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Electroweak Symmetry Breaking
University of Chicago, 2011

• Introduction to Electroweak Symmetry Breaking
  – Review of the SU(2) x U(1) Electroweak theory
  – Constraints from Precision Measurements
  – Experimental Searches for the Higgs

• Theoretical problems with the Standard Model

• Beyond the SM
  – Why are we sure there is physics BSM?
  – What do the LHC and Tevatron tell us?
Exciting times: Large Hadron Collider

- proton-proton collider at CERN running now!
- 7 TeV total energy
- Total integrated luminosity \( \sim 2.5 \text{ fb}^{-1} \)
- Typical energy of quarks and gluons 1-2 TeV

If there is a SM Higgs boson, we expect it soon!
What we know

• The photon and gluon appear to be massless
• The W and Z gauge bosons are heavy
  – $M_W = 80.399 \pm 0.023$ GeV
  – $M_Z = 91.1875 \pm 0.0021$ GeV
• There are 6 quarks
  – $M_t = 172.9 \pm 0.9$ GeV
  – $M_t \gg$ all the other quark masses
• There appear to be 3 distinct neutrinos with small but non-zero masses
• The pattern of fermions appears to replicate itself 3 times
  – Why not more?
Abelian Higgs Model

• Why are the W and Z boson masses non-zero?
• U(1) gauge theory with single spin-1 gauge field, $A_\mu$

\[
L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}
\]

\[
F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu
\]

• U(1) local gauge invariance:

\[
A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)
\]

• Mass term for $A$ would look like:

\[
L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu
\]

• Mass term violates local gauge invariance
• We understand why $M_A = 0$

Gauge invariance is guiding principle
Non-Abelian Higgs Mechanism

- Vector fields $A^{a}_{\mu}(x)$ and scalar fields $\varphi_{i}(x)$ of SU(N) group

$$
\phi = \begin{pmatrix}
\phi_1 \\
\vdots \\
\phi_N
\end{pmatrix}
$$

$$
L_{\Phi} = (D_{\mu} \Phi)^{+} (D^{\mu} \Phi) - V(\Phi),
$$

$$
V(\Phi) = \mu^{2} \Phi^{+} \Phi + \lambda (\Phi^{+} \Phi)^{2}
$$

- L is invariant under the non-Abelian symmetry:

$$
\phi_i \rightarrow (1 - i \eta^{a} \tau^{a})_{ij} \phi_j
$$

$$
D_{\mu} \phi = \left( \partial_{\mu} - i g \tau^{a} A^{a}_{\mu} \right) \phi
$$

- $\tau_{a}$ are group generators, $a=1…N^{2}-1$ for SU(N)

For SU(2): $\tau^{a}=\sigma^{a}/2$  \hspace{1cm} $\sigma$ are Pauli matrices
Non-Abelian Higgs Mechanism, 2

\[ D_\mu \phi = \left( \partial_\mu - ig \tau^a A^a_\mu \right) \phi \]

\[ (D_\mu \Phi)^+(D^\mu \Phi) \rightarrow \ldots + g^2 (\tau^a \phi^+)_i (\tau^b \phi)_i A^a_\mu A^{b\mu} + \ldots \]

\[ \rightarrow \phi \rightarrow 0 \ldots + g^2 (\tau^a \phi^+)_i (\tau^b \phi^+)_i A^a_\mu A^{b\mu} + \ldots \]

- \( \tau^a \phi^+_0 \neq 0 \)
  \( \Rightarrow \) Massive vector boson + Goldstone boson

- \( \tau^a \phi^+_0 = 0 \)
  \( \Rightarrow \) Massless vector boson + massive scalar field

**Simplest, but not the only way, to give gauge bosons mass**
Standard Model Synopsis

- **Group:** $SU(3) \times SU(2) \times U(1)$
  - QCD
  - Electroweak

- **Gauge bosons:**
  - $SU(3)$: $G_{\mu}^i$, $i=1\ldots8$
  - $SU(2)$: $W_{\mu}^i$, $i=1,2,3$
  - $U(1)$: $B_{\mu}$

- **Gauge couplings:** $g_s$, $g$, $g'$

- **Complex SU(2) Higgs doublet:** $\Phi$

*Minimal Model*
SM Higgs Mechanism

- Standard Model includes complex Higgs SU(2) doublet
  \[ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \]

- With SU(2) x U(1) invariant scalar potential
  \[ V = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2 \quad \text{Invariant under } \Phi \rightarrow -\Phi \]

- If \( \mu^2 < 0 \), then spontaneous symmetry breaking
- Minimum of potential at:
  \[ \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \Phi \rightarrow e^{i\varphi^a \sigma^a / v} \begin{pmatrix} 0 \\ \frac{h + v}{\sqrt{2}} \end{pmatrix} \]

  - Choice of minimum breaks gauge symmetry
More on SM Higgs Mechanism

• Couple $\Phi$ to SU(2) x U(1) gauge bosons ($W_i^\mu$, i=1,2,3; $B^\mu$)

$$L_S = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

$$D_\mu = \partial_\mu - i \frac{g}{2} \sigma^i W^i_\mu - i \frac{g'}{2} B_\mu$$

• Gauge boson mass terms from:

$$(D_\mu \Phi)^+ D^\mu \Phi \rightarrow \ldots + \frac{1}{8}(0, v)(gW^a_\mu \sigma^a + g'B^a_\mu)(gW^b_\mu \sigma^b + g'B^b_\mu) \begin{pmatrix} 0 \\ v \end{pmatrix} + \ldots$$

$$\rightarrow \ldots + \frac{v^2}{8} \left( g^2 (W^1_\mu)^2 + g^2 (W^2_\mu)^2 + (-gW^3_\mu + g'B_\mu)^2 \right) + \ldots$$
More on SM Higgs Mechanism

• With massive gauge bosons:

\[ W_\mu^\pm = \left( \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}} \right) \]

\[ Z_\mu^0 = \left( \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}} \right) \]

\[ M_W = \frac{g_\nu}{2} \]

\[ M_Z = \sqrt{g^2 + g'^2} \frac{\nu}{2} \]

• Orthogonal combination to Z is massless photon

\[ A_\mu^0 = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2 + g'^2}} \]
More on SM Higgs Mechanism

• Weak mixing angle defined:

\[ Z = - \sin \theta_W B + \cos \theta_W W^3 \]
\[ A = \cos \theta_W B + \sin \theta_W W^3 \]

\[ \cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \quad \sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \]

→ Natural Relationship: \( M_W = M_Z \cos \theta_W \)

\[ \rho = \frac{M_W}{M_Z \cos \theta_W} = 1 \]
W, Z, Higgs Couplings

• Lagrangian in terms of massive gauge bosons and Higgs boson:

\[ L = g M_W W^{+\mu} W^-_\mu h + \frac{g M_Z}{\cos \theta_W} Z^\mu Z_\mu h \]

• Higgs couples to gauge boson mass

• Spontaneous symmetry breaking gives W/Z mass \( \Rightarrow \) longitudinal polarization
Muon decay

- Consider $\nu_\mu e \rightarrow \mu \nu_e$

- Fermi Theory:

- EW Theory:

For $|k| \ll M_W$, $2\sqrt{2}G_F = g^2/2M_W^2$
Higgs Parameters

• $G_F$ measured precisely

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

$$v^2 = (\sqrt{2}G_F)^{-1} = (246 GeV)^2$$

• Higgs potential has 2 free parameters, $\mu^2$, $\lambda$

$$V = \mu^2 \Phi^+ \Phi + \lambda(\Phi^+ \Phi)^2$$

• Trade $\mu^2$, $\lambda$ for $v^2$, $M_h^2$

$$V = M_h^2 \frac{h^2}{2} + M_h^2 \frac{h^3}{2v} + M_h^2 \frac{h^4}{8v^2}$$

$$v^2 = -\frac{\mu^2}{2\lambda}$$

$$M_h^2 = 2v^2 \lambda$$

– Large $M_h \rightarrow$ strong Higgs self-coupling
– A priori, Higgs mass can be anything
What about fermion masses?

• Fermion mass term:
  \[ L = m \bar{\Psi} \Psi = m \left( \bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L \right) \]

• Left-handed fermions are SU(2) doublets
  \[ Q_L = \begin{pmatrix} u \\ d \end{pmatrix} \]

• Scalar couplings to fermions:
  \[ L_d = -\lambda_d \bar{Q}_L \Phi d_R + h.c. \]

• Effective Higgs-fermion coupling
  \[ L_d = -\lambda_d \frac{1}{\sqrt{2}} (\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ v + h \end{pmatrix} d_R + h.c. \]

• Mass term for down quark:
  \[ \lambda_d = \frac{M_d \sqrt{2}}{v} \]
Fermion Masses, 2

• $M_u$ from $\Phi_c = i\sigma_2 \Phi^*$ (not allowed in SUSY)

\[
\Phi_c = \begin{pmatrix}
\phi^0 \\
-\phi^-
\end{pmatrix}
\]

\[
L = -\lambda_u \overline{Q}_L \Phi_c u_R + h c
\]

• For 3 generations, $\alpha, \beta = 1, 2, 3$ (flavor indices)

\[
L_Y = -\frac{(v + h)}{\sqrt{2}} \sum_{\alpha, \beta} \left( \lambda_{u}^{\alpha \beta} \overline{u}_L^\alpha u_R^\beta + \lambda_{d}^{\alpha \beta} \overline{d}_L^\alpha d_R^\beta \right) + h.c.
\]

* SUSY always has at least 2 Higgs doublets
Fermion masses, 3

- Unitary matrices diagonalize mass matrices

\[
\begin{align*}
  u_L^\alpha &= U^\alpha_\beta u_L^{m\beta} \\
  d_L^\alpha &= U^\alpha_\beta d_L^{m\beta} \\
  u_R^\alpha &= V^\alpha_\beta u_R^{m\beta} \\
  d_R^\alpha &= V^\alpha_\beta d_R^{m\beta}
\end{align*}
\]

- Yukawa couplings are \textit{diagonal} in mass basis
- No flavor changing effects in Higgs sector
- Not necessarily true in models with extended Higgs sectors
Review of Higgs Couplings

• Higgs couples to fermion mass
  – Largest coupling is to heaviest fermion
    \[ L = -\frac{m_f}{v} \bar{f}f h = -\frac{m_f}{v} (\bar{f}_L f_R + \bar{f}_R f_L) h \]
  – Top-Higgs coupling plays special role?
  – No Higgs coupling to neutrinos
• Higgs couples to gauge boson masses
  \[ L = g M_W W^{+\mu} W^-_{\mu} h + \frac{g M_Z}{\cos \theta_W} Z^{\mu} Z_{\mu} h + .... \]
• Only free parameter is Higgs mass!
Basics of Radiative Corrections

- Four free parameters in gauge-Higgs sector \((g, g', \mu, \lambda)\)
  - Conventionally chosen to be
    - \(\alpha = 1/137.0359895(61)\)
    - \(G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}\)
    - \(M_Z = 91.1875 \pm 0.0021 \text{ GeV}\)
    - \(M_h\)
  - Express everything else in terms of these parameters

\[
\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_w^2} = \frac{\pi\alpha}{2 \left(1 - \frac{M_w^2}{M_Z^2}\right) M_w^2} \Rightarrow \text{Predicts } M_W
\]
Inadequacy of Tree Level Calculations

• Mixing angle is predicted quantity
  – On-shell definition \( \cos^2 \theta_W = \frac{M_W^2}{M_Z^2} \)
  – Predict \( M_W \)

\[
M_W^2 = \pi \sqrt{2} \frac{\alpha}{G_F} \left( 1 - \frac{4\pi\alpha}{\sqrt{2} G_F M_Z^2} \right)^{-1}
\]

• Plug in numbers:
  • \( M_W \) predicted = 80.939 GeV
  • \( M_W \) experimental = 80.399 \( \pm \) 0.023 GeV

– Need to calculate beyond tree level
Modification of tree level relations

\[ G_F = \frac{\pi \alpha}{\sqrt{2} M_w^2 \sin^2 \theta_W} \left( \frac{1}{1 - \Delta r} \right) \]

- \( \Delta r \) is a physical quantity which incorporates 1-loop corrections

- Contributions to \( \Delta r \) from top quark and Higgs loops

\[ \Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2} \left( \frac{\cos^2 \theta_W}{\sin^2 \theta_W} \right) \]

\[ \Delta r^h = \frac{11G_F M_W^2}{24\sqrt{2}\pi^2} \left( \ln \frac{M_h^2}{M_W^2} \right) \]

Extreme sensitivity of precision measurements to \( m_t \)

* Lots of other corrections from gauge boson loops, etc
Masses inferred from precision measurements and Higgs searches*

* Includes LHC searches
Higgs Boson

- Standard Model Higgs expected to be light

\[ \Delta \chi^2 = 4 \] gives 95% confidence level limit

- This assumes the Standard Model!
Higgs Limits

• From Gfitter (2011)
  – If you don’t include direct search limits for Higgs, 95% CL upper bound: $M_h < 169$ GeV
  – If you include LEP, Tevatron, LHC limits, 95% CL upper bound: $M_h < 143$ GeV
  – Test of consistency of Standard Model

Not hard to fit bounds with new physics
http://gfitter.desy.de/
Higgs Branching Ratios

![Graph showing branching ratios for Higgs boson decays into various products, with axes labeled as Branching ratios and M_h (GeV). The graph includes curves for bb, WW, ZZ, ττ, gg, cc, γγ, and Zγ.]
More Branching Ratios
Total Higgs Width

- Small $M_h$, Higgs is narrower than detector resolution
- As $M_h$ becomes large, width also increases
  - No clear resonance
  - For $M_h \approx 1.4$ TeV, $\Gamma_{\text{tot}} \approx M_h$

\[
\Gamma(h \rightarrow W^+W^-) \approx \frac{\alpha}{16\sin^2\theta_W} \frac{M_h^3}{M_W^2} \\
\approx 330\text{GeV} \left(\frac{M_h}{1\text{TeV}}\right)^3
\]
Higgs production at Hadron Colliders

• Many possible production mechanisms; Importance depends on:
  – Size of production cross section
  – Size of branching ratios to observable channels
  – Size of background
• Importance varies with Higgs mass
• Need to see more than one channel to establish Higgs properties and verify that it is a Higgs boson
Production Mechanisms in Hadron Colliders

• Gluon fusion
  – Largest rate for all $M_h$ at LHC and Tevatron
  – Gluon-gluon initial state
  – Sensitive to top quark Yukawa $\lambda_t$

In Standard Model, $b$-quark loop contribution small

Counts number of heavy fermions
Gluon Fusion

- Lowest order cross section:
  - $\tau_q = 4m_q^2/M_h^2$
  - Light Quarks: $F_{1/2} \rightarrow (m_b/M_h)^2 \log^2(m_b/M_h)$
  - Heavy Quarks: $F_{1/2} \rightarrow -4/3$

$$\hat{\sigma}_{gg \rightarrow h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi^2} \left| \sum_q F_{1/2}(\tau_q) \right|^2 \delta(1 - \frac{M_h^2}{\hat{s}})$$

- Rapid approach to heavy quark limit: Counts number of heavy fermions
- NNLO corrections calculated in heavy top limit
Gluon Fusion

• Integrate parton level cross section with gluon parton distribution functions:
  \[ \hat{\sigma}_{gg \to h} = C_0 \delta \left(1 - \frac{M_h^2}{\hat{s}}\right) \]
  \[ \hat{s} = x_1 x_2 S \]
  \[ \sigma(pp \to h) = \int dx_1 dx_2 g(x_1, \mu_F) g(x_2, \mu_F) \hat{\sigma}_{gg \to h}(x_1 x_2 S) \]

  \[ \sigma(pp \to h) = C_0 \int_{M_h^2/S}^{x_1} dx_1 g(x_1, \mu_F) g\left(\frac{M_h^2}{Sx_1}, \mu_F\right) \]

  \[ C_0 \to \frac{\alpha_s(\mu_R)^2}{576\pi v^2} \]

  – \( S \) is hadronic center of mass energy

• Rate depends on \( \mu_R, \mu_F \) at \( O(\alpha_s^3) \)
  – \( \mu_R, \mu_F \) arbitrary renormalization/factorization scales
  – Numerically significant

• Uncertainty from gluon parton distribution functions
Higher order corrections to $gg \rightarrow h$

Rates depend on renormalization scale, $\alpha_s(\mu_R)$, and factorization scale, $g(\mu_F)$

Bands show $.5M_h < \mu < 2M_h$

LO and NLO $\mu$ dependence bands don’t overlap

$\mu$ dependence used as estimate of theoretical uncertainty

$K \equiv \frac{\sigma_{NLO}}{\sigma_{LO}}$

These corrections are large!
Vector Boson Fusion

- \( W^+W^- \rightarrow X \) is a real process: \( \sigma_{pp\rightarrow WW\rightarrow X}(s) = \int dz \left. \frac{dL}{dz} \right|_{pp/WW} \sigma_{WW\rightarrow X}(zs) \)
- Rate increases at large \( s \): \( \sigma \approx (1/ M_W^2) \log(s/M_W^2) \)
- Integral of cross section over final state phase space has contribution from \( W \) boson propagator:

\[
\int \frac{d\theta}{(k^2 - M_W^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos \theta) + M_W^2)^2}
\]

Peaks at small \( \theta \)

- Outgoing jets are mostly forward and can be tagged

\( V \)

\( h \)

\( k=W,Z \) momentum
W(Z)-strahlung

- W(Z)-strahlung ($q\bar{q} \rightarrow Wh, Zh$) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to *weak* coupling
- Theoretically very clean channel
Producing the Higgs at the Tevatron

NNLO or NLO rates

\[ \frac{M_h}{2} < \mu < \frac{M_h}{4} \]
Higgs at the Tevatron

• Largest rate, \( gg \rightarrow h, h \rightarrow bb \), is overwhelmed by background

\[ \sigma(gg \rightarrow h) \sim 1 \text{ pb} \ll \sigma(bb) \]
Looking for the Higgs at the Tevatron

- **High mass:** Look for $h \rightarrow WW^*$
  Large $gg \rightarrow h$ production rate

- **Low Mass:** $h \rightarrow bb$, Huge QCD $bb$ background
  Use associated production with W or Z
Tevatron Higgs Exclusion

Limits normalized to Standard Model predictions

Tevatron Exclusion: [100 GeV < M_h < 109 GeV], [156 GeV < M_h < 177 GeV]
Gluon fusion counts generations

- 4^{th} generation (b',t') increases rate by factor of 9

Look for $gg \rightarrow h \rightarrow W^+W^-$

Excludes $124 \text{ GeV} < M_h < 286 \text{ GeV}$ if heavy 4^{th} generation
Production Mechanisms at the LHC

Bands show scale dependence

All important channels calculated to NLO or NNLO
Do some numbers…

• ATLAS and CMS have ~ 2.5 fb⁻¹ of data
• For $M_h=120$ GeV:
  – $\sigma$(gluon fusion) = 17 pb
  – 42,500 Higgs events
  – But we have to see them:
    • Branching ratio $h\rightarrow\gamma\gamma = 2 \times 10^{-3} \Rightarrow 85$ events
    • Branching ratio $h\rightarrow$4 leptons = $8 \times 10^{-5}$ ($l=e,\mu$) $\Rightarrow$ 3.4 events
• For $M_h=180$ GeV:
  – $\sigma$(gluon fusion) = 7 pb
  – 17,500 Higgs events
    • Branching ratio $h\rightarrow\gamma\gamma = 1 \times 10^{-4} \Rightarrow 1.75$ events
    • Branching ratio $h\rightarrow$4 leptons = $3 \times 10^{-4}$ ($l=e,\mu$) $\Rightarrow$ 5.2 events

Event numbers further reduced by detector efficiency…
Search Channels at the LHC

$gg \rightarrow h \rightarrow \gamma \gamma$
- Small BR ($10^{-3} - 10^{-4}$)
- Only measurable for $M_h < 140$ GeV

• Largest Background: QCD continuum production of $\gamma \gamma$
• Also from $\gamma$-jet production, with jet faking $\gamma$, or fragmenting to $\pi^0$
• Fit background from data

$gg \rightarrow h \rightarrow bb$ has huge QCD background: Must use rare decay modes of $h$
$h \rightarrow \gamma \gamma$

$M_h = 120$ GeV; $L = 100$ fb$^{-1}$

Monte Carlo predictions

Signal + background

Background subtracted

Data
Higgs Decays to Photons

- Dominant contribution is W loops
- Contribution from top is small

\[ \Gamma(h \rightarrow \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_w^2 M_h^2 M_W^2} \left( 7 - \frac{16}{9} + \ldots \right)^2 \]
h\rightarrow\gamma\gamma

- Sensitive to new physics in loops

**Factor of 5-10 from SM sensitivity**
Golden Channel: $h \rightarrow ZZ \rightarrow 4$ leptons

- Reconstruct Higgs mass

Monte Carlo predictions

- Below $M_h \sim 130$ GeV, rate is too small for discovery
What about $h \rightarrow W^+W^-$?

- Large rate (good)
- Look for $W \rightarrow l\nu$
  - Can’t reconstruct mass peak (bad)
- Background from $q\bar{q} \rightarrow Z^*$
  $\rightarrow W^+W^-$ (vector decay)
- Signal from $gg \rightarrow h \rightarrow W^+W^-$ (scalar decay)
  - Angular distributions help

![Graph showing signal and background events](image-url)
Limit from $h \rightarrow W^+W^-$

- CMS: $147 < M_h < 194$ GeV ruled out at 95% cl
- SM Higgs boson expected sensitivity $136 < M_h < 200$ GeV

Source of rumors, blog posts, etc....
Many Channels contribute to Limits

\[ [146 < M_h < 232 \text{ GeV}, 256 < M_h < 282, 296 < M_h < 466 \text{ GeV}] \]
Higgs Limits from the LHC

95% CL exclusion:

[145< \( m_h \) <216 Gev, 226< \( m_h \) < 288, 310< \( m_h \) <440 GeV] CMS
If the SM Higgs exists, we’ll know soon

<table>
<thead>
<tr>
<th>ATLAS + CMS (\approx 2 \times) CMS</th>
<th>95% CL exclusion</th>
<th>3(\sigma) sensitivity</th>
<th>5(\sigma) sensitivity</th>
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</thead>
<tbody>
<tr>
<td>1 fb(^{-1})</td>
<td>120 - 530</td>
<td>135 - 475</td>
<td>152 - 175</td>
</tr>
<tr>
<td>2 fb(^{-1})</td>
<td>114 - 585</td>
<td>120 - 545</td>
<td>140 - 200</td>
</tr>
<tr>
<td>5 fb(^{-1})</td>
<td>114 - 600</td>
<td>114 - 600</td>
<td>128 - 482</td>
</tr>
<tr>
<td>10 fb(^{-1})</td>
<td>114 - 600</td>
<td>114 - 600</td>
<td>117 - 535</td>
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</tbody>
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Is it a Higgs?

- How do we know what we’ve found?
- 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
  \[ V = \frac{M_h^2}{2}h^2 + \frac{M_h^2}{2\nu}h^3 + \frac{M_h^2}{8\nu^2}h^4 \]
Can we reconstruct the Higgs potential?

\[ V = \frac{M_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \]

• Fundamental test of model!

• We have no idea how to measure \( \lambda_4 \)
Within the next 1-2 years, we should know whether or not a SM-like Higgs exists
We can already put meaningful limits on many models
The fun is just beginning