Strange Particle Production with Neutrinos

Mohammad Sajjad Athar[1]

M Rafi Alam[1] S Chauhan[1] S K Singh[1]
I Ruiz Simo[2]
L Alvarez-Ruso[3] M J Vicente Vacas[3]

[1]Aligarh Muslim University, India

[2]University of Granada, Spain

[3]University of Valencia & IFIC, Spain

NuInt'2014, Surrey, UK

Processes

Single Hyperon Production

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

Processes

Single Hyperon Production

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

Eta Production

$$\nu_\mu n \rightarrow \mu^- p \eta \qquad \bar{\nu}_\mu p \rightarrow \mu^+ n \eta$$

Processes

Single Hyperon Production

$$\bar{\nu}_\mu p \to \mu^+ \Sigma^0$$
$$\bar{\nu}_\mu p \to \mu^+ \Lambda$$
$$\bar{\nu}_\mu n \to \mu^+ \Sigma^-$$

Eta Production

$$\nu_\mu n \to \mu^- p \eta \qquad \bar{\nu}_\mu p \to \mu^+ n \eta$$

Associated Production ($\Delta S = 0$)

$$\nu_\mu n \to \mu^- K^+ \Lambda \qquad \bar{\nu}_\mu p \to \mu^+ K^0 \Lambda$$
$$\nu_\mu p \to \mu^- K^+ \Sigma^+ \qquad \bar{\nu}_\mu p \to \mu^+ K^0 \Sigma^0$$
$$\nu_\mu n \to \mu^- K^+ \Sigma^0 \qquad \bar{\nu}_\mu p \to \mu^+ K^+ \Sigma^-$$
$$\nu_\mu n \to \mu^- K^0 \Sigma^+ \qquad \bar{\nu}_\mu n \to \mu^+ K^0 \Sigma^-$$

Processes

Single Hyperon Production

$$\bar{\nu}_\mu p \to \mu^+ \Sigma^0$$
$$\bar{\nu}_\mu p \to \mu^+ \Lambda$$
$$\bar{\nu}_\mu n \to \mu^+ \Sigma^-$$

Eta Production

$$\nu_\mu n \to \mu^- p \eta \qquad \bar{\nu}_\mu p \to \mu^+ n \eta$$

Associated Production ($\Delta S = 0$)

$$\nu_\mu n \to \mu^- K^+ \Lambda \qquad \bar{\nu}_\mu p \to \mu^+ K^0 \Lambda$$
$$\nu_\mu p \to \mu^- K^+ \Sigma^+ \qquad \bar{\nu}_\mu p \to \mu^+ K^0 \Sigma^0$$
$$\nu_\mu n \to \mu^- K^+ \Sigma^0 \qquad \bar{\nu}_\mu p \to \mu^+ K^+ \Sigma^-$$
$$\nu_\mu n \to \mu^- K^0 \Sigma^+ \qquad \bar{\nu}_\mu n \to \mu^+ K^0 \Sigma^-$$

Single Kaon Production ($\Delta S = 1$)

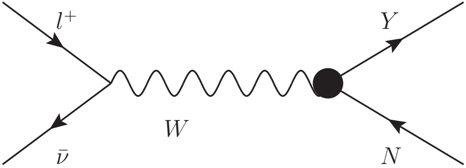
$$\nu_\mu p \to \mu^- K^+ p \qquad \bar{\nu}_\mu p \to \mu^+ K^- p$$
$$\nu_\mu n \to \mu^- K^0 p \qquad \bar{\nu}_\mu p \to \mu^+ \bar{K}^0 n$$
$$\nu_\mu n \to \mu^- K^+ n \qquad \bar{\nu}_\mu n \to \mu^+ K^- n$$

Outline

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

Single Hyperon Production

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



Generally, these processes are Cabibbo suppressed as compared to the $\Delta S = 0$ associated production of hyperons. However, for $E_{\bar{\nu}} < 2$ GeV, the associated production of hyperons is kinematically suppressed by the phase space.

Transition matrix element

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \sin\theta_c l^\mu J_\mu$$

Transition matrix element

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \sin\theta_c l^\mu J_\mu$$

l^μ is leptonic current and $J_\mu(\Delta S = 1)$ is the strangeness changing hadronic current

$$J_\mu = \langle Y(p')|V_\mu - A_\mu|N(p)\rangle$$

Vector and Axial Vector Currents

$$\langle Y(p')|V_\mu|N(p)\rangle = \bar{u}_Y(p')\left[\gamma_\mu f_1 + i\sigma_{\mu\nu}\frac{q^\nu}{M+M_Y}f_2 + \frac{f_3}{M+M_Y}q^\mu\right]u_N(p)$$

$$\langle Y(p')|A_\mu|N(p)\rangle = \bar{u}_Y(p')\left[\gamma_\mu\gamma_5 g_1 + i\sigma^{\mu\nu}\gamma_5\frac{q^\nu}{M+M_Y}g_2 + \frac{g_3}{M+M_Y}q_\mu\gamma_5\right]u_N(p)$$

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 in weak interactions:

(a) The assumptions of T invariance implies that all the form factors $f_i(q^2)$ and $g_i(q^2)$ are real.

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 in weak interactions:

(b) Assumed that $\Delta S = 0$ and $\Delta S = 1$ weak currents along with the electromagnetic currents transform as octet representation under SU(3).

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 in weak interactions:

(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.

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 in weak interactions:

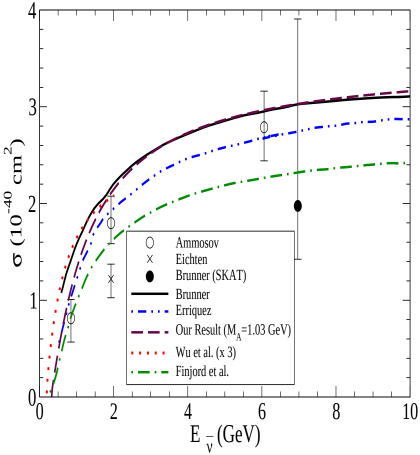
(d) The assumption of SU(3) symmetry and G invariance together implies absence of second class currents leading to

$$f_3(q^2) = g_2(q^2) = 0$$

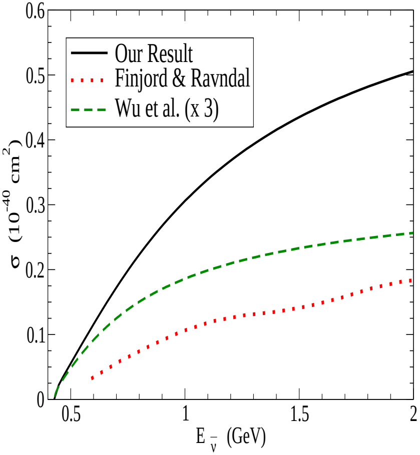
FF	$p \to \Sigma^0$	$p \to \Lambda$
$f_1(q^2)$	$\frac{-1}{\sqrt{2}}(f_1^p(q^2) + 2f_1^n(q^2))$	$-\sqrt{\frac{3}{2}}f_1^p(q^2)$
$f_2(q^2)$	$\frac{-1}{\sqrt{2}}(f_2^p(q^2) + 2f_2^n(q^2))$	$-\sqrt{\frac{3}{2}}f_2^p(q^2)$
$g_1(q^2)$	$\frac{-1}{\sqrt{2}}\frac{D-F}{D+F}g_A(q^2)$	$\frac{D+3F}{\sqrt{6}(D+F)}g_A(q^2)$

F and D are determined from the semileptonic decays and are taken as 0.463 and 0.804 respectively.

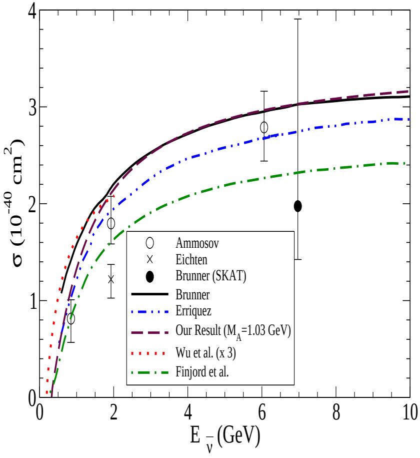
$$
\begin{aligned}
f_1^{p,n}(q^2) &= \frac{1}{1-\frac{q^2}{4M^2}}\left[G_E^{p,n}(q^2) - \frac{q^2}{4M^2}G_M^{p,n}(q^2)\right] \\
f_2^{p,n}(q^2) &= \frac{1}{1-\frac{q^2}{4M^2}}\left[G_M^{p,n}(q^2) - G_E^{p,n}(q^2)\right]
\end{aligned}
$$

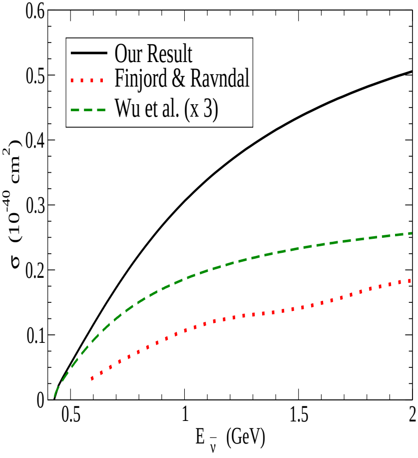


σ vs $E_{\bar{\nu}_\mu}$, for $\bar{\nu}_\mu + p \to \mu^+ + \Lambda$ process.



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





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

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

C.H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

Inside Nucleus

1. Fermi motion and Pauli blocking effects of initial nucleons are considered.
2. The Fermi motion effects are 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

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

Phys. Rev. D **88**, 077301 (2013)
Phys. Rev. D **74**, 053009 (2006).

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

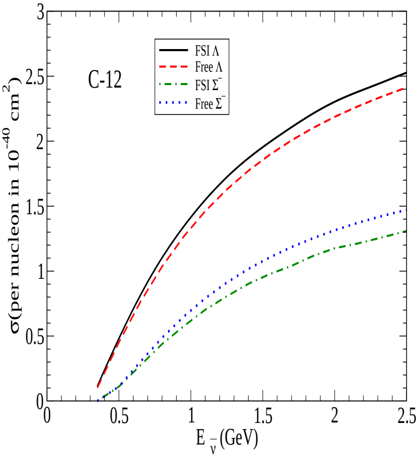
- $\Lambda + n \rightarrow \Sigma^- + p$,
- $\Lambda + n \rightarrow \Sigma^0 + n$,
- $\Sigma^- + p \rightarrow \Lambda + n$,
- $\Sigma^- + p \rightarrow \Sigma^0 + n$, etc.

Final state interaction(FSI) effect

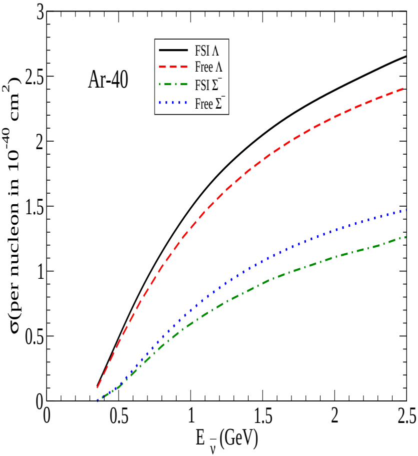
The produced hyperons are further affected by the FSI within the nucleus through the hyperon-nucleon quasielastic and charge exchange scattering processes like

- $\Lambda + n \to \Sigma^- + p$,
- $\Lambda + n \to \Sigma^0 + n$,
- $\Sigma^- + p \to \Lambda + n$,
- $\Sigma^- + p \to \Sigma^0 + n$, etc.

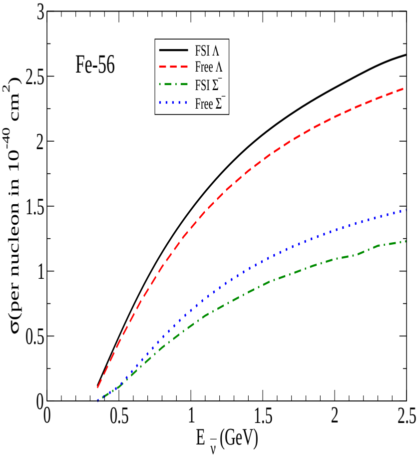
This has been taken into account by using a MC code where Y-N scattering xsec is the basic input, the details of the prescription is given in **PRD 74, 053009, 2006**.



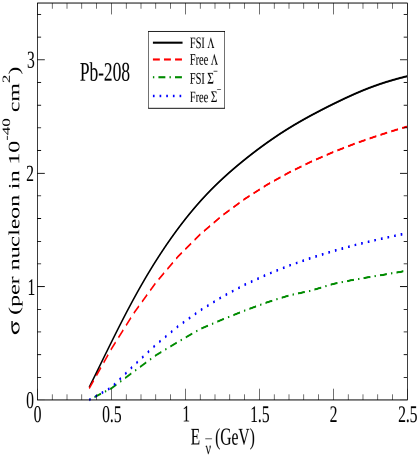
σ vs $E_{\bar{\nu}_\mu}$ in ^{12}C for quasielastic hyperon production.



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

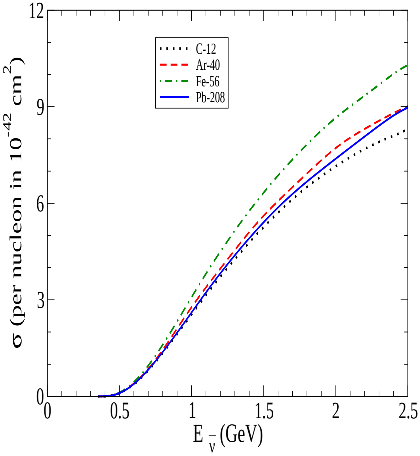


σ vs $E_{\bar{\nu}_\mu}$ in ^{56}Fe for quasielastic hyperon production.

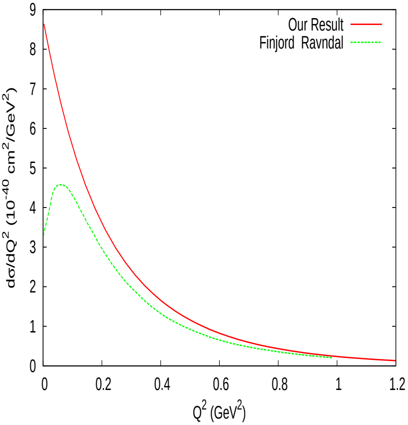


σ vs $E_{\bar{\nu}_\mu}$ in ^{208}Pb for quasielastic hyperon production.

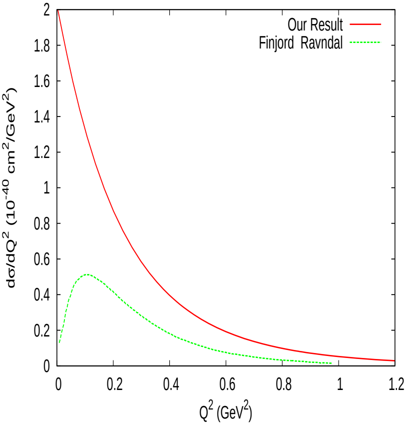
- $\Lambda + p \rightarrow \Sigma^+ + n$,
- $\Sigma^0 + p \rightarrow \Sigma^+ + n$



σ vs $E_{\bar{\nu}_\mu}$ for Σ^+ production.



Q^2 distribution at $E_{\bar{\nu}} = 2GeV$ for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ process.



Q^2 distribution at $E_{\bar{\nu}} = 2GeV$ for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$ process.

Hyperon giving rise to pions

As the decay modes of hyperons to pions is highly suppressed in the nuclear medium(E Oset et al. Phys. Rep. **188**, 79 1990), making them live long enough to pass through the nucleus and decay outside the nuclear medium.

Hyperon giving rise to pions

As the decay modes of hyperons to pions is highly suppressed in the nuclear medium(E Oset et al. Phys. Rep. **188**, 79 1990), 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.

Pion Production through Δ excitation

$$\bar{\nu}_l(k) + N(p) \rightarrow l^+(k') + \Delta(p_\Delta)$$
$$\hookrightarrow N'(p') + \pi(k_\pi)$$

Pion Production through Δ excitation

$$\bar{\nu}_l(k) + N(p) \to l^+(k') + \Delta(p_\Delta)$$
$$\hookrightarrow N'(p') + \pi(k_\pi)$$

Cross Section in local density approximation

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

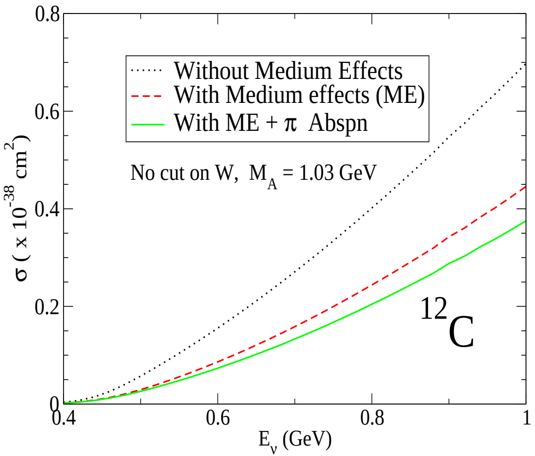
Pion Production through Δ excitation

$$\bar{\nu}_l(k) + N(p) \rightarrow l^+(k') + \Delta(p_\Delta)$$
$$\hookrightarrow N'(p') + \pi(k_\pi)$$

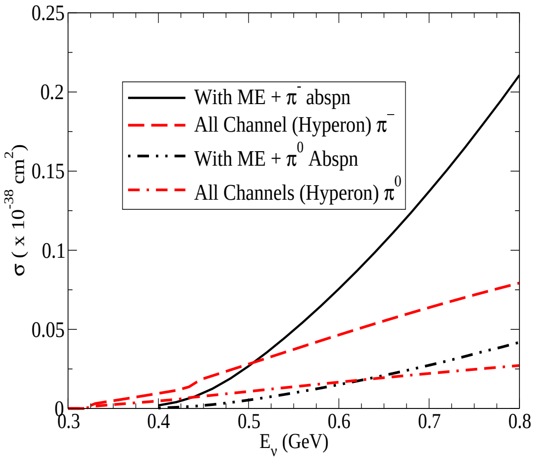
Cross Section in local density approximation

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

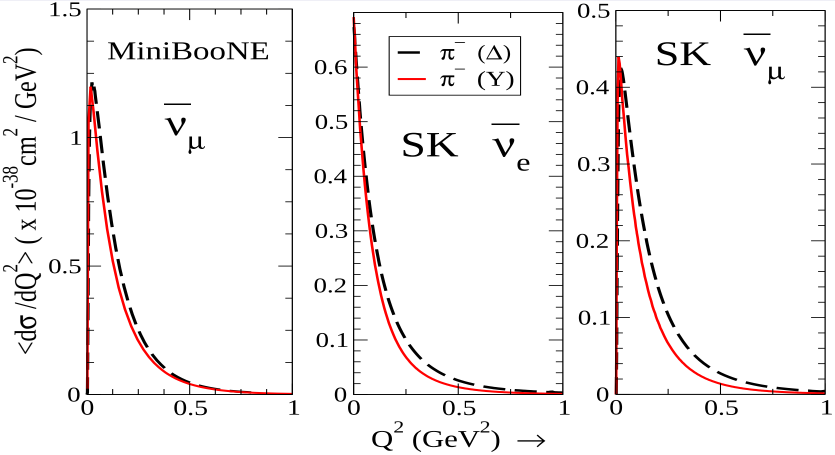
Eur. Phys. J. A **43**, 209 (2010).
J. Phys. G **37**, 015005 (2010).



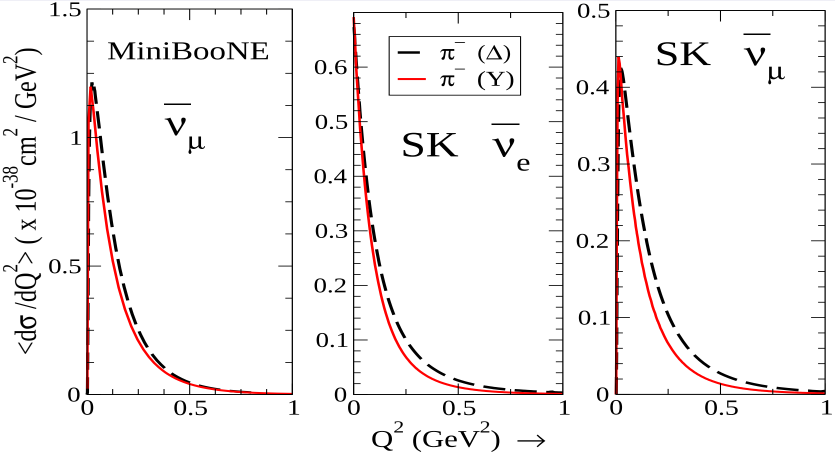
Eur. Phys. J. A **43**, 209 (2010).



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



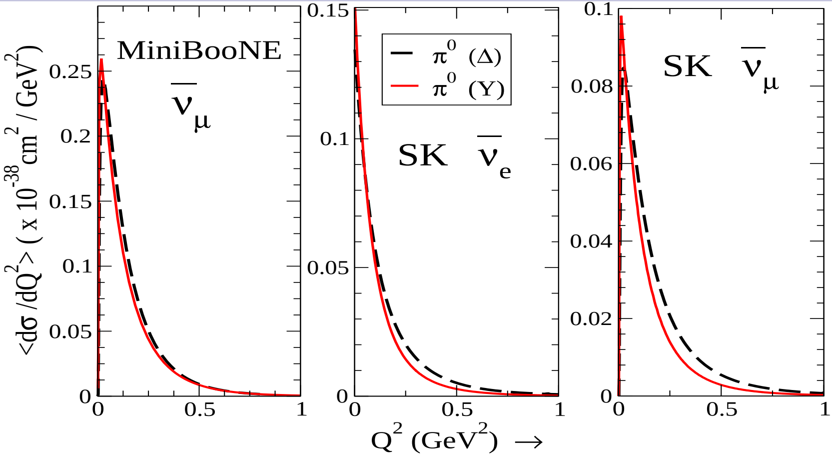
Q^2 distribution (a) for $\bar{\nu}_\mu$ induced reaction in ^{12}C averaged over the MiniBooNE flux and (b & c) for ^{16}O averaged over the SuperK flux for e^+ & μ^+. The results are presented for the incoherent π^- production with medium effect and pion absorption, and for the π^- production from the quasielastic hyperon production



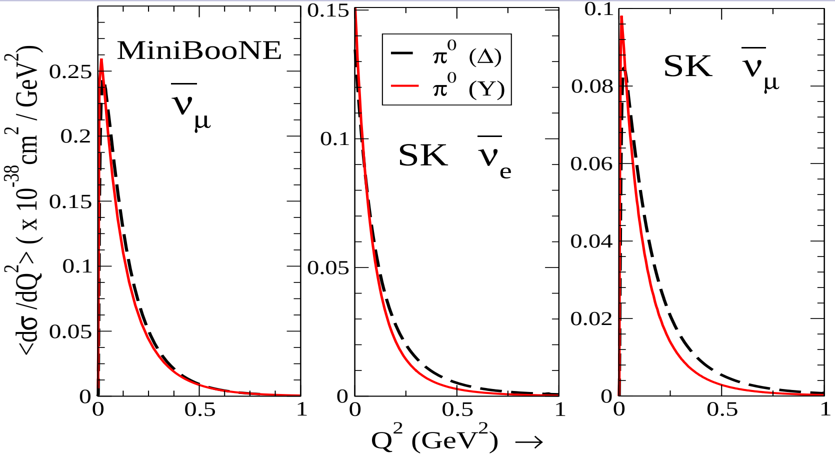
Q^2 distribution (a) for $\bar{\nu}_\mu$ induced reaction in ^{12}C averaged over the MiniBooNE flux and (b & c) for ^{16}O averaged over the SuperK flux for e^+ & μ^+. The results are presented for the incoherent π^- production with medium effect and pion absorption, and for the π^- production from the quasielastic hyperon production

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

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



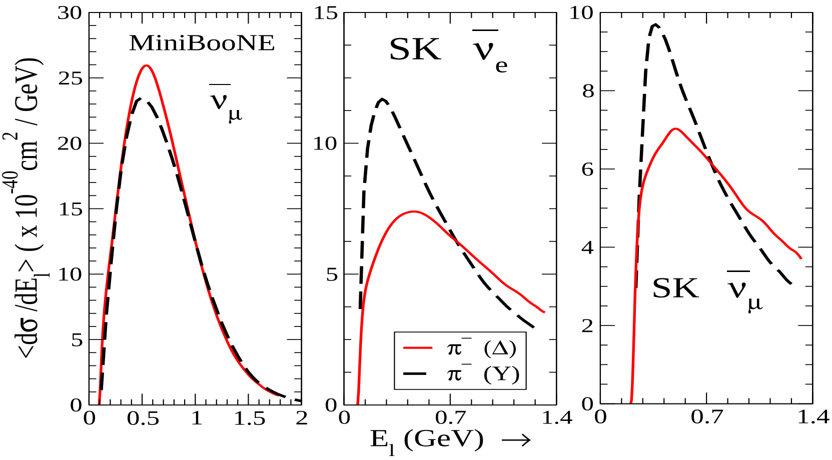
Q^2 distribution (a) for $\bar{\nu}_\mu$ induced reaction in ^{12}C averaged over the MiniBooNE flux and (b & c) for ^{16}O averaged over the SuperK flux for e^+ & μ^+. The results are presented for the incoherent π^0 production with medium effect and pion absorption, and for the π^- production from the quasielastic hyperon production



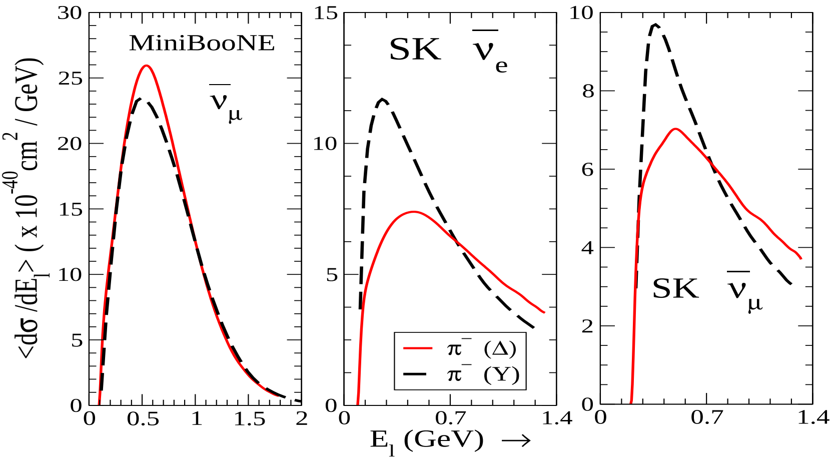
Q^2 distribution (a) for $\bar{\nu}_\mu$ induced reaction in ^{12}C averaged over the MiniBooNE flux and (b & c) for ^{16}O averaged over the SuperK flux for e^+ & μ^+. The results are presented for the incoherent π^0 production with medium effect and pion absorption, and for the π^- production from the quasielastic hyperon production

scaled by a factor of 1.3 i.e $\sim$ 30%

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

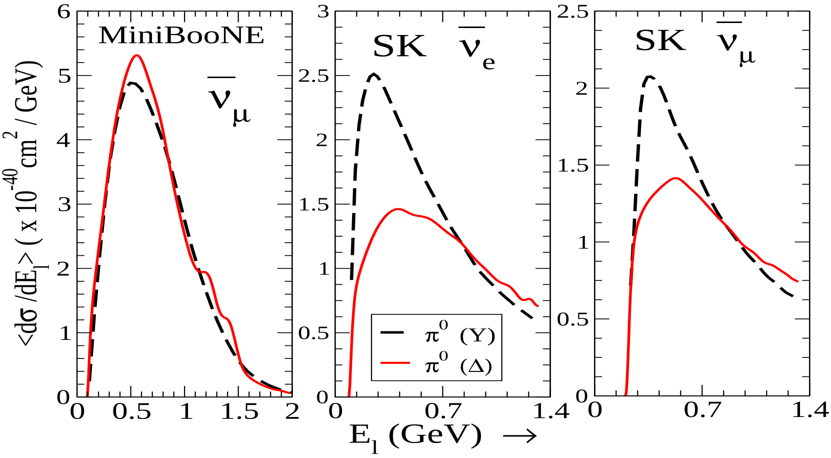


Lepton energy distributions for π^- production.

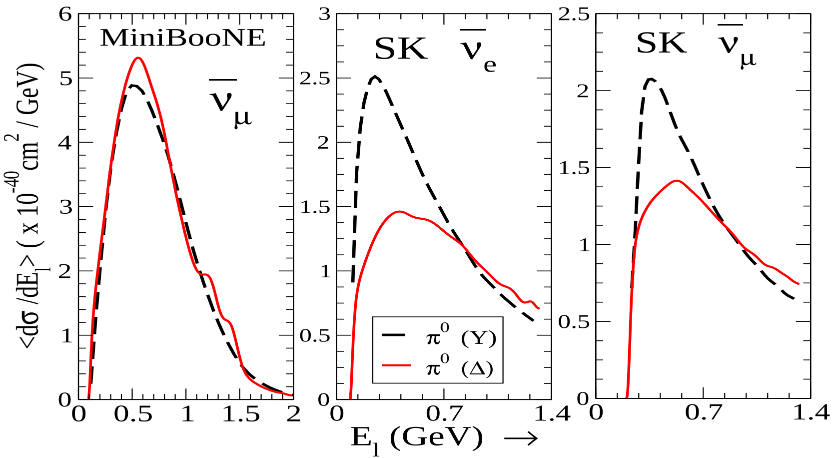


Lepton energy distributions for π^- production.

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



Lepton energy distributions for π^0 production.

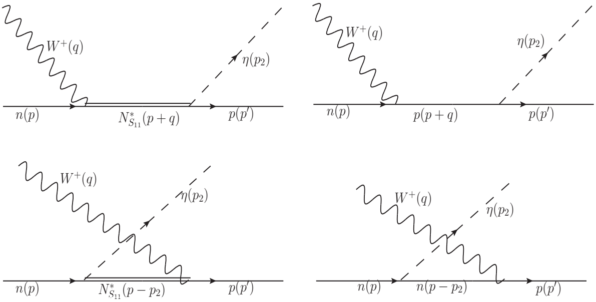


Lepton energy distributions for π^0 production.

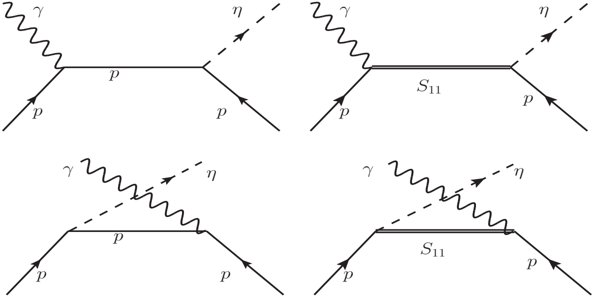
scaled by a factor of 1.3 i.e $\sim$ 30%

Outline

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



- N(1535) $I\ (J^P)\ \ \frac{1}{2}\ (\frac{1}{2}^-)$
- N(1650) $I\ (J^P)\ \ \frac{1}{2}\ (\frac{1}{2}^-)$



- N(1535) I $\left(J^P\right)$ $\frac{1}{2}$ $\left(\frac{1}{2}^-\right)$
- N(1650) I $\left(J^P\right)$ $\frac{1}{2}$ $\left(\frac{1}{2}^-\right)$

Photoproduction of Eta Mesons

$$\gamma(q) + p(p) \rightarrow p(p') + \eta(p_2)$$

Cross section in lab frame:

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

The transition amplitude is $\mathcal{M}_r^{(s)}$

$$|\mathcal{M}_r^{(s)}|^2 \quad = \quad e^2 \varepsilon_\mu^{*(s)} \varepsilon_\nu^{(s)} H^{\mu\nu}$$

For unknown photon polarization:

$$\overline{\sum}_{s=\pm 1} \varepsilon_\mu^{*(s)} \varepsilon_\nu^{(s)} \longrightarrow -g_{\mu\nu}.$$

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:

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

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

where

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

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

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

For the resonant terms, currents corresponding to s-channel $J^{\mu}_{R(s)}$ and the u-channel $J^{\mu}_{R(u)}$ are:

$$
\begin{aligned}
J^{\mu}_{R(s)} &= i g_{\eta N S_{11}} \bar{u}_{N^*}(p') \not{p}_{\eta} \frac{\not{p} + \not{q} + M_R}{(p+q)^2 - M_R^2 + i\Gamma_R M_R} O^{\mu}_{R} u_N(p) \\
J^{\mu}_{R(u)} &= i g_{\eta N S_{11}} \bar{u}_{N^*}(p') O^{\mu}_{R} \frac{\not{p} - \not{p}_2 + M_R}{(p-p_{\eta})^2 - M_R^2 + i\Gamma_R M_R} \not{p}_{\eta} u_N(p),
\end{aligned}
$$

where

$$
O^{\mu}_{R} \equiv \pm \frac{F_2^N(q^2=0)}{2M} i\sigma^{\mu\rho} q_{\rho} \gamma_5
$$

+(-) sign for s(u) channel diagram.
$g_{\eta N S_{11}}$ is fixed using the resonant decay width.

$\Gamma(S_{11} \to N\phi)$ partial decay width is:

$$\Gamma_{S_{11}\to N\Phi} = C_\Phi \left(\frac{g_\Phi}{f_\pi}\right)^2 \frac{|\vec{p}_{CM}|}{8\pi} \frac{(W^2-M^2)^2 - m_\Phi^2(W^2+M^2-2MM_R)}{W^2}$$

where $C_\Phi = 3$ for pion and $C_\Phi = 1$ for eta meson and

$$|\vec{p}_{CM}| = \frac{1}{2W}\sqrt{[W^2-(M+m_\Phi)^2] \quad [W^2-(M-m_\Phi)^2]}.$$

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

$N^*(1535) \to$	$N\pi$	$35-50\%$
$N^*(1535) \to$	$N\eta$	$(42\pm10)\%$
$N^*(1535) \to$	$N\pi\pi$	$1-10\%$
$N^*(1650) \to$	$N\pi$	$50-90\%$
$N^*(1650) \to$	$N\eta$	$5-15\%$
$N^*(1650) \to$	ΛK	$3-11\%$

$S_{11}^{+}(P^*)$

$$g_\pi^{1650} = -0.105$$
$$g_\eta^{1650} = -0.088$$
$$g_\eta^{1535} = 0.284$$
$$g_\pi^{1535} = 0.092$$

$S_{11}^{-}(N^*)$

$$g_\pi^{1650} = 0.131$$
$$g_\eta^{1650} = 0.0868$$
$$g_\eta^{1535} = 0.286$$
$$g_\pi^{1535} = 0.106$$

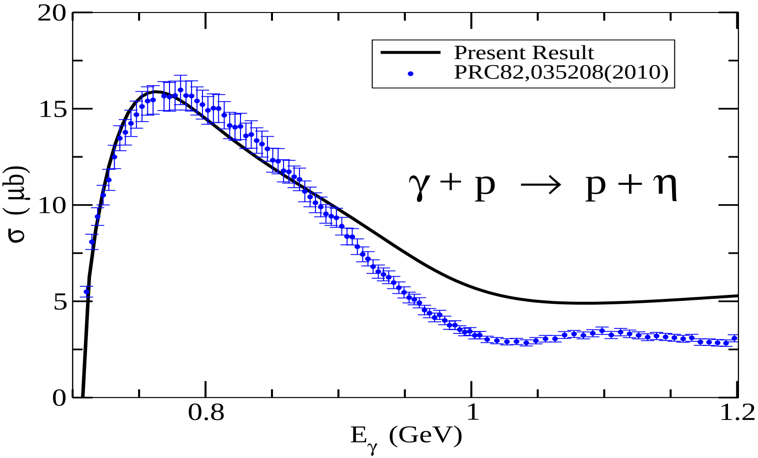
$A_{\frac{1}{2}}$ is generally parameterized as(following MAID convention):

$$A^{p,n}_{\frac{1}{2}} = \sqrt{\frac{2\pi\alpha_e}{M}\frac{(M_R+M)^2}{M_R^2-M^2}}\frac{M_R-M}{2M}F_2^N(0)$$

Table: 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)
E. McNicoll *et. al.* Phys. Rev. C **82** (2010) 035208

Weak production of η Mesons

The current has structure $V-A$

Hadronic currents for nonresonant terms using χPT is obtained as,

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

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

where

$$O^{\mu}_N \equiv f^V_1(q^2)\gamma^{\mu}+f^V_2(q^2)i\sigma^{\mu\rho}\frac{q_{\rho}}{2M_N}-f_A(q^2)\gamma^{\mu}\gamma^5-f_P(q^2)q^{\mu}\gamma^5$$

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

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

$$J^{\mu}_{R(u)} = \frac{gV_{ud}}{2\sqrt{2}} i g_{\eta} \bar{u}_N(p') O^{\mu}_R \frac{\not{p}-\not{p}_2+M_R}{(p-p_{\eta})^2 - M_R^2 + i\Gamma_R M_R} \not{p}_{\eta} u_N(p),$$

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 $F^V_{1,2}$, are given in terms of the electromagnetic transition form factors of protons and neutrons as

$$F^V_1(Q^2) = F^p_1(Q^2) - F^n_1(Q^2); \quad F^V_2(Q^2) = F^p_2(Q^2) - F^n_2(Q^2).$$

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

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

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

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

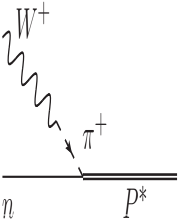
$$A_{\frac{1}{2}}(Q^2) = A_{\frac{1}{2}}(0)\left(1+\alpha\, Q^2\right)\, e^{-\beta Q^2}$$

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

Table: 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.

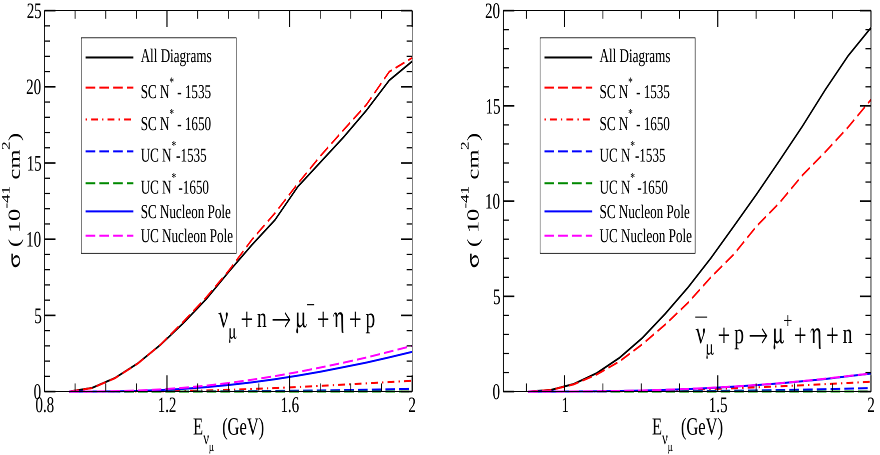


$$F_A(Q^2) = F_A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2};$$

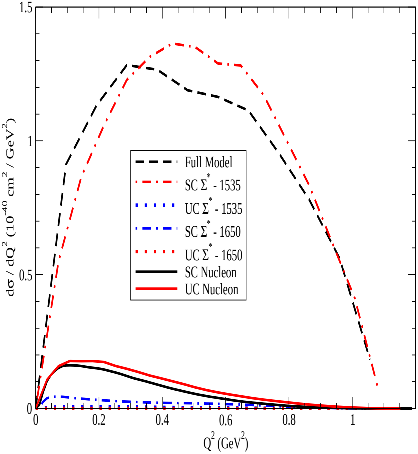
$$F_P(Q^2) = \frac{(M_R-M)M}{Q^2+m_\pi^2}F_A(Q^2).$$

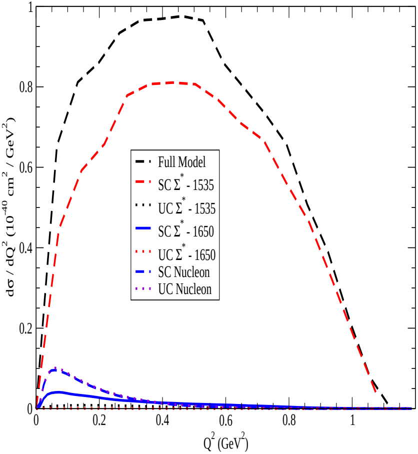
$F_A(0) = 2g_\eta$ $\quad$ $M_A = 1.03 GeV$

arXiv:*1311.2293*



arXiv:*1311.2293*

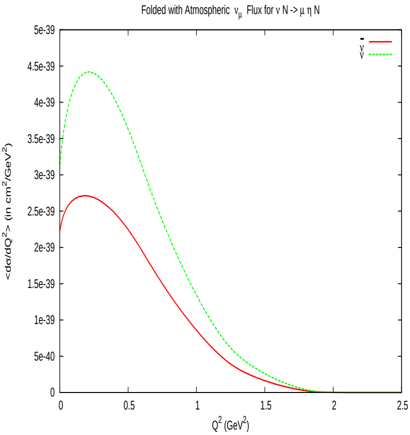


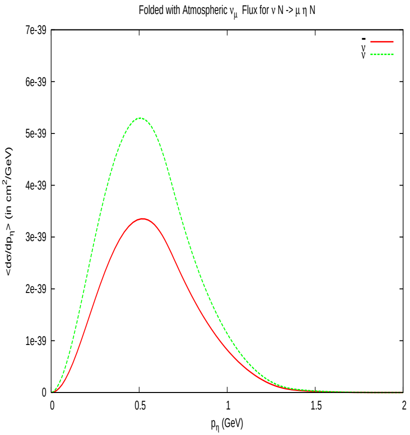


Neutrino **Antineutrino**

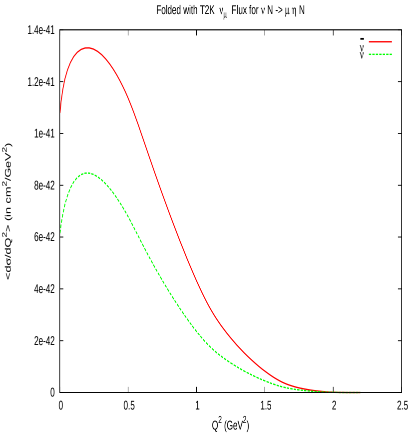
$E_{\nu(\bar{\nu})} = 1.5 GeV$

Atmospheric

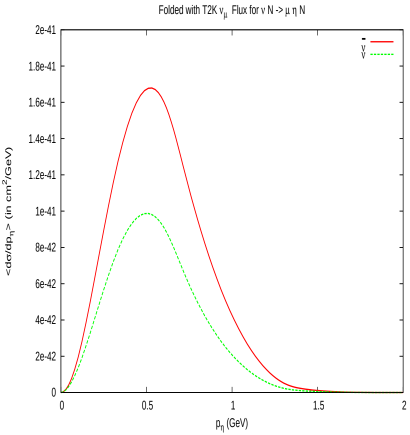




T2K



Folded with T2K ν_μ Flux for ν N -> μ η N
$\bar{\nu}$
ν
1.4e-41
1.2e-41
1e-41
8e-42
6e-42
4e-42
2e-42
0
0
0.5
1
1.5
2
2.5
$<d\sigma/dQ^2>$ (in cm^2/GeV^2)
Q^2 (GeV^2)



Folded with T2K ν_μ Flux for ν N -> μ η N
$\bar{\nu}$
ν
2e-41
1.8e-41
1.6e-41
1.4e-41
1.2e-41
1e-41
8e-42
6e-42
4e-42
2e-42
0
0
0.5
1
1.5
2
$<d\sigma/dp_\eta>$ (in cm^2/GeV)
p_η (GeV)

Outline

Processes

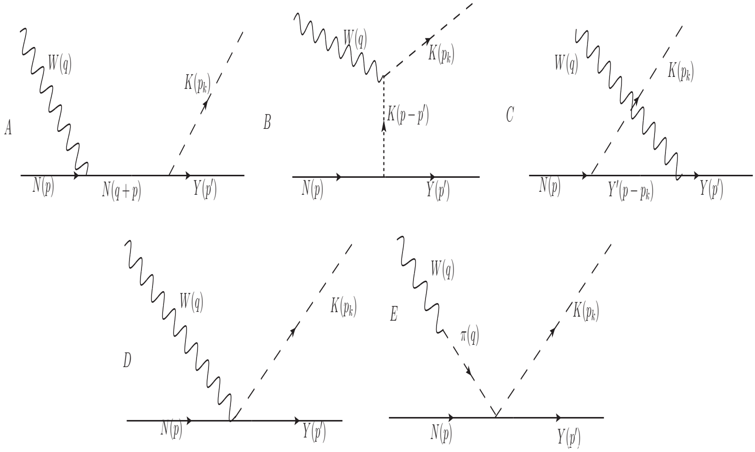
Neutrino

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

Anti-neutrino

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

Feynman diagram



$$j^\mu|_s = iA_{SY}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M}{(p+q)^2-M^2}\mathcal{H}^\mu u_N(p)$$

$$j^\mu|_u = iA_{UY}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\mathcal{H}^\mu\frac{\not{p}-\not{p}_k+M_{Y'}}{(p-p_k)^2-M_{Y'}^2}\not{p}_k\gamma^5 u_N(p)$$

$$j^\mu|_t = iA_{TY}V_{ud}\frac{\sqrt{2}}{2f_\pi}(M+M_Y)\,\bar{u}_Y(p')\gamma_5\,u_N(p)\;\;\frac{q^\mu-2p_k^\mu}{(p-p')^2-m_k^2}$$

$$j^\mu|_{CT} = iA_{CT}V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\left(\gamma^\mu+B_{CT}\,\gamma^\mu\gamma^5\right)u_N(p)$$

$$j^\mu|_{\pi F} = iA_\pi V_{ud}\frac{\sqrt{2}}{4f_\pi}\,\bar{u}_Y(p')(\not{q}+\not{p}_k)u_N(p)\frac{q^\mu}{q^2-m_\pi^2}$$

$$\mathcal{H}^\mu = F_1^V\gamma^\mu+i\frac{F_2^V}{2M}\sigma^{\mu\nu}q_\nu-G_A\left(\gamma^\mu-\frac{\not{q}q^\mu}{q^2-m_\pi^2}\right)\gamma^5,$$

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

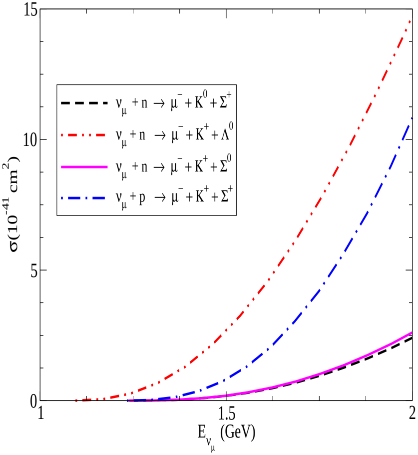
The standard form factors for weak CC transitions of the SU(3) baryon octets.

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

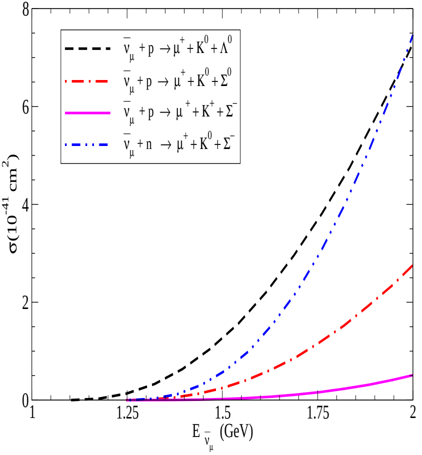
Couplings for $\Delta S = 0$ K production

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 $\bar{\nu}$

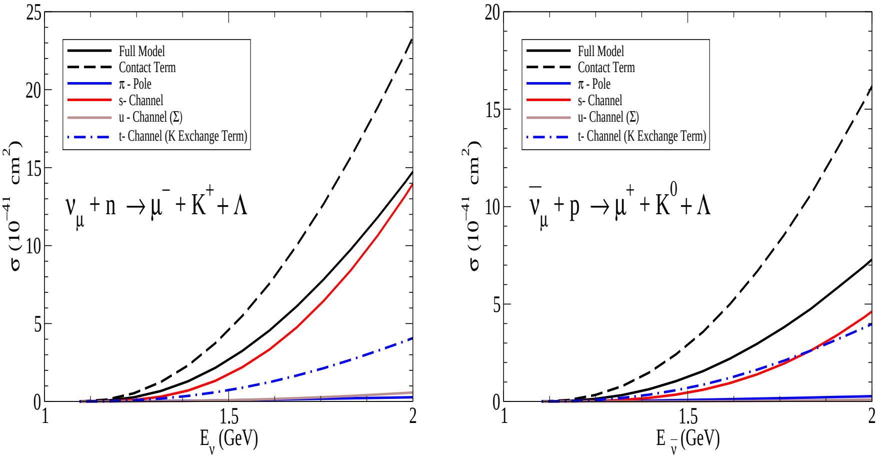


15
10
5
0
1
1.5
2
σ(10^-41 cm^2)
E_νμ (GeV)
νμ + n → μ⁻ + K⁰ + Σ⁺
νμ + n → μ⁻ + K⁺ + Λ⁰
νμ + n → μ⁻ + K⁺ + Σ⁰
νμ + p → μ⁻ + K⁺ + Σ⁺

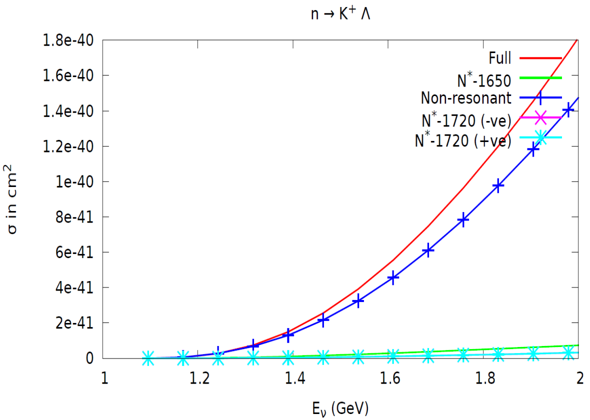


8
6
4
2
0
1
1.25
1.5
1.75
2
σ(10^-41 cm^2)
E_ν̄μ (GeV)
ν̄μ + p → μ⁺ + K⁰ + Λ⁰
ν̄μ + p → μ⁺ + K⁰ + Σ⁰
ν̄μ + p → μ⁺ + K⁺ + Σ⁻
ν̄μ + n → μ⁺ + K⁰ + Σ⁻

arXiv:*1311.2293*

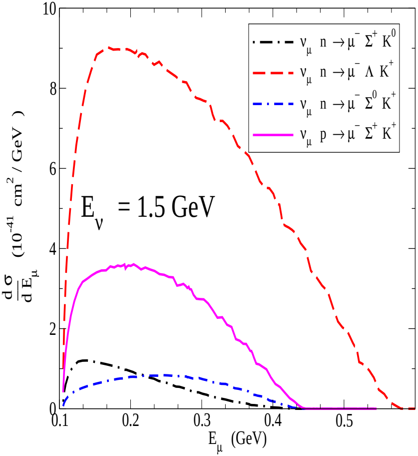


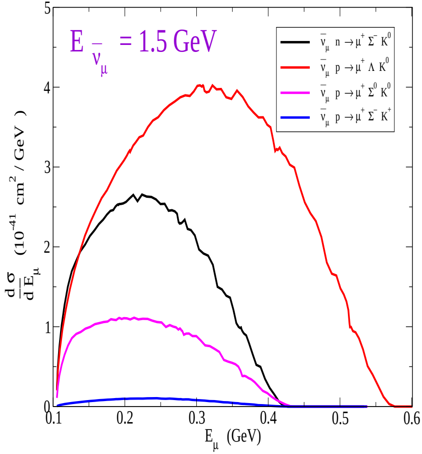
With Resonance

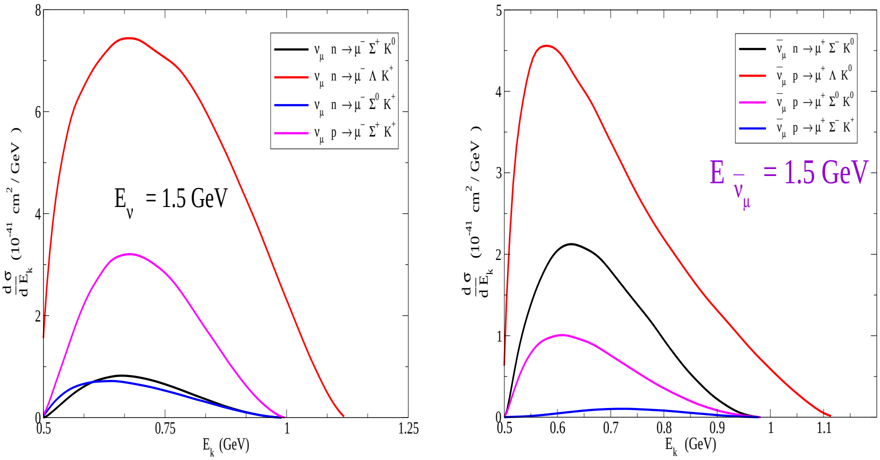


- N(1650) I (J^P) $\frac{1}{2}$ $(\frac{1}{2}^-)$
- N(1720) I (J^P) $\frac{1}{2}$ $(\frac{3}{2}^+)$

arXiv:*1311.2293*






E_ν = 1.5 GeV
$\nu_\mu\ n \rightarrow \mu^-\ \Sigma^+\ K^0$
$\nu_\mu\ n \rightarrow \mu^-\ \Lambda\ K^+$
$\nu_\mu\ n \rightarrow \mu^-\ \Sigma^0\ K^+$
$\nu_\mu\ p \rightarrow \mu^-\ \Sigma^+\ K^+$
$\frac{d\sigma}{dE_k}$ (10^{-41} cm^2 / GeV)
E_k (GeV)
$E_{\bar{\nu}_\mu}$ = 1.5 GeV
$\bar{\nu}_\mu\ n \rightarrow \mu^+\ \Sigma^-\ K^0$
$\bar{\nu}_\mu\ p \rightarrow \mu^+\ \Lambda\ K^0$
$\bar{\nu}_\mu\ p \rightarrow \mu^+\ \Sigma^0\ K^0$
$\bar{\nu}_\mu\ p \rightarrow \mu^+\ \Sigma^-\ K^+$

Comparison of total cross section for the CC $\nu_\mu/\bar{\nu}_\mu$ induced $K\Lambda$ channel with the results of Shrock et al. PRD12 (1975) 2049.

Process		$\sigma \times 10^{-41} cm^2$ E_{ν_μ} =1.2 GeV	E_{ν_μ} =1.6 GeV	E_{ν_μ} =2 GeV
$\nu_\mu n \to \mu^- \Lambda K^+$	Present Work	0.2	4.0	15.0
	Shrock et al.	0.14	1.8	5.4
$\bar{\nu}_\mu p \to \mu^+ \Lambda K^0$	Present Work	0.1	2.0	8.0
	Shrock et al.	0.12	1.4	4.1

Outline

Phys. Rev. D 85, 013014 (2012)
Phys. Rev. D 82, 033001 (2010)

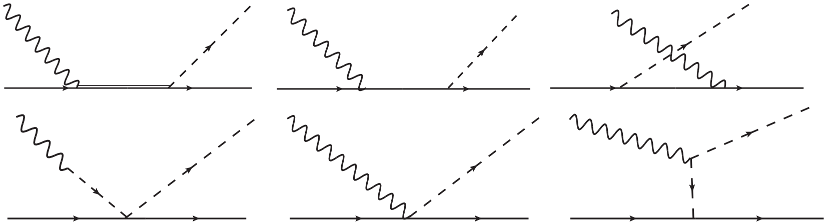


Figure: Feynman diagrams contributing to the $J^{\mu(H)}$

Phys. Rev. D 85, 013014 (2012)
Phys. Rev. D 82, 033001 (2010)

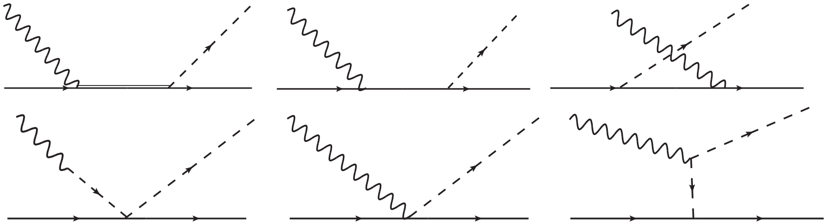


Figure: Feynman diagrams contributing to the $J^{\mu(H)}$

For the background terms we have used

Chiral Perturbation Theory (χPT)

Phys. Rev. D 85, 013014 (2012)
Phys. Rev. D 82, 033001 (2010)

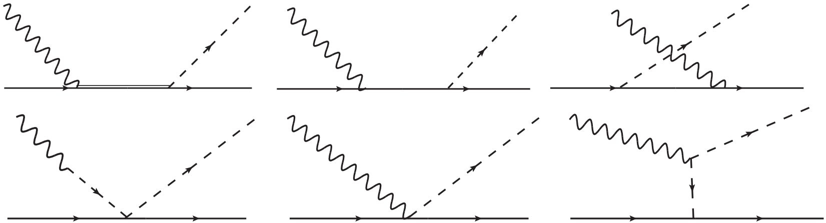


Figure: Feynman diagrams contributing to the $J^{\mu(H)}$

For the background terms we have used

Chiral Perturbation Theory (χPT)

Resonant Term $\Sigma^*(1385)$

Used in $\bar{\nu}$ induced K-production

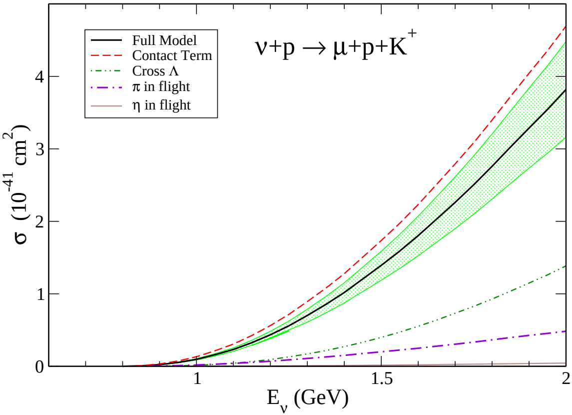
Currents for $\Delta S = 1$ K production

$$
\begin{aligned}
J^\mu|_{CT} &= iA_{CT} V_{us} \frac{\sqrt{2}}{2f_\pi} \bar{N}(p')\,(\gamma^\mu + B_{CT}\,\gamma^\mu\gamma_5)\,N(p) \\
j^\mu|_{Cr\Sigma} &= iA_{Cr\Sigma} V_{us}(D-F)\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\left(\gamma^\mu + i\frac{\mu_p+2\mu_n}{2M}\sigma^{\mu\nu}q_\nu + (D-F)(\gamma^\mu - \frac{q^\mu}{q^2-M_k^2}\not{q})\gamma^5\right)\frac{\not{p}-\not{p}_k+M_\Sigma}{(p-p_k)^2-M_\Sigma^2}\not{p}_k\gamma^5 N(p), \\
j^\mu|_{Cr\Lambda} &= iA_{Cr\Lambda} V_{us}(D+3F)\frac{\sqrt{2}}{4f_\pi}\bar{N}(p')\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu - \frac{D+3F}{3}(\gamma^\mu - \frac{q^\mu}{q^2-M_k^2}\not{q})\gamma^5\right)\frac{\not{p}-\not{p}_k+M_\Lambda}{(p-p_k)^2-M_\Lambda^2}\not{p}_k\gamma^5 N(p), \\
J^\mu|_{\Sigma} &= iA_\Sigma(D-F)V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{p}_k\gamma_5\frac{\not{p}+\not{q}+M_\Sigma}{(p+q)^2-M_\Sigma^2}\left(\gamma^\mu + i\frac{(\mu_p+2\mu_n)}{2M}\sigma^{\mu\nu}q_\nu(D-F)\left\{\gamma^\mu - \frac{q^\mu}{q^2-{M_k}^2}\not{q}\right\}\gamma^5\right)N(p) \\
J^\mu|_{\Lambda} &= iA_\Lambda V_{us}(D+3F)\frac{1}{2\sqrt{2}f_\pi}\bar{N}(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M_\Lambda}{(p+q)^2-M_\Lambda^2}\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu\frac{(D+3F)}{3}\left\{\gamma^\mu - \frac{q^\mu}{q^2-{M_k}^2}\not{q}\right\}\gamma^5\right)N(p) \\
J^\mu|_{KP} &= iA_{KP} V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{q}\,N(p)\frac{q^\mu}{q^2-M_k^2} \\
J^\mu|_{\pi} &= iA_\pi\frac{M\sqrt{2}}{2f_\pi}V_{us}(D+F)\frac{2{p_k}^\mu - q^\mu}{(q-p_k)^2-{m_\pi}^2}\bar{N}(p')\gamma_5 N(p) \\
J^\mu|_{\eta} &= iA_\eta\frac{M\sqrt{2}}{2f_\pi}V_{us}(D-3F)\frac{2{p_k}^\mu - q^\mu}{(q-p_k)^2-{m_\eta}^2}\bar{N}(p')\gamma_5 N(p) \\
J^\mu|_{\Sigma^*} &= -iA_{\Sigma^*}\frac{C}{f_\pi}\frac{1}{\sqrt{6}}V_{us}\frac{p_k^\lambda}{P^2-M_{\Sigma^*}^2+i\Gamma_{\Sigma^*}M_{\Sigma^*}}\bar{N}(p')P_{RS_{\lambda\rho}}(\Gamma_V^{\rho\mu}+\Gamma_A^{\rho\mu})N(p)
\end{aligned}
$$

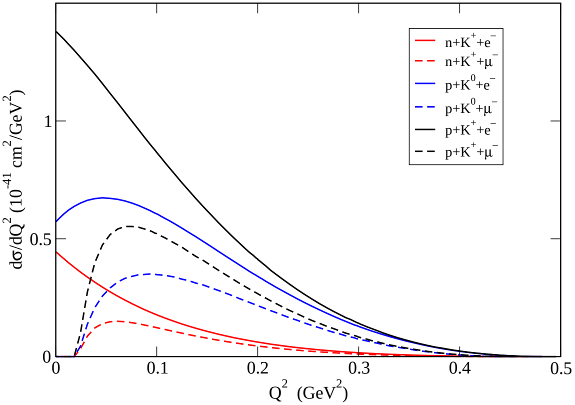
Process	B_{CT}	A_{CT}	A_{Σ}	A_{Λ}	$A_{Cr\Sigma}$	$A_{Cr\Lambda}$	A_{KP}	A_{π}	A_{η}	A_{Σ^*}
$\nu n \rightarrow l^- K^+ n$	D-F	-1	0	0	-1	0	-1	-1	-1	0
$\nu p \rightarrow l^- K^+ p$	-F	-2	0	0	$-\frac{1}{2}$	1	-2	1	-1	0
$\nu n \rightarrow l^- K^0 p$	-D-F	-1	0	0	$\frac{1}{2}$	1	-1	2	0	0
$\bar{\nu} n \rightarrow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



Q^2 Distribution



Q^2 Distribution

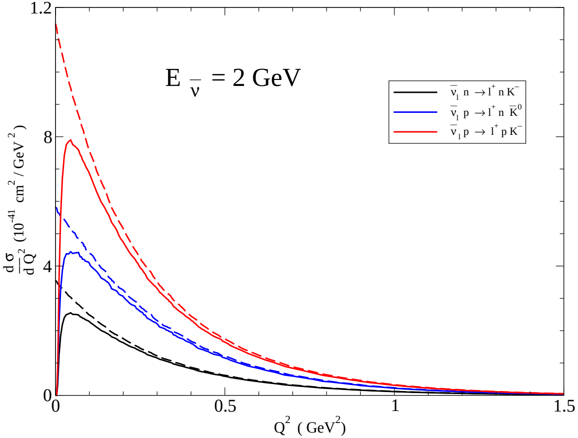
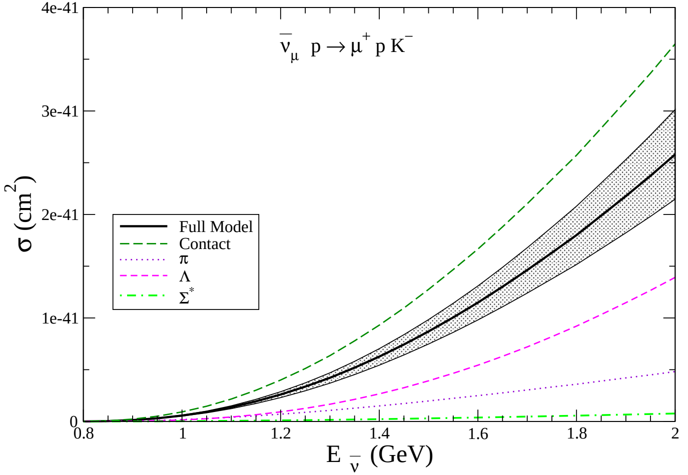


Figure: Differential Cross-section for the processes $\bar{\nu}_\mu N \to \mu^+ N' \bar{K}$ (Solid lines) and $\bar{\nu}_e N \to e^+ N' \bar{K}$ (Dashed lines)

σ for $\bar{\nu}_\mu + p \to \mu^+ + K^- + p$



Outline

Conclusion

- We have presented the results for single hyperon production, η production, associated particle production and single K-production.

Conclusion

- We have presented the results for single hyperon production, η production, associated particle production and single K-production.
- The study may be useful in the analysis of neutrino as well as antineutrino experiments at MINERνA, NOνA, T2K and others.

Conclusion

- We have presented the results for single hyperon production, η production, associated particle production and single K-production.
- The study may be useful in the analysis of neutrino as well as antineutrino experiments at MINERνA, NOνA, T2K and others.
- We find the contribution of contact term to be significant in single kaon production as well as in the associated particle production processes.

Conclusion

- We have presented the results for single hyperon production, η production, associated particle production and single K-production.
- The study may be useful in the analysis of neutrino as well as antineutrino experiments at MINERνA, NOνA, T2K and others.
- We find the contribution of contact term to be significant in single kaon production as well as in the associated particle production processes.
- We find $S_{11}(1535)$ dominance in η production.

Conclusion

- We have presented the results for single hyperon production, η production, associated particle production and single K-production.
- The study may be useful in the analysis of neutrino as well as antineutrino experiments at MINERνA, NOνA, T2K and others.
- We find the contribution of contact term to be significant in single kaon production as well as in the associated particle production processes.
- We find $S_{11}(1535)$ dominance in η production.
- We find the contribution from $S_{11}(1650)$ interference terms in Λ production through A.P.P. process to be about 15-20% at 1.5-2GeV, while from $S_{11}(1720)$ the contribution is almost negligible.

Thanks

Thank You