Unscrambling New Models

- The case for new physics
- Composite Higgs models
  - $\rightarrow$ Top-quark Seesaw Theory and alternatives
  - $\rightarrow$ Standard Model in Extra Dimensions
- Conclusions for the Linear Collider

Talk at LCWS 2000 - Fermilab, October 24, 2000

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Fundamental particles observed so far:

$$SU(3)_C \times SU(2)_W \times U(1)_Y$$

3 generations of quarks and leptons

THERE MUST BE SOMETHING ELSE!

Otherwise,

WW **scattering violates unitarity above** $1-3$ **TeV.**

There exist some forms of matter which are yet unknown and are within the reach of future collider experiments.

Finding them is definitely worth billions of dollars.

Standard Model

Higgs doublet gets a VEV $\Rightarrow W, Z$, fermion masses

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + iG^0\right) \end{pmatrix}$$

≈ 246 GeV

longitudinal Z

Higgs boson

LEP: $M_h > 113$ **GeV**

Unitarity and triviality bound: $M_h \lesssim 500 - 800$ **GeV**

Electroweak data: $M_h < 170$ **GeV at 95%CL**

< 270 **GeV at 99%CL**

Highly sensitive to physics beyond the Standard Model

The electroweak data confirms that there is new physics to be discovered (at least one Higgs boson.)

Theories without a Higgs boson

The effects of the Higgs boson on the electroweak data may be mimicked by some new physics at the TeV scale.
(e.g., Bagger, Falk, Swartz, hep-ph/9908327)

Building models of this sort is a challenge.

Technicolor

Unbroken, non-Abelian gauge symmetry.

Strongly-coupled interaction at ~ 1 TeV.

New chiral fermions under the $SU(2)_W$ symmetry.

Many new chiral fermions: ruled-out by the electroweak data if they are weakly coupled or if the dynamics is QCD-like.

Technicolor interactions are nonperturbative at the electro-weak scale, and the dynamics may be different than in QCD.

Hard to tell whether particular models are consistent with the electroweak data. If they are consistent, then:

- **Experimental test: WW scattering at $\sqrt{s} > 1$ TeV**
- **At low energy: potentially light spinless particles (pseudo-Nambu-Goldstone bosons).**

Rest of this talk: assume that a Higgs boson exists.

Theories with a Higgs boson

Hierarchy problem: **why $v/M_{\mathrm{Planck}} \sim 10^{-16}$?**

Answer #1:

v is controlled by the supersymmetry breaking scale *and* **supersymmetry is broken dynamically.**

(MSSM, NMSSM, etc. *see R. Godpole's talk)*

Answer #2:

Gravity is modified at short distance, so that it becomes strongly-coupled above $1 - 10$ TeV.

(Known cases require extra spatial dimensions accessible to gravitons, *see N. Arkani-Hamed's talk)*

Answer #3:

The Higgs doublet is no longer a physical degree of freedom above $\sim 1 - 10$ TeV.

(Composite Higgs models)

Composite Higgs Models

Have a decoupling limit in which

the low-energy theory is

given by the Standard Model

$\Rightarrow$ manifestly consistent with

the electroweak data!

1. Bottom-up approach to Higgs compositeness

At $\mathcal{O}(100)$ GeV:

$$\mathcal{L} = -\underbrace{\frac{\lambda_h}{2}}_{\text{quartic Higgs coupling}}\left(H^\dagger H\right)^2 - {M_H^0}^2\left(H^\dagger H\right) - \underbrace{\lambda_t}_{\text{top-Yukawa coupling}}\,\overline{\psi}_L^3 t_R i\sigma^2 H^* + \text{h.c.}$$

Scale dependence: $\lambda_t(\mu)$, $\lambda_h(\mu)$.

If λ_t, $\lambda_h \sim 4\pi$ at $\mu = M_c$, then H is not likely to be a relevant degree of freedom above M_c.

$M_c =$ "compositeness scale".

Standard Model with $M_h \lesssim v$: the compositeness scale is too high, $M_c \gg 1$ TeV.

Physics beyond the Standard Model changes the RGE's and may bring M_c down to the TeV scale.

Generic example:

heavy vector-like fermions which couple to H.

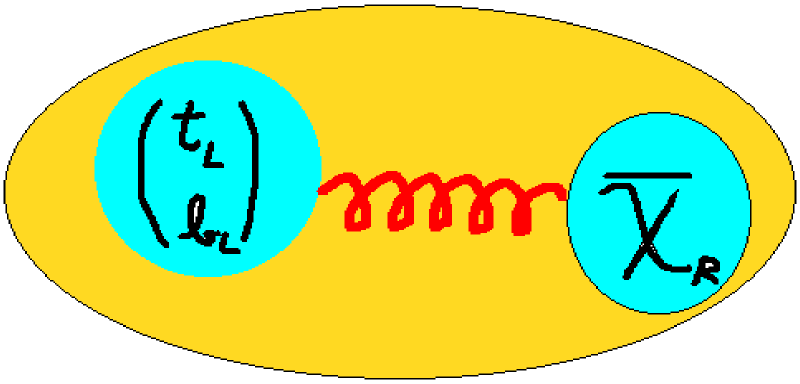
The left- and right-handed components have the same gauge quantum numbers.

contributions to the electroweak observables are suppressed by $m_t/m_{\text{vector-like}}$.

(as opposed to chiral fermions)

2. Top-down approach to Higgs compositeness

Specify some constituents and some binding interaction that produces a bound state with the quantum numbers of the Higgs doublet.



Typical constituents: **vector-like fermions, and some of the observed fermions**
(the top-quark is a prime candidate)

Typical binding interaction: **new heavy gauge bosons**

Top-Quark Seesaw Theory

Heavy vector-like quark (χ) which mixes with the top-quark.

χ_L, χ_R have same $SU(3)_C \times SU(2)_W \times U(1)_Y$ charges as t_R.

(B. Dobrescu, C. Hill, 1997)

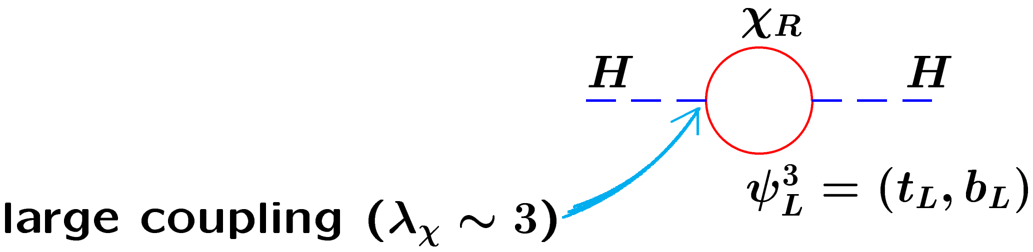
Fermion masses and Higgs Yukawa coupling:

$$\mathcal{L} = -\left(\overline{\psi}_L^3 \ , \ \overline{\chi}_L\right) \begin{pmatrix} 0 & \lambda_\chi H \\ m_{\chi t} & m_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + \mathrm{h.c.}$$

If $m_{\chi\chi} \gg m_{\chi t}, \lambda_\chi v$, **then:**

$$m_t \approx \frac{\lambda_\chi v}{\sqrt{2}} \frac{m_{\chi t}}{m_{\chi\chi}} \left[1 + O\left(m_{\chi t}^2 / m_{\chi\chi}^2\right)\right]$$

The Top-Quark Seesaw Theory is a class of Composite Higgs Models!



The Higgs couplings become non-perturbative at a scale in the TeV range ("compositeness scale").

$\Rightarrow$ **The Higgs doublet is a $\overline{\chi}_R \psi_L^3$ bound state**

(Chivukula, Dobrescu, Georgi, Hill, 1998)

Binding interaction:

a spontaneously-broken, strongly-coupled gauge interaction

E.g., topcolor: $SU(3) \times SU(3) \to SU(3)_C$ (C. Hill, 1991)
$+\ U(1)$'s to split the t and b masses

or larger gauge symmetry,

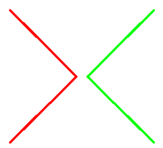
including gauged family or flavor symmetries

(G. Burdman, N. Evans, hep-ph/9811357)

Effects of heavy gauge boson exchanges below M_c:

four-quark interaction:
(attractive and non-confining)

$$\left(\overline{\psi}^{\mathbf{3}}_{L}\chi_{R}\right)\left(\overline{\chi}_{R}\psi^{\mathbf{3}}_{L}\right)$$



Top-Quark Seesaw Theory: above M_c

Open questions:

- topcolor breaking
  (similar with dynamical supersymmetry breaking)
- origin of flavor
  (same as in the Standard Model or the MSSM)
- embedding in string theory
- ...

Phenomenology of the Top-Quark Seesaw Theory

* At the electroweak scale: Standard Model + other potentially light particles

* At a few TeV: new quark(s), scalars from an extended composite Higgs sector

* High energy [above $M_c \sim \mathcal{O}(10)$ TeV]: interesting strong interactions

Alternative models

H. Georgi and A. K. Grant, hep-ph/0006050

"A topcolor jungle gym"

- all the light quarks carry topcolor
- there are many composite SU(2) doublets
- electroweak singlet quarks can be lighter than in the seesaw model.

R. S. Chivukula, A. G. Cohen, E. H. Simmons, hep-ph/9603311

"New Strong Interactons at the Tevatron ?,"

- colorons (strongly-interacting heavy gauge bosons) that couple to all three generations

H. He, T. Tait and C. P. Yuan, hep-ph/9911266

“New topflavor models with seesaw mechanism,”

• third family quarks, but not leptons, experience a new $SU(2)$ gauge interaction

A. Aranda and C. D. Carone, hep-ph/0007020
"Bosonic topcolor"

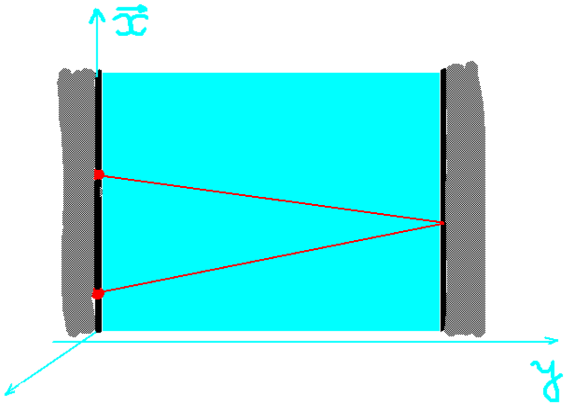
- electroweak symmetry breaking is triggered by new strong dynamics affecting the third generation
- transmitted to the light fermions via a fundamental Higgs doublet

M. A. Luty, J. Terning and A. K. Grant, hep-ph/0006224

"Electroweak symmetry breaking by strong supersymmetric dynamics at the TeV scale,"

- The MSSM Higgs sector is the dual of strongly coupled supersymmetric gauge theory.
- Elegant solution to the μ problem.

Standard Model in extra dimensions



$L_y \lesssim \mathcal{O}(1)$ TeV^{-1}

from the electroweak data

$(4+\delta)$-dimenional boson = 4D boson + tower of heavy bosons.

$(4+\delta)$-dimenional fermion = 4D chiral fermion + tower of heavy vector-like fermions.

QCD and top-quark in extra dimensions:

H.-C. Cheng, B.D., C. Hill, hep-ph/9912343

The Higgs doublet is a bound-state of the top-bottom left-handed doublet and the tower of KK modes of the right-handed top quark.

Binding provided by KK gluons.

Self-breaking of the standard model gauge symmetry

N. Arkani-Hamed, H.-C. Cheng, B.D., L. Hall, hep-ph/0006238

Observed fermions and gauge bosons in (two or four) extra dimensions:

$SU(3)_C \times SU(2)_W \times U(1)_Y$ **are attractive strongly-coupled interactions in certain fermion–anti-fermion channels.**

Standard Model quantum numbers $\Rightarrow$ most attractive channel is a composite up-type Higgs doublet:

scalar	made of	$SU(3)\times SU(2)\times U(1)$ representation	binding strength	relative binding for $\hat{g}_1 = \hat{g}_2 = \hat{g}_3$
$H_{\mathcal{U}}$	$\overline{\mathcal{Q}}_+\mathcal{U}_-$	$(1, 2, +1/2)$	$\frac{4}{3}\hat{g}_3^2 + \frac{1}{15}\hat{g}_1^2$	1
$H_{\mathcal{D}}$	$\overline{\mathcal{Q}}_+\mathcal{D}_-$	$(1, 2, -1/2)$	$\frac{4}{3}\hat{g}_3^2 - \frac{1}{30}\hat{g}_1^2$	0.93
$\tilde{q}$	$\overline{\mathcal{Q}}_+\mathcal{D}^c_-$	$(3, 2, +1/6)$	$\frac{2}{3}\hat{g}_3^2 + \frac{1}{30}\hat{g}_1^2$	0.5
X	$\overline{\mathcal{Q}}_+\mathcal{U}^c_-$	$(3, 2, -5/6)$	$\frac{2}{3}\hat{g}_3^2 - \frac{1}{15}\hat{g}_1^2$	0.43
$H_{\mathcal{E}}$	$\overline{\mathcal{L}}_+\mathcal{E}_-$	$(1, 2, -1/2)$	$\frac{3}{10}\hat{g}_1^2$	0.21
$\tilde{q}'$	$\overline{\mathcal{L}}^c_+\mathcal{U}_-$	$(3, 2, +1/6)$	$\frac{1}{5}\hat{g}_1^2$	0.14
$\tilde{q}''$	$\overline{\mathcal{L}}_+\mathcal{D}_-$	$(3, 2, +1/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07
X'	$\overline{\mathcal{Q}}^c_+\mathcal{E}_-$	$(3, 2, -5/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07

"String" scale input (in extra dimensions):

$\boldsymbol{SU(3)_C \times SU(2)_W \times U(1)_Y}$

+ 3 generations of quarks and leptons
+ flavor symmetry breaking

(no fundamental Higgs field)

TeV scale output:

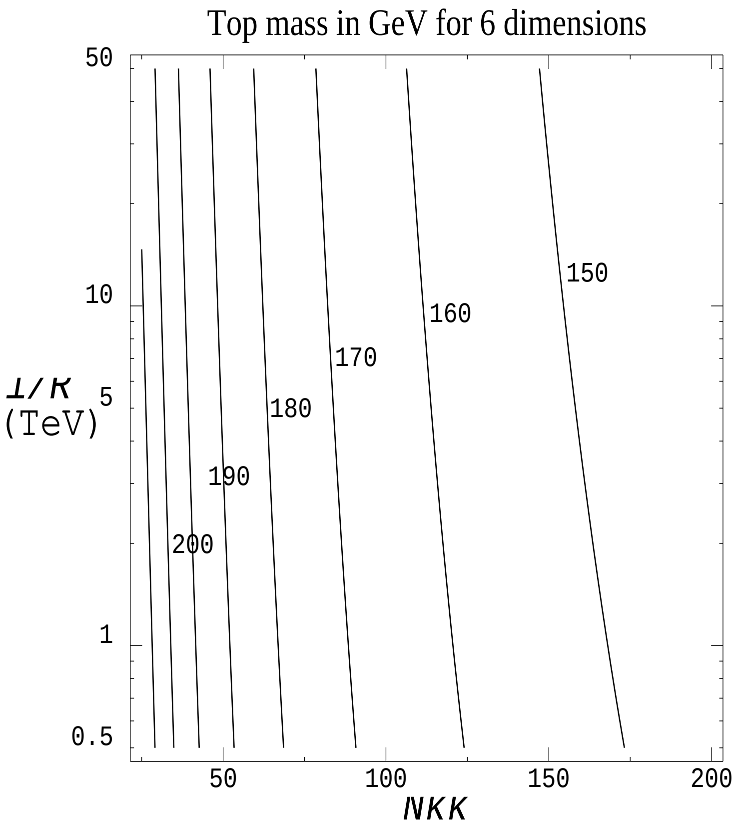
same as above
+ Electroweak symmetry breaking
+ Higgs boson
+ potentially light scalars

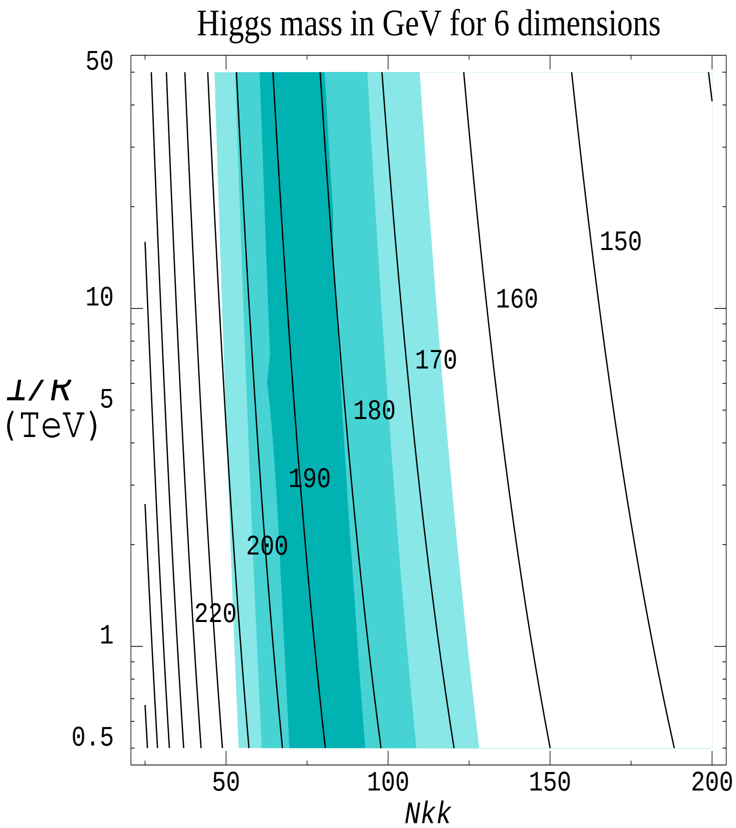
Standard Model & interesting phenomenology

Predictions of the Minimal Model

N. Arkani-Hamed, H.-C. Cheng, B.D., L. Hall, hep-ph/0006238

Infrared fixed points: m_t and M_h predictions from the Renormalization Group Equations are rather insensitive to the unknown effects of the strongly coupled theory at the ultraviolet scale.





2 extra dimensions: two Higgs doublet model, below the compactification scale

4 extra dimensions: two Higgs doublet model, and a bound state having the quantum numbers of a bottom-squark!

Conclusions for the Linear Collider

Good news: exciting possibilities for new physics.

Disentangling the new physics requires as many experiments as possible.

The precision offered by a linear e^+e^- collider is a great advantage.

1. *"Optimistic" scenario:*

Higgs boson below the WW threshold, allowing measurements of many branching fractions, *and* **several other new particles light enough to be produced.**

2. "Pessimistic" scenario:

The only new particle with mass below ~ 1 TeV is a Standard Model Higgs boson with a mass of ~ 250 GeV.

$\Rightarrow$ only the Higgs couplings to WW and ZZ may be measured.

Homework:

how precise are these measurements at a linear e^+e^- collider, and how do they compare with the LHC capability.

Even in the "pessimistic" case the LC is useful for confirming that this is the scenario realized in Nature.

Setting upper bounds on other Higgs couplings, such as $hb\bar{b}$, constrains alternatives to the Standard Model.

Rather than: "315 physicists failed to discover supersymmetry", we should say: "it has been found out that our world is less supersymmetric than previously known".

Establishing the Standard Model is perhaps the most important scientific achievement of our time.

Desirable features of the linear collider:

1. Flexibility

E.g., Universal Extra Dimensions

(*all* Standard Model fields propagate in δ extra dimensions of radius $1/R$)

T. Appelquist, H.-C. Cheng, B.D., in progress

Free parameters: $M_h, 1/R$, δ, and a cut-off scale M_s.

Kaluza-Klein number is conserved $\Rightarrow$ the usual constraints ($1/R > 3-5$ *TeV from tree level contributions to* $G_{\rm Fermi}$, *etc.*) do <u>not</u> apply!

Constraints on weak isospin violation from the electroweak data $\longrightarrow 1/R > 300$ GeV for $\delta = 1$
(the fit gives larger M_h when $1/R$ is small)

Kaluza-Klein modes are produced in pairs.

If $1/R = 300$ GeV and $M_h = 250$ GeV, then it would be best to run the LC at $\sqrt{s} > 600$ GeV.

If $1/R \gg 300$ GeV and $M_h = 160$ GeV, then it would be best to run the LC at $\sqrt{s} \approx 300$ GeV.

...

2. Upgradability

Many important questions to be addressed at higher energies:

* origin of flavor (quark and lepton masses, CKM elements, strong CP problem, why 3 generations)
* are there new gauge interactions?
* origin of supersymmetry breaking
* is quantum gravity relevant at a multi-TeV scale?
* are there extra dimensions?
* are the observed particles composite?
* ...

10 years from now the list of unanswered questions may be significantly longer.