Physics 290e:
Electroweak Interactions
Overview and Introduction

Sept 8, 2021

- ▸ bCourses Link
- ▸ Suggested Topics
- ▸ Sign-up Sheet

The (Extended) Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} D \psi$$

gauge sector

$$+ \psi_i \lambda_{ij} \psi_j h + \text{h.c.}$$

flavour sector

$$+ |D_\mu h|^2 - V(h)$$

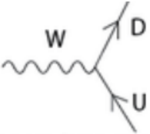
Higgs sector

$$+ \frac{1}{M} L_i \lambda^\nu_{ij} L_j h^2 \text{ or } L_i \lambda^\nu_{ij} N_j$$

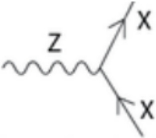
ν mass sector

Let's start by reviewing what we know

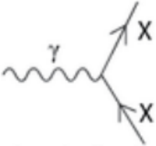
Fermion-Boson Vertices for the Electroweak Interactions



U is a up-type quark;
D is a down-type quark.



X is any fermion in the Standard Model.



X is electrically charged.

- Charged current interactions are (V-A) ($SU(2)_L$ gauge group) mediated by the $W^{\pm}$
  - For quarks, weak basis not the same as mass basis: CKM matrix to map between them
  - For leptons:
    - In SM ν is massless: No mass basis
    - Because ν mass, they oscillate among species
    - But no evidence of charged lepton flavor violation to date (is tiny in SM)
  - Neutral current interactions through both $SU(2)_L$ and $U(1)$
    - Both γ and Z are mixtures of the two neutral gauge mediators
    - $\sin\theta_W$ specifies the mixing

The Weinberg Angle θ_W

- We have two couplings: g and g'
- Can always express the ratio as

$$\tan\theta_W = \frac{g}{g'}$$

- Then

$$\begin{aligned} \sin\theta_W &= \frac{g}{\sqrt{g^2 + g'^2}} \\ \cos\theta_W &= \frac{g'}{\sqrt{g^2 + g'^2}} \end{aligned}$$

- And our LaGrangian becomes:

$$\begin{aligned} \mathcal{L}_{NC} &= -\left[\overline{\chi}\gamma^\mu \left(gI_3(W_3)_\mu + g' B_\mu \frac{Y}{2}\right)\chi\right] \\ &= -\sqrt{g^2 + g'2}\left[\overline{\chi}\gamma^\mu \left(\sin\theta_W I_3(W_3)_\mu + \cos\theta_W B_\mu \frac{Y}{2}\right)\chi\right] \end{aligned}$$

- Now we can pick out the piece that couples to charge and identify it with the photon

The photon, the Z and the $W^{\pm}$

- Define photon field as piece that couples to charge

$$A_\mu = B_\mu \cos\theta_W + (W_3)_\mu \sin\theta_W$$

- The Z is the orthogonal combination

$$Z_\mu = -B_\mu \sin\theta_W + (W_3)_\mu \cos\theta_W$$

- Because photon couples to charge, we can relate e to the couplings and θ_W:

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

- The $W^{\pm}$ bosons are

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

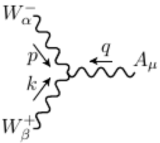
  and their coupling remains g. Using standard conventions

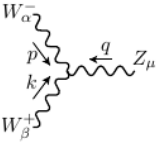
$$\frac{g^2}{8} = \frac{G_F M_W^2}{\sqrt{2}}$$

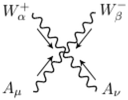
- $\sin\theta_W$ is a parameter to be measured (many different techniques)

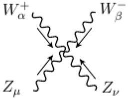
$$\sin^2\theta_W \sim 0.23$$

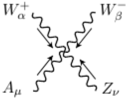
Boson-Boson EW vertices











- Fully determined by gauge invariance and defn of γ as boson that couples to charge
- 3-Boson couplings of W to γ and Z
  - No $Z \to ZZ$ coupling in SM
- 4-Boson couplings of WW to Z and γ
  - No $ZZ \to ZZ$ coupling in SM

Charge Current Quark Electroweak Interactions

- Write hadronic current

$$J^\mu = -\frac{g}{\sqrt{2}} \left(\overline{u}\ \overline{c}\ \overline{t}\right) \gamma_\mu \frac{(1-\gamma_5)}{2} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- V_{CKM} gives mixing between strong (mass) and (charged) weak basis
- Often write as

$$V_{CKM} = \begin{pmatrix} V_{ud} & Vus & V_{ub} \\ V_{cd} & Vcs & V_{cb} \\ V_{td} & Vts & V_{tb} \end{pmatrix}$$

- Wolfenstein parameterization:

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Here λ is the $\approx \sin\theta_C$.

The CKM Matrix (Continued)

- From previous page:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- From the explicit form (dropping terms of λ^2 or higher)

$$\rho + i\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- Unitarity insures $VV^\dagger = V^\dagger V = 1$. Thus

$$\sum_i V_{ij}V_{ik}^* = \delta_{jk} \text{ column orthogonality}$$

$$\sum_j V_{ij}V_{kj}^* = \delta_{ik} \text{ row orthogonality}$$

- Eg:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The Unitarity Triangle

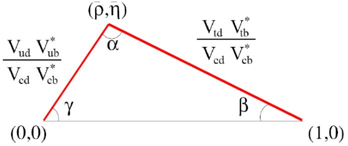
- From previous page

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Divide by $|V_{cd}^* V_{cb}|$:

$$\frac{V_{ud}V_{ub}^*}{|V_{cd}^* V_{cb}|} - 1 + \frac{V_{td}V_{tb}^*}{|V_{cd}^* V_{cb}|} = 0$$

- Think of this as a vector equation in the complex plane
- Orient so that base is along x-axis

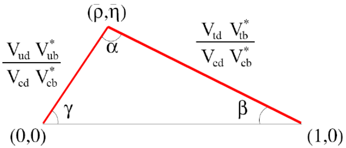


- Also from previous page:

$$\rho + i\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

The Measurement Game Plan

- Want to test if matrix is unitary
  - Failure of unitarity means new physics
- Make *many* measurements of sides and angles to over-constrain the triange and test that it closes



$$\alpha \equiv arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$$
$$\beta \equiv arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$$
$$\gamma \equiv arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

The Fermion Quantum Numbers

- Follow same prescription as for the leptons
- W_μ coupling is left handed: $\gamma_\mu(1-\gamma^5)/2$, B coupling is left-right symmetric: γ_μ
  - Left handed weak isodoublets, right handed weak isosinglets
  - Y value for multiplets chosen to enforce $Q = I_3 + Y/2$

fermion	Q	I_3^L	Y_L	Y_R
ν_ℓ	0	$\frac{1}{2}$	-1	-
ℓ	-1	$-\frac{1}{2}$	-1	-2
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{4}{3}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{2}{3}$

Predicted Z Couplings to Fermions

- The Z current specified by

$$Z_\mu = -B_\mu \sin\theta_W + (W_3)_\mu \cos\theta_W$$

- Together with the LaGrangian from page 18 this gives (with some math)

$$J^Z_\mu = J^3_\mu - \sin^2\theta_W j^{EM}_\mu$$

- The neutral weak coupling is NOT (V-A) but rather $C_V\gamma_\mu + C_A\gamma_m u(1-\gamma^5)$
- Values of C_V and C_A can be calculated from $\sin^2\theta_W$
- Weak NC vector and axial vector couplings are:

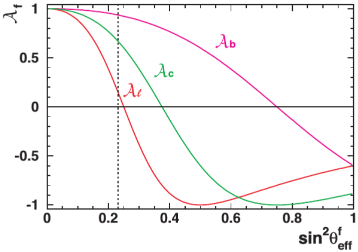
f	Q_f	C_A	C_V
ν	0	$\frac{1}{2}$	$\frac{1}{2}$
e	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$

Forward-Backward Asymmetry

- Angular distribution in QED: $1 + \cos^2\theta$
- Here θ is angle between ingoing e^- direction and outgoing fermion f direction
- Parity violating weak interactions add a $\cos\theta$ term
- Can see this effect either by measuring angular distribution or integrating over positive and negative $\cos\theta$

  Both have been done
- The integrated quantity

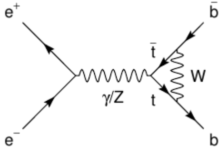
$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

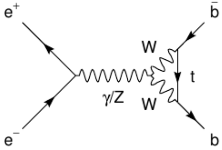


- Different asymmetries for leptons, for u-type and for d-type quarks
- Note: e^+e^- channel has t-channel Feynman diagram

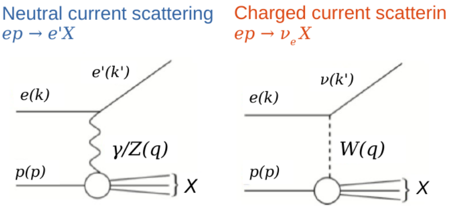
Measuring the Quark Couplings at LEP

- Asymmetry measurements require distinguishing f and $\overline{f}$
- No clean way to do this for light quarks
  - Can try to measure jet charge, but large systematic uncertainties
  - We saw results from later HERA measurements on page 6
- Variety of techniques possible for "tagging" bottom and charm ("Heavy Flavor")
  - Some distinguish q and $\overline{q}$ while others don't
- Want to determine
  - $A_{FB}^{b,c}$: Different τ_3 for b and c leads to different couplings
  - R_b and R_c: Sensitive to couplings but also in case of R_b to Zbb vertex

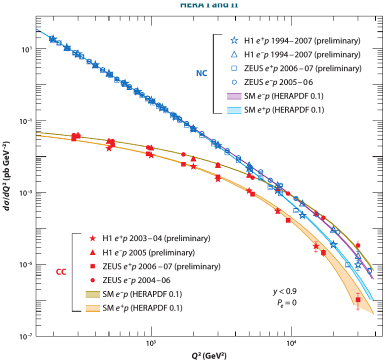




Hera: DIS at large Q^2

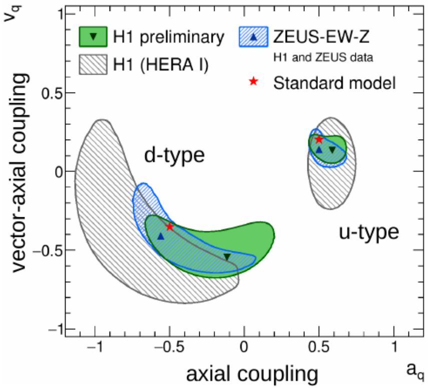


- Electron-proton collider
  - e^+ and e^-: $E_e = 27.6$ GeV
  - $E_p = 920$ GeV
  - Unpolarized running 1993-2000
  - Longitudinally polarized leptons
- Fits to high statistics data to determine EW parameters
- Leave vector and axial vector couplings of e, u-quarks and d-quarks free
- Constrain SM parameters
- Global PDF fits

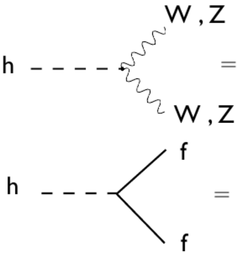


Measurements of NC couplings of quarks

- Axial and vector couplings determined by weak I_3 and Y
- Same equations as for leptons, but different numbers
- These couplings measured well at LEP, SLC
- HERA provides an alternative method



Quark Interactions with the Higgs: Yukawa Couplings



$$= gM_W \quad , \quad \frac{gM_Z}{\cos\theta_W}$$

$$= \frac{gM_f}{2M_W}$$

- Coupling to W^+W^- and ZZ defined by $\mathcal{L}$
- Coupling to fermions with strength that depends on fermion mass
  - These are known as the Yukawa couplings
- Current LHC measurements provide strong constraints on the W and Z and τ couplings to the Higgs, but how about the quark Yukawas?
  - Indirect constraints on Ht coupling from ggF (top loop)
  - First observation of ttH production in 2018
  - First observation of $H \to b\bar{b}$ in 2018
  - Only limits on first and second generation quarks so far

BSM Physics: Searches for FCNC Interactions

- In SM, GIM mechanism suppresses FCNC
  - Unitarity of CKM matrix means FCNC only possible due to differences between quark masses
  - This is why, eg $BR(K_L^0 \to \mu^+\mu^-) = 6.8 \times 10^{-9}$
- FCNC possible for BSM interactions
  - Because SM rate small, possible to see small BSM couplings if they exist
- Searches possible in many modes, eg:
  - $t \to Zq$
  - $b \to s\gamma$ or $s\ell^+\ell^-$

Goals for this semester

- This semester will concentrate on phenomenology of the EW interaction
  - Flavor Sector
    - Coupling of fermions (quarks and/or leptons) to gauge bosons
    - CKM matrix: real and imaginary elements
    - Searches for BSM terms that violate flavor symmetries
  - Gauge Sector
    - Measurements of 3 and 4 boson vertex couplings
    - EFT formalism and constraints on BSM interactions
  - Higgs Sector
    - Demonstration that the Higgs couples to mass
    - Direct searches for additional Higgs bosons
    - Indirect limits the EWSB sector from precision Higgs measurements
  - ν mass sector
    - Strictly speaking, much of ν physics outside the SM
    - But "natural" extension of SM possible
    - Nature of ν mass term not yet determined
    - Dirac or Majorana?
    - If Majorana, ν only fermion where mass doesn't come from Higgs mechanism