The Big Deal with the Little Higgs

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Outline

Hierarchy Problem, Goldstone-Bosons and Little Higgs

- Higgs as Pseudo-Goldstone Boson
- Nambu-Goldstone Bosons
- The Little Higgs mechanism

Examples of Models

Phenomenology

- For example: Littlest Higgs
- Neutrino masses
- Effective Field Theories
- Electroweak Precision Observables
- Direct Searches
- Reconstruction of Little Higgs Models
- Pseudo Axions in LHM
- T parity and Dark Matter

Conclusions

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The Higgs Mechanism in the Standard Model

Electroweak Theory: $SU(2) \times U(1)$ gauge theory

$$U = \exp[ig\theta^a \tau^a/2], \quad V = \exp[ig'\theta_Y Y/2]$$

$$Q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L \to U Q_L, \qquad f_R \to f_R, \qquad \mathbf{W}_\mu \to U \mathbf{W}_\mu U^\dagger + \frac{i}{g}(\partial_\mu U) U^\dagger$$

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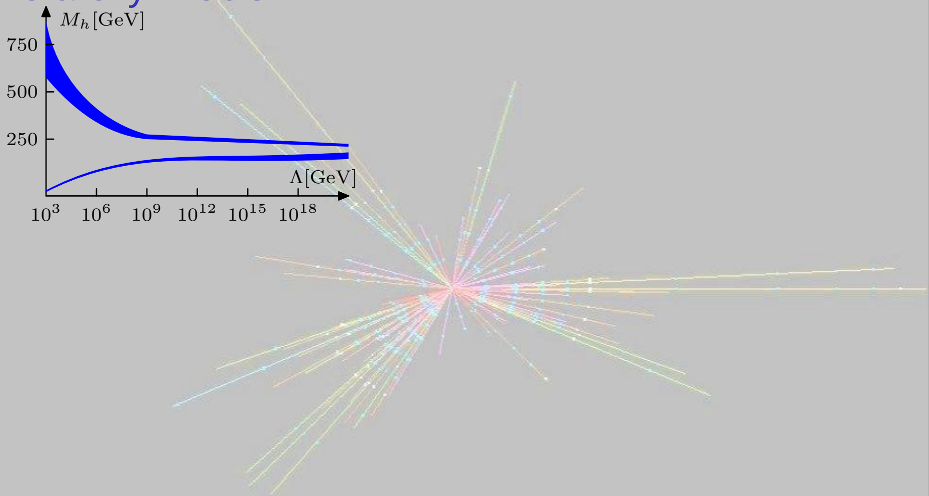
- Spontaneous symmetry breaking: Higgs gets a Vacuum Expectation value (VEV):

$$\mathcal{V}(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \Rightarrow \Phi \to \exp[i\pi/v] \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$$|D_\mu \Phi|^2 \to \frac{1}{2} M_W^2 W_a^2, \qquad -Y_d \overline{Q}_L \Phi d_R \to -m_d \overline{d}_L d_R$$

Hierarchy Problem



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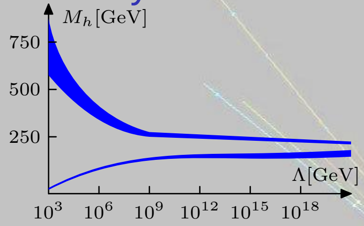

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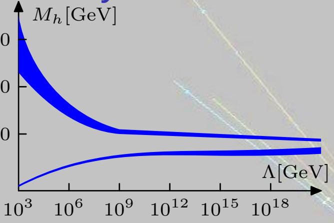

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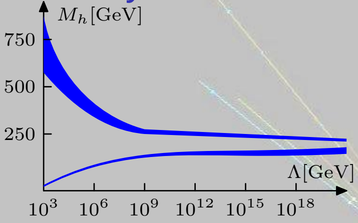

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Problem: Naturally, $m_h \sim \mathcal{O}(\Lambda^2)$:

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

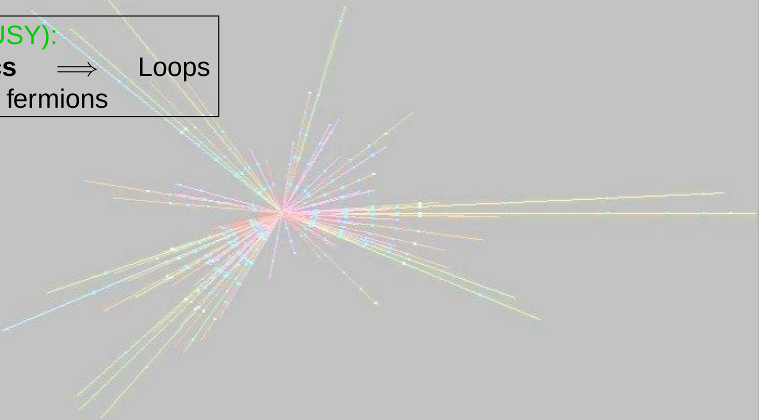
◊ *Light* Higgs favoured by EW precision observables ($m_h < 0.5$ TeV)

- $m_h \ll \Lambda \quad \Leftrightarrow \quad$ Fine-Tuning !?
- **Solution:** Mechanism for eliminating loop contributions

Higgs as Pseudo-Goldstone Boson

Invent (approximate) symmetry to protect particle mass

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



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

Collective Symmetry Breaking eliminates quadratic divergences @ 1-loop level $\Longrightarrow$ 3-scale model

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Nonlinear Realization (Example $SU(3) \to SU(2)$):

$$\mathcal{V}(\Phi) = \left(f^2 - (\Phi^\dagger \Phi)\right)^2 \Rightarrow \Phi = \exp\left[\frac{i}{f}\begin{pmatrix} 0 & \vec{\pi} \\ \vec{\pi}^\dagger & \pi_0 \end{pmatrix}\right]\begin{pmatrix} 0 \\ f+\sigma \end{pmatrix} \equiv e^{i\pi}\Phi_0$$

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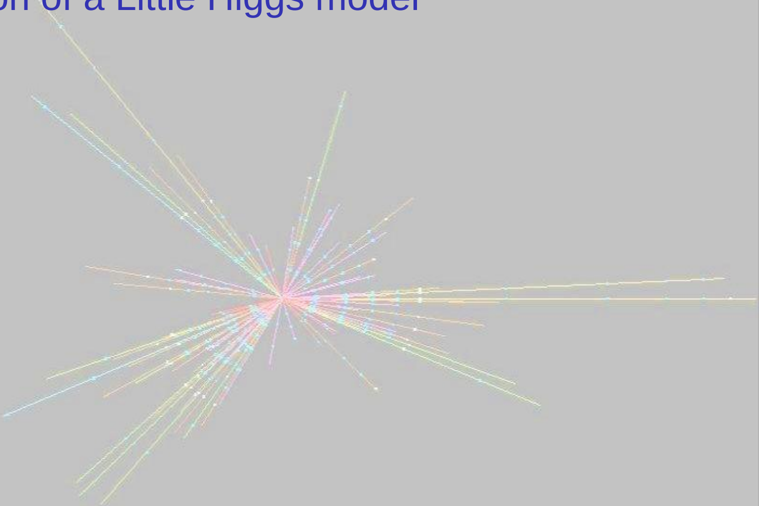
$$\Phi \to U_2 \Phi = (U_2 \Phi U_2^\dagger) U_2 \Phi_0 = e^{i(U_2 \pi U_2^\dagger)}\Phi_0 \qquad U_2 = \begin{pmatrix} \hat{U}_2 & 0 \\ 0 & 1 \end{pmatrix}$$

$\Rightarrow$ $\boxed{\vec{\pi} \to \hat{U}_2 \vec{\pi}, \quad \pi_0 \to \pi_0}$ $\vec{\pi} \in$ fundamental $SU(2)$ rep., π_0 singlet

Construction of a Little Higgs model

- $\vec{\pi} \equiv h$??



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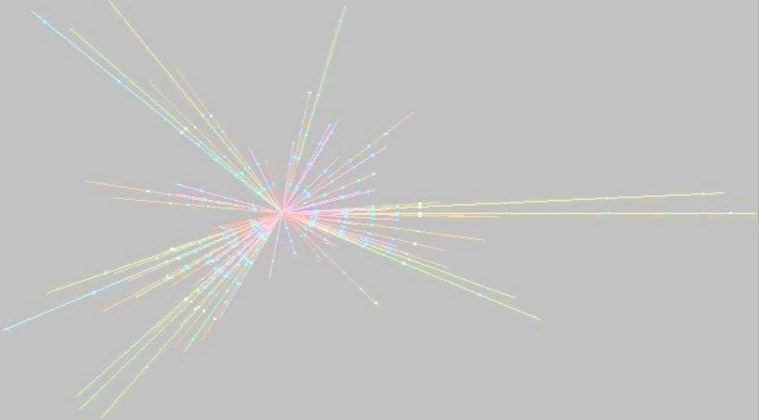

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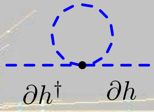
- Gauge and Yukawa interactions?
- Expanding the kinetic term:

$$f^2|\partial\Phi|^2 = |\partial h|^2 + \frac{1}{f^2}(h^\dagger h)|\partial h|^2 + \ldots$$



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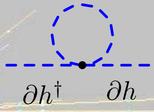

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$\to$ Theory becomes stronlgy interacting at $\Lambda = 4\pi f$.

- Bad news Easy attempts: no potential or quadratic divergences again
- **Collective Symmetry breaking:** Two ways of model building:

  1. simple Higgs representation , doubled gauge group
  2. simple gauge group, doubled Higgs representation

Prime Example: Simple Group Model

- enlarged gauge group: $SU(3) \times U(1)$; globally $U(3) \to U(2)$
- **Two** nonlinear Φ representations $\boxed{\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2}$

$$\Phi_{1/2} = \exp\left[\pm i \frac{f_{2/1}}{f_{1/2}} \Theta\right] \begin{pmatrix} 0 \\ 0 \\ f_{1/2} \end{pmatrix} \qquad \Theta = \frac{1}{\sqrt{f_1^2 + f_2^2}} \begin{pmatrix} \begin{matrix} \eta & 0 \\ 0 & \eta \end{matrix} & h^* \\ h^T & \eta \end{pmatrix}$$

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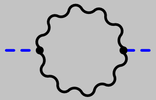
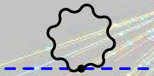
Coleman-Weinberg mechanism: Radiative generation of potential

 $+$ 

$$= \frac{g^2}{16\pi^2} \Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2 \right) \sim \frac{g^2}{16\pi^2} f^2$$

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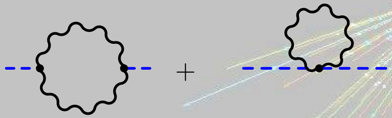

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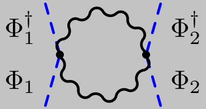
but: 

$$= \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2 \Rightarrow \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) f^2 (h^\dagger h)$$

Yukawa interactions and heavy Top

Simplest Little Higgs (“μ Model”) Schmaltz (2004), Kilian/Rainwater/JR (2004)

Field content ($SU(3)_c \times SU(3)_w \times U(1)_X$ quantum numbers)

$\Phi_{1,2}$	$: (1,3)_{-\frac{1}{3}}$	Ψ_ℓ	$: (1,3)_{-\frac{1}{3}}$	${u_{1,2}}^c$	$: (\bar{3},1)_{-\frac{2}{3}}$
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Lagrangian $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{\text{Yuk.}} + \mathcal{L}_{\text{pot.}}$ $\Psi_{Q,L} = (u,d,U)_L, \Psi_\ell = (\nu,\ell,N)_L$:

$$\mathcal{L}_{\text{Yuk.}} = -\lambda_1^u \overline{u}_{1,R} \Phi_1^\dagger \Psi_{T,L} - \lambda_2^u \overline{u}_{2,R} \Phi_2^\dagger \Psi_{T,L} - \frac{\lambda^d}{\Lambda} \epsilon^{ijk} \overline{d}_R^b \Phi_1^i \Phi_2^j \Psi_{T,L}^k$$
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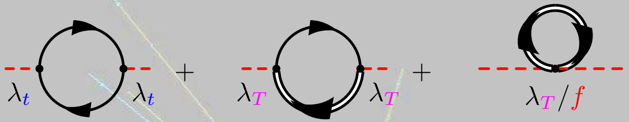
Hypercharge embedding (remember: $\text{diag}(1,1,-2)/(2\sqrt{3})$):

$$Y = X - T^8/\sqrt{3} \qquad D_\mu \Phi = (\partial_\mu - \frac{1}{3} g_X B_\mu^X \Phi + i g W_\mu^w) \Phi$$

Cancellations of Divergencies in Yukawa sector



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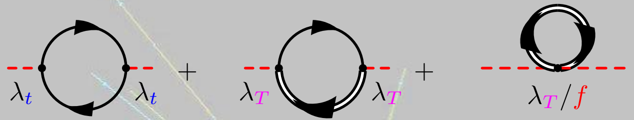

$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2 - m_T^2)} \left\{ \lambda_t^2 (k^2 - m_T^2) + k^2 \lambda_T^2 - \frac{m_T}{F} \lambda_T k^2 \right\}$$

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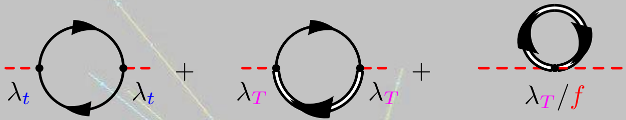

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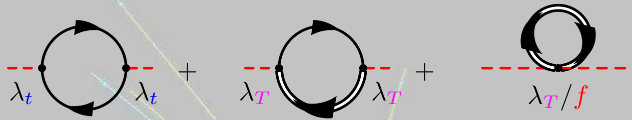

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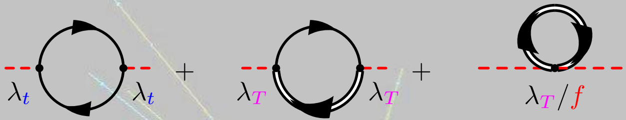
Cancellations of Divergencies in Yukawa sector

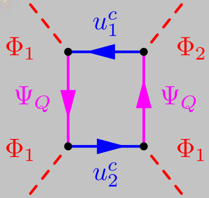


$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2-m_T^2)} \left\{ \lambda_t^2(k^2-m_T^2) + k^2\lambda_T^2 - \frac{m_T}{F}\lambda_T k^2 \right\}$$

Little Higgs global symmetry imposes relation

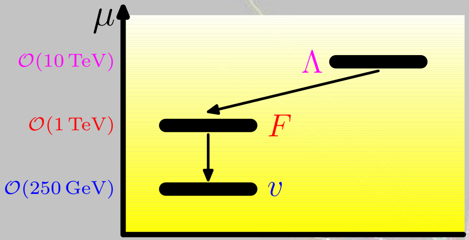
$$\boxed{\frac{m_T}{F} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}} \quad \Longrightarrow \quad \textbf{Quadratic divergence cancels}$$

Collective Symm. breaking: $\lambda_t \propto \lambda_1\lambda_2$, $\lambda_1 = 0$ *or* $\lambda_2 = 0 \Rightarrow SU(3) \to [SU(3)]^2$



$$\sim \frac{\lambda_1^2\lambda_2^2}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2$$

Scales and Masses



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

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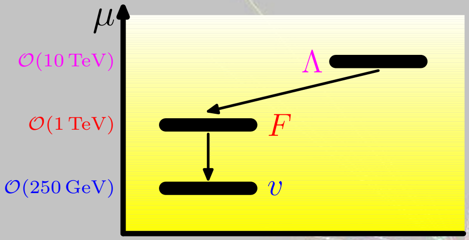

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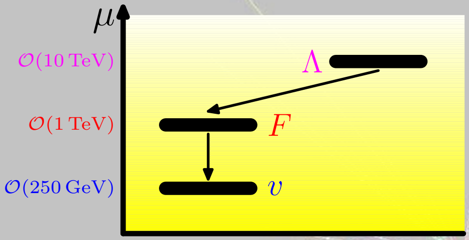

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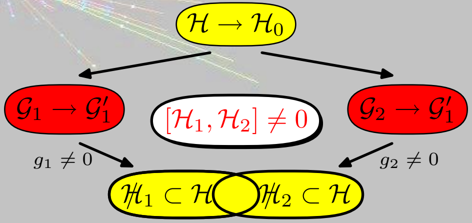
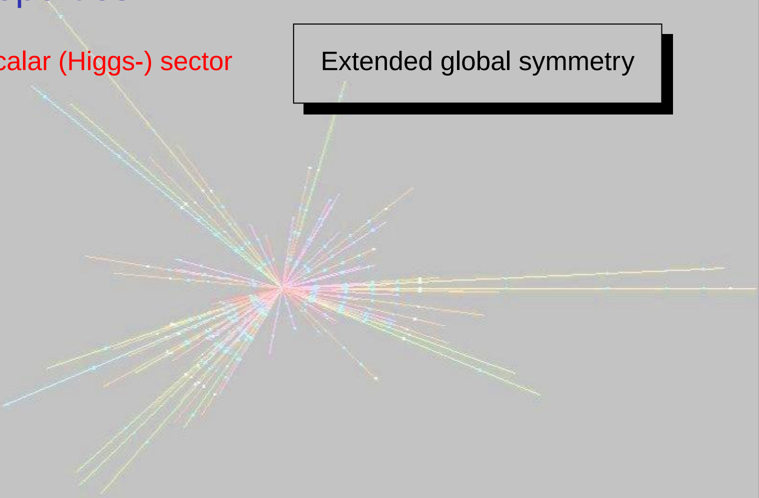


$$M_H \sim g_1 g_2 \, \Lambda / 16\pi^2$$

Generic properties

- Extended scalar (Higgs-) sector

Extended global symmetry



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- **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, $\langle h \rangle = v$, $M_h \sim v$, $M_\Phi \sim F$, $\mathrm{i} \cdot \langle \Phi \rangle \sim v^2/F$

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- Extended top sector: new heavy quarks, t, t' loops $\Rightarrow$ $M_h^2 < 0$ $\Rightarrow$ EWSB

Outline

Hierarchy Problem, Goldstone-Bosons and Little Higgs
- Higgs as Pseudo-Goldstone Boson
- Nambu-Goldstone Bosons
- The Little Higgs mechanism

Examples of Models

Phenomenology
- For example: Littlest Higgs
- Neutrino masses
- Effective Field Theories
- Electroweak Precision Observables
- Direct Searches
- Reconstruction of Little Higgs Models
- Pseudo Axions in LHM
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Conclusions

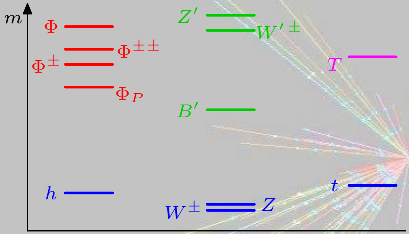
Little Higgs Models

Plethora of "Little Higgs Models" in 3 categories:

- **Moose Models**
  - Orig. Moose (Arkani-Hamed/Cohen/Georgi, 0105239)
  - Simple Moose (Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker, 0206020)
  - Linear Moose (Casalbuoni/De Curtis/Dominici, 0405188)
- **Simple (Goldstone) Representation Models**
  - Littlest Higgs (Arkani-Hamed/Cohen/Katz/Nelson, 0206021)
  - Antisymmetric Little Higgs (Low/Skiba/Smith, 0207243)
  - Custodial $SU(2)$ Little Higgs (Chang/Wacker, 0303001)
  - Littlest Custodial Higgs (Chang, 0306034)
  - Little SUSY (Birkedal/Chacko/Gaillard, 0404197)
- **Simple (Gauge) Group Models**
  - Orig. Simple Group Model (Kaplan/Schmaltz, 0302049)
  - Holographic Little Higgs (Contino/Nomura/Pomarol, 0306259)
  - Simplest Little Higgs (Schmaltz, 0407143)
  - Simplest Little SUSY (Roy/Schmaltz, 0509357)
  - Simplest T parity (Kilian/Rainwater/JR/Schmaltz,...)

Varieties of Particle spectra

- $$\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$$
  Arkani-Hamed/Cohen/Katz/Nelson, 2002



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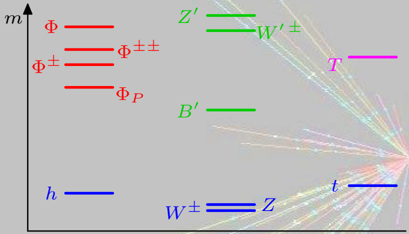

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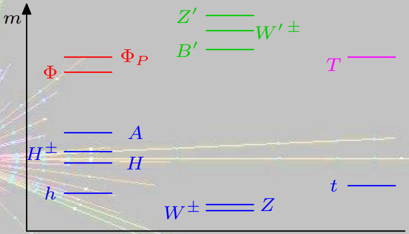

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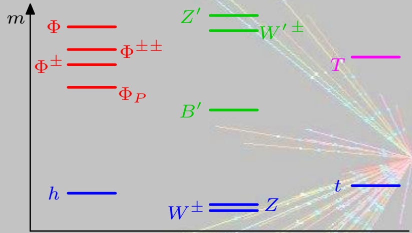

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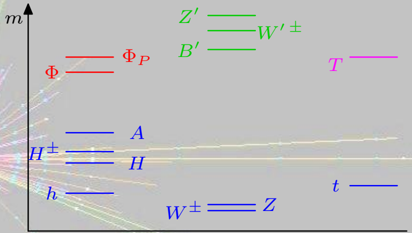
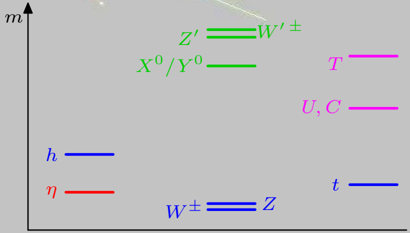


- $\mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2}, \mathcal{G} = \frac{SU(3) \times U(1)}{SU(2) \times U(1)}$ $\Longrightarrow$

  Schmaltz, 2004



- $[SU(4)]^4 \rightarrow [SU(3)]^4$

  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'

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Symmetry breaking:

$$SU(5) \to SO(5) \quad \text{(global)}$$
$$[SU(2) \times U(1)]^2 \to SU(2)_L \times U(1)_Y \quad \text{(local)}$$

1 heavy triplet X_μ,
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The unbroken Lagrangian: $\mathcal{L} = \mathcal{L}_0^{(3)} + \mathcal{L}_0^{(1)} + \mathcal{L}_0^{G}$.

$$\mathcal{L}_0^{(3)} = -\frac{1}{2g_1^2}\,\mathrm{Tr}\,\mathbf{A}_{1\mu\nu}\mathbf{A}_1{}^{\mu\nu} - \frac{1}{2g_2^2}\,\mathrm{Tr}\,\mathbf{A}_{2\mu\nu}\mathbf{A}_2{}^{\mu\nu} - 2\,\mathrm{tr}\,A_1{}^\mu J^{(3)}{}_\mu$$
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Gauge group generators:

$$T_1^a = \frac{1}{2}\begin{pmatrix}\tau^a & & \\ & 0 & \\ & & 0\end{pmatrix},\; T_2^a = \frac{1}{2}\begin{pmatrix}0 & & \\ & 0 & \\ & & -\tau^{a*}\end{pmatrix},\quad \begin{aligned} Y_1 &= \tfrac{1}{10}\,\mathrm{diag}(3,3,-2,-2,-2) \\ Y_2 &= \tfrac{1}{10}\,\mathrm{diag}(2,2,2,-3,-3)\end{aligned}$$

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Triplet current: $J^{(3)}{}_\mu = J^{(3),a}_\mu \frac{\tau^a}{2}$ Singlet current: $J^{(1)}{}_\mu$

Couplings not unique, but: (Anomaly cancellation!)

$$\mathcal{L}_0^G = \frac{F^2}{8}\,\mathrm{Tr}(D_\mu \Xi)(D^\mu \Xi)^*, \qquad \Xi = \left(\exp \frac{2i}{F}\Pi\right)\Xi_0, \qquad \Xi_0 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & h & \phi \\ h^\dagger & 0 & h^T \\ \phi^\dagger & h^* & 0 \end{pmatrix}, \qquad \phi = \begin{pmatrix} \sqrt{2}\,\Phi^{++} & \Phi^+ \\ \Phi^+ & \Phi_0 + i\Phi_1 \end{pmatrix}.$$

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$$\mathcal{L}_t = \sum_Q \bar{\mathbf{Q}}\, i\not{D}\,\mathbf{Q} + \mathcal{L}_Y - \lambda_2 F(\bar{T}_L T_R + \text{h.c.}).$$

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Use a global $SU(3)$ subsymmetry

$$\chi_L = \begin{pmatrix} i\tau^2 T_L & i q_L & 0 \\ -i q_L^T & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \boxed{\mathcal{L}_Y = \lambda_1 F\,\bar{t}_R\,\mathrm{Tr}\left[\Xi^*(iT_2^2)\Xi^*\hat{\chi}_L\right] + \text{h.c.}}$$

Neutrino masses

Kilian/JR, 2003; del Aguila et al., 2004; Han/Logan/Wang, 2005

- *Naturalness does not require cancellation mechanism for light fermions*

Lepton-number violating interactions can generate **neutrino masses** (due to presence of triplet scalars)

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EWSB: Generation of neutrino masses $\boxed{m_\nu \sim g_N v^2 / F}$

Caveat: m_ν too large compared to observations

$\Rightarrow g_N$ small, e.g. F/Λ', where Λ' : scale of lepton number breaking

Heavy Vector Fields

Mixing of the gauge fields:

$$A_1{}^{\mu} = W^{\mu} + g_X c^2 X^{\mu}, \qquad B_1{}^{\mu} = B^{\mu} + g_Y c'^2 Y^{\mu},$$

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Expand the Goldstone Lagrangian

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$$+ \frac{1}{2} \operatorname{tr}(D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu h)^\dagger (D^\mu h) - \frac{1}{6F^2} \operatorname{tr}\left[V^{(3)} \cdot V^{(3)}\right] + \ldots,$$

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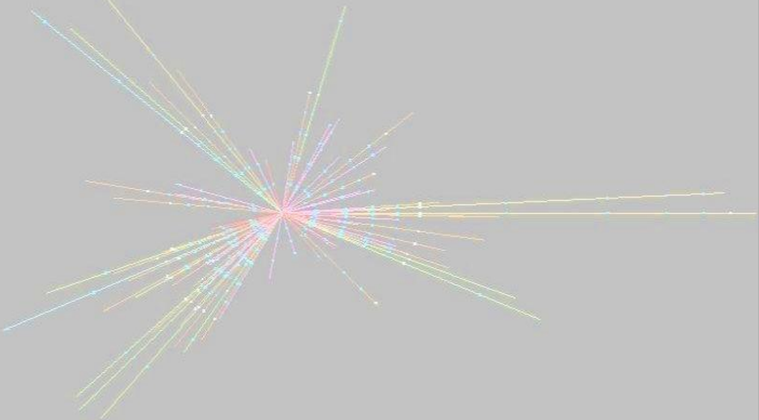
Heavy vector masses: $M_X = g_X F/2$ $\qquad$ $M_Y = g_Y F/(2\sqrt{5})$

Higgs current

$$V_\mu = i\left[h(D_\mu h)^\dagger - (D_\mu h) h^\dagger\right] \qquad \mathbf{1}_0 : \quad V^{(1)} = \operatorname{tr} V, \qquad \mathbf{3}_0 : \quad V^{(3)} = V - \frac{1}{2} \operatorname{tr} V.$$

Effective Field Theories

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



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Toy model: Two interacting scalar fields φ, Φ

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

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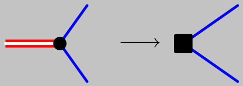
Completing the square:

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



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

Integrating out

Integrating out the X and Y vector fields $\Rightarrow$

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In the Littlest Higgs e.g.

$$f^{(3)}_{VV} = -\frac{1}{6F^2}\left(1 + \frac{3}{2}(c^2 - s^2)^2\right)$$

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Coleman-Weinberg potential of the scalar fields @ 1-loop:

$$\mathcal{L}^{CW}_0 = -\frac{1}{2}M^2_\phi\,\text{tr}[\phi\phi^\dagger] + \mu^2(h^\dagger h) - \lambda_4(h^\dagger h)^2 - \lambda_{2\phi}\text{i}\left(h^\dagger\phi h^* - h^T\phi^\dagger h\right)$$
$$- \lambda_{2\phi\phi}\,\text{tr}[(\phi\phi^\dagger)(hh^\dagger)] - \lambda_{4\phi}\text{i}(h^\dagger h)\left(h^\dagger\phi h^* - h^T\phi^\dagger h\right) - \lambda_6(h^\dagger h)^3$$

Sensitive to UV completion, dimensionless parameters k and k'. EWSB $\Rightarrow$ Constraints on k, k'

Integrate out the heavy scalar (Power counting!)

$$\phi' = \phi - \frac{2\mathrm{i}\lambda_{2\phi}}{M_\phi^2}\left(1 + \frac{D^2}{M_\phi^2} + \frac{2\lambda_{2\phi\phi}}{M_\phi^2} hh^\dagger\right)^{-1} \times \left(1 + \frac{\lambda_{4\phi}}{\lambda_{2\phi}} h^\dagger h\right) hh^T$$

Higgs mass up to order v^4/F^2

$$m_H^2 = 2\lambda_4^{\text{eff}} v^2$$

$$= -2v^2 \left(\frac{e^2}{s_w^2 c^2} + \frac{e^2}{c_w^2 c'^2}\right) k \cdot \frac{\left(\frac{e^2}{s_w^2 s^2} + \frac{e^2}{c_w^2 s'^2}\right) k + \frac{\lambda_t^2}{c_t^2} k'}{\left(\frac{e^2}{s_w^2 s^2 c^2} + \frac{e^2}{c_w^2 s'^2 c'^2}\right) k + \frac{\lambda_t^2}{c_t^2} k'}$$

(Remember $\mu^2 = m_H^2/2$)

EWSB $\lambda_4^{\text{eff}} > 0 \quad \Rightarrow \quad \boxed{\frac{\lambda_{2\phi}^2}{M_\phi^4} < \frac{1}{8F^2}}$

Equations of Motion (EOM)

- Couplings $V - J$ induce after SSB anom. couplings of W, Z to fermions
- Applying EOM eliminates corrections from field redefinitions

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Custodial-$SU(2)$ Conserving Terms

$$0 = \mathrm{tr}[V^{(3)}{}_\mu \frac{\delta\mathcal{L}}{\delta W_\mu}] = \mathrm{tr}[V^{(3)} \cdot V^{(3)}] - \frac{2}{g^2}\,\mathrm{tr}[V^{(3)}{}_\mu D_\nu W^{\mu\nu}] - 2\,\mathrm{tr}[V^{(3)} \cdot J^{(3)}]$$

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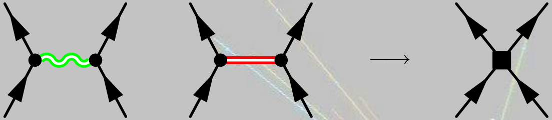
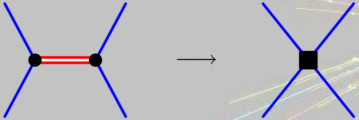
Custodial-$SU(2)$ Violating Terms

$$\boxed{\mathcal{L}^{(1)} = \mathcal{L}^{\text{EW}}_{g,gf} + f^{(1)}_{JJ}\,\mathcal{O}^{(1)}_{JJ} + f_{VB}\,\mathcal{O}_{VB} + f^{(1)}_{VV}\,\mathcal{O}^{(1)}_{VV}}$$

Effective Dim. 6 Operators

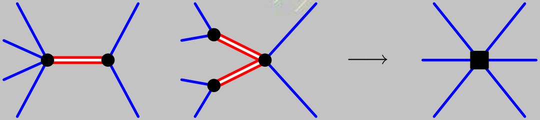


$$\mathcal{O}^{(I)}_{JJ} = \frac{1}{F^2}\,\mathrm{tr}[J^{(I)}\cdot J^{(I)}]$$

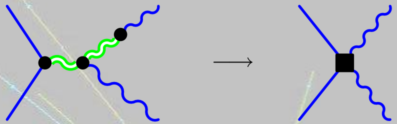


$$\mathcal{O}'_{h,1} = \frac{1}{F^2}\left((Dh)^\dagger h\right)\cdot\left(h^\dagger(D^h)\right) - \frac{v^2}{2}|Dh|^2$$

$$\mathcal{O}'_{hh} = \frac{1}{F^2}(h^\dagger h - v^2/2)\,(Dh)^\dagger\cdot(Dh)$$



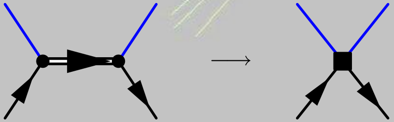
$$\mathcal{O}'_{h,3} = \frac{1}{F^2}\frac{1}{3}(h^\dagger h - v^2/2)^3$$



$$\mathcal{O}'_{WW} = -\frac{1}{F^2}\frac{1}{2}(h^\dagger h - v^2/2)\,\mathrm{tr}\, W_{\mu\nu}W^{\mu\nu}$$

$$\mathcal{O}_B = \frac{1}{F^2}\frac{i}{2}(D_\mu h)^\dagger(D_\nu h)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(h^\dagger h - v^2/2)B_{\mu\nu}B^{\mu\nu}$$



$$\mathcal{O}_{Vq} = \frac{1}{F^2}\overline{q}h(\not{D}h)q$$

Oblique Corrections: S, T, U

- All low-energy effects order v^2/F^2
- Low-energy observables parameterized by ΔS, ΔT, 2 parameters for contact interactions (no ΔU here)

$\mathcal{O}_{VW}, \mathcal{O}_{VB} \Rightarrow$ Change in gauge couplings g and g'

$$g = \frac{e}{s_w} \left[1 + M_W^2 (f_{VW} + 2 f_{VB}) \right]$$
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S **parameter** $(\mathcal{O}_{VW}, \mathcal{O}_{VB})$

$$\boxed{\Delta S = 8\pi v^2(f_{VW} + 2f_{VB})}$$

$SU(2)_c$**-violating sector** $(\mathcal{O}'_{h,1})$

$$\boxed{\alpha\Delta T = \Delta M_W^2/M_W^2 = -2v^2 f_{VV}^{(1)} - \frac{2v^2\lambda_{2\phi}^2}{M_\phi^4}}$$

Shift in physical vector masses:

$$\boxed{M_W^2 = \left(\frac{ev}{2s_w}\right)^2 (1+x)} \qquad \boxed{M_Z^2 = \left(\frac{ev}{2s_w c_w}\right)^2 (1+y)}$$

$$x = \alpha\left(\Delta S/(4s_w^2) + \Delta T\right) \qquad y = \alpha \Delta S/(4s_w^2 c_w^2)$$

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Four-Fermion Interactions

Very low energies ⇒ Fermi theory

$$\sqrt{2}\, G_F = \frac{1}{v^2}(1+z) \quad \text{with} \quad z = -\alpha \Delta T - \frac{v^2}{4} f_{JJ}^{(3)}.$$

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G_F-M_Z-α **scheme** (muon decay, LEP I, Bhabha), define the parameters $\hat{v}_0$ and $\hat{s}_0$ by

$$\hat{v}_0 = (\sqrt{2}\, G_F)^{-1/2} \quad \text{and} \quad M_Z = \frac{e\hat{v}_0}{2\hat{s}_0\hat{c}_0} \qquad \Longrightarrow$$

$$s_w^2 = \hat{s}_0^2\left(1 + \frac{\hat{c}_0^2}{\hat{c}_0^2 - \hat{s}_0^2}(y+z)\right) \qquad c_w^2 = \hat{c}_0^2\left(1 - \frac{\hat{s}_0^2}{\hat{c}_0^2 - \hat{s}_0^2}(y+z)\right)$$

Constraints on LHM

Constraints from contact IA: ($f_{JJ}^{(3)}, f_{JJ}^{(1)}$) $c^2 \lesssim F/4.5$ TeV $c'^{\,2} \lesssim F/10$ TeV

◊ **Constraints evaded** $\Longleftrightarrow$ $c, c' \ll 1$
$B', Z', W'^{,\pm}$ superheavy ($\mathcal{O}(\Lambda)$) *decouple from fermions*

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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 $(W^\pm, W'^\pm)$

$$\frac{\Delta S}{8\pi} = -\left[\frac{c^2(c^2-s^2)}{g^2} + 5\frac{c'^2(c'^2-s'^2)}{g'^2}\right]\frac{v^2}{F^2} \rightarrow 0 \qquad \alpha\Delta T \rightarrow \frac{5}{4}\frac{v^2}{F^2} - \frac{2v^2\lambda^2_{2\phi}}{M^4_\phi} \gtrsim \frac{v^2}{F^2}$$

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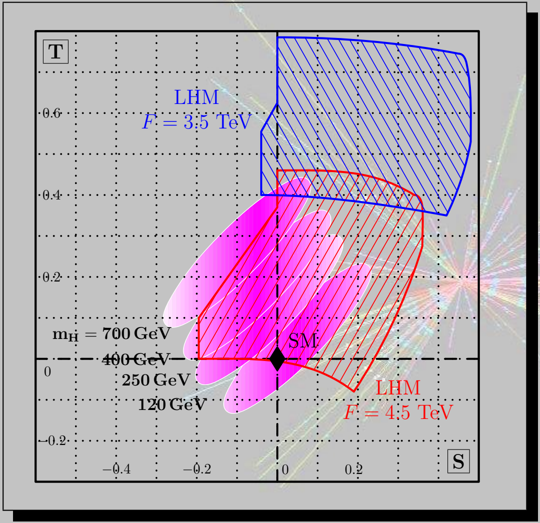
General models

- Triplet sector: (almost) identical to Littlest Higgs (ΔS only)
- More freedom in $U(1)$ sector: (ΔT)

EW Precision Observables



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

$$\Delta S = \frac{1}{12\pi} \ln \frac{m_H^2}{m_0^2}$$

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

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

Making the Higgs heavier reduces amount of fine-tuning

Direct Searches

- **Heavy Gauge Bosons:** Detection:

  Resonance in $e^+e^- \to f\bar{f}$, Drell-Yan $\Rightarrow$ Tevatron: $M_{B'} \gtrsim 650$ GeV

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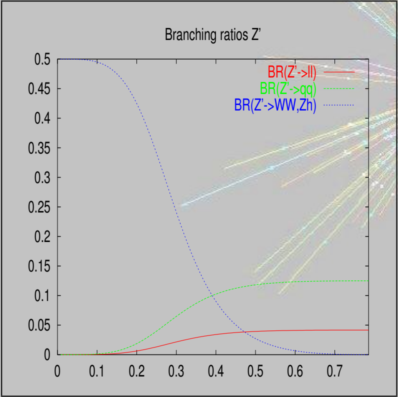

Total width Z', fixed $M_{Z'}$:

$$\Gamma_{Z'} = \frac{g^2}{96\pi}\left(\cot^2 2\phi + 24\tan^2\phi\right) M_{Z'}$$

Determination of $\mathbf{F}$, $\mathbf{c}$, $\mathbf{s}$

$\mathcal{O}(10^2)$ lepton events
@ LHC w. 300 fb^{-1}

Heavy Scalars:

- Φ_P : $e^+e^-, q\bar{q} \to \Phi_P h$, $\Phi_P \to h Z_L$
- $\Phi^\pm$: $e^+e^-, q\bar{q} \to \Phi^+ W_L^-$, $\Phi^\pm \to W_L Z_L$
- $\Phi^{\pm\pm}$: $e^-e^- \to \nu\nu\Phi^{--}$, $\Phi^{\pm\pm} \to W_L^- W_L^-$
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- **Heavy Quarks:**

T production @ LHC: $bq \to T q'$

Decay $T \to W_L^+ b, th, tZ$ Perelstein/Peskin/Pierce, 2003

Total cross section

$$\Gamma_T = m_T \lambda_T^2/(16\pi)$$

BRs (limit $g \to 0$):

$$\Gamma(T \to th) \approx \Gamma(T \to tZ) \approx \frac{1}{2}\Gamma(T \to bW^+) \approx \frac{m_T \lambda_T^2}{64\pi}$$

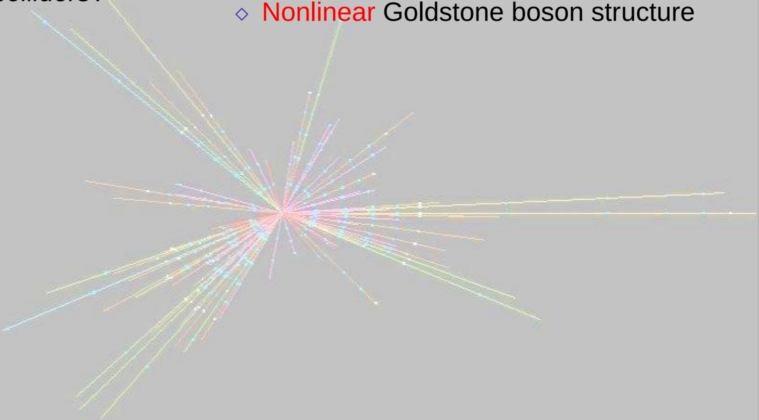
Determination of $\mathbf{m_T}, \lambda_T$

Reconstruction of LHM

How to unravel the structure of LHM @ colliders?

Kilian/JR, 2003; Han et al., 2005

- Symmetry structure
  $\Rightarrow$ Quadr. Div. Cancell.
- Nonlinear Goldstone boson structure



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Vectors:

- Direct Search (LHC) M_V, F, c, c'
- ILC: Contact Terms $e^+e^- \to \ell^+\ell^-, [\nu\bar{\nu}\gamma] \Rightarrow M_{B'} \lesssim 10[5]$ TeV
- Higgsstr., WW fusion: $HZff$, $HWff$ angular distr./energy dependence $\Rightarrow f_{VJ}^{(1/3)}$
- Check from TGC (ILC: per mil precision), GigaZ $\Rightarrow f_{JJ}^{(3)}$

Combining $\Rightarrow$ Determination of *all* coefficients in the gauge sector

Scalars:
Affected by scalars and vectors

- ΔT, $f^{(1)}_{VV}$, B' known $\Rightarrow (\lambda_{2\phi}/M^2_\phi)^2$
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- Higgs BRs $\Rightarrow f^{(1)}_{VV}, f^{(3)}_{VV}$; (take care of t)
  $f^{(3)}_{VV}$ **Goldstone contr.** $\Rightarrow$ **Evidence for nonlinear nature**
- HH production $\Rightarrow f_{h,3}$ (difficult!)

LHC $\bowtie$ ILC $\Rightarrow$ 1-2 % accuracy @ Higgs measurements **Reconstruction of scalar sector** up to $F \sim 2$ TeV

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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

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Include all observables in a combined fit if Little Higgs signals are found (sufficient data from LHC and ILC)

Pseudo Axions in LHM

Kilian/Rainwater/JR, 2004

- broken diagonal generator: η in QCD; *couples to fermions as a pseudoscalar*, behaves as a axion
- analogous particles: techni-axion, topcolor-axion, (N)MSSM-axion

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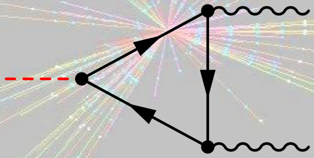
QCD-(PQ) axion: $\mathcal{L}_{\text{Ax.}} = \frac{1}{\Lambda} \frac{\alpha_s}{8\pi^2} A_g \eta G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad \tilde{G}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} G_{\rho\sigma}$

Anomalous $U(1)_\eta$:



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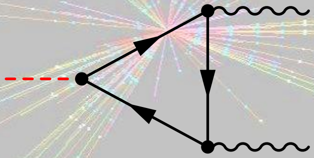

- **explicit symmetry breaking** $\Rightarrow m_\eta$ and $g_{\eta\gamma\gamma}$ independent $\Rightarrow$ axion bounds *not applicable*
- *no new hierarchy problem* $\Rightarrow m_\eta \lesssim v \sim 250\,$GeV
- η EW singlet, couplings an to SM particles v/F suppressed

Example: Simple Group Model

Scalar Potential: $\mu \Phi_1^\dagger \Phi_2 +$ h.c. + Coleman-Weinberg pot.:

$$\boxed{m_\eta \; = \; \sqrt{\kappa}\,\mu \; \geq \; \sqrt{2}\,\mu} \qquad m_H^2 = -2(\delta m^2 + m_\eta^2)$$

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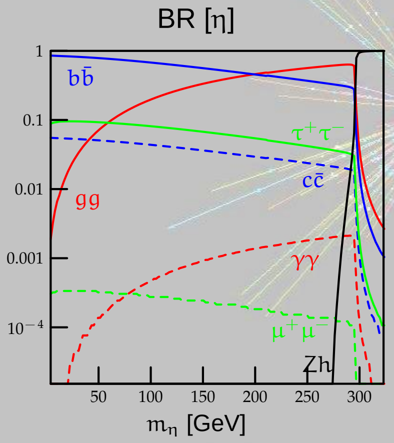


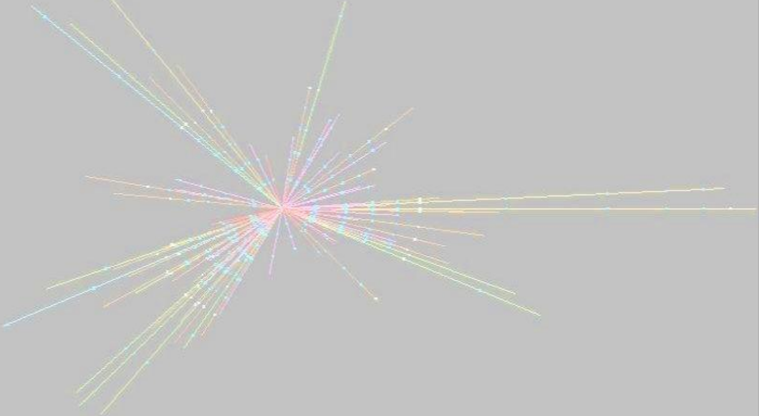
new Higgs decays ($H \to Z\eta$, $H \to \eta\eta$)

BR$(H \to \eta\eta) < 10^{-4}$ [~ 5–10% OSG]

m_H[GeV]	m_η[GeV]	BR$(Z\eta)$
341	223	0.1 %
375	193	0.5 %
400	167	0.8 %
422	137	1.0 %
444	96	1.2 %
464	14	1.4 %

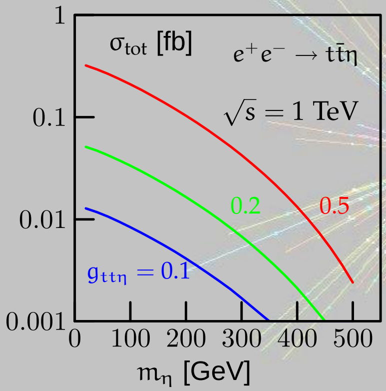
Pseudo Axions at LHC and ILC

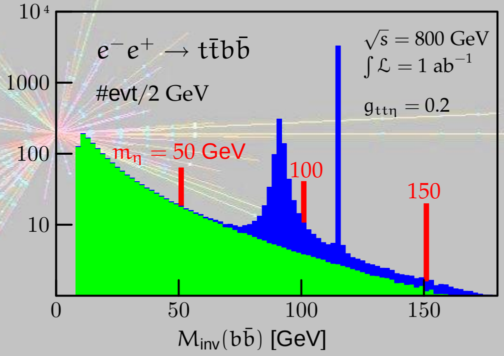
- LHC: **Gluon Fusion** (axial $U(1)_\eta$ anomaly), Peak in diphoton spectrum



Pseudo Axions at LHC and ILC

- LHC: **Gluon Fusion** (axial $U(1)_\eta$ anomaly), Peak in diphoton spectrum
- ILC: **associated production** Problem: Cross section vs. bkgd.

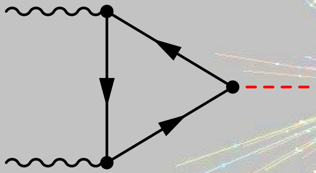




Possibility: $Z^* \to H\eta$ (analogous to A in 2HDM) Kilian/JR/Rainwater (in prep.)

Pseudo Axions at the Photon Collider

- Photon Collider as precision machine for Higgs physics (s channel resonance, anomaly coupling)



- S/B analogous to LC
- η in the μ model with (almost) identical parameters as A in MSSM
  ($\hookrightarrow$ Mühlleitner et al. (2001))

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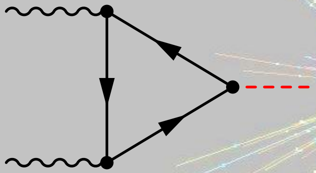

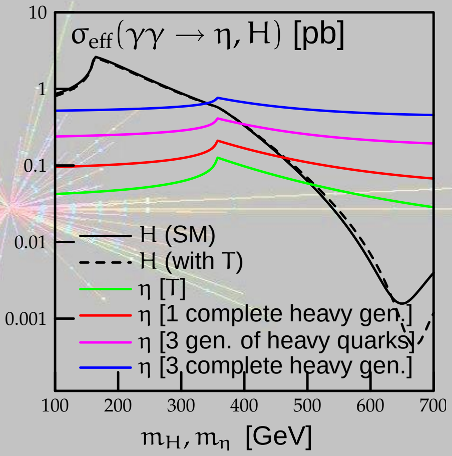

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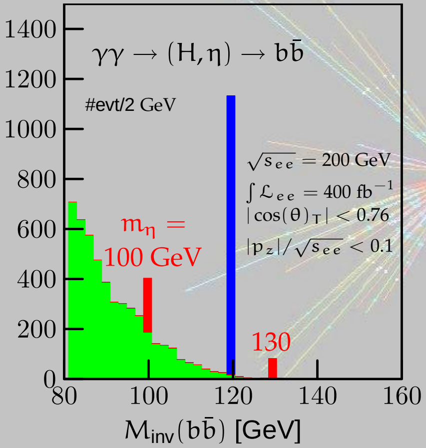
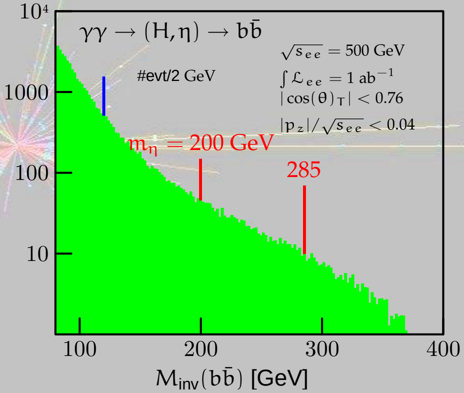
$g_{bb\eta} = 0.4 \cdot g_{bbh}$

m_η	100	130	200	285
$\Gamma_{\gamma\gamma}$[keV]	0.15	0.27	1.1	3.6





T parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005

- T parity: $T^a \to T^a, \quad X^a \to -X^a$, automorphism of coset space
- analogous to R parity in SUSY, KK parity
- Bounds on f relaxed, *but:* pair production!
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

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Littlest Higgs: A' LTP

$W', Z' \sim$ 650 GeV

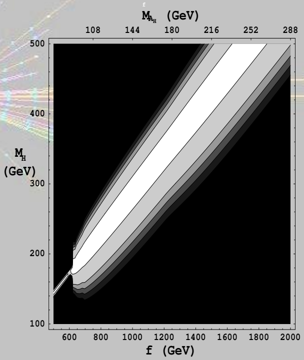
$\Phi \sim$ 1 TeV

$T, T' \sim$ 0.7-1 TeV

Annihilation:

$A'A' \to h \to WW, ZZ, hh$

0/10/50/70/100



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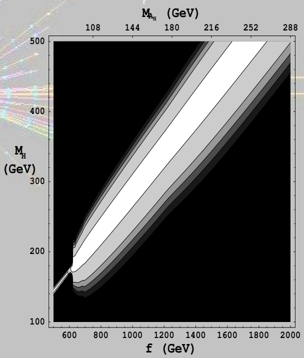

- T parity Simple Group model: Pseudo-Axion η LTP

Kilian/Rainwater/JR/Schmaltz

Outline

Hierarchy Problem, Goldstone-Bosons and Little Higgs

- Higgs as Pseudo-Goldstone Boson
- Nambu-Goldstone Bosons
- The Little Higgs mechanism

Examples of Models

Phenomenology

- For example: Littlest Higgs
- Neutrino masses
- Effective Field Theories
- Electroweak Precision Observables
- Direct Searches
- Reconstruction of Little Higgs Models
- Pseudo Axions in LHM
- T parity and Dark Matter

Conclusions

Conclusions

Little Higgs elegant alternative to SUSY Gauge/Global Symmetry structure stabilizes EW scale

- Generics: new heavy gauge bosons, scalars, quarks

Little Higgs *in accord w EW precision observ.* **w/o Fine Tuning** (M_H!)

- New developments: Pseudo-Axions, T-parity, LH Dark Matter

UV embedding, GUT, Flavor ?

***Clear* experimental signatures:**
direct search [Gauge & Top sector, LHC (ILC)] $\longleftrightarrow$
precision observables [Gauge, Scalar, Top sector ILC (LHC)]

Strategy for Reconstruction by *Complementarity* of ILC & LHC