Review of ν_e Appearance Oscillation Experiments

PIC 2013

The XXXIII International Symposium on Physics in Collision

IHEP, Beijing, P. R. China

03 - 07 September 2013.

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Outline

- Introduction
  - Overview of ν Oscillations
    - *Specifically ν_e appearance*
- Overview of Present Efforts and Goals
  - T2K
  - MINOS
- Future
  - Near: NOνA
  - Far: LBNE (USA)-LAGUNA/LBNO(Europe), Hyper-K (Japan)

How Many ν's?

- Most precise measurements of the number of light, active neutrino types, N_ν :
  - Z production in e^+e^- Collisions.

$$N_\nu = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\mathrm{SM}}$$

The combined result (4 LEP experiments) is $N_\nu = 2.984 \pm 0.008$

(ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and LEP Electroweak Working Group, and SLD Electroweak Group, and SLD Heavy Flavor Group, Phys. Reports 427, 257 (2006).)

- Cosmological constraints

Cosmological observables (CMB, lensing, galaxy and cluster distributions, etc. are sensitive to total neutrino mass sum:

Current upper bound from cosmology

$\Sigma m_\nu < 0.23$ eV at 95% C.L. (Planck+WP+highL+BAO)

- We have directly observed three types in reactor and accelerator experiments:

ν_e : Reines and Cowan (Reactor) → 1956

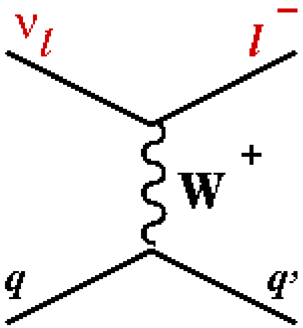
ν_μ : Lederman, Schwartz, & Steinberger (BNL) → 1962

ν_τ : DONuT (FNAL) → 2000

How do $\nu_{e,\mu,\tau}$ interact?

- To identify the neutrino type they must interact through "Charged Current" interaction - CC:

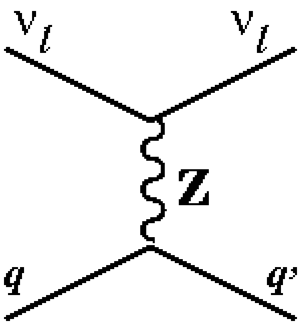
$E_{visible} \sim E_\nu$



What "flavor" of lepton is produced tells you what "flavor" of neutrino interacted

- Neutrinos can also interact are via "Neutral Current" - NC:

$E_{visible} < E_\nu$



You don't know what "flavor" of neutrino interacted

Neutrino Masses and Mixing

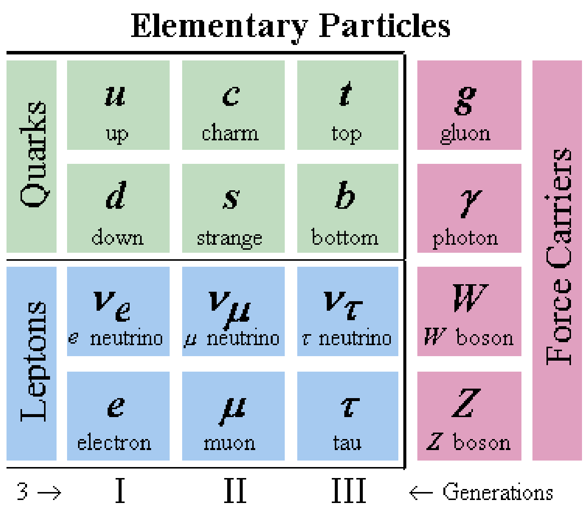
- 1969-90s Ray Davis Measures Solar ν_e Flux at
Homestake Deep Underground Mine ~1/3 Expected!
Gallex, Sage, SuperK, SNO, Kamland (Reactor)
  - Interpretation: solar $\nu_e \rightarrow 1/3\ \nu_e + 1/3\nu_\mu + 1/3\nu_\tau$ (roughly)

- 1980s IMB, Kamioka, measure atm. ν_μ flux, less than
expected. SuperK; K2K, MINOS (Accelerators) Confirm
  - Interpretation: atm. $\nu_\mu \rightarrow 1/2\nu_\mu + 1/2\nu_\tau$

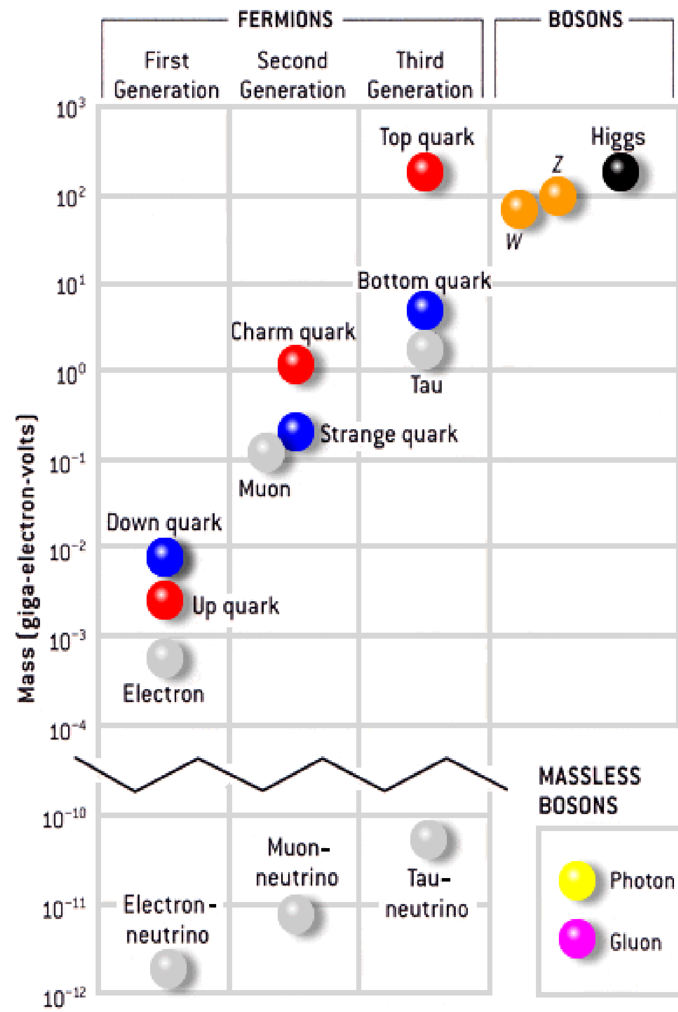
What's going on... Neutrino Oscillations Established:
→ Neutrinos are not mass eigenstates
→ Neutrino Masses & Mixing Measurements Era Began

→ Evidence for physics beyond the Standard Model

OK Now What?



- Neutrinos are the lightest fermions that make up the universe as described by the Standard Model.
- Neutrinos are very hard to detect, because they are electrically neutral and can only interact via the weak force (CC or NC)
- Neutrinos have unique properties



Big Questions...

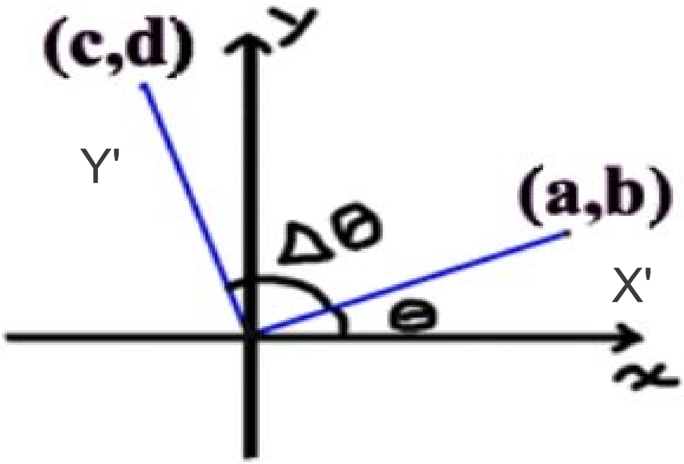
- There are fundamental questions about the nature of this new physics:
  - How are these masses are generated?
  - Is it related to standard model physics?
    - Higgs Mechanism? Seesaw mechanism?
  - What implications does it have for the early universe?
    - Matter – antimatter asymmetry?
- At present Neutrino Physics is an experimentally driven field:
  - Study of neutrino masses and mixings is our only known window into this new physics

$\nu_{e,\mu,\tau}$ Not Mass Eigenstates!

Simple two neutrino family first…

Standard 2D Rotation Matrix →

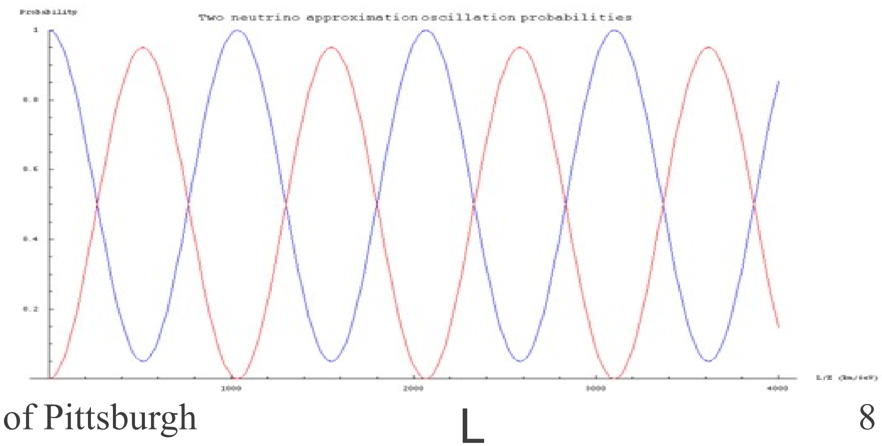
$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$



With x'=$\alpha(\rightarrow\mu)$, y'=$\beta(\rightarrow\tau)$ and x=m_1 and y=m_2 + QM:

($\Delta m^2 = m_1^{2} - m_2^{2}$, “wavelength” ~$E/\Delta m^2$)

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\text{GeV}}{\text{eV}^2\,\text{km}}\right) \longrightarrow$$



But ν oscillations involve (at least) 3 flavors

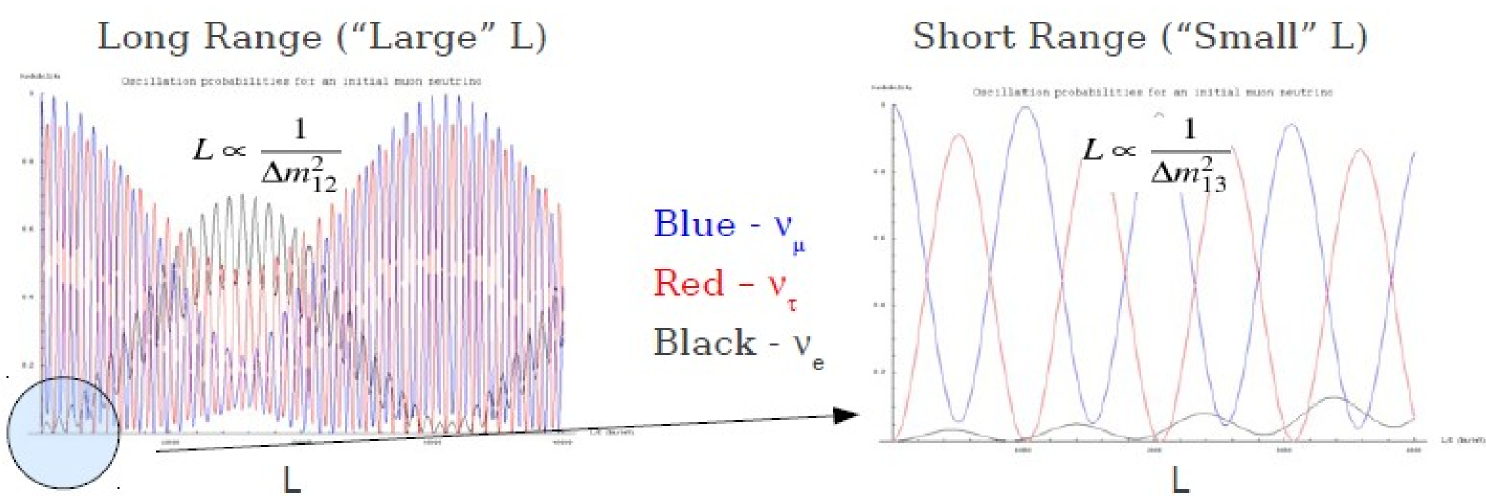
- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \boxed{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}} \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix} \boxed{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric ν oscillations
($\Delta m^2 = m_3{}^2 - m_2{}^2$)

We'll get back to this part
$\nu_\mu \rightarrow \nu_e$ *Oscillations*

Solar ν oscillations
($\Delta m^2 = m_2{}^2 - m_1{}^2$)



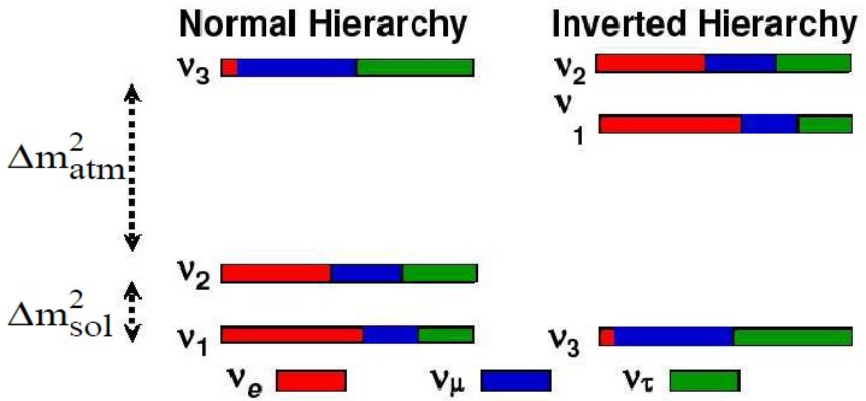
What Do We Know?

Solar+KamLAND → $\theta_{12} = 33.5^\circ \pm 1^\circ$

SK, MINOS, T2K → $\theta_{23} = 45^\circ \pm 4^\circ$

Daya Bay, Reno, Double Chooz → $\theta_{13} = 8.7^\circ \pm 0.5^\circ$

(T2K: $\Theta_{13} \neq 0$ → More later)



$\Delta m^2_{12} = (7.65 + \pm 0.23) \times 10^{-5}$ eV^2

sign of the mass difference, $\Delta m^2_{21} > 0$.

$\Delta m^2_{32} (\approx \Delta m^2_{31}) = (2.40 \pm 0.12) \times 10^{-3}$ eV^2

What Don't We Know?

- Sign of the mass difference: $\Delta m^2_{31} > 0?$
- Value CP Violating Phase: δ
- Θ_{23} Maximal? Octant?
- Are Neutrinos Dirac or Majorana?
- Are they any more ν's? (sterile)

Types of Oscillation Experiments

Some specific examples:

- Nuclear reactors produce a high flux of anti-ν_e's with E ~ 1 MeV

→ Disappearance Type Oscillation Experiment
→ Baselines of ~1 km required

$$P_{\nu_e\to\nu_e} = 1-\sin^2\theta_{13}\sin^2\frac{1.27\Delta m^2_{31}L}{E} + \text{smaller sol. term}$$

$$\boxed{\frac{\Delta m^2_{31}L}{4E_\nu} = 1.27\frac{\Delta m^2_{31}}{\text{eV}^2}\frac{L}{\text{km}}\frac{\text{GeV}}{E_\nu}\sim\frac{\pi}{2} \quad \Rightarrow L \sim 0.5\,\text{km}\,\frac{E_\nu}{\text{MeV}}}$$

- Accelerators can produce a high flux of ν_μ with E ~ Several GeV

→ Appearance Type Oscillation Experiment
→ Baselines of several ~100 km required

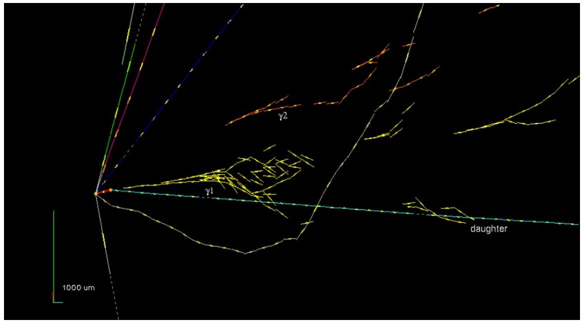
$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{1.27\Delta m^2_{32}L}{E} + \text{terms}\left(\delta,\ \text{matter effects:}\,\text{sign}(\Delta m^2_{31})\right)$$

$\nu_\mu \rightarrow \nu_\tau$ Appearance

A detailed discussion of this topic would require another talk....

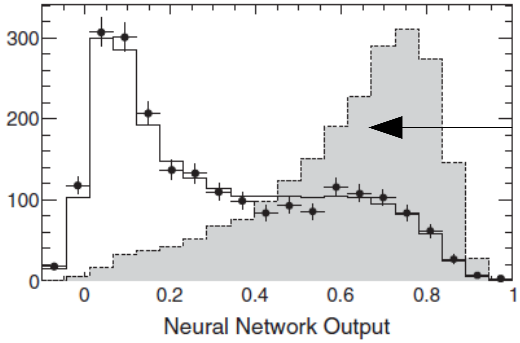
The disappeared ν_μ seem to be oscillating (*almost!*) all into ν_τ's:

- OPERA: 3 tau neutrino interactions observed with ~60% of the exposed emulsion stacks scanned
  - → 7×10^{-4} probability that these 3 events are background



- Super-K using atmospheric data:
  - → 3.8σ appearance significance (see PRL 110, 181802)
  - → Statistical study based on a neural network analysis of zenith angle distribution

+: Data



Tau signal MC simulation (shaded)

$\nu_\mu \rightarrow \nu_e$ Appearance

The disadvantage/advantage of ν_e appearance experiments using long-baseline beams is that they are sensitive to multiple unknowns…

$$P(\nu_\mu \rightarrow \nu_e)_{vacuum} =$$
$$\sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\Delta_{atm}$$
$$+\cos^2\theta_{23}\sin^2(2\theta_{12})\sin^2\Delta_{\odot}$$
$$\mp J_r\sin\delta_{CP}\sin^2\Delta_{atm}\sin\Delta_{\odot}$$
$$+J_r\cos\delta_{CP}\sin\Delta_{atm}\cos\Delta_{atm}\sin\Delta_{\odot}$$

(- neutrinos, + antineutrinos)

$$J_r = \cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})$$

- *dominant term* $\approx \frac{1}{2}\sin^2(2\theta_{13})$ *at osc. max.*
- *small for accelerator longbaseline L/E's*
- *sub-leading CP violating phase terms.*

$$\boxed{\begin{aligned}\Delta_{\odot} &= 1.27\Delta m^2_{12}L/E\\ \Delta_{atm} &= 1.27\Delta m^2_{13}L/E\end{aligned}}$$

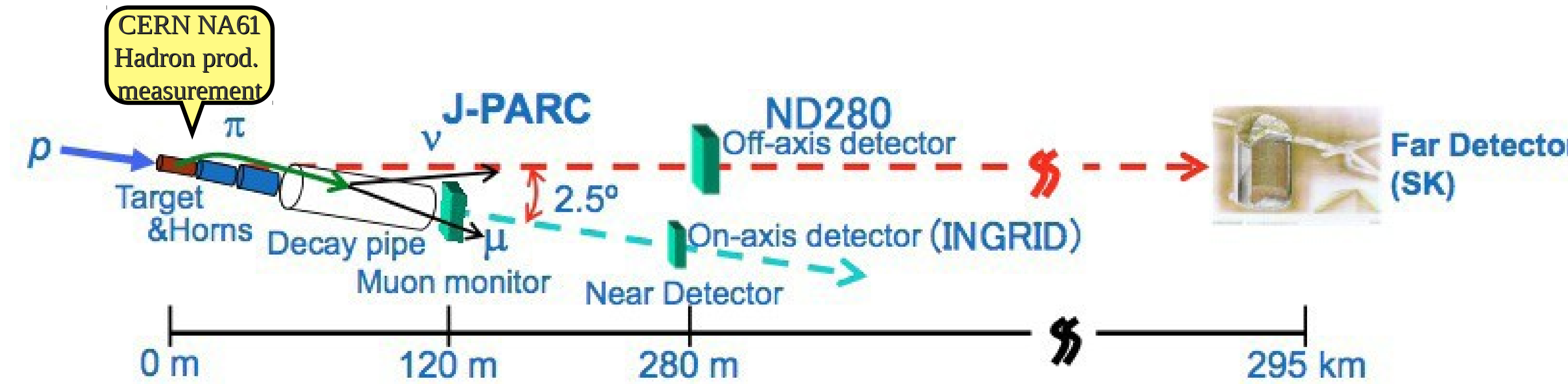
Sensitive to θ_{13}, δ_{CP}, θ_{23}, Δm^2_{13}

The T2K Experiment
(Tokai to Kamioka)

Goals:

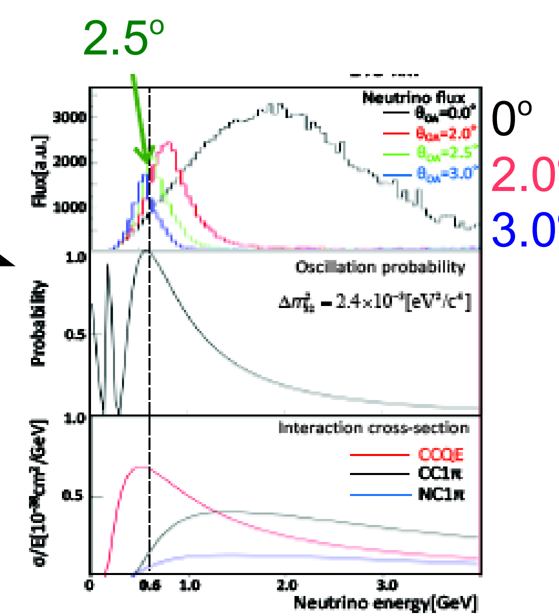
- Observe electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$)
- Precision measurement of muon neutrino disappearance

Overview of T2K: Beam

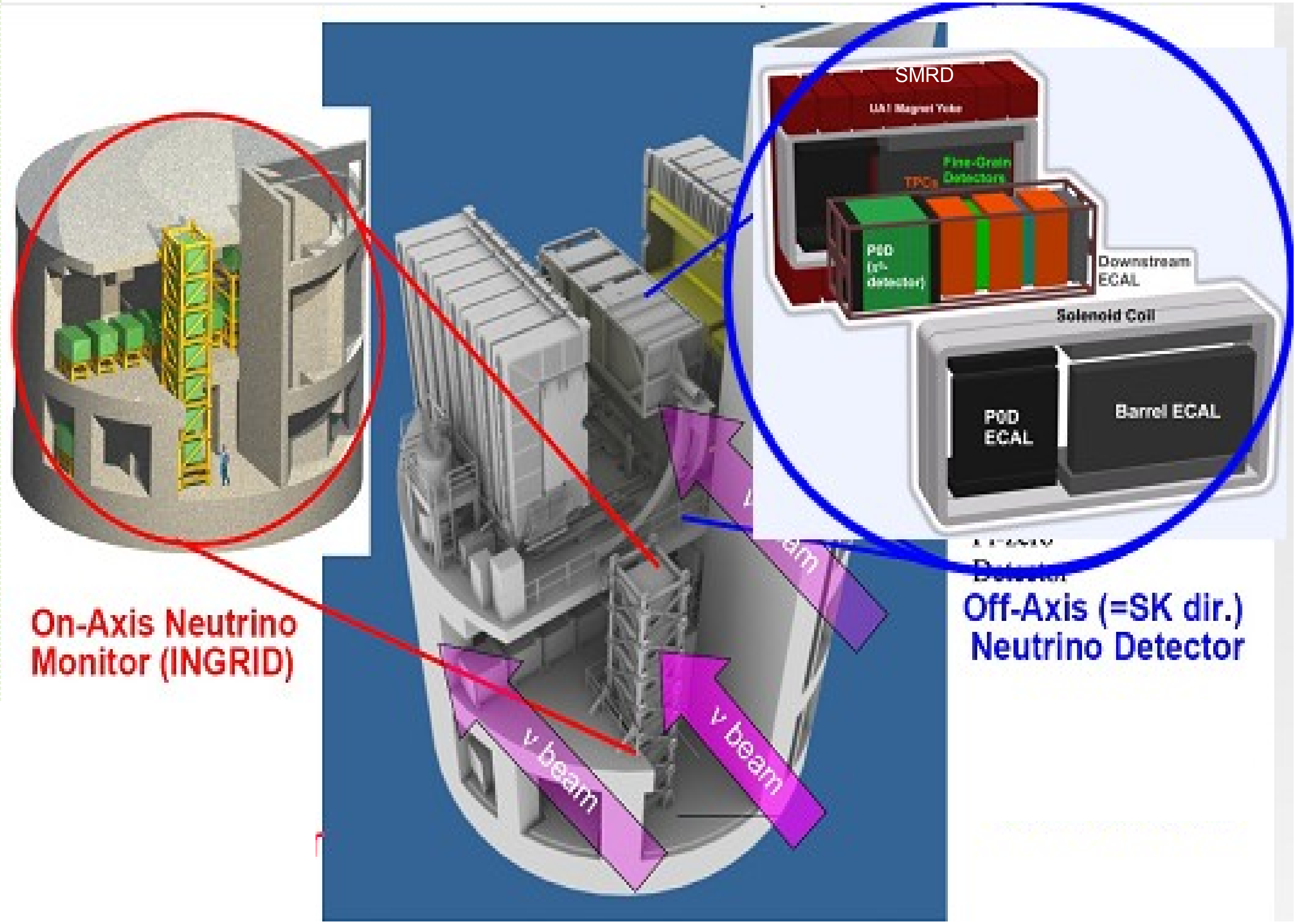


First Use of Off-axis ν_μ Beam:

- Intense & high quality beam (Beam direction stability < 1mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak
- Low energy narrow band beam
- E_ν peak around oscillation maximum (~0.6GeV)
- Small high energy tail → reduces NC feed-down background events in T2K (e.g. NC π^0 production is one of the largest backgrounds)
- π,K production at target was measured using CERN NA61 exp.



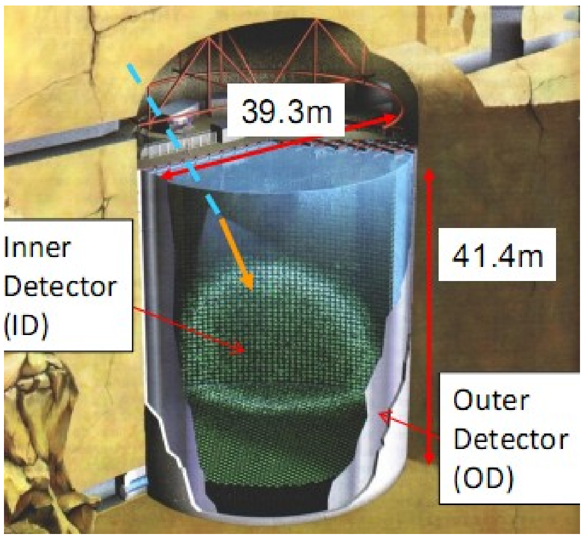
Overview of T2K: Near Detectors

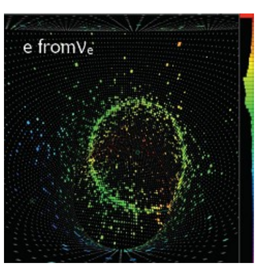


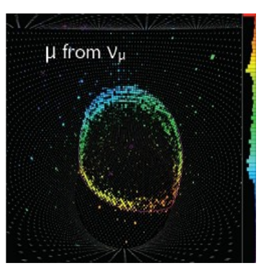
On-Axis Detector (INGRID) Monitor ν:
- **Beam direction**
- **Beam Intensity**

Off-Axis Detector:
- **In SK Direction**
- **Measure:**
  - **ν flux**
  - **Cross sections measurements using water targets to reduce systematic errors on oscillation parameters**

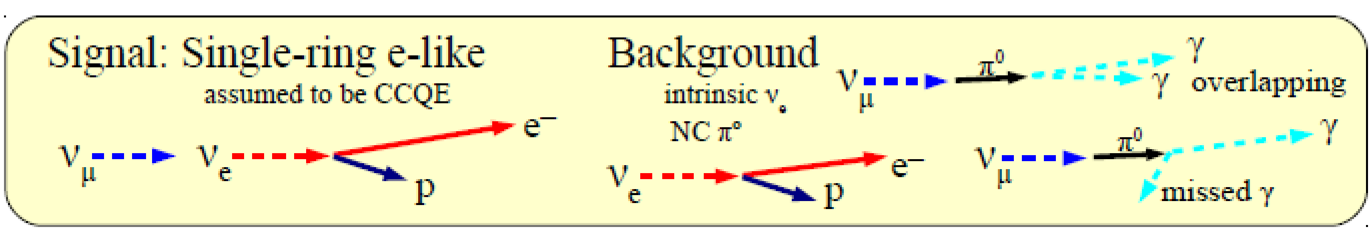
The T2K Far Detector: Super-Kamiokande

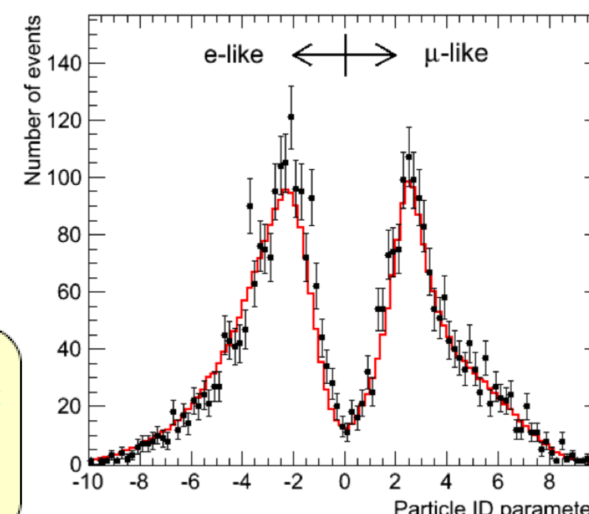




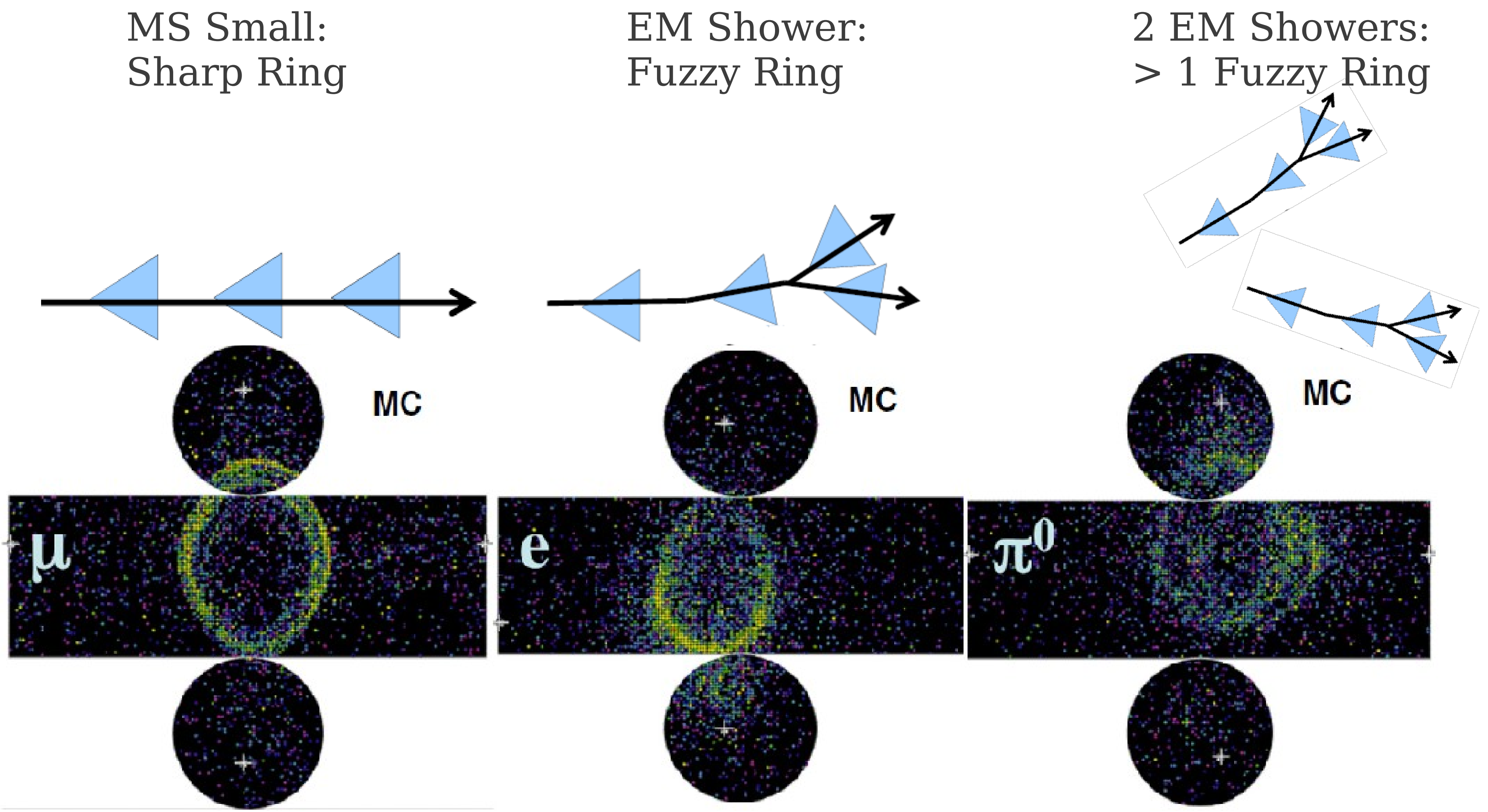


- 50 kt Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
- Typically >60% ν_e signal eff. >95% π^o rejection
  - 32 kt inner volume (22.5 kt fiducial)
  - 2 m outer volume to identify entering particles
- Probability to mis-id muon as electron is ~1%
- Dead-time free DAQ
- All triggers in ±0.5 ms of neutrino arrival time recorded
- GPS time recorded in real-time for every spill

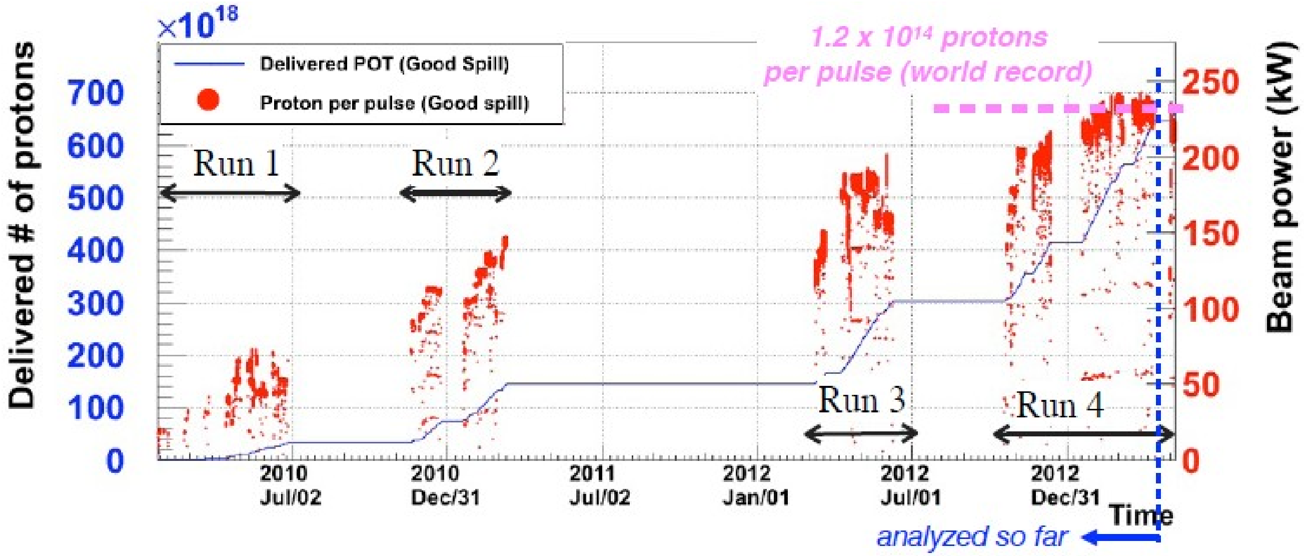




Far Detector: Particle ID

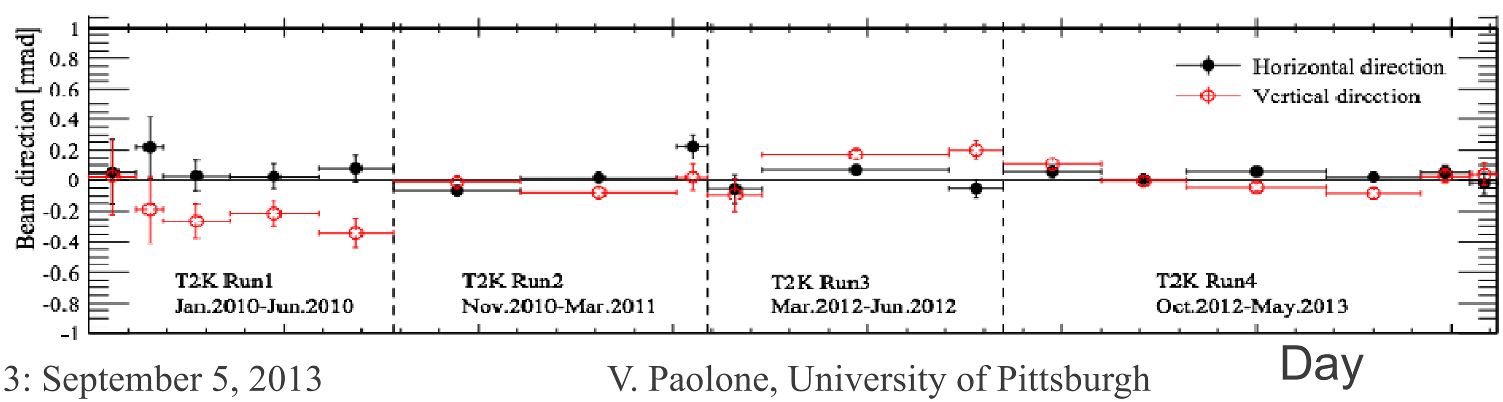


Recorded Data: Run 1-4



- **Total : x 10^{20} POT**
  - Run 1: 0.32 x 10^{20}
  - Run 2: 1.11 x 10^{20}
  - Run 3: 1.58 x 10^{20}
  - Run 4: 3.62 x 10^{20}
- **Intensity:**
  - ~220 kW stable operation for Run 4

Required Beam direction stability < 1mrad achieved:



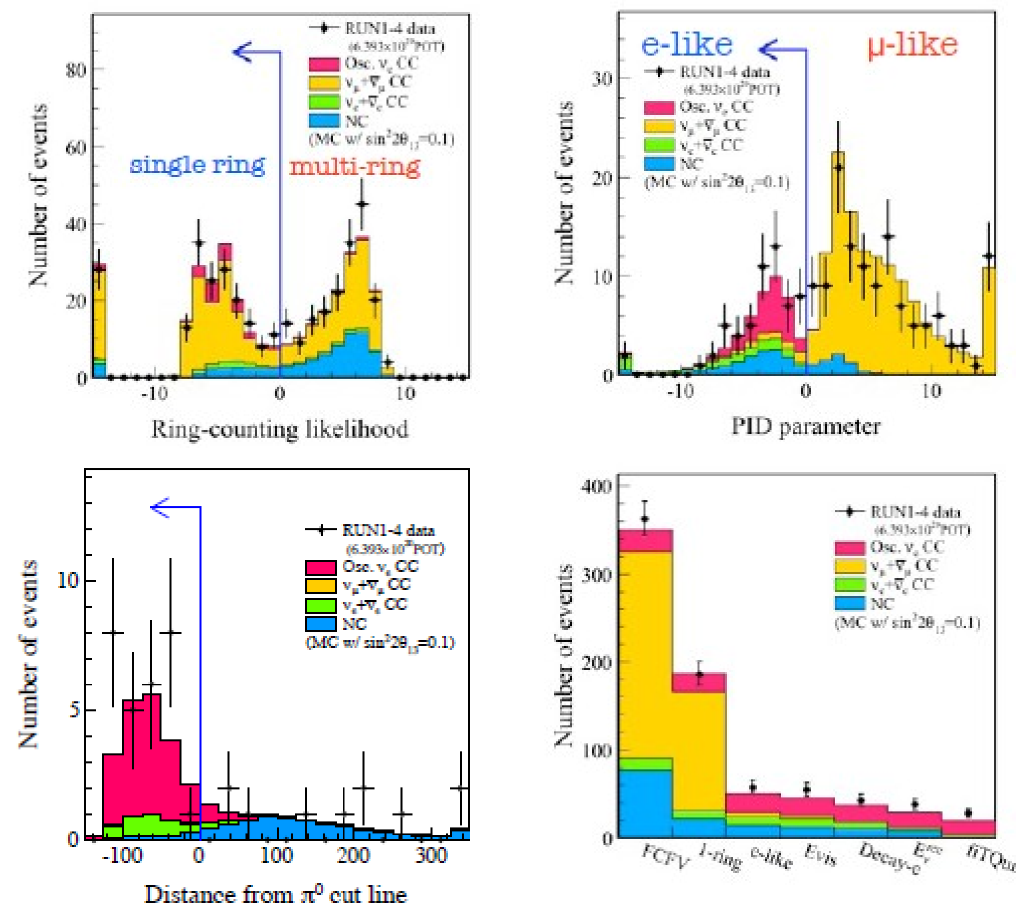
(~1 mrad shift corresponds to ~2% energy shift at peak)

T2K: Event Selection

ν_e Selection Cuts:

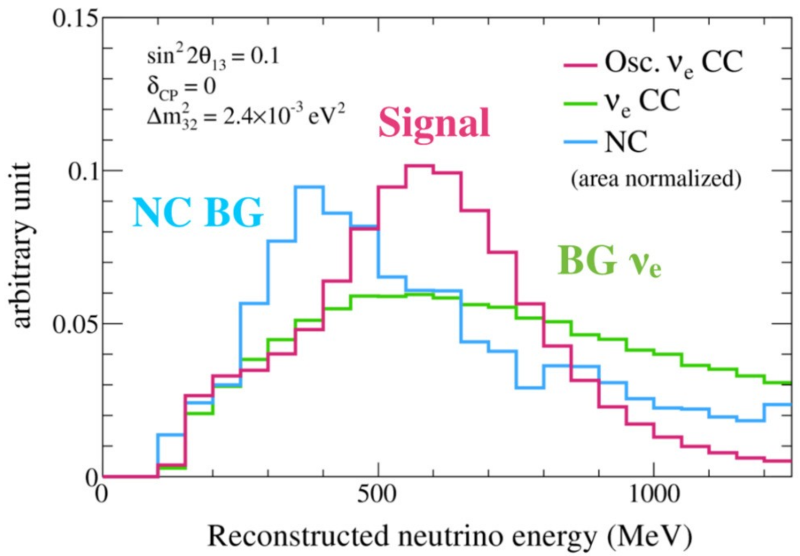
- # veto hits < 16
- Fid. Vol. = 200 cm
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- $0 < E_\nu < 1250$ MeV

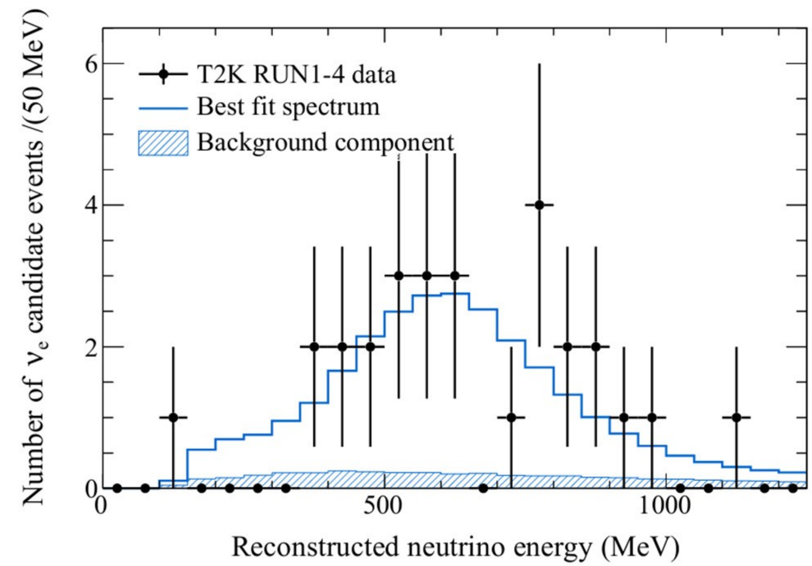
→ 28 events for 6.39×10^{20} POT



T2K: Final ν_e Sample

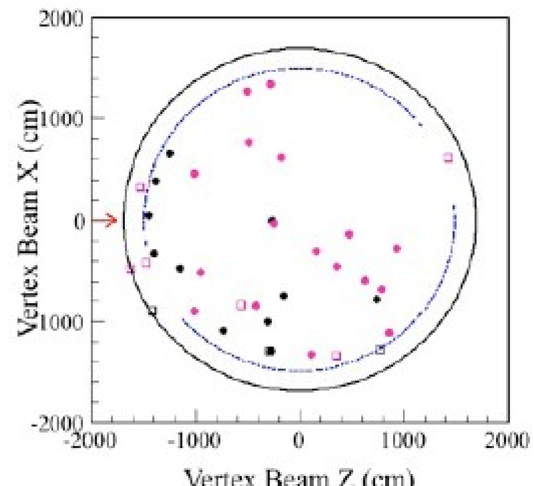
$0 < E_\nu < 1250$ MeV





$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

ν_e Vertex Distribution in SK:



(Different colors for different run periods)

Expected ν_e Events: 6.39×10^{20} POT

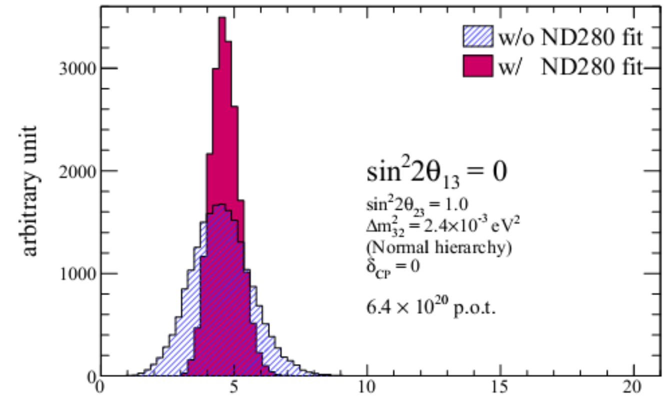
Predicted # of events w/ 6.4×10^{20} POT:

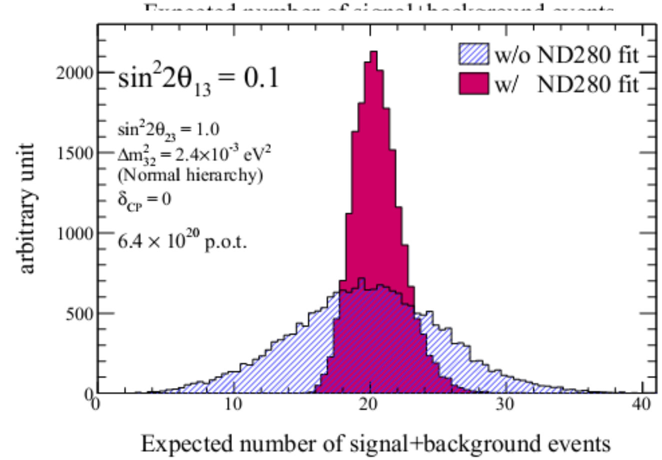
Event category	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
ν_e signal	0.38	16.42
ν_e background	3.17	2.93
ν_μ background (mainly NCπ^0)	0.89	0.89
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.20	0.19
Total		
Total	4.64	20.44

Systematic uncertainties:

Error source	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
Beam flux + ν int. in T2K fit	4.9 %	3.0 %
ν int. (from other exp.)	6.7 %	7.5 %
Far detector	7.3 %	3.5 %
Total	11.1 %	8.8 %

Significant reduction of errors when Near Detector results used





Oscillation Parameter Fitting Procedure

Flux prediction
w/ Hadron production measurement (CERN NA61)

ND280 ν_μ measurements in CCQE and nonQE samples

detector uncertainties

ν int. cross section model & uncertainties
NEUT + uncertainties set from external data

Flux & ν int. cross section *fit*
to constrain flux and ν int. cross section uncertainties

fit result (flux & ν int. cross section information) is extrapolated into oscillation parameter fit

ν_e candidate events

Oscillation parameter *fit*
to extract $\sin^2 2\theta_{13}$ (δ_{CP} is scanned)

Other ν int. cross section uncertainties (uncorrelated between ND and far detector)

Far detector uncertainties
set from atm.-ν & π^0 control sample

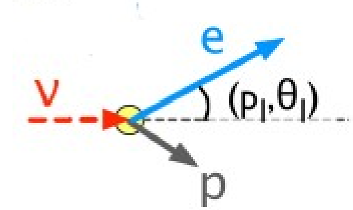
$\nu_\mu \rightarrow \nu_e$: Fitting Methods

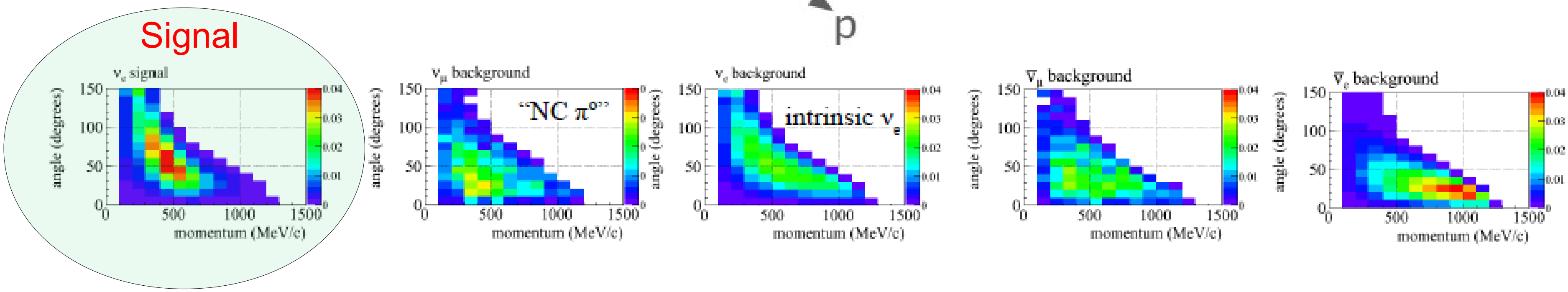
Two analysis methods used:

- Fit using 2D-distributions of electron momentum & angle → Result presented here
- Maximum likelihood Fit using reconstructed neutrino energy distribution

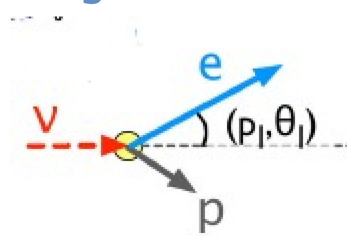
→ Both methods result in consistent values

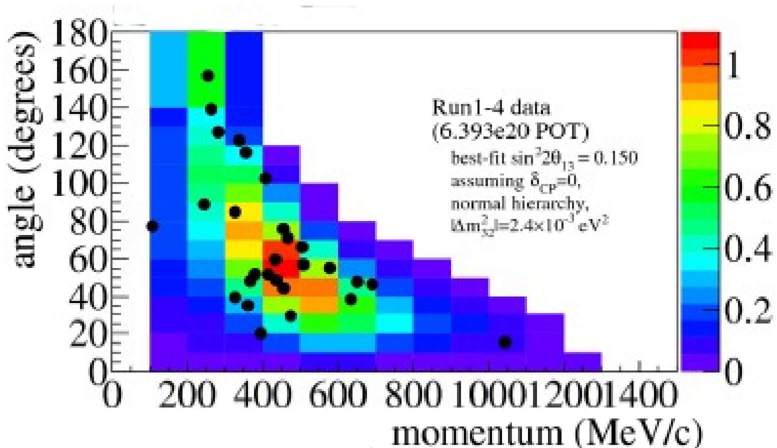
Using method 1: Differences in electron momentum and angle distributions allow signal and background separation and exploits detector measured variables:

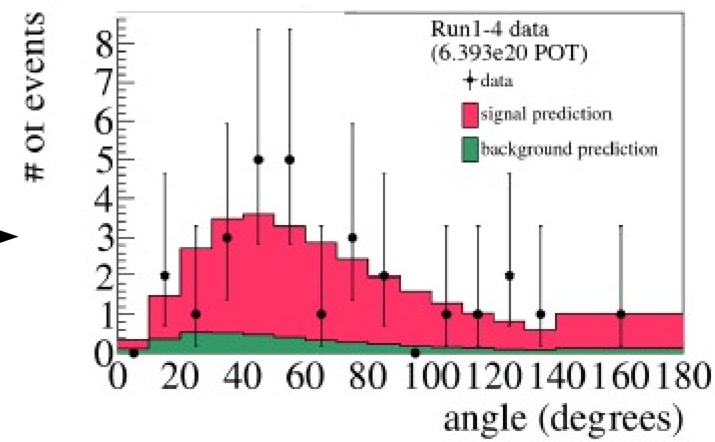


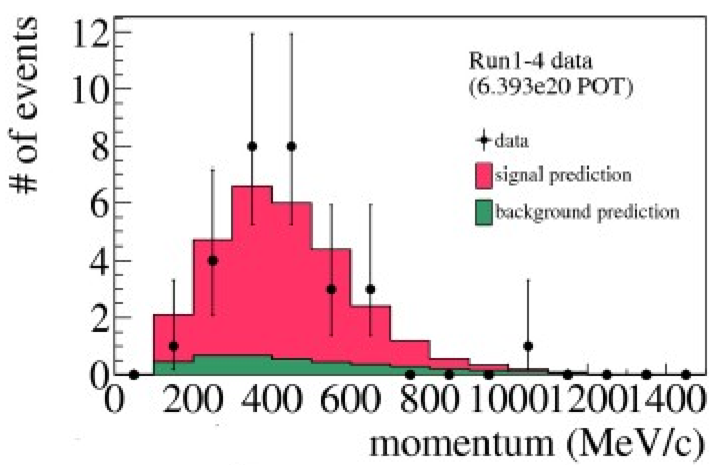


Analysis Result









Normal Hierarchy assuming:
δ_{cp} = 0 and $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{32} = 1$

→ Best Fit: $\sin^2 2\theta_{13} = 0.150$

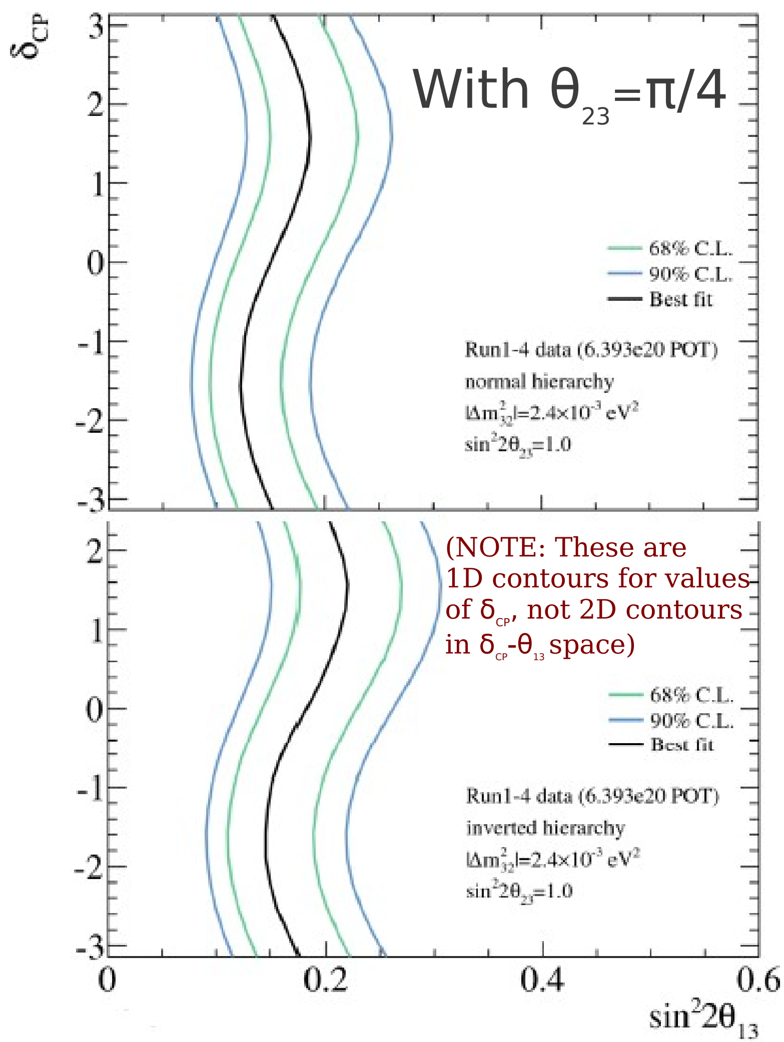
→ 68% C.L. $0.116 < \sin^2 2\theta_{13} < 0.189$

→ 90% C.L. $0.097 < \sin^2 2\theta_{13} < 0.218$

T2K: Fit Summary

	Run1-4 (p-θ)	Run1-4 (Erec)	Run4 only	Run1-3 (2013 analysis)
POT	6.39e20	6.39e20	3.38e20	3.01e20
Observed number of events	28	28	17	11
<u>Normal hierarchy</u>				
Best fit	0.150	0.152	0.180	0.112
90% C.L.	0.097 - 0.218	0.099 - 0.222	0.105 - 0.280	0.050 - 0.204
68% C.L.	0.116 - 0.189	0.118 - 0.193	0.131 - 0.237	0.072 - 0.164
<u>Inverted hierarchy</u>				
Best fit	0.182	0.184	0.216	0.136
90% C.L.	0.119 - 0.261	0.120 - 0.264	0.129 - 0.332	0.062 - 0.244
68% C.L.	0.142 - 0.228	0.143 - 0.230	0.160 - 0.283	0.088 - 0.198

Results: Allowed regions of θ_{13} for different δ_{CP} values



Best fit w/ 68% C.L. error @ $\delta_{CP}=0$

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

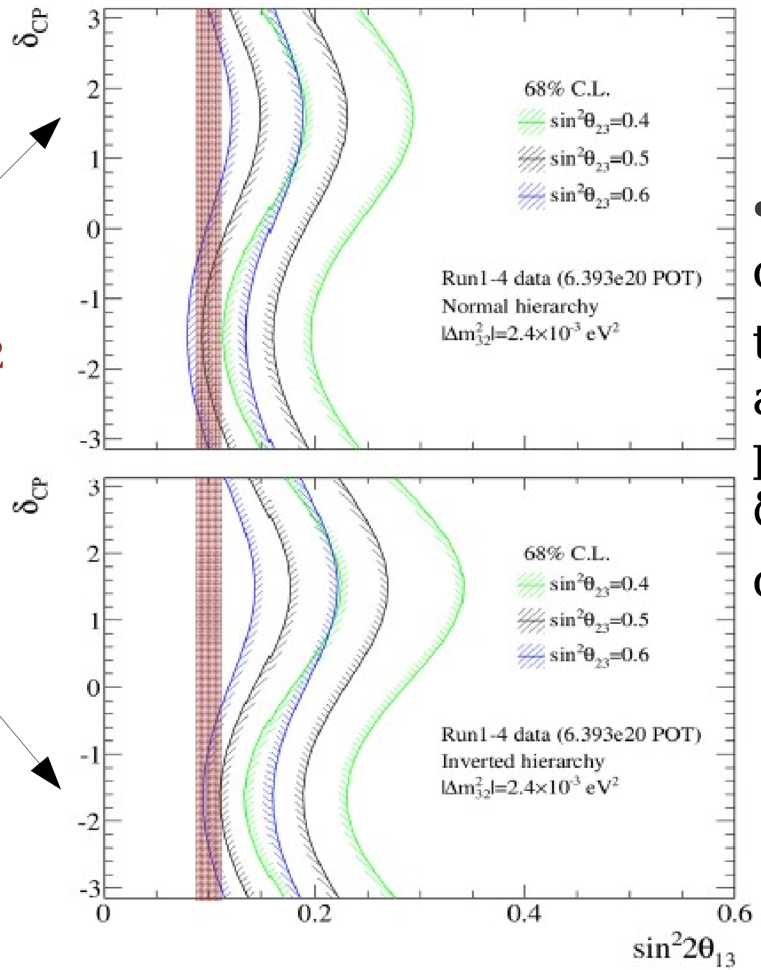
→ $\sqrt{(2\Delta \ln L)}$ significance of non-zero θ_{13} yields 7.5σ

θ_{13} vs δ_{CP} scan for $\theta_{23} \neq \pi/4$

- Significant dependency on value of θ_{23} !

(NOTE: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space)

Pink band represents PDG2012 reactor average value of $\sin^2 2\Theta_{13}=(0.098\pm0.013)$



- Improved measurements of θ_{23} will be important to extract information about oscillation parameters (including δ_{CP}) in LBL appearance oscillation experiments

ν_μ Disappearance

$$P(\nu_\mu \to \nu_e) \sim \underline{\sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{32}\cdot L}{4E}} + (\text{solar term})$$

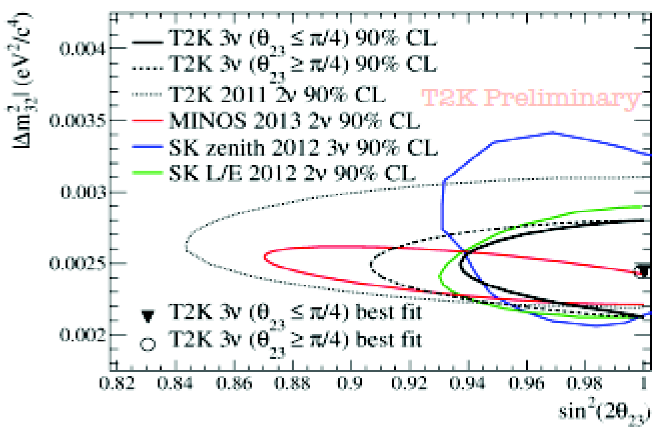
$$+ (\text{interference or "CP" terms}) + (\text{matter term})$$

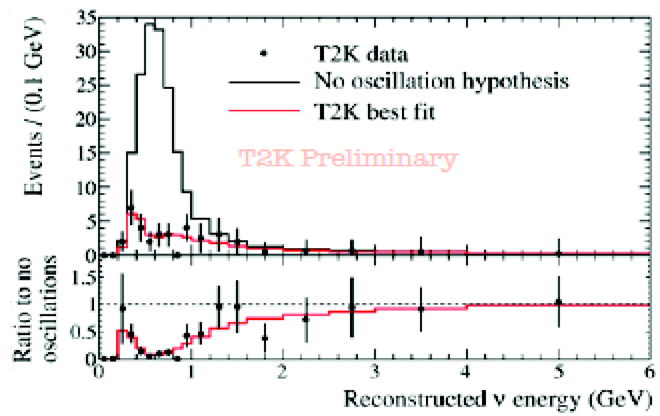
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\underline{\cos^4\theta_{13}\cdot \sin^2 2\theta_{23}} + \sin^2 2\theta_{13}\cdot \sin^2\theta_{23}\right)\cdot \sin^2 \frac{\Delta m^2_{31}\cdot L}{4E}$$

$$+ (\text{matter term})$$

Leading

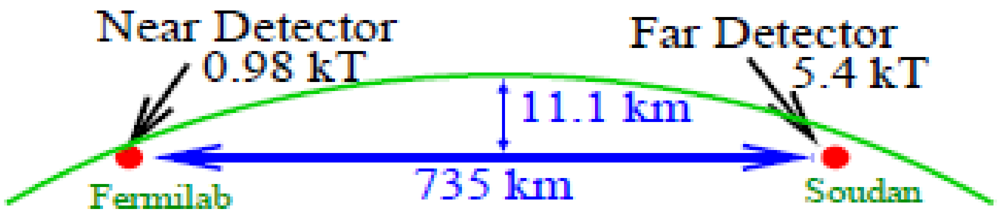
Differentiates 1st/2nd octants of θ_{23}





- T2K combined $\nu_e+\nu_\mu$ analysis is underway
- In the future, results will be reported in $\sin^2\theta_{23}$ rather than $\sin^2 2\theta_{23}$

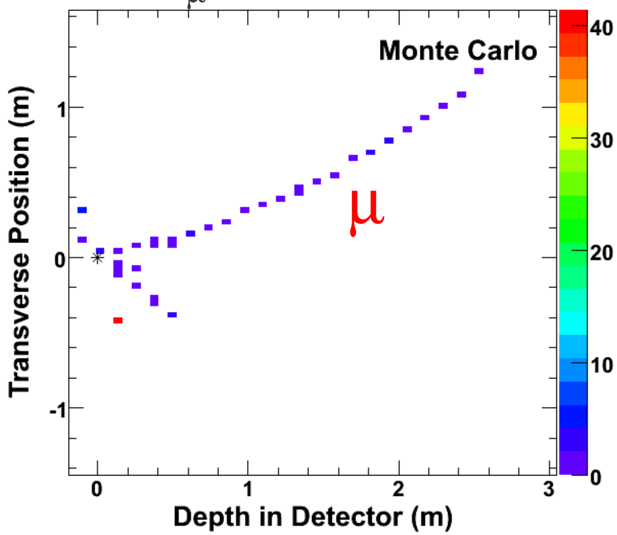
MINOS

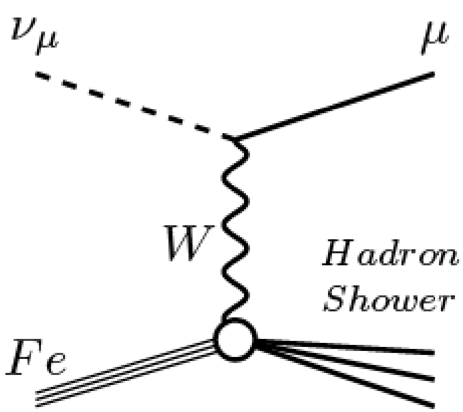


- Baseline: L=735 km, < E >= 3 GeV
- Completed Data Taking in 2012
- Neutrino mode > 10^{21} PoT
- Antineutrino mode 3.3×10^{20} PoT

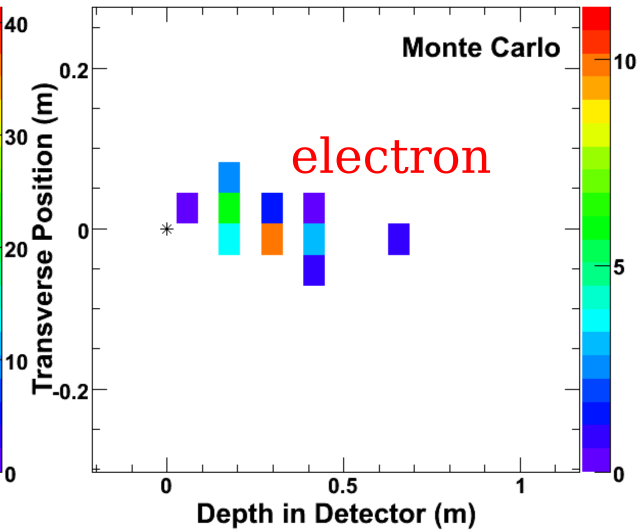
MINOS Events

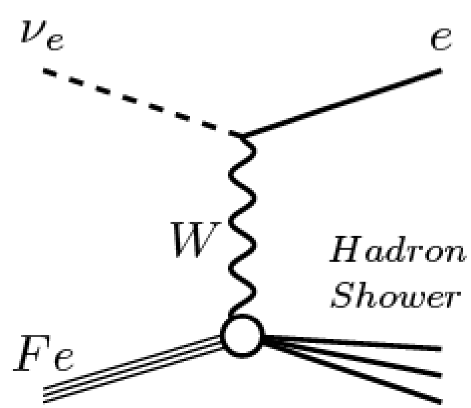
ν_μ CC event



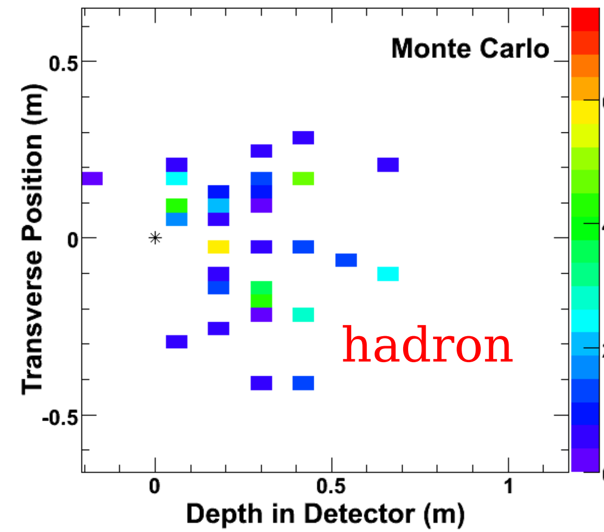


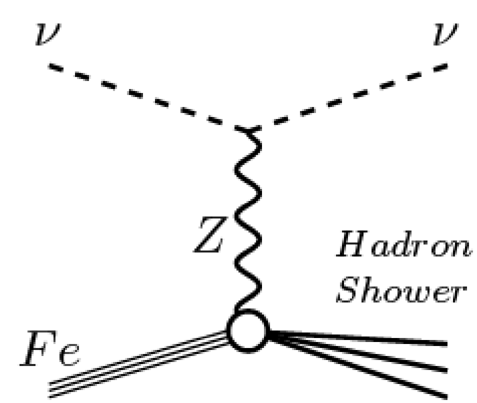
ν_e CC event





NC event





Graphics from João A. B. Coelho/Tufts

MINOS: ν_e Appearance (2012)

3.3×10^{20} POT anti-ν mode running:

Candidate Event Yields

LEM>0.6:	Observed:	20
	Predicted:	17.5 bkg + 3.7 sig
LEM>0.7:	Observed:	12
	Predicted:	10.5 bkg + 3.1 sig

Prediction assuming $\sin^2(2\theta_{13})=0.1$, $\delta=0$, $\Delta m^2>0$

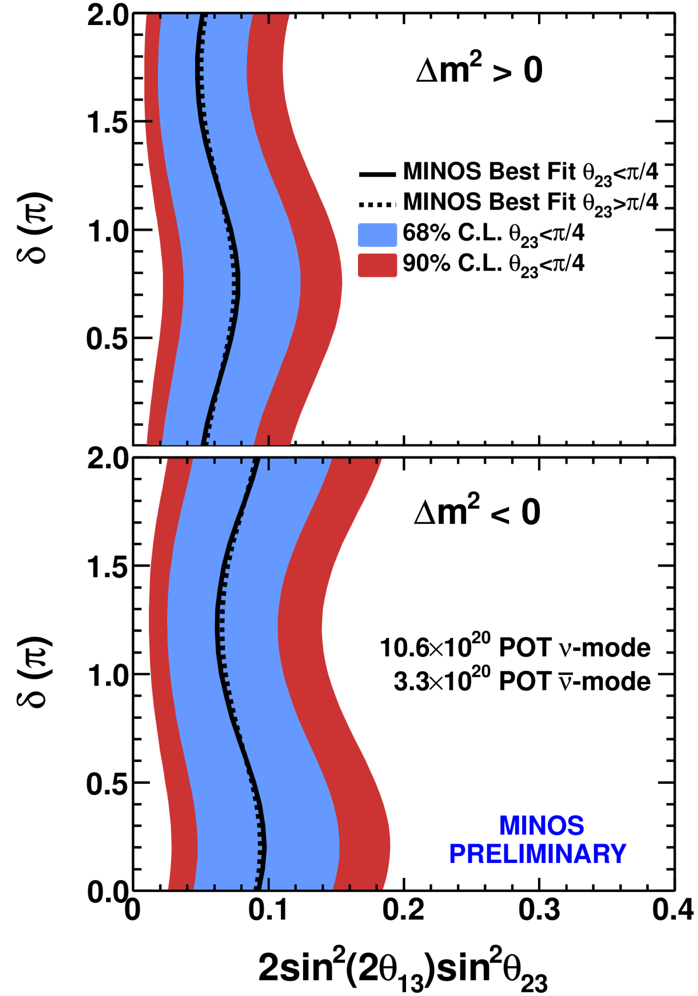
10.6×10^{20} POT ν mode running:

Candidate Event Yields

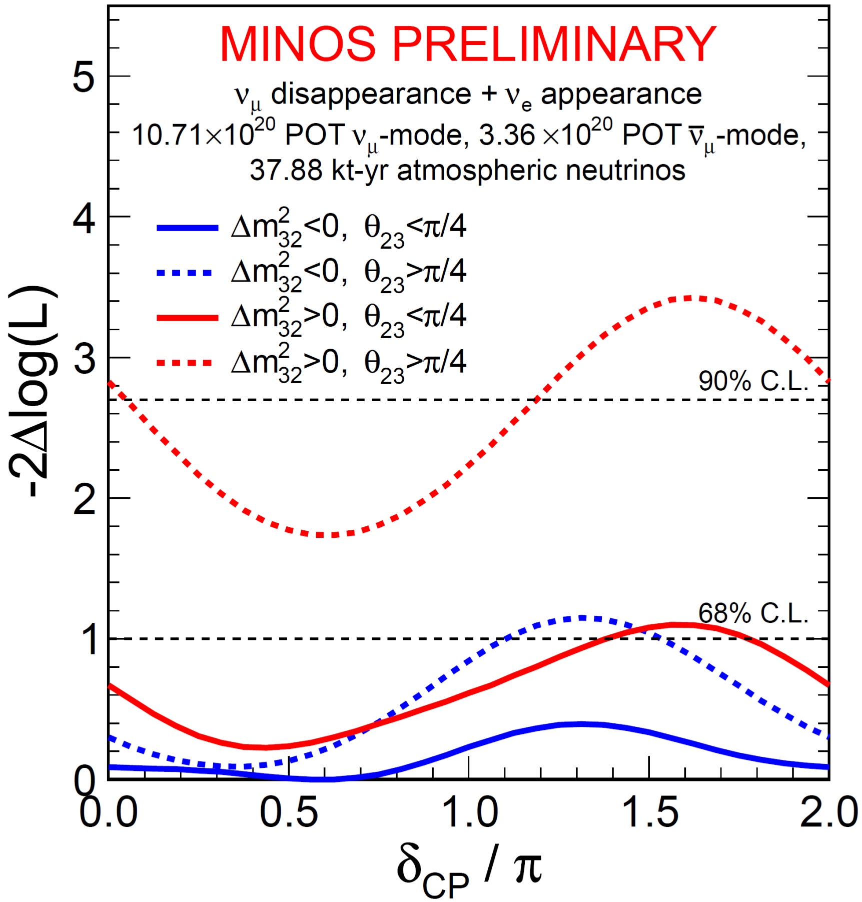
LEM>0.6:	Observed:	152
	Predicted:	128.6 bkg + 32.5 sig
LEM>0.7:	Observed:	88
	Predicted:	69.1 bkg + 26.0 sig

Prediction assuming $\sin^2(2\theta_{13})=0.1$, $\delta=0$, $\Delta m^2>0$

(LEM is a PID variable)



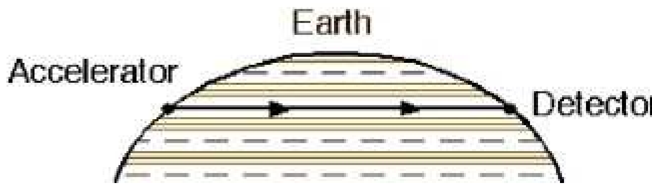
MINOS on δ_{CP}



- **Preliminary combined fit of both appearance and disappearance data: 3-flavor**
- **Fit in 4D likelihood surfaces: (θ_{13}, δ_{CP}, θ_{23}, Δm^2_{32})**
  - **Constraint for θ_{13} from the combination of Daya Bay+RENO+ Double Chooz measurements.**
  - **Others fixed to global average**
- **Normal hierarchy and upper octant disfavored at 81% C.L.**

From João A. B. Coelho/Tufts FNAL 08-14-13 Talk

Matter Effects

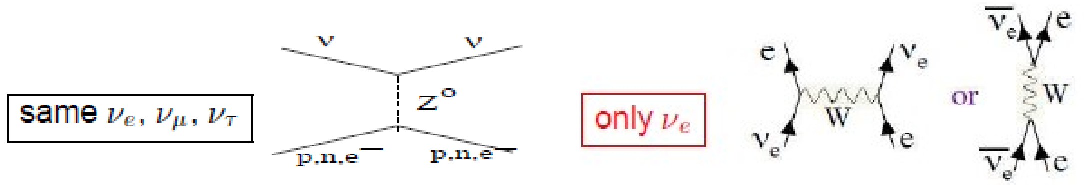


ν's interact with n,p,e–

What if neutrinos are not propagating in vacuum?

When ν's travel long baselines through the earth: Energy levels are altered of propagating eigenstates (changes the effective mass).

- Raises effective mass of ν_e
- Lowers effective mass of anti-ν_e
- Sensitive to the sign of Δm^2.



$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2\, T_4$$

With:

$T_1 = \sin^2\theta_{23} \sin^2[(1-x_\nu)\Delta]/(1-x_\nu)^2$

$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \sin(x_\nu\Delta)/x_\nu \sin[(1-x_\nu)\Delta]/(1-x_\nu)$

$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin(x_\nu\Delta)/x_\nu \sin[(1-x_\nu)\Delta]/(1-x_\nu)$

$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(x_\nu\Delta)/x_\nu^{\,2}$

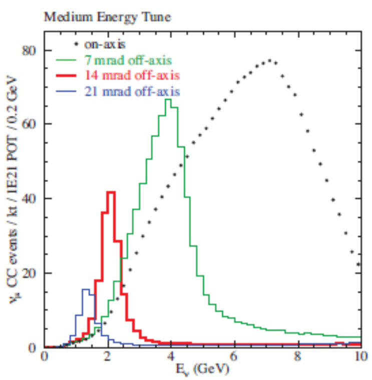
and:

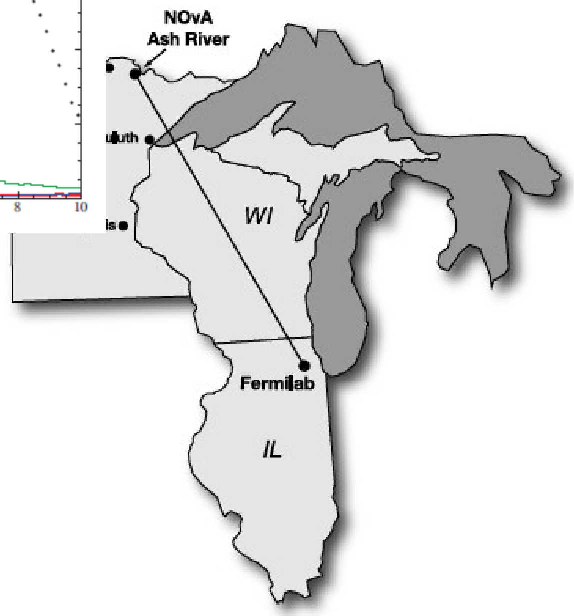
$\Delta \equiv \Delta m^2_{31} L/4E$, $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ ~1/30, $\mathbf{x_\nu \equiv 2\sqrt{2} G_F N_e E/\Delta m^2_{31}}$

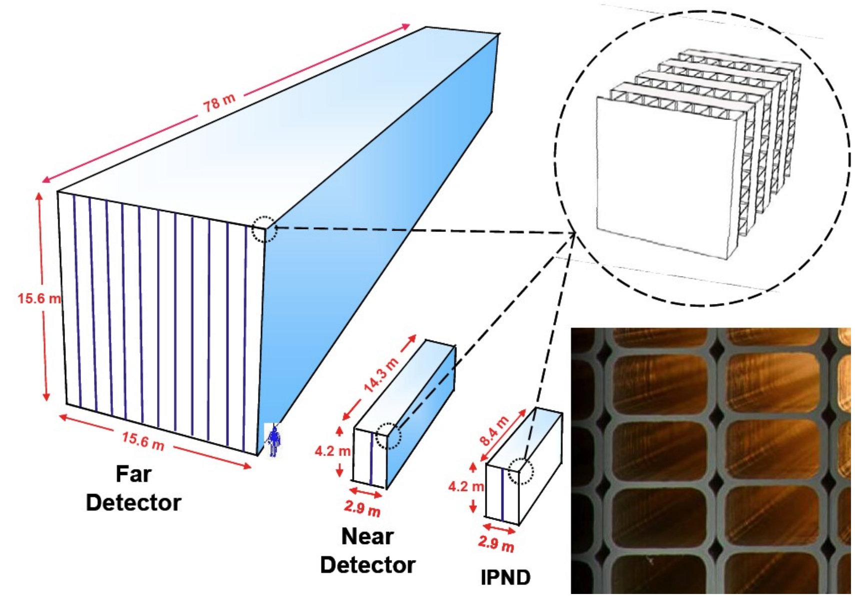
NOvA Experiment

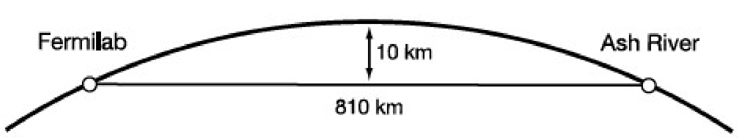
Will study $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-ν_e using off axis beam

(Just started taking data)



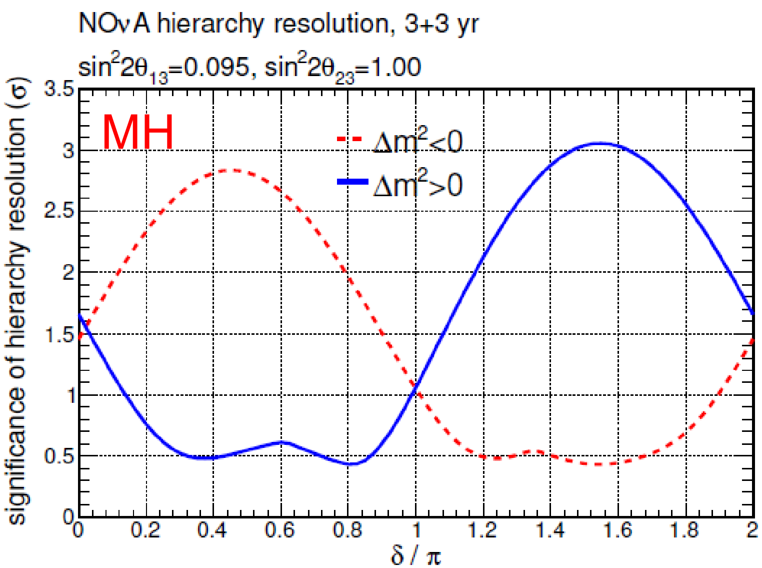




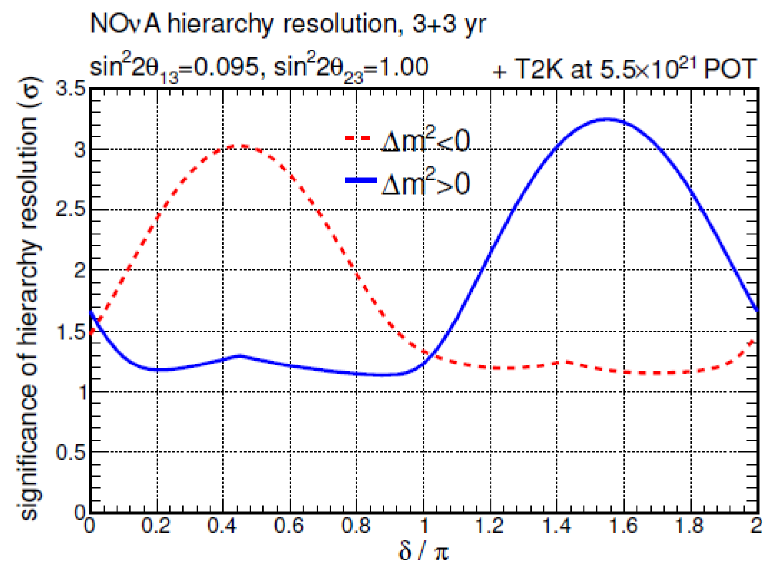


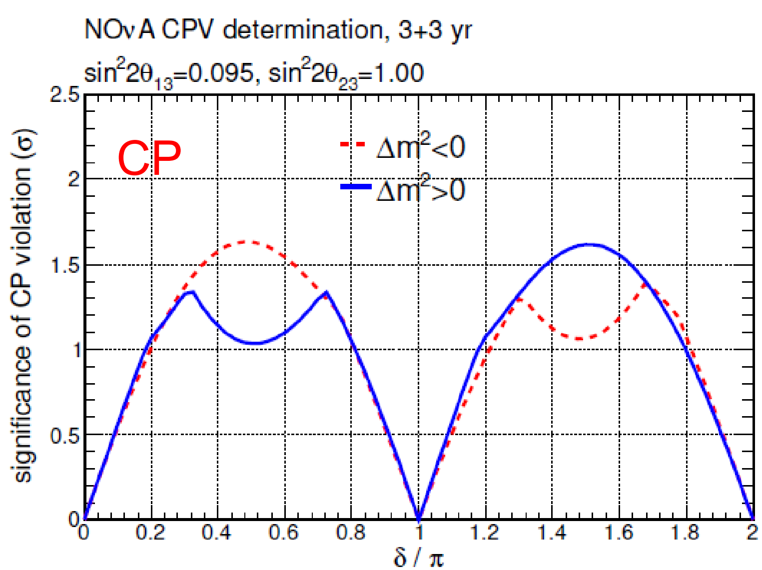
14 kt, 65% active far detector, 15.6 m plastic cells filled with liquid scintillator

NOνA Sensitivities

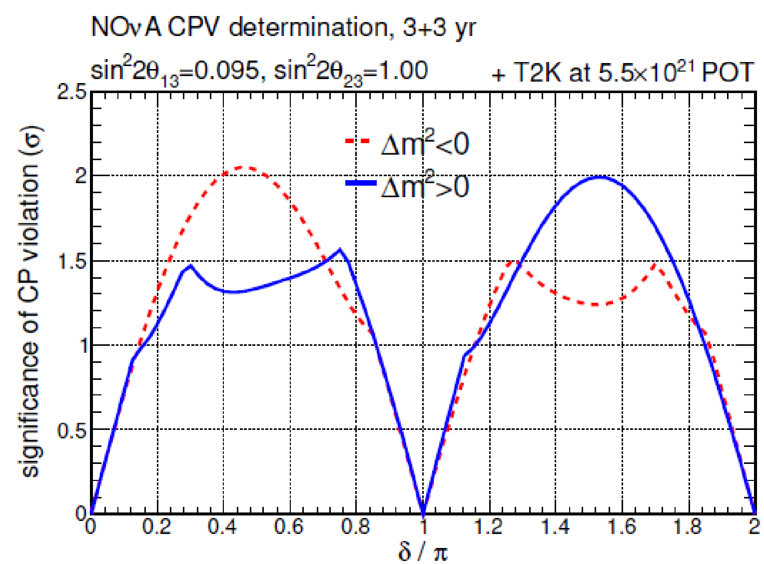


Increased sensitivity when combining experiments:
+ T2K





+ T2K



(From A. Waldron U of Sussex, EPS 2013)

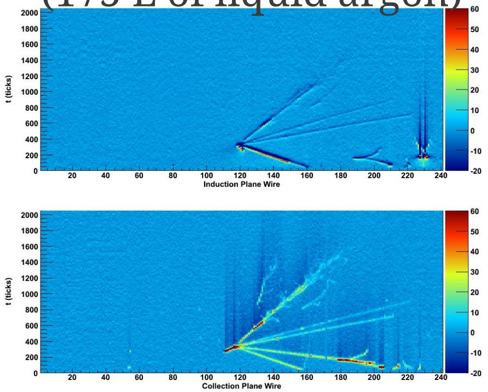
Future: LBNE

Planning underway for a next generation appearance experiment optimized for improved δ and hierarchy sensitivity.

Very long baseline L~1300 km beam, Fermilab→Sanford (SURF)

Initial beam power ~700 kW

ArgoNeut Event
(175 L of liquid argon)

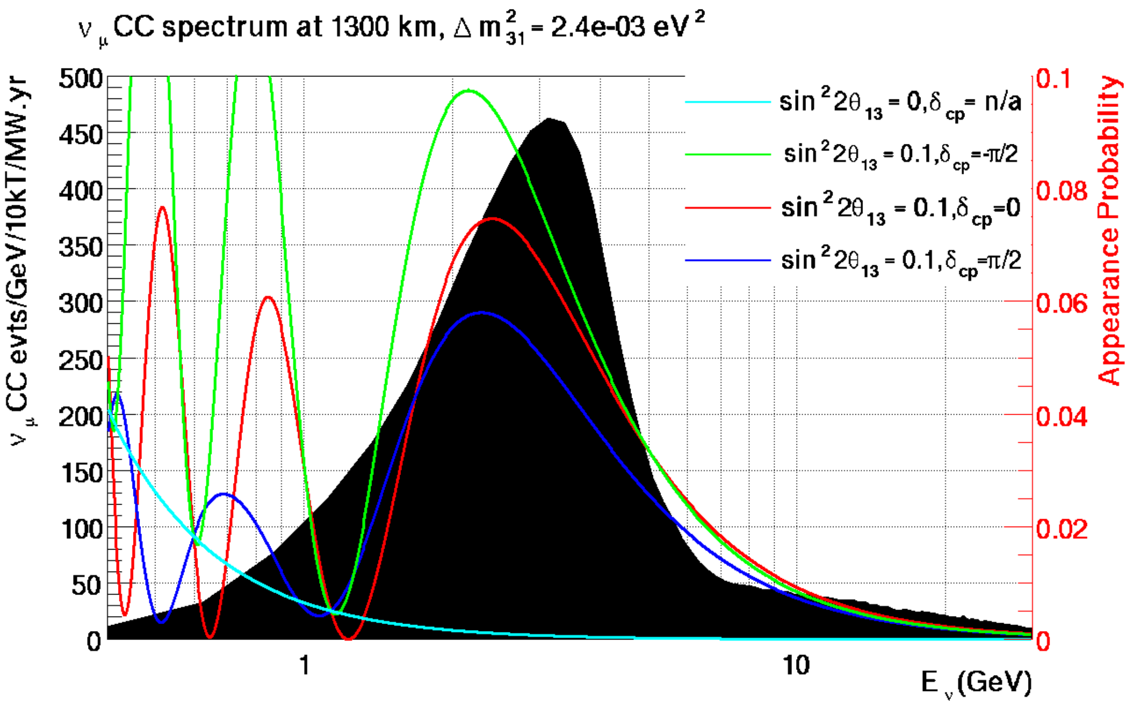


Far Detector Technology: 34 kt LAr TPC
at a depth of 4850 feet

LBNE: Very LBL

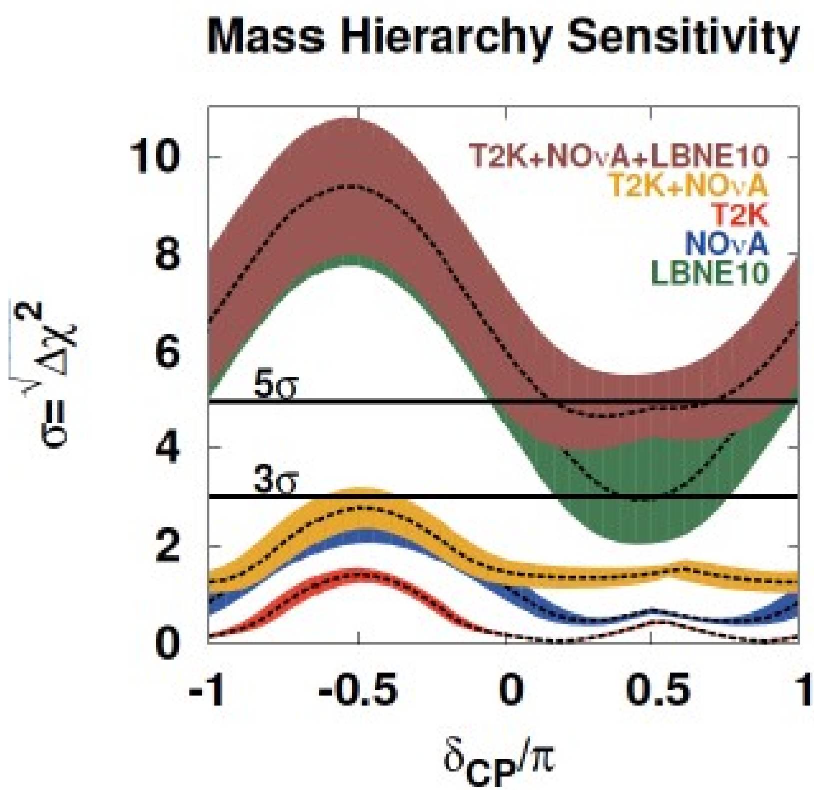
1300km optimized baseline:

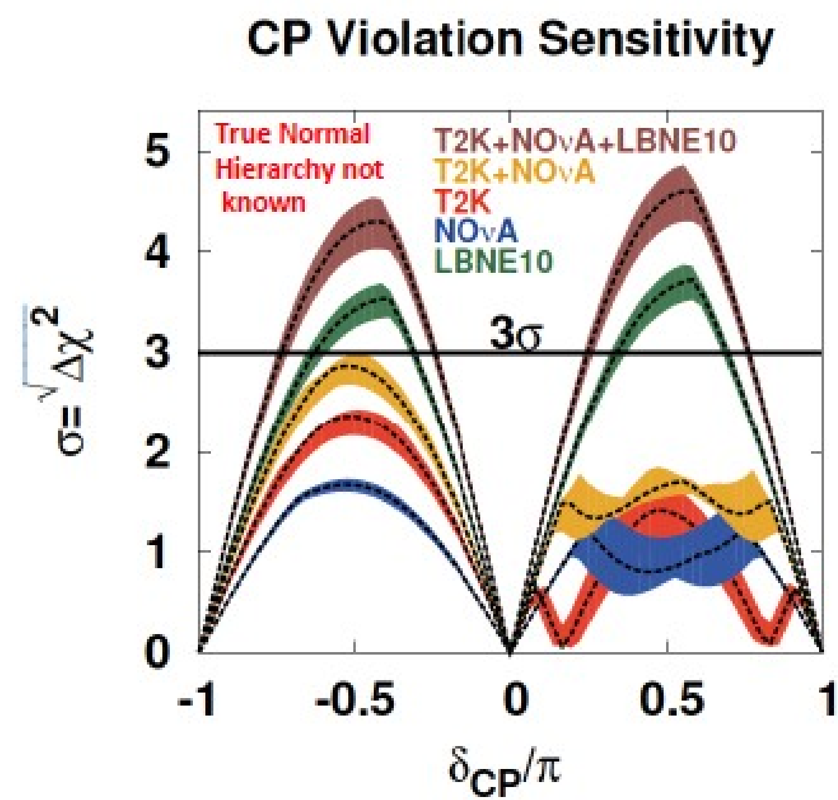
- Observe multiple oscillation peaks
- Mass Hierarchy(MH): Need Matter → Longer baseline is better
- δ_{CP}: Need long enough baseline to resolve degeneracy with MH but short enough baseline to record enough events



- $\sin^2(2\theta_{13})$ determines size of event sample
- δ_{CP} affects amplitude of oscillations
- Mass differences affects frequency of oscillations
- MH effects both amplitude and frequency

LBNE Sensitivities





LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$) T2K 750 kW x 5 yr (7.8x10^{21}pot) ν NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$) (3.8 x10^{21}pot)

Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

Best sensitivities will be achieved when combining all appearance experiments

→ T2K, NOνA, and LBNE

Summary and Outlook

- Neutrino physics is now in an era of precision measurements
  - It is a window into new physics
  - Measuring in detail the elements of the mixing/mass matrix is the only window we have to probe this new physics

- At this point Neutrino physics is experimentally driven
  - We need to over constrain the parameters in the mixing and mass matrix to check if we have the full story
    - Are there any inconsistencies in the model?

- Neutrino measurements are hard to make and expensive
  - Need statistics…
  - Will need to combine results from different experiments to get a clearer picture.
    - That has already started.

Blank