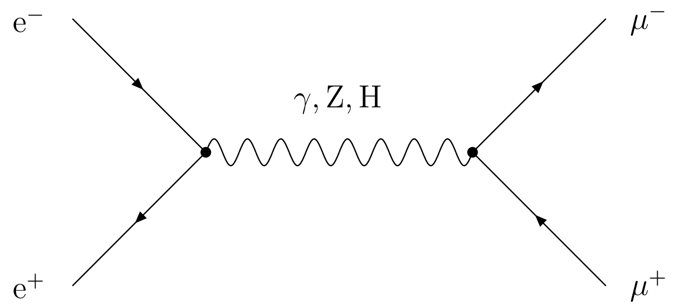
Particle Physics Major Option Exam, January 2008

SOLUTIONS

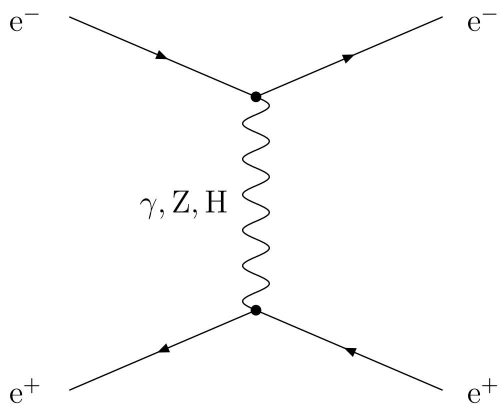
Question 1

Part i) *Draw the lowest order Standard Model Feynman diagrams for the process* $e^+e^- \to \mu^+\mu^-$ *and the additional diagram(s) for* $e^+e^- \to e^+e^-$. *Discuss the relative importance of the different diagrams at* $\sqrt{s} = m_Z$.

For $e^+e^- \to \mu^+\mu^-$ have three possible s-channel diagrams:



For $e^+e^- \to e^+e^-$ have three possible t-channel diagrams:



[1]

At $\sqrt{s} = m_Z$, the s-channel Z diagram dominates, although the $t - channel$ $e^+e^- \to e^+e^-$ diagram is important for small electron scattering angles (i.e. small q^2). The Higgs diagrams are negligible due to smallness of electron mass (i.e. Higgs-electron coupling).

(26 October 2012)

Part ii) *The forward-backward asymmetry is defined as* $A_{\mathrm{FB}} = (\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})/(\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})$, *where* $\sigma_{\mathrm{F}} = \sigma(\cos\theta > 0)$ *and* $\sigma_{\mathrm{B}} = \sigma(\cos\theta < 0)$. *Explain: a) why* A_{FB} *for* $\mathrm{e^+e^-} \to \mathrm{e^+e^-}$ *is different from that for* $\mathrm{e^+e^-} \to \mu^+\mu^-$ *and b) why for centre-of-mass energies in the range* $\sqrt{s} = m_{\mathrm{Z}} \pm \Gamma_{\mathrm{Z}}$, A_{FB} *for* $\mathrm{e^+e^-} \to \mu^+\mu^-$ *depends strongly on* $\sqrt{s}$.

a) For electrons A_{FB} has a large contribution from the s-channel photon exchange diagram which results in a large asymmetry, i.e. many more electrons produced in the forward direction. [2]

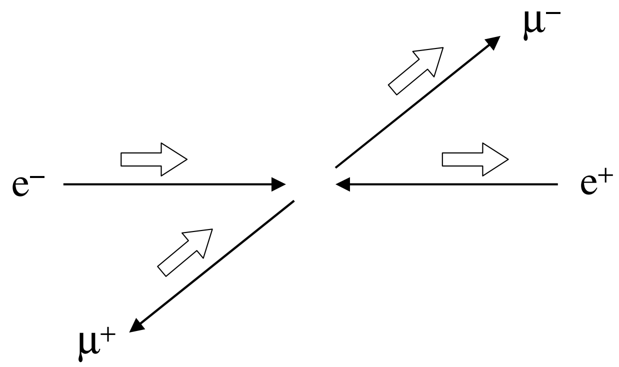
b) Away from resonance interference with the γ exchange diagram leads to a strong energy-dependence. [1]

Part iii) *The matrix elements for the process* $\mathrm{e^+e^-} \to \mathrm{Z} \to \mu^+\mu^-$ *at* $\sqrt{s} = m_{\mathrm{Z}}$ *are:*

$$|M_{RR}|^2 = \kappa(c_R^{\mathrm{e}})^2(c_R^{\mu})^2(1+\cos\theta)^2, \qquad |M_{LL}|^2 = \kappa(c_L^{\mathrm{e}})^2(c_L^{\mu})^2(1+\cos\theta)^2,$$
$$\text{and } |M_{RL}|^2 = \kappa(c_R^{\mathrm{e}})^2(c_L^{\mu})^2(1-\cos\theta)^2, \qquad |M_{LR}|^2 = \kappa(c_L^{\mathrm{e}})^2(c_R^{\mu})^2(1-\cos\theta)^2,$$

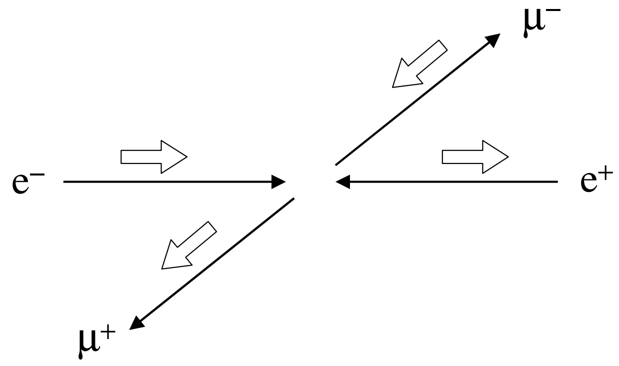
where $\kappa = g_{\mathrm{Z}}^4 m_{\mathrm{Z}}^2/\Gamma_{\mathrm{Z}}^2$, *and* $g_{\mathrm{Z}}\, c_L$ *and* $g_{\mathrm{Z}}\, c_R$ *are the coupling strengths of the* Z *to left- and right-handed particles. Draw diagrams indicating the helicities of the initial- and final-state particles for the matrix elements* M_{RR} *and* M_{RL} *and explain clearly why only four of the possible sixteen helicity combinations give non-zero matrix elements.*

For the RR combination we have:



[1.5]

For the RL combination we have:



[1.5]

(26 October 2012)

The interaction is of the form $\frac{1}{2}\gamma^\mu(c_{\rm V} - \gamma^5 c_{\rm A})$ and for any combination of vector/axial-vector couplings the chiral nature of the interaction and the fact that chiral states correspond to helicity states for ultra-relativistic particles only certain helicity combinations contribute. For example:

$$\begin{aligned}(1-\gamma^5)\gamma^\mu(1-\gamma^5) &= (1-\gamma^5)(1+\gamma^5)\gamma^\mu \\ &= (1-\gamma^5\gamma^5)\gamma^\mu = 0\end{aligned}$$

[2]

Part iv) *For unpolarised electrons and positrons, the differential cross section for* $\rm e^+e^- \to Z \to \mu^+\mu^-$ *can be written in the form* $d\sigma/d\Omega = A(1+\cos^2\theta) + B\cos\theta$. *Using* $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2 s}\langle|M|^2\rangle$, *find expressions for A and B in terms of the Z couplings to left- and right-handed particles and show that*

$$\sigma(\mathrm{e^+e^-} \to \mathrm{Z} \to \mu^+\mu^-) = \frac{g_{\rm Z}^4}{48\pi\Gamma_{\rm Z}^2}\left[(c_R^{\rm e})^2 + (c_L^{\rm e})^2\right]\left[(c_R^\mu)^2 + (c_L^\mu)^2\right].$$

Assuming lepton universality, $c_L^{\rm e} = c_L^\mu = c_L$ *and* $c_R^{\rm e} = c_R^\mu = c_R$, *use the measurement of* $\sigma(\mathrm{e^+e^-} \to \mathrm{Z} \to \mu^+\mu^-) = 2.00 \times 10^{-37}\,\mathrm{m}^2$ *to obtain a value for* $c_R^2 + c_L^2$.

Starting from

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2 s}\langle|M|^2\rangle$$

Summing over all possible diagrams and averaging over four possible initial states.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{4}\frac{1}{64\pi^2 s}(|M_{RR}|^2 + |M_{LR}|^2 + |M_{RL}|^2 + |M_{LL}|^2)$$

Using the matrix elements given:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} &= \frac{1}{256\pi^2 m_{\rm Z}^2}(|M_{RR}|^2 + |M_{LR}|^2 + |M_{RL}|^2 + |M_{LL}|^2) \\ &= \frac{g_{\rm Z}^4 m_{\rm Z}^2}{256\pi^2 m_{\rm Z}^2\Gamma_{\rm Z}^2}\{((c_R^e)^2(c_R^\mu)^2 + (c_R^e)^2(c_L^\mu)^2 + (c_L^e)^2(c_R^\mu)^2 + (c_L^e)^2(c_L^\mu)^2)(1+\cos^2\theta) \\ &\quad +(2(c_R^e)^2(c_R^\mu)^2 - 2(c_R^e)^2(c_L^\mu)^2 - 2(c_L^e)^2(c_R^\mu)^2 + 2(c_L^e)^2(c_L^\mu)^2)\cos\theta\} \\ &= A(1+\cos^2\theta) + B\cos\theta,\end{aligned}$$

with

$$\begin{aligned}A &= \frac{g_{\rm Z}^4}{256\pi^2\Gamma_{\rm Z}^2}\left[(c_R^e)^2 + (c_L^e)^2\right]\left[(c_R^\mu)^2 + (c_L^\mu)^2\right] \\ B &= \frac{2g_{\rm Z}^4}{256\pi^2\Gamma_{\rm Z}^2}\left[(c_L^e)^2 - (c_R^e)^2\right]\left[(c_L^\mu)^2 - (c_R^\mu)^2\right]\end{aligned}$$

[4]

To obtain total cross-section integrate over solid angle

$$\begin{aligned}
\sigma &= \int A(1+\cos^2\theta) + B\cos\theta \mathrm{d}\Omega \\
&= 2\pi \int_{-1}^{+1} A(1+\cos^2\theta) + B\cos\theta \mathrm{d}(\cos\theta) \\
&= 2\pi A \left[x + \frac{x^3}{3}\right]_{-1}^{+1} \\
&= \frac{16}{3}\pi A \\
&= \frac{16}{3}\pi \frac{g_Z^4}{256\pi^2 \Gamma_Z^2} \left[(c_R^e)^2 + (c_L^e)^2\right] \left[(c_R^\mu)^2 + (c_L^\mu)^2\right] \\
&= \frac{g_Z^4}{48\pi\Gamma_Z^2} \left[(c_R^e)^2 + (c_L^e)^2\right] \left[(c_R^\mu)^2 + (c_L^\mu)^2\right]
\end{aligned}$$

With lepton universality and converting cross section to natural units

$$\begin{aligned}
\sigma &= \frac{g_Z^4}{48\pi\Gamma_Z^2}(c_R^2 + c_L^2)^2 \\
(c_R^2 + c_L^2)^2 &= \frac{48\pi\Gamma_Z^2}{g_Z^4} \frac{2.00 \times 10^{-37}}{(0.197 \times 10^{-15})^2} \\
&= 0.0152 \\
c_R^2 + c_L^2 &= 0.123
\end{aligned}$$

Part v) *For the process* $e^+e^- \to Z \to \mu^+\mu^-$ *obtain an expression for* A_{FB} *in terms of* c_L *and* c_R. *Taking* $A_{FB} = 0.017$ *and the result you obtained for* $c_R^2 + c_L^2$, *determine values for* $|c_L|$ *and* $|c_R|$.

$$\begin{aligned}
\sigma_F &= 2\pi \int_0^1 A(1+\cos^2\theta) + B\cos\theta \mathrm{d}(\cos\theta) \\
&= 2\pi \left[Ax + A\frac{x^3}{3} + B\frac{x^2}{2}\right]_0^{+1} \\
&= 2\pi \left(\frac{4}{3}A + \frac{1}{2}B\right) \\
\text{similarly} \quad \sigma_B &= 2\pi \left(\frac{4}{3}A - \frac{1}{2}B\right) \\
A_{FB} &= \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3B}{8A} \\
&= \frac{3}{8}\frac{(c_L^2 - c_R^2)^2}{(c_L^2 + c_R^2)^2}
\end{aligned}$$

Using the the measured value of 0.017 and $c_R^2 + c_L^2 = 0.123$ gives

$$\begin{aligned}(c_L^2 - c_R^2)^2 &= 0.0007 \\ c_L^2 - c_R^2 &= \pm 0.026\end{aligned}$$

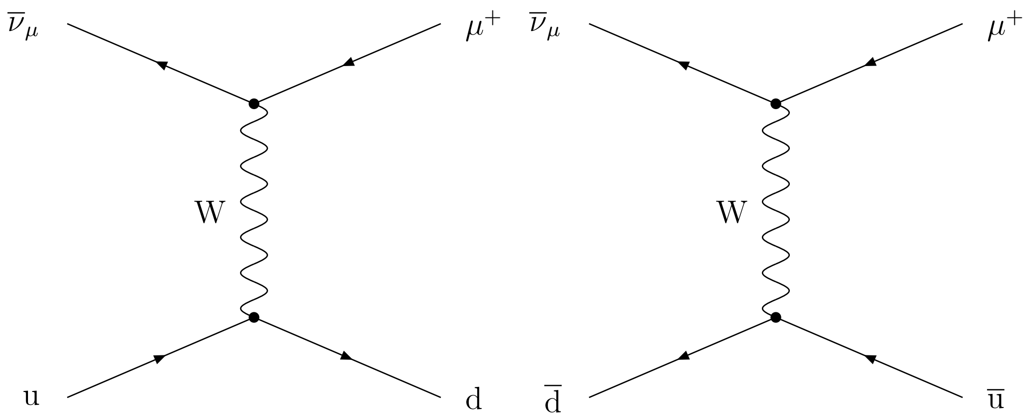
Two possible solutions, $|c_L| = 0.27$ and $|c_R| = 0.22$ or $|c_L| = 0.22$ and $|c_R| = 0.27$. Full marks given for either solution. [4]

Part vi) *Discuss briefly how $|c_L|$ and $|c_R|$ are determined for the different lepton flavours when universality is not assumed.*

By measuring asymmetries/cross-sections for electrons can determine couplings to electrons, i.e. measure $\mathcal{A}_e$. Using this the other cross section and asymmetry measurements give $\mathcal{A}_\mu$. Can also use A_{LR} to get $\mathcal{A}_e$. [2]

Question 2

Part i) *Draw Feynman diagrams for the possible $\overline{\nu}_\mu$ charged-current weak interactions with the constituents of the proton assuming that the only* u, d, $\overline{\text{u}}$, *and* $\overline{\text{d}}$ *are present.*



The diagrams involving a down or anti-up quark are forbidden by charge conservation (i.e. wrong type of W involved).

Part ii) *The differential cross sections for the charged-current weak interactions of high energy $\overline{\nu}_\mu$ with quarks/anti-quarks are:*

$$\frac{d\sigma_{\overline{\nu}\text{q}}}{d\Omega^*} = \frac{G_F^2 \hat{s}}{16\pi^2}(1+\cos\theta^*)^2, \qquad \text{and} \qquad \frac{d\sigma_{\overline{\nu}\overline{\text{q}}}}{d\Omega^*} = \frac{G_F^2 \hat{s}}{4\pi^2}$$

where θ^* is the polar angle of the final-state μ^+ in the centre-of-mass frame. Explain the angular dependences of these cross sections.

Part iii) *In $\overline{\nu}_\mu$ deep-inelastic scattering, y is defined as $y \equiv (p_2.q)/p_2.p_1$, where p_1 and p_2 are the respective four-momenta of the $\overline{\nu}_\mu$ and the struck quark, and q is the four momentum of the virtual W-boson. Neglecting particle masses, show that*

$$y = \frac{1}{2}(1-\cos\theta^*), \qquad \frac{d\sigma_{\overline{\nu}_\mu \text{q}}}{dy} = \frac{G_F^2 \hat{s}}{\pi}(1-y)^2, \qquad \text{and} \qquad \frac{d\sigma_{\overline{\nu}_\mu \overline{\text{q}}}}{dy} = \frac{G_F^2 \hat{s}}{\pi},$$

where $\hat{s}$ is the centre-of-mass energy of the neutrino−quark system.

Working in the centre-of-mass frame and neglecting particle masses, $p_1 = (E, 0, 0, E)$, $p_2 = (E, 0, 0, -E)$ and $p_3 = (E, E\sin\theta^*, 0, E\cos\theta^*)$

$$\begin{aligned} y &= \frac{p_2.q}{p_2.p_1} \\ &= \frac{p_2.(p_1 - p_3)}{2E^2} \\ &= \frac{p_2.(0,0,0,E(1-\cos\theta^*))}{2E^2} \\ &= \frac{1}{2}(1-\cos\theta^*) \end{aligned}$$

To calculate differential cross sections in terms of y, start from

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^*}\frac{\mathrm{d}\Omega^*}{\mathrm{d}y}$$

No azimuthal dependence, so integrate of ϕ

$$\frac{\mathrm{d}\Omega^*}{\mathrm{d}y} = 2\pi\sin\theta^*\frac{\mathrm{d}\theta^*}{\mathrm{d}y}$$

Using $y = \frac{1}{2}(1-\cos\theta^*)$

$$\begin{aligned} \frac{\mathrm{d}y}{\mathrm{d}\theta^*} &= \frac{1}{2}\sin\theta^* \\ \text{gives} \quad \frac{\mathrm{d}\Omega^*}{\mathrm{d}y} &= 4\pi \end{aligned}$$

From which it immediately follows that

$$\begin{aligned} \frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \overline{\mathrm{q}}}}{\mathrm{d}y} &= \frac{G_\mathrm{F}^2\hat{s}}{\pi}, \\ \text{and} \quad \frac{\mathrm{d}\sigma_{\overline{\nu}\mathrm{q}}}{\mathrm{d}y} &= \frac{G_\mathrm{F}^2\hat{s}}{4\pi}(1+\cos\theta^*)^2 \\ \frac{\mathrm{d}\sigma_{\overline{\nu}\mathrm{q}}}{\mathrm{d}y} &= \frac{G_\mathrm{F}^2\hat{s}}{\pi}(1-y)^2. \end{aligned}$$

Part iv) *Many neutrino experiments employ detectors made of iron which contains an equal number of neutrons and protons. By considering the $\overline{\nu}_\mu$ interactions with protons and neutrons in terms of the parton distribution functions for the* proton, *$u(x), d(x), \overline{u}(x)$ and $\overline{d}(x)$, show that*

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu N}}{\mathrm{d}y} \equiv \frac{1}{2}\left(\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{n}}}{\mathrm{d}y} + \frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{p}}}{\mathrm{d}y}\right) = \frac{G_\mathrm{F}^2}{2\pi}s\left[f_{\overline{\mathrm{q}}} + (1-y)^2 f_\mathrm{q}\right],$$

(26 October 2012)

where s is the centre-of-mass energy of the neutrino–nucleon system, and f_{q} and $f_{\overline{\mathrm{q}}}$ are the fractions of the momentum of the nucleon carried by the quarks and anti-quarks respectively.

For anti-neutrino proton scattering we have

FIX Bracket in wrong place!

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{p}}}{\mathrm{d}y} = \frac{G_{\mathrm{F}}^2}{\pi}\hat{s}(1-y)^2(u(x)\mathrm{d}x + \overline{d}(x)\mathrm{d}x)$$

Using $\hat{s} = xs$

FIX

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{p}}}{\mathrm{d}y} = \frac{G_{\mathrm{F}}^2}{\pi}s(1-y)^2(xu(x)\mathrm{d}x + x\overline{d}(x)\mathrm{d}x)$$

Similarly for anti-neutrino neutron scattering

FIX

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{n}}}{\mathrm{d}y} = \frac{G_{\mathrm{F}}^2}{\pi}s(1-y)^2(xu_n(x)\mathrm{d}x + x\overline{d}_n(x)\mathrm{d}x)$$

FIX

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{n}}}{\mathrm{d}y} = \frac{G_{\mathrm{F}}^2}{\pi}s(1-y)^2(xd(x)\mathrm{d}x + x\overline{u}(x)\mathrm{d}x)$$

Giving

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu N}}{\mathrm{d}y} \equiv \frac{1}{2}\left(\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{n}}}{\mathrm{d}y} + \frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \mathrm{p}}}{\mathrm{d}y}\right) = \frac{G_{\mathrm{F}}^2}{2\pi}s\int_0^1 x(u+d)(1-y)^2 + x(\overline{u}+\overline{d})\mathrm{d}x$$

$$= \frac{G_{\mathrm{F}}^2}{2\pi}s(f_q(1-y)^2 + f_{\overline{\mathrm{q}}})$$

Part v) *For a beam of 100 GeV $\overline{\nu}_\mu$, the total $\overline{\nu}_\mu$ charged-current deep-inelastic nucleon cross section is measured to be*

$$\sigma_{\overline{\nu}_\mu N} = \frac{1}{2}(\sigma_{\overline{\nu}_\mu \mathrm{p}} + \sigma_{\overline{\nu}_\mu \mathrm{n}}) = 3.4 \times 10^{-41}\ \mathrm{m}^2$$

and the mean value of y is measured to be 0.34. Use these results to determine f_{q} and $f_{\overline{\mathrm{q}}}$. [9]

Integrating the above expression

$$\sigma = \frac{G_{\mathrm{F}}^2}{2\pi}s\int_0^1 (f_q(1-y)^2 + f_{\overline{\mathrm{q}}})\mathrm{d}y$$

$$= \frac{G_{\mathrm{F}}^2}{2\pi}s\left(f_{\overline{\mathrm{q}}} + \frac{1}{3}f_q\right)$$

In terms of the laboratory frame neutrino energy $s = 2m_N E_\nu$ so

$$\sigma = \frac{G_{\mathrm{F}}^2}{\pi}m_N E_\nu\left(f_{\overline{\mathrm{q}}} + \frac{1}{3}f_q\right)$$

Using the values given find

$$\left(f_{\overline{\mathrm{q}}} + \frac{1}{3}f_q\right) = \frac{\pi}{0.94 \times 100 G_{\mathrm{F}}^2}\frac{3.4 \times 10^{-41}}{(0.197 \times 10^{-15})^2}$$

$$= 0.215$$

The mean value of y is given by:

$$\begin{aligned} \overline{y} &= \frac{\int y f_{\overline{\mathrm{q}}} + y(1-y)^2 f_q \mathrm{d}y}{\int f_{\overline{\mathrm{q}}} + y(1-y)^2 f_q} \\ &= \frac{\frac{1}{2} f_{\overline{\mathrm{q}}} + \frac{1}{12} f_q}{f_{\overline{\mathrm{q}}} + \frac{1}{3} f_q} \end{aligned}$$

The denominator can be obtained from $(f_{\overline{\mathrm{q}}} + \frac{1}{3} f_q) = 0.215$ obtained from the cross section:

$$\frac{1}{2} f_{\overline{\mathrm{q}}} + \frac{1}{12} f_q = 0.34 \times 0.215$$

Combining this with the expression from the cross section and solving the simultaneous equation gives $f_q = 0.41$ and $f_{\overline{\mathrm{q}}} = 0.08$.

Question 3

Write brief notes on **three** *of the following:*

(a) *Electron-proton* elastic *scattering;* [10]

(b) *The proton wave-function. You should include a discussion of the reasons for the symmetries of the different parts of the wave-function;* [10]

(c) *The differences in the methods for detecting for $\overline{\nu}_{\mathrm{e}}$ from nuclear reactors, ν_{e} from the sun, and atmospheric ν_{μ}. You should include a brief discussion of relevant energy thresholds for the different reactions;* [10]

(d) *CP violation in the Standard Model.* [10]

Answers in the form of a logically ordered bullet-pointed list are acceptable. Diagrams and simple calculations should be included where appropriate.

a) Electro-proton elastic scattering

The main points are:

- Elastic - proton remains intact
- Virtual photon interacts with proton as a whole (i.e. coherently)
- Only one independent variable - scattering angle fully determines kinematics, i.e. ($x = 1$)
- Rutherford scattering is non-relativistic recoilless limit
- Mott scattering electron relativistic, no recoil.
- Both Mott and Rutherford scattering purely electric interaction
- Charge distribution described by form factor

- Form factor is FT of charge distribution
- At relativistic energies with proton recoil Rosenbluth formula
- Both electric term and magnetic term
- Experimentally Ge and Gm show that magnetic and electric distributions are the same using anomalous magnetic moment of
- Proton has rms radius of 1 fm
- Discussion of experimental measurement at low energy
- High energy measure GM
- Due to form factor elastic scattering cross-section falls away rapidly with q^2.

b) The proton wave-function.

- Baryon wave-functions have flavour, colour, spin, and space parts
- Overall anti-symmetric (fermions)
- Space part symmetric (L=0)
- Colour confinement requires quarks be in a colour singlet state
- Colour singlet = $\frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr)$ is anti-symmetric under particle exchange
- Thus, flavour x spin is symmetric
- Spin and isospin are SU(2) symmetries
- Combine two particles in SU(2) (either spin or isospin) to symmetric triplet and anti-sym singlet
- Combination of three particles gives 4 symmetric states and two mixed symmetry states.
- Mixed sym states are either symmetric or anti-symmetric under interchange of particles 1 ¡-¿ 2, but no overall symmetry
- symmetric spin states correspond to spin=3/2 i.e. Delta etc
- spin-half wave-function is linear combination of MS(spin)xMS(flavour) and MA(spin)xMA(flavour)

c) Neutrino Detection

- Reactor/solar neutrinos ∼1 MeV (nuclear physics)
- Atmospheric neutrinos ∼1 GeV
- CC or NC interactions
- CC interactions with atomic electrons or nuclei
- High CC thresholds for reactions with atomic electrons (E¿11 GeV for numu) - extra marks for derivation
- Lower CC thresholds for interactions with nucleons - extra marks for derivation
- Solar neutrinos:

  Cerenkov radiation to detect elastic scattering of electrons

  Radiochemical experiments

  SNO uses D20 to simultaneously detect CC, ES, and NC reactions (extra marks for brief discussion)
- Reactor neutrinos:

  Reactors produce large flux of $\overline{\nu}_{\mathrm{e}}$

  detector via inverse β-reaction $\overline{\nu}_{\mathrm{e}} + \mathrm{p} \rightarrow \mathrm{e}^{+} + \mathrm{n}$

  Low energy so large background, use coincidence in time of annihilation photons and photon from neutron capture

  Mention K2K or CHOOZ
- Atmospheric neutrinos

  High energy so easier to detect muon/electron

  Cerenkov rings in Super-Kamiokande

d) CP Violation in the SM

- Universe is matter dominated - no evidence of regions of anti-matter (lack of annihilation photons at matter−anti-matter boundary)
- To obtain small excess of anti-matter require CP violation at level of $10^9 + 1$ baryons to every 10^9 anti-baryons in early universe.
- Describe parity.
- Describe charge conjugation.
- Assuming CPT, CP violation implies violation of T.
- In SM two place where CP arises: PMNS matrix and CKM matrix.
- CKM and PMNS matrices are unitary.
- For three generations can have a complex phase which gives CP violation
- Not possible for two generations.
- CP violation observed in kaon system
- Describe main features of CP violation in kaons

  CP eigenstates

  CP even decays to $\pi\pi$ and CP odd decays to $\pi\pi\pi$

  CP states roughly correspond to KS and KL

  At long distance have pure KL beam

  But KL observed to decay to $\pi\pi$ at level of 0.1 %

  explained by CP violation in mixing
- CP violation enters in box diagrams because $V_{ij} \neq V_{ij}^*$
- CP violation in SM not sufficient to explain baryon dominated universe