The Higgs Boson (?) Beyond the LHC: Theory

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Fermi National Accelerator Laboratory

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QCD + Electroweak Theory +

Pointlike \( (r \leq 10^{-18} \text{ m}) \) quarks and leptons

Interactions: \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \) gauge symmetries
QCD + Electroweak Theory +

Pointlike \((r \leq 10^{-18} \text{ m})\) quarks and leptons

Interactions: \(SU(3)_c \otimes SU(2)_L \otimes U(1)_Y\) gauge symmetries
A hitherto unknown agent hides the electroweak symmetry

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions
Gauge symmetry (group-theory structure) tested in

\[ e^+ e^- \rightarrow W^+ W^- \]
Electroweak symmetry validated at LEP

![Graph showing σ_{WW} dependence on √s (GeV)]

- Red dashed line: No ZWW vertex
- Yellow dotted line: Only υ_e exchange
- Blue solid line: Standard model

LEP data

- Purple dots: LEP data

02/17/2005
Standard-model Higgs boson hides electroweak symmetry, gives masses to $W^\pm$ and $Z^0$, ensures good high-energy behavior.

Something must do this job
Origin of fermion mass?

*By decree, Weinberg & Salam add interactions between fermions and scalars that give rise to quark and lepton masses.*

\[ \zeta_e \left[ (\bar{e}_L \Phi)e_R + \bar{e}_R (\Phi^\dagger e_L) \right] \quad \leadsto \quad m_e = \frac{\zeta_e v}{\sqrt{2}} \]
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\]

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fermion mass implies physics beyond standard model
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fermion mass implies physics beyond standard model

Highly economical, but is it true?
Fermion Masses

Running mass $m(m) \ldots m(U)$
Summer 2012 Discovery Evidence …
## Known before today …

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>2011 - 2012</th>
<th>$m_H = 126.0$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W, Z \to bb$</td>
<td>$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>$\sqrt{s} = 7$ TeV: $\int L dt = 4.6 - 4.7$ fb$^{-1}$</td>
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</tr>
<tr>
<td>$H \to WW^{(*)} \to ll\nu\nu$</td>
<td>$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$\sqrt{s} = 8$ TeV: $\int L dt = 5.9$ fb$^{-1}$</td>
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<tr>
<td>$H \to ZZ^{(*)} \to 4l$</td>
<td>$\sqrt{s} = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$</td>
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<td>$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>$\mu = 1.4 \pm 0.3$</td>
<td></td>
</tr>
</tbody>
</table>

| Signal strength ($\mu$) | -1 | 0 | 1 |

+ Tevatron evidence for $b\bar{b}$
LHC affords multiple looks at the new boson

3 production mechanisms, ≥ 5 decay channels

\[ \gamma \gamma, ZZ^*, WW^*, b \text{ pairs, } \tau^+\tau^- \]
Standard-Model Higgs-Boson Branching Fractions

\[ \Gamma_H \approx 4.2 \text{ MeV} \]
### H → 2 fermions

<table>
<thead>
<tr>
<th>MH</th>
<th>H → bb</th>
<th>H → τ τ</th>
<th>H → μ μ</th>
<th>H → cc</th>
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<tbody>
<tr>
<td>[GeV]</td>
<td></td>
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<tr>
<td>125.5</td>
<td>5.69E-01</td>
<td>+3.3</td>
<td>-3.3</td>
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<td>-3.4</td>
<td>6.08E-02</td>
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### H → gauge bosons

<table>
<thead>
<tr>
<th>MH</th>
<th>H → gg</th>
<th>H → γ γ</th>
<th>H → Z γ</th>
<th>H → WW</th>
<th>H → ZZ</th>
<th>Γ_{H}</th>
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<tr>
<td>[GeV]</td>
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<tr>
<td>125.5</td>
<td>8.52E-02</td>
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<td>+4.9</td>
<td>-4.8</td>
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<tr>
<td>126.0</td>
<td>8.48E-02</td>
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<td>-9.9</td>
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<td>+4.9</td>
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<tr>
<td>126.5</td>
<td>8.42E-02</td>
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<td>2.28E-03</td>
<td>+4.8</td>
<td>-4.7</td>
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</table>

### H → 4 fermions

<table>
<thead>
<tr>
<th>MH</th>
<th>H → l+ l- l+ l-</th>
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<th>H → e+ e- e+ e-</th>
<th>H → e+ e- μ+ μ-</th>
<th>H → l+ l- ν_1 ν_2</th>
<th>H → l+ l- ν_1 ν_2</th>
<th>H → e+ ν_1 e- ν_2</th>
<th>H → e+ ν_1 e- ν_2</th>
<th>ΔBR</th>
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<tbody>
<tr>
<td>l=e, μ, τ</td>
<td>l=e, μ</td>
<td>l=e, μ or τ</td>
<td>l=e or μ</td>
<td>ν = any</td>
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<td>(%)</td>
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<td></td>
<td></td>
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<td>[GeV]</td>
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<tr>
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<td>8.44E-03</td>
<td>1.23E-01</td>
<td>2.68E-01</td>
</tr>
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</table>
Fully accounts for EWSB (W, Z couplings)?
Couples to fermions?

*Top from production, need direct observation for b, τ*
Distinguishing SM, bosogamous Higgs bosons

\[ \sqrt{s} = 7\text{TeV} \]

\[ \Gamma_H \approx 1.1 \text{ MeV} \]
Fully accounts for EWSB (W, Z couplings)?
Couples to fermions?

*Top from production,*

*need direct observation for* $b, \tau$

Accounts for fermion masses?

*Fermion couplings* $\propto$ *masses?*

Are there others?

Quantum numbers?

SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of $M_H \approx 126$ GeV?

Any sign of new strong dynamics?
s-channel formation?

$$\sigma_{\text{peak}}(e^+ e^- \to H) = \frac{4\pi}{M_H^2} \cdot \frac{\Gamma(H \to e^+ e^-)}{\Gamma(H \to \text{all})}$$

$$= 4.89 \times 10^{-31} \text{ cm}^2 \left[ \frac{\text{100 GeV}}{M_H} \right]^2 \cdot \frac{\Gamma(H \to e^+ e^-)}{\Gamma(H \to \text{all})}$$
s-channel formation?

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\[
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\[ \approx 1.5 \times 10^{-39} \text{ cm}^2 \]

\[ \sigma_{\text{peak}}(\mu^+\mu^- \rightarrow H) \approx 6.4 \times 10^{-35} \text{ cm}^2 \]

\[ \approx 5 \times 10^{-9} \]
Higgsstrahlung

\[ \sigma(e^+e^- \rightarrow HZ) = \frac{\pi \alpha^2}{24} \left( \frac{2K}{\sqrt{s}} \right) \frac{(K^2 + 3M_Z^2)}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \frac{(1 - 4x_W + 8x_W^2)}{x_W^2(1 - x_W)^2} \]

\[ x_W = \sin^2 \theta_W; \quad K = \text{c.m. momentum} \]
Vector Boson Fusion

The diagram illustrates the process of Vector Boson Fusion, where a lepton (\(\ell\)) and its antiparticle (\(\bar{\ell}\)) collide, forming a virtual Higgs boson (H) and two vector bosons (V). The cross-section of this process is shown as a function of the center-of-mass energy (Ecm) for different masses of the SM Higgs boson. The graph indicates that the cross-section increases with Ecm, peaking at certain values corresponding to different Higgs masses. The graph also shows two curves: one including fusion (dotted line) and one for Higgs boson production only in the Higgs ZZ channel (HZ only, solid line).
Photon–Photon Collisions

\[ \sigma(E) = 16\alpha^2 \frac{\Gamma(H^0 \rightarrow \gamma\gamma)}{M_H^3} (2J + 1) \ln^2 \left( \frac{E}{m_e} \right) f \left( \frac{M_H}{2E} \right) \]

\[ \rightarrow \gamma\gamma \text{ Collider} \]
Important measurements at any moment depend on what is already known

SM-like or very nonstandard

Discovery of another “Higgs-like object”

Direct evidence for or against new degrees of freedom
Examples of non-standard behavior

Spin $\neq 0$

deviant $\gamma \gamma$ branching fraction

$\rightarrow$ New particles in loops (not too heavy)
Examples of non-standard behavior

Suppression of $WW, ZZ$ modes
Acid test for low-scale technicolor:
Higgs impostor, $\eta_T(126 \text{ GeV})$
+ higher mass (180 GeV?) companion

_Eichten, Lane, Martin_ arXiv:1210.5462

Not a favorable scenario for a Higgs factory!
Examples of non-standard behavior

“Higgs” is not a simple Breit-Wigner, or does not account for all of EWSB

Premium on measuring $\Gamma_H$ (perhaps 1 GeV), seeking remaining contribution, scanning spectral density

van der Bij, arXiv:1204.3435
An early attempt at a shopper’s guide
Requirements for a shopper’s guide

Clearly stated assumptions

Documented uncertainty estimates

*Rich list of observables, including*\[ \Gamma(\mu\mu), M_H, \Delta M_H, \Delta \Gamma_H, \ldots \]

*Rich list of possible machines*

*A time dimension (linear scale)*
### Specifying Physics Program & Requirements

*Inspired by*

<table>
<thead>
<tr>
<th>CTA Physics case: Driver</th>
<th>Sensitivity</th>
<th>Angular Resolution</th>
<th>Energy Resolution</th>
<th>Energy Threshold</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF Physics case: Driver</td>
<td>Integrated Luminosity (+ time)</td>
<td>Polarization</td>
<td>Energy Resolution</td>
<td>Energy Threshold</td>
<td>Energy Range</td>
</tr>
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</table>
Collateral Measurements: $M_W, m_t$?

Will it be important to improve on Tevatron + LHC?
Might we live in a metastable vacuum?
We will learn from other quarters …

SM: $\text{BR}(B_s \rightarrow \mu^+ \mu^-) = (3.54 \pm 0.30) \times 10^{-9}$

MSSM: $\text{BR}(B_s \rightarrow \mu^+ \mu^-) \propto \frac{m_b^2 m_t^2}{M_A^4} \tan^6 \beta$
As you elaborate machine concepts …

Important not to narrow the physics vision by pretending we know the answer

- Couplings
- Distributions
- Mass / width

Searches in the Higgs sector

Searches beyond the Higgs sector

Other parameters: $M_W, m_t$

Back to $Z^0$?