A Phenomenological Study of Photon Production in Low Energy Neutrino Nucleon Scattering

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Outline

1. Introduction
2. Process
   - Diagram and Couplings
   - Cross Section
3. Phenomenology
   - Results
   - Interference Effects

In collaboration with Terry Goldman (LANL)
arXiv:0906.0984 [hep-ph] (submitted for publication in PRD)

Motivation

See previous talk by Richard Hill

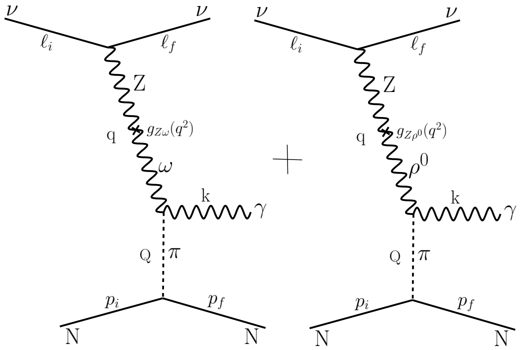
Neutrino experiments are probing the sub-% level and the need for accurate background calculations is increasing.

Why study photon production?

- Some experiments can't distinguish photons and electrons
- Currently included radiative corrections are incomplete
  - Only nucleon bremsstrahlung and radiative Δ decays
- MiniBoone low energy anomaly
  - Possible standard model background
  - Possible $\nu - \bar{\nu}$ differences (Hard to achieve)

See also Harvey, Hill, Hill (2007) and R.J. Hill (2009)

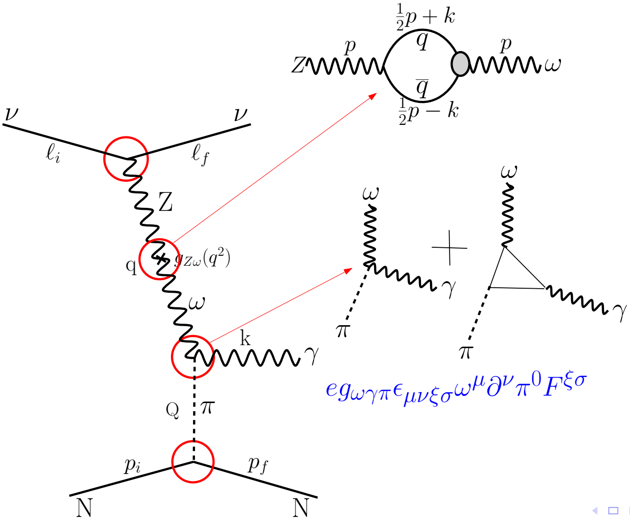
Radiative Process



- Phenomenological couplings from decays
- Full $\omega - Z$ running
- Vector meson dominance
- Fully relativistic treatment
- Interference effects
- Extend to CC processes (π production)
- Extend to higher energy

$$\mathcal{L}_I = e g_{\omega\gamma\pi} \epsilon_{\mu\nu\xi\sigma} \omega^\mu \partial^\nu \pi^0 F^{\xi\sigma} + g_{\pi NN} \bar{\Psi} \gamma^\mu \partial_\mu \vec{\pi} \cdot \vec{\tau} \Psi$$

A Closer Look at the Couplings

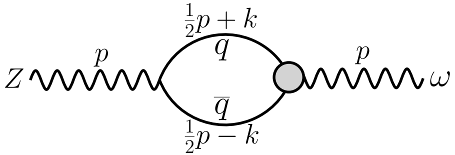


Find couplings phenomenologically

$\omega - \pi - \gamma$ vertex has the "anomaly" form but exists independent of anomaly!

"Dress" $\pi - N - N$ to account for form factors.

$\omega - Z$ Running Calculation



Parameterize $\omega - q\bar{q}$ coupling by $g_{\omega q\bar{q}} M^2/(M^2 - p^2)$

Extract $g_{\omega q\bar{q}} \approx 3.1$ from $\omega \rightarrow \pi^0\, \pi^+\, \pi^-$

1. Evaluate self energy $\Pi_{\mu\nu}$
2. Consider terms contributing to p^2 dependence
3. Drop logarithmic contributions

$$g_{\omega Z}(p^2) = \frac{-g g_{\omega q\bar{q}} M^2 s^2_{\theta W}}{12\pi^2 c_{\theta W}} \int_0^1 dz \int_0^{1-z} dx \frac{p^2 z(z-1) + m_q^2}{p^2 z(z-1) + m_q^2 + x(M^2 - m_q^2)}$$

Assuming $m_q \sim 3\,\mathrm{MeV}$ and $M \sim M_\omega$ at $E \sim 200 - 1000\,\mathrm{MeV}$

$\rightarrow \bar{g}_{\omega Z} \approx 600\,\mathrm{MeV}^2$

$\omega - \pi - \gamma$ Vertex

Use $\Gamma(\omega \to \pi + \gamma)$ from the phenomenological interaction

$$\mathcal{L}_{\mathcal{I}} = e g_{\omega\gamma\pi} \epsilon_{\mu\nu\xi\sigma} \omega^{\mu} \partial^{\nu} \pi^{0} F^{\xi\sigma}$$

Neglecting the π mass, the squared amplitude is

$$\mathcal{A}^2 = -\frac{2e^2 g^2_{\omega\gamma\pi}}{3} k \cdot q = \frac{e^2 g^2_{\omega\gamma\pi} M^4_{\omega}}{6},$$

which implies the decay width

$$\Gamma(\omega \to \pi + \gamma) = \frac{\alpha g^2_{\omega\gamma\pi} M^3_{\omega}}{24}.$$

Fitting to observed decay width yields $g_{\omega\gamma\pi} = 1.8/M_{\omega}$

Amplitude

$$\mathcal{A}^2 = \frac{128 M_n^2 g_{\nu Z}^2 g_{\omega\gamma\pi}^2 g_{\pi NN}^2 g_{\omega Z}^2(q^2)}{(q^2 - M_Z^2)^2 (q^2 - M_\omega^2)^2 (Q^2 - M_\pi^2)^2} \quad \text{Couplings \& Propagators}$$

$$\times \quad \ell_i \cdot \ell_f (p_i \cdot p_f - M_N^2) \left((k \cdot \ell_i)^2 + (k \cdot \ell_f)^2 \right) \quad \text{Kinematics}$$

From this, evaluate cross section in CM frame

- $\ell_i = (E_{\ell_i}, \vec{E}_{\ell_i})$, $\ell_f = (E_{\ell_f}, \vec{E}_{\ell_f})$ — Massless ν momentum
- $p_i = (E_{p_i}, -\vec{E}_{\ell_i})$, $p_f = (E_{p_f}, \vec{p}_{p_f})$ — Nucleon momentum
- $k = (E_k, \vec{E}_k)$ — Photon momentum

Write as a function of the invariant quantity

$$\sqrt{s} = E_{\ell_i} + E_{p_i}$$

Cross Section Formula

$$\frac{d\sigma}{dE_k d\mu} = \frac{M_N^2 g_{\nu Z}^2 g_{\omega\gamma\pi}^2 g_{\pi NN}^2}{(2\pi)^4 E_{\ell_i}(E_{\ell_i} + E_{p_i})} \int dE_{\ell_f} d\phi \frac{g_{\omega Z}^2(q^2) q^2 Q^2 \left((k \cdot \ell_i)^2 + (k \cdot \ell_f)^2\right)}{(q^2 - M_Z^2)^2 (q^2 - M_\omega^2)^2 (Q^2 - M_\pi)^2}$$

Where $q^2 = -2E_{\ell_i}E_{\ell_f}(1 - \mu_{\ell_f})$ and $Q^2 = q^2 - 2k \cdot \ell_i + 2k \cdot \ell_f$

$$\mu_{\ell_f} = \mu\mu_{\ell_f k} + \sqrt{1 - \mu^2}\sqrt{1 - \mu_{\ell_f k}^2} \cos\phi.$$

This is the only source of ϕ dependence in the system.

Momentum conservation then fixes

$$\mu_{\ell_f k} = \frac{1}{2E_{\ell_f}E_k}\left(\sqrt{s}^2 - 2\sqrt{s}(E_{\ell_f} + E_k) + 2E_k E_{\ell_f} - M_N^2\right).$$

Cross Section Formula (Continued)

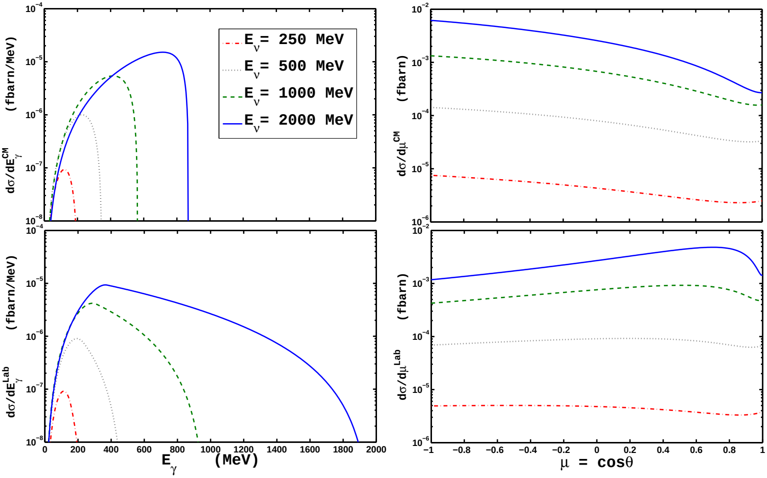
Evaluate in the limit $|q^2| \ll M_Z^2$, $|Q^2| \gg M_\pi^2$ and $g_{\omega Z}(q^2) \sim \bar{g}_{\omega Z}$
Integrating over ϕ

$$\begin{aligned} \frac{d\sigma}{dE_k d\mu} &= \frac{M_N^2 E_k^2 g_{\nu Z}^2 \bar{g}_{\omega Z}^2 g_{\omega\gamma\pi}^2 g_{\pi NN}^2}{(2\pi)^3 E_{\ell_i}(E_{\ell_i}+E_{p_i})M_Z^4} \int dE_{\ell_f} \left(E_{\ell_i}^2(1-\mu)^2 + E_{\ell_f}^2(1-\mu_{\ell_f k})^2\right) \\ &\times \frac{1}{f^2(b-c)^2}\left\{\frac{a-b}{(b^2-1)^{\frac{1}{2}}} + \frac{c^3-2ac^2+abc-b+a}{(c^2-1)^{\frac{3}{2}}}\right\}, \end{aligned}$$

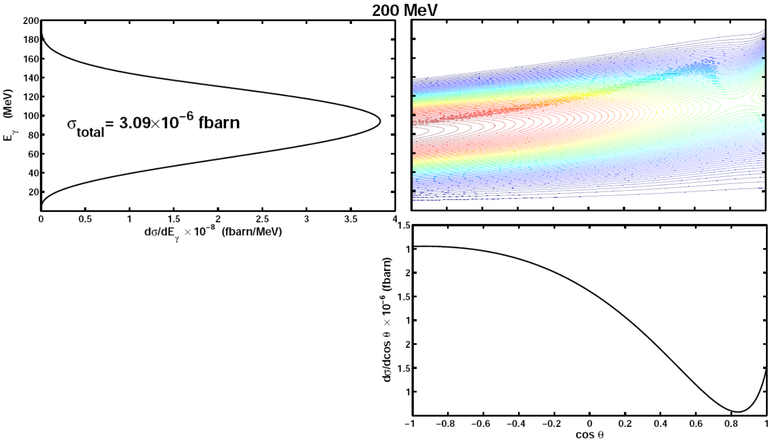
where

$$\begin{aligned} f &= 2E_{\ell_i}E_{\ell_f}\sqrt{1-\mu^2}\sqrt{1-\mu_{\ell_f k}^2} \\ a &= \frac{2E_{\ell_i}E_{\ell_f}(1-\mu\mu_{\ell_f k})}{f} \\ b &= \frac{2E_{\ell_i}E_{\ell_f}(1-\mu\mu_{\ell_f k}) + 2E_k E_{\ell_i}(1-\mu) - 2E_k E_{\ell_f}(1-\mu_{\ell_f k})}{f} \\ c &= \frac{2E_{\ell_i}E_{\ell_f}(1-\mu\mu_{\ell_f k}) + M_\omega^2}{f}. \end{aligned}$$

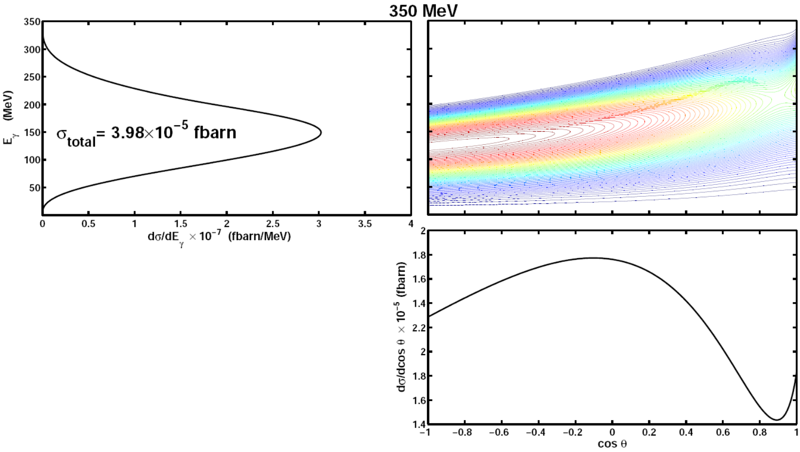
Results


E_ν = 250 MeV
E_ν = 500 MeV
E_ν = 1000 MeV
E_ν = 2000 MeV
dσ/dE_γ^CM (fbarn/MeV)
dσ/dE_γ^Lab (fbarn/MeV)
dσ/dμ^CM (fbarn)
dσ/dμ^Lab (fbarn)
E_γ (MeV)
μ = cosθ

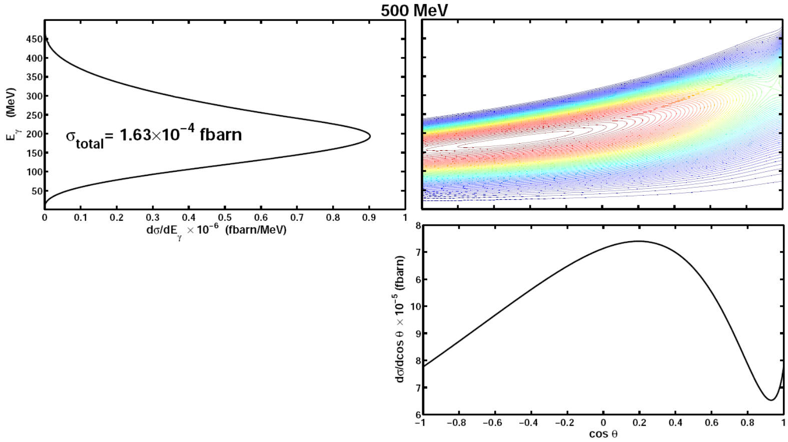
Differential Cross Section $E_\nu = 200$ MeV (ω case)



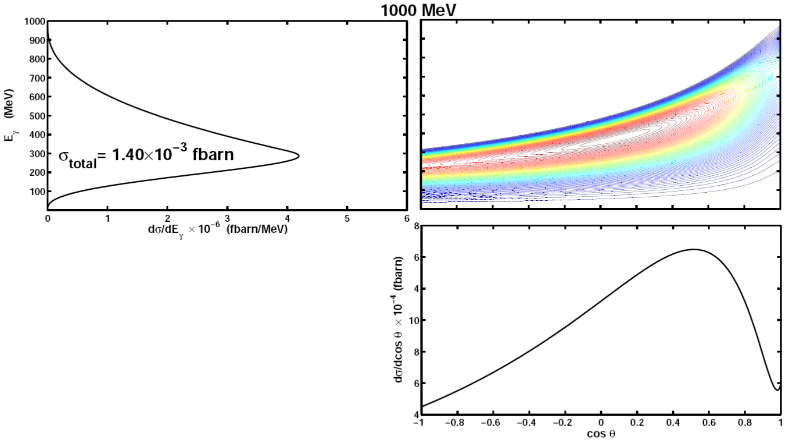
Differential Cross Section $E_\nu = 350$ MeV (ω case)



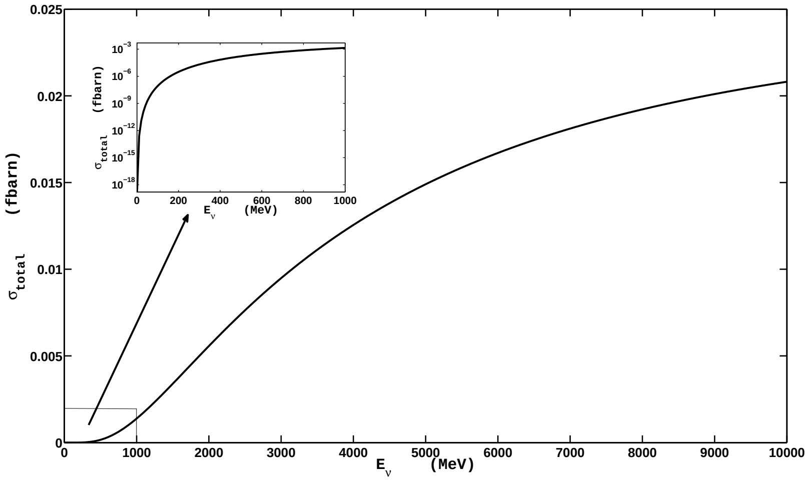
Differential Cross Section $E_\nu = 500$ MeV (ω case)



Differential Cross Section $E_\nu = 1000$ MeV (ω case)



Total Cross Section (ω case)



$\omega - \rho^0$ Diagram Interference

Dominant Effects

- $\omega(\rho) - \pi - \gamma$ vertex
  - $\frac{g_{\rho\gamma\pi}}{g_{\omega\gamma\pi}} = \frac{0.55 M_\omega}{1.8 M_\rho} = 0.31$
- $Z - \omega(\rho)$ mixing
  - Large isospin enhancement of $Z - \rho$ mixing relative to $Z - \omega$

$$\frac{g_{\rho Z}}{g_{\omega Z}} = \frac{g_{Zd\bar{d}} - g_{Zu\bar{u}}}{g_{Zd\bar{d}} + g_{Zu\bar{u}}} \times \frac{g_{\rho q\bar{q}}}{g_{\omega q\bar{q}}}$$

$$\sim 3 \frac{1 - 2s^2_{\theta W}}{2s^2_{\theta W}} \times \sqrt{\frac{\Gamma(\rho \to \pi\pi)}{\Gamma(\omega \to \pi\pi\pi)} \frac{\phi(\omega \to \pi\pi\pi)}{\phi(\rho \to \pi\pi)}} = 4.1$$

$$\sigma^\rho / \sigma^\omega \approx (g_{\rho-\gamma-\pi} / g_{\omega-\gamma-\pi})^2 \times (g_{\rho Z} / g_{\omega Z})^2 \approx 1.6$$

Amplitudes are similar $\to$ large interference

Total cross sections can be between $\{0.07, 5.1\}$ of σ_ω case!

Summary

I present a SM contribution to t-channel photon production in neutrino nucleon scattering.

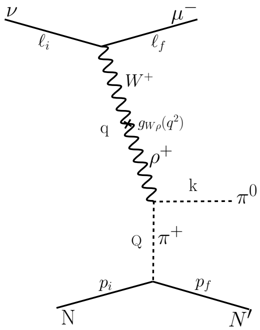
These rates can be large enough to affect current experiments but possess large interference uncertainties.

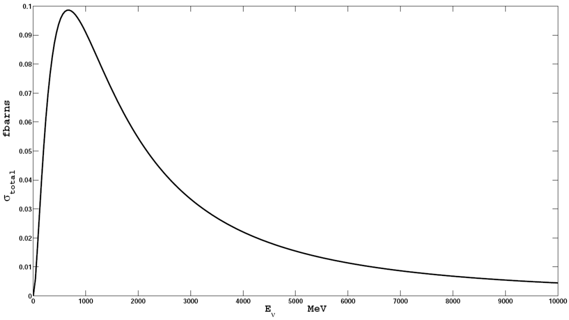
Further Results

- Same cross sections for ν and $\bar{\nu}$
- Vanishing diagram permutations
  - Replace ω with axial vector
  - Exchange ω and π_0
  - Invert exchange so that π_0 couples to neutrino

Measurements of photon (and even π_0) production can help shed light on this process.

Looking Forward to π^0 Production





$$\mathcal{A}^2 = -\frac{64 M_n^2 g_{\nu W}^2 g_{\rho\pi\pi}^2 g_{\pi NN}^2 g_{\rho W}^2(q^2)}{(q^2 - M_W^2)^2 (q^2 - M_\rho^2)^2 (Q^2 - M_\pi^2)^2} Q^2 \Big\{ \ell_i \cdot k \ell_f \cdot k - \frac{M_\pi^2}{2} \ell_i \cdot \ell_f \; \frac{M_\mu^2}{M_\rho^2 M_W^2} k \cdot q \left[\ell_i \cdot k (M_\rho^2 + M_W^2) - q^2 \ell_i \cdot k - \ell_i \cdot q k \cdot q \right]$$

$$+ \frac{M_\mu^2}{2 M_\rho^4 M_W^4} \ell_i \cdot \ell_f \left[(k \cdot q)^2 (M_\rho^4 + M_W^4) - 2 q^2 (k \cdot q)^2 (M_\rho^2 + M_W^2) + q^4 \right] \Big\}$$