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Standard Model and Higgs Physics
FNAL LHC School, 2006

- Introduction to the Standard Model
  - Review of the SU(2) x U(1) Electroweak theory
  - Experimental status of the EW theory
  - Constraints from Precision Measurements
- Searching for the Higgs Boson
- The Importance of the TeV Scale

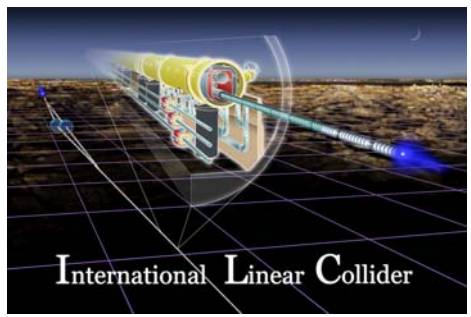
Lecture 1

- Introduction to the Standard Model
  - Just the SU(2) x U(1) part of it….
- Some good references:
  - Chris Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*
  - Michael Peskin, *An Introduction to Quantum Field Theory*
  - David Rainwater, Sally Dawson, TASI2006, http://quark.phy.bnl.gov/~dawson/tasi06

Collider Physics Timeline

Tevatron LHC LHC Upgrade ILC

2006 2007 2012



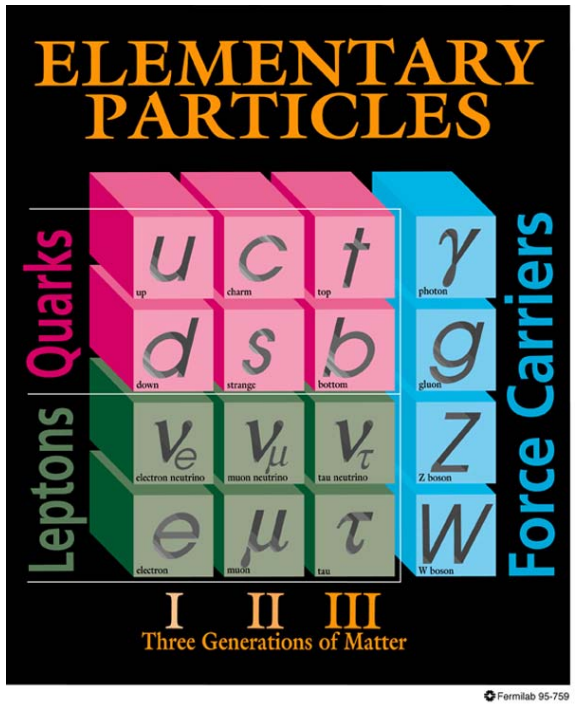
What We Know

- The photon and gluon appear to be massless
- The W and Z gauge bosons are heavy
  - M_W=80.404 $\pm$ 0.030 GeV
  - M_Z =91.1875 $\pm$ 0.0021 GeV
- There are 6 quarks
  - M_t=172.5 $\pm$ 2.3 GeV

    (171.4 $\pm$ 2.1 GeV, ICHEP 2006)
  - M_t >> all the other quark masses

What We Know

- 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_μ

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

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- U(1) local gauge invariance:

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$$

- 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

Abelian Higgs Model, 2

- Add complex scalar field, φ, with charge – e:

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \left| D_\mu \phi \right|^2 - V(\phi)$$

- Where

$$D_\mu = \partial_\mu - ieA_\mu \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

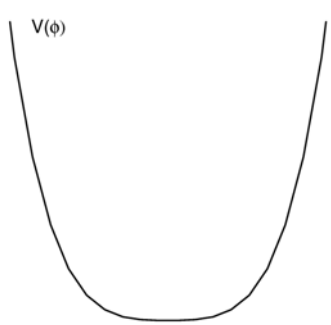
$$V(\phi) = \mu^2 |\phi|^2 + \lambda \left(|\phi|^2 \right)^2$$

- L is invariant under local U(1) transformations:

$$\boxed{\begin{aligned} A_\mu(x) &\to A_\mu(x) - \partial_\mu \eta(x) \\ \phi(x) &\to e^{-ie\eta(x)} \phi(x) \end{aligned}}$$

Abelian Higgs Model, 3

- Case 1: $\mu^2 > 0$
  - QED with $M_A=0$ and $m_\varphi=\mu$
  - Unique minimum at $\varphi=0$



$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left|D_\mu \phi\right|^2 - V(\phi)$$

$$D_\mu \quad = \partial_\mu - ieA_\mu$$

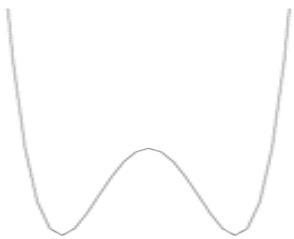
$$V(\phi) = \mu^2\left|\phi\right|^2 + \lambda\left(\left|\phi\right|^2\right)^2$$

By convention, $\lambda > 0$

Abelian Higgs Model, 4

- Case 2: $\mu^2 < 0$

$$V(\phi) = -\left|\mu^2\right|\left|\phi\right|^2 + \lambda\left(\left|\phi\right|^2\right)^2$$



- Minimum energy state at:

$$<\phi> = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$$

Vacuum breaks U(1) symmetry

Aside: What fixes sign (μ^2)?

Abelian Higgs Model, 5

- Rewrite $\phi \equiv \frac{1}{\sqrt{2}} e^{i\frac{\chi}{v}} (v+h)$

  χ and h are the 2 degrees of freedom of the complex Higgs field

- L becomes:

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - evA_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A^\mu A_\mu + \frac{1}{2}\left(\partial_\mu h \partial^\mu h + 2\mu^2 h^2\right)$$
$$+ \frac{1}{2} \partial_\mu \chi \partial^\mu \chi + (h, \chi \text{ interactions})$$

- Theory now has:
  - Photon of mass $M_A = ev$
  - Scalar field h with mass-squared $-2\mu^2 > 0$
  - Massless scalar field χ *(Goldstone Boson)*

Abelian Higgs Model, 6

- What about mixed χ-A propagator?
  - Remove by gauge transformation

$$A'_\mu \equiv A_\mu - \frac{1}{ev}\partial_\mu \chi$$

$$\boxed{L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2v^2}{2}A'^\mu A'_\mu + \frac{1}{2}\left(\partial_\mu h \partial^\mu h\right) - V(h)}$$

- χ field disappears
  - We say that it has been *eaten* to give the photon mass
  - χ field called Goldstone boson
  - *This is Abelian Higgs Mechanism*
  - This gauge (unitary) contains only physical particles

Higgs Mechanism summarized

Spontaneous breaking of a gauge theory by a non-zero VEV of a scalar field results in the disappearance of a Goldstone boson and its transformation into the longitudinal component of a massive gauge boson

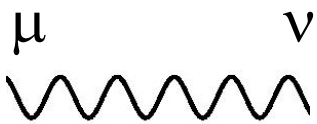
R_ξ gauges

Mass of Goldstone boson χ depends on ξ

$\xi=1$: Feynman gauge with massive χ

$\xi=0$: Landau gauge

$\xi\to\infty$: Unitarity gauge

Gauge Boson, A 

$$\frac{-i}{k^2-M_A^2}\left(g^{\mu\nu}-\frac{k^\mu k^\nu}{k^2-\xi M_A^2}(1-\xi)\right)$$

Higgs, h

$$\frac{i}{k^2-M_h^2}$$

Goldstone Boson, χ, or Faddeev-Popov ghost

$$\frac{i}{k^2-\xi M_A^2}$$

Non-Abelian Higgs Mechanism

- Vector fields $A^a_\mu(x)$ and scalar fields $\varphi_i(x)$ of SU(N) group

$$\Phi = \begin{pmatrix} \phi_1 \\ \cdot \\ \cdot \\ \cdot \\ \phi_N \end{pmatrix}$$

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

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

- L is invariant under the non-Abelian symmetry:

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

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

- τ_a are group generators, a=1…N^2-1 for SU(N)

For SU(2): $\tau^a = \sigma^a/2$

Non-Abelian Higgs Mechanism, 2

- In exact analogy to the Abelian case

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

$$\rightarrow \overset{\phi \to \phi_0}{} \ldots + g^2 (\tau^a \phi_0{}^+)_i (\tau^b \phi_0)_i A^a_\mu A^{b\mu} + \ldots$$

- $\tau^a \varphi_0 \neq 0$ $\Rightarrow$ Massive vector boson + Goldstone boson
- $\tau^a \varphi_0 = 0$ $\Rightarrow$ Massless vector boson + massive scalar field

Non-Abelian Higgs Mechanism, 3

- Consider SU(2) example $D_\mu \phi = \left(\partial_\mu - ig \frac{\sigma^a}{2} A_\mu^a \right) \phi$
- Suppose φ gets a VEV:

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Gauge boson mass term

$$\left| D_\mu \phi \right|^2 \to \frac{1}{2} g^2 (0, v) \tau^a \tau^b \begin{pmatrix} 0 \\ v \end{pmatrix} A_\mu^a A^{b\mu}$$

- Using the property of group generators, $\{\tau^a, \tau^b\} = \delta^{ab}/2$
- Mass term for gauge bosons:

$$\boxed{L_{mass} = \frac{g^2 v^2}{8} A_\mu^a A^{a\mu}}$$

Standard Model Synopsis

- Group: $\underbrace{SU(3)}_{\text{QCD}} \times \underbrace{SU(2) \times U(1)}_{\text{Electroweak}}$
- Gauge bosons:
  - SU(3): G_μ^i, i=1…8
  - SU(2): W_μ^i, i=1,2,3
  - U(1): B_μ
- Gauge couplings: g_s, g, g'
- SU(2) Higgs doublet: Φ

SM Higgs Mechanism

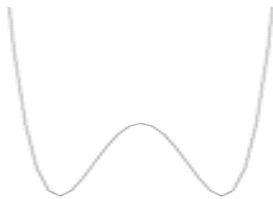
- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

- With SU(2) x U(1) invariant scalar potential

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

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at: $\langle \Phi \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$
  - Choice of minimum breaks gauge symmetry
  - Why is $\mu^2 < 0$?



More on SM Higgs Mechanism

- Couple Φ to SU(2) x U(1) gauge bosons (W_i^μ, i=1,2,3; B^μ)

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

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

Justify later: $Y_\Phi = 1$

- Gauge boson mass terms from:

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

$$\to \ldots + \frac{v^2}{8}\left(g^2 (W_\mu^1)^2 + g^2 (W_\mu^2)^2 + (-gW_\mu^3 + g' B_\mu)^2\right) + \ldots$$

More on SM Higgs Mechanism

- With massive gauge bosons:

$$M_W = gv/2$$
$$M_Z = \sqrt{(g^2+g'^2)}\,v/2$$

$$W_\mu^{\pm} = (W_\mu^{1} \mp W_\mu^{2)} / \sqrt{2}$$
$$Z_\mu^{0} = (g\, W_\mu^{3} - g' B_\mu) / \sqrt{(g^2+g'^2)}$$

- Orthogonal combination to Z is massless photon

$$A_\mu^{0} = (g'\, W_\mu^{3} + g B_\mu) / \sqrt{(g^2+g'^2)}$$

More on SM Higgs Mechanism, 2

- Weak mixing angle defined

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

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

$$M_W = M_Z \cos\theta_W$$

More on SM Higgs Mechanism

- Generate mass for W,Z using Higgs mechanism
  - Higgs VEV breaks SU(2) x U(1)$\rightarrow$U(1)$_{em}$
  - Single Higgs doublet is minimal case
- Just like Abelian Higgs model
  - Goldstone Bosons $\chi \rightarrow \omega^{\pm}, z$
- Before spontaneous symmetry breaking:
  - Massless W_i, B, Complex Φ
- After spontaneous symmetry breaking:
  - Massive $W^{\pm}$,Z; massless γ; physical Higgs boson h

Fermi Model

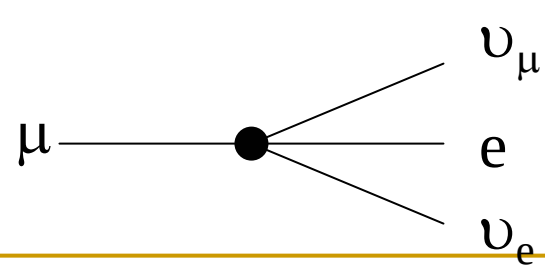
- Current-current interaction of 4 fermions

$$L_{FERMI} = -2\sqrt{2}G_F J_\rho^+ J^\rho$$

- Consider just leptonic current

$$J_\rho^{lept} = \bar{\nu}_e \gamma_\rho \left(\frac{1-\gamma_5}{2}\right) e + \bar{\nu}_\mu \gamma_\rho \left(\frac{1-\gamma_5}{2}\right) \mu + hc$$

- Only left-handed fermions feel charged current weak interactions (maximal P violation)
- This induces muon decay



$G_F = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$

This structure known since Fermi

Now include Leptons

- Simplest case, include an SU(2) doublet of left-handed leptons

$$\Psi_L = \begin{pmatrix} \nu_L = \frac{1}{2}(1-\gamma_5)\nu \\ e_L = \frac{1}{2}(1-\gamma_5)e \end{pmatrix}$$

- Right-handed electron, $e_R=(1+\gamma_5)e/2$, is SU(2) singlet
  - No right-handed neutrino

**Standard Model has massless neutrinos—discovery of non-zero neutrino mass evidence for physics beyond the SM*

Leptons, 2

- Couple gauge fields to leptons

$$L_{leptons} = \bar{e}_R i\gamma^\mu \left(\partial_\mu - i\frac{g'}{2} YB_\mu \right) e_R$$
$$+ \overline{\Psi}_L i\gamma^\mu \left(\partial_\mu - i\frac{g'}{2} YB_\mu - i\frac{g}{2}\sigma_i W_i^{\ \mu} \right) \Psi_L$$

Leptons, 3

- Write in terms of charged and neutral currents

$$L_{leptons} = (kinetic) + g\left(W_\mu^+ J^{\mu+} + W_\mu^- J^{\mu-} + Z_\mu J_Z^\mu\right) + eA_\mu J_{em}^\mu$$

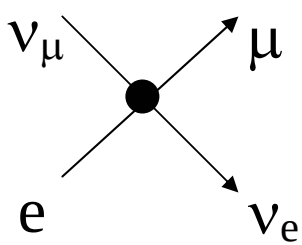
$$J_{em}^\mu = -Q_{em}\bar{e}\gamma^\mu e$$

$$J^{+\mu} = -\frac{1}{\sqrt{2}}\left(\bar{e}_L\gamma^\mu\nu_L\right)$$

$$J_Z^\mu = -\frac{1}{2\cos\theta_W}\left(\bar{\nu}_L\gamma^\mu\nu_L + \bar{e}_L\gamma^\mu\left[-1+2\sin^2\theta_W\right]e_L + \bar{e}_R\gamma^\mu\left[2\sin^2\theta_W\right]e_R\right)$$

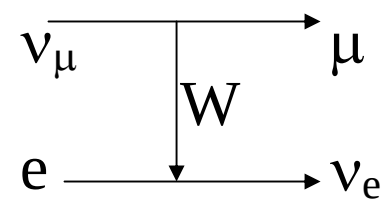
Muon decay

- Consider $\nu_\mu e \to \mu \nu_e$
- Fermi Theory:



$$-i2\sqrt{2}G_F g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

- EW Theory:



$$\frac{ig^2}{2}\frac{1}{k^2-M_W^2}g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

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

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

For $|k| >> M_W$, $\sigma \sim 1/E^2$

Parameters of SU(2) x U(1) Sector

- $g, g', \mu, \lambda \Rightarrow$ Trade for:
  - α=1/137.03599911(46) from $(g-2)_e$ and quantum Hall effect
  - G_F=1.16637(1) x 10^{-5} GeV^{-2} from muon lifetime
  - M_Z=91.1875$\pm$0.0021 GeV
  - Plus Higgs and fermion masses

Now Add Quarks to Standard Model

- Include color triplet quark doublet

$$Q_L = \begin{pmatrix} u_{iL} \\ d_{iL} \end{pmatrix} \qquad \text{i=1,2,3 for color}$$

  - Right handed quarks are SU(2) singlets, $u_R=(1+\gamma_5)u$, $d_R=(1+\gamma_5)d$
- With weak hypercharge
  - $Y_{uR}=4/3$, $Y_{dR}=-2/3$, $Y_{QL}=1/3$

$$\boxed{Q_{em}=(I_3+Y)/2}$$

Quarks, 2

- Couplings of charged current to W and Z's take the form:

$$L_{Zqq} = -\frac{g}{4\cos\theta_W}\bar{q}\gamma^{\mu}\left[L_q(1-\gamma_5)+R_q(1+\gamma_5)\right]qZ_{\mu}$$

$$L_{Wqq} = -\frac{g}{2\sqrt{2}}\left(\bar{u}\gamma^{\mu}(1-\gamma_5)dW_{\mu}^{+}+\bar{d}\gamma^{\mu}(1-\gamma_5)uW_{\mu}^{-}\right)$$

$$\boxed{\begin{aligned} L_q &= I_3 + 2Q_{em}\sin^2\theta_W \\ R_q &= 2Q_{em}\sin^2\theta_W \end{aligned}}$$

What about fermion masses?

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L\right) \quad \leftarrow$$

Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

- Scalar couplings to fermions:

$$L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

- Effective Higgs-fermion coupling

$$L_d = -\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + h.c.$$

- Mass term for down quark: $\boxed{\lambda_d = -\frac{M_d \sqrt{2}}{v}}$

Fermion Masses, 2

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

$$\Phi_c = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}$$

$$L = -\lambda_u \overline{Q}_L \Phi_c u_R + hc$$

$$\boxed{\lambda_u = -\frac{M_u\sqrt{2}}{v}}$$

- For 3 generations, α, β=1,2,3 (flavor indices)

$$\boxed{L_Y = -\frac{(v+h)}{\sqrt{2}} \sum_{\alpha,\beta} \left(\lambda_u^{\alpha\beta} \bar{u}_L^{\alpha} u_R^{\beta} + \lambda_d^{\alpha\beta} \bar{d}_L^{\alpha} d_R^{\beta} \right) + h.c.}$$

Fermion masses, 3

- Unitary matrices diagonalize mass matrices

$$\boxed{\begin{aligned} u_L^\alpha &= U_u^{\alpha\beta} u_L^{m\beta} \qquad & d_L^\alpha &= U_d^{\alpha\beta} d_L^{m\beta} \\ u_R^\alpha &= V_u^{\alpha\beta} u_R^{m\beta} \qquad & d_R^\alpha &= V_d^{\alpha\beta} d_R^{m\beta} \end{aligned}}$$

  - Yukawa couplings are ***diagonal*** in mass basis
  - Neutral currents remain flavor diagonal
  - Not necessarily true in models with extended Higgs sectors

- Charged current:

$$\boxed{J^{+\mu} = \frac{1}{\sqrt{2}} \bar{u}_L^\alpha \gamma^\mu d_L^\alpha = \frac{1}{\sqrt{2}} \bar{u}_L^{m\alpha} \gamma^\mu (U_u^+ V_d)_{\alpha\beta} d_L^{\beta m}}$$

CKM matrix

Basics

- Four free parameters in gauge-Higgs sector
  - Conventionally chosen to be
    - α=1/137.0359895(61)
    - G_F =1.16637(1) x 10^{-5} GeV $^{-2}$
    - M_Z=91.1875 $\pm$ 0.0021 GeV
    - M_H
  - Express everything else in terms of these parameters

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{\pi\alpha}{2\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2}$$

$\Rightarrow$ Predicts M_W

Inadequacy of Tree Level Calculations

- Mixing angle is predicted quantity
  - On-shell definition $\cos^2\theta_W = M_W^2/M_Z^2$
  - Predict M_W

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

$$s_W{}^2 c_W{}^2 = \frac{\pi\alpha}{G_F M_Z^2}$$

  - Plug in numbers:
    - M_W predicted =80.939 GeV
    - M_W(exp) =80.404 $\pm$ 0.030 GeV
  - Need to calculate beyond tree level

Modification of tree level relations

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W} \frac{1}{(1-\Delta r)}$$

- Δr is a physical quantity which incorporates 1-loop corrections

- Contributions to Δr from top quark and Higgs loops

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

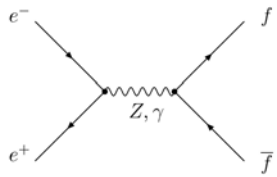
$$\Delta r^h = \frac{11G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2} - \frac{5}{6}\right)$$

Extreme sensitivity of precision measurements to m_t

Where are we with Z's?

- At the Z pole:
  - 2 x 10^7 unpolarized Z's at LEP
  - 5 x 10^5 Z's at SLD with P_e ~75%
- What did we measure at the Z?
  - Z lineshape $\Rightarrow \sigma$, Γ_Z, M_Z
  - Z branching ratios
  - Asymmetries
- W^+W^- production at 200 GeV
  - Searches for Zh

$e^+e^- \rightarrow f\bar{f}$



$$\frac{d\sigma}{dz}\left(e^+e^- \rightarrow f\bar{f}\right) = \frac{N_c \pi \alpha^2 Q_f^2}{2s}(1+z^2)$$

γ exchange

$$-\frac{N_c \alpha Q_f M_Z^2 (s - M_Z^2)}{\left[(s-M_Z^2)^2 + M_Z^2 \Gamma_Z^2\right]}\left[(R_e + L_e)(R_f + L_f)(1+z^2) + 2(R_e - L_e)(R_f - L_f)z\right]$$

γ-Z interference

Changes sign at pole

$$+\frac{N_c G_F^2 M_Z^4 s}{64\pi\left[(s-M_Z^2)^2 + M_Z^2 \Gamma_Z^2\right]}\begin{bmatrix}(R_e^2 + L_e^2)(R_f^2 + L_f^2)(1+z^2) \\ +2(R_e^2 - L_e^2)(R_f^2 - L_f^2)z\end{bmatrix}$$

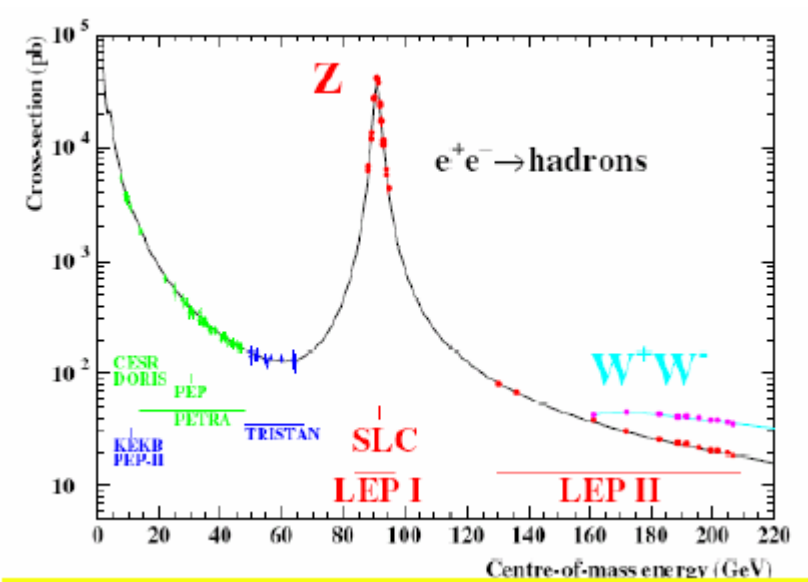
Z exchange

$z = \cos\theta$

$e^+e^- \to f\bar{f}$ (#2)

- Assume energy near the Z-pole, so include only Z exchange

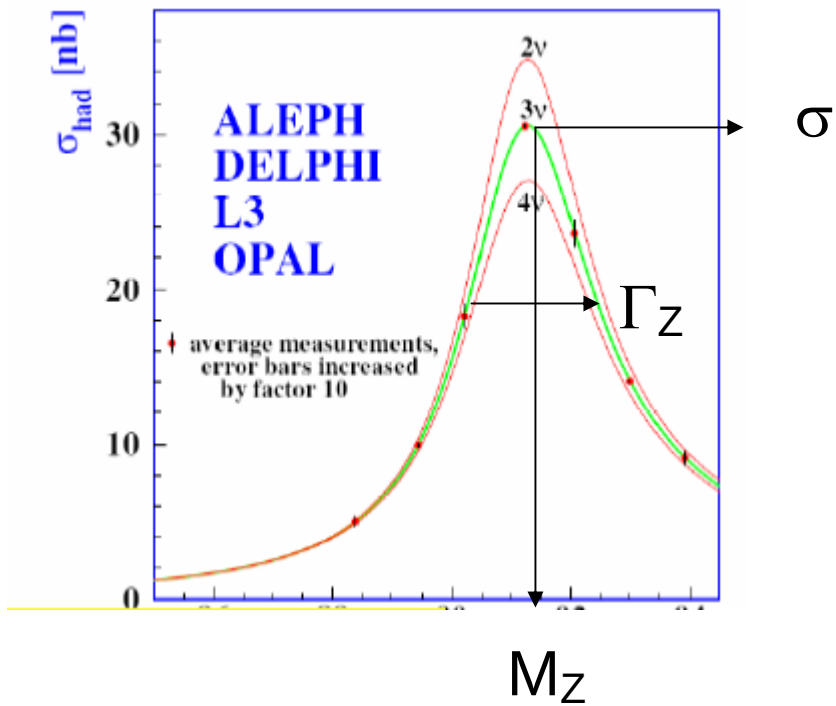
$$\frac{d\sigma}{dz}\left(e^+e^- \to f\bar{f}\right) = \frac{N_c G_F^2 M_Z^4 s}{64\pi\left[(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2\right]}\left((R_e^2+L_e^2)(R_f^2+L_f^2)(1+z^2) + 2(R_e^2-L_e^2)(R_f^2-L_f^2)z\right)$$



Contributes only to asymmetries if acceptance is symmetric

$$\sigma_{Z-peak}\left(e^+e^- \to f\bar{f}\right) = \frac{N_c G_F^2 M_Z^4}{24\pi\Gamma_Z^2}(R_e^2+L_e^2)(R_f^2+L_f^2)$$

Z cross section



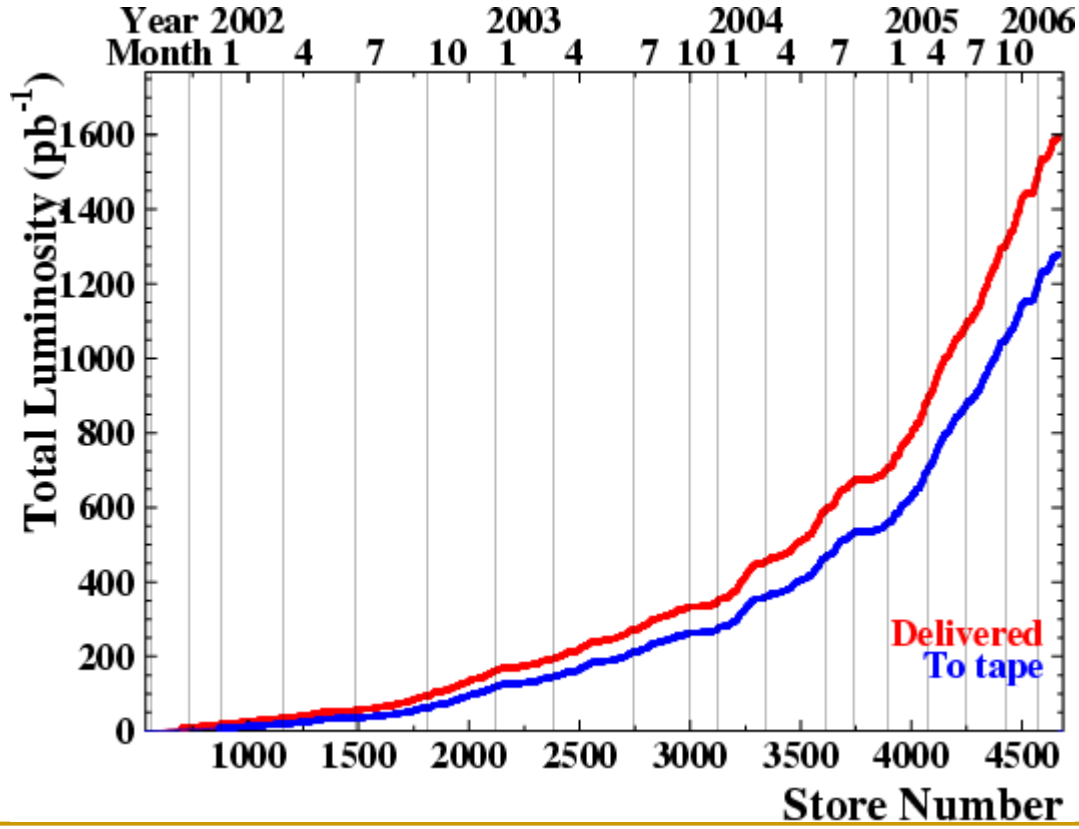
Requires precise calibration of energy of machine

Number of light neutrinos: $N_\upsilon = 2.9840 \pm 0.0082$

Tevatron

Tevatron running $p\bar{p}$ at $\sqrt{s}$=2 TeV

Scheduled to shut down 2009-2010



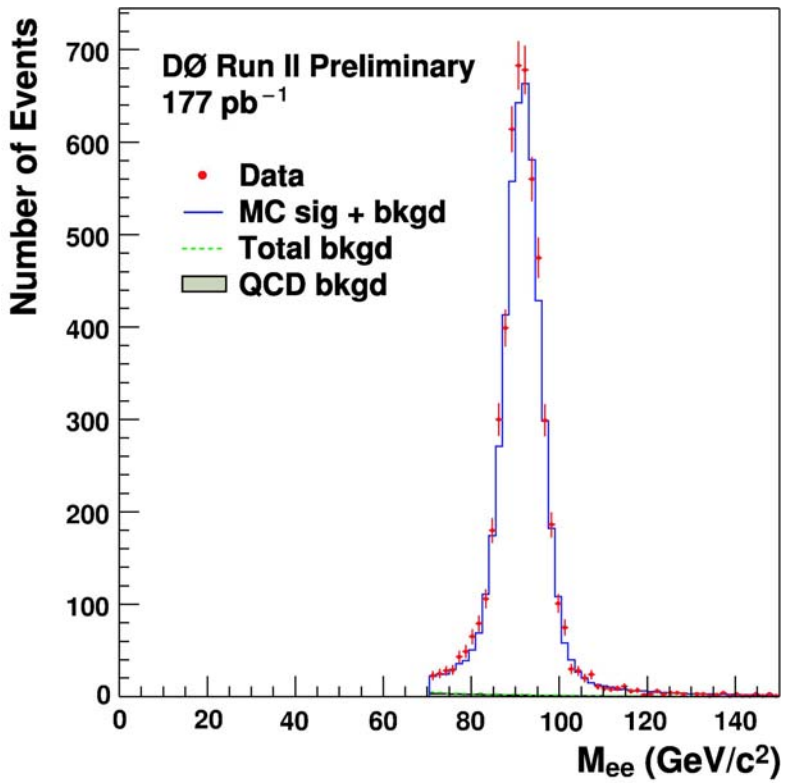
Z's at the Tevatron

- Z-production $q\bar{q} \to Z \to e^+e^-$
- Amplitude has pole at M_Z

$$\frac{1}{(p_e + p_{\bar{e}})^2}$$

- Invariant mass distribution of e^+e^-

$$m_{ee}^2 = \left(p_e + p_{\bar{e}}\right)^2 \approx M_Z^2$$



W's at the Tevatron

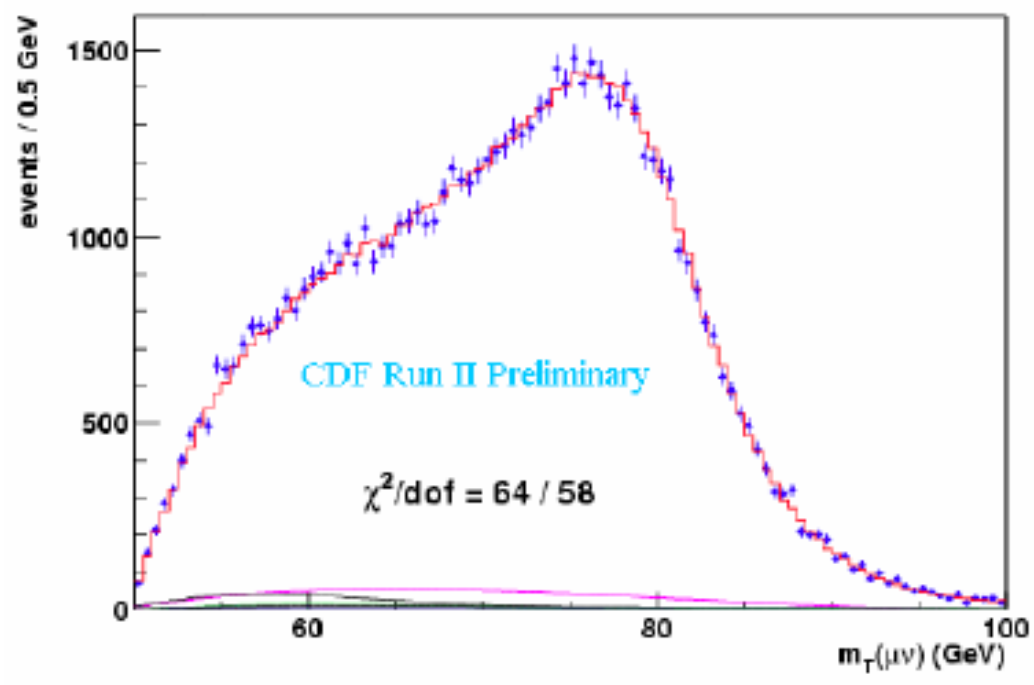
- Consider $W \rightarrow e\nu$
- Invariant mass of the leptonic system

$$m_{e\nu}^2 = \left(E_e + E_\nu\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2 - \left(p_{ez} + p_{\nu z}\right)^2$$

- Missing transverse energy of neutrino inferred from observed momenta
- Can't reconstruct invariant mass
- Define transverse mass observable

$$\begin{aligned} m_T^2 &= \left(E_{eT} + E_{\nu T}\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2 \\ &= 2\,\vec{p}_{eT}\,\vec{p}_{\nu T} = 2E_{eT}E_{\nu T}(1-\cos\phi) \end{aligned}$$

W Mass Measurement



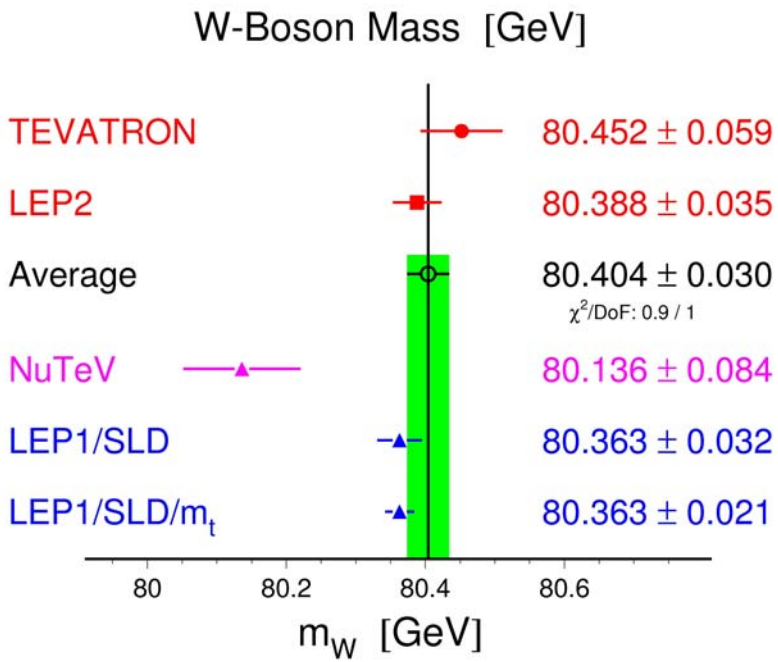
Location of peak gives M_W

Shape of distribution sensitive to Γ_W

Statistics enough to best LEP 2

World Average for W mass

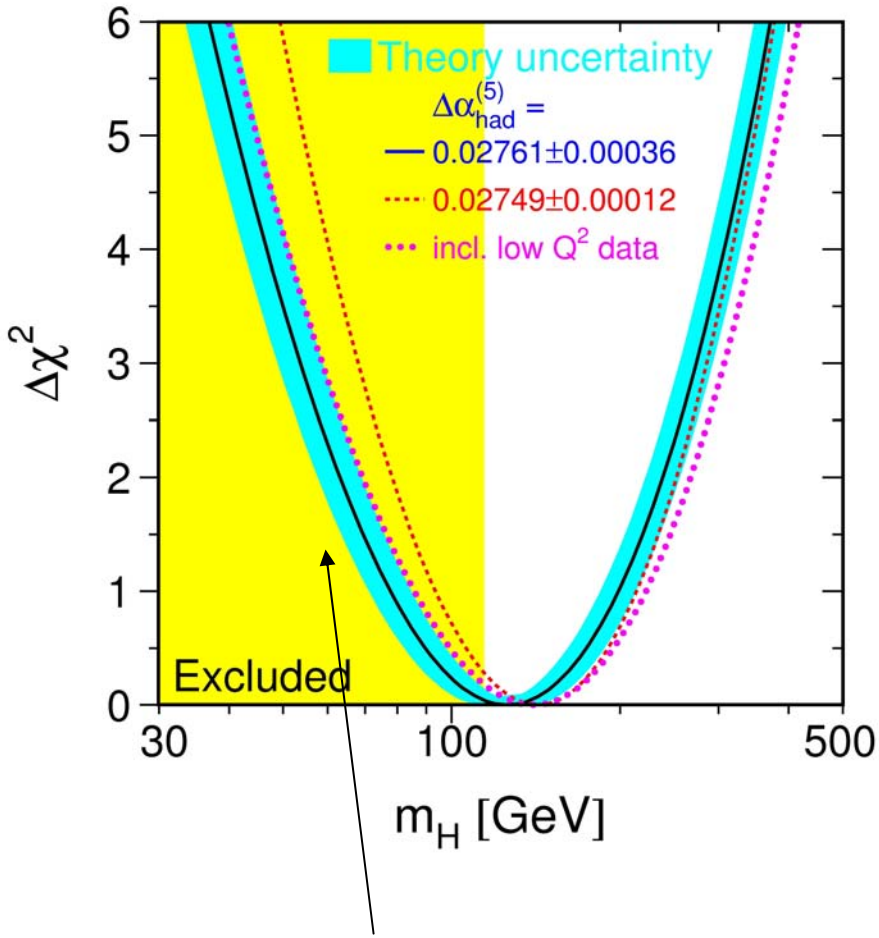
- Direct measurements (Tevatron/LEP2) and indirect measurements (LEP1/SLD) in excellent agreement
- Indirect measurements *assume* a Higgs mass



LEPEWWG home page, 2006

Data prefer light Higgs

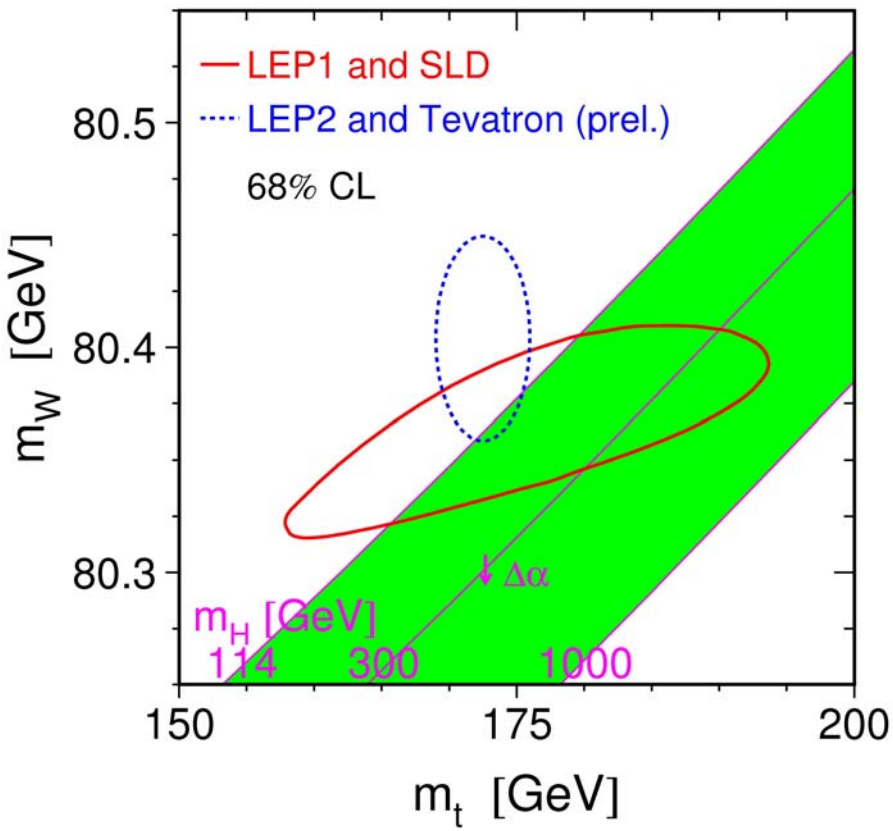
- Low Q^2 data not included
  - Doesn't include atomic parity violation in cesium, parity violation in Moller scattering, & neutrino-nucleon scattering (NuTeV)
  - Higgs fit not sensitive to low Q^2 data
- M_h< 207 GeV
  - 1-side 95% c.l. upper limit, including direct search limit
  - (M_h < 166 GeV ICHEP 2006)



Direct search limit from $e^+e^- \rightarrow Zh$

Top Quark mass pins down Higgs Mass

- Data prefer a light Higgs



2006

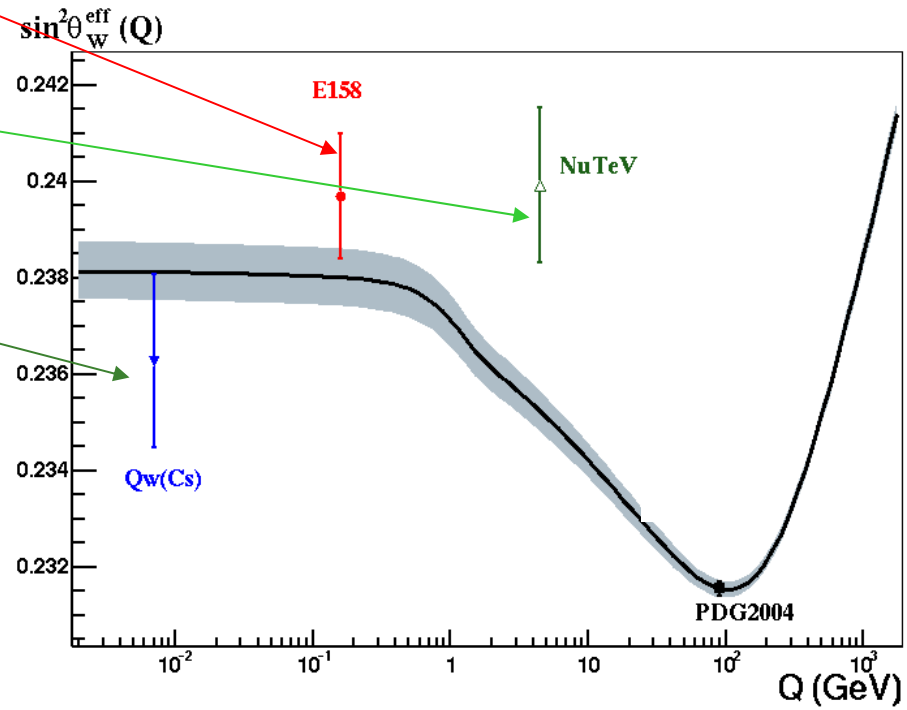
Understanding Higgs Limit

$$M_W = 80.364 - 0.0579 \ln\left(\frac{M_h}{100\ GeV}\right) - 0.008 \ln^2\left(\frac{M_h}{100\ GeV}\right)$$
$$-0.5098\left(\frac{\Delta\alpha_{had}{}^{(5)}(M_Z)}{0.02761} - 1\right) + 0.525\left[\left(\frac{M_t}{172\ GeV}\right)^2 - 1\right]$$
$$-0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$

M_W(experiment)=80.404 ± 0.030

$\sin^2\theta_w$ depends on scale

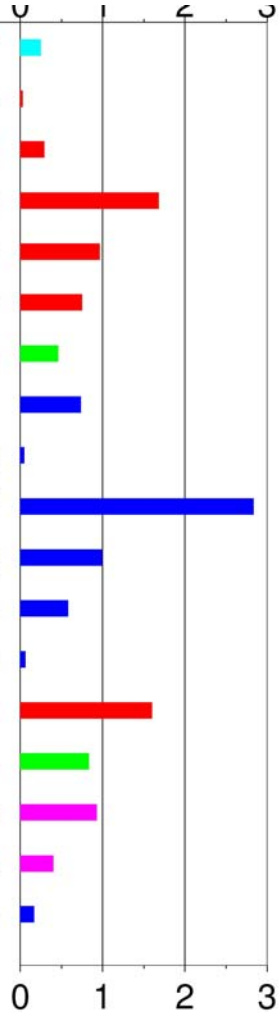
- Moller scattering, $e^-e^- \rightarrow e^-e^-$
- ν-nucleon scattering
- Atomic parity violation in Cesium



Electroweak Theory is Precision Theory

We have a model….
And it works to the 1% level

Gives us confidence to predict the future!

2006

$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.404 ± 0.030	80.376
Γ_W [GeV]	2.115 ± 0.058	2.092
m_t [GeV]	172.5 ± 2.3	172.9