Long Baseline Oscillations Part 2

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TRISEP School

Schedule

- First Lecture
  - Reminders from Monday's lectures:
    - What do we want to measure with neutrinos, again?
  - What does "long baseline" mean?
  - What neutrino sources are available?
  - How do neutrinos interact?
- Second Lecture
  - What can neutrino detectors measure?
  - What neutrino detectors are in use now for long baselines?
  - Putting it all together—the 2-detector experiment paradigm
  - Where are we now? (T2K and NOvA, detour to SBN)
  - Coping strategies: how can you get to precision?
  - Next Steps for long baselines: (DUNE and HyperK)

(at "long baseline" energies)?

Topics: Neutrino Detectors

- Introduction
  - Detector requirements (for long baseline oscillations)
- Detectors
  - Cerenkov Detectors
  - Scintillator (partially already covered)
  - Sampling Calorimeters
  - Liquid Argon TPC's

Oscillation Detector Goals

- Identify flavour of neutrino $P = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
  - Need charged current events!
  - Accelerator sources: Lepton Identification (e,μ,τ)
- Measure neutrino energy
  - Charged Current Quasi-elastic Events $\bar{\nu} p \rightarrow l^+ n$
    - In principle, all you need is the lepton angle and energy *(derive)* $\nu n \rightarrow l^- p$
  - Everything Else
    - Need to measure energy of lepton and of X, where X is the hadronic shower, the extra pion(s) that is (are) made..

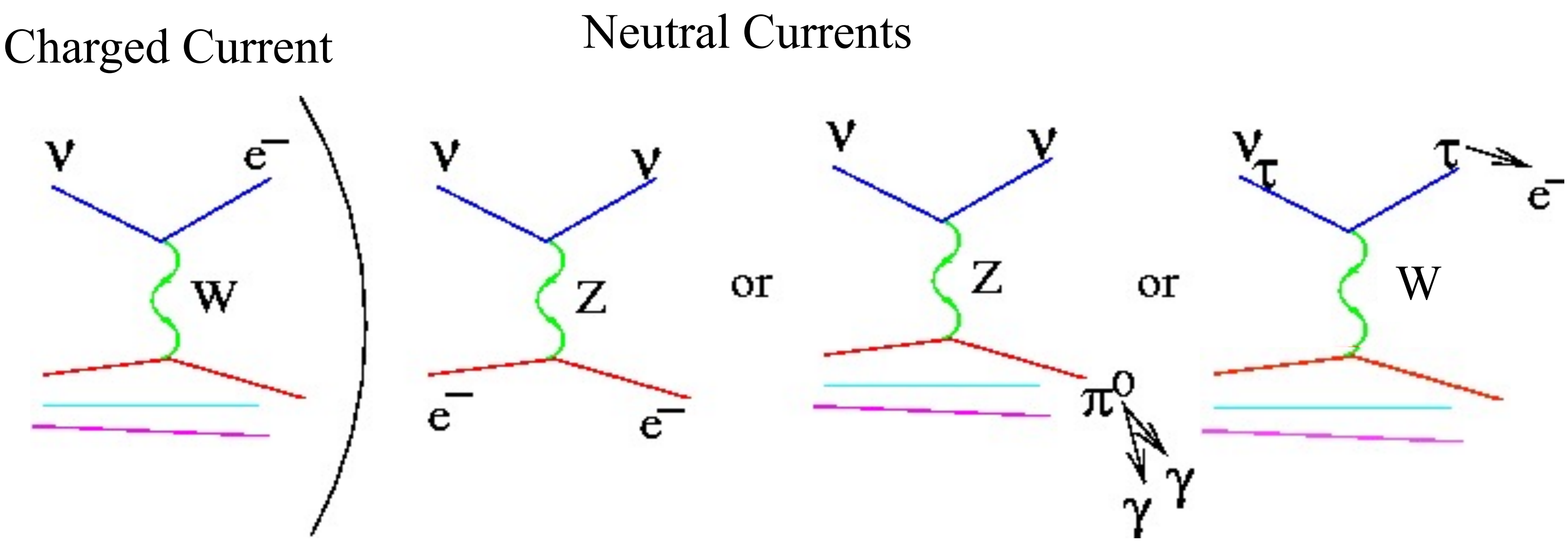
$$\nu N \rightarrow lX$$

Neutrino Oscillation Goals vs ν Sources

- Atmosphere (ν_μ, ν_e and anti-ν_μ, anti-ν_e)
  - Need to identify at least muons
  - Get baseline from direction of outgoing e or μ
- Conventional Beams (ν_μ, %ν_e)
  - Identify muon and electron in final state
- Remember question from Tuesday:
  - Do you need a magnetic field in your detector?
    - Depends on whether you need to distinguish ν_μ, ν_e from anti-ν_μ, anti-ν_e

Detectors and Backgrounds…

- Depending on your detector, you may see lots of things that look like signal but aren't…



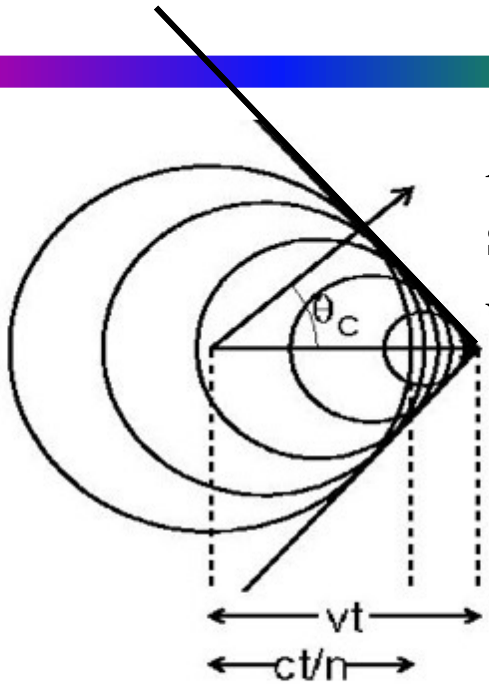
Very Incomplete Survey of ‘Long Baseline” Neutrino Detectors

- Cerenkov Detectors
  - Water Cerenkov
  - Heavy Water Cerenkov
- Scintillator Detectors
  - Liquid Scintillator (been there, done that)
  - Segmented scintillator
- Active/Passive Detectors
  - Steel plus tracker
  - Emulsion
  - Ice (in backups)
- Liquid Argon TPC

Given what you’ve heard from Michelle, will concentrate on Water Cerenkov and Liquid Argon TPC

CERENKOV DETECTORS

Cerenkov Light



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

$$\beta \equiv \frac{v}{c} \qquad \beta > \frac{1}{n}$$

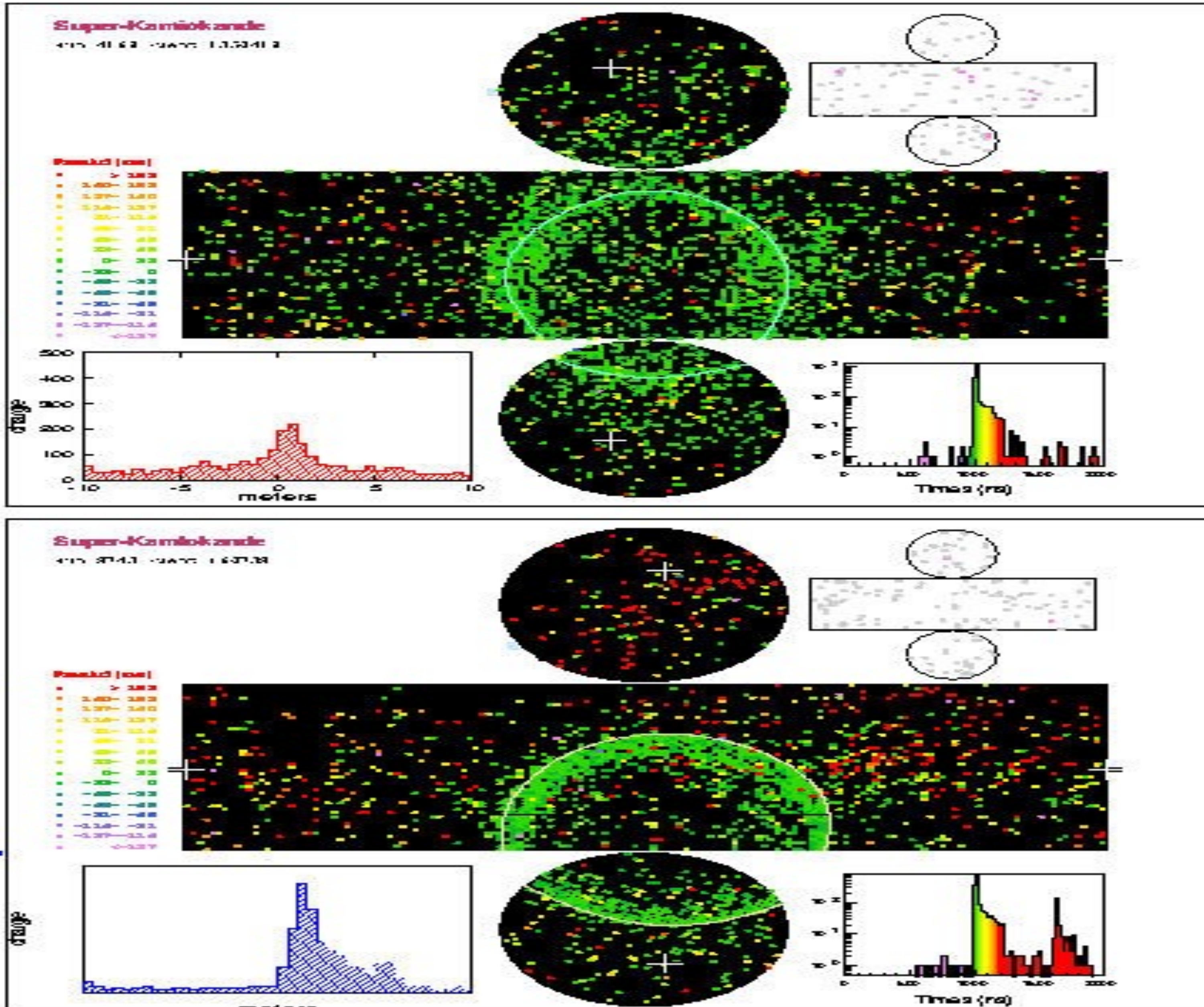
$$\theta_c = \cos^{-1}(1/n(\lambda))$$

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

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

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

e-like



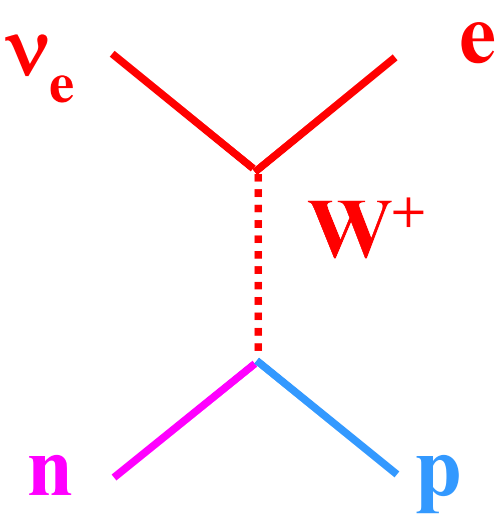
μ-like

2GeV
neutrino
interaction

Measuring Neutrino Energy

- Should be easy, right?
  - Assume neutron or proton at rest
  - IF you know initial direction of neutrino…
  - Final direction and energy of electron should suffice to get to the neutrino energy

$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$



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

$E_\mu = T_\mu + m_\mu$	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

- Caveats:
  - lots of things that look quasi-elastic are NOT, if you can't see pions!
  - Need to include details on initial neutron momentum, binding energy, nuclear physics!

ACTIVE/PASSIVE DETECTORS

Steel/Scintillator Detector (MINOS)

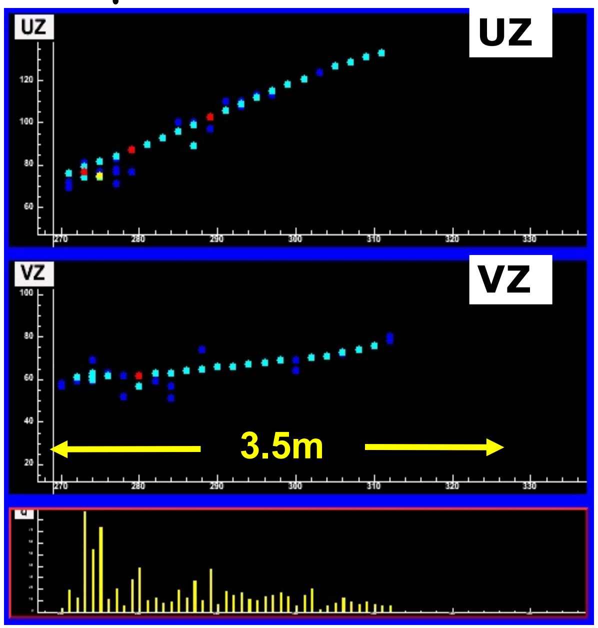
1T Magnetic field!

- 8m octagon steel & scintillator calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 5.4 kton total mass
  - 95,000 strips
- ν peak energies of 3-6GeV all the way to 50GeV

MINOS Event Topologies

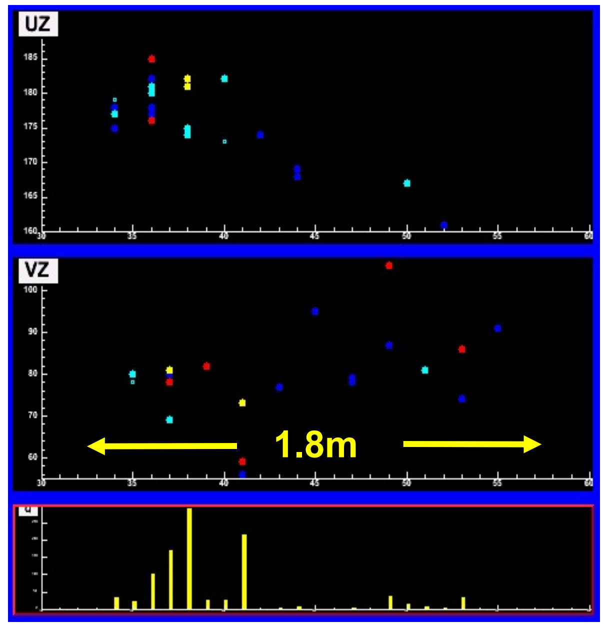
Courtesy Chris Smith, FNAL Seminar

ν_μ CC Event



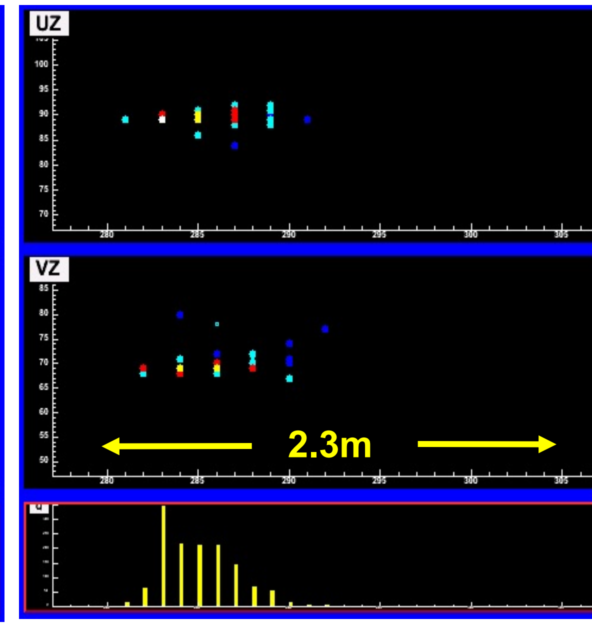
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

ν_e CC Event



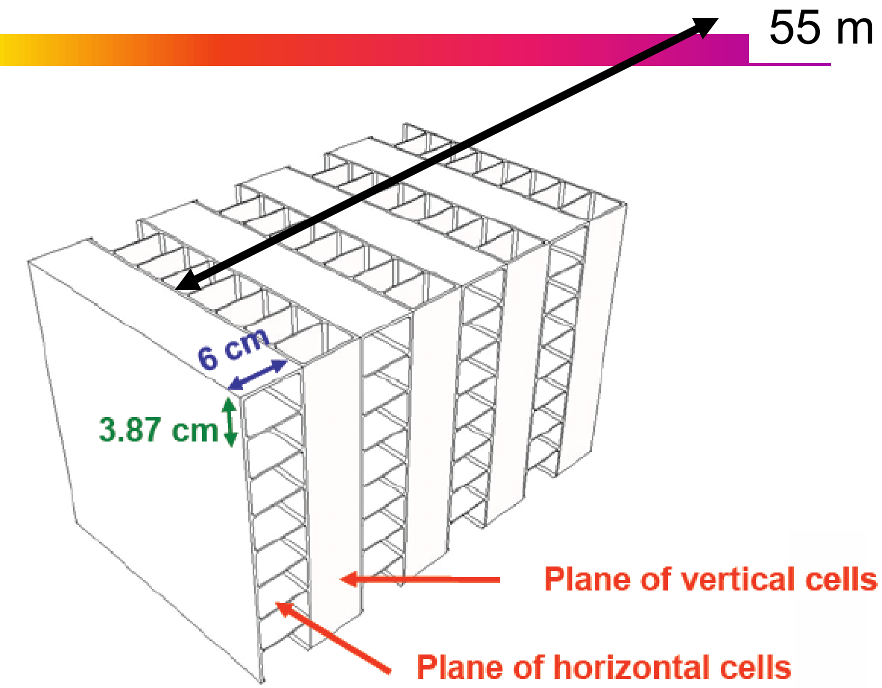
- Short event with typical EM shower profile

$$E_\nu = E_{shower} + P_\mu$$

Shower energy resolution: 55%/√E

Muon momentum resolution: 6% range; 13% curvature

Segmented Scintillator (NOvA)



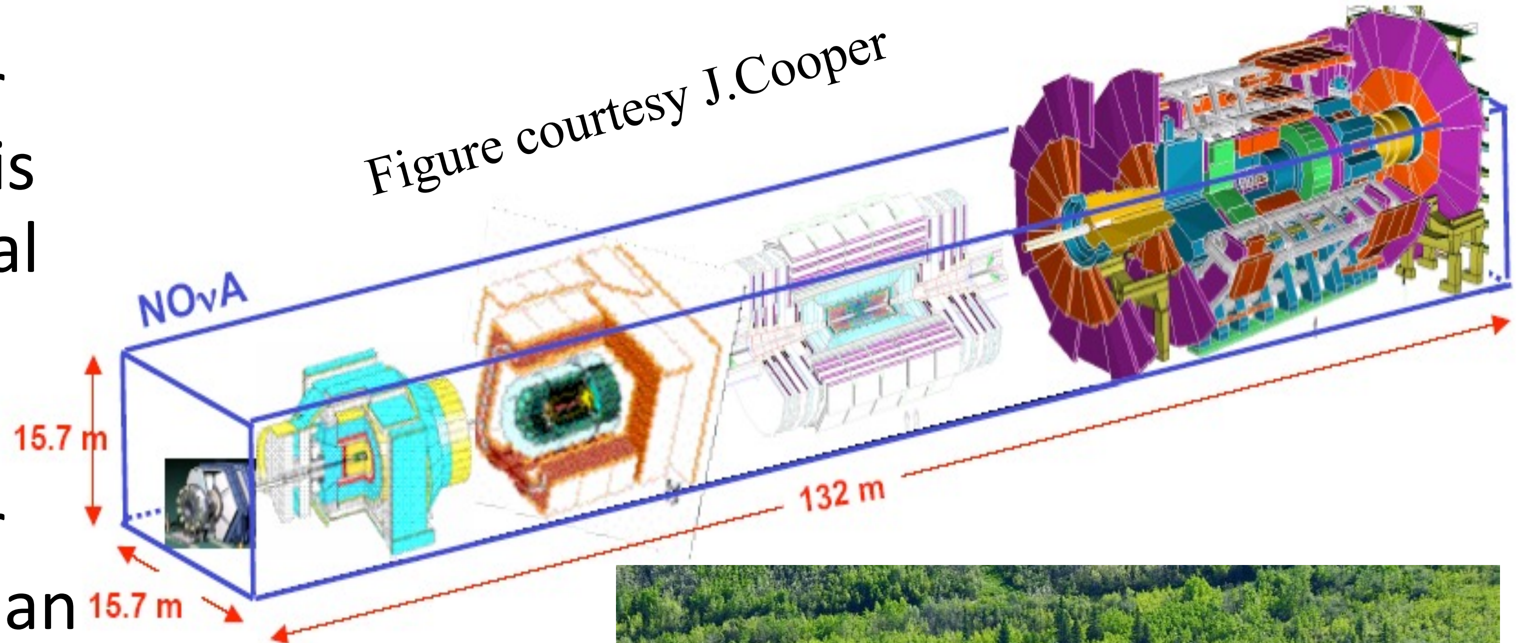
- PVC extrusions
  - 16m tall x 16m wide x 55m long
  - 3.9 cm transverse, 6.6 cm wide in beam direction
- All Liquid Scintillator
  - 85% scintillator, 15% PVC

To Build:
Glue Planes of Extrusions together
Rotate them from horizontal to vertical
Fill Extrusions with Liquid Scintillator
Each box gets a WLS fiber loop (bent at far end)
Instrument WLS fibers with Advanced PhotoDiodes, repeat

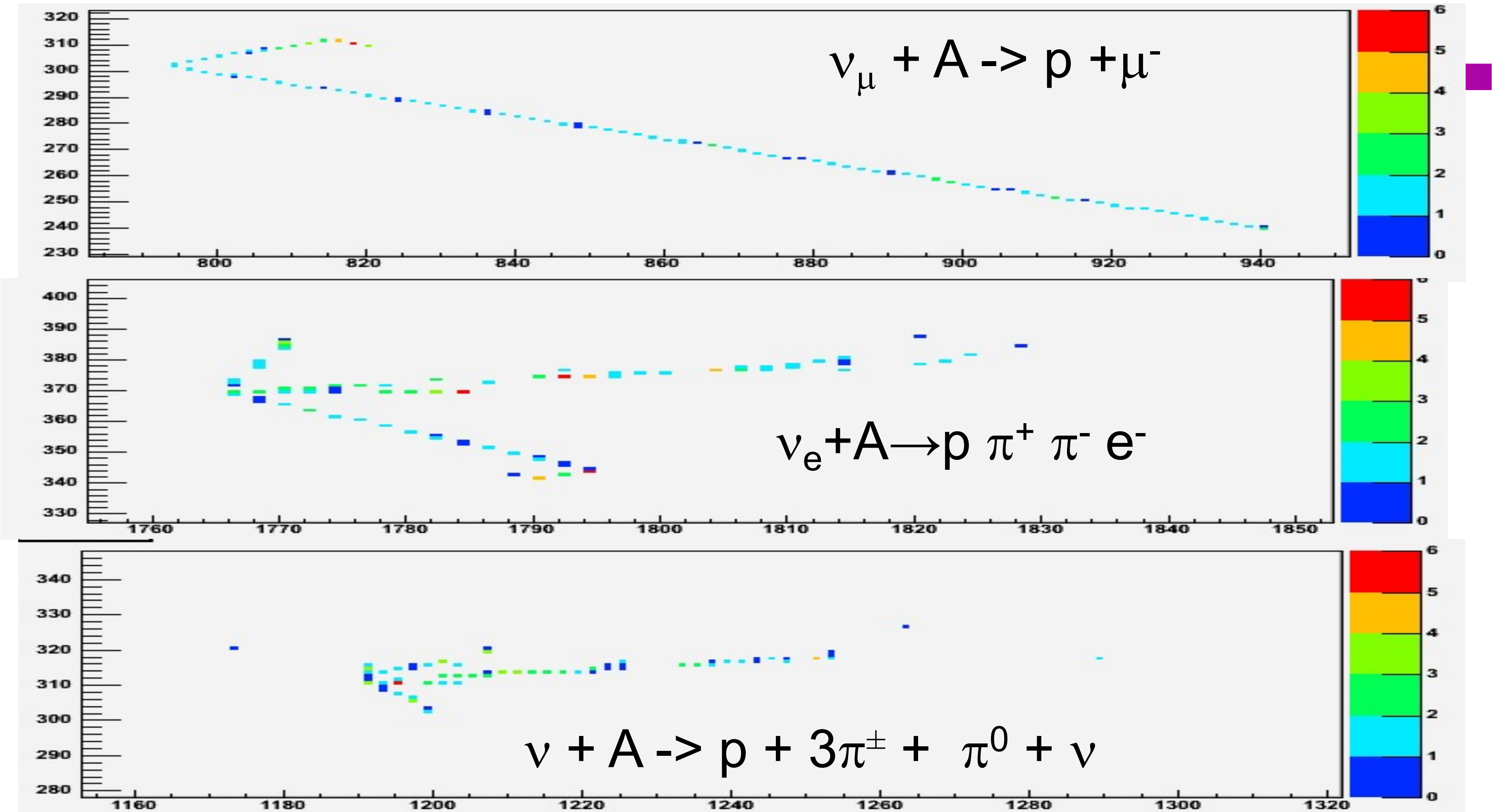
Detector Volume

- Scaling detector volume is not trivial

- NOvA detector larger than ATLAS+CMS +CDF+D0 together, at 14kTon



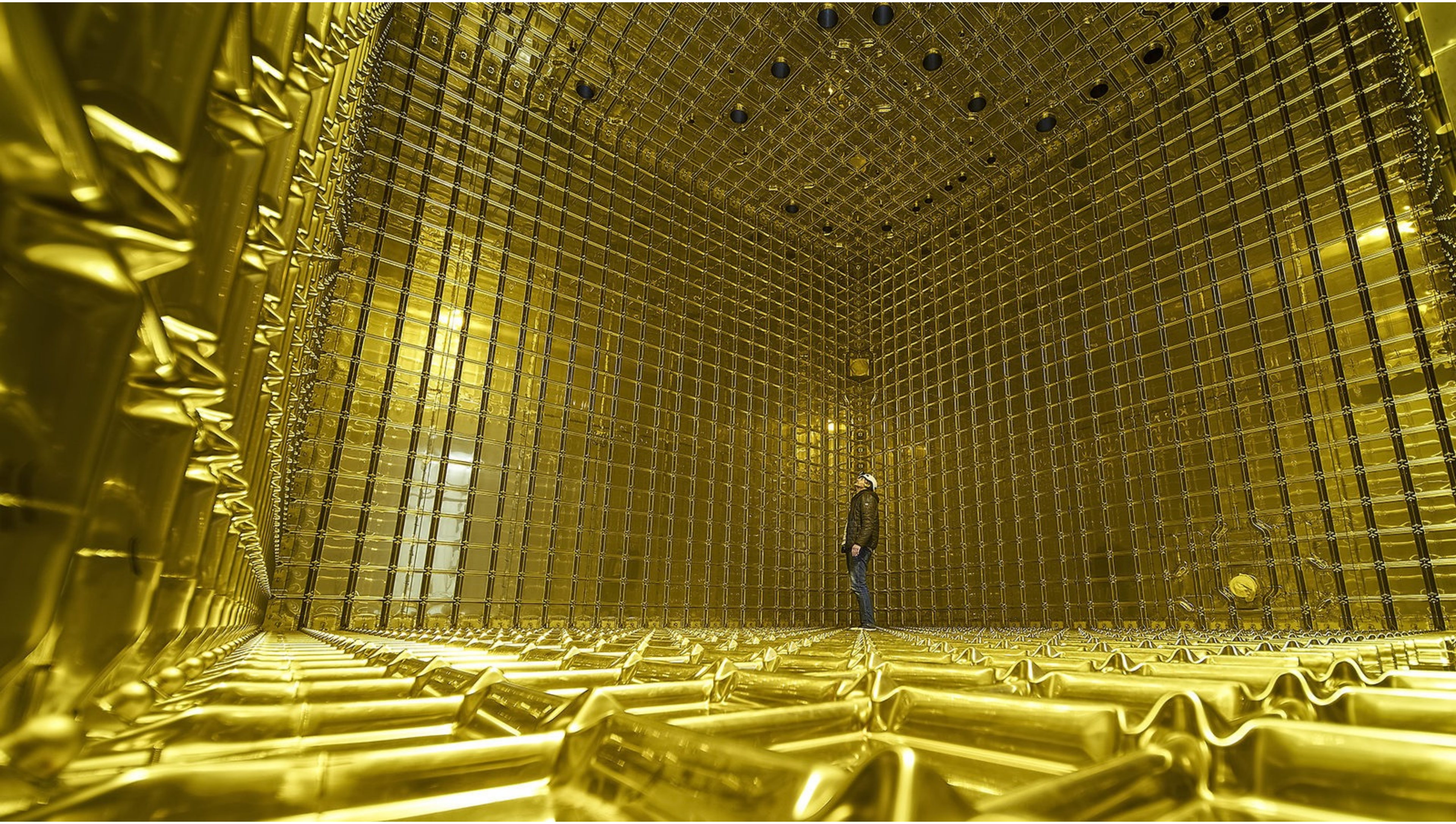
Scintillator Events (2GeV)



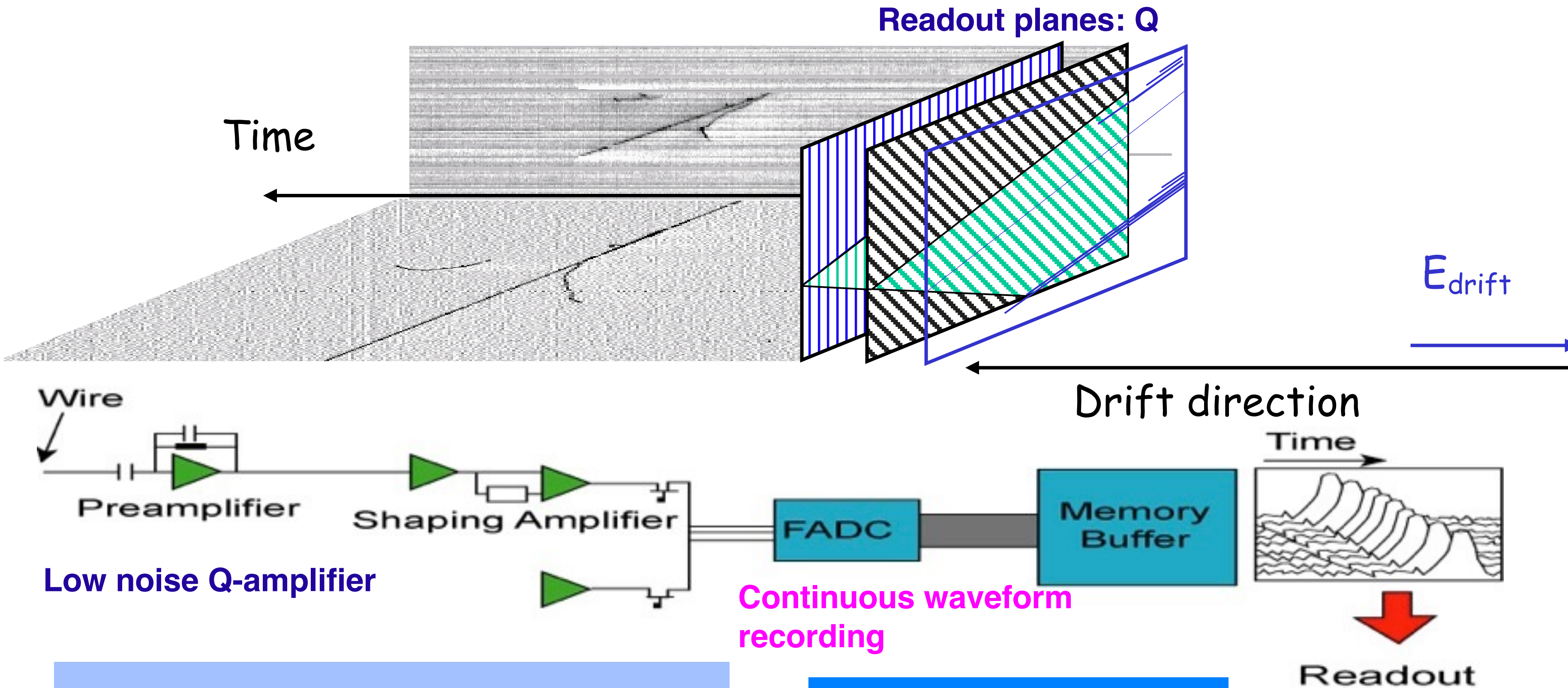
One unit is 4.9 cm (horizontal)
4.0 cm (vertical)
Energy measurement: muon plus everything else

Particle ID:
- particularly "fuzzy" e's
- long track, not fuzzy (μ)
- large energy deposition (proton?)
- gaps in tracks (π^0 ?)

LIQUID ARGON TPC



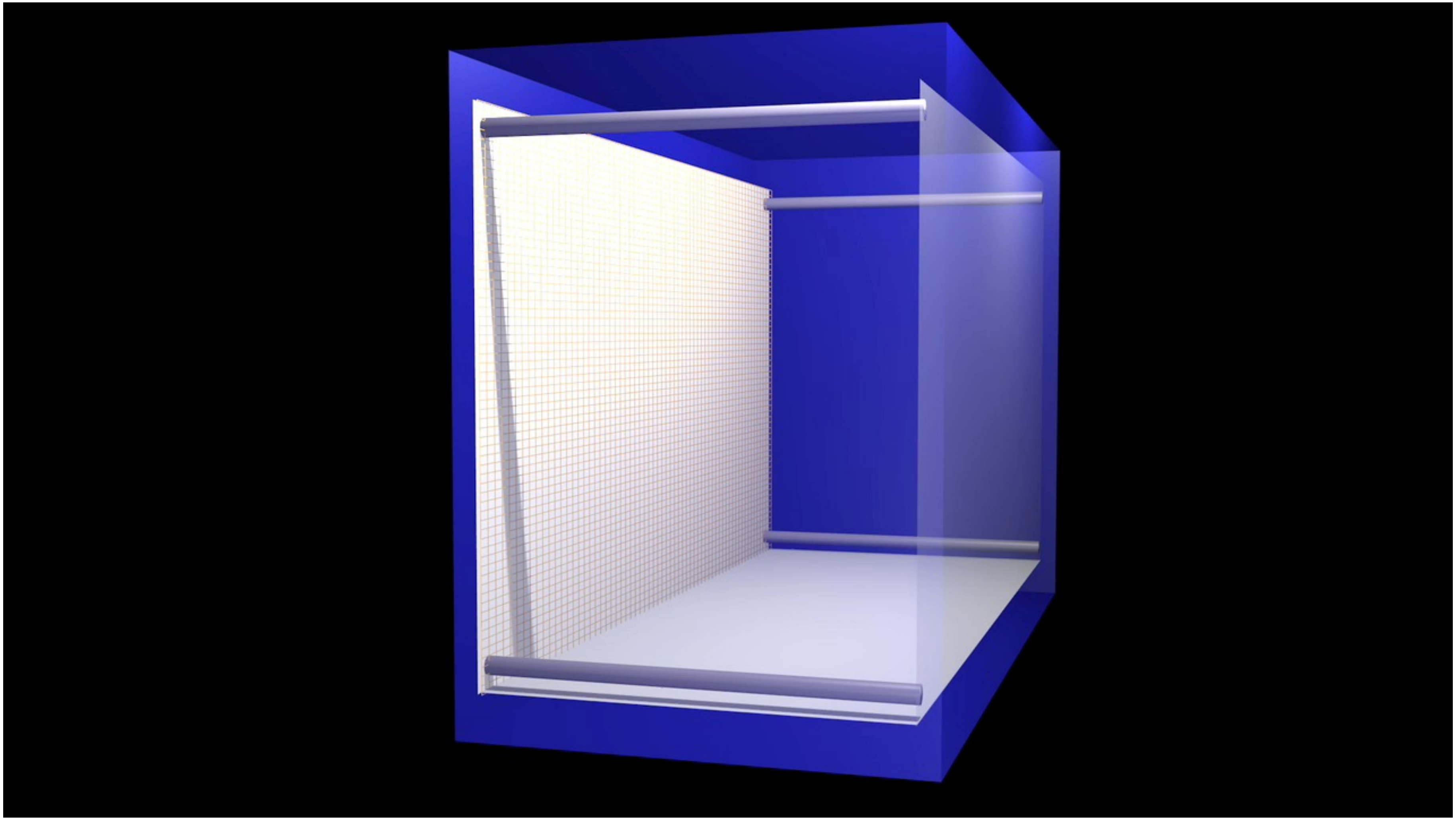
Liquid Argon Time Projection Chamber



- Ingredients
  - Very pure argon
  - Strong electric field
  - Several planes of wires

dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar
Density: 1.4 g/cm3
Xo=14cm
lINT =83cm

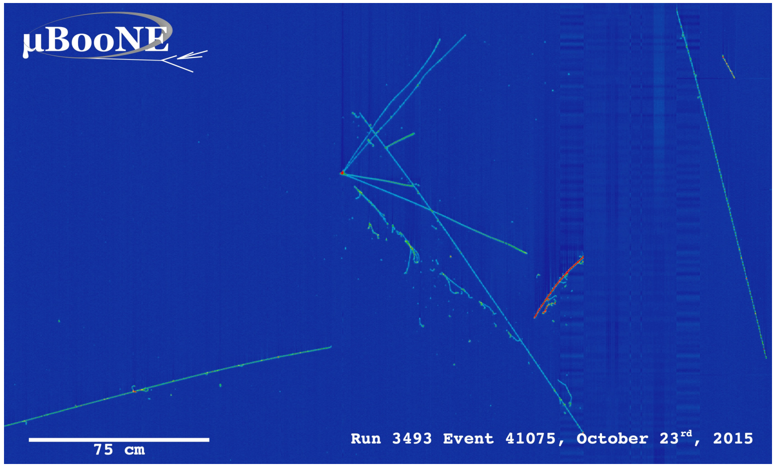
Liquid Argon Time Projection Chamber

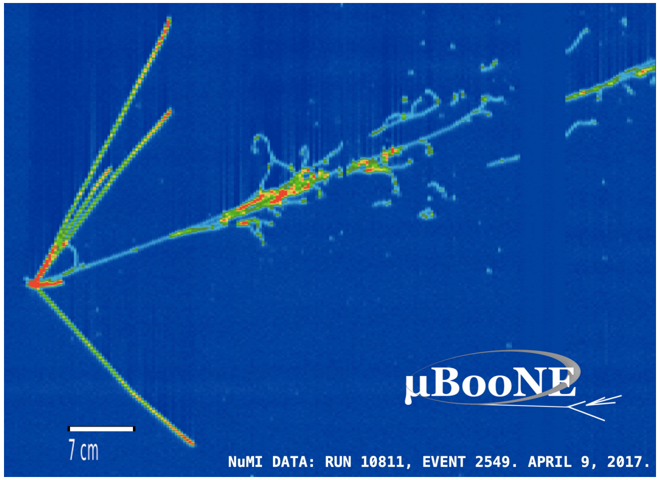


MicroBooNE/ICARUS/ProtoDUNE

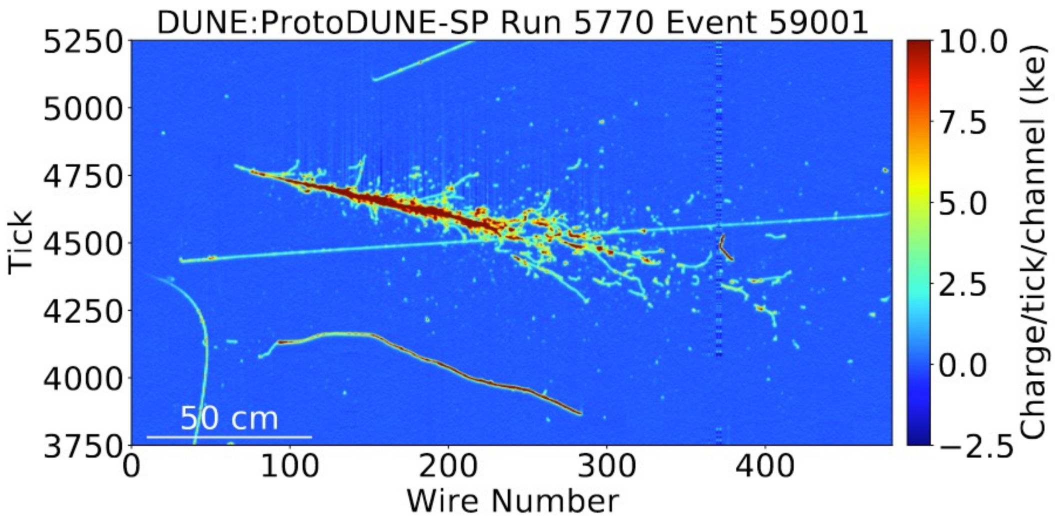
- Active mass: from 87 tons to 770 tons
- Wire spacing: 3mm (both)
- Electron drift distance: 1.5m-2.5m
- 54000 wires/10000 wires
- Collect scintillation light from Argon (timing)
- ICARUS: <E_ν> ~ 0.8-20GeV, L=1-730km
  - Took data in Italy and now in the US (FNAL)
- MicroBooNE: <E_ν>~0.8GeV, L=1km
- ProtoDUNE: π,e,p data in CERN test beam
- DUNE: <E_ν> ~ 2-3GeV, L=1200km
  - Runnning by 2028?

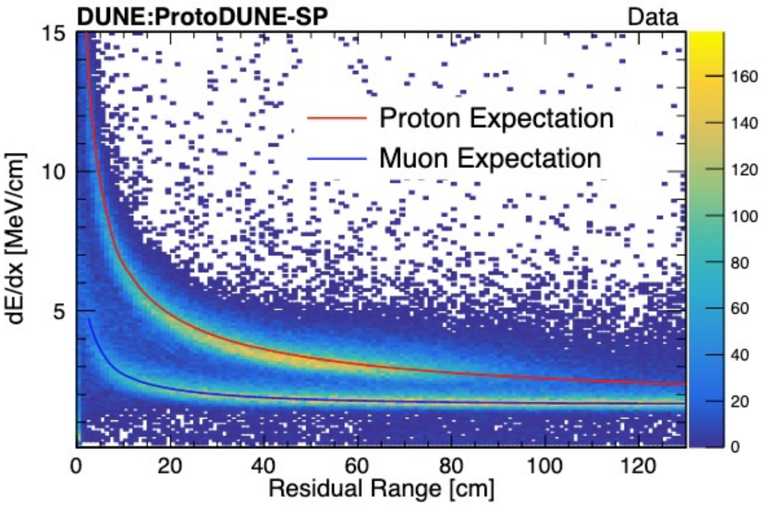
ν and e Events in Liquid Argon





https://microboone-exp.fnal.gov





JINST 15, P12004 (2020) arXiv:2007.06722

Detector Summary

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal ν Energy Range
		ν_e	ν_μ	ν_τ		
Liquid Ar TPC	0.77	✓	✓		Not yet	huge
Water Cerenkov	50 (or 1000*)	✓	✓	✓ **		<2GeV 10-1000GeV*
Emulsion/Pb/Fe	0.27	✓	✓	✓		>.5GeV
Scintillator++	14	✓	✓			huge
Steel/Scint.	5.4		✓		✓	>.5GeV

*if you include ICECUBE…
**sort of…ask me if you're curious

Moral of this story: how you measure a neutrino's energy varies greatly…

WE HAVE BEAM + DETECTOR, NOW WHAT?

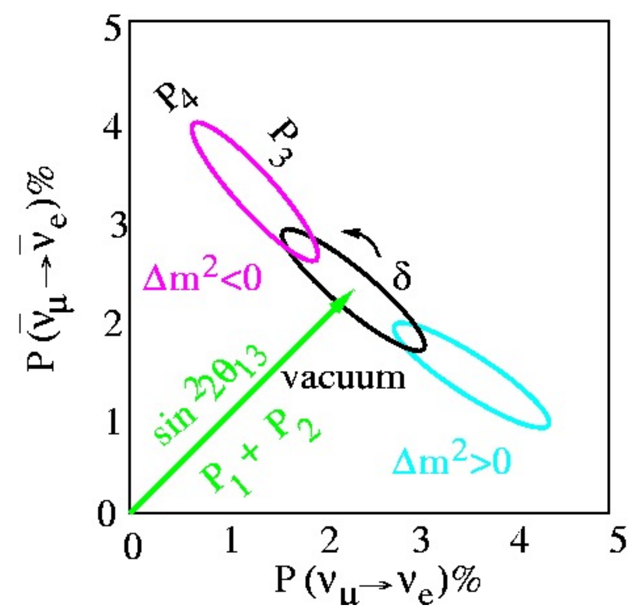
Recall ν Oscillation Probabilities

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

$$\begin{aligned}
P_1 &= \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}\\
P_2 &= \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}\\
P_3 &= J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}\\
P_4 &= \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}
\end{aligned}$$



Minakata & Nunokawa JHEP 2001

In the words of Ken Peach

"When I was on an experiment to determine ε'/ε, once we were close to getting the result out, I realized something:

All the theorists asked 'what value did you measure?'

All the experimentalists asked 'what uncertainty on the measurement did you end up getting?' "

So I can't help but focus on what the uncertainties are…call me an experimentalist…

Measuring Oscillation Probabilities

$$N_{far} = \phi_{\nu_\mu} \sigma_{\nu_x} P(\nu_\mu \to \nu_x) \varepsilon_x M_{far} + B_{far}$$

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

$$P(\nu_\mu \to \nu_x) = \frac{N_{far} - B_{far}}{\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far}}$$

B_{far}= Backgrounds at far detector, from any flux

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i} (P) \sigma_{\nu_i} \varepsilon_{ix} M_{far}$$

Need to understand Signal and Background Cross sections, and efficiencies!

Uncertainties on Probabilities

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + \frac{N_{far} - B_{far}}{(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)^2}[\delta(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)]^2$$

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + f(N_{far} - B_{far})\left(\left[\frac{\delta\varphi_{\nu_\mu}}{\varphi_{\nu_\mu}}\right]^2 + \left(\frac{\delta\sigma_{\nu_x}}{\sigma_{\nu_x}}\right)^2 + \left(\frac{\delta\varepsilon_{\nu_x}}{\varepsilon_{\nu_x}}\right)^2\right)$$

3 Regimes:

$$N_{far} >> B_{far}$$

$$N_{far} \approx B_{far}$$

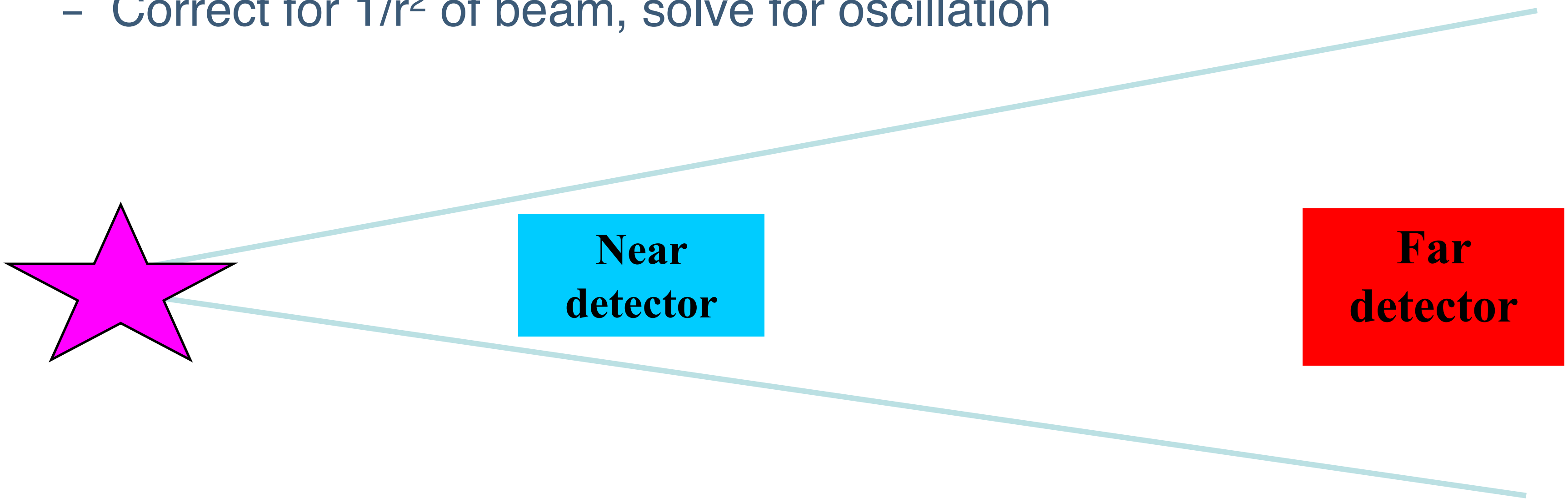
$$N_{far} << B_{far}$$

Where we are now:

Given the size of $\sin^2 2\theta_{13}$, looking for small oscillation probability difference between ν and anti-ν to measure CP violation

Near Detector Strategy (in theory)

- Make two detectors :
  - Near detector sees beam before oscillations
  - Far detector measures beam after oscillations
  - Require Neutrino Flavor and Neutrino Energy measurement
  - Correct for $1/r^2$ of beam, solve for oscillation



Near Detector Strategy (cont'd)

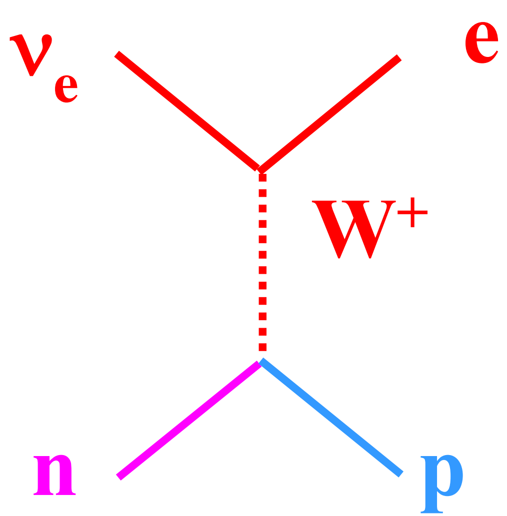
$$B_{far} = \int dE_\nu \sum_{i=\mu,e} N_{near,i}(E_\nu) \left(\frac{\int \phi_{\nu_i\, far} \sigma_{\nu_i} \varepsilon_{ix}(E_\nu) dE_\nu}{\int \phi_{\nu_i\, near} \sigma_{\nu_i} \varepsilon_{ix}(E_\nu) dE_\nu} \right) \frac{M_{far}}{M_{near}}$$

- But ratios don't cancel everything
- Underlying problem: fluxes may be different
- Also, ν_μCC oscillations may create change on TOP of what you are trying to measure
- All of these terms are functions of energy
  - Uncertainties in energy dependence of cross sections translate into far detector uncertainties…

Measuring Neutrino Energy

- Should be easy, right?
  - Assume neutron or proton at rest
  - IF you know initial direction of neutrino…
  - Final direction and energy of electron should suffice to get to the neutrino energy

$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$



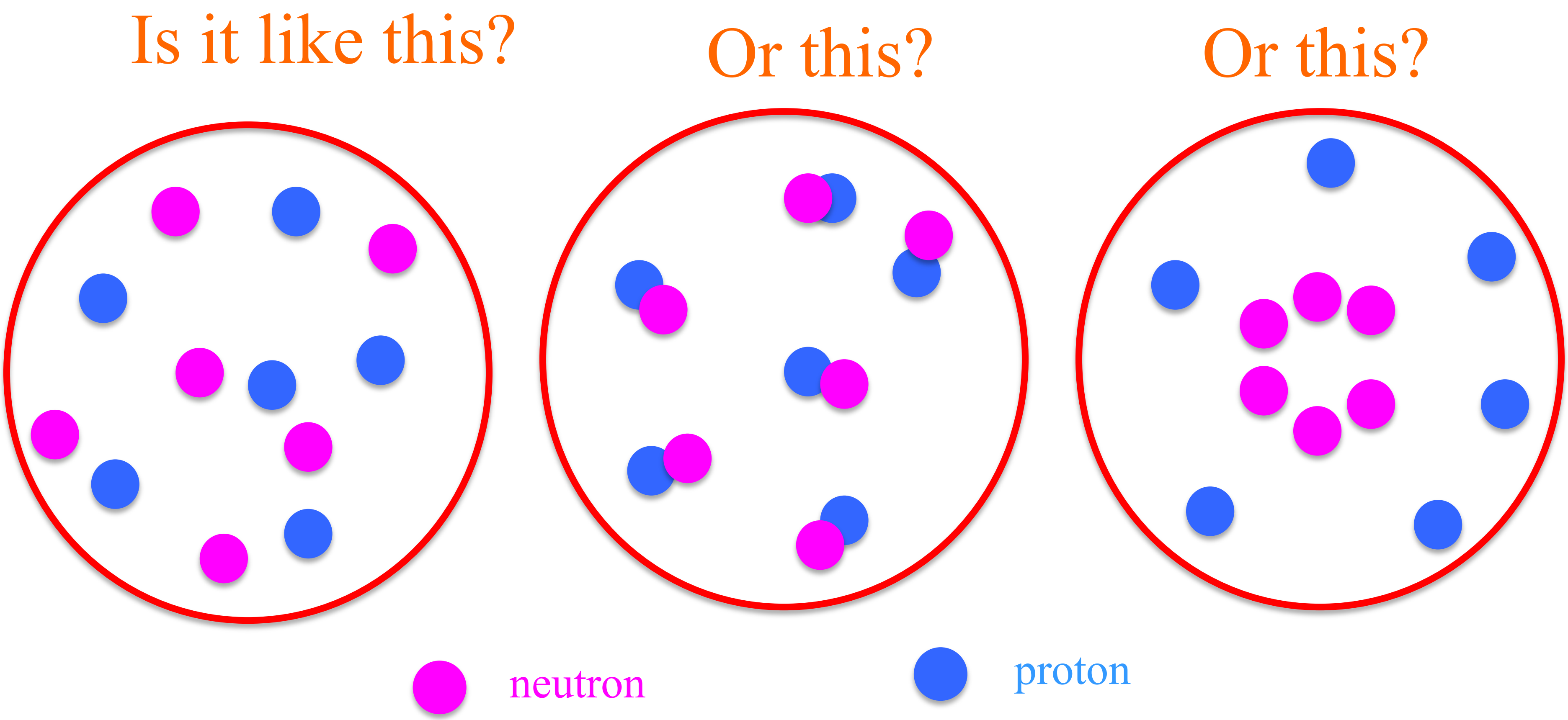
$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\mu - \left[(M_n - E_B)^2 + m_\mu^2 - M_p^2\right]}{2\left[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

$E_\mu = T_\mu + m_\mu$	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

Understanding Nuclear Effects

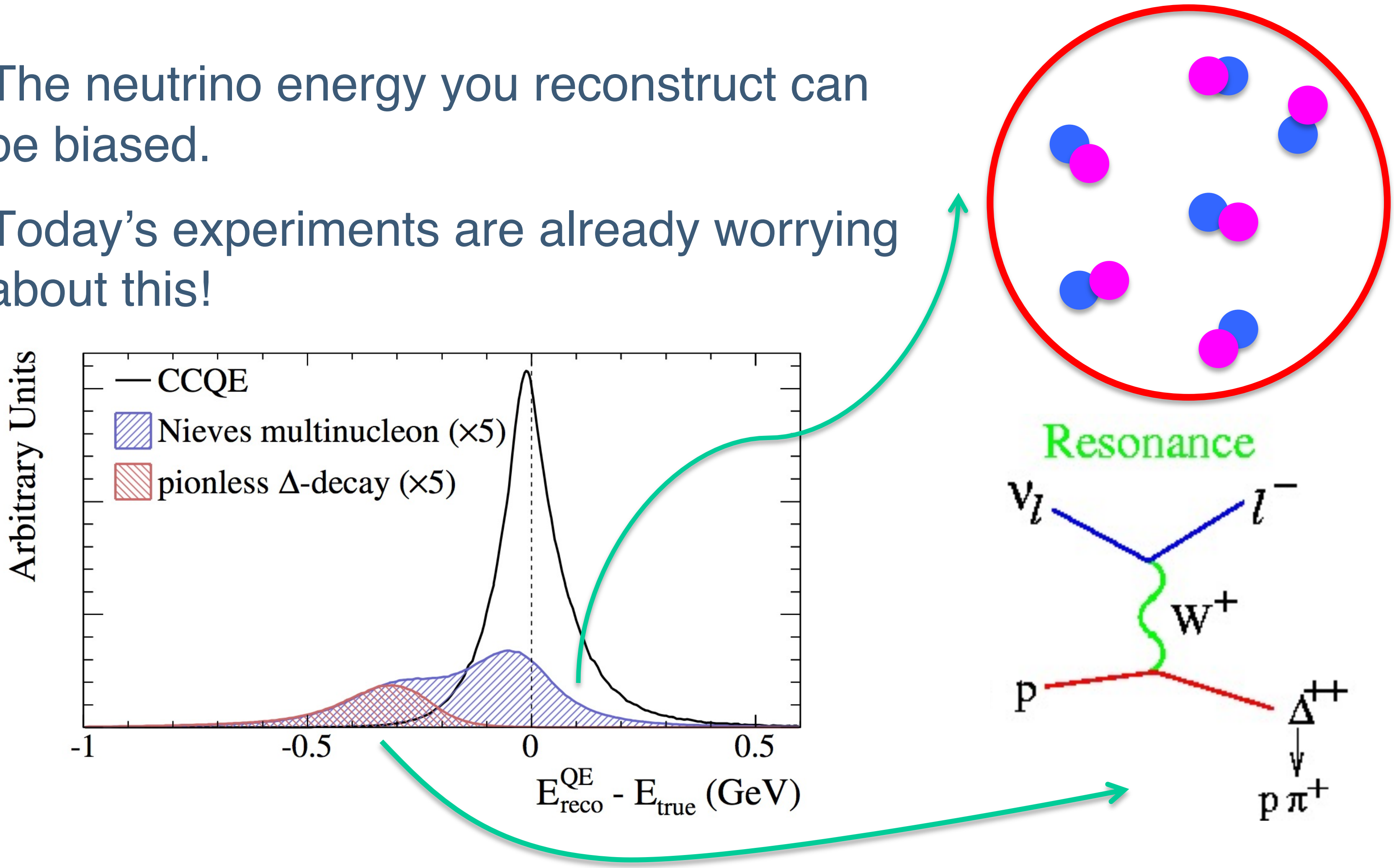
- Why is this in a long baseline neutrino lecture? Isn't it nuclear physics?
  - Yes, nuclear physicists are interested in using neutrinos as probe of the nucleus and that's why they've joined neutrino experiments
  - Yes, but we need to understand it in order to measure oscillation probabilities
    - Signal is affected: visible energy in detector must be used to reconstruct neutrino energy, but this could be affected by nuclear environment
    - Background is also affected: bare nucleon models can't predict the whole story here either, and Near Detectors can't tell you everything

What really happens in a nucleus?

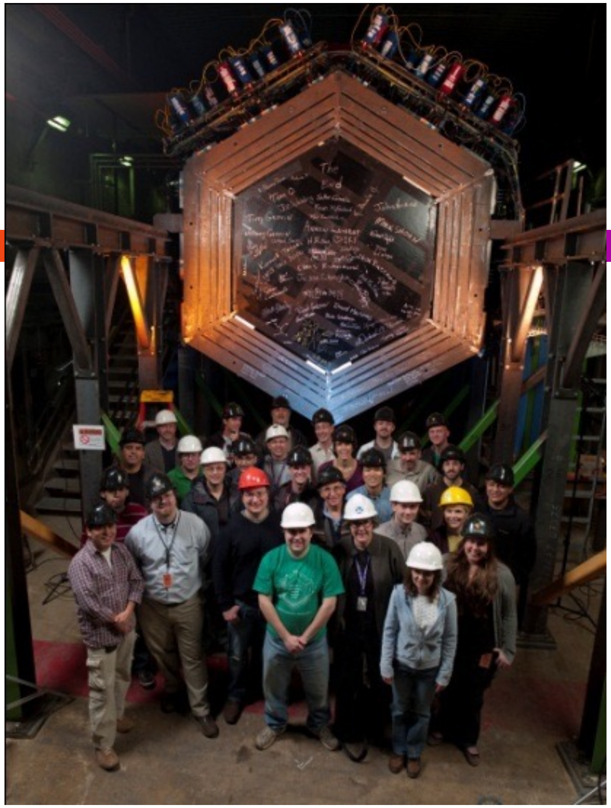


What does this mean?

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

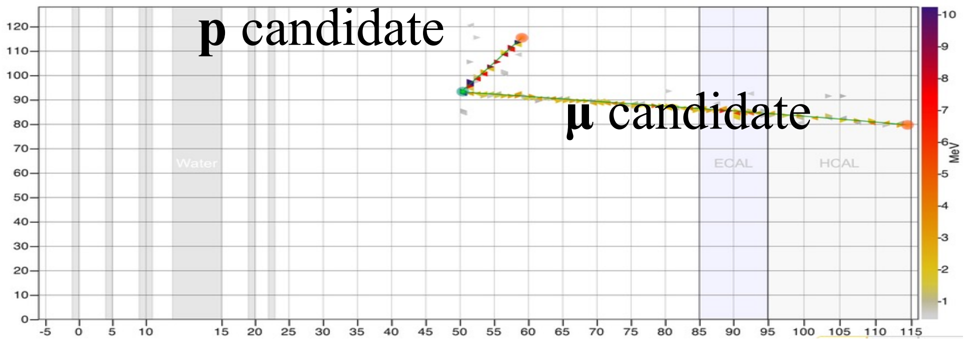


Coping Strategy:MINERvA

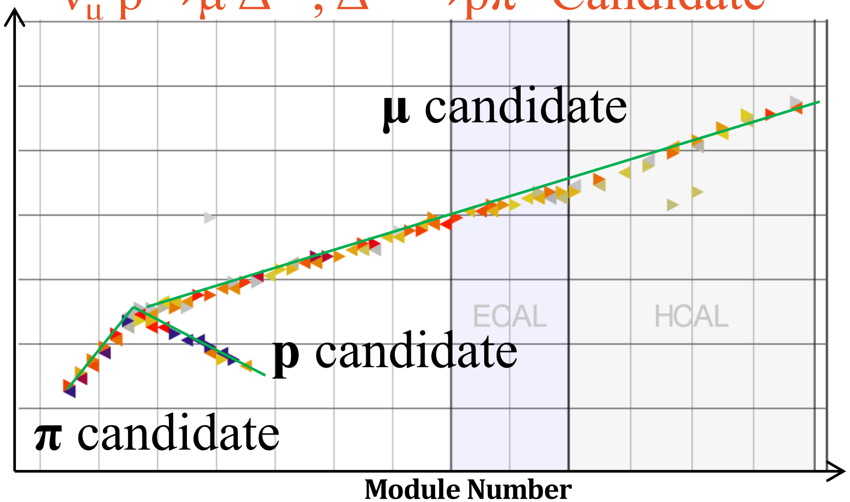


- MINERvA is studying ν interactions with
  - High intensity, wide range of energies
- MINERvA detector provides
  - Reconstruction in C, Fe, Pb, He, H_2O
  - Broad range of final states
  - Signal and Background Processes for Oscillation experiments

$\nu_\mu\ n \rightarrow \mu^- p$ Candidate



$\nu_\mu\ p \rightarrow \mu^- \Delta^{++},\ \Delta^{++} \rightarrow p\pi^+$ Candidate



Two ways to look at effects of nucleus

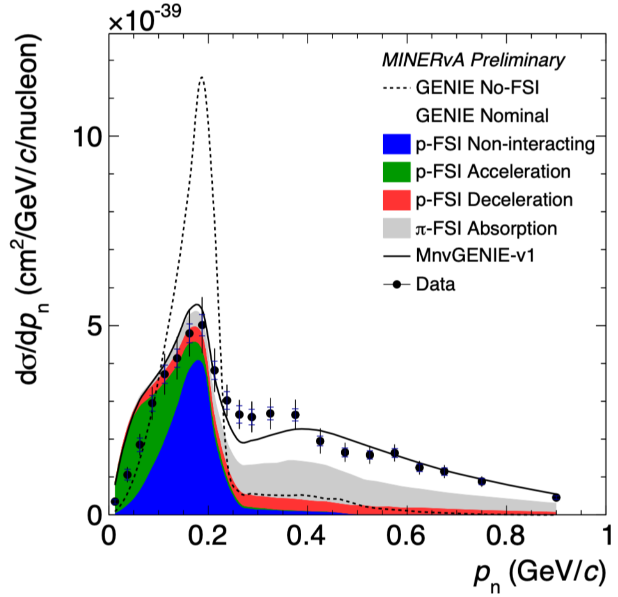
- Looking at initial neutron momentum for neutrinos on Carbon

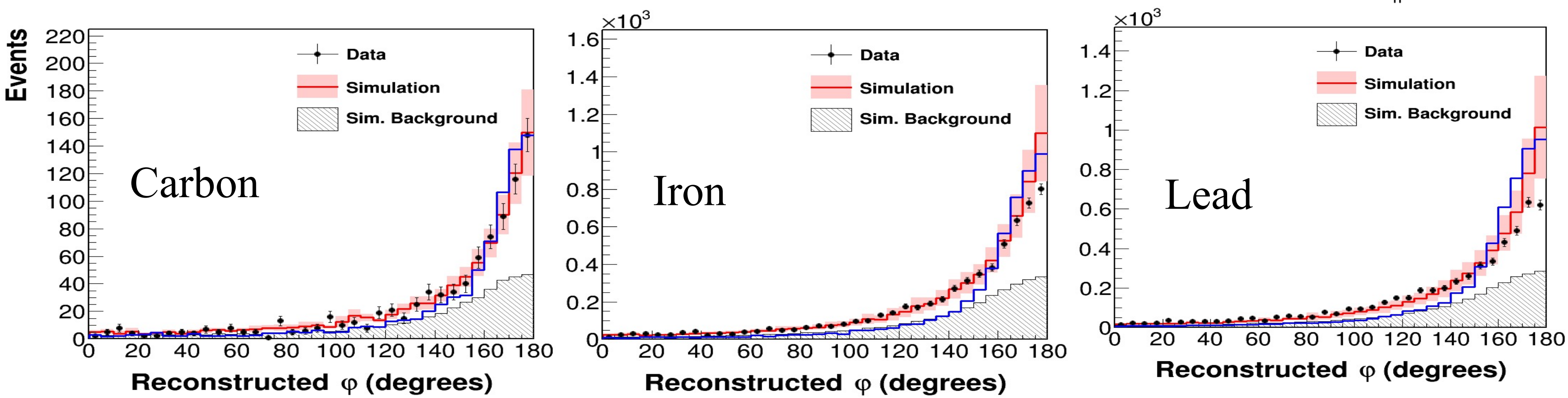
X. Lu et al, PRL 121, 022504 (2018)

- Looking at angle between neutrino-proton plane and neutrino-muon plane:

M. Betancourt et al, PRL 119, 082001 (2017)

These results get incorporated by oscillation experiments to improve their predictions



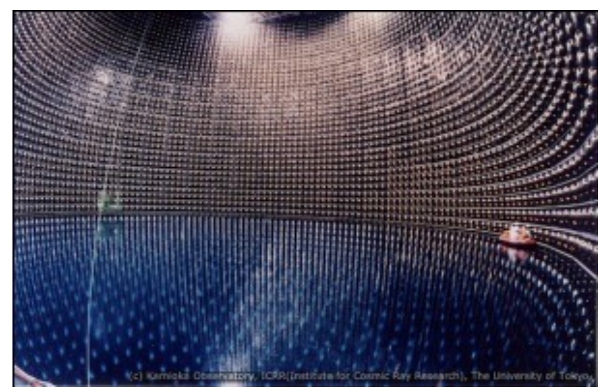


Current Long Baseline Experiments:

- Two accelerator experiments probing "atmospheric anomaly"
- Near and Massive Far Detectors: 14-50kton
- Very intense beams of protons: 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)

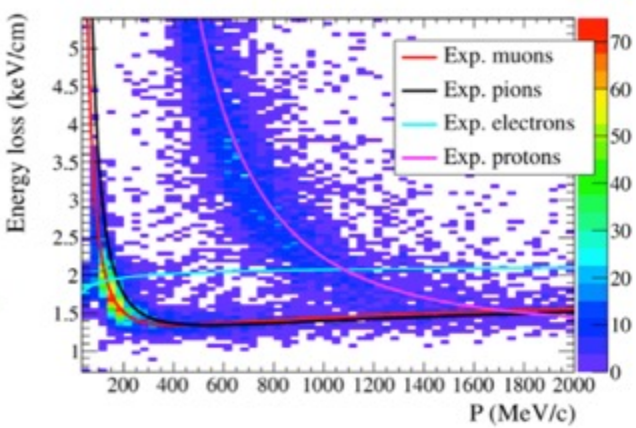


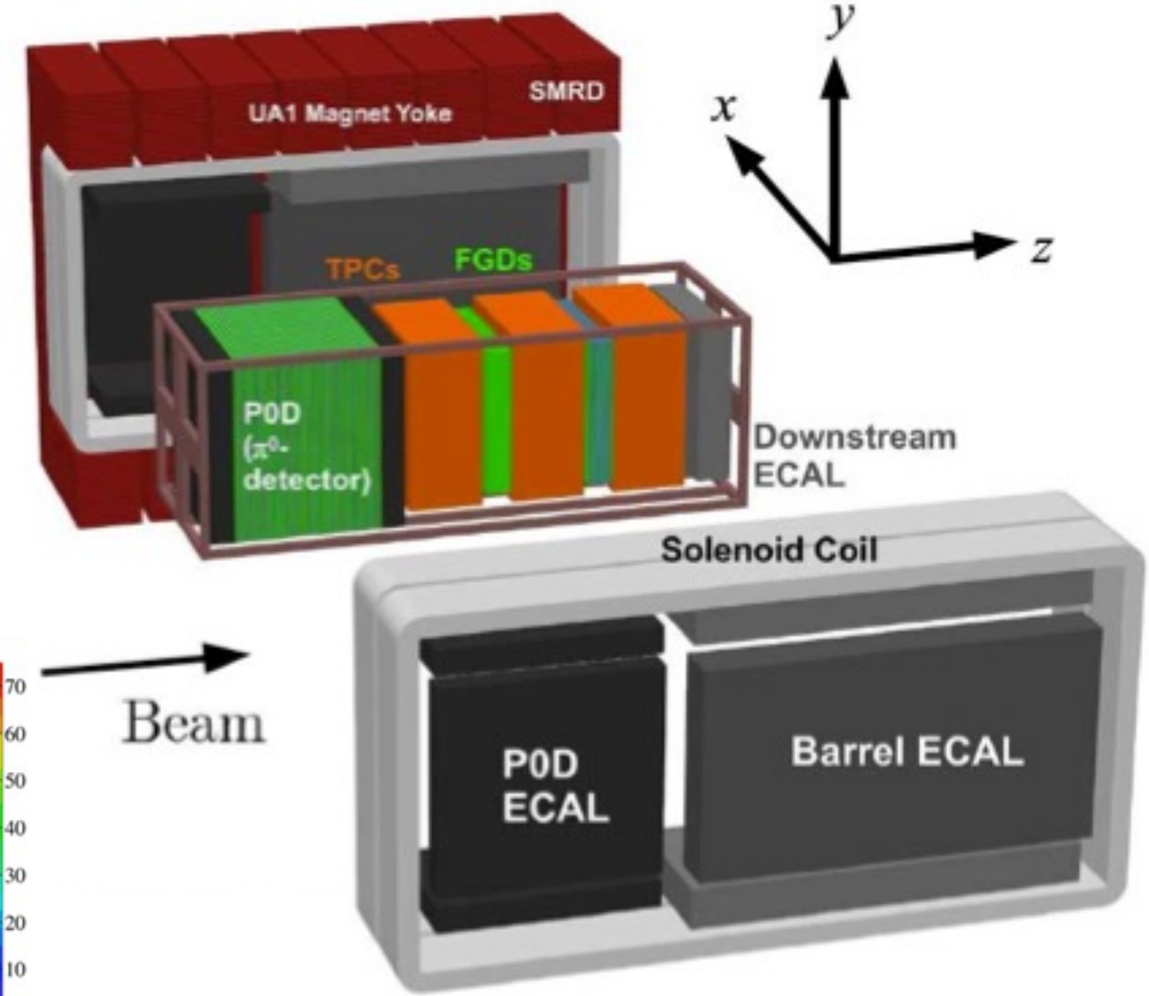
Road to precision

- Case study: T2K ν_e appearance
  - Off axis beam at 700MeV
  - Water Cerenkov detector at 295km
  - Note that for best oscillation results, want to fit both ν_e and ν_μ spectra: since Δm^2_{23} and θ_{23} comes into both oscillation probabilities
  - Extensive near detector suite
  - Hadron production measurements on target from neutrino beamline
  - Have seen ν_e appearance at over 5 sigma
    - Have only taken small fraction (<10%) of expected protons on target
  - What are the uncertainties in this measurement?

Near Detector for ν_e appearance

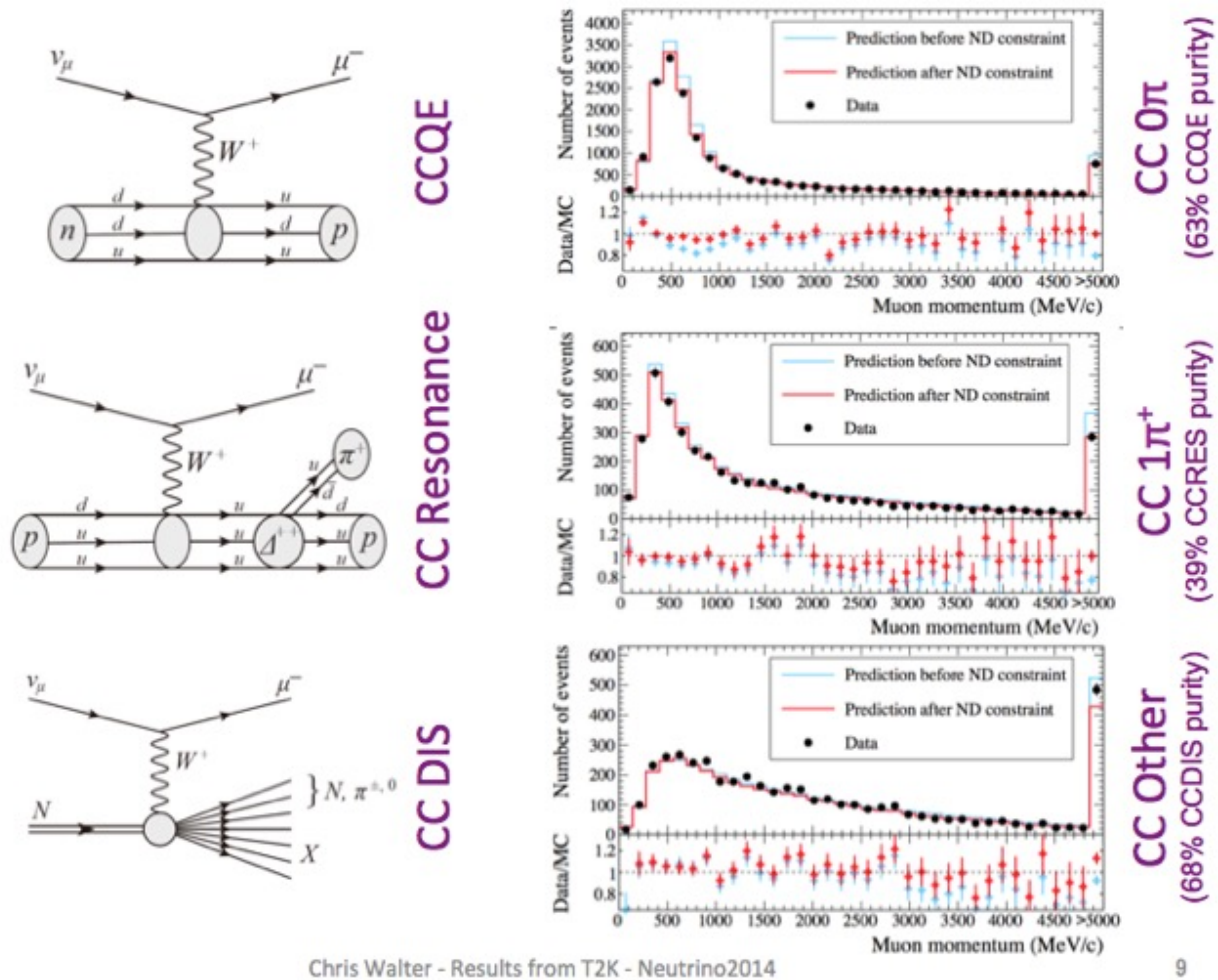
- Note lack of water Cerenkov technology here: rate @280m is too high
- Fine grained scintillator detectors (FGDs) as target, plus water target
- TPC's for excellent particle ID between FGD's
- In a magnetic field





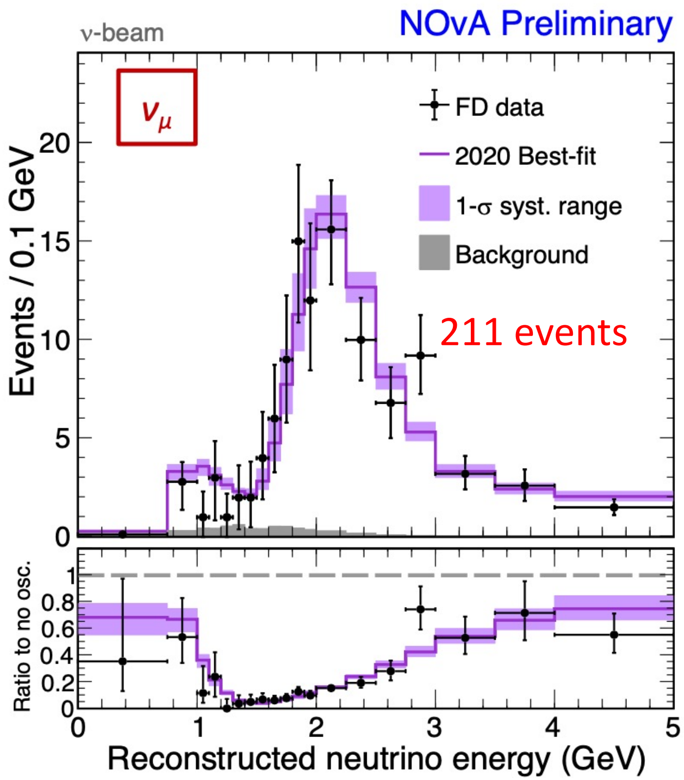
T2K Near Detector Event Samples

- Note that the statistics are all from Charged Current (CC) ν_μ events
- Interactions are in carbon, not in Oxygen
- Additional uncertainty is incorporated for that difference

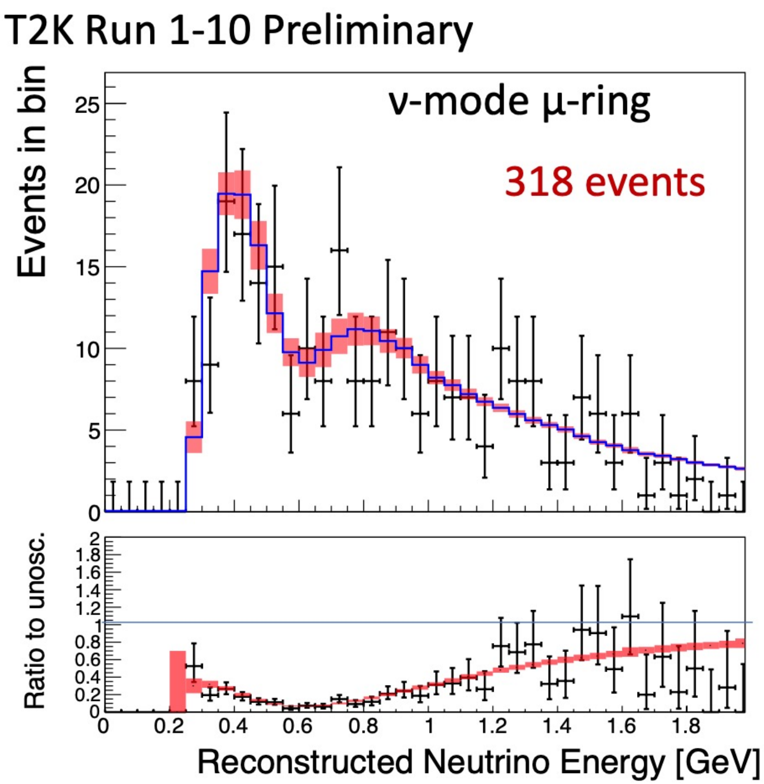


Precision Evidence of ν_μ Disappearance

- Use two detectors, near and far, separated by >200km
- Without oscillations they would have seen hundreds more events!



Himmel, A, Neutrino 2020

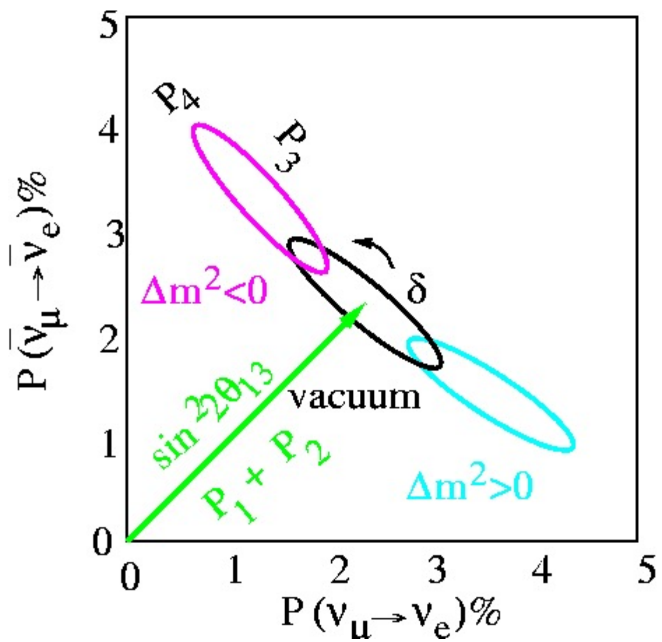


Dunne, P. Neutrino 2020

What about $\nu_\mu \rightarrow \nu_e$ Appearance?

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

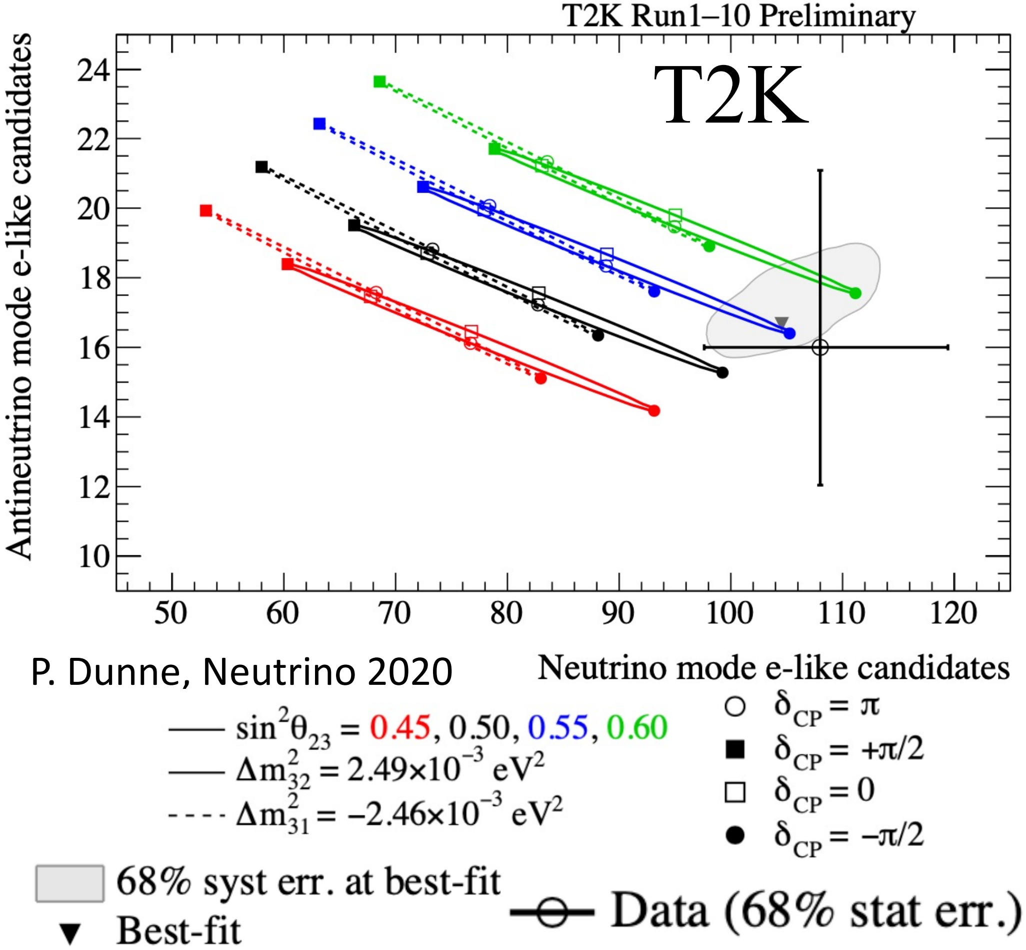
$$
\begin{aligned}
P_1 &= \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2} \\
P_2 &= \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2} \\
P_3 &= J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} \\
P_4 &= \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}
\end{aligned}
$$



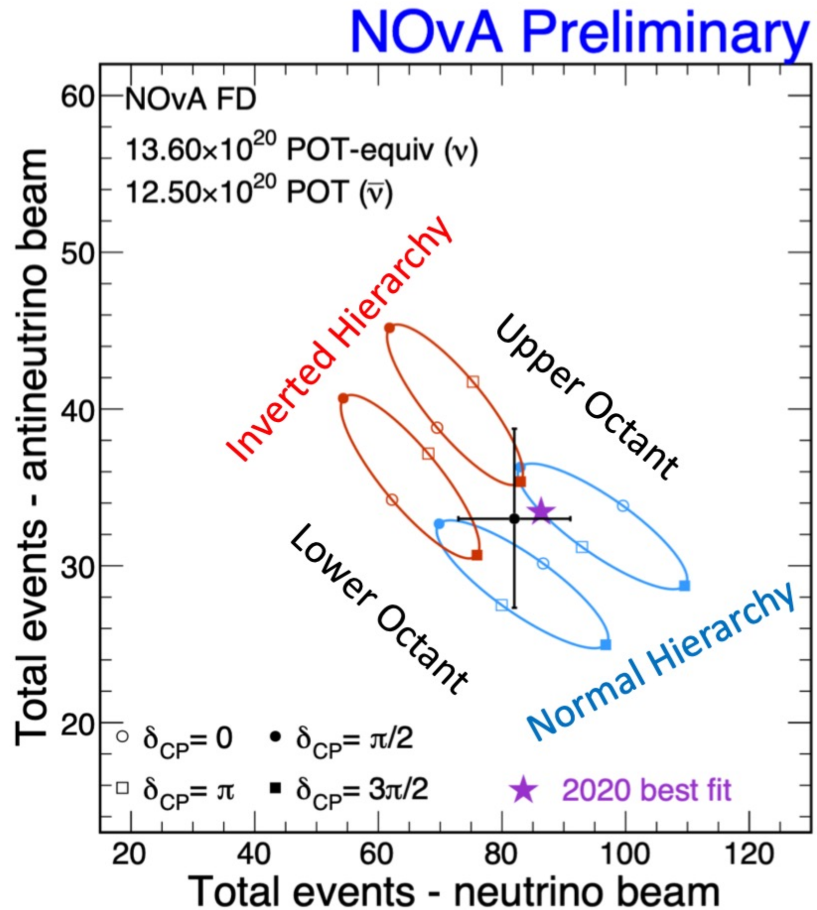
Minakata & Nunokawa JHEP 2001

Appearance of ν_e in a ν_μ beam

- Both experiments have run in neutrino and antineutrino beams



P. Dunne, Neutrino 2020



A. Himmel, Neutrino 2020

Reminder from Monday

NOνA and T2K recent results

Global picture

- Results from NOvA and T2K in the $\delta_{CP} - \sin^2\theta_{23}$-plane are not inconsistent
  - More consistent for IO, but also for NO they are still statistically in agreement
- The best fit in the global analysis remains for Normal Ordering
  - but IO disfavored only with 1.6 σ
- T2K, NOvA and reactor experiments are statistically in agreement with each other
- Mild preference for the upper octant of θ_{23} ($\sin^2\theta_{23} > 0.5$)

Esteban et al., status of global fits 2020, arXiv:2007.14792

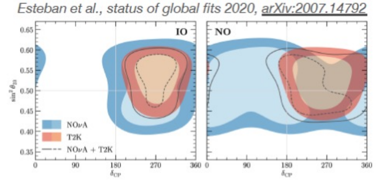
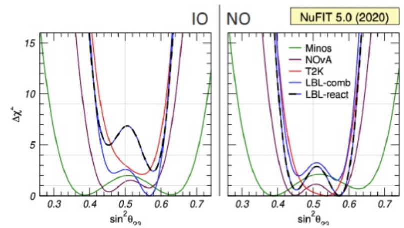


Figure 3. 1σ and 2σ allowed regions (2 dof) for T2K (red shading), NOvA (blue shading) and their combination (black curves). Contours are defined with respect to the local minimum for IO (left) or NO (right). We are fixing $\sin^2\theta_{13} = 0.0224$, $\sin^2\theta_{12} = 0.310$, $\Delta m^2_{21} = 7.40 \times 10^{-5}$ eV^2 and minimize with respect to $|\Delta m^2_{3\ell}|$.



Slide: A. Schukraft, WIN 2021

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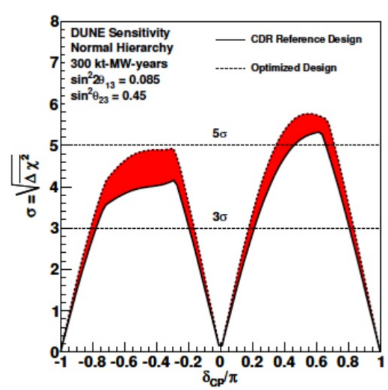
Michelle Dolinski, TRISEP 2021

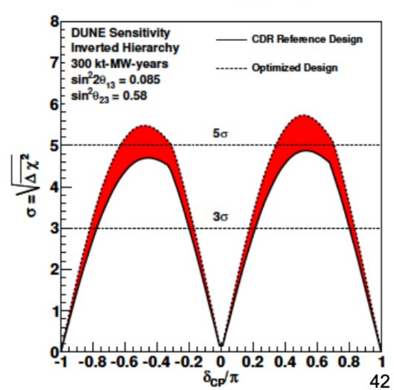
DUNE Sensitivity

arXiv:1512.06148

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} + \delta_{CP})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$





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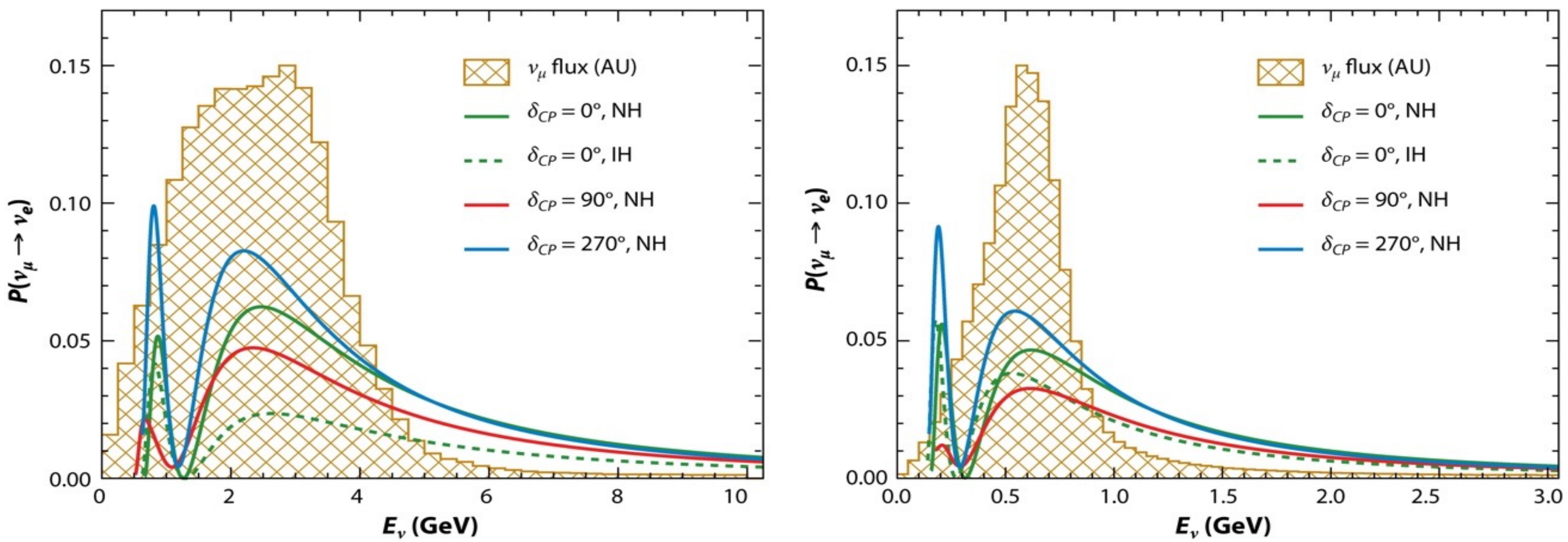
Next Steps: more detector, more beam

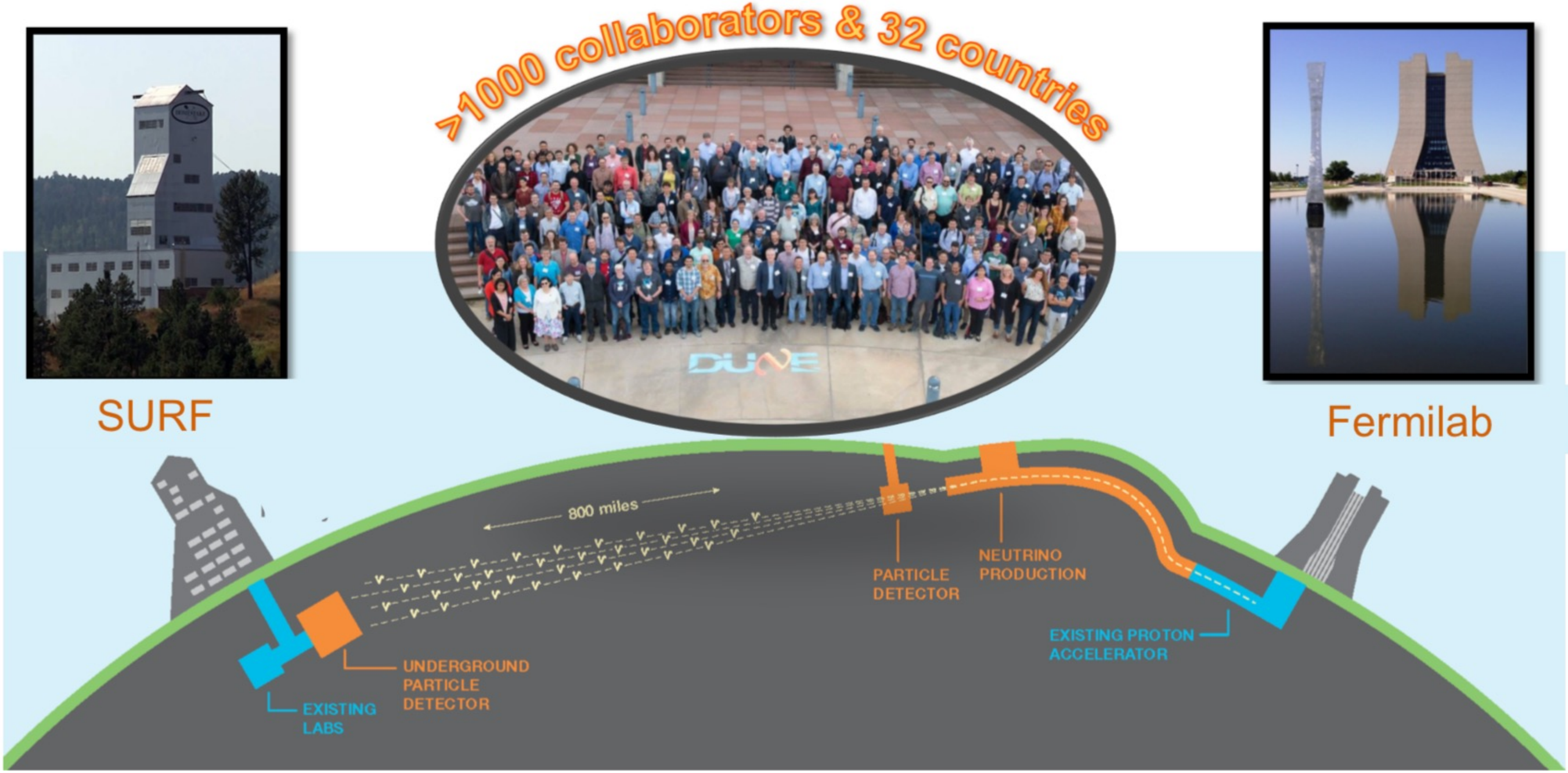
- DUNE
  - 1300km, 40kton, MW-beam
  - Broad Band experiment: 1-6 GeV neutrinos
  - Liquid Argon Detector
- Hyper-K
  - 295km, ~1Mton, MW-beam
  - 400-600MeV neutrinos
  - Water Cerenkov detector



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

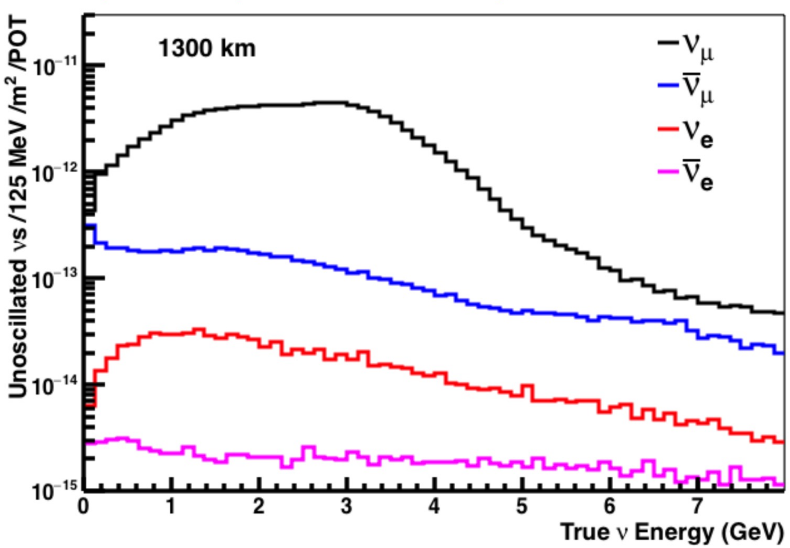
Next steps in Long Baseline Experiment: DUNE

- 120GeV protons, 3-horns, go 1300km through the earth, detector on axis

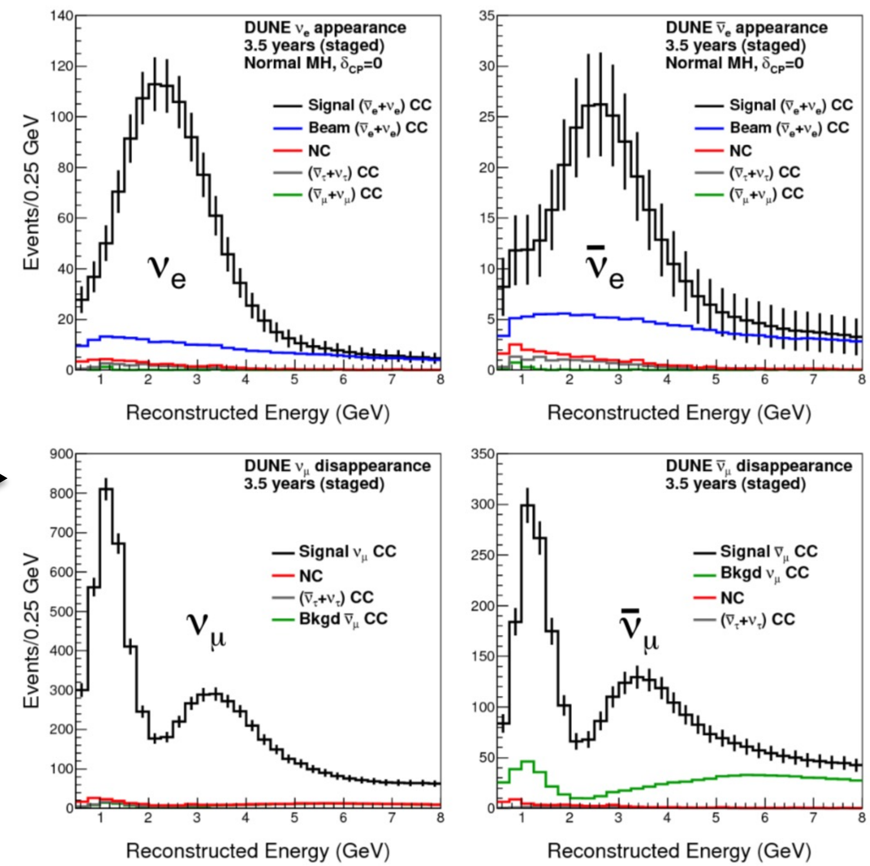


Predicted Event Spectra at DUNE

Neutrino Flux at 1300 km
(CDR Optimized Beam)

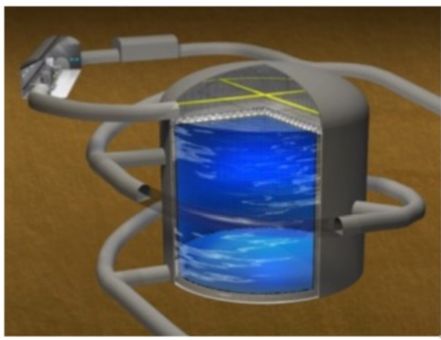


DUNE Conceptual Design Report (CDR)
arXiv:1512.06148



Next step in Long Baseline Experiment: Hyper-K

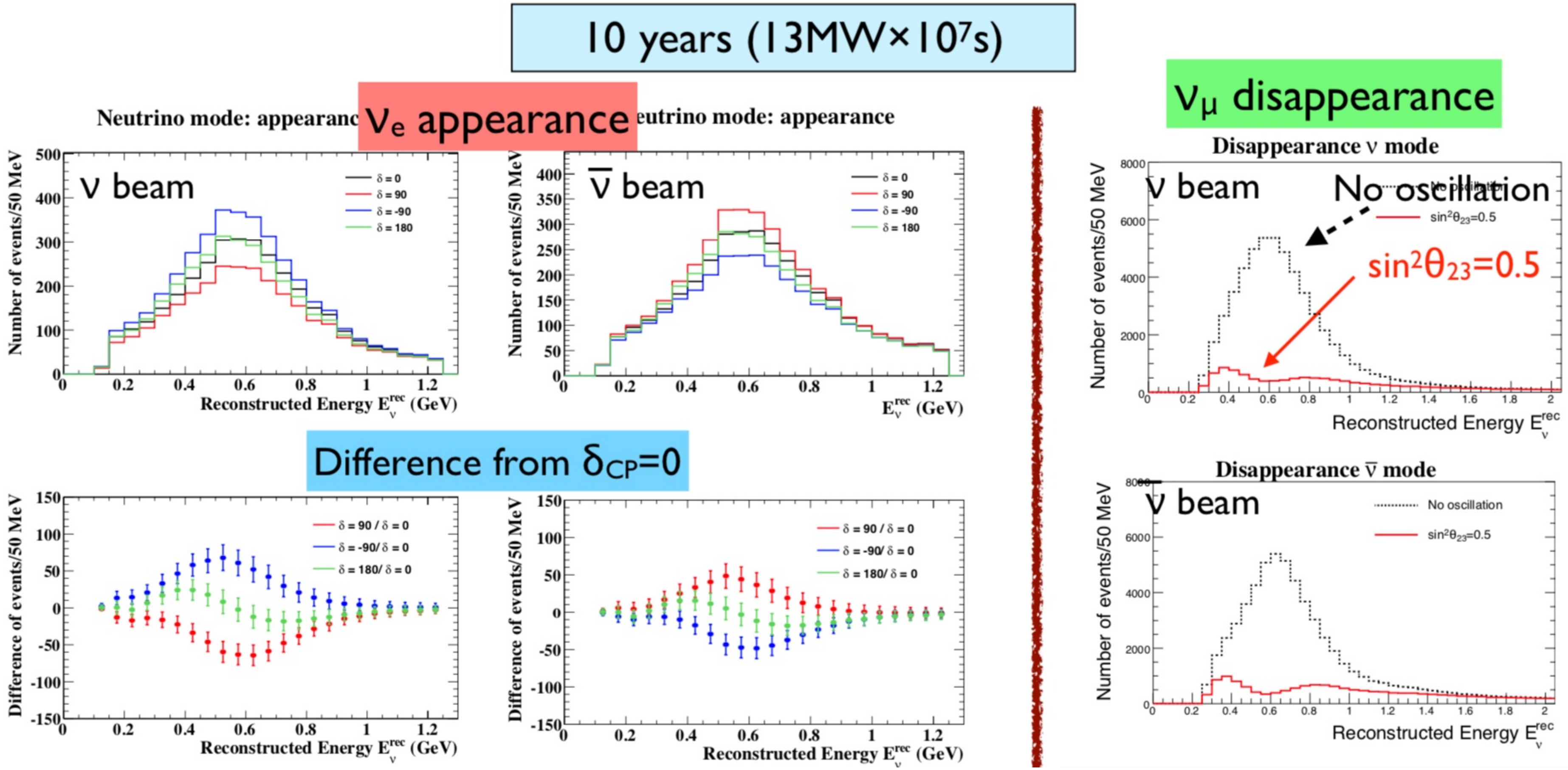
- Use more intense version of beam going to T2K now, and much larger version of Super-Kamiokande water Cerenkov detector



Hyper-K

J-PARC
Accelerator Complex

Hyper-K Event Distributions



Shiozawa, Masato. (2018, June). Hyper-Kamiokande.
Zenodo. http://doi.org/10.5281/zenodo.1286768

What else can DUNE and Hyper-K measure?

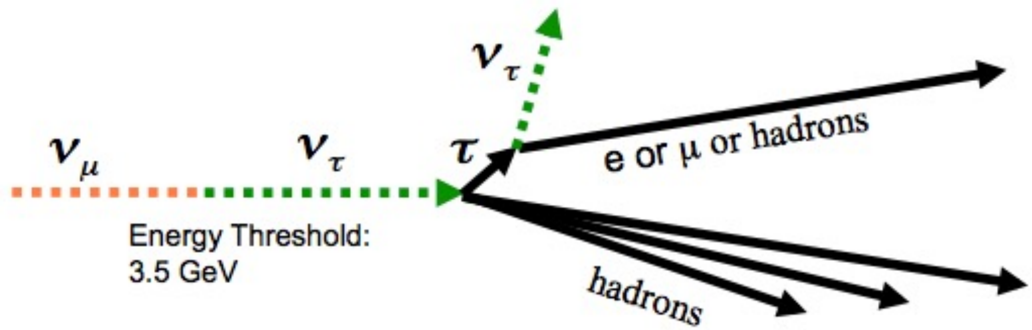
- Proton Decay
- Supernovae Neutrinos
- Amospheric neutrinos
- Solar Neutrinos
- Non-Standard interactions
  - There is a lot of earth that the neutrinos pass through…a small effect can add up after a long distance

Long Baseline Oscillations Summary

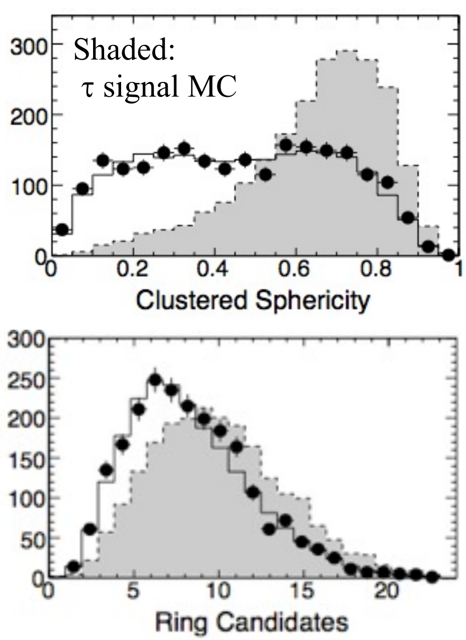
- Neutrino Sources
  - Solar, Atmospheric, Reactor fluxes have taught us a huge amount about neutrino mass and mixing
  - ***Need accelerator sources for CP violation***
  - Will need to understand those fluxes well
- Interactions
  - The higher the neutrino energy, the more processes that are available in interaction
  - **Will need to understand those processes and how the nucleus affects them** (signal and background)
- Detectors
  - Many ways to detect neutrinos, **always hungry for more detector mass**
  - Two promising technologies for accelerator beams: one provides very high information per event, one provides less but can be built much more cheaply per kiloton
- Measurements
  - Have entered the era of precision long baseline oscillations!
  - Testing the framework is still an important goal: one number not enough

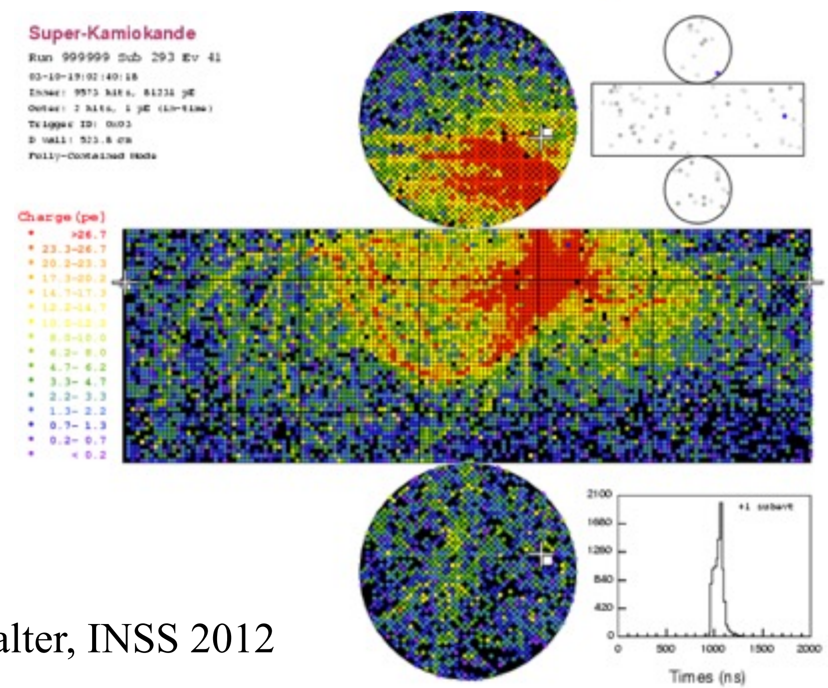
τ neutrinos in Super-K

- Signal characteristics:
  - high energy
  - extra pions
  - more spherically symmetric due to decay of heavy τ



Phys. Rev. Lett. 110, 181802 (2013)





C. Walter, INSS 2012