

Deep inelastic scattering
One pion production
Weak quasielastic production of single hyperons

from nucleons and nuclei



M Sajjad Athar

Aligarh Muslim University
Aligarh, India

Deep inelastic $\nu_l(\bar{\nu}_l) - A$ scattering

Differential scattering cross section is given by

$$\frac{d^2\sigma^{\nu_l(\bar{\nu}_l)}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left\{ y^2 x F_{1A}(x, Q^2) - \frac{Mxy}{2E_\nu} F_{2A}(x, Q^2) \pm xy \left(1 - \frac{y}{2}\right) F_{3A}(x, Q^2) \right\}$$

$$F_{1A}(x_A) = 2 \sum_{i=p,n} AM \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(\mathbf{p})} \int_{-\infty}^{\mu_i} dp^0 S_h^i(p^0, \mathbf{p}, \rho^i(\mathbf{r})) \left[\frac{F_1^N(x_N)}{M} + \frac{1}{M^2} p_x^2 \frac{F_2^N(x_N)}{\nu} \right]$$

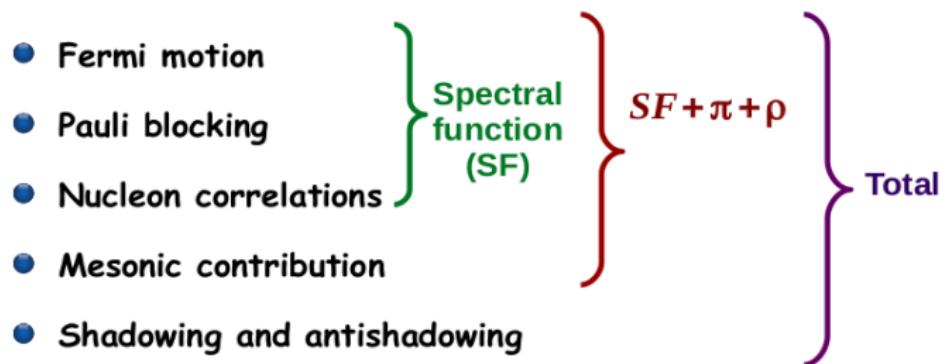
$$F_{2A}(x_A) = 2 \sum_{i=p,n} \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(\mathbf{p})} \int_{-\infty}^{\mu_i} dp^0 S_h^i(p^0, \mathbf{p}, \rho^i(\mathbf{r})) F_2^N(x_N) C$$

$$C = \left[\frac{Q^2}{q_z^2} \left(\frac{p^2 - p_z^2}{2M^2} \right) + \frac{(p \cdot q)^2}{M^2 \nu^2} \left(\frac{p_z Q^2}{p \cdot q q_z} + 1 \right)^2 \frac{q_0 M}{p_0 q_0 - p_z q_z} \right]$$

$$F_{3A}(x_A, Q^2) = 2 \sum_{i=p,n} \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M}{E(\mathbf{p})} \int_{-\infty}^{\mu_i} dp^0 S_h^i(p^0, \mathbf{p}, \rho^i(\mathbf{r})) \frac{p^0 \gamma - p_z}{(p^0 - p_z \gamma) \gamma} F_3^N(x_N)$$

Deep inelastic $\nu_l(\bar{\nu}_l) - A$ scattering

We have considered the following NME:

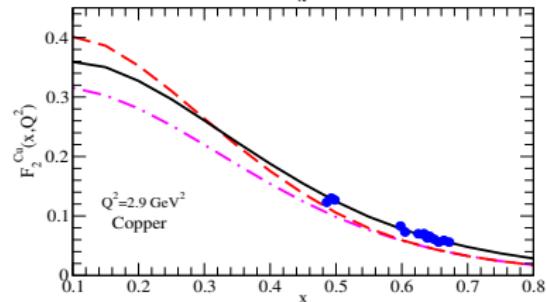
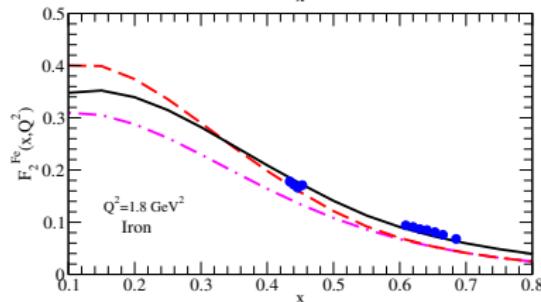
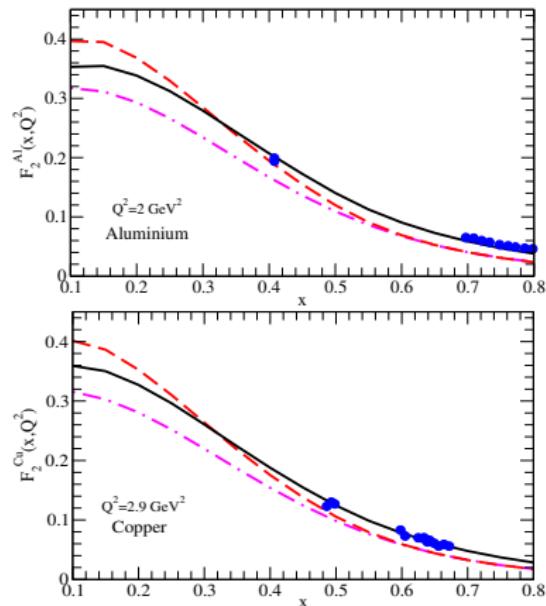
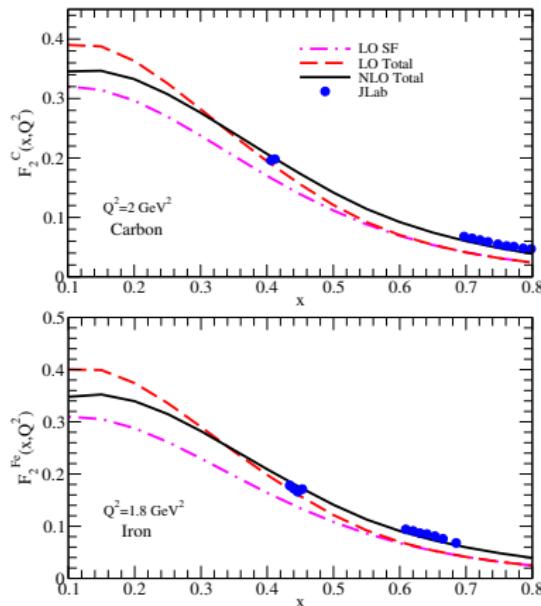


$$F_{iA}(x, Q^2) = F_{iA}^{SF}(x, Q^2) + F_{iA}^{\pi}(x, Q^2) + F_{iA}^{\rho}(x, Q^2) + F_{iA}^{\text{Shadowing}}(x, Q^2); i = 1 - 3$$

The results are presented at the leading order(LO) and next to the leading order(NLO)

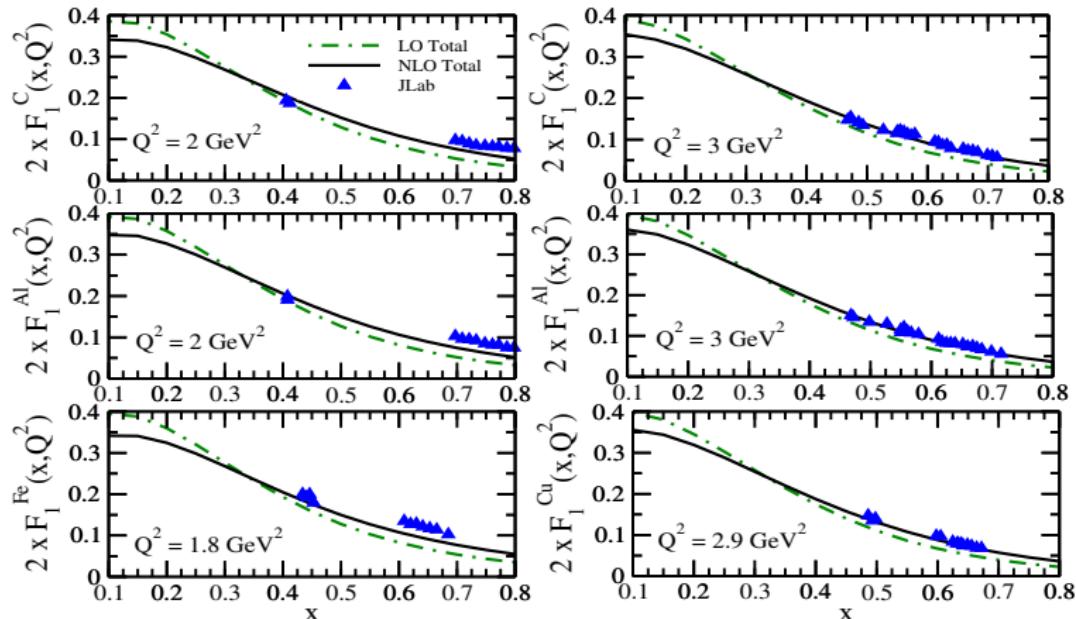
Electromagnetic Nuclear Structure Function

$F_{2A}^{EM}(x, Q^2)$ vs x



- At LO(SF \rightarrow Full): $\sim 15\%$ increase at low x in ${}^{12}\text{C}$, and difference vanishes at high x .
- At NLO: Results at low x get suppressed while at high x results get enhanced compared to LO results.
- NME depends on 'A'.

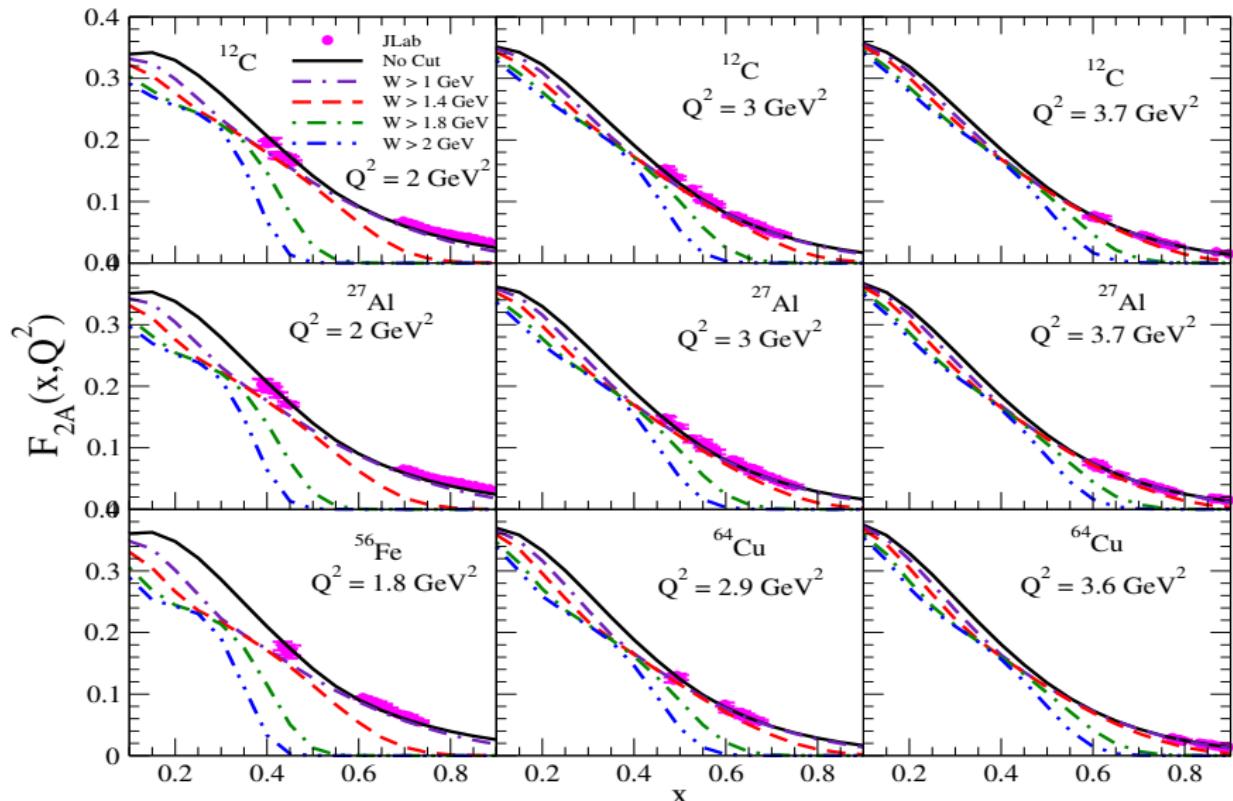
Electromagnetic Nuclear Structure Function $2xF_1A(x, Q^2)$ vs x



- Qualitatively similar in nature to that found in $F_{2A}^{EM}(x, Q^2)$.
- Quantitatively some variation, specially in low x region.

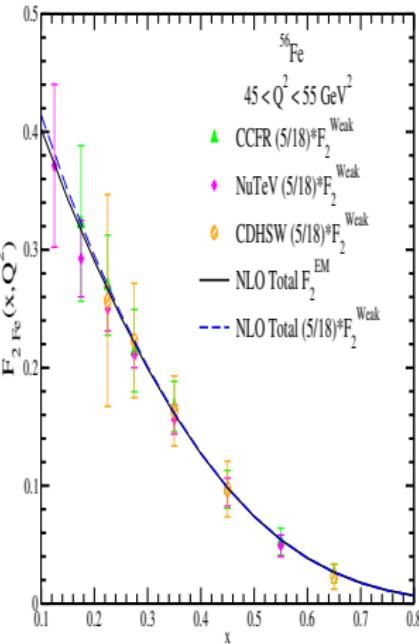
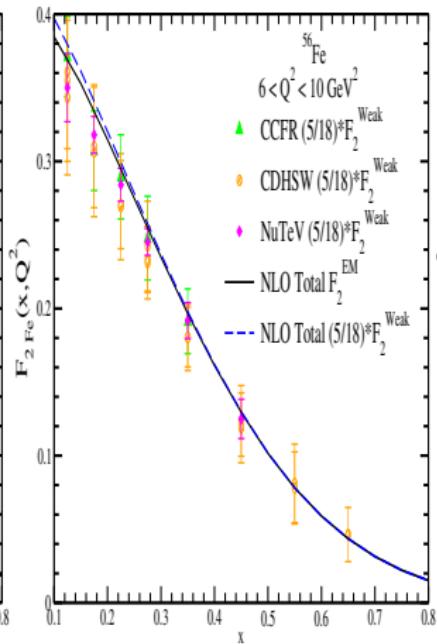
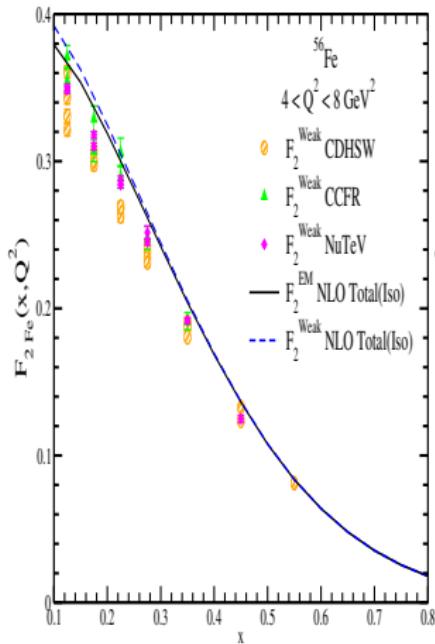
Deep Inelastic Scattering

$F_{2A}^{EM}(x, Q^2)$ for $l^- - A$

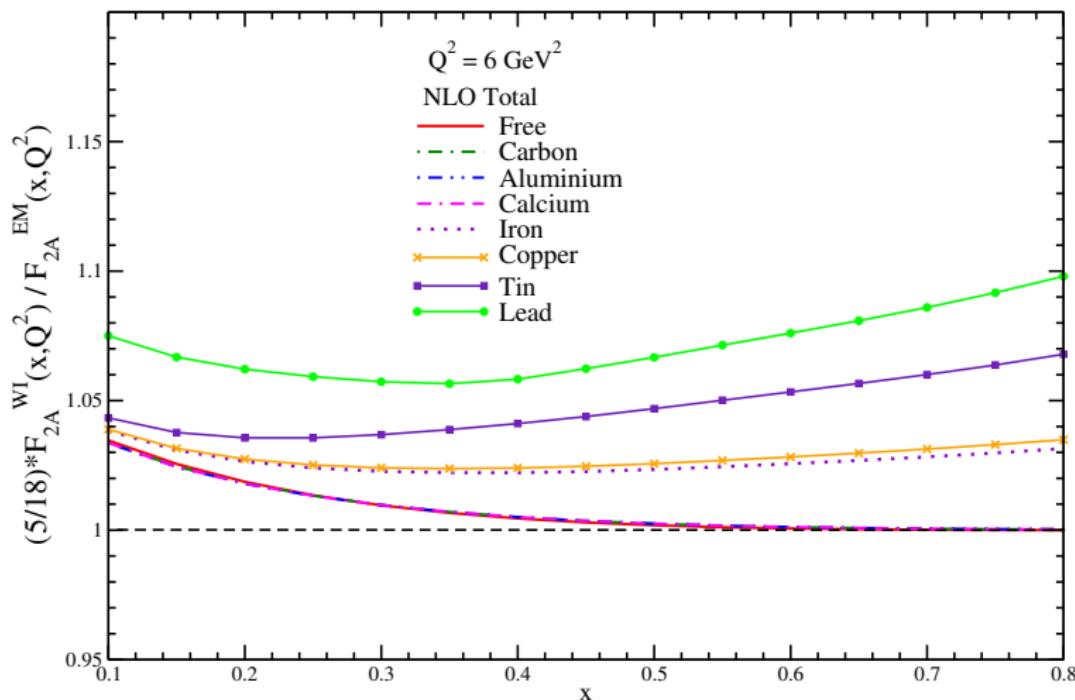


Deep Inelastic Scattering

$F_{2A}^{EM}(x, Q^2)$ and $F_{2A}^{Weak}(x, Q^2)$ (*Nucl. Phys. A* **955**, 58 (2016))

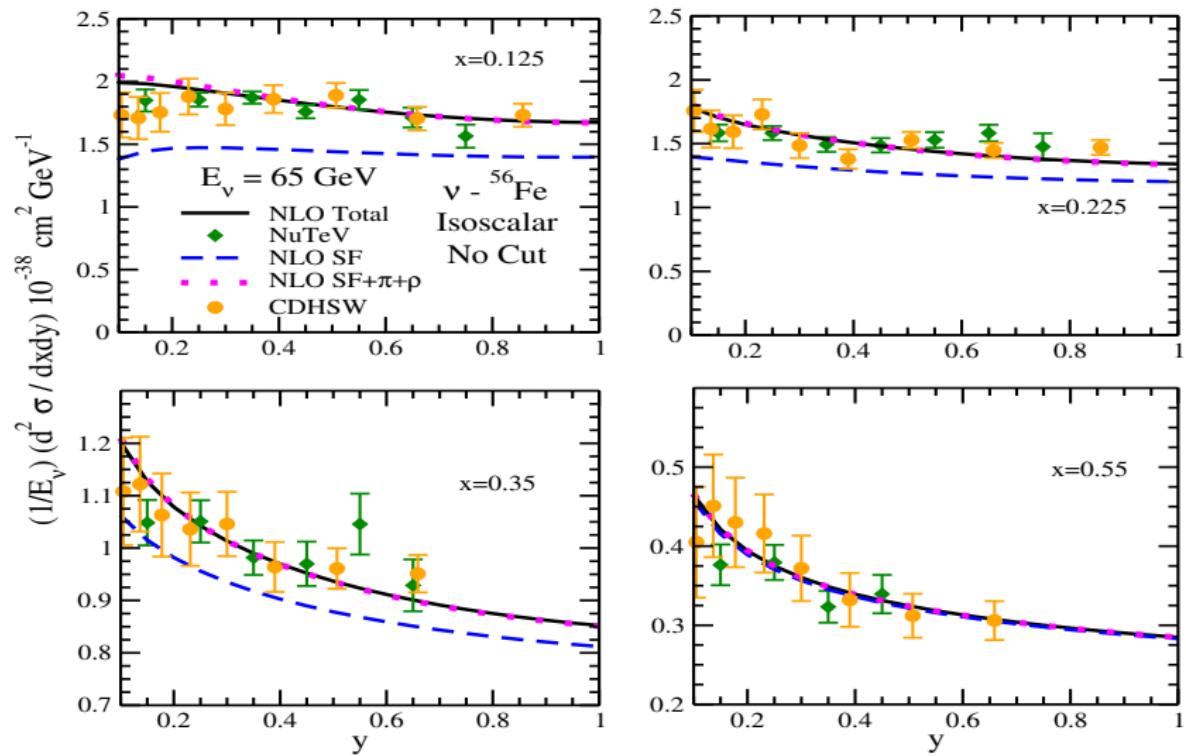


$$\frac{5}{18} F_{2A}^{Weak}(x, Q^2) \text{ vs } x (\text{Nucl. Phys. A } \mathbf{955}, 58 (2016))$$



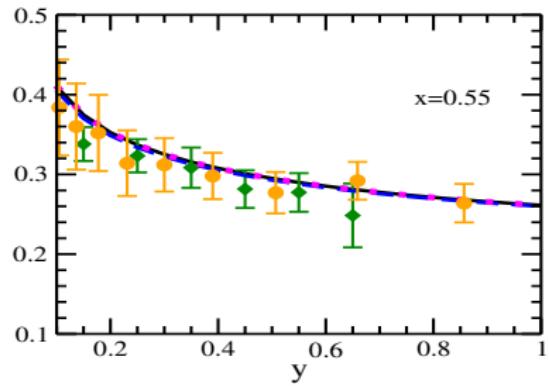
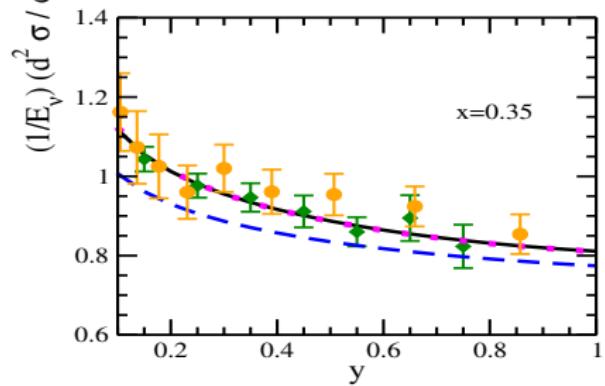
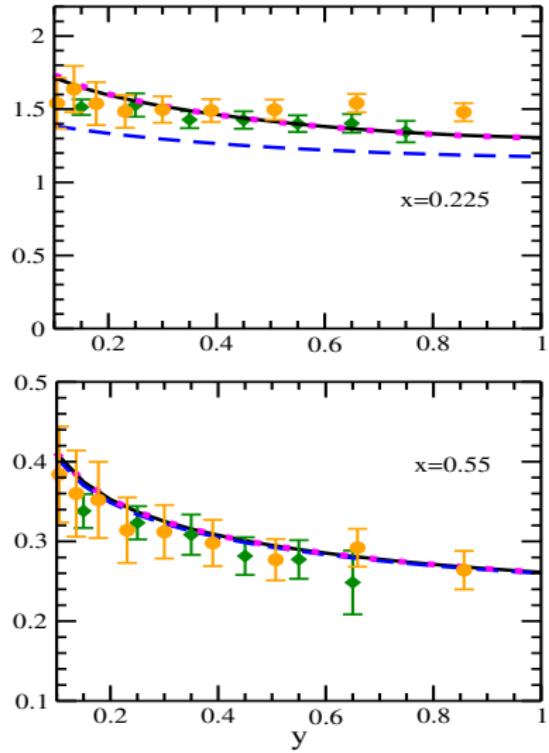
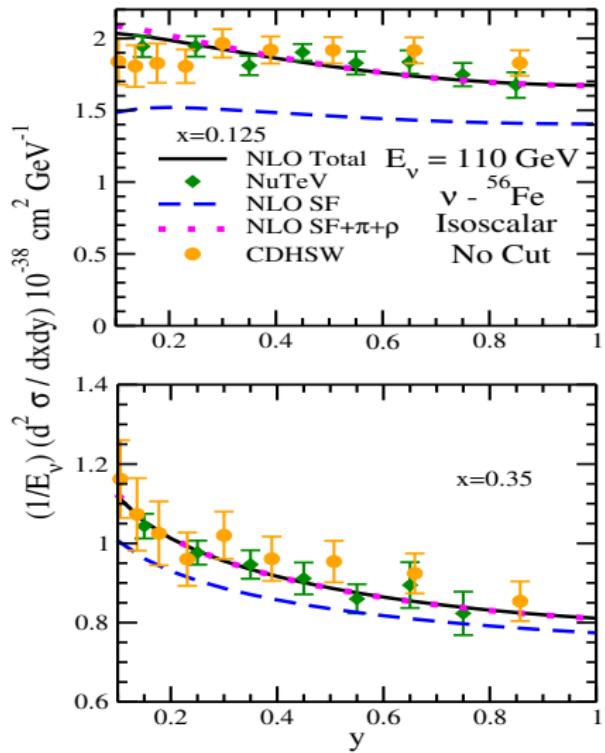
Deep Inelastic Scattering

$\frac{1}{E_\nu} \frac{d^2\sigma}{dxdy}$ for $\nu - {}^{56}\text{Fe}$ at $E_\nu = 65 \text{ GeV}$



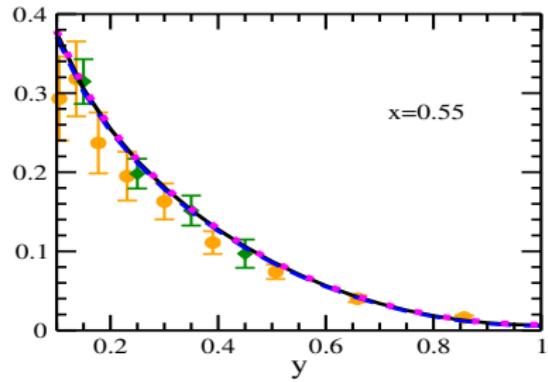
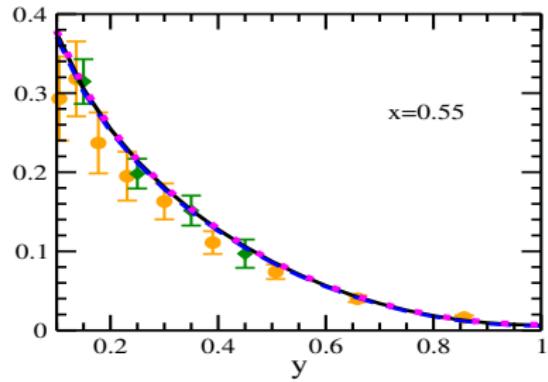
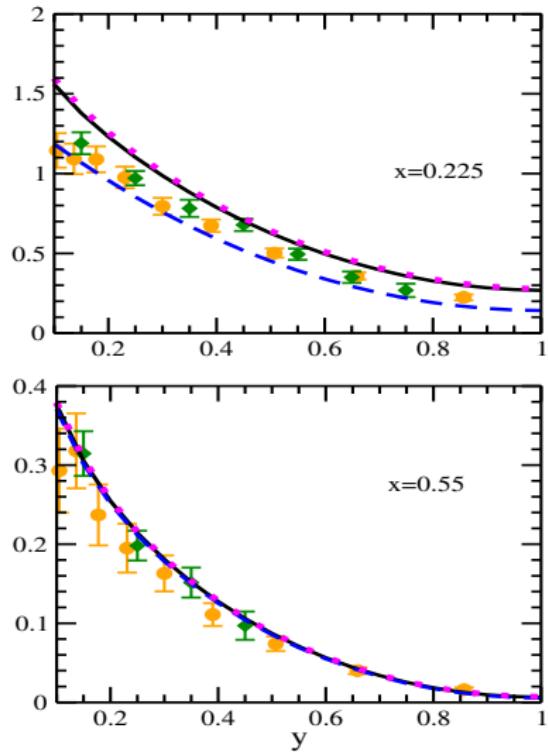
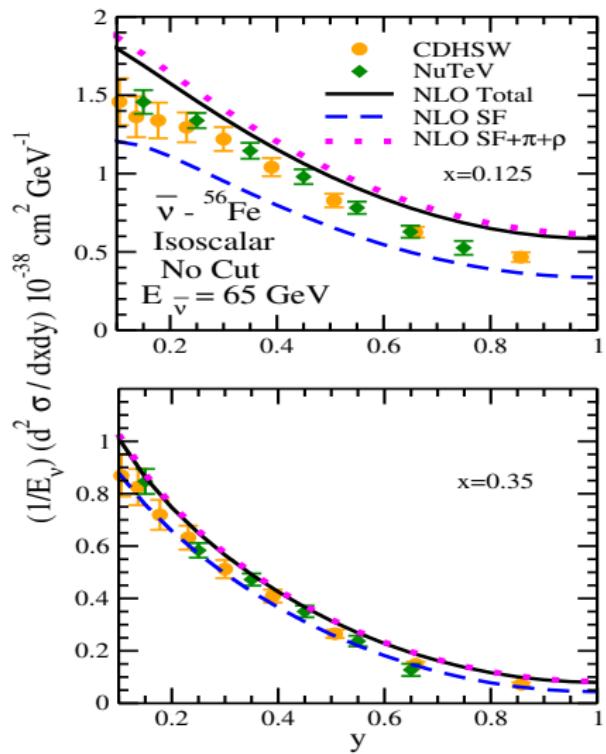
Deep Inelastic Scattering

$$\frac{1}{E_\nu} \frac{d^2\sigma}{dx dy} \text{ for } \nu - {}^{56}\text{Fe at } E_\nu = 110 \text{ GeV}$$



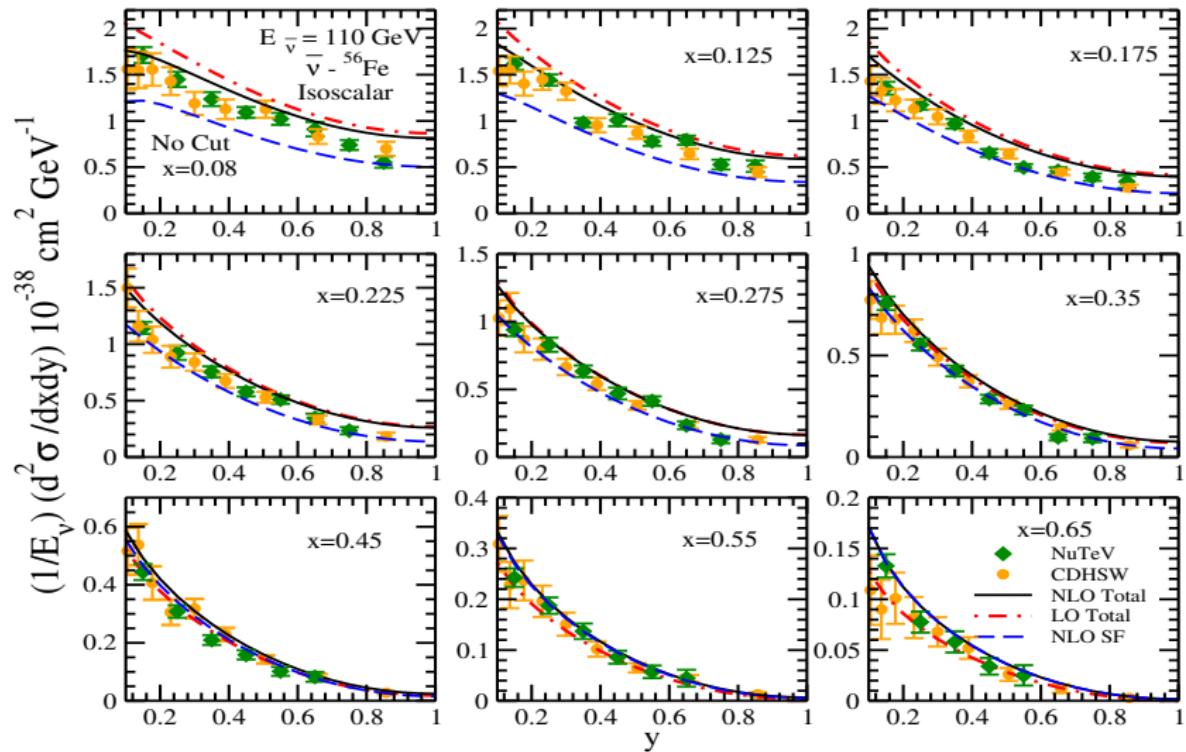
Deep Inelastic Scattering

$\frac{1}{E_{\bar{\nu}}} \frac{d^2\sigma}{dx dy}$ for $\bar{\nu} - {}^{56}\text{Fe}$ at $E_{\bar{\nu}} = 65 \text{ GeV}$



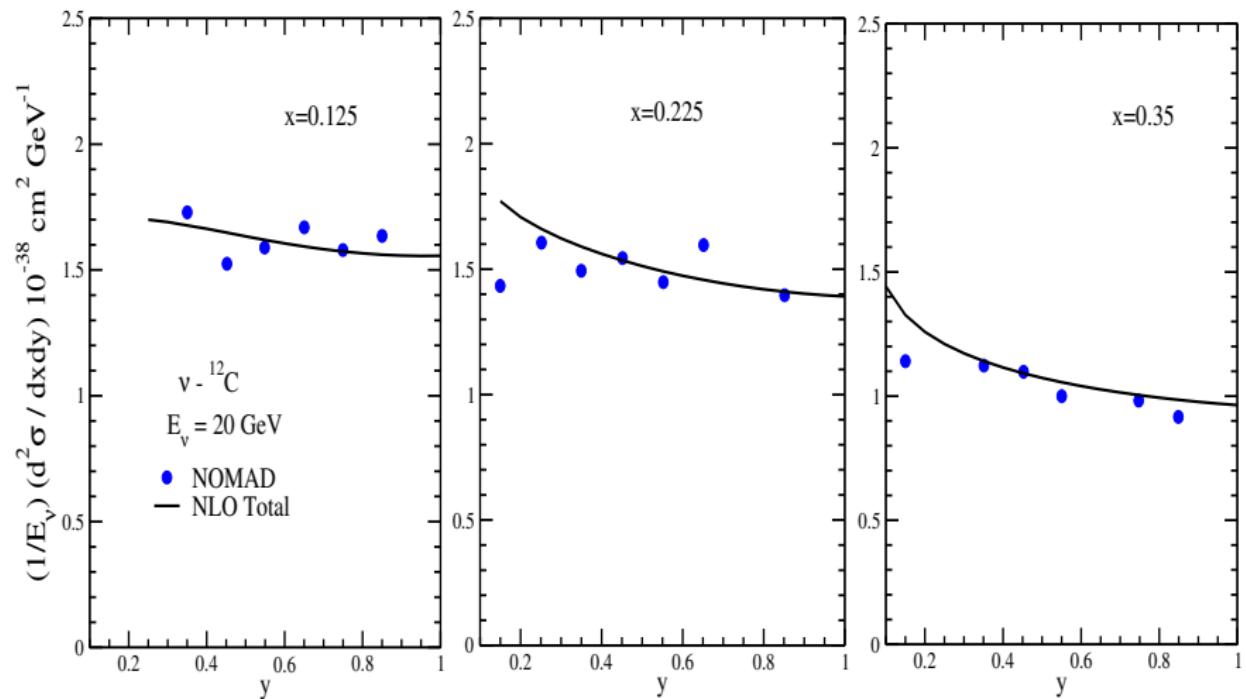
Deep Inelastic Scattering

$\frac{1}{E_{\bar{\nu}}} \frac{d^2\sigma}{dxdy}$ for $\bar{\nu} - {}^{56}\text{Fe}$ at $E_{\bar{\nu}} = 110$ GeV



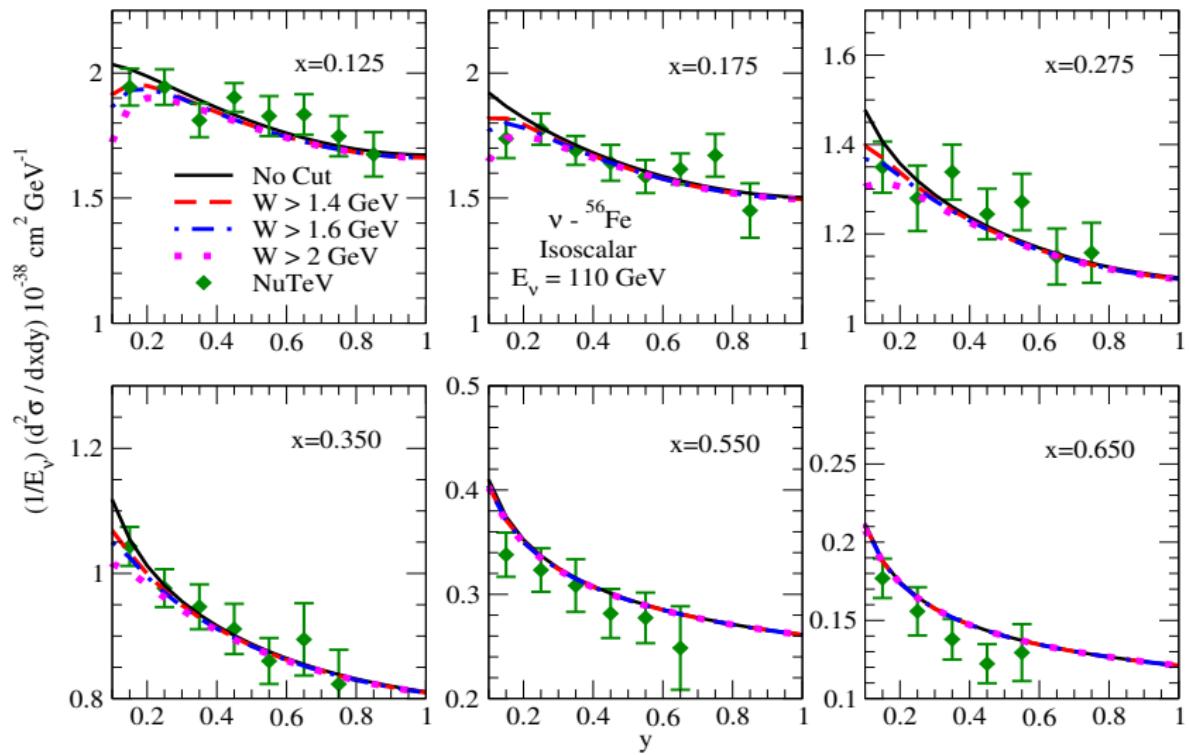
Deep Inelastic Scattering

$\frac{1}{E_\nu} \frac{d^2\sigma}{dxdy}$ for $\nu - {}^{12}\text{C}$ at $E_\nu = 20 \text{ GeV}$



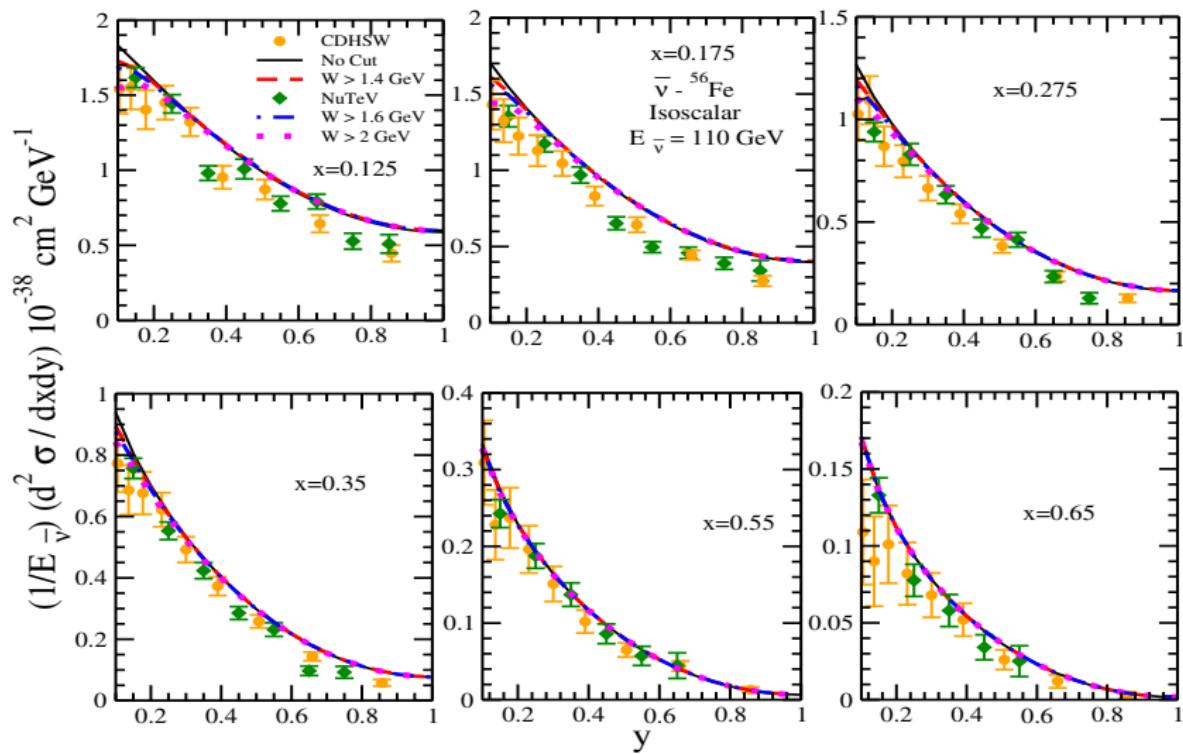
Deep Inelastic Scattering

$\frac{1}{E_\nu} \frac{d^2\sigma}{dxdy}$ for $\nu - {}^{56}\text{Fe}$ at $E_\nu = 110$ GeV



Deep Inelastic Scattering

$\frac{1}{E_{\bar{\nu}}} \frac{d^2\sigma}{dx dy}$ for $\bar{\nu} - {}^{56}\text{Fe}$ at $E_{\bar{\nu}} = 110 \text{ GeV}$



References

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- H. Haider, F. Zaidi, M. Sajjad Athar, S. K. Singh and I. Ruiz Simo, “Nuclear medium effects in structure functions of nucleon at moderate Q^2 ,” *Nucl. Phys. A* **943**, 58 (2015).
- H. Haider, I. Ruiz Simo and M. Sajjad Athar, “ $\nu(\bar{\nu})$ - ^{208}Pb deep inelastic scattering,” *Phys. Rev. C* **85**, 055201 (2012).
- H. Haider, I. R. Simo, M. S. Athar and M. J. V. Vacas, “Nuclear medium effects in $\nu(\bar{\nu})$ -nucleus deep inelastic scattering,” *Phys. Rev. C* **84**, 054610 (2011).
- M. Sajjad Athar, I. Ruiz Simo and M. J. Vicente Vacas, “Nuclear medium modification of the $F_2(x, Q^2)$ structure function,” *Nucl. Phys. A* **857**, 29 (2011).

$\nu/\bar{\nu}$ induced single pion production(SPP)

Charged current(CC)

$$\nu_l p \rightarrow l^- p \pi^+$$

$$\nu_l n \rightarrow l^- n \pi^+$$

$$\nu_l n \rightarrow l^- p \pi^0$$

$$\bar{\nu}_l n \rightarrow l^+ n \pi^-$$

$$\bar{\nu}_l p \rightarrow l^+ p \pi^-$$

$$\bar{\nu}_l p \rightarrow l^+ n \pi^0$$

$l = e, \mu$

Neutral current(NC)

$$\nu_l p \rightarrow \nu_l n \pi^+$$

$$\nu_l p \rightarrow \nu_l p \pi^0$$

$$\nu_l n \rightarrow \nu_l n \pi^0$$

$$\nu_l n \rightarrow \nu_l p \pi^-$$

$$\bar{\nu}_l p \rightarrow \bar{\nu}_l p \pi^0$$

$$\bar{\nu}_l p \rightarrow \bar{\nu}_l n \pi^+$$

$$\bar{\nu}_l n \rightarrow \bar{\nu}_l n \pi^0$$

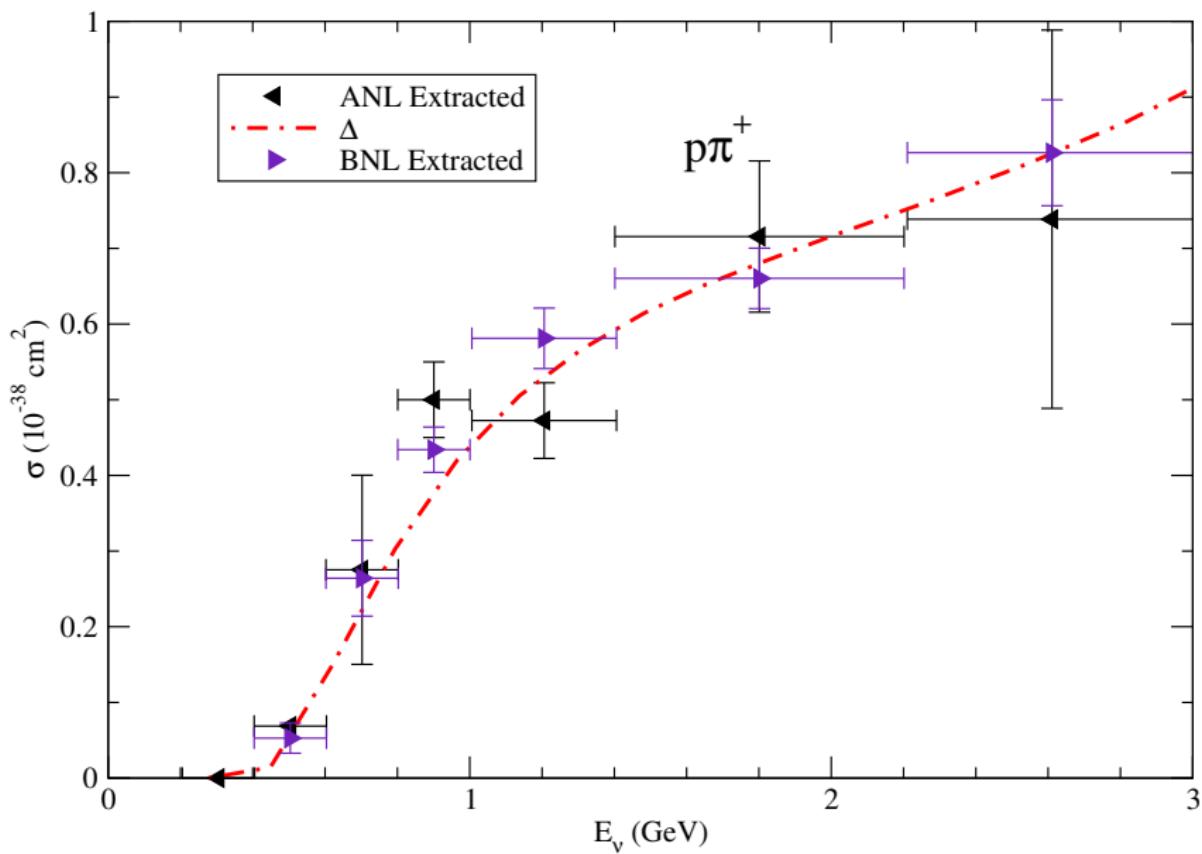
$$\bar{\nu}_l n \rightarrow \bar{\nu}_l p \pi^-$$

One Pion Production

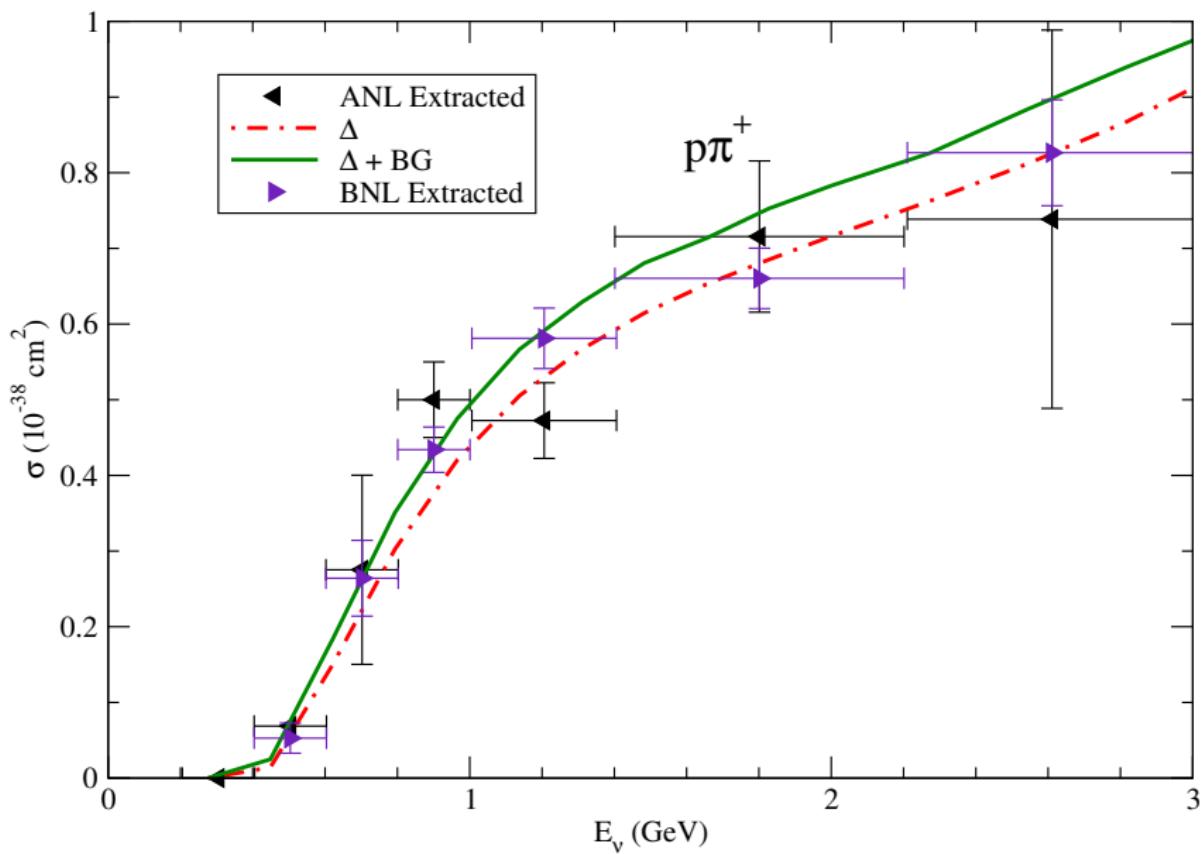
- We have considered non-resonant background terms, $P_{33}(1232)$ resonance, and other higher resonances like $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$, $S_{11}(1650)$ and $P_{13}(1720)$.
- For the non-resonant background terms a microscopic approach based on SU(2) non-linear sigma model has been used.
- The vector form factors for the resonances are obtained by using the relationship between the electromagnetic resonance form factors and helicity amplitudes provided by MAID (Eur. Phys. J. Special Topics 198, 141 **2011**).
- Axial coupling $C_5^A(0)=1.0$ and $M_A=1.026\text{GeV}$, in the case of $P_{33}(1232)$ resonance is obtained by fitting the ANL and BNL ν -deuteron reanalyzed scattering data.
(C. Wilkinson et al., Phys. Rev. D 90 112017 **2014**).

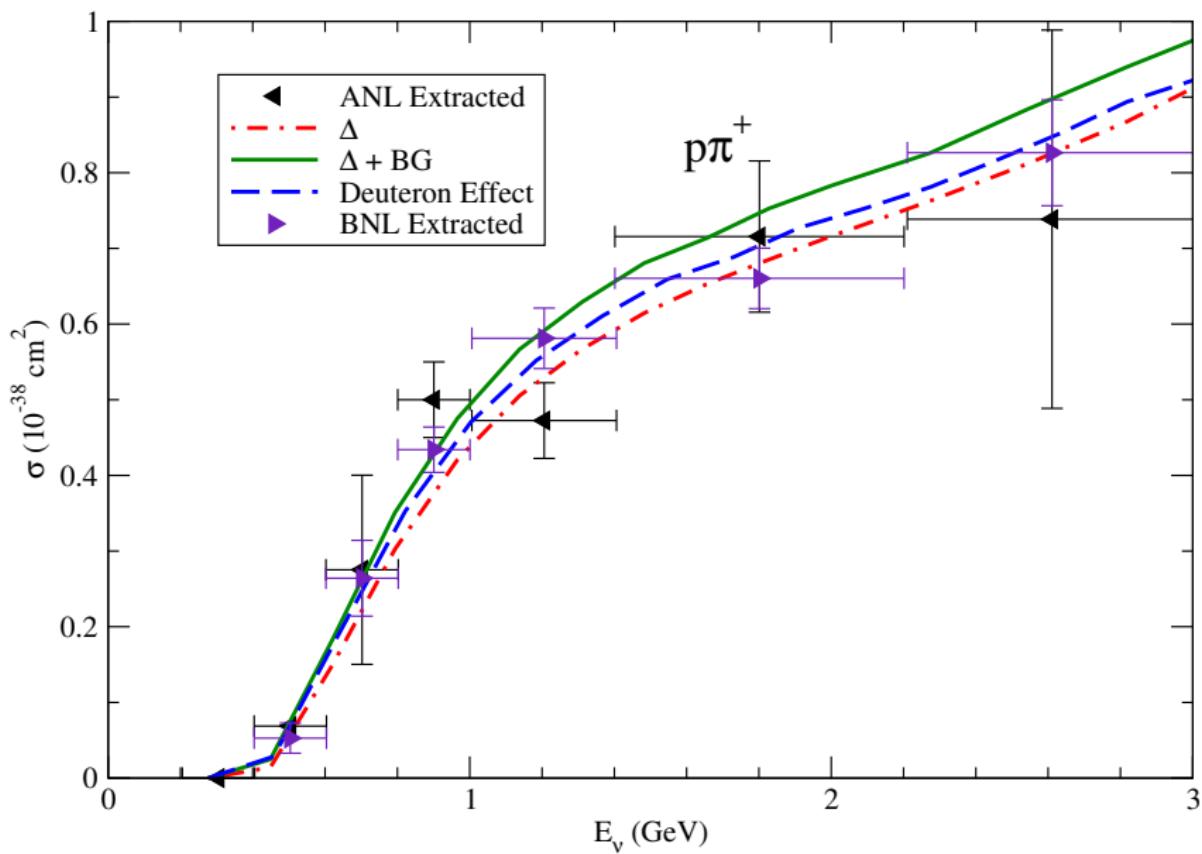
M. Rafi Alam, M. Sajjad Athar, S. Chauhan and S. K. Singh,
“Weak charged and neutral current induced one pion production off the nucleon,”
Int. J. Mod. Phys. E **25**, 1650010 (**2016**).

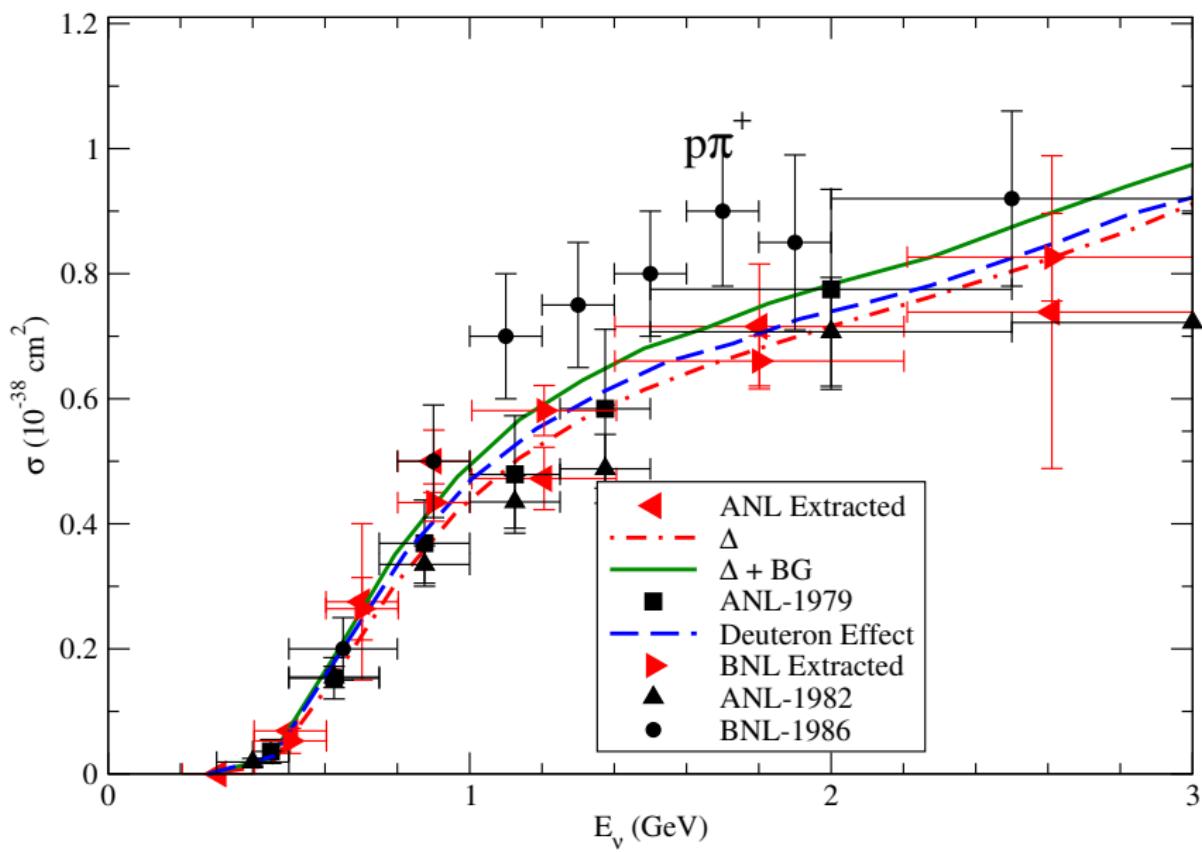
$$\nu_\mu p \rightarrow \mu^- p\pi^+$$



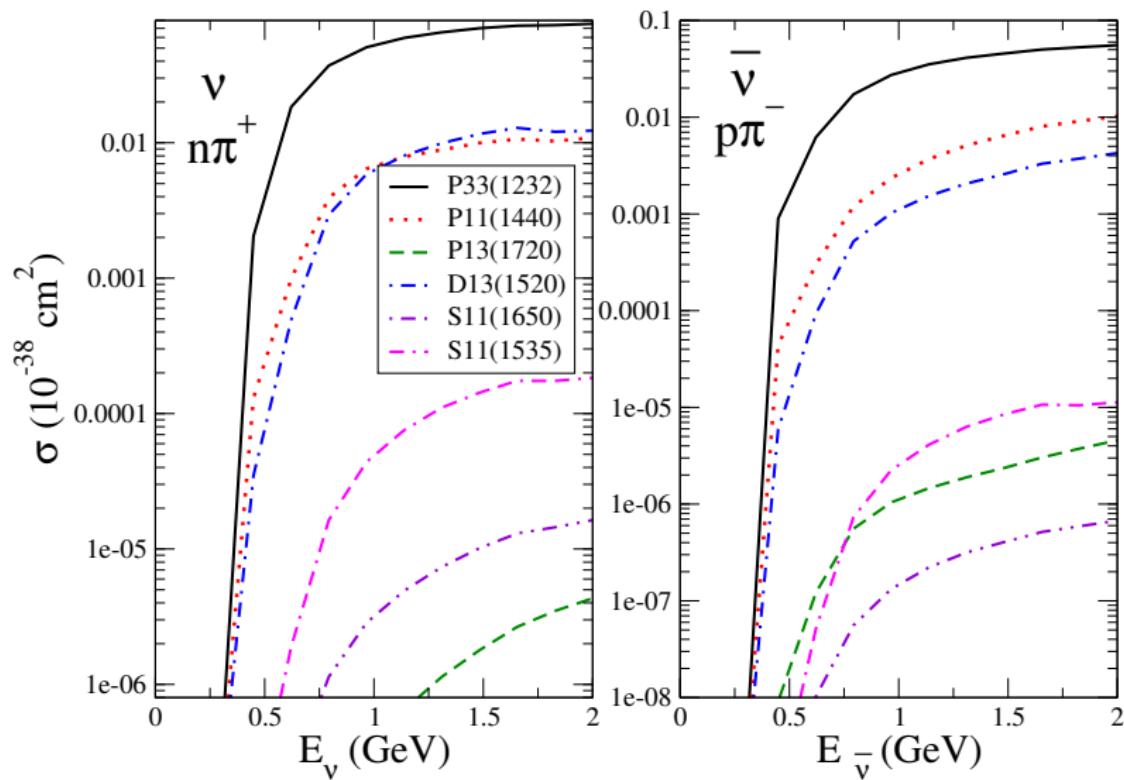
$$\nu_\mu p \rightarrow \mu^- p\pi^+$$



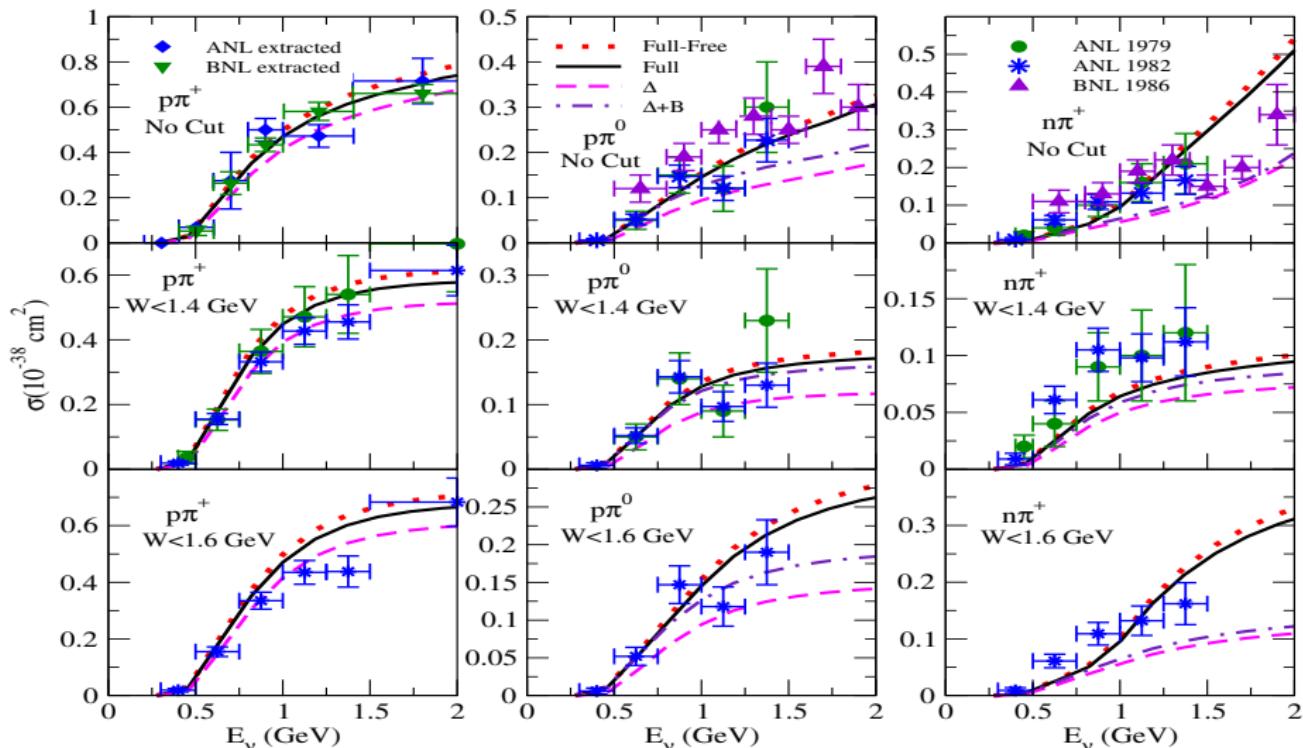




The results are presented for the total scattering cross section for $\nu_\mu n \rightarrow \mu^- n\pi^+$ (Left panel) and $\bar{\nu}_\mu p \rightarrow \mu^+ p\pi^-$ (Right panel) processes where the individual contribution of various resonances have been shown.



Neutrino induced Charged-current pion production

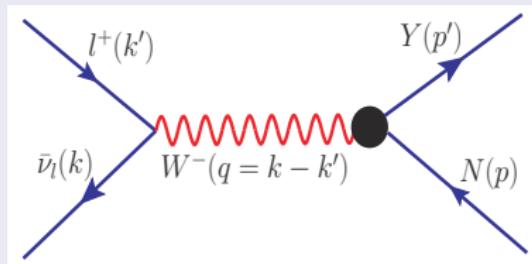


dashed line: results in the $\Delta(1232)$ dominance model, **dashed-dotted line:** include NRB terms; **solid line:** full calculation, with deuteron effect.
dotted line: results of the full calculation without deuteron effect.

$|\Delta S| = 1$ processes

Antineutrino induced Single Hyperon Production

$$\begin{aligned}\bar{\nu}_l(k) + p(p) &\rightarrow l^+(k') + \Lambda(p') \\ \bar{\nu}_l(k) + p(p) &\rightarrow l^+(k') + \Sigma^0(p') \\ \bar{\nu}_l(k) + n(p) &\rightarrow l^+(k') + \Sigma^-(p')\end{aligned}$$



These processes are Cabibbo suppressed as compared to the $\Delta S = 0$ associated production of hyperons.

$$\begin{array}{lll} \bar{\nu}_l + n(p) \rightarrow l^+ + p(n) + \pi^-(\pi^0) & \nu_e / \nu_\mu \\ \bar{\nu}_l + p \rightarrow l^+ + \Lambda & E_{th} \sim 0.15/0.28 \text{ GeV} \\ \bar{\nu}_l + p \rightarrow l^+ + \Delta & E_{th} = 0.19/0.32 \text{ GeV} \\ & E_{th} = 0.34/0.48 \text{ GeV} \end{array}$$

Differential cross section

$d\sigma$ for the process

$$\bar{\nu}_l(k) + N(p) \rightarrow l^+(k') + Y(p'),$$

$$d\sigma = \frac{1}{(2\pi)^2} \frac{1}{4E_\nu \sqrt{s}} \delta^4(k + p - k' - p') \frac{d^3 k'}{2E_{k'}} \frac{d^3 p'}{2E_{p'}} |\mathcal{M}|^2$$

- $q = p' - p = k - k'$
- $s = (q + p)^2$
- $E_\nu = \frac{s - M^2}{2\sqrt{s}}$ is the CM neutrino energy
- \mathcal{M} is the transition matrix element

Transition matrix element

Vector operator

$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}_{B'}(p') \left[\mathcal{O}_{V(B'B)}^\mu(p', p) - \mathcal{O}_{A(B'B)}^\mu(p', p) \right] u_B(p) \times \bar{u}_l(k') \gamma_\mu (1 + \gamma_5) v_{\nu_l}(k)$$

Axial vector operator

- $G \rightarrow G_F \cos \theta_c$ for strangeness conserving processes.
- $G \rightarrow G_F \sin \theta_c$ for $|\Delta S| = 1$ processes considered here.

$$\mathcal{O}_{V(B'B)}^\mu(p', p) = f_1^{B'B}(Q^2) \gamma_\mu + \frac{i \sigma^{\mu\nu} q_\nu}{M_B + M'_B} f_2^{B'B}(Q^2) + \frac{q^\mu}{M_B + M'_B} f_3^{B'B}(Q^2).$$

Vector FF

Magnetic FF

Induced scalar FF

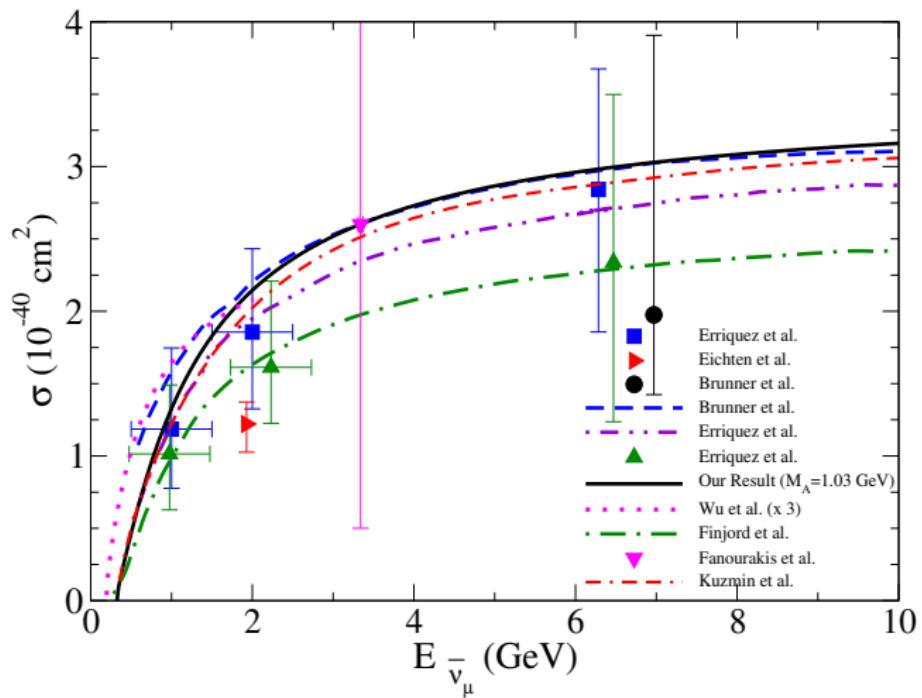
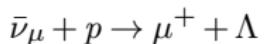
$$\mathcal{O}_{A(B'B)}^\mu(p', p) = g_1^{B'B}(Q^2) \gamma_\mu \gamma_5 + \frac{i \sigma^{\mu\nu} q_\nu}{M_B + M'_B} \gamma_5 g_2^{B'B}(Q^2) + \frac{q^\mu}{M_B + M'_B} \gamma_5 g_3^{B'B}(Q^2).$$

Axial vector FF

Weak Electric FF

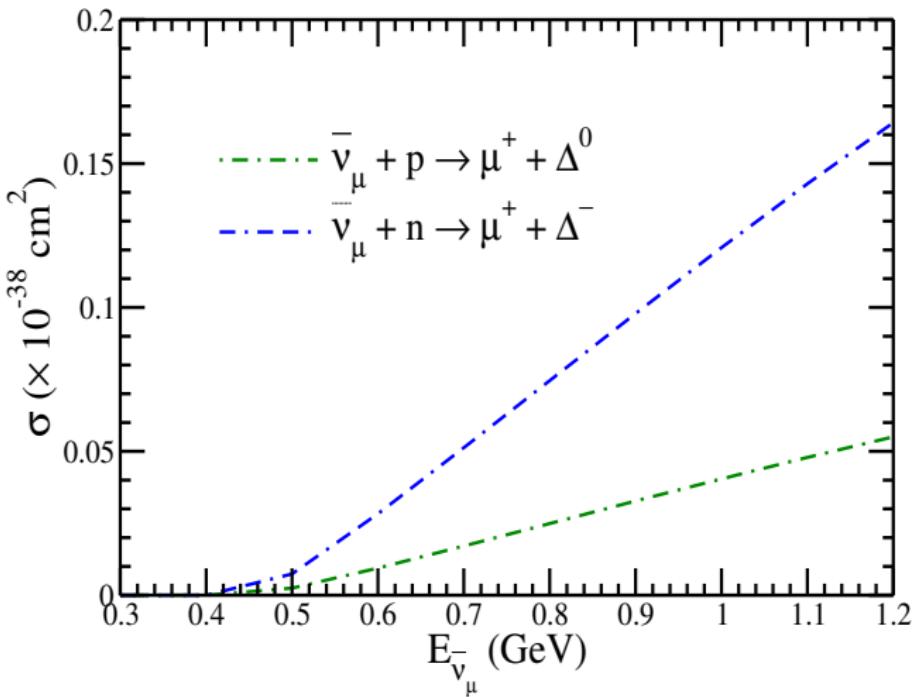
Induced pseudoscalar FF

Λ production cross section off the free nucleon target.
J. Phys. G **42**, 055107 (2015)



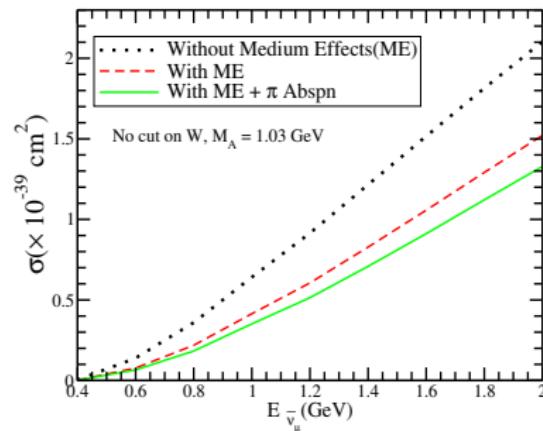
Data: 1977, 1978 (Gargamelle,CERN), 1980(BNL), 1990(SKAT)

σ vs E_ν for the processes $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^0$ and $\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^-$

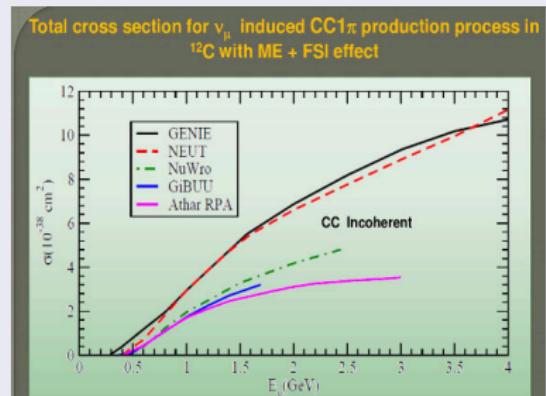


$\bar{\nu}_\mu + {}^{12}C$ Scattering—Effect of Nuclear Medium & FSI

Delta dominance model



Comparison with the different models



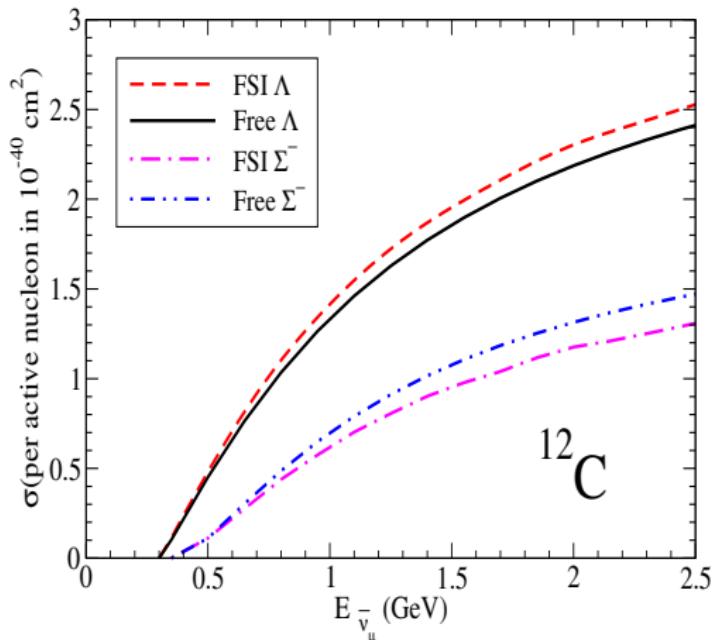
Eur. Phys. J. A **43**, 209 (2010).

$E_{\bar{\nu}_\mu}$ (GeV)	σ with ME (% reduction)	σ with ME + π absorption (% reduction)
0.8	42	14
1.0	36	15
1.4	31	14
1.8	28	15

σ vs $E_{\bar{\nu}_\mu}$ in ^{12}C

The produced hyperons are affected by the FSI within the nucleus through the hyperon-nucleon quasielastic and charge exchange scattering processes like

- $\Lambda + n \rightarrow \Sigma^- + p, \quad \Lambda + n \rightarrow \Sigma^0 + n,$
- $\Sigma^- + p \rightarrow \Lambda + n, \quad \Sigma^- + p \rightarrow \Sigma^0 + n, \text{ etc.}$



FSI leads to an enhancement in the Λ production cross section and a suppression in the Σ^- production cross section

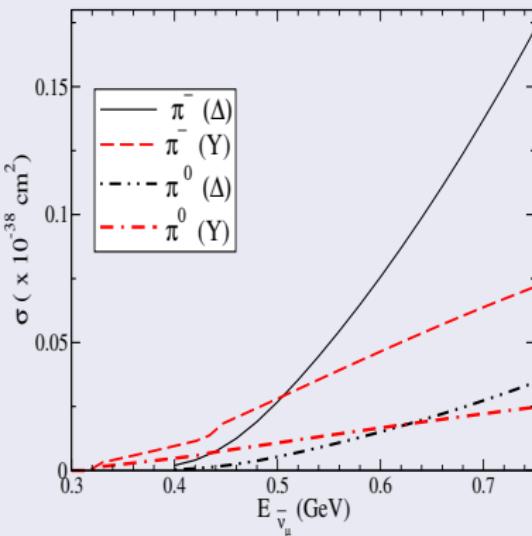
% change in σ		
$E_{\bar{\nu}}$ (GeV)	Λ	Σ^-
0.65	+5	-9
1.1	+6	-11
2.0	+5	-11

HYPERON GIVING RISE TO PIONS

As the decay modes of hyperons to pions are highly suppressed in the nuclear medium, making them live long enough to pass through the nucleus and decay outside the nuclear medium.

Therefore, the produced pions are less affected by the strong interaction of nuclear field, and their FSI have not been taken into account.

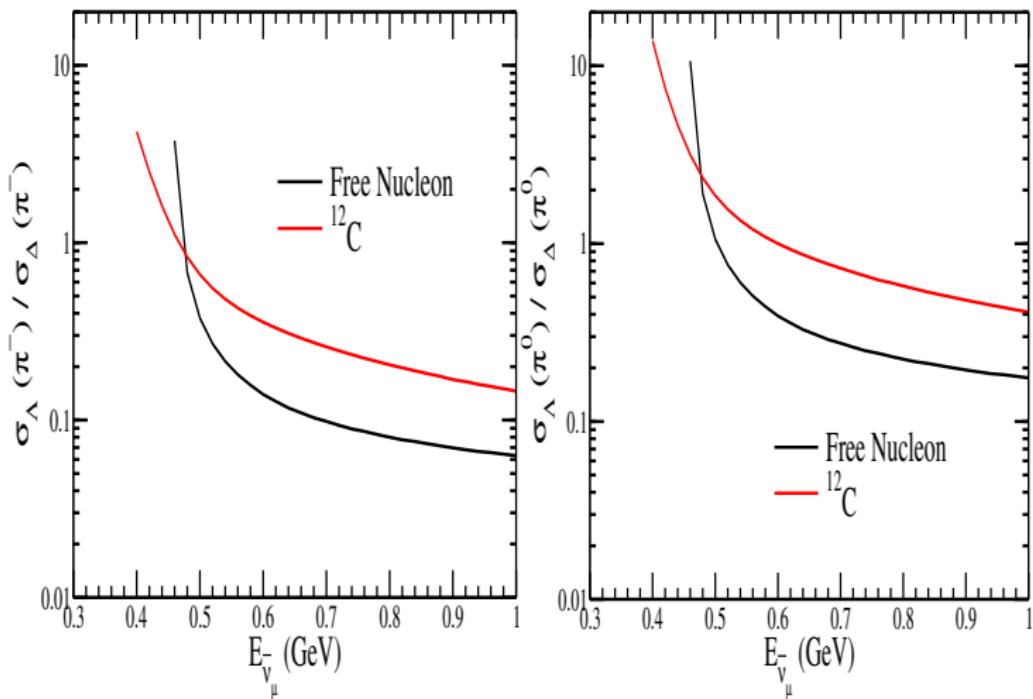
σ vs $E_{\bar{\nu}_\mu}$



Phys. Rev. D **88**, 077301 (2013)

Ratio $\frac{\sigma_\Delta}{\sigma_\Delta}$ vs $E_{\bar{\nu}_\mu}$

Comparison of π^- (LHS) and π^0 (RHS) production cross section off the free nucleon and nucleon bound in nuclei



% contribution pi from the Λ and from the Δ

- *In Nucleon*

$\sigma_{\Lambda}(\pi^-) \sim 14(10)\%$ of $\sigma_{\Delta}(\pi^-)$ at $E_{\bar{\nu}_{\mu}} = 600(700)\text{MeV}$, and
 $\sigma_{\Lambda}(\pi^0) \sim 40(28)\%$ of $\sigma_{\Delta}(\pi^0)$ at $E_{\bar{\nu}_{\mu}} = 600(700)\text{MeV}$.

- *In the Carbon Nucleus*

$\sigma_{\Lambda}(\pi^-) \sim 36(26)\%$ of $\sigma_{\Delta}(\pi^-)$ at $E_{\bar{\nu}_{\mu}} = 600(700)\text{MeV}$, and
 $\sigma_{\Lambda}(\pi^0) \sim 100(73)\%$ of $\sigma_{\Delta}(\pi^0)$ at $E_{\bar{\nu}_{\mu}} = 600(700)\text{MeV}$.

In the nucleus pions from the Λ and the pions from the Δ are compatible processes, if nuclear medium effects are taken into account.

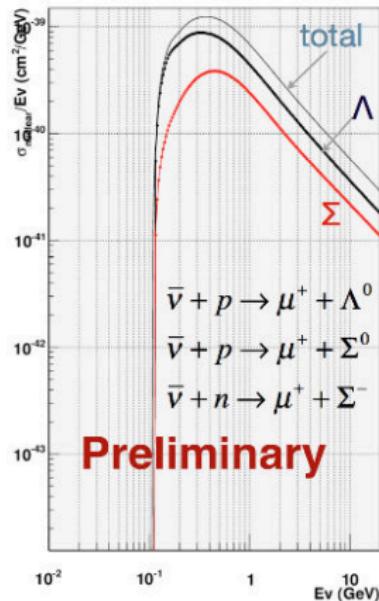
Ongoing devel. highlight - QE Hyperon production

Simulation of three new $\Delta S=1$ channels in GENIE:

- $\bar{\nu}_\ell + p \rightarrow \ell^+ + \Lambda^0$
- $\bar{\nu}_\ell + p \rightarrow \ell^+ + \Sigma^0$
- $\bar{\nu}_\ell + n \rightarrow \ell^+ + \Sigma^-$

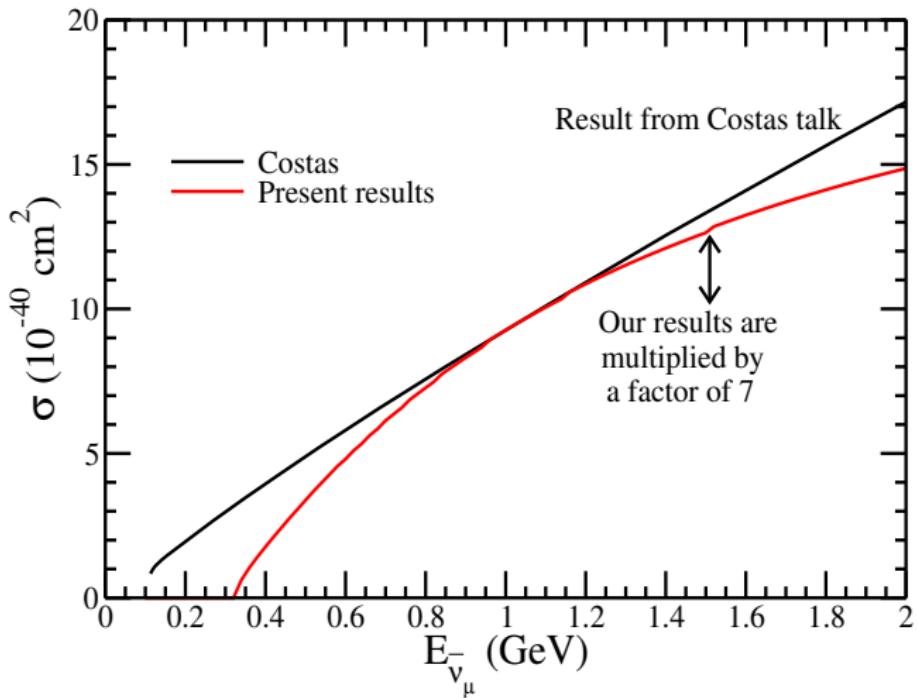
Implementing SU(3) model of Pais,
Ann. Phys. 63, 361 (1971); Cabibo
and Chilton, v136, N6B (1965)

$$\sigma_{\Delta S} \approx \tan^2 \theta_C \cdot \sigma_{QE} = 0.05 \sigma_{QE}$$



Being implemented by E. Poage, E. Morrissey and H. Gallagher.

Comparison of σ vs $E_{\bar{\nu}_\mu}$ for the process $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$



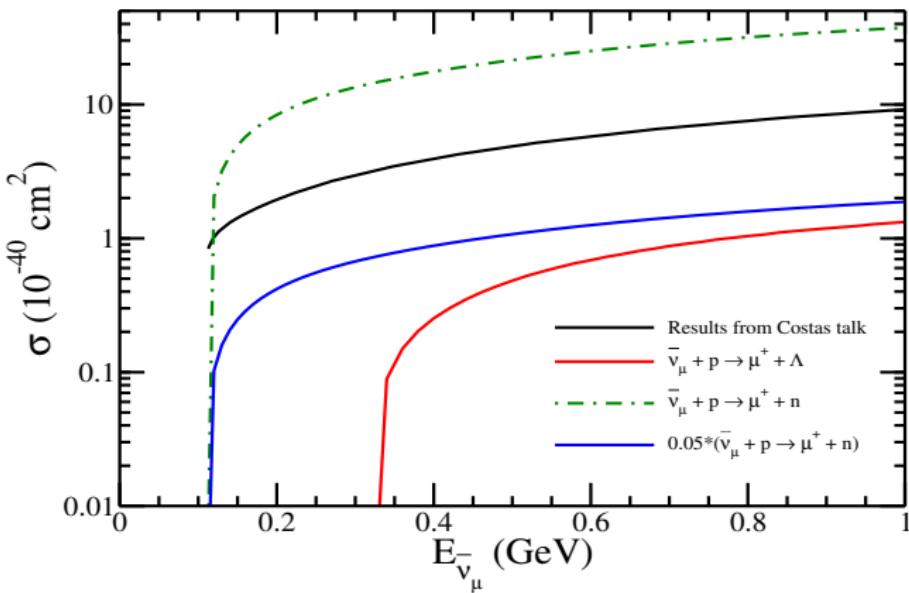
Comparison of the present results and Costas results

CCQE cross section(σ_{CCQE}) for $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

$$\sigma_{\Delta S} = \tan^2 \theta_c \times \sigma_{CCQE} = 0.05 \times \sigma_{CCQE}$$

σ_Λ for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ (Present Model)

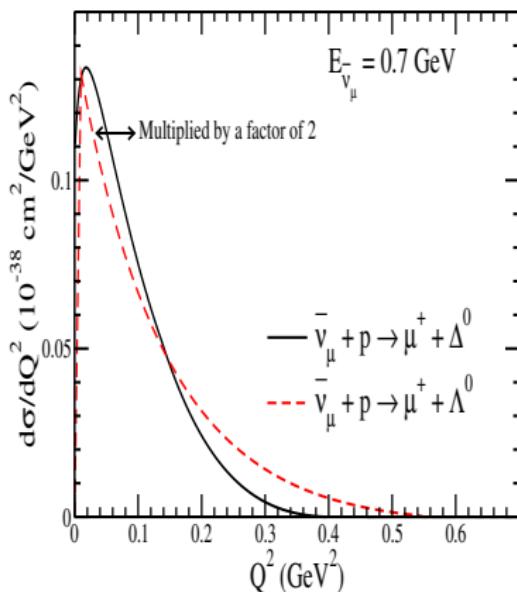
Costas presented result



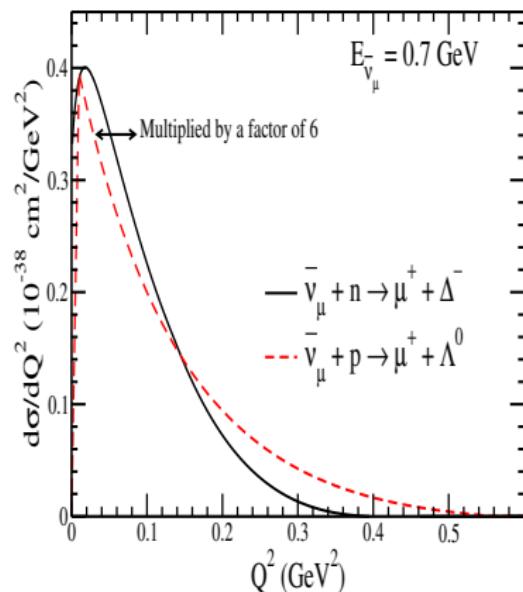
Comparison of $d\sigma/dQ^2$ vs Q^2 for the processes:(Free Nucleon Target)

- (a) $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^0$ and $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$
(b) $\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^-$ and $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$

Λ production is about 50% of the Δ^0 production cross section from the free proton target



Λ production from free proton target is about 16% of the Δ^- production cross section from the free neutron target

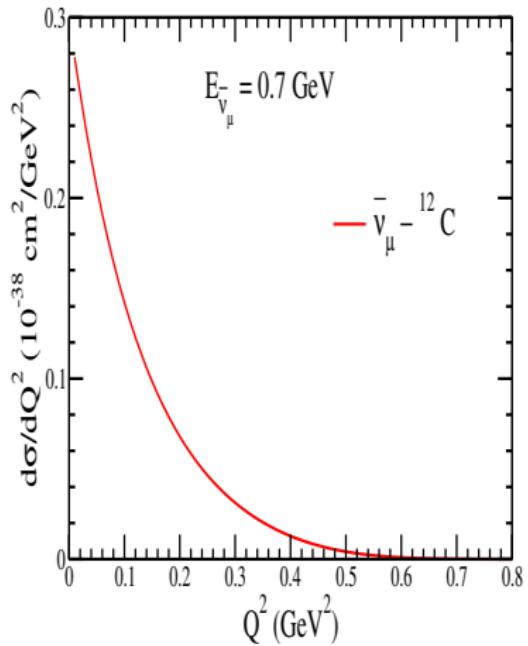
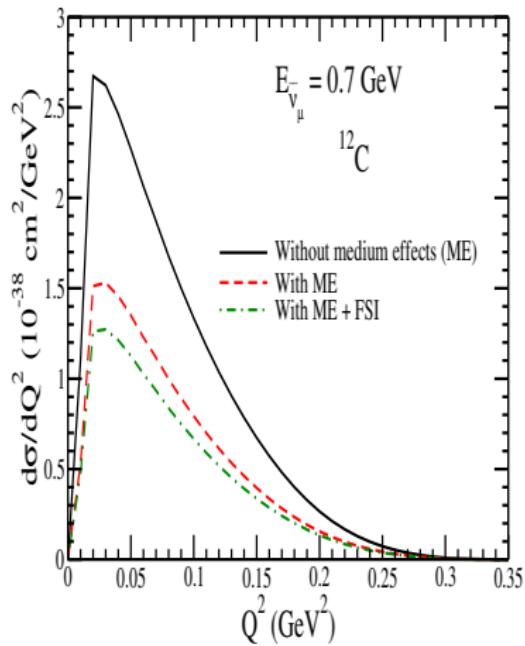


$d\sigma/dQ^2$ vs Q^2 for the processes: (Carbon Nucleus as the Target)



(a) LHS: In the Δ dominance model

(b) RHS: Through Λ production



Polarization Observables

Longitudinal component of polarization 3-vector

$$\frac{d\sigma}{dQ^2} P_L(Q^2) = \frac{G_F^2 \sin^2 \theta_c}{8\pi} \left[\frac{\left(E_{\bar{\nu}_\mu}^2 - E_\mu^2 + m_\mu^2 \right) m_Y \mathcal{A}(Q^2, E_{\bar{\nu}_\mu}) + |\vec{q}|^2 \mathcal{B}(Q^2, E_{\bar{\nu}_\mu})}{|\vec{q}| E_{p'} m_N E_{\bar{\nu}_\mu}^2} \right]$$

Polarization Observables

Longitudinal component of polarization 3-vector

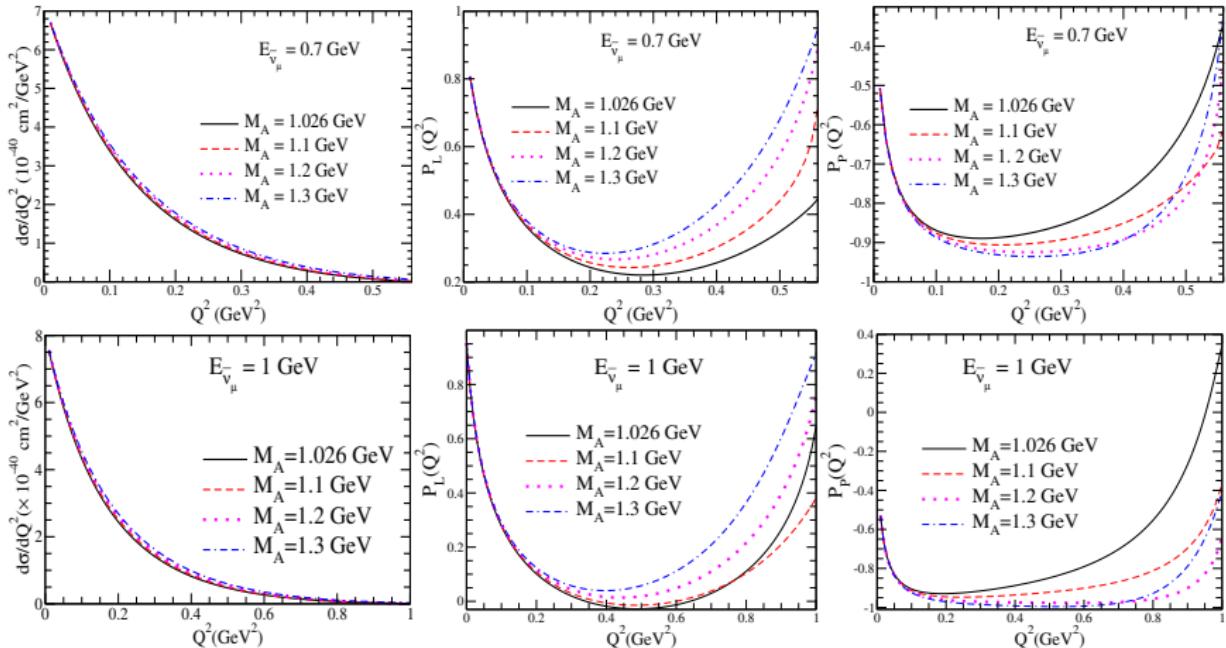
$$\frac{d\sigma}{dQ^2} P_L(Q^2) = \frac{G_F^2 \sin^2 \theta_c}{8\pi} \left[\frac{\left(E_{\bar{\nu}_\mu}^2 - E_\mu^2 + m_\mu^2 \right) m_Y \mathcal{A}(Q^2, E_{\bar{\nu}_\mu}) + |\vec{q}|^2 \mathcal{B}(Q^2, E_{\bar{\nu}_\mu})}{|\vec{q}| E_{p'} m_N E_{\bar{\nu}_\mu}^2} \right]$$

Perpendicular component of polarization 3-vector

$$\frac{d\sigma}{dQ^2} P_P(Q^2) = -\frac{G_F^2 \sin^2 \theta_c}{4\pi} \frac{|\vec{k}'|}{|\vec{q}|} \frac{\mathcal{A}(Q^2, E_{\bar{\nu}_\mu}) \sin \theta}{m_N E_{\bar{\nu}_\mu}}$$

Quasielastic production of polarized hyperons in antineutrino-nucleon reactions
F. Akbar, M. Rafi Alam, M. Sajjad Athar and S.K. Singh
Phys. Rev. D 94 114031 (2016).

M_A -dependence: $\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2 .
 $\bar{\nu}_\mu p \rightarrow \mu^+ \Lambda$ at $E_{\bar{\nu}_\mu} = 0.7$ and 1 GeV .



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BACK UP SLIDES

Deep Inelastic Scattering

$\frac{1}{E_\nu} \frac{d^2\sigma}{dx dy}$ for $\nu - {}^{56}\text{Fe}$ at $E_\nu = 10 \text{ GeV}$

