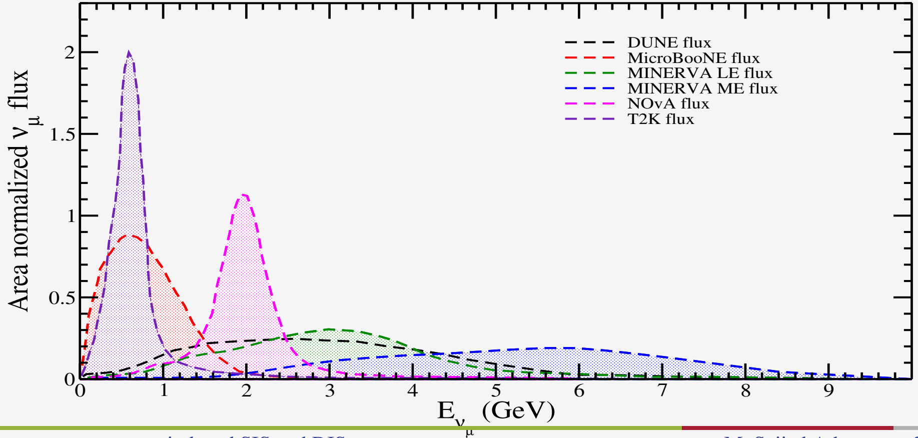
# Interaction of neutrinos with nucleon/nuclear targets in the shallow and deep inelastic scattering regions

**M. Sajjad Athar**
Aligarh Muslim University, Aligarh
September 6, 2023

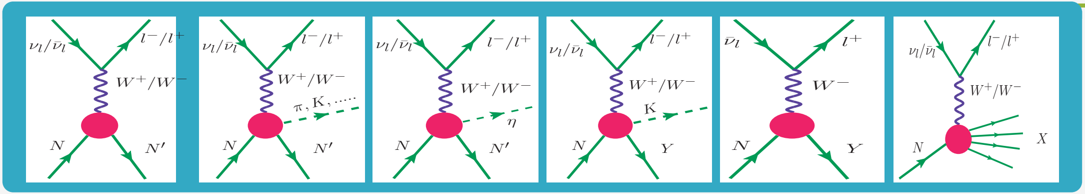
# Outline

# Neutrinos from the accelerators

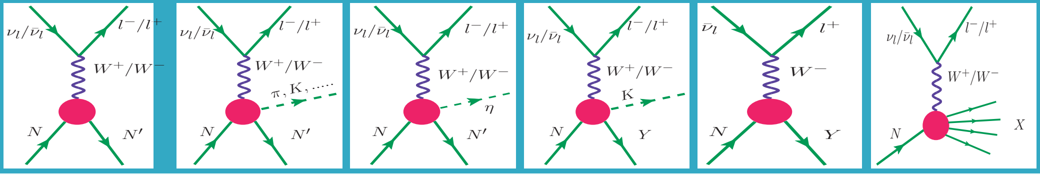
The ongoing accelerator experiments like NOvA, MINERvA and T2K, and the upcoming DUNE experiment have (anti)neutrino peak energy in the few GeV energy region.

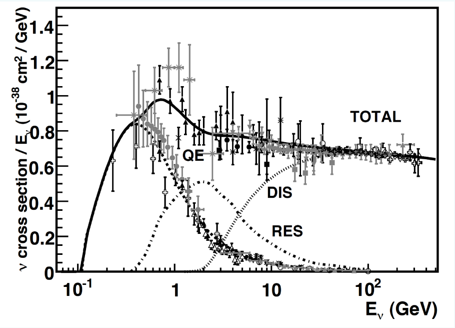


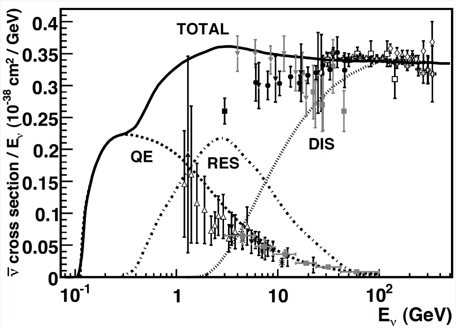
# Various neutrino interaction processes



# Various neutrino interaction processes



# Importance of the understanding of neutrino cross section

## Neutrino-nucleon cross sections are important

# Importance of the understanding of neutrino cross section

## Neutrino-nucleon cross sections are important

- Weak form factors: especially in the axial vector sector
  - Axial vector form factor
  - Psuedoscalar form factor
  - Weak electric form factor

# Importance of the understanding of neutrino cross section

## Neutrino-nucleon cross sections are important

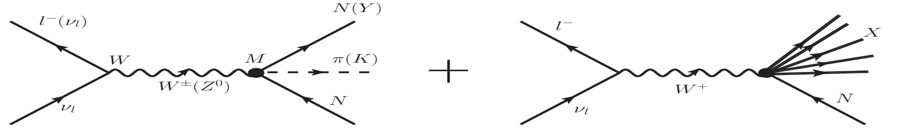
- Weak form factors: especially in the axial vector sector
  - Axial vector form factor
  - Psuedoscalar form factor
  - Weak electric form factor
- Information about symmetry properties like
  - T invariance
  - G invariance; second class currents
  - PCAC, etc.

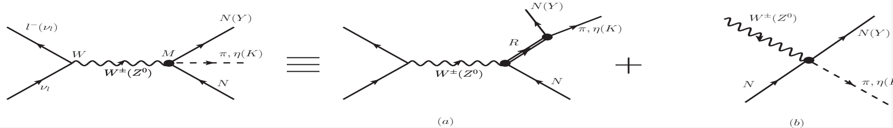
# Importance of the understanding of neutrino cross section

## Neutrino-nucleon cross sections are important

- Weak form factors: especially in the axial vector sector
    - Axial vector form factor
    - Psuedoscalar form factor
    - Weak electric form factor
- Information about symmetry properties like
    - T invariance
    - G invariance; second class currents
    - PCAC, etc.
- Weak structure functions: especially $F_{4,5}$
    - Valence and sea quark distribution inside the nucleon

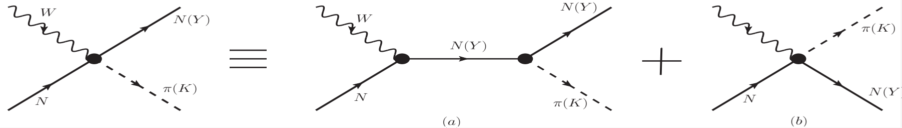
# Generic Feynman diagrams: Meson production




Resonance excitation

Non-resonant(Born) terms




Born terms

Pole diagrams

Contact term

# Nucleon and Delta resonances: PDG

## First resonance region

| Resonances $R_{IJ}$ | $\pi N$ branching ratio (%) | $\eta N$ branching ratio (%) | $\pi\pi N$ branching ratio (%) | $K\Lambda$ branching ratio (%) | $K\Sigma$ branching ratio (%) |
|---|---|---|---|---|---|
| $P_{33}(1232)$ | 100 | – | – | – | – |
| $P_{11}(1440)$ | 55 – 75 | < 1 | 17 – 50 | – | – |
| $D_{13}(1520)$ | 55 – 65 | 0.07 – 0.09 | 25 – 35 | – | – |
| $S_{11}(1535)$ | 32 – 52 | 30 – 55 | 3 – 14 | – | – |
| $S_{31}(1620)$ | 25 – 35 | – | 55 – 80 | – | – |
| $S_{11}(1650)$ | 50 – 70 | 15 – 35 | 8 – 36 | 5 – 15 | – |
| $D_{15}(1675)$ | 38 – 42 | < 1 | 25 – 45 | – | – |
| $F_{15}(1680)$ | 60 – 70 | < 1 | 20 – 40 | – | – |
| $D_{33}(1700)$ | 10 – 20 | – | 10 – 55 | – | – |
| $D_{13}(1700)$ | – | 60 – 90 | – | – | |
| $P_{11}(1710)$ | 5 – 20 | 10 – 50 | – | 5 – 25 | – |
| $P_{13}(1720)$ | 8 – 14 | 1 – 5 | 50 – 90 | 4 – 5 | – |
| $S_{11}(1895)$ | 2 – 18 | 15 – 40 | – | 13 – 23 | 6 – 20 |
| $P_{13}(1900)$ | 1 – 20 | 2 – 14 | 40 – 80 | 2 – 20 | 3 – 7 |
| $F_{35}(1905)$ | 9 – 15 | – | – | – | – |

# Nucleon and Delta resonances: PDG

## Second resonance region

| Resonances $R_{IJ}$ | $\pi N$ branching ratio (%) | $\eta N$ branching ratio (%) | $\pi\pi N$ branching ratio (%) | $K\Lambda$ branching ratio (%) | $K\Sigma$ branching ratio (%) |
|---|---|---|---|---|---|
| $P_{33}(1232)$ | 100 | – | – | – | – |
| $P_{11}(1440)$ | 55 – 75 | $< 1$ | 17 – 50 | – | – |
| $D_{13}(1520)$ | 55 – 65 | 0.07 – 0.09 | 25 – 35 | – | – |
| $S_{11}(1535)$ | 32 – 52 | 30 – 55 | 3 – 14 | – | – |
| $S_{31}(1620)$ | 25 – 35 | – | 55 – 80 | – | – |
| $S_{11}(1650)$ | 50 – 70 | 15 – 35 | 8 – 36 | 5 – 15 | – |
| $D_{15}(1675)$ | 38 – 42 | $< 1$ | 25 – 45 | – | – |
| $F_{15}(1680)$ | 60 – 70 | $< 1$ | 20 – 40 | – | – |
| $D_{33}(1700)$ | 10 – 20 | – | 10 – 55 | – | – |
| $D_{13}(1700)$ | – | 60 – 90 | – | – | |
| $P_{11}(1710)$ | 5 – 20 | 10 – 50 | – | 5 – 25 | – |
| $P_{13}(1720)$ | 8 – 14 | 1 – 5 | 50 – 90 | 4 – 5 | – |
| $S_{11}(1895)$ | 2 – 18 | 15 – 40 | – | 13 – 23 | 6 – 20 |
| $P_{13}(1900)$ | 1 – 20 | 2 – 14 | 40 – 80 | 2 – 20 | 3 – 7 |
| $F_{35}(1905)$ | 9 – 15 | – | – | – | – |

# Nucleon and Delta resonances: PDG

## Third and higher resonance regions

| Resonances $R_{IJ}$ | $\pi N$ branching ratio (%) | $\eta N$ branching ratio (%) | $\pi\pi N$ branching ratio (%) | $K\Lambda$ branching ratio (%) | $K\Sigma$ branching ratio (%) |
|---|---|---|---|---|---|
| $P_{33}(1232)$ | 100 | – | – | – | – |
| $P_{11}(1440)$ | 55 – 75 | $< 1$ | 17 – 50 | – | – |
| $D_{13}(1520)$ | 55 – 65 | 0.07 – 0.09 | 25 – 35 | – | – |
| $S_{11}(1535)$ | 32 – 52 | 30 – 55 | 3 – 14 | – | – |
| $S_{31}(1620)$ | 25 – 35 | – | 55 – 80 | – | – |
| $S_{11}(1650)$ | 50 – 70 | 15 – 35 | 8 – 36 | 5 – 15 | – |
| $D_{15}(1675)$ | 38 – 42 | $< 1$ | 25 – 45 | – | – |
| $F_{15}(1680)$ | 60 – 70 | $< 1$ | 20 – 40 | – | – |
| $D_{33}(1700)$ | 10 – 20 | – | 10 – 55 | – | – |
| $D_{13}(1700)$ | – | 60 – 90 | – | – | |
| $P_{11}(1710)$ | 5 – 20 | 10 – 50 | – | 5 – 25 | – |
| $P_{13}(1720)$ | 8 – 14 | 1 – 5 | 50 – 90 | 4 – 5 | – |
| $S_{11}(1895)$ | 2 – 18 | 15 – 40 | – | 13 – 23 | 6 – 20 |
| $P_{13}(1900)$ | 1 – 20 | 2 – 14 | 40 – 80 | 2 – 20 | 3 – 7 |
| $F_{35}(1905)$ | 9 – 15 | – | – | – | – |

# Definition of SIS

- In $\nu(\bar{\nu})$ interactions with nucleons and nuclei, SIS refers to processes, where quark fragmented meson production from DIS transforms into non-resonant meson production.

# Definition of SIS

- In $\nu(\bar{\nu})$ interactions with nucleons and nuclei, SIS refers to processes, where quark fragmented meson production from DIS transforms into non-resonant meson production.
- SIS region is dominated by non-resonant contributions, in the kinematic region where $Q^2$ is small and the invariant mass of the hadronic system(W) is above pion production threshold($m_N + m_\pi \sim 1080$ MeV).

# Definition of SIS

- In $\nu(\bar{\nu})$ interactions with nucleons and nuclei, SIS refers to processes, where quark fragmented meson production from DIS transforms into non-resonant meson production.
- SIS region is dominated by non-resonant contributions, in the kinematic region where $Q^2$ is small and the invariant mass of the hadronic system(W) is above pion production threshold($m_N + m_\pi \sim 1080$ MeV).
- The pion production region is dominated by $\Delta(1232)$ excitation and its subsequent decay to $N\pi$. With the increase in W, other higher resonances contribute.

# Definition of SIS

- In $\nu(\bar{\nu})$ interactions with nucleons and nuclei, SIS refers to processes, where quark fragmented meson production from DIS transforms into non-resonant meson production.
- SIS region is dominated by non-resonant contributions, in the kinematic region where $Q^2$ is small and the invariant mass of the hadronic system(W) is above pion production threshold($m_N + m_\pi \sim 1080$ MeV).
- The pion production region is dominated by $\Delta(1232)$ excitation and its subsequent decay to $N\pi$. With the increase in W, other higher resonances contribute.

- In the region of high $W$, other mesons also start getting produced, both from resonant as well as non-resonant processes.

# Definition of SIS

- In $\nu(\bar{\nu})$ interactions with nucleons and nuclei, SIS refers to processes, where quark fragmented meson production from DIS transforms into non-resonant meson production.
- SIS region is dominated by non-resonant contributions, in the kinematic region where $Q^2$ is small and the invariant mass of the hadronic system(W) is above pion production threshold($m_N + m_\pi \sim 1080$ MeV).
- The pion production region is dominated by $\Delta(1232)$ excitation and its subsequent decay to $N\pi$. With the increase in W, other higher resonances contribute.

- In the region of high $W$, other mesons also start getting produced, both from resonant as well as non-resonant processes.
- This non-resonant meson production intermixes with resonant meson production in a regime of similar effective hadronic mass W of the interaction.

# Definition of SIS

- In $\nu(\bar{\nu})$ interactions with nucleons and nuclei, SIS refers to processes, where quark fragmented meson production from DIS transforms into non-resonant meson production.
- SIS region is dominated by non-resonant contributions, in the kinematic region where $Q^2$ is small and the invariant mass of the hadronic system(W) is above pion production threshold($m_N + m_\pi \sim 1080$ MeV).
- The pion production region is dominated by $\Delta(1232)$ excitation and its subsequent decay to $N\pi$. With the increase in W, other higher resonances contribute.

- In the region of high $W$, other mesons also start getting produced, both from resonant as well as non-resonant processes.
- This non-resonant meson production intermixes with resonant meson production in a regime of similar effective hadronic mass W of the interaction.
- Since experimentally mesons from resonance decay cannot be separated from non-resonant produced mesons, therefore, SIS for all practical experimental purposes is defined as inclusive meson production that includes non-resonant plus resonant meson production and the interference between them.

- With the further increase in $Q^2$ non-resonant interactions begin to take place with quarks within the nucleon indicating the start of Deep Inelastic Scattering (DIS).

- With the further increase in $Q^2$ non-resonant interactions begin to take place with quarks within the nucleon indicating the start of Deep Inelastic Scattering (DIS).

- Thus, the SIS region encompasses the transition from strong interactions described in terms of hadronic degrees of freedom to those among quarks and gluons.

- With the further increase in $Q^2$ non-resonant interactions begin to take place with quarks within the nucleon indicating the start of Deep Inelastic Scattering (DIS).
- Thus, the SIS region encompasses the transition from strong interactions described in terms of hadronic degrees of freedom to those among quarks and gluons.
- In practice, it is difficult to kinematically have a well-defined DIS region which separates from the SIS region (region where perturbative QCD goes to nonperturbative QCD) or a SIS region which separates from the Resonance region (nonperturbative QCD to resonant meson production), and therefore, science of this complex region has to be better understood.

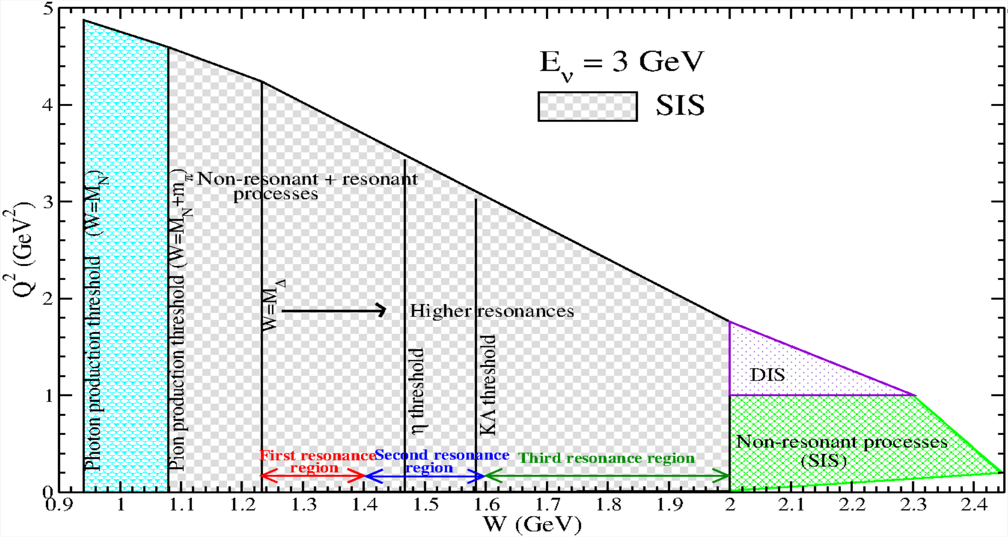
- With the further increase in $Q^2$ non-resonant interactions begin to take place with quarks within the nucleon indicating the start of Deep Inelastic Scattering (DIS).

- Thus, the SIS region encompasses the transition from strong interactions described in terms of hadronic degrees of freedom to those among quarks and gluons.

- In practice, it is difficult to kinematically have a well-defined DIS region which separates from the SIS region (region where perturbative QCD goes to nonperturbative QCD) or a SIS region which separates from the Resonance region (nonperturbative QCD to resonant meson production), and therefore, science of this complex region has to be better understood.

- Presently both theoretically as well as experimentally it is poorly understood.

# Kinematic region defining SIS and DIS




J.Phys.G 48 (2021) 034001

# Importance of the SIS region

- Theoretically, this SIS energy region becomes quite intriguing and challenging.

# Importance of the SIS region

- Theoretically, this SIS energy region becomes quite intriguing and challenging.
- There is no information on the axial vector sector for second and higher resonances.

# Importance of the SIS region

- Theoretically, this SIS energy region becomes quite intriguing and challenging.
- There is no information on the axial vector sector for second and higher resonances.
- In nuclear targets, the nuclear medium effect on the $\Delta(1232)$ resonance production has been studied.

# Importance of the SIS region

- Theoretically, this SIS energy region becomes quite intriguing and challenging.
- There is no information on the axial vector sector for second and higher resonances.
- In nuclear targets, the nuclear medium effect on the $\Delta(1232)$ resonance production has been studied.
- In order to understand this SIS region, one has to understand the effect of nuclear medium for the resonances lying in the second and higher resonance regions.

# Transition matrix element for the single meson production

$$\mathscr{M} = \frac{G_F}{\sqrt{2}}\, j_\mu^{(L)}\, j_{CC,NC}^{\mu\,(H)}$$

Fermi coupling constant

Leptonic Current

Hadronic Current

- Leptonic current is

$$j_\mu^{(L)} = \bar{u}(k')\gamma_\mu(1\pm\gamma_5)u(k)$$

- Hadronic current $j_{CC}^{\mu(H)}$ describes hadronic matrix element for

$$W^\pm + N \to B' + m$$

- Hadronic current $j_{NC}^{\mu(H)}$ describes hadronic matrix element for

$$Z + N \to B' + m$$

- $j_{CC(NC)}^{\mu(H)}$ receives contribution from
  - Resonance excitations
  - Nonresonant Born terms

# Transition matrix element for the single meson production

$$\mathscr{M} = \frac{G_F}{\sqrt{2}} j_\mu^{(L)} j_{CC,NC}^{\mu\,(H)}$$

Fermi coupling constant

Leptonic Current

Hadronic Current

- Leptonic current is

$$j_\mu^{(L)} = \bar{u}(k')\gamma_\mu(1 \pm \gamma_5)u(k)$$

- Hadronic current $j_{CC}^{\mu(H)}$ describes hadronic matrix element for

$$W^\pm + N \to B' + m$$

- Hadronic current $j_{NC}^{\mu(H)}$ describes hadronic matrix element for

$$Z + N \to B' + m$$

- $j_{CC(NC)}^{\mu(H)}$ receives contribution from
  - Resonance excitations
  - Nonresonant Born terms

# Transition matrix element for the single meson production

$$\mathscr{M} = \frac{G_F}{\sqrt{2}}\, j_\mu^{(L)}\, j_{CC,NC}^{\mu\,(H)}$$

Fermi coupling constant

Leptonic Current

Hadronic Current

- Leptonic current is

$$j_\mu^{(L)} = \bar{u}(k')\gamma_\mu(1 \pm \gamma_5)u(k)$$

- Hadronic current $j_{CC}^{\mu(H)}$ describes hadronic matrix element for

$$W^\pm + N \rightarrow B' + m$$

- Hadronic current $j_{NC}^{\mu(H)}$ describes hadronic matrix element for

$$Z + N \rightarrow B' + m$$

- $j_{CC(NC)}^{\mu(H)}$ receives contribution from
  - Resonance excitations
  - Nonresonant Born terms

# Transition matrix element for the single meson production

$$\mathscr{M} = \frac{G_F}{\sqrt{2}} j_\mu^{(L)} j_{CC,NC}^{\mu\,(H)}$$

Fermi coupling constant

Leptonic Current

Hadronic Current

- Leptonic current is

$$j_\mu^{(L)} = \bar{u}(k')\gamma_\mu(1 \pm \gamma_5)u(k)$$

- Hadronic current $j_{CC}^{\mu(H)}$ describes hadronic matrix element for

$$W^{\pm} + N \rightarrow B' + m$$

- Hadronic current $j_{NC}^{\mu(H)}$ describes hadronic matrix element for

$$Z + N \rightarrow B' + m$$

- $j_{CC(NC)}^{\mu(H)}$ receives contribution from
  - Resonance excitations
  - Nonresonant Born terms

# Transition matrix element for the single meson production

$$\mathscr{M} = \frac{G_F}{\sqrt{2}} j_\mu^{(L)} j_{CC,NC}^{\mu\,(H)}$$

Fermi coupling constant

Leptonic Current

Hadronic Current

- Leptonic current is

$$j_\mu^{(L)} = \bar{u}(k')\gamma_\mu(1 \pm \gamma_5)u(k)$$

- Hadronic current $j_{CC}^{\mu\,(H)}$ describes hadronic matrix element for

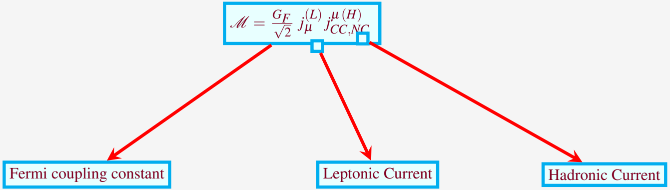
$$W^\pm + N \to B' + m$$

- Hadronic current $j_{NC}^{\mu\,(H)}$ describes hadronic matrix element for

$$Z + N \to B' + m$$

- $j_{CC(NC)}^{\mu\,(H)}$ receives contribution from
  - Resonance excitations
  - Nonresonant Born terms

# Transition matrix element for the single meson production




- Leptonic current is

$$j_\mu^{(L)} = \bar{u}(k')\gamma_\mu(1 \pm \gamma_5)u(k)$$

- Hadronic current $j_{CC}^{\mu(H)}$ describes hadronic matrix element for

$$W^\pm + N \to B' + m$$

- Hadronic current $j_{NC}^{\mu(H)}$ describes hadronic matrix element for

$$Z + N \to B' + m$$

- $j_{CC(NC)}^{\mu(H)}$ receives contribution from
  - Resonance excitations
  - Nonresonant Born terms

# Spin $\frac{1}{2}$ resonance

$$j^{\mu}_{\frac{1}{2}} = \bar{u}(p')\Gamma^{\mu}_{\frac{1}{2}}u(p)$$

Adjoint Dirac Spinor

N-$R_{\frac{1}{2}}$ transition vertex

Dirac Spinor

## Transition vertex

- Positive parity state

$$\Gamma^{\mu}_{\frac{1}{2}^{+}} = V^{\mu}_{\frac{1}{2}} - A^{\mu}_{\frac{1}{2}}$$

- Negative parity state

$$\Gamma^{\mu}_{\frac{1}{2}^{-}} = \left[V^{\mu}_{\frac{1}{2}} - A^{\mu}_{\frac{1}{2}}\right]\gamma_5$$

$$V^{\mu}_{\frac{1}{2}} = \left[\frac{f_1(Q^2)}{(2M)^2}\left(Q^2\gamma^{\mu} + \not{q}q^{\mu}\right) + \frac{f_2(Q^2)}{2M}i\sigma^{\mu\alpha}q_{\alpha}\right]\gamma_5; \qquad A^{\mu}_{\frac{1}{2}} = g_1(Q^2)\gamma^{\mu} + \frac{g_3(Q^2)}{M}q^{\mu}$$

# Spin $\frac{1}{2}$ resonance

$$j^{\mu}_{\frac{1}{2}} = \bar{u}(p')\Gamma^{\mu}_{\frac{1}{2}}u(p)$$

Adjoint Dirac Spinor

N-$R_{\frac{1}{2}}$ transition vertex

Dirac Spinor

**Transition vertex**

- Positive parity state

$$\Gamma^{\mu}_{\frac{1}{2}^+} = V^{\mu}_{\frac{1}{2}} - A^{\mu}_{\frac{1}{2}}$$

- Negative parity state

$$\Gamma^{\mu}_{\frac{1}{2}^-} = \left[V^{\mu}_{\frac{1}{2}} - A^{\mu}_{\frac{1}{2}}\right]\gamma_5$$

$$V^{\mu}_{\frac{1}{2}} = \left[\frac{f_1(Q^2)}{(2M)^2}\left(Q^2\gamma^{\mu} + \not{q}q^{\mu}\right) + \frac{f_2(Q^2)}{2M}i\sigma^{\mu\alpha}q_{\alpha}\right]\gamma_5; \qquad A^{\mu}_{\frac{1}{2}} = g_1(Q^2)\gamma^{\mu} + \frac{g_3(Q^2)}{M}q^{\mu}$$

# Spin $\frac{1}{2}$ resonance

$$j^{\mu}_{\frac{1}{2}} = \bar{u}(p')\Gamma^{\mu}_{\frac{1}{2}} u(p)$$

Adjoint Dirac Spinor — N-$R_{\frac{1}{2}}$ transition vertex — Dirac Spinor

**Transition vertex**

- Positive parity state $$\Gamma^{\mu}_{\frac{1}{2}^+} = V^{\mu}_{\frac{1}{2}} - A^{\mu}_{\frac{1}{2}}$$
- Negative parity state $$\Gamma^{\mu}_{\frac{1}{2}^-} = \left[V^{\mu}_{\frac{1}{2}} - A^{\mu}_{\frac{1}{2}}\right]\gamma_5$$

$$V^{\mu}_{\frac{1}{2}} = \left[\frac{f_1(Q^2)}{(2M)^2}\left(Q^2\gamma^{\mu} + \not{q}q^{\mu}\right) + \frac{f_2(Q^2)}{2M} i\sigma^{\mu\alpha}q_{\alpha}\right]\gamma_5; \qquad A^{\mu}_{\frac{1}{2}} = g_1(Q^2)\gamma^{\mu} + \frac{g_3(Q^2)}{M}q^{\mu}$$

# $N - R_{\frac{1}{2}}$ transition form factors

- ★ Isospin symmetry relates weak vector form factors with electromagnetic form factors
- ★ EM form factors are derived from the helicity amplitudes extracted from the real and/or virtual photon scattering experiments

# $N - R_{\frac{1}{2}}$ transition form factors

- ★ Isospin symmetry relates weak vector form factors with electromagnetic form factors
- ★ EM form factors are derived from the helicity amplitudes extracted from the real and/or virtual photon scattering experiments

- ✠ Experimentally, the information regarding the axial vector form factors is scarce
- ✠ PCAC and PDDAC relates $g_1(0)$ with $g_{RN\pi}$
- ✠ Generalized GT relation gives $g_3$ in terms of $g_1$
- ✠ $g_{RN\pi}$ is obtained using partial decay width of the $R \to N\pi$

# Spin $\frac{3}{2}$ resonances

$$J_\mu^{\frac{3}{2}} = \bar{\psi}^\nu(p')\Gamma_{\nu\mu}^{\frac{3}{2}} u(p)$$

Rarita-Schwinger Spinor

N-$R_{\frac{3}{2}}$ transition vertex

Dirac Spinor

## Transition vertex

- Positive Parity states:

$$\Gamma_{\nu\mu}^{\frac{3}{2}^+} = \left[V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}\right]\gamma_5$$

- Negative Parity states

$$\Gamma_{\nu\mu}^{\frac{3}{2}^-} = V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}$$

# Spin $\frac{3}{2}$ resonances

$$J_{\mu}^{\frac{3}{2}} = \bar{\psi}^{\nu}(p')\Gamma_{\nu\mu}^{\frac{3}{2}} u(p)$$

Rarita-Schwinger Spinor

N-$R_{\frac{3}{2}}$ transition vertex

Dirac Spinor

## Transition vertex

- Positive Parity states:

$$\Gamma_{\nu\mu}^{\frac{3}{2}^{+}} = \left[V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}\right]\gamma_5$$

- Negative Parity states

$$\Gamma_{\nu\mu}^{\frac{3}{2}^{-}} = V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}$$

# Spin $\frac{3}{2}$ resonances

$$J_\mu^{\frac{3}{2}} = \bar{\psi}^\nu(p')\Gamma_{\nu\mu}^{\frac{3}{2}} u(p)$$

Rarita-Schwinger Spinor

N-$R_{\frac{3}{2}}$ transition vertex

Dirac Spinor

**Transition vertex**

- Positive Parity states:

$$\Gamma_{\nu\mu}^{\frac{3}{2}^+} = \left[V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}\right]\gamma_5$$

- Negative Parity states

$$\Gamma_{\nu\mu}^{\frac{3}{2}^-} = V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}$$

# Spin $\frac{3}{2}$ resonances

$$J_\mu^{\frac{3}{2}} = \bar{\psi}^\nu(p')\Gamma_{\nu\mu}^{\frac{3}{2}} u(p)$$

Rarita-Schwinger Spinor

N-$R_{\frac{3}{2}}$ transition vertex

Dirac Spinor

## Transition vertex

- Positive Parity states:

$$\Gamma_{\nu\mu}^{\frac{3}{2}^+} = \left[ V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}} \right] \gamma_5$$

- Negative Parity states

$$\Gamma_{\nu\mu}^{\frac{3}{2}^-} = V_{\nu\mu}^{\frac{3}{2}} - A_{\nu\mu}^{\frac{3}{2}}$$

# $N - R_{\frac{3}{2}}$ transition form factors

$$V^{\frac{3}{2}}_{\nu\mu} = \left[\frac{C_3^V}{M}(g_{\mu\nu}\not{q} - q_\nu\gamma_\mu) + \frac{C_4^V}{M^2}(g_{\mu\nu}q\cdot p' - q_\nu p'_\mu) + \frac{C_5^V}{M^2}(g_{\mu\nu}q\cdot p - q_\nu p_\mu) + g_{\mu\nu}C_6^V\right]$$

- CVC $\Rightarrow C_6^V = 0$; Isospin symmetry relates $C_i^V$ (i=3–5) in terms of EM form factors

# $N - R_{\frac{3}{2}}$ transition form factors

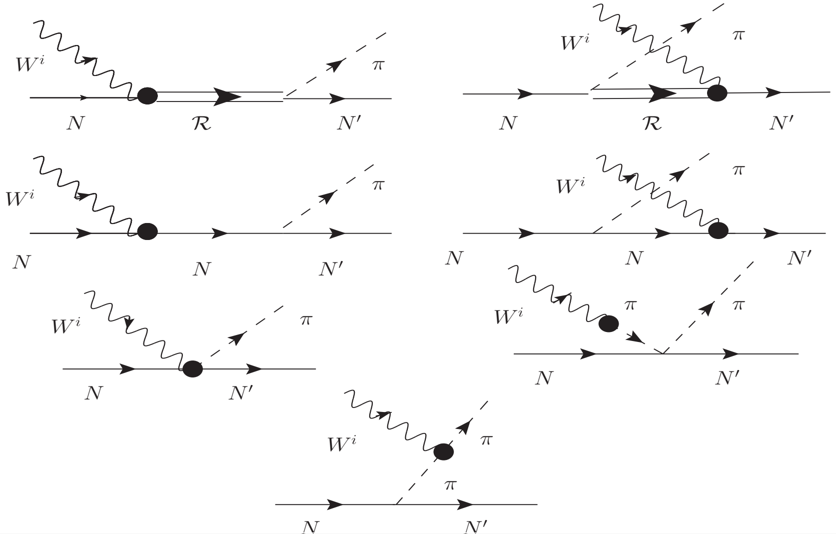
$$V^{\frac{3}{2}}_{\nu\mu} = \left[ \frac{C_3^V}{M}(g_{\mu\nu}\not{q} - q_\nu\gamma_\mu) + \frac{C_4^V}{M^2}(g_{\mu\nu}q\cdot p' - q_\nu p'_\mu) + \frac{C_5^V}{M^2}(g_{\mu\nu}q\cdot p - q_\nu p_\mu) + g_{\mu\nu}C_6^V \right]$$

- CVC $\Rightarrow C_6^V = 0$; Isospin symmetry relates $C_i^V$ (i=3–5) in terms of EM form factors

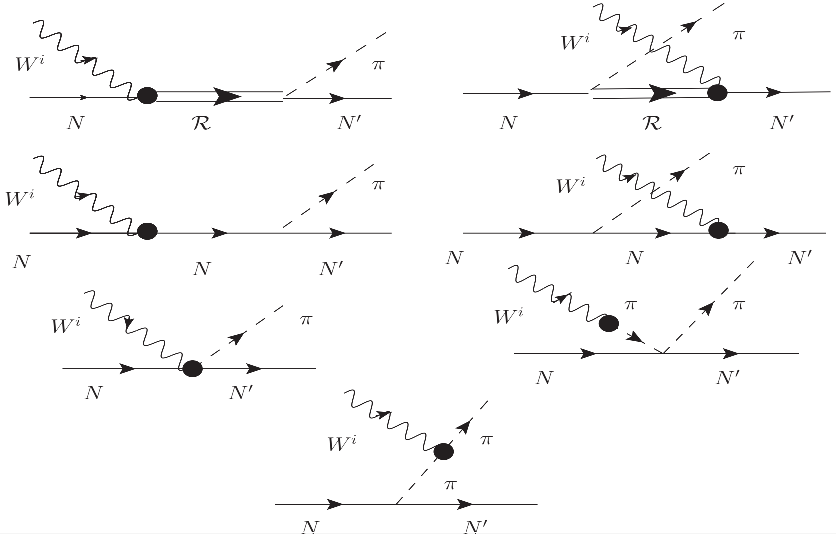
$$A^{\frac{3}{2}}_{\nu\mu} = -\left[ \frac{C_3^A}{M}(g_{\mu\nu}\not{q} - q_\nu\gamma_\mu) + \frac{C_4^A}{M^2}(g_{\mu\nu}q\cdot p' - q_\nu p'_\mu) + C_5^A g_{\mu\nu} + \frac{C_6^A}{M^2}q_\nu q_\mu \right]\gamma_5$$

- Information about the axial vector form factors is poorly known
- For $\Delta$, Adler's model guided by SU(6) quark model is adopted, i.e., $C_3^A = 0$ and $C_4^A = -\frac{C_5^A}{4}$
- For higher resonances, $C_{3,4}^A$ are taken as zero
- PCAC and generalized GT relation relates $C_6^A$ to $C_5^A$
- $C_5^A(0)$ is obtained in terms of $g_{RN\pi}$

# Single pion production: Feynman diagrams



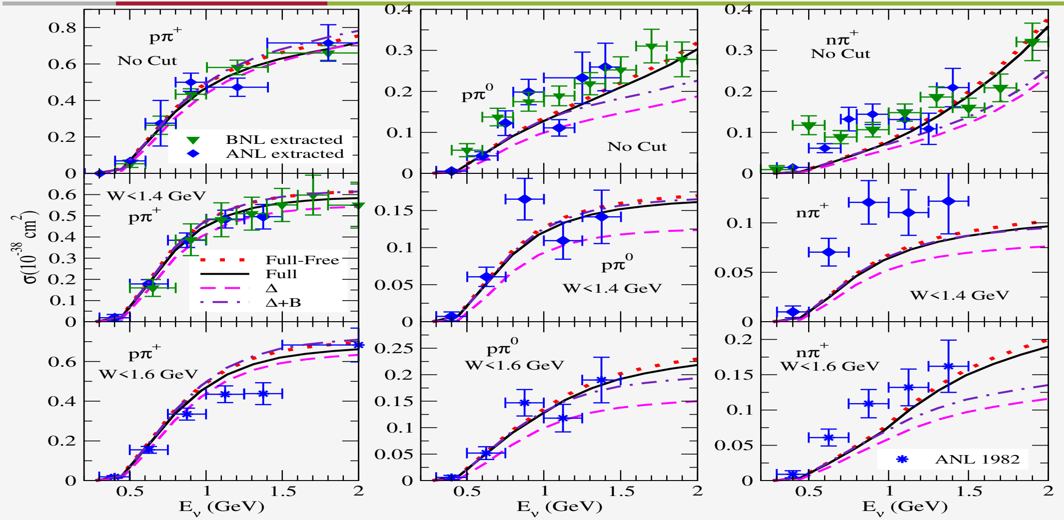
# Single pion production: Feynman diagrams




**Resonances considered**

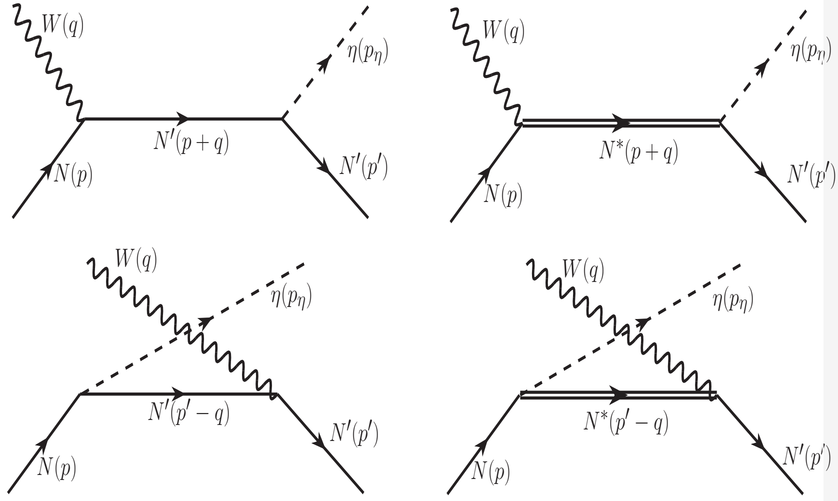
- $P_{33}(1232)$
- $P_{11}(1440)$
- $S_{11}(1535)$
- $D_{13}(1520)$
- $S_{31}(1620)$
- $S_{11}(1650)$
- $D_{33}(1700)$
- $P_{13}(1720)$

# σ for CC neutrino induced pion production processes




Progress in Particle & Nuclear Physics 129 (2023) 104019

# Eta production: Feynman diagrams

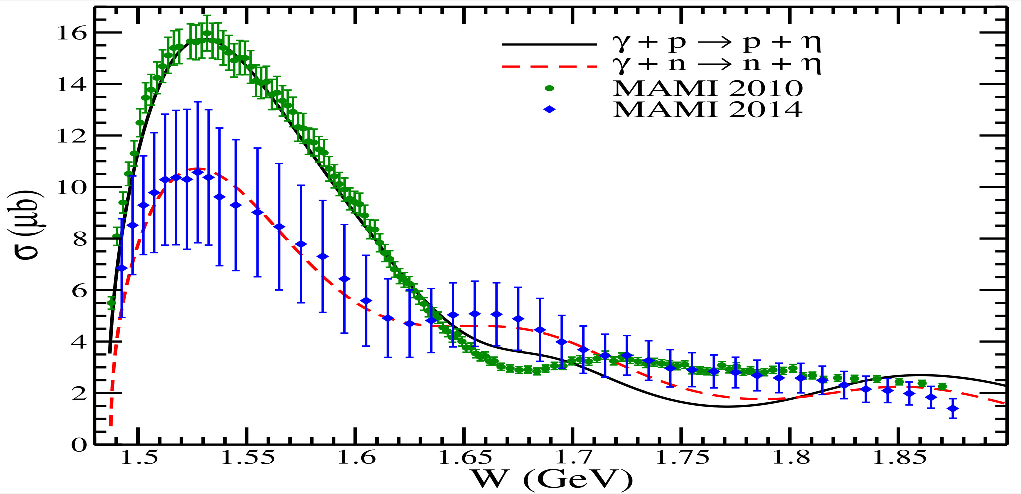



Phys. Rev. D 107, 033002 (2023)

**Resonances considered**

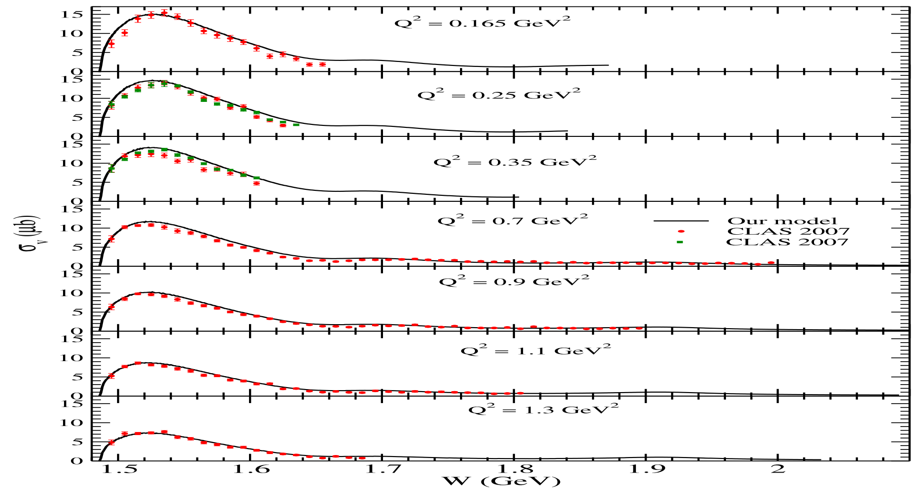
- $S_{11}(1535)$
- $S_{11}(1650)$
- $P_{11}(1710)$
- $P_{11}(1880)$
- $S_{11}(1895)$

# σ for eta photoproduction processes



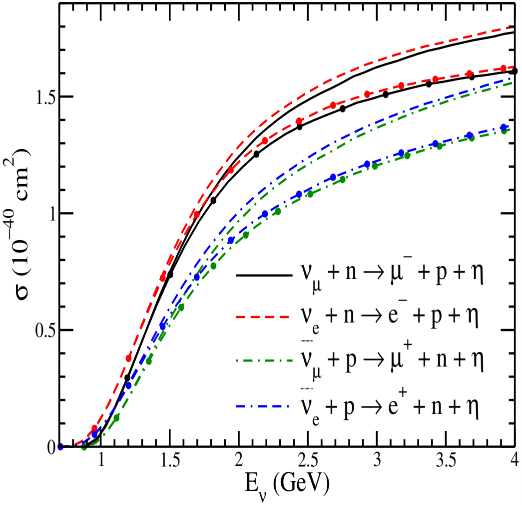

arXiv: 2307.12686

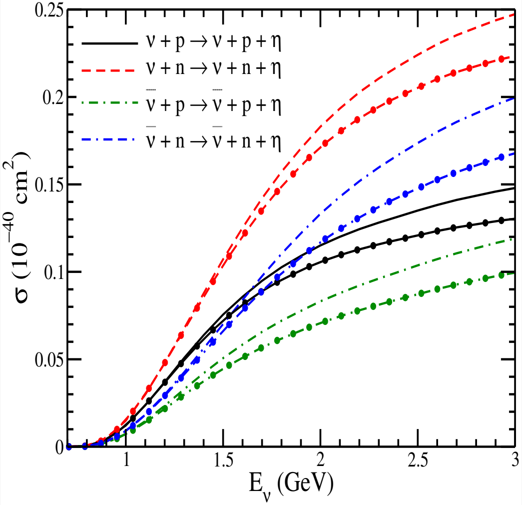
# σ for eta electroproduction processes




arXiv: 2307.12686

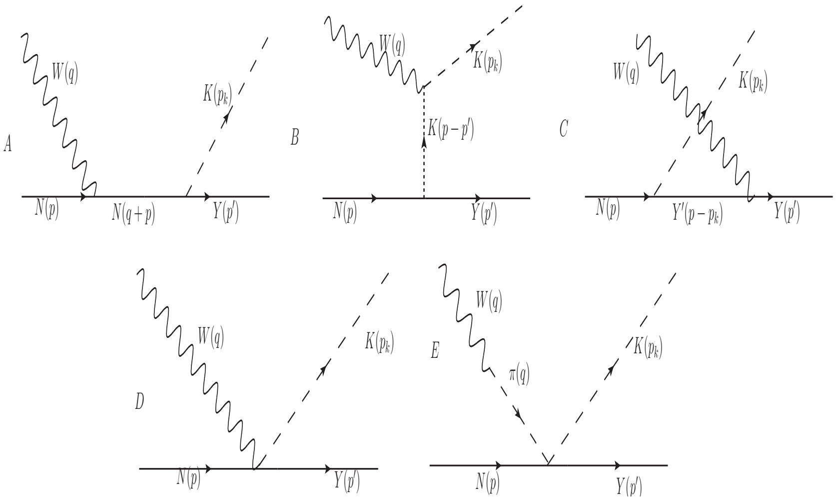
# $\sigma$ for CC and NC induced eta production processes




arXiv: 2307.12686 Lines with solid dots show $S_{11}(1535)$ contribution only

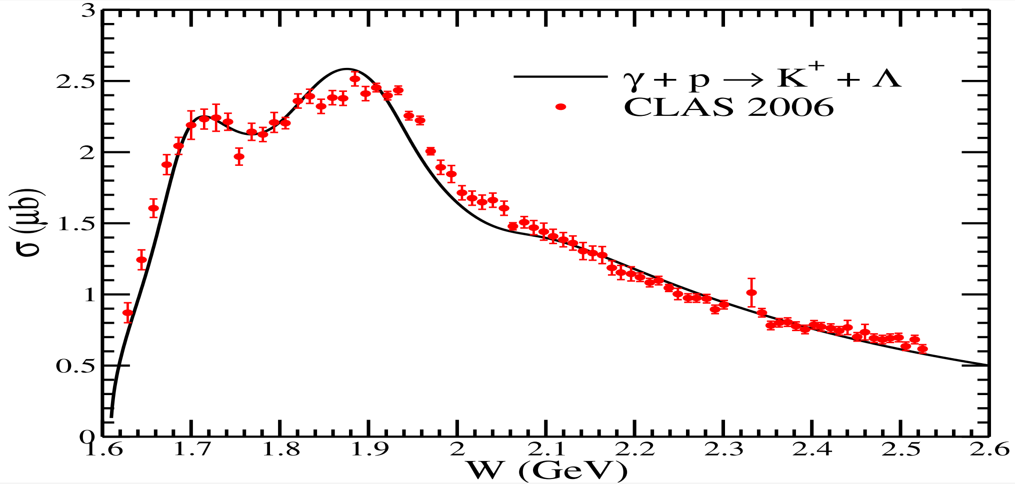
# Associated particle production: Feynman diagrams




**Resonances considered**

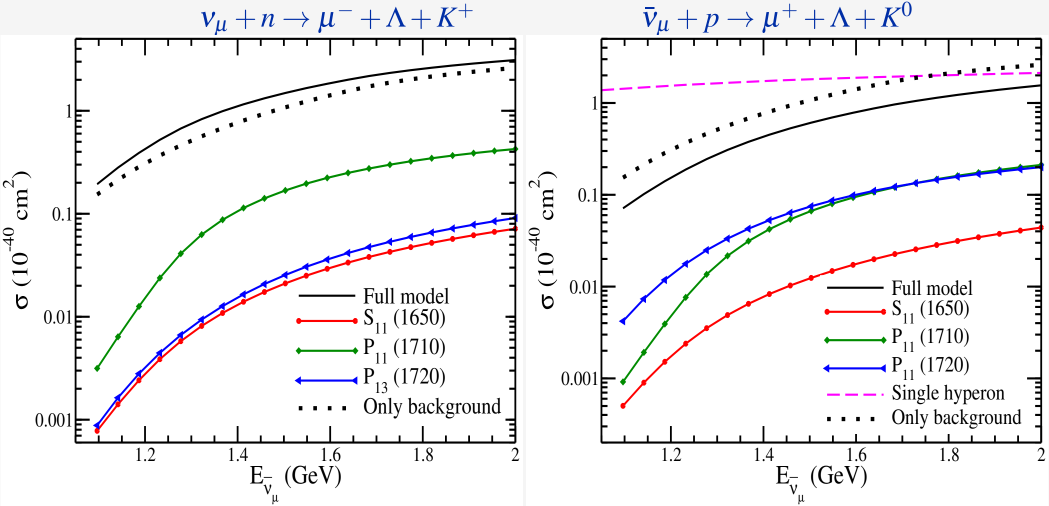
- $S_{11}(1650)$
- $P_{11}(1710)$
- $P_{13}(1720)$

# $\sigma$ for $K\Lambda$ photoproduction processes




Int. J. Mod. Phys. E 29 (2020) 07, 2050051

# $\sigma$ for CC induced $K\Lambda$ production processes

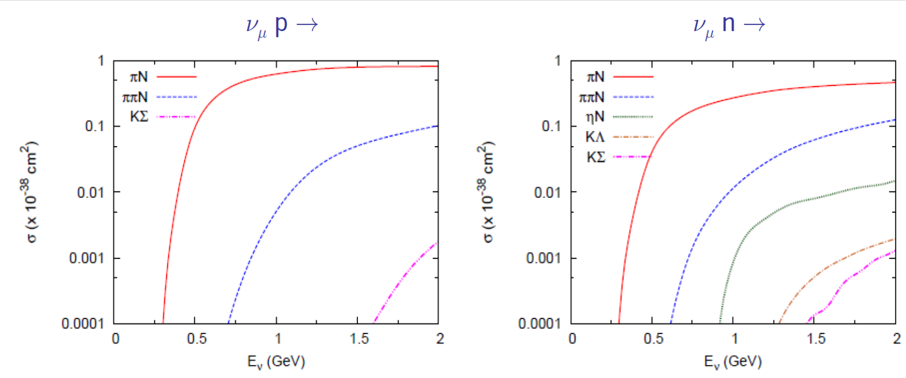



Progress in Particle & Nuclear Physics 129 (2023) 104019

# Dynamically coupled channel approach

**Nakamura et al., Phys. Rev. D 92, 074024 (2015)**

- Resonance and non-resonant amplitudes are added coherently.
- Unitarization is restored using the Lippmann-Schwinger equation.



# Production of pions inside the nucleus

The nuclear medium modifications in the weak sector have only been studied for $\Delta$ resonance

Modification in the width $\tilde{\Gamma}$

$$\frac{\tilde{\Gamma}}{2} \rightarrow \frac{\tilde{\Gamma}}{2} - Im\Sigma_\Delta$$

and in mass $M_\Delta$ of the $\Delta$ resonance

$$M_\Delta \rightarrow M_\Delta + Re\Sigma_\Delta$$

To evaluate $\Delta$ self energy

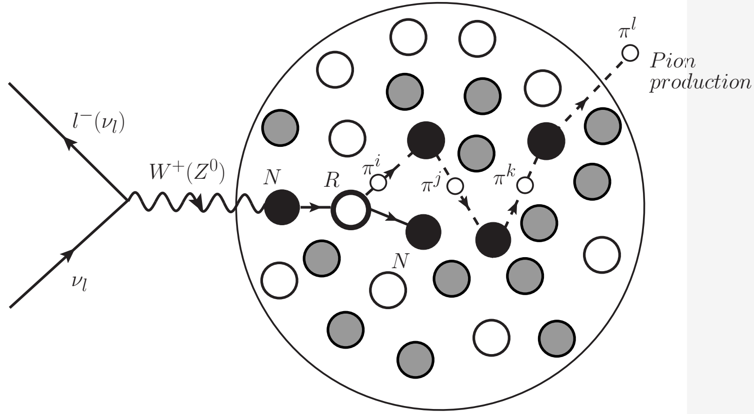
- Many body expansion in terms of ph and $\Delta$h excitations and spin-isospin induced interaction

Imaginary part of $\Delta$ self energy accounts for

- Quasielastic corrections($WN \rightarrow N\pi$)
- Two body absorption($WNN \rightarrow NN$) and
- Three body absorption($WNNN \rightarrow NNN$)

# FSI of produced pions: elastic and QE scattering

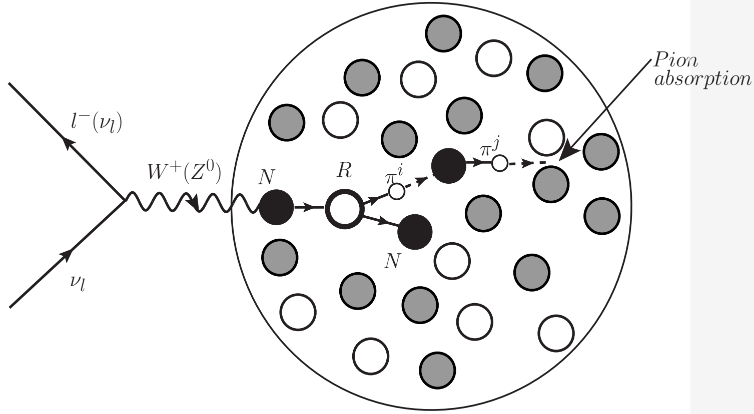
$$\pi^+ + n \to \pi^0 + p; \qquad \pi^- + p \to \pi^0 + n; \qquad \pi^i + N \to \pi^i + N$$




The Physics of Neutrino Interactions (CUP) 2020

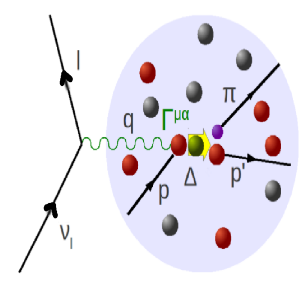
# FSI of produced pions: absorption and QE like events

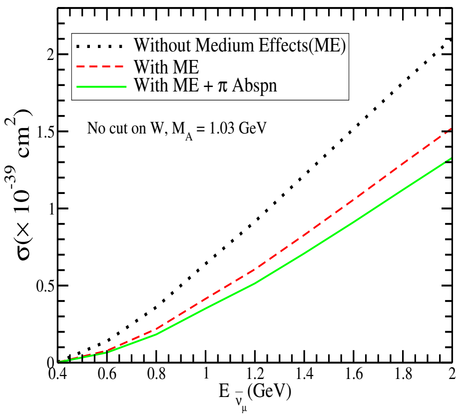
$$\pi^+ + n \to p; \qquad \pi^- + p \to n; \qquad \pi^0 + N \to N'$$




The Physics of Neutrino Interactions (CUP) 2020

# NMEs in Δ production & it's subsequent decay



# CC $\nu_l/\bar{\nu}_l - N$ DIS

**The DCX is given by**

$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\Big\{\Big[y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\Big]F_{1N}(x,Q^2) + \Big[\Big(1-\frac{m_l^2}{4E_\nu^2}\Big) - \Big(1+\frac{M_N x}{2E_\nu}\Big)y\Big]F_{2N}(x,Q^2)$$

$$\pm \Big[xy\Big(1-\frac{y}{2}\Big) - \frac{m_l^2 y}{4E_\nu M_N}\Big]F_{3N}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_{4N}(x,Q^2) - \frac{m_l^2}{E_\nu M_N}F_{5N}(x,Q^2)\Big\}.$$

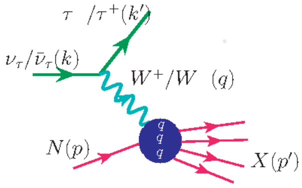
# CC $\nu_l/\bar{\nu}_l - N$ DIS

**The DCX is given by**

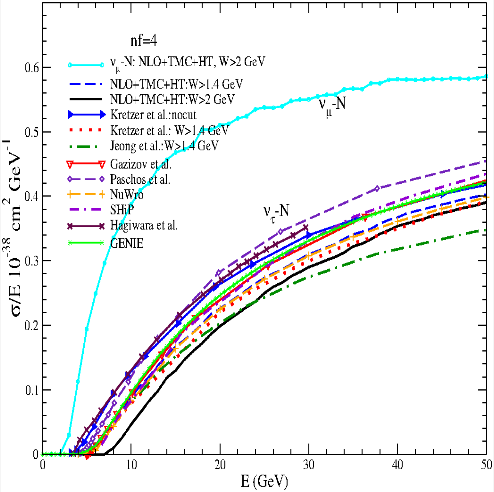
$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\left\{\left[y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\right]F_{1N}(x,Q^2) + \left[\left(1-\frac{m_l^2}{4E_\nu^2}\right) - \left(1+\frac{M_N x}{2E_\nu}\right)y\right]F_{2N}(x,Q^2)\right.$$
$$\left. \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_l^2 y}{4E_\nu M_N}\right]F_{3N}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_{4N}(x,Q^2) - \frac{m_l^2}{E_\nu M_N}F_{5N}(x,Q^2)\right\}.$$

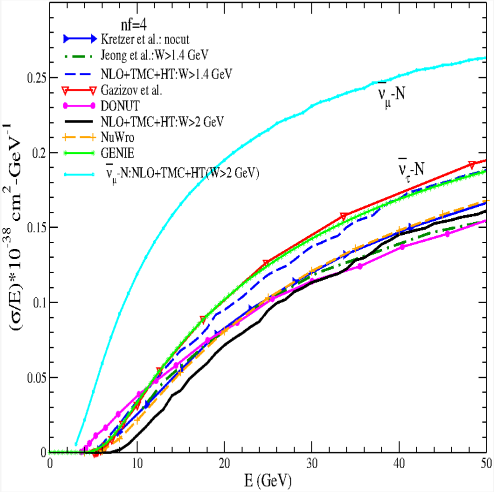
$$\frac{m_l^2}{2M_N(E-m_l)} \le x \le 1; \qquad a-b \le y \le a+b,$$

$$a = \frac{1-m_l^2\left(\frac{1}{2M_N E x}+\frac{1}{2E^2}\right)}{2\left(1+\frac{M_N x}{2E}\right)}, \quad b = \frac{\sqrt{\left(1-\frac{m_l^2}{2M_N E x}\right)^2 - \frac{m_l^2}{E^2}}}{2\left(1+\frac{M_N x}{2E}\right)}.$$



# $\sigma_{\nu_\tau(\bar{\nu}_\tau)-N}$




Phys. Rev. D 102, 113007 (2020)

# $\nu_l - A$ DIS process: Theoretical model

Differential cross section for $\nu_l/\bar{\nu}_l$ induced DIS process off nuclear target is given by

$$\frac{d^2\sigma_A}{dxdy} = \frac{G_F^2 y}{16\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 L^{\alpha\beta} W^A_{\alpha\beta},$$

The nuclear hadronic tensor $(W^A_{\alpha\beta})$ is written in terms of $F_{iA}(x,Q^2)$; $i = 1-5$ as:

$$W^A_{\alpha\beta} = -g_{\alpha\beta} F_{1A}(x,Q^2) + \frac{p_\alpha p_\beta}{p\cdot q} F_{2A}(x,Q^2) - \frac{i}{2p\cdot q}\epsilon_{\alpha\beta\rho\sigma} p^\rho q^\sigma F_{3A}(x,Q^2) + \frac{q_\alpha q_\beta}{p\cdot q} F_{4A}(x,Q^2) + (p_\alpha q_\beta + p_\beta q_\alpha) F_{5A}(x,Q^2).$$

# $\nu_l - A$ DIS process: Theoretical model

Differential cross section for $\nu_l/\bar{\nu}_l$ induced DIS process off nuclear target is given by

$$\frac{d^2\sigma_A}{dxdy} = \frac{G_F^2 y}{16\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 L^{\alpha\beta} W^A_{\alpha\beta},$$

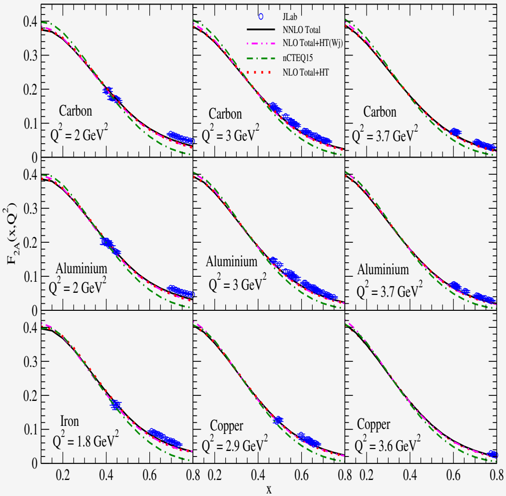
The nuclear hadronic tensor ($W^A_{\alpha\beta}$) is written in terms of $F_{iA}(x,Q^2)$; $i = 1-5$ as:

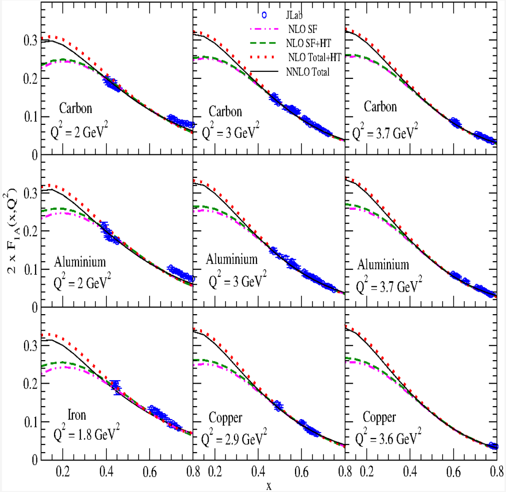
$$W^A_{\alpha\beta} = -g_{\alpha\beta}F_{1A}(x,Q^2) + \frac{p_\alpha p_\beta}{p\cdot q}F_{2A}(x,Q^2) - \frac{i}{2p\cdot q}\epsilon_{\alpha\beta\rho\sigma}p^\rho q^\sigma F_{3A}(x,Q^2) + \frac{q_\alpha q_\beta}{p\cdot q}F_{4A}(x,Q^2) + (p_\alpha q_\beta + p_\beta q_\alpha)F_{5A}(x,Q^2).$$

## NME which have been recently considered:

- Fermi motion, binding energy and nucleon correlations through spectral function.
- The spectral functions has been calculated using Lehmann's representation for the relativistic nucleon propagator.
- Nuclear many body theory is used to calculate it for an interacting Fermi sea in nuclear matter.
- Pion and rho meson cloud contributions following the many body field theoretical approach.
- Shadowing and antishadowing effects.

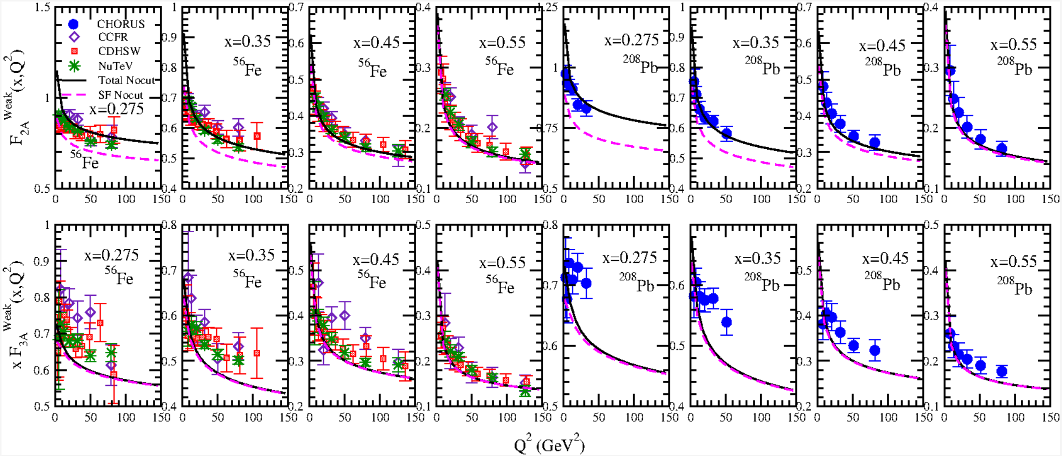
# EM structure functions



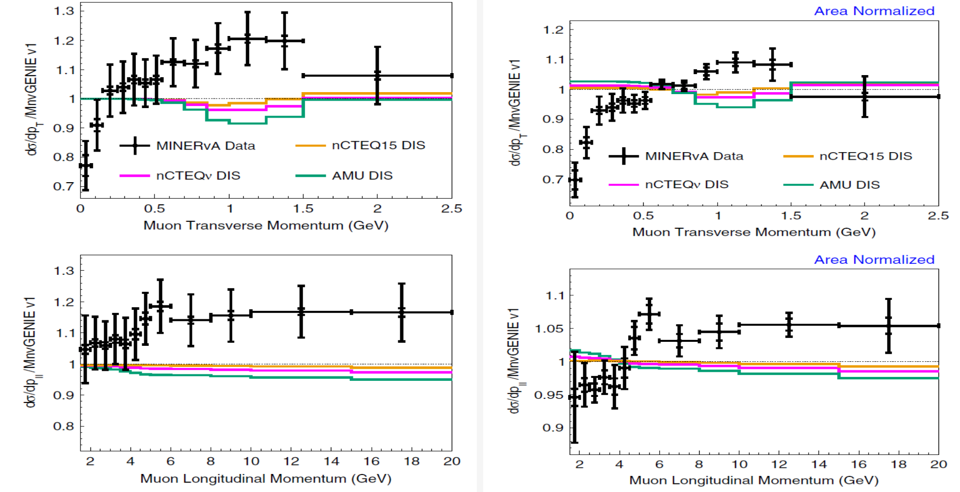

Phys. Rev. D 99, 093011 (2019)

# Weak structure functions




Phys. Rev. D 101, 033001 (2020).

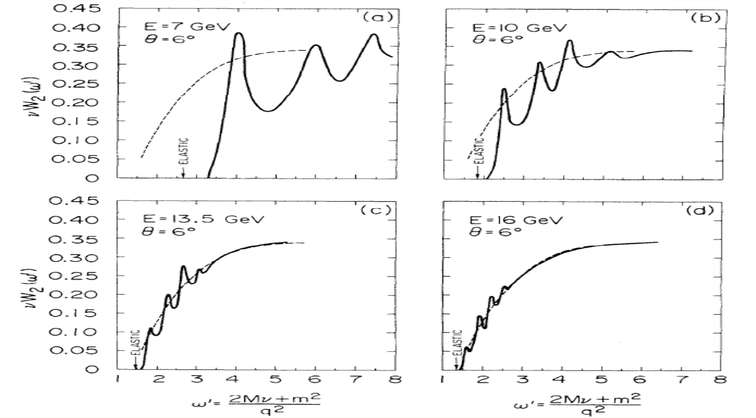
# Differential cross section ratios




A. Filkins et al. (MINERvA Collaboration), Phys. Rev. D 101, 112007 (2020)

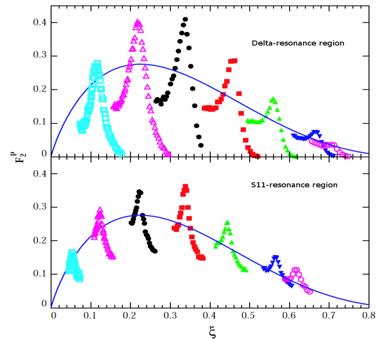
# What is QH-duality?

- **Bloom and Gilman anlyzed inclusive $ep$ scattering data and observed that the structure function in the resonance region closely resembles the scaling function measured in the DIS region.**



## QH-duality is categorized as:

- Local duality: "The equivalence of the averaged resonance and scaling structure functions appeared to hold for each resonance, over restricted regions in $W$"

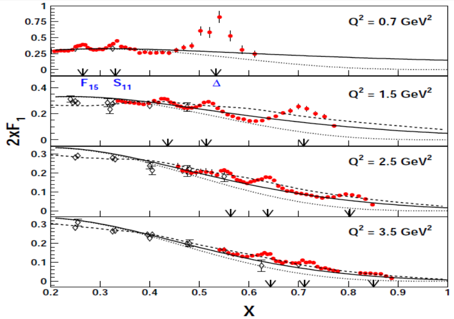


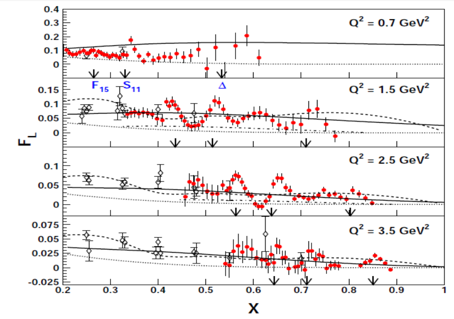

Melnitchouk et al., Phys. Rep. 406 (2005), 127.

- Global duality: "When local QH-duality is observed for higher moments of the structure functions"

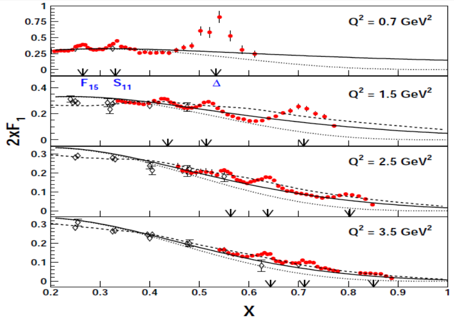
- Two component duality: The resonance contributions are taken to be dual to valence quarks, whereas the nonresonant background is dual to the sea

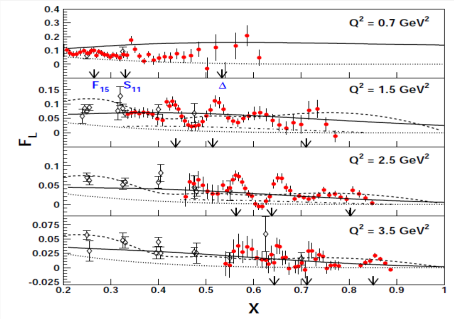
# Electromagnetic structure functions



# Electromagnetic structure functions

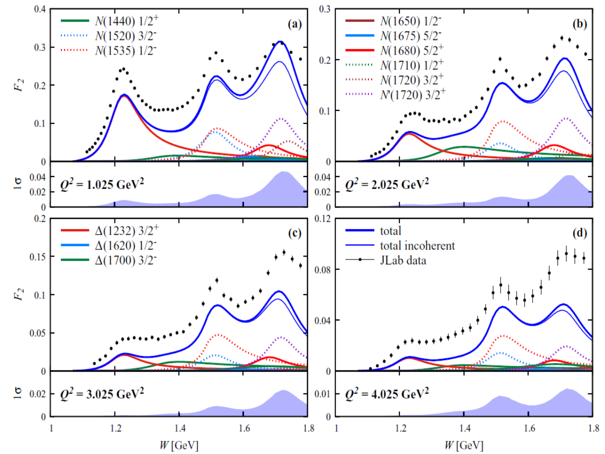



- The mass peak regions move to the large $x$ values with increasing $Q^2$.
- Peak positions are somewhat different for longitudinal and transverse structure functions.
- Above $Q^2 \geq 1\ GeV^2$, the mass peaks are relatively more prominent for $F_L$ than $2xF_1$, signifies their $W$ dependence.

Liang et al., Phys.Rev.C 105 (2022) 6, 065205.

# Electromagnetic structure functions

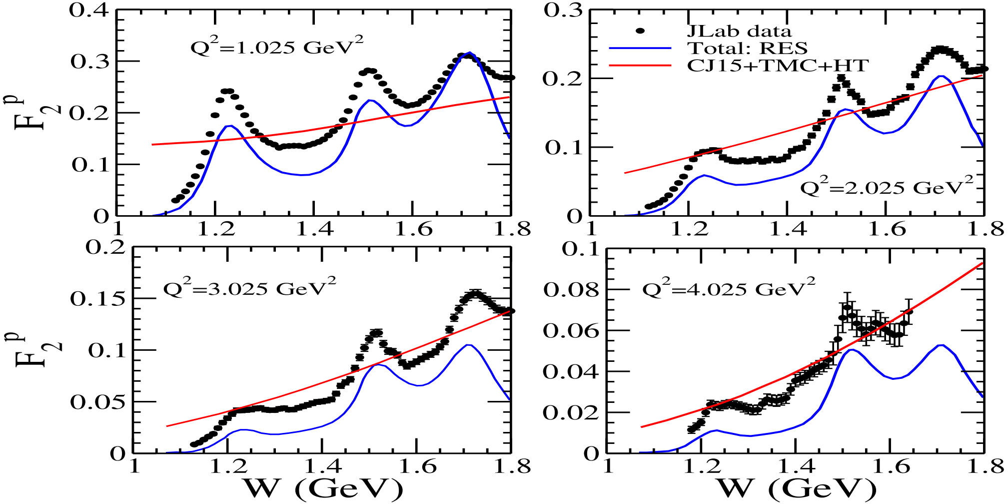



Hiller Blin et al., Phys. Rev. C 104, 025201 (2021).

## What is observed?

- These results correspond to the $W$ and $Q^2$ Kinematic regions covered by E00002 at Hall C and CLAS experiments.
- The contributions from the $\Delta(1232)$ $3/2^+$ resonance to $F_2$ decrease rapidly with $Q^2$, so at $Q^2 > 2\ GeV^2$ the tail from the $N(1440)$ $1/2+$ state becomes essential.
- In the $2^{nd}$ resonance region, the contribution from the $N(1535)1/2^-$ becomes dominant with the increase in $Q^2$.
- In the $3^{rd}$ resonance region, the biggest impact stemming from the $N'(1720)$ $3/2+$ state, and $N(1680)$ $5/2+$ and $N(1720)$ $3/2+$ resonances give subleading contributions.

# $F_2^p$ vs. $W$ at fixed $Q^2$




Blin et al., PR C 104, 025201 (2021)

# $\nu_l/\bar{\nu}_l - p$ scattering – QH-Duality

- Neutrino interactions have particular features which distinguish them from electromagnetic probes.
- For the charged current reaction $\nu_\mu \, p \to \mu^- \, \Delta^{++}$, for example, only isospin-3/2 resonances are excited, and in particular the $P_{33}(1232)$ resonance.
- Because of isospin symmetry constraints, the neutrino–proton structure functions ($F_2^{\nu p}$, $2xF_1^{\nu p}$ and $xF_3^{\nu p}$) for these resonances are three times larger than the neutrino–neutron structure functions.
- In this case the resonance structure functions are significantly larger than the LT functions, $F_i^{\nu p(\mathrm{res})} > F_i^{\nu p(\mathrm{LT})}$, and quark-hadron duality is clearly violated for a proton target.

# $\nu_l/\bar{\nu}_l - n$ scattering – QH-Duality

- In neutrino–neutron scattering, in addition to isospin-3/2 resonances, all the isospin-1/2 resonances can also be excited.
- However, the total contribution of the three isospin-1/2 resonances have been found (Lalakulich et al. PR C 75, 015202 (2007)) to be smaller than that from the leading $P_{33}(1232)$ resonance.
- $F_i^{\nu n(\text{res})} < F_i^{\nu n(\text{LT})}$, so that quark-hadron duality does not hold for this case either.
- In $\nu$ scattering, duality for the average of proton and neutron structure functions holds with better accuracy than electron scattering.

# Conclusion

★ In the intermediate energy region corresponding to the transition between resonance excitations and DIS, we are yet to find a method best suited to describe the inclusive lepton or (anti)neutrino scattering processes.

# Conclusion

- ★ In the intermediate energy region corresponding to the transition between resonance excitations and DIS, we are yet to find a method best suited to describe the inclusive lepton or (anti)neutrino scattering processes.
- ★ Currently, there is no sharp kinematic boundary to distinguish between the DIS and SIS regions, and better understanding is required.

# Conclusion

- ★ In the intermediate energy region corresponding to the transition between resonance excitations and DIS, we are yet to find a method best suited to describe the inclusive lepton or (anti)neutrino scattering processes.
- ★ Currently, there is no sharp kinematic boundary to distinguish between the DIS and SIS regions, and better understanding is required.
- ★ To fix the things at the nucleon level we need proton/deuteron targets.

# Conclusion

- ★ In the intermediate energy region corresponding to the transition between resonance excitations and DIS, we are yet to find a method best suited to describe the inclusive lepton or (anti)neutrino scattering processes.
- ★ Currently, there is no sharp kinematic boundary to distinguish between the DIS and SIS regions, and better understanding is required.
- ★ To fix the things at the nucleon level we need proton/deuteron targets.
- ★ Theoretical as well as Experimental efforts to understand medium modification in a wide region of $x$ and $Q^2$ are required.

# Conclusion

- ★ In the intermediate energy region corresponding to the transition between resonance excitations and DIS, we are yet to find a method best suited to describe the inclusive lepton or (anti)neutrino scattering processes.
- ★ Currently, there is no sharp kinematic boundary to distinguish between the DIS and SIS regions, and better understanding is required.
- ★ To fix the things at the nucleon level we need proton/deuteron targets.
- ★ Theoretical as well as Experimental efforts to understand medium modification in a wide region of $x$ and $Q^2$ are required.
- ★ Progress in Particle & Nuclear Physics 129 (2023) 104019; 186pp


MILES TO GO


Thank You