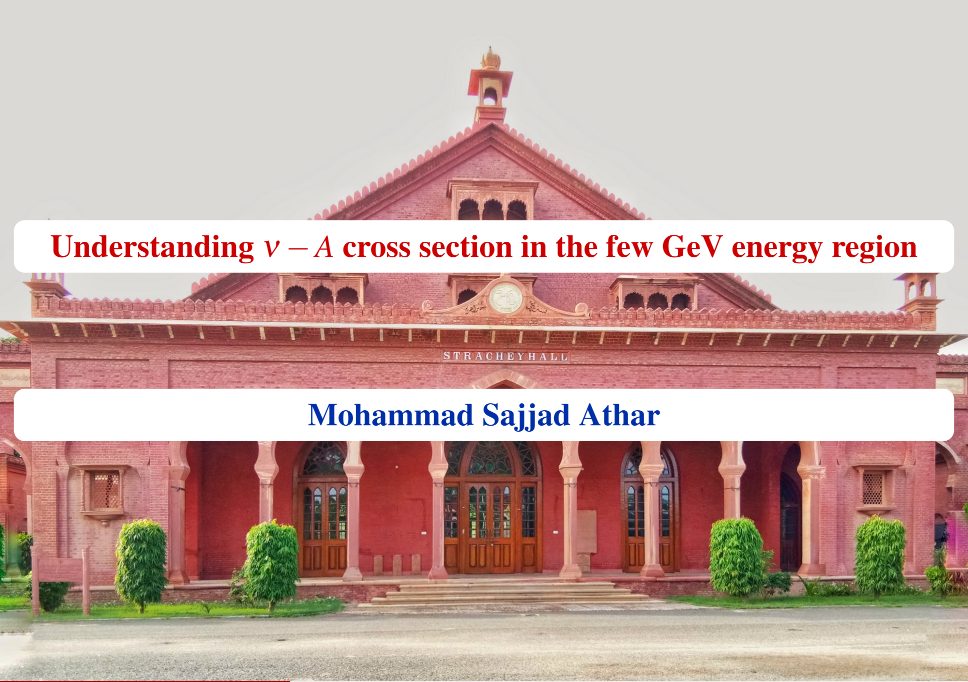
Understanding $\nu - A$ cross section in the few GeV energy region

Mohammad Sajjad Athar



Outline

1. *Introduction*
2. *Quasielastic Scattering*
3. *Single Pion Production*
4. *Quasielastic Hyperon Production*
5. *Conclusions*

Importance of Neutrino Interactions

Good understanding of neutrino interaction cross sections is important for:

- neutrino detection, energy reconstruction, neutrino flux calibration
- determination of backgrounds
- reduction of systematic errors
- needed in the quest for CP violation and mass hierarchy

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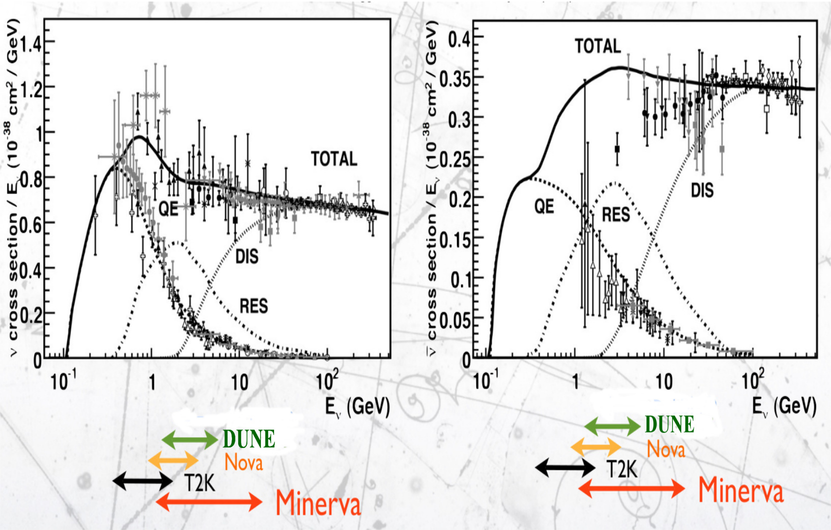
ND vs FD: These detectors are exposed to the

- different fluxes with different flavor composition
- different geometry, acceptance and targets

$\nu(Left)$ / $\bar{\nu}(Right)$ cross sections vs energy



List of all possible neutrino reactions

Quasielastic reactions

$$\nu_l n \to l^- p \qquad \bar{\nu}_l p \to l^+ n \qquad l = e, \mu, \tau;$$

Single pion production

$$\nu_l N \to l^- N' \pi^i \qquad \bar{\nu}_l N \to l^+ N' \pi^j \qquad N, N' = n, p; \quad i, j = +, -, 0$$

Deep inelastic scattering

$$\nu_l N \to l^- X \qquad \bar{\nu}_l N \to l^+ X$$

Single Hyperon Production

$$\bar{\nu}_l N \quad \to \quad l^+ Y \qquad Y =, \Lambda, \Sigma^0, \Sigma^-$$

List of all possible neutrino reactions (Contd.)

Single Kaon production

$\nu_l N \rightarrow l^- N' K$ $\quad$ $\bar{\nu}_l N \rightarrow l^+ N' \bar{K};$ $\quad$ $K = K^+, K^0;$ $\quad$ $\bar{K} = K^-, \bar{K}^0$

Single η Production

$\nu_l N \rightarrow l^- N' \eta$ $\quad$ $\bar{\nu}_l N \rightarrow l^+ N' \eta$

Associated particle production

$\nu_l + N \rightarrow l^- Y K$ $\quad$ $\bar{\nu}_l + N \rightarrow l^+ Y K$

$\nu_l/\bar{\nu}_l(k) + N(p) \longrightarrow l^{\pm}(k') + N(p')$

$$\mathscr{M} = \frac{G_f \cos\theta_c}{\sqrt{2}} \bar{u}(k')\gamma_\mu(1 \pm \gamma_5)u(k) \;\; \bar{u}(p') \left[V^\mu(p',p) - A^\mu(p',p)\right] u(p)$$

$$V^\mu(p',p) \;=\; f_1(Q^2)\gamma_\mu + \frac{i\sigma^{\mu\nu}q_\nu}{M+M'} f_2(Q^2) + \frac{2q_\mu}{M+M'} f_3(Q^2)$$

Vector FF **Magnetic FF** **Scalar FF**

$$A^\mu(p',p) \;=\; g_1(Q^2)\gamma_\mu\gamma_5 + i\sigma_{\mu\nu}\gamma_5 \frac{q^\nu}{M+M'} g_2(Q^2) + \frac{2q^\mu}{M+M'}\gamma_5 g_3(Q^2)$$

Axial vector FF **Electric FF** **Pseudoscalar FF**

$$g_1(Q^2) = \frac{g_1(0)}{(1+\frac{Q^2}{M_A^2})^2} \qquad g_2(Q^2) = \frac{g_2(0)}{(1+\frac{Q^2}{M_2^2})^2}; \qquad M_2 = M_A$$

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Symmetry properties of the weak hadronic current

- T invariance $\Rightarrow$ all form factors to be real
- CVC $\Rightarrow f_3(Q^2) = 0$
- G invariance $\Rightarrow f_3(Q^2) = 0$ and $g_2(Q^2) = 0$
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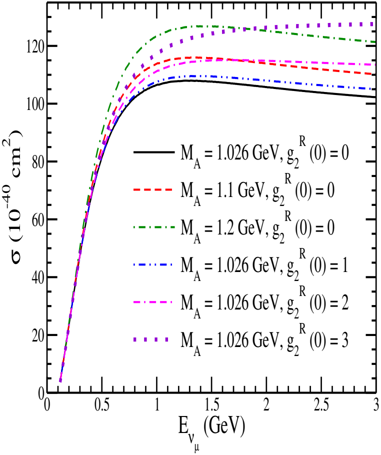
★ G violation $\Rightarrow g_2(Q^2) \neq 0$

★ T invariance $\Rightarrow$ Real values of $g_2(Q^2)$

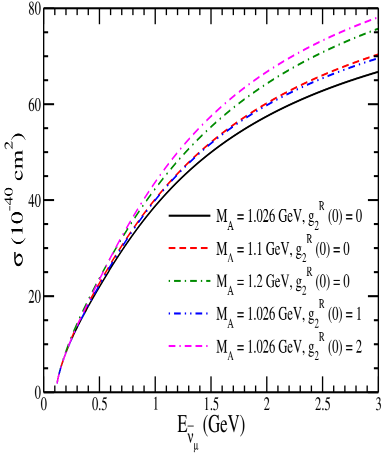
★ T violation $\Rightarrow$ Imaginary values of $g_2(Q^2)$

σ vs $E_{\nu_\mu(\bar{\nu}_\mu)}$: $g_2^R(0)$ vs. M_A

$\nu_\mu + n \longrightarrow \mu^- + p$

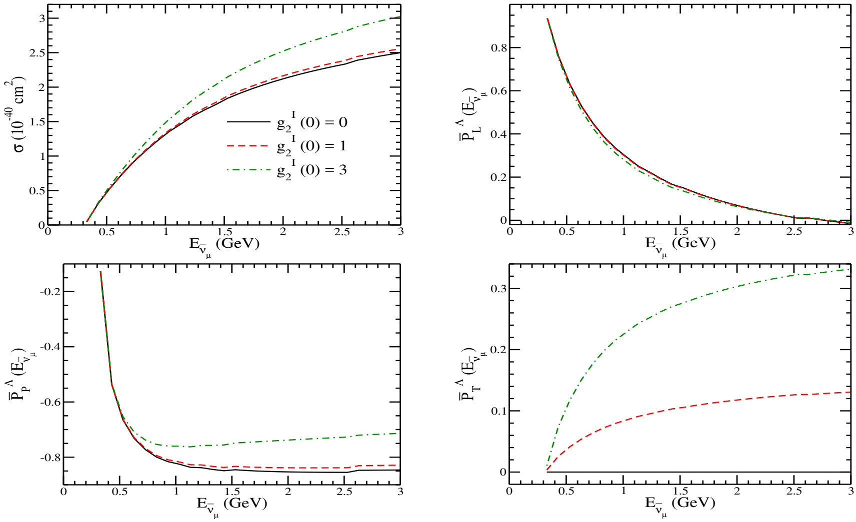


$\bar{\nu}_\mu + p \longrightarrow \mu^+ + n$



Phys. Rev. D 98, 033005 (2018).

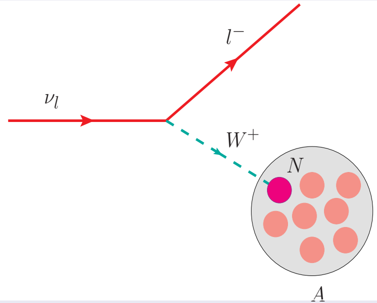
σ, $\overline{P}_L$, $\overline{P}_P$ and $\overline{P}_T$ vs $E_{\bar{\nu}_\mu}$ for $\bar{\nu}_\mu + p \longrightarrow \mu^+ + \Lambda$ process: $g_2^I(0)$ variation



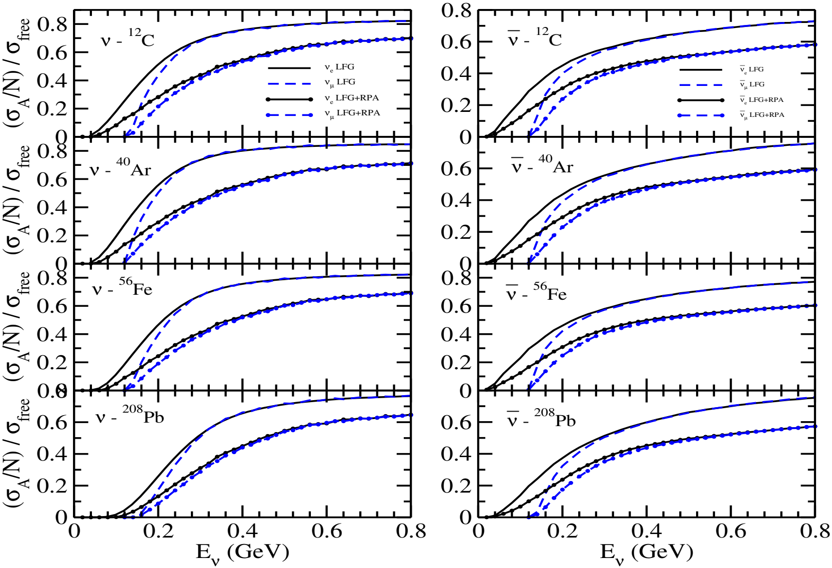
Phys. Rev. D 98, 033005 (2018).

Nuclear medium effects

- *Fermi motion & binding energy*
- *Pauli blocking*
- *Multinucleon effects*
- *Final state interaction(FSI)effect*



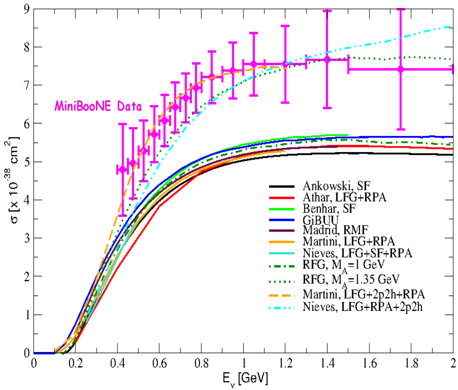
σ vs. E_ν for ^{12}C, ^{40}Ar, ^{56}Fe and ^{208}Pb targets



Dytman et al., Nucl. Phys. Proc. Suppl. 229, 167 (2012)

Cross Section

CCQE on ^{12}C



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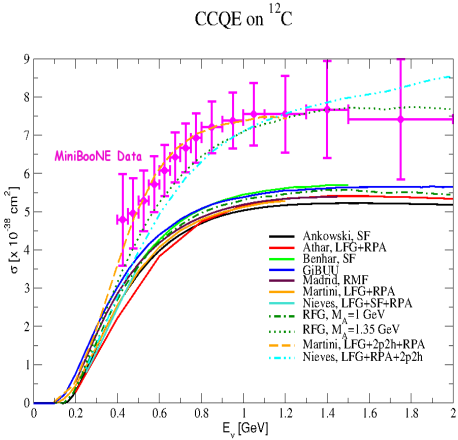
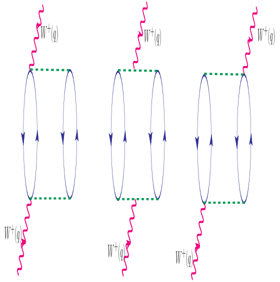


2p-2h Excitations



Marco Martini
Juan Nieves

Different versions of Monte Carlo Generators

GENIE 2.8.0

Rel. FGM (Smith & Moniz): $M_A = 1\ GeV$
Bodek-Richie model that simulates short range nucleon correlations
2p-2h (Valencia)

GENIE 2.8.4

Rel. FGM (Smith & Moniz): $M_A = 1\ GeV$
RPA (Valencia)
2p-2h (Valencia)
Tuned to inclusive MINERvA CCQE data

NuWro

Local FGM+RPA+2p-2h: $M_A = 1.16\ GeV$
SF+2p-2h ($M_A = 1.2\ GeV$)
RFG+TEM ($M_A = 1.14\ GeV$)

NEUT

Local FGM+RPA+2p-2h
SF+2p-2h with a raised value of M_A
Local FGM+RPA+2p-2h (Martini)
SuSA

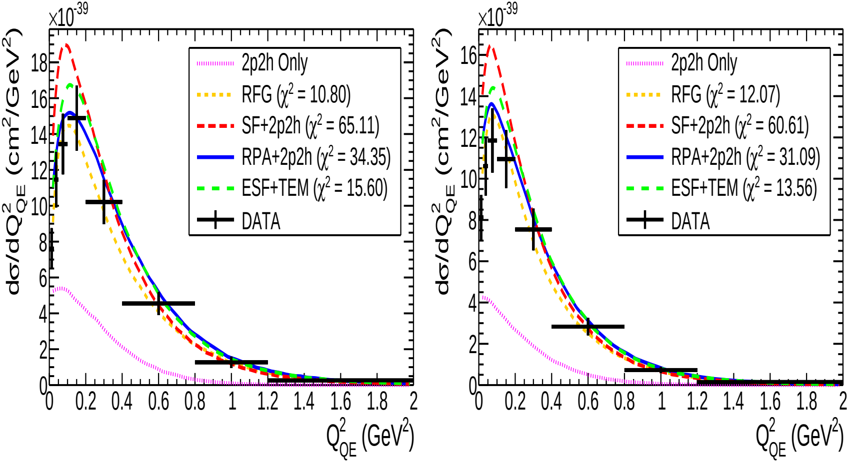
NEUT 5.3.2

RFGM+RPA+2p-2h: $M_A = 1.15\ GeV$
2p-2h is normalised to 27%

Wilkinson et al., Phys. Rev. D 93, 072010 (2016)
Predictions for MINERvA

RFG (Smith & Moniz) + relativistic RPA + 2p2h (Valencia model) M_A=1.01GeV

Neutrino **Antineutrino**



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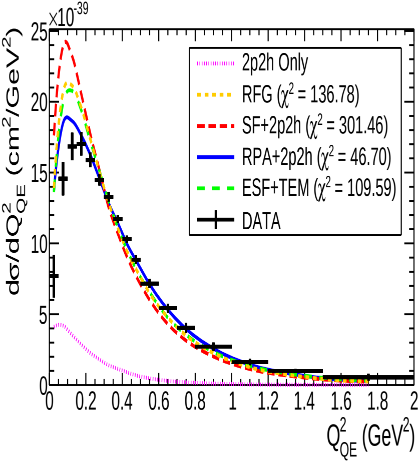
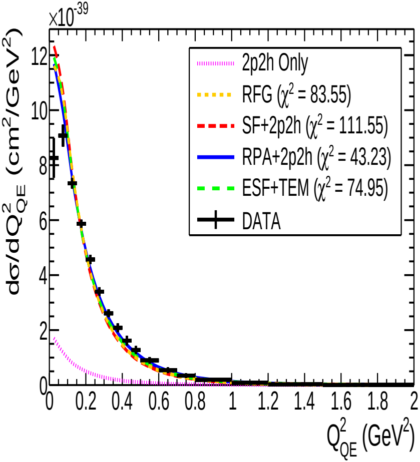
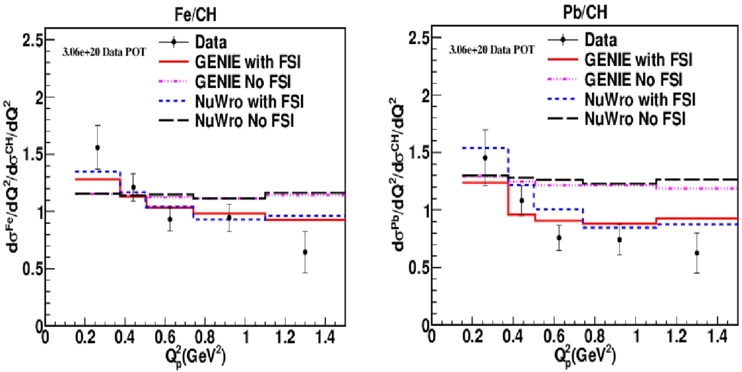


Antineutrino



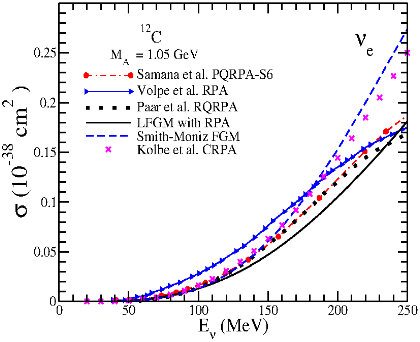
Betancourt et al., (MINERvA Collab); Phys. Rev. Lett. 119, 082001 (2017)

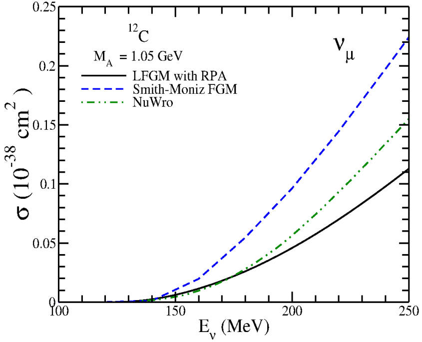


Aguilar-Arevalo et al. (MiniBooNE Collab); Phys. Rev. Lett. 120, 141802 (2018)

- Charged Kaon Decay at Rest (KDAR) Experiment
- First Measurement of Monoenergetic ν_μ Charged Current Interactions

At E_{ν_μ}=236 MeV $\sigma_{CC} = 0.27 \pm 0.09 \pm 0.08\ \times 10^{-38}\ cm^2/\text{neutron}$





Akbar et al., J. Phys. G **44**, 125108 (2017)

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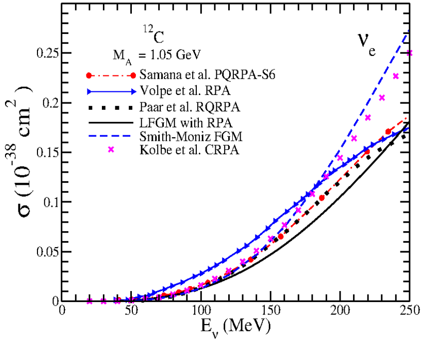
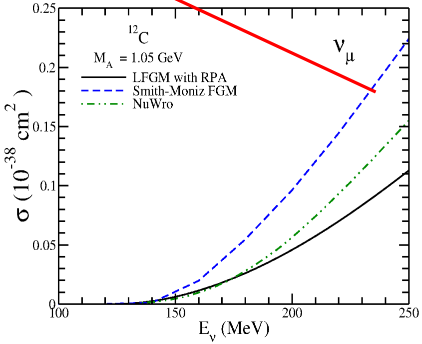
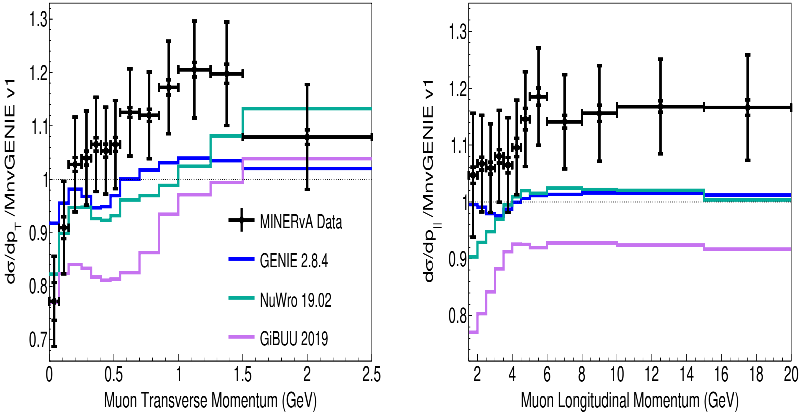




Akbar et al., J. Phys. G **44**, 125108 (2017)

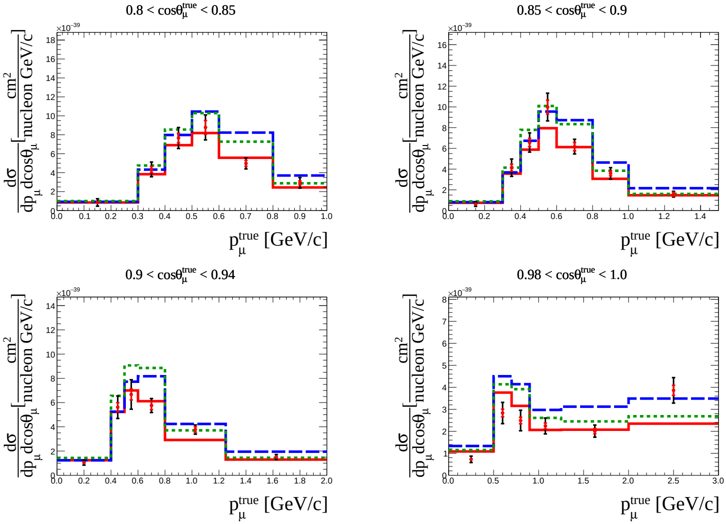
Filkins et al., Phys. Rev. D 101, 112007 (2020): The MINERvA Collaboration



Abe et al., Phys. Rev. D 101, 112001 (2020): T2K Collaboration Neutrino induced CC0π production

solid red line: Neut 5.4.1 (LFG+RPA model with 2p2h)
green dashed line: SuSA2 model

dashed blue line: Martini et al.



Single pion production

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$$\nu_l(k) + N(p) \rightarrow l^-(k') + \mathscr{R}(p_R)$$
$$\hookrightarrow N'(p') + \pi(k_\pi)$$

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Resonant Contribution

- Pion production through resonance excitation is

$$\nu_l(k) + N(p) \rightarrow l^-(k') + \mathscr{R}(p_R)$$
$$\hookrightarrow \quad N'(p') + \pi(k_\pi)$$

$$\bar{\nu}_l(k) + N(p) \rightarrow l^+(k') + \mathscr{R}(p_R)$$
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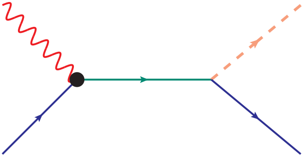
Δ or Higher Resonance

- Higher Resonances

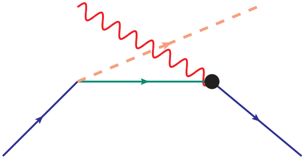
Resonances R_{IJ}	M_R [GeV]	Γ_0^{tot} (GeV)	πN branching ratio (%)
$P_{33}(1232)$	1.232	0.117	100
$P_{11}(1440)$	1.430	0.350	55 – 75
$D_{13}(1520)$	1.515	0.115	55 – 65
$S_{11}(1535)$	1.535	0.150	35 – 55
$S_{31}(1620)$	1.630	0.140	20 – 30
$S_{11}(1650)$	1.655	0.140	50 – 90
$D_{15}(1675)$	1.675	0.150	35 – 45
$F_{15}(1680)$	1.685	0.130	65 – 70
$D_{33}(1700)$	1.700	0.150	12
$P_{13}(1720)$	1.720	0.250	11
$F_{35}(1905)$	1.880	0.330	9 – 15
$P_{31}(1910)$	1.890	0.280	15 – 30
$F_{37}(1950)$	1.930	0.285	35 – 45

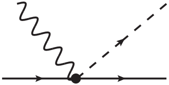
Non-resonant background

Nucleon Pole

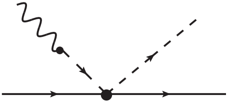


Cross Nucleon Pole

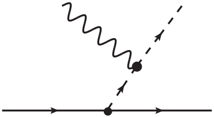




Contact term

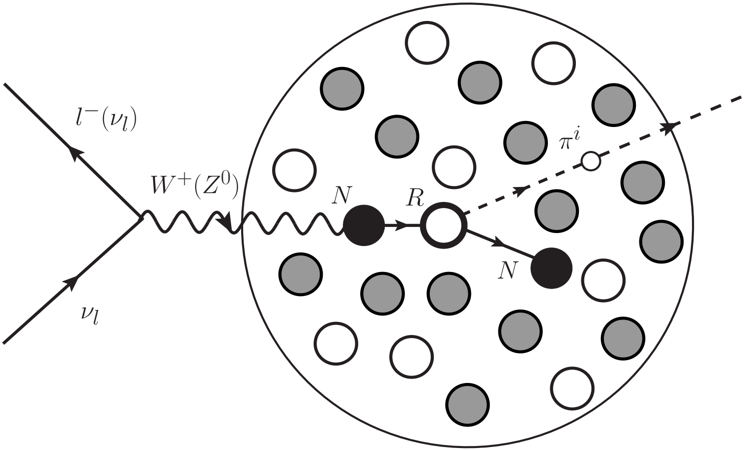


Pion Pole



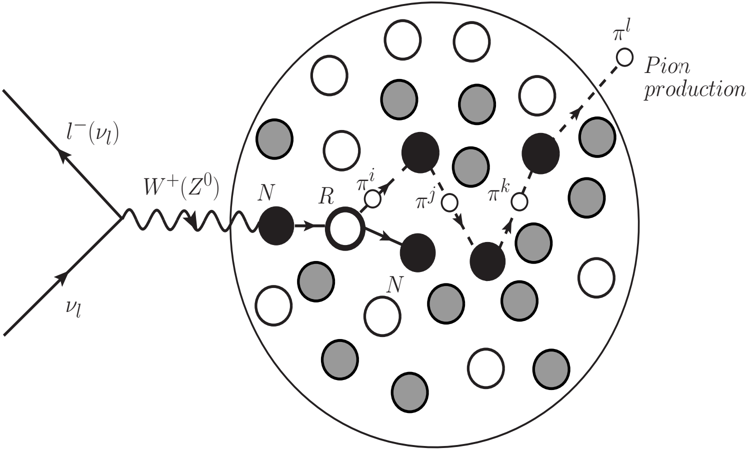
Pion in Flight

Production of pions in the final state



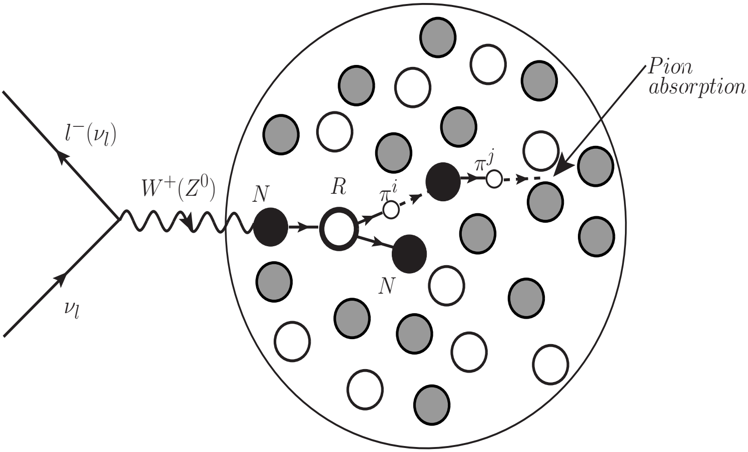
Production of pions with FSI

$\pi^+ + n \to \pi^0 + p$
$\pi^- + p \to \pi^0 + n$
$\pi + N \to \pi + N$

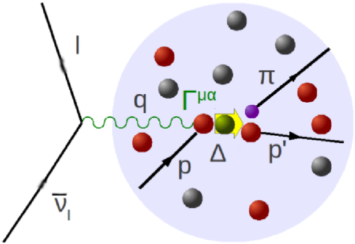


Production of pions giving rise to QE like events

$\pi^+ + n \to p$
$\pi^- + p \to n$
$\pi + N \to N'$



Inside the nucleus



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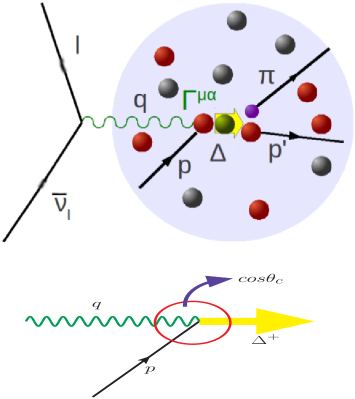

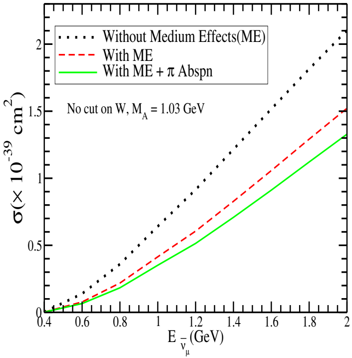

Eur. Phys. J. A **43**, 209 (2010).

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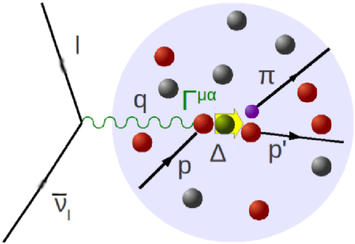

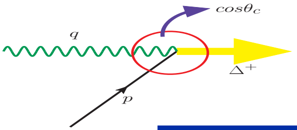

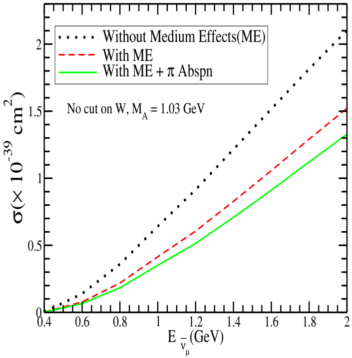

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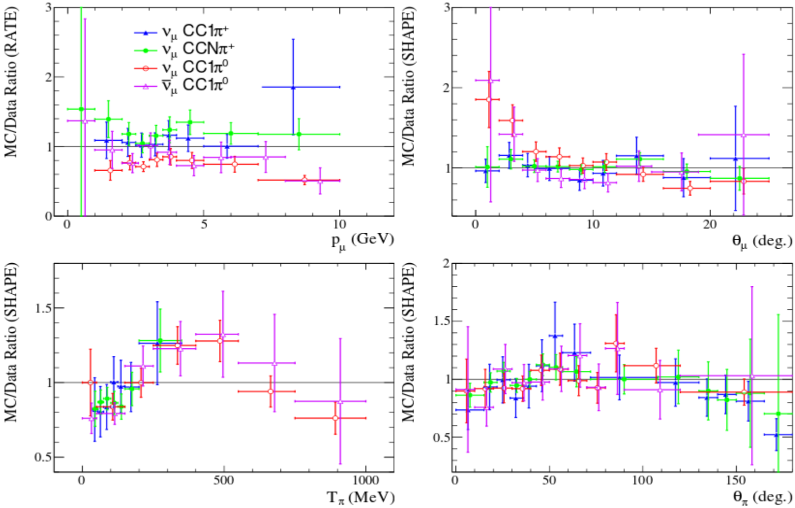
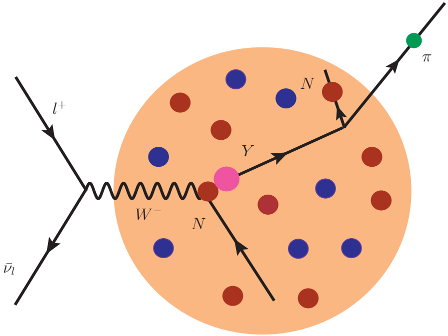
$E_{\bar{\nu}_\mu}$ (GeV)	σ with ME (% reduction)	σ with ME + π absorption (% reduction)
0.8	42	14
1.0	36	15
1.4	31	14
1.8	28	15

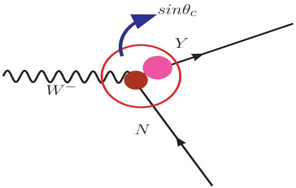
MINERvA Collab; Phys. Rev. D 100, 072005 (2019)



Quasielastic Hyperon Production

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



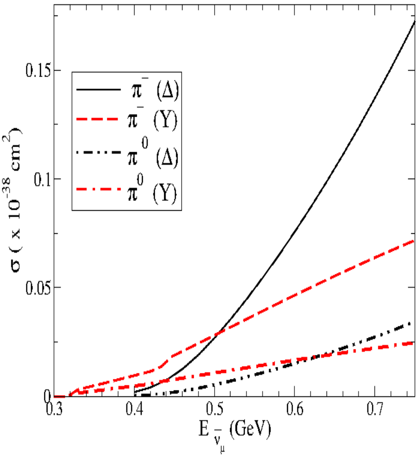


$|\Delta S| = 1$ processes are Cabibbo suppressed as compared to $|\Delta S| = 0$ processes by a factor of $tan^2\theta_c$ =0.054.

Hyperon giving rise to pions

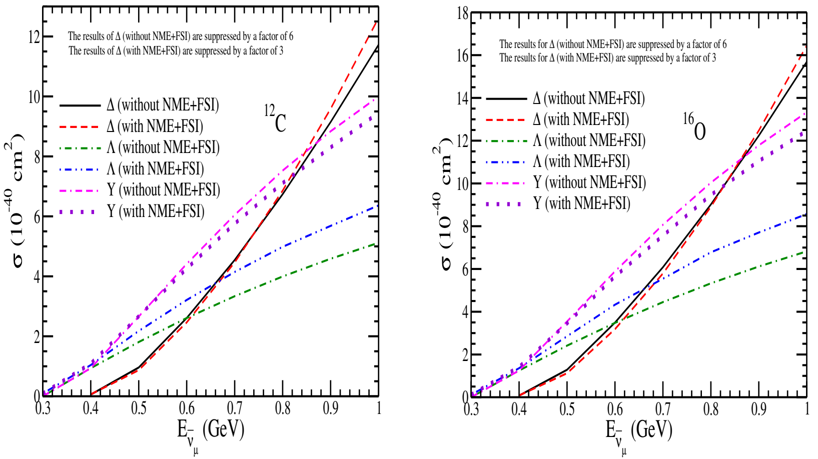
As the decay modes of hyperons to pions are highly suppressed in the nuclear medium, making them live long enough to pass through the nucleus and decay outside the nuclear medium.

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



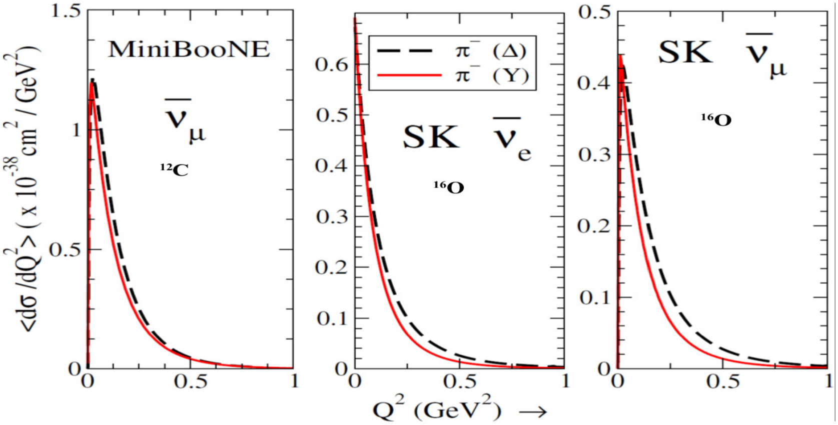
Phys. Rev. D **88**, 077301 (2013)

Results for π^- production in ^{12}C and ^{16}O



Front. Phys. 7, 13 (2019).

Phys. Rev. D 88, 077301 (2013)



scaled by a factor of 2.5 i.e $\sim 40\%$

Conclusions

We have moved closer in the last one decade but still there are many more unanswered questions than the solutions we have come up with.

The road is long and terrain is difficult.


Thank you