Neutrino Interferometry at DUNE: Preparing for the Deep Underground Neutrino Experiment

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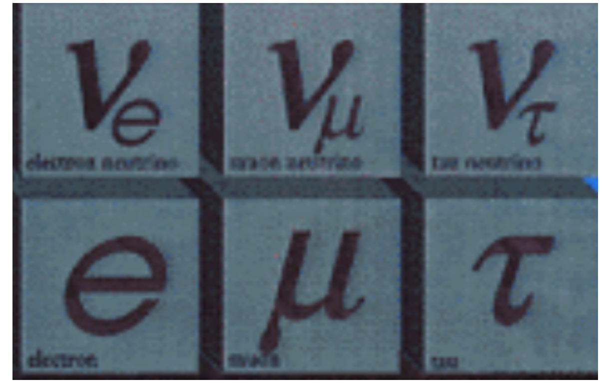
Why are you studying neutrinos?

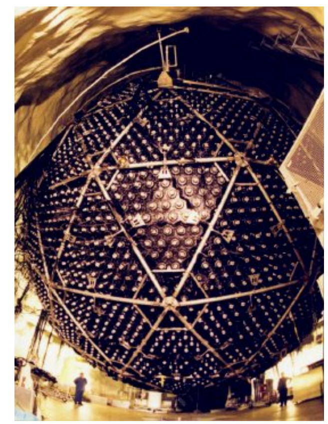
- I was asked this yesterday afternoon in the Banff Upper Hot Springs…

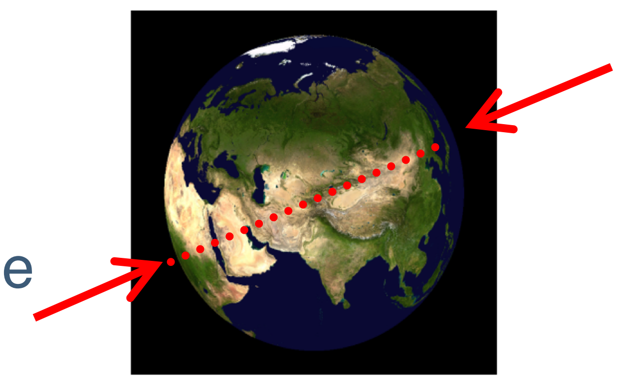
  - More of them than protons by almost a factor of a billion
  - They may be the reason that the universe is dominated by matter
  - Their masses may have been generated by a completely different mechanism than the masses of all the other fermions
  - They give us a new way of looking inside the nucleus
  - They are a clear indication that the standard model is broken!

Neutrino Surprises



- The Standard Model predicts
  - neutrinos come in three flavors
  - neutrinos have no mass
- BUT…they change flavor over time
  - Neutrinos from the sun: only 1/3 of ν_e's produced in the sun arrive at the earth as ν_e's and 2/3 $(\nu_\mu + \nu_\tau)$'s
  - Neutrinos from the atmosphere: ν_μ's become ν_τ's by the time they cross the diameter of the earth
  - Neutrinos from reactors: anti- ν_e's disappear and then reappear!
- So they must not be traveling at the speed of light, so they have mass!





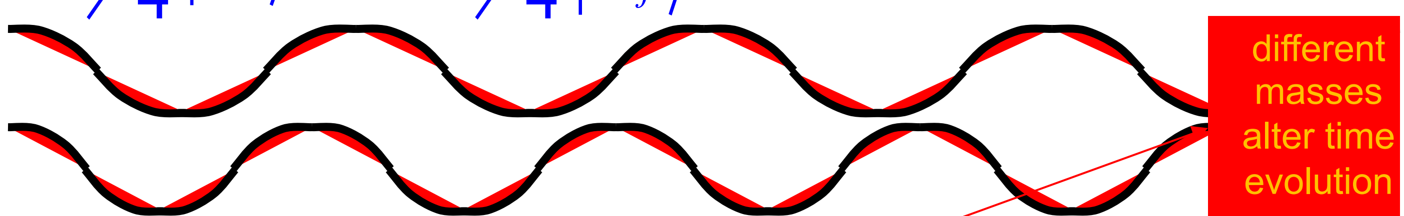
Minimal Oscillation Formalism

- 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!

$$|\nu_\alpha\rangle = \cos{}^{\pi}\!/_{4}\,|\nu_i\rangle + \sin{}^{\pi}\!/_{4}\,|\nu_j\rangle$$



time

$$|\nu_\beta\rangle = -\sin{}^{\pi}\!/_{4}\,|\nu_i\rangle + \cos{}^{\pi}\!/_{4}\,|\nu_j\rangle$$

Oscillation Formalism (cont'd)

- So, still for two flavors…

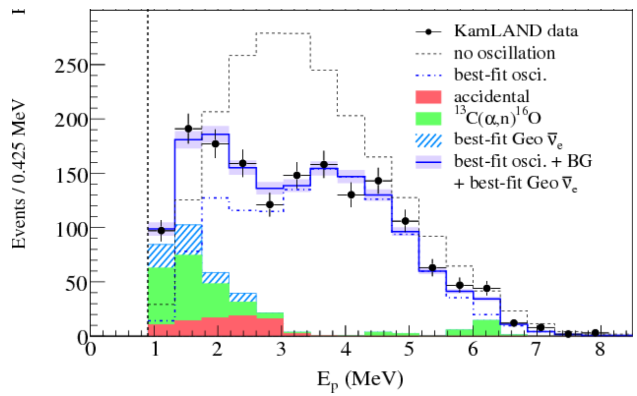
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

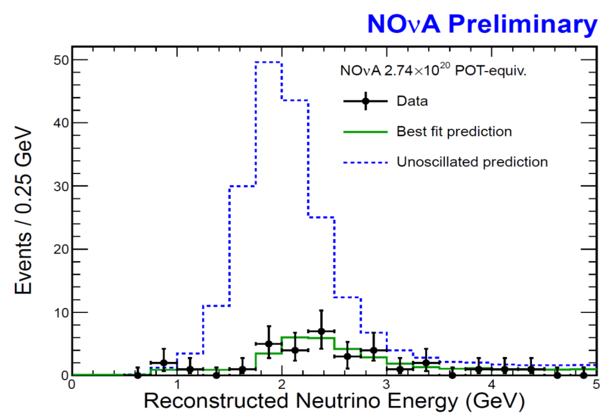
- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, Δm^2, and mixing angles, θ.
- But the signals:
- Reactor ν's: E=3MeV, L=180km
- Accelerator ν's: E=2000MeV, L=810km
- There must be more than two mass eigenstates

Experimental Details:

L: Baseline

E: Neutrino Energy





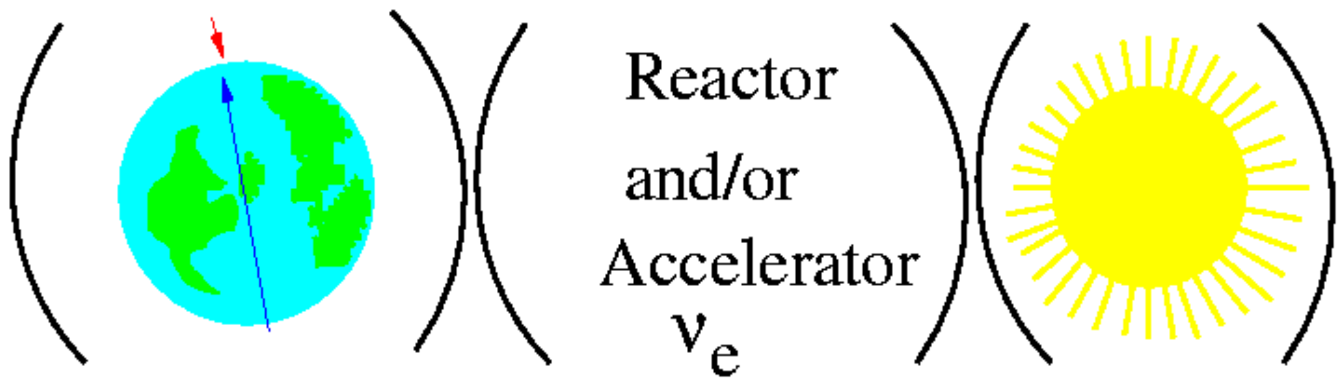
Three Generation Mixing

Lesson learned from studying quarks:
3x3 Unitary matrix is defined by 3 mixing angles and one phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

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

U=



- Note the new mixing in the middle, and the phase δ

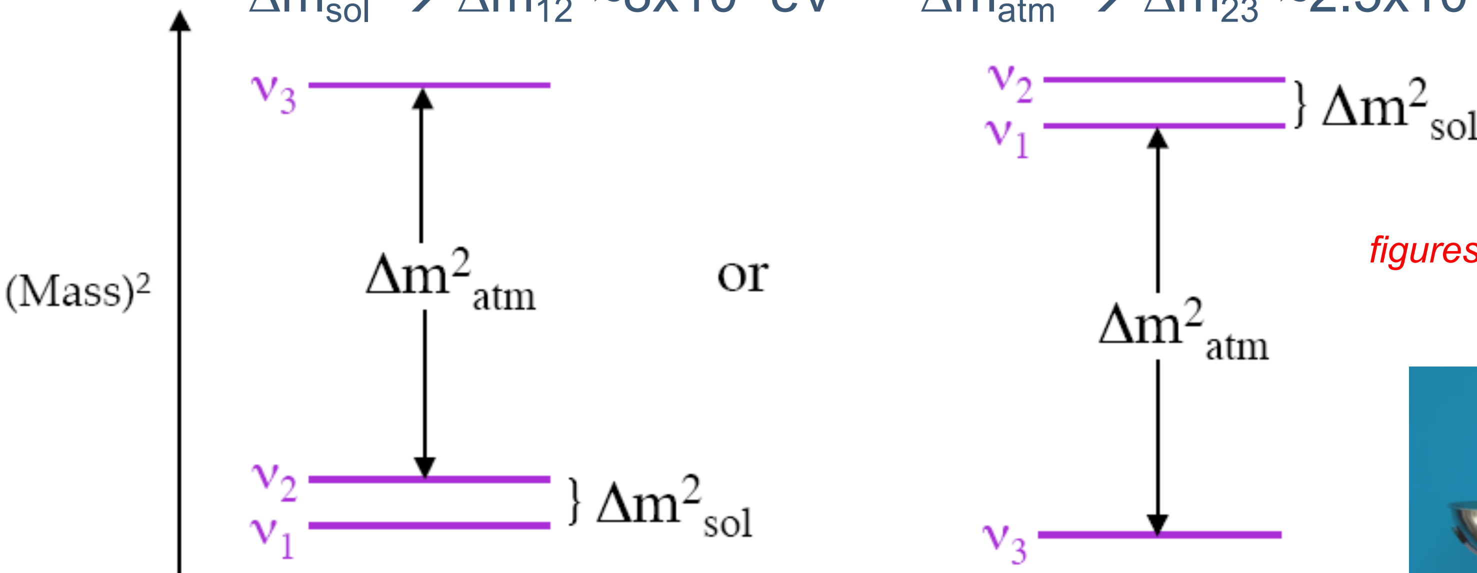
Why is CP violation so important?

- The early Universe had a lot of energy to make matter and antimatter in equal amounts
- Where is the antimatter today?
  - look for annihilations.
- As far away as we can tell, today there aren't big matter and anti-matter collisions
- Maybe neutrinos oscillate differently from anti-neutrinos!

What else don't we know yet?

- Do neutrino mass states have the same mass structure as the charged fundamental particles?

$\Delta m_{sol}^2 \rightarrow \Delta m_{12}^2 \approx 8x10^{-5} eV^2$ $\Delta m_{atm}^2 \rightarrow \Delta m_{23}^2 \approx 2.5x10^{-3} eV^2$



figures courtesy B. Kayser

- By sending neutrinos through the earth, you can become sensitive to this difference because the earth is full of electrons

3-generation $\nu_\mu \rightarrow \nu_e$ Probabilities

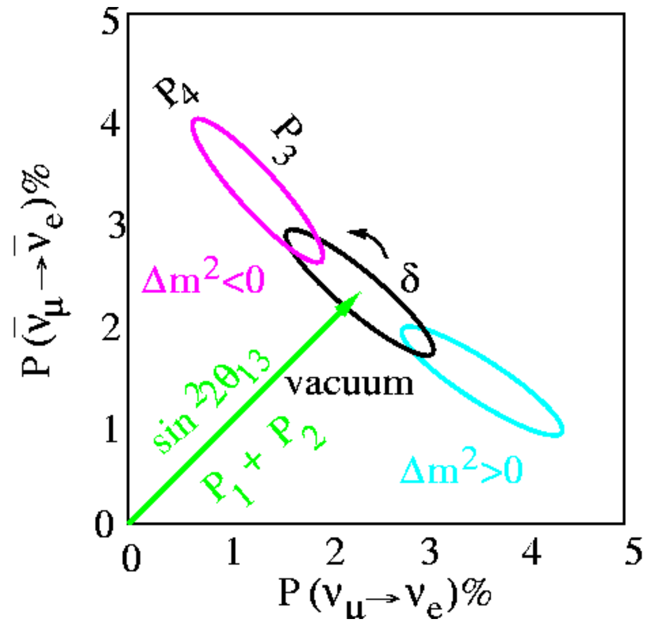
- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

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

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

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

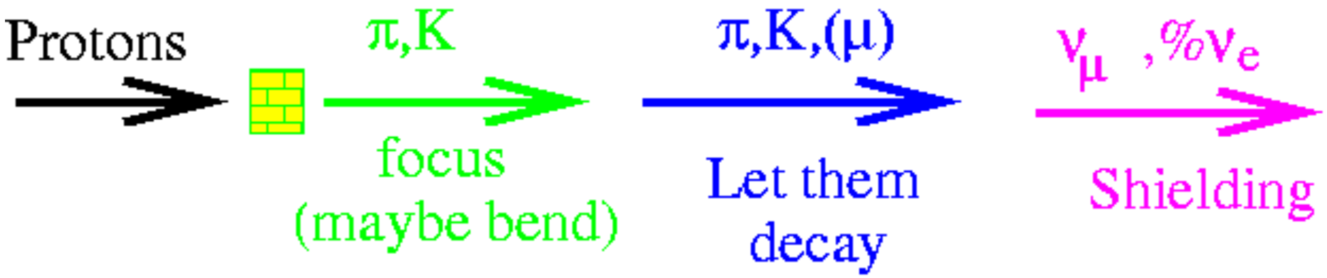
$$P_4 = \mp J \sin\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13} L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$



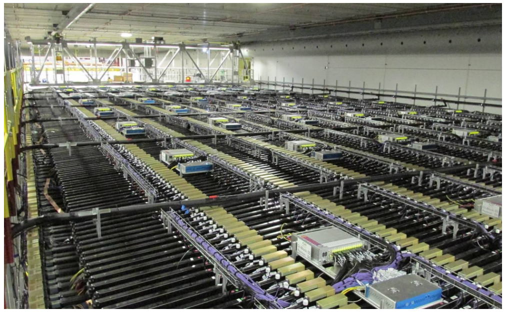
Minakata & Nunokawa JHEP 2001

- Much more complicated than 2-generation mixing
- Interference between atmospheric and solar terms is where CP violation arises
- Size of that interference is function of all angles, including θ_{13}
- Measurement at one L and E is not enough!

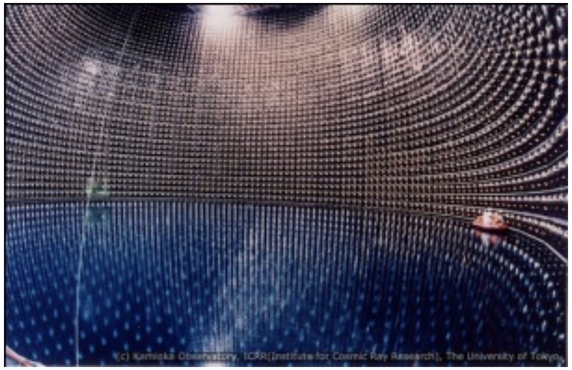
Accelerator ν Beams



- Massive Detectors: 14-50kton, Intense proton beams: 400-700kW
- NOvA
  - 810km, mostly under WI
  - 2GeV neutrinos
  - Liquid Scintillator Detector (sees charged particles)

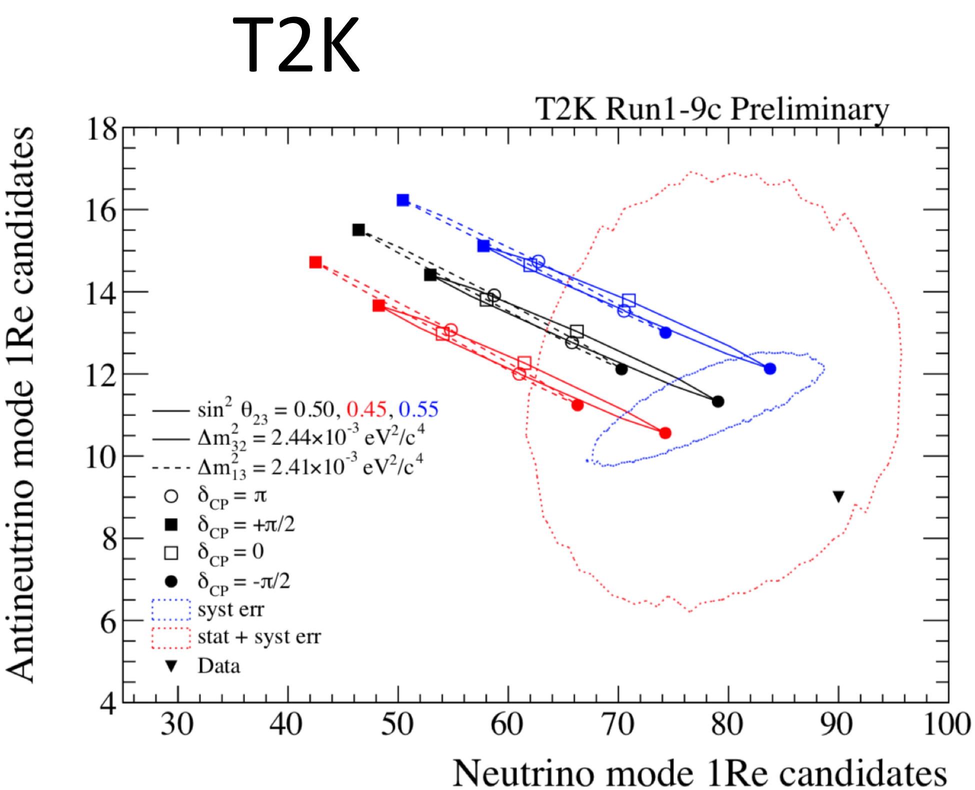


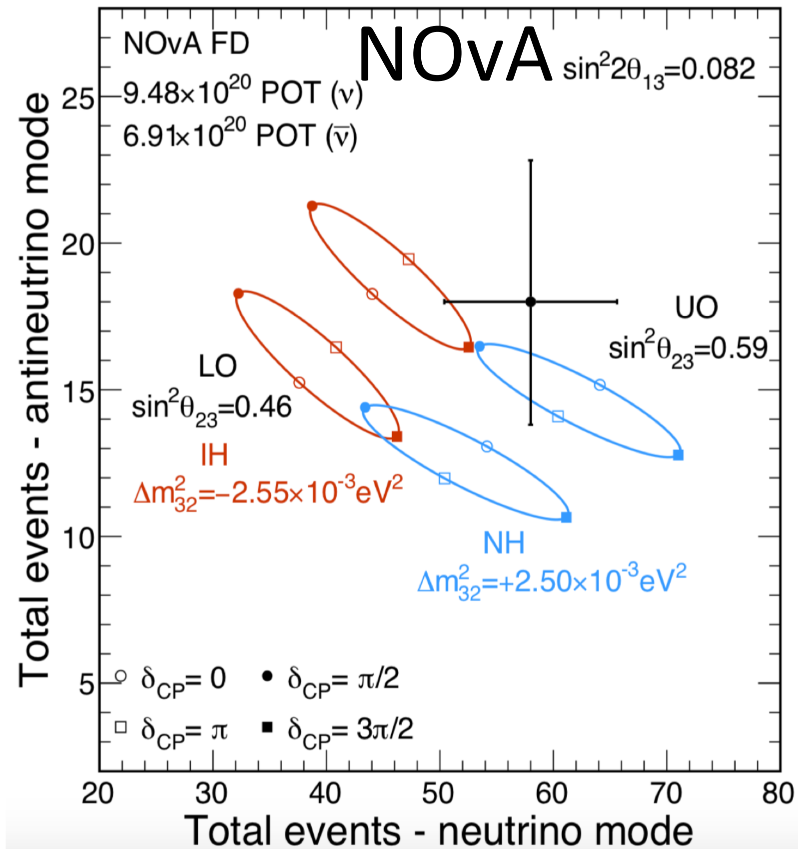
- T2K
  - 295km E to W under Japan
  - 700MeV neutrinos
  - Water Cerenkov detector (sees e and μ)



Looking for ν_e's in beam of ν_μ's

- Remember the probability plots? Translate to event plots…



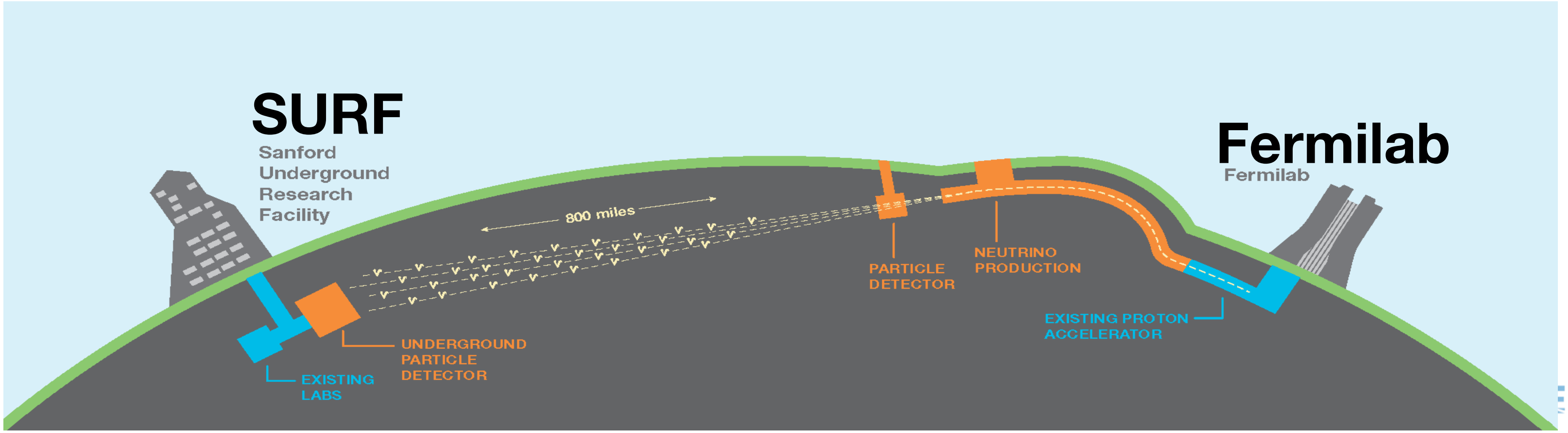


Wascko, Morgan. (2018, June). T2K Status, Results, and Plans. Zenodo. http://doi.org/10.5281/zenodo.1286752

Sanchez, Mayly. (2018, June). NOvA Results and Prospects. Zenodo. http://doi.org/10.5281/zenodo.1286758

Next: Testing the Oscillation Framework

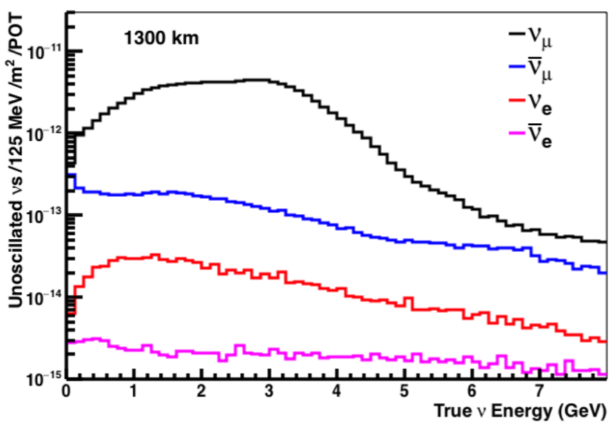
- Today's neutrino experiments cover narrow energy bands
- Want to see ν_e appearance across broad energy range
  - Need intense beam and huge detector
  - Need to distinguish neutrino flavor
  - Need to understand how neutrinos leave energy in a detector in the first place!

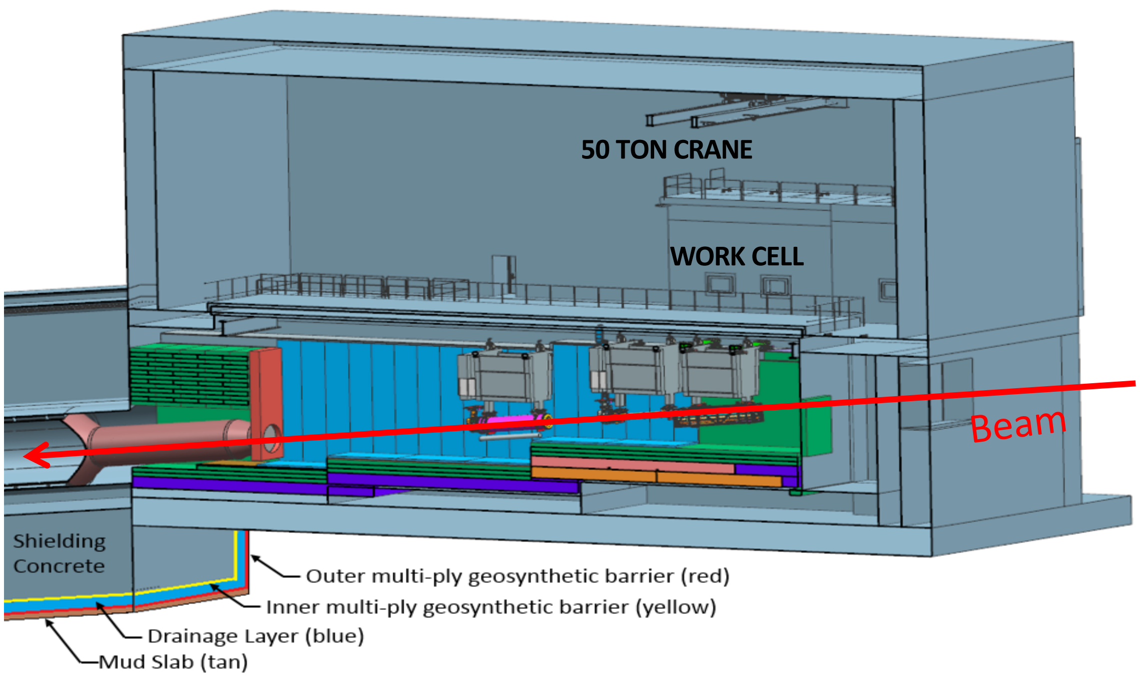


Preparing a beamline for DUNE

- Need to provide huge proton power, & target that survives it
- Need to focus outgoing charged particles using 100's of kAmps
- Need enough shielding to stay safe

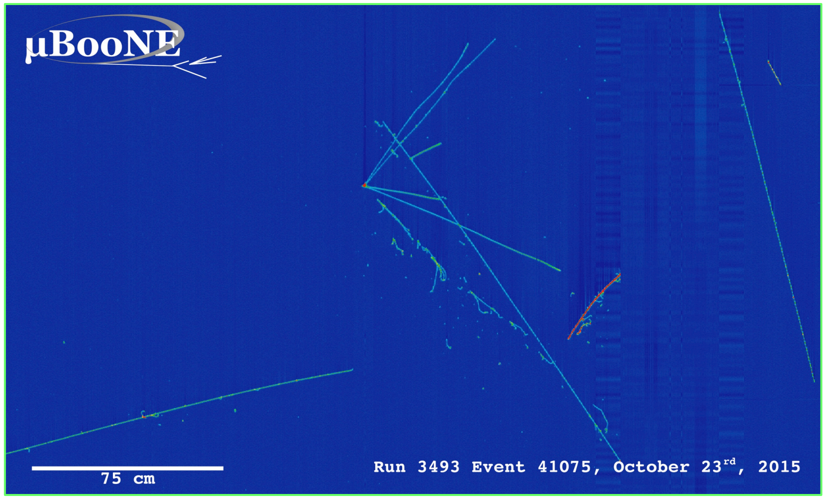
Neutrino Flux at 1300 km
(CDR Optimized Beam)

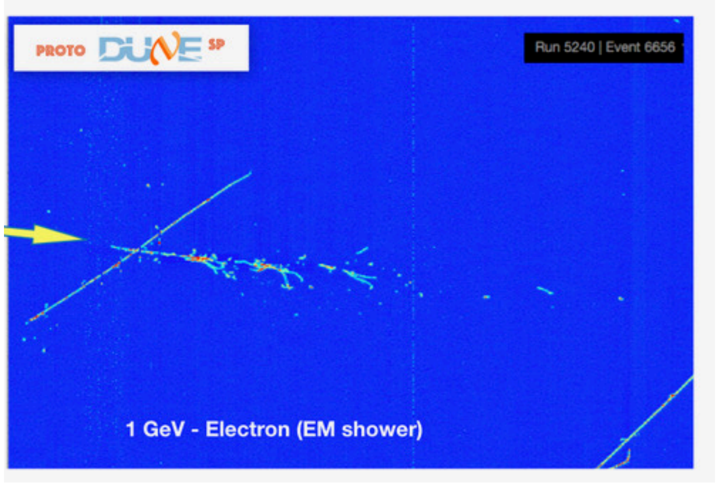


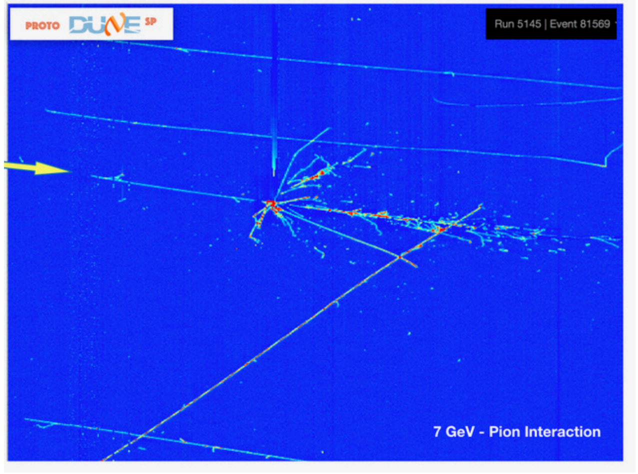


Preparing Detectors for DUNE

- Liquid Argon Detection Technique: electronic bubble chamber
- Need pure Liquid Argon in high electric field
- Examples: MicroBooNE, ICARUS
- 1kton-scale detectors at CERN, scalable design in test beam

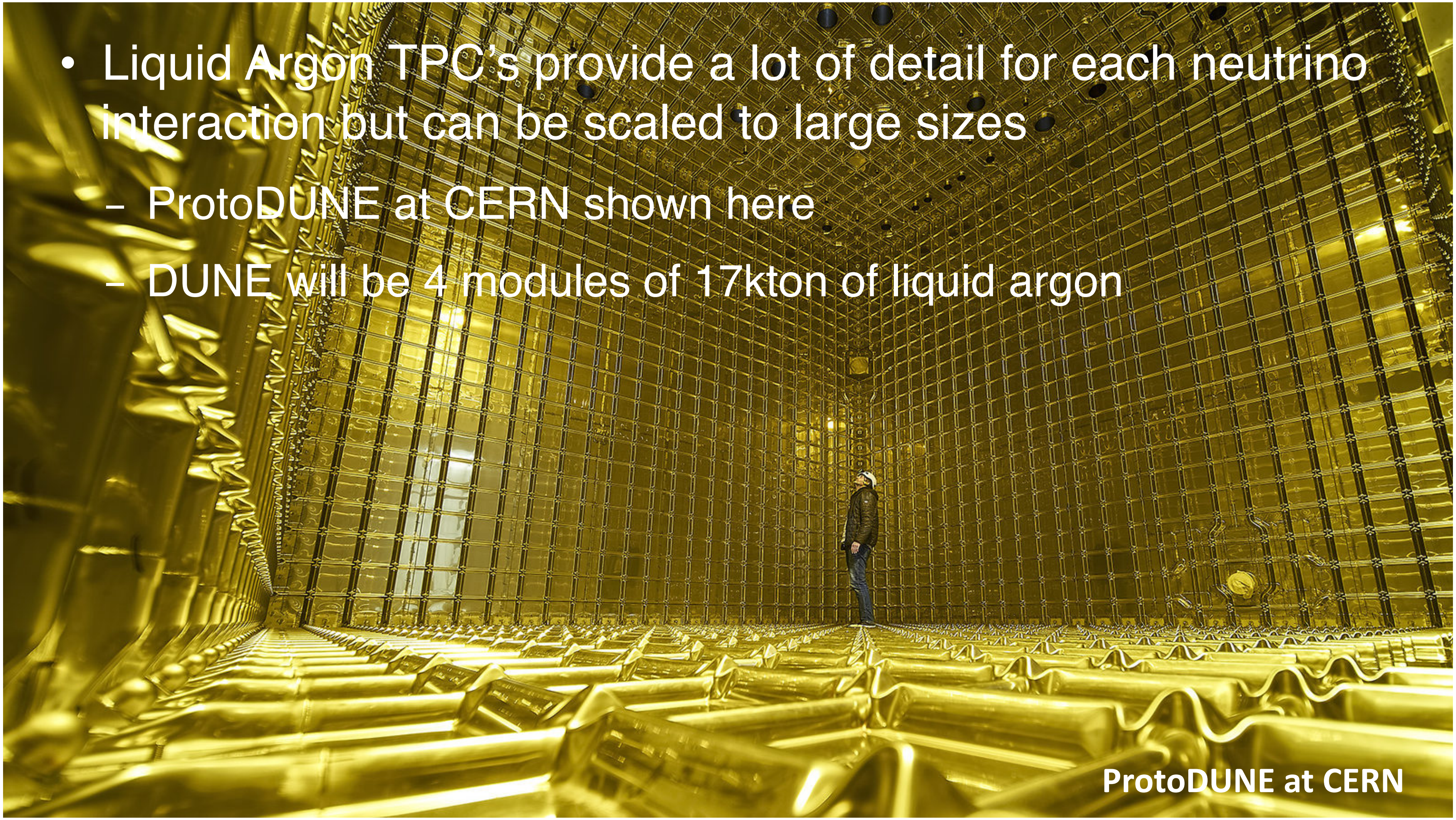






Preparing Detectors for DUNE

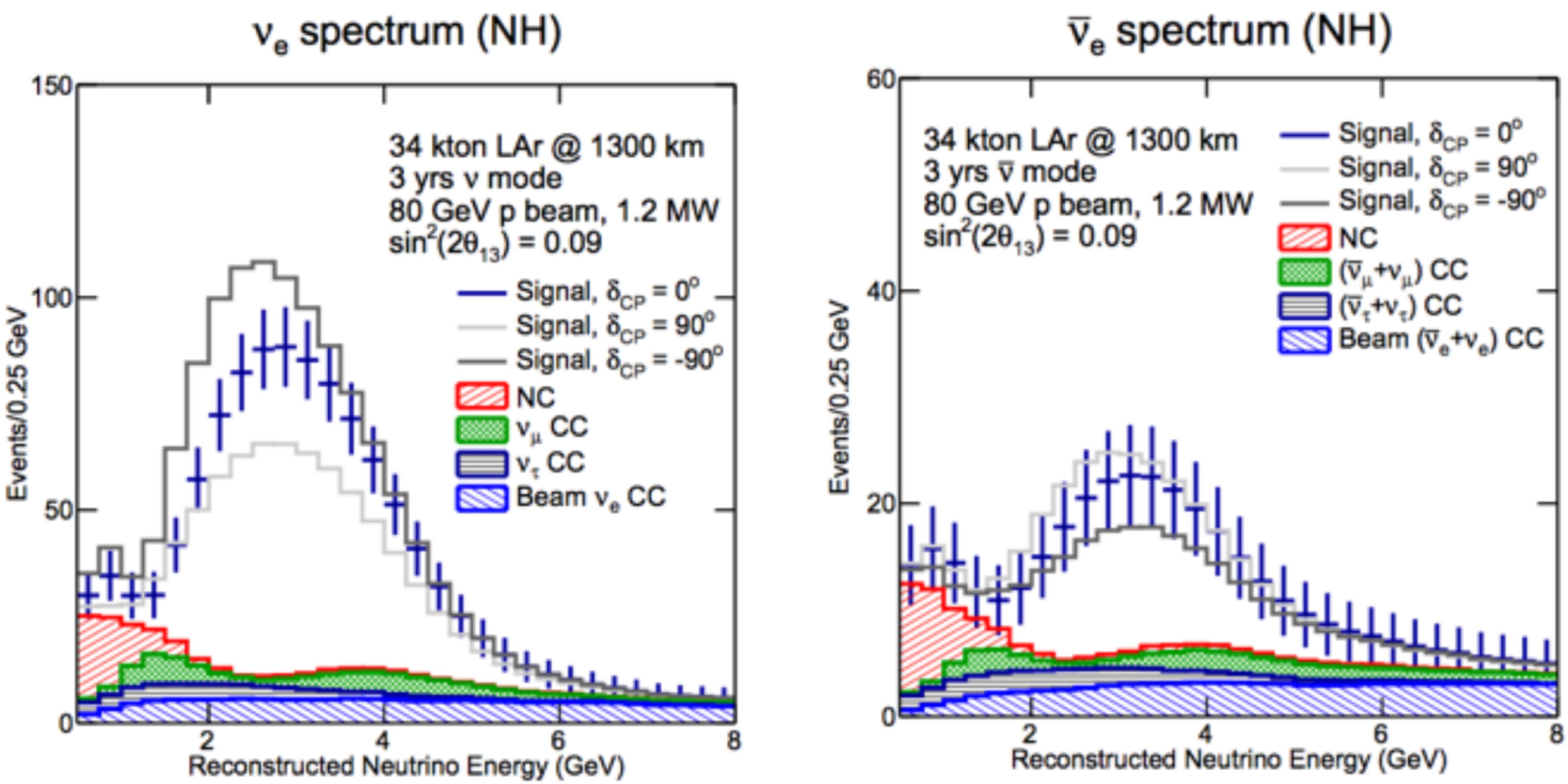
- Liquid Argon TPC's provide a lot of detail for each neutrino interaction but can be scaled to large sizes
  - ProtoDUNE at CERN shown here
  - DUNE will be 4 modules of 17kton of liquid argon



ProtoDUNE at CERN

Electron Appearance Signatures

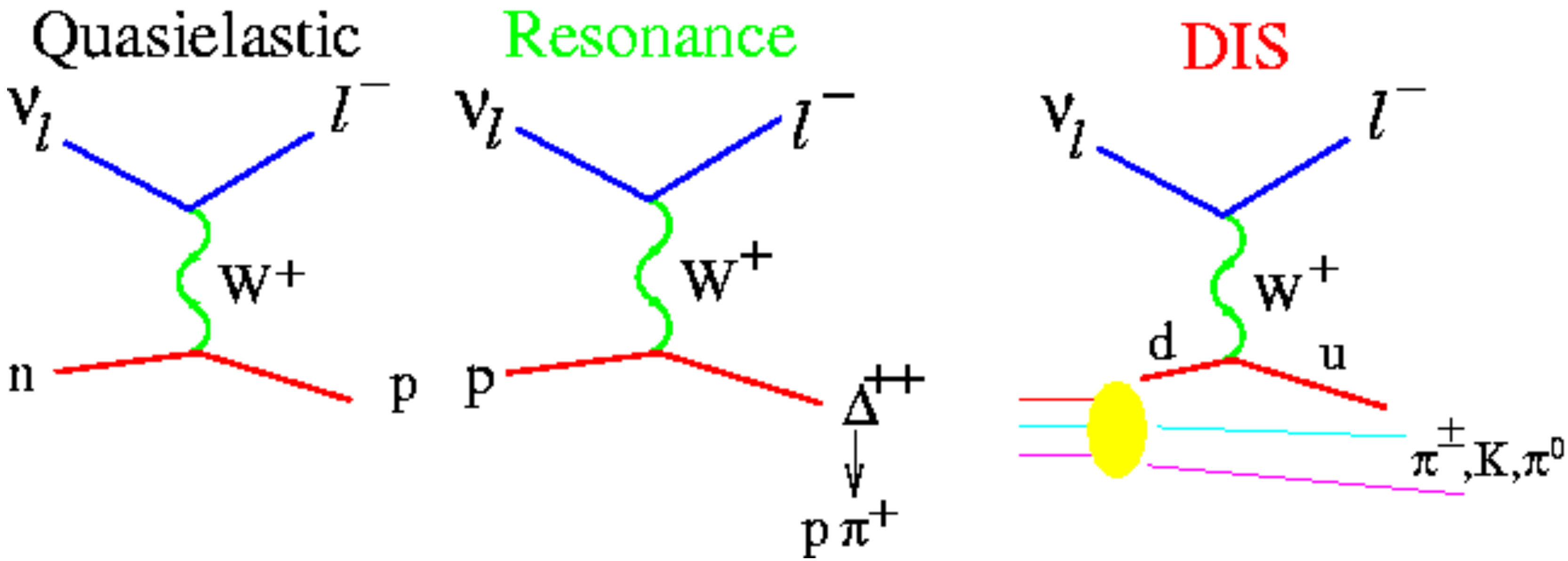
- Adding this all together: predicted energy spectra



- How do Neutrinos Deposit their energies in Detectors anyway?

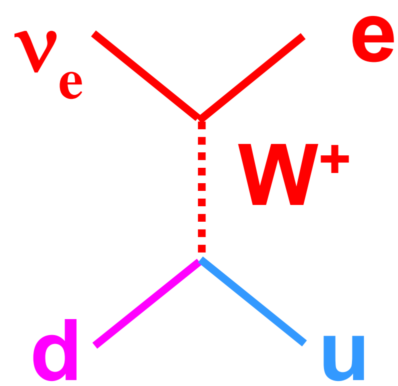
Neutrino Interactions at a few GeV

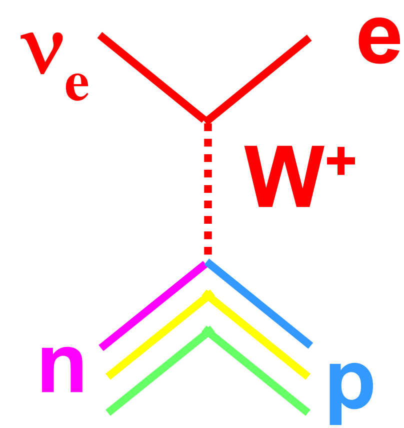
- Optics analogy: the wavelength of your probe determines what you can see
- High energy neutrinos can transfer more momentum, which means they can see smaller structure (quarks)

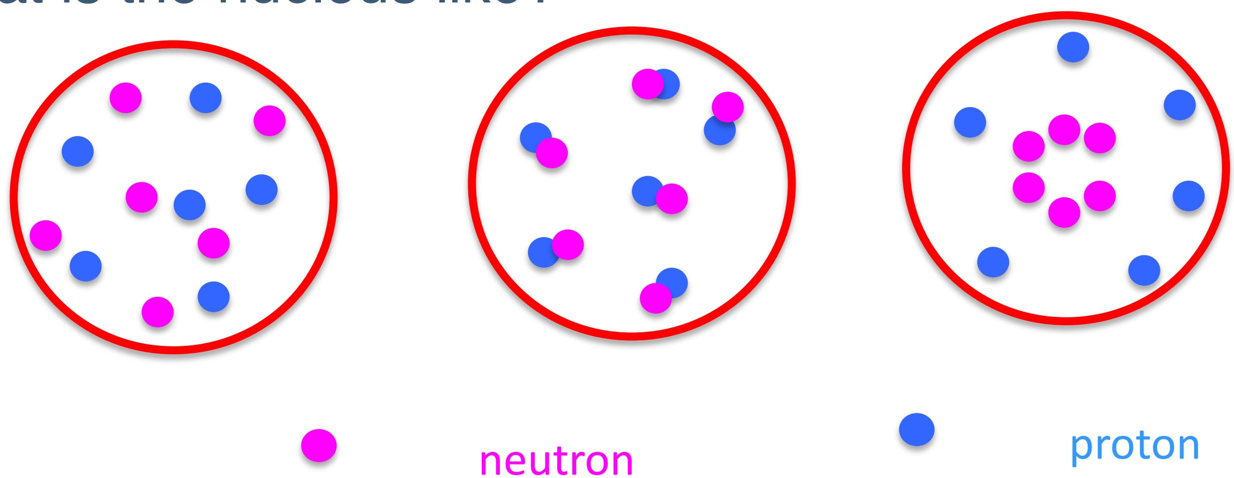


Complication: the nucleus

- Neutrinos may interact with individual quarks
- The quarks are in a proton or neutron
- The protons and neutrons are inside a nucleus
- What is the nucleus like?

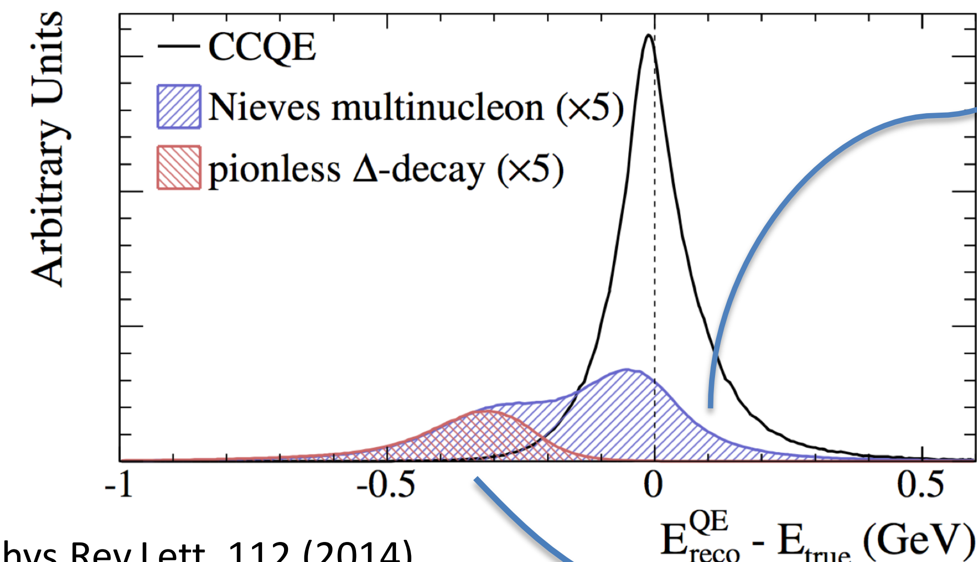




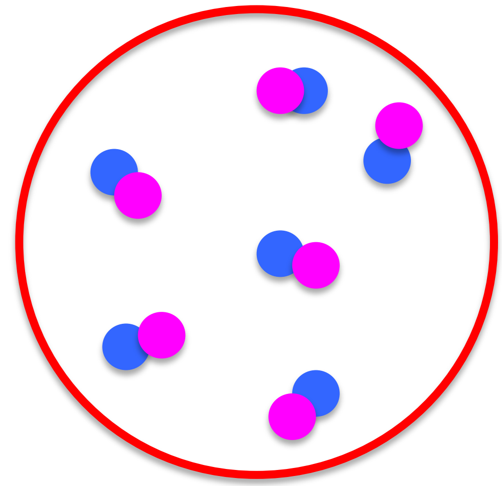


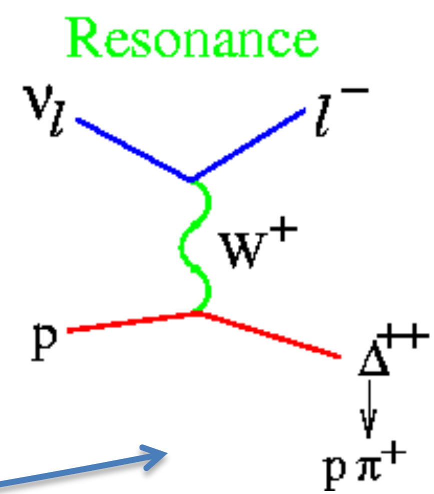
What does this mean for oscillation experiments?

- The neutrino energy you reconstruct can be biased.
- Today's experiments are already worrying about this!



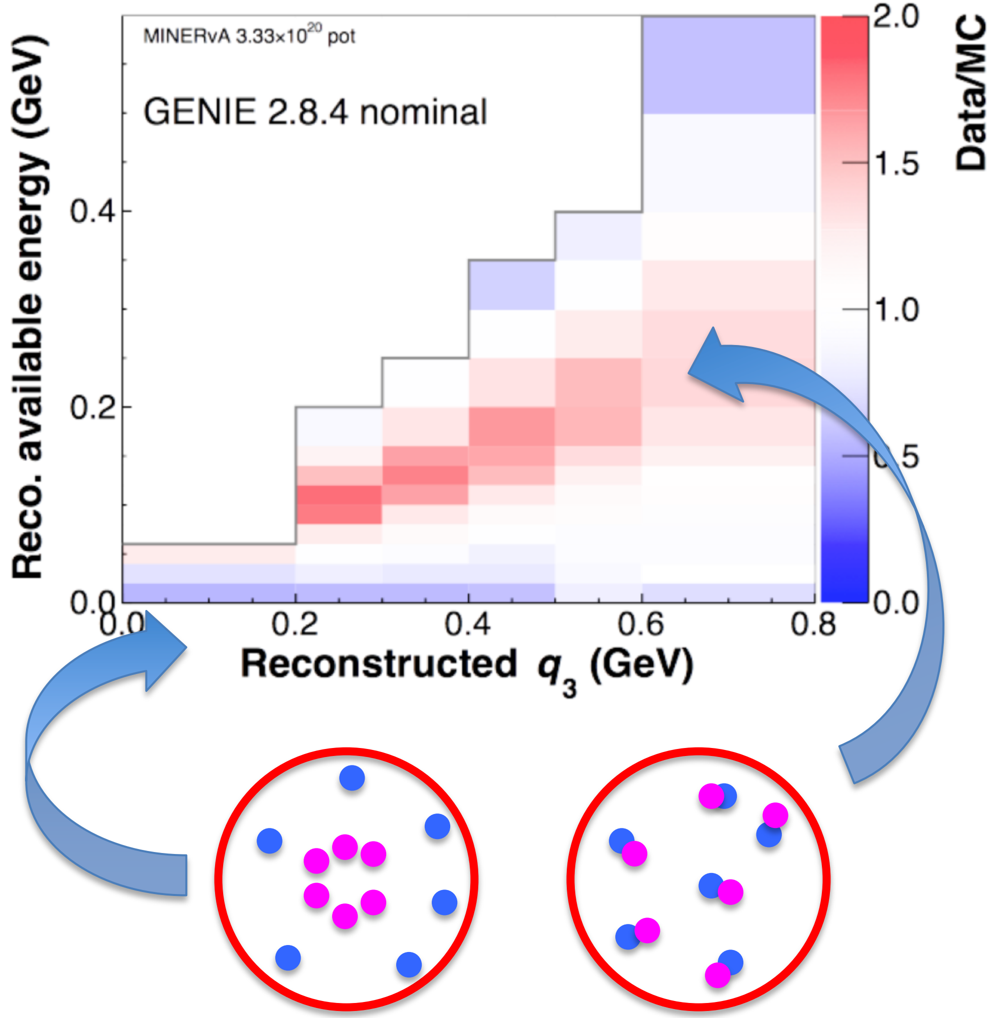
T2K, Phys.Rev.Lett. 112 (2014)





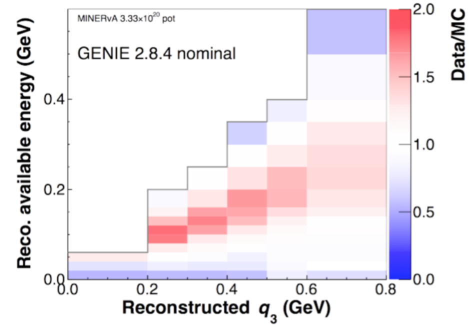
Preparing for DUNE at MINERvA

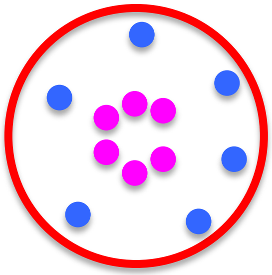
- MINERvA: cross section experiment at Ferimlab using fine-grained scintillator detector
- Cross section measured in two variables that show how the neutrino's energy is split between the outgoing muon and nuclear products.
- Oscillation experiments depend on modeling this split correctly!
- Does this model have any predictive power?

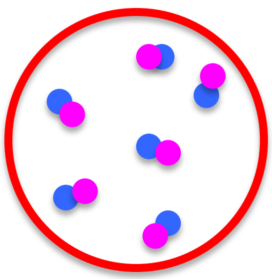


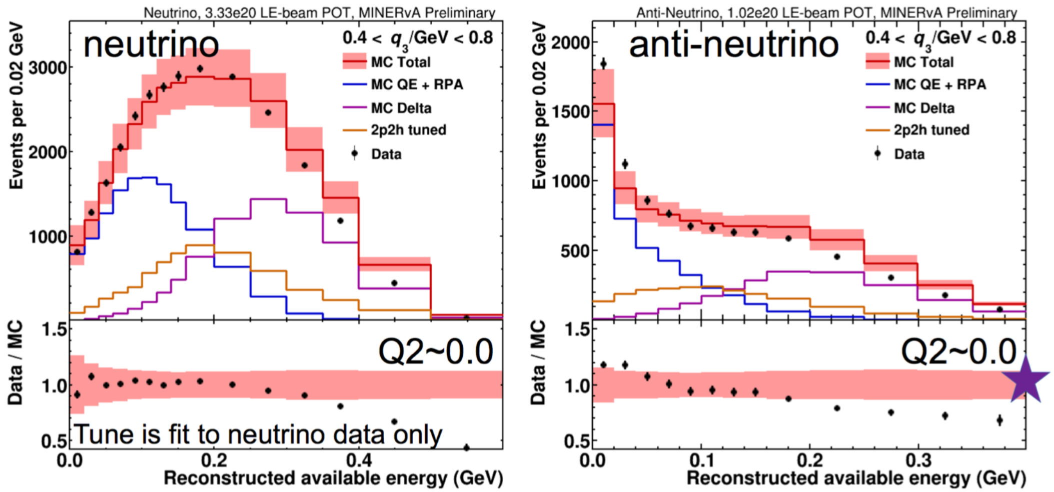
MINERvA Phys. Rev. Lett. 116, (2016)

Tune model with neutrinos, test with antineutrinos







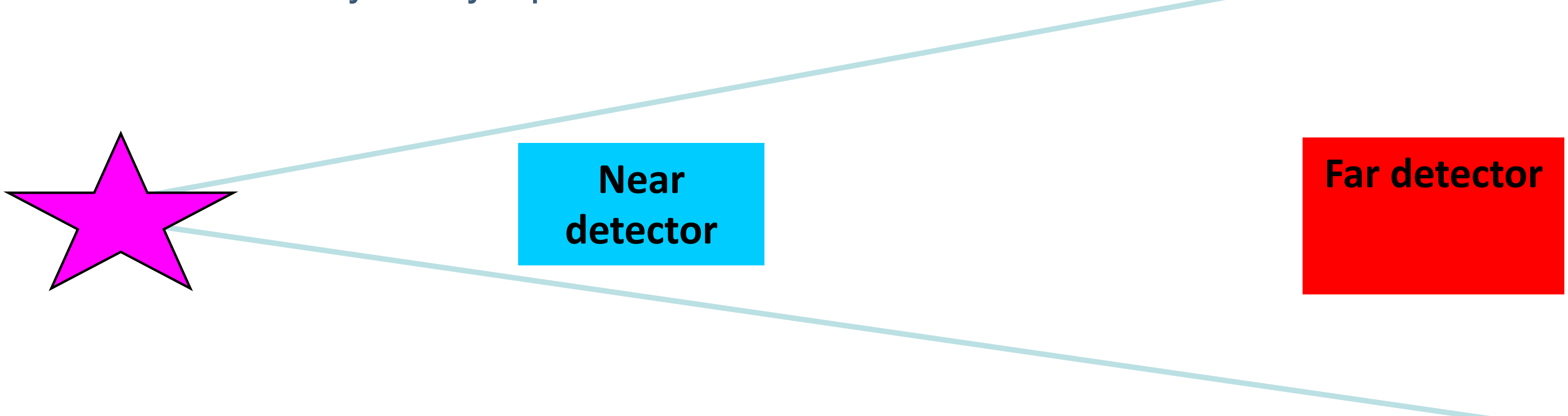


Phys. Rev. Lett. 116, (2016) and
Phys. Rev. Lett. 120, (2018)

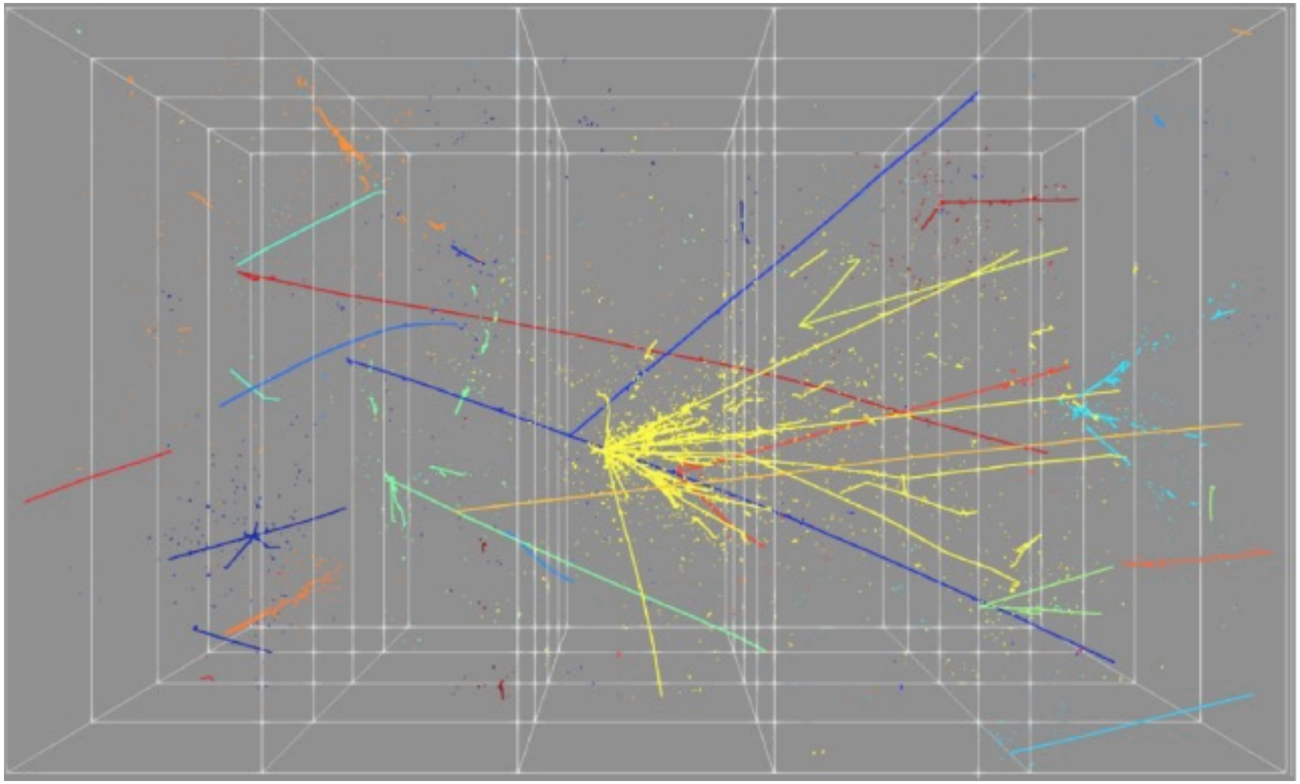
- Field of Precision Neutrino Interactions is expanding rapidly
- Demands from oscillation experiments are high, but beamlines are intense, rich data sets abound!

Back to
Predicting Neutrino Events and Energies

- Rates at far detector depend on many things:
  - flux, cross section, detector response
- Need several handles to get the best predictions
  - Capable Near Detectors
  - Reliable models of neutrino interactions
    - Informed by today’s precise neutrino interaction measurements



Neutrino Pileup?



For a 4x3x5m^3 detector at ~1km distance: each color is different neutrino
37M Charged Current ν_μ interactions per year (80 GeV protons, 1.5x10^{21} POT)

- Beam is so intense in near detector hall, need design change
- Challenge: still need to measure how well the far detector design can identify interactions!
- Solution: Modular design, pixels instead of wires to read out signals

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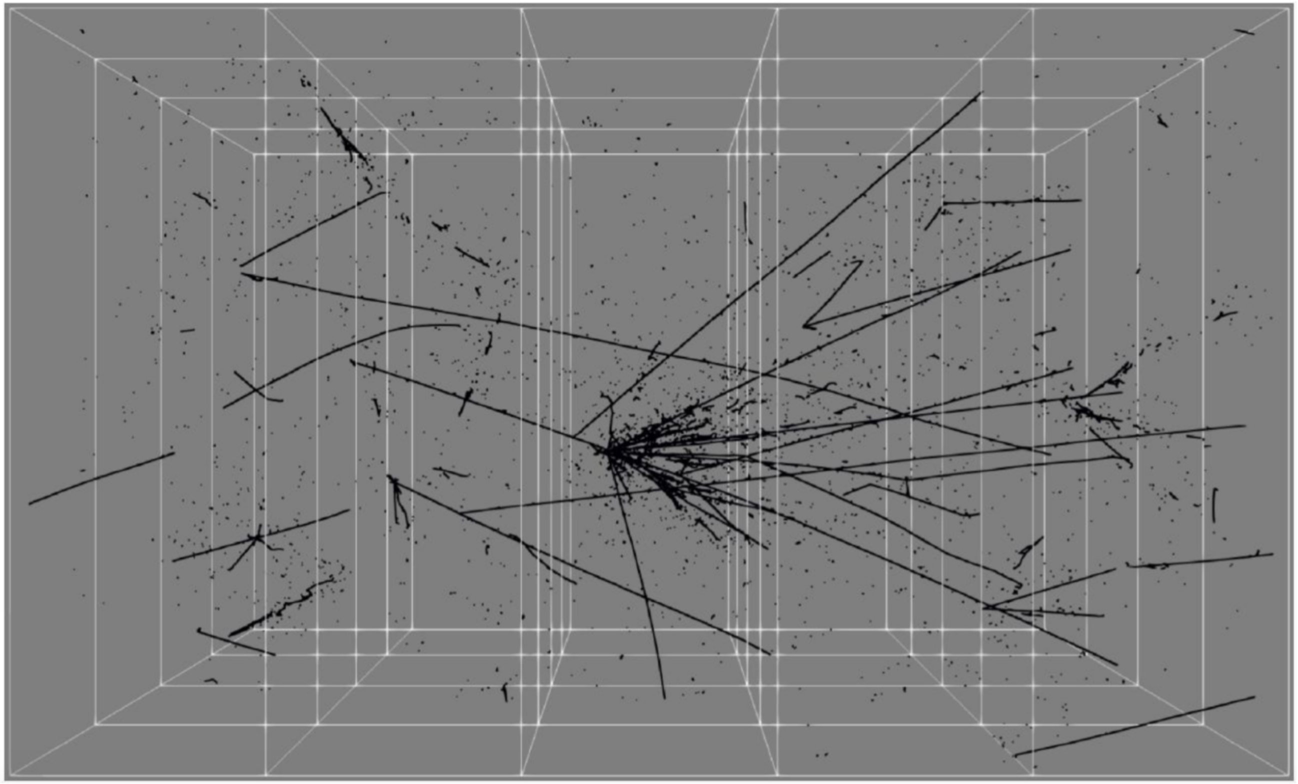

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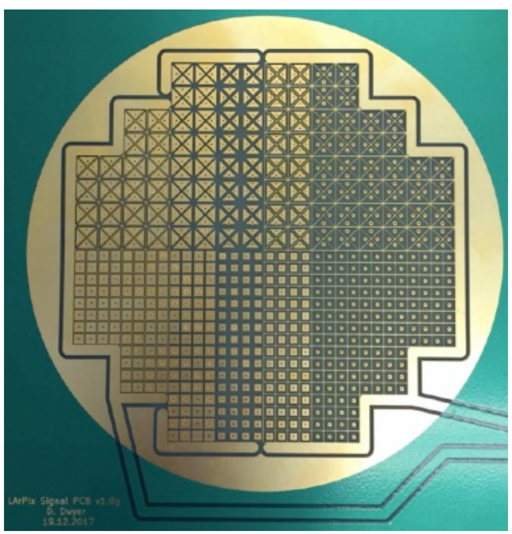
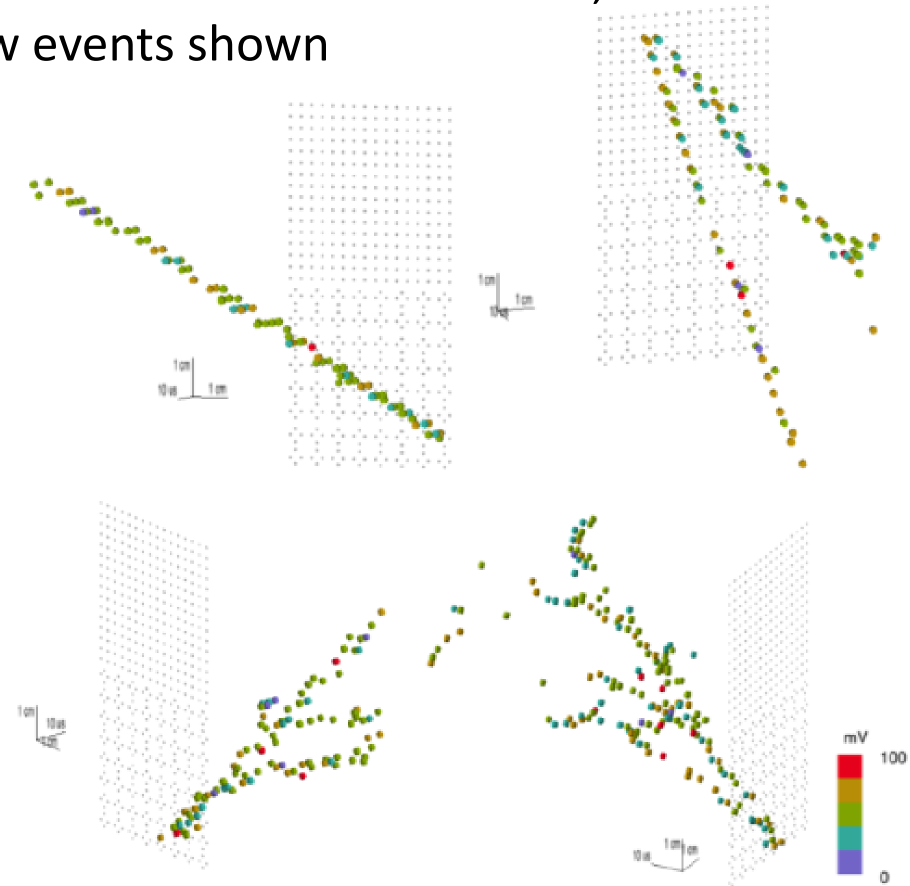
From wires to pixels in a TPC

- Pileup is reduced if you are reading out much less Argon per channel
- Challenge: exponential growth of number of readout channels
- Need low power on each readout channel to not boil the argon!



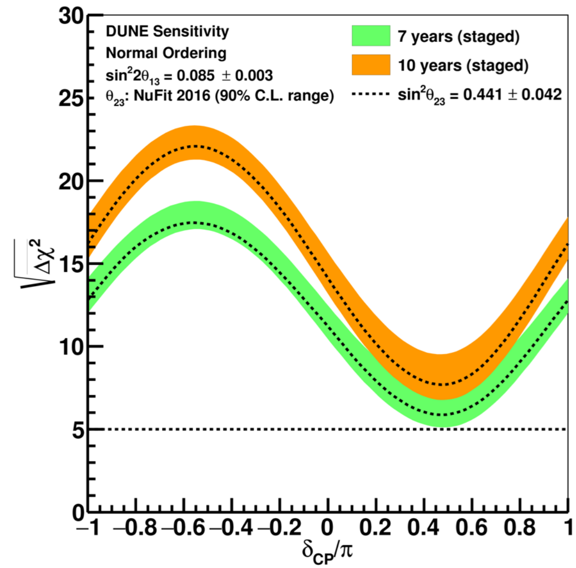
Cosmic ray interactions in test system using pixels across a 4.8x9.6cm^2 area, 60cm drift
Raw events shown



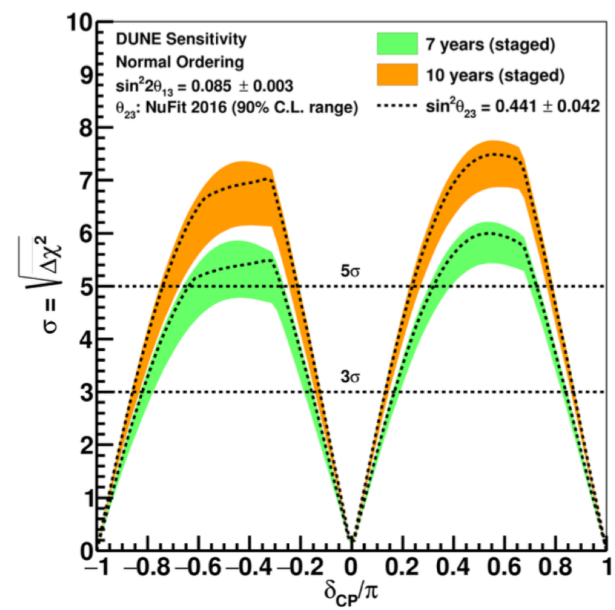
D. Dwyer et al, JINST 13 (2018) no.10, P10007

DUNE Physics Reach

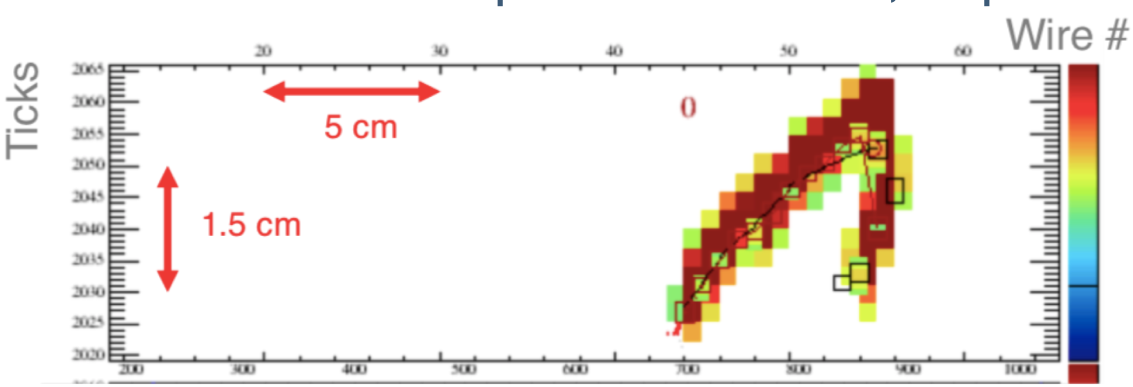
- Mass Ordering: should get to see this in first few years of run
- CP Violation: definitive test over 50% of parameter space!
- Able to test the framework with broad energy range
- Sensitive to supernovae burst, expect



Mass hierarchy



CP VIOLATION



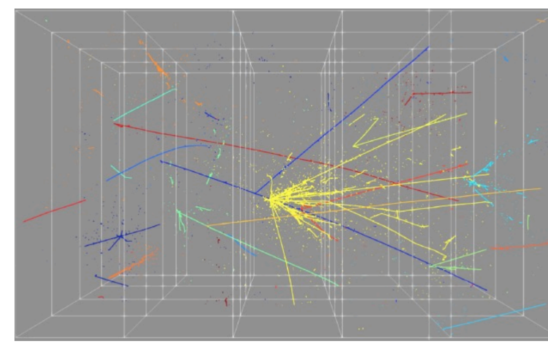
DUNE Simulation 30 MeV ν (supernovae)

Fermilab YORK UNIVERSITY DUNE

Conclusions

- Neutrino Interferometry is a powerful tool to explore the universe
  - Glimpse into why we are here
  - Input on what gives particles their masses

- Big Questions lead to Big Challenges
  - Better understanding of neutrino interactions
  - Higher power neutrino beamlines
  - Bigger better detectors
  - New detector ideas:
    "neutrino event pileup" is real



- Always need to be ready for surprises: DUNE's broad band neutrino energy and unique detector capabilities ensures we will be ready!

Thank you!   Merci!

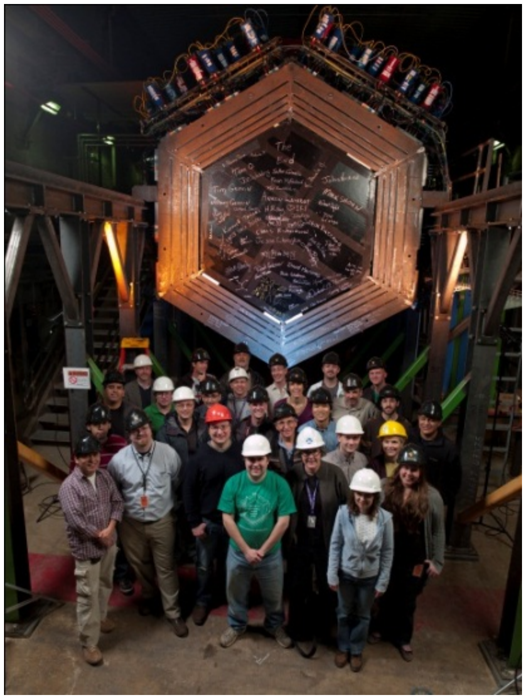


Photo credit: R. Hahn, Fermilab