Weak Quasielastic Production of Hyperons

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Outline

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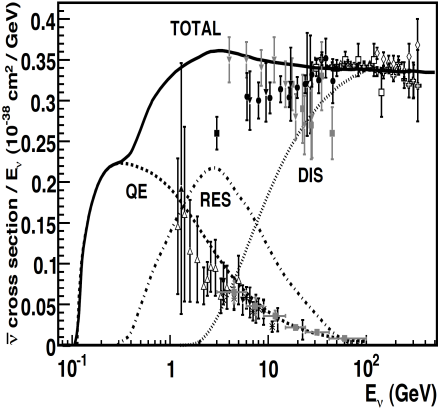
σ *vs* $E_{\bar{\nu}_l}$

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



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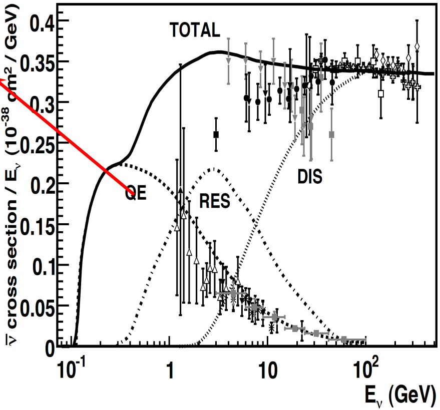
$\bar{\nu}_l p \to l^+ n$



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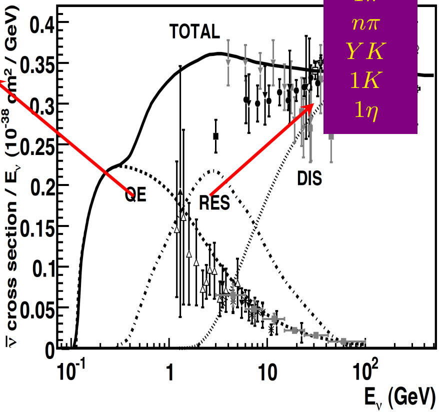

1π
$n\pi$
YK
$1K$
1η

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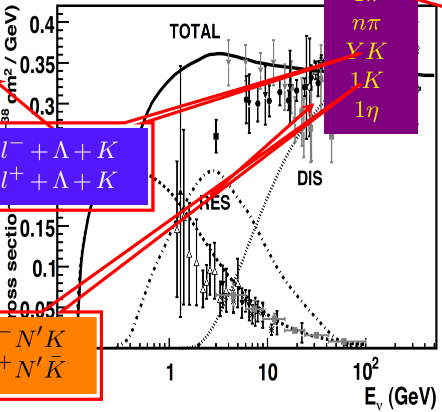
$\bar{\nu}_l n \to l^+ n \pi^-$
$\bar{\nu}_l p \to l^+ p \pi^-$
$\bar{\nu}_l p \to l^+ n \pi^0$

$\nu_l + N \to l^- + \Lambda + K$
$\bar{\nu}_l + N \to l^+ + \Lambda + K$

$\nu_l N \to l^- N' K$
$\bar{\nu}_l N \to l^+ N' \bar{K}$



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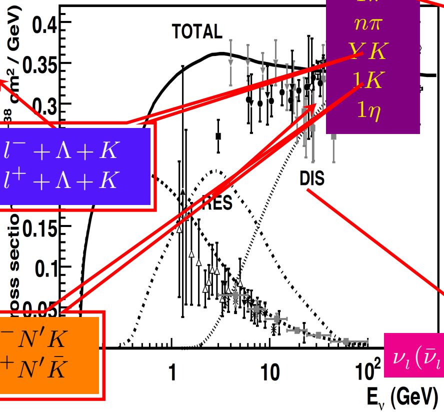
$\nu_l(\bar{\nu}_l) + N \to l^-(l^+) + X$



$\sigma \ vs \ E_{\bar{\nu}_l}$

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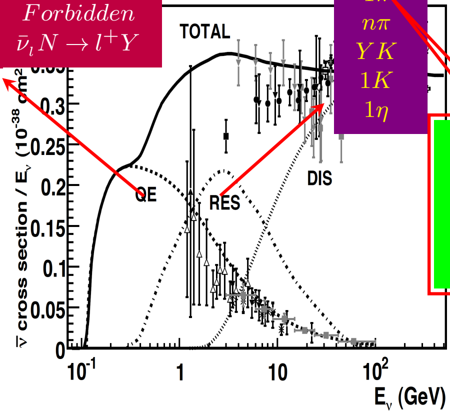
$\Delta S = 0$	$\Delta S = 1$
$\nu_l n \to l^- p$	$Forbidden$
$\bar{\nu}_l p \to l^+ n$	$\bar{\nu}_l N \to l^+ Y$

1π
$n\pi$
YK
$1K$
1η



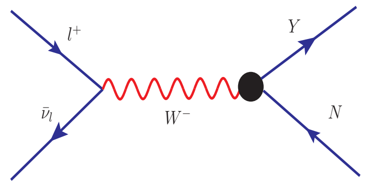
$Y \to N\pi$

$\Lambda^0 \to p\pi^-$	63.9%
$\Lambda^0 \to n\pi^0$	35.8%
$\Sigma^- \to n\pi^-$	99.85%
$\Sigma^0 \to \Lambda\gamma$	100%

$|\Delta S| = 1$ *processes*

Antineutrino induced Single Hyperon Production

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



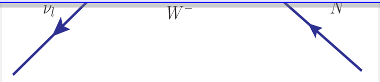
These processes are Cabibbo suppressed as compared to the $\Delta S = 0$ associated production of hyperons.

$|\Delta S| = 1$ processes

Antineutrino induced Single Hyperon Production

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

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



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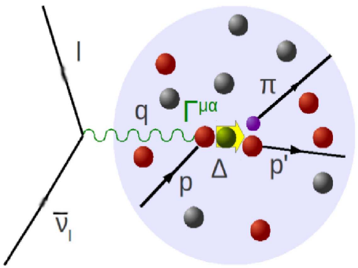
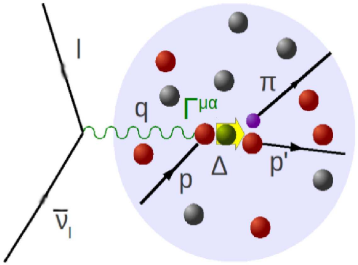
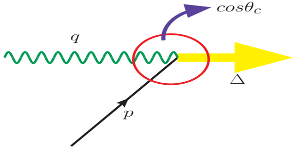
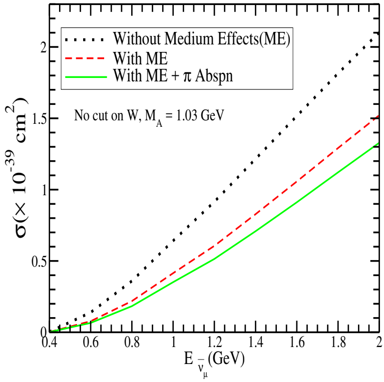
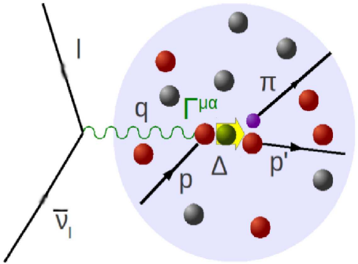

l
q
Γ^μα
π
Δ
p
p'
ν̄_l

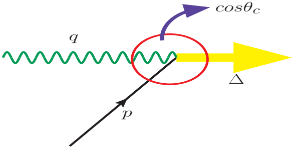


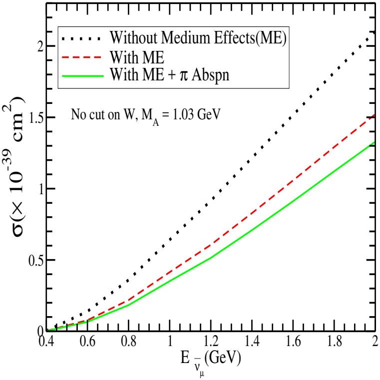




Eur. Phys. J. A **43**, 209 (2010).







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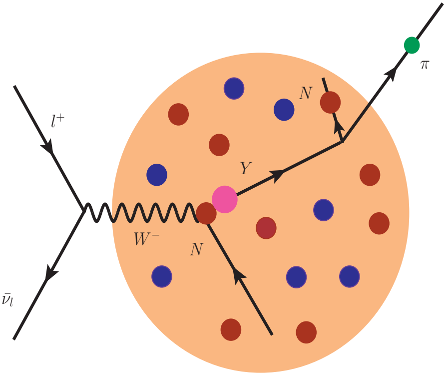
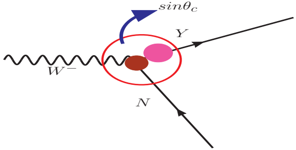
$E_{\bar{\nu}_\mu}$(GeV)	σ with ME (% reduction)	σ with ME + π absorption (% reduction)
0.8	42	14
1.0	36	15
1.4	31	14
1.8	28	15





$|\Delta S| = 1$ 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.*

Outline

Differential cross section

$d\sigma$ for the process

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

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

- $q = p' - p = k - k'$
- $s = (q+p)^2$
- $E_\nu = \frac{s-M^2}{2\sqrt{s}}$ is the CM neutrino energy
- $\mathcal{M}$ is the transition matrix element

Transition matrix element

$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}_{B'}(p') \left[\mathcal{O}^{\mu}_{V(B'B)}(p',p) - \mathcal{O}^{\mu}_{A(B'B)}(p',p) \right] u_B(p) \times \bar{u}_l(k') \gamma_\mu (1+\gamma_5) v_{\nu_l}(k)$$

Transition matrix element

Vector operator

$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}_{B'}(p') \left[\mathcal{O}^{\mu}_{V(B'B)}(p',p) - \mathcal{O}^{\mu}_{A(B'B)}(p',p) \right] u_B(p) \times \bar{u}_l(k') \gamma_\mu (1+\gamma_5) v_{\nu_l}(k)$$

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Transition matrix element

Vector operator → $\mathcal{O}^{\mu}_{V(B'B)}$; Axial vector operator → $\mathcal{O}^{\mu}_{A(B'B)}$

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- $G \to G_F \cos\theta_c$ for strangeness conserving processes.
- $G \to G_F \sin\theta_c$ for $|\Delta S| = 1$ processes considered here.

Transition matrix element

Vector operator

Axial vector operator

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Vector FF

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Vector FF

Magnetic FF

Induced scalar FF

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Transition matrix element

Vector operator

Axial vector operator

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Vector FF

Magnetic FF

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Axial vector FF

Transition matrix element

Vector operator

Axial vector operator

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Vector FF

Magnetic FF

Induced scalar FF

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Axial vector FF

Electric FF

Transition matrix element

Vector operator — Axial vector operator

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Vector FF — Magnetic FF — Induced scalar FF

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Axial vector FF — Electric FF — Induced pseudoscalar FF

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

(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.*

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

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

Form factors: vector and axial vector

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

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

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

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

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FF	$n \to \Sigma^-$	$p \to \Lambda$
$f_1(Q$		
$f_2(Q$		
$g_1(Q$		$Q^2)$

We assume dipole form for the axial form factor

$$g_A(Q^2) = \frac{g_A(0)}{(1+\frac{Q^2}{M_A^2})^2}$$

$$g_A(0) = D(0) + F(0) = 1.267$$

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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.

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  - 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).):

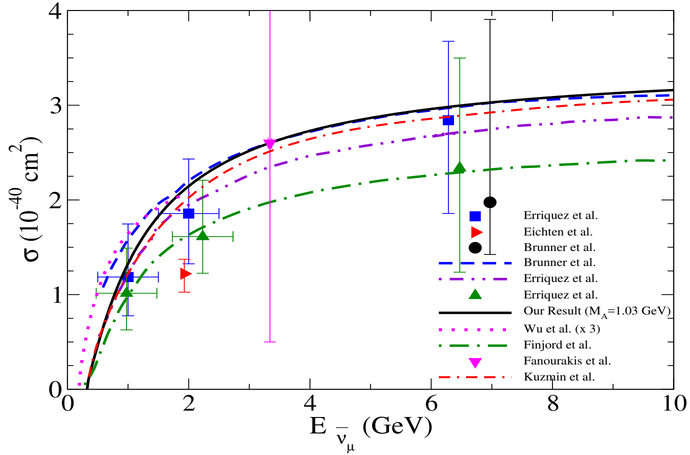
$$g_3^{NY}(Q^2) = \frac{(m_N + m_Y)^2}{(m_K^2+Q^2)} g_1^{NY}(Q^2).$$

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	$F-D$	$\frac{M_{\Sigma^-}}{M_p}\frac{(\mu_p+2\mu_n)}{2}$

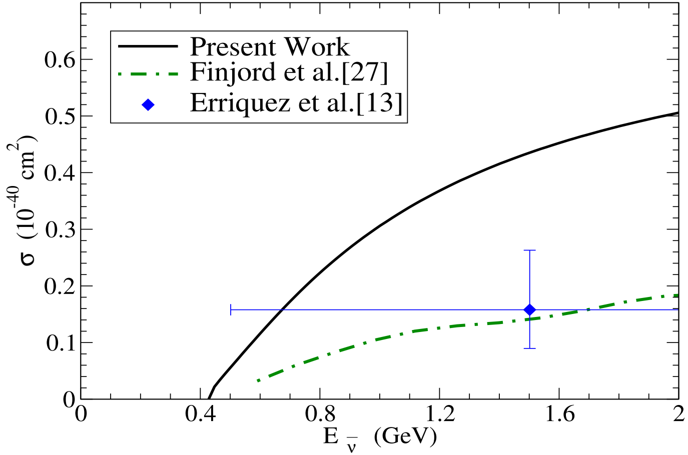
$$F = 0.463, \qquad D = 0.804, \qquad \mu_p = 1.7928, \qquad \mu_n = -1.913$$

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



J. Phys. G **42**, no. 5, 055107 (2015).

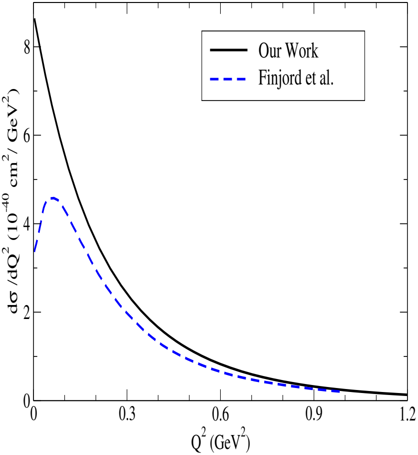
σ vs $E_{\bar{\nu}_\mu}$, for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$ process.



J. Phys. G **42**, no. 5, 055107 (2015).

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

$\frac{d\sigma}{dQ^2}$ vs Q^2



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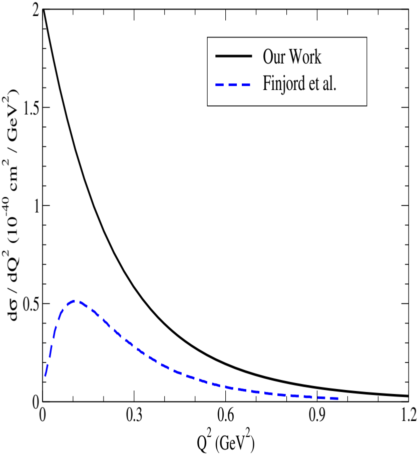

J. Phys. G **42**, no. 5, 055107 (2015).

Finjord and Ravndal, Nucl. Phys. B 106 228 (1976)

Outline

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

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

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Local Fermi momentum for neutrons and protons:

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

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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

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

FSI of hyperons

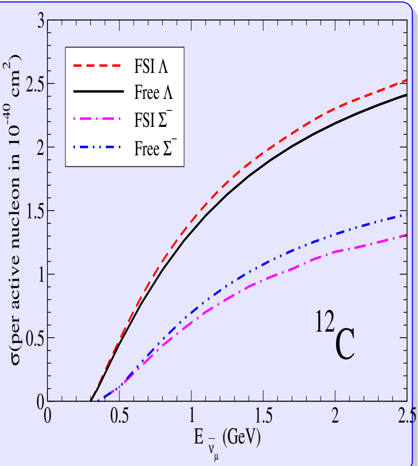
An initial hyperon is taken at a position r inside the nucleus which interacts with a nucleon to produce a new hyperon state within a short distance dl *with a probability* $P = P_Y dl$,

$$P_Y = \sigma_{Y+n\rightarrow f}(E)\ \rho_n(r)\ +\ \sigma_{Y+p\rightarrow f}(E)\ \rho_p(r),$$

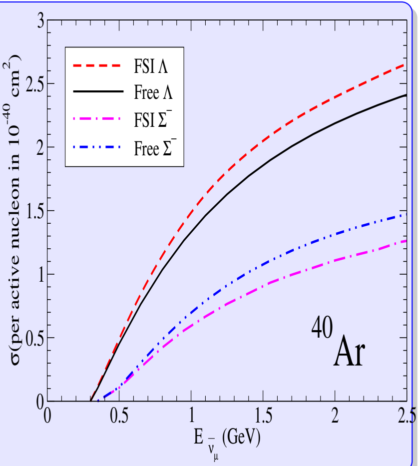
- P_Y *is probability per unit length*
- $f \rightarrow Y(\Sigma \text{ or } \Lambda)\ +\ N(n \text{ or } p)$.
- *E is energy in of the hyperon-nucleon state in CM system.*
- $\rho_n(r)(\rho_p(r))$ *is the local density of neutron(proton) in the nucleus.*

S. K. Singh and M. J. Vicente Vacas,
2006 Phys. Rev. D **74** 053009.

σ vs $E_{\bar{\nu}_\mu}$ in ^{12}C.



σ vs $E_{\bar{\nu}_\mu}$ in ^{40}Ar.



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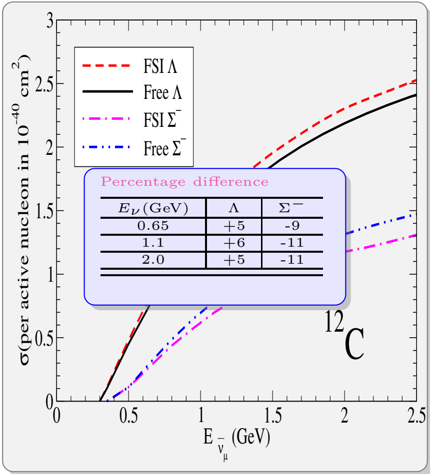
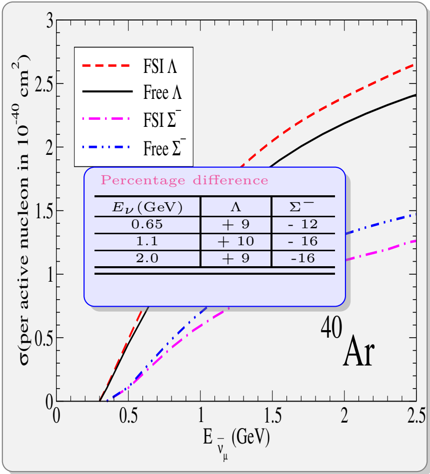


Percentage difference

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

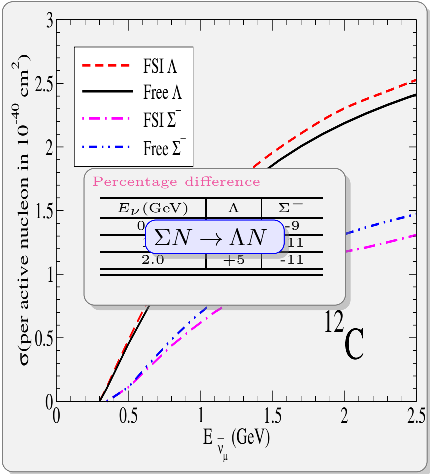
σ vs $E_{\bar{\nu}_\mu}$ in ^{40}Ar.



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 ^{12}C.



Percentage difference

E_ν(GeV)	Λ	Σ^-
0 [illegible]	[illegible]	-9
1 [illegible]	[illegible]	[illegible]11
2.0	+5	-11

$\Sigma N \rightarrow \Lambda N$

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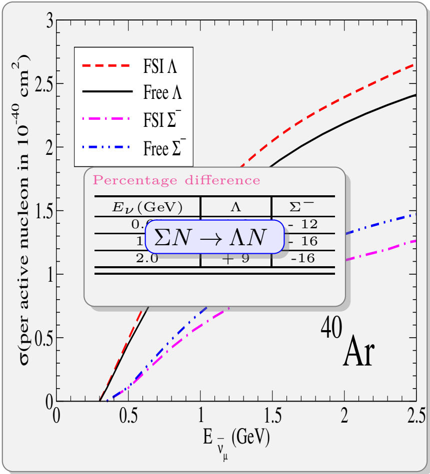

Percentage difference

E_ν(GeV)	Λ	Σ^-
0. [illegible]	[illegible]	- 12
1 [illegible]	[illegible]	- 16
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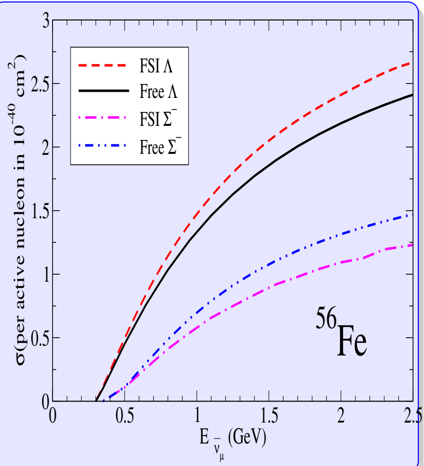
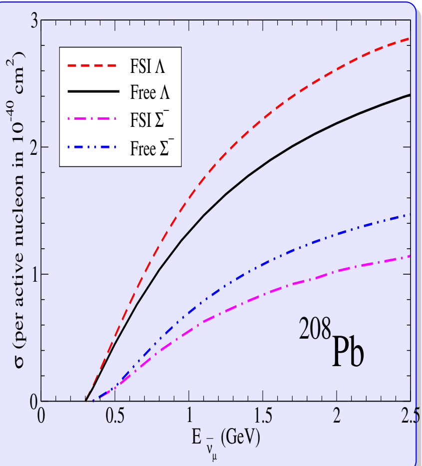
σ vs $E_{\bar{\nu}_\mu}$ in ^{56}Fe.



σ vs $E_{\bar{\nu}_\mu}$ in ^{208}Pb.



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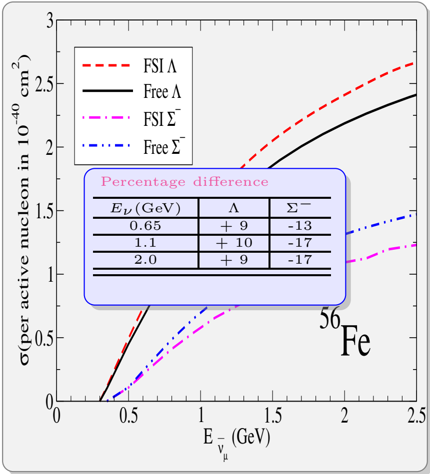
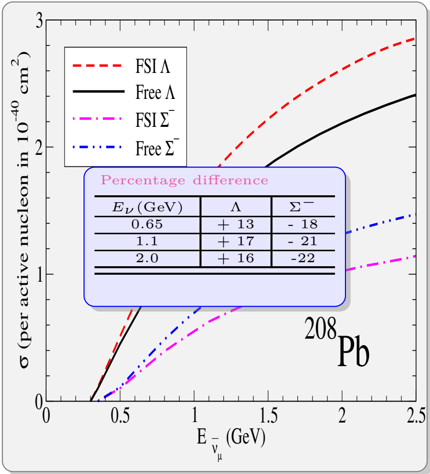


Percentage difference

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

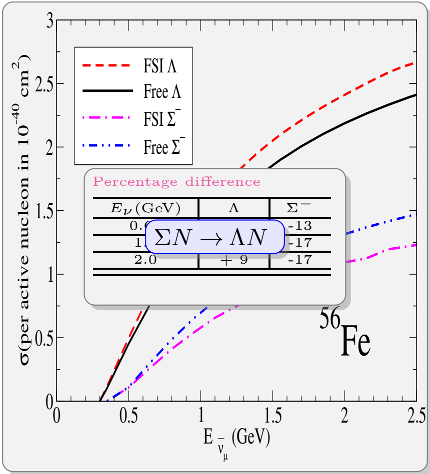
σ vs $E_{\bar{\nu}_\mu}$ in ^{208}Pb.



Percentage difference

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

σ vs $E_{\bar{\nu}_\mu}$ in ^{56}Fe.



Percentage difference

E_ν(GeV)	Λ	Σ^-
0.		-13
1.		-17
2.0	+ 9	-17

$\Sigma N \to \Lambda N$

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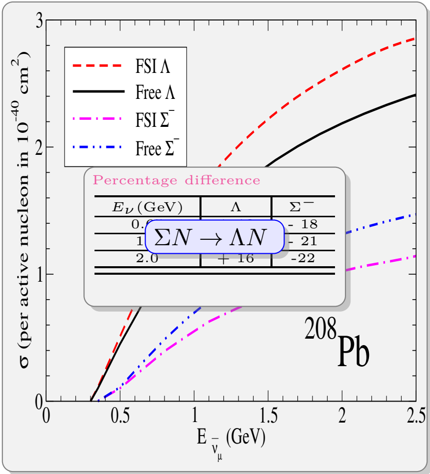

Percentage difference

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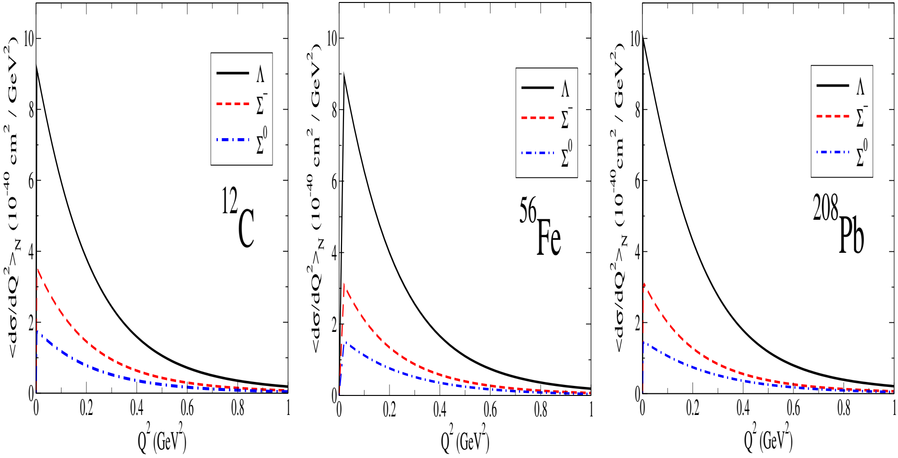
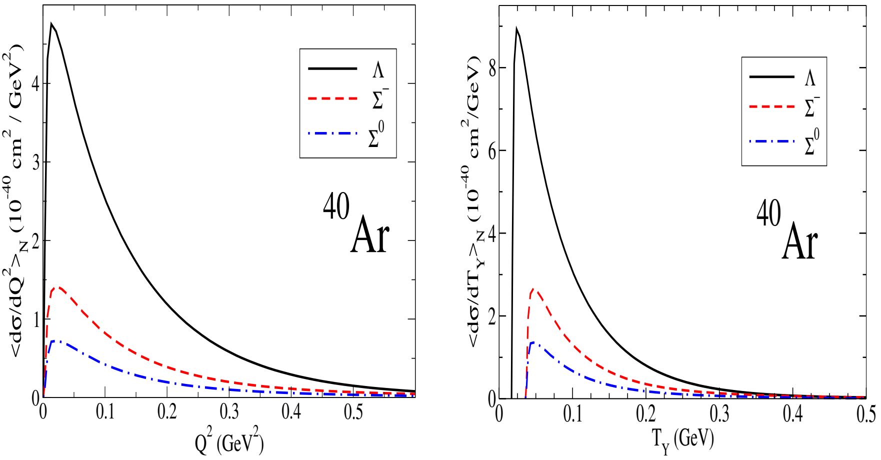
1		- 21
2.0	+ 16	-22

$\Sigma N \to \Lambda N$

$\left\langle \frac{d\sigma}{dQ^2} \right\rangle_N$ vs Q^2 in ^{12}C, ^{56}Fe and ^{208}Pb averaged over MINERνA flux.



$\left\langle \frac{d\sigma}{dQ^2} \right\rangle_N$ *vs* Q^2 *and* $\left\langle \frac{d\sigma}{dT_Y} \right\rangle_N$ *vs* T_Y *in* ^{40}Ar *(per active nucleon N) averaged over MicroBooNE flux.*



Outline

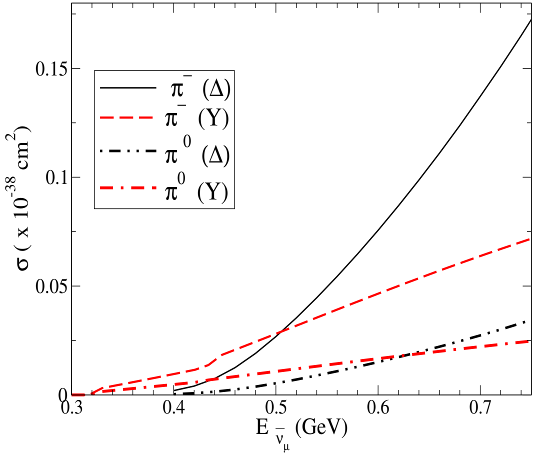
Hyperon giving rise to pions

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.

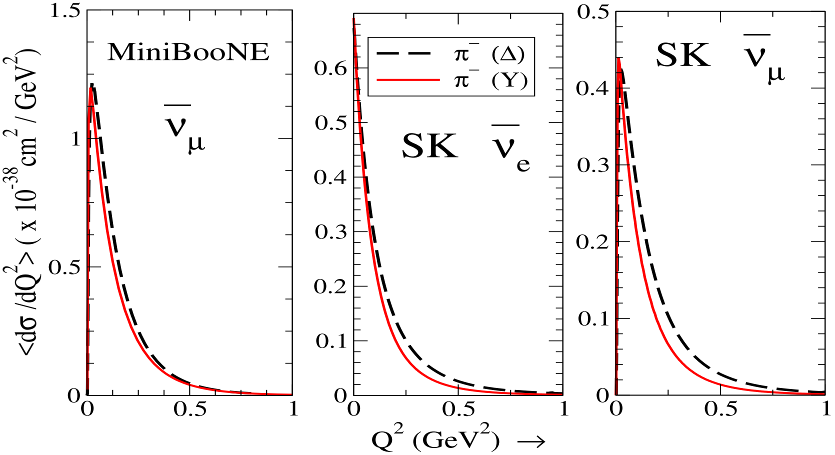
Hyperon giving rise to pions

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.

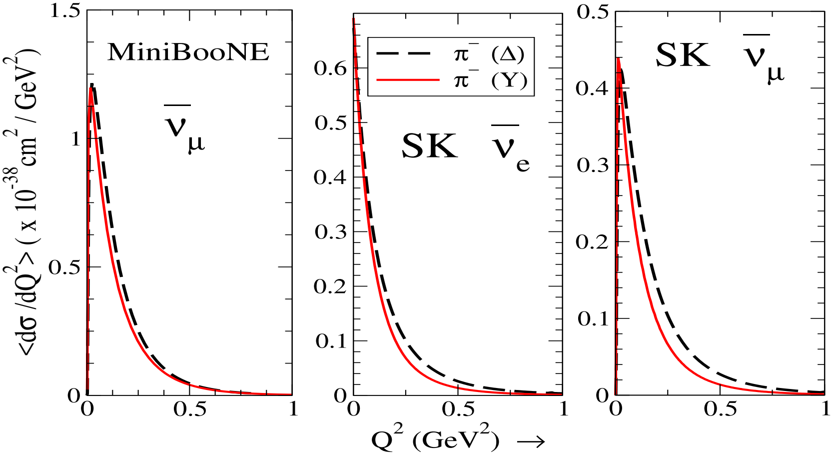
σ vs $E_{\bar{\nu}_\mu}$



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



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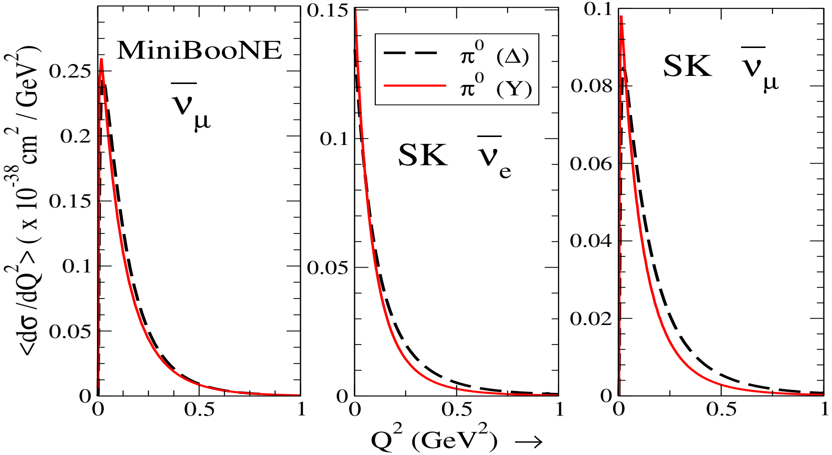
scaled by a factor of 2.5 i.e $\sim 40\%$

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



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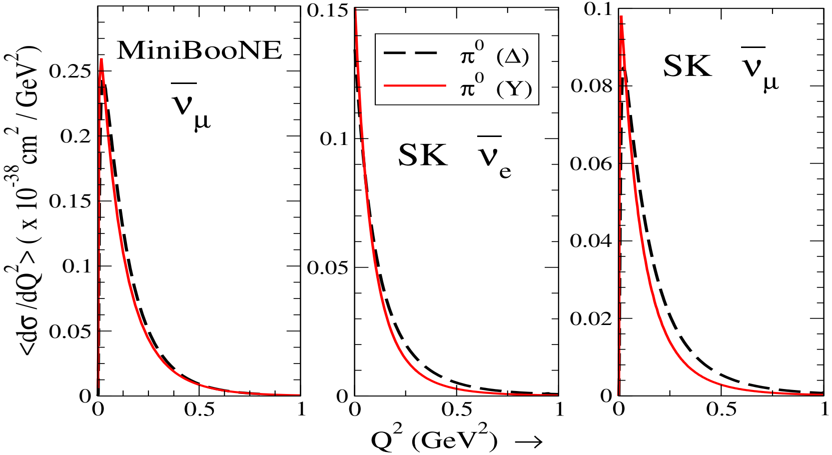

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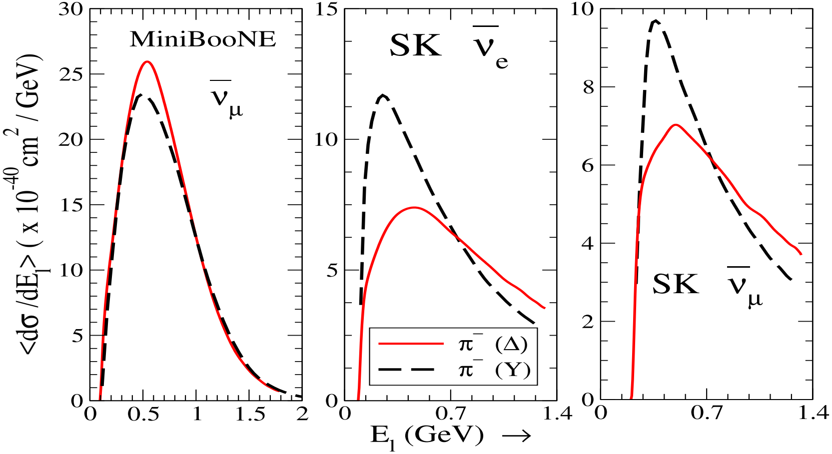
scaled by a factor of 1.3 i.e $\sim 30\%$

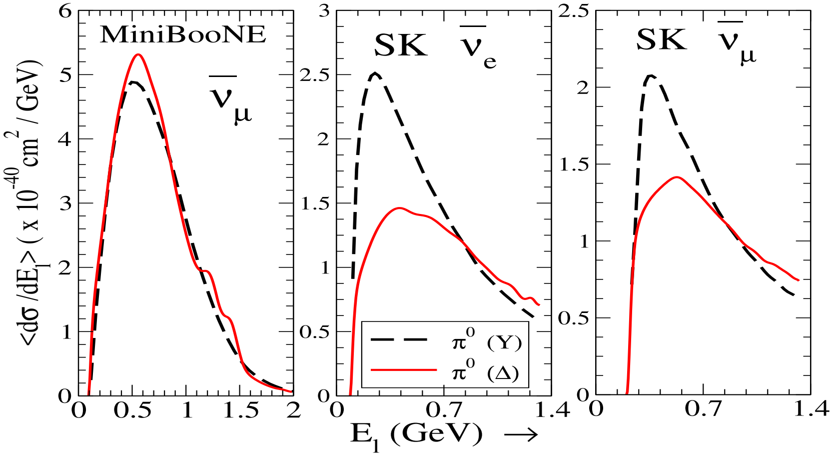
Phys. Rev. D **88**, 077301 (2013)

Lepton energy distributions for π^- production



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

Lepton energy distributions for π^0 production.



scaled by a factor of 1.3 i.e ~ 30%

Outline

Hyperons and their polarization in antineutrino reactions

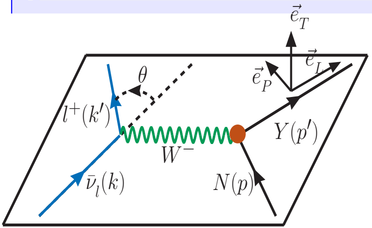
Measuring polarization effects in $\bar{\nu}_l N \to l^+ Y$ scattering process may provide a sensitive way to determine

- axial dipole mass M_A
- electric neutron form factor, $G_E^n(Q^2)$
- pseudoscalar form factor in the strangeness sector: $g_3(Q^2)$

Hyperon polarization

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

$$N = n, p; \qquad Y = \Lambda, \Sigma.$$



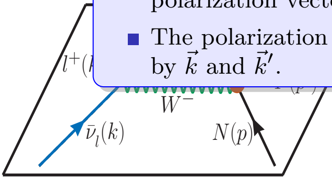
Unit vectors along:

- longitudinal direction, $\vec{e}_L = \frac{\vec{p'}}{|\vec{p'}|} = \frac{\vec{q}}{|\vec{q}|}$
- transverse direction, $e_{\vec{T}} = \frac{\vec{k}\times\vec{k'}}{|\vec{k}\times\vec{k'}|}$
- perpendicular direction, $\vec{e}_P = \vec{e}_L \times e_{\vec{T}}$

Hyperon polarization

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

- We assume T–invariance and the absence of second class currents.
- As the consequence of this, transverse component of the polarization vector vanishes.
- The polarization vector lies in scattering plane defined by $\vec{k}$ and $\vec{k}'$.



$= \frac{\vec{q}}{|\vec{q}|}$

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

Hyperon polarization

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

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

where

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

is final spin density matrix.

Hyperon polarization

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

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

Hyperon polarization

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$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 \sin^2\theta_c}{8\pi m_N E_{\bar{\nu}_\mu}^2}\mathcal{N}(Q^2,E_{\bar{\nu}_\mu}),$$

Hyperon polarization

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

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

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 \sin^2\theta_c}{8\pi m_N E_{\bar{\nu}_\mu}^2}\mathcal{N}(Q^2, E_{\bar{\nu}_\mu}),$$

- Longitudinal component, $P_L(Q^2) = \frac{m_Y}{E_{p'}}\ \vec{\xi}\cdot\vec{e}_L$.
- Perpendicular component, $P_P(Q^2) = \vec{\xi}\cdot\vec{e}_P$.
- Transverse component, $P_T(Q^2) = 0$.

Components of polarization

Longitudinal component of polarization 3-vector

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

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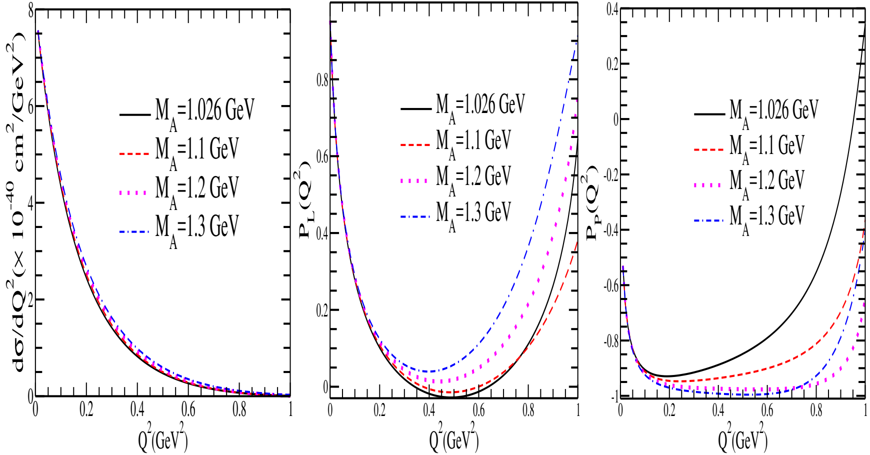
Perpendicular component of polarization 3-vector

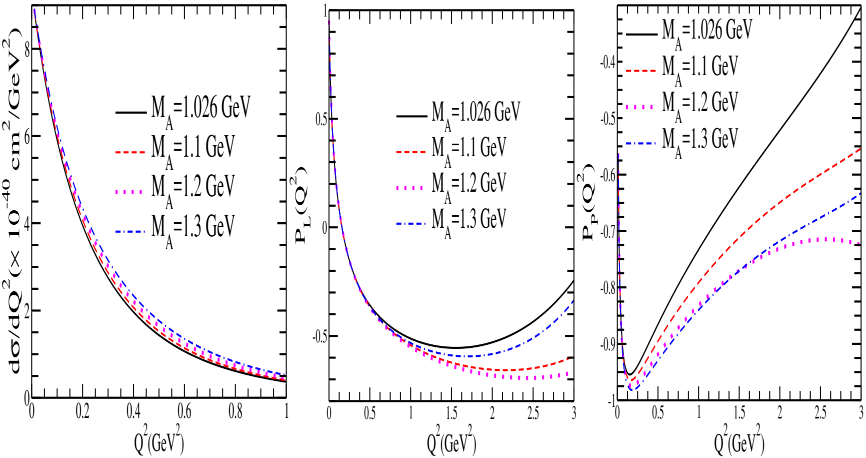
$$\frac{d\sigma}{dQ^2}P_P(Q^2) = -\frac{G_F^2 \sin^2\theta_c}{4\pi}\frac{|\vec{k}'|}{|\vec{q}|}\frac{\mathcal{A}(Q^2, E_{\bar{\nu}_\mu})\sin\theta}{m_N E_{\bar{\nu}_\mu}}$$

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.



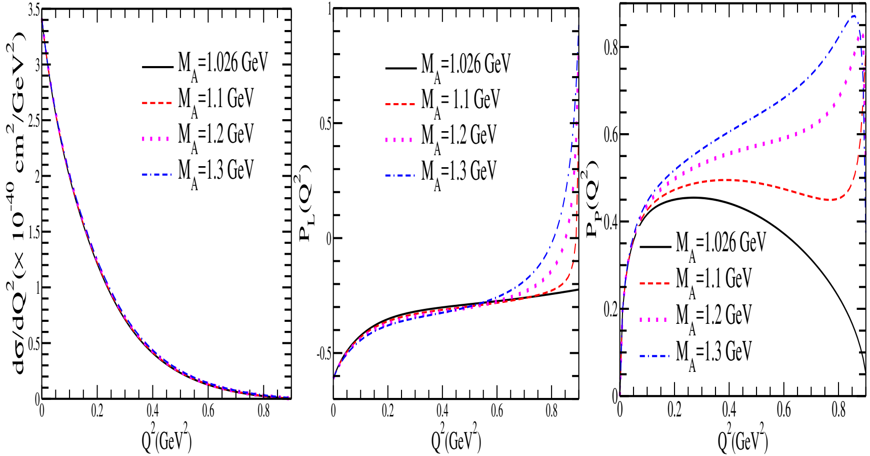
arXiv:1608.02103

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 $E_{\bar{\nu}_\mu}$=3 GeV.



arXiv:1608.02103

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.



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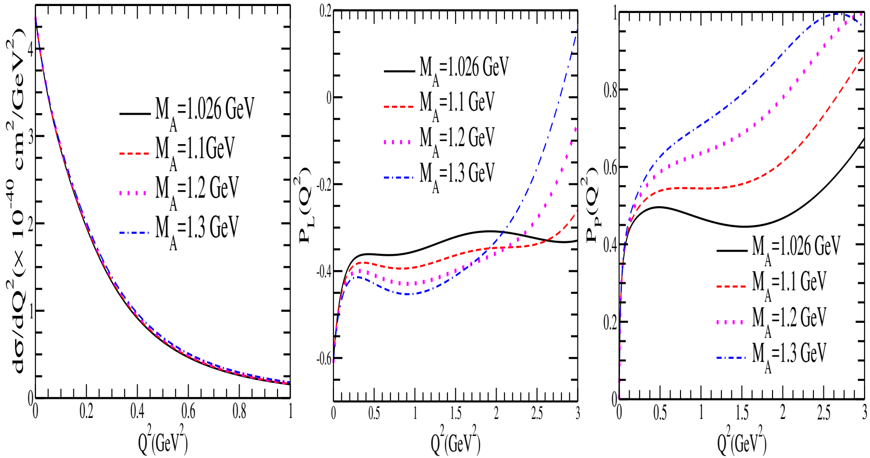
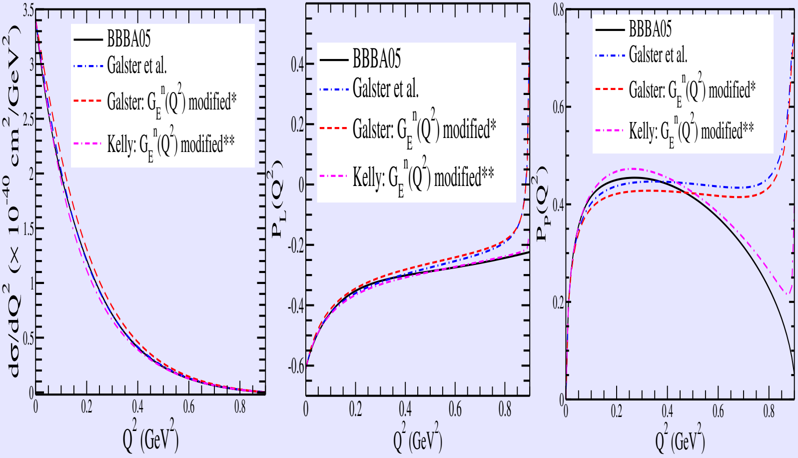


arXiv:1608.02103

$G_E^n(Q^2)$–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.



arXiv:1608.02103

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

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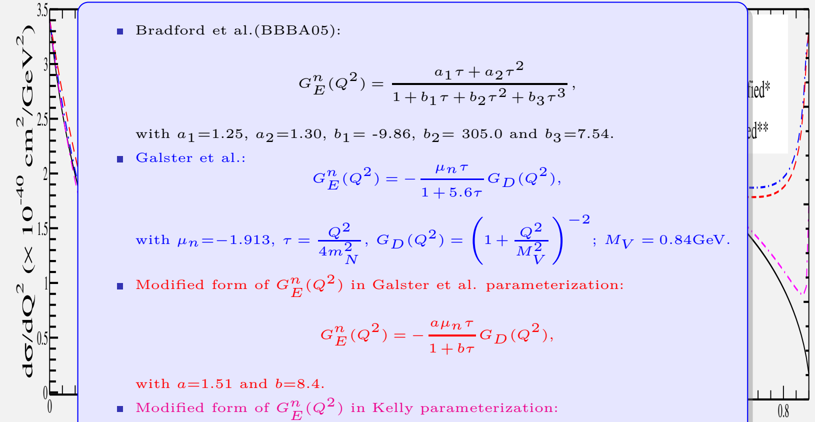

- Bradford et al.(BBBA05):

$$G_E^n(Q^2) = \frac{a_1\tau + a_2\tau^2}{1 + b_1\tau + b_2\tau^2 + b_3\tau^3},$$

with a_1=1.25, a_2=1.30, b_1= -9.86, b_2= 305.0 and b_3=7.54.

- Galster et al.:

$$G_E^n(Q^2) = -\frac{\mu_n\tau}{1+5.6\tau}G_D(Q^2),$$

with $\mu_n=-1.913$, $\tau = \frac{Q^2}{4m_N^2}$, $G_D(Q^2) = \left(1+\frac{Q^2}{M_V^2}\right)^{-2}$; $M_V = 0.84$GeV.

- Modified form of $G_E^n(Q^2)$ in Galster et al. parameterization:

$$G_E^n(Q^2) = -\frac{a\mu_n\tau}{1+b\tau}G_D(Q^2),$$

with a=1.51 and b=8.4.

- Modified form of $G_E^n(Q^2)$ in Kelly parameterization:

$$G_E^n(Q^2) = \frac{G_M^n(Q^2)}{\mu_n}\frac{a_1\tau}{1+a_2\sqrt{\tau}+a_3\tau},$$

with a_1=2.6316, a_2=4.118 and a_3=0.29516.

arXiv:

*Platchko ... 2015).

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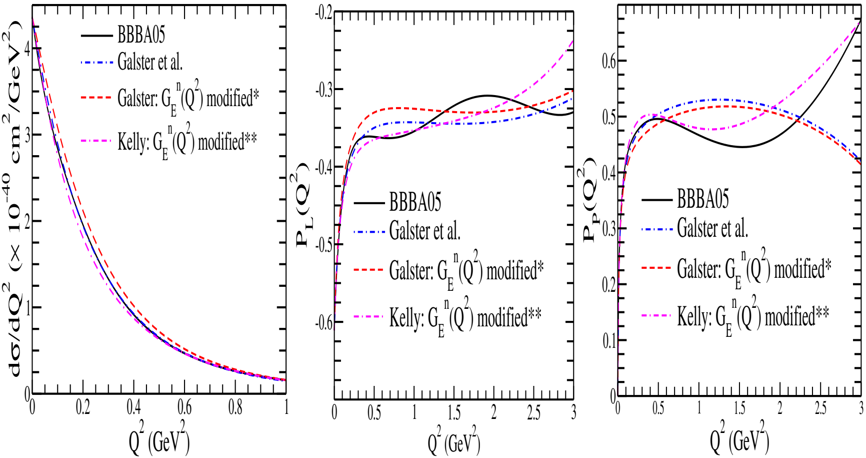
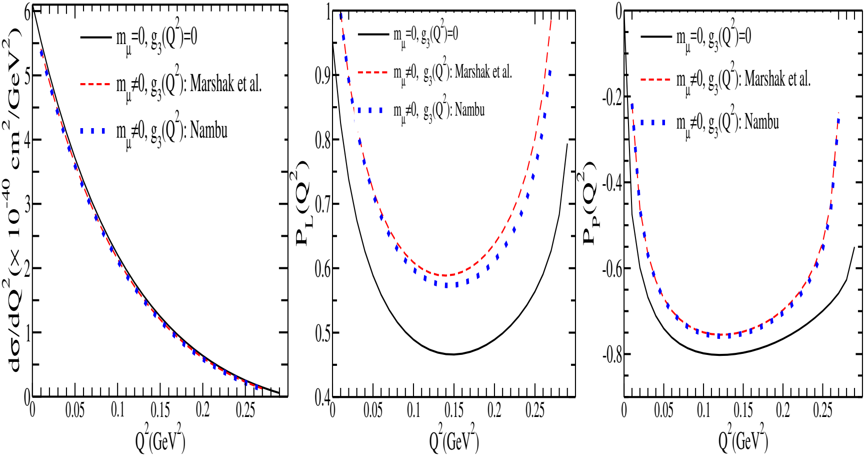


arXiv:1608.02103

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



arXiv:1608.02103

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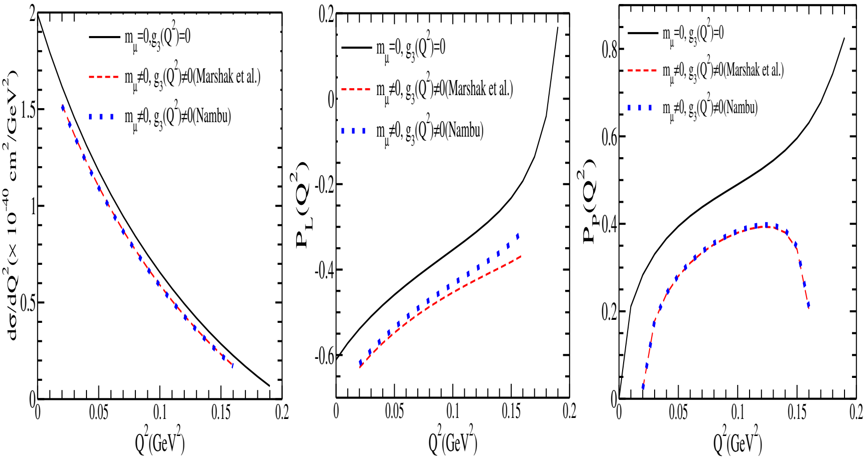
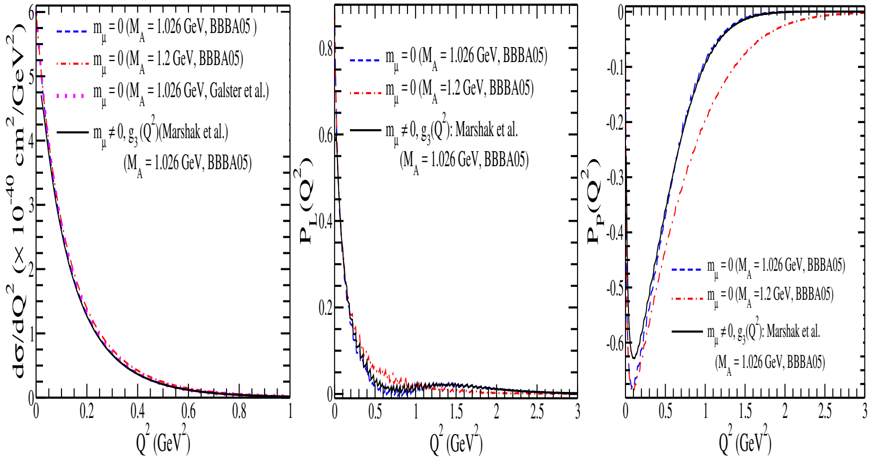


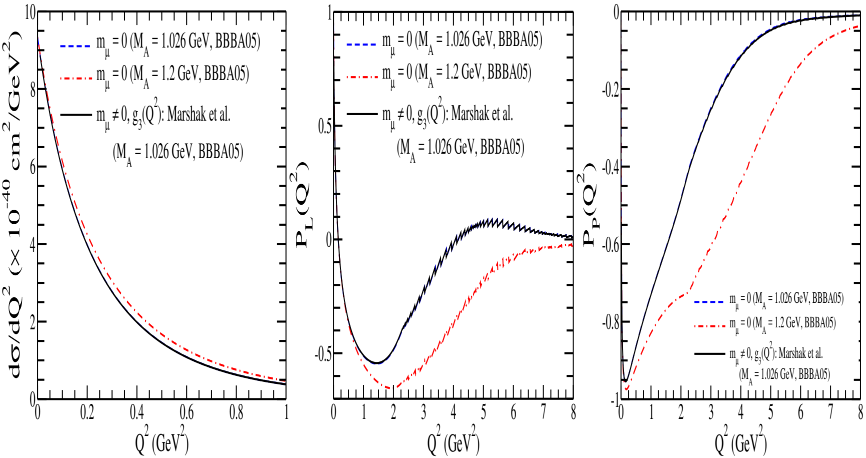
arXiv:1608.02103

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



arXiv:1608.02103

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



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Outline

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!

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

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

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

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

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

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