PHYS 5326 – Lecture #21

Monday, Apr. 9, 2003
Dr. Jae Yu

• Higgs Mass Theoretical Upper Bounds
• SM Higgs Production Processes in Hadron Colliders
• Winter 03 Experimental Results
Higgs Particles

• What are the Higgs particles we are looking for?
  – Standard Model Higgs: Single neutral scalar
  – MSSM Higgs: Five scalar and pseudoscalar particles
    • $h^0, H^0, H^{+/-}$ and $A^0$
  – Higgs in Other Models

• What are the most distinct characteristics of Higgs particles?
  – In both SM and MSSM, the Higgs particles interact with fermions through Yukawa coupling whose strength mostly is set by the fermion masses.
Theoretical $M_H$ Upper Bound in SM

From the $SU_2 \times U_1$ L

$$L = |D\phi|^2 - \frac{\lambda}{2} \left[ |\phi|^2 - \frac{v^2}{2} \right]^2 - g_d \overline{d_L}\phi d_R - g_u \overline{u_L}\phi^c u_R + h.c.$$ 

Where, the scale $v$ is the EWSB scale, $v = \frac{1}{\sqrt{2}} \sqrt{\frac{G_F}{\lambda}} \approx 246 \text{ GeV}$, and the mass of the Higgs particle and fermions are

$$M_H = \lambda v^2$$

$$m_f = \frac{g_f v}{\sqrt{2}}$$

Where $\lambda$ is the quartic coupling and $g_f$ is the Yukawa coupling.
Theoretical $M_H$ Upper Bound in SM

While $M_H$ cannot be predicted in SM, internal consistency and extrapolation to high energies can provide upper and lower bounds.

Based on the general principle of t-E uncertainty, particles become unphysical if their masses grow indefinitely. Therefore $M_H$ must be bound to preserve the unitarity in the perturbative regime. and the mass of the Higgs particle and fermions are

From an asymptotic expansion of a $W_L W_L$ S-wave scattering, an upper limit on $M_H$ can be obtained:

$$M_H^2 \leq \frac{2\sqrt{2}\pi}{G_F} \approx (850 \text{ GeV})^2$$
Theoretical $M_H$ Upper Bound in SM

The SM tells that there is no new physics between EWSB scale (~1TeV) and the GUT scale ($10^{19}$GeV). This can provide a restrictive upper limit because the SM can extend to a scale $\Lambda$ before a new type of strong short range interaction can occur between the fundamental particles.

From the variation of quartic Higgs coupling, $\lambda$, and the top-Higgs Yukawa coupling, $g_t$, with energy parameterized by $t=\log(\mu^2/v^2)$, and requiring $\lambda(\Lambda)$ to be finite, one can obtain the Higgs mass upper bound

$$M_H^2 \leq \frac{8\pi^2 v^2}{3 \log \left( v^2 / \lambda^2 \right)}$$
Theoretical $M_H$ Upper Bound in SM

For the central $m_t = 175\text{GeV}$

<table>
<thead>
<tr>
<th>$\Lambda_{SM}$</th>
<th>$M_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TeV</td>
<td>$55 \leq M_H \leq 700\text{GeV}$</td>
</tr>
<tr>
<td>$10^{19}\text{GeV}$</td>
<td>$130 \leq M_H \leq 190\text{GeV}$</td>
</tr>
</tbody>
</table>
SM Higgs Properties

• Profiles of Higgs Particles determined by its mass
• The Yukawa coupling of Higgs to fermions set by the fermion mass, $m_f$, and to the electroweak gauge bosons by their masses, $M_V$.

$$g_{ffH} = \left[\sqrt{2}G_F\right]^{1/2} m_f$$
$$g_{VVH} = 2\left[\sqrt{2}G_F\right]^{1/2} M_V^2$$

Physical observables, the total decay width, lifetime and branching ratio to specific final states are determined by these parameters.
Higgs Decay to Fermions

Higgs partial decay width to fermions are

\[ \Gamma(H \rightarrow f \bar{f}) \]

\[ = N_c \frac{G_F}{4\sqrt{2}\pi} g_{ffH} m_f^2 \left( M_H^2 \right) M_H \]

Number of color quantum numbers, 1 or 3

For \( M_H = 100 \text{GeV} \),
\( m_b(M_H^2) \approx 3 \text{GeV} \),
\( m_c(M_H^2) \approx 0.6 \text{GeV} \)
Higgs Decay to Gauge Boson Pairs

\[ \Gamma(H \rightarrow VV) = \delta_V \frac{G_F}{16\sqrt{2\pi}} M_H^3 (1 - 4x + 12x^2) \beta_V \]

Where \( x = \frac{M_V^2}{M_H^2} \) and \( \delta_V = 2 \) or 1 for W or Z

\[ \Gamma(H \rightarrow VV^*) = \frac{3G_F^2 M_V^4}{16\pi^3} M_H R(x) \delta_V \]

Where \( \delta_W = 1 \) and \( \delta_Z = \frac{7}{12} - 10 \sin^2 \theta_W / 9 + 40 \sin^4 \theta_W / 27 \)

\[ \Gamma(H \rightarrow \gamma\gamma) = \frac{3G_F^2 \alpha^2}{128\sqrt{2\pi}} M_H^3 \left| \frac{4}{3} N_c e^2 \right|^2 \left( \frac{2}{4} \right) \]

Valid in the limit \( M_H^2 << 4M_W^2, 4M_\tau^2 \)
Summary of SM Higgs Branching Ratio
Higgs Production Processes at Hadron Colliders

Gluon fusion: \[ gg \rightarrow H \]

WW, ZZ Fusion: \[ W^+W^-, ZZ \rightarrow H \]

Higgs-strahlung off W, Z: \[ q\bar{q} \rightarrow W^*, Z^* \rightarrow W, Z + H \]

Higgs Bremsstrahlung off top: \[ q\bar{q}, gg \rightarrow t\bar{t} + H \]
Hadron Collider SM Higgs Production $\sigma$

$\sigma(pp \rightarrow H + X) \ [pb]$
$\sqrt{s} = 14 \text{ TeV}$
$M_H = 175 \text{ GeV}$
CTEQ4M

$\sigma(pp \rightarrow H + X) \ [pb]$
$\sqrt{s} = 2 \text{ TeV}$
What do we know as of Winter 03?

Winter 2003

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull</th>
<th>( \sigma_{\text{meas}}^{(0)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \alpha_{\text{em}}^{(0)}(m_Z) )</td>
<td>0.02761 ± 0.00036</td>
<td>-0.16</td>
</tr>
<tr>
<td>( m_Z ) [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>0.02</td>
</tr>
<tr>
<td>( \Gamma_Z ) [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>-0.36</td>
</tr>
<tr>
<td>( \sigma_{\text{had}}^{(0)} ) [nb]</td>
<td>41.540 ± 0.037</td>
<td>1.67</td>
</tr>
<tr>
<td>( R_{b} )</td>
<td>20.767 ± 0.025</td>
<td>1.01</td>
</tr>
<tr>
<td>( A_{b}^{(0)} )</td>
<td>0.01714 ± 0.00095</td>
<td>0.79</td>
</tr>
<tr>
<td>( A_{b}(P_{T}) )</td>
<td>0.1465 ± 0.0032</td>
<td>-0.42</td>
</tr>
<tr>
<td>( R_{b} )</td>
<td>0.21644 ± 0.00065</td>
<td>0.99</td>
</tr>
<tr>
<td>( R_{c} )</td>
<td>0.1718 ± 0.0031</td>
<td>-0.15</td>
</tr>
<tr>
<td>( A_{b}^{(0)} )</td>
<td>0.0995 ± 0.0017</td>
<td>-2.43</td>
</tr>
<tr>
<td>( A_{c}^{(0)} )</td>
<td>0.0713 ± 0.0036</td>
<td>-0.78</td>
</tr>
<tr>
<td>( A_{b} )</td>
<td>0.922 ± 0.020</td>
<td>-0.64</td>
</tr>
<tr>
<td>( A_{c} )</td>
<td>0.670 ± 0.026</td>
<td>0.07</td>
</tr>
<tr>
<td>( A_{b}(\text{SLD}) )</td>
<td>0.1513 ± 0.0021</td>
<td>1.67</td>
</tr>
<tr>
<td>( \sin^{2}\theta_{W}^{\text{eff}}(Q_{b}) )</td>
<td>0.2324 ± 0.0012</td>
<td>0.82</td>
</tr>
<tr>
<td>( m_{W} ) [GeV]</td>
<td>80.426 ± 0.034</td>
<td>1.17</td>
</tr>
<tr>
<td>( \Gamma_{W} ) [GeV]</td>
<td>2.139 ± 0.069</td>
<td>0.67</td>
</tr>
<tr>
<td>( m_{t} ) [GeV]</td>
<td>174.3 ± 5.1</td>
<td>0.05</td>
</tr>
<tr>
<td>( \sin^{2}\theta_{W}(\nuN) )</td>
<td>0.2277 ± 0.0016</td>
<td>2.94</td>
</tr>
<tr>
<td>( Q_{W}(Cs) )</td>
<td>-7.283 ± 0.49</td>
<td>0.12</td>
</tr>
</tbody>
</table>

LEP EWWG: http://www.cern.ch/LEPEWWG

114 < \( m_{H} \) < 300 + 700 GeV
Homework Assignment

• Study the summary SM Higgs branching ratio plot in slide 10 and plan experimental strategies to search for Higgs particles in the following two scenarios
  – $M_H = 115 \text{GeV}$
  – $M_H > 150 \text{GeV}$
• Due: Wednesday, Apr. 16