Why Neutrino Interactions Matter

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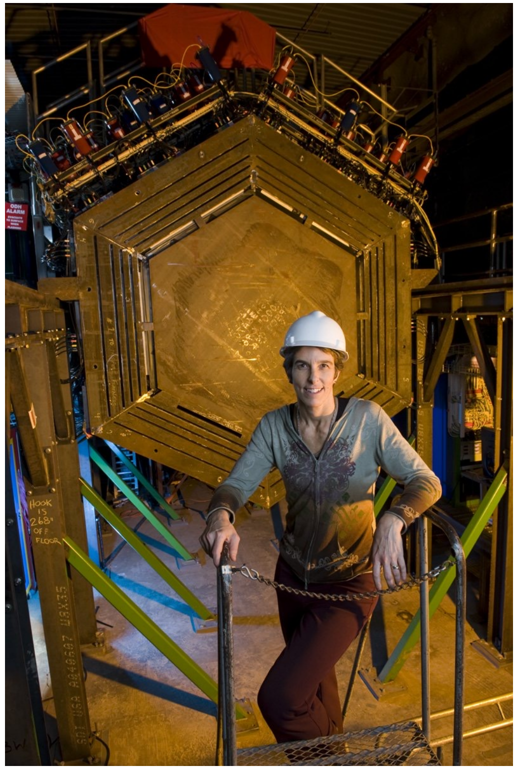
NuSTEC School and Workshop

Who am I?

- This is the end of my fifth year as a prof at York U., with a joint appointment with Fermilab.
- Before that, I worked 20 years as a Scientist at Fermilab
- Before that, I was a postdoc for U of Rochester, also doing a neutrino experiment at Fermilab
- Before that, I was a grad student at U of Chicago, working on a Kaon Experiment at Fermilab
- Have seen different aspects of particle physics:
  - Graduate thesis looking for CP-violation in rare Kaon decays
  - Spent postdoc years studying weak interactions with high energy (~100GeV) neutrinos
  - Started working on neutrino oscillations (~GeV neutrinos)
    - Initially worked on neutrino beam designed for MINOS
    - Started worrying about neutrino interactions-enter MINERvA!
    - Collaborator on T2K & DUNE, Co-spokesperson of MINERvA



Top ten reasons to study* Neutrino Interactions

1. To understand the weak interaction
2. To understand the structure of the nucleus
3. There is lots of non-perturbative QCD here, keeps Lattice QCD folks busy
4. To improve precision in neutrino oscillation experiments
5. You can’t find Beyond the Standard Model Physics until you account for the standard model neutrino interactions!
6. We need to predict the backgrounds to your dark matter experiment
7. For measurement: You get to be involved with all the parts of an analysis
8. Your work will get used by lots of other experiments

Reason 9: it makes an awesome thesis topic!

- Even if you ARE on an oscillation experiment, there's some chance your thesis will be a neutrino cross section measurement
- NOvA: https://novaexperiment.fnal.gov/theses/
  - 13 out of 63 Doctoral Theses were on cross sections
- T2K: https://t2k.org/docs/thesis
  - 57 out of 138 PhD+Masters theses have been on cross sections!

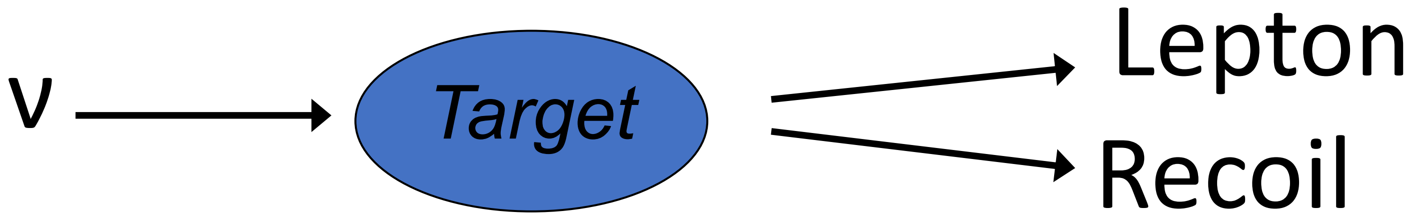
As of August 12, 2023

	Dates	Source	Primary Energy (GeV)	P [kW]	M [kt]	L [km]	E [GeV]
K2K	1999 - 2004	KEK PS	12	5.2	22.5	250	0.9
T2K	2010 - present	JPARC	30	515	22.5	295	0.6
T2HK	2027	JPARC	30	[500,1 300]	188	295	0.6
MINOS	2005 - 2012	Fermilab Main Injector	120	240	5.4	735	3.6
MINOS+	2013 - 2016	Fermilab Main Injector	120	700	5.4	735	6.2
NOvA	2014- present	Fermilab Main Injector	120	400 - 960	14	810	1.8
DUNE	>2030	Fermilab Main Injector	120	1000 - 2400	40	1350	2.2
CNGS / OPERA	2008 - 2012	CERN PS	400	512	1.25	730	1.25

From Mark Messier, INSS23

Reason 10: to learn more about neutrinos

- *Quick wakeup question: what can we learn about neutrinos WITHOUT seeing them interact?*
- Creation of that final state may require energy to be transferred from the neutrino



  - In charged-current reactions, where the final state lepton is charged, this lepton has mass
  - The recoil may be a higher mass object than the initial state, or it may be in an excited state

K. McFarland, INSS 2013

Outline

- Neutrino Oscillations
  - Why Cross Sections Matter for Signal Processes
  - Why Cross Sections Matter for Backgrounds
- Beyond the Standard Model Searches
  - Dark Photon Searches
  - Neutral Heavy Lepton Searches
  - Proton Decay Searches

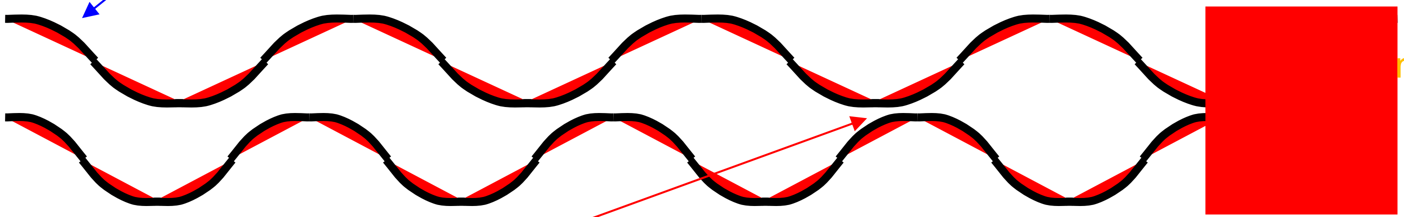
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos\pi/4\,|\nu_i\rangle + \sin\pi/4\,|\nu_j\rangle$$



different mass states alter time evolution

time →

$$|\nu_\beta\rangle = -\sin\pi/4\,|\nu_i\rangle + \cos\pi/4\,|\nu_j\rangle$$

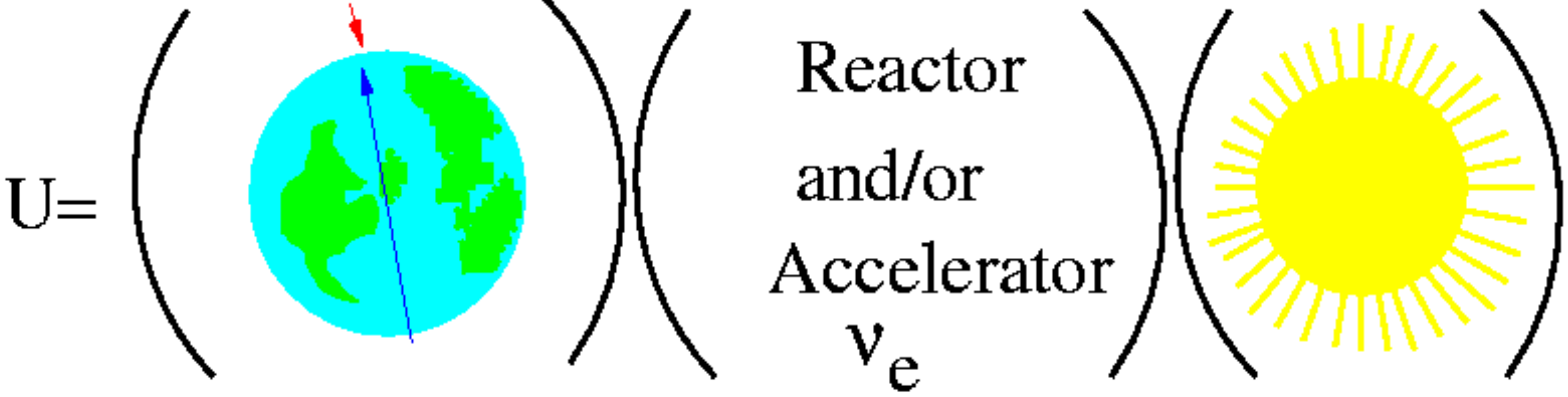
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

3-Generation Neutrino Oscillation Mixing

Unitary matrix defined by 3 mixing angles and a phase

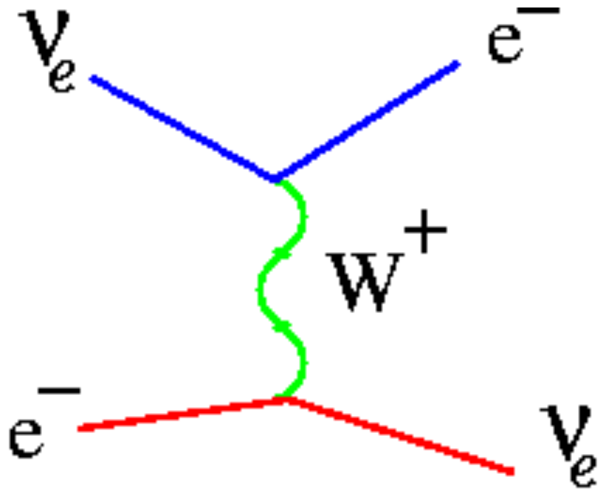
Call angles $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ denote $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

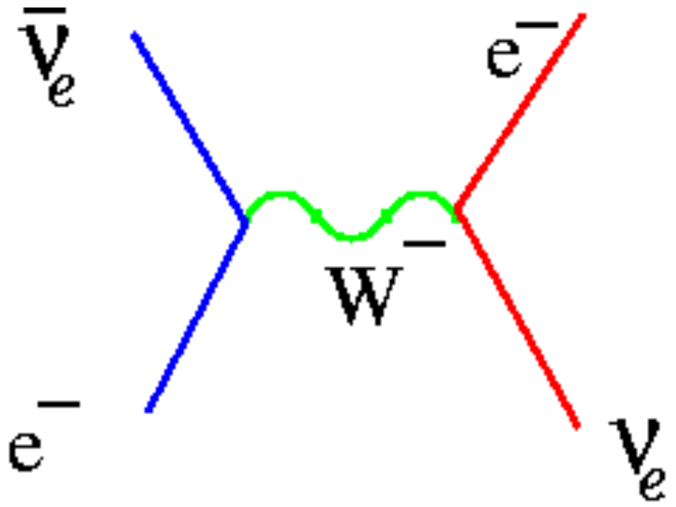
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Good News and Bad News: Matter Effects

- The oscillation probability changes differently for electron neutrinos vs antineutrinos when they propagate through matter:





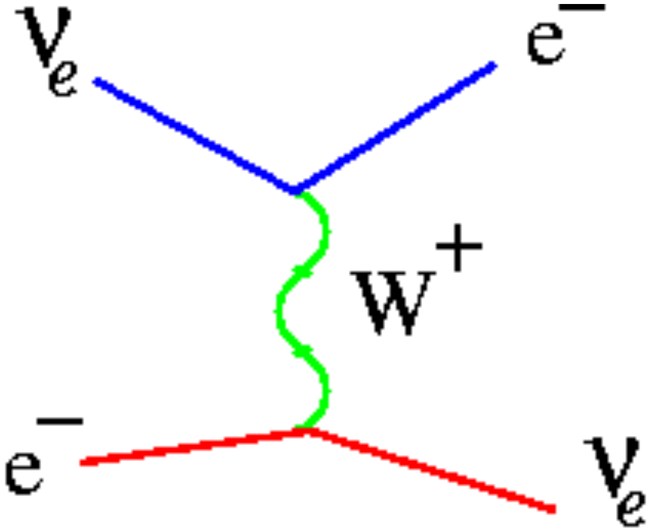
Wolfenstein, PRD (1978)

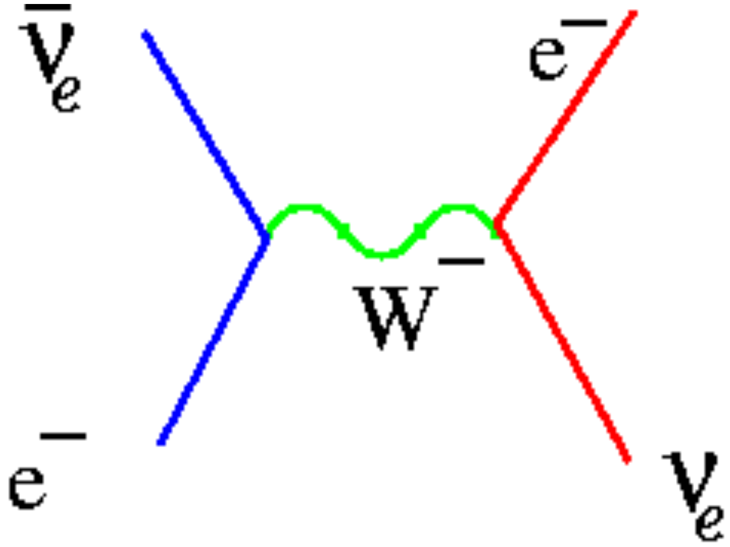
  - Can’t treat neutrinos propagating through earth simply as mass eigenstates, have to take into account electron flavor
  - This would give an apparent CP violation just because the earth is not CP-symmetric

Additional Complication: Matter Effects, with math…

- Remember the 2-generation formula?

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$





Wolfenstein,
PRD (1978)

$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e$^-$ density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2} \qquad L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

ν Oscillation Probabilities

- ν_μ Disappearance: $1-\sin^2 2\theta_{23}\sin^2(\Delta m^2_{32}L/4E)$
- ν_e Disappearance:

$$P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1-\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{31}L/4E\right)-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta m^2_{21}L/4E\right)$$

- ν_e appearance in a ν_μ beam: even more complicated…
- $P(\nu_\mu\rightarrow\nu_e)=P_1+P_2+P_3+P_4$

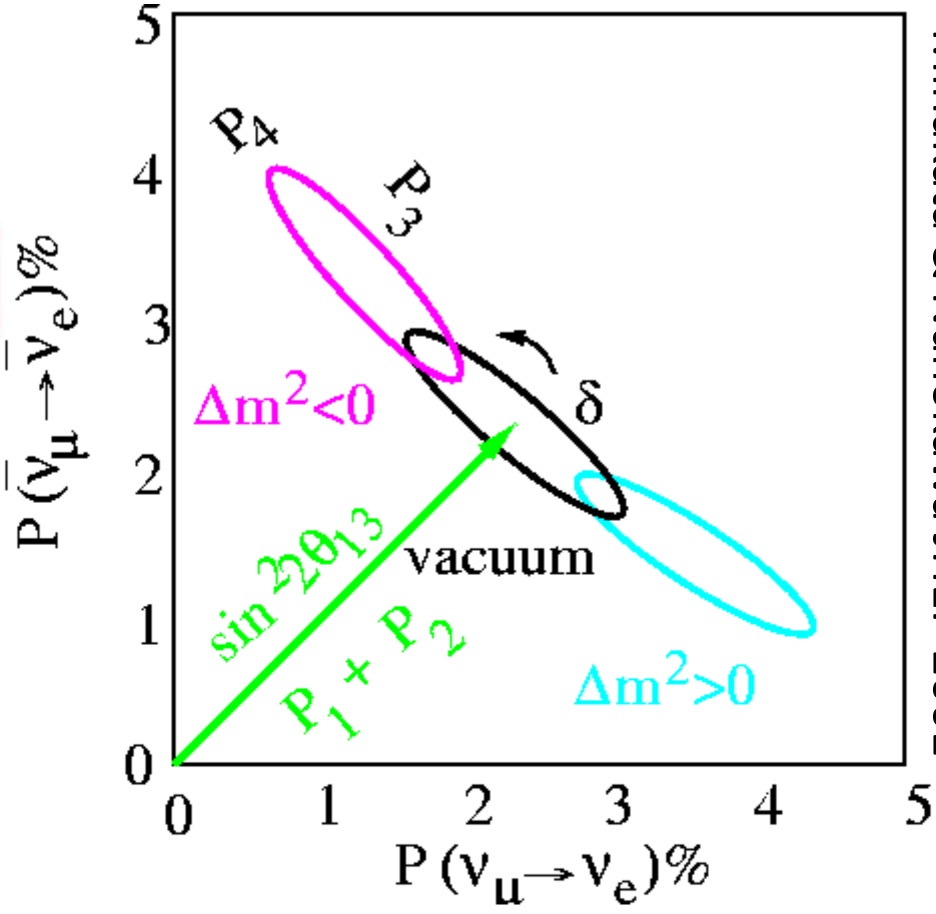
$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

For one energy and basline:



Minakata & Nunokawa JHEP 2001

Comparison with the quark sector

- Weak eigenstates and Mass eigenstates in the quark sector have a very different mixing matrix, first proposed by Cabibbo Kobayashi Maskawa.
- There is an industry in the field to make precision electroweak measurements to constrain all the elements of that matrix
- We need to understand neutrino interactions if we are ever going to get to where the quark sector is

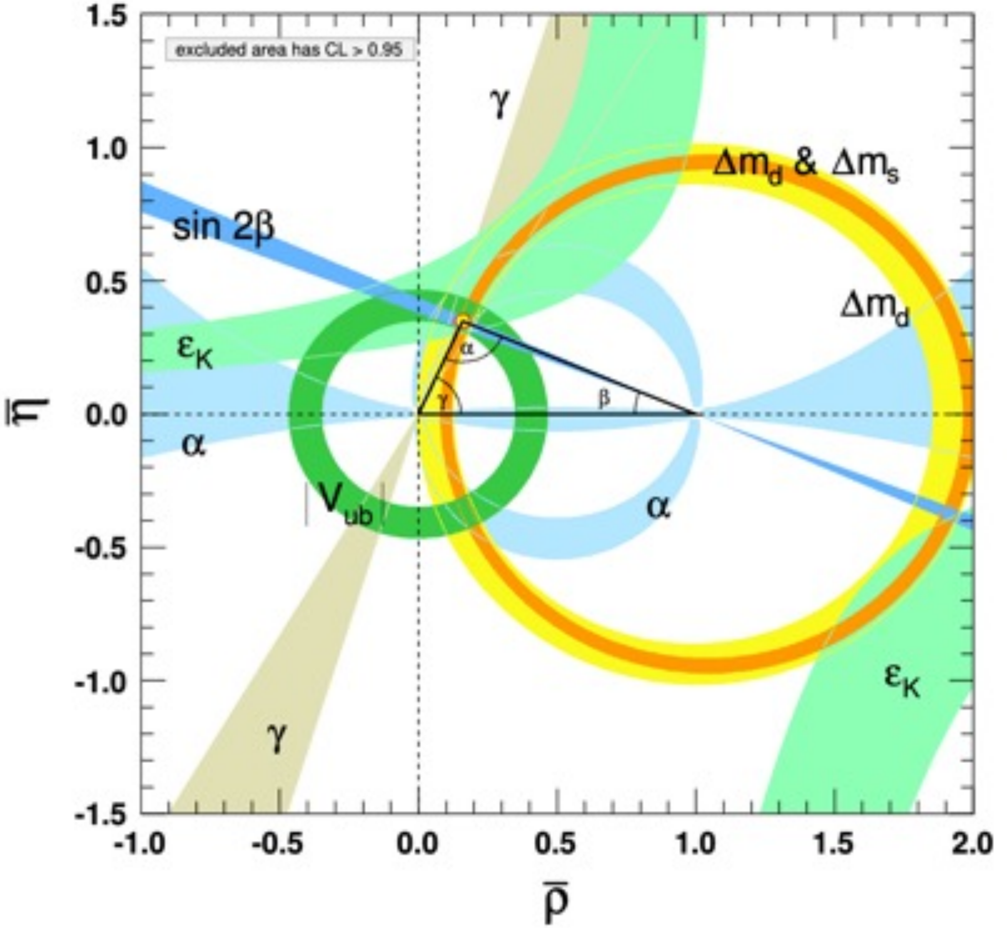


Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

Particle Data Group (PDG), Review of Particle Properties, 2022

Measuring Oscillation Probability:

$$\Phi_\beta(t) = \Phi_\alpha(0)P_{\alpha\to\beta}(t) = \Phi_\alpha(L=0)P_{\alpha\to\beta}({}^{L}/_{E})$$

$$N = \Phi\sigma\mathrm{M}\epsilon$$

$$N(E_\nu) = \Phi(E_\nu)\sigma(E_\nu)\mathrm{M}\epsilon(E_\nu)$$

- Must know or measure Neutrino Flavor
- Distance between creation and detection
- Neutrino Energy
  - No source we can use today is monochromatic!
  - Initial state: neutrino plus nucleus or electron
  - Final state: a bunch of stuff you only measure so well, sometimes you only measure the charged lepton
- Neutrino or Antineutrino?
  - Accelerator-based beams are always a mixture of both
  - Atmospheric neutrinos are also a mixture
  - Reactors and the sun are only one or the other

Measuring Oscillation Probabilities

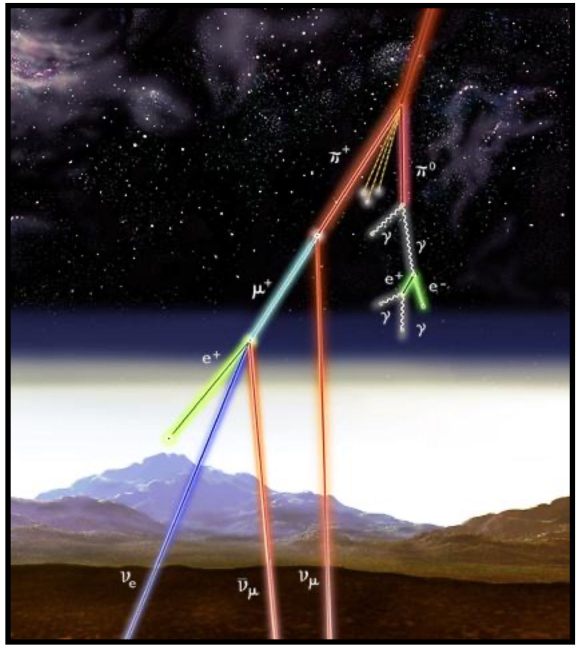
For a given number N_β of ν_β events in a detector,
If you are starting with a source of ν_α: look for

$$N_\beta(E) = \Phi_\alpha(E) P_{\alpha\to\beta}\left({}^{L}/_{E}\right)\sigma_\beta(E) \mathrm{M} \epsilon_\beta(E)$$

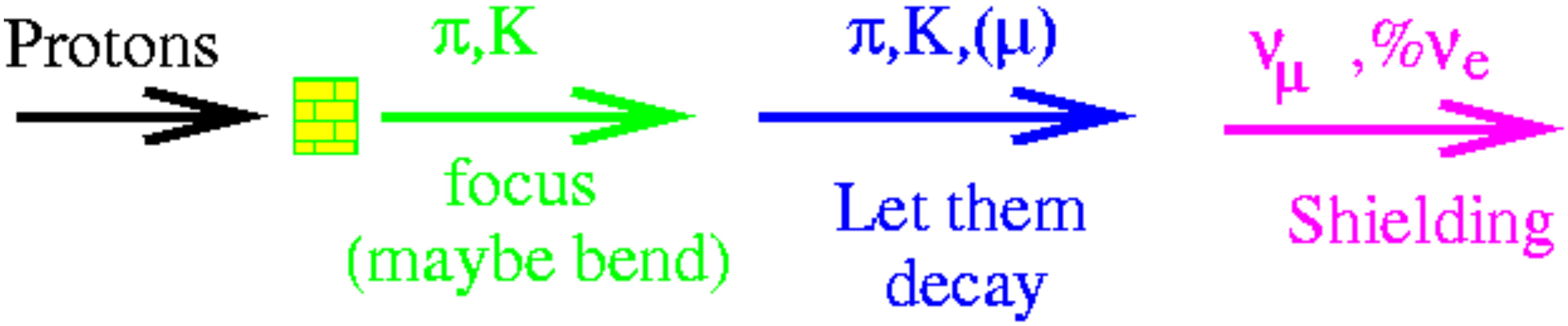
ϕ=flux, σ= cross section ε=efficiency M=detector mass

Simple, right? It would be if you could know what Energy you were at, then all you have to do is count e's and μ's

Neutrino Beams from Accelerators

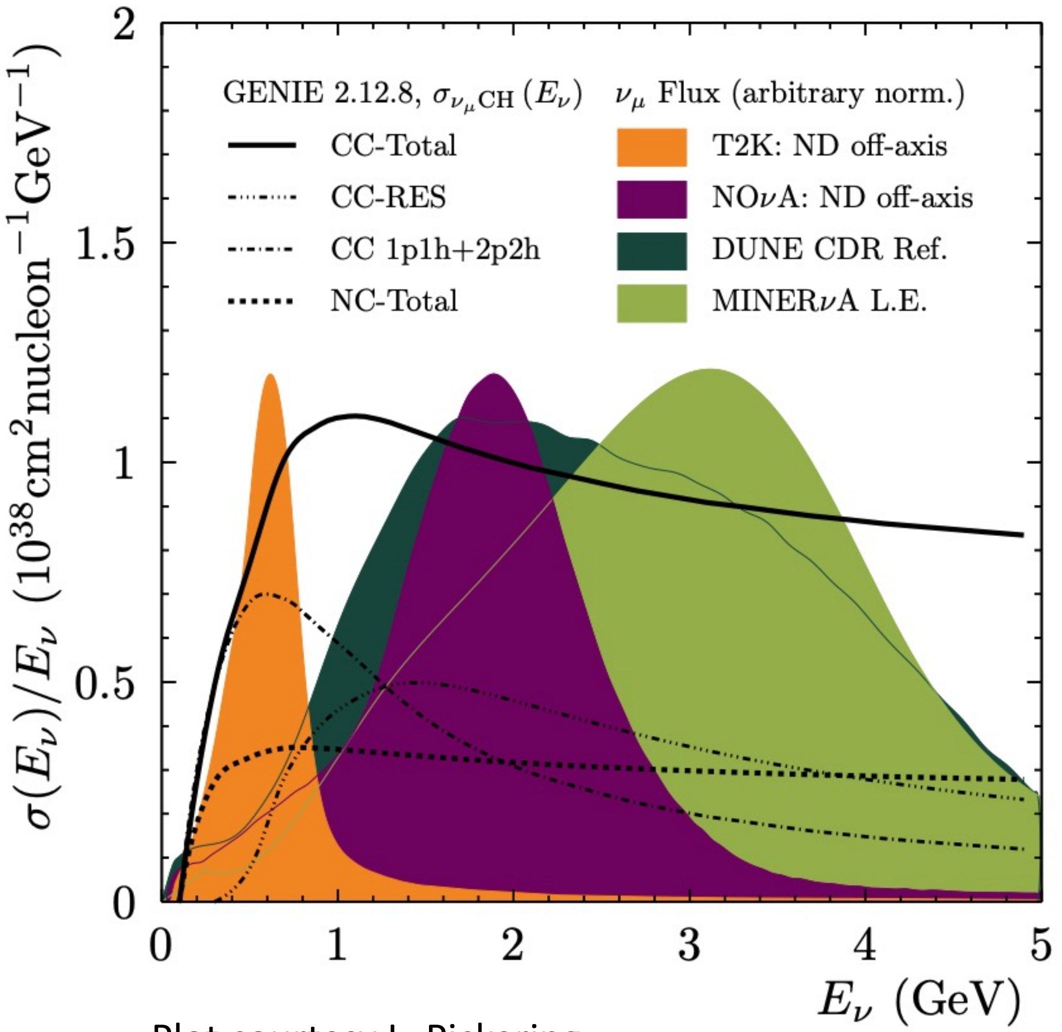


- High energy protons strike block of material
- Unstable particles (π,K) are produced
- Trick: focus the charged particles before they decay to neutrinos
- Next trick: Give the particles time to decay but not too much time, so mostly ν_μ beam



Neutrino Beams from Accelerators

- The fine art of making a neutrino beam and determining its uncertainties could fill several 30 minute lectures.
- Key Facts:
  - Can only estimate neutrino energy based on what you see in the detector, there are no monochromatic neutrino energy beams in use

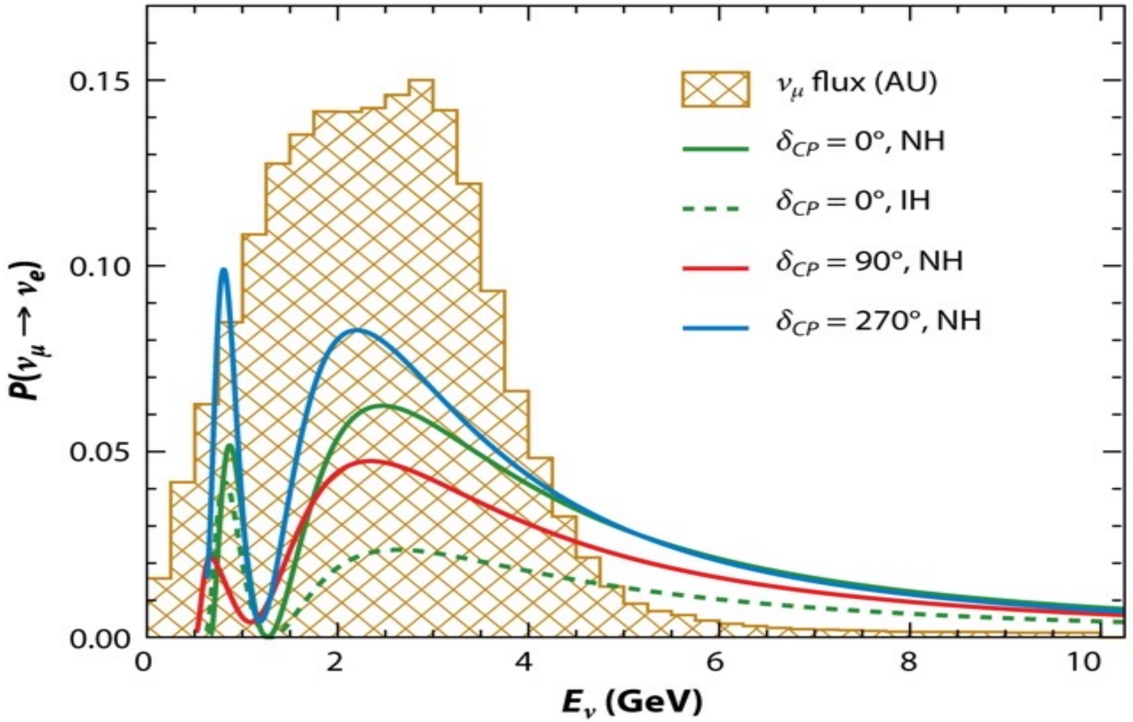


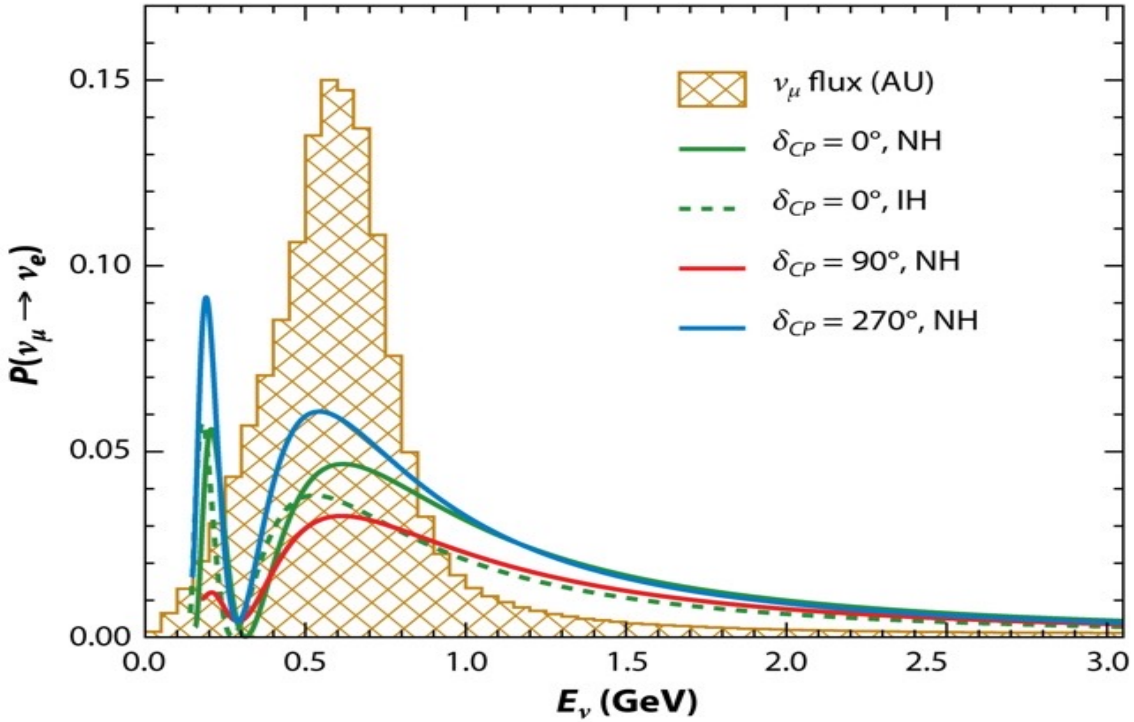
Plot courtesy L. Pickering

Neutrino Energy Spectra Compared to Oscillations

- DUNE
  - 1300km baseline
  - 40kton Liquid Argon Detector

- Hyper-K and T2K
  - 295km baseline
  - 260kton Water Cerenkov





Diwan MV, et al. 2016.
Annu. Rev. Nucl. Part. Sci. 66:47–71

Seeing Neutrinos: Thresholds and processes

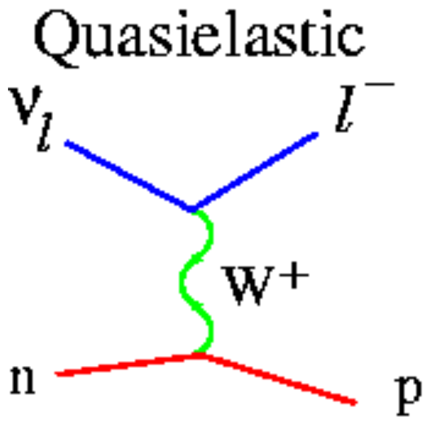
Process	Considerations	Threshold (typical)
$\nu N \rightarrow \nu N$ (elastic)	Target nucleus is often free (recoil is very small)	None ("CEνNS")
$\nu_e n \rightarrow e^- p$	In some nuclei (mostly metastable ones), this reaction is exothermic if proton not ejected	None for free neutron and some others.
$\nu e \rightarrow \nu e$ (elastic)	Most targets have atomic electrons	~ 10eV – 100 keV
anti-$\nu_e p \rightarrow e^- n$	$m_n > m_p$ & m_e. Typically more to make recoil from stable nucleus.	1.8 MeV (free p). More for nuclei.
$\nu_\ell n \rightarrow \ell^- p$ (quasielastic)	Final state nucleon is ejected from nucleus. Massive lepton	~ 10s MeV for ν_e +~100 MeV for ν_μ
$\nu_\ell N \rightarrow \ell^- X$ (inelastic)	Must create additional hadrons. Massive lepton.	~ 200 MeV for ν_e +~100 MeV for ν_μ

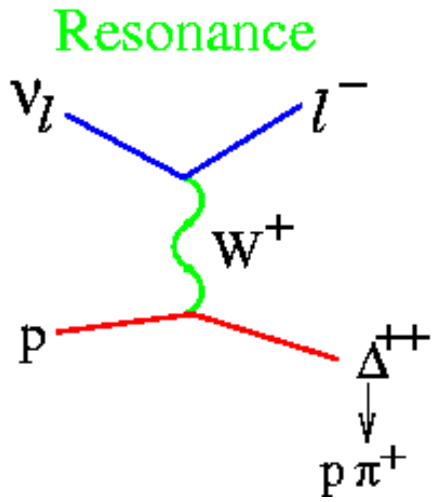
- Energy of neutrinos determines available reactions, and therefore experimental technique

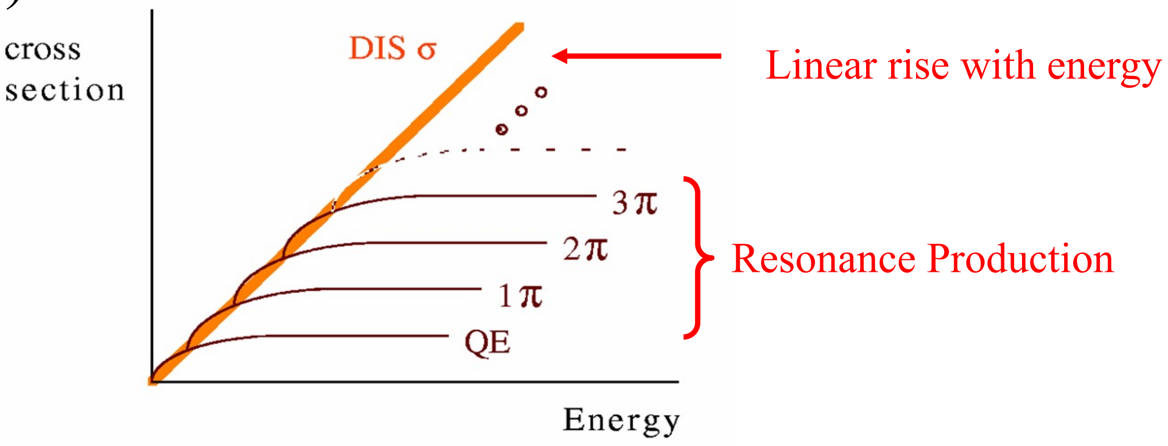
K. McFarland, INSS 2013

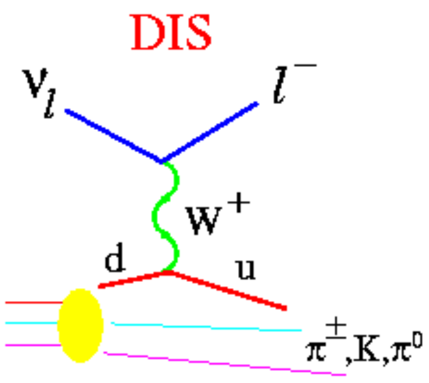
From Quasi-elastic to Inelastic Scattering

- Charged - Current: $W^{\pm}$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0 \quad (N^* \text{ or } \Delta)$
    $n + \pi^+$
  - Shallow and
    Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$

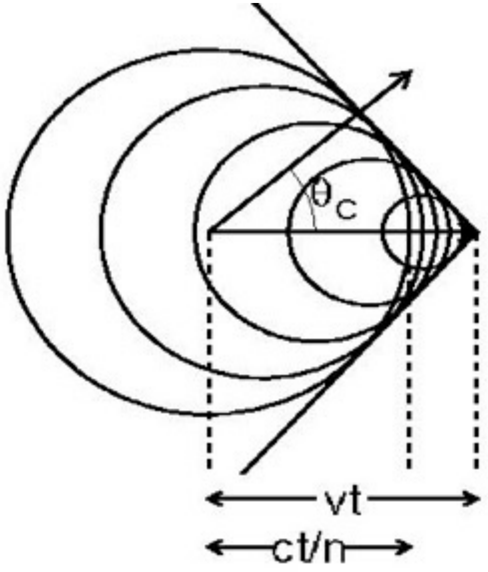






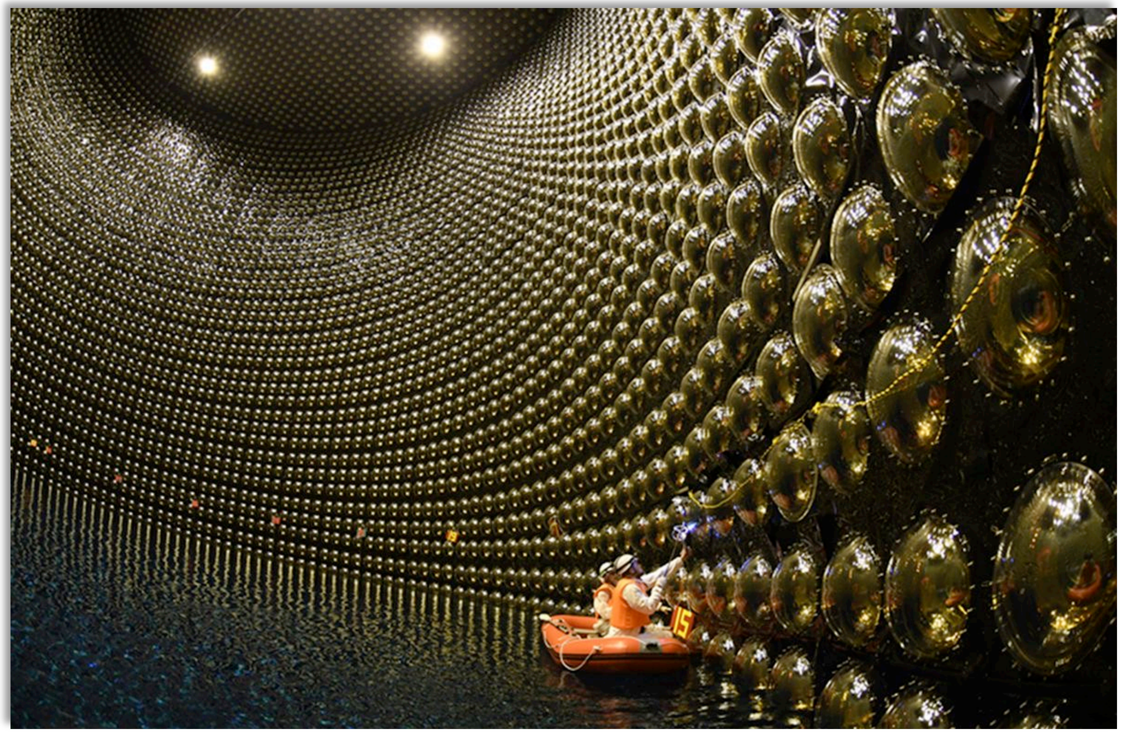


First Detection Strategy: Cerenkov Light



particle	p (threshold)
e	660keV
μ	137MeV
$\pi^{\pm}$	175MeV
K	650MeV
p	1300MeV

As **CHARGED** particles move faster than the speed of light in that medium, they emit a "shock wave" of light



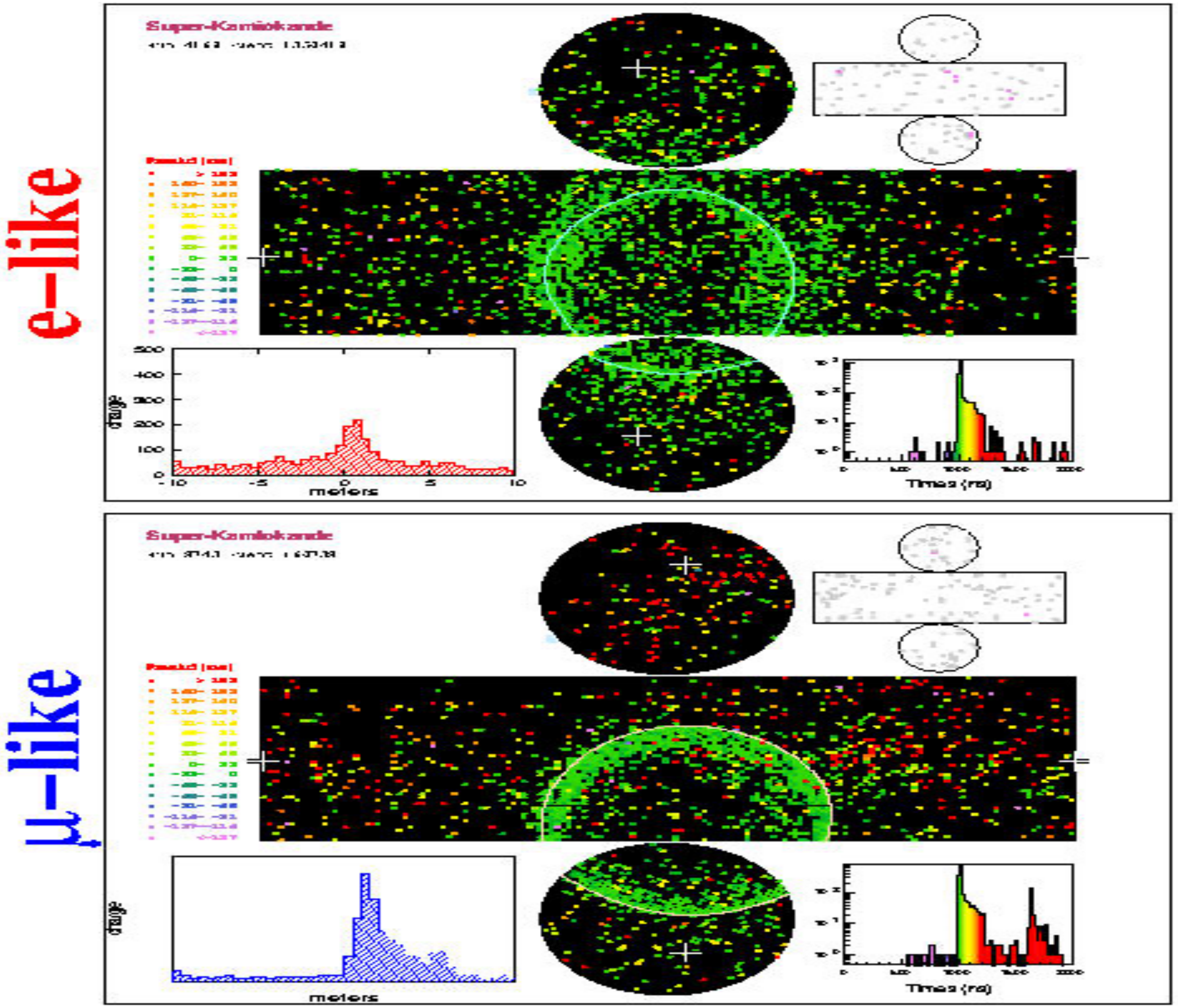
- For water, n(280-580nm)~1.33-6, so $p_{threshold}$≈1.3*mass
- Threshold Angle: 42°

$$\theta_c = \cos^{-1}(1/n(\lambda))$$

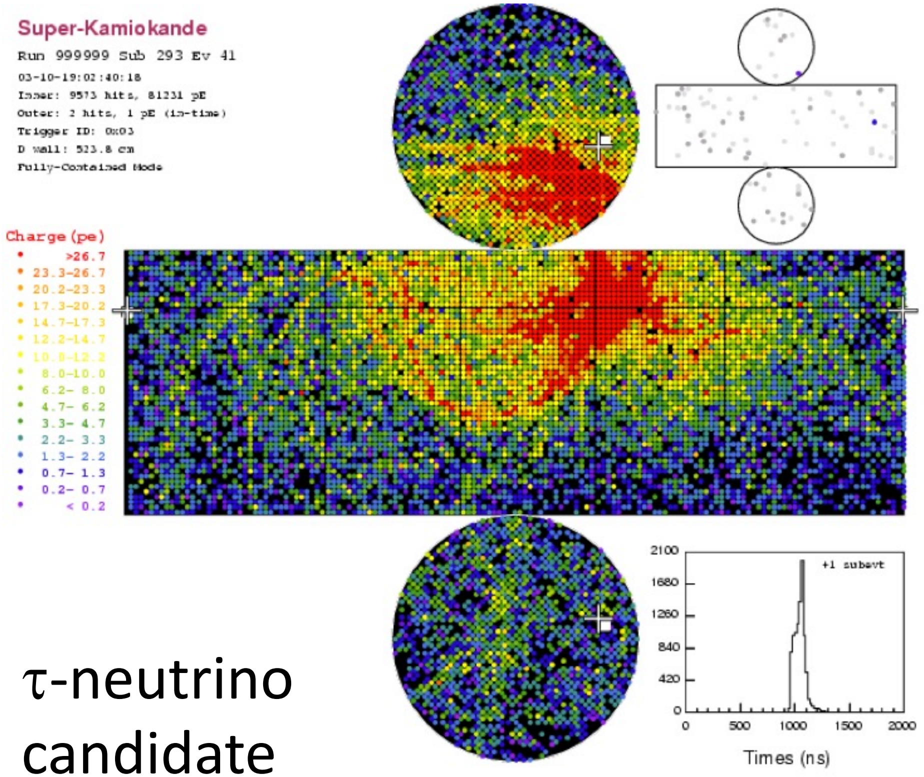
$$\beta \equiv \frac{v}{c}$$

$$p_{threshold} = \frac{m}{\sqrt{n^2 - 1}}$$

Cerenkov Light Detection in Practice



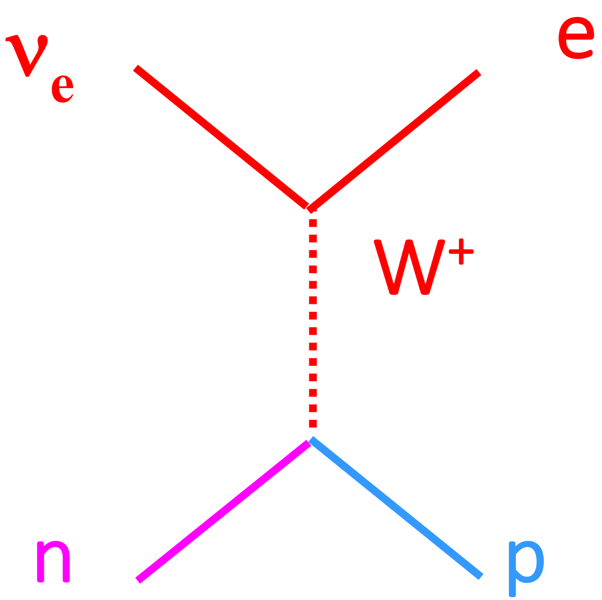
Super-Kamiokande: 50kton of Water “viewed” by phototubes



τ-neutrino candidate

How Can a Cerenkov Detector Measure a Neutrino's Energy?

- If you could see all the particles the neutrino made….use conservation of energy (and momentum)
- What if you only see the final electron or muon?
  - If initial neutron was at rest, it's like a billiard ball system:



$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - \left[(M_n - E_B)^2 + m_\mu^2 - M_p^2\right]}{2\left[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

Challenges with this strategy

- Not all interactions that look quasielastic are quasielastic
- Pions might be missed (can look for their decay electron)
- Pions might be absorbed in the nucleus
- E_ν^{QE} assumes initial state nucleon is at rest
- Correlated pairs of nucleons in initial state mean different Center of Mass energy than what you assume

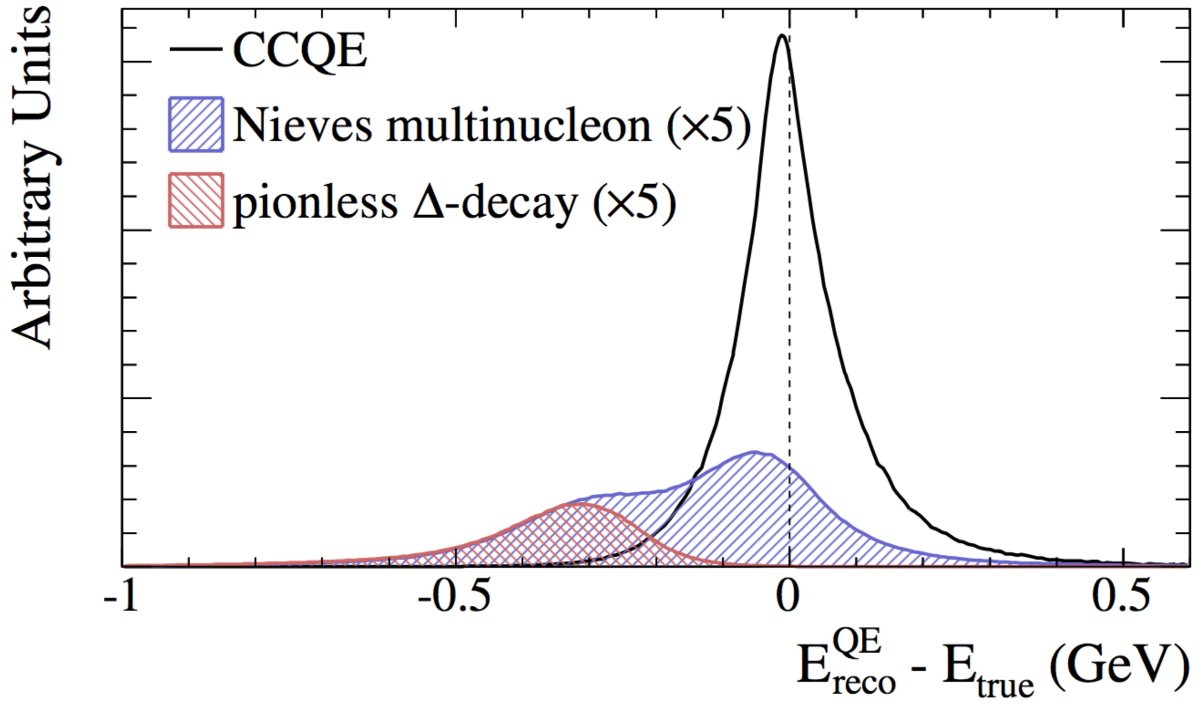
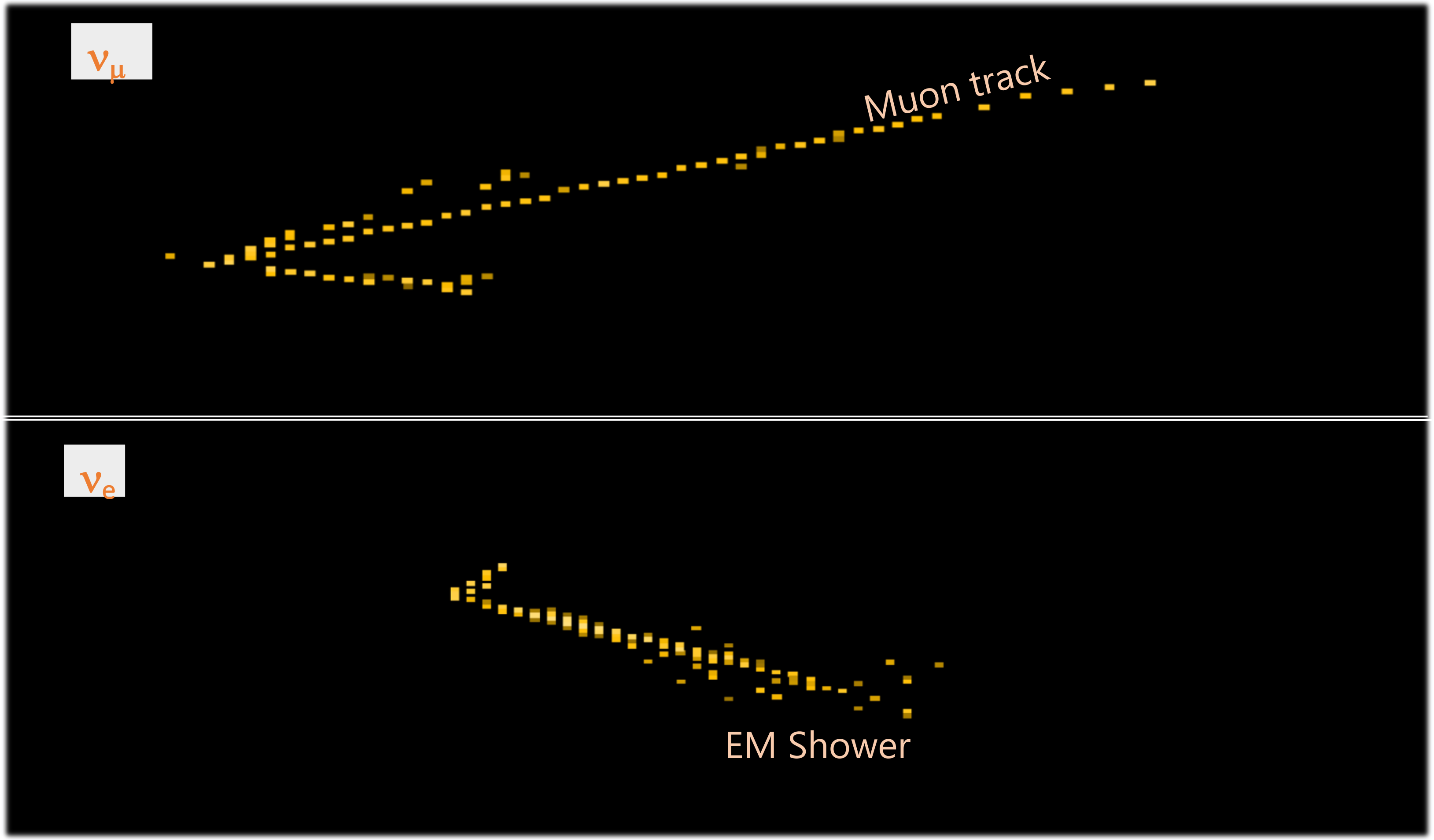


Figure from T2K, *Phys.Rev.Lett.* 112 (2014) 18, 181801

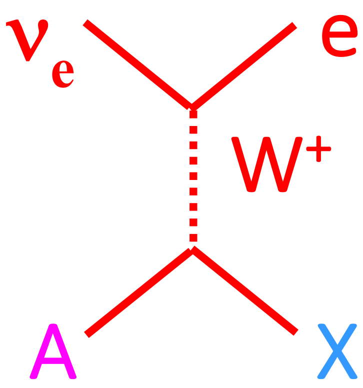
Slide from Z. Vallari, 2-24 FNAL JETP

Next Detector Strategy: "Totally Active" Detector

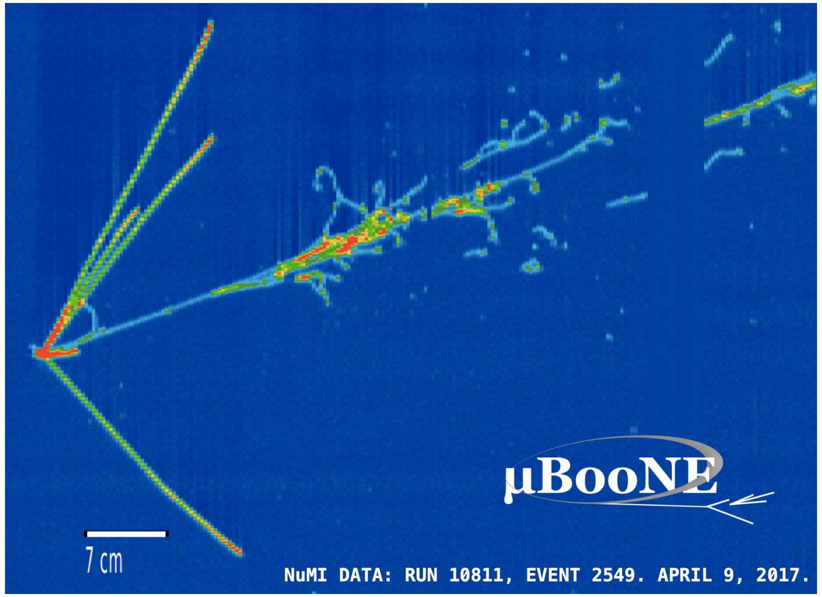
- NOvA uses liquid scintillator, very low thresholds. Neutrino energy is estimated from a **combination of lepton and hadronic components**:
  - Muon energy is reconstructed via track length.
  - Calorimetric energy estimation is done separately for EM and hadronic clusters.
- NOvA event selection uses all charged current interactions for both ν_μ and ν_e channels.

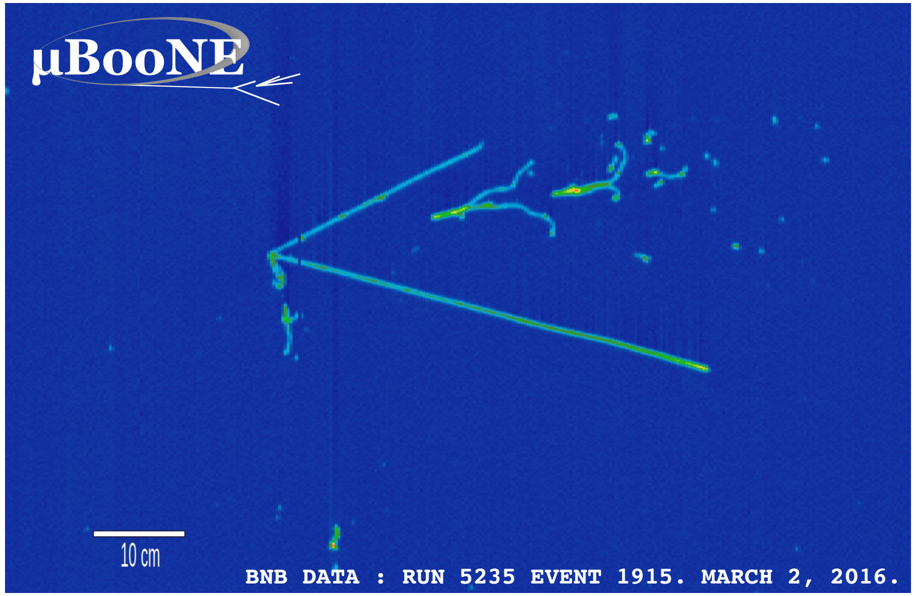


What does a neutrino look like @ DUNE?



- Similar to NOvA: add up the lepton and hadron ”visible” energy, but using Liquid Argon Time Projection Chamber (MicroBooNE, ICARUS, SBND)
- Electrons (right) look very different from muons (left)





These are Images from another Liquid Argon Detector, another neutrino beam, but “tracks” will look the same

Why is measuring Hadron Energy Difficult?

- What could you measure about final state hadronic system
  - Do you track charged particles so you can measure their total kinetic energy?
  - Can you distinguish between p, π^+, π^+, π^0
  - What about neutrons, do you see those?

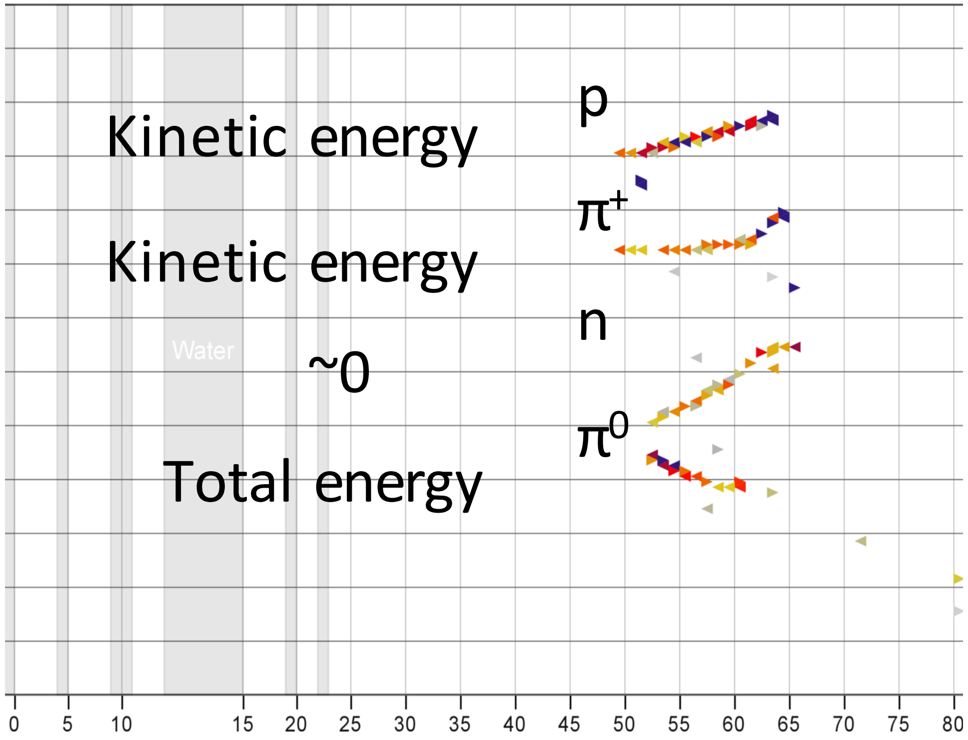


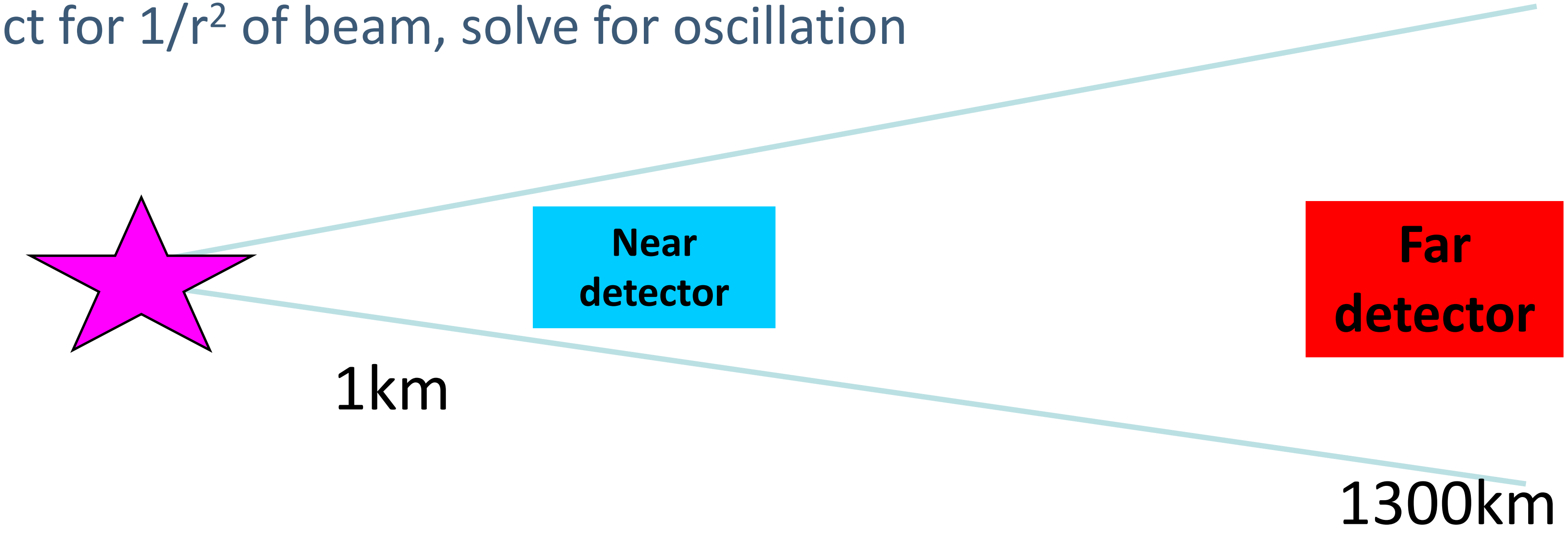
Figure courtesy P. Rodrigues

Example from MINERvA at right,
3.3cm plastic granularity
Similar in spirit to ~3cm wire pitch Liquid Argon (but different density, Z)

Phys. Rev. D 94, 013012 (2016)

Near Detector Strategy

- Use two detectors to measure oscillations precisely:
  - Near detector sees beam before oscillations
  - Far detector measures beam after oscillations
  - Ideally, near and far detectors made of same material (Ar)
  - Correct for $1/r^2$ of beam, solve for oscillation

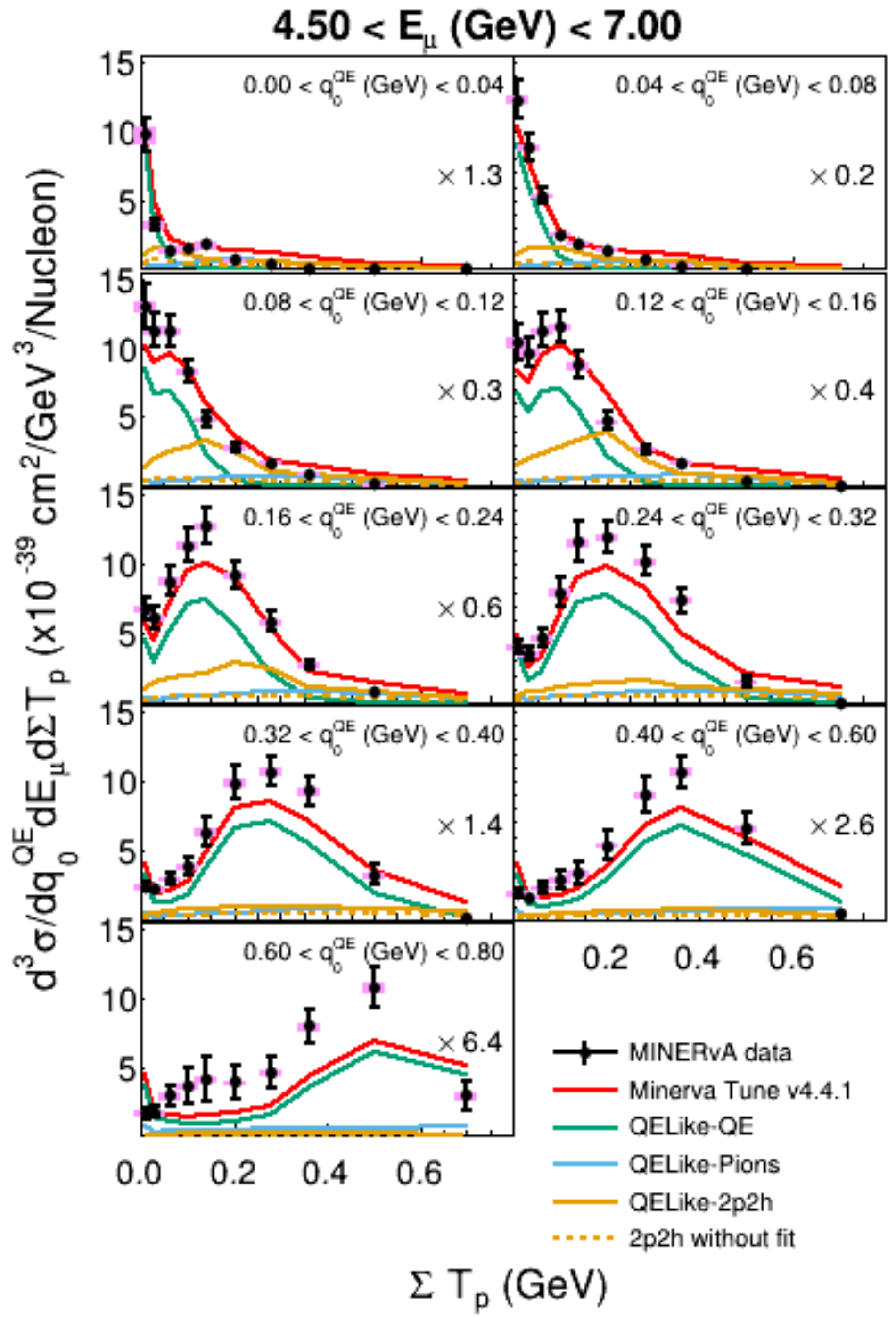


Words you should probably never believe…

- “One Size Fits All”
- “This won’t hurt much”
- “It’s not you it’s me”
- “Cross Section Uncertainties cancel in a 2-Detector Experiment”
  - Disappearance Probabilities are huge, Far Detector flux and backgrounds very different from Near Detector Flux
  - Near Detector ν_e flux is very different from Near Detector ν_μ flux
  - If you are measuring probability versus energy, visible energy scale does NOT cancel!

MINERvA's Lesson on Energy

- Comparing the two different ways that experiments measure ν energy
- For events that only have a muon and protons:
  - Use a detector that can measure both:
    - Energies of those protons that made it out of the nucleus
    - Energy that you would have predicted from muon angle and energy
  - See if you can predict the relationship between the two
- News from MINERvA: our current models don't do such a great job predicting that relationship



Ref: D. Ruterbories *et al*, *Phys.Rev.Lett.* 129 (2022)

But enough about signals, what about backgrounds?

- Neutrino Interactions matter because even if oscillations are large, you still have to predict backgrounds.
- Imagine you are looking for electron neutrinos:
  - How do you identify that you had an electron neutrino?
  - What else looks like an electron? Photons
  - What produces photons but no muons? Neutral Current π^0 production
- So as you learn about calculating neutrino cross sections at this meeting, don't forget about Neutral Current Interactions!

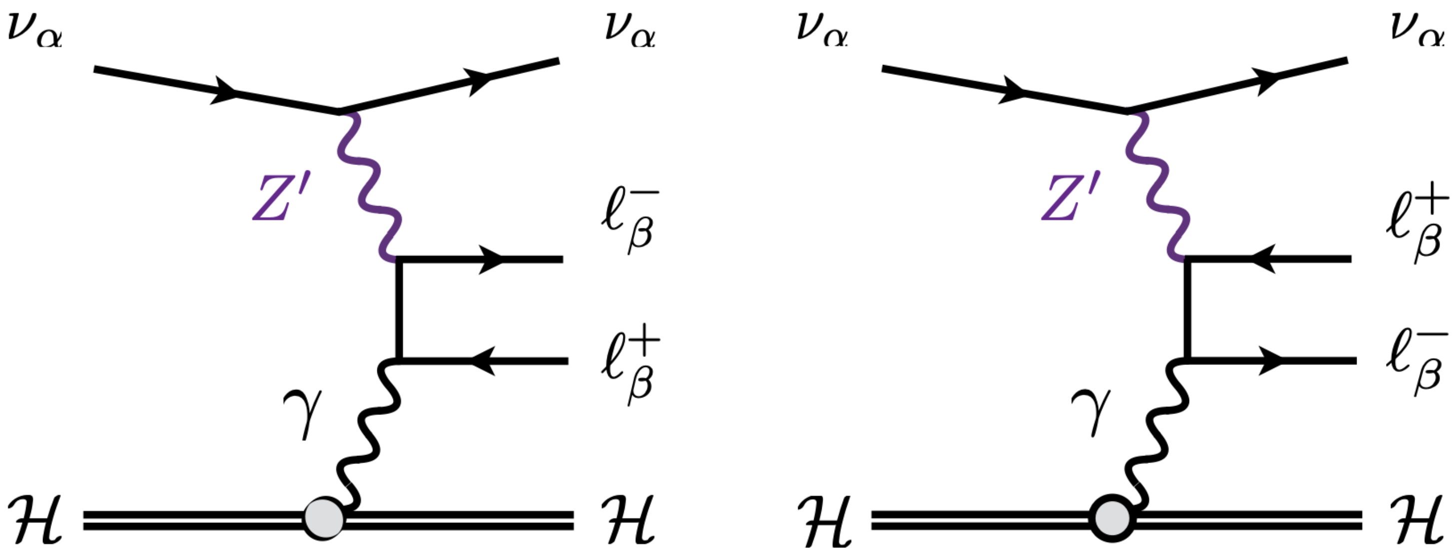
Beyond the Standard Model Searches

- "Standard" Neutrino Interactions are backgrounds to BSM searches!
- Dark Matter Searches
- Neutral Heavy Lepton Searches
- Yes, even Proton Decay searches!

- If you see a direct search for a BSM particle and there is no neutrino interaction background mentioned, think carefully about what might be there

What can you look for when you have 10^{21} protons hitting a target?

- Neutrino Tridents



Diagrams from Neutrino Non-Standard Interactions: A Status Report

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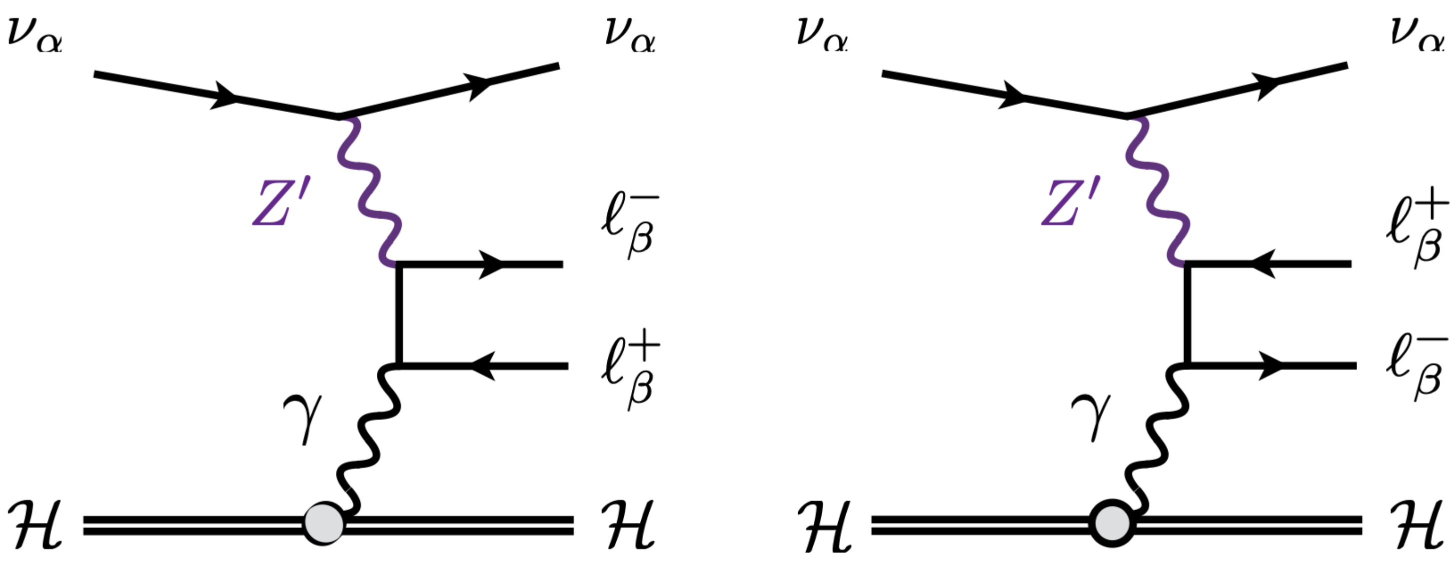
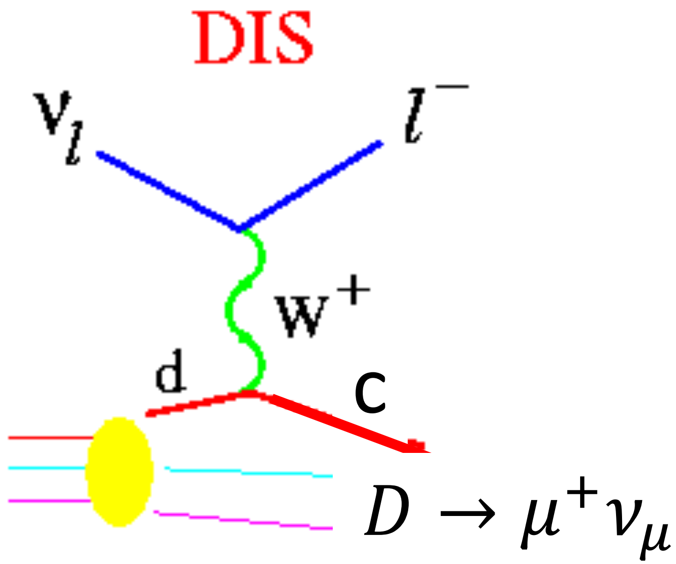


Diagrams from Neutrino Non-Standard Interactions: A Status Report

But…What does Charm Production look like?



What can you look for when you have 10^{21} protons hitting a target?

- Dark Photons

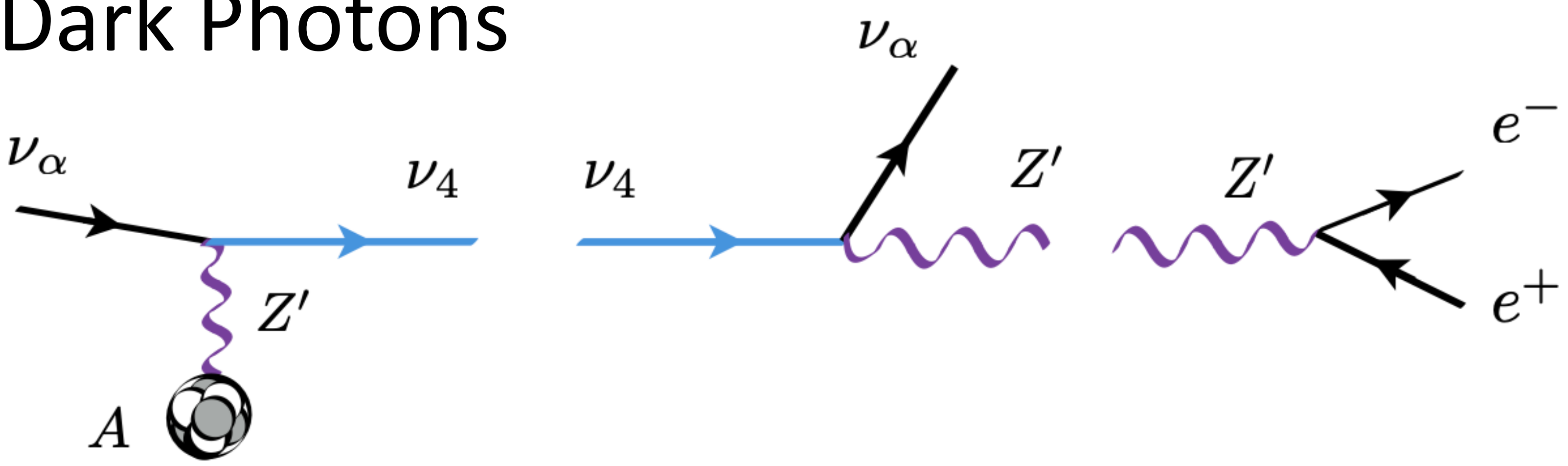


Figure from Neutrino Non-Standard Interactions: A Status Report

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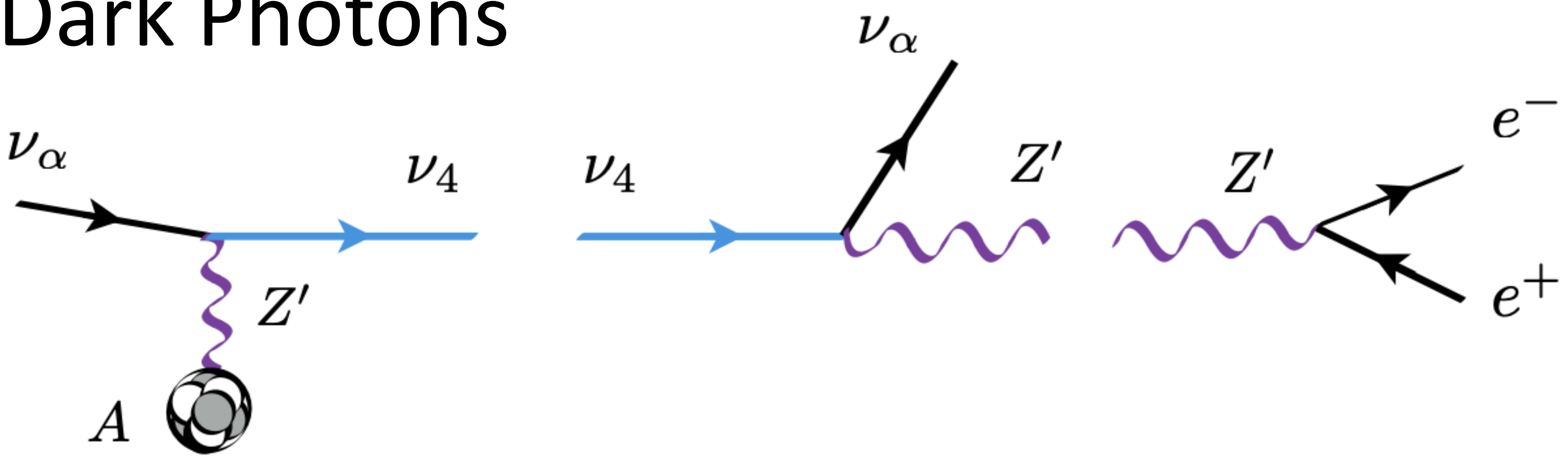
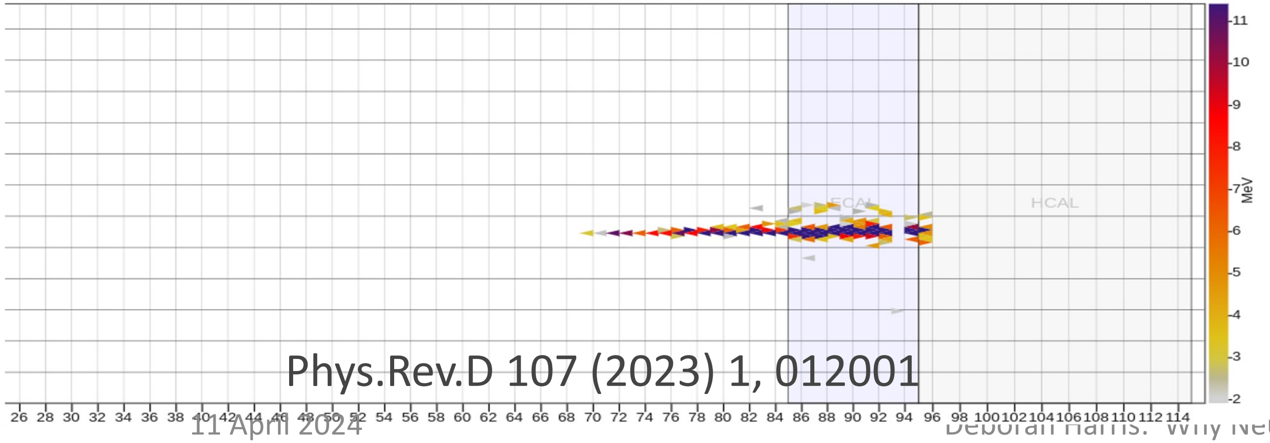


Figure from Neutrino Non-Standard Interactions: A Status Report



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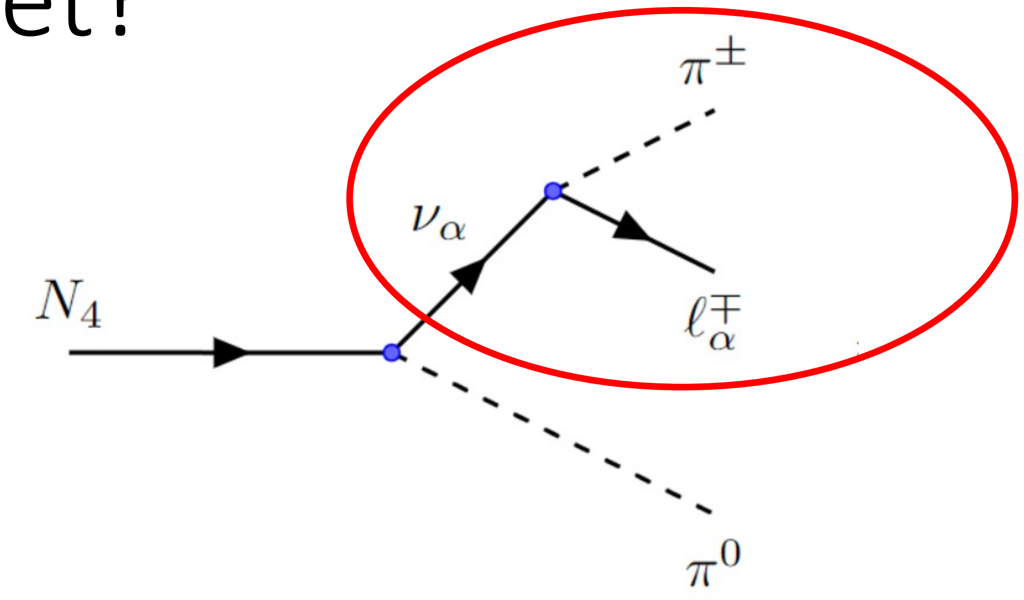
MINERvA event candidate for Neutrino-electron scattering, or NC Coherent π^0 Production

What can you look for when you have 10^{21} protons hitting a target?

- **Neutral Heavy Leptons,** first proposed in 1987 even before many were convinced neutrinos had mass (Physics Letters B, Volume 187, Issues 3–4, 26 March 1987)
- Inspired by See-Saw Mechanism to explain light neutrino masses
- Recent effort to get this into modern generators: *Phys.Rev.D* 107 (2023) 5, 055003



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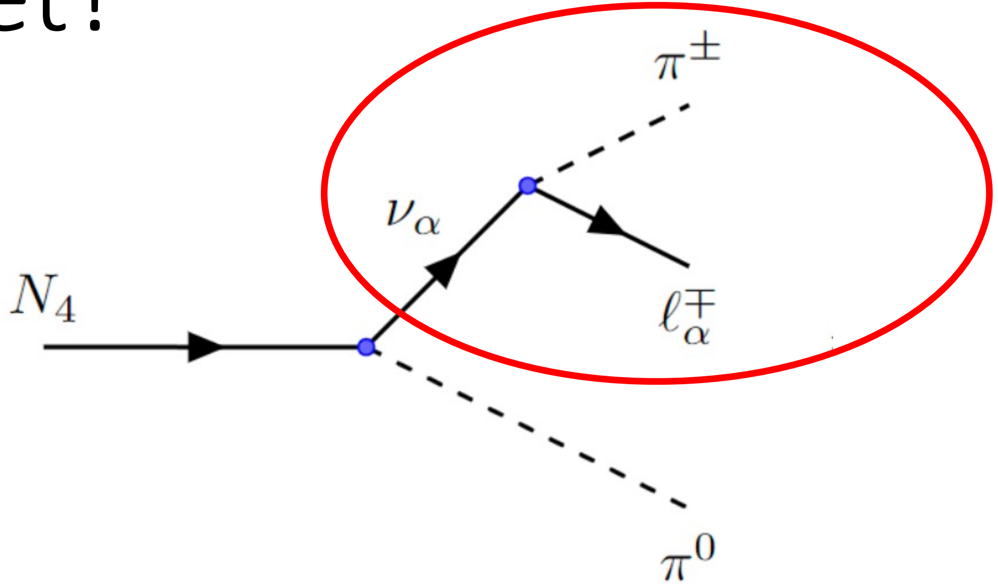

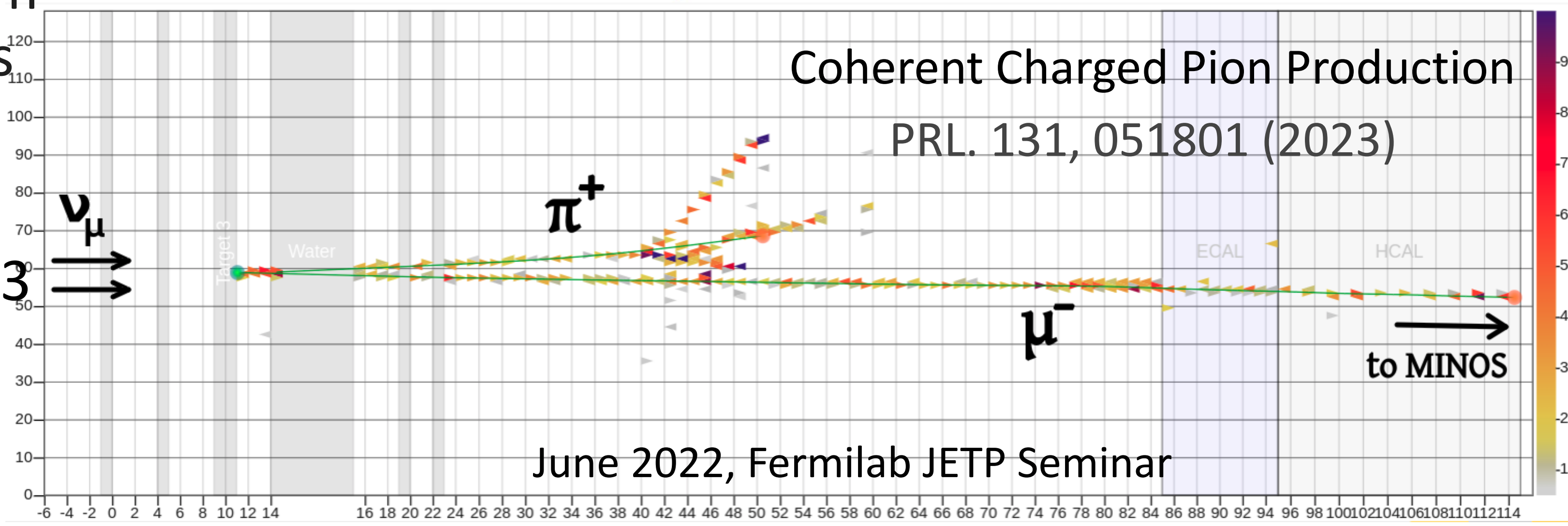

Why Neutrino Interactions Matter

- Can't make precision oscillation measurements without them!
  - Need to know how neutrino energy is translated to particles we and do not see
  - Need to extend all the work on QE interactions to Pion production and beyond
  - Don't forget that we also need models for Neutral Current Interactions
  - Didn't have time to cover:
    - How the lepton mass changes the cross section
    - $\frac{\nu_e}{\nu_\mu}$ but also $\frac{\bar{\nu}_e}{\bar{\nu}_\mu}$ not to mention ν_τ and $\bar{\nu}_\tau$
- Can't search for Beyond the Standard Model Physics without knowing the neutrino backgrounds