A (critical) overview of electroweak symmetry breaking

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Outline

• The standard Higgs, big vs. little hierarchy

• EWSB in supersymmetry & little hierarchy of MSSM
  • Buried Higgs
  • Bigger quartic (D-terms, NMSSM, fat higgs, …)

• Strong dynamics & related models
  • Technicolor
  • Monopole condensate
  • Warped extra dimensions
  • Realistic RS, Higgsless
  • Composite Higgs
  • Little Higgs
The SM, big vs. little hierarchy

• Standard higgs mechanism very successful

• EWP analysis suggests light higgs boson

• Hard to understand how higgs remains light, sensitive to any new physics…

\[ \Delta m_H^2 \propto \frac{g^2}{16\pi^2} \Lambda^2 \]

(From GFITTER group at this conference)
• This is usually referred to big hierarchy problem: why is \( m_h \ll \Lambda \)

• Usual resolution: \( \Lambda \sim 1 \text{ TeV} \), where new physics shows up that makes higgs insensitive to higher scales (SUSY partners, strong dynamics, …)

• “Little hierarchy”: why have we not seen any trace of indirect hint for these new particles?

• In most models EWP forces new particles more like 5-10 TeV, a new tuning of \( \sim 1 \% \) is emerging
• Called “LEP paradox” Barbieri & Strumia

• Suppression scale of higher dim. op’s (~ masses of heavy particles) must be > 1 TeV

<table>
<thead>
<tr>
<th>Dimensions six operators</th>
<th>$m_h = 115 \text{ GeV}$</th>
<th>$c_i = -1$</th>
<th>$c_i = +1$</th>
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<tbody>
<tr>
<td>$(H^\dagger \tau^a H)W^a_{\mu\nu}B_{\mu\nu}$</td>
<td>9.7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>H^\dagger D_\mu H</td>
<td>^2$</td>
<td>4.6</td>
</tr>
<tr>
<td>$\frac{1}{2}(\bar{L}<em>{\gamma</em>{\mu}}\tau^a L)^2$</td>
<td>7.9</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>$i(H^\dagger D_\mu \tau^a H)(\bar{L}<em>{\gamma</em>{\mu}}\tau^a L)$</td>
<td>8.4</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>$i(H^\dagger D_\mu \tau^a H)(\bar{Q}<em>{\gamma</em>{\mu}}\tau^a Q)$</td>
<td>6.6</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>$i(H^\dagger D_\mu H)(\bar{L}<em>{\gamma</em>{\mu}} L)$</td>
<td>7.3</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td>$i(H^\dagger D_\mu H)(\bar{Q}<em>{\gamma</em>{\mu}} Q)$</td>
<td>5.8</td>
<td>3.4</td>
<td></td>
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<tr>
<td>$i(H^\dagger D_\mu H)(\bar{E}<em>{\gamma</em>{\mu}} E)$</td>
<td>8.2</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>$i(H^\dagger D_\mu H)(\bar{U}<em>{\gamma</em>{\mu}} U)$</td>
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<td>3.3</td>
<td></td>
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<tr>
<td>$i(H^\dagger D_\mu H)(\bar{D}<em>{\gamma</em>{\mu}} D)$</td>
<td>2.1</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

(Barbieri, Strumia `99)

• SUSY: somewhat special, R-parity protects from tree-level EWP corrections, $m_{\text{SUSY}}$ can be lower, BUT…
I. The little hierarchy in the MSSM

• In SUSY: 2 Higgs doublets $H_u, H_d$

• Only source of quartic is due to “D-terms”: the scalar terms needed to supersymmetrize gauge interactions

\[
V(H_u, H_d) = (m_{H_u}^2 + \mu^2)|H_u|^2 + (m_{H_d}^2 + \mu^2)|H_d|^2
- B_\mu(H_uH_d + \text{h.c.}) + \frac{g^2}{2}(H_u^\dagger \tau H_u + H_d^\dagger \tau H_d)^2 + \frac{g'^2}{2}(H_u^\dagger H_u - H_d^\dagger H_d)^2
\]

• Higgs potential:

• Minimizing this:

\[
M_Z^2 = 2 \left( \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \right)
\]
Expression for Higgs mass (at large $\tan \beta$):

$$m_{Higgs}^2 = M_Z^2 + \frac{3m_t^2 \lambda_t^2}{4\pi^2} \log \frac{m_{\tilde{t}}}{m_t}$$

Need $m_{Higgs} > 114$ GeV

Need large stop-top splitting

But contribution to $m_{Hu}^2$:

$$m_{Hu}^2 = m_0^2 - \frac{3\lambda_t^2 m_{\tilde{t}}^2}{4\pi^2} \log \frac{\Lambda_{UV}^2}{m_{t}^2}$$

And for large $\tan \beta$ $M_Z^2 \sim -2m_{Hu}^2$

Implies <1% tuning generically (large $A_t$ can help a bit)
Possible ways out:

- Higgs is lighter than LEP bound but has weird decays

- Need additional contribution to quartic, eg.
  - Additional D-term from bigger group
  - Bigger NMSSM-like quartic (fat Higgs)
Hiding the Higgs at LEP

(Dobrescu, Matchev; Dermisek, Gunion; Chang, Fox, Weiner;...)

• Higgs searched for in many channels at LEP

• For SM, MSSM $m_h > 114$ GeV

• If Higgs has unusual decays, then might need dedicated search that was not (fully) done at LEP

• The situation ~ 1 year ago:
### LEP Higgs bounds

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Limit (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow b\bar{b}, \tau\bar{\tau}$</td>
<td>115</td>
</tr>
<tr>
<td>$h \rightarrow jj$</td>
<td>113</td>
</tr>
<tr>
<td>$h \rightarrow \gamma\gamma$</td>
<td>117</td>
</tr>
<tr>
<td>$h \rightarrow WW^<em>, ZZ^</em>$</td>
<td>110</td>
</tr>
<tr>
<td>$h \rightarrow$ invisible</td>
<td>115</td>
</tr>
<tr>
<td>$h \rightarrow \eta\eta \rightarrow 4b$</td>
<td>110</td>
</tr>
<tr>
<td>$h \rightarrow \eta\eta \rightarrow 4\tau, 4c, 4g$</td>
<td>86</td>
</tr>
</tbody>
</table>

This is low enough to remove the little hierarchy of SUSY – lots of models that try to use this
• Most popular possibility

\[ h \rightarrow 2A \rightarrow 4\tau \]

• Can be naturally obtained in NMSSM

• But: new LEP analysis from ALEPH excludes possibility when \( h \rightarrow 4\tau \) is \( \sim 100\% \)

(Dermisek, Gunion; Chang, Fox, Weiner)
ALEPH bound on $h \rightarrow 4\tau$ of order 105-110 GeV!

(Cranmer, Yavin, Beacham, Spagnolo, ALEPH collab. '09, see I. Yavin poster at this conference)
• Still possible: $h \rightarrow 4\tau$ around 50%, and the rest to jets

• Additional analysis of Cranmer et al. Aleph group under way to constrain $h \rightarrow 2\tau + 2j$ (and also $h \rightarrow 4j$ channels)

• For $h \rightarrow 4j$ and $h \rightarrow 2\tau + 2j$ jets are merged: need to use jet substructure to distinguish from QCD

(Dermisek, Gunion `10)
The updated bounds

<table>
<thead>
<tr>
<th>Decay channel</th>
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<tr>
<td>$h \rightarrow b\bar{b}, \tau\bar{\tau}$</td>
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<td>$h \rightarrow \eta\eta \rightarrow 4b$</td>
<td>110</td>
</tr>
<tr>
<td>$h \rightarrow \eta\eta \rightarrow 4\tau$</td>
<td>$105 - 110$</td>
</tr>
<tr>
<td>$h \rightarrow \eta\eta \rightarrow 4c, 4g$</td>
<td>86</td>
</tr>
</tbody>
</table>

Need to use $h \rightarrow 4j$ or more complicated final states if want to hide the higgs at LEP.
An interesting possibility: $h \rightarrow 4j$

- Already mentioned by Chang, Fox, Weiner & D. E. Kaplan et al.

- Simple realistic model “Buried higgs” based on SU(3)xU(1) extension of SM with global sym. breaking scale $f \sim 350$ GeV

- Leading higgs decay $h \rightarrow 2\eta$ where $\eta$ is an SU(2)xU(1) singlet pGB

- The $\eta$ decays via triangle diagrams to 2g

(Bellazzini, C.C., Falkowski, Weiler `09)
• The $h$ decays

LEP bound from $h \rightarrow bb$

• The $\eta$ decays

$f = 350$ GeV, $\mu_V = 500$ GeV, $M_c = 400$ GeV, $M_\tau = 200$ GeV
• $h \rightarrow 4g$ around 80% (the rest the SM $h \rightarrow 2b$)
• $h \rightarrow \gamma\gamma gg$ of order $10^{-4}$
• $h \rightarrow \tau\tau gg$ of order $10^{-3} - 10^{-5}$
• $h \rightarrow 4\mu$ and $h \rightarrow \tau\tau\mu\mu$ very suppressed...

• LEP bound: model indep. $m_h > 78$ GeV

• OPAL $h \rightarrow 2\eta \rightarrow 4j$ analysis (assuming $m_h < 86$ GeV):
Charming Higgs

• A variation of previous model where $\eta \rightarrow 2c$ is dominant

• $\eta$ does not have to be below 10 GeV

(Bellazzini, C.C., Falkowski, Weiler `09)
• $h \rightarrow 4j$ very difficult to discover at the LHC (buried in QCD background)

• Likely need jet substructure analysis or similar techniques to distinguish from background
  
  (Chen, Nojiri, Streethawong `10; Falkowski, Krohn, Shelton, Wang `10)

• Other interesting possibility:

  $h \rightarrow$ hidden sector $\rightarrow$ lepton jets

• Lots of non-isolated leptons – is it really viable at Tevatron?
  
  (Falkowski, Ruderman, Volansky, Zupan `10)
Other SUSY approaches

- **NMSSM**: quartic from $\lambda S H_u H_d$

- But $\lambda$ cannot be too large either to avoid Landau pole before $M_{\text{GUT}}$. Requires $m_h \approx 150$ GeV

- **Fat Higgs**: around Landau pole weakly coupled Seiberg-dual, can have $m_h \sim 400$ GeV (Harnik, Kribs, Larson, Murayama `03)

- **Dine-Seiberg-Thomas**: NMSSM-like effective theory
  
  $$W \supset \frac{1}{M} (H_u H_d)^2$$

  type term like when integrating out massive $S$
• Additional quartic from **extra D-term**

• Usually D-terms decouple if gauge breaking fully supersymmetric

• If $m_{\text{soft}} \sim$ VEV for field breaking the additional gauge symmetry D-term does not decouple

• Can raise Higgs mass to $\sim 400$ GeV

  (Batra, Delgado, Kaplan, Tait `03)
II. Models of strong dynamics

• Don’t necessarily need elementary Higgs to break symmetry

• Example: QCD

• Quark-antiquark (or LH and RH quarks) strongly attract, form vacuum condensate:

\[ \langle u_L u_R \rangle = \langle d_L d_R \rangle \sim f_\pi^3 \]

• This breaks EWS and gives mass to W, Z, just too small contribution

• Technicolor: new strong interaction with \( f_{TC} \sim v = 246 \) GeV. Scaled-up QCD
Issues with technicolor-like theories

• Electroweak precision: $S$-parameter usually too large (but not calculable). If like scaled-up QCD

$$S \sim 0.28 N_D \frac{N_{TC}}{3}$$

• Fermion masses: usually hard to get large enough top mass without also generating large FCNC’s

For $m_t$ need $\Lambda_F < 10$ TeV     To avoid FCNC $\Lambda_F > 10^4$ TeV

$$\frac{1}{\Lambda_F^2} \bar{q}q \bar{\psi} \psi$$  $$\frac{1}{\Lambda_F^2} \bar{q}q \bar{q}q$$
• **Walking technicolor:** large anomalous dimension for $\bar{\psi}\psi$ relieves some of the tension in $\Lambda_F$

• **Conformal technicolor:** can the anomalous dim. of $\bar{\psi}\psi$ be so large that $\bar{\psi}\psi$ is almost like a free field ($d \sim 1+\varepsilon$)? (Luty, Okui ‘04)

• Talk by V. Rychkov: upper bound on anomalous dimension from general principles (crossing)

• Can not sufficiently suppress FCNC’s w/o hierarchy hitting back… (Rattazzi, Rychkov, Tonni, Vichi ‘08–’10)
EWSB via monopole condensation

(C.C., Shirman, Terning `10)

• An interesting alternative to technicolor, no new gauge group, use strong interaction between monopoles of $\text{U}(1)_Y$

• Toy model:

<table>
<thead>
<tr>
<th></th>
<th>$\text{SU}(3)_c$</th>
<th>$\text{SU}(2)_L$</th>
<th>$\text{U}(1)^\text{el}_Y$</th>
<th>$\text{U}(1)^\text{mag}_Y$</th>
</tr>
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<tbody>
<tr>
<td>$Q$</td>
<td>$\square$</td>
<td>$\square$</td>
<td>$\frac{1}{6}$</td>
<td>3</td>
</tr>
<tr>
<td>$L$</td>
<td>1</td>
<td>$\square$</td>
<td>$-\frac{1}{2}$</td>
<td>$-9$</td>
</tr>
<tr>
<td>$\bar{U}$</td>
<td>$\square$</td>
<td>1</td>
<td>$-\frac{2}{3}$</td>
<td>$-3$</td>
</tr>
<tr>
<td>$\bar{D}$</td>
<td>$\square$</td>
<td>1</td>
<td>$\frac{1}{3}$</td>
<td>$-3$</td>
</tr>
<tr>
<td>$\bar{N}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>$\bar{E}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>
Possible condensates

• Assume: $\beta$-function of $U(1)_Y$ not much modified. Magnetic attraction becomes strong: condensate

• Condensate should not carry magnetic charge

• Have quantum number of Higgs

\[
\begin{align*}
Q\bar{D} &\sim (1, 2, \frac{1}{2}) \sim H, \quad Q\bar{U} \sim (1, 2, -\frac{1}{2}) \sim H^*; \\
L\bar{E} &\sim (1, 2, \frac{1}{2}) \sim H, \quad L\bar{N} \sim (1, 2, -\frac{1}{2}) \sim H^*.
\end{align*}
\]

• Assume some of these condensates generated

\[
\langle U_L\bar{U} \rangle \sim \langle D_L\bar{D} \rangle \sim \langle N_L\bar{N} \rangle \sim \langle E_L\bar{E} \rangle \sim \Lambda_{mag}^d
\]

• $\Lambda_{mag}$ is a dynamical of order few x 100 GeV
The Rubakov-Callan effect

- Angular mom. of EM. field: \( \mathbf{J} = q g \mathbf{n} \)
depends on direction from charge to pole

- In head-on scattering this direction changes, even though no force

- Spin of scattered fermion must also flip

- New 4-fermi op’s in modified model with \( U(1)_{EM} \)

\[
\lambda^{(u)}_{ij} u^i_R N_L \left( u^j_L N_R \right)^\dagger
\]

- After condensation large \( m_{\text{top}} \)
Phenomenology of Monocolor

• After EWSB theory vectorlike, expect monopoles to pick up mass of order $\Lambda_{\text{mag}} \sim 500$ GeV – TeV

• Not confined, behave like “ordinary” QED monopole

• No magnetic coupling to Z; electric coupling is there, expect EWPO (S,T) like a heavy fourth generation but magnetic contr. to $\gamma-\gamma$ 2pt function should be small

• **At LHC:** likely pair produced. Due to strong force strong attraction, will always annihilate at LHC. Large radiation, then annihilation. Lots of photons, some of them hard. Cross section $\sim$ pb (A. Weiler)
Warped extra dimension

- Metric exponentially falling
- Mass scales very different at endpoints
- Graviton peaked at Planck
- SM on IR brane

\[ ds^2 = \left( \frac{R}{z} \right)^2 (dx^2 - dz^2) \]

(Randall, Sundrum `99; Maldacena `97; ...
• Related to strong dynamics/technicolor models via AdS/CFT duality

• Fields peaked on UV: elementary (natural mass scale very large)

• Fields peaked on IR: composite of strong dynamics (natural mass scale low)

• If Higgs on IR brane: composite, natural scale TeV
The original RS model

Solves the hierarchy problem.
But: electroweak precision? If all fields on IR brane expect large EWP contributions, large FCNC’s

$R'/R \sim 10^{16}$
Realistic RS model

Still solves hierarchy problem since Higgs on IR
FCNC suppressed since fermions on UV
T-parameter can be protected via custodial sym.
The “canonical” realistic RS model

• Need to put fermions away from IR brane for FCNC
• To protect T-parameter need to include SU(2)\textsubscript{R} custodial symmetry

(Agashe, Delgado, May, Sundrum, `03)
• $S \sim 12\pi \frac{v^2}{m_{KK}^2}$ Bound $m_{KK} > 3$ TeV
• $T$ parameter at tree level suppressed

(Carena, Delgado, Ponton, Tait, Wagner)

• Signals:
• Light top partners
• 3 TeV KK gluon, but mostly coupled to $t_R$

(From Agashe, Belyaev, Krupyvnickas, Perez, Virzi; see also Davoudiasl, Randall, Wang)
• Little hierarchy: NOT solved here either

• Cutoff scale: \[ \Lambda \sim \frac{16\pi^2}{g^2 R' \log \frac{R'}{R}} \sim 10 - 100 \text{ TeV} \]

• Natural Higgs mass \( m_H \sim \Lambda/(4\pi) > 1 \text{ TeV} \)

• Can give theory of flavor (talks by Neubert, Soni)

• To also solve little hierarchy:
  Higgsless (gauge-phobic)
  Pseudo-Goldstone Higgs
Higgsless models

(C.C., Grojean, Murayama, Pilo, Terning  `03)

• Realistic RS: little hierarchy problem

• Simply let Higgs VEV to be big on IR brane

• Higgs VEV will repel gauge boson wave functions, Higgs will simply decouple from theory

Same as for RS, except Higgs VEV $\rightarrow \infty$ on IR brane
• In practice, just implies BC’s for gauge fields

• Typical mass spectrum:

\[
M_W^2 = \frac{1}{R'^2 \log \left( \frac{R'}{R} \right)}
\]

• BUT: w/o higgs at \( \Lambda = 4\pi M_W/g \sim 1.6 \text{ TeV} \) unitarity would be violated??

• Exchange of KK gauge bosons restores unitarity

• Implies sum rules among masses and couplings

\[
\begin{align*}
g_{WWWW} &= g_{WW\gamma}^2 + g_{WWZ}^2 + \sum_i g_{WWZ_i}^2 \\
\frac{4}{3} g_{WWWWW} M_W^2 &= g_{WWZ}^2 M_Z^2 + \sum_i g_{WWZ_i}^2 M_{Z_i}^2
\end{align*}
\]
LHC predictions of Higgsless

(Birkedal, Matchev, Perelstein `04)

- WW scattering not that different from SM
- WZ scattering is very different (new peak due to W’)

\[ WZ \rightarrow WZ \]
• Coupling to fermions not that small, DY will still be leading channel at LHC

Example $Z' \rightarrow l^+l^-$ DY at LHC for a sample point

(Martin and Sanz `09)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (pb)</th>
<th>$\epsilon$</th>
<th>$#$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_i \rightarrow \ell^+\ell^-$</td>
<td>0.045</td>
<td>0.34</td>
<td>152</td>
</tr>
<tr>
<td>$Z \rightarrow \ell^+\ell^-$</td>
<td>1.58</td>
<td>0.032</td>
<td>521</td>
</tr>
</tbody>
</table>
Electroweak precision tests & higgsless

• Dual to technicolor, S usually too large:

\[ S \sim \frac{N}{\pi} \sim \frac{12\pi}{g^2} \frac{M_W^2}{m_{\rho}^2} \]

• S depends on fermions: if elementary too big, if Composite: large negative. Can cancel in between

• S is sufficiently small
• KK modes sufficiently heavy
• Couplings to KK modes small

\[ \text{(Cacciapaglia, C.C., Grojean, Terning, `04)} \]

BUT: 1% level tuning in c
Composite pGB Higgs models

• In technicolor (or Higgsless): S too large: not enough separation between $m_W$ and $m_\rho$

• Other possibility: still strong dynamics, but scales separated more $m_\rho \gg m_W$

• If strong dynamics produces a composite Higgs

• But then Higgs mass expected at the strong scale

• To lower Higgs mass: make it a Goldstone boson

• Higgs mass due to 1-loop electroweak corrections
The minimal example (MCH)

- A 5D model (doesn’t have to be)
- Sym. breaking pattern:
  - SO(5) × U(1) global → SO(4) × U(1) global
- SM subgroup gauged

Higgs potential:

\[ V(h) = 0 \cdot |h|^2 + 0 \cdot |h|^4 + \frac{g^2}{16\pi^2} f^4 \cos^n \left( \frac{|h|}{f} \right) \]

- Tree-level vanishes due to PGB nature
- Generic PGB pot.
• The main difficulty: in Higgs potential everything radiative, again no natural separation between $v$, $f$

\[ m_h^2 \propto \frac{g^2}{16\pi^2} f^2 \]  

\[ \lambda \propto \frac{g^2}{16\pi^2} \]

• Generically would expect $v \sim f$. Need some tuning to avoid

(Carena, Ponton, Santiago, Wagner `07; C.C., Falkowski, Weiler `08)
Experimental consequences of pGB MCH

• Try to find states from extra sector: similar to RS searches ($m_\rho >3$ TeV, KK gluon,...)

• Higgs properties modified due to compositeness ("Higgs form factors")

(Giudice, Grojean, Pomarol, Rattazzi `07)
Little Higgs models

(Arkani-Hamed, Cohen, Katz, Nelson `02)

• Higgs is Goldstone again

• Added ingredient: “collective breaking”: need at least two couplings simultaneously to break symmetry

• Mass suppressed, but quartic is large

\[ m_h^2 \propto \frac{g^2}{16\pi^2} f^2 \]

\[ \lambda \propto g^2 \]

• Now \( \langle h \rangle \sim f/(4\pi) \), really no tuning to get little hierarchy

• But needs lots of additional states to achieve collective breaking, issue with EWP again…
• For collective breaking need new light particles
  ~ 1 TeV, “little partners”

• But new particles themselves will contribute to EWPO’s

• Will force generically \( f > 4 \) TeV

(C.C., Hubisz, Kribs, Meade, Terning `02)
• Way out: ensure no tree-level EWP contribution

• New $Z_2$ parity needed dubbed T-parity (Cheng, Low `03)

• However, full model quite complicated (C.C., Heinonen, Perelstein, Spethmann `08)

• For example, one generation…

<table>
<thead>
<tr>
<th></th>
<th>$SU(5)$</th>
<th>$SU(2)_3$</th>
<th>$U(1)_3$</th>
<th></th>
<th>$SU(5)$</th>
<th>$SU(2)_3$</th>
<th>$U(1)_3$</th>
<th></th>
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<th>$U(1)_3$</th>
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</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>□</td>
<td>1</td>
<td>+2/3</td>
<td>$Q'_1$</td>
<td>□</td>
<td>1</td>
<td>−2/3</td>
<td>$L_1$</td>
<td>□</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>□</td>
<td>1</td>
<td>+2/3</td>
<td>$Q'_2$</td>
<td>□</td>
<td>1</td>
<td>−2/3</td>
<td>$L_2$</td>
<td>□</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
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<td>□</td>
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<td>$q'_3$, $q''_3$</td>
<td>1</td>
<td>□</td>
<td>+1/6</td>
<td>$\ell_3$</td>
<td>1</td>
<td>□</td>
<td>+1/2</td>
</tr>
<tr>
<td>$q_4$</td>
<td>1</td>
<td>□</td>
<td>−7/6</td>
<td>$q'_4$</td>
<td>1</td>
<td>□</td>
<td>+7/6</td>
<td>$\ell_4$</td>
<td>1</td>
<td>□</td>
<td>−1/2</td>
</tr>
<tr>
<td>$q_5$</td>
<td>1</td>
<td>□</td>
<td>−7/6</td>
<td>$q'_5$</td>
<td>1</td>
<td>□</td>
<td>+7/6</td>
<td>$\ell_5$</td>
<td>1</td>
<td>□</td>
<td>−1/2</td>
</tr>
<tr>
<td>$U_{R1}$</td>
<td>1</td>
<td>1</td>
<td>−2/3</td>
<td>$U'_{R1}$</td>
<td>1</td>
<td>1</td>
<td>+2/3</td>
<td>$E_{R1}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$U_{R2}$</td>
<td>1</td>
<td>1</td>
<td>−2/3</td>
<td>$U'_{R2}$</td>
<td>1</td>
<td>1</td>
<td>+2/3</td>
<td>$E_{R2}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$u_R$</td>
<td>1</td>
<td>1</td>
<td>−2/3</td>
<td></td>
<td>$e_R$</td>
<td>1</td>
<td>1</td>
<td>+1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| $d_R$ | 1       | 1         | +1/3     |       | $(\nu_R$ | 1       | 1         | 0      | )
Summary

• Don’t understand how higgs is light and still no trace of new physics

• In SUSY calls for extension of MSSM
  • Hidden higgs
  • Extra quartic

• Strong dynamics models: EWP usually issue
  • Warped extra dimension (composite Higgs, higgsless)
  • Little higgs
  • Technicolor, monopole condensation,…

• None of them fully convincing

• LHC should settle these by ICHEP 2014 (2012?)