Last Time...

- We wrote the electroweak lagrangian
  - Found a way to introduce the asymmetry between left handed and right handed interactions imposed on us by W interactions
    - We out them in different representations of the same group, so they sort of live in different worlds
  - Found two major problems:
    - Fermion mass can’t be introduced as a Dirac mass term as the left-handed and write-handed fermions live in different worlds
    - Vector bosons are massive, but we can’t put their masses in as they are not normal “particles”, they are generators of the group
- We solved it by introducing a new scalar field, the Higgs boson
  - Effectively “generates” fermion masses due to non-zero VEV
  - Also generates effective mass terms for W and Z as they appear in covariant derivative and new field must use it to respect the symmetry
Mass Terms for Leptons

- Fermion masses are introduced via “Yukawa couplings”:
  \[ \Delta \mathcal{L}_e = -\lambda_e \bar{E}_L \cdot \phi e_R + \text{h.c.} \]
  \[ \varphi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix} E_L = (v_e)_L \]

- In Standard Model no right handed neutrinos and neutrino mass is exactly zero
  - Which is at odds with neutrino oscillations
- Could add it as \[ \mathcal{L} = -\lambda_v \bar{E}_L \varphi \nu_R = \lambda_v \bar{\nu}_L \varphi_2 \nu_R \]
- If defined this way, such right-handed neutrino does not couple to Z or W, so the problem is solved
  - But to be consistent with data, lambda has to be an incredibly small number
  - And the neutrino becomes a sterile neutrino (it becomes the only SM particle with no quantum numbers whatsoever)
Weak Mixing Angle

- Gauge bosons responsible for electromagnetism and weak interaction turned out to be mixed together
  - $W^3$ was the third Pauli matrix and B was the one coupling to right-handed fermions

\[
Z_\mu = \cos \theta_w \, W^3_\mu - \sin \theta_w \, B_\mu \\
A_\mu = \sin \theta_w \, W^3_\mu + \cos \theta_w \, B_\mu
\]

- Where $\theta$ is the weak mixing angle ($W$ stands for Weinberg)

\[
M_W = \frac{v}{2} \, g_2, \quad M_\gamma = 0, \quad M_Z = \frac{v}{2} \sqrt{g_1^2 + g_2^2}
\]

- Can be measured experimentally:
  - From $M(W) \sim 80$ GeV, $M(Z) \sim 91$ GeV
Mixing in Standard Model

• As we just saw, SM has mixing between bosons
  • Physical bosons are superpositions of the “native symmetry gauge bosons”

• Can other particles mix?
  • Physical quarks are actually a mixture of “native quark states”
  • As we know now, neutrinos are oscillating, they are also superpositions of “native SM neutrinos”
  • But not charged leptons
    • They do not change from one into another
Charged Lepton Mixing

• In standard model, there is no flavor changing neutral current
  • “Neutral current” means “Z- boson exchange”
  • “Charged current” – W exchange
• In practice that means that Z’s couple only to a couple of the same type fermions, so interaction with Z can’t change a muon into an electron
  • Charged fermions are “diagonal already” – physical mass eigenstates and native eigenstates are the same:

\[
\begin{pmatrix}
m_e & 0 & 0 & 0 \\
0 & m_\mu & 0 & \ldots \\
0 & 0 & m_\tau & \ldots \\
\vdots & \vdots & \vdots & \ddots
\end{pmatrix}
\]
Neutrino Mixing

• They do, but we will talk about this later when we talk about neutrino oscillations.
Quark mixing

• In the lagrangian we wrote things like
  
  \[ E_L = (\nu_e)_L = \left( \frac{1 - \nu L^5}{2} \right) (\nu e) \] and \( e_R \) and \( \nu_R \)

  \[ Q_L = (u_d)_L \] and \( u_R \) and \( d_R \) will be what you write for quarks

• However, nobody told you that these up- and down-quarks are the same as these that form composite particles

  • Hadrons
    • Baryons, mesons
Quark mixing

• In SM the quarks in the lagrangian are not the same as in real life

\[ \bar{u}' = (u', c', t', \ldots) \]
\[ \bar{d}' = (d', s', b', \ldots) \]

• That means that W can change flavor when a quark interacts with it, e.g. W can couple to u’d’ and can’t couple to u’s’, but these primes are not true pure u and d states:

\[ m'_u = S^u_L \ m_u \ S^{u\dagger}_R, \quad m'_d = S^d_L \ m_d \ S^{d\dagger}_R, \quad m'_e = S^e_L \ m_e \ S^{e\dagger}_R \]

• In the Lagrangian, you can rotate your quarks to the mass eigenstate basis

\[ m_u = \begin{pmatrix}
    m_u & 0 & 0 & \cdots \\
    0 & m_c & 0 & \cdots \\
    0 & 0 & m_t & \cdots \\
    \vdots & \vdots & \vdots & \ddots
\end{pmatrix}, \quad m_d = \begin{pmatrix}
    m_d & 0 & 0 & \cdots \\
    0 & m_s & 0 & \cdots \\
    0 & 0 & m_b & \cdots \\
    \vdots & \vdots & \vdots & \ddots
\end{pmatrix}, \]

• But you will need to remember that W can couple across generations
CKM Matrix

• Cabbibo angle $\theta_C = 0.22$ tells you how probable that a $u$ quark will interact with a $W$ and you get either a $d$ or an $s$ quark:

\[
V = \begin{pmatrix}
\cos \theta_C & \sin \theta_C \\
-\sin \theta_C & \cos \theta_C
\end{pmatrix}
\]

• For three generations: CKM matrix
  • Cabbibo
  • Kabayashi
  • Maskawa

• There is a whole sub-field in HEP working these out
  • The hard part is to get those involving $b$’s and figure out complex phases responsible for CP-violation ($V$’s are complex)!
Summary of Gauge Interactions

• Z couples to fermions of the same flavor only
• W couples across generations via CKM
• But also various self-coupling diagrams
Higgs Couplings

- Higgs couples to fermion proportional to their mass
  - It’s VEV “creates” the mass
- Also couples to gauge bosons
  - Its VEV part creates their mass
- And to itself
LHC Higgs Prospects

• Will LHC find SM-like Higgs?
  • Not overnight, but with several years of data it will be found
    • True for the entire mass range
• Can there be no Higgs at all?
  • Let’s for a second forget theorists and their hierarchy problems…
    Here is the real deal:
    • Despite anything, SM (with Higgs) is extremely good in describing currently accessible energies
    • Higgs regulates some striking divergences in SM
    • Consider WW scattering, take out Higgs and probability of $WW \rightarrow WW$ is greater than one above 1 TeV!
  • LHC will either see Higgs or, if it is not there, we will see whatever is playing its role

From my old talk from several years ago
Experimental Tests of SM

• There seem to be a million parameters in SM so you can fit it to any data
  • Not true
    • Some are ad-hoc: masses of fermions, mixing of quarks and neutrinos – we have no clue why they are what they are
      • You can still do checks, as e.g. what if these parameters are not truly parameters: you can measure them in various reactions and compare to each other
    • Others are fundamental: there are many processes, which depend just on a handful of parameters, e.g. $e$, $\cos\theta_W$, Higgs VEV $\nu$, which yields a lot of possible checks to make
Experimental Tests

- Most came from colliders
  - Interesting stuff is not around us anymore, need to make them
    - Below is the cross-section of $e^+e^-$ into hadrons
      - A single plot with a lot of discoveries in it
Experimental Tests

• Previous plot is often plotted as a ratio of the cross-section to hadrons to the cross-section to muon pairs:
• e+e- production cross section to hadrons
  • Vary the number of neutrino generations
Next Time

• Accelerators and Colliders
  • By Peter (hopefully)

• After that: a large new chunk of material about detectors:
  • Passage of particles through matter
  • Detection technologies
  • Particle detector types
  • Building large collider detectors