Littlest Higgs and electroweak precision observables

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ECFA LC Workshop, Montpellier, 2003

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◦ Higgs as Pseudo-Goldstone Boson ◦ Scales and Higgs Masses ◦ Generic properties ◦ Versions of models

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◦ Effective Field Theories ◦ Effective Dim. 6 Operators ◦ Constraints on LHM ◦ EW Precision Observables ◦ Direct Searches ◦ Reconstruction of LHM

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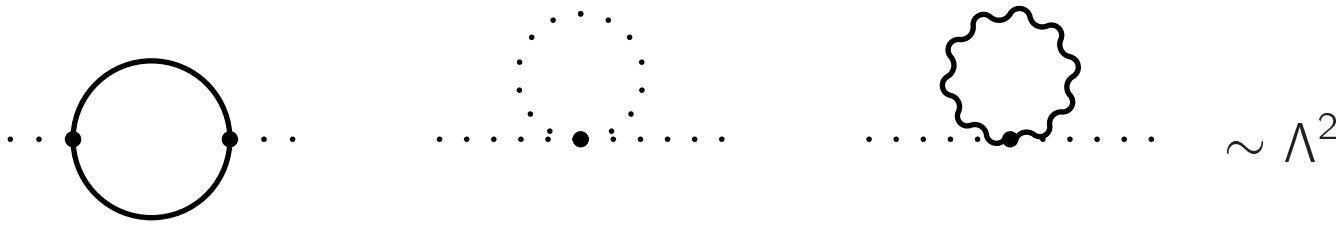
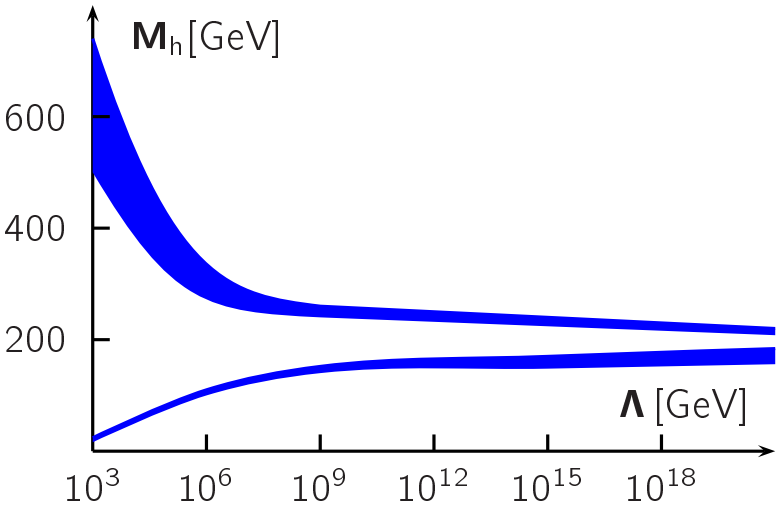
Motivation: Hierarchy Problem

Effective theories below a scale Λ $\Rightarrow$ Loop integration cut off at order $\sim \Lambda$:





☺ *Light* Higgs favoured by electroweak precision observables ($M_h < 0.5\,\mathrm{TeV}$)

☹ **Problem:** Natural Higgs mass is $\mathcal{O}(\Lambda^2)$:

$$\boxed{M_h^2 = m_0^2 + \Lambda^2 \times (\text{loop factors})}$$

$M_h \ll \Lambda \quad \Longleftrightarrow \quad$ Fine-Tuning !?

Solution: Mechanism for elimination of loop contributions

Traditional (SUSY):
Spin-Statistics $\Longrightarrow$ Loops of bosons and fermions

Little Higgs:
Gauge group structure $\Longrightarrow$ Loops of particles of *like statistics*

Old Idea: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

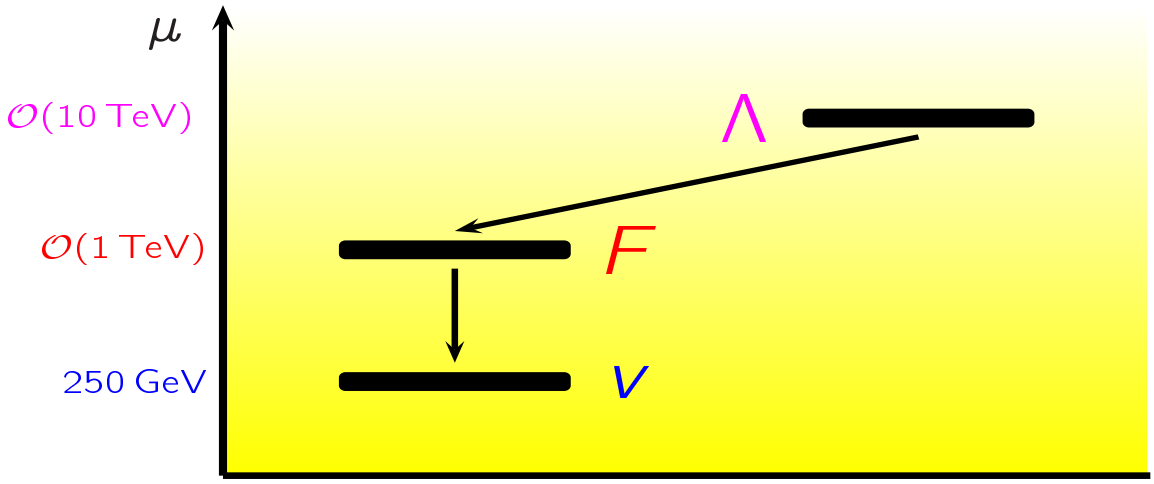
Light Higgs as Pseudo-Goldstone boson $\Leftrightarrow$ spontaneously broken (approximate) *global* symmetry; non-linear sigma model

☹ w/o Fine-Tuning: $v \sim \Lambda/4\pi$

New Ingredience: Arkani-Hamed/Cohen/Georgi/..., 2001

Gauge Group Structure eliminates quadratic divergences @ 1-loop level $\Longrightarrow$ 3-scale model

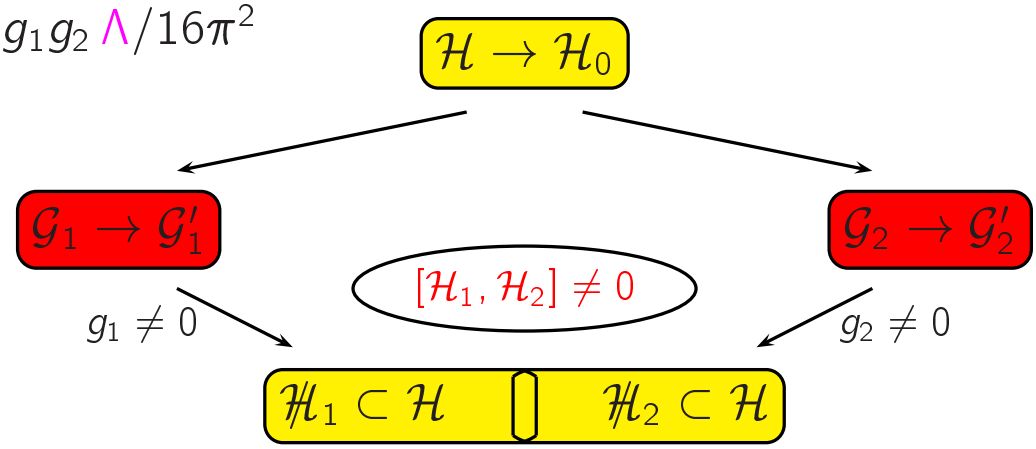
- Scale Λ: global SB, new dynamics, UV embedding
- Scale F: Pseudo-Goldstone bosons, new vector bosons and fermions
- Scale v: Higgs, $W^\pm$, Z, $\ell^\pm$, ...



How does Little Higgs actually work?

Boson masses radiative (Coleman-Weinberg), **but:** Higgs protected by symmetries *against quadratic corrections @ 1-loop level*

$M_H \sim g_1 g_2 \Lambda/16\pi^2$



- Extended scalar (Higgs-) sector
- Extended global symmetry
- **Specific form of the potential:**

$$\mathcal{V}(h,\Phi) = C_1 F^2 \left|\Phi + \frac{\mathrm{i}}{F} h\otimes h\right|^2 + C_2 F^2 \left|\Phi - \frac{\mathrm{i}}{F} h\otimes h\right|^2$$

h massless @ 1-loop level, $\langle h\rangle = v$, $M_h \sim v$

$M_\Phi \sim F$, $\mathrm{i}\cdot\langle\Phi\rangle \sim v^2/F$

h and Φ mix

- **Extended Gauge Sector:**

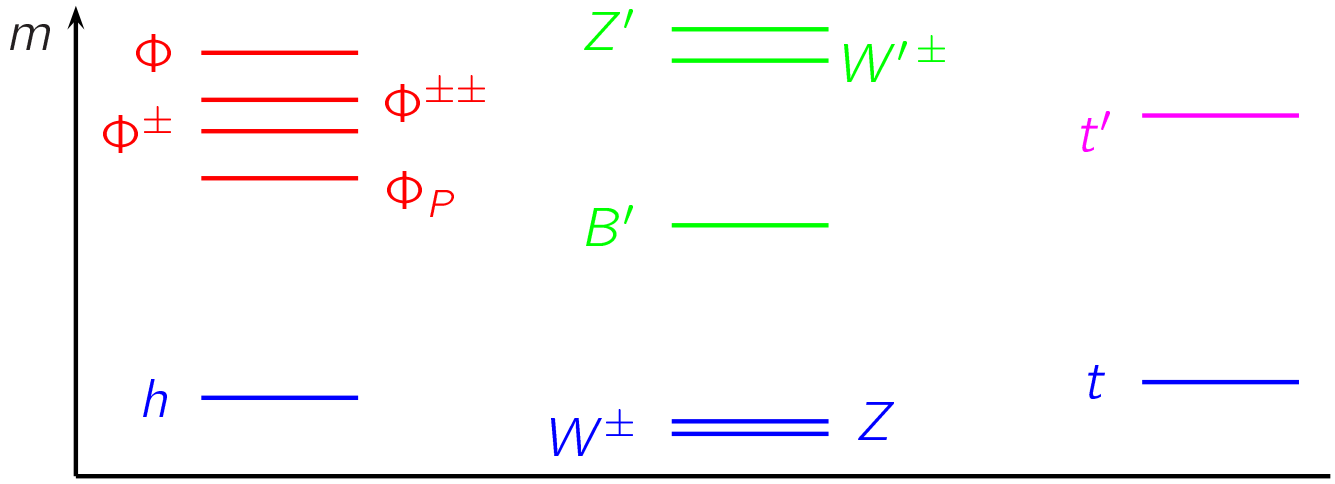
$\mathrm{SM}' \times \mathcal{G} \to \mathrm{SM} \implies$ Duplication of electroweak gauge bosons: B', Z', $W'^{\pm}$

- Extended top sector: new heavy quarks, t, t' loops

$\Rightarrow$ *negative* M_h^2 $\Rightarrow$ EWSB

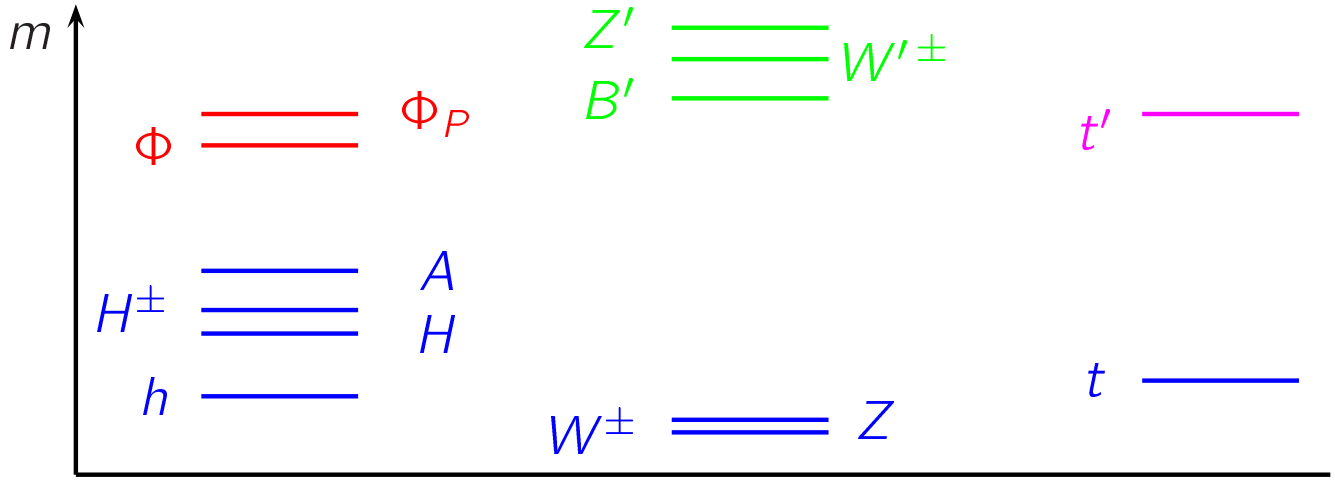
- $\boxed{SU(5) \to SO(5)}$ Arkani-Hamed/Cohen/Katz/Nelson, 2002

  $\mathcal{G} = SU(2) \otimes U(1)$, heavy complex Higgs triplet



- $\boxed{SO(6) \to Sp(6)}$ Low/Skiba/Smith, 2002

  $\mathcal{G} = SU(2) \otimes U(1)$, heavy complex singlet



- $\boxed{[SU(4)]^4 \to [SU(3)]^4}$ Kaplan/Schmaltz, 2003

  2HDM, $h_{1/2}$, $\Phi'_{1,2,3}$, $\Phi'_{P\,1,2,3}$, $Z'_{1,\ldots,8}$, $W'^{\pm}_{1,2}$, q', ℓ'

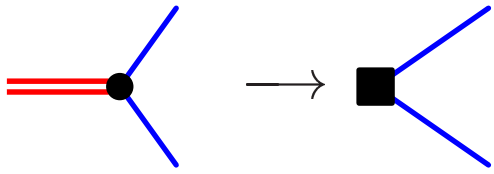
How to *clearly* separate effects of heavy degrees of freedom?

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\ \exp\left[i \int dx \left(\tfrac{1}{2}(\partial\varphi)^2 + \tfrac{1}{2}(\partial\Phi)^2 - \tfrac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi \right) \right],$$

Low-energy effective theory $\Rightarrow$ integrating out heavy degrees of freedom (DOF) in path integrals, set up Power Counting

Completing the square:

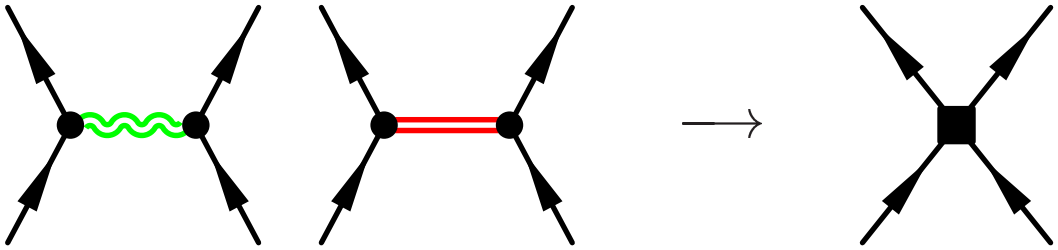
$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1} \varphi^2 :$$



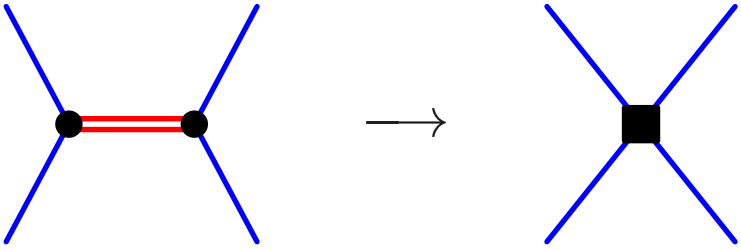
$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi = - \frac{1}{2}\Phi'(M^2 + \partial^2)\Phi' + \frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2,$$

Nonlinear Goldstone structure, heavy DOF:

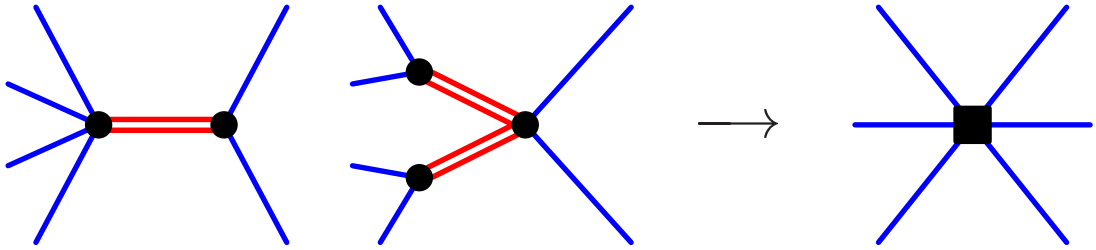
$$V_\mu = \mathrm{i} h \overset{\leftrightarrow}{D}_\mu h^\dagger \qquad \mathcal{O}_{VV}^{(l)} = \frac{1}{F^2}\,\mathrm{tr}[V\cdot V]_{(l)}.$$



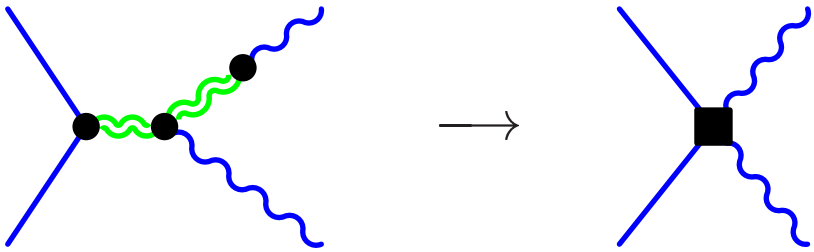
$$\frac{1}{F^2}(\bar{f}f)^2$$



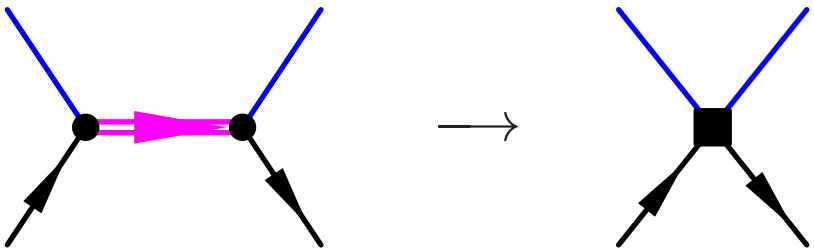
$$\mathcal{O}_{h,1}, \mathcal{O}_{hh} : \frac{1}{F^2} D^2 h^4$$



$$\mathcal{O}_{h,3} : \frac{1}{F^2} h^6$$



$$\mathcal{O}_{W/B}, \mathcal{O}_{BW} : \frac{1}{F^2} D^4 h^2$$



$$\mathcal{O}_{Vq} : \frac{1}{F^2} D h^2 \bar{q} q$$

◇ All low-energy effects order v^2/F^2

☺ Low-energy observables parameterized by ΔS, ΔT, 2 parameters for contact interactions

Constraints from contact IA:

$$c^2 \lesssim F/4.5\,\text{TeV} \qquad c'^2 \lesssim F/10\,\text{TeV}\ .$$

☺ **Constraints evaded** $\Longleftrightarrow$ $\mathbf{c}, \mathbf{c}' \ll \mathbf{1}$.

$B', Z', W'^{,\pm}$ superheavy ($\mathcal{O}(\Lambda)$)

decouple from fermions

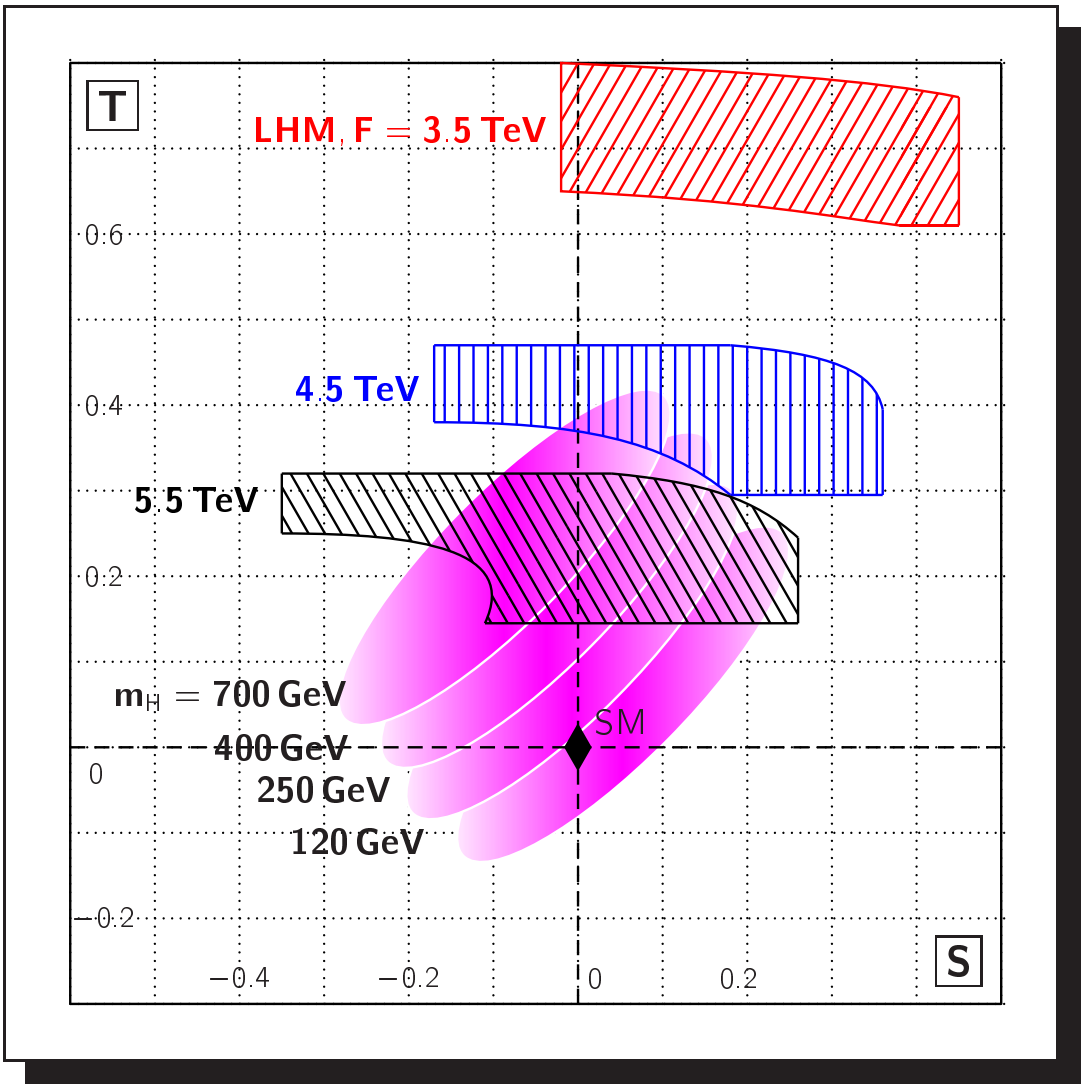
ΔS, ΔT in the Littlest Higgs model, violation of Custodial SU(2):

Csáki et al., 2002; Hewett et al., 2002; Han et al., 2003; Kilian/JR, 2003

◇ Mixing of (Z, B', Z') and $(W^\pm, W'^\pm)$

$$\Delta S = -8\pi\left[\frac{c^2(c^2-s^2)}{g^2} + 5\frac{c'^2(c'^2-s'^2)}{g'^2}\right]\frac{v^2}{F^2} \longrightarrow 0$$

$$\alpha\Delta T \longrightarrow \frac{5}{4}\frac{v^2}{F^2} - \frac{2v^2\lambda_{2\phi}^2}{M_\phi^4} \gtrsim \frac{v^2}{F^2}$$



Higgs mass *variable* (Coleman-Weinberg, UV completion)

$$\Delta S = \frac{1}{12\pi} \ln \frac{m_H^2}{m_0^2} \qquad \Delta T = -\frac{3}{16\pi c_w^2} \ln \frac{m_H^2}{m_0^2}$$

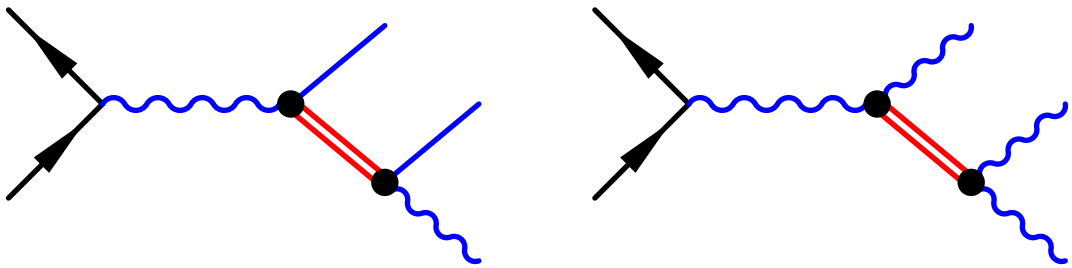
Peskin/Takeuchi, 1992; Hagiwara et al., 1992

- **Heavy Gauge Bosons:**

  Detection: Resonance in $e^+e^- \to f\bar{f}$, Drell-Yan $\Rightarrow$

  Tevatron: $M_{B'} \gtrsim 1.5\,\mathrm{TeV}$

- **Heavy Scalars:**



  - ◇ $\mathbf{\Phi_P}$: $e^+e^-, q\bar{q} \to \Phi_P h, \quad \Phi_P \to h Z_L$
  - ◇ $\mathbf{\Phi^\pm}$: $e^+e^-, q\bar{q} \to \Phi^+ W_L^-, \quad \Phi^\pm \to W_L Z_L$
  - ◇ $\mathbf{\Phi^{\pm\pm}}$: $e^-e^- \to \nu\nu\Phi^{--}, \quad \Phi^{\pm\pm} \to W_L^- W_L^-$
  - ◇ $\mathbf{\Phi^0}$: $e^+e^-, q\bar{q} \to Z_L \Phi,$

    $\Phi \to Z_L Z_L, hh,$ *not* W^+W^-

- **Heavy Quarks:**

  t' production @ LHC, decay $t' \to W_L b, th$

How can we unravel the structure of LHM @ colliders?

- ◇ Symmetry structure ⇒ Quadr. Div. Cancell.
- ◇ Nonlinear Goldstone boson structure

Signals:

- *Anom.* Triple Gauge Couplings: WWZ, $WW\gamma$
- *Anom.* Higgs Coupl.: $H(H)WW$, $H(H)ZZ$
- *Anom.* Top Couplings: ttZ, tbW

Vectors:

- Direct Search (LHC) M_V, F, c, c'
- LC: Contact Terms $e^+e^- \to e^+e^-, \mu^+\mu^-$
  $\Rightarrow M_{B'} \sim 5 - 10\,\text{TeV}$, $e^+e^- \to \nu\bar{\nu}\gamma \Rightarrow M_{B'} \sim 5\,\text{TeV}$
- Higgs-strahlung, WW fusion: $HZff$, $HWff$ angular distr./energy dependence $\Rightarrow f_{VJ}$
- Check from TGC (LC: per mil precision), GigaZ

⇒ **Determination of all coefficients in the gauge sector**

Scalars:

- ΔT, $f_{VV}^{(1)}$, B' known $\Rightarrow (\lambda_{2\phi}/M_\phi^2)^2$
- Higgsstr., WW fusion $\Rightarrow$ Higgs coupl., $f_{VV}^{(3)}$
- Higgs BRs $\Rightarrow f_{VV}^{(1)}, f_{VV}^{(3)}$; (take care of t)
  $f_{VV}^{(3)}$ **Goldstone contr. $\Rightarrow$ Evidence for nonlinear nature**

LHC $\bowtie$ LC $\Rightarrow$ 1-2 % accuracy @ Higgs measurements
Reconstruction of scalar sector up to $F \sim 2\,\mathrm{TeV}$

Top:

- Direct production @ LHC
- $t\bar{t}$ production $\Rightarrow f_{Vq}, v_t, a_t$; accuracy 1-2 %
- tbW from t decays, single t production $g_{ttH}/g_{bbH} \Rightarrow$ *anom. Yukawa coupl.* $\Rightarrow f_{hq}$, nonlin. structure w. $\sim 2.5\%$ accuracy

Little Higgs elegant alternative to SUSY
Gauge group structure stabilizes EW scale

- Generics: new heavy gauge bosons, scalars, quarks

Clear experimental signatures:
direct search [Gauge & Top sector, LHC (LC)]

$\longleftrightarrow$

precision observables [Gauge, Scalar, Top sector LC (LHC)]

Roadmap for Reconstruction
by *Complementarity* of LC & LHC

UV embedding, GUT, Flavor ?

Little Higgs *in accord with EW precision observables* **w/o Fine Tuning** (Higgs mass!)