

# Figures

1.1	Continuous $\beta$ -decay spectrum of RaE.	2
1.2	(a) Four fermions interact for $\beta$ -decay; (b) Interaction of two electrons with a photon field (QED).	7
1.3	$\beta$ -decay spectrum for GT transitions vs. momentum $ \vec{p}_e $ .	9
1.4	$\beta^-$ -decay spectrum with $m_\nu \neq 0$ and $m_\nu = 0$ .	11
1.5	$\beta^-$ -decay process mediated through a $W^-$ boson.	13
1.6	Divergence of cross section at high energies ( $\sigma \propto s$ ).	13
1.7	Interaction of quark with $W$ boson field.	15
1.8	Two instant and one delayed photon in Reines and Cowan's experiment.	19
1.9	Weyl neutrinos.	24
1.10	Dirac neutrinos.	24
1.11	Majorana neutrinos.	25
1.12	Neutrinoless double beta decay ( $0\nu\beta\beta$ ).	25
1.13	(a) $p\bar{p}$ collisions inside the CMS detector at CERN. This event was recorded in 2012 by the compact muon solenoid (CMS) at the large hadron collider (LHC). (b) Experimental confirmation of the Higgs boson.	34
1.14	A $W^+$ -boson interacts at the point $A$ and produces $e^+$ and $\nu_e$ . The $\nu_e$ travels a long distance; it interacts with the detector $B$ and produces a lepton $e^-$ as shown in the top panel.	37
1.15	Neutrino mass hierarchy.	40
2.1	Energy spectrum of Dirac particles with energy gap $2E_0$ .	61
2.2	Mirror reflection resulting $\vec{r} \rightarrow -\vec{r}$ while $ \vec{r} $ remains invariant.	81
2.3	Time reversal $t \rightarrow -t$ .	89
3.1	$\delta$ variation-extremum path.	98
3.2	Contours for Eq. (3.144). $C^+$ is for $\Delta_F^+$ and $C^-$ is for $\Delta_F^-$ .	119

3.3 Propagation of bosons between $x_1$ and $x_2$ for (a) $t_1 > t_2$ and (b) $t_2 > t_1$ .	121
3.4 Contour for the boson propagator $\Delta_F$ .	121
3.5 Position of displaced poles in the contour integration for $\Delta_F$ .	122
3.6 Propagation of a fermion between $x_1$ and $x_2$ for (a) $t_1 > t_2$ and (b) $t_2 > t_1$ .	130
3.7 Interaction of two electromagnetic currents through photon exchange.	138
4.1 $(t_1, t_2)$ plane for integration.	147
4.2 Feynman diagrams for eight basic processes in QED. (a) $e^+e^-$ annihilation, (b) $e^+$ scattering, (c) $e^-$ scattering, and (d) $e^+e^-$ creation, accompanied by the absorption (upper row) and emission (lower row) of a photon.	151
4.3 Feynman diagrams for (a) Compton scattering for $e^-$ , (b) Compton scattering for $e^+$ , (c) pair annihilation, and (d) pair creation.	153
4.4 Feynman diagrams for (a, b) Møller scattering of $e^- - e^-$ , (c, d) Møller scattering of $e^+ - e^+$ , and (e, f) Bhabha scattering of $e^- - e^+$ .	154
4.5 Electron (left) and positron (right) self energy.	155
4.6 Photon self energy.	155
4.7 The vacuum diagram.	156
4.8 The process $e^- \rightarrow e^- + \gamma$ .	158
4.9 Compton scattering of electrons via (a) s-channel and (b) u-channel Feynman diagrams.	159
4.10 Electron self energy as an example of closed loop diagram.	160
5.1 Interaction of a charged particle with the electromagnetic field.	169
5.2 Four point Fermi interaction.	170
5.3 (a) Effect of parity transformation on the process $^{60}\text{Co} \rightarrow ^{60}\text{Ni}^* + e^- + \bar{\nu}_e$ (b) Parity transformation of a muon decaying into a positron.	179
5.4 Recoil momentum spectrum for the decay $^6\text{He} \rightarrow ^6\text{Li} e^- + \bar{\nu}_e$ together with the predictions for pure A and pure T couplings.	181
5.5 Helicity of neutrino indirectly determined in Goldhaber experiment.	184
5.6 Pion decay at rest.	185
5.7 Lepton current connects $\nu_e$ to $e^-$ and $\nu_\mu$ to $\mu^-$ .	190
5.8 Muon-decay at rest.	190
5.9 A schematic representation of muon decay in case of maximum electron energy ( $\epsilon = 1$ ).	195
5.10 Parity violation in the angular distribution.	195
5.11 The higher order corrections to the muon-decay: (a) Vertex correction, (b, c) Self energy correction and (d, e) Bremsstrahlung contributions.	199
5.12 Inverse muon decay: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ .	201
5.13 First order, second order, and higher order diagrams in $V - A$ theory for $\nu_e - e^-$ scattering.	205

5.14 $\nu_l - l^-$ scattering mediated by $W^+$ boson.	206
5.15 Feynman diagram depicting $\nu_\mu \bar{\nu}_\mu \rightarrow W^+ W^-$ via $\mu^-$ exchange.	208
5.16 $e^- e^+ (\mu^- \mu^+) \rightarrow \tau^- \tau^+$ process mediated by a photon exchange.	210
5.17 The production cross section ratio $R_{eX}^{2p} = \frac{\sigma(e^+ e^- \rightarrow eX)}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)}$ vs. the CM energy $\sqrt{s}$ for all $eX$ events with no detected photons.	211
5.18 Normalized (left) electron and (right) muon energy distributions for tau decays compared with V - A (solid line) and V+A (dashed line) spectra.	213
6.1 Feynman diagram for the pion decay at rest, $\pi^-(p) \rightarrow l^-(k) + \bar{\nu}_l(k')$ .	219
6.2 $\beta$ -decay of $A = 12$ nuclei, viz. $^{12}\text{B}$ , $^{12}\text{N}$ , and $^{12}\text{C}^*$ .	228
6.3 Coupling of the axial vector current to a particle of zero mass.	230
6.4 Top panel: (left) pion and (right) kaon decay. Bottom panel: (left) neutron and (right) lambda decay.	238
6.5 Internal Bremsstrahlung and direct emission radiative decays.	252
6.6 Radiative decays corresponding to one quark, two quark, and three quark, transitions.	253
6.7 $K^0 \rightarrow \bar{K}^0$ oscillation via two W bosons exchange.	255
6.8 Probability of neutral kaon oscillation. (a) represents the survival probability of $K^0$ , that is, $P(K^0 \rightarrow K^0)$ , while (b) represents the oscillation probability, $P(K^0 \rightarrow \bar{K}^0)$ , for a fixed $\Delta m \neq 0$ .	256
6.9 Feynman diagrams for the $K^0$ decay into $\mu^+ \mu^-$ with a (a) $u$ -quark exchange and (b) $c$ -quark exchange.	261
6.10 Quark mixing.	261
6.11 Leptonic weak decays of mesons.	266
6.12 Semileptonic weak decays of charmed mesons.	267
6.13 Semileptonic weak decays of charmed baryons.	267
6.14 Nonleptonic decays of charmed mesons.	268
6.15 W boson exchanges.	269
6.16 QCD corrections.	269
6.17 Nucleon–nucleon scattering through a W exchange.	270
6.18 Nucleon–nucleon potential in the meson exchange model. (a) Parity-conserving (PC) potential, (b) PV potential $g\pi(\rho)NN$ and $f\pi(\rho)NN$ are the parity conserving and parity violating couplings.	271
6.19 Gluon radiative diagrams.	272
6.20 Penguin diagrams.	273
7.1 (Left) In a global transformation, $\alpha$ has a fixed value; therefore, $e^{i\alpha}$ has a constant value throughout space–time. (Right) In a local transformation, $e^{i\alpha(x)}$ , where $x = x_\mu$ is a point in space–time, has a different value at each space–time point.	281
7.2 Feynman diagrams representing different terms of Eq. (7.72).	294
7.3 (a) Quark–gluon vertex, (b) triple gluon vertex, and (c) four gluon vertex.	296

7.4 Unbroken symmetry (left). Spontaneously broken symmetry (right).	297
7.5 Phase transition in ferromagnetic materials. For $T > T_c$ (left), all the spin dipoles are randomly oriented. For $T < T_c$ (right), in the ferromagnetic phase, all the spin dipoles are aligned in a parallel direction (spontaneous magnetization).	299
7.6 Paramagnetic material in the absence of external magnetic field (left); in the presence of external magnetic field (right), symmetry is lost.	299
7.7 The potential $V(\phi) = \frac{1}{2}\mu^2\phi^2(x) + \frac{1}{4}\xi\phi^4(x)$ for $\mu^2 > 0$ .	308
7.8 The potential $V(\phi) = \frac{1}{2}\mu^2\phi^2(x) + \frac{1}{4}\xi\phi^4(x)$ for $\mu^2 < 0$ .	309
7.9 Self interaction of the $\eta(x)$ field with three legs and four legs.	310
7.10 The potential $V(\phi)$ for $\mu^2 < 0$ and $\xi > 0$ .	311
7.11 Different interaction terms for $\eta_1$ and $\eta_2$ fields.	312
7.12 New interaction.	314
7.13 Interaction of massless field $\eta_2$ with $A^\mu$ .	314
8.1 $\nu_l - l^-$ neutral current scattering.	338
8.2 Electrons (point particles) getting scattered from a nucleon through electromagnetic (left) and weak (right) interactions.	342
8.3 Inelastic electron–proton scattering ( $e^- p \rightarrow e^- \Delta$ ) through the electromagnetic(left) and weak(right) interactions.	344
8.4 Deep inelastic scattering of an electron from a quark inside a nucleon through electromagnetic interaction (left) with a coupling strength $e$ and weak interaction (right) with vector and axial vector coupling strengths $g_V^e$ and $g_A^e$ , respectively.	345
8.5 $A_{pv}$ vs. $W$ studied in $\bar{e}-^2\text{H}$ scattering experiment.	347
8.6 $Z$ exchange in electron–electron (left) and electron–nucleon(right) scattering.	347
8.7 Electron–positron annihilation to give $f\bar{f}$ through electromagnetic (left) and weak (right) interactions.	350
8.8 Coupling of $W, Z$ bosons with leptons and quarks.	351
8.9 The Drell–Yan mechanism.	352
8.10 Invariant mass spectra for two $Z \rightarrow e^+e^-$ event samples, as measured by UA2.	353
8.11 Evidence for the existence of $Z$ boson at LEP-I.	353
8.12 Transverse mass distribution for $W \rightarrow \mu\nu$ (left) and $W \rightarrow e\nu$ (right) from the CDF II experiment.	354
8.13 The couplings of the Higgs boson to the vector bosons, fermions, and self coupling.	358
8.14 Higgs production mechanisms: $ggF$ , $VBF$ , $VH$ , and $t\bar{t}H$ .	359
8.15 Feynman diagrams for dominant Higgs decay processes.	359
8.16 One-loop contributions to $H \rightarrow \gamma\gamma$ . The third diagram shows a possible non-SM contribution from a charged scalar.	359
8.17 The invariant mass distribution of diphoton candidates, with each event weighted by the signal-to-background ratio in each event category, observed by ATLAS.	360

9.1 (a) Left panel: Interaction of a charged lepton with a photon field. (b) Right panel: Feynman diagram for $e^- - \mu^-$ scattering.	363
9.2 (a) Left panel: Lepton interacting with the $Z^0$ field. (b) Right panel: Feynman diagram for $e^- - \mu^-$ scattering via $Z^0$ field interaction.	364
9.3 $e^- - \mu^-$ scattering in the laboratory frame.	365
9.4 $\frac{d\sigma}{d\Omega}$ vs. $\cos \theta$ at various values of incident electron energies viz. $E_e = 20, 50, 100, 200$ and $500$ MeV evaluated in the Lab frame.	366
9.5 $e^- - \mu^-$ scattering in the center of mass (CM) frame.	367
9.6 (a) Left panel: $\nu_\mu$ interaction with a $W$ field. (b) Right panel: Charged current interaction $\nu_\mu e^- \rightarrow \mu^- \nu_e$ .	368
9.7 (a) Left panel: Neutrino interacting with the $Z^0$ field. (b) Right panel: Electron interacting with the $Z^0$ field.	370
9.8 Neutral current reaction for the process $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ .	370
9.9 (a) Left panel: Neutrinos interacting with the $W^+$ field. (b) Middle panel: Electrons interacting with the $Z^0$ field. (c) Right panel: Neutrinos interacting with the $Z^0$ field.	373
9.10 (a) Left panel: Charged current. (b) Right panel: Neutral current reactions.	374
9.11 Neutral current reaction mediated by a photon.	378
9.12 Interaction of charged leptons with photon, $Z$ and Higgs fields.	379
9.13 Feynman diagram for the $e^- e^+ \rightarrow \mu^- \mu^+$ via $\gamma$ (left), $Z^0$ , and $H^0$ (right).	380
9.14 $d\sigma/d\Omega _{CM}$ vs. $\cos \theta'$ at different values of center of mass energies, viz., $E_{CM} = 10, 20$ , and $40$ GeV for the process $e^- + e^+ \rightarrow \mu^- + \mu^+$ .	383
9.15 Comparison of the differential cross section with different propagators at $E_{CM} = 10$ GeV (upper left panel), $30$ GeV (upper right panel), $50$ GeV (lower left panel), and $90$ GeV (lower right panel) for the process $e^- + e^+ \rightarrow \mu^- + \mu^+$ .	384
10.1 Interaction of an electron with a charge distribution.	386
10.2 Feynman diagram in momentum space for electron scattering from an external source of electromagnetic field.	387
10.3 Leptonic and hadronic vertices for the $e^- - \pi^\pm$ elastic scattering.	389
10.4 Feynman diagram for $e^- - \pi^\pm$ scattering. The quantities in the bracket represent the four momenta of the particles.	390
10.5 (a) Leptonic and (b) hadronic vertices for the elastic $e^- p$ scattering.	391
10.6 Feynman diagram for $e^- p$ scattering. The quantities in the bracket represent the four momenta of the particles.	392
10.7 The brickwall frame.	394
10.8 $\frac{d\sigma}{d\Omega}$ vs. $\cos \theta$ for the elastic $e^- p$ scattering at different incoming electron energies, viz., $E_e = 250, 500, 750$ , and $1000$ MeV.	398
10.9 $\frac{d\sigma}{d\Omega} _{lep}$ vs. $\tan^2 \frac{\theta}{2}$ for a fixed $q^2$ .	399
10.10 Experimental data for the electric and magnetic form factors for the proton.	401

10.11 (a) Quasielastic and (b) Elastic $\nu$ scattering processes on nucleon ( $N = n, p$ and $N' = p, n$ ) target.	403
10.12 Kinematics in the Lab frame showing $\nu_l + n \rightarrow l^- + p$ scattering process.	407
10.13 Axial mass $M_A$ extractions from (quasi)elastic neutrino and antineutrino scattering experiments on hydrogen and deuterium targets (left) and from charged pion electroproduction experiments (right).	410
10.14 $\frac{d\sigma}{dq^2}$ vs. $-q^2$ for the $\nu_\mu + n \rightarrow \mu^- + p$ (left panel) and $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (right panel) at the different (anti)neutrino energies, viz., $E_{\nu_\mu(\bar{\nu}_\mu)} = 500$ MeV and 1 GeV and at $M_A = 1.026$ and 1.2 GeV.	413
10.15 $\sigma$ vs. $E_{\nu_l(\bar{\nu}_l)}$ for the $\nu_l + n \rightarrow l^- + p$ (left panel) and $\bar{\nu}_l + p \rightarrow l^+ + n$ (right panel) with $l = e, \mu$ at $M_A = 1.026$ and 1.2 GeV.	413
10.16 $\sigma$ vs. $E_{\nu_\mu(\bar{\nu}_\mu)}$ for the process $\nu_\mu + n \rightarrow \mu^- + p$ (left panel) and $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (right panel) for different combinations of $M_A$ , and $g_2^R(0)$ .	414
10.17 Feynman diagram for the process $\bar{\nu}_l(k) + N(p) \rightarrow l^+(k') + Y(p')$ , where $N(= p, n)$ and $Y(= \Lambda, \Sigma^0, \Sigma^-)$ represents the initial nucleon and the final hyperon, respectively.	415
10.18 $\sigma$ vs. $E_{\bar{\nu}_\mu}$ , for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ process.	418
10.19 (a) Momentum and polarization directions of the final baryon and lepton. $\hat{e}_L^{h,l}$ , $\hat{e}_P^{h,l}$ , and $\hat{e}_T^{h,l}$ represent the orthogonal unit vectors corresponding to the longitudinal, perpendicular, and transverse directions with respect to the momentum of the final hadron in (b) and the final lepton in (c).	420
10.20 $P_L^\Lambda(Q^2)$ vs. $Q^2$ (left panel) and $P_P^\Lambda(Q^2)$ vs. $Q^2$ (right panel) for the process $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ at the incoming antineutrino energy, $E_{\bar{\nu}_\mu} = 1$ GeV for the polarized $\Lambda$ in the final state, at different values of $g_2^R(0)$ .	421
10.21 $P_L^\Lambda(Q^2)$ vs. $Q^2$ (left panel), $P_P^\Lambda(Q^2)$ vs. $Q^2$ (middle panel) and $P_T^\Lambda(Q^2)$ vs. $Q^2$ (right panel) for the process $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ at the incoming antineutrino energy, $E_{\bar{\nu}_\mu} = 1$ GeV for the polarized $\Lambda$ in the final state, at different values of $g_2^I(0)$ .	422
11.1 Generic Feynman diagrams representing the charged and neutral current induced inelastic processes given in Table 11.1.	426
11.2 Generic Feynman diagrams representing the non-resonant background terms contributing to the inelastic processes.	426
11.3 Feynman diagram for the charged current induced spin 1/2 and 3/2 resonance production (left panel) and for the decay of the resonance into a nucleon and a pion (right panel).	431
11.4 Diagrammatic representation of the helicity amplitudes, $A_{1/2}$ (top) and $S_{1/2}$ (bottom) for spin 1/2 and 3/2 resonances.	435
11.5 Feynman diagram of the process $R_{\frac{1}{2}, \frac{3}{2}} \rightarrow N l^- \bar{\nu}_l$ through pion decay.	438
11.6 $Q^2$ dependence of different form factors of $S_{11}(1650)$ resonance.	440
11.7 $Q^2$ dependence of different form factors of $P_{11}(1440)$ resonance.	440
11.8 Feynman diagram for the decay of a spin 1/2 resonance to a nucleon and a pion.	445

11.9 Feynman diagram for the charged current (left) and neutral current (right) induced spin 3/2 resonance production.	447
11.10 Diagrammatic representation of the helicity amplitude, $A_{3/2}$ for spin 3/2 resonances.	448
11.11 $Q^2$ dependence of different form factors of $D_{13}$ resonance. From left to right panel: $C_3^V$ , $C_4^V$ , and $C_5^V$ as mentioned in Eq. (11.82); $C_5^A$ as mentioned in Eq. (11.97); and $C_i^{n,p}$ , $i = 3, 4, 5$ as mentioned in Eqs. (11.84)–(11.86).	452
11.12 $Q^2$ dependence of different form factors of $P_{13}$ resonance. From left to right panel: $C_3^V$ , $C_4^V$ , and $C_5^V$ as mentioned in Eq. (11.82); $C_5^A$ as mentioned in Eq. (11.97); and $C_i^{n,p}$ , $i = 3, 4, 5$ as mentioned in Eqs. (11.84)–(11.86).	452
11.13 Feynman diagram for the decay of a spin 3/2 resonance in a nucleon and a pion.	455
11.14 Generic Feynman diagrams for the $s$ , $t$ , and $u$ channel Born terms.	464
11.15 Effect of explicit symmetry breaking.	470
11.16 Figure depicting the infinitely steep potential in the $\sigma$ direction.	470
12.1 Feynman diagrams contributing for the process $W^i N \rightarrow N' \pi^{\pm,0}$ , where ( $W^i \equiv W^\pm$ ; $i = \pm$ ) for the charged current processes and ( $W^i \equiv Z^0$ ; $i = 0$ ) for the neutral current processes with $N, N' = p$ or $n$ .	481
12.2 Total scattering cross section for the processes $\nu_\mu p \rightarrow \mu^- p \pi^+$ (left panel) and $\nu_\mu n \rightarrow \mu^- p \pi^0$ (right panel).	489
12.3 Total scattering cross section for neutral current neutrino induced pion production processes with deuteron effect and with no cut on $W$ .	490
12.4 Feynman diagrams for the processes $\nu/\bar{\nu}(k) + N(p) \rightarrow \mu^\mp(k') + \eta(p_\eta) + N'(p')$ .	491
12.5 Total scattering cross section for the charged current $\eta$ meson production for the processes $\nu_\mu + n \rightarrow \mu^- + \eta + p$ and $\bar{\nu}_\mu + p \rightarrow \mu^+ + \eta + n$ .	493
12.6 Feynman diagrams corresponding to the (anti)neutrino induced $\Delta S = 0$ associated particle production processes.	495
12.7 Cross section for neutrino (left) and antineutrino (right) induced $ \Delta S  = 0$ associated kaon production processes.	498
12.8 Feynman diagrams for the process $\nu N \rightarrow l N' K$ . The first row from left to right: contact term (labeled CT in the text), kaon pole term (KP); second row: $u$ channel diagram ( $C\Sigma$ , $C\Lambda$ ) and pion (eta) in flight ( $\pi P$ , $\eta P$ ).	499
12.9 Contribution of the different terms to the total scattering cross section for the $\nu_\mu + p \rightarrow \mu^- + K^+ + p$ (left panel) and $\nu_\mu + n \rightarrow \mu^- + K^0 + p$ (right panel) processes.	501
12.10 Feynman diagrams for the process $\bar{\nu} N \rightarrow l N' \bar{K}$ . The first row from left to right: $s$ channel $\Sigma$ , $\Lambda$ propagator (labeled SC in the text), $s$ channel $\Sigma^*$ resonance (SCR); second row: kaon pole term (KP); contact term (CT) and last row: pion (Eta) in flight ( $\pi P/\eta P$ ).	502
12.11 Total scattering cross section for the processes $\bar{\nu}_\mu p \rightarrow \mu^+ p K^-$ and $\bar{\nu}_\mu n \rightarrow \mu^+ n K^-$ .	505
13.1 $e^- -^{12}\text{C}$ scattering cross section (a) Left: $\theta = 80^\circ$ , $Q^2 \rightarrow 0.06 \text{ GeV}^2$ . The elastic peak is evident at low energy transfer; the excitation of nuclear levels can be seen with increase in energy transfer. (b) Right: $\theta = 135^\circ$ , $Q^2 \sim 0.1 \text{ GeV}^2$ .	508

13.2	$e^- - {}^4\text{He}$ scattering cross section for the beam energy $E_e = 400$ MeV (a) Left: $\theta = 45^\circ$ , $Q^2 \rightarrow 0.08$ GeV <sup>2</sup> , (b) Right: $\theta = 60^\circ$ , $Q^2 \rightarrow 0.1$ GeV <sup>2</sup> .	509
13.3	Electron–proton double differential scattering cross sections at $E_e = 4.879$ MeV; lab scattering angle $\theta = 10^\circ$ .	510
13.4	(a) Left: electron–muon scattering (b) Center: electron–proton elastic scattering, and (c) Right: electron–proton deep inelastic scattering.	511
13.5	Charged lepton–nucleon inclusive scattering process.	512
13.6	Left: A virtual photon interacting with a hadron; Right: A virtual photon interacting with a point Dirac particle inside a hadron.	515
13.7	$\nu W_{2p}^{\text{EM}}(\nu, Q^2)$ vs. $Q^2$ at a fixed $x = \frac{1}{\omega}$ . Experimental data are from SLAC.	516
13.8	A rapidly moving hadron.	517
13.9	Figure on the left depicts the incoherent sum of the contributions and figure on the right represents momentum shared by the charged partons.	517
13.10	Parton density distribution functions using MMHT PDFs parameterization at leading order for $2 \text{ GeV}^2 \leq Q^2 \leq 10 \text{ GeV}^2$ .	520
13.11	Experimental measurements for $\frac{F_2^{en}(x)}{F_2^{ep}(x)}$ vs. $x$ for proton and neutron targets in the case of electromagnetic interaction.	521
13.12	Experimental measurements for $F_2^{ep}(x) - F_2^{en}(x)$ vs. $x$ for proton and neutron targets in the case of electromagnetic interaction.	521
13.13	Left panel: Experimental verification of the Callan–Gross relation for the spin 1/2 nature of quarks. Right panel: Experimental results for the ratio of $R_L^{\text{EM}}(x, Q^2) = \frac{F_L^{\text{EM}}(x, Q^2)}{2xF_1^{\text{EM}}(x, Q^2)}$ .	524
13.14	Head on collision of a quark with a virtual photon. $\lambda$ and $\lambda'$ denote the initial and final helicity states.	525
13.15	Variation of kinematic variables such as $x$ , $y$ , and $W$ is shown in the $Q^2 - \nu$ plane.	526
13.16	(a) Feynman diagram for the (anti)neutrino induced deep inelastic scattering process, (b) Summation over the final hadronic state $X$ and its amplitude square corresponds to the scattering cross section.	527
13.17	Feynman representation for leptonic and hadronic vertices (left and right columns) in the case of weak interaction. Feynman diagram showing the $\nu - N$ scattering for the summed over hadronic states $X$ .	528
13.18	Feynman diagram for $W^\pm$ interactions with quarks and antiquarks.	531
13.19	Experimental observations for the $(\frac{5}{18})$ th rule.	534
13.20	Charged current total cross section for $\nu_l - N$ and $\bar{\nu}_l - N$ processes.	535
13.21	Feynman diagram for the neutral current $\nu_l(\bar{\nu}_l) - N$ DIS process.	536
13.22	Charged and neutral current (anti)neutrino differential cross sections by CHARM collaboration.	537
13.23	Experimental results of nucleon structure functions for (i) Top panel: electromagnetic interaction induced DIS process, (ii) Bottom panel: weak interaction induced DIS process.	540



- 13.24 Diagrammatic representation of (i) upper panel: the process  $\gamma^* q \rightarrow qg$  and (ii) lower panel: the process  $\gamma^* g \rightarrow q\bar{q}$ . 541
- 13.25 Diagrammatic representation of splitting functions. 542
- 13.26 Evolution of parton density distribution functions using MMHT PDFs parameterization from leading order to next-to-next-leading order at  $Q^2 = 2 \text{ GeV}^2$ . 543
- 13.27 Nachtmann variable  $\xi$  and slow rescaling variable  $\bar{\xi}$  vs.  $x$  are shown at different values of  $Q^2$ . 545
- 13.28 Ratio of target mass corrected weak structure functions to the structure functions without TMC by using MMHT PDFs parameterization at NLO for  $Q^2 = 2 \text{ GeV}^2$ . 546
- 13.29 Twist-4 coefficient in the renormalon approach for  $F_1^{\text{EM}}(x, Q^2)$  and  $F_2^{\text{EM}}(x, Q^2)$  obtained by using MMHT PDFs parameterization at NLO for  $Q^2 = 2 \text{ GeV}^2$  and  $10 \text{ GeV}^2$ . 547
- 13.30 Experimental observations for the Adler sum rule. 550
- 13.31 Allowed kinematical region for  $\nu_l - N$  scattering in the  $Q^2 - \nu$  plane for  $E_\nu=3 \text{ GeV}$ (left panel) and  $E_\nu=7 \text{ GeV}$  (right panel) for  $Q^2 \geq 0$ . 552
- 13.32  $F_2^p$  structure function data on protons from SLAC and Jefferson Lab in the resonance region for  $0.06 < Q^2 < 3.30 \text{ GeV}^2$ . The solid curve is a fit to deep inelastic data at  $5 \text{ GeV}^2$ . 553
- 13.33  $W^2$  distribution of  $\nu_\mu$ -water target interactions in GENIE showing the quasi-elastic scattering, the resonance interactions, and the DIS region. The  $W$  distribution is further split into the three regions, KNO scaling-based model only region, PYTHIA only region, and the transition between the two regions used in the AGKY model. 554
- 13.34 Diagrammatic representation of resonance excitations for  $l + N \rightarrow l + R$ . 555
- 13.35 Top left panel: Duality for the isoscalar nucleon  $F_2^{eN}$  structure function.  $F_2^{eN}$  vs.  $\xi$ , for  $Q^2 = 0.2, 0.5, 1$  and  $2 \text{ GeV}^2$ , compared with several leading twist parameterizations at  $Q^2 = 10 \text{ GeV}^2$ . Top right panel: Ratio  $I_2^{eN}$  of the integrated  $F_2^{eN}$  in the resonance region to the leading twist functions (valence and total). Bottom left panel: Duality for the isoscalar nucleon  $2xF_1^{eN}$  structure function vs.  $\xi$ . The results are compared with the MRST parameterization at  $Q^2 = 10 \text{ GeV}^2$ , using  $F_L$  and  $F_2$  (dotted) and the Callan–Gross (CG) relation,  $F_2 = 2xF_1$  (dot-dashed). Bottom right panel: Ratio  $I_1^{eN}$  of the integrated  $2xF_1^{eN}$  in the resonance region to the leading twist function. 557
- 13.36 Figure from (upper) Comparison of the Rein–Sehgal  $F_2$  structure functions vs.  $\xi$  for neutron, proton, and the isoscalar nucleon target at  $Q^2 = 0.4, 1$  and  $2 \text{ GeV}^2$  (left to right in each figure) with the appropriate DIS scaling functions at  $Q^2 = 10 \text{ GeV}^2$ . 559
- 13.37 Duality for the neutrino–nucleon  $F_2^{\nu N}$ ,  $2xF_1^{\nu N}$  and  $xF_3^{\nu N}$  structure functions in the resonance region at several  $Q^2$  values, indicated against their spectra. (Left)  $F_2^{\nu N}$  vs.  $\xi$ . The results are compared with leading twist parameterizations (valence and total) at  $Q^2 = 10 \text{ GeV}^2$ . (Center)  $2xF_1^{\nu N}$  vs.  $\xi$ . The results are compared with the exact expression in Eq. (11.46) (dotted) and Callan–Gross relation (dot-dashed). (Right)  $xF_3^{\nu N}$  vs.  $\xi$ . The results are compared with several leading twist parameterizations. 559

14.1	Charged current induced total scattering cross section per nucleon per unit energy of the incoming particles vs. neutrino (left panel) and antineutrino (right panel) energy.	563
14.2	Diagrammatic representation of Pauli blocking.	567
14.3	Neutrino–nucleus scattering in the impulse approximation.	569
14.4	Neutrino–nucleus scattering with (a) final state interactions (b) exchange currents due to mesons and (c) exchange currents due to $\Delta$ .	570
14.5	Nucleons in a square well potential states.	580
14.6	Fermi momentum $p_F(r)$ versus $r$ for various nuclei.	584
14.7	Diagrammatic representation of the particle–hole ( $p - h$ ) excitation induced by $W(Z)$ boson in the large mass limit of IVB ( $M_{W(Z)} \rightarrow \infty$ ).	585
14.8	RPA effects in the $1p - 1h$ contribution to the $W/Z$ self-energy, where particle–hole, $\Delta$ –hole, $\Delta$ – $\Delta$ , etc. excitations contribute.	590
14.9	Ratio $\frac{\sigma_A/N}{\sigma_{\text{free}}}$ vs. $E_\nu$ , for neutrino (left panel) and antineutrino (right panel) induced processes in $^{12}\text{C}$ , $^{40}\text{Ar}$ , $^{56}\text{Fe}$ , and $^{208}\text{Pb}$ .	596
14.10	$\frac{d\sigma}{dp_\mu}$ vs. $p_\mu$ for the $\nu_\mu(\bar{\nu}_\mu)$ induced reactions on $^{12}\text{C}$ target at $E_\nu = 1 \text{ GeV}$ .	597
14.11	The fractional suppression in cross section $\delta\sigma_{\text{model}} (= \frac{\sigma_{\text{free}} - \sigma_{\text{model}}}{\sigma_{\text{free}}})$ vs. $E_\nu$ , where $\sigma_{\text{free}}$ is the cross section obtained for free nucleons and $\sigma_{\text{model}}$ is the interacting nucleon cross section in $^{40}\text{Ar}$ obtained by using different nuclear models.	597
14.12	$\Delta_I = \frac{\sigma_{\nu_e(\bar{\nu}_e)} - \sigma_{\nu_\mu(\bar{\nu}_\mu)}}{\sigma_{\nu_e(\bar{\nu}_e)}}$ for neutrino (left panel) and antineutrino (right panel) induced processes in $^{12}\text{C}$ and $^{40}\text{Ar}$ targets. Here, $I$ stands for the results of the cross sections obtained (i) for the free nucleon case (solid line), (ii) in the local Fermi gas model (dashed line) and (iii) for LFG with RPA effect (dashed dotted line).	598
14.13	Diagrams showing some typical $2p - 2h$ contributions arising due to the $N - N$ and $N - \Delta$ correlations. Solid (dashed) lines denote nucleon (pion) propagators. Double lines represent $\Delta(1232)$ propagators. Arrows pointing to the right (left) denote particle (hole) states.	599
14.14	Diagrams showing some typical $2p - 2h$ contributions arising due to the meson exchange. Solid (dashed) lines denote nucleon (pion) propagators. Arrows pointing to the right (left) denote particle (hole) states.	600
14.15	“Quasielastic-like” $\nu_\mu$ – $^{12}\text{C}$ cross sections measured by MiniBooNE compared to Martini et al. calculations.	601
14.16	MiniBooNE flux-integrated differential cross sections $d\sigma/dQ^2$ vs. $Q^2$ in units of $10^{-39} \text{ cm}^2/\text{GeV}^2$ for neutrino (upper panels) and antineutrino (lower panels) CCQE-like scattering on carbon.	601
15.1	In a neutrino induced reaction on a nucleon target, when a pion is produced in the nuclear medium and comes out without FSI (final state interaction).	608
15.2	Feynman diagram considered for coherent pion production through $\Delta - h$ excitation.	616
15.3	Feynman diagrams considered for neutrino induced weak coherent pion production for $\Delta$ -resonance.	618

15.4 Pion production inside a nuclear target and its interaction with the nucleons in the nucleus while coming out.	621
15.5 A neutrino induced reaction on a nucleon target when a pion is absorbed in the nuclear medium while coming out.	621
15.6 Definition of impact parameter in scattering processes at high energies.	622
15.7 $\frac{d\sigma}{dQ^2}$ and $\frac{d\sigma}{dp_\pi}$ for the $\nu_\mu(\bar{\nu}_\mu)$ induced charged current one $\pi^+(\pi^-)$ process on $^{12}\text{C}$ target at $E_\nu = 1 \text{ GeV}$ .	624
15.8 $\sigma$ for $\nu_\mu(\bar{\nu}_\mu)$ induced charged current incoherent $\pi^+(\pi^-)$ production on $^{12}\text{C}$ target.	625
15.9 Comparison of theoretical and event generator calculations for the differential cross sections in pion kinetic energy with the MiniBooNE $\nu_\mu \text{ CH}_2 \text{ CC } 1\pi^+$ production data.	625
15.10 $\sigma(E_\nu)$ vs. $E_\nu$ for coherent $\pi^+$ production in $^{12}\text{C}$	626
15.11 (a) $\frac{d\sigma}{dq^2}$ vs. $-q^2$ at $E_\nu=1 \text{ GeV}$ , for coherent $\pi^+$ production in $^{12}\text{C}$ nucleus without (dotted), with(dashed) nuclear medium effects and with nuclear medium and pion absorption effects (solid). (b) $\frac{d\sigma}{dk_\pi}$ vs. $k_\pi$ at $E_\nu=1 \text{ GeV}$ .	627
15.12 $\sigma(E_{\bar{\nu}_\mu})$ vs. $E_{\bar{\nu}_\mu}$ for $\pi^-$ & $\pi^0$ production in $^{12}\text{C}$ , in the $\Delta$ dominance model and via intermediate hyperons.	629
15.13 Feynman diagrams for NC photon emission. The first two diagrams are direct and crossed baryon pole terms with nucleons and resonances in the intermediate state ( $N, \Delta(1232), N^*(1440), N^*(1520)$ , etc.) The third diagram represents t channel meson ( $\pi, \rho, \omega$ ) exchange contributions.	630
16.1 The deep inelastic charged lepton (a) and (anti)neutrino (b) scattering processes with bound nucleons for the electromagnetic and weak interactions, respectively.	632
16.2 Ratio $R(x, Q^2) = \frac{F_{2A}(x, Q^2)}{F_{2D}(x, Q^2)}$ ; ( $A = \text{target nucleus}$ ) vs. $x$ shows the nuclear medium effects in structure function.	633
16.3 $\sigma_L$ and $\sigma_T$ separation using Rosenbluth technique.	637
16.4 The $A$ -dependence of the nCTEQ bound proton PDFs at the scale $Q = 10 \text{ GeV}$ for a range of nuclei from the free proton ( $A = 1$ ) to lead ( $A = 208$ ).	642
16.5 Nuclear correction factor $R$ for the structure function $F_2$ in neutrino and antineutrino scattering from Fe for $Q^2 = 5$ and $20 \text{ GeV}^2$ .	643
16.6 DIS cross section ratios as a function of $x$ for MINERvA data points and various parameterizations of $x$ -dependent nuclear effects.	644
16.7 Differential scattering cross section $\frac{1}{E_\nu} \frac{d^2\sigma}{dx dy}$ vs. $y$ , at different $x$ for $\nu_\mu - ^{56}\text{Fe}$ DIS process at $E_\nu = 65 \text{ GeV}$ .	644
16.8 Representation of neutrino self-energy.	647
16.9 (a) Free field fermion propagator. (b) The term that contributes to the neutrino self-energy in the lowest order.	648
16.10 Diagrammatic representation of the neutrino self-energy.	649
16.11 Diagrammatic representation of intermediate vector boson $W$ self-energy.	650

16.12	Diagrammatic representation of nucleon self-energy in the nuclear medium.	651
16.13	Results for $S_h(\omega, \vec{p})$ vs. $\omega$ are shown for (a) $p < p_F$ and (b) $p > p_F$ in various nuclei like $^{12}\text{C}$ , $^{40}\text{Ca}$ , $^{56}\text{Fe}$ , $^{120}\text{Sn}$ , and $^{208}\text{Pb}$ .	655
16.14	Neutrino self-energy diagram accounting for neutrino–meson DIS (a) the bound nucleon propagator is substituted with a meson ( $\pi$ or $\rho$ ) propagator (b) by including particle–hole ( $1p\text{--}1h$ ), delta–hole ( $1\Delta\text{--}1h$ ), $1p1h - 1\Delta1h$ , etc. interactions.	657
16.15	$R(x, Q^2) = \frac{F_{iA}^{\text{WI}}(x, Q^2)}{F_{iN}^{\text{WI}}(x, Q^2)}$ ; ( $i = 2, 3$ ) vs. $Q^2$ in $^{56}\text{Fe}$ and $^{208}\text{Pb}$ using the full model.	663
16.16	Results are shown for the weak nuclear structure function $F_{2A}^{\text{WI}}(x, Q^2)$ vs. $x$ at $Q^2 = 2, 5 \text{ GeV}^2$ , in $^{12}\text{C}$ , $^{56}\text{Fe}$ and $^{208}\text{Pb}$ .	664
16.17	$F_{2A}^{\text{WI}}(x, Q^2)$ vs. $Q^2$ in $^{56}\text{Fe}$ using the full model.	665
16.18	$F_{2A}^{\text{WI}}(x, Q^2)$ vs. $Q^2$ in $^{208}\text{Pb}$ using the full model.	666
16.19	Results for the ratio $R'(x, Q^2) = \frac{5}{18} \frac{F_{iA}^{\text{WI}}(x, Q^2)}{F_{iA}^{\text{EM}}(x, Q^2)}$ ; ( $i = 1, 2$ ) are obtained by using the full model at NLO in $A = ^{12}\text{C}$ , $^{56}\text{Fe}$ and $^{208}\text{Pb}$ at $Q^2 = 5$ and $20 \text{ GeV}^2$ .	667
16.20	$\frac{1}{E_\nu} \frac{d^2\sigma_A^{\text{WI}}}{dx dy}$ vs. $y$ are shown at different values of $x$ for the incoming beam of energy $E = 35 \text{ GeV}$ .	668
17.1	Different sources of neutrinos.	669
17.2	Neutrino flux as a function of neutrino energy.	670
17.3	Proton–proton chain.	671
17.4	Carbon–nitrogen–oxygen cycle.	672
17.5	Solar neutrino spectrum in the SSM.	673
17.6	Primary cosmic ray flux for the proton (top line with experimental points) and alpha particles (bottom line with experimental points).	677
17.7	Rigidity cut off.	678
17.8	Primary cosmic ray flux for the proton showing knee, ankle, and GZK region.	679
17.9	Schematic diagram of the production of atmospheric neutrinos.	680
17.10	Fractional contribution of pions and kaons to the flux of muons and neutrinos.	680
17.11	$\mu^+$ (solid line) and $\mu^-$ (dashed line) fluxes as a function of the muon momentum at the INO, Super-K and South Pole by integrating over all the zenith and azimuthal bins for the two different heights from the sea level, as well as at the sea level.	681
17.12	All-direction averaged atmospheric neutrino flux for four sites averaging over one year. KAM stands for the SK site, INO for the INO site, SPL for the South Pole, and PYH for the Pyhäsalmi mine.	682
17.13	Typical antineutrino spectra.	685
17.14	Supernova (a) neutrino and (b) antineutrino fluxes.	690
17.15	$\bar{\nu}_e$ energy distributions for (1) $^{238}\text{U}$ (solid), (2) $^{232}\text{Th}$ (dotted), and (3) $^{40}\text{K}$ (dash-dotted) decay.	693
17.16	Typical sketch of neutrino beam production by accelerators.	695

17.17 Flux of neutrinos from the older generation accelerators.	697
17.18 Set up for the narrow band beam (top) and wide band beam (bottom).	698
17.19 MiniBooNE spectra for neutrino ( $\nu_\mu$ ) (left) and antineutrino ( $\bar{\nu}_\mu$ ) (right).	698
17.20 MINERvA spectra for low energy neutrino ( $\nu_\mu$ ) (left) and antineutrino ( $\bar{\nu}_\mu$ ) (right).	698
17.21 Neutrino spectrum for on-axis and different off-axis angles obtained by the T2K experiment.	700
17.22 Neutrino spectrum obtained from the various sources when at rest: $\pi$ and $\mu$ DAR (left), KDAR (center) and IsoDAR (right).	702
17.23 Schematic diagram of a muon storage ring.	704
17.24 Neutrino (solid line) energy spectrum obtained with $^{18}\text{Ne}$ boosted at $\gamma = 250$ and antineutrino (dashed line) energy spectrum obtained with $^6\text{He}$ boosted at $\gamma = 150$ .	705
17.25 Tests of fundamental physics accessible with neutrinos of different energies.	706
18.1 The top figure represents a no oscillation case where at “A”, $\nu_\alpha$ s are produced along with $l_\alpha^+$ and travel a short distance, and at “B”, the same number of $l_\alpha^-$ are detected through charged current interactions ( $\nu_\alpha, l_\alpha^-$ ). The bottom figure represents an oscillation case, where at “A”, $\nu_\alpha$ s are produced along with $l_\alpha^+$ and travel some distance, and at “B”, some of the charged leptons of flavor $l_\beta^-$ are observed which is only possible when on the way, a few $\nu_\alpha$ get converted into $\nu_\beta$ .	712
18.2 Oscillation probability vs. $\frac{\Delta m^2}{4} \frac{L}{E}$ curve for $\sin^2 2\theta = 0.83$ . (a) shows no oscillation scenario in the region $\frac{1}{\Delta m^2} >> \frac{L}{E}$ ; (b) shows the threshold condition for oscillation at $\frac{1}{\Delta m^2} \sim \frac{L}{E}$ and (c) shows the oscillation scenario in the region $\frac{1}{\Delta m^2} << \frac{L}{E}$ .	715
18.3 Transition probability curve for two-flavor neutrino oscillations for different values of $L$ .	717
18.4 Transition probability curve for two-flavor neutrino oscillations for different values of $\Delta m^2$ .	717
18.5 $L^{\text{osc}}$ curves obtained using Eq. (18.30) at $E_\nu=1$ GeV and 3 GeV, for $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$ and $\sin^2(2\theta)=1$ .	718
18.6 Appearance probability curve in three-flavor neutrino oscillations for different values of $\delta_{cp}$ .	728
18.7 Appearance probability curve in three-flavor antineutrino oscillations for different values of $\delta_{CP}$ .	728
18.8 A three-neutrino (mass) <sup>2</sup> spectrum in which the $\nu_2 - \nu_1$ splitting $\Delta m^2$ is much smaller than the splitting $\Delta m_{\text{big}}^2$ between $\nu_3$ and the $\nu_2 - \nu_1$ pair. The later pair may be at either the bottom or the top of the spectrum.	729
18.9 Matter density variation inside the sun.	732
18.10 Matter density variation inside the earth.	733
18.11 (a) Charged current interaction (left). (b) Neutral current interaction (right).	734
18.12 Oscillation probability for $\nu$ and $\bar{\nu}$ in matter and vacuum as illustration of matter effect. Normal and inverted hierarchy, using NOvA experiment parameters, $L = 810$ km, $E = 1\text{--}6\text{GeV}$ , $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$ , $\theta = 8.9^\circ$ .	740

18.13 Pictorial representation of normal neutrino mass ordering and mixing for the three (left) and four (right) neutrino picture.	746
19.1 Origin of the elements through different processes.	749
19.2 Formation of the elements in the universe through the Big Bang nucleosynthesis, stellar nucleosynthesis, and the supernova nucleosynthesis by the s- and r-processes.	750
19.3 Neutrino driven wind.	751
19.4 Timeline of the Big Bang.	753
19.5 Interstellar cloud and the shock wave hitting the cloud.	757
19.6 (a) Accumulation of the matter of the interstellar cloud in a region. (b) Hydrostatic equilibrium.	758
19.7 The Hertzsprung–Russell diagram: This classifies stars according to their luminosity, spectral class, surface temperature and evolutionary stage.	759
19.8 The future of sun (a red giant).	761
19.9 Different layers of a red supergiant.	762
19.10 Planetary nebula and the white dwarf.	763
19.11 Onion like layers in the core of a massive star ( $M_{\text{star}} = 25M_{\odot}$ ). The table shows the duration of fusion taking place during the fusion of various elements.	765
19.12 Photodisintegration of iron nucleus.	766
19.13 Type Ia supernova explosion.	768
19.14 Slow neutron capture process.	769
19.15 Rapid neutron capture process.	770
19.16 Two merging neutron stars.	772
20.1 (a) $(A, Z) \rightarrow (A, Z + 2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$ and (b) $(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$	777
20.2 $nn \rightarrow pp + e^- + e^-$	777
20.3 Flavor changing neutral current processes in higher order loop diagrams in SM.	790
20.4 Flavor changing neutral current processes in some models beyond the standard model (BSM) physics.	790
A.1 Lorentz transformation.	795
B.1 Baryon octet	809
B.2 Pseudoscalar ( $J^P = 0^-$ ) and vector ( $J^P = 1^-$ ) meson nonet.	810