ν *Induced Nuclear Pion Production In Dynamical Coupled Channel Model*

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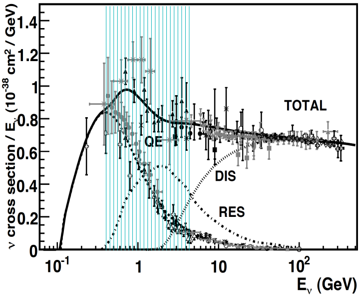
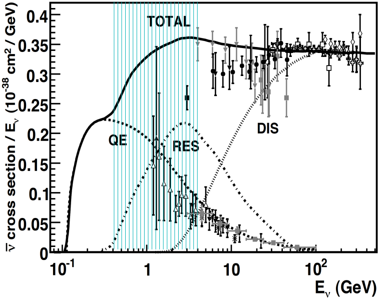
Motivations

Neutrino energy of $\sim$ 1GeV is quite important for oscillation studies





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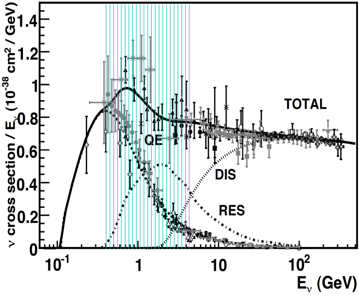

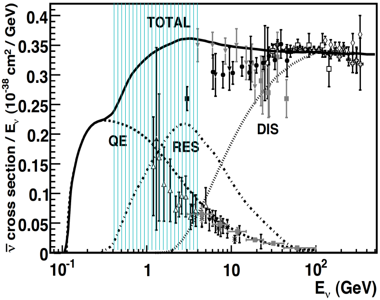

$$\sigma^{Total} = \sigma^{QE} + \sigma^{Inelastic} + \sigma^{DIS}$$

In this energy region the major contribution to the cross section comes from CCQE, CC1π, NC1π production processes.

One pion production from nucleons and nuclei has been a topic of great interest because of the measurements by MiniBooNE, K2K, T2K etc. and the experiments like MINERνA measuring pion production from $\nu/\bar{\nu}$ induced interaction from nuclear targets. Future Experiments like at T2K and DUNE are also proposed to work at different energy region.

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Recently, Wilkinson et al. has reanalyzed ANL and BNL data and it seems the difference between two results have reduced a lot. They tried to avoid the neutrino flux uncertainty of the old bubble chamber experiments.
Reduce Flux uncertainty :
$\sigma(1\pi)/\sigma(0\pi)$

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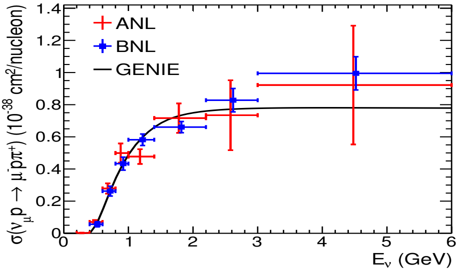


Previous Work

- Valencia Model
  A tree-level non-resonant mechanisms based on SU2 nonlinear sigma model in addition to resonant ones of the Breit-Wigner type.
- Lalakulich et. al
  The amplitudes are taken as a sum of Breit-Wigner functions that represent resonant contributions.
- Giessen model
  a model that contains all 4-star resonances with masses below 1.8 GeV, and included rather phenomenological non-resonant contributions.
- Aligarh Group
  Based on Giessen model but have also taken the interference terms.

Model

The weak interaction Lagrangian for charged-current (CC) processes :

$$L_{int}(x) = \frac{G_F \cos\theta_c}{\sqrt{2}}[l^\mu(x) J_\mu(x) + \text{h.c.}],$$

where $G_F = 1.16637 \times 10^{-5}$ $(\text{GeV})^{-2}$, $cos\theta_c = 0.974$,

$$l^\mu(x) \quad = \quad \bar{\psi}_l(x)\gamma^\mu(1-\gamma_5)\psi_\nu(x)$$

is the lepton current and

$$J^\mu(x) = V^\mu(x) - A^\mu(x)$$

The double differential cross section :

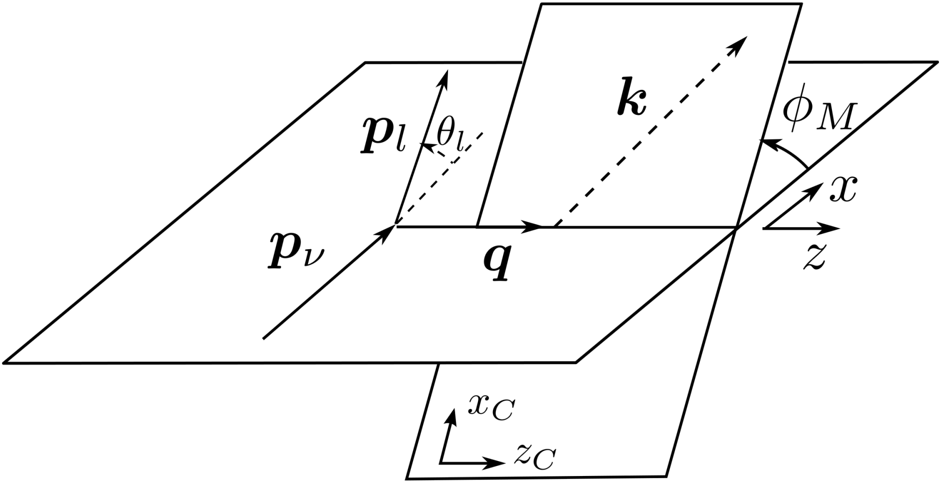
$$\frac{d^3\sigma_{\nu N}}{dE_l d\Omega_l} = \frac{G_F^2 V_{ud}^2}{4\pi^2} \frac{|\vec{p}_l|}{|\vec{p}_\nu|} L^{\mu\nu} W_{\mu\nu}^N$$

Leptonic tensor :

$$L^{\mu\nu} = [\, p_l^\mu p_\nu^\nu + p_l^\nu p_\nu^\mu - g^{\mu\nu}(p_\nu \cdot p_l - m_l^2) + i\epsilon^{\mu\nu\alpha\beta} p_{\nu,\alpha} p_{l,\beta} \,],$$

Hadronic Tensors:

$$W_{\mu\nu}^N = \sum_{s_f^z, p_f} \frac{1}{2} \sum_{s_N^z} (2\pi)^3 \frac{E_N}{m_N} \delta^{(4)}(p_N + q - p_f) \langle F | J_\mu^{\mathrm{N}}(0) | N \rangle \langle F | J_\nu^{\mathrm{N}}(0) | N \rangle^*$$


$\boldsymbol{k}$
ϕ_M
$\boldsymbol{p}_l$
θ_l
x
$\boldsymbol{p}_\nu$
$\boldsymbol{q}$
z
x_C
z_C

The hadron tensor for a two-body meson-baryon final state is given as

$$
\begin{aligned}
W_{\mu\nu}^{\mathrm{N}\to MB} &= \frac{(2\pi)^3}{2} \sum_{s_N^z, s_B^z} \int d\Omega_M^* {\Lambda_\mu}^\lambda {\Lambda_\nu}^\sigma \frac{|\vec{k}^*| E_M(k^*) E_B(p^*) E_N(p_N^*)}{W m_N} \\
&\times \langle MB^{(-)} | J_\lambda^{\mathrm{N}}(0) | N \rangle_{\mathrm{hCM}} \langle MB^{(-)} | J_\sigma^{\mathrm{N}}(0) | N \rangle_{\mathrm{hCM}}^* \; . \qquad (1)
\end{aligned}
$$

The initial nucleon state in hCM is $|N\rangle = |N(p_N^*, s_N^z, t_N^z)\rangle$, while the final meson-baryon state in hCM, $|MB\rangle = |M(k^*, t_M^z) B(p^*, s_B^z, t_B^z)\rangle$, has the momentum k^* (p^*), the isospin z-components t_M^z (t_B^z), and the spin z-component 0 (s_B^z) for the meson (baryon).

Overview of Dynamical Coupled Channel(DCC)

In order to calculate the Hadronic current we start with the construction of effective Hamiltonian,

$$H = H_0 + v + \Gamma\ .$$

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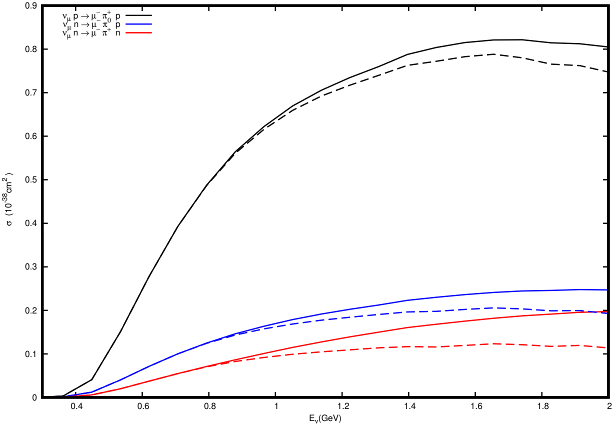
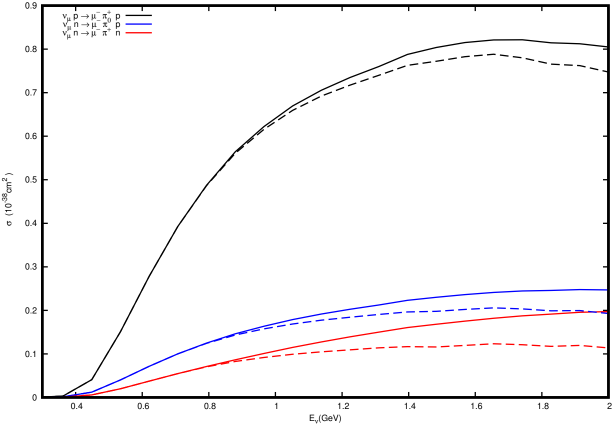
$$H = H_0 + v + \Gamma \; .$$

- H_0 is the free Hamiltonian of the particles.
- v non-resonant interactions among the two-body meson-baryon states and $\pi\pi$ states.
- Γ represents transitions between bare excited states and two-body states such as $\Delta \leftrightarrow \pi N$.

Cross Section



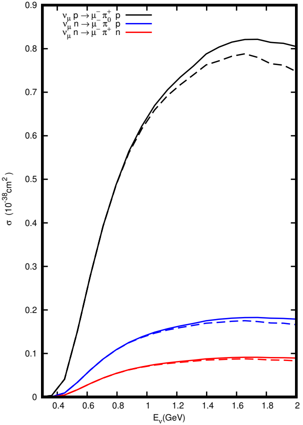
Cross Section

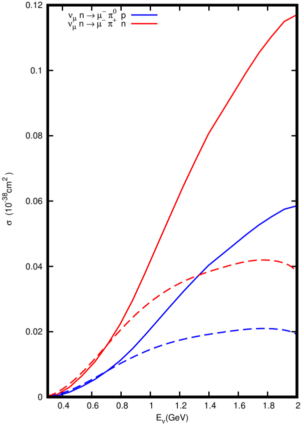


Solid Line : No W-cut
Dashed Line : W$\leq$ 1.4 GeV

Cross Section

Isospin 3/2 and 1/2 components.





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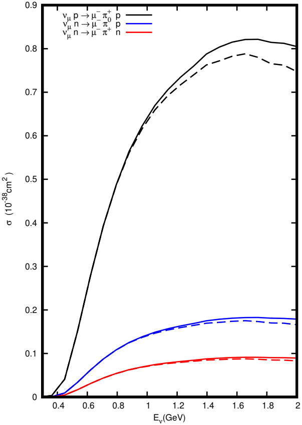

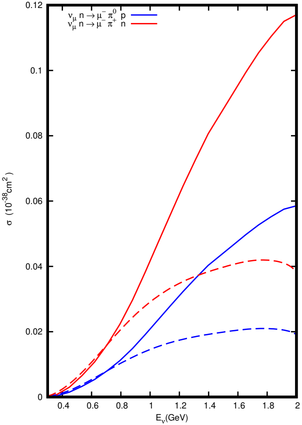

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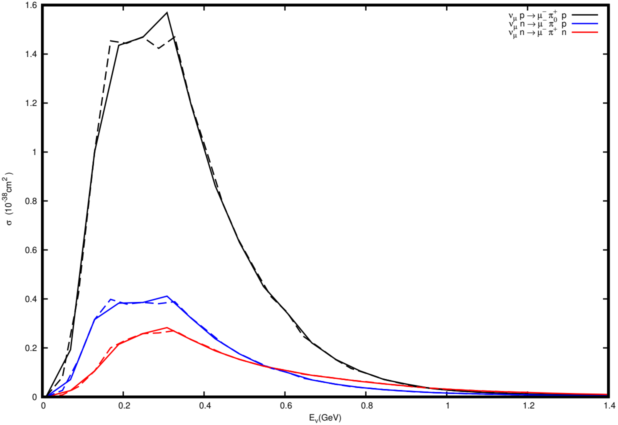
Pion momentum distribution



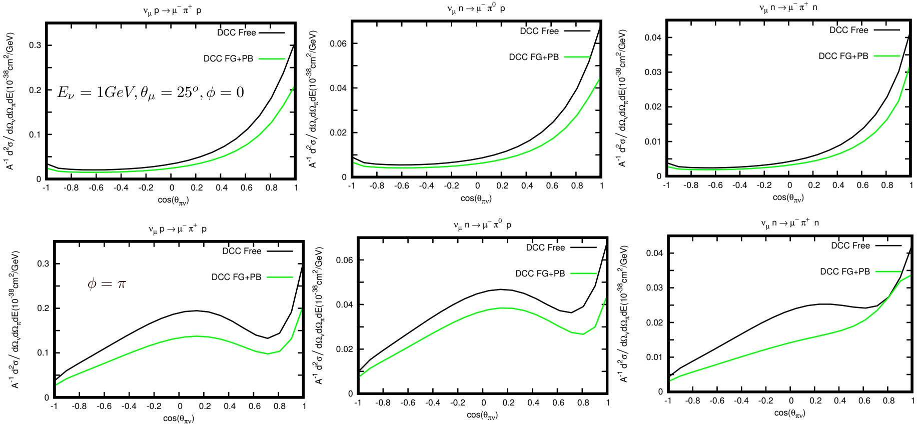
Nuclear Effects

$$\frac{d^3\sigma_{\nu N}}{dE_l d\Omega_l} = \frac{G_F^2 V_{ud}^2}{4\pi^2}\frac{|\vec{p}_l|}{|\vec{p}_\nu|} L^{\mu\nu} W_{\mu\nu}^N$$

$$W^{\mu\nu} \quad = \quad \bar{\sum_i} \sum_f (2\pi)^3 V \delta^4 (P_f + p_l - P_i - p_\nu) < f|J^\mu|i >< f|J^\nu|i >^*,$$

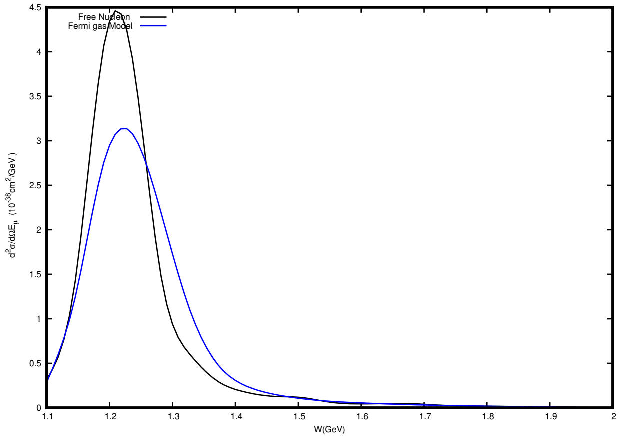
$$
\begin{aligned}
W^{\mu\nu} &= \sum_{s_N, s_{N'}, t_N, i} \frac{3}{4\pi p_F^3} \int d\vec{p}\,\theta(p_F - |\vec{p}|) \frac{m_N}{E_N(p)} \\
&\times \quad N_{t_N} \int d\Omega_* \theta(|\vec{p}\prime| - p_F) \frac{|\vec{k}_c| m_N}{32\pi^2 W} \\
&\times \quad \Lambda^{\mu\mu'} < \pi^i N(p', s_{N'}) | j^{\mu'} | N(p, s_N, t_N) >_{\pi N-\mathrm{cm}} \\
&\times \quad \Lambda^{\nu\nu'} < \pi^i N(p', s_{N'}) | j^{\nu'} | N(p, s_N, t_N) >^*_{\pi N-\mathrm{cm}},
\end{aligned}
$$

Pion Angular distribution



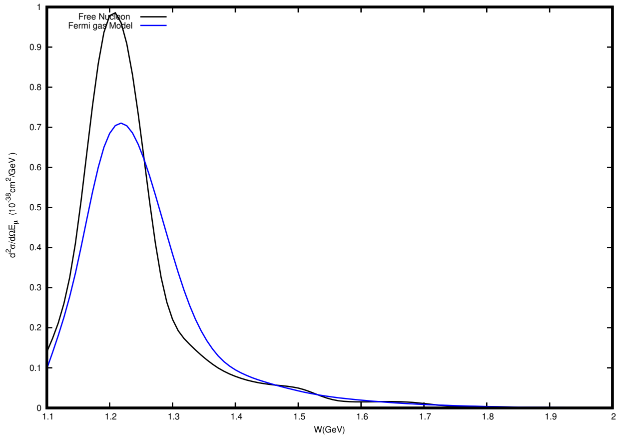
Incluseive π^+ *Lepton energy distribution*

$$E_\nu = 2GeV, \quad \theta_{\nu q} = 10^\circ,$$



Incluseive π^0 Lepton energy distribution

$$E_\nu = 2GeV, \quad \theta_{\nu q} = 10^\circ,$$



1. Check the validity of model for photo and electron scattering data.
2. Include the Final State Interaction.
3. Include the pion absorption effects