Electroweak Symmetry Breaking at the Terascale

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XIII Mexican School of Particles and Fields
The Standard Model is Phenomenally Successful

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

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

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

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

- Minimal approach
- Higgs couplings to fermions and gauge bosons fixed in terms of masses
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

This fit ASSUMES SM
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: $L \approx mf_L f_R$
- SU(2) Higgs allows gauge invariant coupling
  $$L \approx \frac{m_f}{v} f_L \Phi f_R$$
Gauge Higgs Couplings

- Higgs couples to gauge boson masses

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

- WWh coupling vanishes for \(v=0\)! Tests the connection of \(M_W\) to non-zero VEV

\[\begin{align*}
&u &\rightarrow &W &\rightarrow &W \\
&d &\rightarrow &W &\rightarrow &h
\end{align*}\]
No Experimental Evidence for Higgs

- SM requires scalar particle, h, with unknown mass
  - $M_h$ is ONLY unknown parameter of EW sector
- Observables predicted using: $M_Z$, $G_F$, $\alpha$, $M_h$
- 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 $M_W$
Precision Measurements Limit $M_h$

- **LEP EWWG (July, 2008):**
  - $M_t = 172.4 \pm 1.2 \text{ GeV}$
  - $M_h = 84^{+34}_{-26} \text{ GeV}$
  - $M_h < 154 \text{ GeV}$ (one-sided 95% cl)
  - $M_h < 185 \text{ GeV}$ (Precision measurements plus direct search limit)

**Best fit in region excluded by direct searches**
Higgs Mass From Individual Measurements

Consistent?

LEPEWWG
Higgs at the Tevatron

NNLO or NLO rates

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

Use $qq \rightarrow Vh$, $h \rightarrow bb$ at low Higgs mass

Use $gg \rightarrow h$, $h \rightarrow WW$ at high Higgs mass
SM Higgs Searches at Tevatron

95% CL exclusion of SM Higgs at 170 GeV
SM Higgs Searches at Tevatron

CDF/D0 combination with 3 fb\(^{-1}\) coming.
Expected sensitivity < 3 x SM @ \(M_h=115\) GeV
Will Fermilab find the Higgs?

\[ M_h = 160 \text{ GeV} \]

It’s not just luminosity

Herndon, ICHEP 2008
Tevatron Results Starting to Limit $M_h$

Erler, ICHEP08, arXiv:0809.2366
Higgs limit including Tevatron and LEP direct search:

- $\chi^2$ 2$\sigma$ interval: [114.4, 144] GeV
- $\text{CL}_S$-like interpretation 2$\sigma$ interval: [114.2, 154] GeV

Haller, ICHEP08, Gfitter analysis
Light Higgs Theoretically Attractive

- Extrapolate Higgs potential to high scale $\Lambda$

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

- Standard Model is only consistent to Planck scale for $130 \text{ GeV} < M_h < 180 \text{ GeV}$

- Heavy Higgs implies new physics at some low scale
The signs

- All the evidence points towards a light Higgs boson
  - Consistency of precision EW measurements with measured $M_W$ and $M_t$
  - Theoretical prejudices also suggest that if there is a SM Higgs boson, it will be light

- Will we find it at the LHC?
Eagerly Awaiting the LHC

- Sept 10, first particles injected in LHC
- Collisions in spring, 2009
- What can we learn from early data sets? (10 fb\(^{-1}\))
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
  - Including distributions
- Can we distinguish the Standard Model Higgs from all other possibilities?

Tremendous progress on all these fronts
Large Rates for Higgs at the LHC

- Total cross sections known to NLO or NNLO
Production Mechanisms in Hadron Colliders

- **Gluon fusion**
  - Largest rate for all $M_h$ at LHC and Tevatron
  - Rate known to NNLO in large $M_t$ limit
  - Effect is 15-20% for $M_h < 200$ GeV
  - Soft gluon resummation increases rate +6%
  - EW 2-loop effects increase rate 5-8%
Need to go beyond Total Cross Sections

- Higgs production from gluon fusion known at NNLO, including some distributions and summation of large logarithms

Our estimates of scale dependence are inadequate

NNLO Monte Carlos

- NNLO MC for \(gg\rightarrow h\rightarrow\gamma\gamma\) and \(h\rightarrow WW\)

- Photons isolated: Total energy in cone of \(\Delta R=0.3\) less than 6 GeV

- Note impact of NNLO corrections

Catani & Grazzini, hep-ph/0703012
Anastasiou, Melnikov, & Petriello, hep-ph/0501130
Gluon Fusion in Large $M_t$ Limit

- Good approximation for small transverse momenta of accompanying jets and for parton energy $<< M_t$
  - $h + 1$ Jet, $h + 2$ Jets at NLO known
- New: approximate NNLO gluon fusion total rate for finite $M_t$

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>$K^{NLO}$</th>
<th>$K^{NNLO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 GeV</td>
<td>1.800</td>
<td>2.140</td>
</tr>
<tr>
<td>exact</td>
<td>1.797</td>
<td>n.a.</td>
</tr>
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<td>2.136</td>
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<td>280 GeV</td>
<td>1.976</td>
<td>2.420</td>
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<tr>
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<td>approx.</td>
<td>1.959</td>
<td>2.394</td>
</tr>
</tbody>
</table>

Marzani et al, arXiv: 0809.4934
Vector Boson Fusion

- QCD corrections increase LO rate by 5-10%
- Implemented for distributions
- Important channel for extracting couplings
- Need to separate gluon fusion contribution from VBF
  - Central jet veto
  - Many of the backgrounds known at NLO (Zeppenfeld et al)

Del Duca, Frizzo, Maltoni, JHEP05 (2004) 064
When are EW Corrections Needed?

- Electroweak corrections to vector boson fusion are of similar size as QCD corrections (-4%, -7%)
- Partial cancellation between EW & QCD

Ciccolini, Denner, Dittmaier, arXiv:0710.4749
Much work done computing backgrounds

- $\gamma\gamma$ directly measured from sidebands
  - Calculated at NLO
- $WW \rightarrow l\nu l\nu$
  - NLO, NLO+soft gluon resummation, spin correlations in MC@NLO
  - gluon fusion at NNLO
- $ZZ \rightarrow 4l$ can be measured from sidebands
  - NLO known
- $tt$, $tt+jet$ known at NLO
- VV pair production from VBF at NLO
More Backgrounds Needed @ NLO

- $t\bar{t}$ with finite width effects
- $VV+$jets
- $V_{tt}$
- $VV_{bb}$
- $ttjj$
- $ttbb$

Much progress made

I haven’t reviewed the status of implementation of higher order corrections in Monte Carlos
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
Golden Channel: $h \rightarrow ZZ \rightarrow 4$ leptons

- Need excellent lepton ID

- Below $M_h \sim 130$ GeV, rate is too small for discovery
$H \rightarrow ZZ^* \rightarrow 4l$

- Could be early discovery!

$H \rightarrow 2e2\mu$

![Graph showing the number of events at 5σ discovery luminosity with various categories such as Higgs, ZZ*, tt, and Zbb, and an integral $\int L = 9.2 \text{ fb}^{-1}$ shown in CMS.](image)
$H \rightarrow ZZ^* \rightarrow 4l$

- **Data-driven** methods to estimate backgrounds
- **5σ discovery with less than 30 fb$^{-1}$**
Higgs plus jet production may provide better Signal/Background

ATL-PHYS-PROC-2008-014
CMS SM Higgs, 2008

- Improvement in $\gamma\gamma$ channel from earlier studies
- Note: no tth discovery channel
Observation: $gg \rightarrow h \rightarrow \gamma\gamma$, VBF $h \rightarrow \tau\tau$, $h \rightarrow WW \rightarrow l\nu l\nu$, and $h \rightarrow ZZ \rightarrow 4l$
ATLAS SM Higgs, 2008

Discovery:

- Need $\sim 20 \text{ fb}^{-1}$ to probe $M_h=115 \text{ GeV}$
- $10 \text{ fb}^{-1}$ gives $5\sigma$ discovery for $127 < M_h < 440 \text{ GeV}$
- $3.3 \text{ fb}^{-1}$ gives $5\sigma$ discovery for $136 < M_h < 190 \text{ GeV}$

Luminosity numbers include estimates of systematic effects and uncertainties

Herndon, ICHEP 2008
ATLAS SM Higgs, 2008

Exclusion:

- 2.8 fb\(^{-1}\) excludes at 95\% CL \(M_h = 115\) GeV

- 2 fb\(^{-1}\) gives exclusion at 95\% CL for 121 < \(M_h < 460\) GeV

Herndon, ICHEP 2008
Is it **the** Higgs?

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

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

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

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

- $\delta \text{BR}(h \to bb) \sim 2\%$ with $L = 500$ fb$^{-1}$
- New phenomena can cause variations of Yukawa couplings from SM predictions
We expect a Higgs boson or something like it....

\[
A(\ell^+\ell^- \to Z\ell) = -\frac{G_F E^2}{8\sqrt{2}\pi} \left( \frac{M_h^2}{E^2 - M_h^2} \right)
\]

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

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

Expect a light Higgs or New Physics below 1 TeV

Lee, Quigg, Thacker, PRD16, 1519 (1977)
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

- Unitarity arguments suggest new physics is at 1 TeV scale
- 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{d}s)}{\Lambda^2} )</td>
<td>( \Lambda &gt; 1000 ) TeV</td>
</tr>
<tr>
<td>( m_b (\bar{s} \sigma_{\mu\nu} F^{\mu\nu} b) )</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>
<td>( \frac{(D^2 h^+ D^2 h)}{\Lambda^2} )</td>
<td>( \Lambda &gt; 5 ) TeV</td>
</tr>
</tbody>
</table>

New Physics must be at scale \( \Lambda > 5 \) TeV

Schmaltz, hep-ph/0502182
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
  - .....
Higgs Mass Limits *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.....
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

Different resonance structure from SM!

Birkedal, Matchev, Perelstein, hep-ph/0412278
Construct effective Lagrangian without Higgs
- Gauge boson interactions grow with energy
- This Lagrangian violates unitarity

This is counting experiment
- Example: Search for anomalous $W Wγγ$ vertex through gauge boson fusion

Normalized to show difference in shape of signal and background

Eboli et al, hep-ph/0310141
No light Higgs/No KK particles/No techni-$\rho$ Scenario

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

Conclusion

- Theory challenges relate to understanding predictions for signal and background and implementing them in Monte Carlo programs
- Waiting for data!
- Electroweak symmetry breaking sector is win-win