Strange particle production in neutrino interactions

Atika Fatima

Collaborators

M. Sajjad Athar and S. K. Singh

Progress in Particle & Nuclear Physics (in Press) arXiv: 2206.13792, 204 pages

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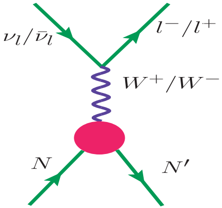
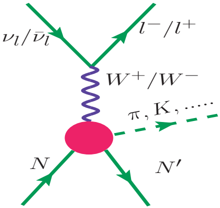
Outline

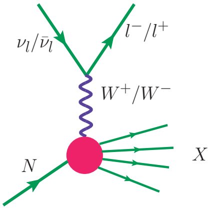
Neutrino interactions



Quasielatic

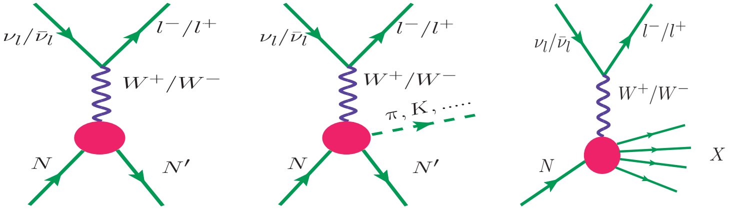


Inelastic



DIS

Neutrino interactions



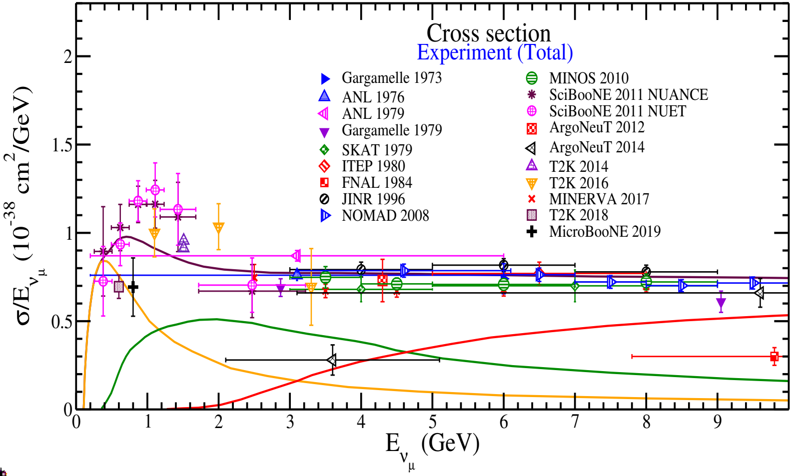
Quasielatic **Inelastic** **DIS**

CC reactions

$$\bar{\nu}_l + N \rightarrow l^+ + Y$$
$$\nu_l(\bar{\nu}_l) + N \rightarrow l^{\mp} + N' + \pi$$
$$\nu_l(\bar{\nu}_l) + N \rightarrow l^{\mp} + N' + n\pi$$
$$\nu_l(\bar{\nu}_l) + N \rightarrow l^{\mp} + N' + K(\bar{K})$$
$$\nu_l(\bar{\nu}_l) + N \rightarrow l^{\mp} + N' + \eta$$
$$\nu_l(\bar{\nu}_l) + N \rightarrow l^{\mp} + Y + K$$

Neutrino cross section vs. neutrino energy

Cross section: theory vs experiment



Hyperon production

The observation of hyperons produced in the antineutrino ($\bar{\nu}_\mu + p \longrightarrow \mu^+ + \Lambda$) induced processes may provide an opportunity to:

- **test the SU(3) symmetry, G invariance and T invariance.**
- **determine the $N - Y$ transition form factors.**
- **get some information about the second class currents.**

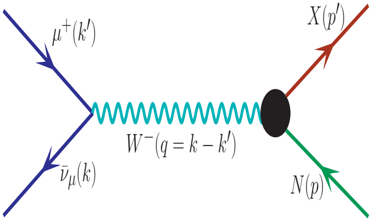
The measurement of the hyperon polarization may determine independently the form factors appearing in the weak hadronic current.

Using high luminosity electron beam at the JLab and MAMI, or antineutrino beam at MicroBooNE and DUNE using LArTPC detector, such studies could be possible.

$|\Delta S| = 1$ quasielastic processes

Antineutrino induced single hyperon production

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



$|\Delta S| = 1$ quasielastic processes

Antineutrino induced single hyperon production

$$\begin{aligned}
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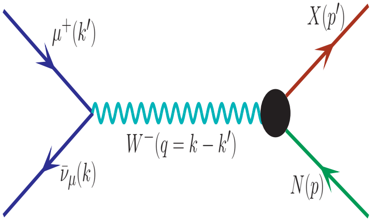
\end{aligned}$$



$$d\sigma = \frac{1}{4M_N E_\nu}(2\pi)^4 \delta^4(k + p - k' - p') \frac{d^3k'}{(2\pi)^3 2E_{k'}} \frac{d^3p'}{(2\pi)^3 2E_{p'}} \overline{\sum} \sum |\mathscr{M}|^2$$

- $q = p' - p = k - k'$ is the four momentum transfer
- $\mathscr{M}$ is the transition matrix element

$$\mathscr{M} = \frac{G_F \sin\theta_c}{\sqrt{2}} l_\mu J^\mu$$

Hadronic current and transition form factors

Vector operator   Axial vector operator

$$J^\mu = \bar{u}_{B'}(p') \left[V^\mu_{B'B}(p',p) - A^\mu_{B'B}(p',p) \right] u_B(p)$$

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

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

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

Symmetry properties

- **SU(3) symmetry** $\Rightarrow f_{1,2}^{NY}(Q^2)$ **in terms of** $f_{1,2}^{NN'}(Q^2)$
- **T invariance** $\Rightarrow$ **form factors are real**
- **CVC** $\Rightarrow f_3(Q^2) = 0$
- **G invariance** $\Rightarrow f_3(Q^2) = 0$ **and** $g_2(Q^2) = 0$
- **PCAC** $\Rightarrow$ **relates** $g_3(Q^2)$ **with** $g_1(Q^2)$ **through GT relation**

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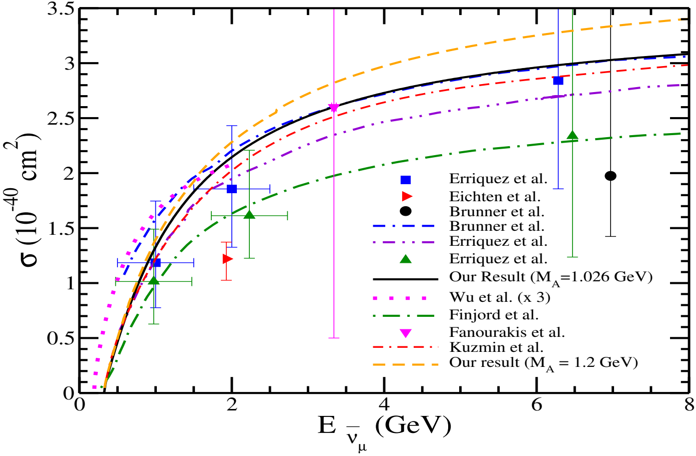
★ $g_2(Q^2) \neq 0 \Rightarrow$ **G violation**
★ **Real values of** $g_2(Q^2) \Rightarrow$ **T invariance**
★ **Imaginary values of** $g_2(Q^2) \Rightarrow$ **T violation**

σ vs. $E_{\bar{\nu}_\mu}$ for the Λ production



AF, MSA, SKS, Front. in Phys. 7 (2019) 13

Kinematics: $\nu_l/\bar{\nu}_l(k) + N(p) \longrightarrow l^{\mp}(k') + \Lambda(p') + K(p_K)$

$$d\sigma = \frac{1}{4ME_\nu(2\pi)^5}\delta^4(k+p-k'-p'-p_K)\frac{d\vec{k}'}{(2E_l)}\frac{d\vec{p}\,'}{(2E_\Lambda)}\frac{d\vec{p}_K}{(2E_K)}\overline{\sum}\sum|\mathscr{M}|^2$$

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$$\mathcal{M} = \frac{G_F}{\sqrt{2}} j_\mu^{(L)} j^{\mu\,(H)}$$

Fermi coupling constant | Leptonic Current | Hadronic Current

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

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

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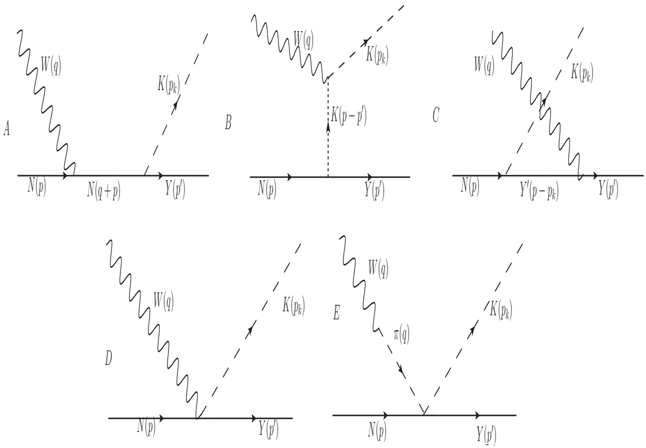
  - Nonresonant Born terms
- Born terms are obtained using non-linear sigma model

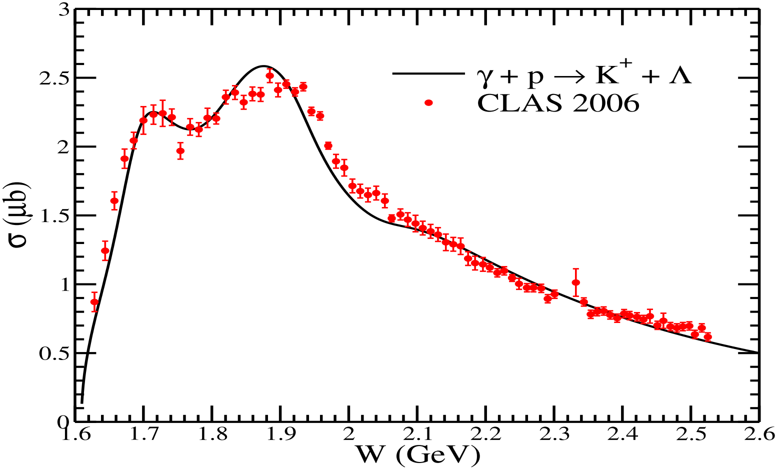
Associated particle production: Feynman diagrams



Resonances considered

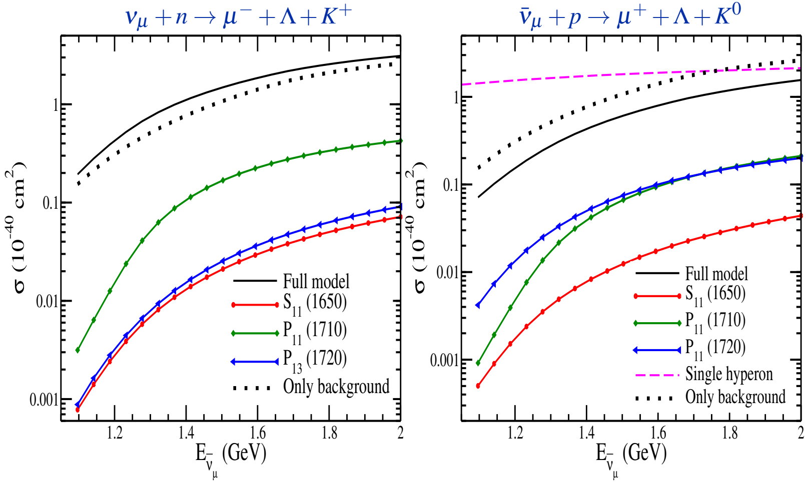
- $S_{11}(1650)$
- $P_{11}(1710)$
- $P_{13}(1720)$

σ for $K\Lambda$ photoproduction processes



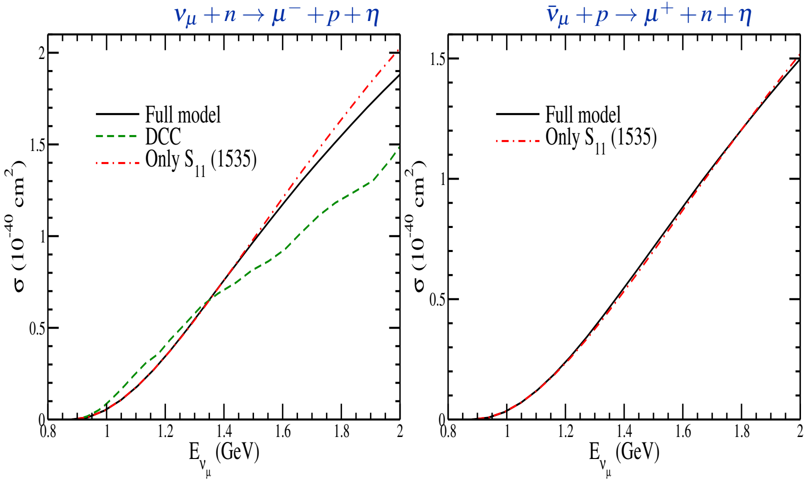
AF, MSA, ZAD, SKS, Int. J. Mod. Phys. E 29 (2020) 07, 2050051

σ for CC induced $K\Lambda$ production processes



MSA, AF, SKS, Progress in Particle & Nuclear Physics (in Press) arXiv: 2206.13792

σ for CC (anti)neutrino induced eta production processes



AF, MSA, SKS, Phys. Rev. D (arXiv: 2211.08830)

Hyperon production in the nuclear medium

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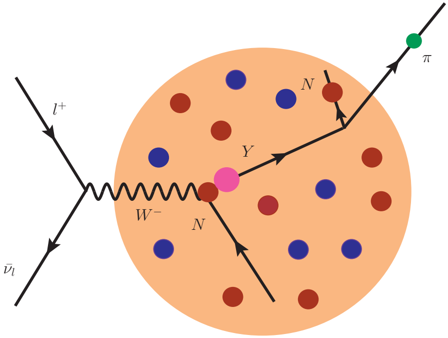

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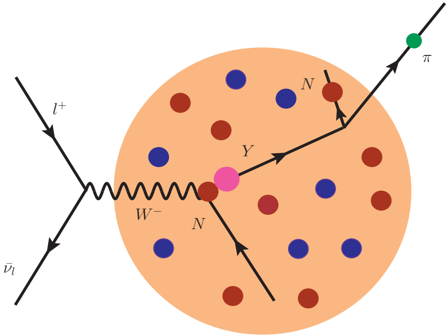
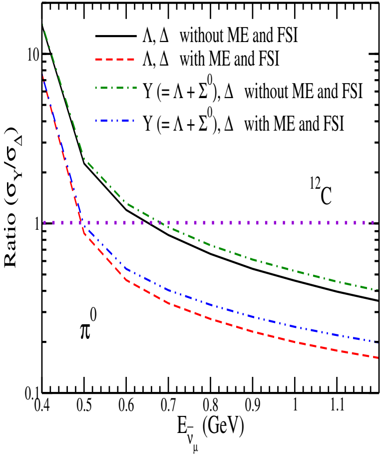


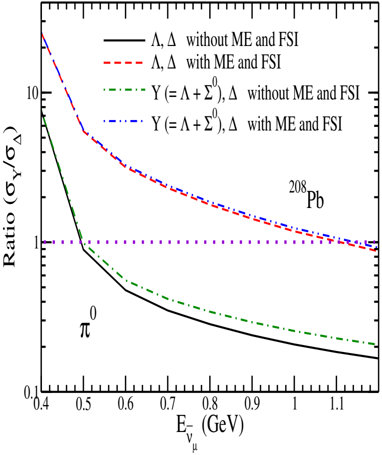
AF, MSA, SKS, Front. in Phys. 7 (2019) 13

- The produced hyperons are affected by FSI within the nucleus through the $N-Y$ elastic processes like
  - $\Lambda N \rightarrow \Lambda N$
  - $\Sigma N \rightarrow \Sigma N$, etc.

  and the charge exchange processes like
  - $\Lambda n \rightarrow \Sigma^- p$
  - $\Lambda n \rightarrow \Sigma^0 n$, etc.
- The probability of the hyperon production changes.

Antineutrino induced π^0 production from Δ and hyperon productions





Conclusion

- The study of hyperon production is important:
  - in modelling the neutrino event generators
  - to understand the axial-vector response of the hadronic sector

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- The effect of FSI increases the total scattering cross section.
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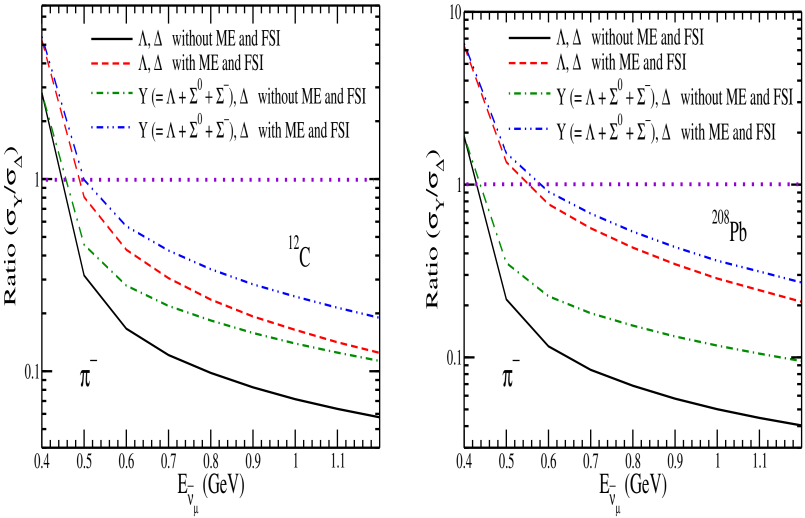
- The effect of FSI increases the total scattering cross section.
- The effect of FSI increases with increase in mass number.
- The pions produced from the hyperon are significant in the antineutrino energy region of about 0.8 GeV.

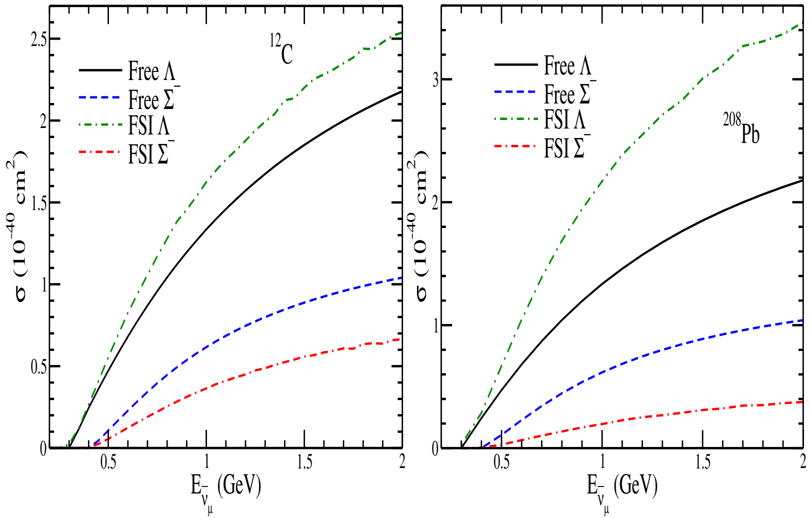

Thank you!

BACKUP

Antineutrino induced π^- production from Δ and hyperon productions



σ for Λ and Σ^- productions in ^{12}C and ^{208}Pb targets



Non-linear sigma model

- **This is an effective field theory(EFT).**
- **EFT is a low energy approximation to some underlying, more fundamental theory. Low is defined with respect to some energy scale.**
- **The basic idea consists of writing down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculating matrix elements with this Lagrangian within some perturbative scheme.**

Meson-Meson Interaction

The lowest order Lagrangian with the minimal number of derivatives describing the interaction of the Goldstone bosons

$$\mathscr{L} = \frac{f_\pi^2}{4} Tr(D_\mu U^\dagger D^\mu U)$$

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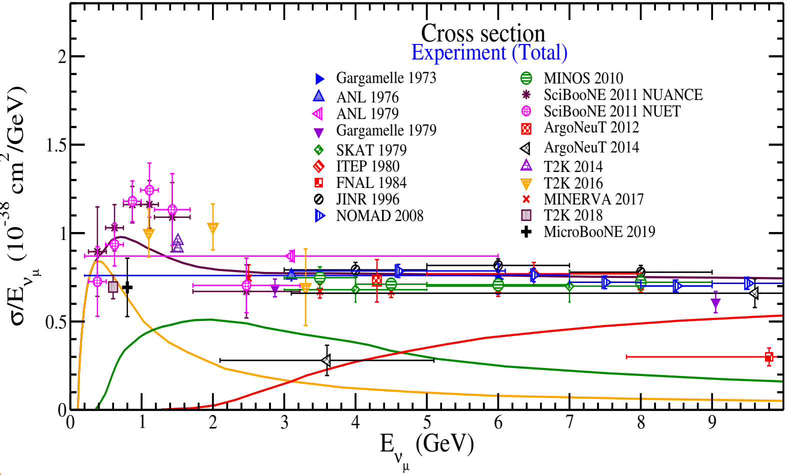
$SU(3)$ representation of pseudoscalar fields

$$\Phi(x) = \sum_{k=1}^{8} \phi_k(x)\lambda_k = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}$$

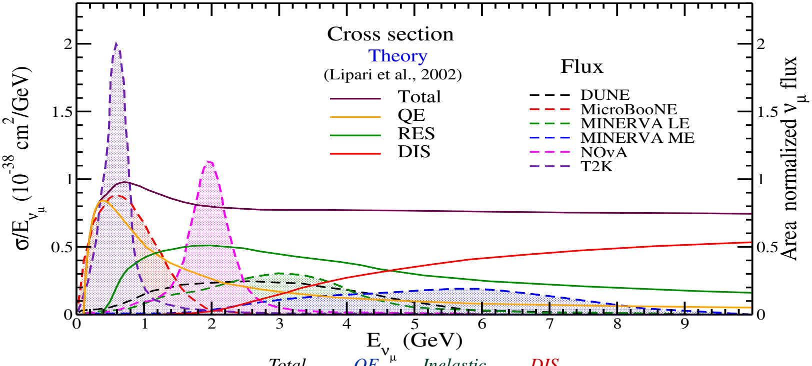
Neutrino cross section vs neutrino energy

Cross section: theory vs experiment



Neutrino cross section vs neutrino energy

Cross section and area normalized flux



$$\sigma^{Total} = \sigma^{QE} + \sigma^{Inelastic} + \sigma^{DIS}$$

$$\sigma^{QE} = \sigma_{\nu_l n \rightarrow l^- p},\ \sigma_{\bar{\nu}_l p \rightarrow l^+ n}$$

$$\sigma^{Inelastic} = \sigma^{1\pi} + \sigma^{2\pi} + \sigma^{\eta} + \cdots + \sigma^{YK} + \sigma^{1K} + \sigma^{1Y} + \cdots$$

Interaction of pseudoscalar fields with baryons

We consider the octet of $\frac{1}{2}^{+}$ baryons. With each member of the octet we associate a complex, four-component Dirac field

Interaction of pseudoscalar fields with baryons

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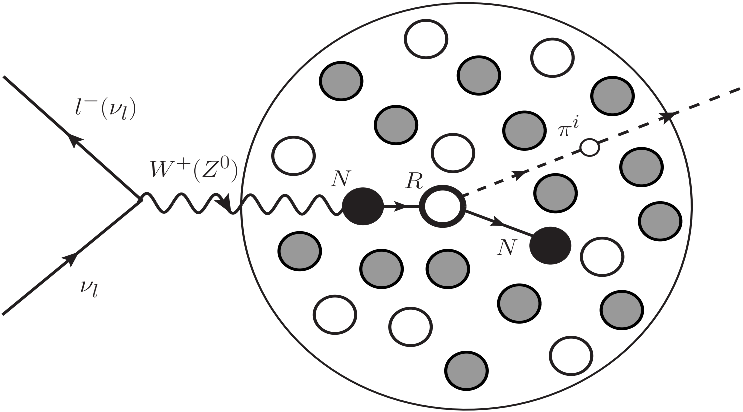
$$B(x) = \sum_{k=1}^{8} \frac{1}{\sqrt{2}} b_k(x) \lambda_k = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix},$$

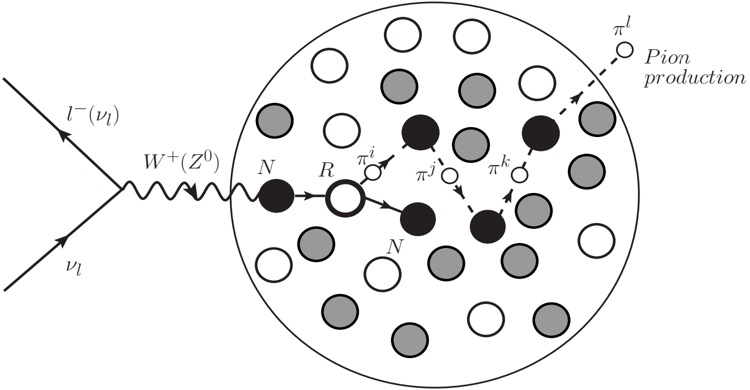
Production of pions in the final state



MSA and SKS, The Physics of Neutrino Interactions (CUP) 2020

FSI of produced pions: elastic and QE scattering

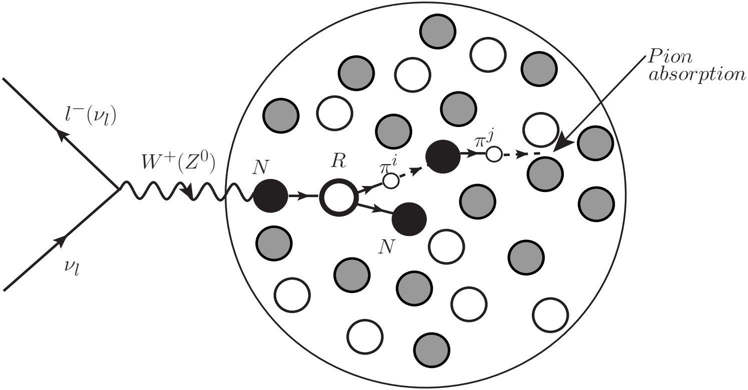
$$\pi^+ + n \rightarrow \pi^0 + p$$
$$\pi^- + p \rightarrow \pi^0 + n$$
$$\pi^i + N \rightarrow \pi^i + N$$



MSA and SKS, The Physics of Neutrino Interactions (CUP) 2020

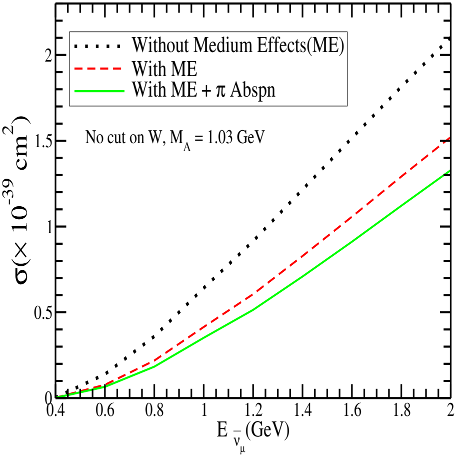
FSI of produced pions: absorption and QE like events

$$\pi^+ + n \rightarrow p$$
$$\pi^- + p \rightarrow n$$
$$\pi^0 + N \rightarrow N'$$



MSA and SKS, The Physics of Neutrino Interactions (CUP) 2020

$\bar{\nu}_\mu$ induced π^- production in the Δ dominance model in ^{12}C target



Phys. Rev. D 75, 093003 (2007)

The lowest-order chiral Lagrangian for the baryon octet in the presence of an external current may be written in terms of the SU(3) matrix B as,

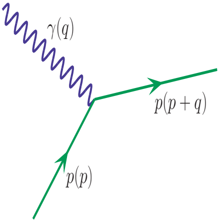
$$\mathcal{L}_{MB}^{(1)} = \mathrm{Tr}\left[\bar{B}\left(i\not{D} - M\right)B\right] - \frac{D}{2}\mathrm{Tr}\left(\bar{B}\gamma^{\mu}\gamma_5\{u_{\mu}, B\}\right) - \frac{F}{2}\mathrm{Tr}\left(\bar{B}\gamma^{\mu}\gamma_5[u_{\mu}, B]\right),$$

covariant derivative of B:

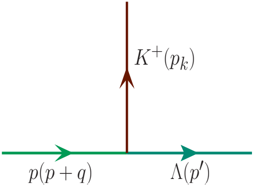
$$D_{\mu}B = \partial_{\mu}B + [\Gamma_{\mu}, B],$$

$$\Gamma^{\mu} = \frac{1}{2}\left[u^{\dagger}(\partial^{\mu} - ir^{\mu})u + u(\partial^{\mu} - il^{\mu})u^{\dagger}\right]$$

Hadronic current for s channel diagram

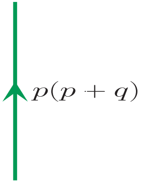


$$\mathcal{L}_{\gamma pp} = -ee_p \bar{p} \gamma_\mu p A^\mu$$



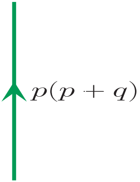
$$\mathcal{L}_{K\Lambda p} = \left(\frac{D+3F}{2\sqrt{3}f_\pi}\right) \bar{\Lambda} \gamma_\mu \gamma_5 p \partial^\mu K^\dagger$$

Hadronic current for *s* channel diagram

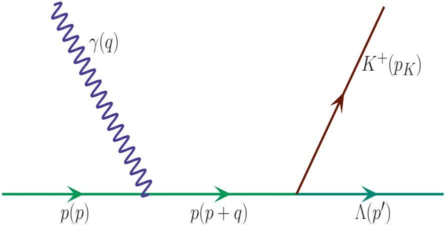


$$i\frac{\not p+\not q+M}{s-M^2}$$

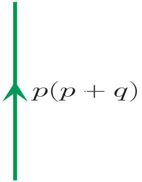
Hadronic current for *s* channel diagram



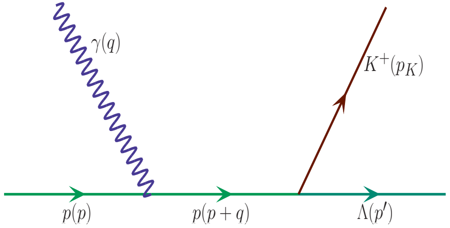
$$i\frac{\not{p}+\not{q}+M}{s-M^2}$$



Hadronic current for s channel diagram



$$i\frac{\not{p}+\not{q}+M}{s-M^2}$$



$$J^\mu|_s = ie\bar{u}(p')\not{p}_k\gamma_5\frac{\not{p}+\not{q}+M}{s-M^2}\left(\gamma^\mu e_p + i\frac{\kappa_p}{2M}\sigma^{\mu\nu}q_\nu\right)u(p)$$