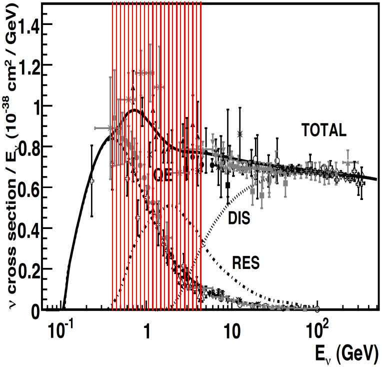
Weak production of strange particles and eta meson off the nucleon

Mohammad Sajjad Athar

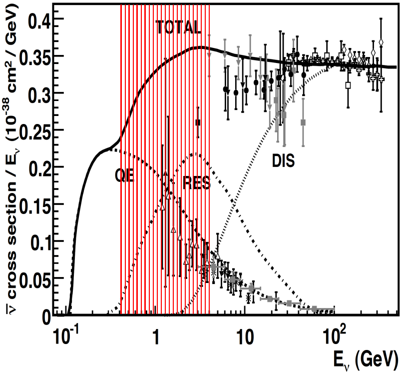
November 12, 2015

Introduction

Neutrino



Anti-neutrino



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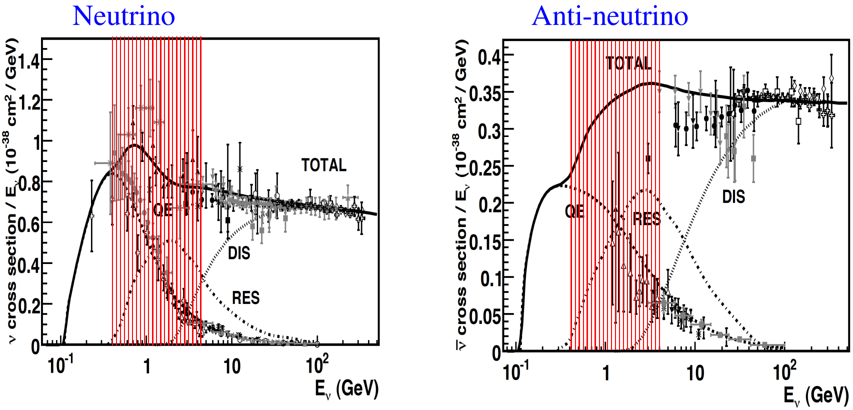
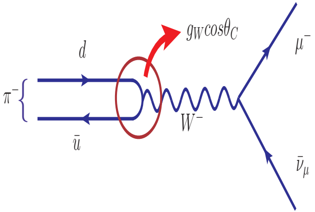


$$\sigma^{Total} = \sigma^{QE}_{\nu_l N \to l N'} + \sigma^{Inelastic} + \sigma^{DIS}$$

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

$\Delta S = 1$ processes are Cabibbo suppressed as compared to $\Delta S = 0$



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- In some of the MC Generators some of the reactions are missing and some are not well described.
- Nucleon Decay searches in Atmospheric neutrino experiments : background estimation of K and η production by neutrinos.
- In the understanding of the basic symmetries of the SM, strange quark content of the nucleon, structure of weak hadronic form factors, etc.

Weak Processes

Single K-meson

$$\begin{aligned} \nu_l p &\to l^- K^+ p \\ \nu_l n &\to l^- K^0 p \\ \nu_l n &\to l^- K^+ n \end{aligned} \qquad \begin{aligned} \bar{\nu}_l p &\to l^+ K^- p \\ \bar{\nu}_l p &\to l^+ \bar{K}^0 n \\ \bar{\nu}_l n &\to l^+ K^- n \end{aligned}$$

Single Hyperon Production

$$\begin{aligned} \bar{\nu}_l p &\to l^+ \Sigma^0 \\ \bar{\nu}_l p &\to l^+ \Lambda \\ \bar{\nu}_l n &\to l^+ \Sigma^- \end{aligned}$$

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Weak Processes

Single K meson

- Selection rule $\Delta S = \Delta Q$ restricts $\Delta S = 1$ single hyperon production to $\bar{\nu}$ rather than ν reactions

$$
\begin{array}{rrrl}
\Delta S = 0, & \Delta Q & = \pm 1 & \textit{Allowed} \\
\Delta S = & \Delta Q & = \pm 1 & \textit{Allowed} \\
\Delta S = & -\Delta Q & = \pm 1 & \textit{Forbidden}
\end{array}
$$

$$
\begin{array}{cccl}
\nu_l + & n & \to l^- + \Sigma^+ & \\
 & 0 & +1 & Q \\
 & 0 & -1 & S
\end{array}
\qquad
\begin{array}{cccl}
\bar{\nu}_l + & n & \to l^+ + \Sigma^- & \\
 & 0 & -1 & Q \\
 & 0 & -1 & S
\end{array}
$$

$$\bar{\nu}_l n \quad \to \quad l^+ \Sigma^-$$

Single η Production

$$\begin{aligned} \nu_l n &\rightarrow l^- p\eta \\ \bar{\nu}_l p &\rightarrow l^+ n\eta \end{aligned}$$

Associated Production(Charged Current Channel)

$$\begin{aligned} \nu_l n &\rightarrow l^- K^+\Lambda \\ \nu_l p &\rightarrow l^- K^+\Sigma^+ \\ \nu_l n &\rightarrow l^- K^+\Sigma^0 \\ \nu_l n &\rightarrow l^- K^0\Sigma^+ \end{aligned}$$

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

Associated Production(Neutral Current Channel)

Similar to electroproduction with additional contribution from axial currents

$$
\begin{array}{lcl@{\qquad\qquad}lcl}
\nu_l n & \to & \nu_l K^0 \Lambda^0 & \bar{\nu}_l n & \to & \bar{\nu}_l K^0 \Lambda^0 \\
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\end{array}
$$

$\nu_l n$ … Λ

$\nu_l p$ … Σ^0

$\nu_l n$ … Σ^-

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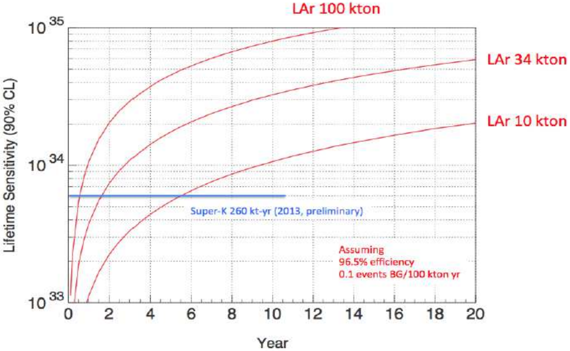
- Uniqueness of proton decay signatures in a LArTPC
- LArTPC technology is expected to out perform water Cherenkov in
  - Detection efficiency
  - Atmospheric neutrino background rejection

  for most nucleon decay modes

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\bar{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8



Proton decay lifetime limit for $p \to K^+\bar{\nu}$ as a function of time for underground LArTPCs

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Other nuclear effects, such as Fermi motion and Pauli blocking will only produce minor changes on the cross section and can easily be implemented in the Monte Carlo codes.

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- Charged current $\Lambda^0 K^+$ and π−production cross sections:

$$\frac{\sigma(\nu_\mu + n \to \mu^- + K^+ + \Lambda)}{\sigma(\nu_\mu + N \to \mu^- + N + m\pi)} = 0.04 \pm 0.03$$

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- Charged current $pK(\Delta S = 1)$ and $\pi-$production cross sections

$$\frac{\sigma(\nu_\mu + N \rightarrow \mu^- + K^+ + p)}{\sigma(\nu_\mu + N \rightarrow \mu^- + N + m\pi)} = 0.03 \pm 0.03$$

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Bubble Chamber using Freon

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$$\frac{\sigma_{SNC}(\Delta S = 0)}{\sigma_{SCC}(\Delta S = 0)} \quad = \quad 0.34^{+0.17}_{-0.09}$$

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- **Estimated**

$$\sigma(\nu_\mu + p \to \mu^- K^+ p) = 1.4 \pm 0.8 \times 10^{-40}\ cm^2$$

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- Ratio of strange particles to all particles

$$R = \frac{\sigma(\nu + d \to \mu^- + strange\ particles)}{\sigma(\nu + d \to \mu^- + all)} \quad \geq \quad 0.052 \pm 0.018$$

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- **Cut on hadronic masses**

$$1.4\ GeV \leq W \leq 3\ GeV$$
$$R \geq 0.075 \pm 0.027$$

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$$\frac{\sigma_{SCC}(\Delta S = 0)}{\sigma_{SCC}(\Delta S = 0) + \sigma_{SCC}(\Delta S = 1)} = 0.74 \pm 0.27$$

Formalism

The general expression for the scattering cross-section is given by,

$$d^9\sigma = \frac{(2\pi)^4}{4ME}\prod_{f=1}^{n}\frac{d\vec{k}_f}{2k_f^0(2\pi)^3}\delta^4(k_i - k_f)\bar{\Sigma}\Sigma|\mathcal{M}|^2,$$

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Hadronic currents are obtained using Chiral Perturbation Theory

Meson-Meson Interaction

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

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

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$SU(3)$ representation of pseudoscalar fields:

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

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

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

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,

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

covariant derivative of B:

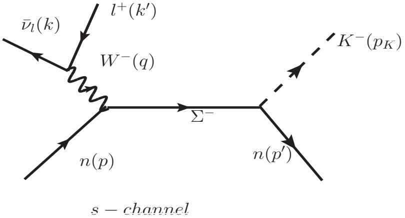
$$D_{\mu}B = \partial_{\mu}B + [\Gamma_{\mu}, B],$$

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

$$\begin{aligned}D^{\mu}U &\equiv \partial^{\mu}U - ir^{\mu}U + iUl^{\mu} \\ D^{\mu}U^{\dagger} &\equiv \partial^{\mu}U^{\dagger} + iU^{\dagger}r^{\mu} - il^{\mu}U^{\dagger},\end{aligned}$$

$$u^{\mu} = i\left[u^{\dagger}(\partial^{\mu} - ir^{\mu})u - u(\partial^{\mu} - il^{\mu})u^{\dagger}\right]$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + K^- + n$$



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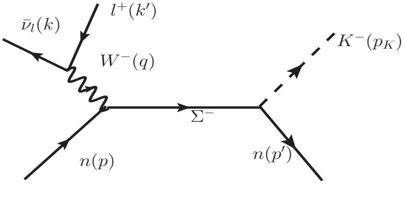
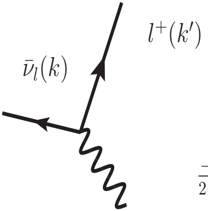


$s - channel$



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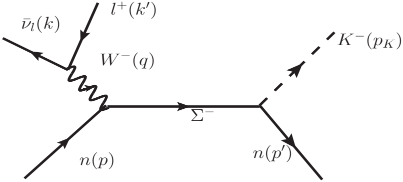

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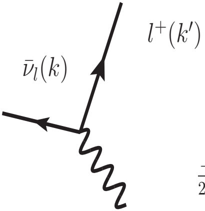
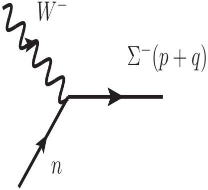
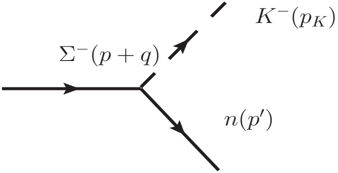


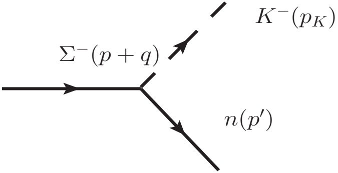
$$\frac{-ig}{2\sqrt{2}} l^+ \gamma^\mu (1 + \gamma_5) \bar{\nu}$$



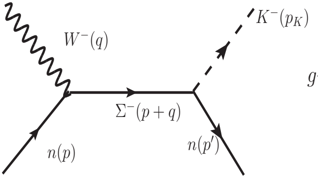
$$\frac{-ig}{2\sqrt{2}} V_{us} [\gamma_\mu + (D - F)\gamma_\mu \gamma_5] \bar{\Sigma}^- W_-$$



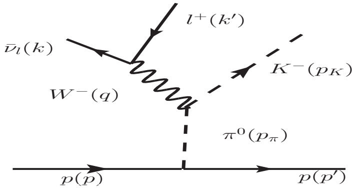
$$\frac{\bar{n}(F-D)\gamma_\sigma\gamma_5\Sigma^-\partial^\sigma K_+}{\sqrt{2}f_\pi}$$

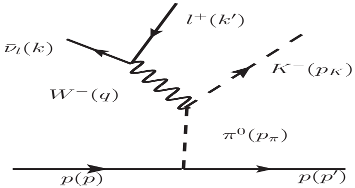


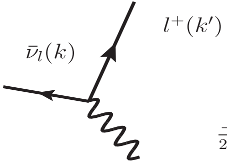
$$\frac{\bar{n}(F-D)\gamma_\sigma\gamma_5\Sigma^-\partial^\sigma K_+}{\sqrt{2}f_\pi}$$



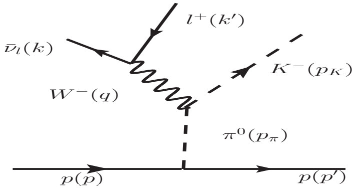
$$g\frac{\bar{n}(F-D)\gamma_\sigma\gamma_5(ip_k^\sigma)(\Sigma^-\bar{\Sigma}^-)V_{us}[\gamma_\mu+(D-F)\gamma_\mu\gamma_5]n}{(\sqrt{2}f_\pi)(2\sqrt{2})}$$

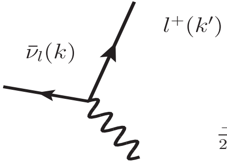

$l^+(k')$
$\bar{\nu}_l(k)$
$K^-(p_K)$
$W^-(q)$
$\pi^0(p_\pi)$
$p(p)$
$p(p')$



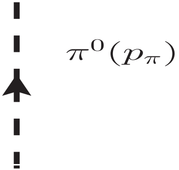


$$\frac{-ig}{2\sqrt{2}} l^+ \gamma^\mu (1+\gamma_5) \bar{\nu}$$

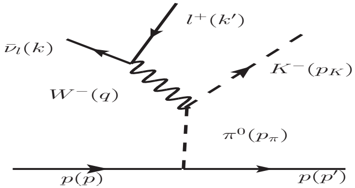


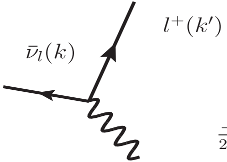


$\frac{-ig}{2\sqrt{2}} l^+ \gamma^\mu (1+\gamma_5) \bar{\nu}$

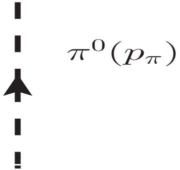


$\frac{i}{p_\pi^2 - m_\pi^2}$

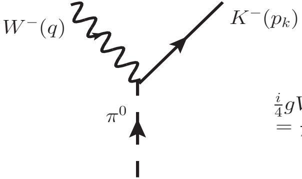




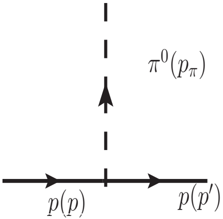
$$\frac{-ig}{2\sqrt{2}} l^+ \gamma^\mu (1+\gamma_5)\bar{\nu}$$



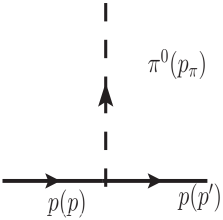
$$\frac{i}{p_\pi^2 - m_\pi^2}$$



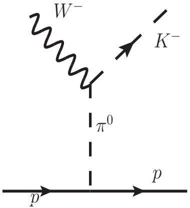
$$\frac{i}{4} g V_{us} W_-(-K_+ D\pi_0 + DK_+\pi_0)$$
$$= \frac{i}{4} g V_{us} (i p_k^\mu)\pi_0$$



$$-\frac{\bar{p}(D+F)\gamma_\sigma\gamma_5\partial^\sigma\pi^0 p}{2f_\pi}$$



$$-\frac{\bar{p}(D+F)\gamma_\sigma\gamma_5\partial^\sigma\pi^0 p}{2f_\pi}$$

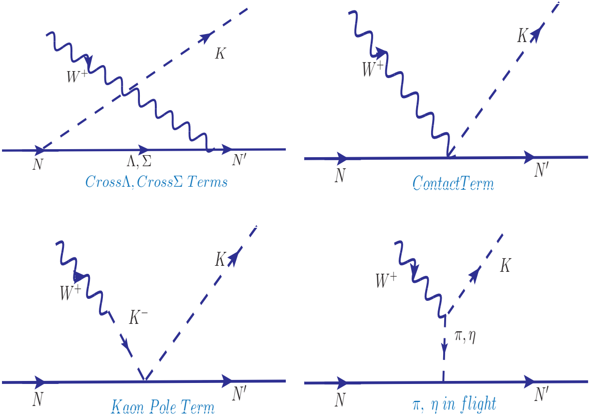


$$\frac{-ig}{2\sqrt{2}}\frac{1}{2\sqrt{2}f_\pi}\frac{V_{us}}{(q-p_K)^2-m_\pi^2}\bar{u}(p')(D+F)\ \not{p}_\pi\gamma_5 u(p)p_K^\mu$$

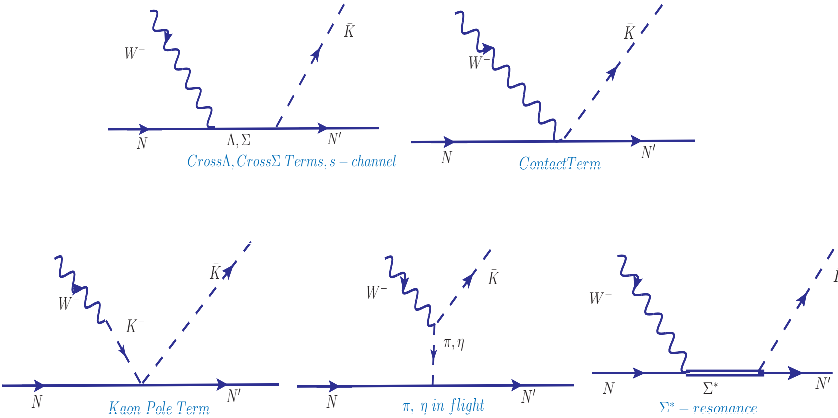
Outline

1. *Single Kaon Production*
2. *Hyperon Production*
   - Pion Production
3. *Eta Production*
4. *Associated Production*

$$
\begin{aligned}
\nu_l p &\rightarrow l^- K^+ p \\
\nu_l n &\rightarrow l^- K^0 p \\
\nu_l n &\rightarrow l^- K^+ n
\end{aligned}
$$



$$\begin{aligned}
\bar{\nu}_l p &\rightarrow l^+ K^- p \\
\bar{\nu}_l p &\rightarrow l^+ \bar{K}^0 n \\
\bar{\nu}_l n &\rightarrow l^+ K^- n
\end{aligned}$$



Currents for single K production by ν off the nucleon

$$J^\mu|_{CT} = iA_{CT}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\,(\gamma^\mu + B_{CT}\,\gamma^\mu\gamma_5)\,N(p)$$

$$j^\mu|_{Cr\Sigma} = iA_{Cr\Sigma}V_{us}(D-F)\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\left(\gamma^\mu + i\frac{\mu_p+2\mu_n}{2M}\sigma^{\mu\nu}q_\nu + (D-F)(\gamma^\mu - \frac{q^\mu}{q^2-M_k^2}\not{q})\gamma^5\right)\frac{\not{p}-\not{p}_k+M_\Sigma}{(p-p_k)^2-M_\Sigma^2}\not{p}_k\gamma^5 N(p),$$

$$j^\mu|_{Cr\Lambda} = iA_{Cr\Lambda}V_{us}(D+3F)\frac{\sqrt{2}}{4f_\pi}\bar{N}(p')\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu - \frac{D+3F}{3}(\gamma^\mu - \frac{q^\mu}{q^2-M_k^2}\not{q})\gamma^5\right)\frac{\not{p}-\not{p}_k+M_\Lambda}{(p-p_k)^2-M_\Lambda^2}\not{p}_k\gamma^5 N(p),$$

$$J^\mu|_\Sigma = iA_\Sigma(D-F)V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{p}_k\gamma_5\frac{\not{p}+\not{q}+M_\Sigma}{(p+q)^2-M_\Sigma^2}\left(\gamma^\mu + i\frac{(\mu_p+2\mu_n)}{2M}\sigma^{\mu\nu}q_\nu + (D-F)\left\{\gamma^\mu - \frac{q^\mu}{q^2-M_k{}^2}\not{q}\right\}\gamma^5\right)N(p)$$

$$J^\mu|_\Lambda = iA_\Lambda V_{us}(D+3F)\frac{1}{2\sqrt{2}f_\pi}\bar{N}(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M_\Lambda}{(p+q)^2-M_\Lambda^2}\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu - \frac{(D+3F)}{3}\left\{\gamma^\mu - \frac{q^\mu}{q^2-M_k{}^2}\not{q}\right\}\gamma^5\right)N(p)$$

$$J^\mu|_{KP} = iA_{KP}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{q}\,N(p)\frac{q^\mu}{q^2-M_k^2}$$

$$J^\mu|_\pi = iA_\pi\frac{M\sqrt{2}}{2f_\pi}V_{us}(D+F)\frac{2p_k{}^\mu - q^\mu}{(q-p_k)^2-m_\pi{}^2}\bar{N}(p')\gamma_5 N(p)$$

$$J^\mu|_\eta = iA_\eta\frac{M\sqrt{2}}{2f_\pi}V_{us}(D-3F)\frac{2p_k{}^\mu - q^\mu}{(q-p_k)^2-m_\eta{}^2}\bar{N}(p')\gamma_5 N(p)$$

$$J^\mu|_{\Sigma^*} = -iA_{\Sigma^*}\frac{C}{f_\pi}\frac{1}{\sqrt{6}}V_{us}\frac{p_k^\lambda}{P^2-M_{\Sigma^*}^2+i\Gamma_{\Sigma^*}M_{\Sigma^*}}\bar{N}(p')P_{RS_{\lambda\rho}}(\Gamma_V^{\rho\mu}+\Gamma_A^{\rho\mu})N(p)$$

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$$j^\mu|_{Cr\Sigma} = iA_{Cr\Sigma} V_{us} (D-F) \frac{\sqrt{2}}{2f_\pi} \bar{N}(p') \left(\gamma^\mu + i \frac{\mu_p + 2\mu_n}{2M} \sigma^{\mu\nu} q_\nu + (D-F)(\gamma^\mu - \frac{q^\mu}{q^2 - M_k^2} \not{q}) \gamma^5 \right) \frac{\not{p} - \not{p}_k + M_\Sigma}{(p-p_k)^2 - M_\Sigma^2} \not{p}_k \gamma^5 N(p),$$

$$j^\mu|_{Cr\Lambda} = iA_{Cr\Lambda} V_{us} (D+3F) \frac{\sqrt{2}}{4f_\pi} \bar{N}(p') \left(\gamma^\mu + i \frac{\mu_p}{2M} \sigma^{\mu\nu} q_\nu - \frac{D+3F}{3} (\gamma^\mu - \frac{q^\mu}{q^2 - M_k^2} \not{q}) \gamma^5 \right) \frac{\not{p} - \not{p}_k + M_\Lambda}{(p-p_k)^2 - M_\Lambda^2} \not{p}_k \gamma^5 N(p),$$

$$J^\mu|_\Sigma = iA_\Sigma (D-F) V_{us} \frac{\sqrt{2}}{2f_\pi} \bar{N}(p') \not{p}_k \gamma_5 \frac{\not{p} + \not{q} + M_\Sigma}{(p+q)^2 - M_\Sigma^2} \left(\gamma^\mu + i \frac{(\mu_p + 2\mu_n)}{2M} \sigma^{\mu\nu} q_\nu + (D-F) \left\{ \gamma^\mu - \frac{q^\mu}{q^2 - {M_k}^2} \not{q} \right\} \gamma^5 \right) N(p)$$

$$J^\mu|_\Lambda = iA_\Lambda V_{us} (D+3F) \frac{1}{2\sqrt{2} f_\pi} \bar{N}(p') \not{p}_k \gamma^5 \frac{\not{p} + \not{q} + M_\Lambda}{(p+q)^2 - M_\Lambda^2} \left(\gamma^\mu + i \frac{\mu_p}{2M} \sigma^{\mu\nu} q_\nu - \frac{(D+3F)}{3} \left\{ \gamma^\mu - \frac{q^\mu}{q^2 - {M_k}^2} \not{q} \right\} \gamma^5 \right) N(p)$$

$$J^\mu|_{KP} = iA_{KP} V_{us} \frac{\sqrt{2}}{2f_\pi} \bar{N}(p') \not{q}\, N(p) \frac{q^\mu}{q^2 - M_k^2}$$

$$J^\mu|_\pi = iA_\pi \frac{M\sqrt{2}}{2f_\pi} V_{us} (D+F) \frac{2{p_k}^\mu - q^\mu}{(q-p_k)^2 - {m_\pi}^2} \bar{N}(p') \gamma_5 N(p)$$

$$J^\mu|_\eta = iA_\eta \frac{M\sqrt{2}}{2f_\pi} V_{us} (D-3F) \frac{2{p_k}^\mu - q^\mu}{(q-p_k)^2 - {m_\eta}^2} \bar{N}(p') \gamma_5 N(p)$$

$$J^\mu|_{\Sigma^*} = -iA_{\Sigma^*} \frac{C}{f_\pi} \frac{1}{\sqrt{6}} V_{us} \frac{p_k^\lambda}{P^2 - M_{\Sigma^*}^2 + i\Gamma_{\Sigma^*} M_{\Sigma^*}} \bar{N}(p') P_{RS_{\lambda\rho}} (\Gamma_V^{\rho\mu} + \Gamma_A^{\rho\mu}) N(p)$$

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$$J^\mu|_\Sigma = iA_\Sigma(D-F)V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{p}_k\gamma_5\frac{\not{p}+\not{q}+M_\Sigma}{(p+q)^2-M_\Sigma^2}\left(\gamma^\mu + i\frac{(\mu_p+2\mu_n)}{2M}\sigma^{\mu\nu}q_\nu + (D-F)\left\{\gamma^\mu - \frac{q^\mu}{q^2-M_k{}^2}\not{q}\right\}\gamma^5\right)N(p)$$

$$J^\mu|_\Lambda = iA_\Lambda V_{us}(D+3F)\frac{1}{2\sqrt{2}f_\pi}\bar{N}(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M_\Lambda}{(p+q)^2-M_\Lambda^2}\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu - \frac{(D+3F)}{3}\left\{\gamma^\mu - \frac{q^\mu}{q^2-M_k{}^2}\not{q}\right\}\gamma^5\right)N(p)$$

$$J^\mu|_{KP} = iA_{KP}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{q}\,N(p)\frac{q^\mu}{q^2-M_k^2}$$

$$J^\mu|_\pi = iA_\pi\frac{M\sqrt{2}}{2f_\pi}V_{us}(D+F)\frac{2p_k{}^\mu - q^\mu}{(q-p_k)^2-m_\pi{}^2}\bar{N}(p')\gamma_5 N(p)$$

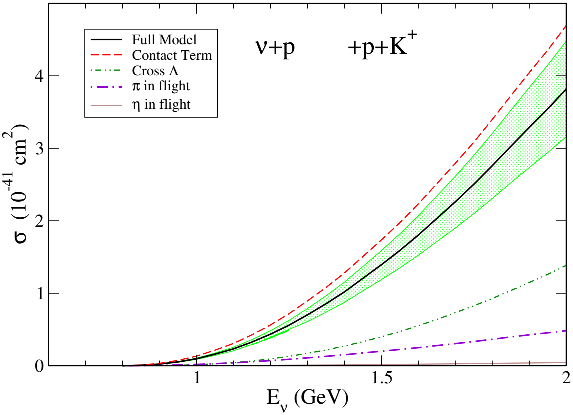
$$J^\mu|_\eta = iA_\eta\frac{M\sqrt{2}}{2f_\pi}V_{us}(D-3F)\frac{2p_k{}^\mu - q^\mu}{(q-p_k)^2-m_\eta{}^2}\bar{N}(p')\gamma_5 N(p)$$

$$J^\mu|_{\Sigma^*} = -iA_{\Sigma^*}\frac{C}{f_\pi}\frac{1}{\sqrt{6}}V_{us}\frac{p_k^\lambda}{P^2-M_{\Sigma^*}^2+i\Gamma_{\Sigma^*}M_{\Sigma^*}}\bar{N}(p')P_{RS_{\lambda\rho}}(\Gamma_V^{\rho\mu}+\Gamma_A^{\rho\mu})N(p)$$

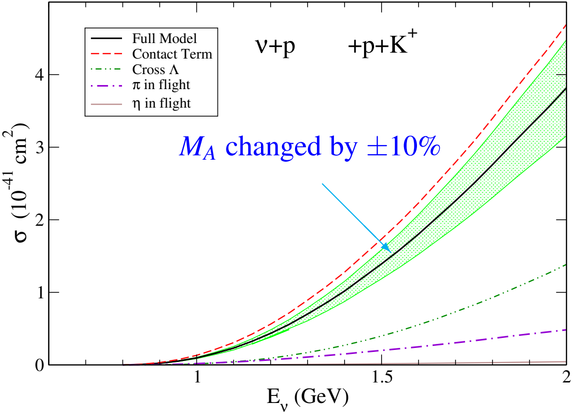
Process	B_{CT}	A_{CT}	A_{Σ}	A_{Λ}	$A_{Cr\Sigma}$	$A_{Cr\Lambda}$	A_{KP}	A_{π}	A_{η}	A_{Σ^*}
$\nu n \rightarrow l^- K^+ n$	D-F	-1	0	0	-1	0	-1	-1	-1	0
$\nu p \rightarrow l^- K^+ p$	-F	-2	0	0	$-\frac{1}{2}$	1	-2	1	-1	0
$\nu n \rightarrow l^- K^0 p$	-D-F	-1	0	0	$\frac{1}{2}$	1	-1	2	0	0
$\bar{\nu} n \rightarrow l^+ K^- n$	D-F	1	-1	0	0	0	-1	1	1	2
$\bar{\nu} p \rightarrow l^+ K^- p$	-F	2	$-\frac{1}{2}$	1	0	0	-2	-1	1	1
$\bar{\nu} p \rightarrow l^+ \bar{K}^0 n$	-D-F	1	$\frac{1}{2}$	1	0	0	-1	-2	0	-1

Table: Constant factors appearing in the hadronic current

σ for $\nu_\mu + p \to \mu^- + K^+ + p$



σ *for* $\nu_\mu + p \rightarrow \mu^- + K^+ + p$



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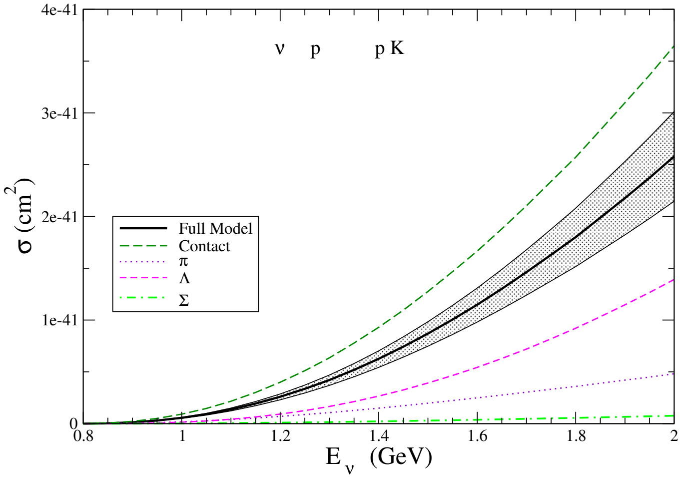

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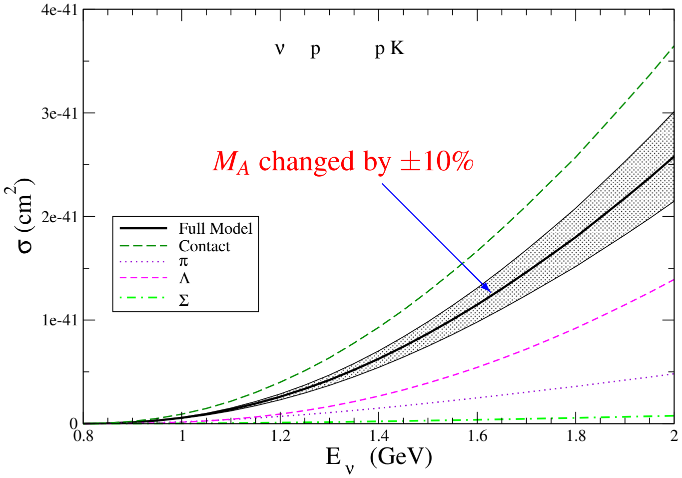

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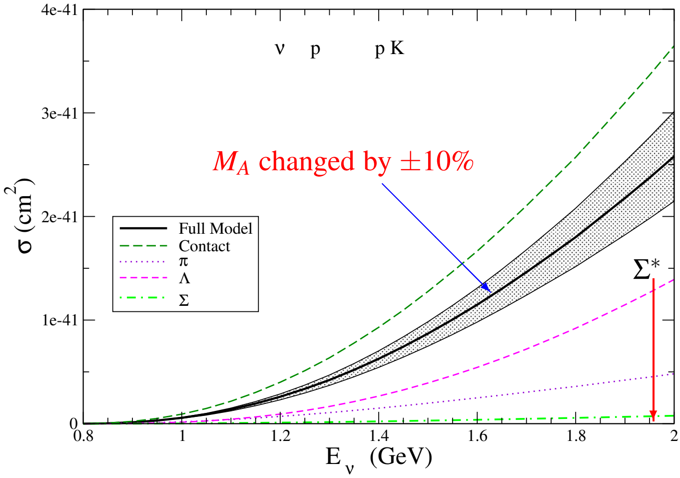
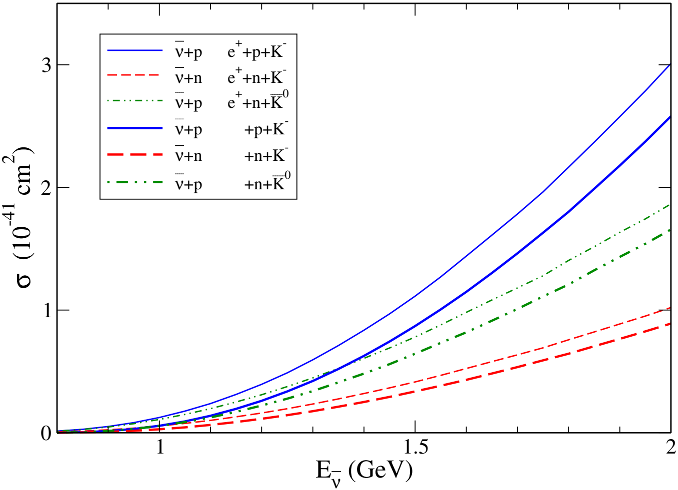


$\bar{\nu}$ *induced K-production*



Outline

Single Hyperon Production

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

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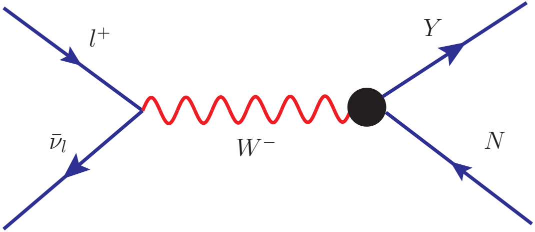
$$



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- Hyperons decay primarily through pionic decay modes
- Therefore contribute to the $\bar{\nu}$ induced pion production processes

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  - PCAC hypothesis

- This will help independently to test in strangeness sector
  - SU(3) symmetry
  - G invariance
  - Absence of FCNC
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Electric FF

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Axialvector FF

Electric FF

Induced Pseudoscalar FF

The six form factors $f_i(q^2)$ and $g_i(q^2)$ $(i = 1, 2, 3)$ are determined using following assumptions about the weak vector and axial vector currents:

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(c) $f_i(q^2)$ $(g_i(q^2))$ occurring in the matrix element of vector(axial vector) current is written in terms of two functions $D(q^2)$ and $F(q^2)$ corresponding to symmetric octet(8^S) and antisymmetric octet(8^A) couplings of octets of vector(axial vector) currents.

$$
\begin{aligned}
f_i(q^2) &= aF_i^V(q^2) + bD_i^V(q^2) \\
g_i(q^2) &= aF_i^A(q^2) + bD_i^A(q^2)
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Transitions	a	b
$p \to \Lambda$	$-\sqrt{\frac{3}{2}}$	$-\sqrt{\frac{1}{6}}$
$n \to \Sigma^-$	-1	1
$p \to \Sigma^0$	$-\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$

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FF	$p \to \Sigma^0$	$p \to \Lambda$
$f_1(q^2)$	$\frac{-1}{\sqrt{2}}(f_1^p(q^2) + 2f_1^n(q^2))$	$-\sqrt{\frac{3}{2}} f_1^p(q^2)$
$f_2(q^2)$	$\frac{-1}{\sqrt{2}}(f_2^p(q^2) + 2f_2^n(q^2))$	$-\sqrt{\frac{3}{2}} f_2^p(q^2)$
$g_1(q^2)$	$\frac{1}{\sqrt{2}} \frac{D-F}{D+F} g_A(q^2)$	$-\frac{D+3F}{\sqrt{6}(D+F)} g_A(q^2)$

- We assume dipole form for the axial form factor

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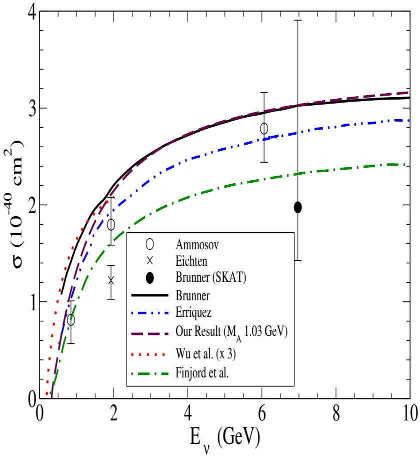
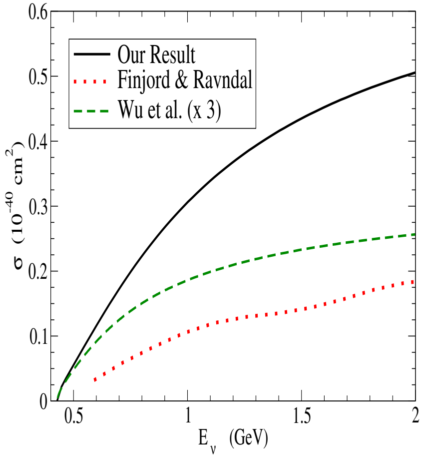
- The contribution of $g_3(q^2)$ is very small as it is proportional to the lepton mass in the matrix element. We neglect its contribution.



σ vs $E_{\bar{\nu}_\mu}$, for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ process.



σ vs $E_{\bar{\nu}_\mu}$, for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$ process.

Inside Nucleus

1. Fermi motion and Pauli blocking effects of initial nucleons are considered.
2. The Fermi motion effect is calculated in a local Fermi gas model, and the cross section is evaluated as a function of local Fermi momentum $p_F(r)$ and integrated over the whole nucleus.

Differential scattering cross section

$$\frac{d\sigma}{dQ^2 dE_l} = 2\int d^3r \int \frac{d^3p}{(2\pi)^3} n_N(p,r) \left[\frac{d\sigma}{dQ^2 dE_l}\right]_{\text{free}},$$

FINAL STATE INTERACTION(FSI) EFFECT

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

- $\Lambda + n \rightarrow \Sigma^- + p$,
- $\Lambda + n \rightarrow \Sigma^0 + n$,
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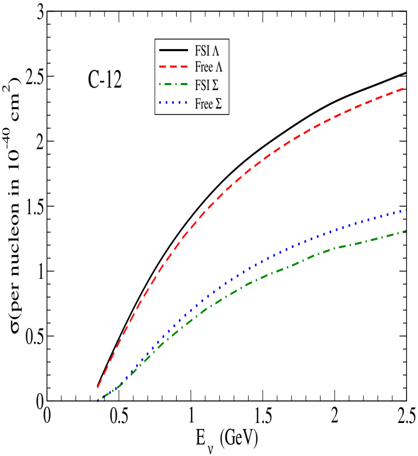
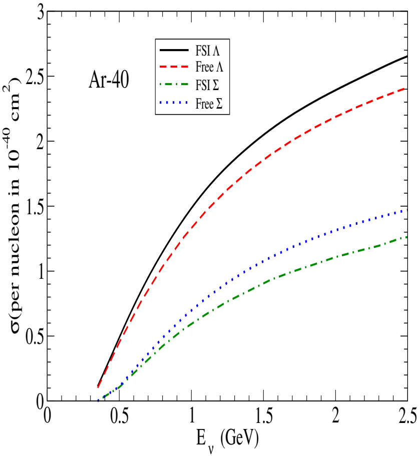
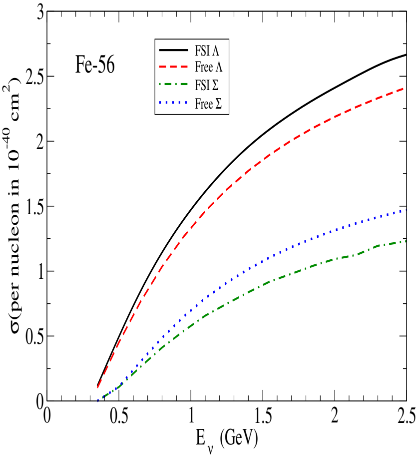
This has been taken into account by using a MC code where Y-N scattering cross section is the basic input.



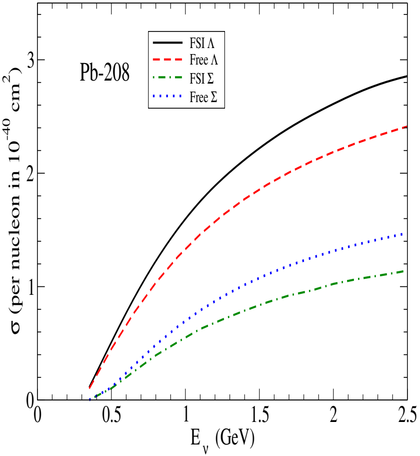
σ vs $E_{\bar{\nu}_\mu}$ in ^{12}C for quasielastic hyperon production.



σ vs $E_{\bar{\nu}_\mu}$ in ^{40}Ar for quasielastic hyperon production.



σ vs $E_{\bar{\nu}_\mu}$ in ^{56}Fe for quasielastic hyperon production.



σ vs $E_{\bar{\nu}_\mu}$ in ^{208}Pb for quasielastic hyperon production.

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.

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

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$$\bar{\nu}_l(k) + N(p) \rightarrow l^+(k') + \Delta(p_\Delta)$$
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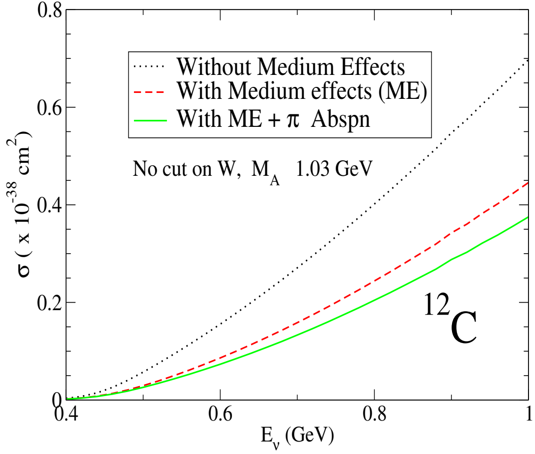
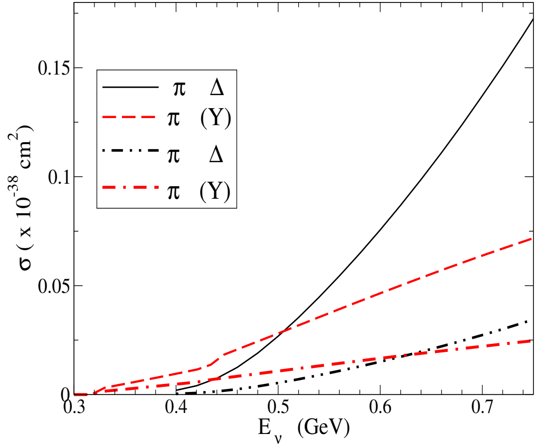
Cross Section in local density approximation

$$\sigma = \frac{1}{(4\pi)^5} \int_{r_{min}}^{r_{max}} \rho_N(r) d\vec{r} \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{k'_{min}}^{k'_{max}} dk' \int_{-1}^{+1} d\cos\theta_\pi$$
$$\times \int_0^{2\pi} d\phi_\pi \frac{\pi |\vec{k}'| |\vec{k}_\pi|}{M E_\nu^2 E_l} \frac{1}{E'_p + E_\pi \left(1 - \frac{|\vec{q}|}{|\vec{k}_\pi|} \cos\theta_\pi\right)} \bar{\sum} \sum |\mathcal{M}_{fi}|^2,$$


0.8
0.6
0.4
0.2
0
0.4
0.6
0.8
1
σ (x 10^-38 cm^2)
E_ν (GeV)
Without Medium Effects
With Medium effects (ME)
With ME + π Abspn
No cut on W, M_A 1.03 GeV
12C


0.15
0.1
0.05
0
0.3
0.4
0.5
0.6
0.7
σ (x 10^-38 cm^2)
E_ν (GeV)
π Δ
π (Y)
π Δ
π (Y)

Outline

- Eta production induced by virtual and real photons is being studied theoretically & experimentally

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In the energy range of $707MeV < E < 1.4GeV$

- *Photoproduction of eta meson off the nucleon*

$$\gamma + N \rightarrow \eta + N$$

- *A tool to study nucleon resonances which is dominated by* $N^*(1535)$
- *This process is comparatively more cleaner and selective to distinguish other resonances*
- ηN *couples only to nucleon resonances with isospin* $I = \frac{1}{2}$

Weak η *Production*

- The $\nu/\bar{\nu}$ induced η production is interesting because
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- Finally, theoretical models like the present one allow to improve the Monte Carlo simulations which are being used to analyze neutrino oscillation experiments.

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- Then use to obtain the isovector form factors for $\nu/\bar{\nu}$ induced scattering

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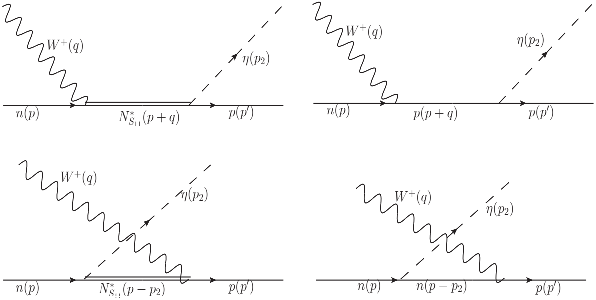
- We make an educated guess for the Q^2 dependence which ultimately remains to be determined experimentally

$$\begin{aligned}\nu_l(k)+n(p) &\rightarrow l^-(k')+p(p')+\eta(p_2)\\ \bar{\nu}_l(k)+p(p) &\rightarrow l^+(k')+n(p')+\eta(p_2).\end{aligned}$$



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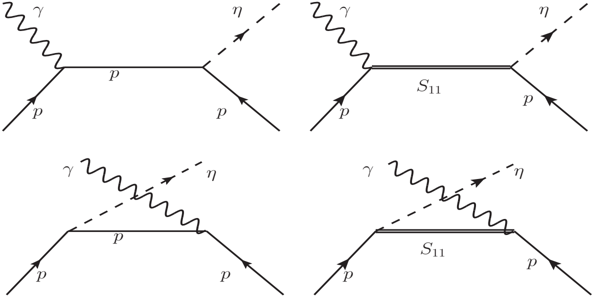

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Cross section in lab frame:

$$d\sigma = (2\pi)^4 \delta^4(p_\eta + p' - q - p) \frac{1}{4q_0 M} \frac{d^3 p_n}{(2\pi)^3 2E_\eta} \frac{d^3 p'}{(2\pi)^3 2E'} \overline{\sum} |\mathcal{M}_r^{(s)}|^2,$$

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And for the polarization states of hadrons which are remain undetected

$$\overline{\sum} |\mathcal{M}_r^{(s)}|^2 = -\frac{1}{4} e^2 g_{\mu\nu} H^{\mu\nu}$$

- The hadronic tensor $H^{\mu\nu}$

$$H^{\mu\nu} = \mathrm{Tr}\left[(\not{p}+\mathrm{M})\tilde{\mathrm{J}}^{\mu}(\not{p}'+\mathrm{M})\mathrm{J}^{\nu}\right], \qquad \tilde{\mathrm{J}}^{\mu} = \gamma_0(\mathrm{J}^{\mu})^{\dagger}\gamma_0$$

- Currents corresponding to the nucleon Born terms are obtained using χPT:

$$J^{\mu}_{N(s)} = \frac{D-3F}{2\sqrt{3}f_\pi}\bar{u}_N(p')\not{p}_\eta\gamma^5\frac{\not{p}+\not{p}+M}{(p+q)^2-M^2}O^{\mu}_N u_N(p)$$

$$J^{\mu}_{N(u)} = \frac{D-3F}{2\sqrt{3}f_\pi}\bar{u}_N(p')O^{\mu}_N\frac{\not{p}-\not{p}_\eta+M}{(p-p_\eta)^2-M^2}\not{p}_\eta\gamma^5 u_N(p),$$

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- where

$$O_N^\mu \equiv f_1^N(q^2)\gamma^\mu + f_2^N(q^2) i\sigma^{\mu\rho}\frac{q_\rho}{2M}$$

- For real photons $q^2 = 0$, therefore, one may write the above expression as,

$$O_N^\mu \equiv f_1^N(0)\gamma^\mu + f_2^N(0) i\sigma^{\mu\rho}\frac{q_\rho}{2M}.$$

$N(u)$ $2\sqrt{3}f_\pi$ $(p-p_\eta)^2-M^2$

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- W is the energy at resonance rest frame, which for on-mass shell reduces to the mass of resonance i.e. $W_{\text{on-mass}} = M_R$.

To fix the coupling, following decay fraction for the N^* resonance are taken

$$\begin{array}{lll}
N^*(1535) \rightarrow & N\pi & 35-50\% \\
N^*(1535) \rightarrow & N\eta & (42\pm 10)\% \\
N^*(1535) \rightarrow & N\pi\pi & 1-10\% \\
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N^*(1650) \rightarrow & N\pi & 50-90\% \\
N^*(1650) \rightarrow & N\eta & 5-15\% \\
N^*(1650) \rightarrow & \Lambda K & 3-11\% \\
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S_{11}^{-}(N^*) & & \\
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g_{\eta}^{1650} & = & 0.0868 \\
g_{\eta}^{1535} & = & 0.286 \\
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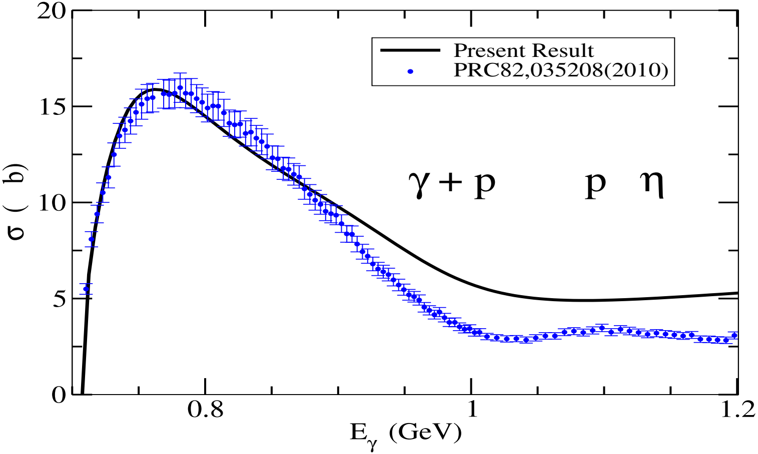
Parameters fitted using the data from the MAMI Crystal Ball experiment

Resonance→	S11(1535)	S11(1650)
Helicity Amplitude↓	$A_\lambda(0)$ 10^{-3}	$A_\lambda(0)$ 10^{-3}
$A^p_{1/2}(0)$	89.38	53.0
$S^p_{1/2}(0)$	-16.5	-3.5

Photoproduction of η Mesons



Crystal Ball detector at the Mainz Microtron(MAMI-C)

Weak production of η Mesons

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where

$$O^{\mu}_N \equiv f_1^V(q^2)\gamma^{\mu}+f_2^V(q^2)i\sigma^{\mu\rho}\frac{q_{\rho}}{2M_N}-f_A(q^2)\gamma^{\mu}\gamma^5-f_P(q^2)q^{\mu}\gamma^5$$

For the resonant $S_{11}(1535)$ and $S_{11}(1650)$ channels the hadronic currents are given by,

$$J^{\mu}_{R(s)} = \frac{gV_{ud}}{2\sqrt{2}} i g_{\eta} \bar{u}_N(p') \not{p}_{\eta} \frac{\not{p} + \not{q} + M_R}{(p+q)^2 - M_R^2 + i\Gamma_R M_R} O^{\mu}_R u_N(p)$$

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where

$$O^{\mu}_R \equiv \frac{F_1^V(q^2)}{(2M)^2}(\not{q} q^{\mu} - q^2\gamma^{\mu})\gamma_5 \pm \frac{F_2^V(q^2)}{2M} i\sigma^{\mu\rho} q_{\rho}\gamma_5$$
$$-F_A(q^2)\gamma^{\mu} \mp \frac{F_P(q^2)}{M} q^{\mu}$$

The isovector form factors $F_{1,2}^V$, are given in terms of the electromagnetic transition form factors of protons and neutrons as

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$F_{1,2}^{p,n}(Q^2)$ are obtained from the helicity amplitudes $A_{\frac{1}{2}}^{p,n}$ and $S_{\frac{1}{2}}^{p,n}$, given as

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$F^{p,n}_{1,2}(Q^2)$ are obtained from the helicity amplitudes $A^{p,n}_{\frac{1}{2}}$ and $S^{p,n}_{\frac{1}{2}}$, given as

$$\begin{aligned} A^{p,n}_{\frac{1}{2}} &= \sqrt{\frac{2\pi\alpha_e}{M}\frac{(M_R+M)^2+Q^2}{M_R^2-M^2}}\left(\frac{Q^2}{4M^2}F^{p,n}_1(Q^2)+\frac{M_R-M}{2M}F^{p,n}_2(Q^2)\right) \\ S^{p,n}_{\frac{1}{2}} &= \sqrt{\frac{\pi\alpha_e}{M}\frac{(M_R-M)^2+Q^2}{M_R^2-M^2}}\frac{(M_R+M)^2+Q^2}{4M_RM}\left(\frac{M_R-M}{2M}F^{p,n}_1(Q^2)-F^{p,n}_2(Q^2)\right) \end{aligned}$$

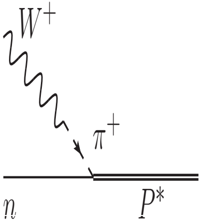
The parameters $A_{\frac{1}{2}}$ and $S_{\frac{1}{2}}$ are generally parameterized as:

$$
\begin{aligned}
A_{\frac{1}{2}}(Q^2) &= A_{\frac{1}{2}}(0)\left(1+\alpha\, Q^2\right)\, e^{-\beta Q^2} \\
S_{\frac{1}{2}}(Q^2) &= S_{\frac{1}{2}}(0)\left(1+\alpha\, Q^2\right)\, e^{-\beta Q^2}\ ,
\end{aligned}
$$

Parameters used for the helicity amplitude

Resonance→	S11(1535)			S11(1650)		
Helicity Amplitude↓	$A_\lambda(0)$ 10^{-3}	α	β	$A_\lambda(0)$ 10^{-3}	α	β
$A^p_{1/2}(Q^2)$	89.38	1.61364	0.75879	53	1.45	0.62
$S^p_{1/2}(Q^2)$	-16.5	2.8261	0.73735	-3.5	2.88	0.76
$A^n_{1/2}(Q^2)$	-52.79	2.86297	1.68723	9.3	0.13	1.55
$S^n_{1/2}(Q^2)$	29.66	0.35874	1.55	10.0	-0.5	1.55

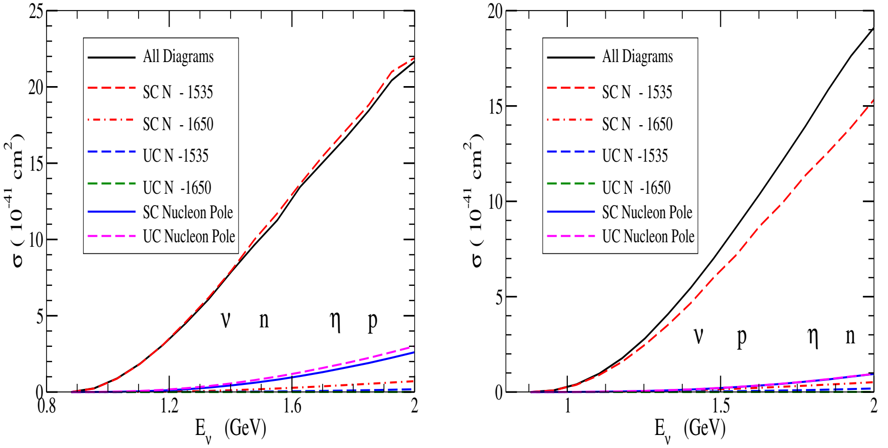
We derived Goldberger-Treiman relation for the axial couplings and assumed a dipole form for Q^2dependence for the axial form factors.



$$
\begin{aligned}
F_A(Q^2) &= F_A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}; \\
F_P(Q^2) &= \frac{(M_R-M)M}{Q^2+m_\pi^2}F_A(Q^2).
\end{aligned}
$$

$F_A(0) = 2g_\eta \qquad M_A = 1.03GeV$

arXiv:*1311.2293*



Outline

Channels Considered

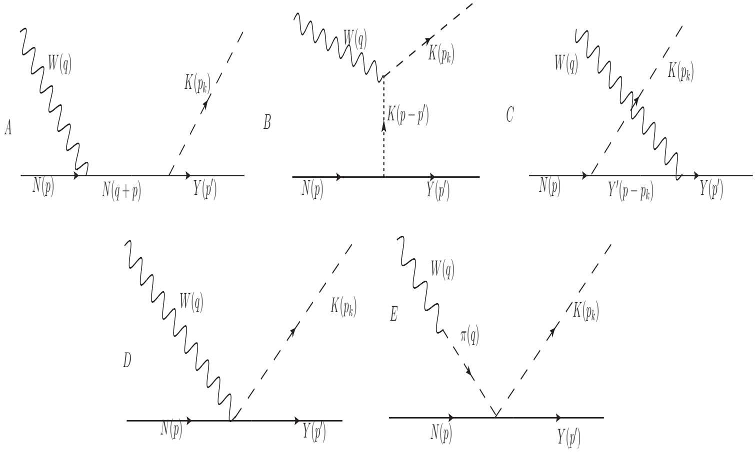
Neutrino

$$\begin{aligned}
\nu_l n &\rightarrow l^-\Sigma^+K^0 \\
\nu_l n &\rightarrow l^-\Lambda K^+ \\
\nu_l n &\rightarrow l^-\Sigma^0K^+ \\
\nu_l p &\rightarrow l^-\Sigma^+K^+
\end{aligned}$$

Anti-neutrino

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

Feynman diagram



$$
\begin{aligned}
j^{\mu}|_s &= iA_{SY}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M}{(p+q)^2-M^2}\mathcal{H}^{\mu}u_N(p) \\
j^{\mu}|_u &= iA_{UY}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\mathcal{H}^{\mu}\frac{\not{p}-\not{p}_k+M_{Y'}}{(p-p_k)^2-M_{Y'}^2}\not{p}_k\gamma^5 u_N(p) \\
j^{\mu}|_t &= iA_{TY}V_{ud}\frac{\sqrt{2}}{2f_\pi}(M+M_Y)\,\bar{u}_Y(p')\gamma_5\,u_N(p)\;\frac{q^{\mu}-2p_k^{\mu}}{(p-p')^2-m_k^2} \\
j^{\mu}|_{CT} &= iA_{CT}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\left(\gamma^{\mu}+B_{CT}\,\gamma^{\mu}\gamma^5\right)u_N(p) \\
j^{\mu}|_{\pi F} &= iA_{\pi}V_{ud}\frac{\sqrt{2}}{4f_\pi}\,\bar{u}_Y(p')(\not{q}+\not{p}_k)u_N(p)\frac{q^{\mu}}{q^2-m_\pi^2} \\
\mathcal{H}^{\mu} &= F_1^V\gamma^{\mu}+i\frac{F_2^V}{2M}\sigma^{\mu\nu}q_\nu-G_A\left(\gamma^{\mu}-\frac{\not{q}q^{\mu}}{q^2-m_\pi^2}\right)\gamma^5,
\end{aligned}
$$

where $\mathcal{H}^{\mu}$ is the transition current for $Y \leftrightarrows Y'$ with $Y = Y' \equiv$ Nucleon and/or Hyperon.

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j^\mu|_s &= iA_{SY}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M}{(p+q)^2-M^2}\mathcal{H}^\mu u_N(p)\\
j^\mu|_u &= iA_{UY}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\mathcal{H}^\mu\frac{\not{p}-\not{p}_k+M_{Y'}}{(p-p_k)^2-M_{Y'}^2}\not{p}_k\gamma^5 u_N(p)\\
j^\mu|_t &= iA_{TY}V_{ud}\frac{\sqrt{2}}{2f_\pi}(M+M_Y)\,\bar{u}_Y(p')\gamma_5\,u_N(p)\;\frac{q^\mu-2p_k^\mu}{(p-p')^2-m_k^2}\\
j^\mu|_{CT} &= iA_{CT}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\left(\gamma^\mu+B_{CT}\,\gamma^\mu\gamma^5\right)u_N(p)\\
j^\mu|_{\pi F} &= iA_\pi V_{ud}\frac{\sqrt{2}}{4f_\pi}\,\bar{u}_Y(p')(\not{q}+\not{p}_k)u_N(p)\frac{q^\mu}{q^2-m_\pi^2}\\
\mathcal{H}^\mu &= F_1^V\gamma^\mu+i\frac{F_2^V}{2M}\sigma^{\mu\nu}q_\nu-G_A\left(\gamma^\mu-\frac{\not{q}q^\mu}{q^2-m_\pi^2}\right)\gamma^5,
\end{aligned}
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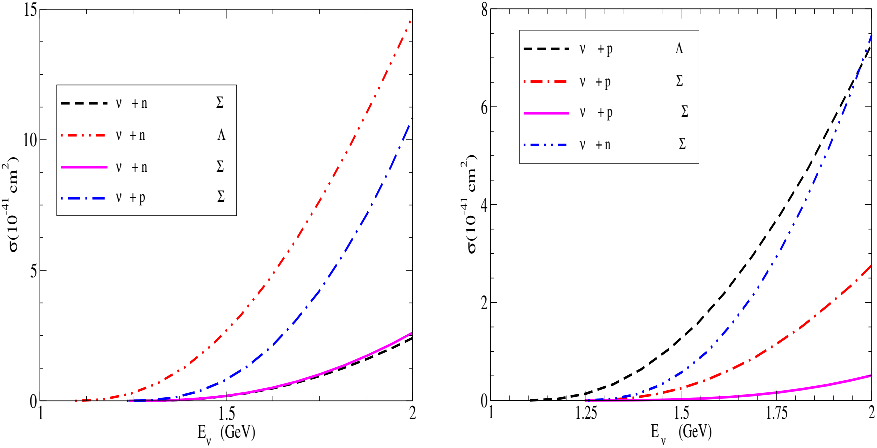
The standard form factors for weak CC transitions of the SU(3) *baryon octets.*

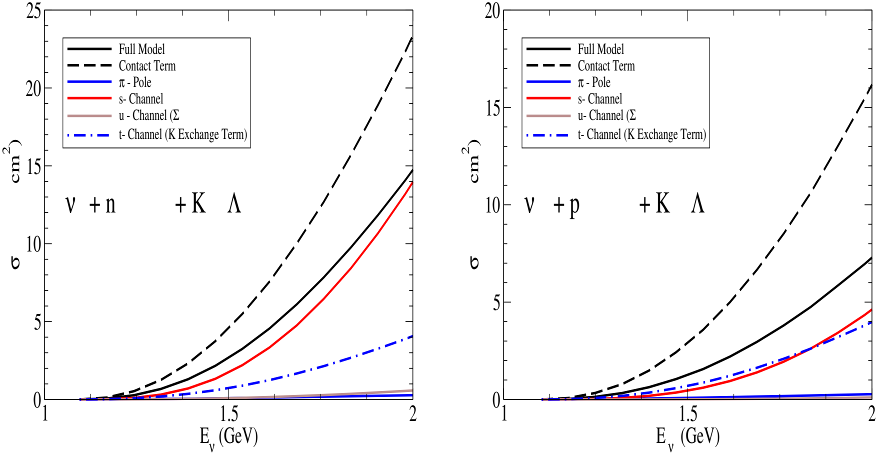
Sl. No.	Weak transition	$F_1(Q^2)$	$F_2(Q^2)$	$G_A(Q^2)$
1	$p \to n$	$f_1^p(Q^2) - f_1^n(Q^2)$	$f_2^p(Q^2) - f_2^n(Q^2)$	$g_A(Q^2)$
2	$p \to \Lambda$	$-\sqrt{\frac{3}{2}} f_1^p(Q^2)$	$-\sqrt{\frac{3}{2}} f_2^p(Q^2)$	$-\sqrt{\frac{1}{6}} \frac{3F+D}{F+D} g_A(Q^2)$
	$n \to \Lambda$	$-\sqrt{\frac{3}{2}} f_1^p(Q^2)$	$-\sqrt{\frac{3}{2}} f_2^p(Q^2)$	$-\sqrt{\frac{1}{6}} \frac{3F+D}{F+D} g_A(Q^2)$
3	$\Sigma^\pm \to \Lambda$	$-\sqrt{\frac{3}{2}} f_1^n(Q^2)$	$-\sqrt{\frac{3}{2}} f_2^n(Q^2)$	$\sqrt{\frac{2}{3}} \frac{D}{F+D} g_A(Q^2)$
4	$\Sigma^\pm \to \Sigma^0$	$\mp \frac{1}{\sqrt{2}} [2f_1^p(Q^2) + f_1^n(Q^2)]$	$\mp \frac{1}{\sqrt{2}} [2f_2^p(Q^2) + f_2^n(Q^2)]$	$\mp \sqrt{2} \frac{F}{F+D} g_A(Q^2)$
5	$p \to \Sigma^0$	$-\frac{1}{\sqrt{2}} [f_1^p(Q^2) + 2f_1^n(Q^2)]$	$-\frac{1}{\sqrt{2}} [f_2^p(Q^2) + 2f_2^n(Q^2)]$	$\frac{1}{\sqrt{2}} \frac{D-F}{F+D} g_A(Q^2)$
	$n \to \Sigma^0$	$\frac{1}{\sqrt{2}} [f_1^p(Q^2) + 2f_1^n(Q^2)]$	$\frac{1}{\sqrt{2}} [f_2^p(Q^2) + 2f_2^n(Q^2)]$	$-\frac{1}{\sqrt{2}} \frac{D-F}{F+D} g_A(Q^2)$
6	$n \to \Sigma^-$	$-f_1^p(Q^2) - 2f_1^n(Q^2)$	$-f_2^p(Q^2) - 2f_2^n(Q^2)$	$\frac{D-F}{F+D} g_A(Q^2)$
	$p \to \Sigma^+$	$-f_1^p(Q^2) - 2f_1^n(Q^2)$	$-f_2^p(Q^2) - 2f_2^n(Q^2)$	$\frac{D-F}{F+D} g_A(Q^2)$

Couplings for $\Delta S = 0$ K production

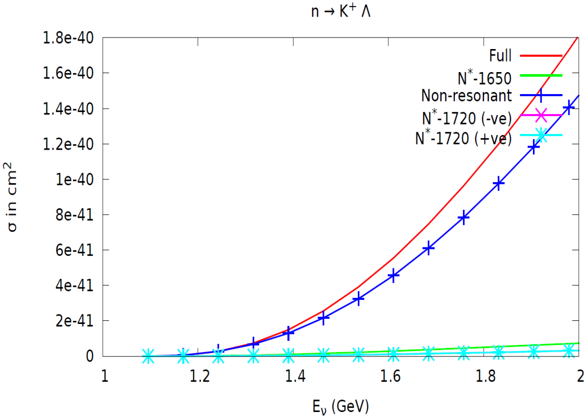
Process	A_{CT}	B_{CT}	A_{SY}	A_{UY} $Y' = \Sigma$	A_{UY} $Y' = \Lambda$	A_{TY}	A_{π}
$\bar{\nu}_l p \to l^+ \Sigma^- K^+$ $\nu_l n \to l^- \Sigma^+ K^0$	0	0	$D-F$	$D-F$	$\frac{1}{3}(D+3F)$	0	0
$\bar{\nu}_l p \to l^+ \Lambda K^0$ $\nu_l n \to l^- \Lambda K^+$	$-\sqrt{\frac{3}{2}}$	$\frac{-1}{3}(D+3F)$	$\frac{-1}{\sqrt{6}}(D+3F)$	$-\sqrt{\frac{2}{3}}(D-F)$	0	$\frac{-1}{\sqrt{6}}(D+3F)$	$\sqrt{\frac{3}{2}}$
$\bar{\nu}_l p \to l^+ \Sigma^0 K^0$ $\nu_l n \to l^- \Sigma^0 K^+$	$\mp\frac{1}{\sqrt{2}}$	$D-F$	$\mp\frac{1}{\sqrt{2}}(D-F)$	$\mp\sqrt{2}(D-F)$	0	$\pm\frac{1}{\sqrt{2}}(D-F)$	$\pm\frac{1}{\sqrt{2}}$
$\bar{\nu}_l n \to l^+ \Sigma^- K^0$ $\nu_l p \to l^- \Sigma^+ K^+$	-1	$D-F$	0	$F-D$	$\frac{1}{3}(D+3F)$	$D-F$	1

Table: Constant factors appearing in the hadronic current. The upper sign corresponds to the processes with $\bar{\nu}$


ν + n Σ
ν + n Λ
ν + n Σ
ν + p Σ
σ(10-41 cm2)
Eν (GeV)
ν + p Λ
ν + p Σ
ν + p Σ
ν + n Σ
σ(10-41 cm2)
Eν (GeV)


Full Model
Contact Term
π - Pole
s- Channel
u - Channel (Σ
t- Channel (K Exchange Term)
ν + n + K Λ
ν + p + K Λ
σ cm2)
Eν (GeV)

With Resonance



- N(1650) I (J^P) $\frac{1}{2}$ $(\frac{1}{2}^-)$
- N(1720) I (J^P) $\frac{1}{2}$ $(\frac{3}{2}^+)$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GOZAIMASU