Graduate Student Summer Talks

NC Pion Production

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Outline

- About pions
- Why are neutral pions important?
- Production types
  - Resonant
  - Coherent
  - Non-resonance background scattering
  - Nuclear final state interactions

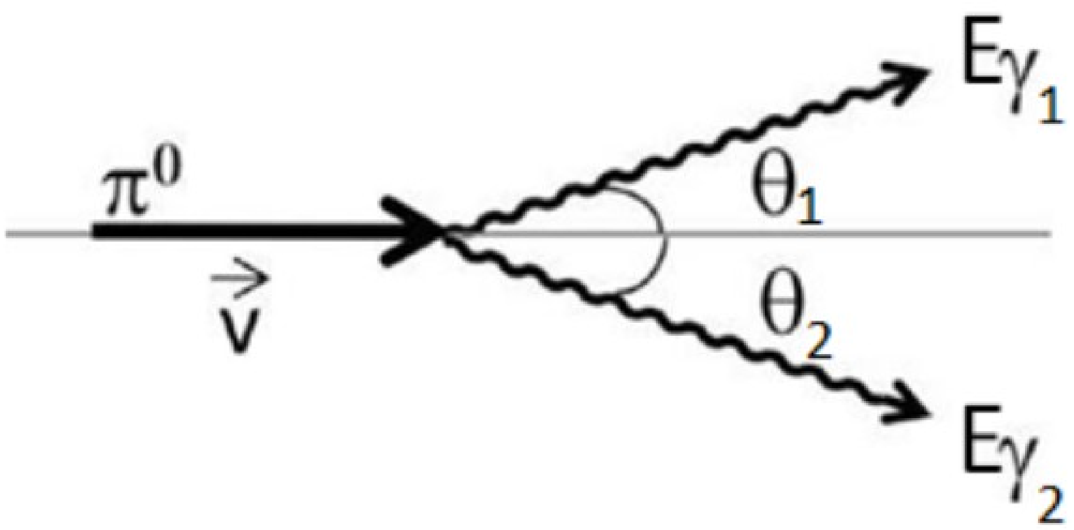
About Pions

- Lightest mesons predicted by Hideki Yukawa in 1935.
- 1947 Cosmic rays showed charged pions
- 1950 Confirmed netural pion at the cyclotron University of California
- Pions imposing an upper limit on the energies of cosmic rays surviving collisions with the CMB, through the Greisen–Zatsepin–Kuzmin limit.
- Pions are understood to be pseudo-Nambu-Goldstone bosons of spontaneously broken chiral symmetry.

Mesons	Charge	Mass	Quarks	Mean Lifetime	Isospin	Decays
π^+	+1e	$139.57\ MeV/c^2$	$u\bar{d}$	$2.6 \times 10^{-8}s$	$\|1,1\rangle$	$\mu^+ + \nu_\mu$, 99.9877%
π^-	-1e	$139.57\ MeV/c^2$	$d\bar{u}$	$2.6 \times 10^{-8}s$	$\|1,-1\rangle$	$\mu^- + \bar{\nu}_\mu$, 99.9877%
π^0	0	$134.98\ MeV/c^2$	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$8.4 \times 10^{-16}s$	$\|1,0\rangle$	$\gamma\gamma$, 98.798%

Neutral Pion Decay

- π^0 decays into 2 photons 98.8%
- Leading Dalitz decay is photon+electron-positron pair 1.2%

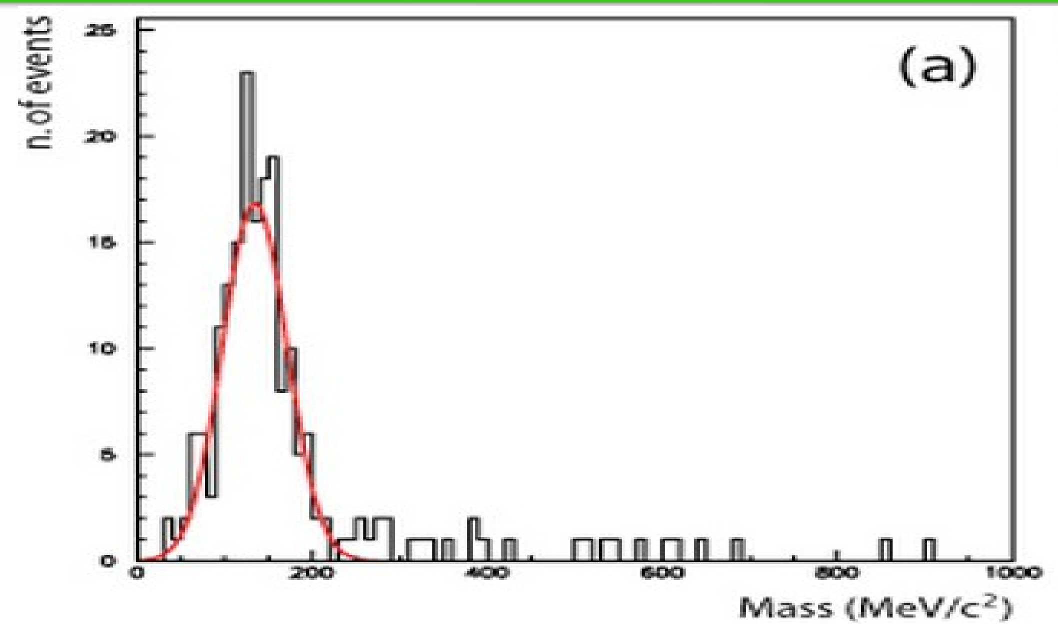


$$\mathcal{M}^2 = 4E_1E_2\sin\left(\frac{\alpha}{2}\right)$$

$$\alpha = \theta_1 + \theta_2$$

Why are π° important

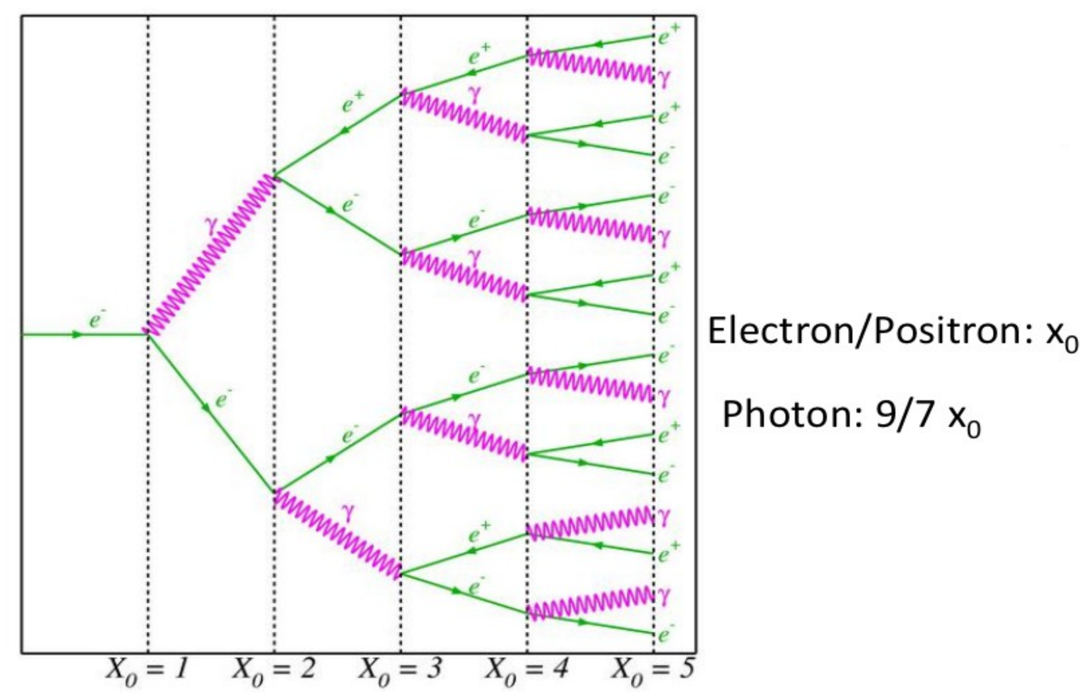
- Particle decay of a well known mass is good for energy calibration



- Main background for ν_e signal.

$$\nu_e + n = e + p$$

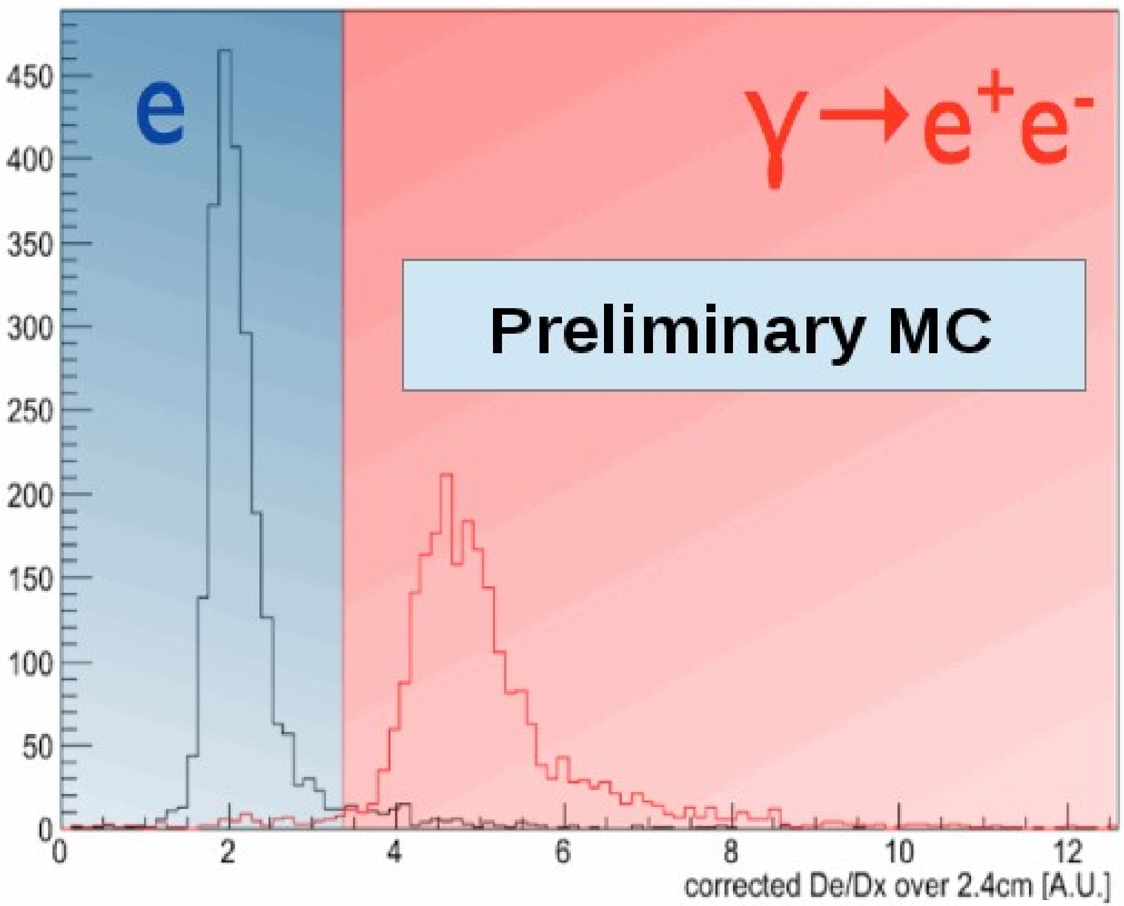
$$\nu + X = \nu + \pi^0 + X$$



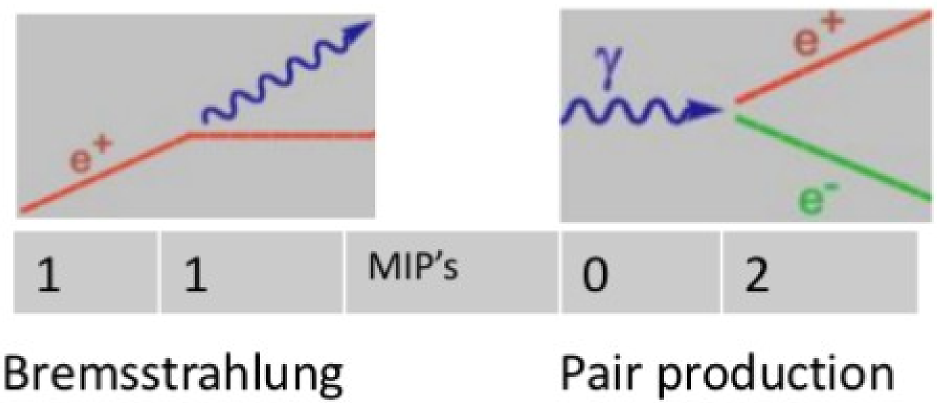
π° with MicroBOOnE

Electron/Photon Separation

Look at dE/dx of first part of the shower. Since a γ shower starts with an electron-positron pair the energy loss will be twice as large.

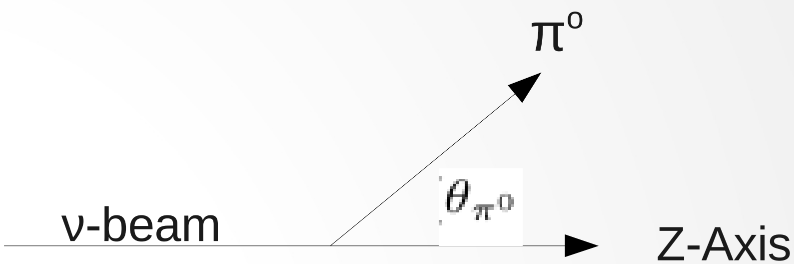


*A. Szelc

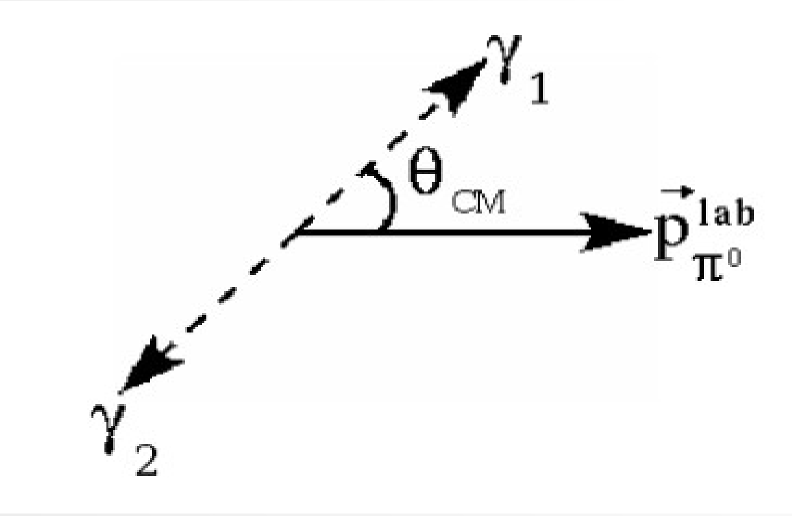


Important Kinematic Variables

- Mass of π^0 ~135MeV(rest)
- Momentum of π^0
- Angle of the π^0 relative to neutrino beam
- Center of mass angle



$$\cos(\theta_{\pi^0}) = \frac{p_{z,\gamma 1} + p_{z,\gamma 2}}{|\vec{p}_{\pi^0}|}$$

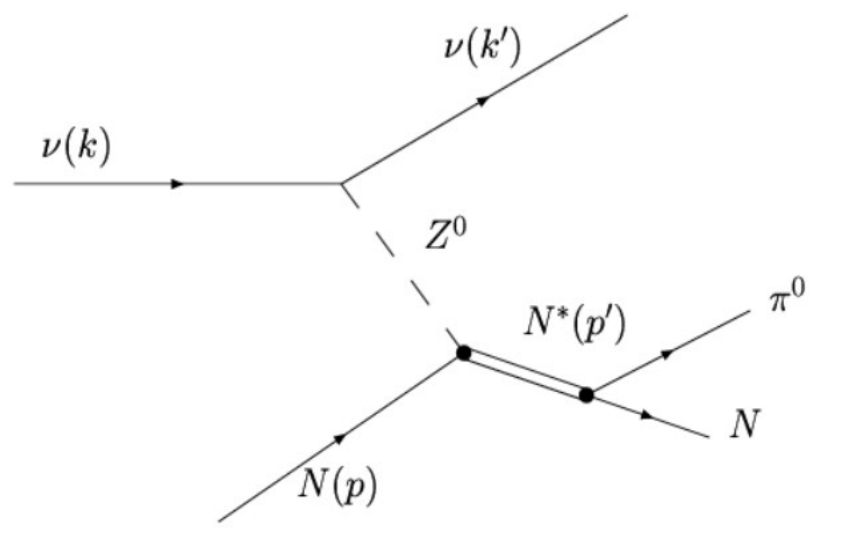


$$\cos(\theta_{CM}) = \frac{E_{\pi^0}}{|\vec{p}_{\pi^0}|} \frac{|E_{\gamma 1} - E_{\gamma 2}|}{E_{\gamma 1} + E_{\gamma 2}}$$

More useful variables ?

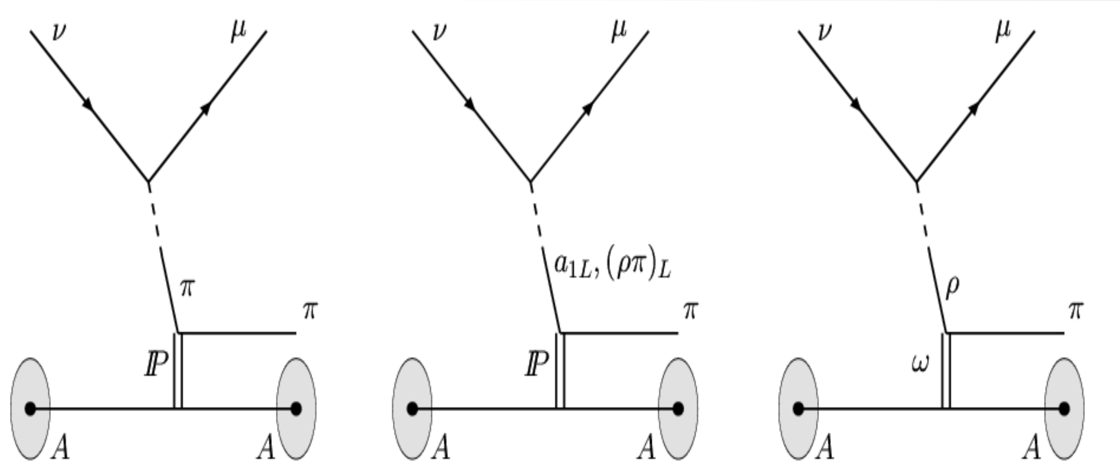
Types of Pion production

Resonant



- Dominant mode
- Rein & Seghal

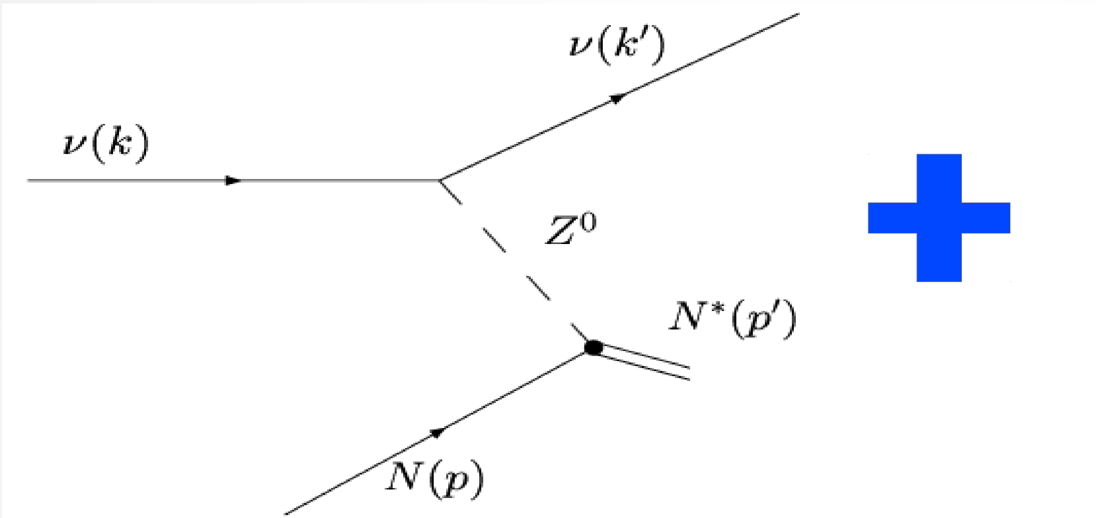
Coherent



- No so dominant
- Many models

* Z^o IVB can also be W± → $\pi^{\pm}$

Resonant Production



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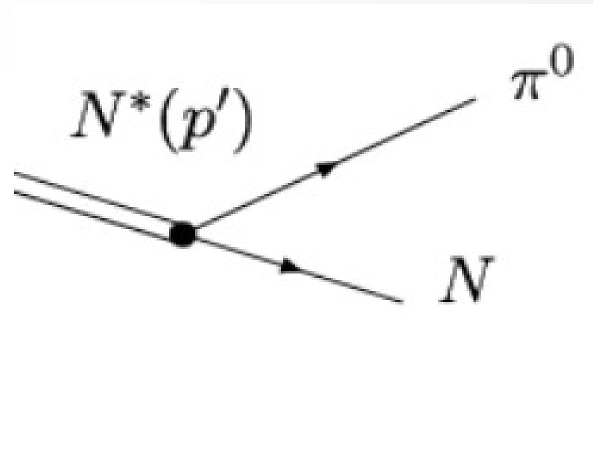


Two step process

$$\mathcal{M}(\nu + N \to \nu + N^*)$$

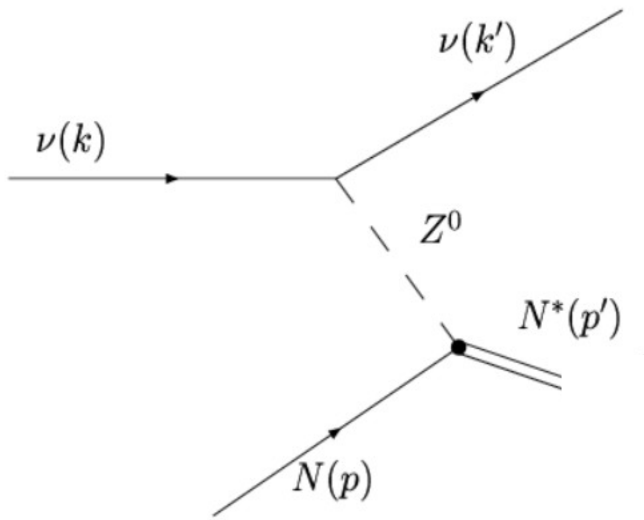
+

$$\mathcal{M}(N^* \to \pi^0 + N)$$

$$\mathcal{M}(\nu + N \to \nu + \pi^0 + N)$$

Resonant Production

$$\mathcal{M}(\nu N \to \nu N^*) = \frac{g_z}{\sqrt{2}} j_l^\mu j_\mu^N$$



Leptonic current

$$j_l^\mu = \bar{u}_\nu(k')\gamma^\mu(1-\gamma^5)u_\nu(k)$$

$$\mathcal{M} = \frac{g_z}{\sqrt{2}}[\bar{u}_\nu(k')\gamma^\mu(1-\gamma^5)u_\nu(k)] < N^*|2m_{N^*}F_\mu^N|N >$$

N-N* current (not known)

$$j_\mu^N = 2m_{N^*}F_\mu^N$$

$$^* \; g_z = \frac{g_w}{\cos(\theta_w)} = \frac{g_e}{\sin(\theta_w)\cos(\theta_w)}$$

Resonant Production

Coupling Z to N

– Z has 3 polarizations

→ Expand in polarization basis

$$j_l^\mu = \bar{u}_\nu(k')\gamma^\mu(1-\gamma^5)u_\nu(k) = 2\sqrt{2}E\sqrt{\frac{-q^2}{Q^2}}[u \cdot e_l^\mu - v \cdot e_R^\mu + \sqrt{2uv} \cdot e_s^\mu]$$

Combine terms

$$u = (E_\nu + E'_\nu + Q)/(2E_\nu)$$

$$v = (E_\nu + E'_\nu - Q)/(2E_\nu)$$

Resonant Production

A clean matrix element

$$\mathcal{M}(\nu N \to \nu N^*) = -4 m_{N^*} E_\nu \left(\sqrt{\tfrac{-q^2}{Q^2}} \langle N^* | u e^\mu_L F_\mu - v e^\mu_R F_\mu | N \rangle + \tfrac{m_N}{m_{N^*}} \sqrt{2uv} \sqrt{\tfrac{-q^2}{Q*^2}} \langle N^* | e^\mu_s F_\mu | N \rangle \right)$$

$$\mathcal{M}(\nu N \to \nu N^*) = -4 m_{N^*} E_\nu \left(\sqrt{\tfrac{-q^2}{Q^2}} \langle N^* | u F_- - v F_+ | N \rangle + \tfrac{m_N}{m_{N^*}} \sqrt{2uv} \langle N^* | F_0 | N \rangle \right)$$

$$F_+ = e^\mu_R F_\mu$$

$$F_- = e^\mu_L F_\mu$$

$$F_0 = \sqrt{\frac{-q^2}{Q*^2}} e^\mu_s F_\mu$$

- Calculate production cross sections

$$\frac{d\sigma}{dq^2\, d\nu} = \frac{1}{32\pi m_N E_\nu^2} \cdot \frac{1}{2} \sum_{\text{spins}} |\mathcal{M}(\nu N \to \nu N^*)|^2 \frac{1}{2\pi} \cdot \frac{\Gamma}{(W - m_{N^*})^2 + \Gamma^2/4}$$

Resonant Production

Production cross sections for each polarization

$$\sigma_L(q^2, W) = \frac{\pi}{k}\frac{m_{N*}}{m_N}\frac{1}{2}\sum_{J_z} |\langle N, j_z - 1|F_-|N*, j_z\rangle|^2 \cdot \delta(W - m_{N*})$$

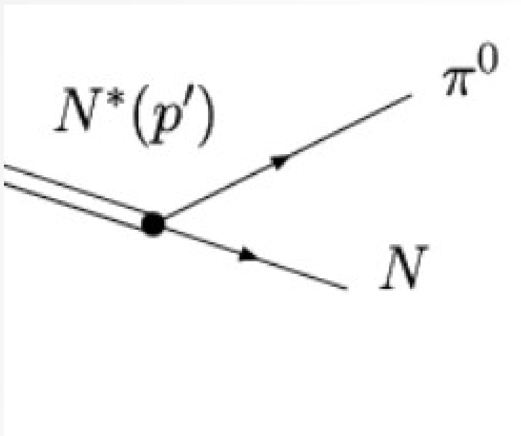
$$\sigma_R(q^2, W) = \frac{\pi}{k}\frac{m_{N*}}{m_N}\frac{1}{2}\sum_{J_z} |\langle N, j_z + 1|F_+|N*, j_z\rangle|^2 \cdot \delta(W - m_{N*})$$

$$\sigma_S(q^2, W) = \frac{\pi}{k}\sqrt{\frac{Q^2}{-q^2}\frac{m_N^2}{m_{N*}^2}}\frac{1}{2}\sum_{J_z} |\langle N, j_z|F_o|N*, j_z\rangle|^2 \cdot \delta(W - m_{N*})$$

Convert narrow width to resonances of finite width by replacing the δ-function in the partial cross sections by a Breit-Wigner factor.

$$\delta(W - m_{N*}) = \frac{1}{2\pi} \cdot \frac{\Gamma}{(W - m_{N*})^2 + \Gamma^2/4}$$

Resonant Production

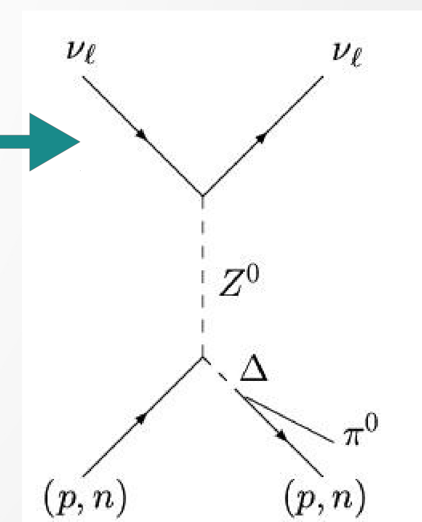


Isospin → Possible N* states

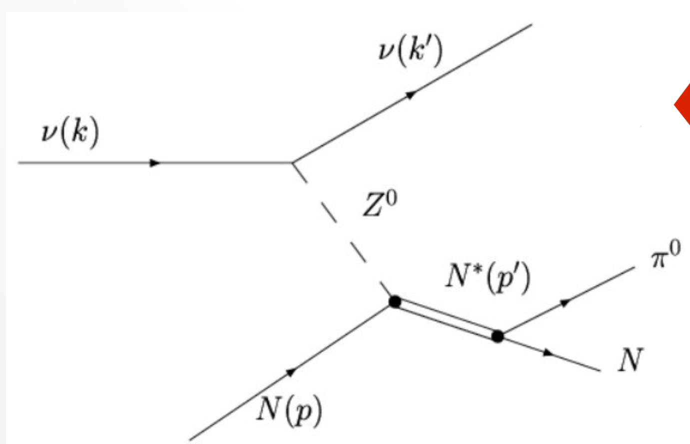
N $\qquad$ π^0 $\qquad$ N*

$$\left|\tfrac{1}{2},\tfrac{1}{2}\right\rangle \oplus \left|1,0\right\rangle = \left|\tfrac{3}{2},\tfrac{1}{2}\right\rangle, \left|\tfrac{1}{2},\tfrac{1}{2}\right\rangle$$

- This constrains the possible states that the N* could have been
- For neutral current channels the Δ(1232) is the dominant resonance



- There are 12 resonances that must be considered



Coherent Production

Coherent production: neutrino interacts with an entire nucleus rather than and individual nucleon.

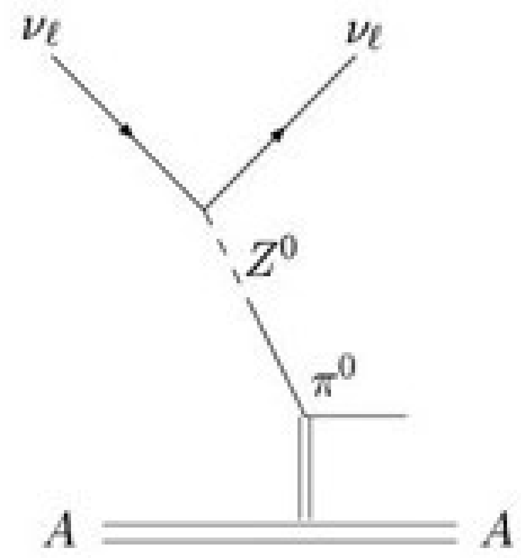
<u>Coherence conditions</u>

- Momentum transfer to any nucleon must be small enough to not break up the nucleus
- No transfer of charge, or any quantum numbers to the nucleus

Lots of different theories not sure which ones are the best?

Coherent Production

What's going on?



- Not really sure...

Coherent Production

A few things that are in common

All models follow the coherence conditions

<u>Getting Started:</u>

- View the weak current as a superposition of virtual hadron states
- Virtual states fluctuate to real states for periods o time on the order of the "coherence" length

$$l_c c = \Delta t_c \simeq \frac{2\nu}{Q^2 + m^2}$$

- If coherence length is of the order of the target nucleus then the weak current will behave like a hadron current.

Coherent Production

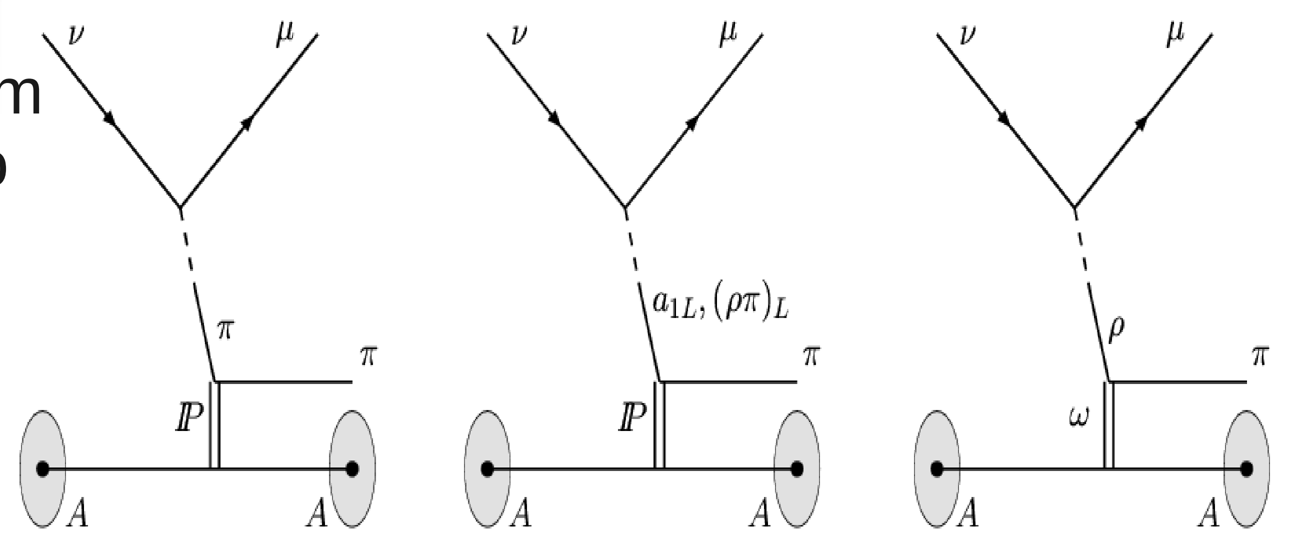
Adler's Theorem:

Relates the neutrino scattering cross section to the pion scattering cross section at $Q^2=0$

- At $Q^2=0$ the cross section is entirely due to the axial current and not the vector current.

Coherent Production

Modify the VMD model from photons/mesons/hadron to weak/mesons/hadron



View the Z as a superposition of virtual mesons

-If the “interaction” completes faster than the time of virtual state then state will be a real meson

Vector Current: ρ meson

Axial Current: π and a1 mesons

Coherent Production

VMD for γ+α→β

*Photons

$$\mathcal{A}(\gamma + \alpha \to \beta) = \sum_{V=\rho^0,\omega,\phi} \frac{e}{g_V} \frac{m_V^2}{Q^2 + m_V^2} \mathcal{A}(V + \alpha \to \beta)$$

A cross section is obtained by assuming a1 as dominant meson.

$$\frac{d^2\sigma(\nu\mathcal{A} \to \nu\pi\mathcal{A})}{dx dy} = \frac{G^2}{2\pi^2} f_\pi^2 m_N E_\nu (1-y) \left(\frac{m_A^2}{Q^2 + m_A^2}\right)^2 \sigma(\pi\mathcal{A} \to \pi\mathcal{A}).$$

Theories diverge! There are different ways to approximate the pion-nucleus scattering cross section.

$$x = \frac{Q^2}{2m_N\nu}$$

$$y = \frac{\nu}{E_\nu}.$$

MicroBooNE To The Rescue

- MicroBooNE is well suited to find and analyze π^0's
- Provide a good high statistics analysis of NC-resonant and NC-coherent pion production
- Make some theorists happy!