Neutral Currents and the Standard Model Lagrangian

Nov 3, 2016

Introduction

- So far, have limited Weak Interactopm discussion to exchange of W bosons ("charged current (CC) interactions")
- We know that Z boson also exists
- But unambiguous observation of neutral current (NC) exchange only occured in 1970's
- Why was it so difficult to see?
  - 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
- Options 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 charged leptons with quarks

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 $\sin(\theta_W)$
  - $\sin(\theta_W)$ measured using ν interactions
- 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

Some Observations

- Charged current interactions observed to be $(V-A)$ couplings with university 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 options listed on page 2 in order to fully define the model

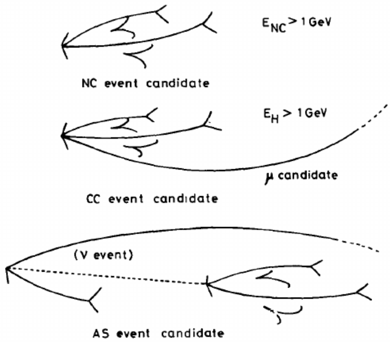
Discovery of Neutral Currents: Gargamelle (I)

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

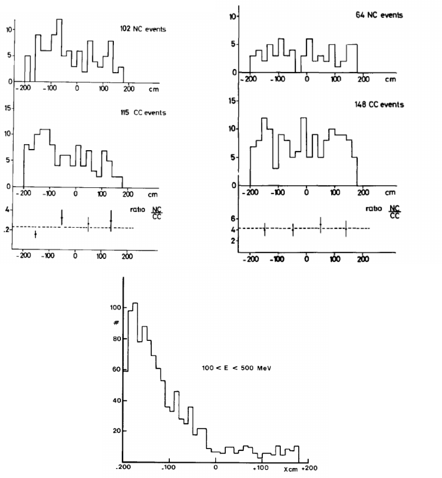
CC Events : $\nu_\mu + N \to \mu^- + X$
$\overline{\nu}_\mu + N \to \mu^+ + X$

NC Events : $\nu_\mu + N \to \nu_\mu + X$
$\overline{\nu}_\mu + N \to \overline{\nu}_\mu + X$

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



Discovery of Neutral Currents: Gargamelle (II)



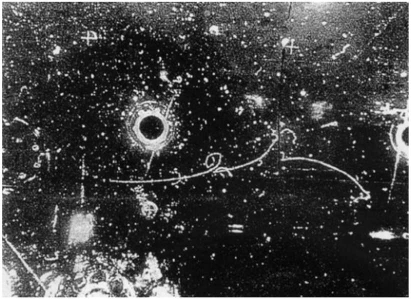
- Stars show exponential fall-off along beam axis
- NC event-rate flat and consistent with CC event-rate vs distance along beam axis
- Event Rates:

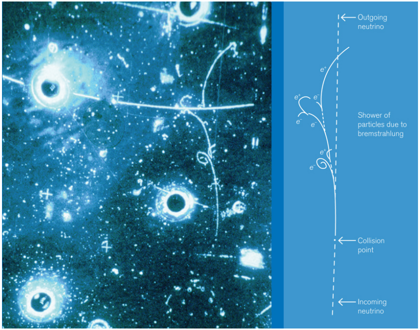
$$(NC/CC)_\nu = 0.21 \pm 0.03$$
$$(NC/CC)_{\overline{\nu}} = 0.45 \pm 0.09$$

- 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 $\nu_\mu e \to \nu_\mu e$

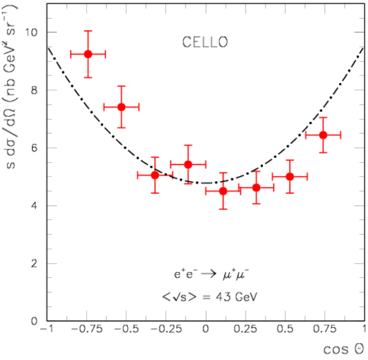


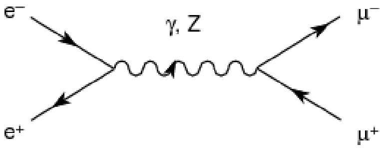


NC Interactions with Charged Leptons: $e^+e^- \rightarrow \mu^+\mu^-$

- 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

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





NC 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

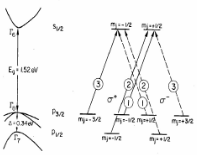
$$A/Q^2 = a_1 + a_2 \left[1 - (1-y)^2\right] / \left[1 + (1-y)^2\right]$$

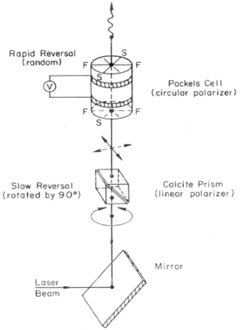
  for isoscalar target, a_1 and a_2 constant

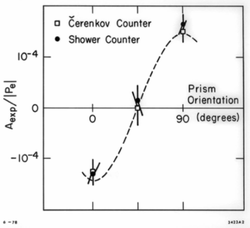
- Measuring A as fn of y allows determination of a_1 and a_2
- These constants depend on quark and lepton couplings to Z

Polarized eD Scattering (I)

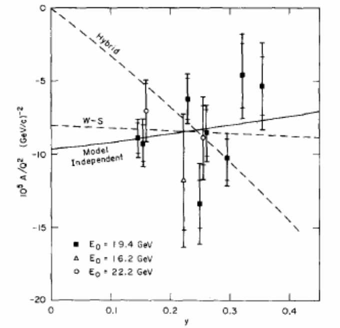
- Polarization obtained from laser optical pumping of Gallium Arsenide (photoemission of e)
- Can change circular polarization of laser to change polarization (two methods)

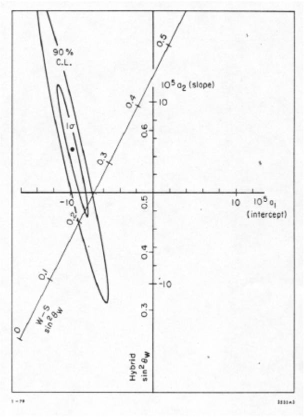






Polarized eD Scattering (II)





- 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

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

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

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

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

- 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 RH WNC:
  - 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:

b^1_μ, b^2_μ, b^3_μ	$SU(2))_L$ triplet
A_μ	$U(1)$ singlet

The Unified Gauge Interaction Lagrangian (I)

- Boson fields:

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

- Lepton fields:
  - Want to couple to left-handed e and ν:

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

  - No RH ν: $R \equiv e_R = \frac{1}{2}(1+\gamma_5)e$

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

The Unified Gauge Interaction Lagrangian (II)

- How about the quark fields?
- For SI we saw

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

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

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

  (constructed to give the quarks the right charge)

- 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!

- Interaction portion of LaGrangian:

$$\begin{aligned}\mathcal{L}_{int} &= \overline{R} i\gamma^{\mu}(\partial_{\mu} + i\frac{g'}{2}A_{\mu}Y)R + \\ &\quad \overline{L} i\gamma^{\mu}(\partial_{\mu} + i\frac{g'}{2}A_{\mu}Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_{\mu})L\end{aligned}$$

- Note: Need to introduce the Higgs to add mass terms. We'll postpone that discussion!

Identifying the Photon Field

- EM coupling proportional to charge
- Pick combination of A and B_3:

$$A^{em} = \frac{g' B_3 + gA}{\sqrt{g^2 + g'^2}}$$

- Orthoginal combination is the Z:

$$Z = \frac{gB^3 - g'A}{g^2 + g'^2}$$

- When we introduce Higgs, this combination will acquire mass
- Charged bosons:

$$W^{\pm} = \frac{B_1 \pm iB_2}{\sqrt{2}}$$

Identifying the Physical Couplings

- Coupling of $W^{\pm}$ is still g. Using standard conventions

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

- For the photon

$$e = \frac{gg'}{\sqrt{g^2 + g'^2}}$$

- Define $g' = g \tan\theta_W$:

$$\sqrt{g^2 + g'^2} = g\sqrt{1 + \tan^2\theta_W} = \frac{g}{\cos\theta_W}$$

- Hence

$$e = \frac{g^2 \tan\theta_W}{g/\cos\theta_W} = g \sin\theta_W$$

- and

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

Put together measurements and check for consistency

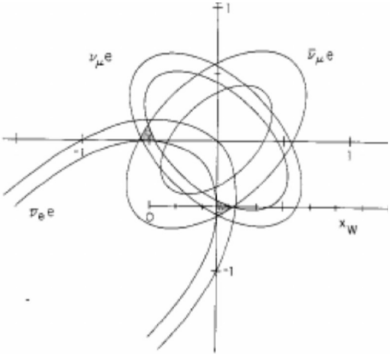


Fig. 6-18. Constraints on the neutral current parameters a_e and v_e from lepton (after F. Büsser, *Neutrino 81*, Proceedings of the 1981 International Conference Physics and Astrophysics, Maui, Hawaii, edited by R. J. Cence, E. Ma, and A. Energy Physics Group, University of Hawaii, Honolulu, 1981, Vol. II, p. 351).

7.3 Deeply Inelastic Lepton–Hadron Scattering 179

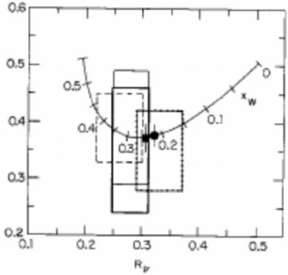


Fig. 7-11. Comparison of the ratios R_ν and $R_{\bar{\nu}}$ of neutral current to charged-current cross sections in the standard model (after F. Büsser, *Neutrino 81*, Proceedings of the 1981 International Conference on Neutrino Physics and Astrophysics, Maui, Hawaii, edited by R. J. Cence, E. Ma, and A. Roberts, High Energy Physics Group, University of Hawaii, Honolulu, 1982, Vol. II, p. 351). Data are from the CITF (thin line), BEBC (thick line), GGM (broken line), HPW (dotted line), CHARM (circle), and CDHS (square) experiments.

Predicted NC Vertex Factors

- From previous numbers

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

and

$$J^{EM} = J_\mu^3 + \frac{1}{2} J_\mu^Y$$

Therefore (see Halzen and Martin) using $\sin^2\theta_W = 0.234$ the 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	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W = -0.03$
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W = 0.19$
d	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W = 00.34$