Indirect Probe of the Higgs Boson from Precision Electroweak Measurements

- Overview
- Electroweak Parameters at Z pole: $M_z$, $\sin^2\theta_W$, ...
  (Patrick Janot's Lecture)

- $M_w$
  - Tevatron Measurement
  - Comparison to LEP-II Measurement

- $M_{\text{top}}$
  - SM Implication of EW Measurements
  - Top Properties.
**Higgs Particles Condensed**

\[ M_{\gamma} = 0 \]
\[ M_{W} = \frac{1}{2} g \langle \phi \rangle_o \]
\[ M_{Z} = \frac{M_{W}}{\cos \theta_W} \]

\[ M_{W} = 37.3 \text{ GeV} / \sin \theta_W \]

\[ M_{e} = g_e \langle \phi \rangle_o \]
\[ M_{t} = g_t \langle \phi \rangle_o \]

\[ g_e \sim 10^{-6} \]
\[ g_t \sim 1 \]

\[ q \propto M_t^2 \]
SM Higgs Mass: No specific prediction

Standard Model Limitations:

\[ 100 < M_H < 1000 \, \text{GeV} \] depending on the scale, \( \Lambda \) where the SM might break down, i.e. new physics must appear.

\[ 130 < M_H < 180 \, \text{GeV} \] @ \( \Lambda = M_{\text{Planck}} \)

Experiments

---

SM Theory

Precision EW meas.s

\[ M_H \ll 200 \, \text{GeV} \]

Direct searches

\[ M_H > 114 \, \text{GeV} \]

\[ m_t = 175 \, \text{GeV} \]

not allowed

Couplings blow up!

Potential unstable

\[ \Lambda \, [\text{GeV}] \]
Elementary particle masses

Mass (GeV)

$g_t \sim 1$
Special ?

$t \quad 10^{-24}$_{s}

Lecture #2
Mw, Mtop, ...

$10^{-24}$_{s}

$Z$

$W$

$e \quad \mu \quad \tau$

$\nu_e \quad \nu_\mu \quad \nu_\tau$

Leptons

$u \quad c \quad 10^{-12}$_{s}

$d \quad s \quad b$

Quarks

$\gamma \quad g$

Force Carriers
EW Precision Measurements

- EW observables probe the Higgs bosons indirectly by means of **quantum corrections**.
- Large quantum corrections to EW observables come from the **top quark**.

\[
\begin{align*}
\frac{M_W}{M_Z \cdot \cos\theta_W} & = 1 + \frac{3G_F M_t^2}{8\sqrt{2}\pi^2} \\
& = 1 + 0.01 \left( \frac{M_t}{175 \text{ GeV}} \right)^2
\end{align*}
\]
**EW Precision Measurements**

- Secondary contributions to EW observables are the Higgs boson contributions: $\ln\left(\frac{M_H^2}{M_W^2}\right)$

\[
M_W = 80.3767 + 0.5235\left[\left(\frac{M_{\text{top}}}{174.3\text{GeV}}\right)^2 - 1\right] \\
- 0.05613 \ln\left(\frac{M_{\text{Higgs}}}{100\text{GeV}}\right) \\
- 1.081\left(\frac{\Delta\alpha}{0.05924} - 1\right) \\
+ \ldots
\]

Input parameters: $\alpha_{\text{em}}(M_0^2), G_F, M_8$
You should go to the masses, learn from them, and synthesize their experience into better, articulated principles and methods, ......

- Mao -
Electroweak Input Parameters

- The EW strengths are specified by 3 parameters:
  - two gauge couple constants: $g, g'$
  - vacuum expectation value of the Higgs field: $v$

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{\pi \alpha}{\sqrt{2} G_F M_W^2} = \frac{e^2}{g^2} = 1 - \frac{e^2}{g'^2} \quad \text{(Tree-level)}$$

- The theory is democratic: any 3 variables may be chosen.
  - Choose the 3 parameters most accurately measured so that the predictions for any other measurements become as precise as possible, allowing sensitive tests of the theory.
  - In the early 1980s, $e$ or $\alpha$, $G_F$, $\sin^2 \theta_W$
  - Since August 1989 when $\delta M_Z = 160$ MeV (LEP), $\alpha_{em}(M_Z^2)$, $G_F$, $M_Z$

- Current accuracy
  - $\delta M_Z : 2.1$ MeV ($2 \times 10^{-5}$) (LEP)
  - $\delta G_F : 1 \times 10^{-5}$ ($\mu$ lifetime)
  - $\delta \alpha(M_Z^2) : 2 \times 10^{-4}$ : dominant uncertainty
Precision Measurements of $M_Z$, $\sin^2 \theta_W$

\[ \frac{M_Z}{W/Z} = 91.1871 \pm 0.0021 \text{ GeV} \]

\[ \sin^2 \theta_W \sim 2 \times 10^{-5} \]

\[ \sigma_{\text{eff}} \approx 1.18 \times 10^{-4} \]

\[ \sigma_{\text{eff}} = 0 + \frac{c}{y} + \frac{d}{z} + \frac{e}{x} \]

\[ M_Z \approx 187 \text{ GeV} \]

\[ \sin^2 \theta_{\text{eff}} \approx 0.23 \pm 0.0017 \]

\[ \sigma_{\text{eff}} (\text{LEP1} + \text{SLC}) \approx 0.23 \times 10^{-5} \]
Dominant uncertainty: hadronic vac. polar. contrib. Can not be reliable calculated.

With application of dispersion relations, measured $R$ values are used to determine it.

$$R = \frac{\sigma(e^+e^- \rightarrow qq)}{\sigma^0(e^+e^- \rightarrow \mu^+\mu^-)}$$

$$\sigma^0(e^+e^- \rightarrow \mu^+\mu^-) = 4 \pi \alpha^2(0) / 3E_{cm}^2$$
W Production

$W^+ W^- \text{ at LEP 2 (} e^+e^- \text{)}$  \hspace{1cm} $W \text{ at Tevatron (} p\bar{p} \text{)}$

\begin{align*}
W W &\rightarrow q\bar{q}q\bar{q} \quad 46\% \quad \sim 2700 \\
W W &\rightarrow q\bar{q}l\nu \quad 44\% \quad \sim 2700 \\
W W &\rightarrow l\nu\nu \quad 10\% \quad \sim 600 \\
\end{align*}

$\sim 10k \text{ events / expt.}$

\begin{align*}
W &\rightarrow l (e, \mu, \tau) + \nu \quad (30\%) \\
W &\rightarrow q\bar{q}' \quad (70\%) \\
\end{align*}

$\sim 40k \text{ events / expt.}$

$(W \rightarrow e\nu, \mu\nu)$

$W \rightarrow g\bar{g}' : \text{ swamped by QCD dijet background.}$
Precision Measurement of $M_W$

**LEP 2 ($e^+e^-$)**

$W^+ \rightarrow e^+\nu$, $W^- \rightarrow u\bar{d}$

$P_i(W^+) + P_i(W^-) = 0$, $i=1,2,3$

$E(W^+) + E(W^-) = E(e^+) + E(e^-)$

$M_W = \sqrt{2P_eP_\nu(1-\cos\theta_{3D})}$

**Tevatron ($p\bar{p}$)**

$W^+ \rightarrow e^+\nu$

$P_i(W^+) = 0$, $i=1,2$

$P_{T_e} = P_{T^\nu}$

$M_T^W = \sqrt{2P_{T_e}P_{T^\nu}(1-\cos\theta_{2D})}$
Precision Measurements of $M_W$

**LEP 2 (e^+e^-)**

OPAL, 183-209 GeV

$M_W = 80.450 \pm 0.039$ GeV

**Tevatron (p\bar{p})**

CDF

$W \rightarrow e\nu$

DO

$W \rightarrow e\nu$

$M_W = 80.452 \pm 0.062$ GeV
Precision Measurements of $M_W$

- $W$ mass from fits to the transverse mass spectrum of $\sim 30K$ $W \rightarrow e\nu$ events and $\sim 15K$ $W \rightarrow \mu\nu$ events.

- DØ also include forward electrons in the endcap (EC) calorimeters, and use $M_T$, $P_T$, and $P_T^Z$.

\[ M_W^{e\nu}(\text{Run1B}) = 80.470 \pm 0.089 \text{ GeV/c}^2 \]
\[ M_W^{\mu\nu}(\text{Run1} + 0) = 80.433 \pm 0.079 \text{ GeV/c}^2 \]

\[ M_W^e(\text{EC}) = 80.691 \pm 0.227 \text{ GeV/c}^2 \]
\[ M_W^{e}(\text{CC + EC}) = 80.482 \pm 0.091 \text{ GeV/c}^2 \]
Precision Measurements of $M_W$

$W$ Prod. $(\frac{d^2\sigma}{dydP_T})$

\[
\begin{array}{|c|c|}
\hline
\text{partons} & P^W_T \quad P^Z_T \\
\text{P}_u, P_d \ (\text{PDFs}) & y^W \quad A^W \\
\hline
\end{array}
\]

$P_T$ Plane

$P - \text{tracking momentum, } E - \text{calorimeter energy}$

<table>
<thead>
<tr>
<th>Lepton Meas.</th>
<th>$E^e \ (Z \rightarrow ee), P^\mu \ (Z \rightarrow \mu\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoil Meas.</td>
<td>Min Bias $+ Z \rightarrow ee \ (ee), \mu\mu \ (\mu\nu)$</td>
</tr>
</tbody>
</table>

\[
\vec{\tilde{p}}_T^\nu = -\vec{p}_T^\ell - \vec{U}
\]

$M_T = \sqrt{2p^L_T p^R_T (1 - \cos \phi_{lep})}$

$dN/dm_t$

$m_t \ (\text{GeV})$

$30, 40, 50, 60, 70, 80, 90, 95$

$dN/dp_T(e)$

$p_T(e) \ (\text{GeV})$

30, 40, 50, 60, 70, 80, 90, 95
**$M_W$ Uncertainties on P, E scale & resolution**

**$P & E$ Scale and Resolution with $Z$**

- $P, E$ scale $\rightarrow Z$ Mass
- $P, E$ resolution $\rightarrow$ width of inv. mass dist.

\[
\frac{\Delta E}{E} = 13.5\% \oplus \kappa, \quad \frac{\Delta P_T}{P_T} = (0.0091 \pm 0.0004) \cdot P_T
\]

**$P$ Scale Checks using known resonances**

(CDF Preliminary)

- $\tau \rightarrow \mu^+\mu^-$
  - $\chi^2/\text{dof} = 18.4/19$
  - $\delta M_{\tau\rightarrow\mu^+\mu^-} = 0.7(\text{stat}) \pm 1.8(\text{sys})$ MeV
  - $\delta M_{\tau\rightarrow\mu^+\mu^-} = 2.1(\text{stat})$ MeV
  - $\delta M_{\tau\rightarrow\mu^+\mu^-} = 3.6(\text{stat})$ MeV

- $T(1s)$, $T(2s)$, $T(3s)$

- $J/\psi \rightarrow \mu^+\mu^-$
  - $\delta M_{J/\psi\rightarrow\mu^+\mu^-} = 0.1(\text{stat}) \pm 1.1(\text{sys})$ MeV

- $\psi(2s) \rightarrow \mu^+\mu^-$
  - $\delta M_{\psi(2s)\rightarrow\mu^+\mu^-} = 0.5(\text{stat})$ MeV

**Lepton**

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Scale ($Z$ stat.)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>$\delta M_W = 72$ MeV</td>
<td>25 MeV</td>
</tr>
<tr>
<td>$\mu$</td>
<td>85 MeV</td>
<td>20 MeV</td>
</tr>
</tbody>
</table>

$P$ Scale using $M_T$ or $M_\psi$ agrees with that using $M_Z$ very well.
\( M_W \) Uncertainties

- **LEP II**
  - 25 MeV (stat.), 30 MeV (syst.)
  - Limited by systematic uncertainties on final state interactions (WW → qqqq)
    - "Hadronization" effect may not be independent between W's in WW → qqqq.

- **Tevatron**
  - \( \delta M(\text{stat.}) \approx \delta M(\text{syst.}) \)
  - \( \delta M(\text{syst.}) \) - limited by \( Z \rightarrow ee, \mu\mu \) sample
    - Lepton E, \( p \) scales + resolution
    - \( W \) Pt, recoil energy response

\[
\begin{array}{c|c|c|c|c}
\text{Error Source} & \text{DO} & \text{CDF} \\
& (C) & (EC) & (C) & (EC) \\
\hline
\text{Statistics} & 70 & 105 & 65 & 100 \\
\ell \text{ Scale, Resol} & 70 & 185 & 80 & 90 \\
W \text{ Pt, } \mathcal{E}_T \text{ Model} & 35 & 50 & 40 & 40 \\
\text{Other Exp.} & 40 & 60 & 5 & 30 \\
\text{Theory} & 30 & 40 & 25 & 20 \\
\text{(PDF's, QED)} & & & & \\
\hline
\text{Total Error} & 120 & 235 & 113 & 143 \\
\text{Mass Value} & 80.440 & 80.766 & 80.473 & 80.465 \\
\text{Combined Mass} & 80.497 \pm 0.098 & 80.470 \pm 0.089 \\
\end{array}
\]
Tevatron $M_W$ Measurements since 1990

$\delta M_W$ (MeV)

$\frac{1}{\sqrt{\text{Lum}}}$ (pb$^{-1}$)

**Table:**

<table>
<thead>
<tr>
<th>Error Source</th>
<th>D0</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(C)</td>
<td>(EC)</td>
</tr>
<tr>
<td>Statistics</td>
<td>70</td>
<td>105</td>
</tr>
<tr>
<td>$L$ Scale, Resol</td>
<td>70</td>
<td>185</td>
</tr>
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<td>35</td>
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Top Production at Hadron Colliders

Tevatron ($t\bar{t}$)

NLO corrections ~20%

Soft gluon resummation

Production Cross Section (pb)

<table>
<thead>
<tr>
<th>Run</th>
<th>LLHC</th>
<th>p\bar{p} 1.8 TeV</th>
<th>pp 2.0 TeV</th>
<th>pp 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td>90%</td>
<td>85%</td>
<td>95%</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td>80%</td>
<td>15%</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>7.0</td>
<td>$\sigma_t$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.78</td>
<td>0.88</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.2</td>
<td>2.4</td>
<td>0.12</td>
</tr>
</tbody>
</table>

$\delta_t = 5.0$ , $7.0$, $800$ (pb)

Theor. uncert. 10-20%

$\delta_t = 0.88$ , 2.4 , 0.12

In pairs via the strong interaction

Singly via the electroweak interaction
Top Decay

- In SM, assuming V-A coupling with a CKM mixing para. \(|V_{tb}|=1\) for the \(t \rightarrow bW\) decay vertex, one gets (LO):
  \[\Gamma(t \rightarrow bW) \approx 175 \text{ MeV} \left(\frac{M_t}{M_W}\right)^3\]
  \[\left(\frac{M_t}{M_W} \gg M_b\right)\]
  \[\rightarrow \Gamma(t \rightarrow bW) \approx 1.5 \text{ GeV}\]
  \[\rightarrow \tau(\text{top}) \approx 4 \times 10^{-25} \text{ s}\]
- Non-perturbative QCD hadronization takes place in a time of order \(\Lambda_{QCD}^{-1} \approx (100 \text{ MeV})^{-1} \approx 10^{-23} \text{ s}\)
  - Top decays as free quark (no top hadrons, no toponium spectroscopy)
  - Top decay will remember its original spin-1/2 state
- \(t \rightarrow Ws\) and \(t \rightarrow Wd\) allowed but suppressed by factors of \(\sim 10^{-3}\) and \(\sim 5 \times 10^{-5}\), respectively.

<table>
<thead>
<tr>
<th>Dilepton</th>
<th>BR = 1/9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton + Jets</td>
<td>BR = 4/9</td>
</tr>
<tr>
<td>All-hadronic</td>
<td>BR = 4/9</td>
</tr>
</tbody>
</table>
b-quark identification (b tagging)

- **Displaced vertices**
  \[ \tau(b) \sim 1.5 \text{ ps} \rightarrow L_{xy}(b) \sim O(\text{mm}) \]
  - Silicon Vertex Detector (SVX)
  - 1 vertex \(\leq 2 \) tracks
  - \( L_{xy}/\sigma_{L_{xy}} > 3.0 \)
  - \( \sigma_{L_{xy}} \sim 100 \mu \)
  - \( \varepsilon(b\text{-tag}) \sim 25\%/b\text{-jet} \ (\sim 4\% \ c\text{-jet}) \)
  - \( \varepsilon(b\text{-tag}) \sim 45\%/\text{event w/ 2b's} \)
  - \( \varepsilon(b\text{-tag}) \sim 0.2\%/\text{jet} \)

- **Semileptonic b decays**
  - \( b \rightarrow \bar{\nu}X \) \( \text{BR} \sim 20\% \)
  - \( b \rightarrow c \rightarrow \bar{\nu}X \) \( \text{BR} \sim 20\% \)
  - \( \varepsilon(b\text{-tag}) \sim 7\%/b\text{-jet} \)
  - \( \varepsilon(b\text{-tag}) \sim 16\%/\text{event w/ 2b's} \)
  - \( \varepsilon(b\text{-tag}) \sim 0.5\%/\text{jet} \)
\( t \bar{t} \) candidate

CDF

Jet 2

Jet 3

Jet 1 (b)

Jet 4 (b)

Primary Vertex

Secondary Vertices

\( W^- \)

\( W^+ \)

\( M_{J\bar{J}} = 79 \text{ GeV}/c^2 \)

\( t \bar{t} \) production
General Selection of $tt$-bar events in the lepton + jet channel

- $tt$ events can be distinguished from other processes by their topology: many particles (leptons, jets, neutrinos) with large transverse energy. E.g. in the lepton + jets channel require:

  - **Leptons**: (from leptonic $W$ decays)
    - Require 1 electron or muon with large transverse energy ($E_T$)
    - Events are mostly $W$'s and $Z$'s ($\sim 100,000$) with some $t \bar{t}$ ($\sim 100$)
    - $S/B \sim 1/1000$

  - **Missing transverse energy**: (from neutrinos)
    - Require large $E_T$
    - Events are mostly $W$'s ($\sim 60,000$) with some $t \bar{t}$ ($\sim 80$)
    - $S/B \sim 1/750$

  - **Jets**: (from $b$ quarks, hadronic $W$ decays, ISR, FSR)
    - Require at least 3 jets with large $E_T$
    - Events are mostly $W + \geq 3$ jets ($\sim 250$) with a larger fraction of $t \bar{t}$ ($\sim 40$)
    - $S/B \sim 1/6$

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- **Kinematic variables which exploit the large top mass can also be used to further strengthen the signal ($t \bar{t}$) over "background" processes.**
Run I $t\bar{t}$-bar cross section measurements

$$\sigma(p\bar{p} \rightarrow t\bar{t} \rightarrow \text{channel}_i) = \frac{N_{\text{obs}} - N_{\text{bkgd}}}{e^{-f} L dt}$$

**Top Cross Sections**

CDF preliminary

- 7.1^{+1.5}_{-1.1} ~ pb
- 5.1^{+1.6}_{-1.1} ~ pb
- 9.3^{+2.8}_{-1.5} ~ pb
- 8.4^{+1.6}_{-1.5} ~ pb
- 4.5^{+1.7}_{-1.5} ~ pb

Theory (4.7 - 5.5)

- 6.4^{+1.7}_{-1.5} ~ pb
- 4.1^{+1.1}_{-0.6} ~ pb
- 8.3^{+1.6}_{-1.5} ~ pb
- 7.3^{+1.3}_{-1.2} ~ pb
- 5.9^{+1.7}_{-1.7} ~ pb

D0

- HAD
- SLT
- DIL
- Combined

No excess observed.

$\Sigma(p\bar{p} \rightarrow t\bar{t})$ (pb)
What we can measure from $t\bar{t}$-bar

- $M_{\text{top}} \to M_{\text{Higgs}}$ information via higher order corrections
  - $M_W - M_{\text{top}} - M_{\text{Higgs}}$ Relation
- Top is very heavy, $g_t (t\bar{t}H \sim M_t^2 / M_W^2) \sim 1$, so understanding its properties may lead to clues about the mechanism behind EWSB.

- Everything we currently know about the top quark is based on $\sim 100$ $t\bar{t}$-bar events / experiment from Run I.
- Run II:
  $\sim 100k$ top events expected.

- Production Cross Section
- Resonance production?
- Production kinematics
- Decay modes
- Branching ratios
- CKM matrix element $|V_{tb}|$
- Rare decays $t \to Zc, \gamma c, t \to WZb, ...$
- Non-SM decays $t \to H^- \bar{c}, t \to \bar{t}, ...$

SM

New Physics?
Top mass measurement

The Transverse view & Pt(v)

We don't know the total longitudinal momentum in any event.

The total transverse momentum of all "detected" particles ~ 0.

\[ P_{T \nu} = - \sum P_{x i}, P_{y \nu} = - \sum P_{y i} \]

\[ P_{t}(q) = t \]

\[ P_{z}(q) \approx 0 \]
Measurement of $M_{\text{top}}$ CDF (1 + jets)

$M_{\text{top}} = 176.1 \pm 5.1 \text{ (stat.)}$
$\pm 5.3 \text{ (syst.)}$ GeV

<table>
<thead>
<tr>
<th>Systematic</th>
<th>$\delta M_{\text{top}}$(GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>4.4</td>
</tr>
<tr>
<td>Initial, Final state rad.</td>
<td>2.6</td>
</tr>
<tr>
<td>Background spectrum</td>
<td>1.3</td>
</tr>
<tr>
<td>b-tagging bias</td>
<td>0.4</td>
</tr>
<tr>
<td>Parton distribution func.</td>
<td>0.3</td>
</tr>
<tr>
<td>Monte Carlo generators</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Measurement of $M_{\text{top}}$ DO (1 + jets)

$M_{\text{top}} = 173.3 \pm 5.6$ (stat.)
$\pm 5.5$ (syst.) GeV
Measurement of $M_{\text{top}}$ CDF
Two leptons, All hadrons

![Diagram showing particle interactions and distributions for top quark mass measurement.](image)
Summary of Run I $M_{top}$ measurements

- 168.4 ± 12.8 GeV/c$^2$ Dilepton
- 173.3 ± 7.8 GeV/c$^2$ Lepton+jets
- 172.1 ± 7.1 GeV/c$^2$ Combined
- 167.4 ± 11.4 GeV/c$^2$ Dilepton
- 175.1 ± 7.4 GeV/c$^2$ Lepton+jets
- 185.0 ± 11.5 GeV/c$^2$ All-Hadronic
- 176.1 ± 6.6 GeV/c$^2$ Combined

The Top quark has the best measured mass of all quarks

$\frac{\Delta M_t}{M_t} \sim 3\%$
pp-colliders

LEP2

Average

NuTeV/CCFR

LEP1/SLD/νN/APV

LEP1/SLD/νN/APV/m_t

CDF

DØ

Average

LEP1/SLD/νN/APV

LEP1/SLD/νN/APV/m_t

80.454 ± 0.060

80.450 ± 0.039

80.451 ± 0.033

80.25 ± 0.11

80.363 ± 0.032

80.373 ± 0.023

176.1 ± 6.6

172.1 ± 7.1

174.3 ± 5.1

169.0 ± 10.0

180.5 ± 10.0

m_t [GeV]

m_H [GeV]

68% CL

113 300 1000

Preliminary
Implication of Precision EW Measurements

Precision EW measurements favor Light Higgs.

\[ \mathcal{M}_{\text{Higgs}} = 88^{+60}_{-37} \text{ GeV}, \quad \mathcal{M}_{\text{Higgs}} = 108^{+57}_{-38} \text{ GeV} \]

\[ \mathcal{M}_{\text{Higgs}} < 196 \sim 222 \text{ GeV at 95\% CL} \]
Implication of Precision EW Measurements

Year 2000

- LEP1, SLD, vN Data
- LEP2, pp Data

$68\%$ CL

$m_H$ [GeV]
113 300 1000 Preliminary

$m_t$ [GeV]
130 150 170 190 210

$M_{Higgs} = 60^{+52}_{-29}$ GeV

$M_{Higgs} < 165 - 196$ GeV @95\%CL

Year 2001

- LEP1, SLD, vN Data
- LEP2, pp Data

$68\%$ CL

$m_H$ [GeV]
113 300 1000 Preliminary

$m_t$ [GeV]
130 150 170 190 210

$M_{Higgs} = 88^{+60}_{-37}$ GeV

$M_{Higgs} = 108^{+57}_{-38}$ GeV

$M_{Higgs} < 206 - 222$ GeV @95\%CL
EW Measurements (last ~10 years)

$M_{W}$ (GeV)

$M_{H}$ (GeV)

$M_{\text{top}}$ (GeV)

1991 $M_{\text{top}}$ limit

1995

2001

1σ prediction

year
Tevatron Run II EW Measurements
→ SM test and $\delta M_{\text{Higgs}} / M_{\text{Higgs}}$

$\delta M_W \sim 25 \text{ MeV} - 20 \text{ MeV}, \delta M_{\text{top}} \sim 2 \text{ GeV} - 1.5 \text{ GeV}$

$\delta M_{\text{Higgs}} / M_{\text{Higgs}} \sim 30\% - 20\%$
### Summary of Top measurements and Future expectations

<table>
<thead>
<tr>
<th>Top quark Property</th>
<th>Run 1 measurement</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (CDF)</td>
<td>$176.1 \pm 4.2 \pm 5.1$ GeV/c$^2$</td>
<td>3.8%</td>
</tr>
<tr>
<td>Mass (DØ)</td>
<td>$172.1 \pm 5.2 \pm 4.9$ GeV/c$^2$</td>
<td>2.9%</td>
</tr>
<tr>
<td>Mass (CDF + DØ)</td>
<td>$174.3 \pm 3.3 \pm 3.9$ GeV/c$^2$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{gg}$ (CDF)</td>
<td>$6.5^{+1.7}_{-1.4}$ pb</td>
<td>25%</td>
</tr>
<tr>
<td>$\sigma_{gg}$ (DØ)</td>
<td>$5.9^{+1.7}_{-1.4}$ pb</td>
<td></td>
</tr>
<tr>
<td>W helicity, $F_0$</td>
<td>$0.91 \pm 0.37 \pm 0.13$</td>
<td>0.4</td>
</tr>
<tr>
<td>W helicity, $F_+$</td>
<td>$0.11 \pm 0.15 \pm 0.06$</td>
<td>0.15</td>
</tr>
<tr>
<td>$R = \frac{B(t\to Wb)}{B(t\to Wq)}$</td>
<td>$0.94^{+0.11}_{-0.05}$</td>
<td>30%</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
<td>$</td>
</tr>
<tr>
<td>$\sigma$(single top)</td>
<td>&lt; 18.6 pb</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma(t\to Wb)$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
<td>$</td>
</tr>
<tr>
<td>$\text{BR}(t\to \gamma q)$ 95% CL</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$\text{BR}(t\to Zq)$ 95% CL</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>

All top quark measurements have been consistent within SM framework, though are presently limited by low statistics.

Run II top measurements will provide much stiffer tests for SM, and because of the proximity of the top mass to the EWSB scale could be sensitive to new physics.
LEP, SLC, Tevatron Run I EW Measurements

→ SM : Higgs around the corner !!

→ Lecture #3 (Monday)