Pions in Neutrino Oscillations

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Neutrino Oscillations

"Strange" experimental results in the 80's and 90's: → Neutrino mass, interaction eigenstates **do not coincide**!
Can be connected through a "rotation matrix"

Usual phenomenological representation: PMNS Matrix: $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

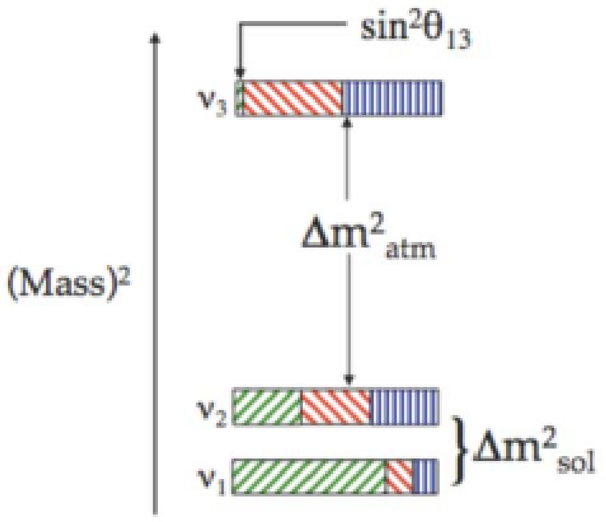
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"Atmospheric" "Interference" "Solar" "Majorana"

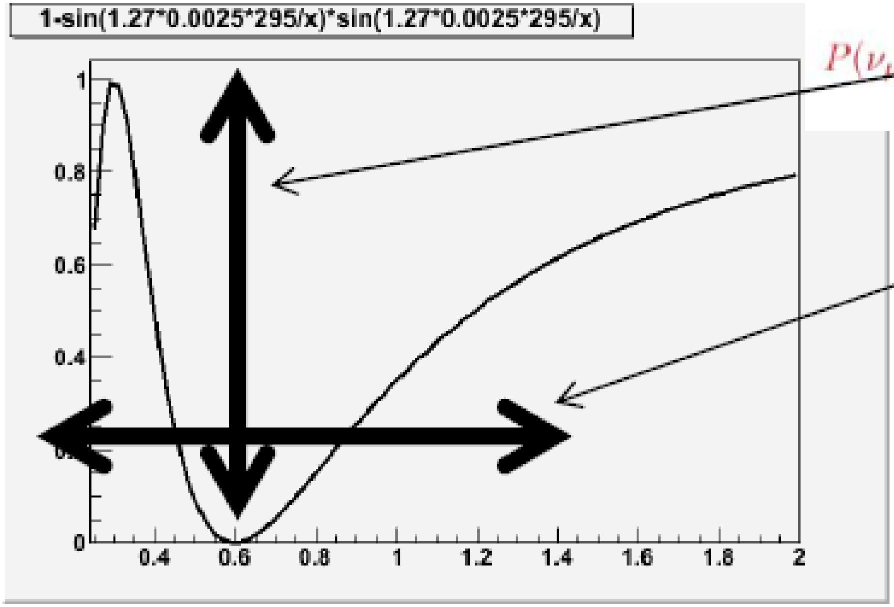
Experimental signature:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(1.27\Delta m^2_{\rm atm}({\rm eV}^2)\frac{L({\rm km})}{E({\rm GeV})}\right)$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m^2_{\rm atm}({\rm eV}^2)\frac{L({\rm km})}{E({\rm GeV})}\right)$$

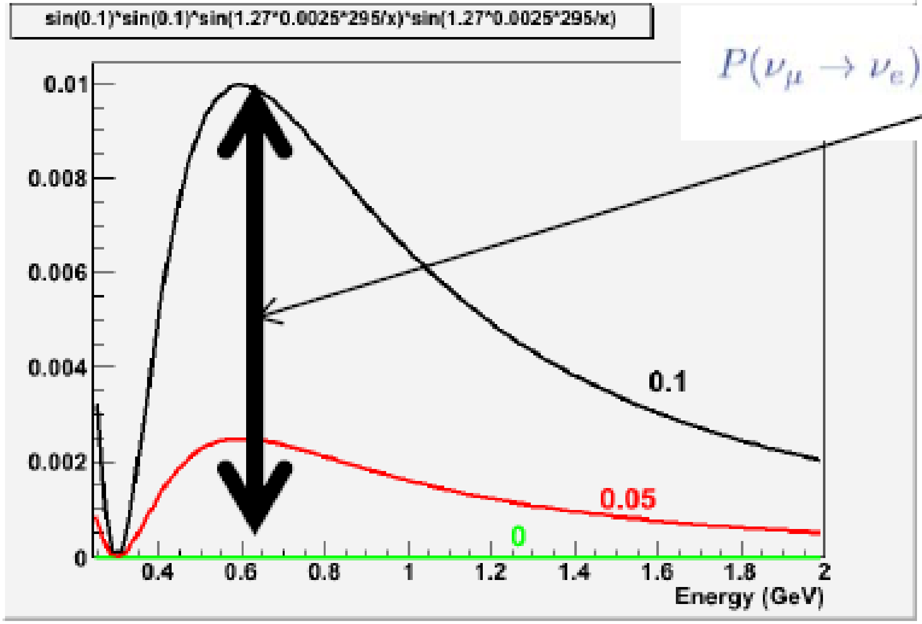


Practical Oscillations



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(1.27 \Delta m^2_{atm} (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

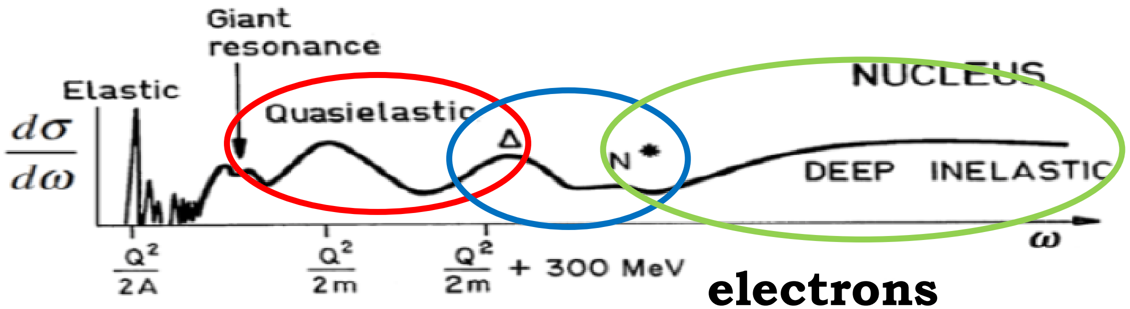
- For the ν_μ measurement, expect missing events
- Measure parameters by position, depth of 'dip'



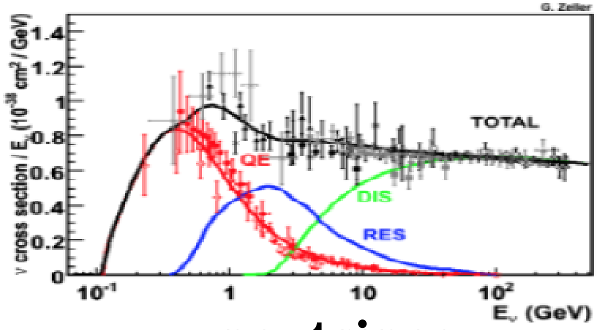
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(1.27 \Delta m^2_{atm} (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

- For the ν_e measurement, expect more events than expected!
- Measure parameters by extra number of events

Neutrino Interactions



electrons



neutrinos

Three (intersecting) interaction regions:
- Quasielastic (QE)
- Resonance creation (RES)
- Deep Inelastic Scattering (DIS)

Two ways to calculate the energy, from the visible products:
- Muon Energy + Calorimetry

$$E_\nu = E_{leptonic} + E_{hadronic}$$

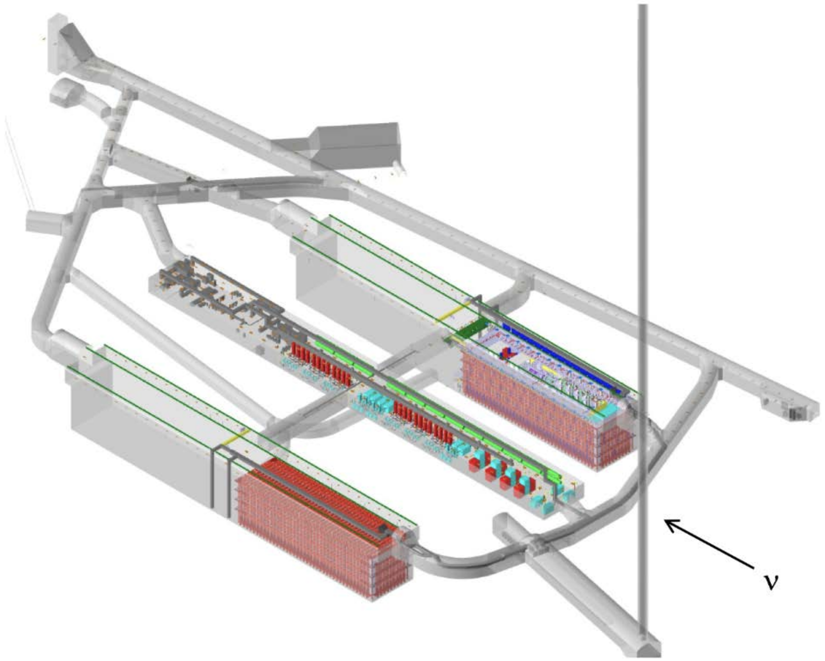
e.g. MINOS: magnetized iron calorimeter

- Muon momentum and angle

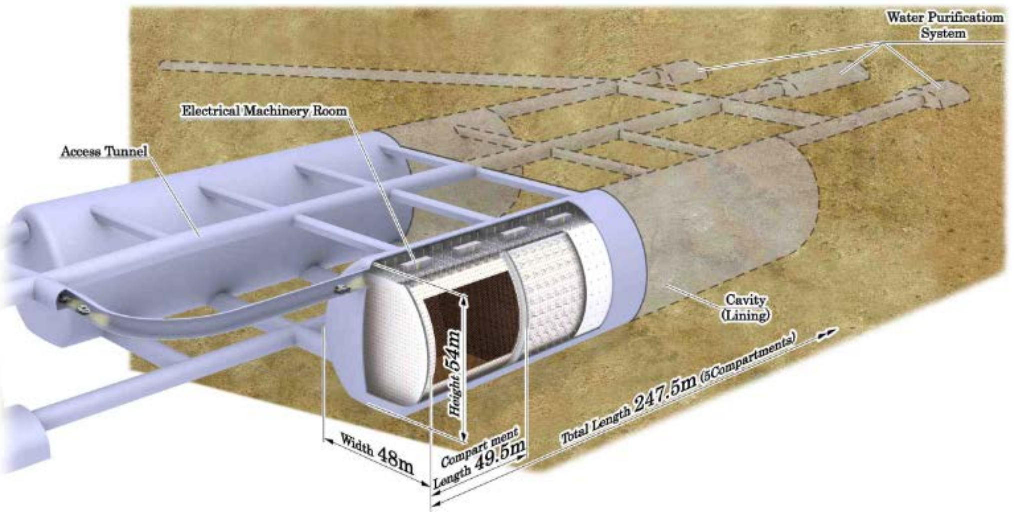
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\ell^2 + 2(m_n - E_b)E_\ell}{2(m_n - E_b - E_\ell + p_\ell cos\theta_\ell)}$$

e.g. T2K: water Cerenkov

Future Oscillation Experiments



DUNE: Liquid-Argon TPC



Hyper-Kamiokande: Water Cerenkov

Same ways to calculate the energy, from the visible products:

- Muon Energy + Calorimetry
- Muon momentum and angle

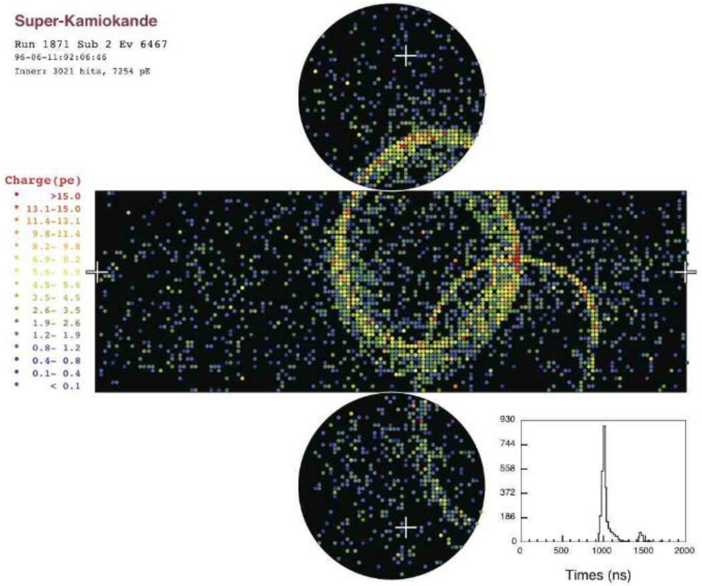
The Problem: Pions in Neutrino Interactions

1. Misidentified or non-identified pions: The interaction is selected as QEL→ The energy is wrongly reconstructed. This can happen due to
- Detector effects (short pion tracks; Cerenkov threshold,…)
- Final State Interactions (pions mutate in nucleus or get absorbed)

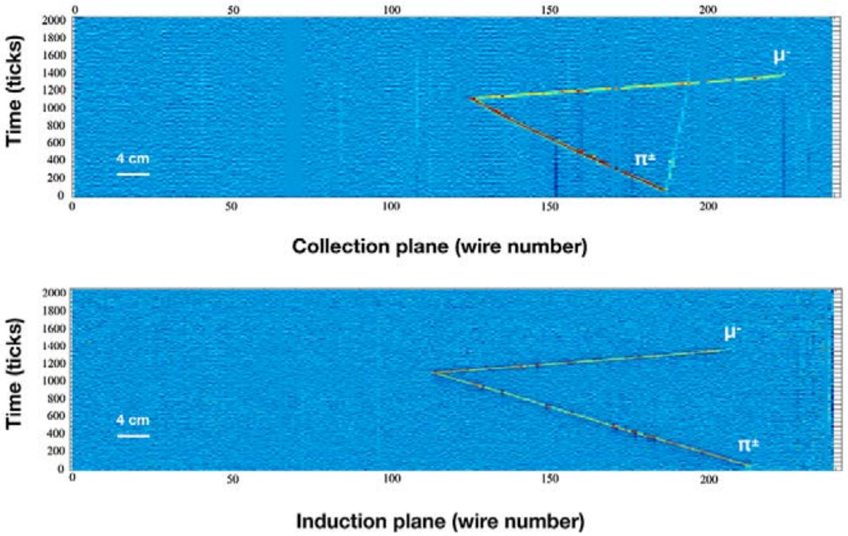
2. Large fraction of interactions are in the Single Pion Production region (unused statistics?)

3. Neutral pions identified as electrons: Important background in electron neutrino appearance studies

4. Pion multiplicity in higher-energy interactions (“Shallow Inelastic Scattering - SIS”) give indications of wrong modelling



Two-track neutrino event in SK
Abe et al, arxiv.org/1109.3262



Two-track neutrino event in LArTPC
Acciari et al, 10.1103/PhysRevD.98.052002

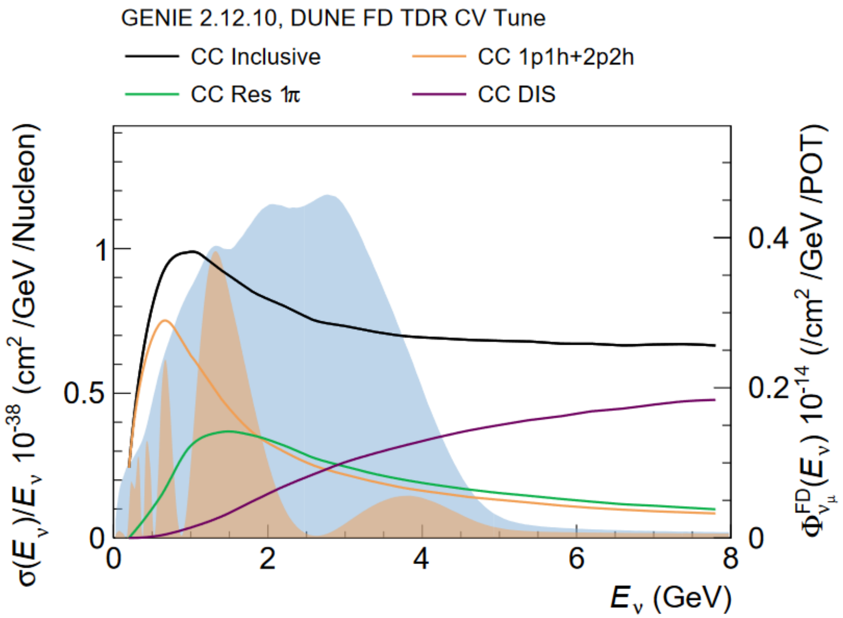
The Solution I: *using* the pion poduction

- The energy, under the hypothesis of SPP interaction, can be reconstructed in a way similar to the QEL case (measuring *both* tracks' parameters:

$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2\left(E_\mu + E_\pi - |\mathbf{p}_\mu|\cos\theta_{\nu,\mu} - |\mathbf{p}_\pi|\cos\theta_{\nu,\pi} - m_N\right)}$$

- Include these interactions in the oscillation analysis, probably doing a *multi-resolution* analysis, to increase the statistics.

- It is not clear if the extra systematic errors improve or not the overall analysis



Up to ***one-third*** of interactions in the oscillation maximum are SPP…
DUNE TDR

The Solution II: improved and pluralistic modelling

- Multitude of neutrino event generators for neutrino interaction Monte-Carlo studies:
GENIE, GiBUU, NEUT, NuWro,…

- Differing outputs, but also differing models *and (sometimes) opaque* fine-tuning

- Some newer theory/phenomenology models not yet included

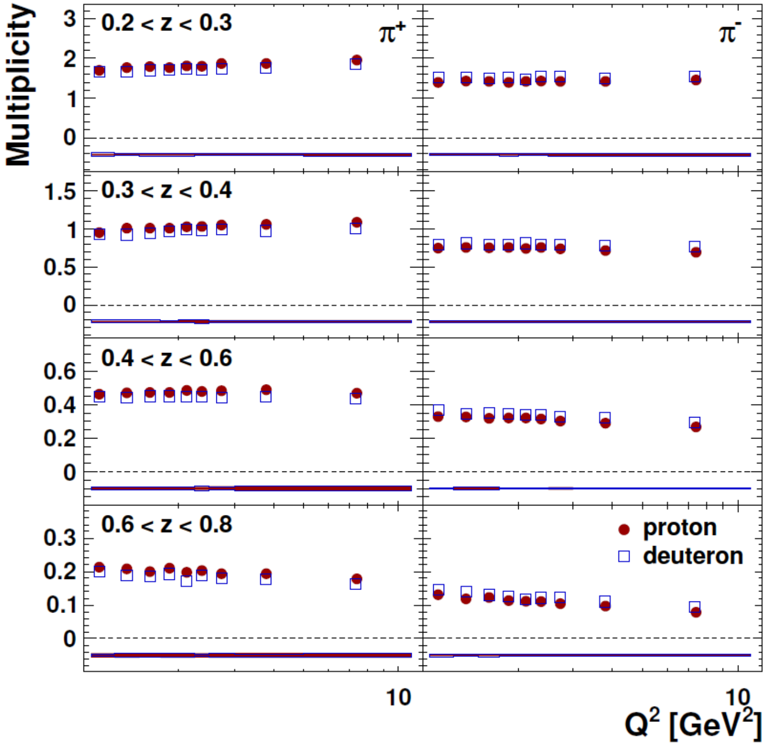
- Generators should all allow the ability to run in “eA” mode (electron neutrino interactions)

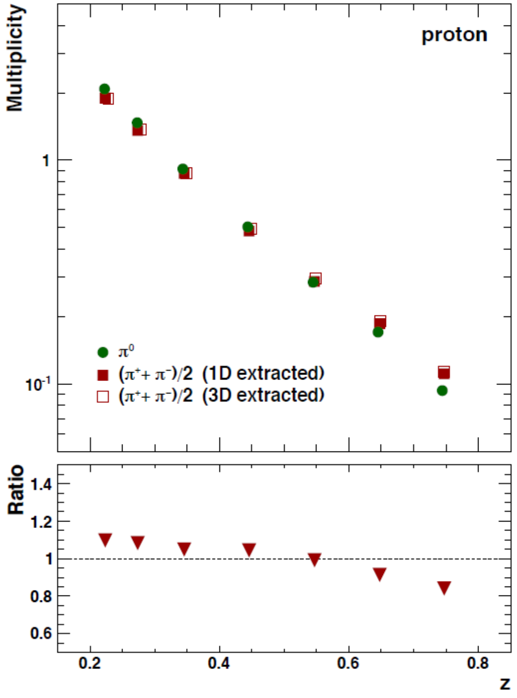
- Include SPP and SIS in the eA modelling and comparison to available data

The Solution III: electron mesoproduction data

- Important work already done by e.g. the “e4nu” collaboration: Mainly in QEL region
- Lots of data of ep, ed interactions from HERMES in highly-usable form:

- Differential π, K multiplicities
- π_0 multiplicities





- Need to organize all this and compae to neutrino generators in “e-mode”
- Data from heavier nuclei (most important for neutrino experiments)→ intensive data-taking in e.g. CLAS

The Solution IV: new types of data

- Charged-current single-pion production neutrino interactions: Only specific combinations allowed

Muon neutrino: μ-π+

Muon antineutrino: μ+π-

- Detectors that include magnetic fields (e.g. Hyper-K near detector, *some* DUNE near detector(?)) can look for and quantify the wrong charge combinations

- These can only be induced by re-interactions of pions inside the nucleus

→ Another powerful handle on controlling the Final State Interactions

Conclusion: Pion Perspectives

- Improvements in modelling

- Use of available data

- Use of *all* future data in the best possible way

Will convert the pions from problems to solutions, in neutrino oscillation physics!

Thank You!