Introduction to Neutrino Interaction Physics
NUFACT08 Summer School

Benasque & Valencia Spain June 9-27 2008

University of Glasgow

11-13 June 2008
Benasque, Spain
Paul Soler

References

1. K Zuber, "Neutrino Physics", Institute of Physics Publishing, 2004.
2. C.H. Kim & A. Pevsner "Neutrinos in Physics and Astrophysics", Harwood Academic Publishers, 1993.
3. K. Winter (editor), "Neutrino Physics", Cambridge University Press (2^{nd} edition), 2000.
4. R.N. Mohapatra, P.B. Pal, "Massive Neutrinos in Physics and Astrophysics", World Scientific (2^{nd} edition), 1998.
5. H.V. Klapdor-Kleingrothaus & K. Zuber, "Particle Astrophysics", Institute of Physics Publishing, 1997.
6. K. McFarland, Neutrino Interaction Physics, lectures at SUSSP61, St Andrews, June 2006, (To be published in Proceedings SUSSP61, Taylor & Francis, 2008).

Contents

1. History and Introduction

1.1 Fermi Theory

1.2 Neutrino discovery

1.3 Parity violation and V-A theory

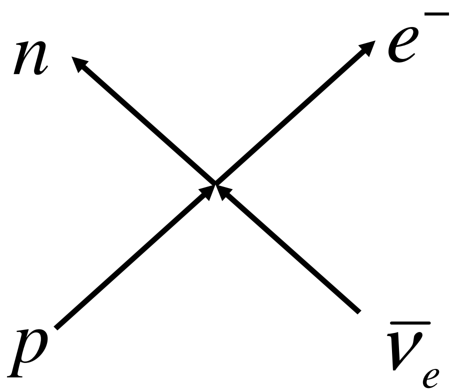
1.4 Neutral currents

1.5 Standard model neutrino interactions

1.1 Fermi theory of beta decay (1932)

- Existence of a point-like four fermion interaction (Fermi, 1932):

$$n \to p + e^- + \nu_e$$



- Lagrangian of the interaction:

$$L(x) = -\frac{G_F}{\sqrt{2}}\left[\bar{\phi}_p(x)\gamma^\mu \phi_n(x)\right]\left[\bar{\phi}_e(x)\gamma_\mu \phi_\nu(x)\right]$$

G_F = Fermi coupling constant = $(1.16637 \pm 0.00001)\times 10^{-5}\ GeV^{-2}$

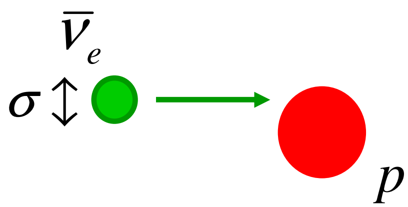
- Gamow-Teller interaction when final spin different to initial nucleus:

$$L(x) = -\frac{G_F}{\sqrt{2}}\sum_i \left[\bar{\phi}_p(x)\Gamma^i \phi_n(x)\right]\left[\bar{\phi}_e(x)\Gamma_i \phi_\nu(x)\right] + h.c.$$

Possible interactions: $\Gamma_i = 1, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu} = S, P, V, A, T$

First neutrino cross-section calculation

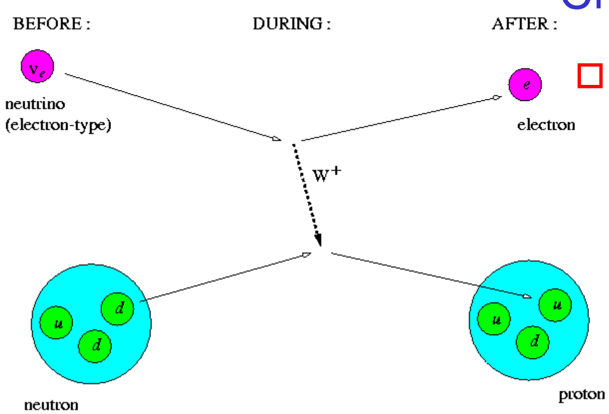
- Bethe-Peierls (1934): calculation of first cross-section for inverse beta reaction $\bar{\nu}_e + p \rightarrow n + e^+$ or $\nu_e + n \rightarrow p + e^-$ using Fermi theory



$\sigma \approx 5\times10^{-44}\ cm^2$ for $E(\bar{\nu}) = 2\ MeV$ Accurate to factor 2

Conversion from natural units: $\hbar c = 197.3\ MeV \cdot fm$

Cross-section: multiply by $(\hbar c)^2 = 0.3894\times10^{-27}\ GeV^2 \cdot cm^2$



- Mean free path of antineutrino in water:

$$\lambda = \frac{1}{n\sigma} \approx 1.5\times10^{21}\ cm \approx 1600 \quad light - years$$

$$n = \frac{\text{num. free protons}}{\text{volume}} \approx 2\frac{N_A}{A}\rho$$

In water: $n = \frac{2\times6\times10^{23}}{18} = 6.7\times10^{22}\ cm^{-3}$

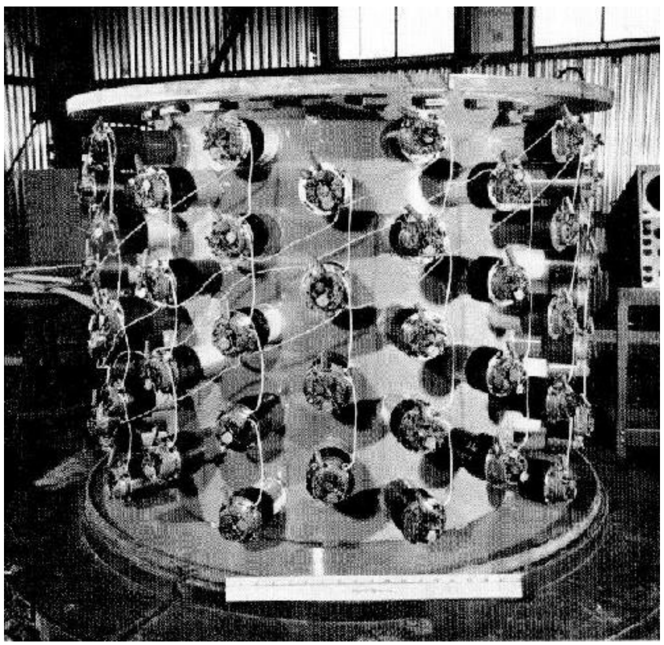
- Probability of interaction:

$$P = 1 - \exp\left(-\frac{L}{\lambda}\right) \approx \frac{L}{\lambda} = 6.7\times10^{-20}\ (m\ water)^{-1}$$

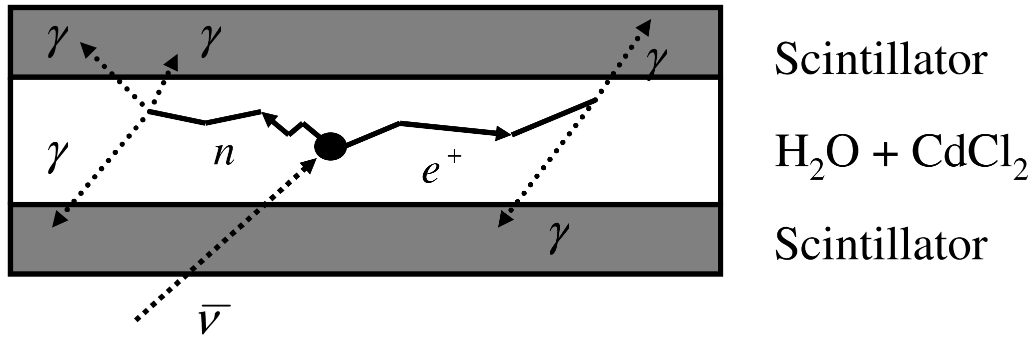
Need very intense source of antineutrinos to detect inverse beta reaction.

1.2 Neutrino discovery (1956)

- Reines and Cowan detect $\bar{\nu}_e + p \rightarrow n + e^+$ in 1953 (Hanford) (discovery confirmed 1956 in Savannah River):
  - Detection of two back-to-back γs from prompt signal $e^+e^- \rightarrow \gamma\gamma$ at t=0.
  - Neutron thermalization: neutron capture in Cd, emission of late γs <t>~ 20 ms



4200 l scintillator



Publication Science 1956:

σ= 6 x10^{-44} cm^2 ± 25% (within 5% expected)

1956: parity violation discovery increases theory cross-section: σ=(10±1.7)x10^{-44} cm^2

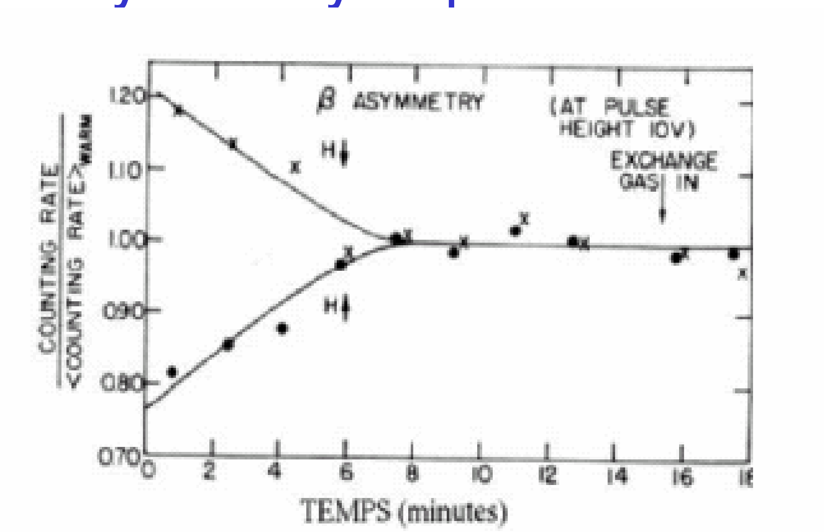
Reanalysis data in 1960:

σ= (12+7-4) x10^{-44} cm^2

Nobel prize Reines 1995

1.3 Parity violation and V-A

- Parity violation in weak decays postulated by Lee & Yang in 1950
- Parity violation confirmed through forward-backward asymmetry of polarized ^{60}Co (Wu, 1957).



$$^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \bar{\nu}_e$$

More electrons emitted in direction opposite to ^{60}Co spins, implying maximal parity violation

- Helicity operator: $$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} \xrightarrow{P} \frac{\vec{\sigma}\cdot(-\vec{p})}{|\vec{p}|} = -H$$

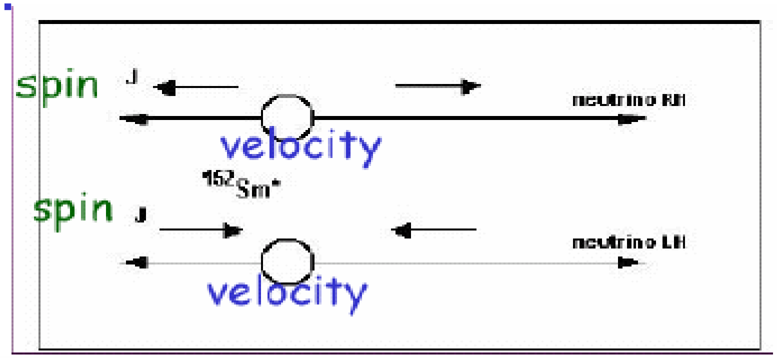
Projects spin along direction of motion

1.3 Parity violation and V-A

- Goldhaber, Grodzins, Sunyar (1958) measure helicity of neutrino from K capture of ^{152}Eu:

$$^{152}Eu(0^-)+e^- \rightarrow {}^{152}Sm^*(1^-)+\nu_e$$

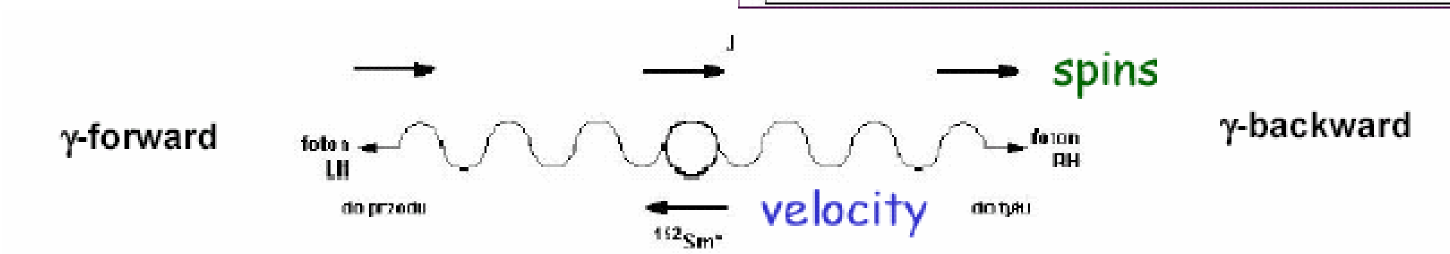
$$^{152}Sm^*(1^-) \rightarrow {}^{152}Sm^*(0^+)+\gamma$$



p_γ=-p_ν

σ_γ=-σ_ν

H_γ=H_ν



Asymmetry of photon spectrum in magnetic field determines helicity of ν_e:

$$H(\nu_e)=-1 \Rightarrow H(\overline{\nu}_e)=+1$$

Neutrinos are "left-handed" ↓↑ Antineutrinos are "right-handed" ↑↑

1.3 Parity violation and V-A

- Left and right handed projection operators:

$$\nu_L = P_L \nu = \frac{1}{2}(1-\gamma_5)\nu \qquad \nu_R = P_R \nu = \frac{1}{2}(1+\gamma_5)\nu$$

- Chirality operator: $\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$
  same as helicity operator for massless neutrinos (E=p).

$$\gamma_5 \nu_L = H\nu_L = -\nu_L \qquad \gamma_5 \nu_R = H\nu_R = +\nu_R$$

- If only ν_L interact and ν_R do not interact, then Γ_i have to transform as: $\bar{e}\Gamma_i \nu \rightarrow \left(\overline{P_L e}\right)\Gamma_i \left(P_L \nu\right) = \bar{e} P_R \Gamma_i P_L \nu$

$$V: P_R \gamma^\mu P_L = \frac{1}{2}\gamma^\mu\left(1-\gamma_5\right) \quad A: P_R \gamma^\mu \gamma_5 P_L = -\frac{1}{2}\gamma^\mu\left(1-\gamma_5\right)$$

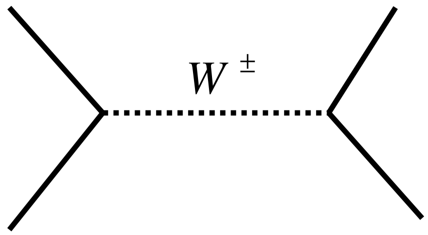
- The only possible coupling is V-A, due to maximal parity violation in weak interactions (Feynman, Gell-Mann, 1958):

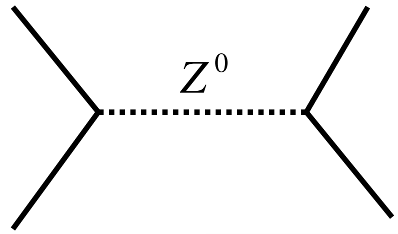
$$L_{V-A} = -\frac{G_F}{\sqrt{2}}\left[\bar{\phi}_p \gamma^\mu (1-g_A\gamma_5)\phi_n\right]\left[\bar{\phi}_e \gamma_\mu (1-\gamma_5)\phi_\nu\right] \text{with } g_A = -1.2573 \pm 0.0028$$

(determined empirically)

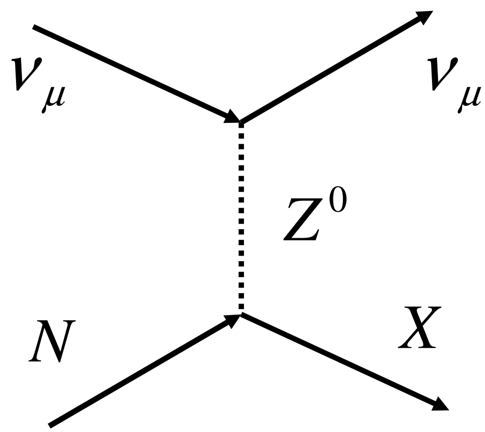
1.4 Neutral currents

- Two types of weak interaction: charged current (CC) and neutral current (NC) from electroweak theory of Glashow, Weinberg, Salam.

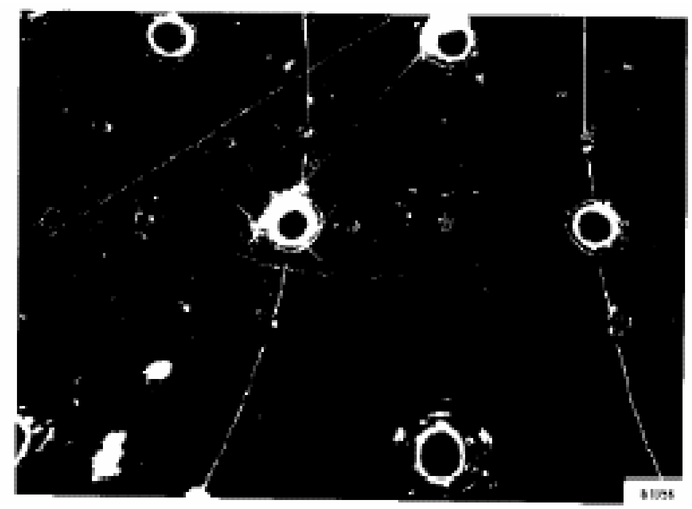


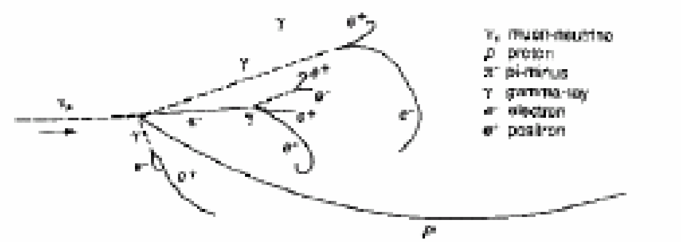


- First example of NC observed in 1973, inside the Gargamelle bubble chamber filled with freon (CF_3Br): no muon!



$$\nu_\mu + N \rightarrow \nu_\mu + X$$





1.5 Standard Model Neutrino Interactions

- Lagrangian for electroweak interactions:

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\left[g\cos\theta_W\, j_\mu^{(3)} - g'\sin\theta_W\, j_\mu^{(Y/2)}\right]Z^\mu +$$
$$+ i\left[g\sin\theta_W\, j_\mu^{(3)} + g'\cos\theta_W\, j_\mu^{(Y/2)}\right]A^\mu$$

- 1st term: charged current interactions (W^+, W^- exchange)
- 2nd term: neutral current interactions (Z^0 exchange)
- 3rd term:electromagnetic interactions (photon exchange)

- Electron charge: $e = g\sin\theta_W = g'\cos\theta_W$

- 3rd term: $e j_\mu^{e.m.} = e(j_\mu^{(3)} + j_\mu^{(Y/2)})$
  (neutrinos only couple to $W^\pm$ and Z^0)

S.M. interactions (cont)

- A) Neutrino electron interaction

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\frac{g}{2\cos\theta_W} j_\mu^{(Z)} Z^\mu + iej_\mu^{e.m}$$

- Where: $j_\mu^{(+)} = \bar{\nu}_{e,L}\gamma_\mu e_L = \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)e$

$$j_\mu^{(-)} = \bar{e}_L\gamma_\mu\nu_{e,L} = \frac{1}{2}\bar{e}\gamma_\mu(1-\gamma_5)\nu_e$$

$$j_\mu^{(Z)} = 2(j_\mu^{(3)} - \sin^2\theta_W j_\mu^{e.m}) =$$

$$= \bar{\nu}_{e,L}\gamma_\mu\nu_{e,L} - \bar{e}_L\gamma_\mu e_L + 2\sin^2\theta_W\bar{e}\gamma_\mu e =$$

$$= \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e - \frac{1}{2}\bar{e}\gamma_\mu(1-\gamma_5)e + 2\sin^2\theta_W\bar{e}\gamma_\mu e$$

$$\Rightarrow j_\mu^{(Z)} = \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e + \bar{e}\gamma_\mu(g_V - g_A\gamma_5)e$$

- With: $g_V = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_A = -\frac{1}{2}$

S.M. interactions (cont)

- B) Quark weak interactions

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^{\mu} + j_\mu^{(-)}W^{\mu+}\right] + i\frac{g}{2\cos\theta_W} j_\mu^{(Z)}Z^{\mu} + iej_\mu^{e.m}$$

- Where:

$$j_\mu^{(+)} = \frac{1}{2}\bar{u}\gamma_\mu(1-\gamma_5)d$$

$$j_\mu^{(-)} = \frac{1}{2}\bar{d}\gamma_\mu(1-\gamma_5)u$$

$$j_\mu^{(Z)} = \bar{u}\gamma_\mu(A_u - B_u\gamma_5)u + \bar{d}\gamma_\mu(A_d - B_d\gamma_5)d$$

- With:

$$A_u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad B_u = \frac{1}{2}$$

$$A_d = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \qquad B_d = -\frac{1}{2}$$

S.M. interactions (cont)

- After introducing Higgs field and spontaneous symmetry breaking:

$$L_{Higgs} = -\left|D_\mu \phi\right| - \mu^2 \left|\phi\right|^2 - \lambda \left|\phi\right|^4$$

- Masses:

$$m_H = \sqrt{2\lambda} v$$

$$m_{W^\pm} = \frac{gv}{2} \qquad \left(\frac{m_{W^\pm}}{m_{Z^0}}\right)^2 = \frac{g^2}{g^2 + g'^2} = \cos^2\theta_W$$

$$m_{Z^0} = \frac{\sqrt{g^2 + g'^2}}{2} v$$

- Vacuum expectation value: $v = \left(\sqrt{2} G_F\right)^{-1/2} \approx 246\ GeV$
- Effective Hamiltonian:

$$H_{eff} = \frac{g^2}{4 m_W^2}\left[j^{(+)\mu} j_\mu^{(-)} + h.c.\right] + \frac{g^2}{8 m_Z^2 \cos^2\theta_W} j^{(Z)\mu} j_\mu^{(Z)} =$$

$$= \frac{G_F}{\sqrt{2}}\left[2 j^{(+)\mu} j_\mu^{(-)} + h.c. + j^{(Z)\mu} j_\mu^{(Z)}\right]$$

S.M. interactions (cont)

- The vector boson masses are then predicted:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W{}^2} = \frac{e^2}{8m_W{}^2 \sin^2\theta_W} = \frac{4\pi\alpha}{8m_W{}^2 \sin^2\theta_W} \qquad \alpha = 1/137.036$$

- Masses:

$$m_W{}^2 = \left(\frac{37.2805}{\sin\theta_W}\right)^2$$

$$m_W = 80.450 \pm 0.058\ GeV$$

$$m_Z = 91.1876 \pm 0.0021\ GeV$$

$$\sin^2\theta_W = 0.22280 \pm 0.00035$$

- Need radiative corrections:

$$m_W = \frac{37.2805}{\sin\theta_W (1-\Delta r)^{1/2}}$$

with $\Delta r \approx 0.03630 \pm 0.0011$ for $m_t = 172.7\ GeV$ $m_H = 117\ GeV$

yields: $m_W = 80.51 \pm 0.11\ GeV$

2. Neutrino Electron Scattering

2.1 Charged current

2.2 Neutral current

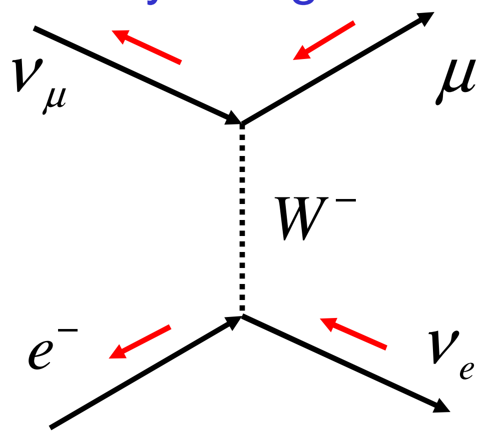
2.3 Interference charged and neutral current

2.4 Mass suppression

2.5 Number of neutrinos

2.1 Neutrino-electron CC scattering

- Only charged current: $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$ (Inverse Muon Decay)



Total spin J=0

$$H_{eff} = \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\mu\right]\left[\bar{e}\gamma_\mu (1-\gamma_5)\nu_e\right]$$

$$s = \left(p_{\nu_\mu} + p_e\right)^2 = 2 m_e E_{\nu_\mu} \; (in\ LAB)$$

$$t = q^2 = -Q^2 = \left(p_{\nu_\mu} - p_\mu\right)^2$$

Inelasticity variable (0<y<1)

$$y = \frac{p_e \cdot \left(p_{\nu_\mu} - p_\mu\right)}{p_e \cdot p_{\nu_\mu}} = \frac{E_{\nu_\mu} - E_\mu}{E_{\nu_\mu}} \; (in\ LAB)$$

$$\frac{d\sigma_{CC}(\nu_\mu e^-)}{dQ^2 dy} = \frac{G_F{}^2}{\pi} \frac{m_W{}^4}{(Q^2 + m_W{}^2)^2} \Rightarrow \sigma_{CC}(\nu_\mu e^-) = \int_0^s \frac{G_F{}^2}{\pi} \frac{m_W{}^4}{(Q^2 + m_W{}^2)^2} dQ^2$$

Total cross-section (ignoring mass terms):

$$\sigma_{CC}(\nu_\mu e^-) \approx \frac{G_F{}^2 s}{\pi} = \frac{2 G_F{}^2 m_e}{\pi} E_{\nu_\mu} \; (in\ LAB)$$

(cross-section proportional to energy!)

Measurement CHARM-II:

$$\sigma(\nu_\mu e^-) = (1.651 \pm 0.093) \times 10^{-41} \left(\frac{E}{1\,GeV}\right) cm^2$$

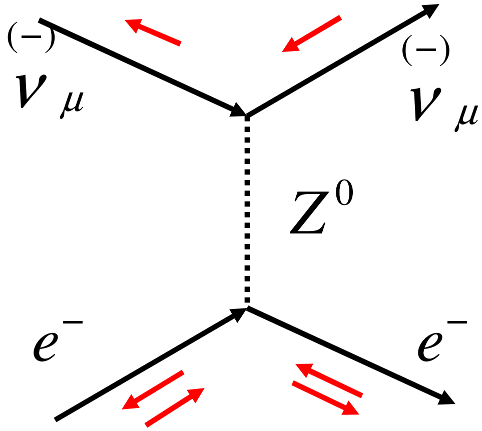
$$\Rightarrow \sigma_{CC}(\nu_\mu e^-) = \frac{2 G_F{}^2 m_e (\hbar c)^2 E_{\nu_\mu}}{\pi} = 1.72 \times 10^{-41} \left(\frac{E_{\nu_\mu}}{1\,GeV}\right) cm^2$$

$$\hbar c = 197.33\ MeV \cdot fm$$

$$G_F = 1.16637 \times 10^{-5}\ GeV^{-2}$$

2.2 Neutrino-electron NC scattering

- Only neutral current: $\overset{(-)}{\nu}_\mu + e^- \rightarrow \overset{(-)}{\nu}_\mu + e^-$ Elastic scattering



$$H_{eff} = \frac{G_F}{\sqrt{2}}\left[\bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\nu_\mu\right]\left[\bar{e}\gamma_\mu (g_V - g_A\gamma_5)e\right]$$

$$\bar{e}\gamma_\mu (g_V - g_A\gamma_5)e = g_L \bar{e}\gamma_\mu (1-\gamma_5)e + g_R \bar{e}\gamma_\mu (1+\gamma_5)e$$

$$g_V = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_L = \frac{1}{2}(g_V + g_A) = -\frac{1}{2} + \sin^2\theta_W$$

$$g_A = -\frac{1}{2} \qquad g_R = \frac{1}{2}(g_V - g_A) = \sin^2\theta_W$$

Couples to e_L and e_R: J=0,1

Right handed current suppressed in backward direction: $1-y = \frac{1+\cos\theta^*}{2}$

$$\frac{d\sigma_{NC}(\nu_\mu e^-)}{dy} = \frac{G_F{}^2 s}{\pi}\frac{m_Z^4}{(Q_{max}{}^2 + m_Z{}^2)^2}\left[\left(-\frac{1}{2}+\sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

$$\frac{d\sigma_{NC}(\bar{\nu}_\mu e^-)}{dy} = \frac{G_F{}^2 s}{\pi}\frac{m_Z^4}{(Q_{max}{}^2 + m_Z{}^2)^2}\left[\left(-\frac{1}{2}+\sin^2\theta_W\right)^2 (1-y)^2 + \sin^4\theta_W\right]$$

2.2 Neutrino-electron NC scattering

- Only neutral current (total cross-section): $\overset{(-)}{\nu}_\mu + e^- \rightarrow \overset{(-)}{\nu}_\mu + e^-$

$$\sigma_{NC}(\nu_\mu e^-) = \frac{G_F{}^2 s}{\pi}\left[\left(-\frac{1}{2}+\sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right] = 0.16\times10^{-41}\left(\frac{E_\nu}{1\,GeV}\right) cm^2$$

$$\sigma_{NC}(\bar{\nu}_\mu e^-) = \frac{G_F{}^2 s}{\pi}\left[\frac{1}{3}\left(-\frac{1}{2}+\sin^2\theta_W\right)^2 + \sin^4\theta_W\right] = 0.13\times10^{-41}\left(\frac{E_\nu}{1\,GeV}\right) cm^2$$

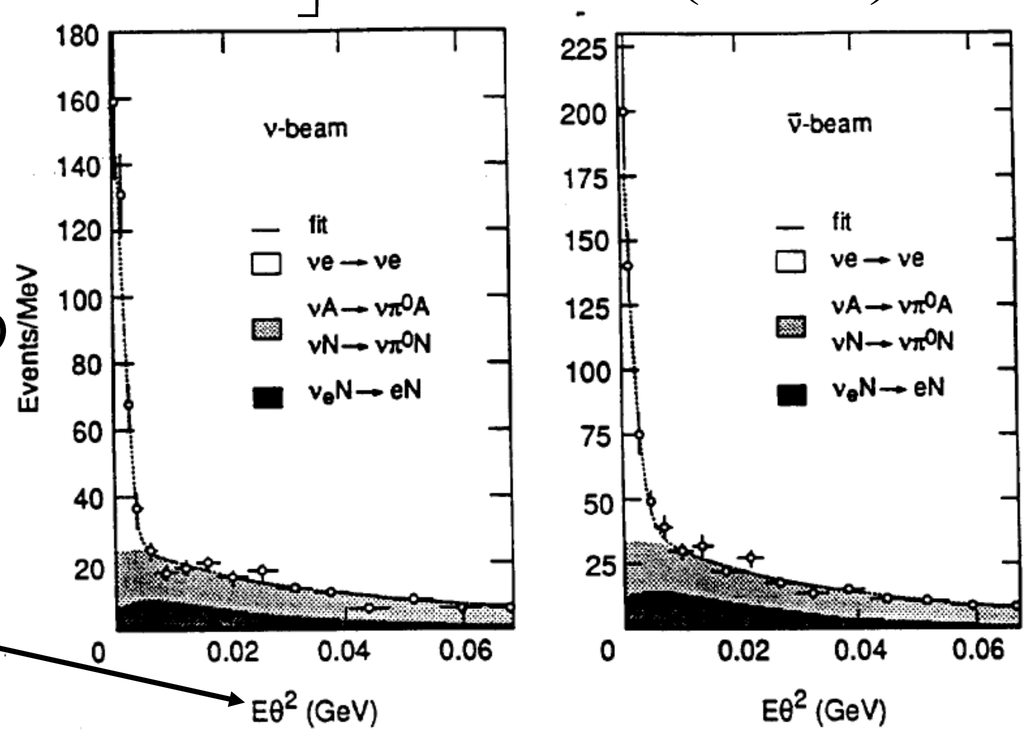
- Can obtain value of $\sin^2\theta_W$ from neutrino electron elastic scattering (CHARM II):

$$\sin^2\theta_W = 0.2324 \pm 0.0058 \pm 0.0059$$

$$g_V = -0.035 \pm 0.017$$

$$g_A = -0.503 \pm 0.017$$

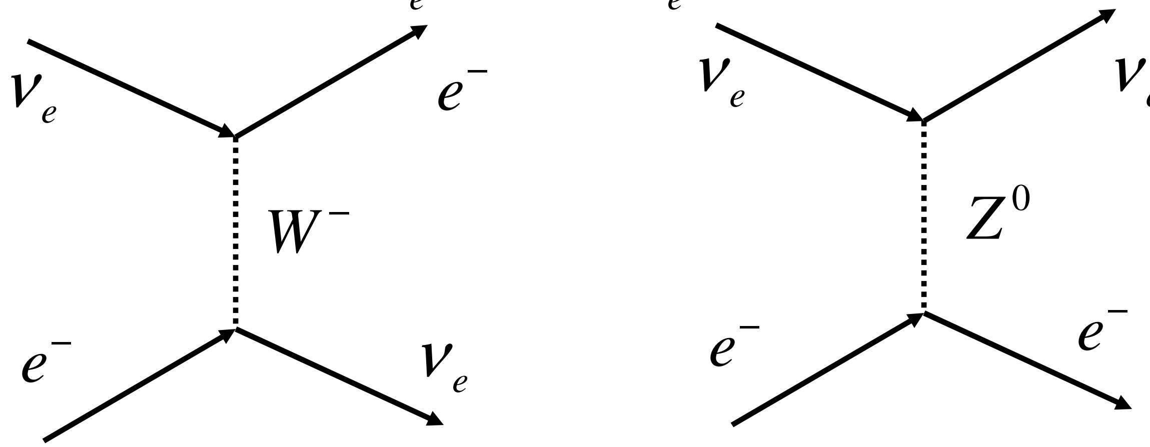
$$E_e\Theta^2 = 2m_e(1-y)$$



2.3 Interference CC and NC

- Tree level Feynman diagrams: both neutral and charged currents

$$\nu_e + e^- \rightarrow \nu_e + e^-$$



- Effective Hamiltonian:

$$H_{eff} = \frac{G_F}{\sqrt{2}} \left\{ \left[\overline{\nu}_e \gamma^\mu (1-\gamma_5) e \right] \left[\overline{e} \gamma_\mu (1-\gamma_5) \nu_e \right] + \left[\overline{\nu}_e \gamma^\mu (1-\gamma_5) \nu_e \right] \left[\overline{e} \gamma_\mu (g_V - g_A \gamma_5) e \right] \right\}$$

$$= \frac{G_F}{\sqrt{2}} \left\{ \left[\overline{\nu}_e \gamma^\mu (1-\gamma_5) \nu_e \right] \left[\overline{e} \gamma_\mu (1 + g_V - (1+g_A) \gamma_5) e \right] \right\}$$

(through a Fierz transformation)

2.3 Interference CC and NC

- Rearranging terms in charged and neutral current contributions for:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

$$g_L = \frac{1}{2}(1 + g_V + 1 + g_A) = -\frac{1}{2} + \sin^2\theta_W + 1 = \frac{1}{2} + \sin^2\theta_W$$

$$g_R = \frac{1}{2}(1 + g_V - (1 + g_A)) = \sin^2\theta_W$$

Then:

$$\frac{d\sigma(\nu_e e^-)}{dy} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

$$\Rightarrow \sigma(\nu_e e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right] = 0.96 \times 10^{-41}\left(\frac{E_\nu}{1\,GeV}\right) cm^2$$

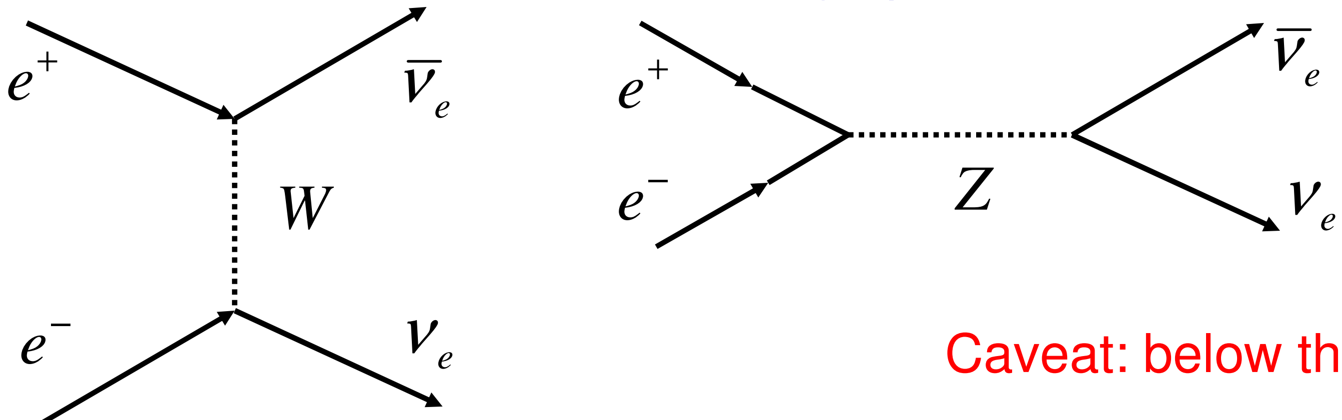
$$\text{Also}: \sigma(\bar{\nu}_e e^-) = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \sin^4\theta_W\right] = 0.40 \times 10^{-41}\left(\frac{E_\nu}{1\,GeV}\right) cm^2$$

These cross-sections are a consequence of the interference of the charged and neutral current diagrams.

2.3 Interference CC and NC

- Neutrino pair production: $e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$

  Contribution from both W and Z graphs.



Caveat: below the Z pole!

Then:

$$\sigma(e^+e^- \rightarrow \nu_e\bar{\nu}_e) = \frac{G_F{}^2 s}{12\pi}\left[\left(\frac{1}{2} + 2\sin^2\theta_W\right)^2 + \frac{1}{4}\right]$$

- Only neutral current contribution to: $e^+ + e^- \rightarrow \nu_\mu + \bar{\nu}_\mu$

$$\sigma(e^+e^- \rightarrow \nu_\mu\bar{\nu}_\mu) = \frac{G_F{}^2 s}{12\pi}\left[\left(\frac{1}{2} - 2\sin^2\theta_W\right)^2 + \frac{1}{4}\right]$$

Neutrino-electron scattering summary

- Summary neutrino electron scattering processes:

Process	Total cross-section
$\nu_\mu + e^- \to \mu^- + \nu_e$	$\frac{G_F{}^2 s}{\pi}$
$\nu_e + e^- \to \nu_e + e^-$	$\frac{G_F{}^2 s}{4\pi}\left[\left(2\sin^2\theta_W - 1\right)^2 + \frac{4}{3}\sin^4\theta_W\right]$
$\overline{\nu}_e + e^- \to \overline{\nu}_e + e^-$	$\frac{G_F{}^2 s}{4\pi}\left[\frac{1}{3}\left(2\sin^2\theta_W + 1\right)^2 + 4\sin^4\theta_W\right]$
$\nu_\mu + e^- \to \nu_\mu + e^-$	$\frac{G_F{}^2 s}{4\pi}\left[\left(2\sin^2\theta_W - 1\right)^2 + \frac{4}{3}\sin^4\theta_W\right]$
$\overline{\nu}_\mu + e^- \to \overline{\nu}_\mu + e^-$	$\frac{G_F{}^2 s}{4\pi}\left[\frac{1}{3}\left(2\sin^2\theta_W - 1\right)^2 + 4\sin^4\theta_W\right]$
$e^+ + e^- \to \nu_e + \overline{\nu}_e$	$\frac{G_F{}^2 s}{12\pi}\left[\frac{1}{2} + 2\sin^2\theta_W + 4\sin^4\theta_W\right]$
$e^+ + e^- \to \nu_\mu + \overline{\nu}_\mu$	$\frac{G_F{}^2 s}{12\pi}\left[\frac{1}{2} - 2\sin^2\theta_W + 4\sin^4\theta_W\right]$

$$s = 2m_e E_\nu \text{ (in the LAB frame)}$$

2.4 Mass suppression

- We have not taken into account the effect of initial and final state masses yet
- For example: $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$

  Threshold $s = m_e{}^2 + 2m_e E_\nu \geq m_\mu{}^2 \Rightarrow E_\nu \geq \dfrac{m_\mu{}^2 - m_e{}^2}{2m_e} \approx 11\,GeV$
- Cross-section modification:

$$\sigma_{CC}(\nu_\mu e^-) = \int_{Q^2_{\min}}^{Q^2_{\max}} \frac{G_F{}^2}{\pi} \frac{m_W{}^4}{(Q^2 + m_W{}^2)^2} dQ^2 = \frac{G_F{}^2}{\pi} \frac{m_W{}^4}{(Q^2_{\max} + m^2_W)(Q^2_{\min} + m^2_W)} \left(Q^2_{\max} - Q^2_{\min}\right) \approx$$

$$\approx \frac{G_F{}^2}{\pi}\left(Q^2_{\max} - Q^2_{\min}\right) = \frac{G_F{}^2}{\pi}\left(s - m_\mu{}^2\right)$$

- Therefore:

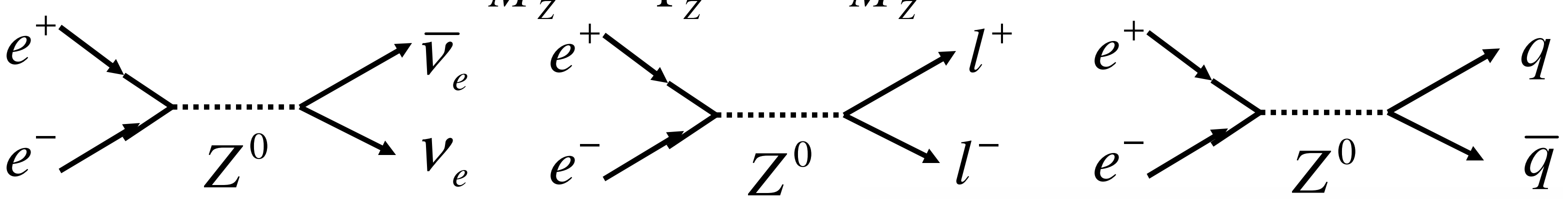
$$\sigma_{CC}(\nu_\mu e^-) = \frac{G_F{}^2 s}{\pi}\left(1 - \frac{m_\mu{}^2}{s}\right) = \sigma^{massless}_{CC}(\nu_\mu e^-)\left(1 - \frac{m_\mu{}^2}{s}\right)$$

2.5 Number of neutrinos

- Width of the Z-pole resonance: Breit-Wigner distribution

$$\sigma(e^+e^- \to f) = \frac{12\pi(\hbar c)^2}{M_Z}\,\frac{s\Gamma_e\Gamma_f}{(s-M_Z{}^2)^2 + s^2\Gamma_Z^2/M_Z}$$

$$\sigma_{peak}(e^+e^- \to f) = \frac{12\pi(\hbar c)^2}{M_Z}\,\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2} = \frac{12\pi(\hbar c)^2}{M_Z} B(Z^0 \to e^+e^-) B(Z^0 \to f\bar{f})$$



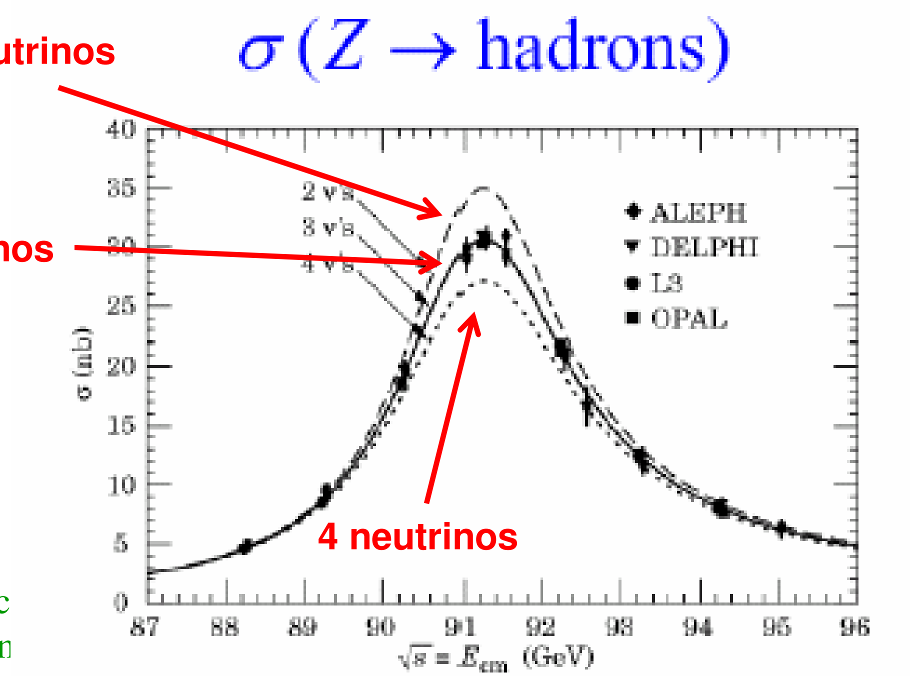
$$\Gamma_Z = \Gamma_{had} + 3\Gamma_{l^+l^-} + N_\nu \Gamma_{\nu\bar{\nu}} = 2490\,MeV$$

$$\Gamma_{had} = \Gamma_u + \Gamma_d + \Gamma_c + \Gamma_s + \Gamma_b = 1741\,MeV$$

$$\Gamma_{l^+l^-} = 83.9\,MeV$$

$$\Gamma_{\nu\bar{\nu}} = 167.1\,MeV$$

$$\Rightarrow N_\nu = 2.9841 \pm 0.0083$$



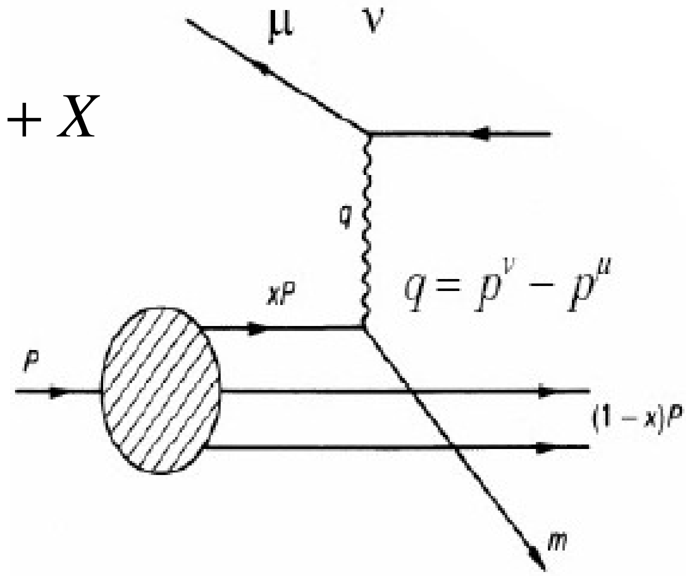
- Only 3 neutrinos with mass less than the Z mass

3. Neutrino Nucleon Deep-Inelastic Scattering

3.1 Definition and variables
3.2 Charged current
3.3 Quark content of nucleons
3.4 Sum rules
3.5 Neutral current
3.6 A case study: $\sin^2\theta_W$ from neutrino interactions
3.7 Charm production in neutrino interactions

3.1 Definition and Variables

- Deep inelastic neutrino-nucleon scattering reactions have large q^2 $\nu_l(p)+N \rightarrow l^-(p')+X$ ($q^2 >> m_N^2, E_\nu >> m_N$):
- Quark-parton model valid due to asymptotic freedom of QCD, which makes quarks behave as free point-like particles.
- Infinite momentum frame: a parton takes a fraction *x (0<x<1)*, of momentum when struck by a neutrino. Final quark state:



$$(xp_N+q)^2 = m_q^2 \Rightarrow x \approx -\frac{q^2}{2p_N \cdot q} \quad if\ q^2 >> m_q^2$$

- Variables in DIS:

$$s=(p+p_N)^2 \approx 2ME_\nu = 2ME$$

$$Q^2 = -q^2 = -(p+p')^2 = 4EE'\sin^2\frac{\theta}{2}$$

$$W^2 = E_X^2 - p_X^2 = -Q^2 + 2M\nu + M^2$$ **Recoil mass**

$$\nu = \frac{q \cdot p_N}{M} = E - E'$$

Bjorken Variables (*0<x<1, 0<y<1*):

$$x = \frac{-q^2}{2q \cdot p_N} = \frac{Q^2}{2M\nu}$$

$$y = \frac{q \cdot p_N}{p \cdot p_N} = \frac{\nu}{E} = \frac{Q^2}{2MEx}$$

3.2 Charged current

- Neutrino proton CC scattering: $\nu_\mu(p) + p \to \mu^-(p') + X$

  $u(x)dx$ = number of u-quarks in proton between x and x+dx

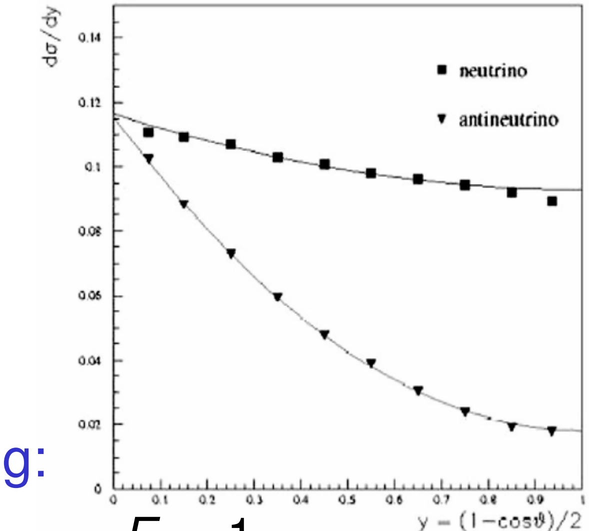
  $u(x) = u_V(x) + u_S(x) \quad d(x) = d_V(x) + d_S(x)$

  In the sea: $u_S(x) = \bar{u}(x) \quad d_S(x) = \bar{d}(x)$

  For proton (uud):

$$\int_0^1 u_V(x)dx = \int_0^1 [u(x) - \bar{u}(x)]dx = 2$$

$$\int_0^1 d_V(x)dx = \int_0^1 \left[d(x) - \bar{d}(x)\right]dx = 1$$



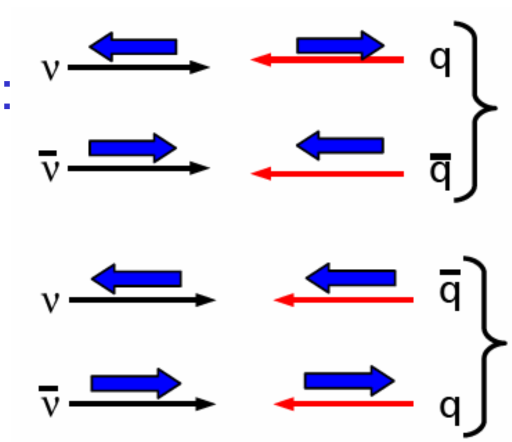
- Neutrino-quark/antineutrino-antiquark scattering:

$$\frac{d\sigma_{CC}(\nu_\mu q)}{dy} = \frac{d\sigma_{CC}(\bar{\nu}_\mu \bar{q})}{dy} = \frac{2G_F^{\,2} m_q E}{\pi}$$

with $y = 1 - \frac{E}{E'} = \frac{1}{2}(1 - \cos\theta)$

- Neutrino-antiquark/antineutrino-quark scattering:

$$\frac{d\sigma_{CC}(\nu_\mu \bar{q})}{dy} = \frac{d\sigma_{CC}(\bar{\nu}_\mu q)}{dy} = \frac{2G_F^{\,2} m_q E}{\pi}(1-y)^2$$



3.2 Charged current

- Scattering off proton: $proton = uud + (u\bar{u}) + (d\bar{d}) + (s\bar{s}) + (c\bar{c})$

$$\frac{d\sigma_{CC}(\nu_\mu p)}{dxdy} = \frac{G_F{}^2 ME}{\pi} 2x\left\{ \left[d(x) + s(x) \right] + \left[\bar{u}(x) + \bar{c}(x) \right](1-y)^2 \right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu p)}{dxdy} = \frac{G_F{}^2 ME}{\pi} 2x\left\{ \left[u(x) + c(x) \right](1-y)^2 + \left[\bar{d}(x) + \bar{s}(x) \right] \right\}$$

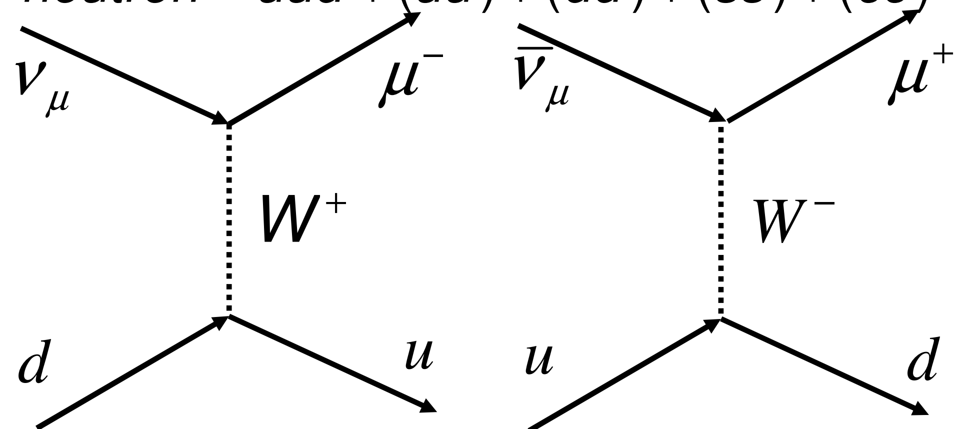
- Neutron (isospin symmetry): $neutron = uud + (u\bar{u}) + (d\bar{d}) + (s\bar{s}) + (c\bar{c})$

$$u_n(x) = d_p(x) \equiv d(x)$$

$$d_n(x) = u_p(x) \equiv u(x)$$

$$s_n(x) = s_p(x) \equiv s(x)$$

$$c_n(x) = c_p(x) \equiv c(x)$$



$$\frac{d\sigma_{CC}(\nu_\mu n)}{dxdy} = \frac{G_F{}^2 ME}{\pi} 2x\left\{ \left[u(x) + s(x) \right] + \left[\bar{d}(x) + \bar{c}(x) \right](1-y)^2 \right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu n)}{dxdy} = \frac{G_F{}^2 ME}{\pi} 2x\left\{ \left[d(x) + c(x) \right](1-y)^2 + \left[\bar{u}(x) + \bar{s}(x) \right] \right\}$$

3.2 Charged current

- Structure functions:

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F{}^2 s}{2\pi}\left[y^2 2xF_1(x,Q^2) + 2\left(1 - y - \frac{Mxy}{2E}\right)F_2(x,Q^2) \pm 2y\left(1 - \frac{y}{2}\right)xF_3(x,Q^2)\right]$$

$F_i\,(x,Q^2)$ are the structure functions, which depend on the helicity structure of q-W interactions. For massless spin-1/2 partons, we have the Callan-Gross relationship*: $2xF_1(x) = F_2(x)$

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F{}^2 s}{2\pi}\left[\left((1-y)^2 + \left(1 - \frac{Mxy}{2E}\right)\right)F_2(x,Q^2) \pm 2y\left(1 - \frac{y}{2}\right)xF_3(x,Q^2)\right] =$$

$$= \frac{G_F{}^2 s}{2\pi}\left[\left(1 + (1-y)^2\right)F_2(x,Q^2) \pm \left(1 - (1-y)^2\right)xF_3(x,Q^2)\right]$$

Assuming massless target

* **Deviations from the Callan-Gross relation are parameterised in terms of the "longitudinal" cross-section (ie.gluon splittting g→qq):**

$$R_L = \frac{\sigma_L}{\sigma_T} = \frac{F_2(x)}{2xF_1(x)}\left(1 + \frac{4Mx^2}{Q^2}\right)$$

3.2 Charged current

- Comparing the y distribution of both cross-sections we can compare the parton distribution functions to the proton structure functions:

$$F_2^{\nu p}(x) = x\left[d(x) + \bar{u}(x) + s(x) + \bar{c}(x)\right]$$
$$xF_3^{\nu p}(x) = x\left[d(x) - \bar{u}(x) + s(x) - \bar{c}(x)\right]$$
$$F_2^{\bar{\nu} p}(x) = x\left[u(x) + c(x) + \bar{d}(x) + \bar{s}(x)\right]$$
$$xF_3^{\bar{\nu} p}(x) = x\left[u(x) + c(x) - \bar{d}(x) - \bar{s}(x)\right]$$

- Also, the neutron structure functions:

$$F_2^{\nu p}(x) = x\left[u(x) + \bar{d}(x) + s(x) + \bar{c}(x)\right]$$
$$xF_3^{\nu n}(x) = x\left[u(x) - \bar{d}(x) + s(x) - \bar{c}(x)\right]$$
$$F_2^{\bar{\nu} n}(x) = x\left[d(x) + c(x) + \bar{u}(x) + \bar{s}(x)\right]$$
$$xF_3^{\bar{\nu} n}(x) = x\left[d(x) + c(x) - \bar{u}(x) - \bar{s}(x)\right]$$

3.2 Charged current

- Scattering off isoscalar target (equal number neutrons and protons):

$$q \equiv u + d + s + c \qquad \bar{q} \equiv \bar{u} + \bar{d} + \bar{s} + \bar{c}$$

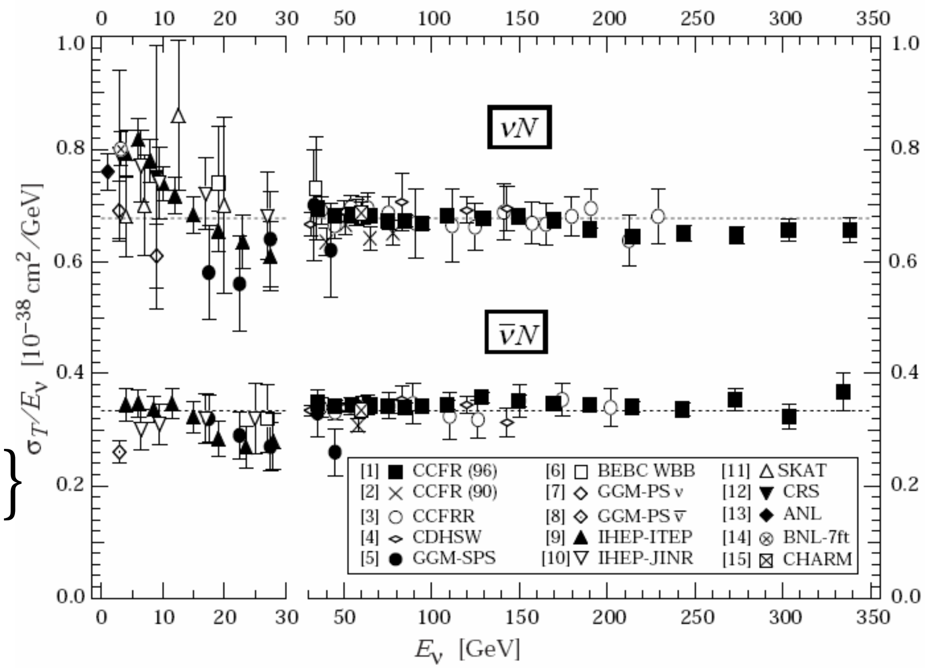
$$F_2^{\nu N}(x) = x\left[q(x) + \bar{q}(x)\right]$$

$$xF_3^{\nu N}(x) = x\left[q(x) - \bar{q}(x) + 2\left(s(x) - c(x)\right)\right]$$

$$xF_3^{\bar{\nu} N}(x) = x\left[q(x) - \bar{q}(x) - 2\left(s(x) - c(x)\right)\right]$$

$$\frac{d\sigma_{CC}(\nu_\mu N)}{dxdy} = \frac{G_F^{\,2} 2ME}{2\pi} x\left\{ q(x) + \bar{q}(x)\,(1-y)^2 \right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu N)}{dxdy} = \frac{G_F^{\,2} 2ME}{2\pi} x\left\{ q(x)(1-y)^2 + \bar{q}(x) \right\}$$



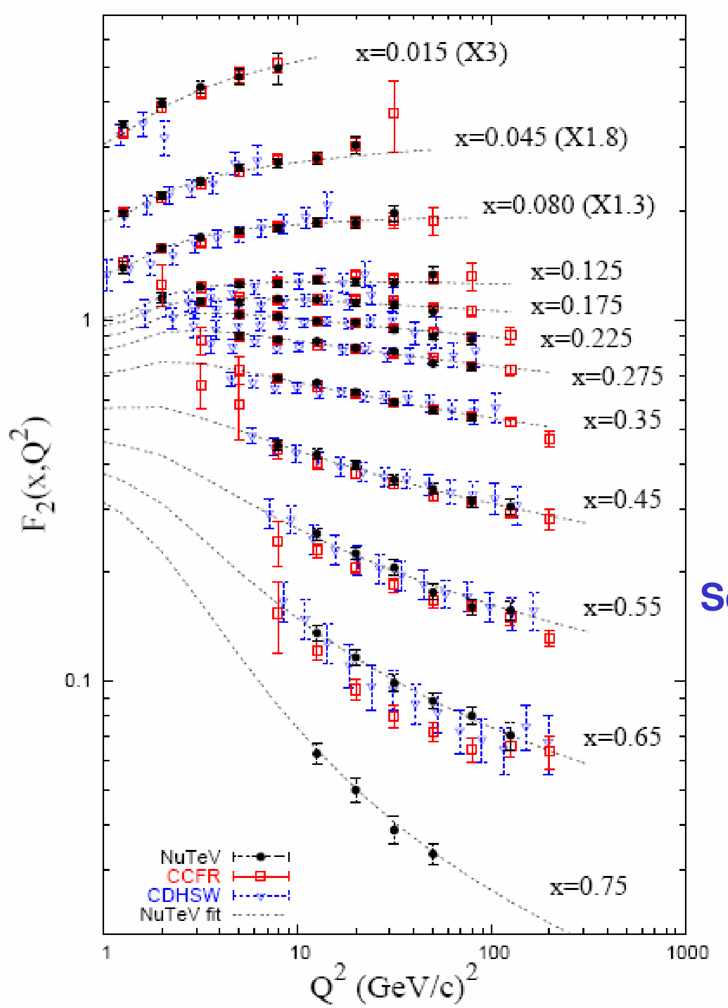
- Total cross-section:

$$\sigma_{CC}(\nu_\mu N) = \frac{G_F^{\,2} s}{2\pi}\left[\langle Q\rangle + \frac{1}{3}\langle \bar{Q}\rangle\right] = (0.677 \pm 0.014)\times 10^{-38}\, cm^2/GeV \times E(GeV)$$

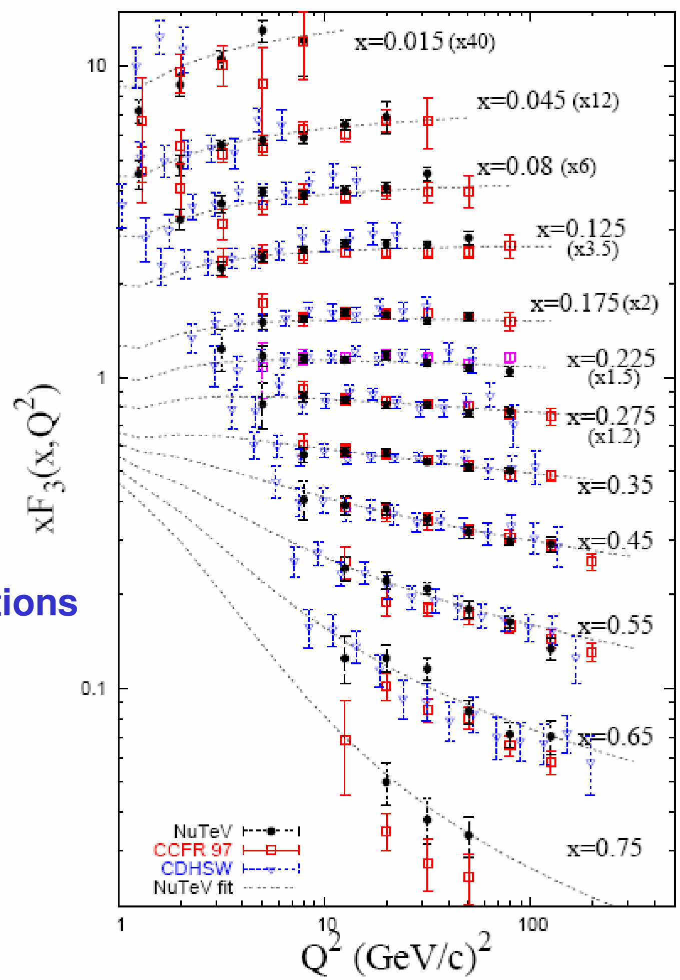
$$\sigma_{CC}(\bar{\nu}_\mu N) = \frac{G_F^{\,2} s}{2\pi}\left[\frac{1}{3}\langle Q\rangle + \langle \bar{Q}\rangle\right] = (0.334 \pm 0.008)\times 10^{-38}\, cm^2/GeV \times E(GeV)$$

3.2 Charged current

- Structure functions:



Scaling violations



3.3 Quark content of nucleons

- Quark content of nucleons from CC cross-sections
- Define: $$U = \int_0^1 xu(x)dx \text{ , } etc.$$
- Experimental values from y distribution of cross-sections yields:

Since $$r \equiv \frac{\sigma_{CC}(\bar{\nu}N)}{\sigma_{CC}(\nu N)} = 0.493 \pm 0.016 \text{ (measured)}$$

then: $$\frac{\overline{Q}}{Q} = \frac{3r-1}{3-r} \approx 0.191 \quad \Rightarrow Q = 0.405 \quad and \quad \overline{Q} = 0.078$$

therefore: $$Q_V = Q - \overline{Q} \approx 0.33 \qquad \frac{\overline{Q}}{Q+\overline{\overline{Q}}} = 0.16 \pm 0.03$$

$$\int_0^1 F_2^{\nu N}(x)dx = Q + \overline{Q} \approx 0.48$$

- Quarks and antiquarks carry 48% of proton momentum, valence quarks only 33% and sea quarks only 7.8% (u and d sea quarks carry 6%, s quarks carry 1.3% and c quarks 0.5%).

3.3 Quark content of nucleons

- Parton distribution functions as a function of x, fitted from structure functions:

$u(x)dx$ = number of u-quarks in proton between x and x+dx

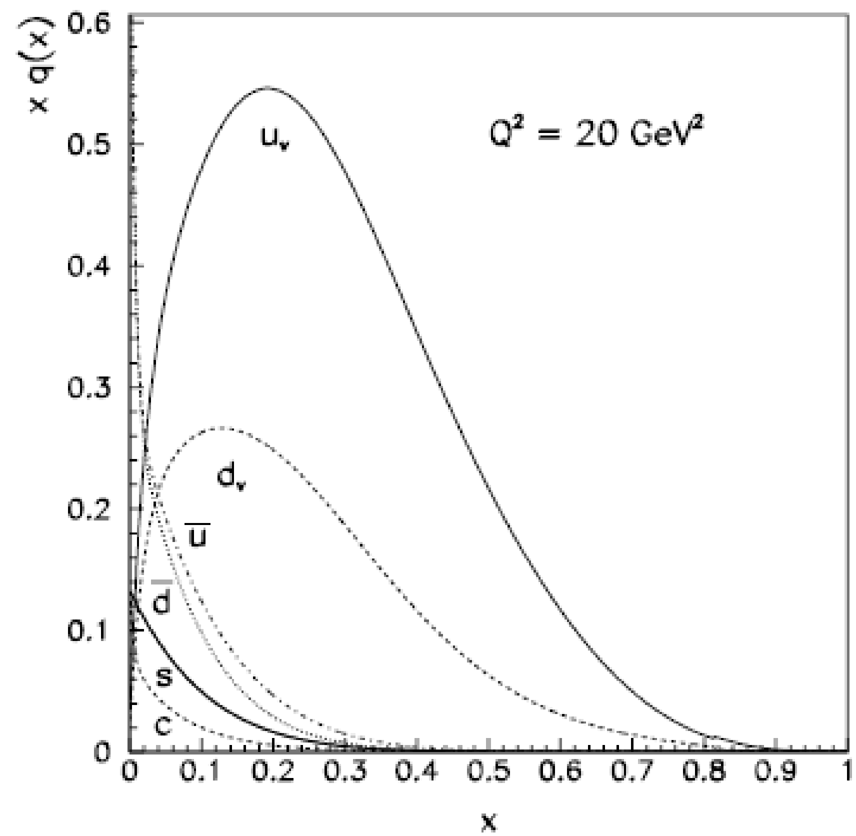
$$u(x) = u_V(x) + u_S(x) \qquad d(x) = d_V(x) + d_S(x)$$

In the sea: $d_S(x) = \bar{d}(x) \qquad u_S(x) = \bar{u}(x)$

For proton (uud):

$$\int_0^1 u_V(x)dx = \int_0^1 \left[u(x) - \bar{u}(x)\right]dx = 2$$

$$\int_0^1 d_V(x)dx = \int_0^1 \left[d(x) - \bar{d}(x)\right]dx = 1$$



3.4 Sum rules

- Sum rules:
  - Gross-Llewellyn Smith: $S_{GLS} = \frac{1}{2}\int_0^1 (F_3^{\nu}(x) + F_3^{\bar{\nu}}(x))dx$

$$S_{GLS} = \int_0^1 (q(x) - \bar{q}(x))dx = 3\left[1 - \frac{\alpha_s}{\pi} - a\left(\frac{\alpha_s}{\pi}\right)^2 - b\left(\frac{\alpha_s}{\pi}\right)^3\right] = 2.64 \pm 0.06$$

  - Adler:

$$S_A = \frac{1}{2}\int_0^1 \frac{1}{x}(F_2^{\nu n}(x) + F_2^{\nu p}(x))dx = \int_0^1 (u_V(x) - d_V(x))dx = 1$$

  - Gottfried:

$$S_G = \frac{1}{2}\int_0^1 \frac{1}{x}(F_2^{\mu n}(x) + F_2^{\mu p}(x))dx = \frac{1}{3}\int_0^1 (u(x) + \bar{u}(x) - d(x) - \bar{d}(x))dx = \frac{1}{3}$$

$S_G = 0.235 \pm 0.026$ Maybe isospin asymmetry: $\bar{u}(x) \neq \bar{d}(x)$

  - Bjorken:

$$S_B = \int_0^1 (F_1^{\bar{\nu}p}(x) + F_1^{\nu p}(x))dx = 1 - \frac{2\alpha_s(Q^2)}{3\pi}$$

3.5 Neutral current

- Neutral currents: $\overset{(-)}{\nu}_\mu + p \to \overset{(-)}{\nu}_\mu + X$

$$\frac{d\sigma_{NC}(\nu_\mu q)}{dy} = \frac{d\sigma_{NC}(\bar{\nu}_\mu \bar{q})}{dy} =$$

$$\frac{G_F{}^2 m_q E_\nu}{2\pi}\left\{(g_V + g_A)^2 + (g_V - g_A)^2(1-y)^2 + \frac{m_q}{E_\nu}(g_A{}^2 - g_V{}^2)y\right\}$$

$$\frac{d\sigma_{NC}(\bar{\nu}_\mu q)}{dy} = \frac{d\sigma_{NC}(\nu_\mu \bar{q})}{dy} =$$

$$\frac{G_F{}^2 m_q E_\nu}{2\pi}\left\{(g_V - g_A)^2 + (g_V + g_A)^2(1-y)^2 + \frac{m_q}{E_\nu}(g_A{}^2 - g_V{}^2)y\right\}$$

- Coupling constants:

$$g_V = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad g_A = \frac{1}{2} \qquad \text{for q=u,c}$$

$$g'_V = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \qquad g'_A = -\frac{1}{2} \qquad \text{for q=d,s}$$

$$\begin{cases} g_L = \frac{1}{2}(g_V + g_A) \\ g_R = \frac{1}{2}(g_V - g_A) \end{cases}$$

3.5 Neutral current

- Neutral currents off nucleons (neglecting c and s quark contributions):

$$\overset{(-)}{\nu}_\mu + N \rightarrow \overset{(-)}{\nu}_\mu + X$$

$$\frac{d\sigma_{NC}(\nu_\mu N)}{dxdy} = \frac{G_F^2 ME}{\pi} x\left\{(g_L^2 + g_L'^2)\left[q + \bar{q}(1-y)^2\right] + (g_R^2 + g_R'^2)\left[\bar{q} + q(1-y)^2\right]\right\}$$

$$\frac{d\sigma_{NC}(\bar{\nu}_\mu N)}{dxdy} = \frac{G_F^2 ME}{\pi} x\left\{(g_R^2 + g_R'^2)\left[q + \bar{q}(1-y)^2\right] + (g_L^2 + g_L'^2)\left[\bar{q} + q(1-y)^2\right]\right\}$$

- Defining: $R_\nu \equiv \frac{\sigma_{NC}(\nu N)}{\sigma_{CC}(\nu N)}$ $\quad R_{\bar{\nu}} \equiv \frac{\sigma_{NC}(\bar{\nu} N)}{\sigma_{CC}(\bar{\nu} N)}$ $\quad r \equiv \frac{\sigma_{CC}(\bar{\nu} N)}{\sigma_{CC}(\nu N)}$

yields: $g_L^2 + g_L'^2 = \frac{R_\nu - r^2 R_{\bar{\nu}}}{1-r^2}$ $\quad g_R^2 + g_R'^2 = \frac{r(R_{\bar{\nu}} - R_\nu)}{1-r^2}$

$$R_\nu = (g_L^2 + g_L'^2) + r(g_R^2 + g_R'^2) = \frac{1}{2} - \sin^2\theta_W + (1+r)\frac{5}{9}\sin^4\theta_W$$

$$R_{\bar{\nu}} = (g_L^2 + g_L'^2) + \frac{1}{r}(g_R^2 + g_R'^2) = \frac{1}{2} - \sin^2\theta_W + \left(1 + \frac{1}{r}\right)\frac{5}{9}\sin^4\theta_W$$

(Llewelyn-Smith relationships)

3.5 Neutral currents

- More relationships from the combination of neutrino and antineutrino tagged interactions:

$$R^{+} = \frac{\frac{d\sigma_{NC}(\nu_\mu N)}{dy} + \frac{d\sigma_{NC}(\overline{\nu}_\mu N)}{dy}}{\frac{d\sigma_{CC}(\nu_\mu N)}{dy} + \frac{d\sigma_{CC}(\overline{\nu}_\mu N)}{dy}} = \frac{1}{2} - \sin^2\theta_W + \frac{10}{9}\sin^4\theta_W$$

$$R^{-} = \frac{\frac{d\sigma_{NC}(\nu_\mu N)}{dy} - \frac{d\sigma_{NC}(\overline{\nu}_\mu N)}{dy}}{\frac{d\sigma_{CC}(\nu_\mu N)}{dy} - \frac{d\sigma_{CC}(\overline{\nu}_\mu N)}{dy}} = \frac{R_\nu - rR_{\overline{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_W$$

(Paschos-Wolfenstein relationship)

- Paschos-Wolfenstein relation removes the effects of sea quark differences (especially at low x) since the neutrino and antineutrino cross-sections are equal. It would also remove error from c quark
- All of these relationships can be used in neutrino experiments to test the electroweak theory and measure $\sin^2\theta_W$

3.6 $\sin^2\theta_W$

- Llewellyn-Smith relationship used to measure $\sin^2\theta_W$ by performing ratios of charged current to neutral current of neutrino nucleon scattering.

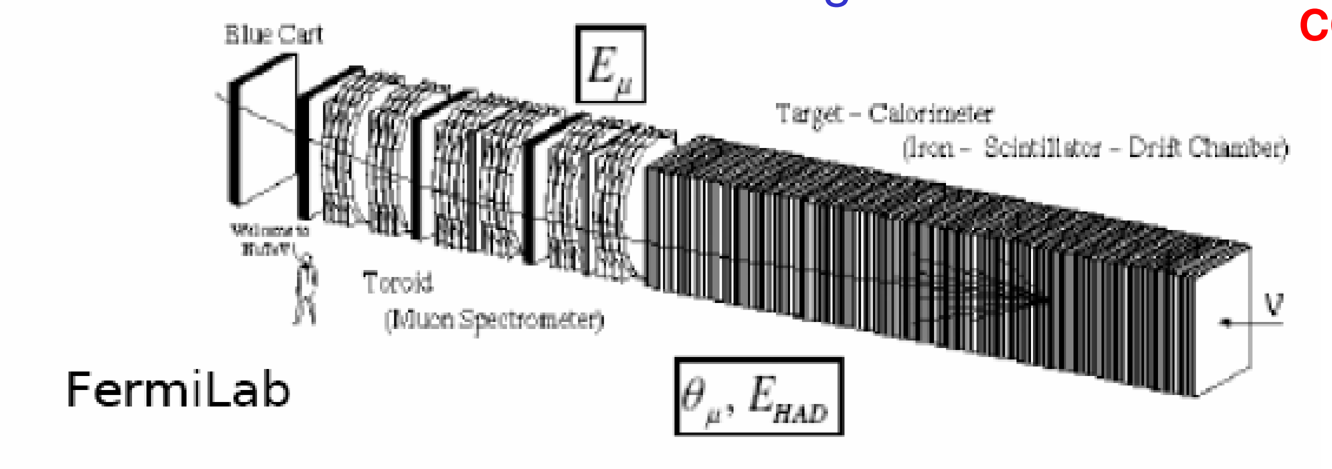
$$R_\nu = \frac{\sigma_{NC}(\nu N)}{\sigma_{CC}(\nu N)} = \frac{1}{2} - \sin^2\theta_W + (1+r)\frac{5}{9}\sin^4\theta_W$$

$$R_{\bar{\nu}} = \frac{\sigma_{NC}(\bar{\nu} N)}{\sigma_{CC}(\bar{\nu} N)} = \frac{1}{2} - \sin^2\theta_W + \left(1+\frac{1}{r}\right)\frac{5}{9}\sin^4\theta_W$$

(Llewelyn-Smith relationships)

- CHARM, CDHS and CCFR and NuTeV are all large sampling calorimeters that can measure large statistics CC and NC data:

CCFR/NuTeV



3.6 $\sin^2\theta_W$

- The ratio of NC to CC data from an average of different experiments (CDHS, CHARM, CCFR, NUTEV) gives a value of $\sin^2\theta_W$
- This on-shell value relates to the W and Z boson masses:

$$\sin^2\theta_W^{on-shell} = 1 - \frac{M_W^2}{M_Z^2}$$

  – For example, the CDHS experiment at CERN obtained:

$$R_\nu = 0.3072 \pm 0.0033 \qquad R_{\bar{\nu}} = 0.382 \pm 0.016$$

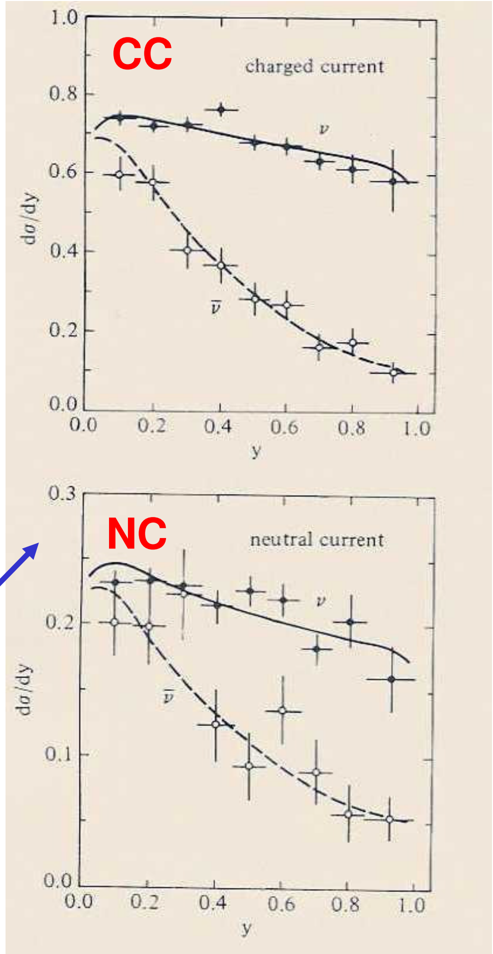
$$\Rightarrow \sin^2\theta_W = 0.233 \pm 0.003 \pm 0.005$$

- The world average value is:

$$World\ average:\ \sin^2\theta_W = 0.2227 \pm 0.00037$$

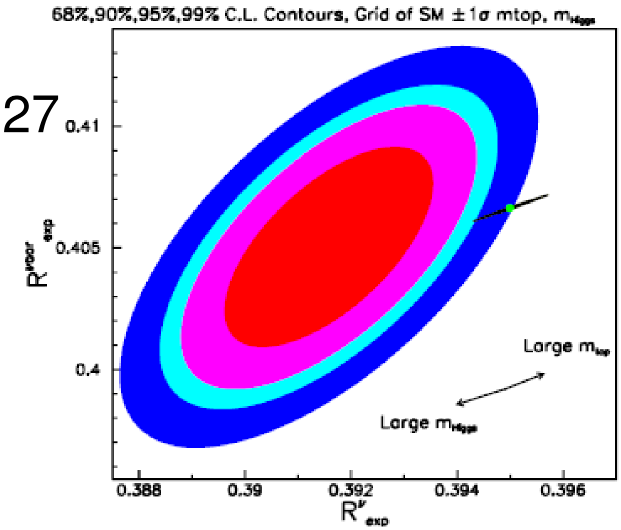
  – Example of data from the CHARM experiment

CHARM data



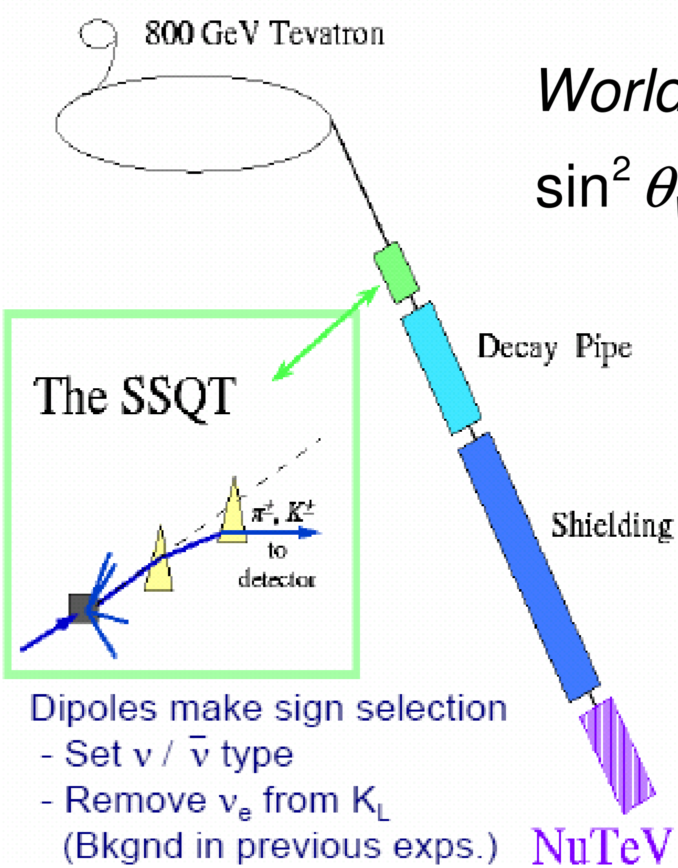
3.6 $\sin^2\theta_W$

- NuTeV experiment at Fermilab uses Paschos-Wolfenstein relationship and obtains reduced systematic errors but their result is >3σ away from world average:



$$NUTEV:\ R_\nu = 0.3916 \pm 0.0013 \quad R_{\bar{\nu}} = 0.4050 \pm 0.0027$$

$$\Rightarrow \sin^2\theta_W = 0.22773 \pm 0.00135 \pm 0.00095$$



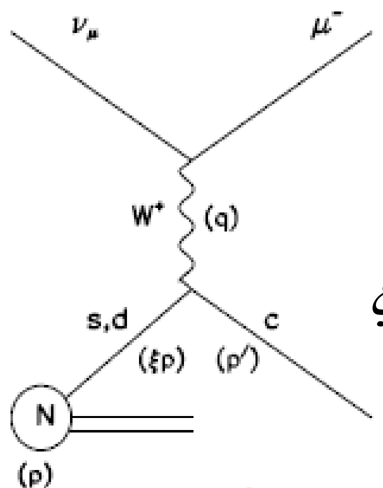
World average:

$$\sin^2\theta_W = 0.2227 \pm 0.00037$$

- Charged current events had a muon (μ^- from neutrinos and μ^+ from antineutrinos) and neutral current events were “short” events.
- Sign-selected neutrino beam, tags neutrino and antineutrino interactions (selected by decay of π^+ and π^-).
- Allows use of Paschos-Wolfenstein formula to reduce systematics.

3.7 Charm production

- Production of charm can be carried out from deep inelastic neutrino scattering from d or s quarks:



$$(q+\xi p)^2 = q^2 + 2\xi p\cdot q + \xi^2 M^2 = p'^2 = m_c^2$$

Therefore:

$$\xi \approx \frac{-q^2+m_c^2}{2p\cdot q} = \frac{Q^2+m_c^2}{2M\nu} = \frac{Q^2+m_c^2}{2M\nu} = \frac{Q^2+m_c^2}{Q^2/x} = x\left(1+\frac{m_c^2}{Q^2}\right)$$

- Slow rescaling model (LO): effect of a heavy quark threshold
- Replace: $x = \dfrac{Q^2}{2M\nu} \rightarrow \xi = x\left(1+\dfrac{m_c^2}{Q^2}\right)$
- Cross-section:

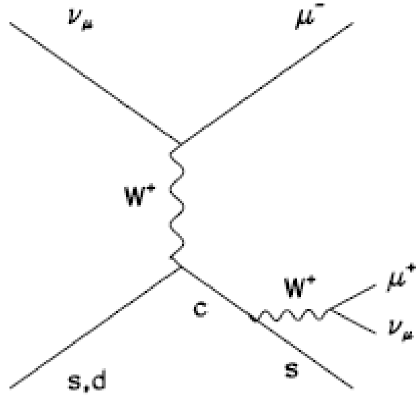
$$\frac{d^3\sigma^\nu}{d\xi dy dz} = \frac{G_F^2 ME\xi}{\pi}\left\{\left[u(\xi,Q^2)+d(\xi,Q^2)\right]\left|V_{cd}\right|^2 + 2s(\xi,Q^2)\left|V_{cs}\right|^2\right\}\left(1-y+\frac{xy}{\xi}\right)D(z)$$

  – Fragmentation of charm quark into hadrons: $D(z) \propto \dfrac{1}{z}\left(1-\dfrac{1}{z}-\dfrac{\varepsilon p}{1-z}\right)^{-2}$

(Petersen function, but there are others)

3.7 Charm production

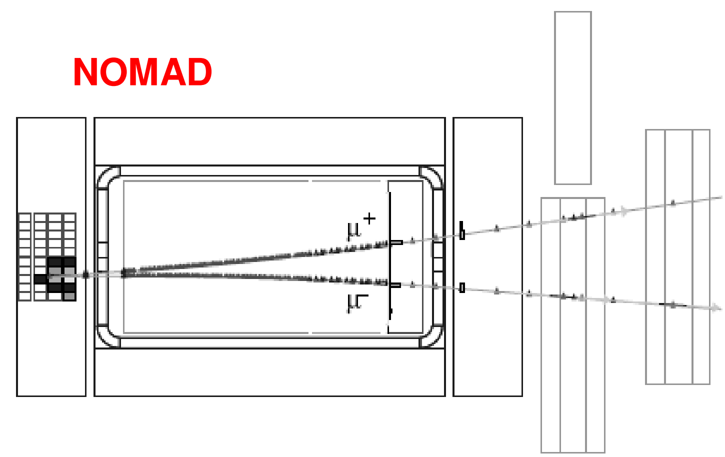
- Production of opposite sign dimuon events is signal of charm production because of semileptonic decay of charm:

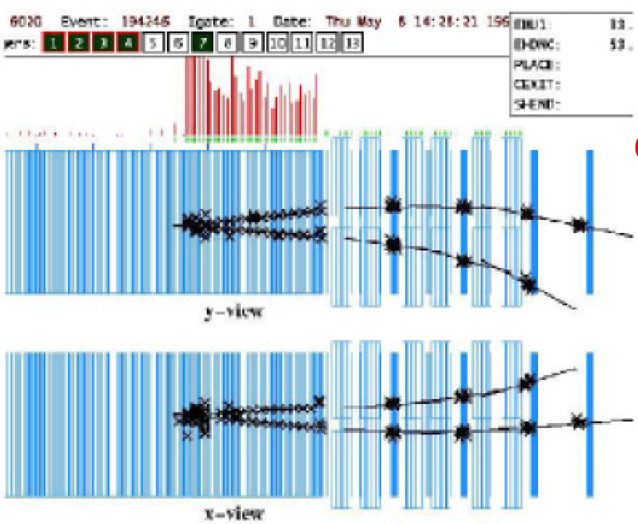


$$\nu_\mu + \begin{pmatrix} d \\ s \end{pmatrix} \longrightarrow \mu^- + \quad c \quad + X$$
$$\hookrightarrow \quad \mu^+ + \nu_\mu + X'$$
$$\overline{\nu}_\mu + \begin{pmatrix} \overline{d} \\ \overline{s} \end{pmatrix} \longrightarrow \mu^+ + \quad \overline{c} \quad + X$$
$$\hookrightarrow \quad \mu^- + \overline{\nu}_\mu + X'$$

- Charm production can probe strange sea, measure charm mass and V_{cd}

NOMAD





CCFR/NUTEV

- High statistics opposite sign dimuon samples were acquired by CDHS, CCFR, NOMAD, CHORUS, NUTEV

3.7 Charm production

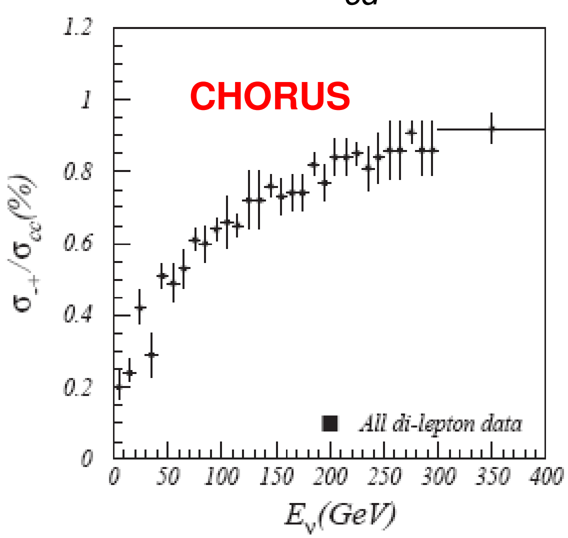
- Some results from opposite sign dimuons:
  - Cross-section: between 0.2%-1% depending on energy
  - Measurement charm mass (average): $\langle m_c^{LO} \rangle = 1.43 \pm 0.10$
  - Strange sea asymmetry
  - Measurement V_{cd} (average):

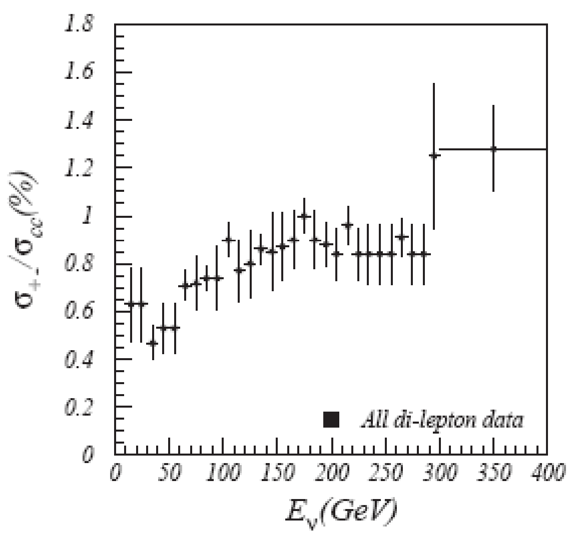
$$m_c^{NLO} = 1.70 \pm 0.019\ (NUTEV)$$

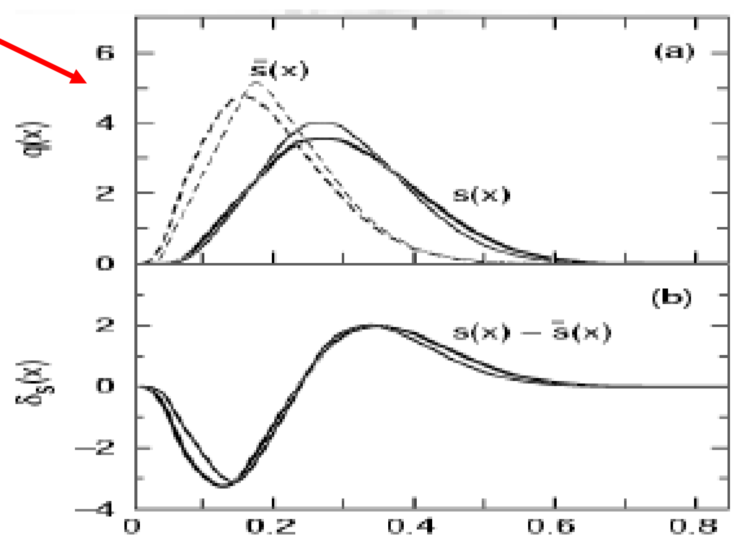
$$m_c^{NLO} = 1.58 \pm 0.09^{+0.04}_{-0.09}\ (NOMAD)$$

$$V_{cd}^{LO} = 0.232 \pm 0.010$$

$$V_{cd}^{NLO} = 0.246 \pm 0.016$$







Review: G di Lellis et al, Phys. Rep. 399, 2004, 227.