Physics 129: Particle Physics
Lecture 24: Weak Neutral Currents and the Z

Nov 17, 2020

- Suggested Reading:
  - Thomson 12.2-12.3, 15.4, 16.1-16.2
  - Griffiths 10.6-10.7
- Some reordering of material for remaining lectures: updated syllabus has been posted
- Will post final project information later this week

Our Weak Interaction Roadmap

- Unlike strong and EM, weak interactions don't conserve parity
  - Vertex selects left-handed state for of particles (and right handed state for anti-particles)
    - Discussed Nov 3
- $W^{\pm}$ coupling to leptons respect flavor familes (e, μ, τ) but coupling to quarks do not
  - Coupling not diagonal in quark flavor: Need to change basis
    - Discussed Nov 5
  - Introduction of this change in basis gives new phenomenology, including mixing and CP violation
    - Mixing discussed Nov 10
    - CP Violation discussed Nov 12
- $W^{\pm}$ has charge, so it couples to photon
  - Cannot write down a weak theory independent of QED
  - Unified electroweak theory includes Z^0 as well as $W^{\pm}$ and γ
    - Today: Why we need the Z
    - Thursday: Experimental observations of W and Z and their couplings
- Need mechanism to give $W^{\pm}$ and Z^0 mass
  - This is the Higgs mechanism
    - Discuss Tues Nov 24

Neutral Currents: Introduction

- So far, have limited Weak Interactopm discussion to exchange of W bosons ("charged current (CC) interactions")
- But we know that Z boson also exists!
- While β-decay observed in 1896 described by Fermi in the 1930s, nambiguous observation of neutral current (NC) exchange only occured in 1970's
- Why was it so difficult to see NCs?
  - GIM mechanism: If $\mathcal{L}$ diagonal in strong basis, is diagonal in weak basis
    $\rightarrow$ no FCNC
    $\rightarrow$ Z couples to $f\overline{f}$ pairs
  - NC interactions of charged particles can occur via photon exchange
    $\rightarrow$ in general, at low q^2, EM interactions swamp WI
- Strategies for observing NC before the discovery of the Z:
  - Neutrino scattering
  - Parity violating effects in interactions of charged leptons
  - Parity violating effects in interactions of quarks

  2nd and 3rd strategies above rely in interference between weak and EM diagrams that contribute to the same process

Overview of History of Standard Model Development

- Glashow,Weinberg,Salam developed unifed, gauge theory of Electroweak interactions in 1960's
  - Called the Weinberg-Salam (WS) model
- First observation of NC's in ν and e interactions occurred after WS model proposed
- NC measurements supported WS
- WS model predicted:
  - Existence of Z
  - M_W and M_Z as function of one parameter $\sin(\theta_W)$
  - $\sin(\theta_W)$ could be measured using ν interactions (before W and Z themselves were observed)
- W and Z discovered at Sp$\overline{\mathrm{p}}$S in 1982,1983
- Precision NC measurements at LEP/SLC ($e^+e^- \to Z$) starting in 1989

Today, will begin by reviewing NC measurements of the 1970's

Then, on to WI Lagrangian

Thurs: Observations of the W and Z

Some Observations

- Charged current interactions observed to be $(V - A)$ couplings with universal strength (once CKM matrix accounted for)
- This does not mean that neutral currents must also be left-handed
  - And in fact, they are NOT
- In original formulation of EW theory and in our discussions, we will assume neutrinos are massless (although we know now that they do have small mass)
  - Take as a postulate that all ν are left-handed and all $\overline{\nu}$ are right-handed
  - Quarks and charged leptons have mass and exist both in left- and right-handed states
  - To full define the theory, need to measure the coupling of the neutral weak boson (the Z) to:
    - Left-handed ν and right-handed $\overline{\nu}$
    - Left-handed ℓ and right-handed $\overline{\ell}$
    - Right-handed ℓ and left-handed $\overline{\ell}$
    - Left-handed q and right-handed $\overline{q}$
    - Right-handed q and left-handed $\overline{q}$
- That means we need to use all 3 strategies listed on page 3 in order to fully define the model

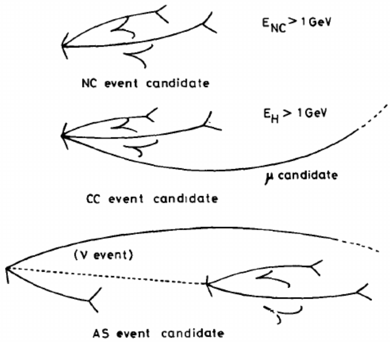
Discovery of Neutral Currents: Gargamelle (I)

- Gargamelle bubble chamber filled with freon
- 83,000 pictures with ν_μ beam, 207,000 with $\overline{\nu}_\mu$
- Look for:

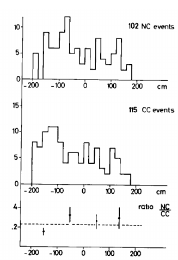
$$\text{CC Events}: \quad \begin{array}{l} \nu_\mu + N \to \mu^- + X \\ \overline{\nu}_\mu + N \to \mu^+ + X \end{array}$$

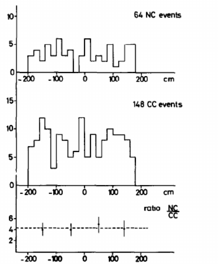
$$\text{NC Events}: \quad \begin{array}{l} \nu_\mu + N \to \nu_\mu + X \\ \overline{\nu}_\mu + N \to \overline{\nu}_\mu + X \end{array}$$

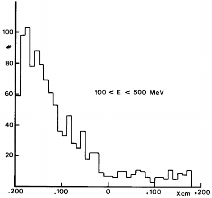
- Remove bckgrnd from neutrons created in chamber walls from ν interactions ("Stars")



Discovery of Neutral Currents: Gargamelle (II)







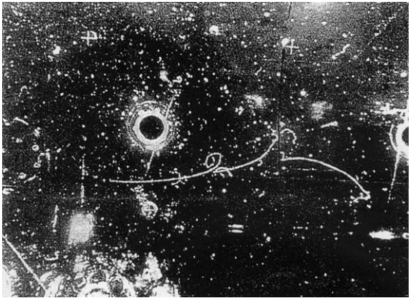
- Stars show exponential fall-off along beam axis
  - Consistent with background
- NC event-rate flat and consistent with CC event-rate vs distance along beam axis
- Event Rates:

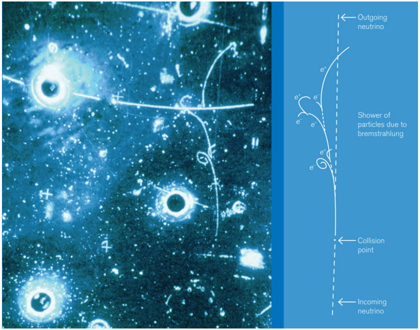
$$(NC/CC)_{\nu} = 0.21 \pm 0.03$$
$$(NC/CC)_{\overline{\nu}} = 0.45 \pm 0.09$$

- We'll see later that these ratios agree with SM predictions
- Difference in ratios for ν and $\overline{\nu}$ shows that NC are not V-A

Discovery of Neutral Currents: Gargamelle (III)

- Also observed $\nu_\mu e \to \nu_\mu e$

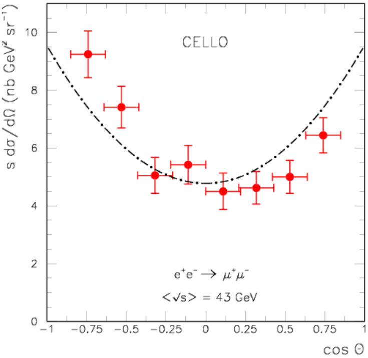


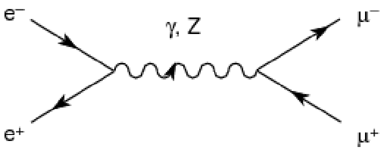


Neutral Current Interactions with Charged Leptons: $e^+e^- \to \mu^+\mu^-$

- For $q^2 << M_Z$, Weak Interaction matrix element much smaller than EM
- Observation of Weak Interaction requires looking for terms not allowed by EM

  $\to$ Parity Violating Effects
- Easiest signature: $e^+e^- \to \mu^+\mu^-$ angular distribution





You have already studied this on Problem Set #8

Neutral Current Interactions: Quark-Lepton Interactions

- Look for interference between weak (NC) and EM scattering amplitudes
- First unambiguous measurement from e-Deuteron scattering:

$$e(polarized) + d(unpolarized) \rightarrow e + X$$

- Measure

$$A \equiv (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$$

- General form using parton model

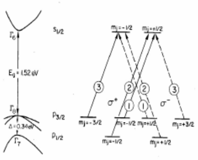
$$A/Q^2 = a_1 + a_2 \left[1 - (1-y)^2\right] / \left[1 + (1-y)^2\right]$$

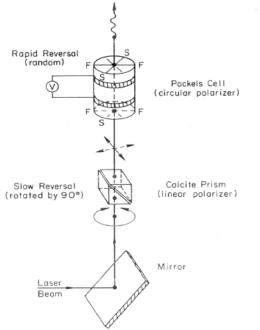
  for isoscalar target, a_1 and a_2 constant

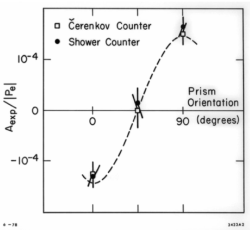
- Measuring A as fn of y allows determination of a_1 and a_2
- These constants depend on quark and lepton couplings to Z

Polarized eD Scattering (I)

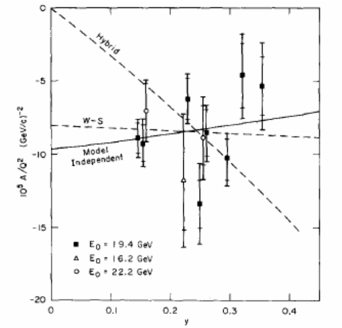
- Polarization obtained from laser optical pumping of Gallium Arsenide (photoemission of e)
- Can change circular polarization of laser to change polarization (two methods)

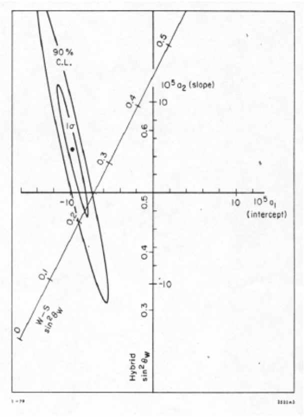






Polarized eD Scattering (II)





- Good agreement with SM predictions
- Provides estimate of the one parameter of the model: $\sin(\theta_W)$
  - To understand this statement, we need to build up the SM description of EW interactions

Building the SM Lagrangian (WS Model)

- Start with CC interactions

$$
\begin{aligned}
J_\mu &= \overline{\nu}\gamma_\mu\left(\frac{1-\gamma_5}{2}\right)e = \overline{\nu}_L\gamma_\mu e_L \\
J^\dagger_\mu &= \overline{e}_L\gamma_\mu\nu_L
\end{aligned}
$$

- Can write these 2 currents in terms of raising and lowering operators of *weak isospin*: A new SU(2) quantum number

$$
\chi_L \equiv \begin{pmatrix} \mu \\ e^- \end{pmatrix}_L \quad \tau_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad \tau_- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}
$$

$$
J_\mu = \overline{\chi}_L\gamma_\mu\tau_+\chi_L \quad J^\dagger_\mu = \overline{\chi}_L\gamma_\mu\tau_-\chi_L
$$

- Since these are 2 components of an SU(2) triplet, there must also be a 3^{rd} component

$$
J^0 = \overline{\chi}_L\gamma_\mu\tau_3\chi_L
$$

- Can J^0 be the Weak Neutral Boson (the Z)?

No! (see next page)

Why isn't J^0 the Z?

- We know there are Right Handed Weak Neutral Currents:
  - ν,$\overline{\nu}$ NC scattering rate not consistent with V-A
  - $e_R D$ scattering not zero
- How can this be?
- In addition to WI, there is EM, which is also NC
- If we unify WI and EM, have 2 neutral currents and can create Z and γ from linear combinations of these
- Expand our gauge group to include both: $SU(2)_L \times U(1)$
  - Two coupling constants g and g'
  - Four gauge bosons:

W^1_μ, W^2_μ, W^3_μ	$SU(2))_L$ triplet	coupling g
B_μ	$U(1)$ singlet	coupling g'

The Unified Gauge Interaction Lagrangian (I)

- Boson fields: Energy tensor of same form as Classical E&M but taking into account boson-boson interactions

$$
\begin{aligned}
\mathcal{L}_{gauge} &= -\frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}f_{\mu\nu}f^{\mu\nu} \\
\vec{F}_{\mu\nu} &= \partial_\mu\vec{W}_\nu - \partial_\nu\vec{W}_\mu + g\vec{W}_\mu\times\vec{W}_\mu \\
f_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu
\end{aligned}
$$

- Lepton fields: incorporate what we know from charged current weak interactions:
  - Left-handed e and ν couple to W

$$\chi_L \equiv \begin{pmatrix} \nu & e \end{pmatrix}_L \quad \text{where} \quad \begin{array}{l} \nu_L = \frac{1}{2}(1-\gamma_5)\nu \\ e_L = \frac{1}{2}(1-\gamma_5)e \end{array}$$

  - No RH ν exists, but RH e does: $\chi_R \equiv e_R = \frac{1}{2}(1+\gamma_5)e$

  LH members are weak iso-doublets and the RH charged leptons are weak iso-singlets. There is no RH neutrino

- We'll come back to the quarks later

The Unified Gauge Interaction Lagrangian (II)

- For Strong Interactions we saw

$$Q = I_3 + \frac{B+S}{2} \equiv I_3 + \frac{Y}{2}$$

- Postulate a similar "weak hypercharge" and require same relation to hold.

$$Y_L = -1 \quad Y_R = -2$$

(constructed to give the leptons the right charge)

$Q = I_3 + \frac{Y}{2}$	
$\chi_L \equiv \begin{pmatrix} \nu & e \end{pmatrix}_L$	$Q(\nu_L) = \frac{1}{2} + \frac{-1}{2} = 0$ $Q(e_L) = -\frac{1}{2} + \frac{-1}{2} = -1$
$\chi_R \equiv e_R = \frac{1}{2}(1+\gamma_5)e$	$Q(e_R) = 0 + \frac{-2}{2} = -1$

- This choice has additional advantage that by giving all members of a multiplet the same Y we have $[I_3, Y] = 0$ and both are simultaneouly observable

  Q is a conserved quantum number!

The Unified Gauge Interaction Lagrangian (III)

- Lepton terms in LaGrangian (kinetic plus interaction):

$$\begin{aligned}\mathcal{L}_{leptons} &= \overline{\chi}_R i\gamma^\mu \left(\partial_\mu + ig' B_\mu \frac{Y}{2}\right)\chi_R + \\ &\quad \overline{\chi}_L i\gamma^\mu \left(\partial_\mu + ig' B_\mu \frac{Y}{2} + ig\frac{\vec{\tau}}{2}\cdot \vec{W}_\mu\right)\chi_L\end{aligned}$$

- Note: Need to introduce the Higgs to add mass terms. We'll postpone that discussion!
- The neutral interaction terms in the LaGrangian are from B_μ and W_3

$$\begin{aligned}\mathcal{L}_{NC} &= -\left[\overline{\chi}_R\gamma^\mu\left(g' B_\mu \frac{Y}{2}\right)\chi_R + \overline{\chi}_L\gamma^\mu\left(g' B_\mu\frac{Y}{2} + g\frac{\tau_3}{2}(W_3)_\mu\right)\chi_L\right] \\ &= -\left[\overline{\chi}\gamma^\mu\left(gI_3(W_3)_\mu + g' B_\mu\frac{Y}{2}\right)\chi\right]\end{aligned}$$

where $I_3 = \tau_3/2$ and we have used the fact that $I_3 = 0$ for χ_R

Changing Basis

- We have two neutral fields: A and B_3
- Before we introduce the Higgs, both are massless. They can mix
  - Such mixing is normal in degenerate perturbation theory
  - Higgs will give mass to one of these states, breaking degeneracy
  - But the massive state is a linear combination of A and B_3
- We can identify one of the neutral bosons as the photon
  - This state must remain massless when Higgs introduced
- Can identify which combination is the photon: it must couple to charge:

$$Q = I_3 + \frac{Y}{2}$$

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)

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

How about the quarks?

- 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)

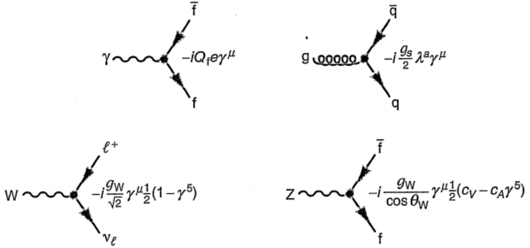
$$J_\mu^Z = J_\mu^3 - \sin^2\theta_W j_\mu^{EM}$$

- 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	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$

Summary of all SM Feynman diagrams (I)

- We have now defined all quark and lepton interactions with gauge bosons

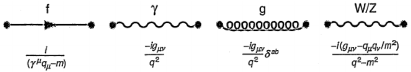


  - Photon-fermion vector interaction with strength eQ for fermion with charge Q
  - Gluon-fermion vector interaction with strength $\frac{g_s}{2}$ only fermions with color (quarks)
  - $W^\pm$-fermion left handed (V-A) interaction with strength $\frac{g_W}{\sqrt{2}}$
  - Z-fermion interaction with vector and axial vector couplings that depend on the weak isospin and weak hypercharge assignments of the fermion
- Propagators and full set of vertices, including three and four boson ones are shown on the next page

  Except for explaining how the W and Z get mass, this is the full standard model

Summary of all SM Feynman diagrams (II)

- Propagators:



- Vertices: