Weak quasielastic production of single hyperons from nucleons and nuclei

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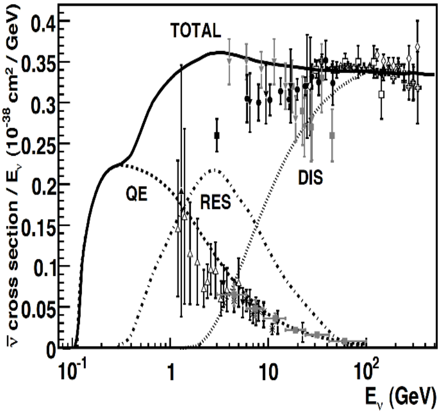
Outline

σ vs $E_{\bar{\nu}_l}$

J. A. Formaggio and G. P. Zeller
Rev. Mod. Phys. **84**, 1307 (2012).



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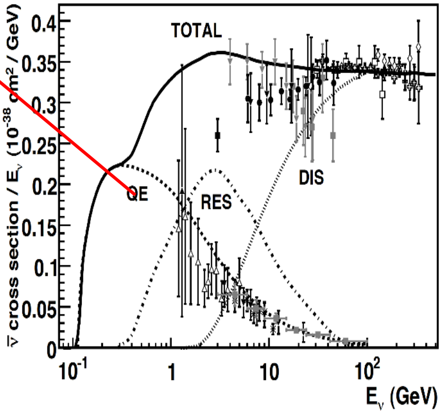

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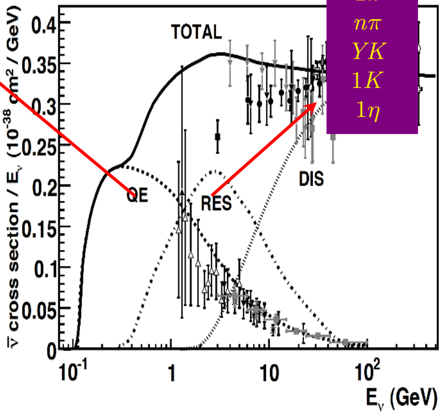

1π
$n\pi$
YK
$1K$
1η

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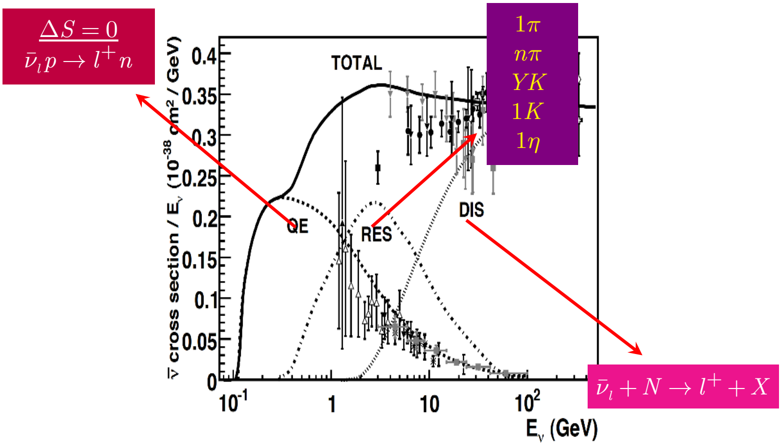

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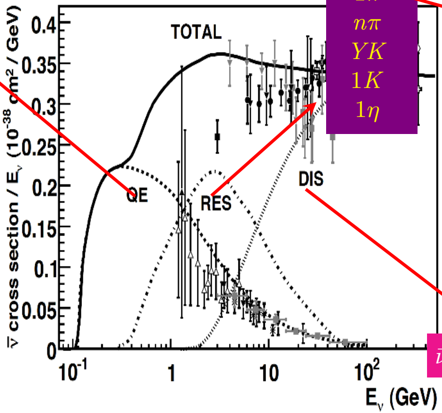

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$$\bar{\nu}_l n \to l^+ n \pi^-$$
$$\bar{\nu}_l p \to l^+ p \pi^-$$
$$\bar{\nu}_l p \to l^+ n \pi^0$$

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

σ vs $E_{\bar{\nu}_l}$

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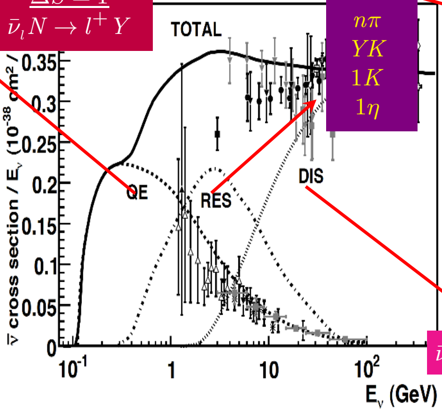
$\underline{\Delta S = 0}$	$\underline{\Delta S = 1}$
$\bar{\nu}_l p \to l^+ n$	$\bar{\nu}_l N \to l^+ Y$



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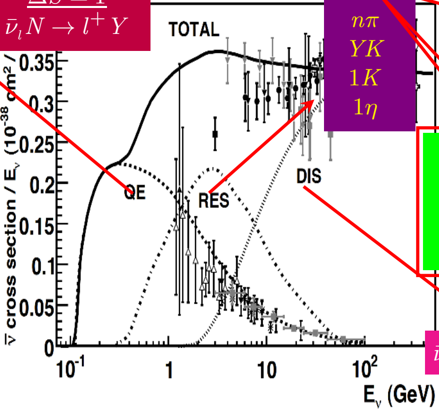

1π
$n\pi$
YK
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$$\bar{\nu}_l n \to l^+ n \pi^-$$
$$\bar{\nu}_l p \to l^+ p \pi^-$$
$$\bar{\nu}_l p \to l^+ n \pi^0$$

$$Y \to N\pi$$

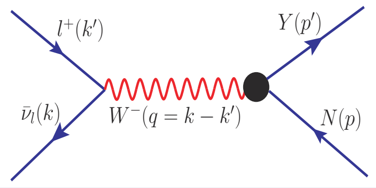
Λ^0	$\to p\pi^-$	63.9%
Λ^0	$\to n\pi^0$	35.8%
Σ^-	$\to n\pi^-$	99.85%

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

$|\Delta S| = 1$ processes

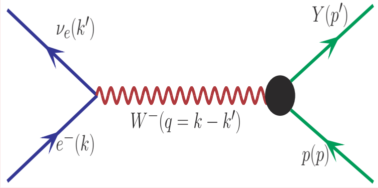
Antineutrino induced Single Hyperon Production

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



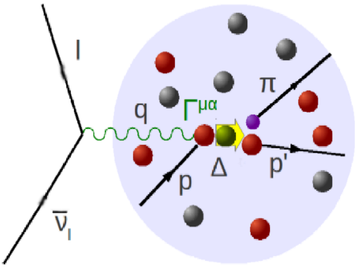
Electron induced Single Hyperon Production

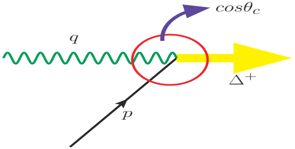
$$e^-(k) + p(p) \rightarrow \nu_e(k') + \Lambda(p')$$
$$e^-(k) + p(p) \rightarrow \nu_e(k') + \Sigma^0(p')$$
$$e^-(k) + p(p) \rightarrow \nu_e(k') + \Delta^0(p')$$

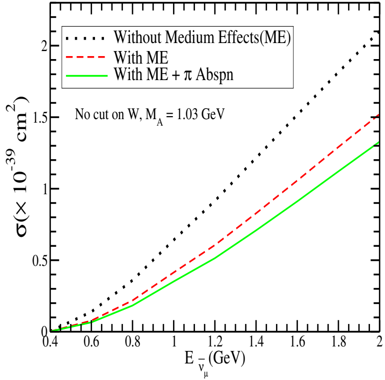


These processes are Cabibbo suppressed as compared to the $\Delta S = 0$ associated production of hyperons.

	ν_e / ν_μ
$\bar{\nu}_l + p \rightarrow l^+ + n + \pi^-$	$E_{th} = 0.15/0.28$ GeV
$\bar{\nu}_l + p \rightarrow l^+ + \Lambda$	$E_{th} = 0.19/0.32$ GeV
$\bar{\nu}_l + p \rightarrow l^+ + \Lambda + K$	$E_{th} = 0.91/1.09$ GeV

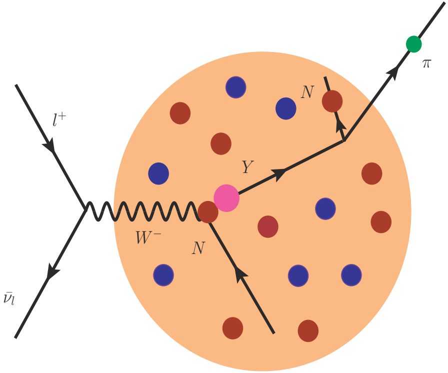


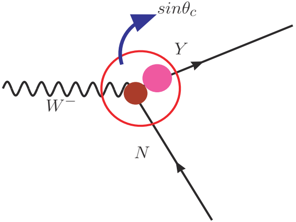




Eur. Phys. J. A **43**, 209 (2010).

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





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

- $|\Delta S| = 1$ *processes are important because they enable us to test the SU(3) symmetry in our understanding of strangeness changing weak processes.*
- *Study of single hyperon production provides an opportunity to measure N-Y transition form factors*

  (which are presently known only at low Q^2 from HSD).
- *In precise predictions of $\bar{\nu} - A$ cross section in 0.3 GeV - 0.8 GeV energy region.*
- *With the availability of luminosity $\sim 10^{39} - 10^{40}/cm^2/sec$ electron beam at the accelerators like JLab and MAMI, it should be possible to study the weak production of Δ and hyperons.*
- *For the energies $E_{\bar{\nu}}$, $E_e < 0.4$ GeV, the Y production cross sections are comparable to the Δ production.*

Differential cross section

$d\sigma$ for the process

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

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

$d\sigma$ for the process

$$e^-(k) + N(p) \rightarrow \nu_e(k') + Y(p'),$$

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

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

Transition matrix element

Vector operator

Axial vector operator

$$\mathcal{M} = \frac{G_F \sin\theta_c}{\sqrt{2}} \bar{u}_{B'}(p') \left[\mathcal{O}^{\mu}_{V(B'B)}(p',p) - \mathcal{O}^{\mu}_{A(B'B)}(p',p)\right] u_B(p) \times \mathcal{L}_\mu$$

- $\mathcal{L}_\mu \to \bar{u}_l(k')\gamma_\mu(1+\gamma_5)u_{\nu_l}(k)$ for antineutrino induced process.
- $\mathcal{L}_\mu \to \bar{u}_{\nu_e}(k')\gamma_\mu(1-\gamma_5)u_e(k)$ for electron induced process.

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

Vector FF

Magnetic FF

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

Axial vector FF

Induced pseudoscalar FF

The assumption of SU(3) symmetry and CVC leads to the determination of $f_1(Q^2)$ and $f_2(Q^2)$ in terms of EM form factors of the nucleon $f_1^N(Q^2)$ and $f_2^N(Q^2)$ and $g_1(Q^2)$ is given in terms of two functions $F^A(Q^2)$ and $D^A(Q^2)$.

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

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

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

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

We assume dipole form for the axial form factor.

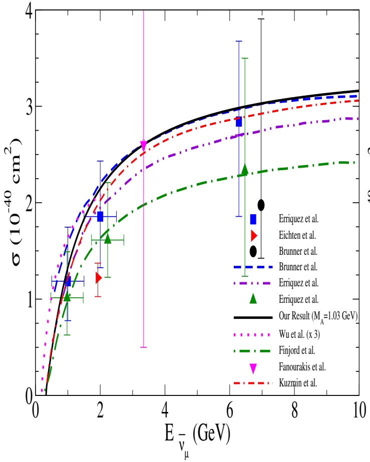
$$g_A(Q^2) = \frac{g_A(0)}{(1+\frac{Q^2}{M_A^2})^2}, \qquad g_A(0) = D(0) + F(0) = 1.267$$

Form factors: pseudoscalar

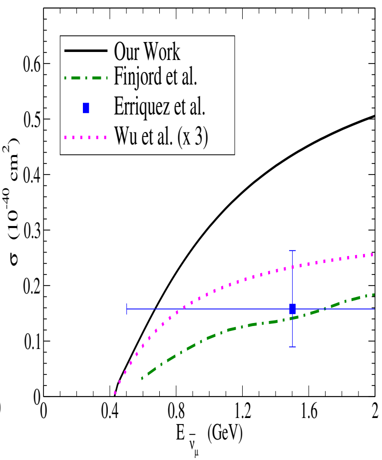
- The pseudoscalar form factor $g_3(Q^2)$ is obtained in terms of axial vector form factor $g_1(Q^2)$ assuming PCAC and Goldberger–Treiman(GT) relation extended to strangeness sector.
  - Marshak et al.(Theory of Weak Interactions in Particle Physics, Wiley-Interscience, 1969.):
$$g_3^{NY}(Q^2) = \frac{(m_N + m_Y)^2}{Q^2} \left(\frac{g_1^{NY}(Q^2)(m_K^2 + Q^2) - m_K^2 g_1^{NY}(0)}{m_K^2 + Q^2} \right).$$
  - Nambu(Phys. Rev. Lett. **4**, 380 (1960).):
$$g_3^{NY}(Q^2) = \frac{(m_N + m_Y)^2}{(m_K^2 + Q^2)} g_1^{NY}(Q^2).$$

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

$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$

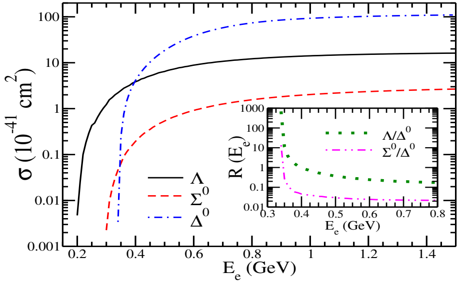


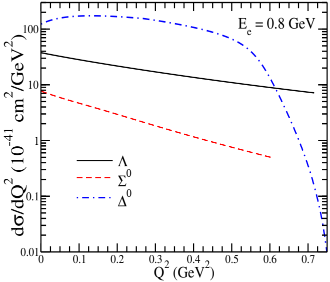
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$

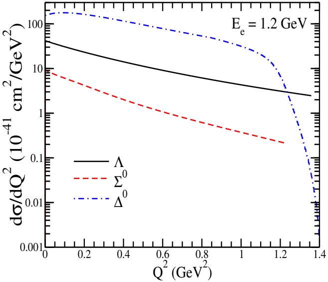


J. Phys. G **42**, 055107 (2015)

- $e^- + p \rightarrow \nu_e + \Lambda$
- $e^- + p \rightarrow \nu_e + \Sigma^0$
- $e^- + p \rightarrow \nu_e + \Delta^0$







arXiv:1704.04580; Eur. Phys. J. A (in press)

Hyperon production

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.
3. Inside the Nucleus: In the local Fermi gas model

$$\sigma_A = \int \rho(\vec{r})\ d^3r\ \sigma_{free}(\bar{\nu}_\mu + N \rightarrow \mu^+ + Y)$$

Local Fermi momentum for neutrons and protons:

$$p_{F_n} = [3\pi^2 \rho_n(r)]^{1/3}; \qquad p_{F_p} = [3\pi^2 \rho_p(r)]^{1/3}$$

$\rho_n(r)$ and $\rho_p(r)$ are the neutrons and protons local densities in the medium.

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 **74**, 053009 (2006)

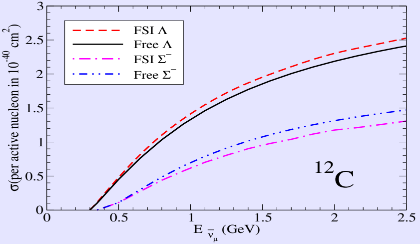
Final state interaction(FSI) effect

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

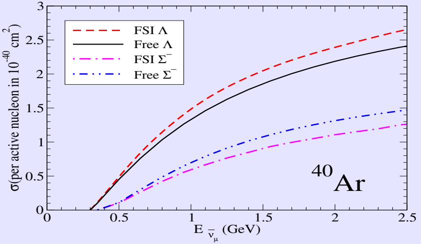
- $\Lambda + n \rightarrow \Sigma^- + p$,
- $\Lambda + n \rightarrow \Sigma^0 + n$,
- $\Sigma^- + p \rightarrow \Lambda + n$,
- $\Sigma^- + p \rightarrow \Sigma^0 + n$,
- $\Lambda + p \rightarrow \Sigma^+ + n$
- $\Sigma^0 + p \rightarrow \Sigma^+ + n$ etc.

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
Singh & Vicente Vacas **PRD 74, 053009, 2006**

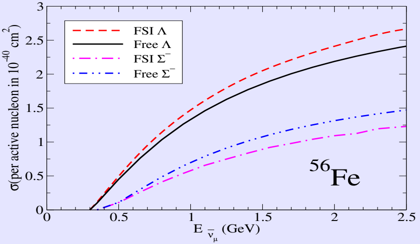
σ vs $E_{\bar{\nu}_\mu}$ in ^{12}C



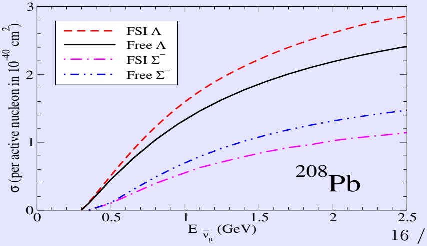
σ vs $E_{\bar{\nu}_\mu}$ in ^{40}Ar



σ vs $E_{\bar{\nu}_\mu}$ in ^{56}Fe

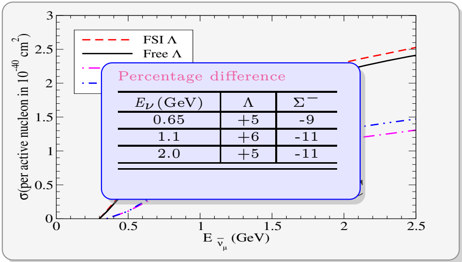


σ vs $E_{\bar{\nu}_\mu}$ in ^{208}Pb



J. Phys. G **42**, 055107 (2015)

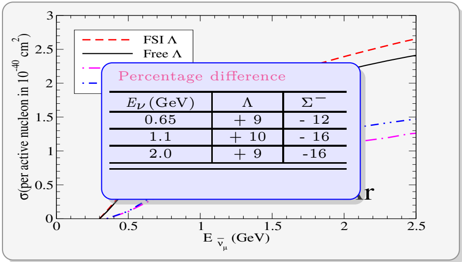
σ vs $E_{\bar{\nu}_\mu}$ in ^{12}C



Percentage difference

E_ν (GeV)	Λ	Σ^-
0.65	+5	-9
1.1	+6	-11
2.0	+5	-11

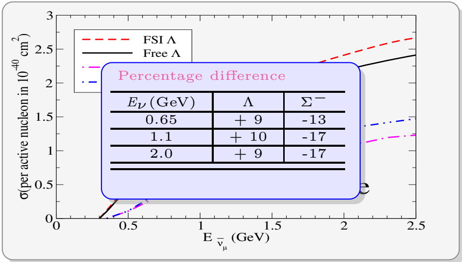
σ vs $E_{\bar{\nu}_\mu}$ in ^{40}Ar



Percentage difference

E_ν (GeV)	Λ	Σ^-
0.65	+ 9	- 12
1.1	+ 10	- 16
2.0	+ 9	-16

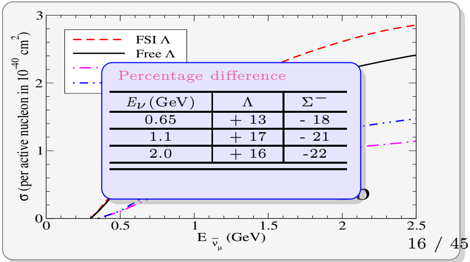
σ vs $E_{\bar{\nu}_\mu}$ in ^{56}Fe



Percentage difference

E_ν (GeV)	Λ	Σ^-
0.65	+ 9	-13
1.1	+ 10	-17
2.0	+ 9	-17

σ vs $E_{\bar{\nu}_\mu}$ in ^{208}Pb



Percentage difference

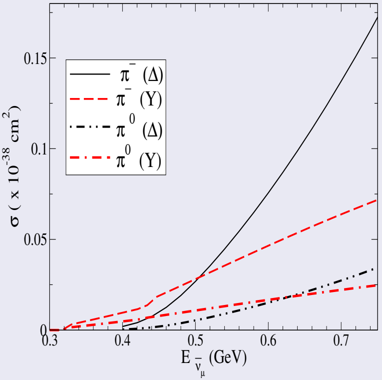
E_ν (GeV)	Λ	Σ^-
0.65	+ 13	- 18
1.1	+ 17	- 21
2.0	+ 16	-22

Hyperon giving rise to pions

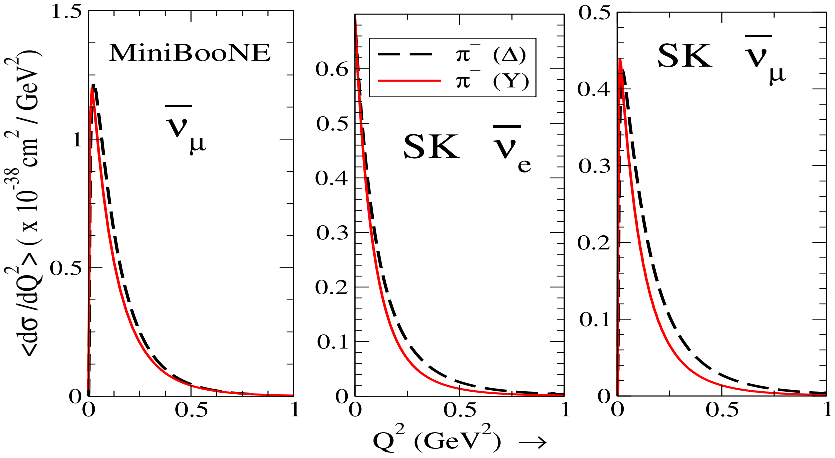
As the decay modes of hyperons to pions are highly suppressed in the nuclear medium, making them live long enough to pass through the nucleus and decay outside the nuclear medium.

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

σ vs $E_{\bar{\nu}_\mu}$

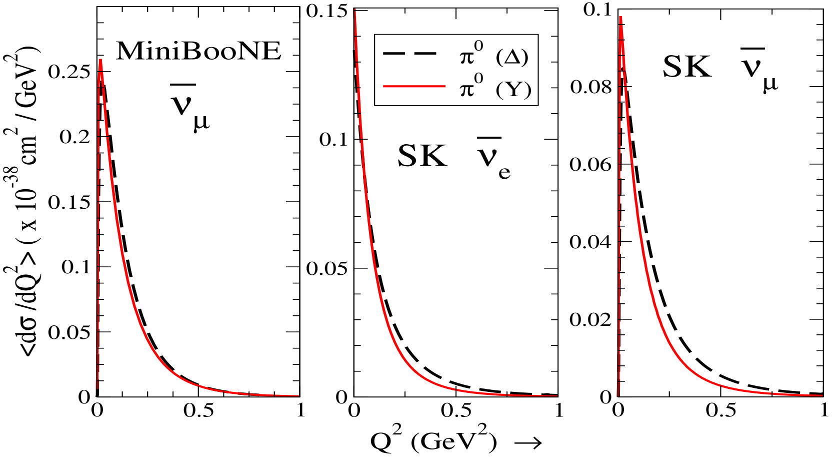


Phys. Rev. D **88**, 077301 (2013)



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

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

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

Measuring polarization of hyperon may provide an alternative way to determine:

- $\bar{\nu}_l N \to l^+ Y$
  - axial dipole mass, M_A
  - electric neutron form factor, $G_E^n(Q^2)$
  - pseudoscalar form factor in the strangeness sector, $g_3(Q^2)$
- $e^- p \to \nu_e Y$
  - axial dipole mass, M_A

In the covariant density matrix formalism, the polarization vector ξ^τ of the hyperon is given as:

$$\xi^\tau = \frac{\mathrm{Tr}[\gamma^\tau \gamma_5 \ \rho_f]}{\mathrm{Tr}[\rho_f]}$$

$$\rho_f = \mathcal{L}^{\alpha\beta} \Lambda(p') J_\alpha \Lambda(p) \tilde{J}_\beta \Lambda(p')$$

is final spin density matrix.

$$\xi^\tau = \left(g^{\tau\sigma} - \frac{p'^\tau p'^\sigma}{m_Y^2} \right) \frac{\mathcal{L}^{\alpha\beta} \, Tr[\gamma_\sigma \gamma_5 \Lambda(p') J_\alpha \Lambda(p) \tilde{J}_\beta]}{\mathcal{L}^{\alpha\beta} \, Tr[\Lambda(p') J_\alpha \Lambda(p) \tilde{J}_\beta]}$$

$$\frac{d\sigma}{dQ^2} = \frac{1}{64\pi m_N^2 {E_e}^2} \overline{\sum} \sum |\mathcal{M}|^2$$

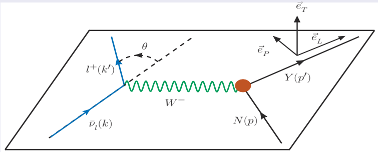
The vector of the hyperon polarization ξ^{τ} is given by

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

The vector of the hyperon polarization $\xi^\mathcal{T}$ is given by

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

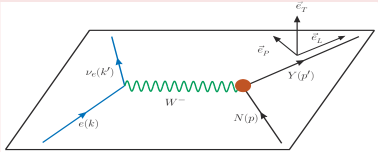
$\bar{\nu}_\mu(k) + N(p) \rightarrow \mu^+(k') + Y(p')$



Unit vectors along:

- longitudinal direction,
  $\vec{e}_L = \frac{\vec{p}'}{|\vec{p}'|} = \frac{\vec{q}}{|\vec{q}|}$
- transverse direction, $\vec{e}_T = \frac{\vec{k}\times\vec{k}'}{|\vec{k}\times\vec{k}'|}$
- perpendicular direction,
  $\vec{e}_P = \vec{e}_L \times \vec{e}_T$

$e^-(k) + N(p) \rightarrow \nu_e(k') + Y(p')$



Unit vectors along:

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- perpendicular direction,
  $\vec{e}_P = \vec{e}_L \times \vec{e}_T$

Component along $\vec{e}_T$ vanishes due to T–invariance and the absence of second class current.

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

$$\vec{\xi} = \xi_L \, \vec{e}_L + \xi_P \, \vec{e}_P$$

$$\xi_L = \vec{\xi} \cdot \vec{e}_L; \qquad \xi_P = \vec{\xi} \cdot \vec{e}_P$$

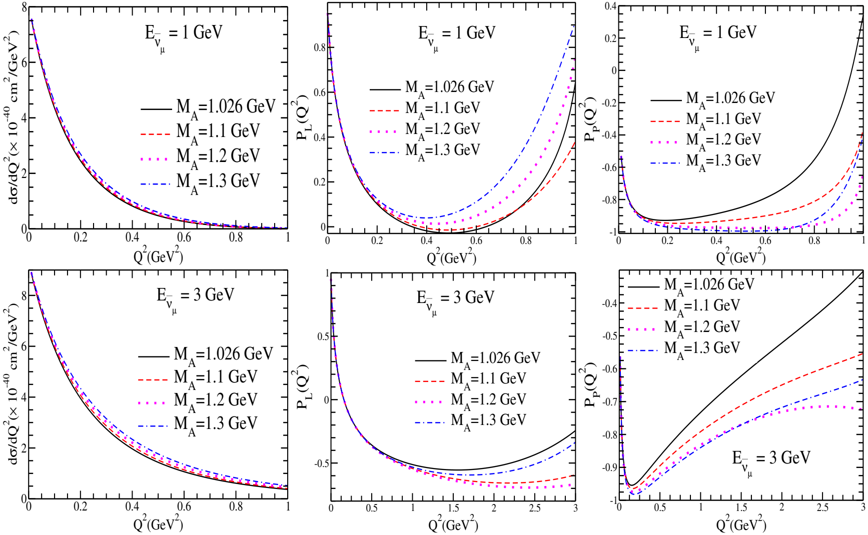
Longitudinal component: $P_L(Q^2) = \frac{m_Y}{E_{p'}} \vec{\xi} \cdot \vec{e}_L$

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

Perpendicular component: $P_P(Q^2) = \vec{\xi} \cdot \vec{e}_P$

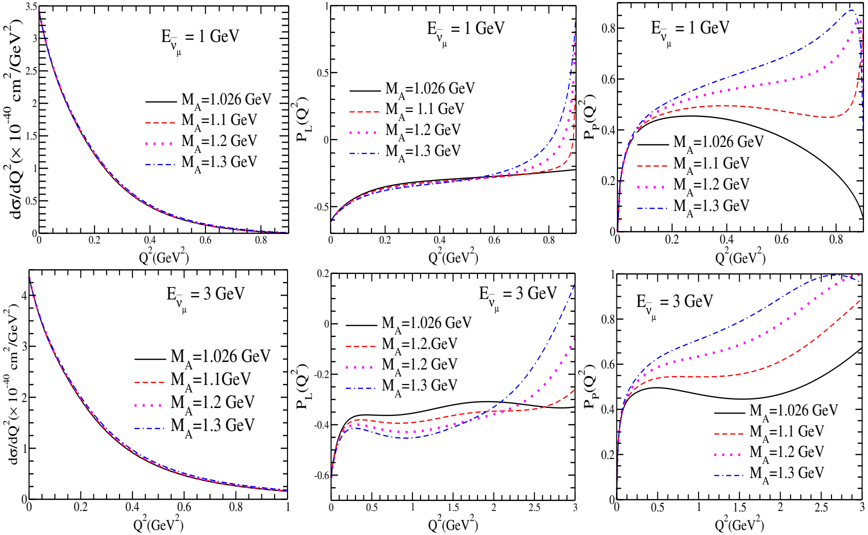
$$\frac{d\sigma}{dQ^2} P_P(Q^2) = -\frac{G_F^2 \sin^2\theta_c}{4\pi} \frac{|\vec{k}'|}{|\vec{q}|} \frac{\mathcal{A}(Q^2, E_{\bar{\nu}_\mu}) \sin\theta}{m_N E_{\bar{\nu}_\mu}}$$

M_A–dependence: $\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $\bar{\nu}_\mu p \rightarrow \mu^+\Lambda$ at $E_{\bar{\nu}_\mu}$=1 GeV and 3 GeV.



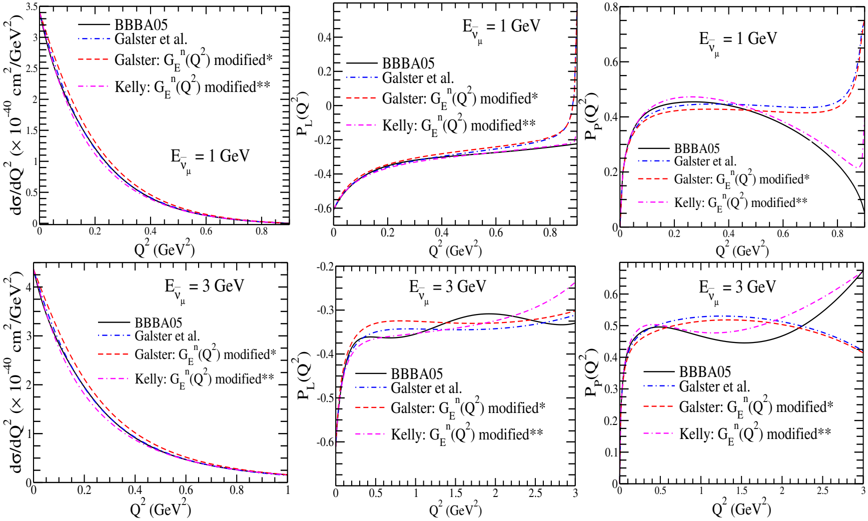
Phys. Rev. D 94, 114031 (2016)

M_A–dependence: $\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $\bar{\nu}_\mu n \rightarrow \mu^+\Sigma^-$ at $E_{\bar{\nu}_\mu}$=1 GeV and 3 GeV.



Phys. Rev. D 94, 114031 (2016)

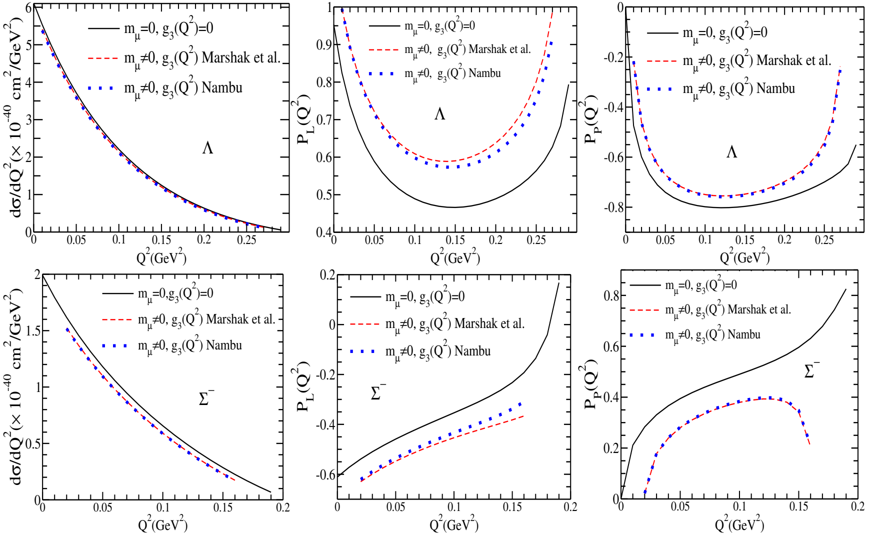
$\underline{G_E^n(Q^2)\text{–dependence:}}$ $\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $\bar{\nu}_\mu n \to \mu^+ \Sigma^-$ at $E_{\bar{\nu}_\mu}$=1 GeV and 3 GeV.



Phys. Rev. D 94, 114031 (2016)

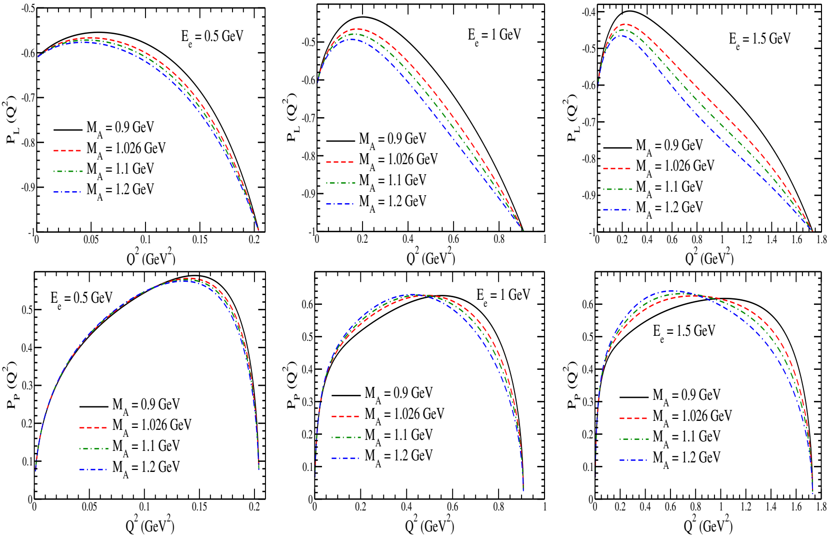
*Platchkov et al., Nucl. Phys. A 510, 740 (1990), **Punjabi et al., Eur. Phys. J. A 51, 79 (2015).

Pseudoscalar FF, $g_3(Q^2)$: $\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $\bar{\nu}_\mu p \rightarrow \mu^+\Lambda$ and $\bar{\nu}_\mu n \rightarrow \mu^+\Sigma^-$ at $E_{\bar{\nu}_\mu} = 0.5$ GeV.



Phys. Rev. D 94, 114031 (2016)

M_A–dependence: $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $e^- p \rightarrow \nu_e \Sigma^0$ at $E_{\bar{\nu}_\mu}$=0.5 GeV, 1 GeV and 1.5 GeV.



arXiv:1704.04580; Eur. Phys. J. A (in Press)

Conclusions

- *The reduction due to nuclear medium and FSI effects in the case of pions obtained from Δ excitation is large enough to compensate for Cabibbo suppression of pions produced through hyperon excitations up to $E_{\bar{\nu}_\mu} < 0.5 GeV$ for π^- production and 650 MeV for π^0 production.*

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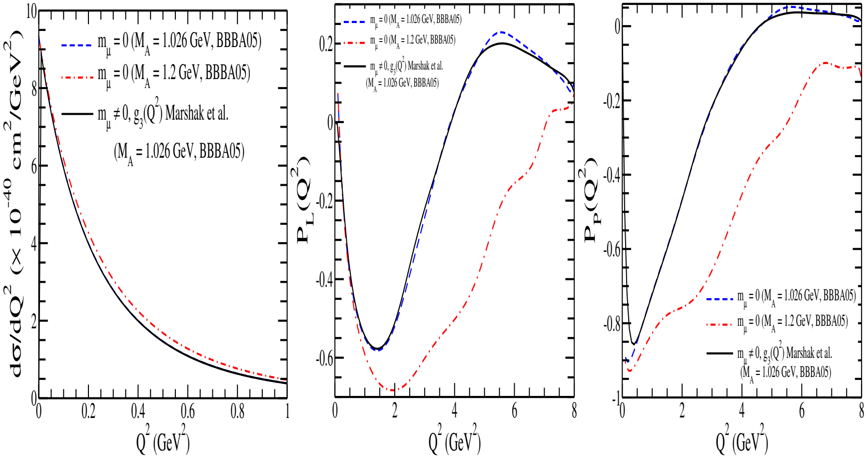
Thank you!

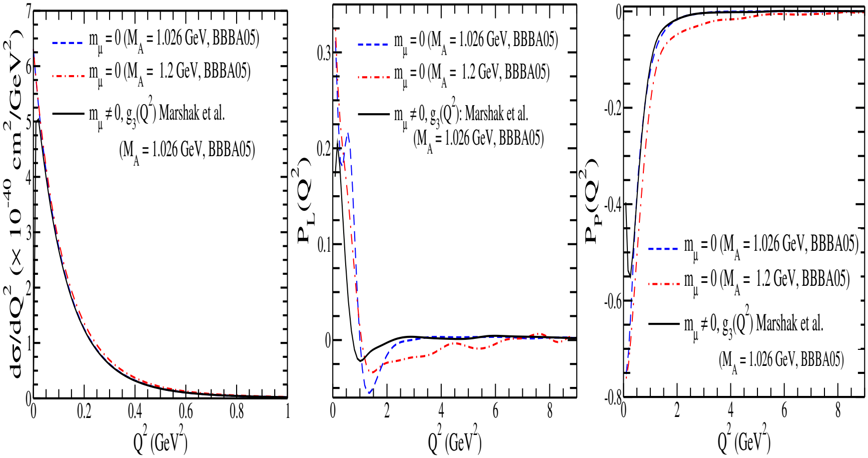
Backup slides

$\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $\bar{\nu}_\mu p \rightarrow \mu^+ \Lambda$ averaged over MINERνA spectrum.



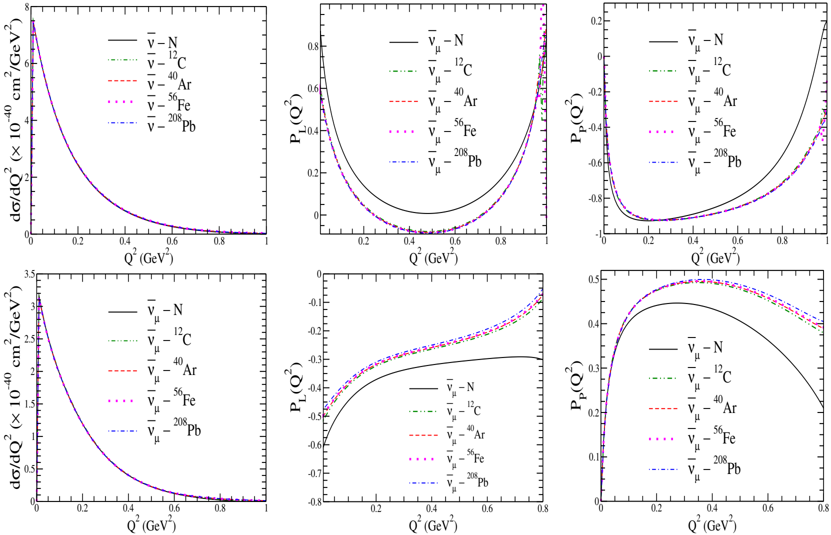
Phys. Rev. D 94, 114031 (2016)

$\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ and $P_P(Q^2)$ distributions vs Q^2. $\bar{\nu}_\mu p \rightarrow \mu^+ \Lambda$ averaged over T2K spectrum.



Phys. Rev. D 94, 114031 (2016)

Nuclear Medium effects: $\frac{d\sigma}{dQ^2}$, $P_L(Q^2)$ *and* $P_P(Q^2)$ *distributions vs* Q^2. $\bar{\nu}_\mu N \rightarrow \mu^+ Y$ *at* $E_{\bar{\nu}_\mu}$=1 *GeV.*



Expression of $\mathcal{N}(Q^2, E_{\bar{\nu}_l})$

$$
\begin{aligned}
\mathcal{N}(Q^2, E_{\bar{\nu}_\mu}) \quad = \quad & f_1^2(2E_{\bar{\nu}_\mu}(\vec{k}\cdot\vec{k}' + 2m_N E_\mu - m_\mu^2) - 2\vec{k}\cdot\vec{k}'(m_Y + E_\mu)) + \\
& \frac{f_2^2}{(m_N + m_Y)^2}(4(\vec{k}\cdot\vec{k}')^2(m_Y + E_\mu - E_{\bar{\nu}_\mu}) + \vec{k}\cdot\vec{k}'(m_N(4(E_\mu^2 + E_{\bar{\nu}_\mu}^2) - m_\mu^2) - \\
& \quad 3m_\mu^2(m_Y + E_\mu - E_{\bar{\nu}_\mu})) - 4m_N m_\mu^2 E_{\bar{\nu}_\mu}^2) + \\
& g_1^2(2(\vec{k}\cdot\vec{k}'(m_Y - E_\mu + E_{\bar{\nu}_\mu}) - E_{\bar{\nu}_\mu}(m_\mu^2 - 2m_N E_\mu))) + \\
& g_3^2((\vec{k}\cdot\vec{k}')^2 m_\mu^2(m_N - m_Y - E_\mu + E_{\bar{\nu}_\mu})) + \\
& \frac{f_1 f_2}{m_N + m_Y}(8(\vec{k}\cdot\vec{k}')^2 + \vec{k}\cdot\vec{k}'(4(m_N - m_Y)(E_\mu - E_{\bar{\nu}_\mu}) - 6m_\mu^2) + \\
& \quad 2m_\mu^2 E_{\bar{\nu}_\mu}(m_N - m_Y)) + \\
& f_1 g_1(-4(\vec{k}\cdot\vec{k}'(E_\mu + E_{\bar{\nu}_\mu}) - m_\mu^2 E_{\bar{\nu}_\mu})) + \\
& \frac{f_2 g_1}{m_N + m_Y}(-4(m_N + m_Y)(\vec{k}\cdot\vec{k}'(E_\mu + E_{\bar{\nu}_\mu}) - m_\mu^2 E_{\bar{\nu}_\mu})) + \\
& g_1 g_3(-2m_\mu^2(\vec{k}\cdot\vec{k}' + E_{\bar{\nu}_\mu}(m_Y - m_N)))
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{A}(Q^2, E_{\bar{\nu}_\mu}) \quad = \quad & f_1^2(-2\vec{k}\cdot\vec{k}' - (m_N - m_Y)(E_\mu - E_{\bar{\nu}_\mu}) + m_\mu^2) + \\
& \frac{f_2^2}{(m_N + m_Y)^2}((2\vec{k}\cdot\vec{k}' - m_\mu^2)(2\vec{k}\cdot\vec{k}' + (m_N - m_Y)(E_\mu - E_{\bar{\nu}_\mu}) - m_\mu^2)) + \\
& g_1^2(2\vec{k}\cdot\vec{k}' + (m_N + m_Y)(E_\mu - E_{\bar{\nu}_\mu}) - m_\mu^2) + \\
& \frac{f_1 f_2}{m_N + m_Y}(-2(2\vec{k}\cdot\vec{k}'(m_Y + E_\mu - E_{\bar{\nu}_\mu}) + m_N(E_\mu - E_{\bar{\nu}_\mu})^2 + \\
& \qquad m_\mu^2(-(m_Y + E_\mu - E_{\bar{\nu}_\mu})))) + \\
& f_1 g_1(2m_Y(E_\mu + E_{\bar{\nu}_\mu})) + f_1 g_3(m_\mu^2(-m_N + m_Y + E_\mu - E_{\bar{\nu}_\mu})) + \\
& \frac{f_2 g_1}{m_N + m_Y}(-4\vec{k}\cdot\vec{k}'(E_\mu + E_{\bar{\nu}_\mu}) + m_N(m_\mu^2 - 2E_\mu^2 + 2E_{\bar{\nu}_\mu}^2) + m_\mu^2(m_Y + E_\mu + 3E_{\bar{\nu}_\mu})) + \\
& \frac{f_2 g_3}{m_N + m_Y}(m_\mu^2(-2\vec{k}\cdot\vec{k}' - (m_N - m_Y)(E_\mu - E_{\bar{\nu}_\mu}) + m_\mu^2)).
\end{aligned}
$$

$$\begin{aligned}
\mathcal{B}(Q^2, E_{\bar{\nu}_\mu}) \quad = \quad & f_1^2((E_\mu + E_{\bar{\nu}_\mu})(2\vec{k}\cdot\vec{k}' + m_Y(m_Y - m_N)) + m_\mu^2(m_Y - 2E_{\bar{\nu}_\mu})) + \\
& \frac{f_2^2}{(m_N + m_Y)^2}(4(\vec{k}\cdot\vec{k}')^2(E_\mu + E_{\bar{\nu}_\mu}) + 2\vec{k}\cdot\vec{k}'((E_\mu + E_{\bar{\nu}_\mu})(m_N(m_Y + 2E_\mu - 2E_{\bar{\nu}_\mu}) + \\
& \quad m_Y^2) - m_\mu^2(m_Y + E_\mu + 3E_{\bar{\nu}_\mu})) + m_\mu^2(-m_N(m_Y(E_\mu + E_{\bar{\nu}_\mu}) + 4E_{\bar{\nu}_\mu}(E_\mu - E_{\bar{\nu}_\mu})) + \\
& \quad m_\mu^2(m_Y + 2E_{\bar{\nu}_\mu}) + m_Y^2(E_\mu - 3E_{\bar{\nu}_\mu}))) + \\
& g_1^2((E_\mu + E_{\bar{\nu}_\mu})(2\vec{k}\cdot\vec{k}' + m_Y(m_N + m_Y)) - m_\mu^2(m_Y + 2E_{\bar{\nu}_\mu})) + \\
& \frac{f_1 f_2}{m_N + m_Y}(2(m_N(E_\mu + E_{\bar{\nu}_\mu})(2\vec{k}\cdot\vec{k}' + m_Y(E_{\bar{\nu}_\mu} - E_\mu)) + m_\mu^2(m_Y(m_Y + E_\mu) - \\
& \quad E_{\bar{\nu}_\mu}(2m_N + m_Y)))) + \\
& f_1 g_1(2E_\mu(2\vec{k}\cdot\vec{k}' + m_Y^2) - 2E_{\bar{\nu}_\mu}(2\vec{k}\cdot\vec{k}' + 4m_N E_\mu - 2m_\mu^2 + m_Y^2)) + \\
& f_1 g_3(m_\mu^2(2\vec{k}\cdot\vec{k}' - m_N(m_Y + 2E_{\bar{\nu}_\mu}) + m_Y(m_Y + E_\mu - E_{\bar{\nu}_\mu}))) + \\
& \frac{f_2 g_1}{m_N + m_Y}(-8(\vec{k}\cdot\vec{k}')^2 + \vec{k}\cdot\vec{k}'(6m_\mu^2 - 4(m_N E_\mu - m_N E_{\bar{\nu}_\mu} + m_Y^2)) \\
& \quad + m_N(m_\mu^2(m_Y - 2E_{\bar{\nu}_\mu}) - 2m_Y(E_\mu + E_{\bar{\nu}_\mu})^2) + m_\mu^2 m_Y(m_Y + E_\mu + 3E_{\bar{\nu}_\mu})) + \\
& \frac{f_2 g_3}{m_N + m_Y}(m_\mu^2((E_\mu + E_{\bar{\nu}_\mu})(2\vec{k}\cdot\vec{k}' + m_Y(m_Y - m_N)) + m_\mu^2(m_Y - 2E_{\bar{\nu}_\mu}))).
\end{aligned}$$

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

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

Different Normalisations

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

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

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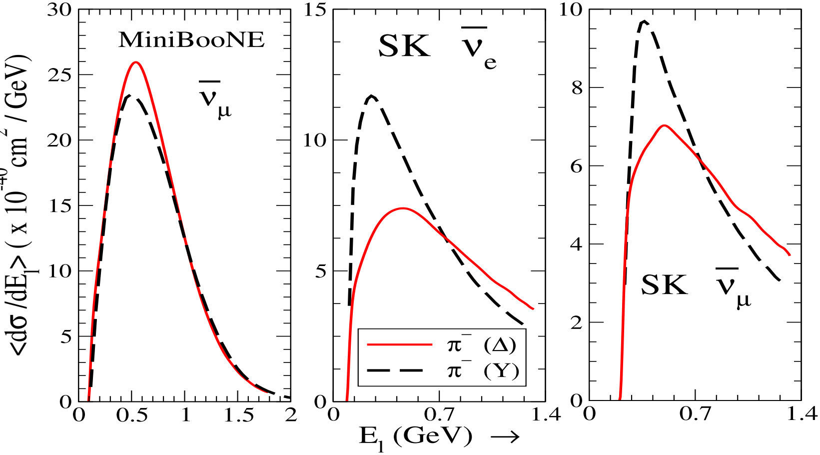
(d) The assumption of SU(3) symmetry and G–invariance together implies absence of second class currents leading to

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

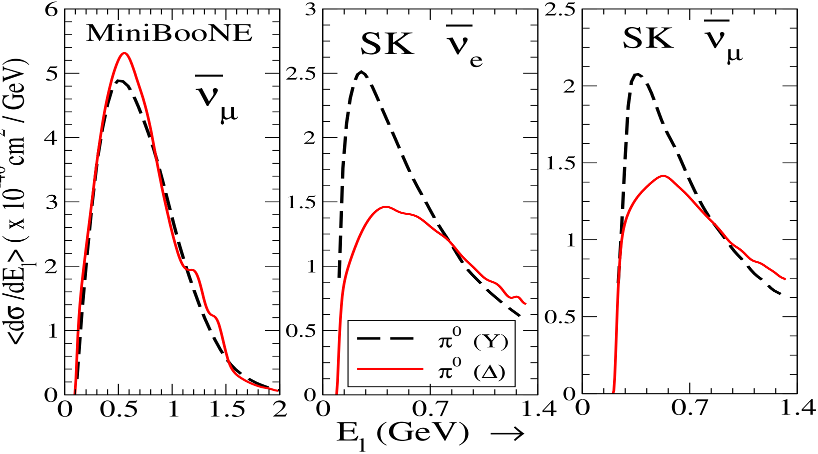
The last two columns correspond to the SU(3) symmetric values of the Cabibbo model.

Transition	g_1/f_1	$f_1^{SU(3)}$	$g_1^{SU(3)}$	f_2/f_1
$n \to p$	–1.2723	$+1$	$-(D+F)$	$\frac{M_n}{M_p}\frac{(\mu_p-\mu_n)}{2}$
$\Lambda \to p$	–0.718	$-\sqrt{\frac{3}{2}}$	$\frac{1}{\sqrt{6}}(D+3F)$	$\frac{M_\Lambda}{M_p}\frac{\mu_p}{2}$
$\Sigma^- \to n$	+0.34	–1	$F-D$	$\frac{M_{\Sigma^-}}{M_p}\frac{(\mu_p+2\mu_n)}{2}$

$$F = 0.463, \qquad D = 0.804, \qquad \mu_p = 1.7928, \qquad \mu_n = -1.913$$



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



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

$e^-(k) + N(p) \longrightarrow \nu_e(k') + Y(p')$

The vector of the hyperon polarization ξ^τ is given by

$$\vec{\xi} = \left[\vec{k}\,\alpha(Q^2) + \vec{p}\,'\beta(Q^2)\right].$$

$$\frac{d\sigma}{dQ^2} = \frac{1}{64\pi m_N^2 {E_e}^2}\overline{\sum}\sum|\mathcal{M}|^2,$$

Longitudinal component of polarization 3-vector

$$P_L(Q^2) = \frac{m_Y}{E_{p'}}\left(\frac{\alpha(Q^2)\ \vec{k}\cdot\vec{p}\,' + \beta(Q^2)\ |\vec{p}\,'|^2}{|\vec{p}\,'|\ \mathcal{J}^{\alpha\beta}\mathcal{L}_{\alpha\beta}}\right)$$

Perpendicular component of polarization 3-vector

$$P_P(Q^2) = \frac{(\vec{k}\cdot\vec{p'})^2 - |\vec{k}|^2|\vec{p}\,'|^2}{|\vec{p}\,'||\vec{p'}\times\vec{k}|\ \mathcal{J}^{\alpha\beta}\mathcal{L}_{\alpha\beta}}\alpha(Q^2).$$

Expression of $\alpha(Q^2)$

$$
\begin{aligned}
\alpha(Q^2) \quad = \quad & 32\Big[f_1^2(Q^2)\Big((m_N+m_Y)\Big((m_N-m_Y)^2-t\Big)\Big) \\
+ \quad & \frac{f_2^2(Q^2)}{(m_N+m_Y)^2}\Big((m_N+m_Y)t\Big((m_N-m_Y)^2-t\Big)\Big) \\
+ \quad & g_1^2(Q^2)\Big((m_N-m_Y)\Big(t-(m_N+m_Y)^2\Big)\Big) \\
+ \quad & f_1(Q^2)g_1(Q^2)\Big(-2m_Y\Big(m_N^2+2m_e^2+m_Y^2-2s-t\Big)\Big) \\
+ \quad & \frac{f_1(Q^2)f_2(Q^2)}{(m_N+m_Y)}\left(\Big(m_N^2-m_Y^2\Big)^2-4m_Nm_Yt-t^2\right) \\
+ \quad & \frac{f_2(Q^2)g_1(Q^2)}{(m_N+m_Y)}\Big(m_N^4+m_N^2\Big(m_e^2-2(s+t)\Big) \\
- \quad & 2m_Nm_e^2m_Y-m_e^2\Big(3m_Y^2+t\Big)\ -\Big(m_Y^2+t\Big)\Big(m_Y^2-2s-t\Big)\Big)\Big]
\end{aligned}
$$

Expression of $\beta(Q^2)$

$$
\begin{aligned}
\beta(Q^2) \quad = \quad & \frac{16}{m_Y}\Big[f_1^2(Q^2)\Big(-2m_N^3 m_Y + m_N^2\Big(m_e^2+2m_Y^2-t\Big) \; +2m_N m_Y(s+t) + \Big(m_Y^2-t\Big)\Big(m_e^2-2s-t\Big)\Big) \\
+ \quad & \frac{f_2^2(Q^2)}{(m_N+m_Y)^2}(m_N+m_Y)\Big(m_e^2(m_N-m_Y)\Big(m_N^2+m_Y^2\Big) - t\Big(m_N^3+m_N^2 m_Y + m_N\Big(m_e^2-m_Y^2-2s\Big) \\
- \quad & m_e^2 m_Y + m_Y^3\Big) + t^2(m_N+m_Y)\Big) \\
+ \quad & g_1^2(Q^2)\Big(2m_N^3 m_Y + m_N^2\Big(m_e^2+2m_Y^2-t\Big) - 2m_N m_Y(s+t) \; + \Big(m_Y^2-t\Big)\Big(m_e^2-2s-t\Big) \\
+ \quad & f_1(Q^2)g_1(Q^2)\Big(2\Big(m_N^2\Big(-m_e^2+2s+t\Big) + m_e^2\Big(m_Y^2+2s+t\Big) + m_Y^2 t - 2s^2 - 2st - t^2\Big)\Big) \\
+ \quad & \frac{f_1(Q^2)f_2(Q^2)}{(m_N+m_Y)}\Big(2\Big(m_N^4(-m_Y) + m_N^3\Big(m_e^2-t\Big) \; + m_N^2 m_Y\Big(m_Y^2+s\Big) \\
+ \quad & m_N\Big(m_e^2\Big(m_Y^2-t\Big) + t\Big(m_Y^2+2s+t\Big)\Big) - \; m_Y\Big(m_Y^2-t\Big)(s+t)\Big)\Big) \\
+ \quad & \frac{f_2(Q^2)g_1(Q^2)}{(m_N+m_Y)}\Big(2\Big(m_N^4(-m_Y) + m_N^3\Big(t-m_e^2\Big) \; - m_N^2 m_Y\Big(m_e^2+m_Y^2-3s-2t\Big) \\
+ \quad & m_N\Big(m_e^2(s+t) + t\Big(m_Y^2-t\Big)\Big) + m_Y\Big(m_e^2\Big(m_Y^2+2s+t\Big) + \; (s+t)\Big(m_Y^2-2s-t\Big)\Big)\Big)\Big)\Big]
\end{aligned}
$$