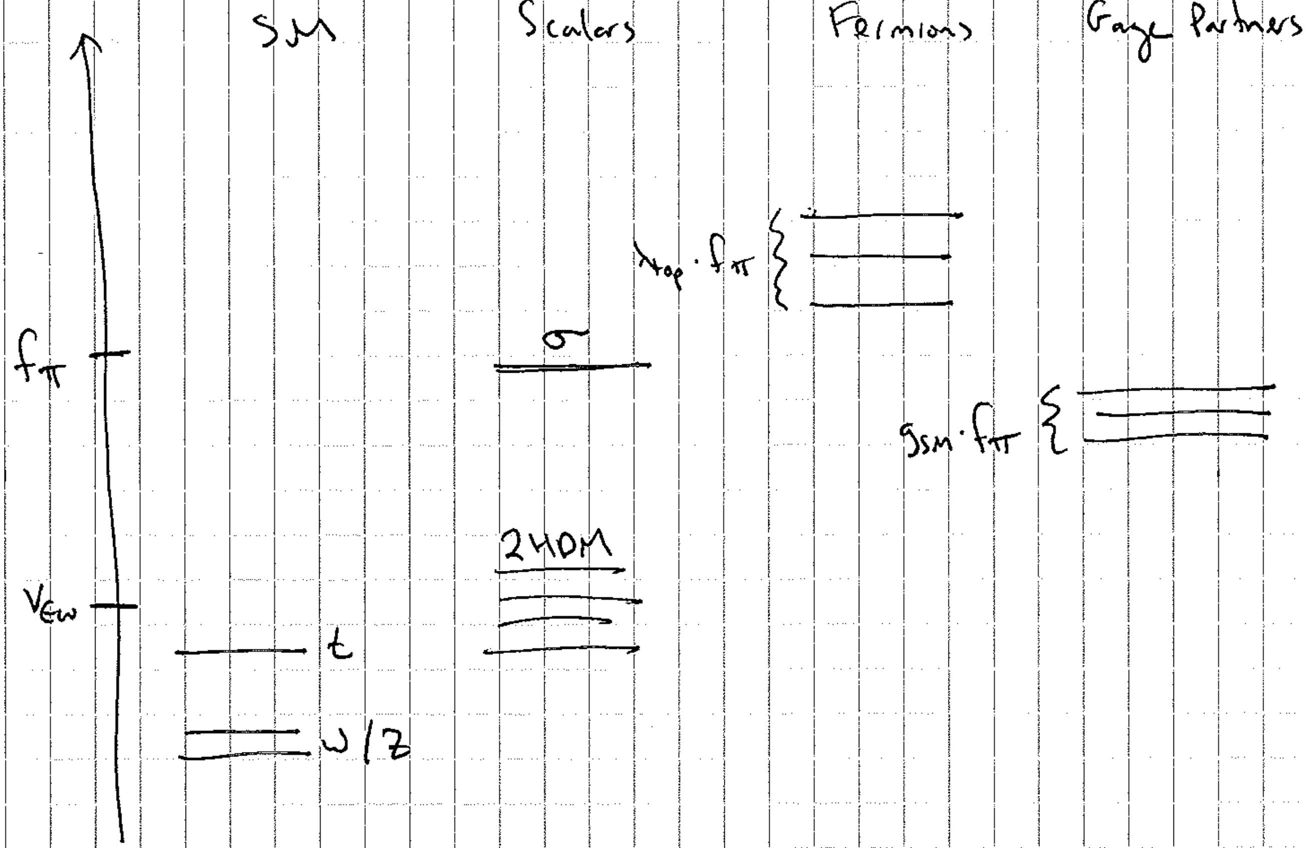
$\Rightarrow$ One linear combination is massive gauge partner

$$m_{W'}^2 = \frac{1}{4}\left(g_L^2 + g_R^2\right) f^2$$

Radiative correction to Higgs mass

$$\Delta m^2 = \frac{9}{512} \underbrace{\frac{g_L^2 g_R^2}{g_L^2 + g_R^2}}_{g_{SM}^2} \underbrace{(g_L^2 + g_R^2) f^2}_{m_{W'}^2} \underbrace{\log\left(\frac{\Lambda^2}{m_{W'}^2}\right)}_{\text{log enhancement}}$$

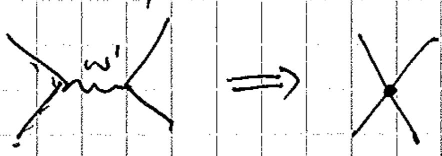
Generic LH Spectrum



A little tension!

$m_{t'}$ $\downarrow$ to minimize correction to Higgs potential

$m_{W'}$ $\uparrow$ to ~~minimize~~ satisfy bounds from LEP, Tevatron and LHC

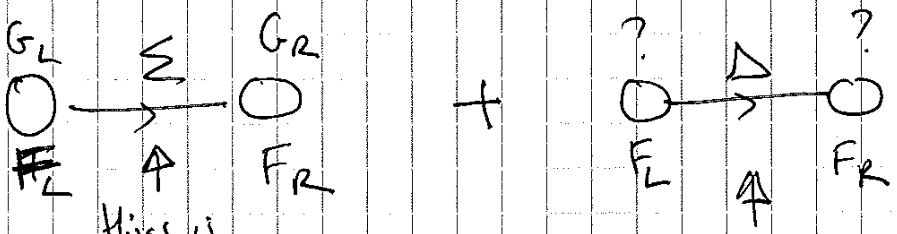


and resonance search

but $\lambda_{top} > g_{SM}$.

$\Rightarrow m_{t'} \gtrsim m_{W'}$

No reason not to have separate dynamics break symmetries!



Higgs is here

Decay constant f_{Higgs}

(extra uneaten goldstones!)

Some other symmetry breaking dynamics

Decay constant: f_{other}

$$m_{t'} \simeq \lambda_{top} f_{Higgs} < m_{W'} \simeq g_{SM} f_{other}$$

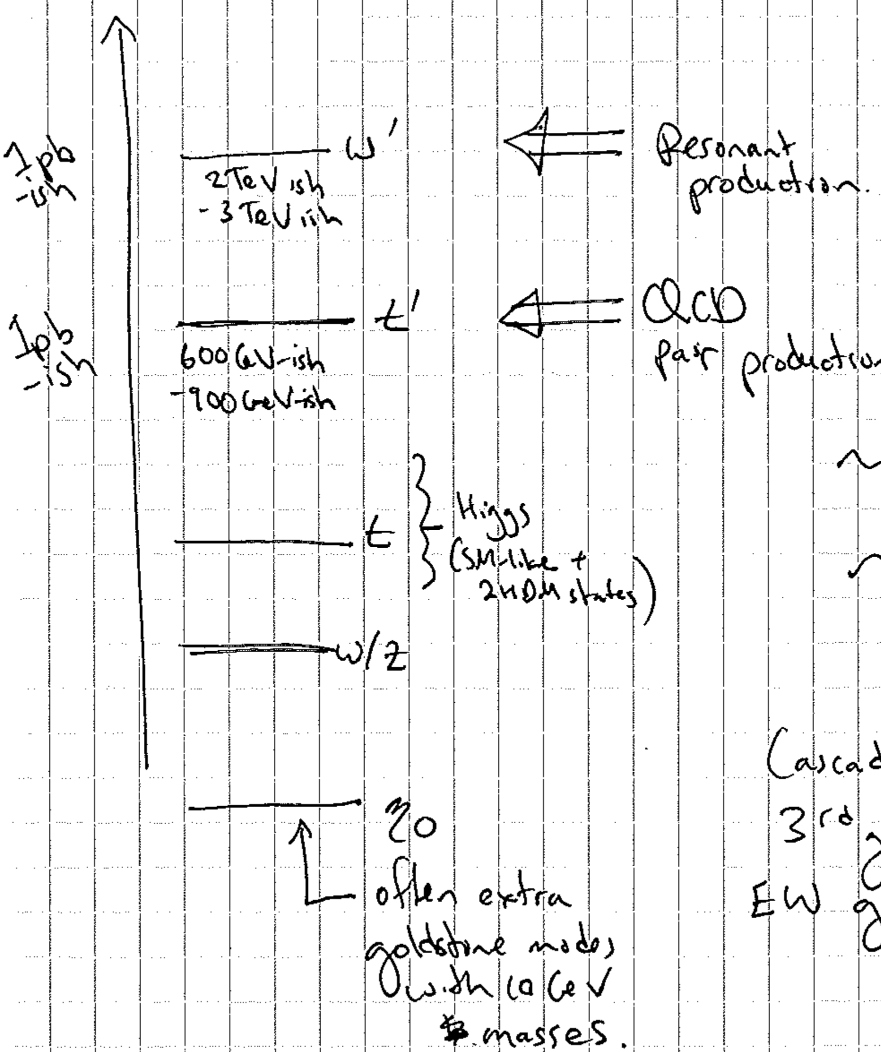
Reduces all* tension on LH models without imposing $\mathbb{Z}_2$-symmetry (i.e. T-parity)

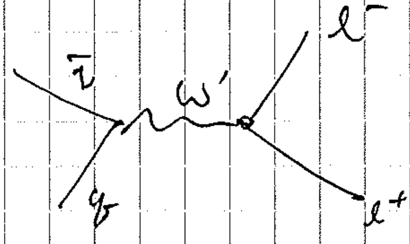
That's all for specific model building

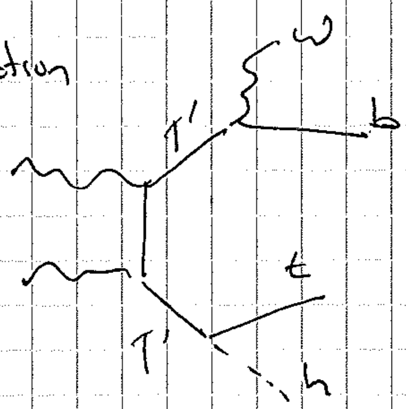
Next time, ~~gauge~~ generic theory of gauge partners

A few words about LHC signatures...

What to expect at LHC?







Cascade decays with lots of 3rd generation fermions & EW gauge bosons / Higgs bosons.

[See Figure 5, left panel of 1006.1356,

$m_{h^0} = 125$ GeV, naturally.]

Reason this is called the "Bestest" :)