Neutrino Experiments Lecture IV

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Fermilab

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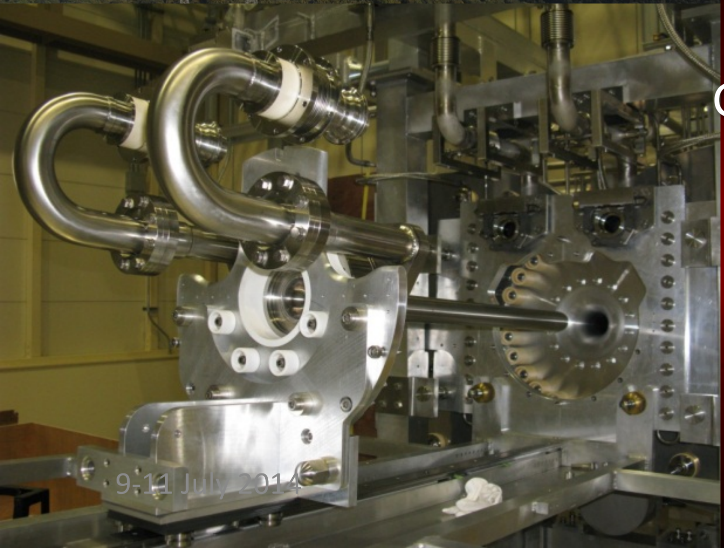
Invisibles School 2014

Gif-sur-Yvette, FRANCE



Schedule

- Lecture 1 (9 July)
  - What do we know how to measure right now?
  - What neutrino sources are available?
- Lecture 2 (10 July)
  - How do neutrinos interact in matter?
  - How do non-neutrino particles interact in matter?
  - What neutrino detectors are out there?
- Lecture 3 (11 July)
  - Absolute Mass and Majorana Mass Measurements
- Lecture 4 (11 July)
  - Oscillation Measurements

Adding together the Ingredients

(Recent) Experiments with Published Data

Neutrino Source/ Detector Type	Solar	Reactor	Atmos-pheric	Accelerator-based
Cerenkov	Super-K, SNO		Super-K	T2K, MiniBooNE
Liquid Scintillator		Kamland, Daya Bay, Double Chooz, RENO		
Segmented Scintillator				
Steel plus Active			MINOS	MINOS
Lead plus emulsion				OPERA
Ice plus PMT's			ICECUBE	
Liquid Argon TPC				ICARUS

What Parameters have been "Measured"?

Neutrino Source/ Detector Type	Solar	Reactor	Atmospheric	Accelerator-based
Cerenkov	θ_{12}, Δm_{12}^2		θ_{23}, Δm_{23}^2, τ app.	θ_{23}, Δm_{23}^2, θ_{13}, Δm_{13}^2, 4th gen., τ app.
Liquid Scintillator		θ_{12}, Δm_{12}^2, θ_{13}, Δm_{13}^2		
Segmented Scintillator				
Steel plus Active			θ_{23}, Δm_{23}^2	θ_{23}, Δm_{23}^2, (θ_{13}, Δm_{13}^2 search), 4th gen.
Lead plus emulsion				τ appearance
Ice plus PMT's			θ_{23}, Δm_{23}^2	
Liquid Argon TPC				τ app., 4th generation

Recall ν Oscillation Probabilities

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

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

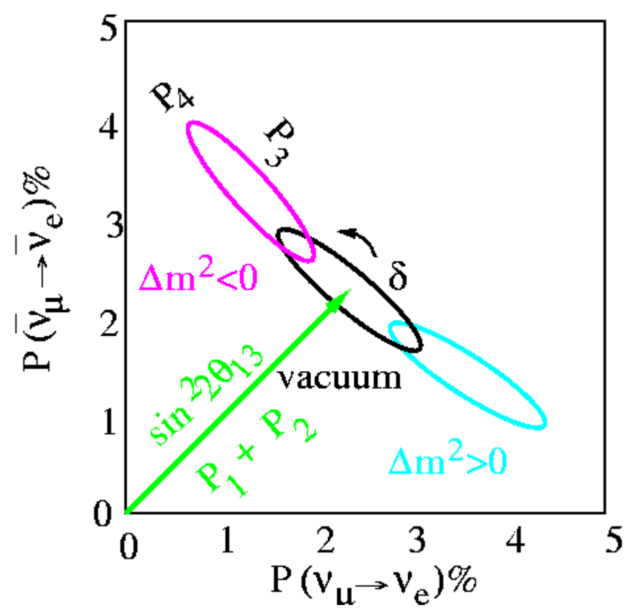
- ν_e appearance in a ν_μ beam: even more complicated…
- $P(\nu_\mu\rightarrow\nu_e)=P_1+P_2+P_3+P_4$

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

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

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

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



Minakata & Nunokawa JHEP 2001

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 will start with how to make the measurements,
But I have to tell you how the uncertainties come in

Measuring Oscillation Probabilities

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

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

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

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:

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

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

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

Problem:

Don't always know *a priori* which regime you are in

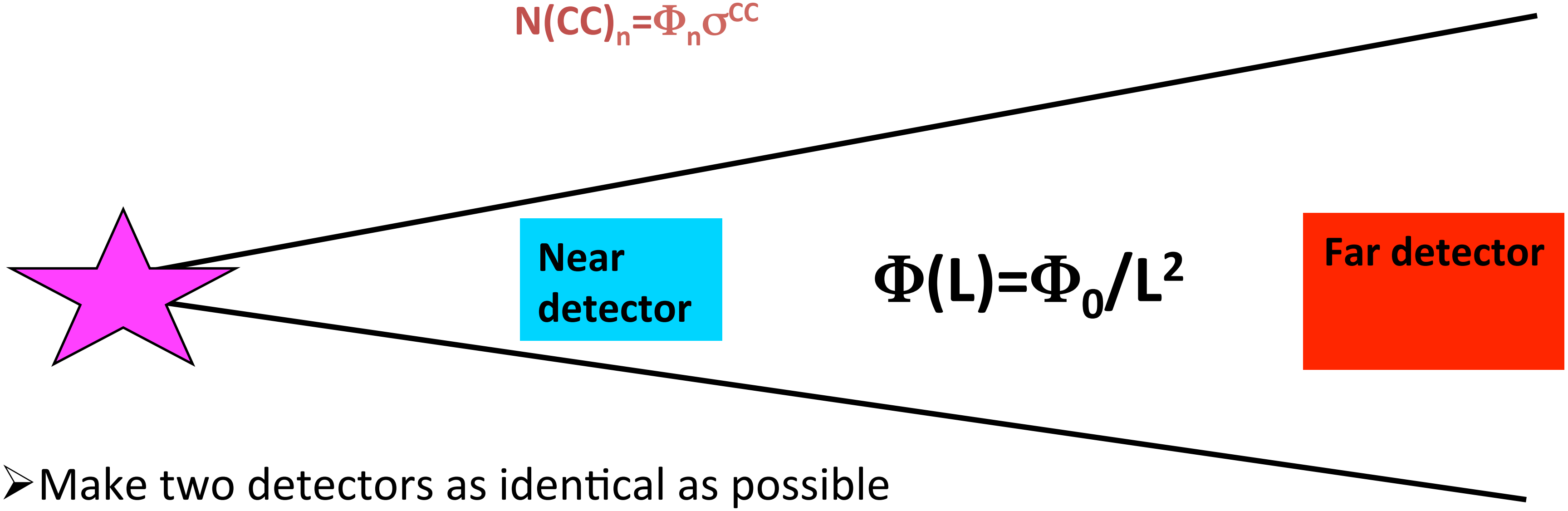
---depends on Δm^2,

---depends on $\sin^2 2\theta_{13}$

Two detector experiment (in theory)

$N(NC)_n = \Phi_n \sigma^{NC}$

$N(CC)_n = \Phi_n \sigma^{CC}$



$N(NC)_f = \Phi_f \sigma^{NC}$

$N(CC)_f = \Phi_f \sigma^{CC}$

- Make two detectors as identical as possible
  - same scintillator, water, steel etc.
- Measure ν spectrum in the near detector
- Predict the ν spectrum in the far detector
- Cross section uncertainties should cancel…
- Detector efficiency uncertainties should cancel…
- Simple, right?

2 Detector Strategy, low background, ν_e disappearance measurement

$$N_{near} = \varphi_{\nu_e near}\sigma_{\nu e}\varepsilon_e M_{near} T(truth \rightarrow reconstructed)$$

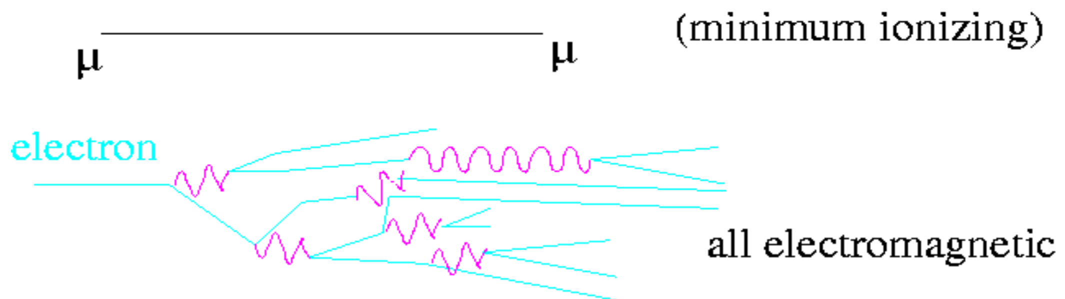
$$N_{far} = \varphi_{\nu_e far}\sigma_{\nu e}\varepsilon_e M_{far} P(osc) T(truth \rightarrow reconstructed)$$

$$P(osc) = \frac{N_{far} T_{far}^{-1}(truth \rightarrow reconstructed)\phi_{far}\sigma_{\nu e}\varepsilon_{ef} M_{far}}{N_{near} T_{near}^{-1}(truth \rightarrow reconstructed)\phi_{near}\sigma_{\nu e}\varepsilon_{en} M_{near}}$$

$$P(osc) = \frac{N_{far} T_{far}^{-1}(truth \rightarrow reconstructed) L_{near}^{2}\sigma_{\nu e}\varepsilon_{ef} M_{far}}{N_{near} T_{near}^{-1}(truth \rightarrow reconstructed) L_{far}^{2}\sigma_{\nu e}\varepsilon_{en} M_{near}}$$

Detector Strategy, low background, ν_μ to ν_e appearance measurement

- Same as previous slide, but different:
  - Ratio of ν_e to ν_μ efficiencies: recall



  - Ratio of ν_e to ν_μ cross sections
    - Although energy distributions are different, so also need to know cross section as function of energy
  - Ratio of Truth to reconstructed matrices for ν_e versus ν_μ
    - See above diagram for why this will be different

What about backgrounds?

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

Backgrounds come from several sources

$$N_{near} = \sum_{i=\mu,e} \phi_{\nu_i\, near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}$$

Build near detector with same ε

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

Simulations better at predicting ratios absolute levels

$$B_{far} = \sum_{i=\mu,e} N_{near,i}\frac{\phi_{\nu_i\, far}}{\phi_{\nu_i\, near}}\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}}\frac{\varepsilon_{ix}}{\varepsilon_{ix}}\frac{M_{far}}{M_{near}}$$

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…

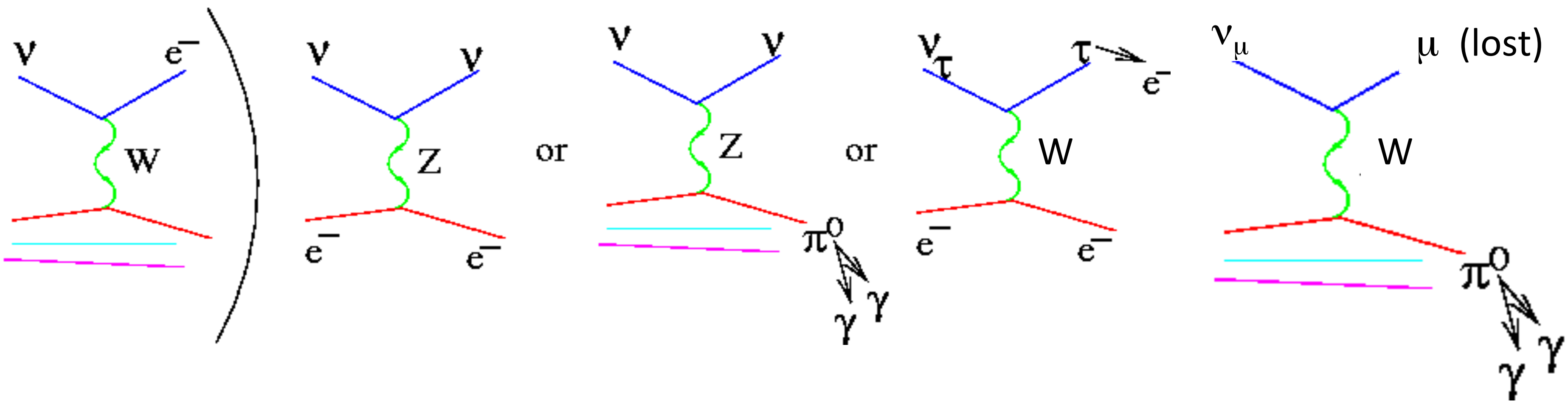
"Two Detector" θ_{13} Experiments

	Reactor	Accelerator
Detector Efficiency	IDENTICAL	Different at least in size, and possibly in technology
Event Rate/unit mass	Differs by 4 to 20?	Differs by a million
Neutrino Flux	Scales as $1/L^2$	Near detector sees line source, far detector sees point source
Backgrounds	Different due to different overburdens	Different due to $\nu_\mu \rightarrow \nu_\tau$ oscillations (and ν_τ don't interact via W exchange)
Cross Sections	Near and far detectors have comparable cross section compositions	ν_e's in near detector are from beam, ν_e's in far detector have very different energy spectrum (hence different cross sections)

Consequences: Reactor Experiments show Far/Near event ratios,
Accelerator experiments never do

Backgrounds to ν_μ to ν_e measurement

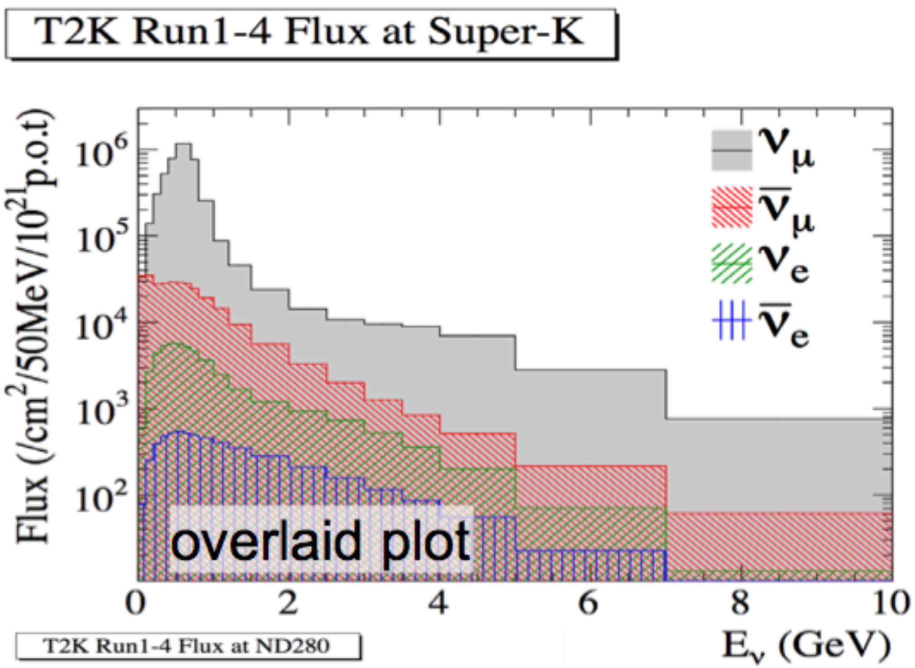
- Remember, these will depend on
  - Neutrino energy of beam
  - Detector technology
  - Beamline design (how many muons decay compared to pions?)

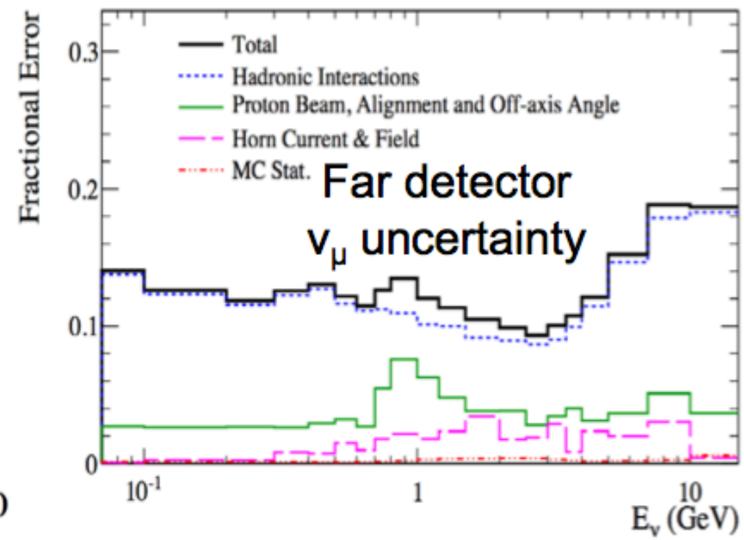


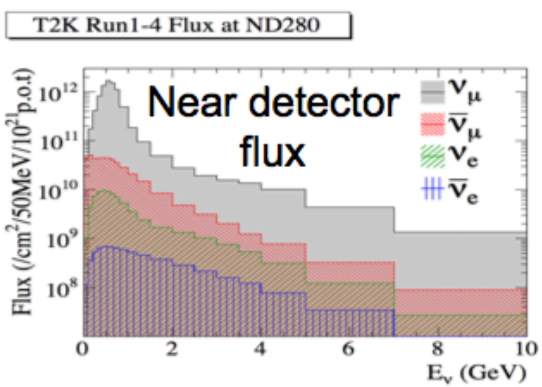
Road to precision

- 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?

Few words about the T2K Flux







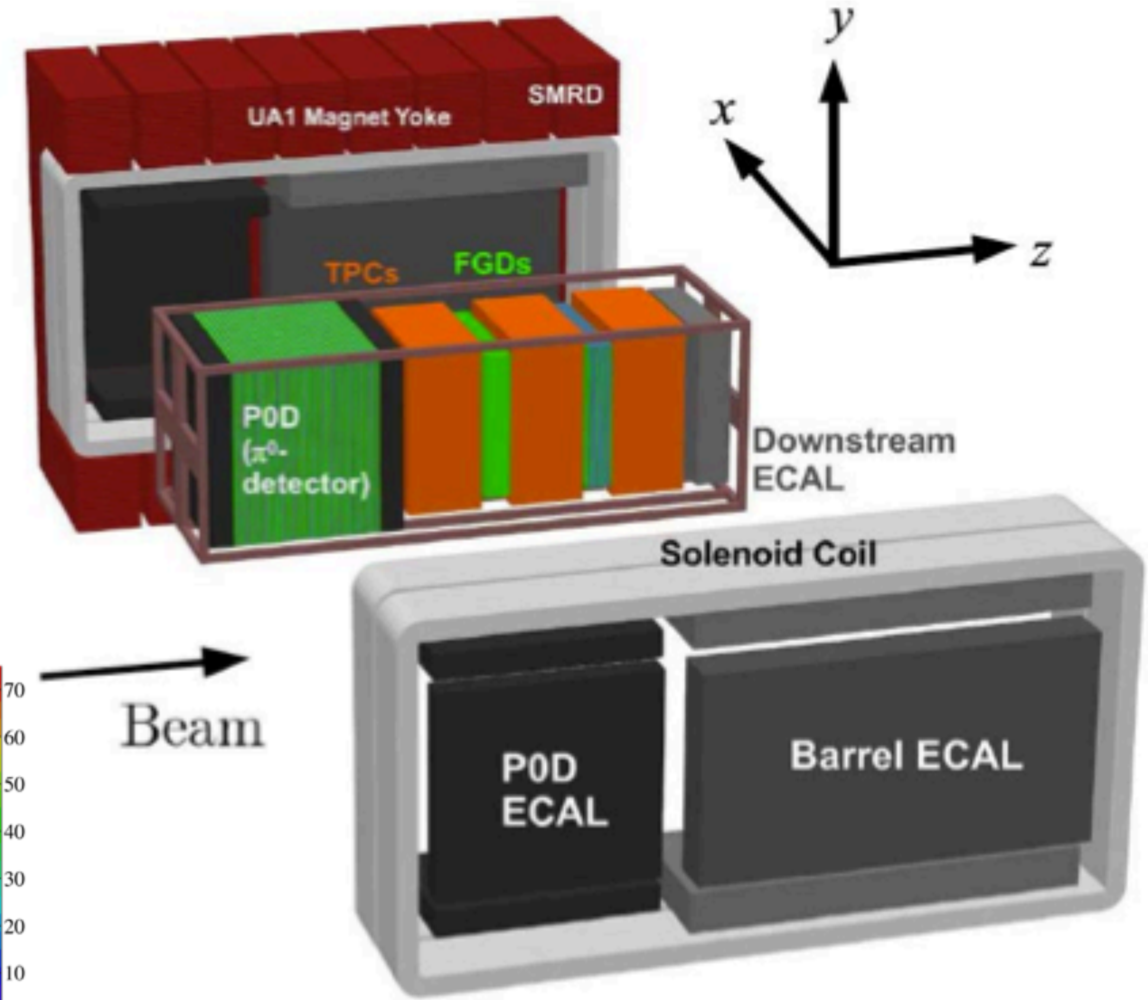
- A priori prediction of flux at Super-K has 10-15% uncertainties from 0.1 to 5 GeV
- Off-axis near (ND280) and Far (Super-K) fluxes are not identical, but highly correlated

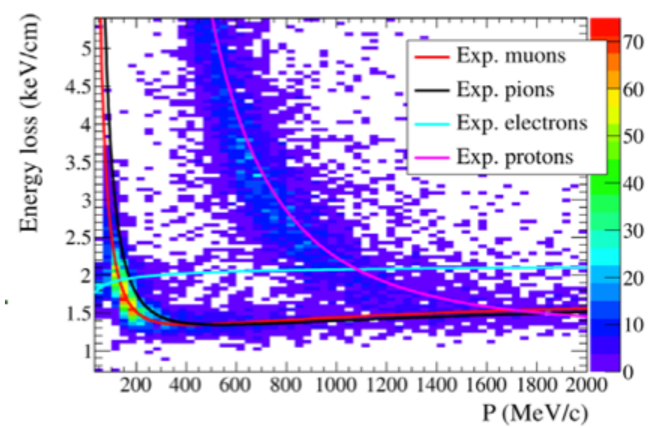
K. McFarland: Oscillations @ T2K

Fermilab JETP, August 2013

Near Detector for ν_e appearance

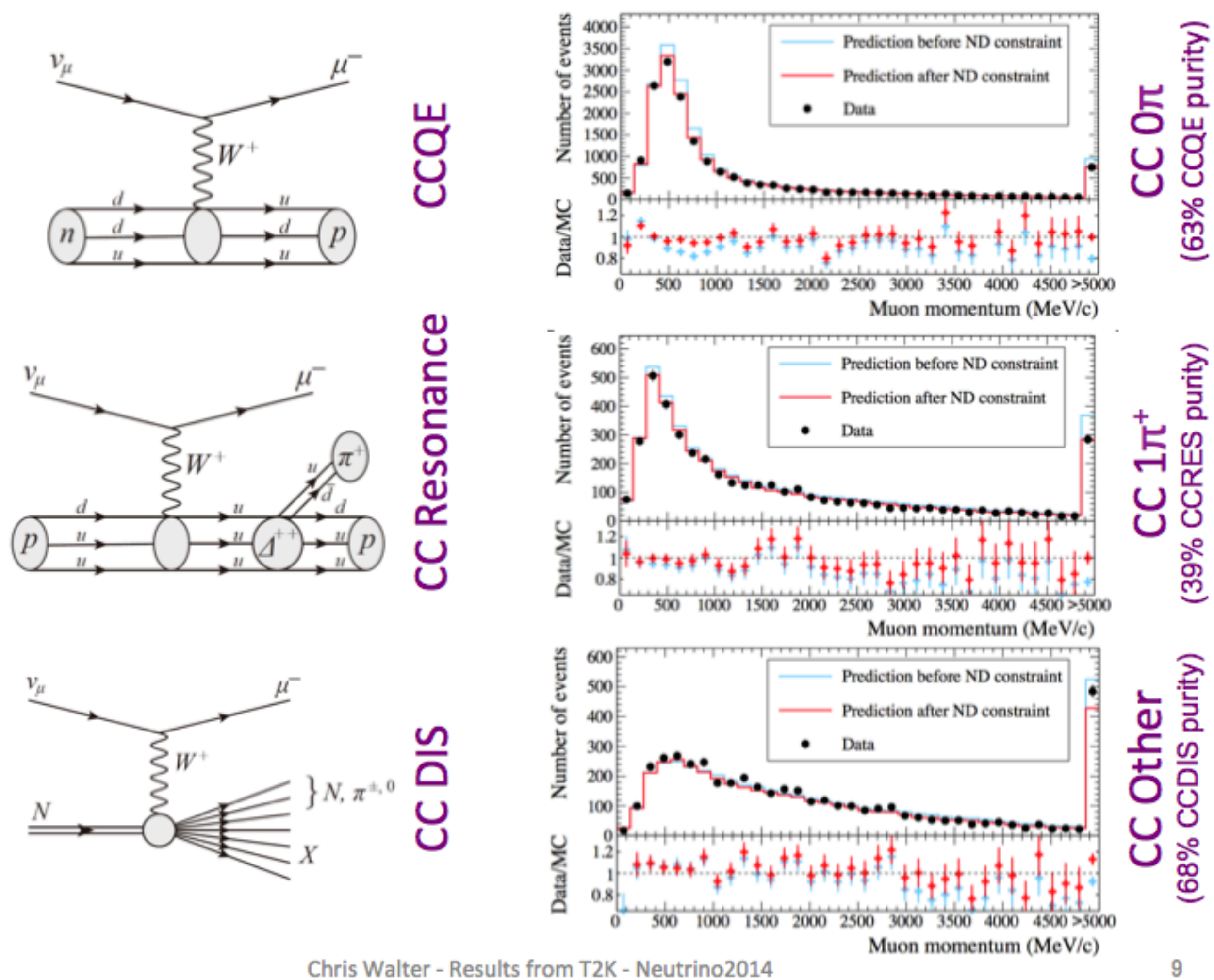
- Note lack of water Derenkov technology here: rate @280m is too high
- Fine grained scintillator detectors (FGDs) as target, plus water target
- TPC's for excellent particle ID between FGD's
- In a magnetic field



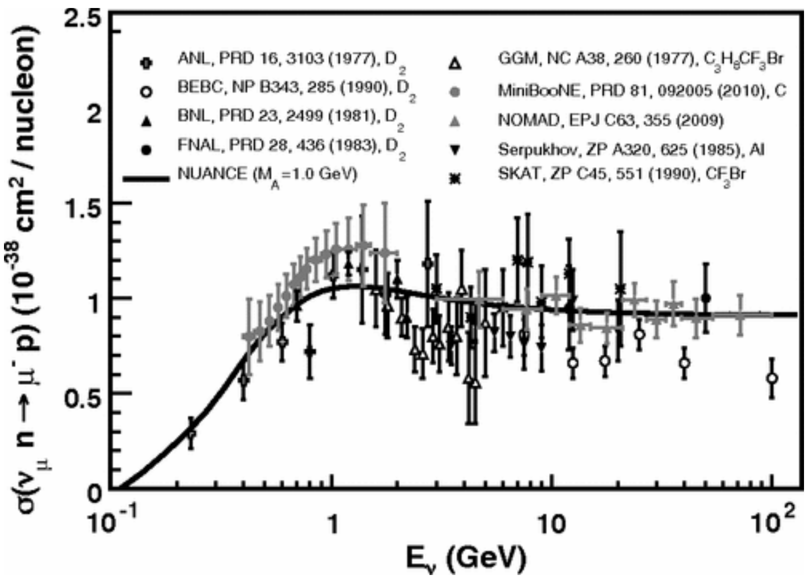


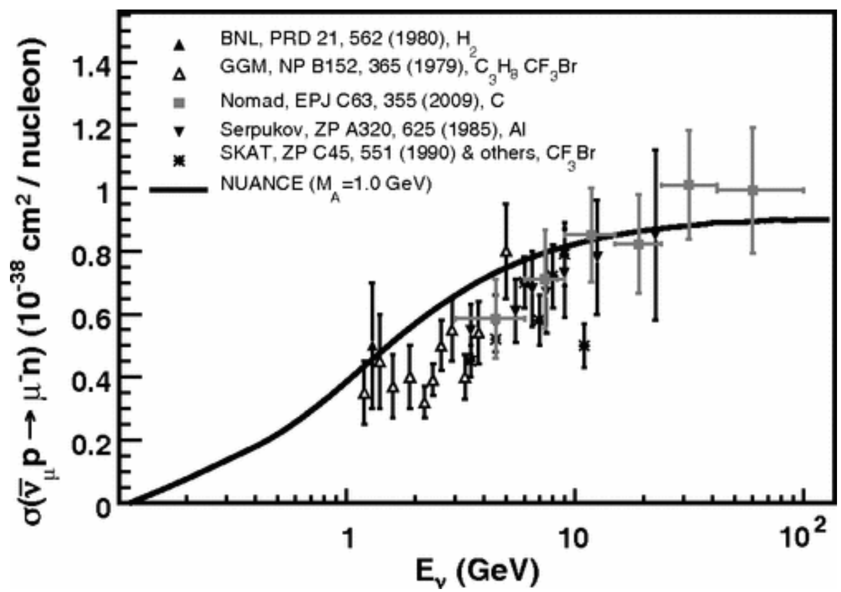
T2K Near Detector Event Samples

- 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



What about other Cross Section Measurements?





Formaggio and Zeller, Rev Mod Phys.84.1307

Total rates uncertain at 10-20%, different measurements of same process sometimes differ by 40%, often blamed on “nuclear effects”

- ν_e cross sections even less well-known, see Day and McFarland, Phys.Rev. D86 (2012) 053003

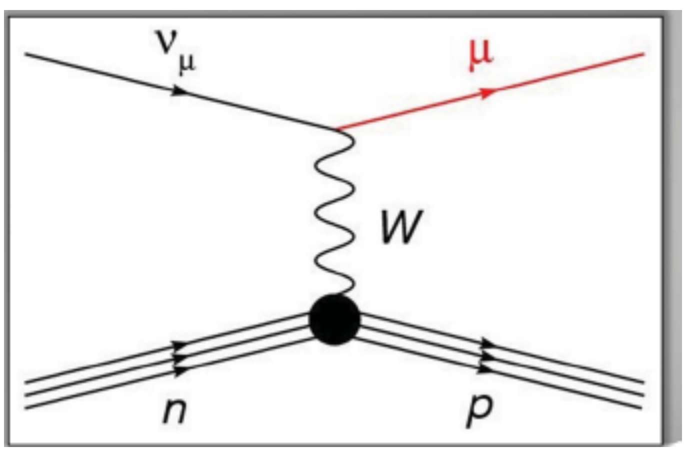
Understanding Nuclear Effects

- Why is this in a neutrino school? 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)

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



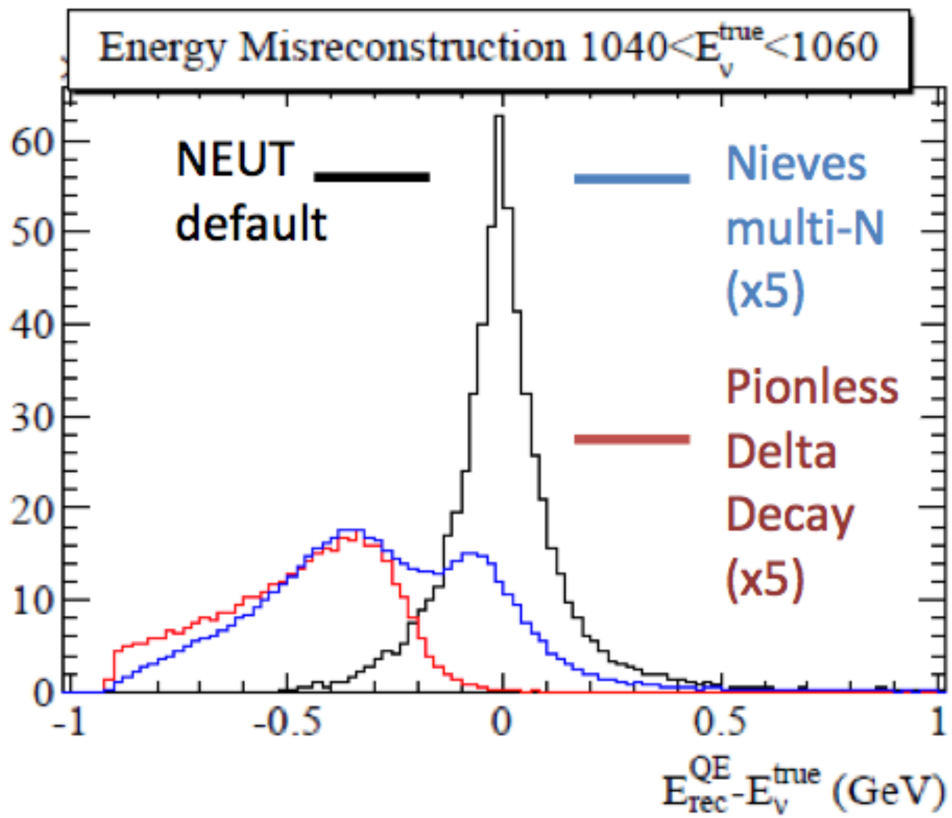
$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right) E_\ell - \left[\left(M_n - E_B\right)^2 + m_\ell^2 - M_p^2\right]}{2\left[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)\right]}$$

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

Mis-Modeling Nuclear Effects

- Can cause problems with energy reconstruction for CCQE events

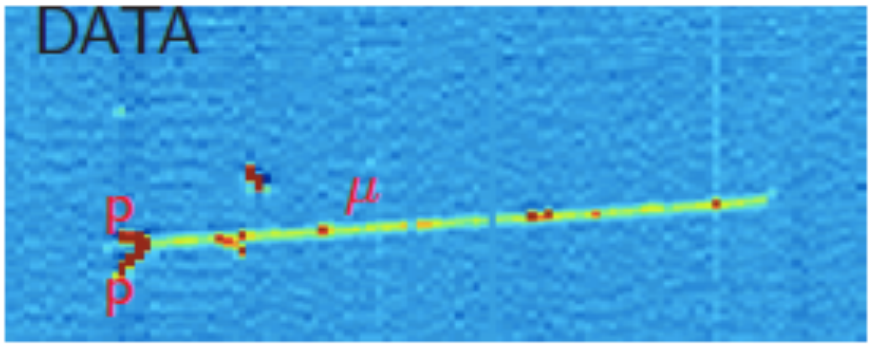
Nieves, J. et al, J. Phys. Conf. Ser. 408(2013) 12040

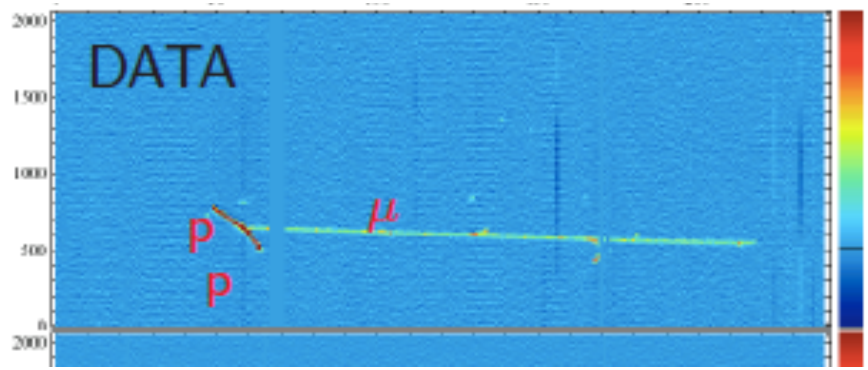


If nucleons are correlated inside the nucleus, then the "standard" assumptions about what the initial state neutron is doing are wrong

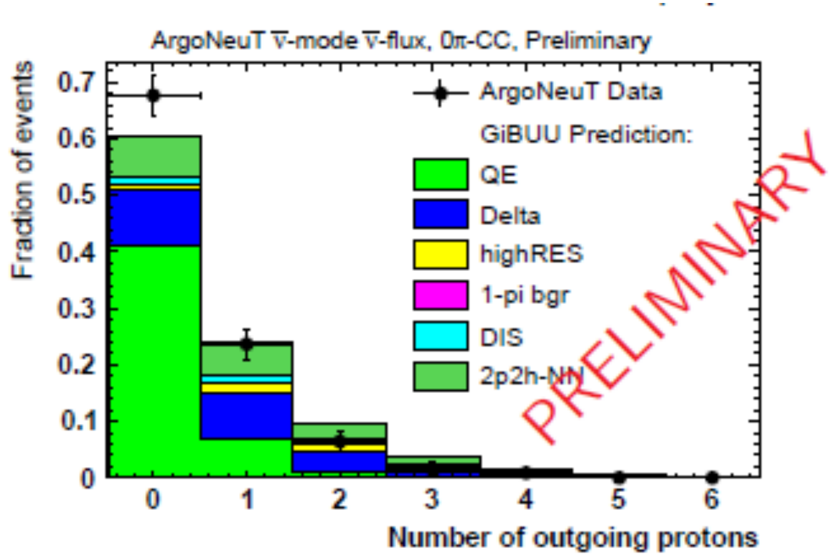
Seeing inside the nucleus at Argoneut

- “A picture is worth a thousand words”



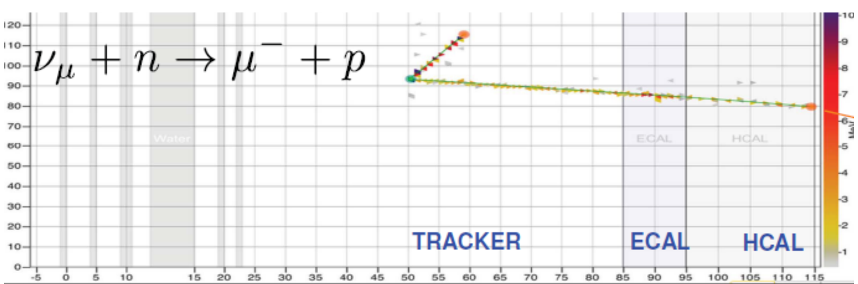


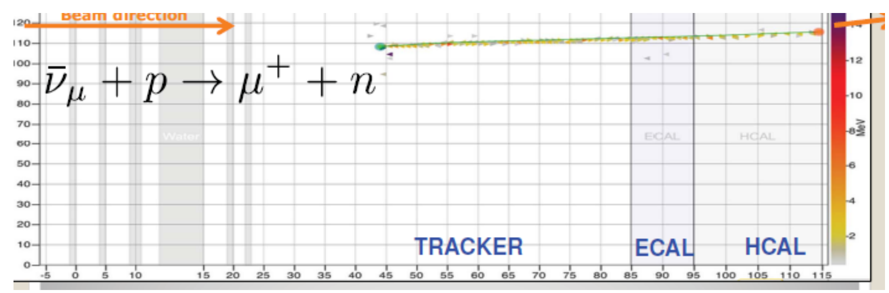
- Argoneut: Liquid Argon TPC that was in the NuMI beamline (~3GeV)
- New results on antineutrinos *(Szelc)*
- This data will constrain standard neutrino event generators because final state is so clear
- Challenge will be to correctly simulate acceptance for these extra protons

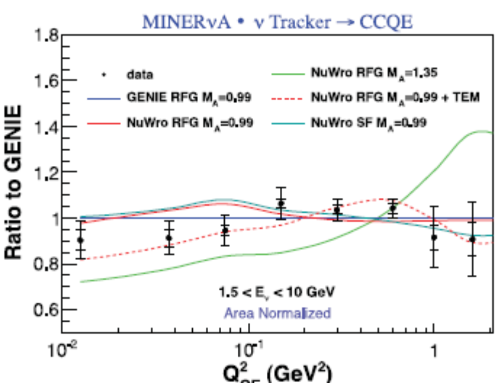


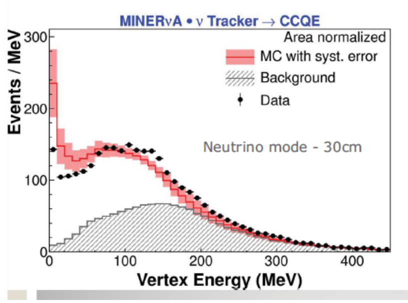
Seeing inside the nucleus at MINERvA

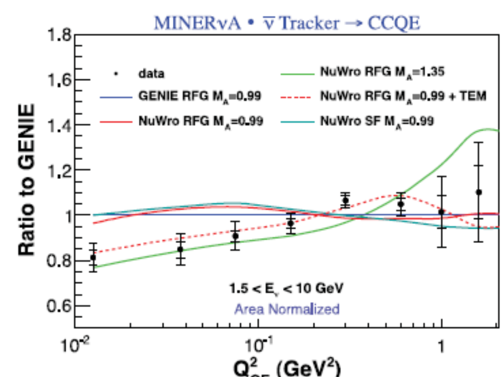
- MINERvA is a scintillator-based detector in the NuMI beamline (~3GeV) designed to look at interactions on plastic as well as a range of nuclear targets
- MINERvA has measured Q^2 distributions for ν and anti-ν, and also looks at the energy near the interaction vertex
- Sees evidence for np correlations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

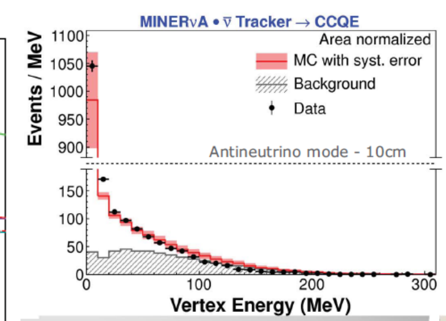












Phys. Rev. Lett. 111, 022501 and 022502 (2013)

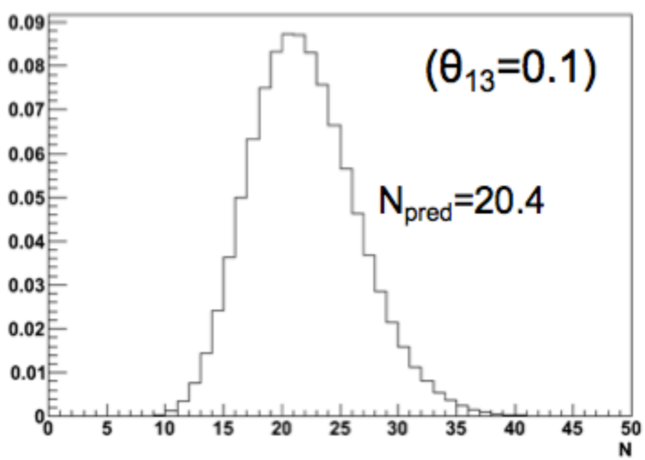
T2K fit of near and far data samples

$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$$

Systematic parameter constraint term. Systematic parameters may be naturally floated in fits.

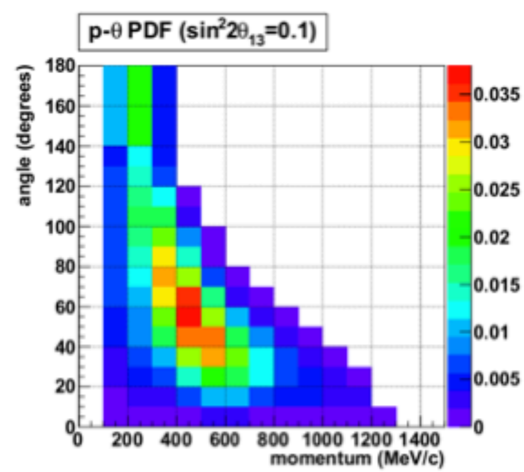
$$Poisson(N_{obs})_{\text{mean}=N_{\text{pred}}}$$

L_{norm} is the probability to have N_{obs} when the predicted number of events is the Poisson distribution with mean = N_{pred}.



$$\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$$

L_{shape} is the product of the probabilities that each event has (p_i, θ_i).
φ: Predicted p-θ distribution (PDF) .



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Near Detector Fit χ^2

$$\Delta\chi^2 = 2\sum_{i}^{p,\cos\theta\ bins} N_i^{pred}(\vec{b},\vec{x},\vec{d}) - N_i^{data} + N_i^{data}\ln[N_i^{data}/N_i^{pred}(\vec{b},\vec{x},\vec{d})]$$

$$+\sum_{i}^{E_\nu\ bins}\sum_{j}^{E_\nu\ bins}(1-b_i)(V_b^{-1})_{i,j}(1-b_j) + \sum_{i}^{xsec\ pars}\sum_{j}^{xsec\ pars}(x_i^{nom}-x_i)(V_x^{-1})_{i,j}(x_j^{nom}-x_j)$$

$$+\sum_{i}^{p,\cos\theta\ bins}\sum_{j}^{p,\cos\theta\ bins}(d_i^{nom}-d_i)(V_d^{-1})_{i,j}(d_j^{nom}-d_j)$$

b = flux nuisance parameters
x = cross section nuisance parameters
d = detector/reconstruction model nuisance parameters
V_b, V_x, V_d = covariance matrices (pre-fit uncertainties)

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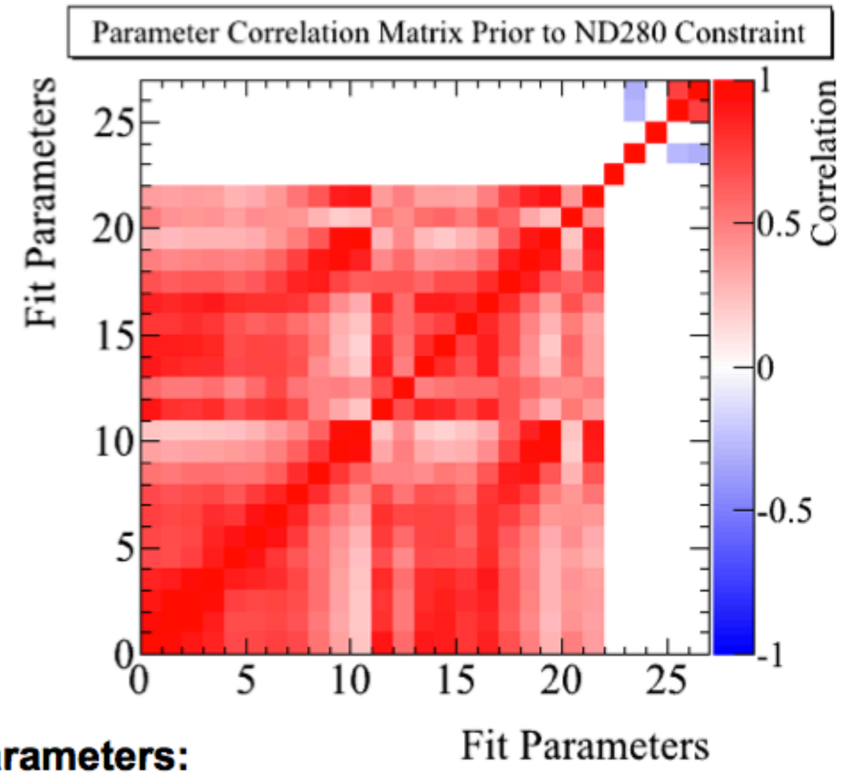
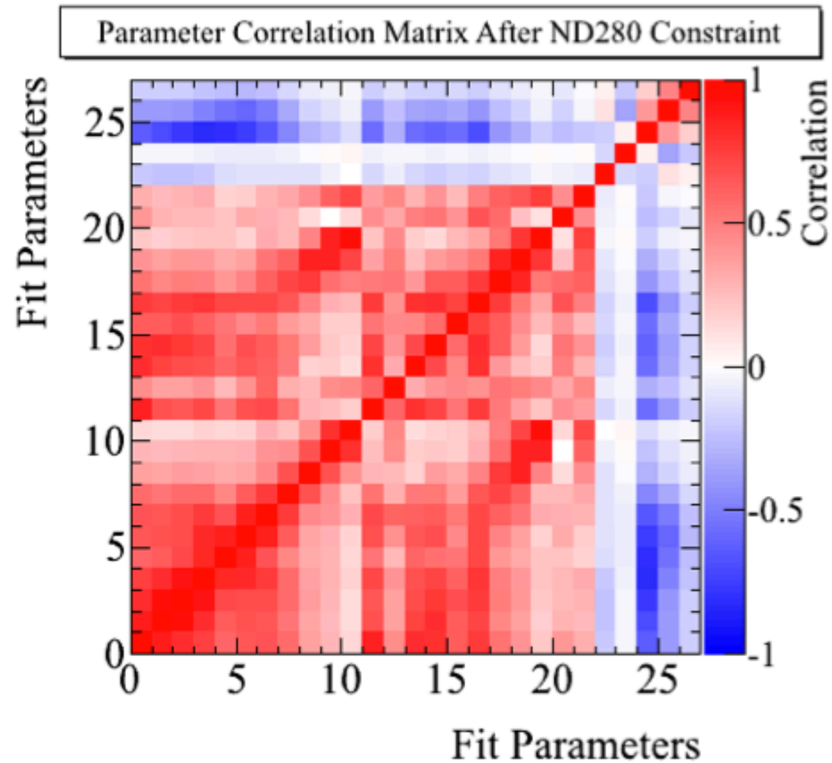
$$N_i^{pred}(\vec{b},\vec{x},\vec{d}) = d_i\sum_{j=1}^{MC\ Events} b_j x_j^{norm} w_j^x(\vec{x})$$

← Pre-calculated weight function for cross section parameters with nor linear response

Correlations between flux and cross section uncertainties





Parameters:

0-10: SK ν_{μ} flux

11-12: SK $\bar{\nu}_{\mu}$ flux

13-19: SK ν_{e} flux

20-21: SK ν_{e} flux

22: M_A^{QE}

23: M_A^{RES}

24: CCQE Norm.

25: CC1π Norm.

26: NC1π^0 Norm.

The constraint from the measured event rates causes anti-correlations between flux and cross section nuisance parameters

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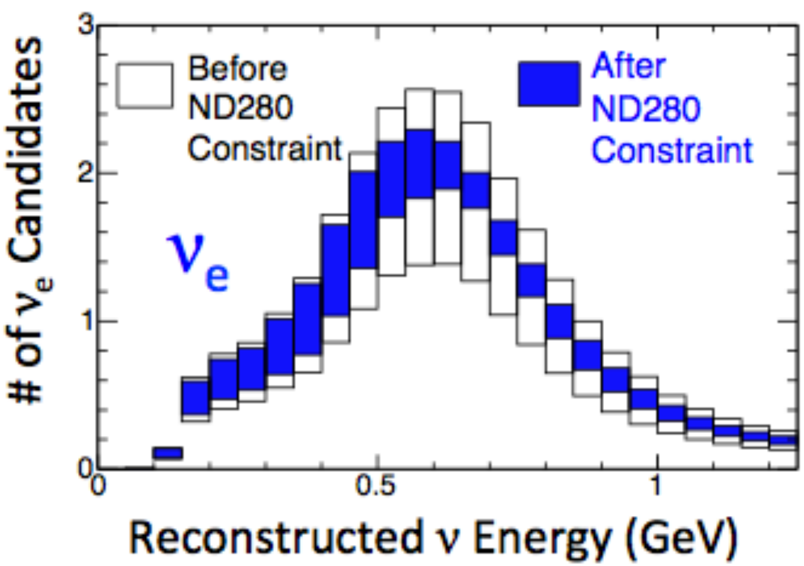
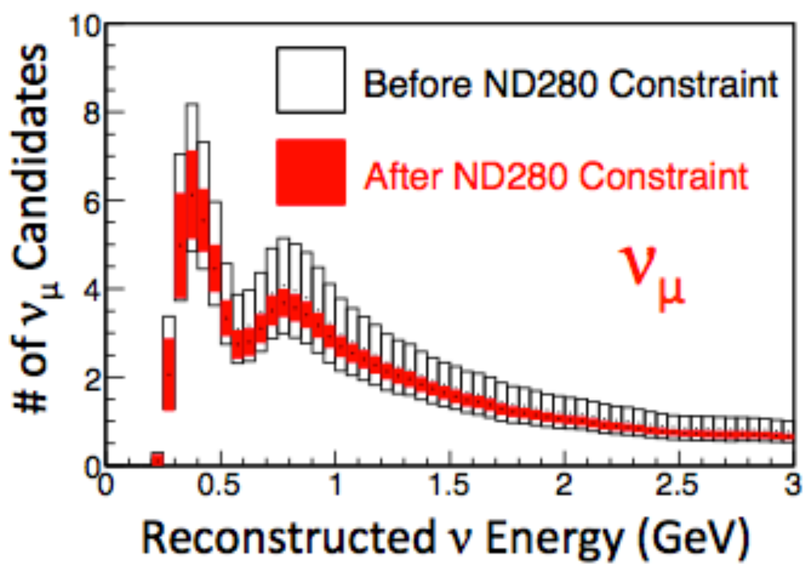
Putting this all together…

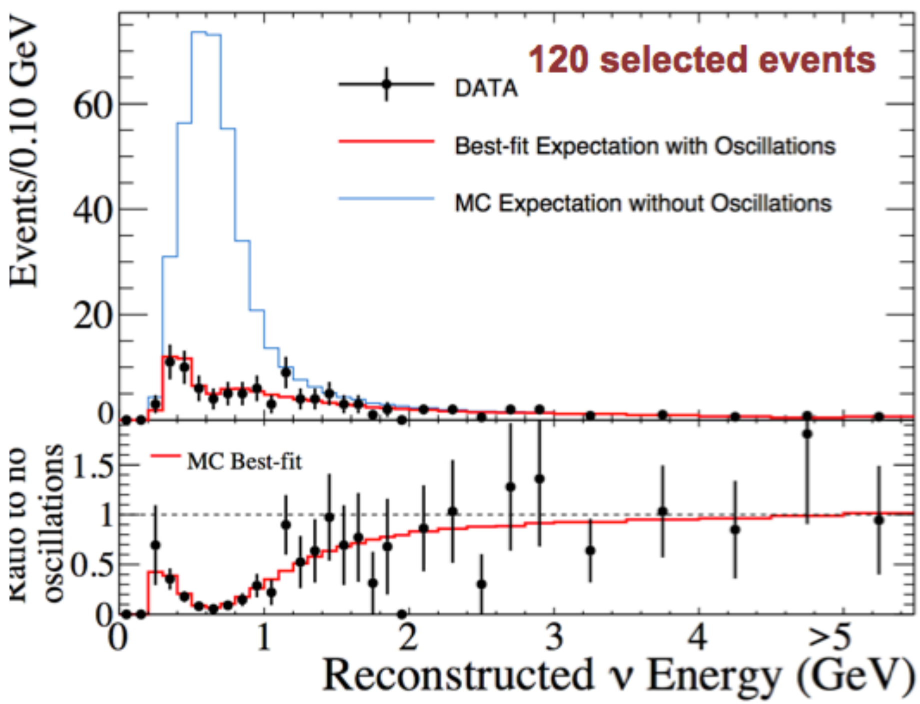
- Prediction is made for far detector energy spectra (for θ_{13}=0, best fit Δm^2) based on a fit to near detector AND EXTERNAL data samples
- (I'm leaving out many other steps of verifying that detectors work as expected)

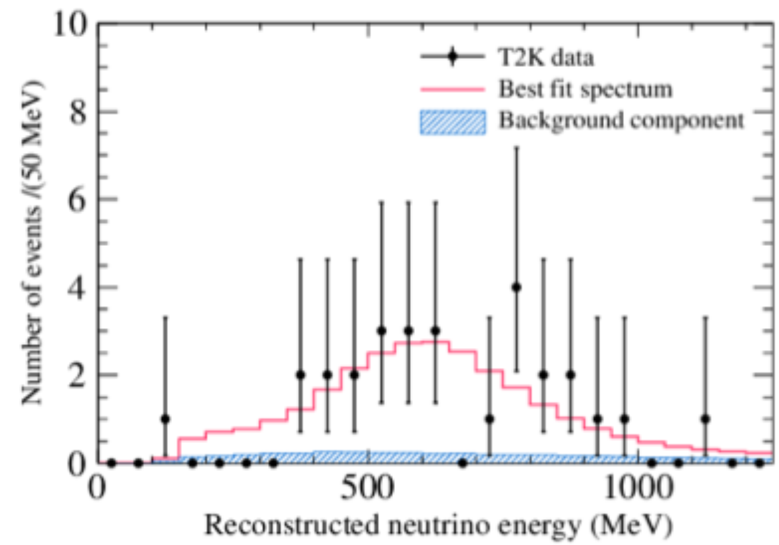
Source	$\delta N(\nu_e$'s) (%)	$\delta N(\nu_\mu$'s) (%)
Flux + xsec (ND280)	3.1	2.7
Xsec (external)	4.7	5.0
π hadronic interactions	2.3	3.5
SK Detector	2.9	3.6
Total	6.8	7.6





T2K Far Detector Event Spectra





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

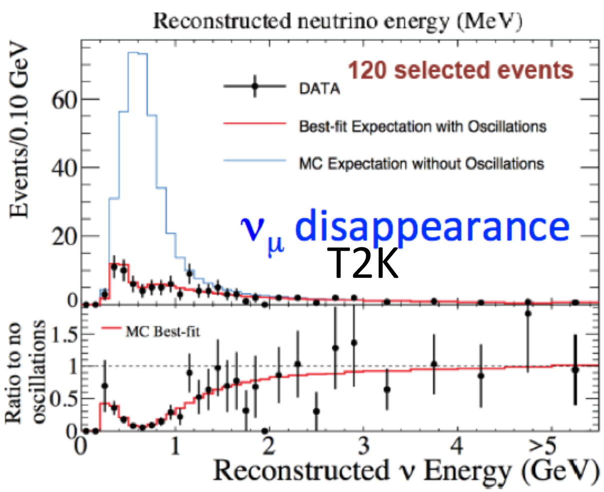
$$P_{\mu\to\mu} \approx 1 - \sin^2(\Phi) + \sin^2(\Phi) 4\cos^4\theta_{13}\left(\sin^2\theta_{23} - \frac{1}{2\cos^2\theta_{13}}\right)^2$$

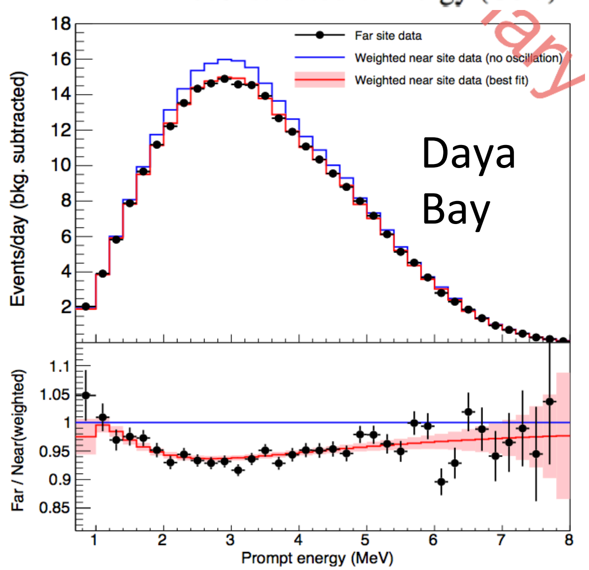
C. Walter, ν2014

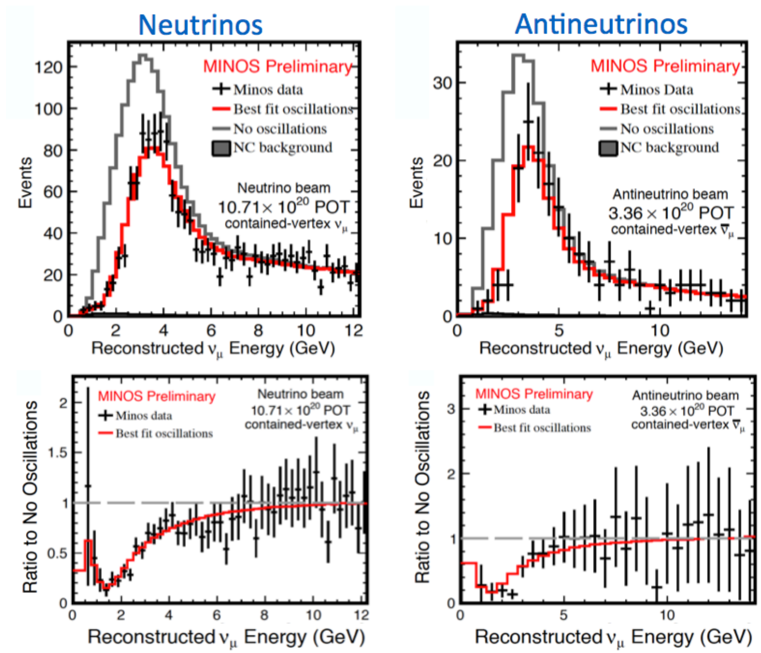
Back to World's measurements

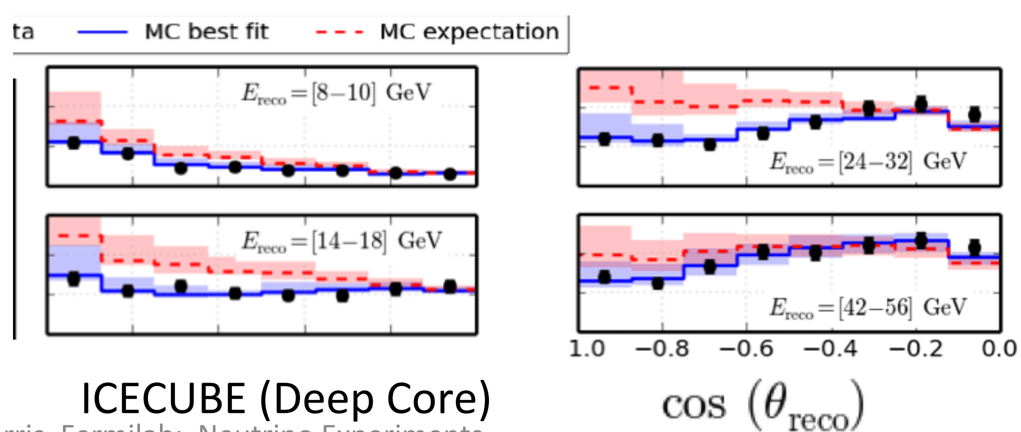
Neutrino Source/ Detector Type	Solar	Reactor	Atmospheric	Accelerator-based
Cerenkov	θ_{12}, Δm_{12}^2		θ_{23}, Δm_{23}^2, τ app.	θ_{23}, Δm_{23}^2, θ_{13}, Δm_{13}^2, 4th gen., τ app.
Liquid Scintillator		θ_{12}, Δm_{12}^2, θ_{13}, Δm_{13}^2		
Segmented Scintillator				
Steel plus Active			θ_{23}, Δm_{23}^2	θ_{23}, Δm_{23}^2, (θ_{13}, Δm_{13}^2 search), 4th gen.
Lead plus emulsion				τ appearance
Ice plus PMT's			θ_{23}, Δm_{23}^2	
Liquid Argon TPC				τ app., 4th generation

Signatures of $\Delta m^2_{\text{"atm"}}$









ICECUBE (Deep Core)

For those of you keeping score

	Energy (GeV)	Distance (km)	Detector	Source
MINOS	3-6	735	Steel/Scint	Accelerator
T2K	0.7	295	Water C	Accelerator
Daya Bay	0.001-6	1.6-1.9	Scintillator	Reactor
Ice Cube	8-56	1000	Ice	Atmospheric

MINOS (Sousa, ν2014)

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

T2K (Walter, ν2014)

		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

Daya Bay (Zhang, ν2014)

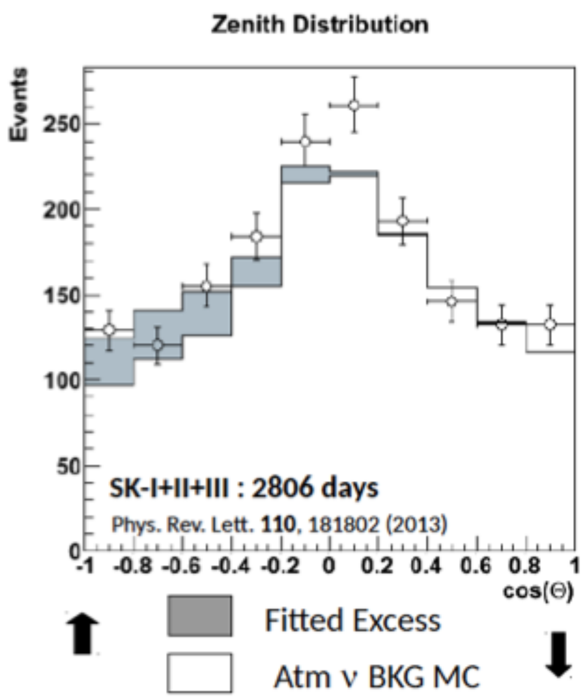
$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$

$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$

$\chi^2/NDF = 134.7/146$

ν_τ Appearance Results (Δm^2_{32}, $\sin^2 2\theta_{23}$)

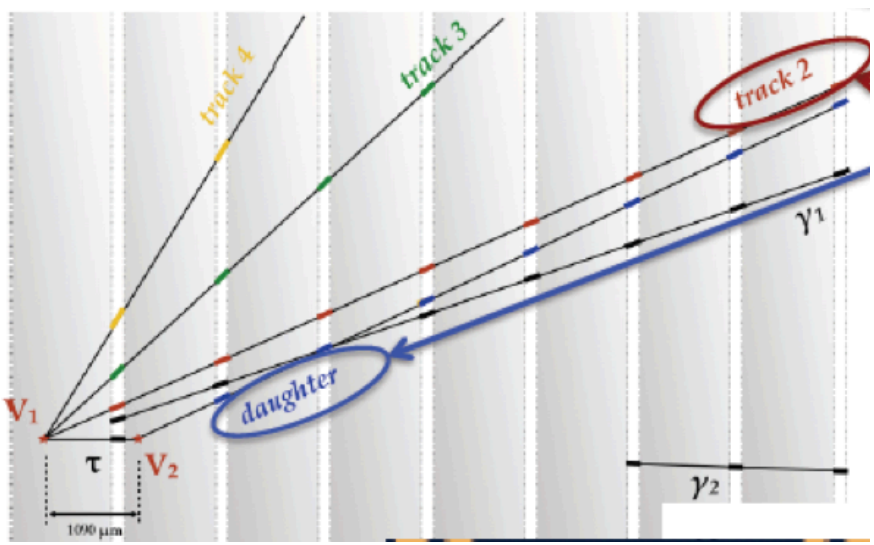
- SuperK (water cerenkov) ν_τ appearance, 10k km



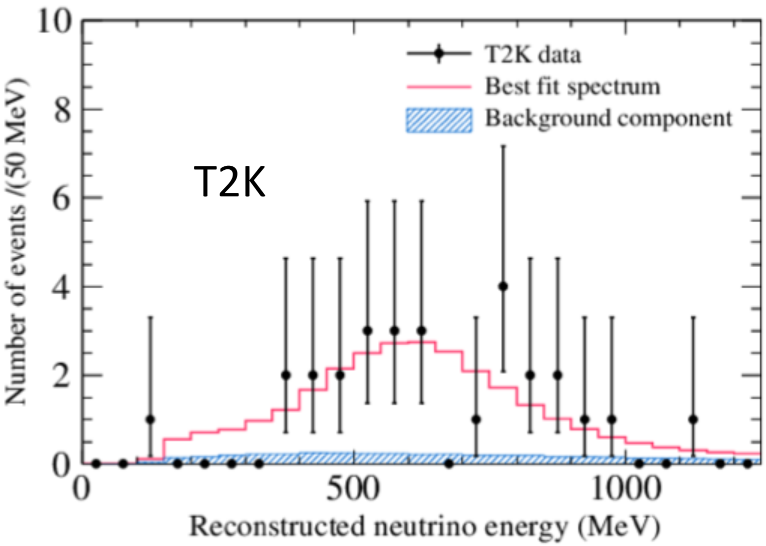
180.1 ±44.3 (stat) +17.8-15.2 (sys) events, a **3.8 σ** excess (Expected 2.7 σ significance)

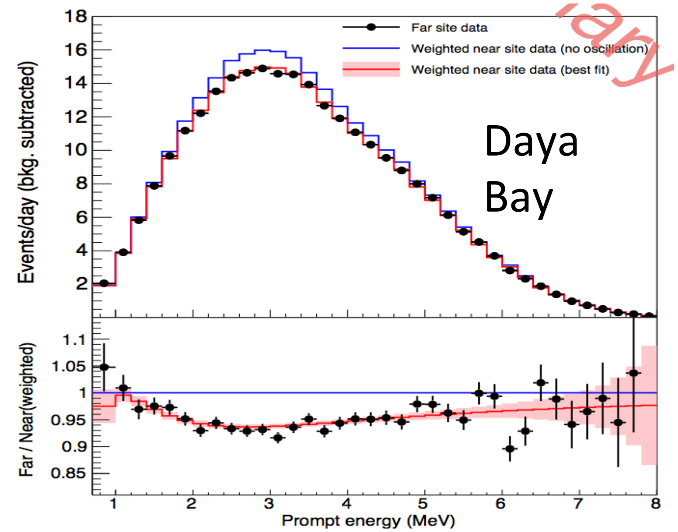
- OPERA, 730km, Lead-emulsion

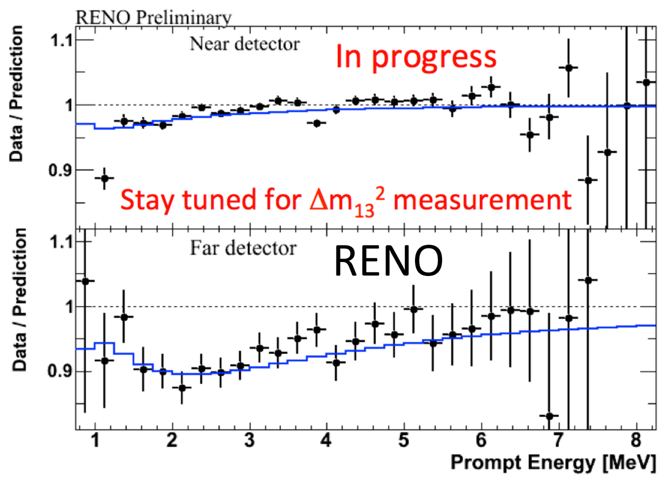
Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV^2	Total background	Observed
$\tau \to h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \to \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \to e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4

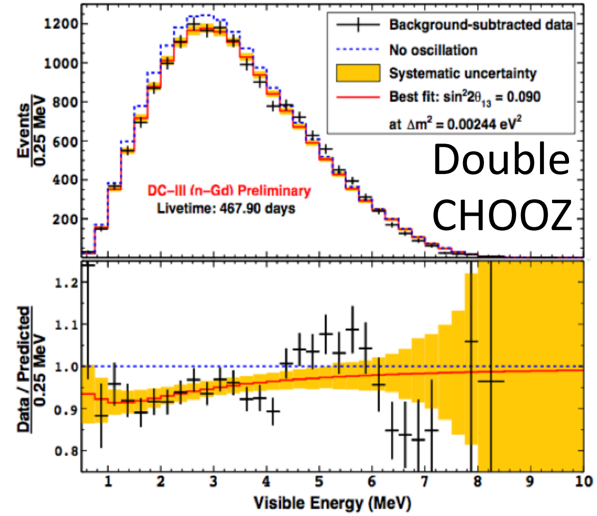


Signatures of "smallest mixing angle" (θ_{13})





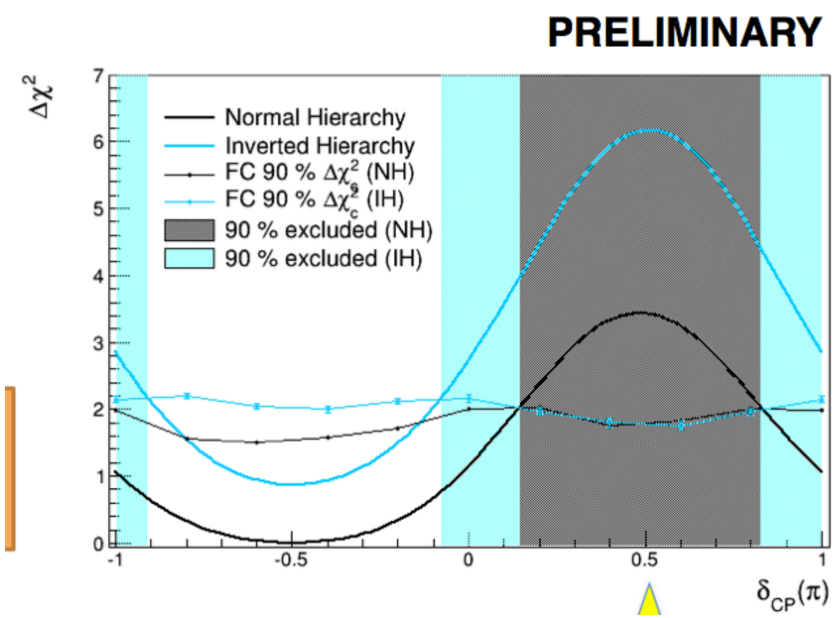




Who is measuring what?

RENO

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008(stat.) \pm 0.010(syst.)$$



T2K: appearance, but no point in trying to extra θ_{13} because of "complications" from δ_{cp} and mass hierarchy

Daya Bay
(Zhang, ν2014)

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

Double CHOOZ
Kerret ν2014

$$\sin^2(2\theta_{13}) = (0.09 \pm 0.03)$$

$$(\chi^2/n.d.f. = 51.4/40)$$

Experiments Planned or Starting to take Data

Neutrino Source/ Detector Type	Solar	Reactor	Atmos-pheric	Accelerator-based
Cerenkov				T2K (more POT), T2Hyper-K, LBN?
Liquid Scintillator		JUNO		
Segmented Scintillator				NOvA
Steel plus Active			MINOS+	MINOS+
Lead plus emulsion				
Ice plus PMT's			PINGU	
Liquid Argon TPC				MicroBooNE, LBN?

What new measurements are being planned in the near or far future?

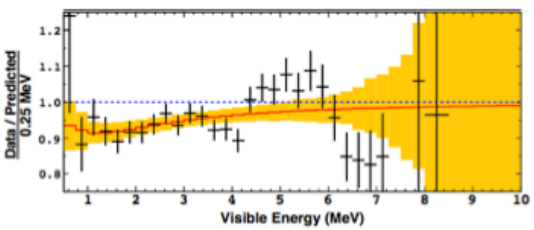
ν Source/Detector Type	Solar	Reactor	Atmospheric	Accelerator
Cerenkov				CP-phase δ
Liquid Scintillator	Majorana neutrino search: Kamland-Zen			
Liquid Scintillator	Majorana neutrino search: SNO+			
Liquid Scintillator		4^{th} gen.		
Segmented Scintillator				Mass Hierarchy and CP-phase δ
Steel plus Active			Mass Hierarchy	4^{th} gen.
Lead plus emulsion				
Ice plus PMT's			Mass Hierarchy	
Liquid Argon TPC				4^{th} gen, Mass Hierarchy and CP-phase δ

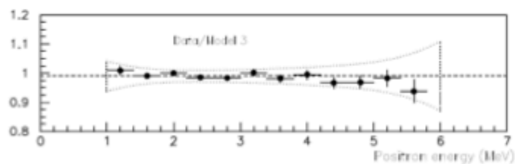
4^{th} Generation Neutrinos

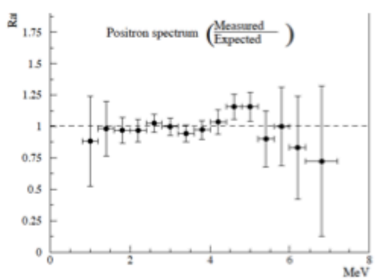
- Several mysteries abound in recent experiments, some more recent than others
  - LSND ν_e appearance (anti-ν_e)
  - MiniBooNE ν_e appearance (ν_e and anti-ν_e)
  - Reactor Anomalies: fewer reactor neutrinos seen at near detector sites than expected, plus "5 MeV excess"
- These point towards at least one sterile neutrino, or maybe more (since there would be a fourth mass eigenstate, or several more)
- There are numerous ideas around for addressing these mysteries, all making use of the techniques you have heard about in this course
  - Bonus is that the mass squared splittings are much larger, so the baselines are much shorter
  - The hard part is that these effects are small and so precision measurements will be the only way to move forward here!

Reactor Anomalies

Double Chooz, this conference

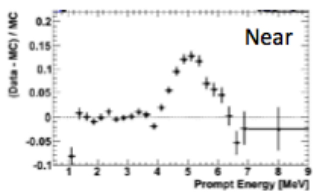


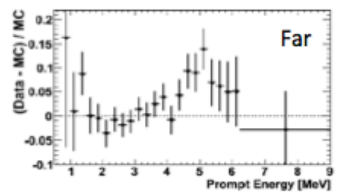




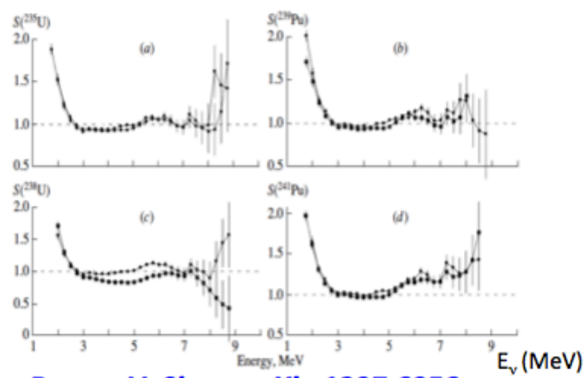
CHOOZ, Phys.Lett. B466 (1999) 415-430

RENO, this conference





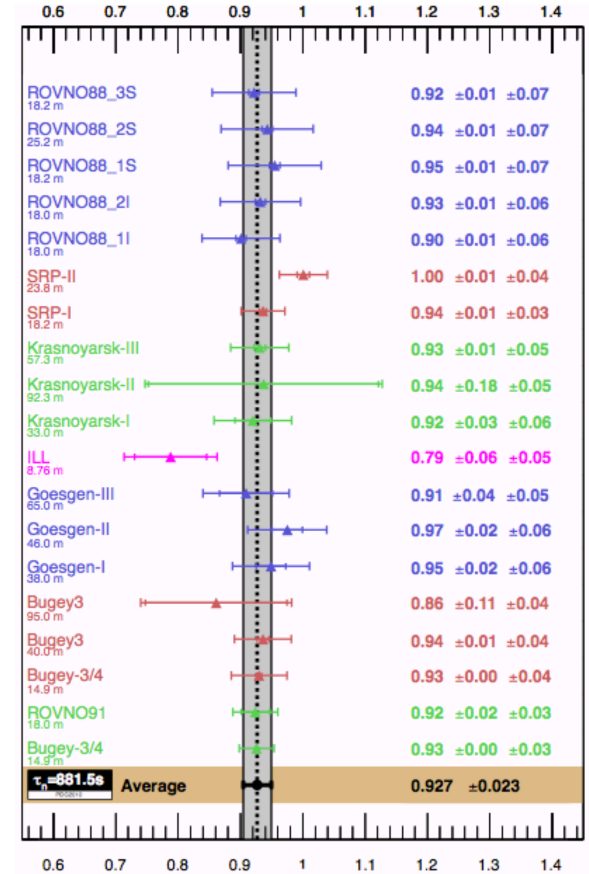
Bugey, Phys.Lett. B374 (1996) 243-248



Rovno, V. Sinev, arXiv:1207.6956

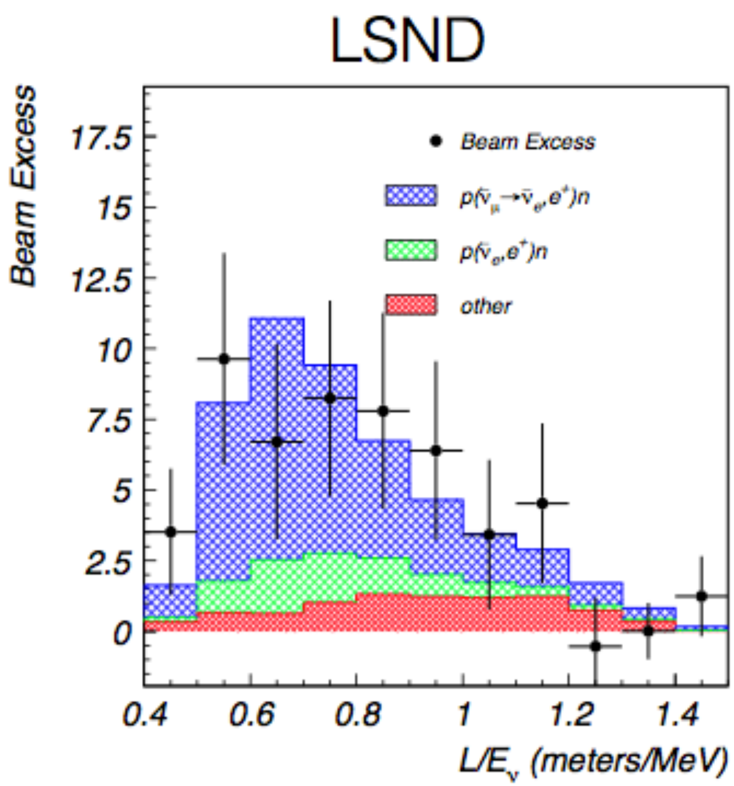
Lhuillier, ν2014

Reactor anomaly

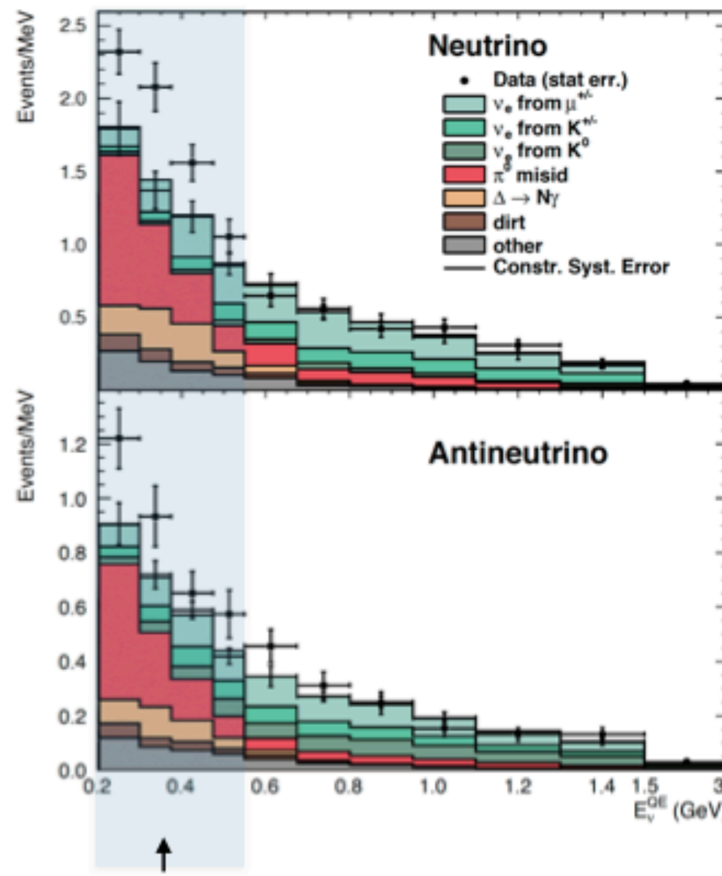


Spitz, ν2014

Accelerator Anomalies



Spitz, ν2014



The "low energy excess"

4^{th} Generation Neutrinos

- These anomalies point towards at least one sterile neutrino, or probably more (since there would be a fourth mass eigenstate, or several more)
- There are numerous ideas around for addressing these mysteries, all making use of the techniques you have heard about in this course
  - Bonus is that the mass squared splittings are much larger, so the baselines are much shorter
  - The hard part is that these effects are small and so precision measurements will be the only way to move forward here!

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 much less but can be built much more cheaply per kiloton
- Absolute and Majorana mass measurements
  - Each provides unique information: want to see both, on >1 element
- Measurements
  - Have entered the era of precision oscillations
  - Testing the framework is still an important goal: one number not enough!

Thank you


ONLY THOSE WHO SEE THE INVISIBLE
CAN DO THE IMPOSSIBLE
MAMALLAPURAM SPECIAL GRADE TOWN PANCHAYAT