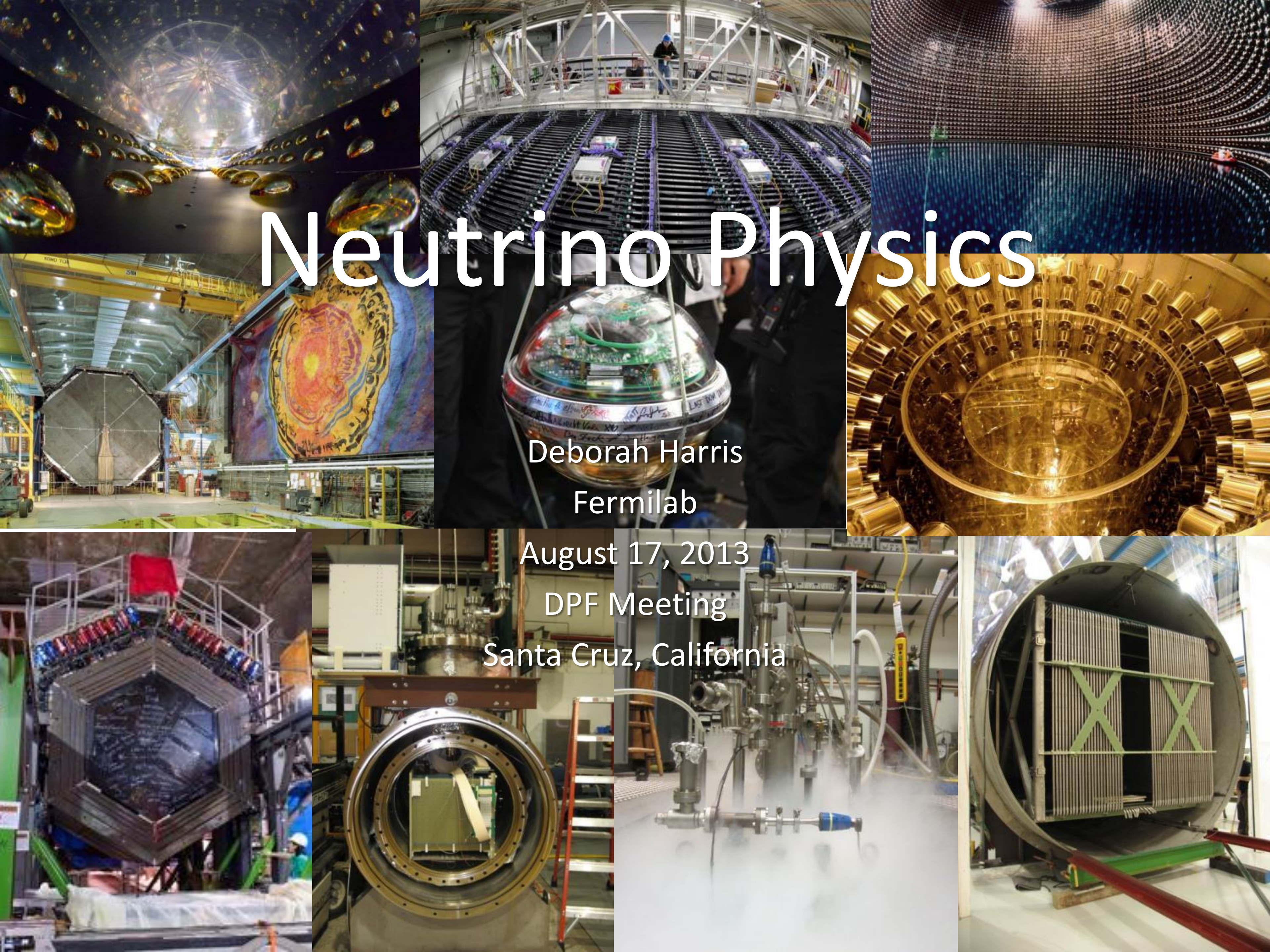


Neutrino Physics

Deborah Harris
Fermilab

August 17, 2013
DPF Meeting
Santa Cruz, California

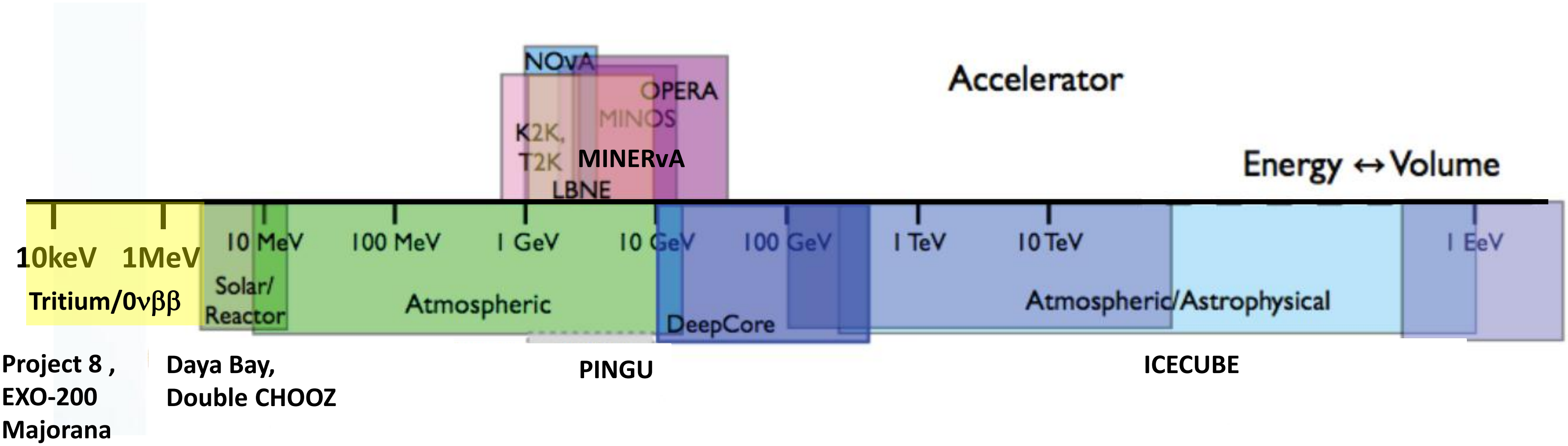
Preamble

- 40 minutes is a short time to cover…
  - 32 talks
  - (at least) 17 different detectors
- You heard two excellent talks in Monday’s plenary session
  - Patrick Huber on What Neutrinos have Told Us
  - Bonnie Fleming on Possibilities for Neutrino Physics
- I have taken liberties with this talk, and not all parallel session talks will be covered at the same level
  - Priority given to talks with data, and topics not already covered by Patrick and Bonnie

Top ten reasons to study neutrinos

1. Neutrinos are among the most abundant particles in the universe
2. Neutrinos have been around since the universe was 1 second old
3. Neutrinos are signals from the highest energy accelerators in the universe
4. Neutrinos will teach us about how mass is generated
5. What other fermion could be its own antiparticle?
6. Neutrinos can see inside the nucleus like none else
7. Neutrinos will tell us if we really understand flavor
8. Neutrinos may be the reason that we enjoy such a healthy baryon asymmetry
9. Neutrinos can access physics up to the GUT energy scales
10. Neutrinos broke the standard model and will tell us what is beyond

Energy Scales in Neutrino Physics



Graphic taken from D.Williams

- Reason number 11: Neutrinos can be directly studied from keV (10^3) to EeV (10^{18}) energies
- Heard talks here from both ends of this spectrum, and much from the middle

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DPF 2013 Neutrino Parallel Sessions, I (Red means Data!)

- Neutrinos are signals from the highest energy accelerators in the universe
  - WHITEHORN, Nathan on high energy neutrinos in ICECUBE
- Neutrinos may teach us about how mass is generated
  - KUNDE, Gerd J on direct mass measurement with electron capture spectroscopy
  - OBLATH, Noah on Project 8
- What other fermion could be its own antiparticle?
  - CHAVES, Jason on EXO 200 Status and results
  - KRAVITZ, Scott on Barium Tagging in EXO-200
  - GIOVANETTI, Graham on the MAJORANA Demonstrator

DPF 2013 Neutrino Parallel Sessions, II

- Neutrinos can see inside a nucleus like none else
  - RAKOTONDRAVOHITRA, Laza on Quasi-elastic scattering at MINERvA
  - HANSEN, Damon on CCQE scattering in T2K P0D
  - ADAM, Jeanine on CC electron neutrino scattering in T2K P0D
  - BODEK, Arie on Transverse Enhancement Models and Meson Exchange Currents
  - Dr. SZELC, Andrzej on Argoneut Update

DPF 2013 Neutrino Parallel Sessions, III

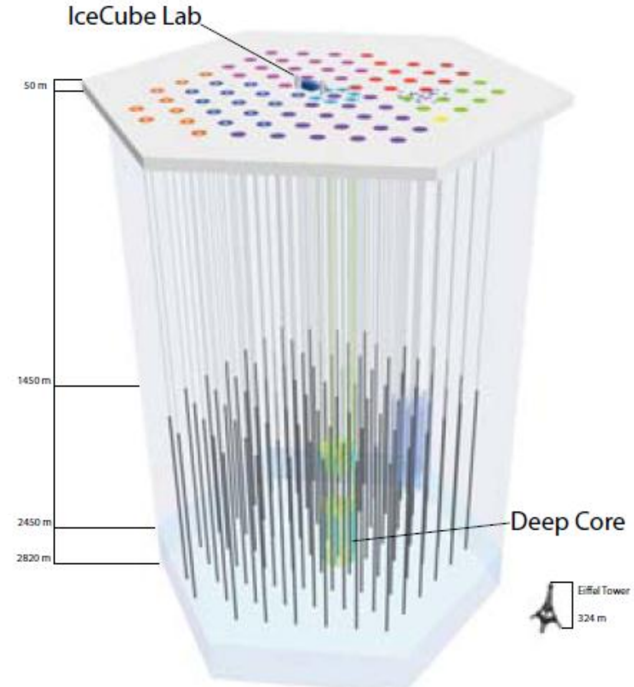
- Neutrinos will tell us if we really understand flavor
  - WORCESTER, Elizabeth on Daya Bay results
  - CARR, Rachel on Double CHOOZ Results on Gd Capture
  - HIGNIGHT, Joshua on T2K Results on ν_e appearance
  - IMBER, James on T2K /SK Joint fits
  - RADOVIC, Alexander on MINOS ν_μ / ν_e joint fits
  - WILLIAMS, Dawn on ICECUBE's Oscillation Results and PINGU
  - FRIEND, Megan on future T2K sensitivity
  - BIAN, Jianming on NOvA status and ν_e sensitivities
  - SACHDEV, Kanika on predicting NOvA backgrounds
  - BAIRD, Michael on NOvA sensitivities on ν_μ disappearance

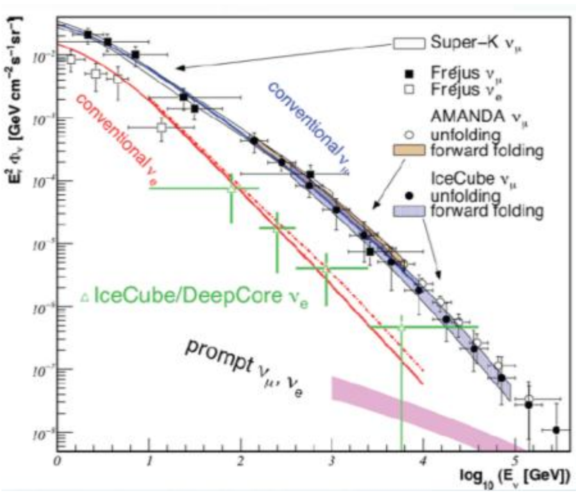
DPF 2013 Neutrino Parallel Sessions, IV

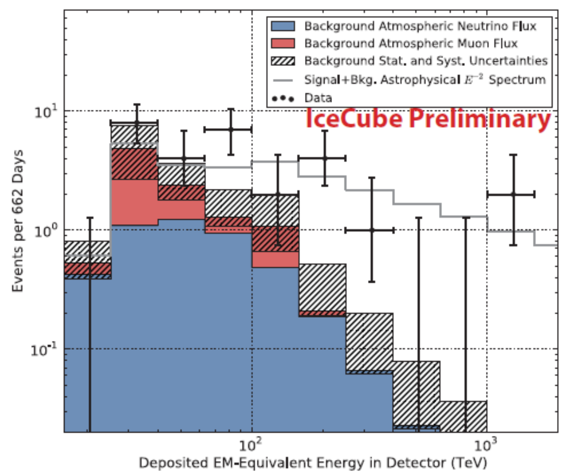
- Neutrinos may be the reason that we enjoy such a healthy baryon asymmetry
  - BASS, Matthew on LBNE Physics Sensitivities
  - Dr. SZELC, Andrzej on Lariat
  - GRANT, Christopher on CAPTAIN
  - GUARDINCERRI, Elena on LBNE Near Detector
  - ANGHEL, Ioana on Fast Photosensor development for Water Cerenkov neutrino detectors
  - SHAEVITZ, Mike on Daedalus Experiment
- Neutrinos broke the standard model and will tell us what is beyond
  - ZHURIDOV, Dmitry on neutrino magnetic moments from NSI
  - AHMED, Rashed on tau neutrinos as probe of NSI
  - SPITZ, Joshua on testing Lorentz Invariance with Double CHOOZ
  - AURISANO, Adam on MINOS sterile neutrino results
  - COLLIN, Gabriel on MicroBooNE
  - SHAEVITZ, Mike on IsoDAR Experiment

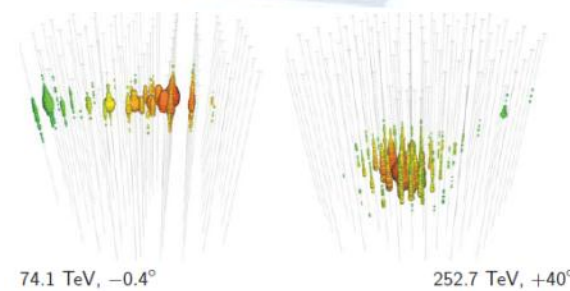
Seeing the highest energy accelerators

- ICECUBE:
  - 1km^3 volume
  - 86 strings, 5160 PMTs
  - See atmospheric ν_e flux above 80GeV for 1st time
  - See evidence for astrophysical neutrinos: above prediction from atmospheric sources
  - No evidence (yet) for clustering





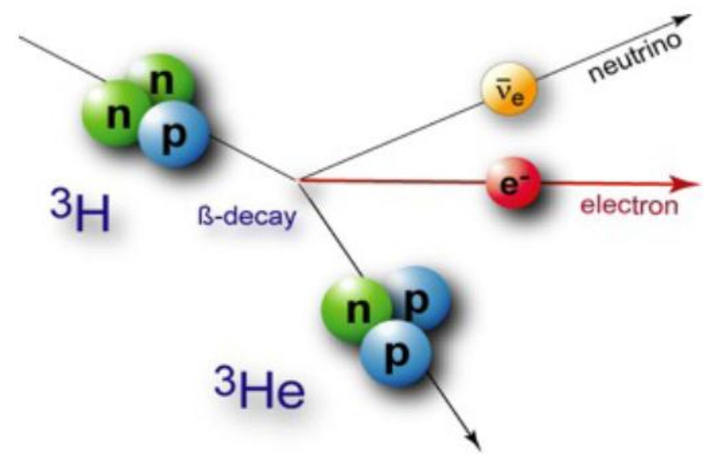




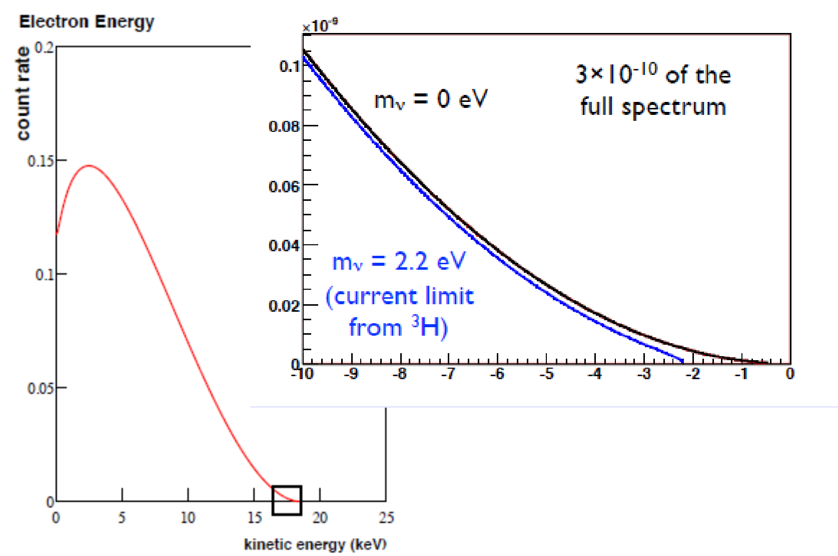
Whitehorn, Williams

Neutrinos and Mass Generation

- Neutrino masses are so much lower than other fermion masses, they could have been generated in a different way
- Want to learn the absolute mass spectrum for the neutrinos, that will guide us to how the mass was generated

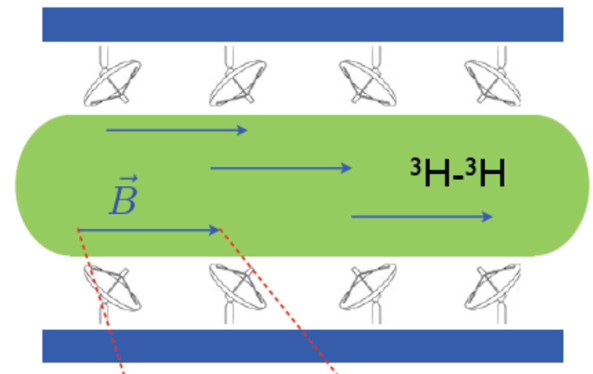


- Current best limit from KATRIN looking at Tritium beta decay in magnetic spectrometer (2.2eV)
- We heard at DPF about two other techniques
  - Tritium decay at Project 8
  - Electron Capture on Holmium

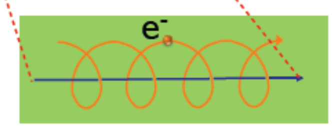


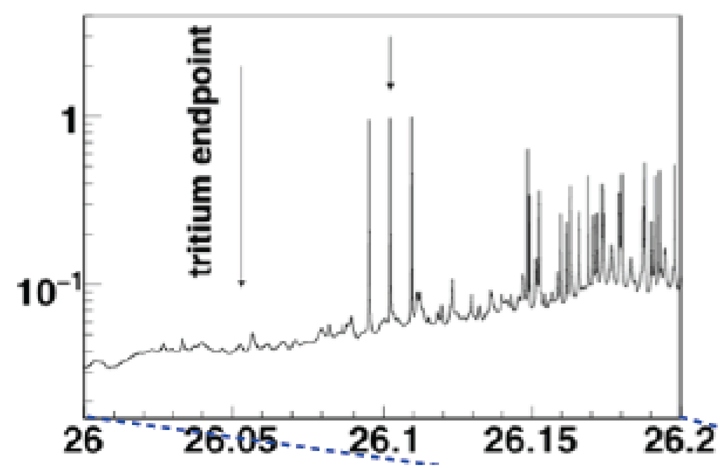
Measuring Mass with Tritium in new way

- Project 8 Concept: *(Oblath)*
  - trap a volume of tritium (atomic)
  - watch decay electrons process around constant magnetic field
  - measure the cyclotron frequency to get e- Energy
  - Highest Energy electrons give lowest frequency signals
- Working to prove the principle:
  - Start with ^{83m}Kr volume
  - Look for 18 and 30keV conversion electrons
  - Added bonus: see e- lose energy as it processes in field
  - 7TB of data taken in Jan. 2012, must improve data-taking technique



$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

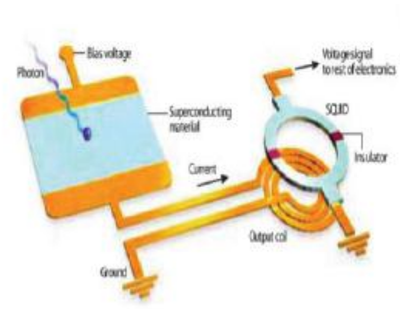


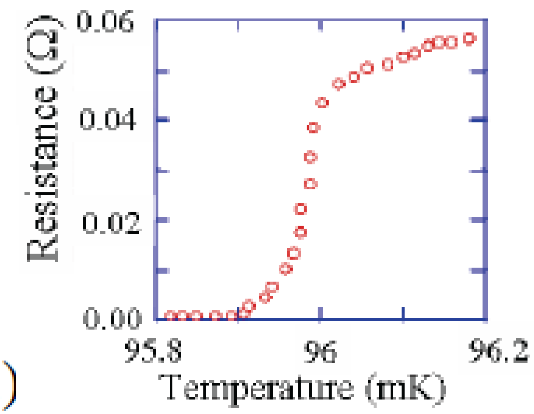


simulation

Mass Measurement using Electron Capture Spectroscopy

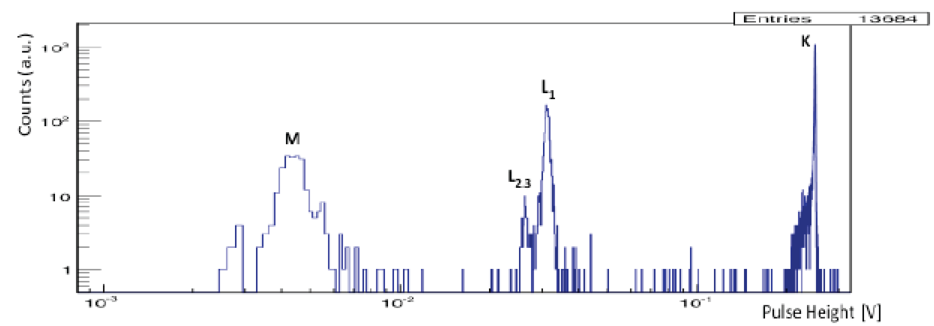
- Study electron capture in ^{163}Ho (2.3KeV-2.8KeV electron capture energy) *(Kunde)*
- See small changes in energy using transition edge sensor

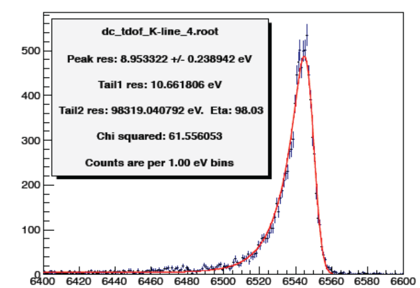




$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e (E.C.)$$

- Practice technique by looking at ^{55}Fe
  - See huge dynamic range and get several lines of these decays
  - Energy resolution achieved: 9.0±0.2 eV!
  - Expect improvements with ^{163}Ho from atomic physics
  - Will use ^{163}Ho later this year

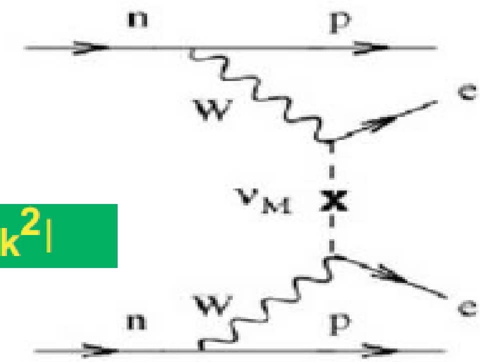




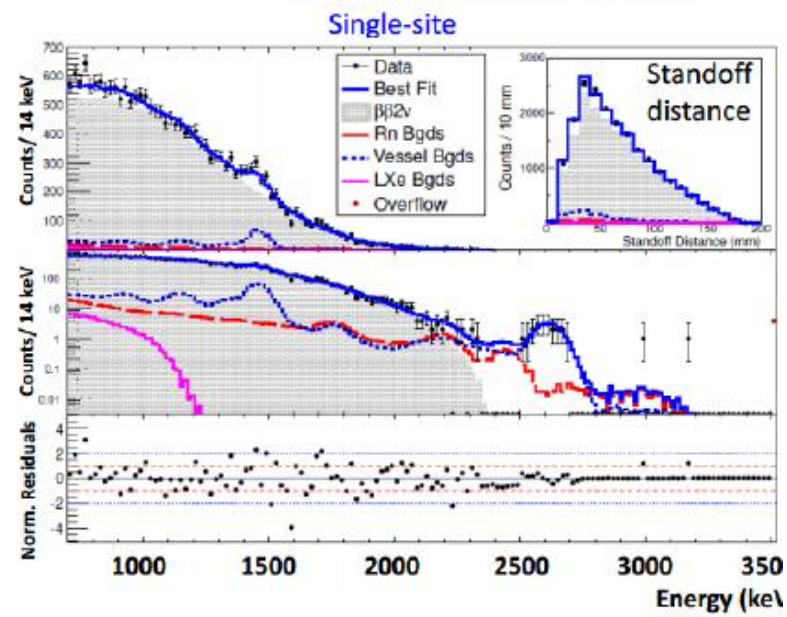
Can a Fermion be its own antiparticle? $0\nu\beta\beta$

- Neutrino-less Double Beta Decay
  - Also a sensitive probe of absolute ν mass
  - EXO-200: 200kg of liquid Xenon in WIPP
  - MAJORANA Demonstrator: 30kg of ^{78}Ge at SURF
  - EXO: Study 2ν mode as calibration (and background)
    - Presented here: best measurement of the 2ν mode half-life
  - EXO-200: Trying to improve sensitivity by x1(with barium tagging! (Daughter of decay)
  - Expected EXO sensitivity: ~0.2eV
  - Expected Majorana Sensitivity: 0.1-0.2eV

$$m_{\beta\beta} = \left|\Sigma_k m_{\nu k} U_{ek}^2\right|$$



$$T_{1/2}^{2\nu\beta\beta} = (2.172 \pm 0.017 \pm 0.060) \cdot 10^{21}\ \text{yr}$$
(stat.) (sys.)



EXO: Jason Chaves, Kravitz,
Majorana: Giovanetti

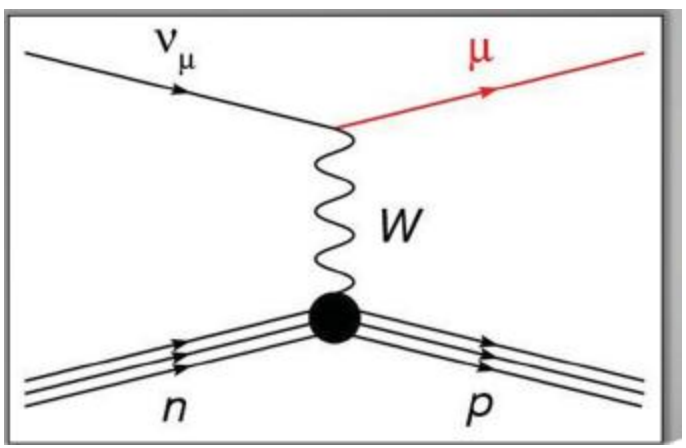
Using Neutrinos to see inside nucleus

- Why is this in a DPF session? Isn't it nuclear physics? Two answers
  - 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

"Simplest" ν interaction on nuclei: Quasi-elastic

- Important because they are dominant channel for T2K and significant fraction of NOvA events
- Clean identification of outgoing lepton possible
- "Theoretically" clean kinematic reconstruction
  - But have to assume something about initial state of proton/neutron inside the nucleus to get Energy and Momentum transferred (Q^2)

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

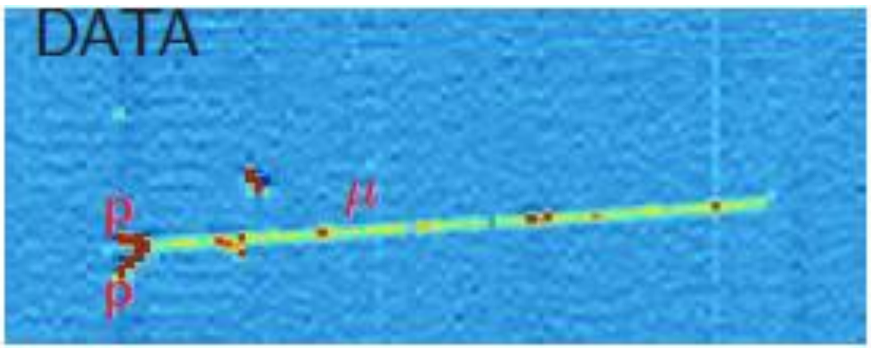


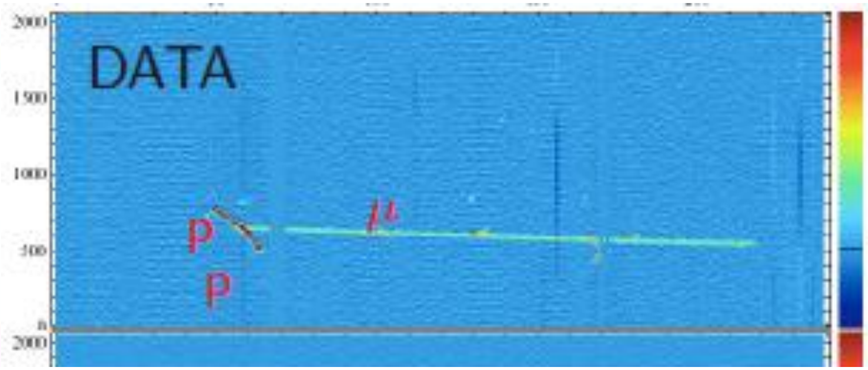
$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\ell - \left[(M_n - E_B)^2 + m_\ell^2 - M_p^2\right]}{2\left[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)\right]}$$

$$Q^2_{QE} = -m_\ell^2 + 2E_\nu^{QE}\left(E_\ell - \sqrt{E_\ell^2 - m_\ell^2}\cos(\theta_\ell)\right)$$

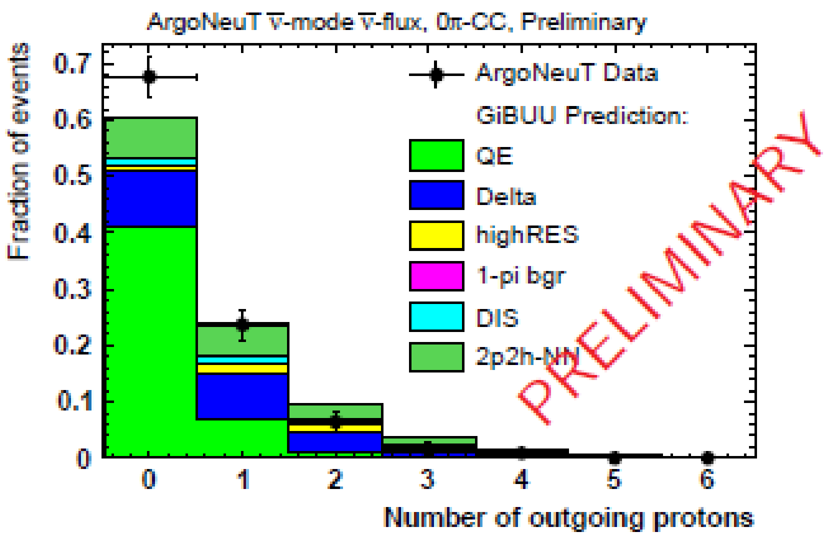
Seeing inside the nucleus at Argoneut

- "A picture is worth a thousand words"



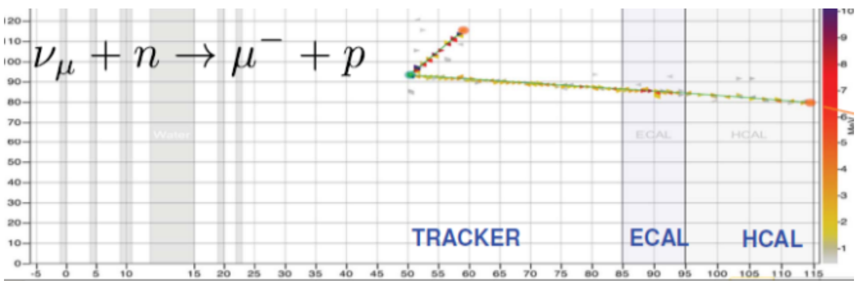


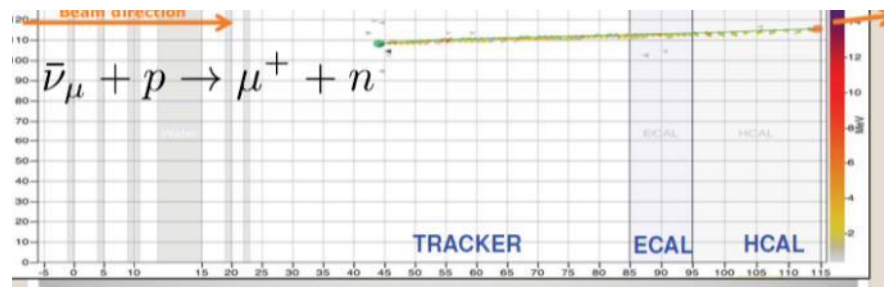
- Argoneut: Liquid Argon TPC that was in the NuMI beamline (~3GeV)
- New results on antineutrinos *(Szelc)*
- This data will constrain standard neutrino event generators because final state is so clear
- Challenge will be to correctly simulate acceptance for these extra protons
- Two test beam detector plans described at DPF: LARIAT *(Szelc)* and CAPTAIN *(Grant)*

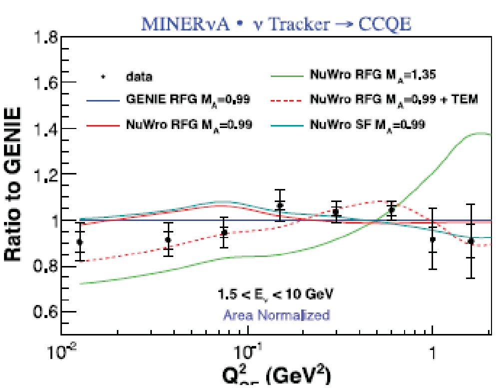


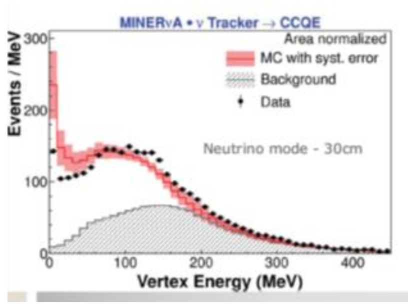
Seeing inside the nucleus at MINERvA

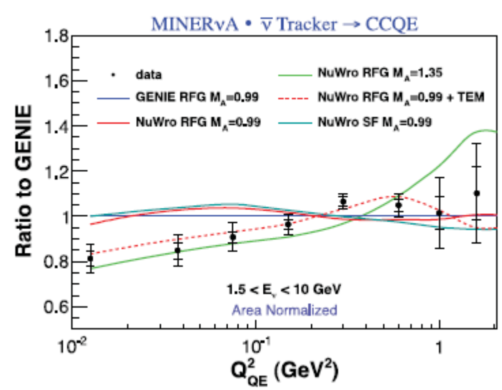
- MINERvA is a scintillator-based detector in the NuMI beamline (~3GeV) designed to look at interactions on plastic as well as a range of nuclear targets
- MINERvA has measured Q^2 distributions for ν and anti-ν, and also looks at the energy near the interaction vertex
- Sees evidence for np correlations in the nucleus: would give pp final state in ν scattering, nn final state in νbar scattering *(Rakotondravohitra)*

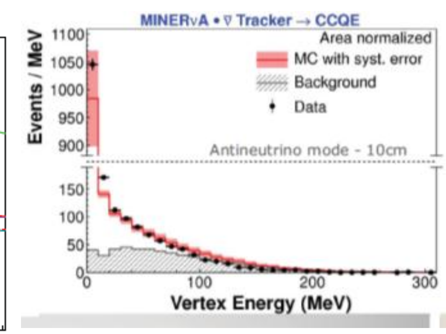






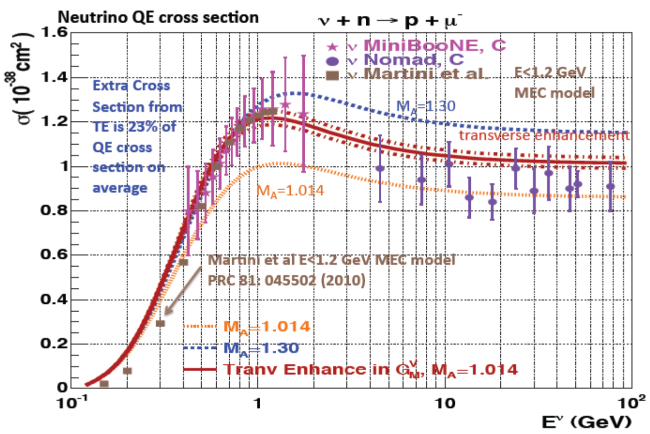


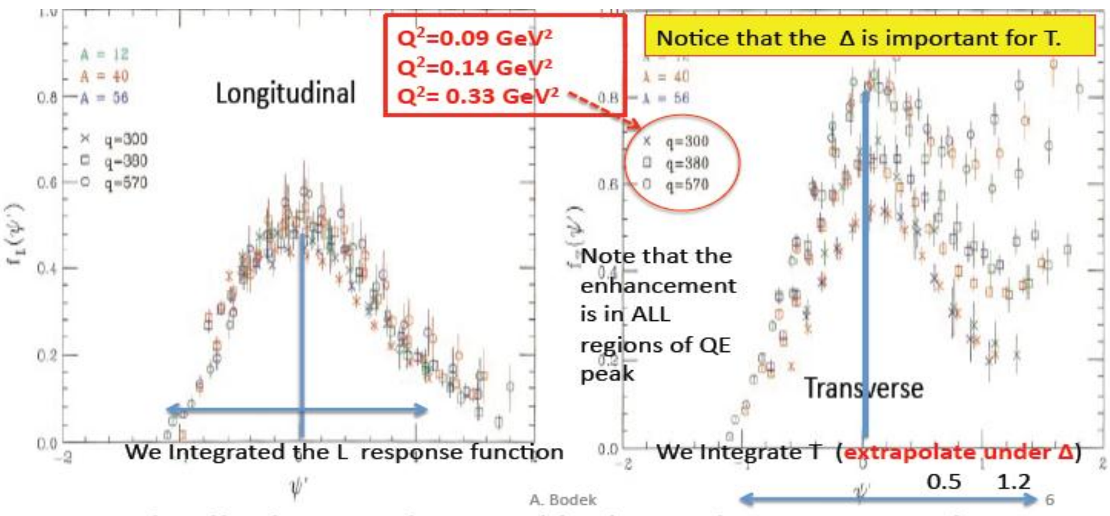


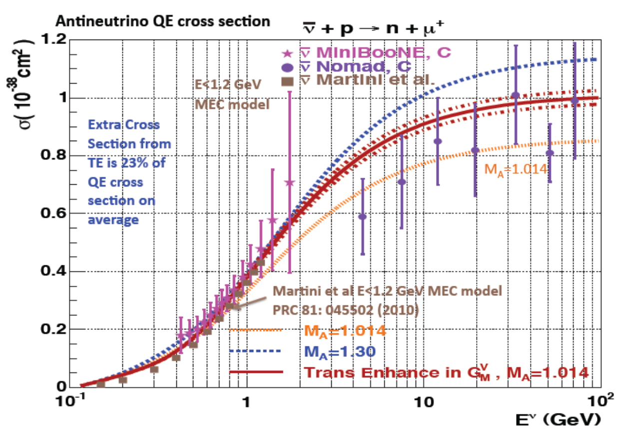


Seeing inside the nucleus with Electron Scattering

- Nuclear physicists have made much progress on understanding the nucleus with charged electron scattering
- They also see differences in cross sections from what you would see if there were no correlations between nucleons in the nucleus *(Bodek)*
- Applying this to neutrino Quasi-elastic measurements agrees better with data than current "out of the box" models

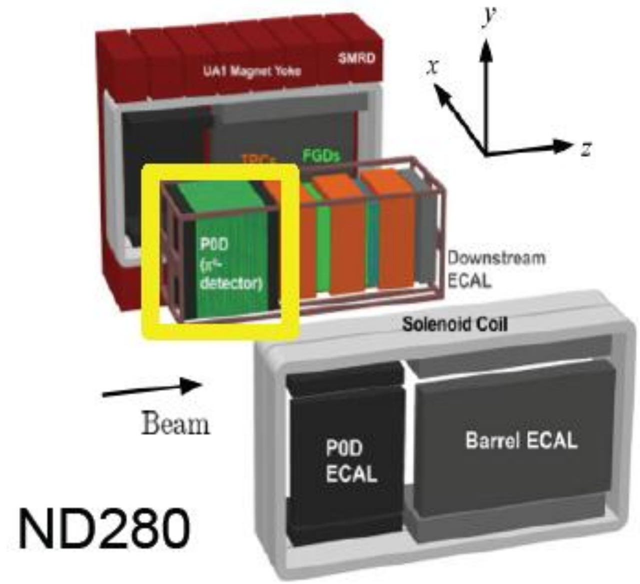


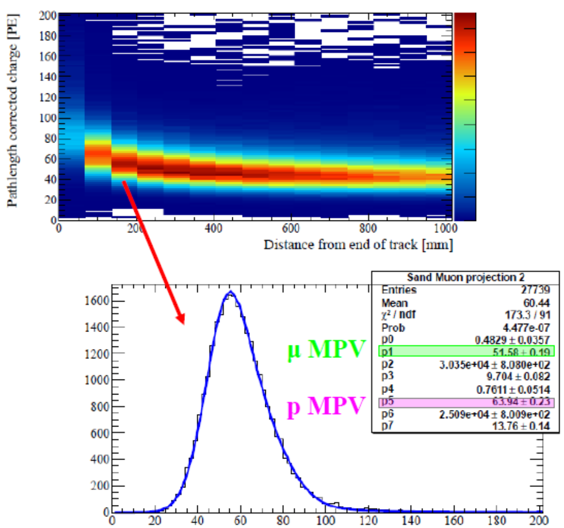


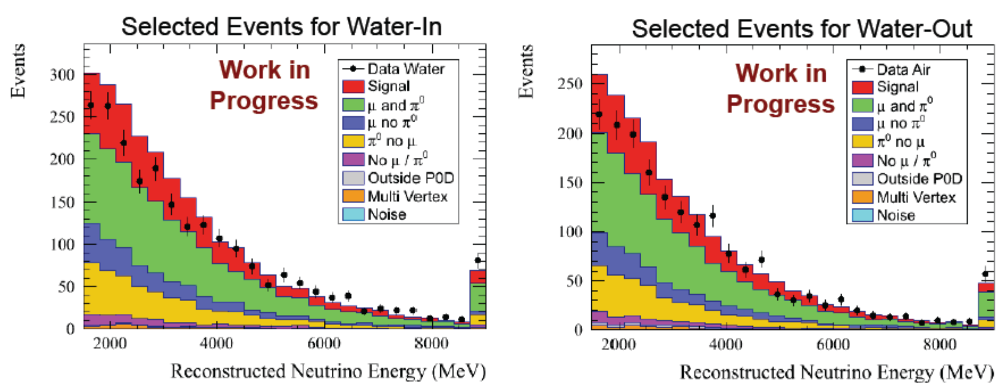


Seeing inside the nucleus at T2K

- T2K is a long baseline experiment using Super-Kamiokande and a beam with a peak energy of ~700MeV
- T2K has a near detector to measure cross sections specifically on water
- First glimpse at ν_e events at high energies *(Adam)*
- Also trying to make CCQE measurement on water *(Hansen)*







Do we really understand flavor?

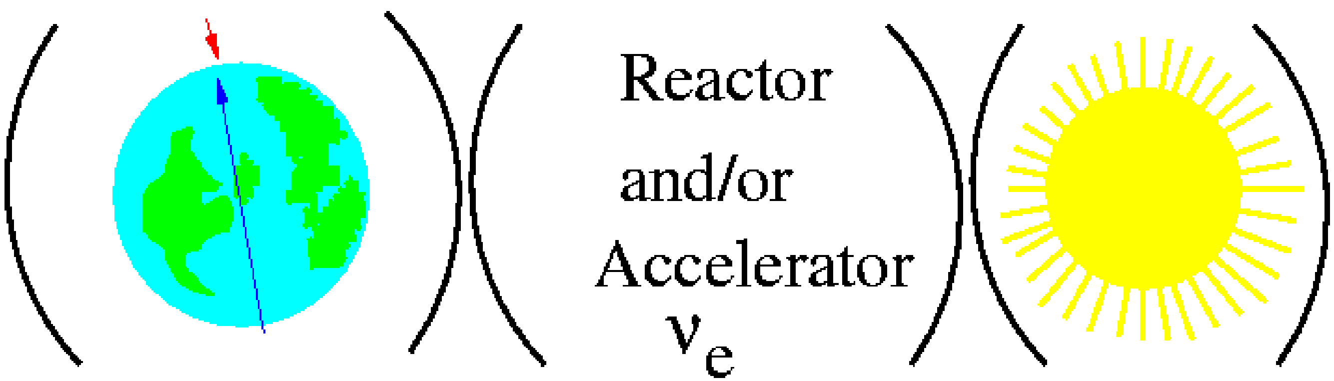
- Everything I needed to know about flavor I learned from the quarks…

Lesson Learned from CKM: 3 mixing angles and a phase

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

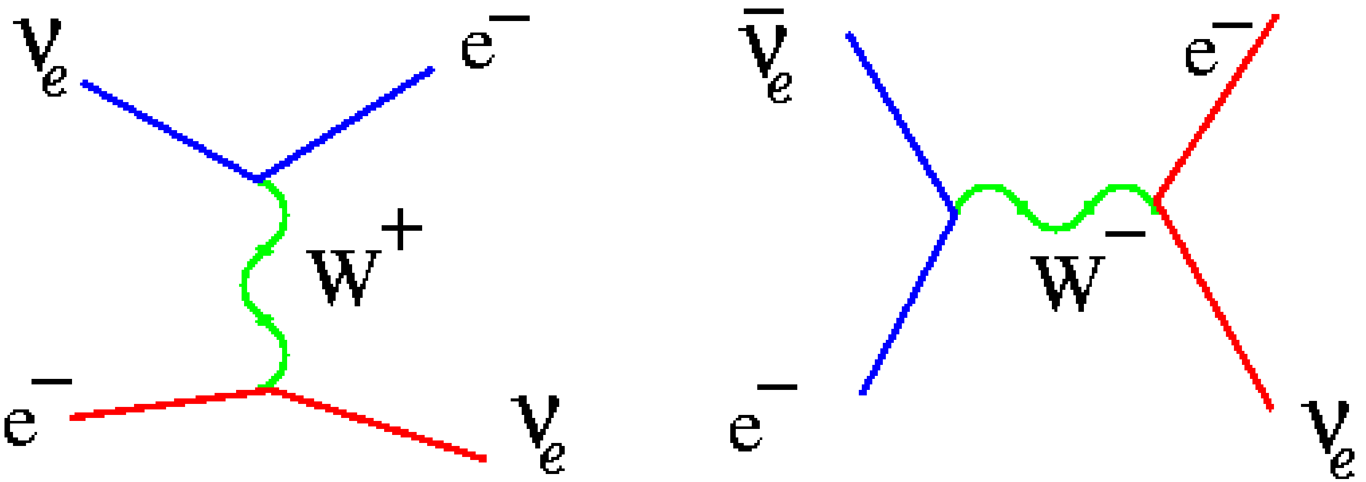
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

U=



Additional Complication: Matter Effects

- The oscillation probability changes differently for electron neutrinos vs antineutrinos when they propagate through matter in a straightforward way



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 Bonus: Matter Effects

- Bonus: the way the oscillation probabilities change depend on whether the “electron-like” neutrino mass eigenstates are on the top or the bottom of the spectrum.
- We know from numerous experiments that there are two mass differences: large and small, but we don’t know how they are ordered

- One of these looks much more like the quark masses, all the more reason to measure it!

ν Oscillation Probabilities

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

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

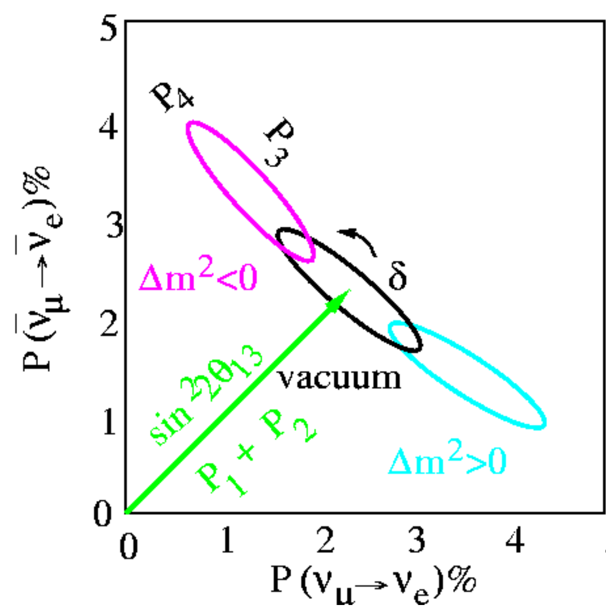
- ν_e appearance in a ν_μ beam: even more complicated…
- $P(\nu_\mu\to\nu_e)=P_1+P_2+P_3+P_4$

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

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

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

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



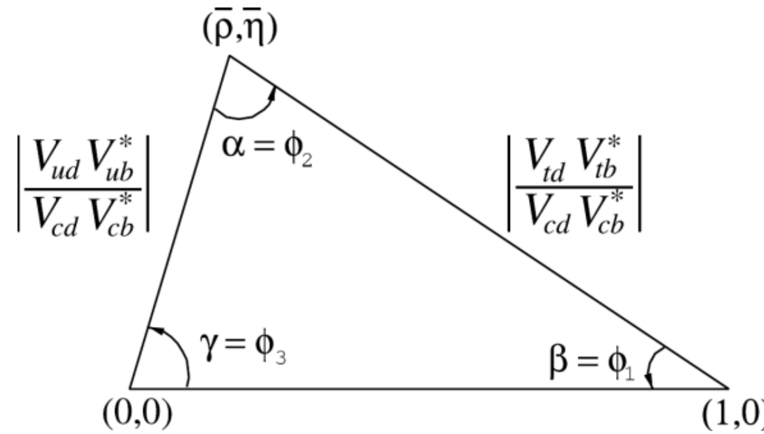
Minakata & Nunokawa JHEP 2001

Stages of ν Flavor Physics

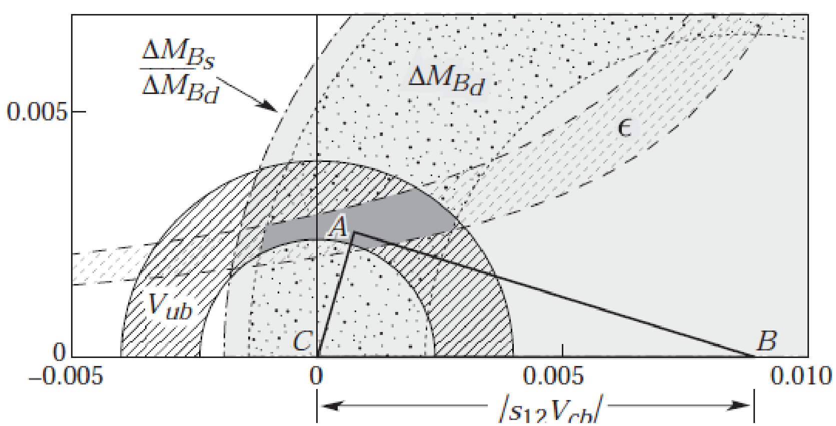
- Stage 1: Denial (1960's through 1998)
- Stage 2: Are all the mixing angles non-zero? (1998-2012)
- Stage 3: Can a 3-generation mixing matrix explain every example we have of flavor change? (2012 and beyond)
- Stage 4: Are neutrino masses arranged like the quark masses?
- Stage 5: Do neutrinos actually violate CP?

Comparison with Quark Sector

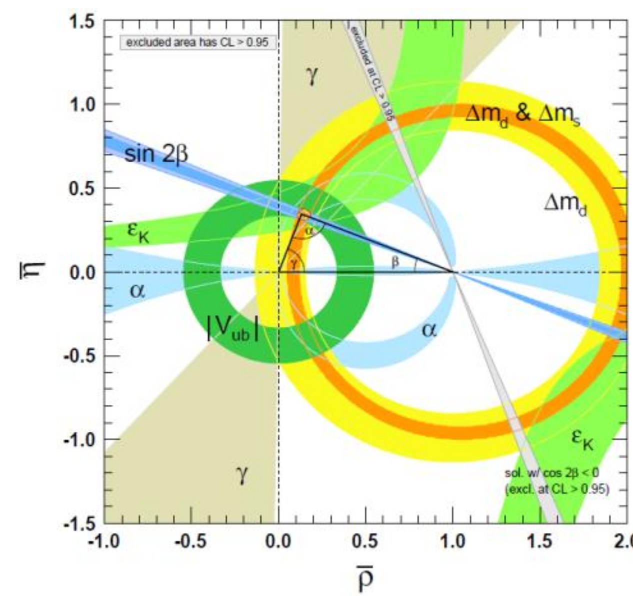
- CKM Matrix Elements were understood to be part of a unitary matrix, which implied the following triangle would close itself
- Measurements needed in kaon and B meson sectors to confirm or refute this



PDG, 1998

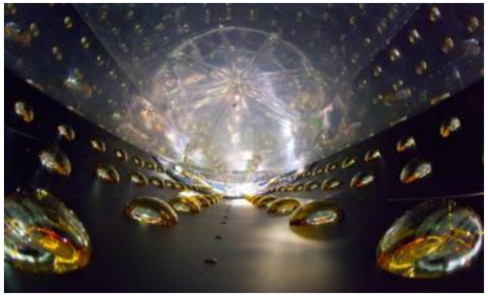


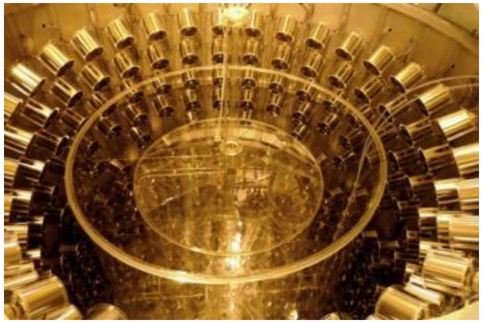
PDG, 2012

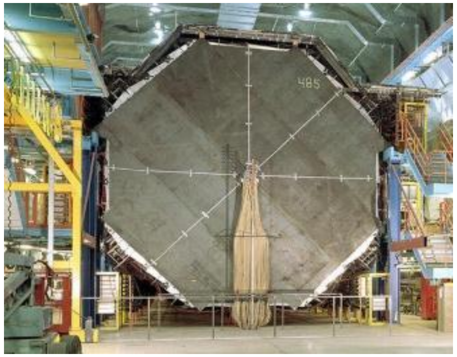


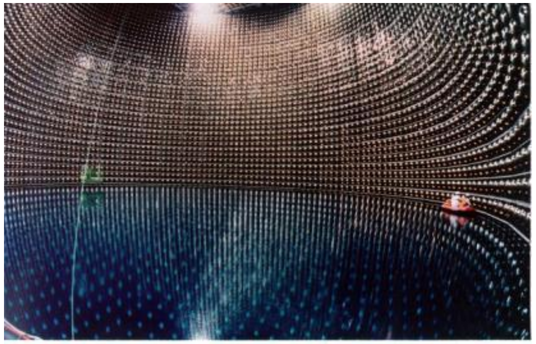
Oscillation Results at DPF

- Daya Bay
  - Reactor experiment in China (3MeV νbars), near and far liquid scintillator detectors
- Double Chooz
  - Reactor experiment in France (3MeV νbars), currently only far liquid scintillator detector
- MINOS
  - 3GeV ν_μ accelerator experiment in US, 735km baseline, magnetized steel scintillator detectors near and far
- ICE CUBE
  - Ice Cerenkov detector at South Pole looking at atmospheric νs
- T2K
  - 700MeV ν_μ accelerator experiment in Japan, 295km, Water Cerenkov far detector, water/scintillator/TPC near detectors





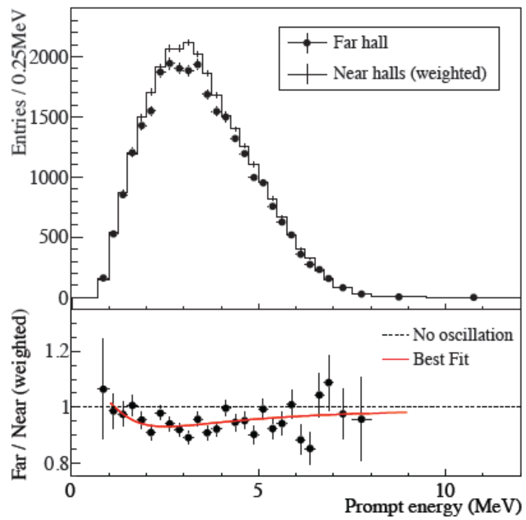


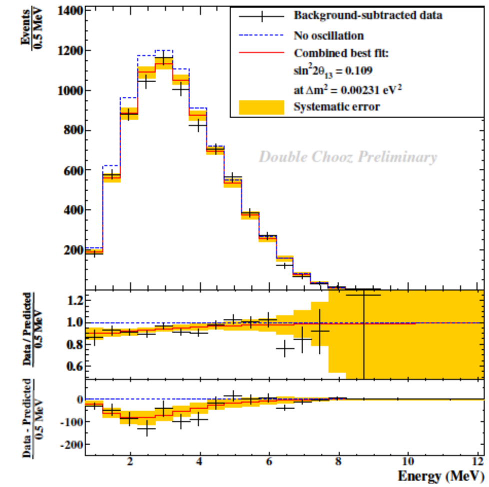


(Other 5159 not shown)

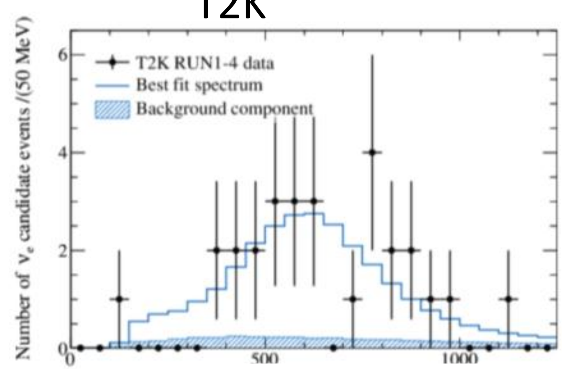
Stage 2: Evidence last mixing angle (Θ_{13}) is >0

- Broad range of energies:
  - Reactors (Daya Bay, Double Chooz) at few MeV
    - Double Chooz reactor off, Gd capture: $\sin2^2\Theta_{13} = 0.091 \pm 0.035$ *(Carr)*
    - Daya Bay has near and far detectors *(Worcester)*
  - Accelerators (T2K, MINOS) at 1-3 GeV
    - T2K: see 28 events, predict 4.6 background events, new improved π^0 background rejection technique *(Hignight)*
    - MINOS: see 152 events, 129 background in ν mode, 20 events on 18.5 background events in νbar mode (Radovic)
  - Atmospheric Neutrinos (PINGU) to look, but at 10-100GeV, using mass hierarchy *(Williams)*



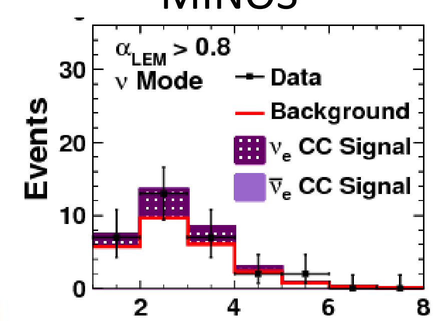


T2K



Reconstructed Energy (MeV)

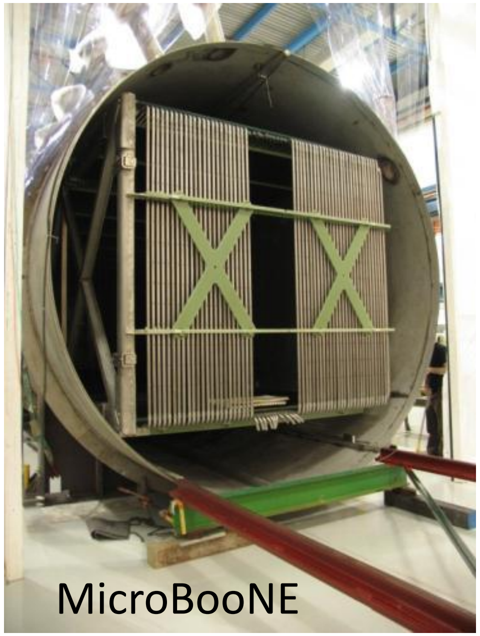
MINOS



Reconstructed Energy (GeV)

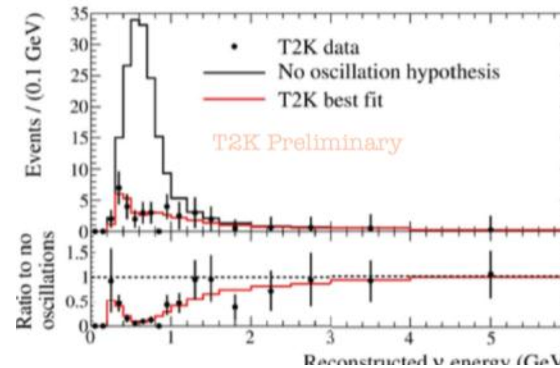
Stage 3: Are 3 angles and a phase enough?

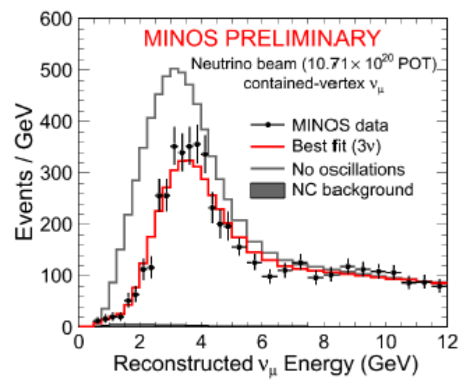
- Seeing Largest Mass Splitting across many energies
  - MINOS, T2K, Deep Core (ICECUBE)
- Electron Neutrino Appearance:
  - T2K, MINOS
  - Immediate future
    - NOvA: 2GeV accelerator ν_μ's in US, 810km baseline, liquid scintillator detectors near and far, starting to take data in 2013 *(Bian, Baird, Sachdev)*
    - MicroBooNE: 1GeV ν_μ accelerator experiment in US, 1km baseline, Liquid Argon TPC to start taking data in 2014 *(Collin)*
  - Farther ahead
    - LBNE *(Bass, Guardincerri)*
    - Other ideas: ISODAR, Deadalus *(Shaevitz)*

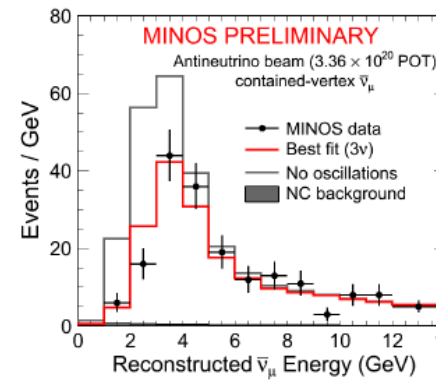


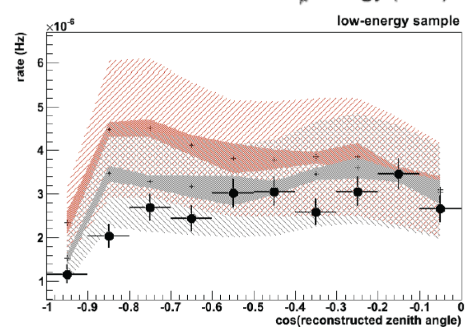
Stage 3: seeing the largest mass splitting (Δm^2_{23})

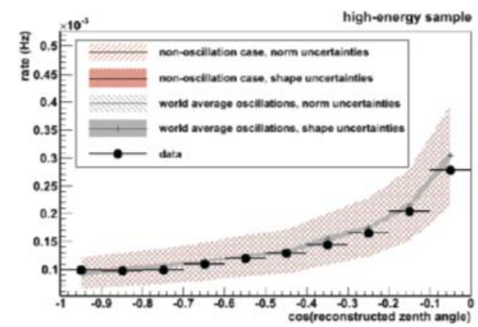
- T2K: 700MeV at 295km
- MINOS: 3.5GeV at 735km, ν and νbar, plus atmospheric ν's *(Radovic)*
- ICECUBE (Deep Core): disappearance 20-100GeV, no disappearance 100GeV-1TeV *(Williams)*
- Stay tuned:
  - Daya Bay analyzing shape of reactor ν's to measure mass splitting! (Δm_{13}^2, instead of Δm_{23}^2), eventual sensitivity comparable to MINOS *(Worcester)*
  - T2K with full POT statistics would get to 4×10^{-5} eV^2 error *(Friend)*
  - NOvA will have strong constraints on this *(Baird)*





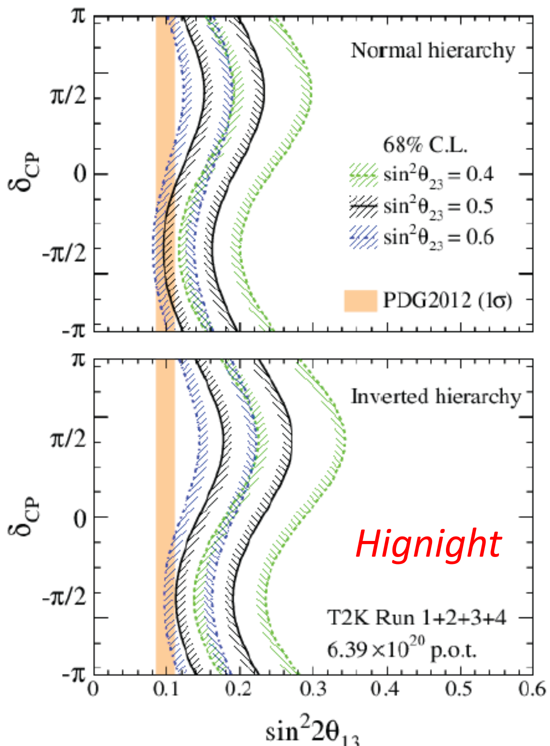




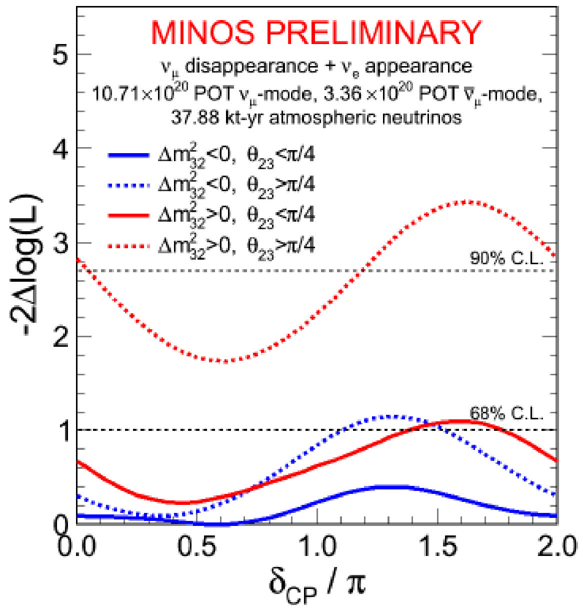


Stage 4: seeing mass hierarchy through ν_e appearance

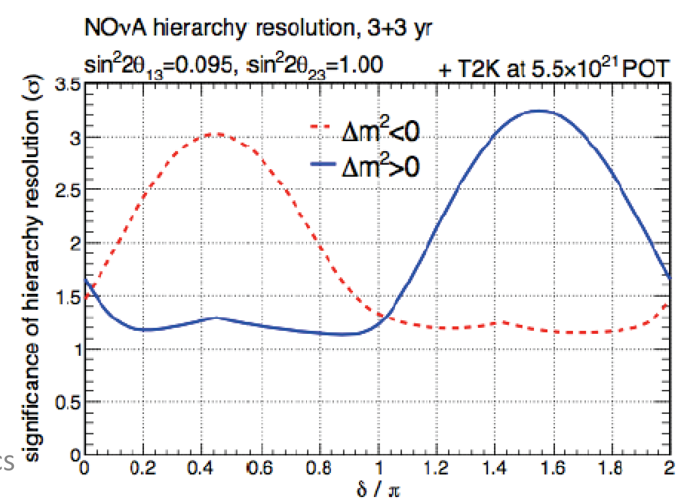
- Recall that appearance depends on mass hierarchy and CP-violating phase δ, and even whether Θ_{23} is above or below 45°
  - T2K considering ν and νbar running, adding reactor Θ_{13} *(Friend)*
  - NOvA showed mass hierarchy sensitivities with T2K *(Bian)*



*Note that these are 1D contours for various values of δ_{CP}, not 2D contours

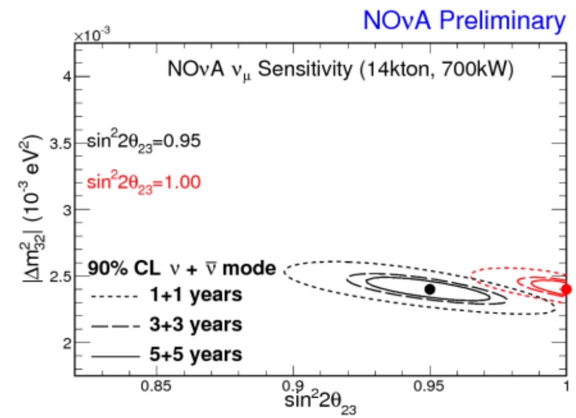


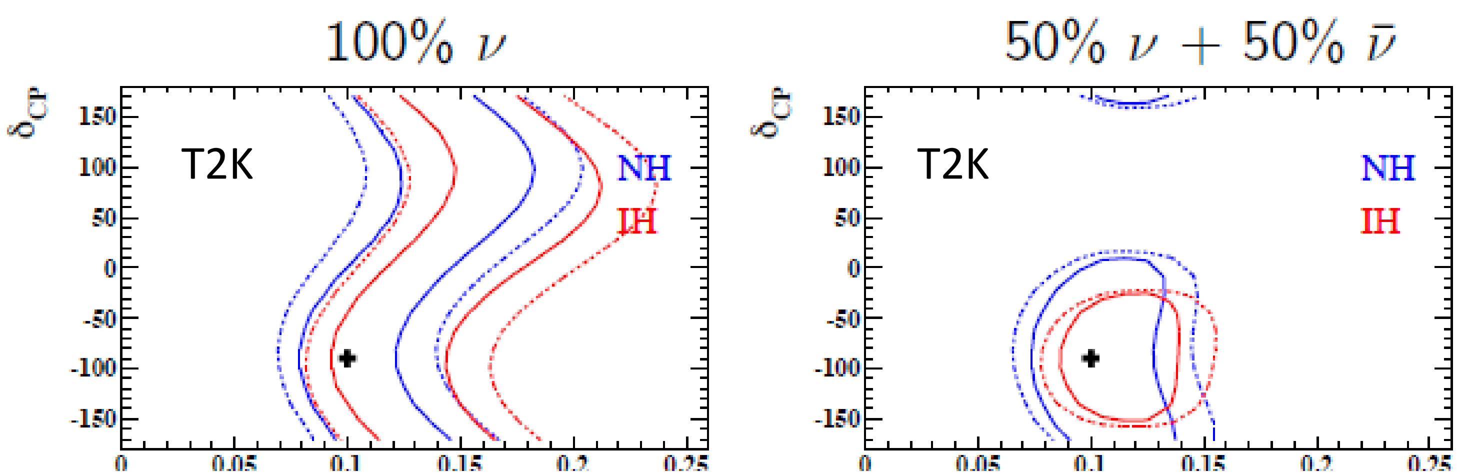
Radovic



Current Generation, Ultimate Sensitivities

- NOvA has statistical precision to making precise Δm^2_{23} measurement, regardless of CP phase or mass hierarchy *(Baird)*
- T2K sill also have good statistics and systematics to get to Δm^2_{23} *(Friend)*
- T2K also showed "full statistics" sensitivites, considering partial running in anti-neutrino beam *(Friend)*

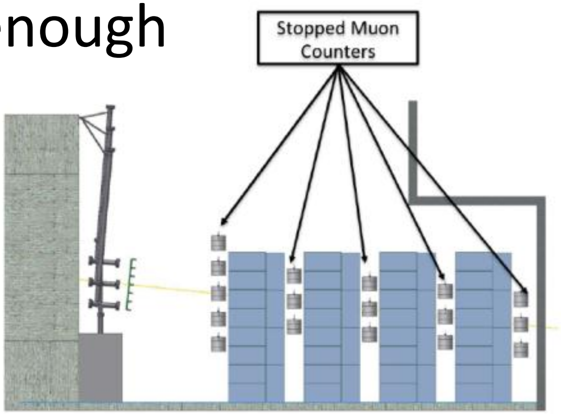




Note: this looks even better when reactor Θ_{13} is added,
But would still only give "hint" at delta

Stage 5: Can we see if there really is CP violation in the lepton sector?

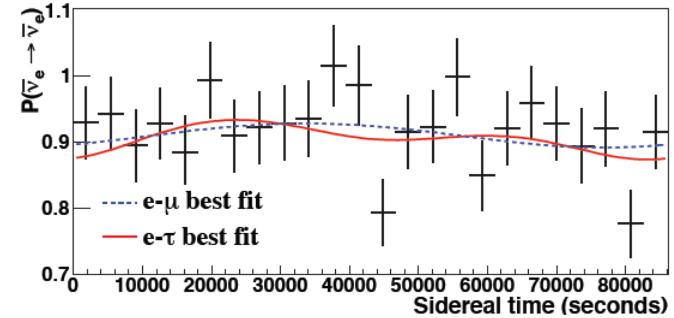
- Big range of ideas going forward
  - "preferences" for mass hierarchy or delta may come soon, but we can't forget what statistical tests really mean
  - We want to see this in as many ways as possible
  - Should not stop thinking about ways to improve on current plans
  - Should not think that 1 experiment is enough
- LBNE is gathering momentum
  - Clever ideas on beamline monitoring *(Guardincerri)*
  - New attention to accurate simulations *(Bass)*
    - with knowledge of interactions and their current uncertainties
    - With better description of detector capabilities



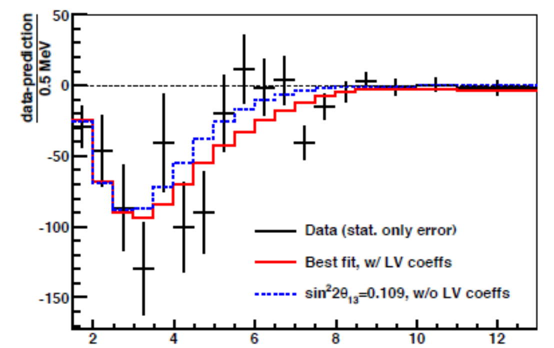
Are there any (more) surprises out there?

- Double Chooz: *(Spitz)*
  - Search for Lorentz violation
  - Search for n-nbar oscillations

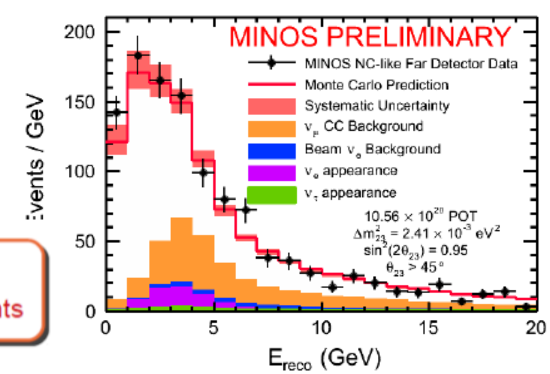
$$\overline{\nu}_e p \rightarrow e^+ n$$



- MINOS: *(Aurisano)*
  - Search for sterile neutrinos by comparing NC events in near and far detectors
  - Stay tuned: MINOS+ will have improved sensitivity to sterile neutrino sector through ν_μ disappearance



Observed: 1221 events
Expected: 1183 ± 34(stat) ± 36(syst) events



Summary

- These are exciting days in Neutrino Physics
- Have running experiments from keV to EeV to see very broad range of physics
- Progress is fast when you think about how recently we were in the denial phase of oscillation physics
- New ideas for absolute mass measurements, we should keep pressure on to make those work as well
- Current generation of accelerator-based experiments have many options ahead of us (ν vs anti- ν running), have to strive for best way to get the best measurements as a field
  - Very likely that the sum will be greater than each of the parts, especially if we coordinate!