Phenomenology (confirmation) of EW theory/sector of SM [part (I): neglect generational mixing

(Overview)

— So far, we have developed theory (or model) of EW sector of SM, based in part on experimental observations of weak (charged current) and EM interactions ... plus more theoretical considerations (such as group theory, renormalizability etc.)

— Next, we study phenomenology, i.e., work out predictions of this theory for "future" experiments: needless to say, by now they have been spectacularly verified! (So far in our course, we we had "postdictions", i.e., the theory accomodated existing data.)

— Indeed, EW theory (circa late 1960's) predicted "new" particles, i.e., W, Z & H bosons, which must be (much) heavier than the accessible energies $\lesssim \mathcal{O}(\text{GeV})$ at that time (of course accounting for why these particles had not been seen on-shell so far.)

— So, a "direct" confirmation of existence of (i.e., "real" production of) these new particles would require (much) higher energy colliders (which was realized for W, Z in 1980's) and 2010's for Higgs boson

— However, indirect effects of (i.e., from exchange of virtual (off-shell) heavy W, Z, H can be observed even at low energies: for example, 4-fermion (contact) charged current weak interaction from $\boxed{W_\mu^\pm}$ exchange (as in radioactive or muon decay: again, this is not really a "prediction" of EW theory)

— So, $\boxed{Z_\mu}$ exchange will give 4-fermion (again, local) neutral current weak interaction at low energies: this is a prediction of EW theory, which was verified in 1970's, indeed serving as 1st confirmation of EW theory (we will discuss 2 examples of neutral currents where mere measurement of a non-zero value for observables is evidence for Z_μ exchange [i.e., not much accuracy is needed here]

— Remarkably, these neutral current measurements — done with (some) precision — also enabled complete fixing of values of 3 parameters of the EW theory, i.e., $\boxed{v, g, g'}$. Recall that $\boxed{G_F}$ measured in β or muon-decay determines $\boxed{v}$, while $\boxed{e}$ fixes one combination of g, g' so that a "3rd" measurement was needed to pin down the other combination of g, g'.

- As a slight detour, let's understand how neutral current (again, $\boxed{Z_\mu}$ exchange) did this job: $\boxed{g_Z}$ actually "cancels" between coupling at Z_μ vertex and M_Z^2 from propagator (at low energies), just like for W_μ exchange. So, overall coefficient of 4-fermion operator is simply $\sim 1/v^2$ ($\sim G_F$) in both cases.

- However, $\boxed{Q_Z^{(V)}} = T_{3L} - 2Q\,\boxed{\sin^2\theta_W}$ (but not $Q_Z^A = T_{3L}$) depends on a different combination of g, g' than does e, i.e., $\boxed{\sin^2\theta_W = g'^2/(g^2+g'^2)}$ vs. $e = gg'/\sqrt{g^2+g'^2}$, so that measurement of 2 neutral currents (i.e., from Ⓩ & photon exchange) gives us $\boxed{g \;\&\; g'}$ separately

- Once g, g' & v are known as above, then EW theory also predicts details of properties of $\boxed{W, Z}$ (e.g., masses: $\boxed{M_{W,Z} \sim g, g_Z\, v}$ & couplings: Q_Z^V for other than those used in above measurement fermions), i.e., not just existence of these particles

- Again, $\boxed{M_{W,Z}}$ were predicted in 1970's (as a result of neutral current measurements) so that future higher energy collider experiments could do a targeted search for these particles; indeed W, Z were discovered with these masses in 1980's

- Verification of other properties of W, Z followed in early 1990's
- At even higher energy experiments in late 1990's/early 2000's, pairs of (W, Z) were (directly/on-shell) produced, in part, "using" $\boxed{Z W^+ W^-}$ vertex, i.e., tri-linear gauge interaction, a tell-tale feature of non-abelian nature of EW gauge theory [cf. this is absent in QED. Also, $Z W^+ W^-$ is difficult to probe at low energies, i.e., in virtual exchanges of W, Z.]
- Finally, another energy upgrade (i.e., LHC) led to discovery of Higgs boson (in 2010's) and studies of its properties
- Just out of curiosity/for completeness' sake, 4 Nobel prizes are part of above history: Glashow, Salam, Weinberg for developing EW theory [awarded in 1979, i.e., of course after confirmation of neutral currents, but before actual W, Z discovery!]; Rubbia, van der Meer (experimentalists) for W, Z discovery (in 1984); 't Hooft, Veltman in 1999 for (theoretical) precision calculations of EW theory and Higgs, Englert in 2013 for (theory) prediction of Higgs boson

Outline of phenomenlogy topics/processes

[in above order increasing energy, i.e., chronological starting with earliest]

(1). Low-energy neutrino (ν) scattering

(2). Forward-backward asymmetry in $\boxed{e^+e^- \to \mu^+\mu^-}$ at low energies

confirmation of EW theory + led to $M_{W,Z}$ prediction (1970's)

(3) Decay width of Z boson
[e^+e^- collisions at energy $= M_Z$ (on-shell Z) in LEP1/CERN experiment]

verification of W, Z properties in early 1990's (post their discovery in 1980's)

(4). $e^+e^- \to \boxed{W^+W^-}$ @ LEP②
[i.e., higher energy: $\gtrsim$ ② M_W]

(late) 1990's: confirmation of $W^+W Z$ (non-abelian) verte

(5). Higgs boson production and decay at LHC (pp collisions) and future e^+e^- colliders

$\gtrsim$ 2010's: verification of EWSB mechanism

[Just as heads-up, we will skip details of calculation/algebra in these notes, leaving them for HW (official or informal) and/or textbook.]

- Part II will deal with flavor sector (stemming from SM fermion mass terms/Yukawa couplings)