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PH4442 Adv. Ptcl. Phys. Week 8

The Electroweak SM

So far we know:

mid 1960s → V-A theory (4-fermion int.) works (agrees w/ data) but:

- not renormalisable
- violates unitarity limit at high E_{cm}.

Intermediate Vector Boson (IVB) ~ saves unitarity limit but not (easily) renormalisable

Yang-Mills theories (w/ compact Lie groups) are renormalisable ('t Hooft 1971)

→ gauge bosons → IVB ✓

Naively, gauge symmetry only holds with massless gauge bosons

For now, consider them as massless (fermions too); restore masses later w/ Higgs mechanism.

Need to choose gauge trans. to build in:

parity violation

transitions between fermion types $(\nu, \rightleftarrows \ell)$

flavour mixing (CKM)

Weak neutral currents (Z) emerge as a prediction!

Goal: construct Yang-Mills gauge theory
using all 3 lepton families + 6 quarks } not all known in 1960s
(do ~~not~~ include right-handed neutrinos).
Want transitions like $u \leftrightarrow d'$, $e^- \leftrightarrow \nu_e$

w/ amplitudes like

$$\mathcal{M} \sim j_\mu^{had} \, j^\mu_{lep} \, , \quad j^\mu \sim V^\mu - A^\mu$$

Choose gauge group + its representations to give
desired transitions, $\not{P}$, ...

$\Rightarrow$ put left-chiral components in doublets

$$\underbrace{\tfrac{1}{2}(1-\gamma^5)}_{P_L} \begin{pmatrix} \psi_\nu \\ \psi_e \end{pmatrix} , \qquad \tfrac{1}{2}(1-\gamma^5) \begin{pmatrix} \psi_u \\ \psi_{d'} \end{pmatrix}$$

or use names of ptcls as label for wave func.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L ,$$

left-handed

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L , \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

flavour eigenstates

Gauge group : $SU(2) \times U(1)$ ~ direct prod.
i.e. apply both transformations

$SU(2)$ = set of unitary 2×2 matrices
w/ determinant $= +1$.

= Lie group w/ 3 generators (see App. A)

$\vec{T} = (T_1, T_2, T_3)$ = "weak isospin operators"

$[T_i, T_j] = i \epsilon_{ijk} T_k$ (Lie algebra)

$\psi \to \psi' = U_T \psi$

group elements

$U_T = \exp\left[i g \vec{\alpha}(x) \cdot \vec{T} \right]$ some representation of the generators.

gauge coupling

$\vec{\alpha} = (\alpha_1, \alpha_2, \alpha_3)$
= arb. func. of x.

For the left-handed doublets, U_T from fundamental (2-D) representation

$\Rightarrow$ generators are $T_i = \frac{1}{2} \tau_i$, $i = 1, 2, 3$

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Pauli matrices (here usually τ, not σ)

Why $SU(2)$?

Preserve normalisation of states → unitary

i.e. $UU^{+} = U^{+}U = I$

$\Rightarrow \det(UU^{+}) = |\det U|^2 = 1$

$\Rightarrow \det U = e^{i\theta}$

w/o loss of generality choose $\theta = 0$

$\Rightarrow \det U = 1$ — "special"

For right-chiral components use singlet (trivial) representation: $T_i = 0$, $i = 1, 2, 3$ — satisfies $[T_i, T_j] = i\epsilon_{ijk}T_k$

$\Rightarrow U_T$ = multiplication by $\underline{1}$. no ν_R, explicitly left out

---

not same $U(1)$ as in QED

For $U(1)$ ← group of unitary 1×1 matrices

= mult. by complex phase factor

1 enerator = scalar (1×1 matrix)

called "(weak) hypercharge Y"

$\psi \to \psi' = U_Y \psi$

$U_Y = \exp\left[i \frac{g'}{2} Y \beta(x) \right]$, Y = hypercharge depends on ptcl.

arb. func. of x

g' = gauge coupling.

Y related to ptcl. charge Q & eigenvalue $\underline{t_3}$ of 3rd component of isospin T_3:

Left-handed doublets: $t_3 = \begin{cases} +1/2 & u, c, t, \nu_e, \nu_\mu, \nu_\tau \\ -1/2 & d', s', b', e, \mu, \tau \end{cases}$

For (all) right-handed singlets assign $t_3 = 0$

To get right charge assignments,

$$Q = t_3 + \frac{Y}{2}$$ Gell-Mann - Nishijima formula

sometimes $\frac{Y}{2} \to Y$.

$\Rightarrow Y = 2(Q - t_3)$

no ν_R! If included, they are "sterile"

$$= \begin{cases} -1 & \nu_{e,L}, \ell_L \quad \ell = e, \mu, \tau \\ -2 & e_R, \mu_R, \tau_R \\ +1/3 & u_L, c_L, t_L, d'_L, s'_L, b'_L \\ +4/3 & u_R, c_R, t_R \\ -2/3 & d_R, s_R, b_R \end{cases}$$

For $SU(2)_L \times U(1)_Y$ symmetry to hold, replace $\partial^\mu \to D^\mu$ or covariant deriv.

i.e. Dirac eq becomes $(i\gamma_\mu D^\mu - M)\psi = 0$

But, in our gauge group, left- & right- components transform differently, $-M\psi$ breaks gauge sym.

$\Rightarrow$ set all $M \to 0$ for now, restore later w/ Higgs mechanism.

The covariant derivative is (cf. Yang-Mills)

$$D^\mu = \partial^\mu + i g \vec{T} \cdot \vec{W}^\mu + i \frac{g'}{2} Y B^\mu$$

$(W_1^\mu, W_2^\mu, W_3^\mu)$ ~ gauge fields

$$\vec{T} = \begin{cases} \frac{\vec{\tau}}{2} & \text{for doublets (left)} \\ 0 & \text{" isospin (SU(2)) singlets (right)} \end{cases}$$

Will find: mixture of $W_1^\mu, W_2^\mu \rightarrow W^\pm$

" " $W_1^3, B^\mu \rightarrow \gamma, Z$

Consider left-handed leptons

D^μ contains $\vec{\tau} \cdot \vec{W}^\mu = \sqrt{2} \left[\tau_+ W^{(+)\mu} + \tau_- W^{(-)\mu} \right] + \tau_3 W_3^\mu$

where

$$\left.\begin{aligned} \tau_+ &= \tfrac{1}{2}(\tau_1 + i\tau_2) = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\ \tau_- &= \tfrac{1}{2}(\tau_1 - i\tau_2) = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \end{aligned}\right\} \text{raising, lowering ops.}$$

$$W^{(\pm)\mu} = \frac{1}{\sqrt{2}} \left(W_1^\mu \mp i W_2^\mu \right)$$

$\tau_\pm$ have expected effect on doublet, e.g.

$$\tau_+ \psi_{e,L} \sim \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \sim \psi_{\nu,L}$$

For left-chiral leptons, $Y = 2(Q - t_3) = \underline{\underline{-1}}$ (ν_l and l)

$0 - \frac{1}{2}$ (ν_l)

or $-1 - (-1/2)$ (l)

$$D^\mu = \partial^\mu + \frac{ig}{\sqrt{2}}\left(\tau_+ W^{(+)\mu} + \tau_- W^{(-)\mu}\right) + \frac{ig}{2}\tau_3 W_3^\mu - i\frac{g'}{2} B^\mu$$

How to get Feynman rules?

Recall earlier w/ Dirac eq. $\gamma_\mu D^\mu \psi = 0$ $(m = 0)$

$D^\mu = \partial^\mu + iqA^\mu$ ← EM

write as $\gamma_\mu \partial^\mu \psi = -iq\gamma_\mu A^\mu \psi$ ← perturbation

→ power series in $e = -q$

→ $S^{(1)}_{fi} = q \int d^4x' \, \bar{\phi}_f(x') \, \not{A}(x') \, \phi_i(x')$

→ Feynman rules for QED

Here, $-ig\vec{T}\cdot\vec{W}^\mu - i\frac{g'}{2} Y B^\mu$ goes to r.h.s.,

gets bracketed by isospin singlets / doublets

+ fields that carry hypercharge for init / final states

⇒ amplitude gets terms like

$$\mathcal{M} \sim -\frac{ig}{\sqrt{2}} \bar{\nu}_L \gamma_\mu \tau_+ e_L W^{(+)\mu}$$ also – changes e to ν

⇒ absorbs W^+

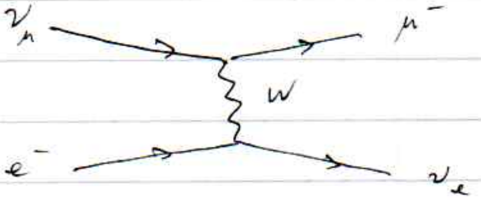
$$\sim \underbrace{(1 \quad 0)}_{\bar{\nu}_L} \underbrace{\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}}_{\tau^+} \underbrace{\begin{pmatrix} 0 \\ 1 \end{pmatrix}}_{e_L} = 1$$

⇒ $W^\pm = \frac{W_1 \mp iW_2}{\sqrt{2}}$

= charged W

$\Rightarrow$ non zero contribution for e.g.

$\nu_\mu e^- \to \mu^- \nu_e$



$$\mathcal{M} = \frac{g^2}{8 M_W^2} \left[\bar{\mu} \gamma_\mu \tfrac{1}{2}(1-\gamma^5)\, \tau_- \nu_\mu \right] \left[\bar{\nu}_e \gamma^\mu \tfrac{1}{2}(1-\gamma^5)\, \tau_+ e \right]$$

$(1 \;\; 0)$ $\qquad \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$ $\qquad \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

for W propagator

use $\dfrac{i g^{\mu\nu}}{M_W^2}$ for $|q^2| \ll M_W^2$

$$\rightarrow \;\sim \frac{G_F}{\sqrt{2}} [\;\;][\;\;]$$

$\sim$ same story for all fermions & W

Vertex factors:

$$-\frac{ig}{\sqrt{2}} \gamma^\mu \frac{1}{2}(1-\gamma^5) \qquad \text{(leptons)}$$

$$-\frac{ig}{\sqrt{2}} \underbrace{V_{ij}}_{\text{CKM}} \gamma^\mu \frac{1}{2}(1-\gamma^5) \qquad \text{(quarks)}$$

<u>mass</u> eigenstates

always connects $t_3 = +1/2$ & $t_3 = -1/2$

Z boson & weak mixing angle

Also get amplitudes containing } e.g. init & final neutrinos.

$$-\frac{ig}{2}\bar{\nu}_L \gamma_\mu \tau_3 \nu_L W_3^\mu$$

$$+ \quad \frac{ig'}{2}\bar{\nu}_L \gamma_\mu \nu_L B^\mu$$

Use $\underset{\begin{pmatrix}1&0\\0&-1\end{pmatrix}}{\tau_3}\ \underset{\begin{pmatrix}1\\0\end{pmatrix}}{\nu_L} = \nu_L$

B^μ = photon? No, should not couple to ν

$\Rightarrow$ form combination $A^\mu = a W_3^\mu + b B^\mu$

Find a, b such that this does not couple to ν

i.e. want $a\left(\frac{-g}{2}\right) + b\left(\frac{g'}{2}\right) = 0$

Preserve normalisation: $a^2 + b^2 = 1$

$$\Rightarrow \quad a = \frac{g'}{\sqrt{g^2+g'^2}} \equiv \sin\theta_W$$ "weak / Weinberg mixing angle"

$$b = \frac{g}{\sqrt{g^2+g'^2}} \equiv \cos\theta_W$$

i.e. $A^\mu = \cos\theta_W B^\mu + \sin\theta_W W_3^\mu$ } identify this as the photon

The orthogonal combo is the Z:

$$Z^\mu = -\sin\theta_W B^\mu + \cos\theta_W W_3^\mu$$

so the original fields are

$$B^\mu = \cos\theta_W A^\mu - \sin\theta_W Z^\mu$$

$$W_3^\mu = \sin\theta_W A^\mu + \cos\theta_W Z^\mu$$

A neutral current amplitude for ν has both

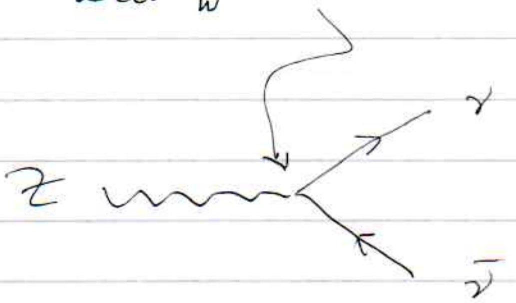
$$\mathcal{M} \sim -\frac{ig}{2}\bar{\nu}_L \gamma_\mu \nu_L W_3^\mu + \frac{ig'}{2}\bar{\nu}_L \gamma_\mu \nu_L B^\mu$$

$$= \frac{i}{2}\underbrace{\left(-g\sin\theta_W + g'\cos\theta_W\right)}_{=0 \text{ by construction}} \bar{\nu}_L \gamma_\mu \nu_L A^\mu$$

$$-\frac{i}{2}\underbrace{\left(g\cos\theta_W + g'\sin\theta_W\right)}_{\simeq \sqrt{g^2+g'^2} = \frac{g}{\cos\theta_W}} \bar{\nu}_L \gamma_\mu \nu_L Z^\mu$$

$\Rightarrow$ neutral-current ν coupling is

$$\frac{-ig}{2\cos\theta_W}\gamma_\mu \frac{1}{2}(1-\gamma^5) \quad \leadsto \text{vertex factor}$$



In same manner, find coupling of $e^- + A^\mu$ is

$$g' \cos\theta_W = g \sin\theta_W \equiv e$$

Usually use g, e instead of g, g', or

$1.166 \times 10^{-5}\ \text{GeV}^{-2} \rightarrow G_F = \dfrac{\sqrt{2}\, g^2}{8 M_W^2}$ ← $M_W = 80.4$ GeV, $\quad \alpha = \dfrac{e^2}{4\pi} = \dfrac{1}{137} \Rightarrow$

$$\Rightarrow g \approx 0.65 \quad , \quad e \approx 0.303$$

For coupling of Z to e^- find vertex factor

skip to summary

$$-\frac{i g}{2\cos\theta_W} \gamma_\mu \left(c_{V,e} - c_{A,e} \gamma^5 \right)$$

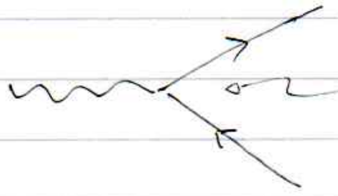
where $c_{V,e} = -\frac{1}{2} + 2 \sin^2\theta_W$ (vector coupling)

$c_{A,e} = -\frac{1}{2}$ (axial vector coupling)

same for all 3 families

Summary of Couplings

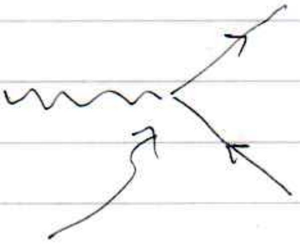
fermion - photon : same as QED



$iq_f \gamma^\mu$

charge

fermion - W



ν_e, (u, c, t)

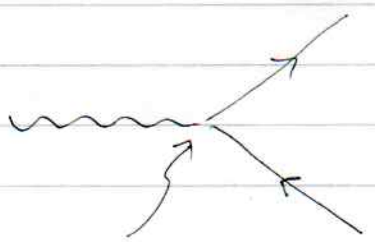
l, (d', s', b')

$\frac{1}{2}(1-\gamma^5)$ selects left-chiral

$$\frac{-ig}{\sqrt{2}} \gamma^\mu \frac{1}{2}(1-\gamma^5) \quad \left[\times \; V_{ij} \right]$$

if d, s, b mass eigenstates

fermion - Z



Z

f

$\bar{f}$

$$\frac{-ig}{2\cos\theta_W} \gamma^\mu \left(c_{V,f} - c_{A,f} \gamma^5 \right)$$

or write $c_{V,f} - c_{A,f}\gamma^5 = c_{L,f} \cdot (1-\gamma^5) + c_{R,f} \cdot (1+\gamma^5)$

where $c_{L,f} = \frac{1}{2}\left(c_{V,f} - c_{A,f} \right)$

$c_{R,f} = \frac{1}{2}\left(c_{V,f} + c_{A,f} \right)$

$$c_{V,f} = t_{3,f} - 2\,Q_f \sin^2\theta_W$$

$$c_{A,f} = t_{3,f}$$

$$c_{L,f} = t_{3,f} - Q_f \sin^2\theta_W$$

$$c_{R,f} = -Q_f \sin^2\theta_W$$

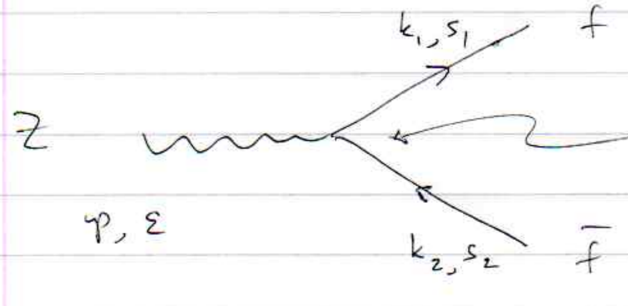
Table $\rightarrow$ slide

Decay rate of Z boson

Cheat: use couplings just derived

" $M_Z = 91.2$ GeV $\sim$ exp.

" $M_W = M_Z \cos\theta_W$ $\sim$ from Higgs mech.



$$\frac{-ig}{2\cos\theta_W}\gamma^\mu (c_V - c_A\gamma^5)$$

$$\Rightarrow \mathcal{M} = \bar{u}(k_1,s_1)\left(\frac{-ig}{2\cos\theta_W}\gamma^\mu(c_V - c_A\gamma^5)\right) v(k_2,s_2)\,\varepsilon_\mu$$

$$= \frac{-ig}{2\cos\theta_W}\,\bar{u}\,\not{\varepsilon}\,(c_V - c_A\gamma^5)\,v$$

suppress k, s
to simplify
notation

Sum over final-state spins

$$\sum_{s_1,s_2}' |\mathcal{M}|^2 = \sum_{s_1,s_2}' \frac{g^2}{4\cos^2\theta_W}\left[\bar{u}\gamma^\mu(c_V - c_A\gamma^5)v\right]\left[\bar{u}\gamma^\nu(c_V - c_A\gamma^5)v\right]^* \varepsilon_\mu \varepsilon_\nu^*$$

$$= \frac{g^2}{4\cos^2\theta_W} \mathrm{Tr}\left[\gamma^\mu(c_V - c_A\gamma^5)\not{k}_2\, \overline{\gamma^\nu(c_V - c_A\gamma^5)}\, \not{k}_1\right]\varepsilon_\mu \varepsilon_\nu^*$$

We found $\overline{\gamma^\nu(c_V - c_A\gamma^5)} = \gamma^\nu(c_V - c_A\gamma^5)$

Move to left past $\not{k}_2\gamma^\nu \to$ 2 sign changes cancel

Then $(c_V - c_A\gamma^5)^2 = c_V^2 - 2c_V c_A\gamma^5 + c_A^2 \underbrace{(\gamma^5)^2}_{=1}$

$$= c_V^2 + c_A^2 - 2c_V c_A \gamma^5$$

$$\Rightarrow \sum_{s_1,s_2}' |\mathcal{M}|^2 = \frac{g^2}{4\cos^2\theta_W}\mathrm{Tr}\left[(c_V^2 + c_A^2 + 2c_V c_A\gamma^5)\not{\varepsilon}\not{k}_2\not{\varepsilon}^*\not{k}_1\right]$$

$$= \frac{g^2}{\cos^2\theta_W}\Big[(c_V^2 + c_A^2)\Big((\varepsilon\cdot k_2)(\varepsilon^*\cdot k_1) + (\varepsilon\cdot k_1)(\varepsilon^*\cdot k_2) - (\varepsilon\cdot\varepsilon^*)(k_1\cdot k_2)\Big)$$

$$- 2c_V c_A\, i\, \epsilon_{\mu\nu\rho\sigma}\varepsilon^\mu k_2^\nu \varepsilon^{\rho *} k_1^\sigma\Big]$$

Suppose Z polarised w/ $\varepsilon^\mu = (0,0,0,1)$

spin along $\hat{z}$

$\Rightarrow \varepsilon^* = \varepsilon$, then

$\epsilon_{\mu\nu\rho\sigma}$ antisymmetric $\mu \leftrightarrow \rho$

$\varepsilon^\mu k_2^\nu \underbrace{\varepsilon^{\rho *}}_{=\varepsilon^\rho} k_1^\sigma$ symmetric $\mu \leftrightarrow \rho$

$\Big\}\to$ contract to 0

$$\Rightarrow \sum_{s_1,s_2}' |\mathcal{M}|^2 = \frac{g^2(c_V^2 + c_A^2)}{\cos^2\theta_W}\left[2(\varepsilon\cdot k_1)(\varepsilon\cdot k_2) + k_1\cdot k_2\right]$$

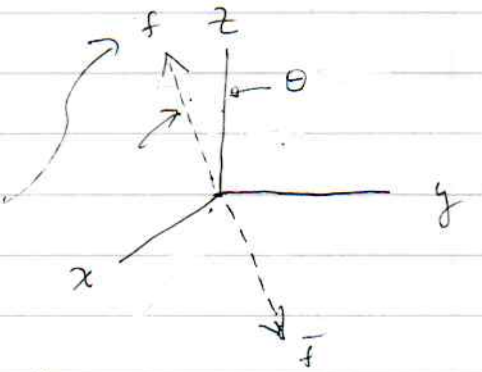
Consider rest frame of Z, $|\vec{k}_1| = |\vec{k}_2| \simeq \frac{M_Z}{2}$

$m_f \ll M_Z$ (Ok except top)

$$k_1 = \frac{M_Z}{2}(1, \sin\theta, 0, \cos\theta)$$

$$k_2 = \frac{M_Z}{2}(1, -\sin\theta, 0, -\cos\theta)$$

in x, z plane



$$\Rightarrow \sum_{s_1,s_2}' |\mathcal{M}|^2 = \frac{g^2(c_V^2 + c_A^2)M_Z^2 \sin^2\theta}{2\cos^2\theta_W}$$

Recall formula for 2-body decay rate in c.m.

$$d\Gamma = \frac{1}{32\pi^2 M^2}\sum_{s_1,s_2}' |\mathcal{M}|^2 \, p^* \, d\Omega$$

$p^* = |\vec{k}_1| = |\vec{k}_2| = \frac{M_Z}{2}$

$\sum' |\mathcal{M}|^2$ indep. of ϕ $\Rightarrow$ $d\Omega = d\cos\theta \underbrace{\int d\phi}_{2\pi}$

$$\Rightarrow \frac{d\Gamma}{d\cos\theta} = \frac{g^2(c_V^2 + c_A^2)M_Z}{64\pi\cos^2\theta_W}\sin^2\theta$$

$$\Gamma(Z\to f\bar{f}) = \int \frac{d\Gamma}{d\cos\theta}\, d\cos\theta = \frac{g^2(c_V^2 + c_A^2)M_Z}{48\pi\cos^2\theta_W}$$

let $x = \cos\theta$, $\int \sin^2\theta \, d\cos\theta = \int_{-1}^{1}(1-x^2)\,dx = 4/3$

$= \Gamma(Z\to f\bar{f})$ for <u>any</u> Z polarisation since z-axis arbitrary

Now use $M_W = M_Z \cos\theta_W$ ~ Ch. 11, Higgs mech

$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2} = \frac{\sqrt{2}}{8}\frac{g^2}{M_Z^2\cos^2\theta_W}$$

$$\Rightarrow \Gamma(Z \to f\bar{f}) = \frac{G_F M_Z^3 (c_V^2 + c_A^2)}{6\pi\sqrt{2}}$$

Now use $M_Z = 91.2$ GeV

$G_F = 1.166 \times 10^{-5}$ GeV^{-2}

$\sin^2\theta_W = 0.233$

to find

$\Gamma(Z \to \nu_e\bar{\nu}_e) = 166$ MeV

$\Gamma(Z \to e^+e^-) = 83.9$ MeV

$\Gamma(Z \to u\bar{u}) = 96.6$ MeV

$\Gamma(Z \to d\bar{d}) = 124$ MeV

Sum over $q = u, d, s, c, b$ not t ← $m_t = 174$ GeV

Quarks come in $N_c = 3$ colours

Suppose N_ν $(=3?)$ neutrino families

$$\Gamma_Z = N_\nu \Gamma(Z \to \nu\bar{\nu}) + 3\Gamma(Z \to e^+e^-) + 2N_c \Gamma(Z \to u\bar{u}) + 3N_c \Gamma(Z \to d\bar{d})$$

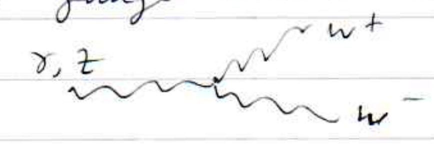
$= 2.44$ GeV for $N_\nu = 3$

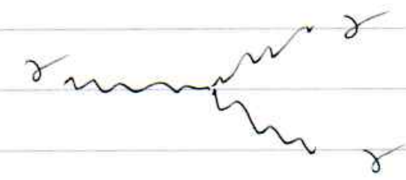
$\longrightarrow 2.4940 \pm 0.0009$ GeV (higher order electroweak + QCD corr.)

Measured: 2.4955 ± 0.0023 GeV $\Rightarrow$ confirms $N_c = 3$ colours

$N_\nu = 3$ ν families

Self interaction of gauge bosons (brief)

SU(2) non-Abelian $\Rightarrow$ gauge bosons have self interaction, e.g. 

Contrast to QED, no 

Recall QED (Maxwell eqs.) $\quad \partial_\mu F^{\mu\nu} = j^\nu$ — current from charged fermions

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

Corresponding eqs. for W_1, W_2, W_3

$$\partial_\nu F^{\mu\nu,a} - g\,\epsilon_{abc} W_\nu^{\,b} F^{\mu\nu,c} = J^{\mu,a}$$

$\uparrow$ current from fermion, Higgs

$$F_{\mu\nu}^{a} = \partial_\mu W_\nu^{a} - \partial_\nu W_\mu^{a} - g\,\epsilon_{abc} W_\mu^{\,b} W_\nu^{\,c}$$

$\uparrow$ extra term!

Extra term represents self-interaction current, present even in absence of fermion, Higgs fields

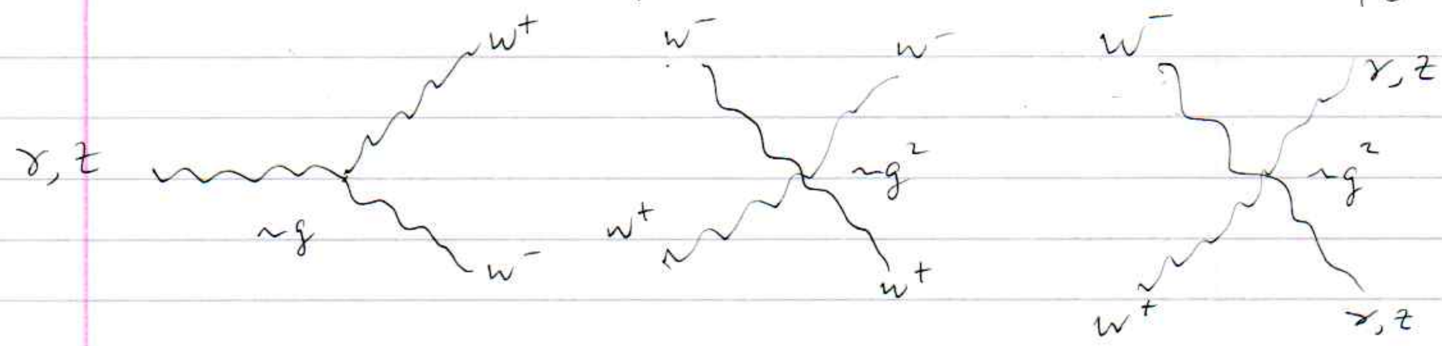
Amplitudes involve interaction Hamiltonian

$$H_{int} \sim g\,\epsilon_{abc} W_\mu^{\,a} W_\nu^{\,b} F^{\mu\nu,c}$$

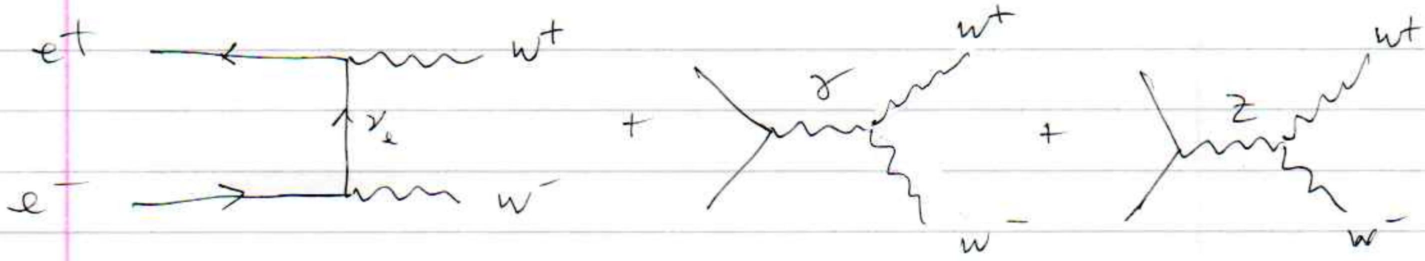
$\uparrow$ contains terms w/ 1 + 2 powers of W

$\Rightarrow$ triple + quartic gauge boson interactions

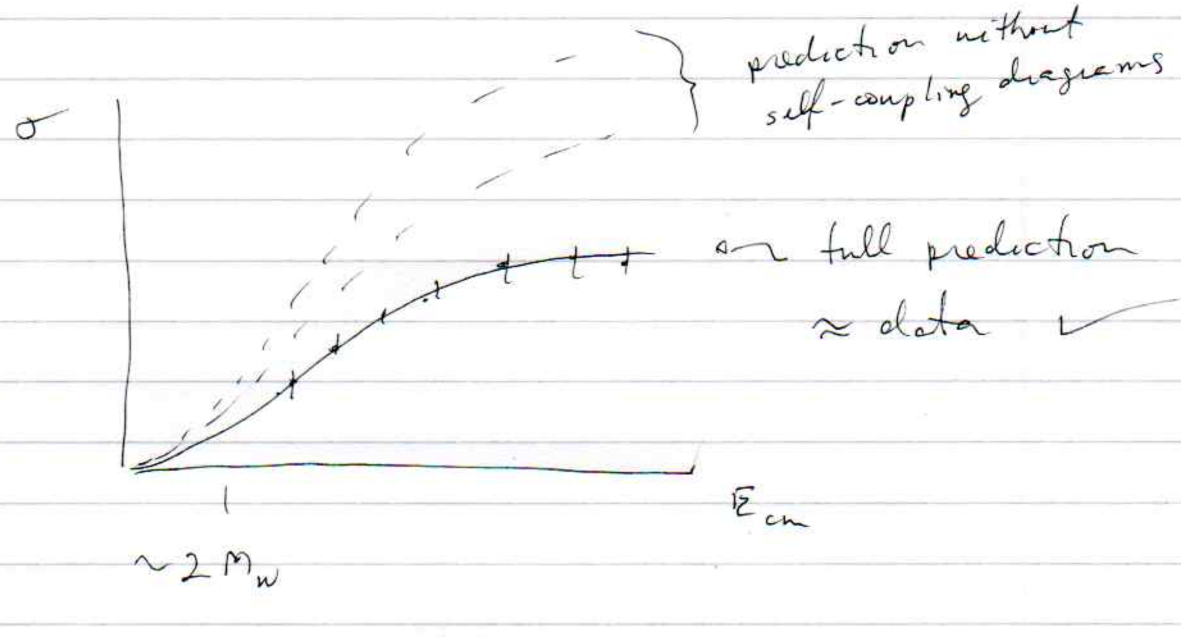
$\sim g$ (triple), $\quad \sim g^2$ (quartic)



Tested e.g. w/ $e^+e^- \to W^+W^-$ (LEP)



Measure $\sigma(e^+e^- \to W^+W^-)$ vs E_{cm} at LEP



$\longrightarrow$ slides