Electroweak Symmetry Breaking at the Terascale

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Perspectives in Particle Physics
Stony Brook
We have a model….
And it works to the 1% level

- Consistency of precision measurements at multi-loop level used to constrain models with new physics
- If a new model predicts some deviation from the SM, it has to be small

This fit ASSUMES SM
The Standard Model is Phenomenally Successful

- SM breaks electroweak symmetry and generates mass for the W and Z with a single scalar doublet, $\Phi$

$$ V = \lambda \left( |\Phi|^2 - v^2 \right)^2 $$

$$ \lambda = \frac{M_h^2}{2v^2} $$

$$ v = \left( \sqrt{2} G_F \right)^{-1/2} $$

- Minimal approach

- Higgs couplings to fermions and gauge bosons fixed in terms of masses
Higgs Couplings Fixed

- **Standard model** is chiral theory
  - $t_L$ is SU(2) doublet, $t_R$ is SU(2) singlet
  - Quark and lepton masses are forbidden by SU(2) x U(1) gauge symmetry
  - Mass term connects left and right-handed fermions: $L \approx m_f \bar{f}_L f_R$
  - SU(2) Higgs allows gauge invariant coupling

\[ L \approx \frac{m_f}{v} \bar{f}_L \Phi f_R \]
Gauge Higgs Couplings

- Higgs couples to gauge boson masses

\[ (D_\mu \Phi)^\dagger (D_\mu \Phi) \rightarrow \left( \frac{g v}{2} \right)^2 W^+ \mu W^- \mu \left( 1 + \frac{h}{v} \right) + \ldots \]

- WWh coupling vanishes for v=0! Tests the connection of M_W to non-zero VEV
No Experimental Evidence for Higgs

- SM requires scalar particle, h, with unknown mass
  - $M_h$ is ONLY unknown parameter of EW sector
- Observables predicted in terms of: $M_Z$, $G_F$, $\alpha$, $M_h$
- Higgs and top quark masses give quantum corrections:
  \[ \approx M_t^2, \log (M_h) \]

Everything is calculable…. testable theory
Understanding Higgs Limit

Theory: Input $M_Z$, $G_F$, $\alpha$ → Predict $M_W$

![Graph showing W-boson mass and limits on $m_t$](image)

March, 08
LEP EWWG (March, 2008):

- $M_t = 172.6 \pm 1.4$ GeV
- $M_h = 87^{+36}_{-27}$ GeV
- $M_h < 160$ GeV (one-sided 95% cl)
- $M_h < 190$ GeV (Precision measurements plus direct search limit)

*Best fit in region excluded from direct searches*
Light Higgs Theoretically Attractive

- Extrapolate Higgs potential to high scale $\Lambda$

$$V = \lambda \left( \Phi^+ \Phi - v^2 \right)^2$$

- Standard Model is only consistent to GUT scale for small range of Higgs masses

- Heavy Higgs implies new physics at some low scale
Higgs at the Tevatron

NNLO or NLO rates

$M_h/2 < \mu < M_h/4$
Higgs Branching Ratios

\[ BR(H) \]

\[ M_H \text{ [GeV]} \]
SM Higgs Searches at Tevatron
Will Fermilab find the Higgs?

➢ It’s not just luminosity
Fermilab Sensitivity
Eagerly Awaiting the LHC

- Aug 1, first particles injected in LHC; Beam commissioning starts
- About 2 months to get collisions at 10 TeV
  - Few pb\(^{-1}\) before winter shut-down ~ end of November
- 2009 run will be at 14 TeV
  - 100 days of physics, 2-3 fb\(^{-1}\)
Large Rates for Higgs at the LHC
Improvement in LHC Higgs Studies

- Many analyses with full GEANT simulations
- New (N)NLO Monte Carlos for signal and background
- New approaches to match parton showers and matrix elements
  - ALPGEN MC+MLM matching
  - SHERPA MC
Golden Channel: $H \rightarrow ZZ \rightarrow 4$ leptons

- Need excellent lepton ID

- Below $M_h \sim 130$ GeV, rate is too small for discovery
SM Higgs, 2008

- Improvement in $\gamma\gamma$ channel from earlier studies
- Note: no tth discovery channel
Initial LHC Running

- Standard Model Higgs could be discovered with 5σ significance with 5 fb⁻¹
- 1 fb⁻¹ could exclude a Standard Model Higgs boson at 95% confidence level

Assumes detector is well understood
LHC Higgs Theory Challenges

- Precise predictions for Higgs production & backgrounds
- Understanding uncertainties on predictions
  - PDFs, scale uncertainties, model dependence
- Implementing NLO/NNLO in useful Monte Carlo programs
- Can we distinguish the Standard Model Higgs from all other possibilities?
Is it \textit{the} Higgs?

- Measure couplings to fermions & gauge bosons
  \[
  \frac{\Gamma(h \rightarrow b\bar{b})}{\Gamma(h \rightarrow \tau^+\tau^-)} \approx 3 \frac{m_b^2}{m_{\tau}^2}
  \]

- Measure spin/parity
  \[J^{PC} = 0^{++}\]

- Measure self interactions
  \[V = \frac{M_h^2}{2} h^2 + \frac{M_h^2}{2\nu} h^3 + \frac{M_h^2}{8\nu^2} h^4\]

Need good ideas here!
Higgs Couplings Difficult

Extraction of couplings requires understanding NLO QCD corrections for signal & background

Ratios of couplings easier

Logan, hep-ph/0409026
ILC Goal: Precision Measurements of Yukawa Couplings

- $\delta BR(h \rightarrow bb) \sim 2\%$ with $L = 500$ fb$^{-1}$
- New phenomena can cause variations of Yukawa couplings from SM predictions
Is the Higgs a Scalar?

- Weak boson fusion sensitive to tensor structure of HVV coupling
- Alternative structures from higher dimension operators

\[ T^{\mu\nu} = c_1 g^{\mu\nu} + c_2 \left( p_1 \cdot p_2 g^{\mu\nu} - p_1^\mu p_2^\nu \right) + c_3 \epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta} \]

- SM
- CP even
- CP odd

Loop induced
Need to Measure CP of Higgs

- Azimuthal angle between tagged jets sensitive to $c_2$, $c_3$
- Structure of dips only depends on hVV vertex tensor structure

Not so pretty if admixture of CP even/odd

Figy, Hankele, Klamke, Zeppenfeld, hep-ph/0609075
On Very General Grounds.....

- We expect a Higgs boson or something like it....

\[ A(W_L^+W_L^- \rightarrow Z_LZ_L) = -\frac{G_F E^2}{8\sqrt{2\pi}} \left( \frac{M_h^2}{E^2 - M_h^2} \right) \]

Unitarity → Light Higgs: \[ M_h < 800 \text{ GeV} \]

No Higgs: \[ \Lambda_c \sim 1.2 \text{ TeV} \leftarrow \text{Unitarity violation} \]

- Expect a light Higgs or New Physics below 1 TeV

Lee, Quigg, Thacker, PRD16, 1519 (1977)
Light Scalars are *unnatural*

- Higgs mass grows with high scale, $\Lambda$

\[(a \text{ priori } \Lambda = M_{\text{pl}})\]

\[\delta M_H^2 = \frac{G_F}{4\sqrt{2}\pi^2} \Lambda^2 \left( 6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2 \right)\]

\[= -\left( \frac{\Lambda}{0.7 \text{ TeV}} \right)^2 \left( \frac{200 \text{ GeV}}{200 \text{ GeV}} \right)^2\]

Points to 1 TeV as scale of new physics

$M_H \leq 200 \text{ GeV}$ requires $\Lambda \sim \text{TeV}$
Quantum Corrections Connect Weak and Planck Scales

Quantum corrections drag weak scale to Planck scale

Tevatron/LHC Energies

Weak
$10^3$ GeV

GUT
$10^{16}$

Planck
$10^{19}$ GeV

$\delta M_H^2 \approx M_{Pl}^2$
Standard Model is Effective Low Energy Theory

- We don’t know what’s happening at high energy
  - We haven’t found the Higgs!
- Effective theory approach: \[ L \approx L_{SM} + \sum_i f_i \frac{O_i}{\Lambda^2} + \ldots \]
- Compute deviations from SM due to new operators and compare with experimental data

LHC job is to probe physics which generates these operators
Little Hierarchy Problem

- Need new physics at 1 TeV to get light Higgs
- Much possible new physics is excluded at this scale
  - Look at possible dimension 6 operators
  - Many more operators than shown here
  - Limits depend on what symmetry is violated

<table>
<thead>
<tr>
<th>New operators</th>
<th>Experimental limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{(\bar{d}s)(\bar{s}d)}{\Lambda^2})</td>
<td>(\Lambda &gt; 1000) TeV</td>
</tr>
<tr>
<td>(\frac{m_b(s \sigma_{\mu\nu} F_{\mu\nu} b)}{\Lambda^2})</td>
<td>(\Lambda &gt; 50) TeV</td>
</tr>
<tr>
<td>(\frac{(h^+ D_\mu h)^2}{\Lambda^2})</td>
<td>(\Lambda &gt; 5) TeV</td>
</tr>
<tr>
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<td>(\Lambda &gt; 5) TeV</td>
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</tbody>
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New Physics must be at scale \(\Lambda > 5\) TeV

Schmaltz, hep-ph/0502182
Explosion of Creativity
Many New Models...

- **Supersymmetry**
  - Trusty standard
  - NMSSM, MSSM with CP violation

- **Little Higgs**
  - Higgs is pseudo Goldstone boson

- **Extra dimensions**
  - Higgs is component of gauge field in extra-D
  - Higgsless: Symmetry breaking from boundary conditions

- **Strong electroweak symmetry breaking**
  - Technicolor, top-color
  - .....
Precision Measurements in Models beyond the SM

- S,T,U approach assumes **new physics** is dominantly in gauge boson 2-point functions

- For example, parameterize:
  \[ M_W^2 = (\ldots)S + (\ldots)T + (\ldots)U \]

- Neglects box and vertex contributions

\[
\begin{align*}
\frac{\alpha}{4s_\theta^2c_\theta^2} S &= \frac{\Pi_{zz}(M_Z^2)}{M_Z^2} - \frac{\Pi_{zz}(0)}{M_Z^2} \\
\alpha T &= \frac{\Pi_{ww}(0)}{M_w^2} - \frac{\Pi_{zz}(0)}{M_Z^2}
\end{align*}
\]
Higgs Mass Limits \textit{ASSUME} Standard Model

- It’s easy to construct models which evade Higgs mass limits
- All you need is large $\Delta \rho = \alpha \Delta T$
  - Models typically have new particles.....
Light Higgs, But Not SM Higgs

- Could be 2-Higgs doublet model....
- Could be supersymmetry...

SUSY particles have mass of a few TeV, just the LHC scale!
The Higgs and the Dark Side

- SM has only 2 dimension 2 scalar operators: $\Phi^+\Phi$, $L^+L$
- Higgs could provide window to high scale hidden sector

\[ L \approx \frac{c_n}{\Lambda^n} |\Phi^+\Phi| O^{n-2} \]

- Such an operator could be generated by additional Higgs singlets or doublets which couple only to SM Higgs
Singlet/Inert Doublet

- New Higgs mixes with SM Higgs
  - Inert doublet, or 1 singlet, gives 2 neutral Higgs bosons: H, h
- New decay: $H \rightarrow hh$
- h could be dark matter candidate

Cao, Ma, Rajasekaran, arXiv:0708.2929
What if no Higgs?

- Technicolor models unitarize $WW$ scattering with $\rho$-like particle
- Extra dimension models have new possibilities for EWSB
  - Higgs could be 5th dimension of gauge field
  - Or….generate EWSB from boundary conditions on branes (Higgsless)
- Models generically have “tower” of Kaluza-Klein particles (massive vector particles): $V_n$
Experimental Signatures of Extra-D Higgsless Models

- Look for massive $W$, $Z$, $\gamma$ like particles in vector boson fusion
- Need small couplings to fermions to avoid precision EW constraints
- Narrow resonances in $WZ$ channel

LHC: $pp \rightarrow WZ + X$

Different resonance structure from SM!

Birkedal, Matchev, Perelstein, hep-ph/0412278
No light Higgs/No KK particles/No techni-$\rho$ Scenario

- No resonance
  - Effective Lagrangian couplings grow with energy
- Counting experiments
- Very hard!

Conclusion

Grannis, APS 2003