Discovery 1983 - real triumph
(Rubbia & van der Meer - Nobel)

$M_Z = 91.1876 \pm .0021$ GeV

— 1/18/07

Parametrize EFT as

$$\mathcal{L}_{EW} = \mathcal{L}_{GB} + \mathcal{L}_{Break}$$

gauge boson, <u>symmetric</u>

masses, etc. constrain ...

(also: ~> more issues)

SU(2) A^a_μ, $F^a_{\mu\nu}$

U(1) B_μ, $B_{\mu\nu}$

$$\mathcal{L}_{GB} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{L}_{break} = -M_W^2 W^+_\mu W^{\mu -} - \frac{1}{2} M_Z^2 Z_\mu Z^\mu \quad \text{w/ } W^\pm = \frac{1}{\sqrt{2}}(A^1 \mp i A^2)$$

Fermion couplings: $\mathcal{L}_{F,G} + \mathcal{L}_{F,B}$

given by <u>charges</u>

$\psi_{I,L}$: doublets $l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$ $q_i = \begin{pmatrix} u_i \\ d_i' \end{pmatrix}$

recall $= Vd$

$\psi_{I,R}$: singlets $\bar{e}_i$ $\cancel{\bar{\nu}_i}$ $\bar{u}_i$, $\bar{d}_i$

not SM later

write as LH ferm.

$U(1)$ charge: Y ; want $[Q_Y, Q^a] = 0$

$\overset{ex}{\rightsquigarrow}$ $Y \propto Q_{em} - T_3$ (HW)

or $Q_{em} = T_3 + Y$

← norm: conventions differ

(Trick: average charges of doublet)

$Y_\ell = -\frac{1}{2}$ $\quad Y_q = \frac{1}{6}$

$Y_{\bar{e}} = 1$ $\quad Y_{\bar{u}} = -\frac{2}{3}$ $\quad Y_{\bar{d}} = \frac{1}{3}$

$$D_\mu = \partial_\mu - i g_2 A_{(2)\mu} - i g_1 Y B_\mu \left(-i g_3 A_{(3)\mu}\right)$$

$$\mathcal{L}_{F,G} = i \sum_I \Psi_I^\dagger \bar{\sigma}^\mu D_\mu \Psi_I$$

w/ (now) $\Psi_I = \ell_i \quad (1, 2, -1/2)$

$\bar{e}_i \quad (1, 1, 1)$

$q_i \quad (3, 2, 1/6)$

$\bar{u}_i \quad (\bar{3}, 1, -2/3)$

$\bar{d}_i \quad (\bar{3}, 1, 1/3)$

note $m \bar{e} e$, etc $\in \mathcal{L}_{F,B}$

Neutral currents

$$g_1 Y B + g_2 T^3 A^3 \quad ; \quad -\frac{1}{4}\left(F^{3\,2}_{\mu\nu} + B^{2}_{\mu\nu}\right)$$

$$Q = T^3 + Y \quad \longleftrightarrow \quad A_\mu \; .$$

$s_W = \sin\theta_W$
$c_W = \cos\theta_W$

orthogonal $\begin{pmatrix} B \\ A^3 \end{pmatrix} = \begin{pmatrix} c_W & -s_W \\ +s_W & c_W \end{pmatrix} \begin{pmatrix} A \\ Z \end{pmatrix}$

coupling to A:

$$g_1 Y c_W + g_2 T^3 s_W = e\left(T^3 + Y\right)$$

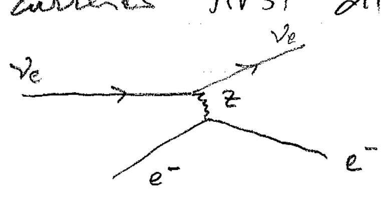
$$\Longleftrightarrow \quad \boxed{\tan\theta_W = \frac{g_1}{g_2} \qquad e = g_1 c_W}$$

coupling to Z: $\quad -g_1 Y s_W + g_2 T^3 c_W$

$$\underset{ex}{=} \frac{e}{s_W c_W}\left(T^3 - s_W^2 Q\right)$$

$U(1)_{em}$ unbroken $\longleftrightarrow$ $A = c_W B + s_W A^3$ <u>massless</u>

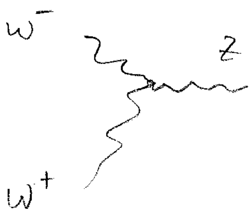
Neutral currents first discovered 1973



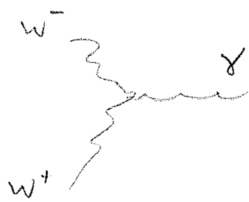
(note - Z couples to ν's, unlike A)

$\rightsquigarrow \quad s_W^2 \simeq .23 \qquad$ (PDB; scheme dependent $\Rightarrow$ variations)

Also, note non-abelian $\Rightarrow$



and



+ quartic.

Fermion masses

quarks (2 comp) $\psi_\alpha, \bar{\psi}_\alpha$ $= 12 \quad (\times 3)$

$\alpha = u\, d\, s \dots$

leptons $\lambda_\alpha, \bar{\lambda}_\alpha$ $= 12$

$\alpha = \nu_e\, e\, \nu_\mu\, \mu \dots$

if masses, $g_i = 0$: $U(48)$ symmetry (global)

extensions of SM : ~ different facets or extensions of this symm.

"know" $SU(3) \times U(1)_{em}$ = gauged.

$SU(2) \times U(1)_Y \simeq$ gauged; masses break.

Quarks let $\not{D} = \bar{\sigma}^\mu D_\mu$

$$\mathcal{L}_F = i \sum_\alpha \psi_\alpha^\dagger \not{D} \psi_\alpha + \bar{\psi}_\alpha^\dagger \not{D} \bar{\psi}_\alpha \qquad \text{sym}$$

	gauge	global
$g_1 = 0,\ g_2$	$SU(2)_L$	$SU(2)_R \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{''}} \times \dots$ custodial $\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix} \to U \begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}$
g_1, g_2	$SU(2)_L \times U(1)_Y$	

approx sym.

restored if $\sin\theta_W = 0$

$+ \mathcal{L}_m$ ... breaks

$SU(3) \times U(1)_{em} \Rightarrow$

$$\mathcal{L}_m = u_i \underset{\uparrow\, 3\times 3}{M^u_{ij}} \bar{u}_j + d_i M^d_{ij} \bar{d}_j$$

breaks $SU(2)_L \times SU(2)_R$

Simplification:

$$M^u = U_L \underset{\uparrow}{m^u} U_R^\dagger$$

diag

$$M^d = \underbrace{D_L \overset{\downarrow}{m^d} D_R^\dagger}_{\text{unitary, } SU(3)}$$

$$\bar{u} \to U_R \bar{u}$$
$$\bar{d} \to D_R \bar{d}$$

eliminate U_R, D_R (symm)

but

$$u \to u U_L^\dagger$$
$$d \to d D_L^\dagger$$

$\rightsquigarrow$ non-trivial effect:

couples to W^a_μ

$$J^{a\mu} = \begin{pmatrix} u_i \\ d_i \end{pmatrix}^\dagger \frac{\tau^a}{2} \bar{\sigma}^\mu \begin{pmatrix} u_i \\ d_i \end{pmatrix} \to \begin{pmatrix} u^\dagger U_L \\ d^\dagger D_L \end{pmatrix} \frac{\tau^a}{2} \bar{\sigma}^\mu \begin{pmatrix} U_L^\dagger u \\ D_L^\dagger d \end{pmatrix}$$

$$= \begin{pmatrix} u^\dagger \\ d^\dagger D_L U_L^\dagger \end{pmatrix} \frac{\tau^a}{2} \bar{\sigma}^\mu \begin{pmatrix} u \\ U_L D_L^\dagger d \end{pmatrix}$$

$\Rightarrow d' = V d$

$V = U_L D_L^\dagger$: CKM matrix. Note GIM mechanism (cancel in J^3 - no FCNC's)

$\therefore$

$$\mathcal{L}_m = \sum_i \left(m_i^u u_i \bar{u}_i + m_i^d d_i \bar{d}_i \right)$$
$$= \sum_i q_i \cdot \begin{pmatrix} m_i^u \\ 0 \end{pmatrix} \bar{u}_i + q_i \cdot \begin{pmatrix} 0 \\ m_i^d \end{pmatrix} \bar{d}_i$$

so these SU(2) "vectors" break $SU(2)_L \times U(1)_Y \to U(1)_{em}$.

Leptons

$$\mathcal{L}_F = i \sum_\alpha \lambda^+_\alpha \not{D} \lambda_\alpha + \bar{\lambda}^+_\alpha \not{D} \bar{\lambda}_\alpha \qquad \text{symm}$$

$$+ \mathcal{L}_m$$

SM$^-$: $\quad e_i M^e_{ij} \bar{e}_j \longrightarrow \sum_i M^e_i e_i \bar{e}_i = \sum_i l_i \cdot \begin{pmatrix} 0 \\ M^e_i \end{pmatrix} \bar{e}_i$

But: $\quad \nu$ masses, mixings observed $\Rightarrow$ extend SM$^-$

$\uparrow$ tiny $\lesssim$ eV $\quad \uparrow$ large

Possibilities

- $\bar{\nu}_i$ ... RH neutrinos
- $\nu_i M^\nu_{ij} \nu_j$ ... Majorana masses

related

explicitly violates L : $l_i \to e^{i\alpha_i} l_i$

$\bar{e}_i \to e^{-i\alpha_i} e_i$

small $M_\nu \Rightarrow$ small

Test : $\quad Z \to Z+2 + 2e^-$ $\qquad$ "$0\nu\beta\beta$"

more soon ...

– 1/23/07