Recent Developments in Neutrino Oscillations

H. A. Tanaka (UBC/IPP)

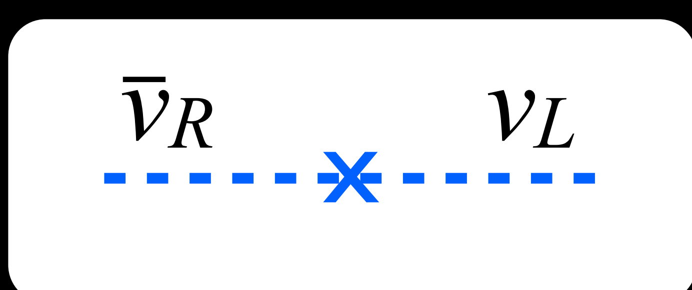
LISHEP, 4-9 July 2011, Rio de Janeiro, Brazil

Mass and Mixing:

Opportunities following discovery of non-zero neutrino mass

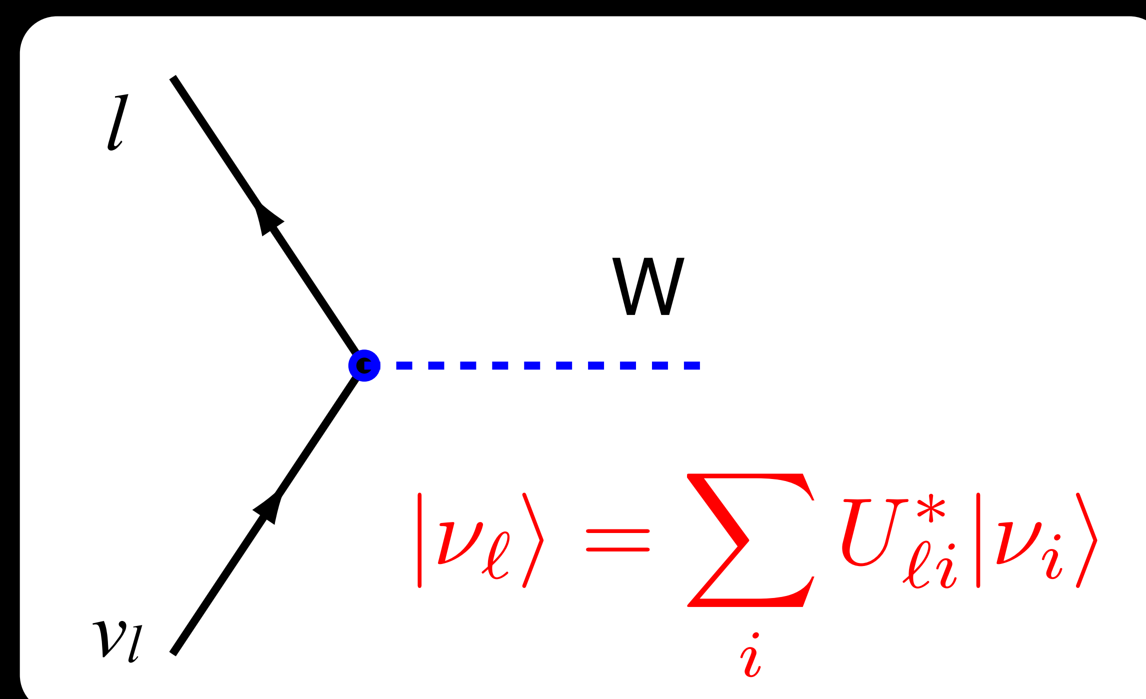
Mass:

- Neutrino masses very small (<1 eV)
- Neutrinos are unique in the SM in having the option to have:
  - Dirac mass (like quarks) $\mathcal{L}_D = -m_D(\overline{\nu}_L \nu_R + \overline{\nu}_R \nu_L)$
  - Majorana mass (self-conjugate) $\mathcal{L}_M = -m_M(\overline{\nu}_R \nu_R^c + \overline{\nu}_R^c \nu_R)$



Mixing:

- also know that the neutrinos “mix” like quarks
- flavor/mass states related by non-trivial unitary transformation



The Big Questions:

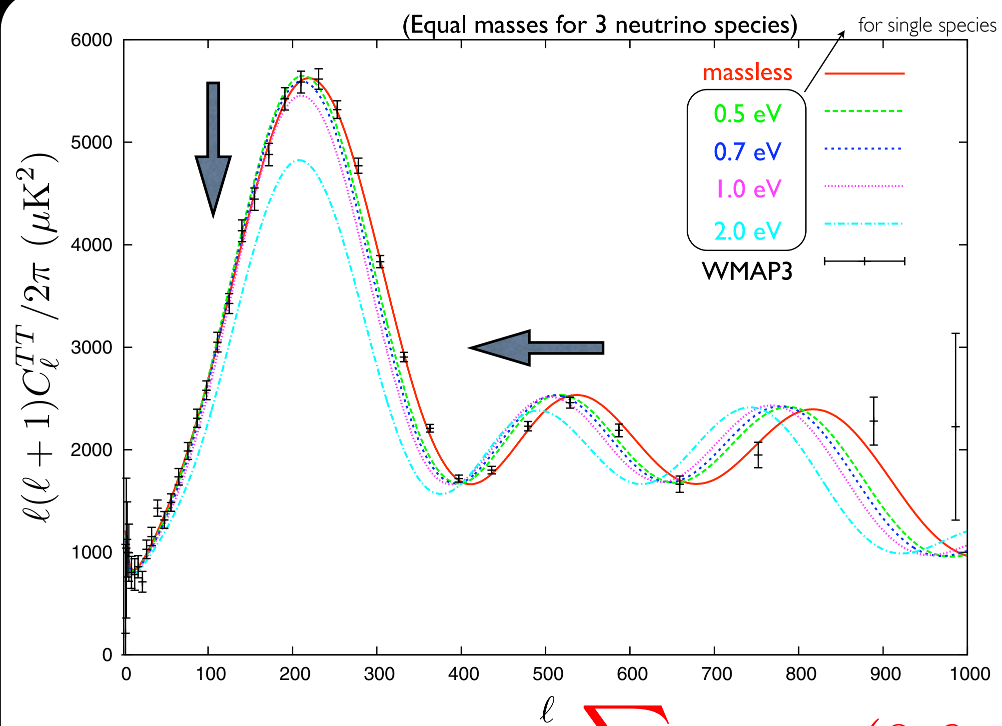
Neutrinos play a role in outstanding problems:

- **Key to persistent cosmological problems?**
  - Their mixing (and resulting CP violation) may be related to the matter/ anti-matter asymmetry of the universe (leptogenesis)
- **Window to physics at a very high scale?**
  - Their mass may be of a completely different nature from other particles (Majorana mass).
  - “Seesaw” mechanism relates small neutrino masses to 10^{15} eV scale
- **“Standard” mixing/mass of neutrinos pose their own question**
  - Why is the mixing so large, different from quarks?
  - Why are neutrino masses small compared to other leptons/quarks?
  - Is there a pattern to the mixing/masses?

Key Questions

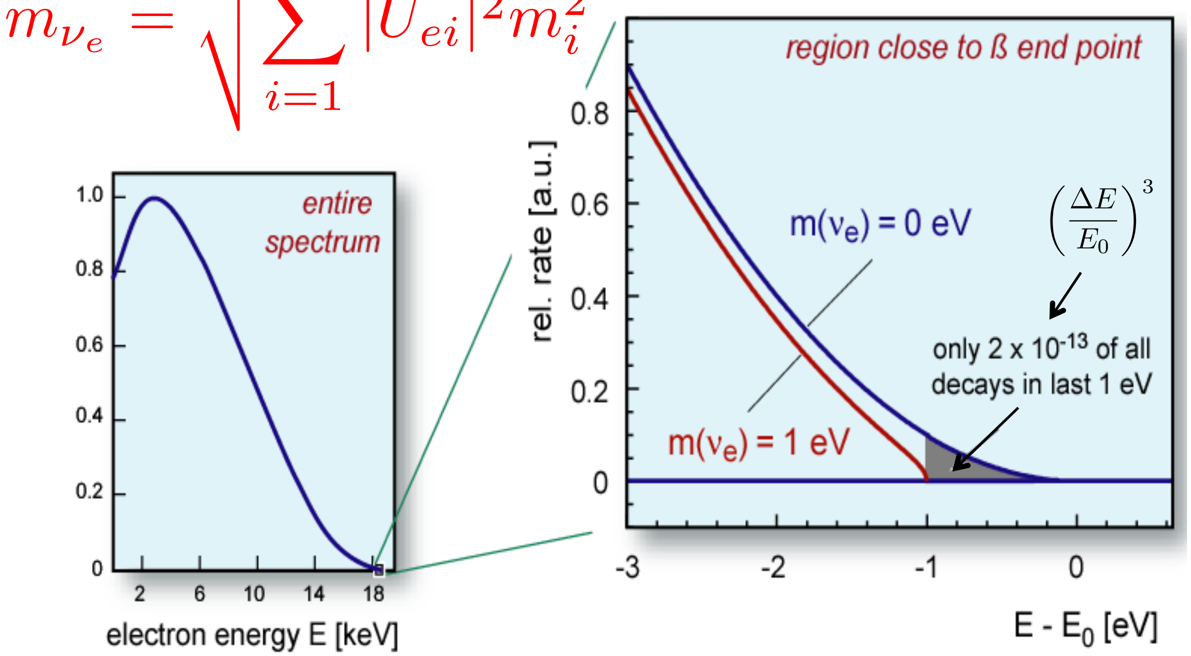
- **Are neutrinos their own antiparticles?**
  - Do neutrinos have Majorana masses?
  - Key ingredient to the “see-saw” and Leptogensis
- **What is the mixing/mass structure of neutrinos?**
  - Is there CP violation in the lepton sector?
    - Gatekeeper: is $\theta_{13} \neq 0$?
  - Is there structure/pattern to neutrino masses?
    - Need precision measurements
- **Is there more?**
  - sterile neutrinos? CPT violation? . . . .

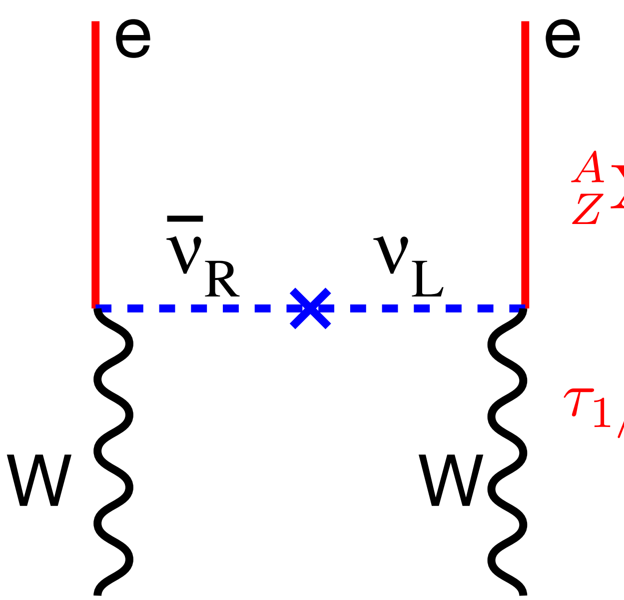
Probing Mass/Mixing



$$\sum m_\nu < (0.6 - 1.3)\mathrm{eV}$$

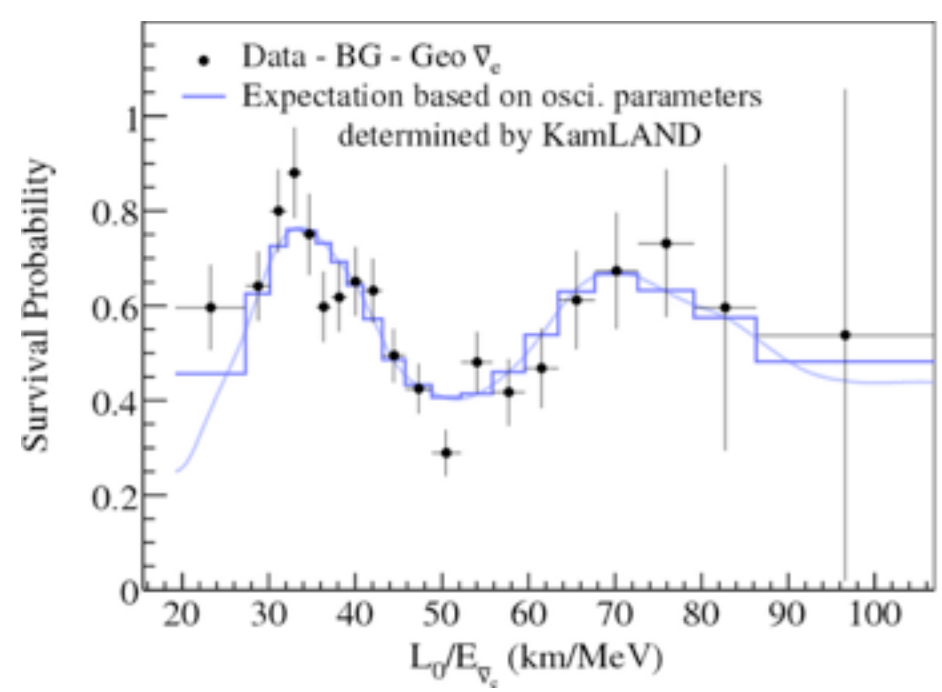
$$m_{\nu_e} = \sqrt{\sum_{i=1}^{n_\nu} |U_{ei}|^2 m_i^2}$$





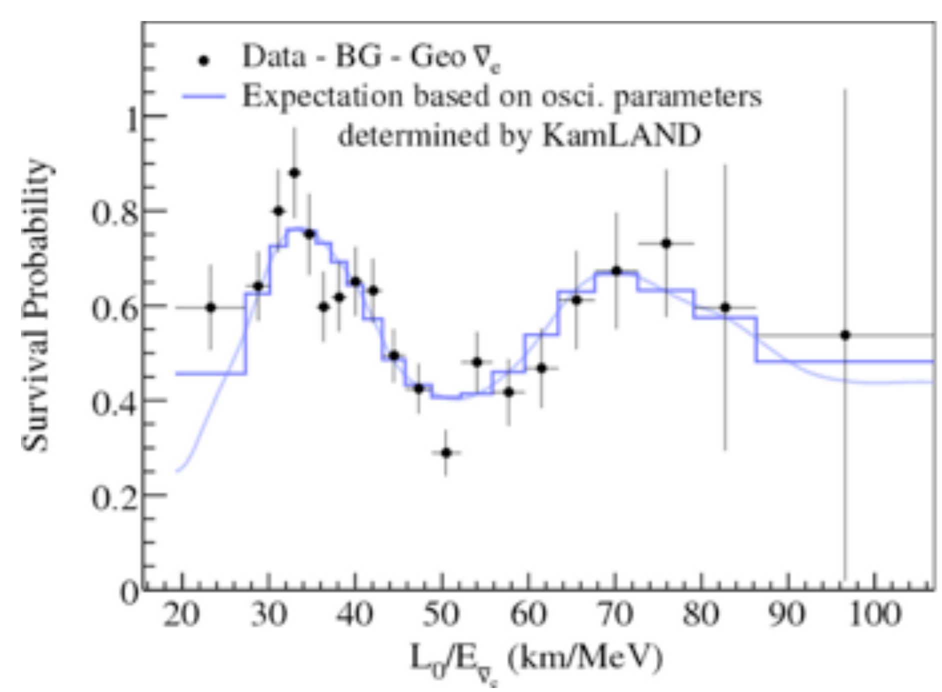
$$^A_Z\mathrm{X} \to e^- + e^- + \ ^A_{Z+2}\mathrm{Y}$$

$$\tau_{1/2} = \frac{1}{\langle m_{ee}\rangle G_{0\nu}|\mathcal{M}_{0\nu}|^2}$$



$$P_{\nu_\alpha\to\nu_\beta}(L/E; \Delta m^2_{ij}, U_{\ell i}) \neq 0$$

Probing Mass/Mixing

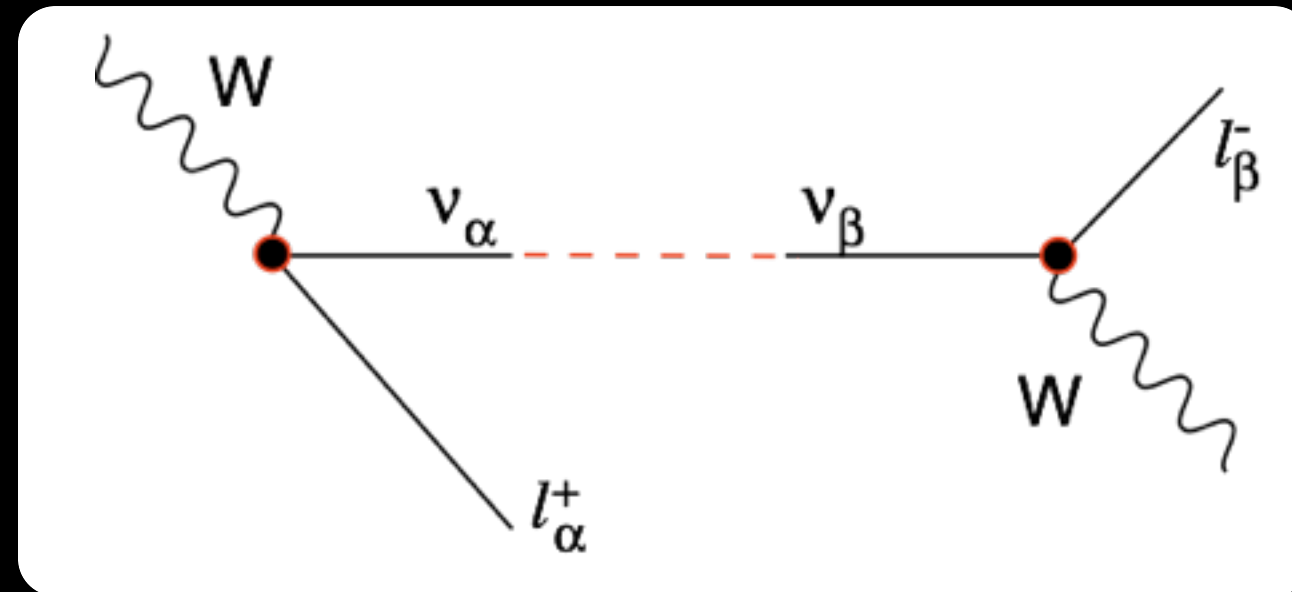


$$P_{\nu_\alpha \to \nu_\beta}(L/E; \Delta m^2_{ij}, U_{\ell i}) \neq 0$$

Neutrino Oscillations

- Neutrinos produced in weak decays are linear combinations of mass/energy eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$



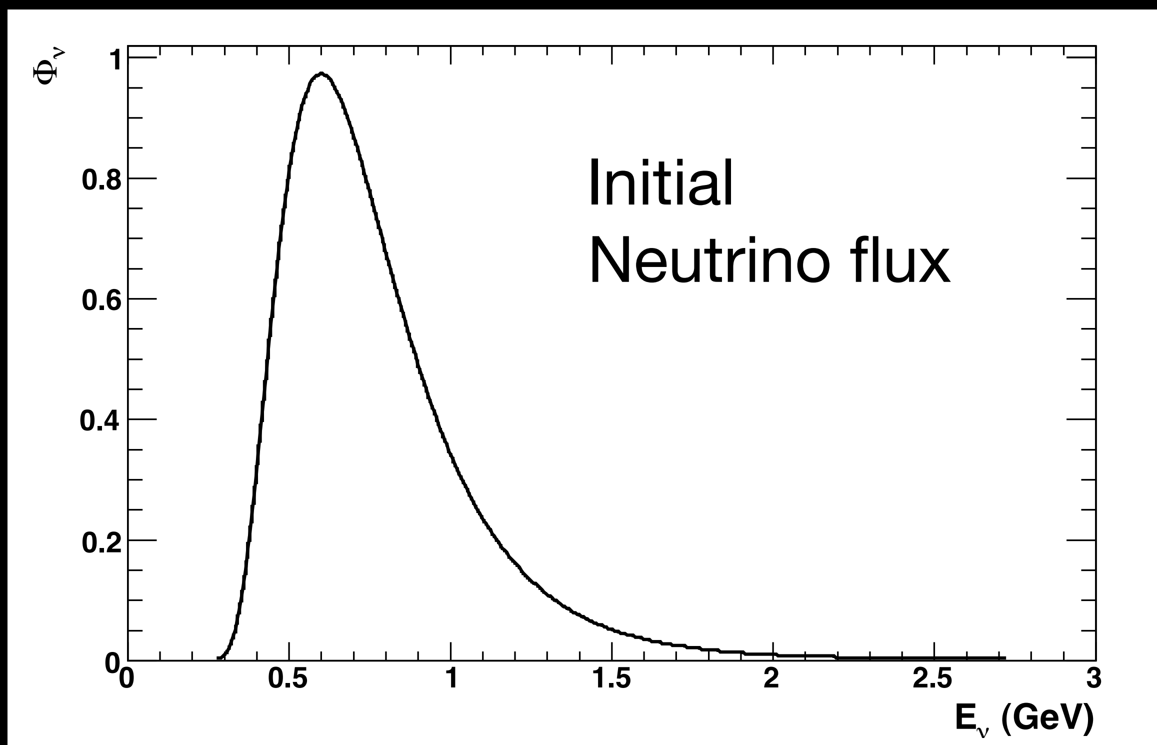
- Time evolution: state acquires component of another neutrino flavor

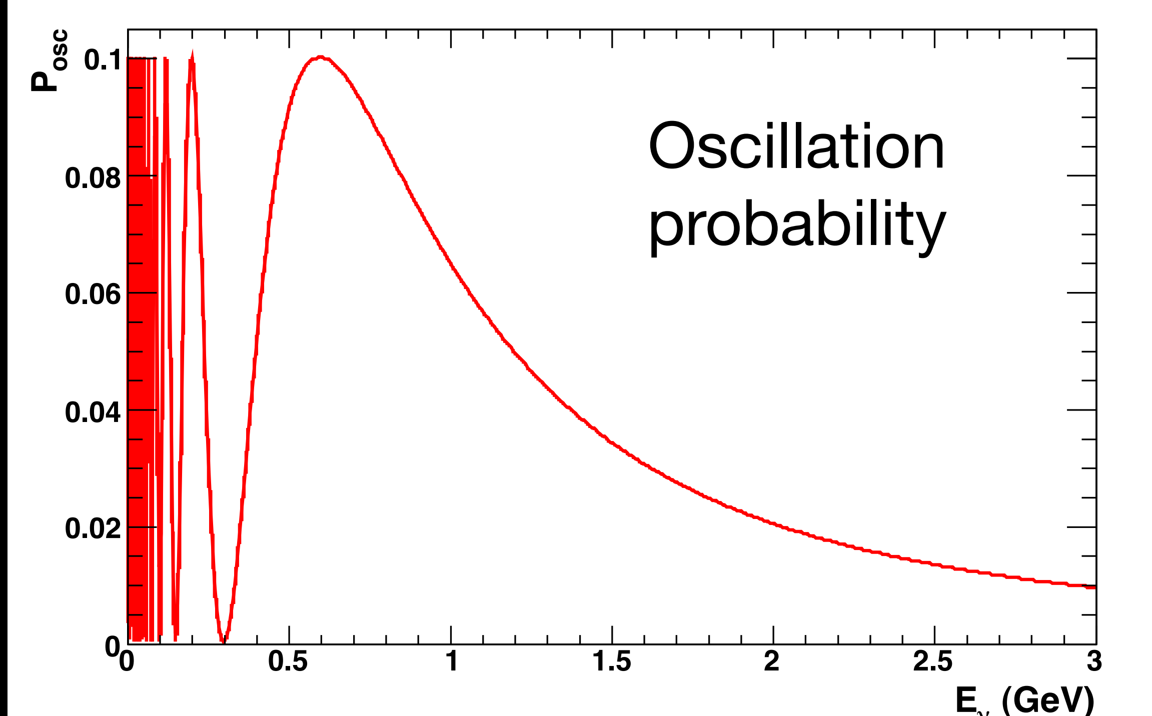
$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = \quad & \delta_{\alpha\beta} \\ & -4\Sigma_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] \\ & +2\Sigma_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[2.54\Delta m^2_{ij}(L/E)] \end{aligned}$$

- Amplitudes determined by mixing parameters (U_{ai})
- Wavelengths determined by mass differences Δm^2_{ij} (L in km, E in GeV)

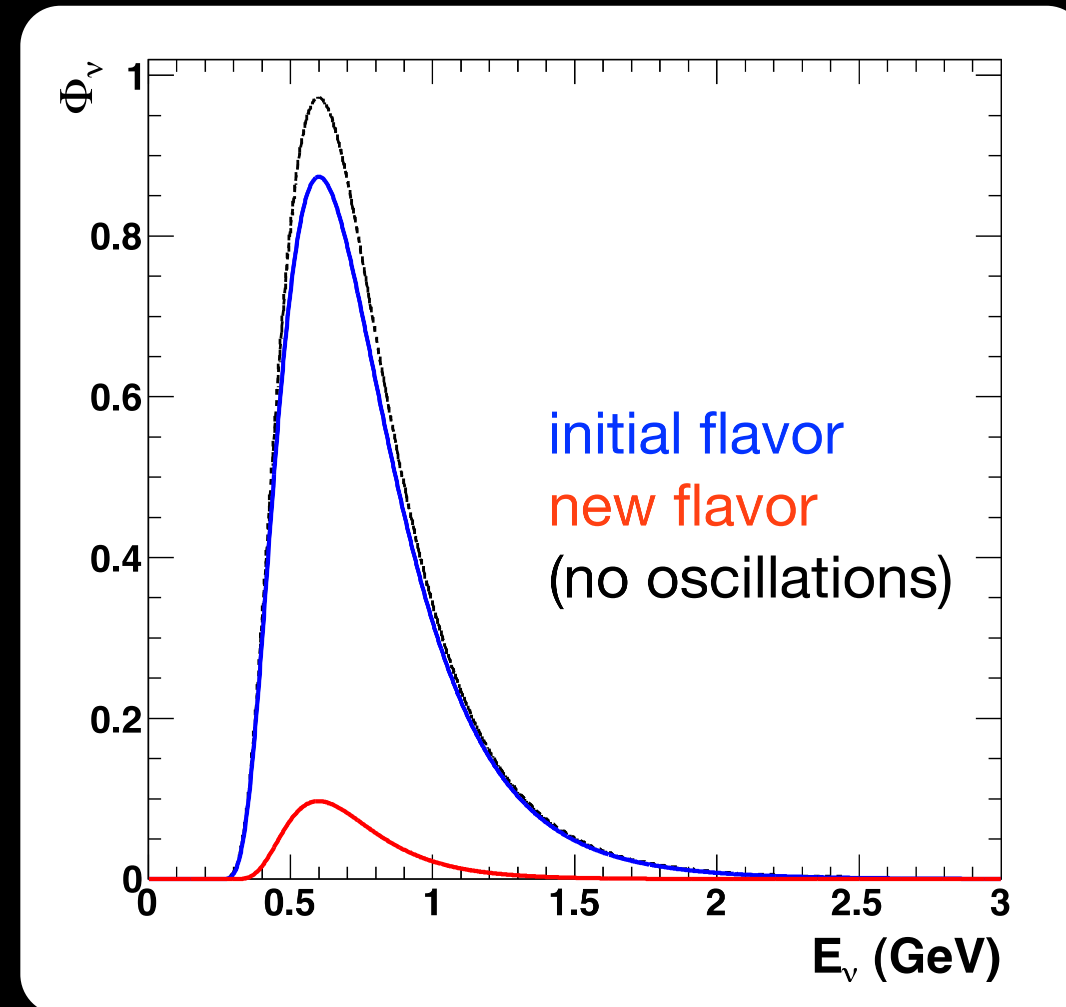
Only positive indications of neutrino mass and mixing thus far.

Experiment





L



Disappearance:

- fewer interactions in original flavor

Appearance:

- interactions in new flavor

Amplitudes: mixing matrix U_{ij}

E_ν dependence: mass differences Δm_{ij}^2

Typically, experiments have detectors at L=0 to assess “initial state”

Current Knowledge

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The mixing matrix:

$$|U_{\mathrm{MNSP}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$

$\sin^2 2\theta_{13} < 0.19$

$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$

Is $\theta_{13} \neq 0$?

Is θ_{23} maximal (45°)?

Is $\delta \neq 0$ (CP violation)?

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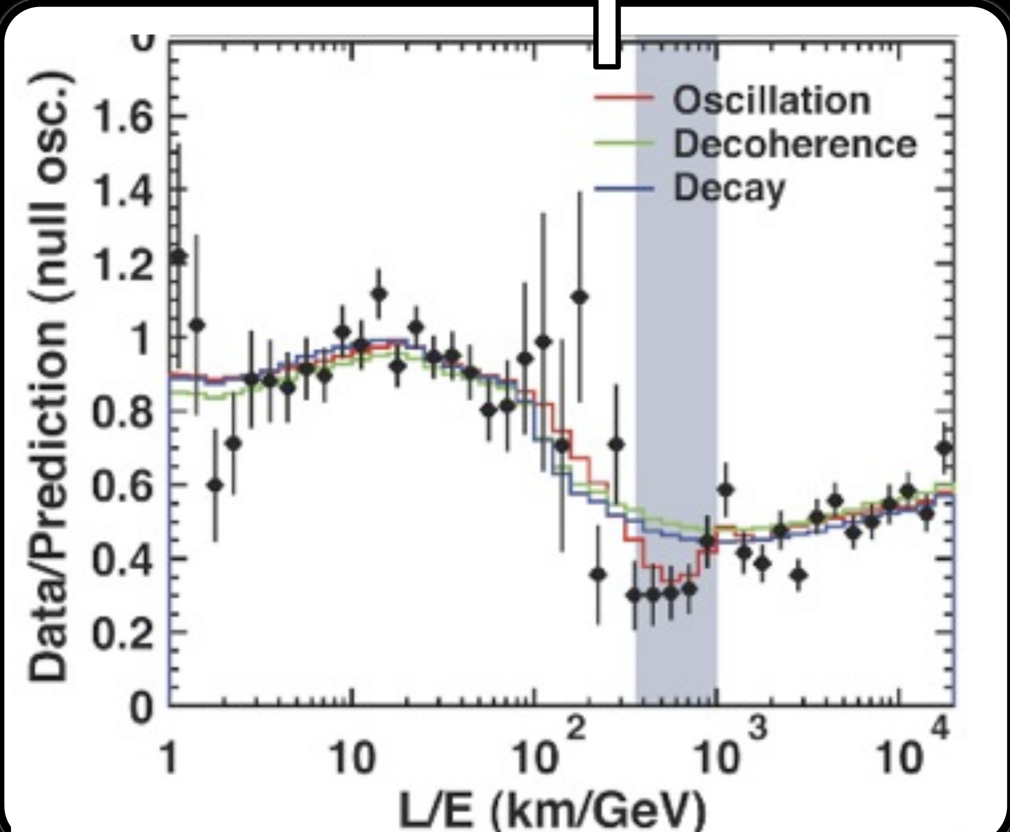

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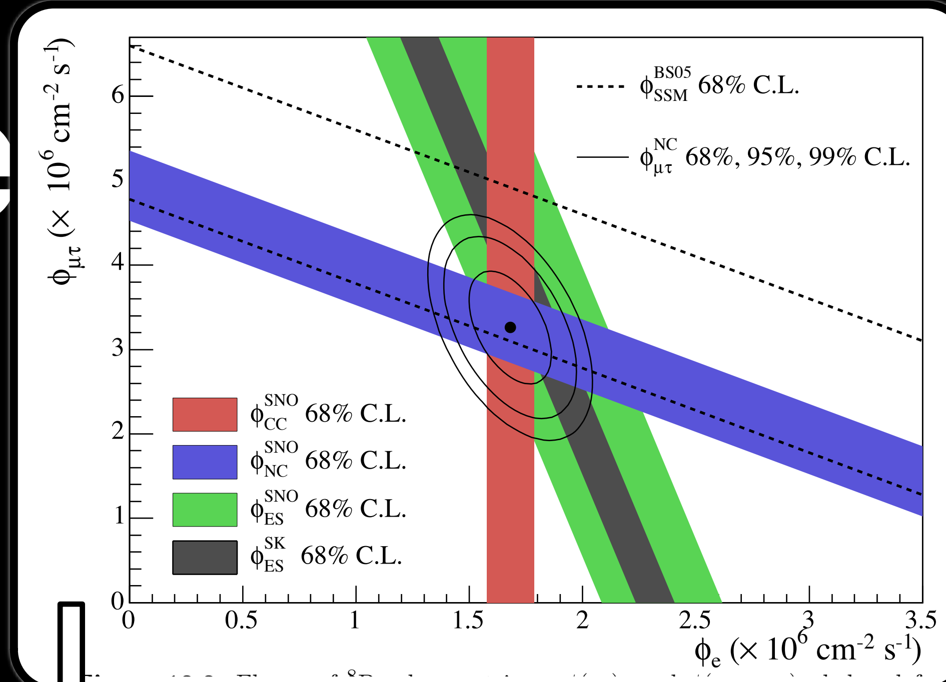

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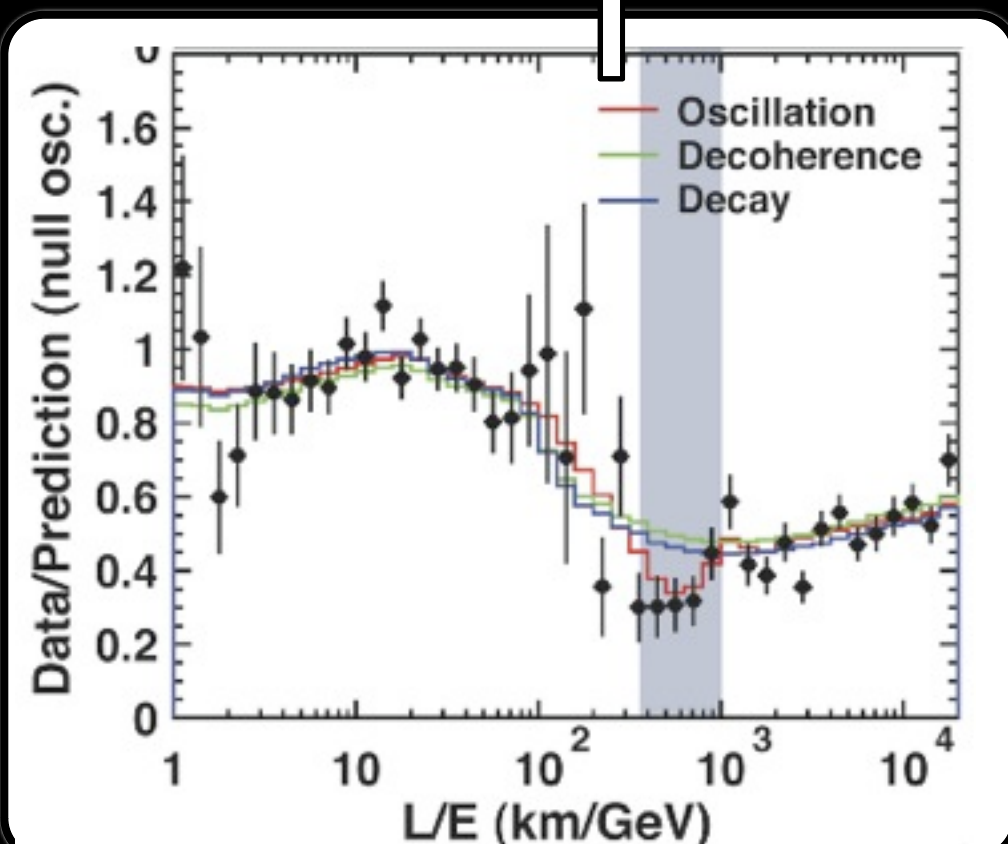

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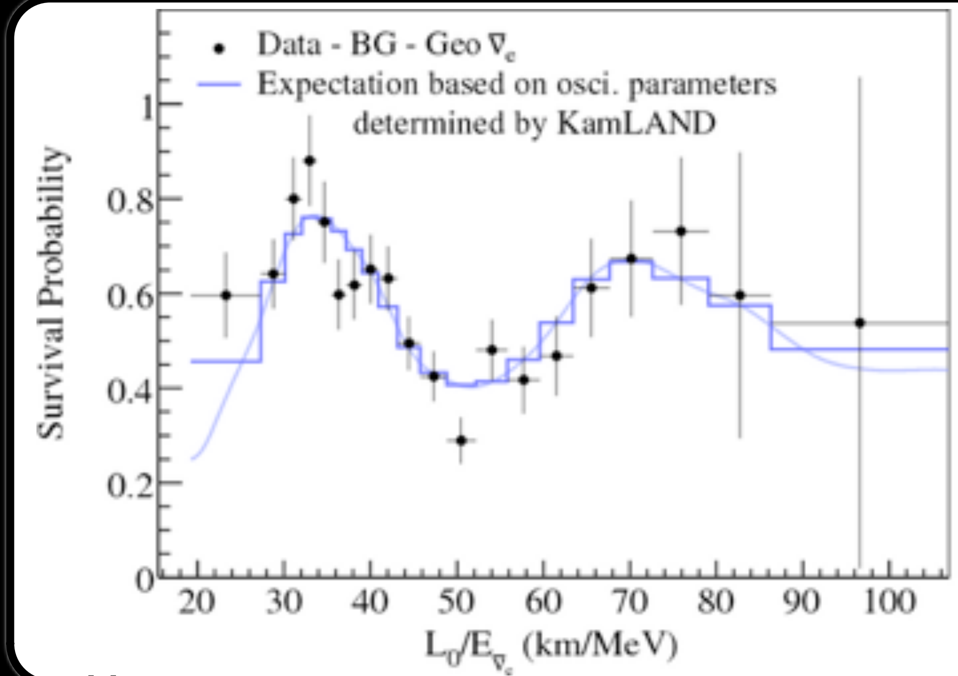
Terrestrial:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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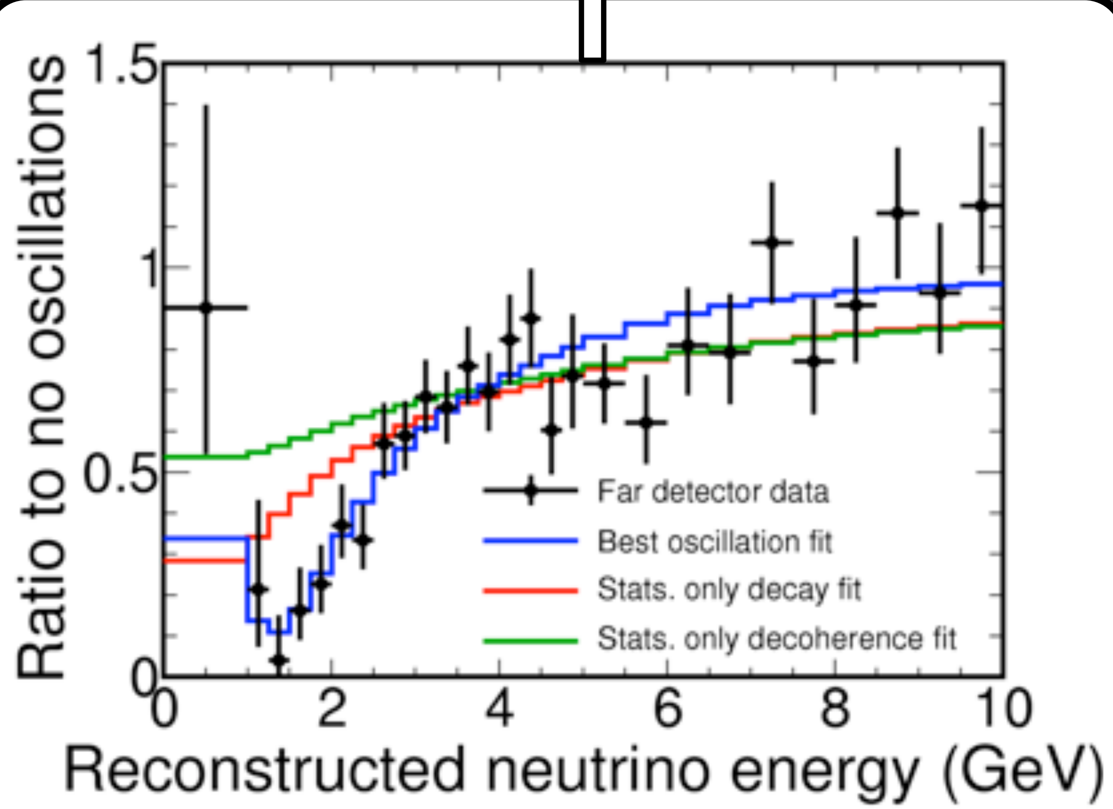
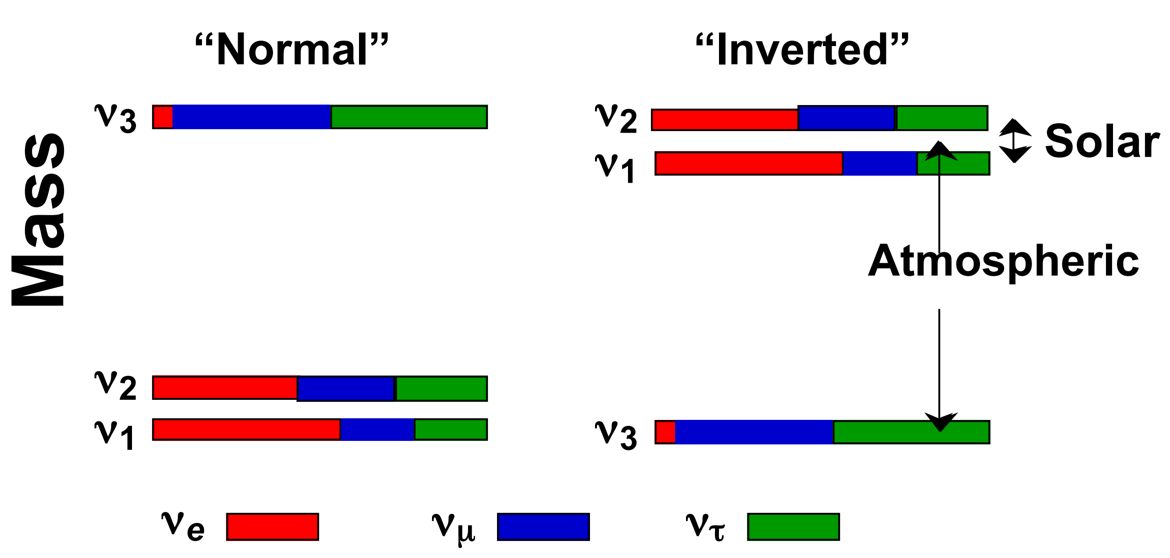


$$\Delta m^2_{12} \sim 7.8 \times 10^{-5} \mathrm{eV}^2/c^4$$

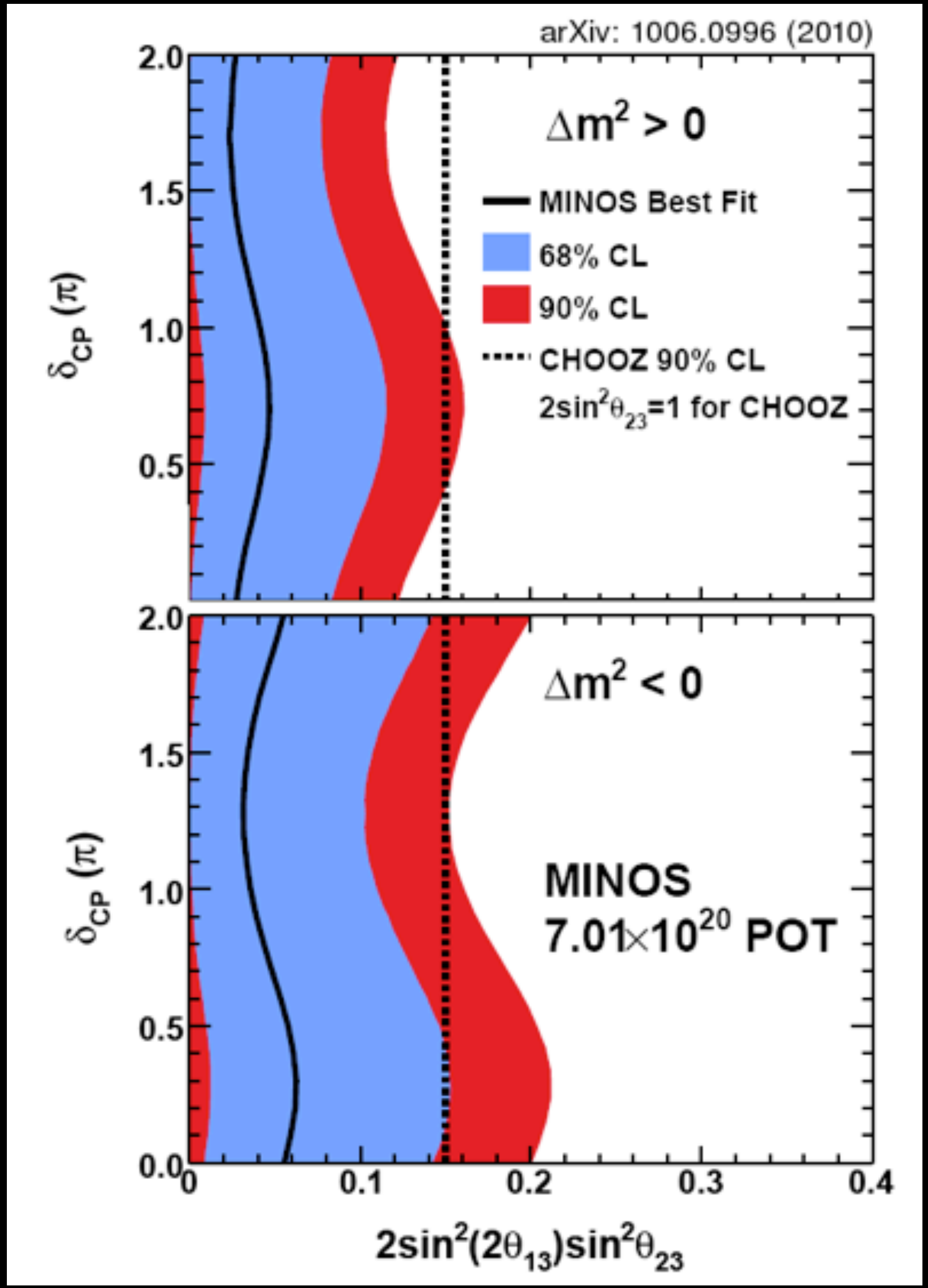
$$\Delta m^2_{23} \sim 2.4 \times 10^{-3} \mathrm{eV}^2/c^4$$



θ_{23} and θ_{13}

θ_{23}: **Possibly maximal mixing**

- Precision measurement (ν_μ disappearance)
- Is the oscillation to ν_τ? (ν_τ appearance)



θ_{13}: **Last unmeasured mixing angle**

- 3 flavor mixing allows CP violation if $\delta \neq 0$

$$\nu_\alpha \to \nu_\beta \neq \bar{\nu}_\alpha \to \bar{\nu}_\beta$$

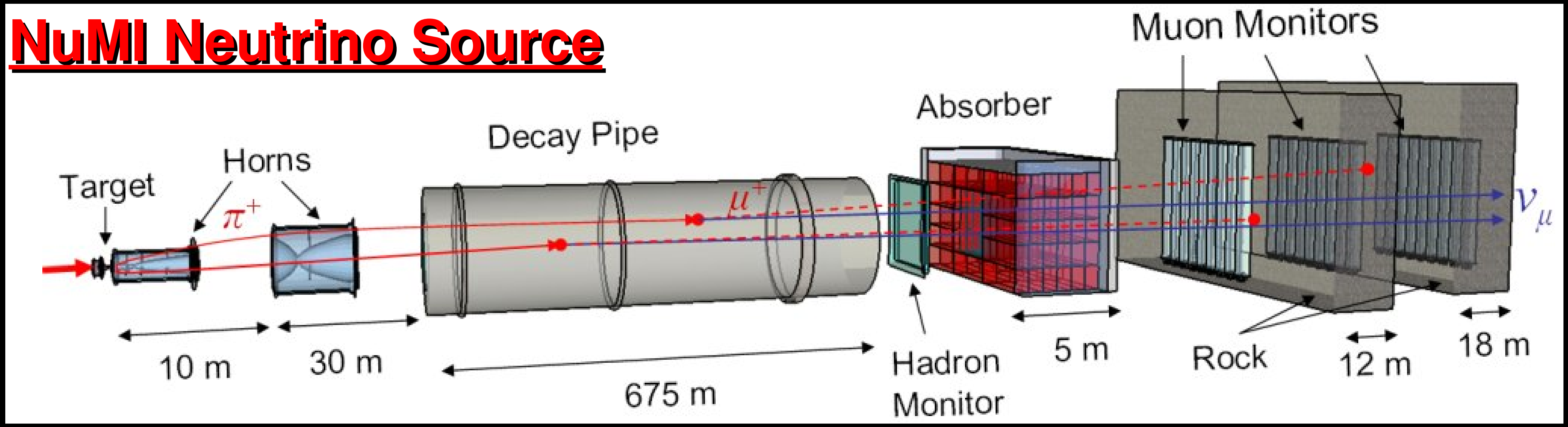
- Two methods for detecting θ_{13}:
  - $\bar{\nu}_e$ disappearance with reactor source
    $$P(\nu_e \to \nu_e) \sim 1 - \sin^2 2\theta_{13} \sin^2 \Delta m^2_{23}(L/E)$$
  - ν_μ from accelerator

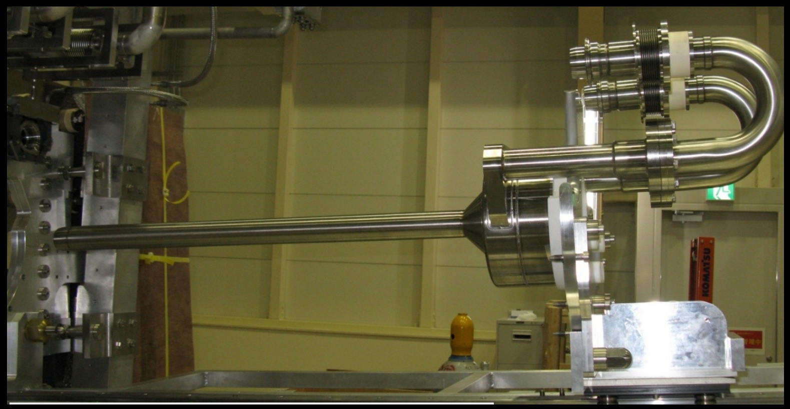
$$\begin{aligned} P(\nu_\mu \to \nu_e) &\sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \times \sin^2 \Delta_{31} \\ &+ \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times \sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta) \\ &+ \sin^2 2\theta_{12} \cos^2\theta_{23} \cos^2\theta_{13} \times \sin^2\Delta_{21} \end{aligned}$$

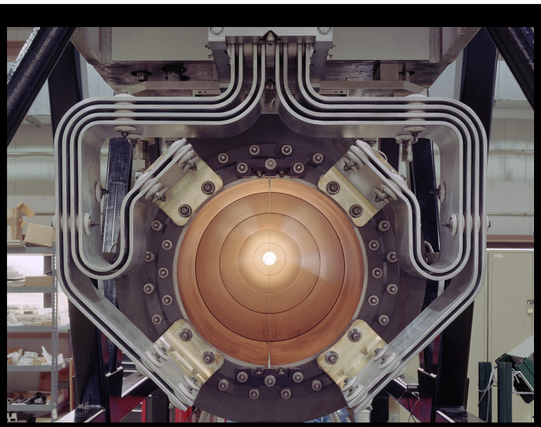
B. Kayser, NuSAG Mar 2006

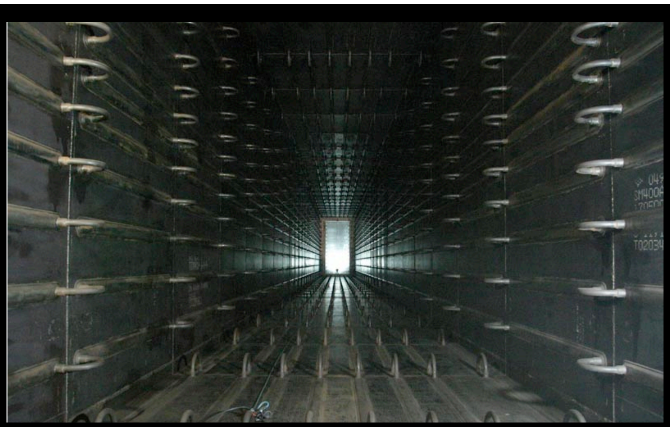
$$\Delta_{ij} = 1.27\Delta m^2_{ij}(L/E)$$

Accelerator-based beam









- O(1 GeV) ν_μ produced from secondary particle decays:

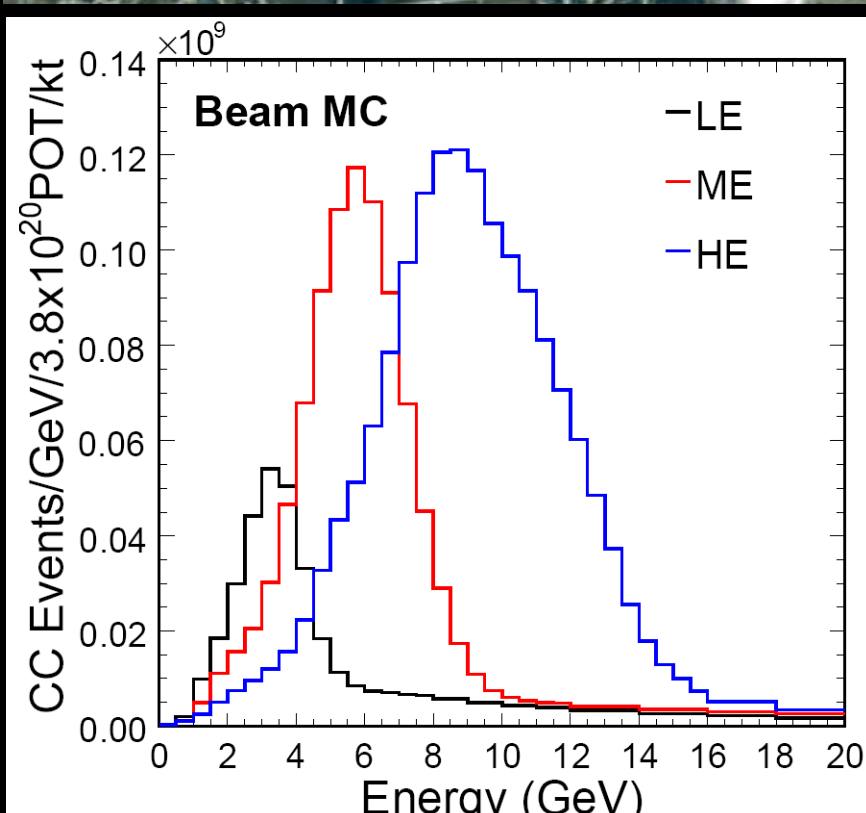
$$
\begin{aligned}
p + A \to\ & \pi^+ + X \\
& \hookrightarrow \mu^+ + \nu_\mu \\
& \qquad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu
\end{aligned}
$$

$$
\begin{aligned}
p + A \to\ & K + X \\
& \hookrightarrow \mu + \nu_\mu & (K_{\mu 2}) \\
& \quad\ \ \pi + \mu + \nu_\mu & (K_{\mu 3}) \\
& \quad\ \ \pi + e + \nu_e & (K_{e3})
\end{aligned}
$$

- other neutrino species produced at O(10$^{-(2-3)}$) level

$$\theta_{23}$$

MINOS:

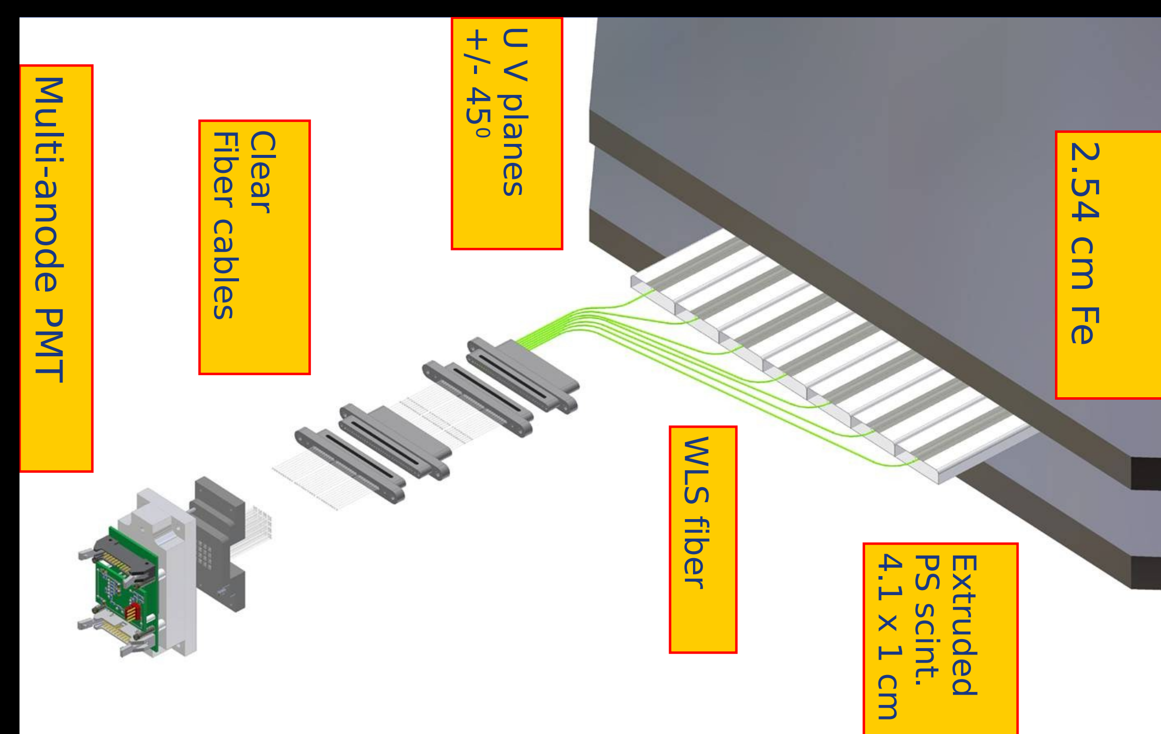


NEAR

FAR

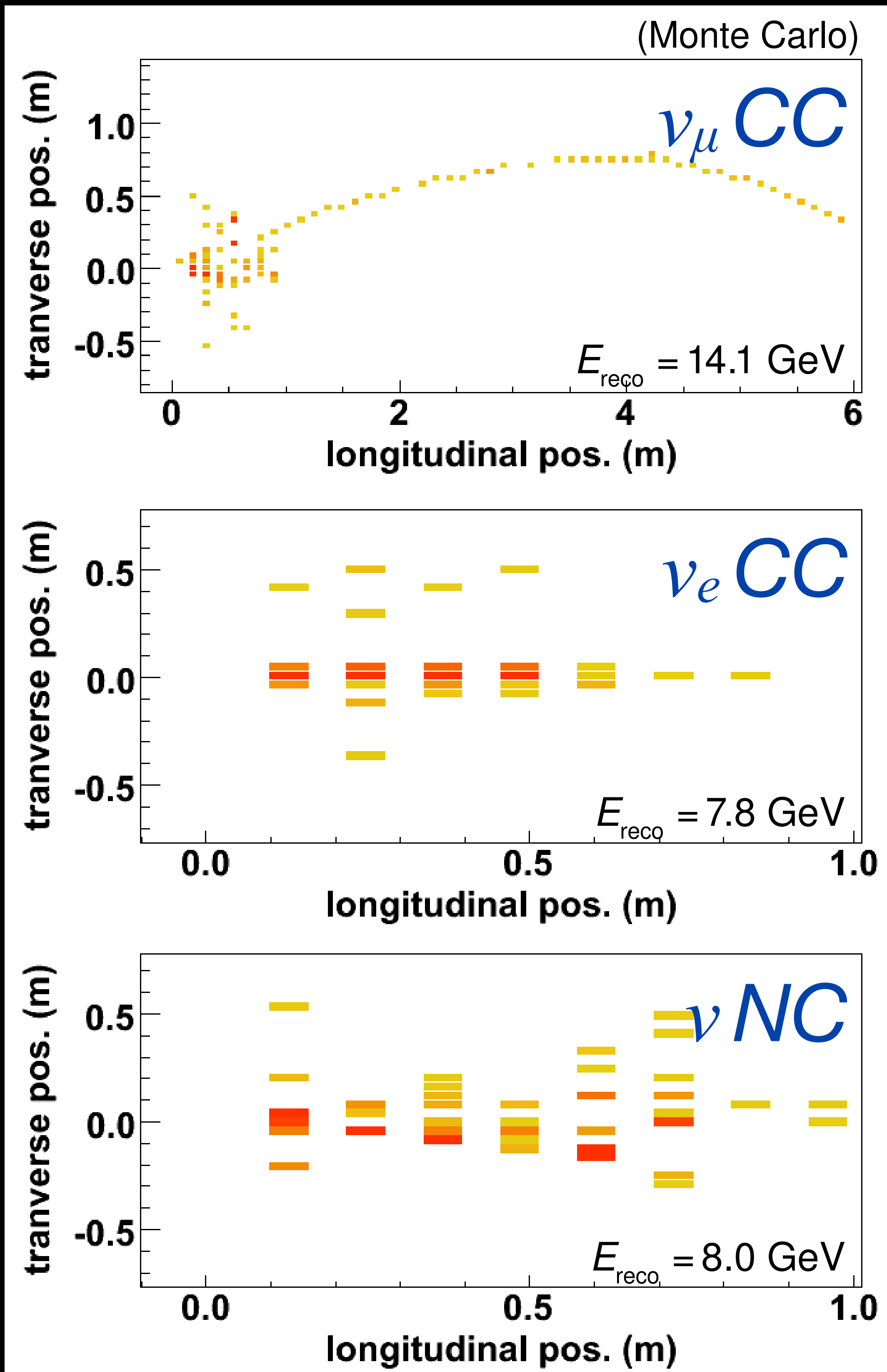
1 kt near detector + 4.5 kt far detector

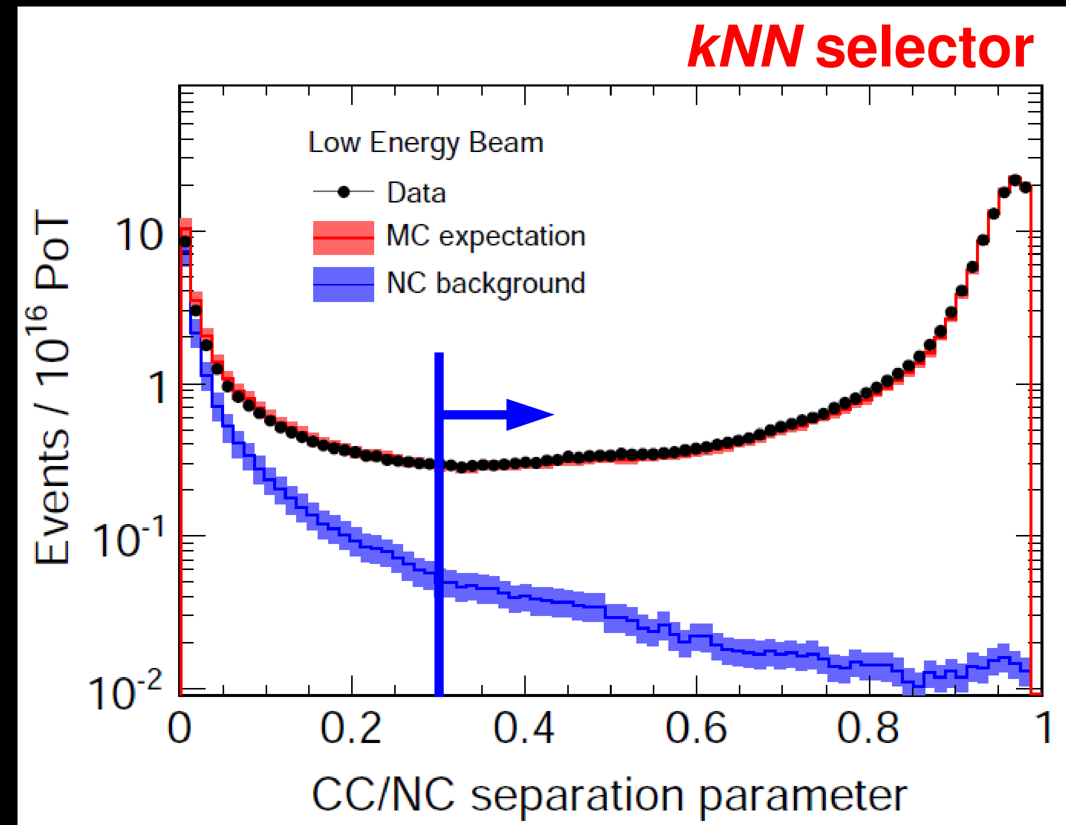
- scintillator (1 cm x 4.1 cm strips) tracker/ calorimeter in alternating U/V planes
- interspersed with magnetized steel plates (1")



~3 GeV ν_μ beam, L=735 km far detector

ν_μ CC/NC separation

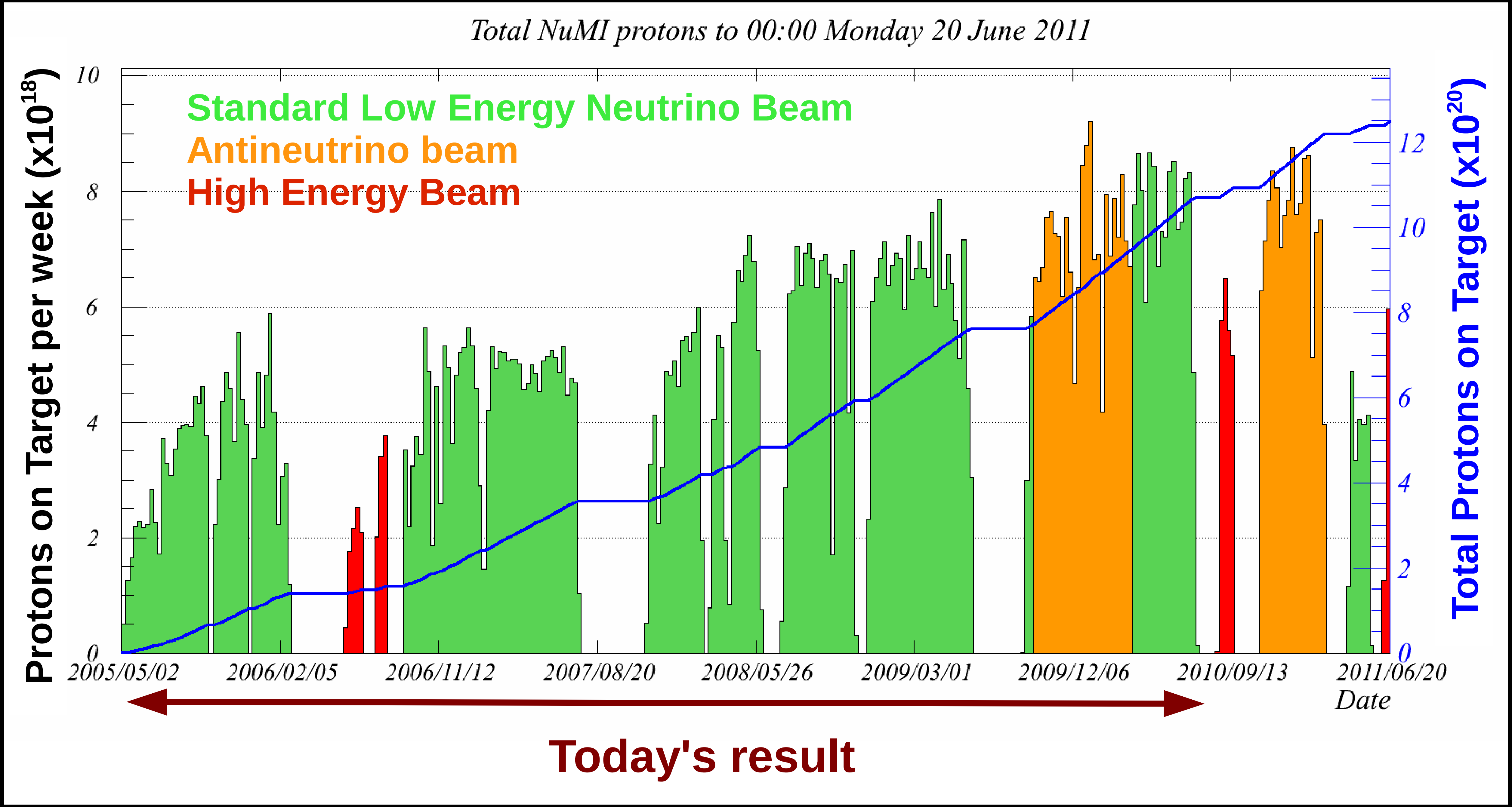




- CC/NC discrimination based on event length, transverse profile, energy deposition
- Improvements to shower energy estimator and selection for ν_μ CC with short muons
- Energy spectrum extrapolated to far detector using near detector data.

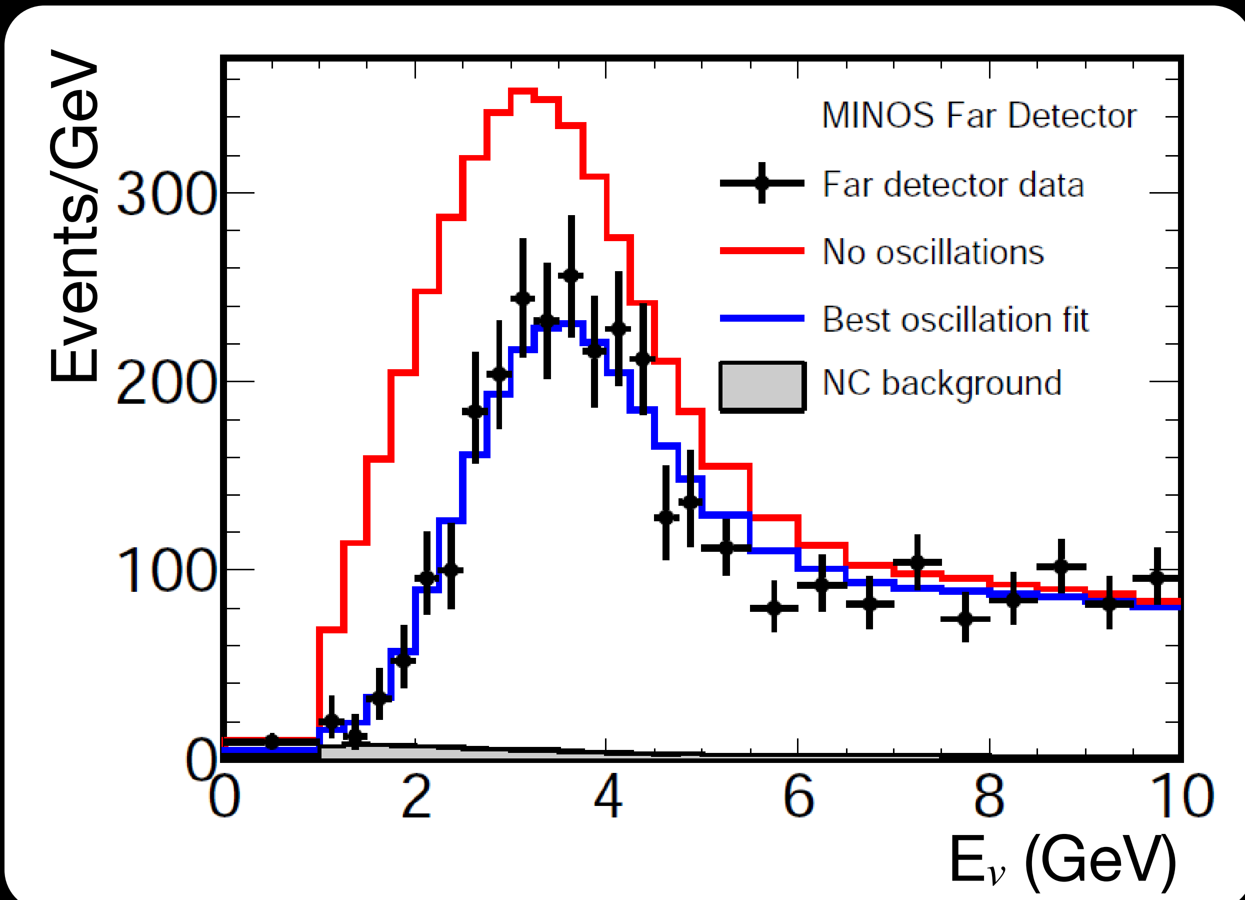
slides based on FNAL Users' Meeting
R. B. Patterson (6/2011)

Beam to NuMI:



Total NuMI protons to 00:00 Monday 20 June 2011
Standard Low Energy Neutrino Beam
Antineutrino beam
High Energy Beam
Protons on Target per week (x10^18)
Total Protons on Target (x10^20)
10
8
6
4
2
0
12
10
8
6
4
2
0
2005/05/02
2006/02/05
2006/11/12
2007/08/20
2008/05/26
2009/03/01
2009/12/06
2010/09/13
2011/06/20
Date
Today's result

ν_μ disappearance



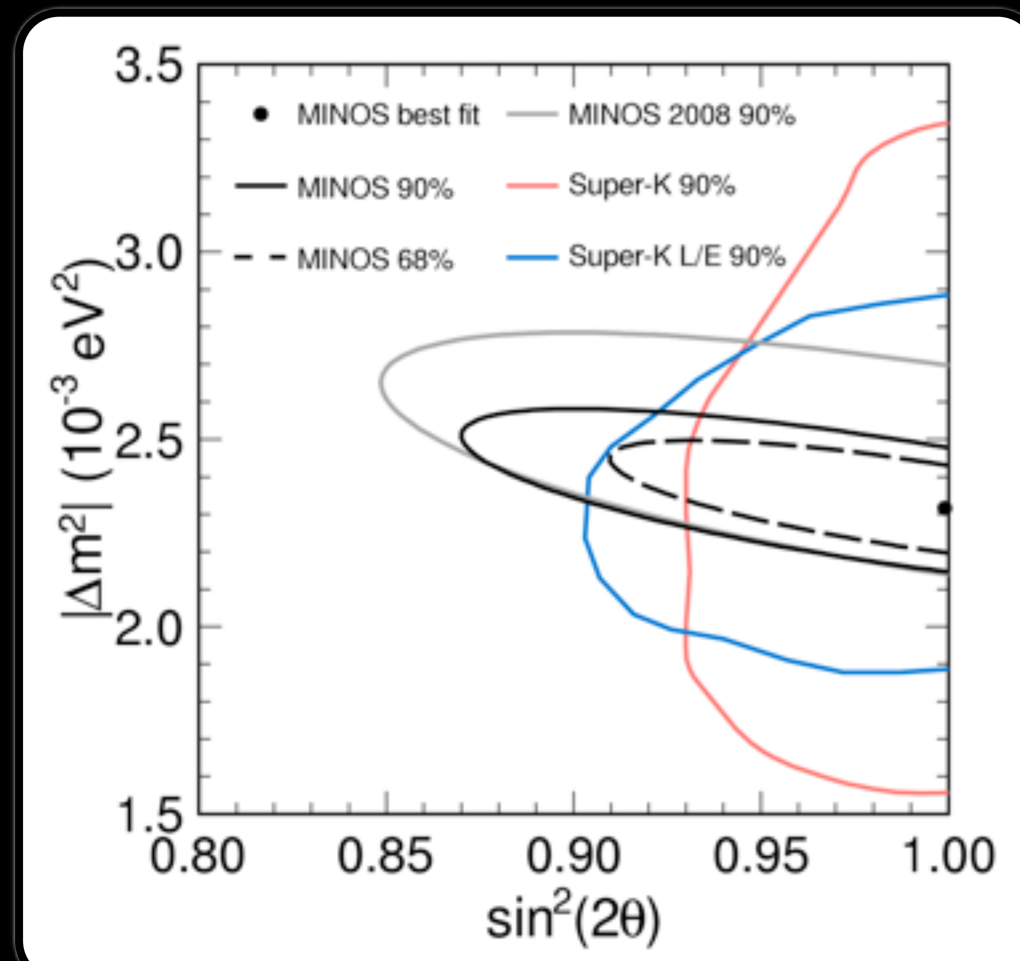
- Observed spectrum shows energy-dependent deficit relative to null oscillation expectation
- alternate mechanisms (decay/ decoherence) strongly ruled out

- Precision measurements of parameters:

$$\Delta m^2_{atm} = 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2/c^4$$

$$\sin^2 2\theta_{atm} > 0.90 \ (90\% \ \mathrm{C.L.})$$

PRL 106, 181801 (2011)



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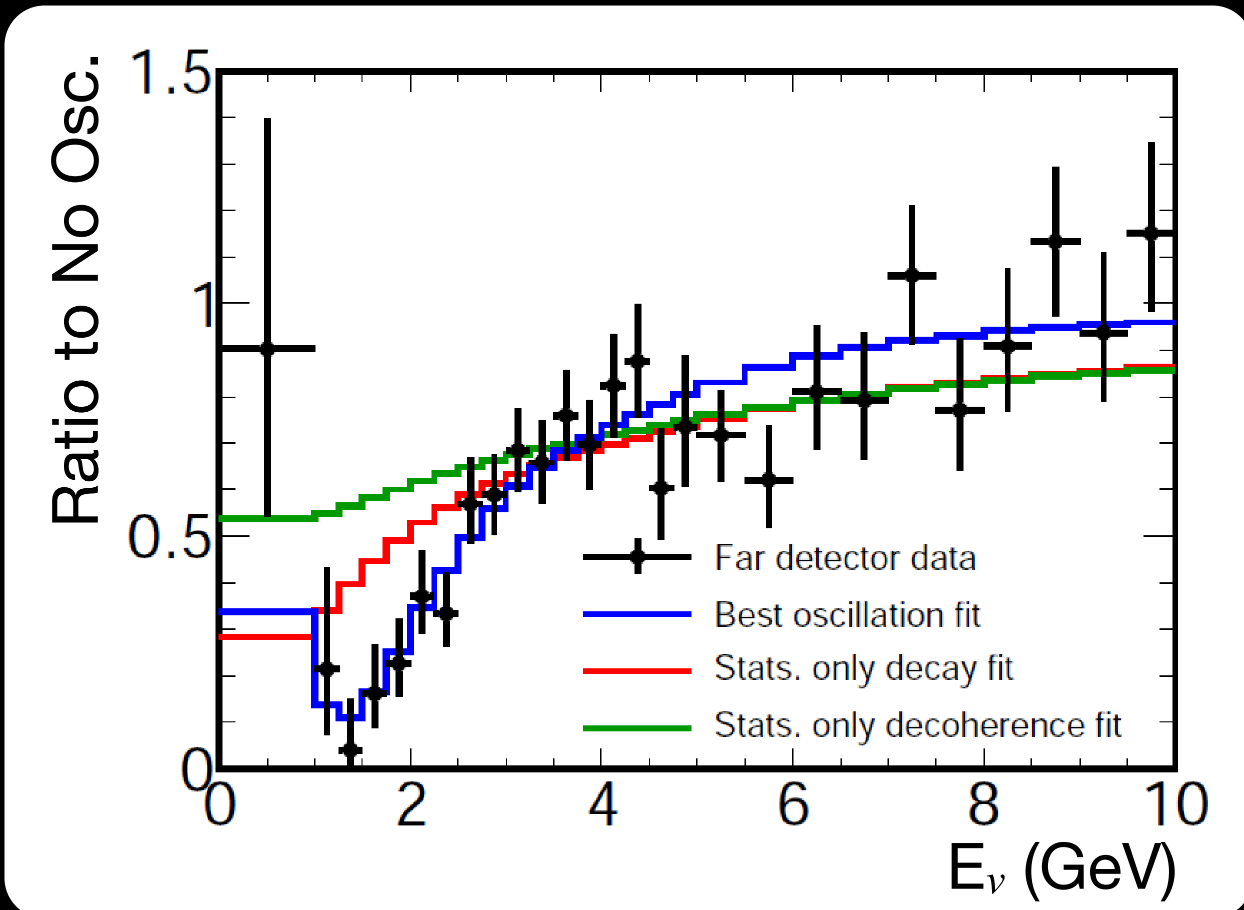

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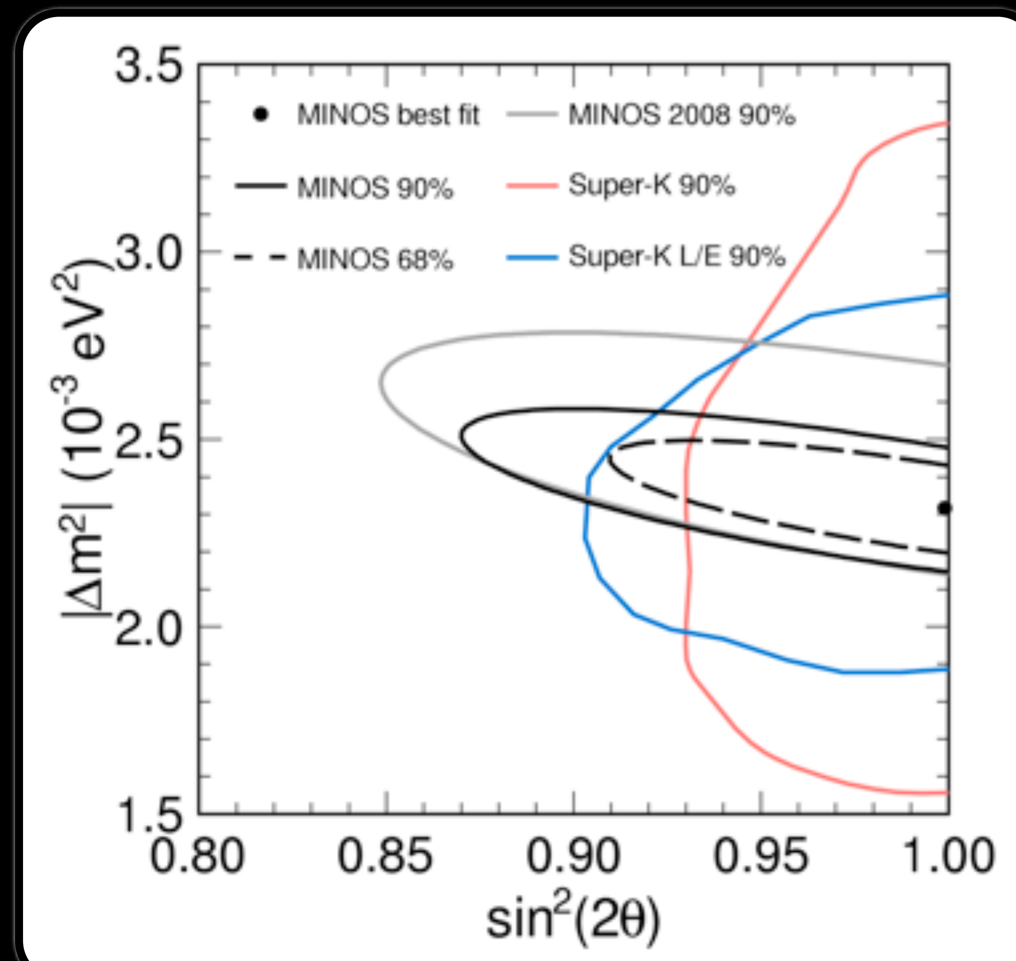
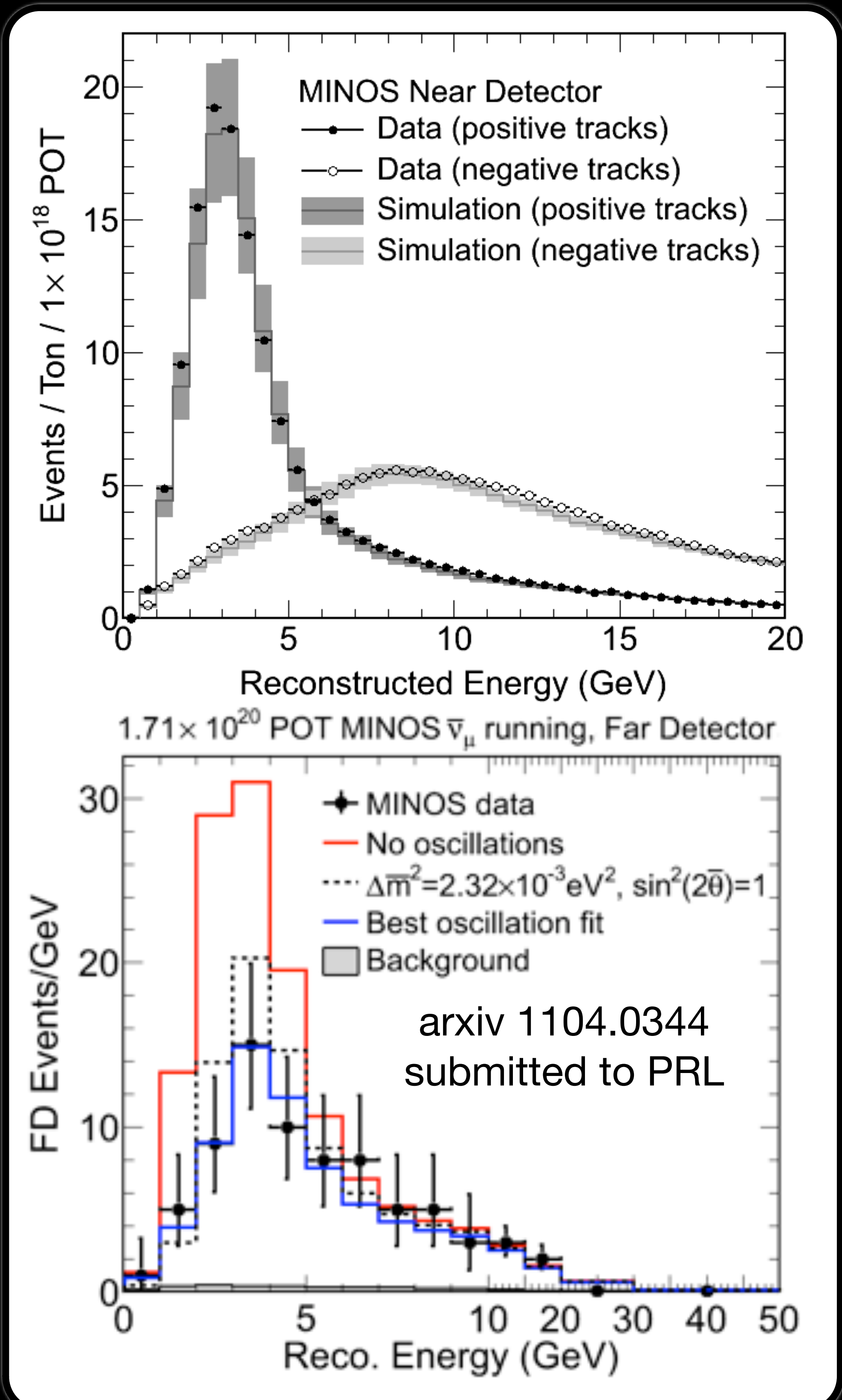


PRL 106, 181801 (2011)

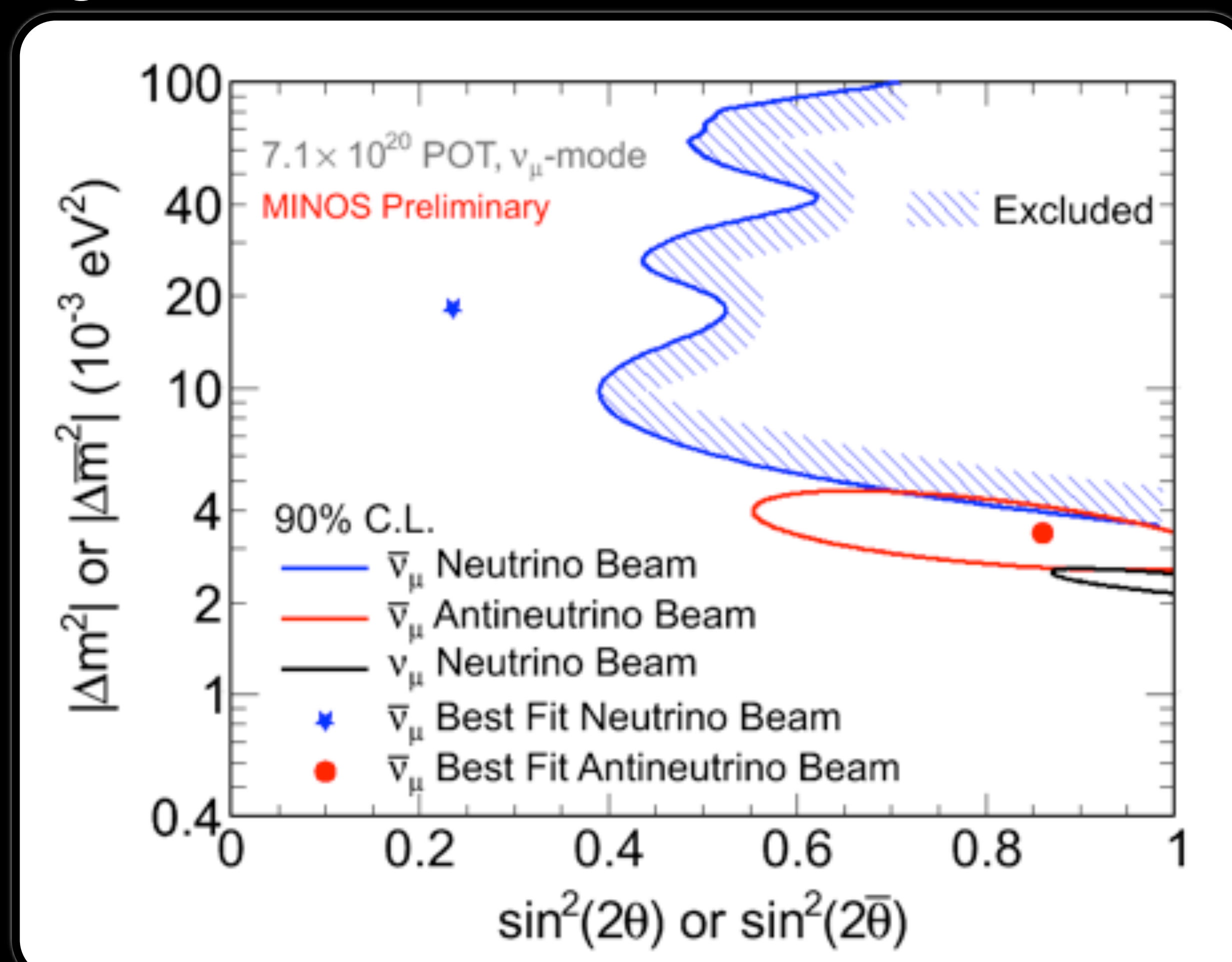
$\bar{\nu}_\mu$ disappearance



- Produce anti-neutrino-enhanced beam by switching the polarity of the horn

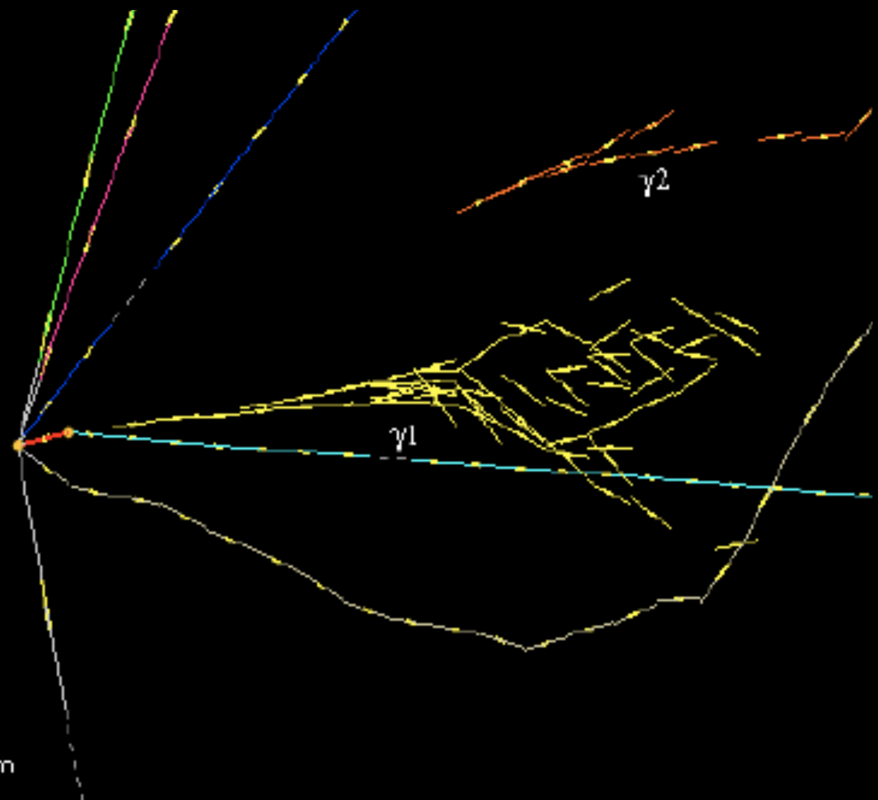
$$p + A \rightarrow \pi^- + X \\ \hookrightarrow \mu^- + \bar{\nu}_\mu$$

- Suppress wrong-sign (neutrino) interactions by sign selection in the detector.



ν_τ appearance

ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$): interpretation is $x = \tau$



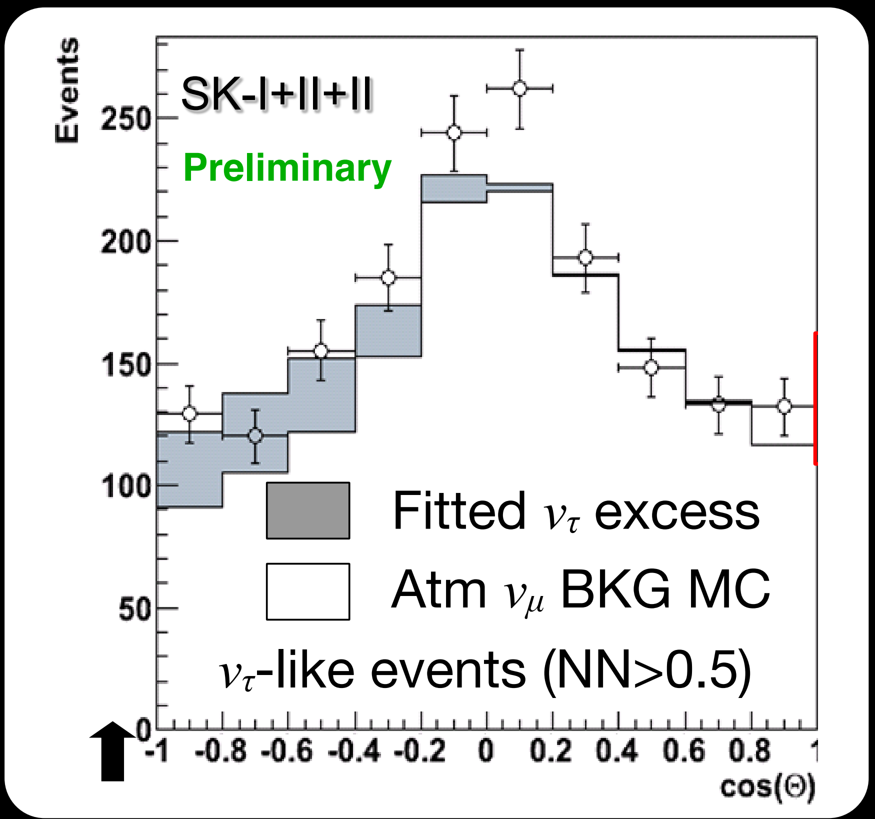
OPERA:

- LBL experiment using CERN SPS to produce beam above ν_τ threshold
- Emulsion to detect τ decay topologically

$$\nu_\tau + A \rightarrow \tau^- + X$$
$$\hookrightarrow \pi^- + \pi^0$$
$$\hookrightarrow \gamma + \gamma$$

Super-Kamiokande:

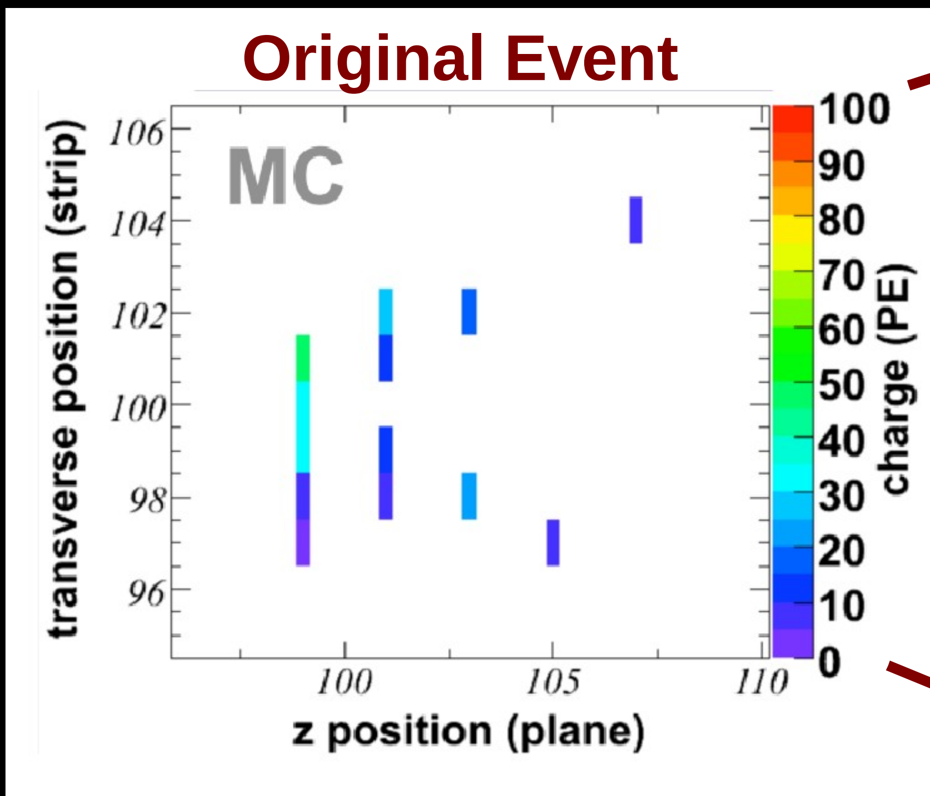
- Detect ν_τ production with NN using
  - particle identification, visible energy
  - event topology variables, decay electrons
- Excess seen where ν_μ observed to disappear



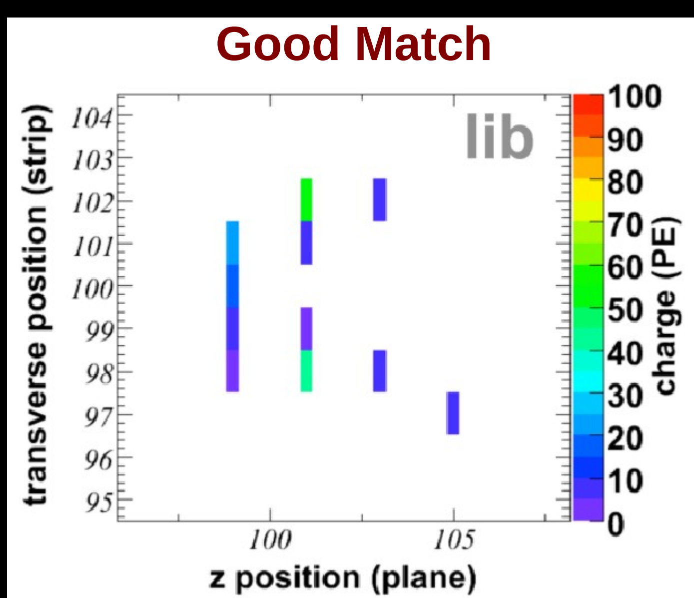
$$\theta_{13}$$

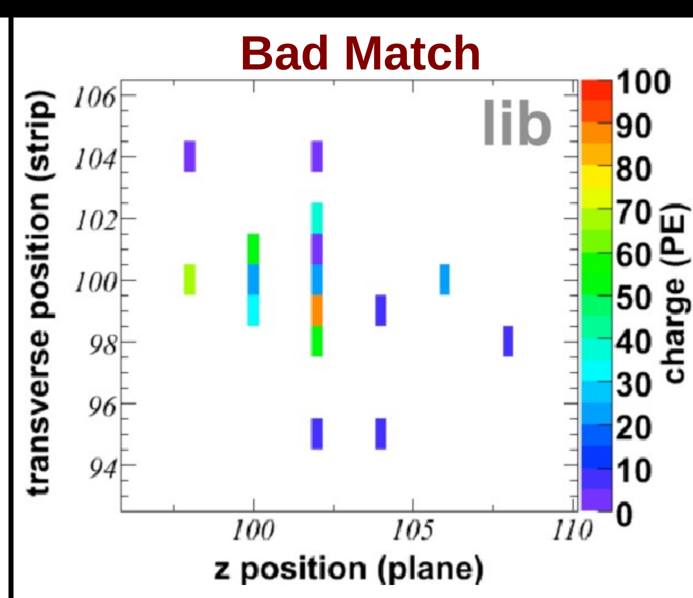
MINOS $\nu_\mu \to \nu_e$

slides based on FNAL seminar
L. Whitehead (6/2011)



- ν_e /NC discrimination
- "Library Event Matching"
  - Compare strip location/charge of event to a library of O(10^7) signal/background events
  - Select N events based on likelihood that events came from the same underlying energy deposition.





Three discriminants:

- Fraction of signal/background matches
- Charge overlap with matches
- EM fraction in matches

Combined into ANN with energy

MINOS $\nu_\mu \rightarrow \nu_e$

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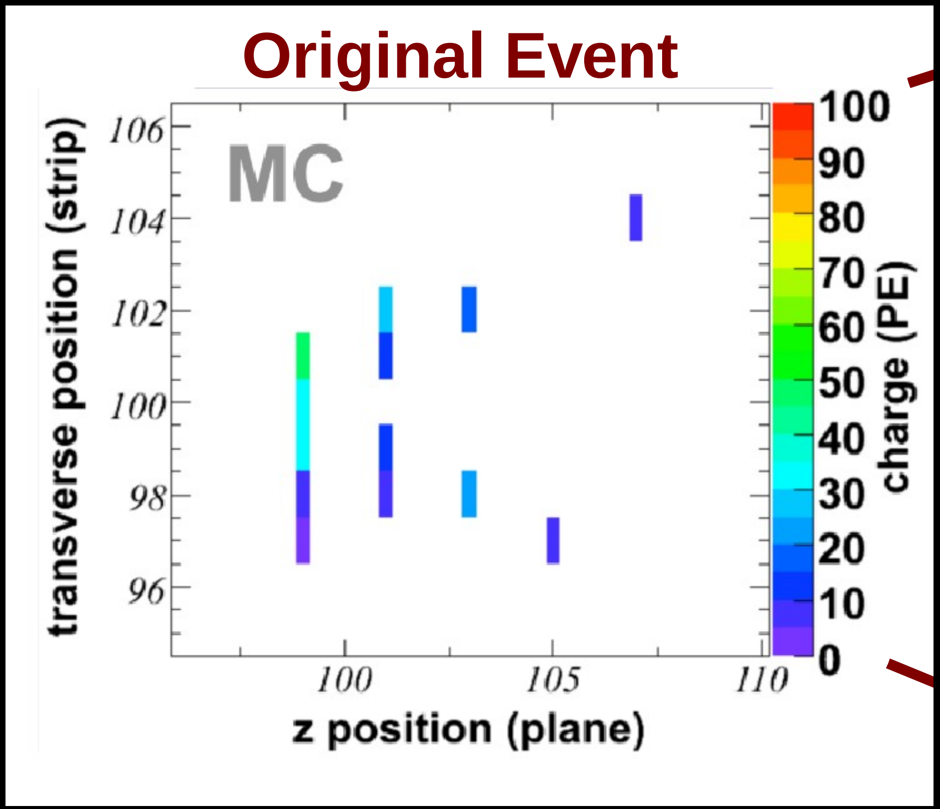

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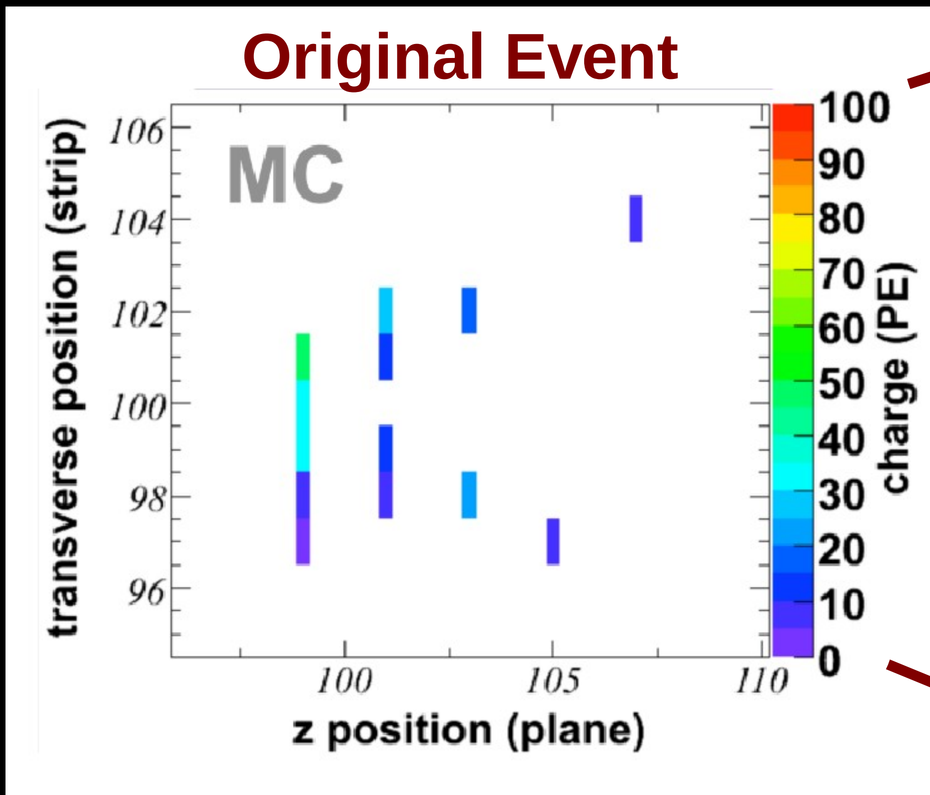

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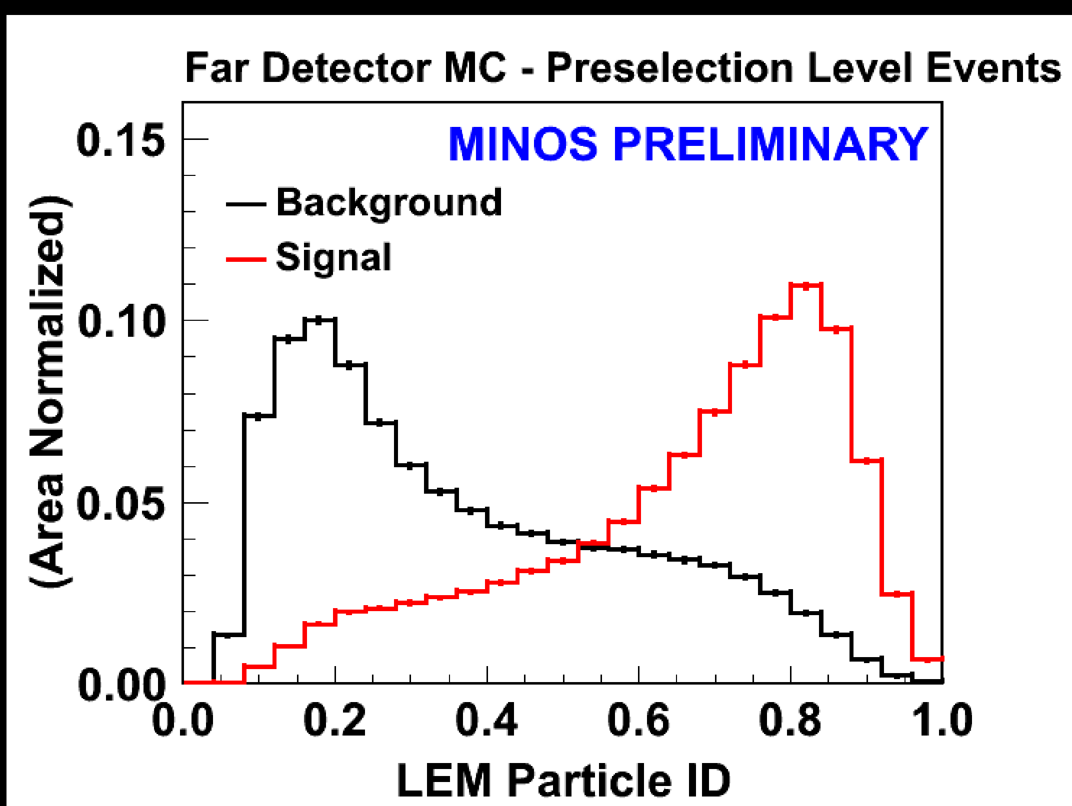

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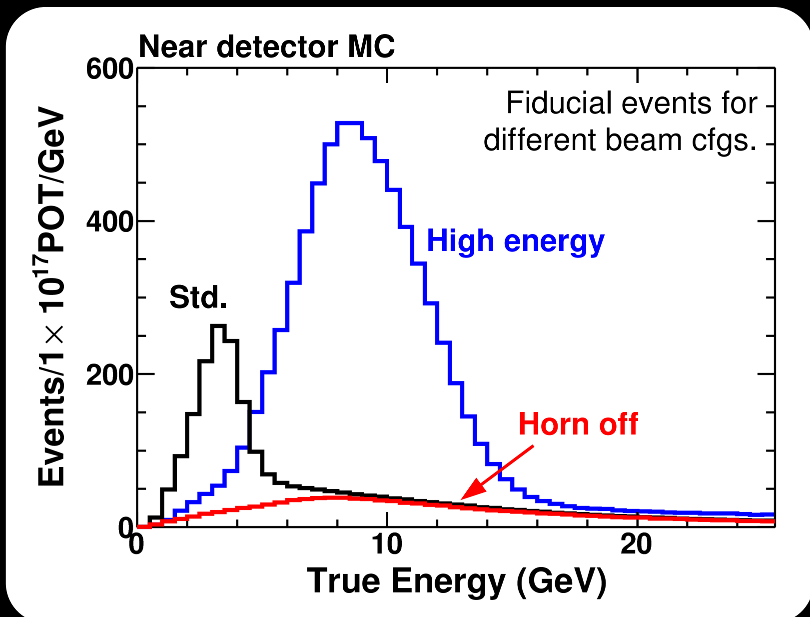
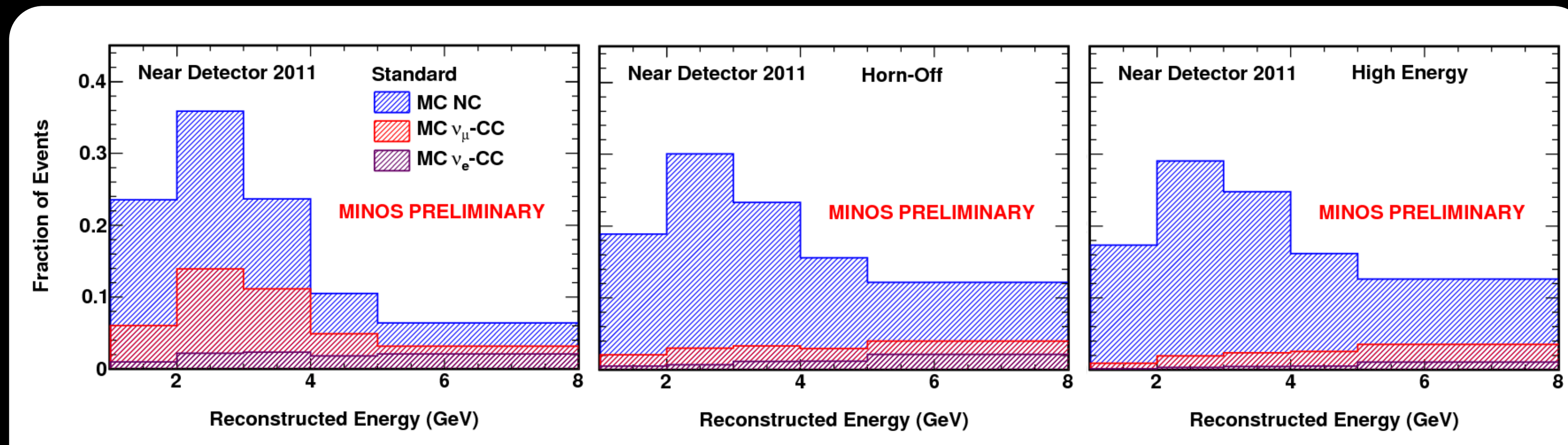
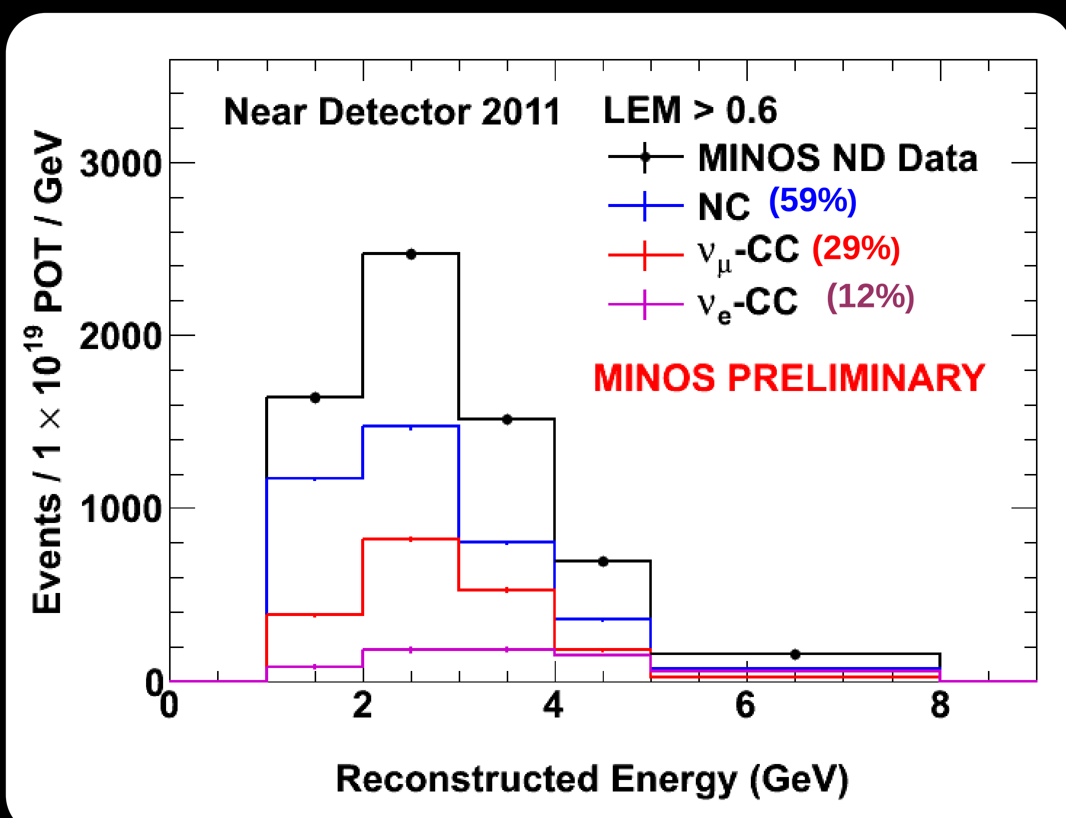
Background:



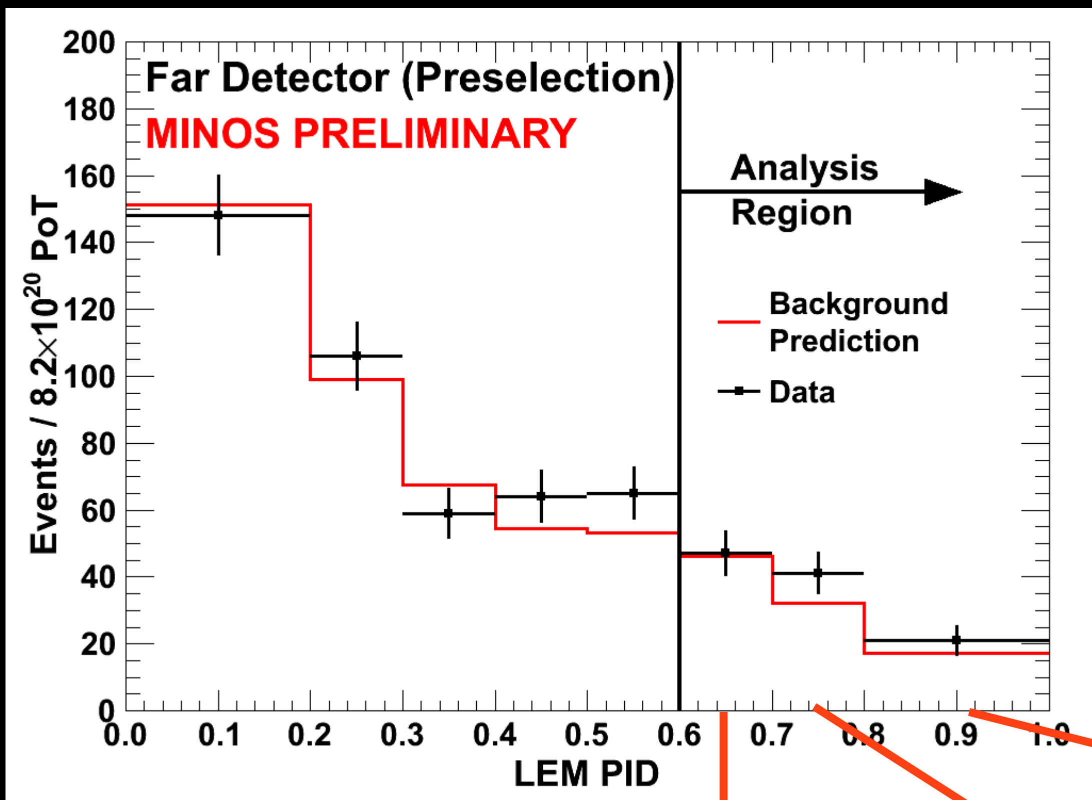


Standard | Horn Off | High energy

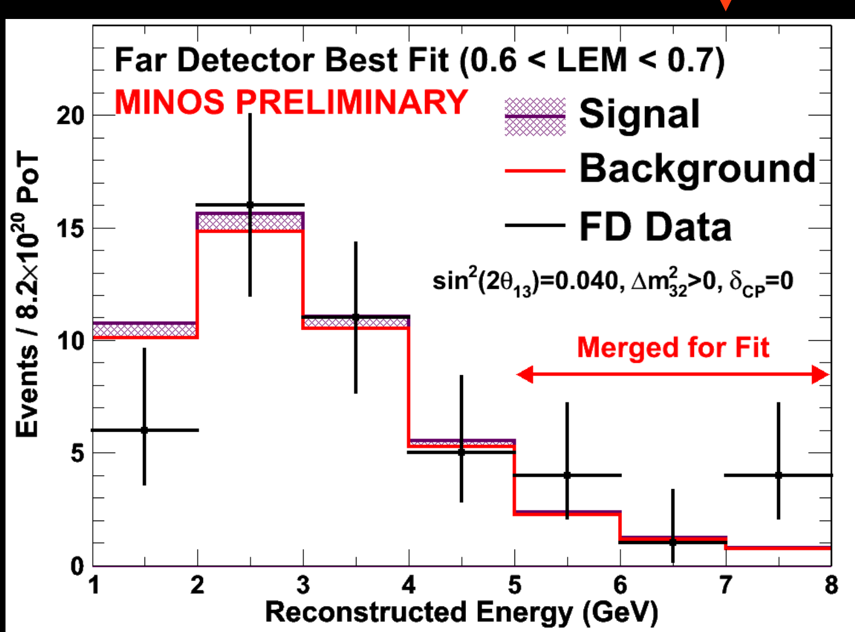


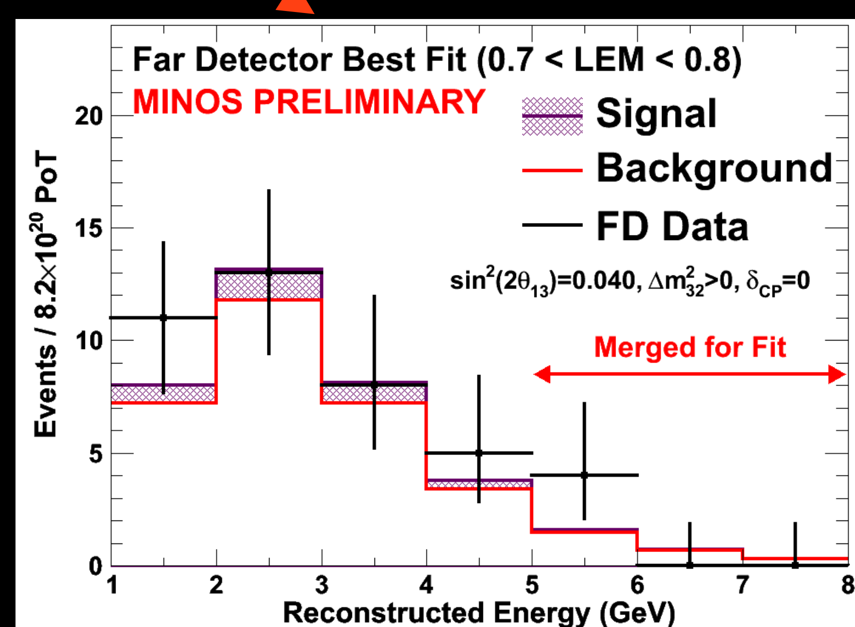
- Vary composition of ND events by changing beam configuration (E_ν spectrum)
- Fit for contribution of each background component in the standard beam
- MC only estimate would have much larger uncertainty (5.7% vs. ~20%)

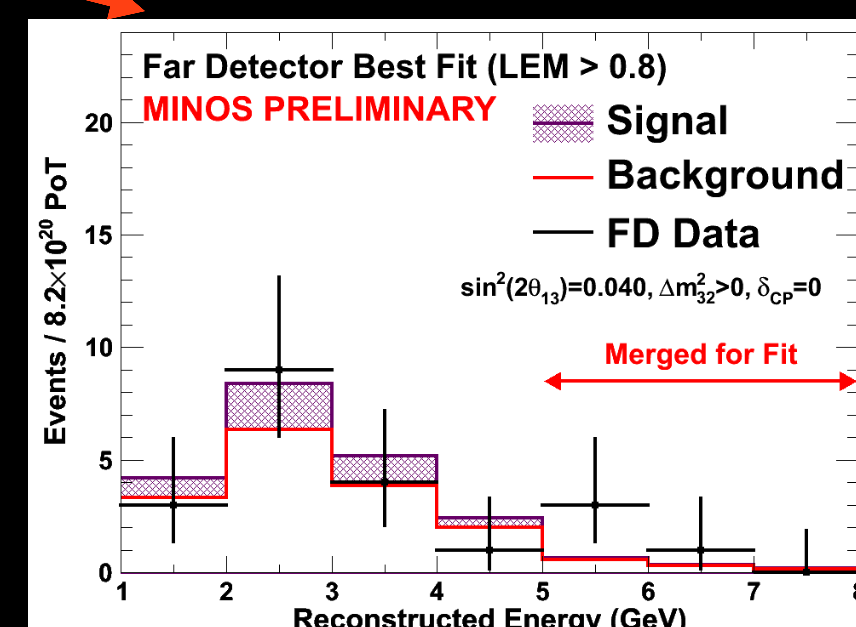
Signal Region



- Events with LEM>0.6:
  Bkg. Expectation: 49.5±7.0±2.8 events
  Observe: 62 events
- Signal Extraction:
  - Fit LEM x Energy simultaneously
  - Best fit gives $\sin^2 2\theta_{13} = 0.040$







T2K

L=295 km

E~600 MeV

$$1.27 \times \Delta m^2_{23} \frac{L}{E} \sim \frac{\pi}{2}$$

Produce intense beam of ~600 MeV ν_μ

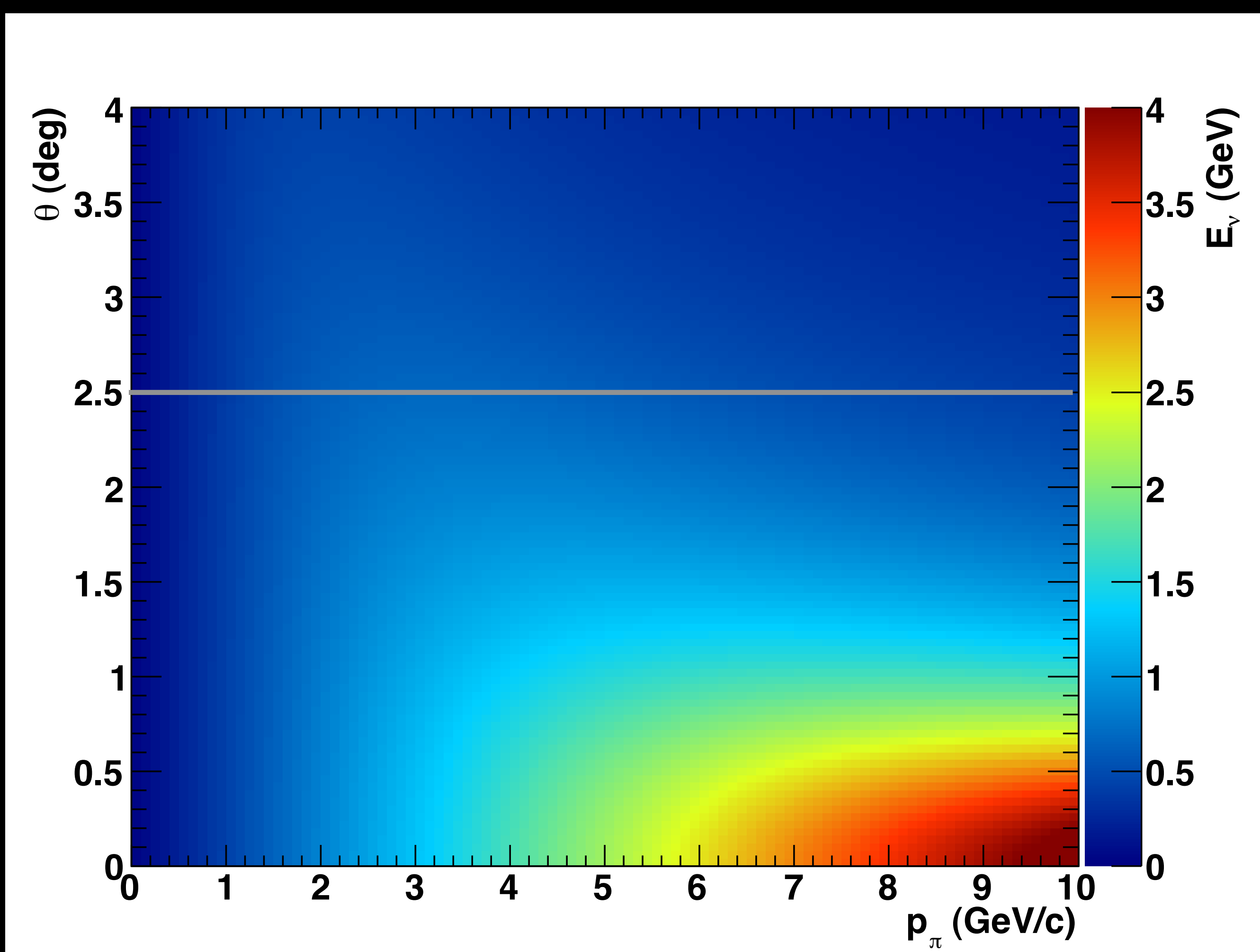
- 295 km away from source, look for
  - ν_e appearance due to $\theta_{13} \neq 0$, $\nu_\mu \rightarrow \nu_e$
  - ν_μ disappearance due to $\nu_\mu \rightarrow \nu_\tau$ (θ_{23})

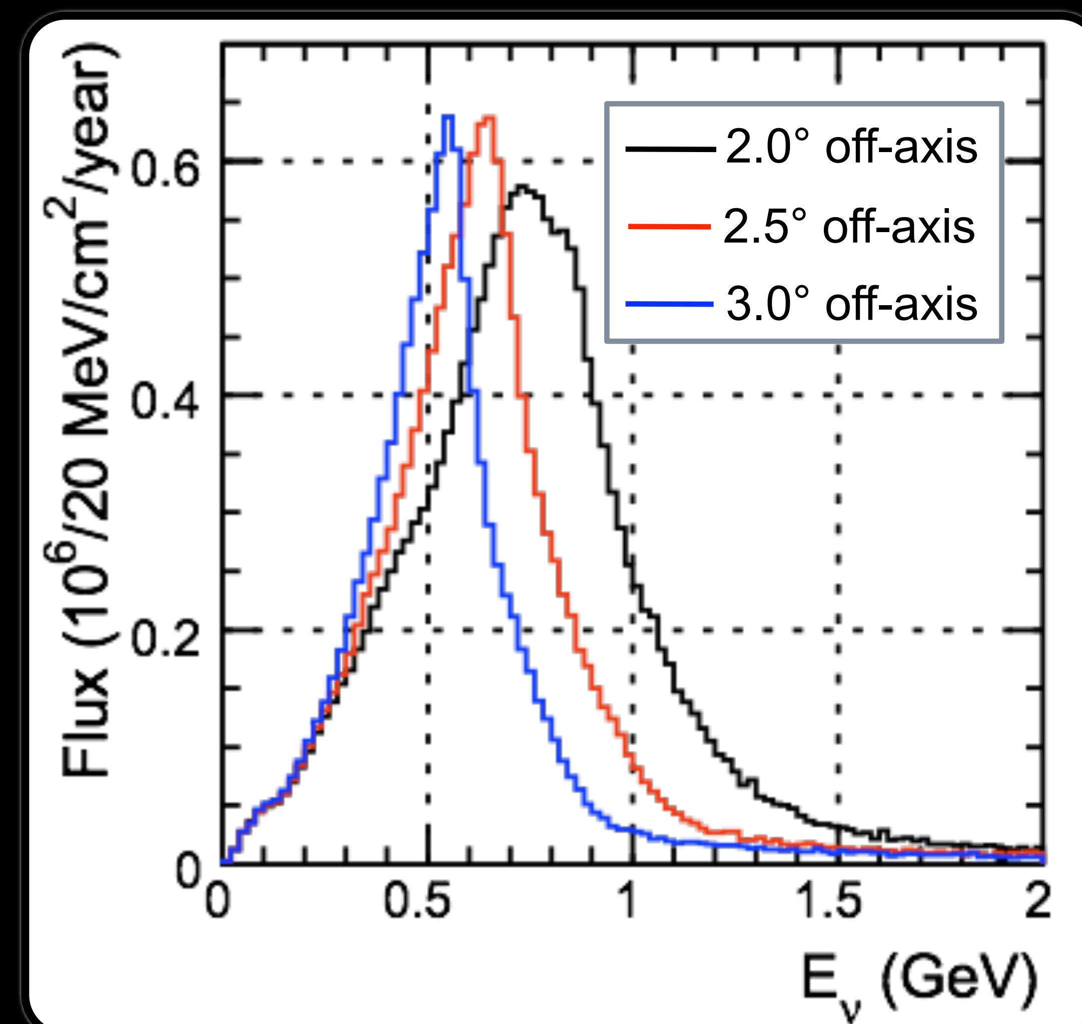
at Super Kamiokande (SK) “far” Detector

Off-Axis Beam Concept

- Neutrinos produced with wide energy spectrum
- Can we “focus” neutrinos to the right energy (600 MeV@295 km)?
- No, but we can exploit kinematics.

$$p(30\text{GeV}) + \text{C} \to \pi^{+} + X$$
$$\hookrightarrow \nu_{\mu} + \mu^{+}$$





- Tune angle to maximize flux at oscillation maximum
- Reduce high energy neutrinos

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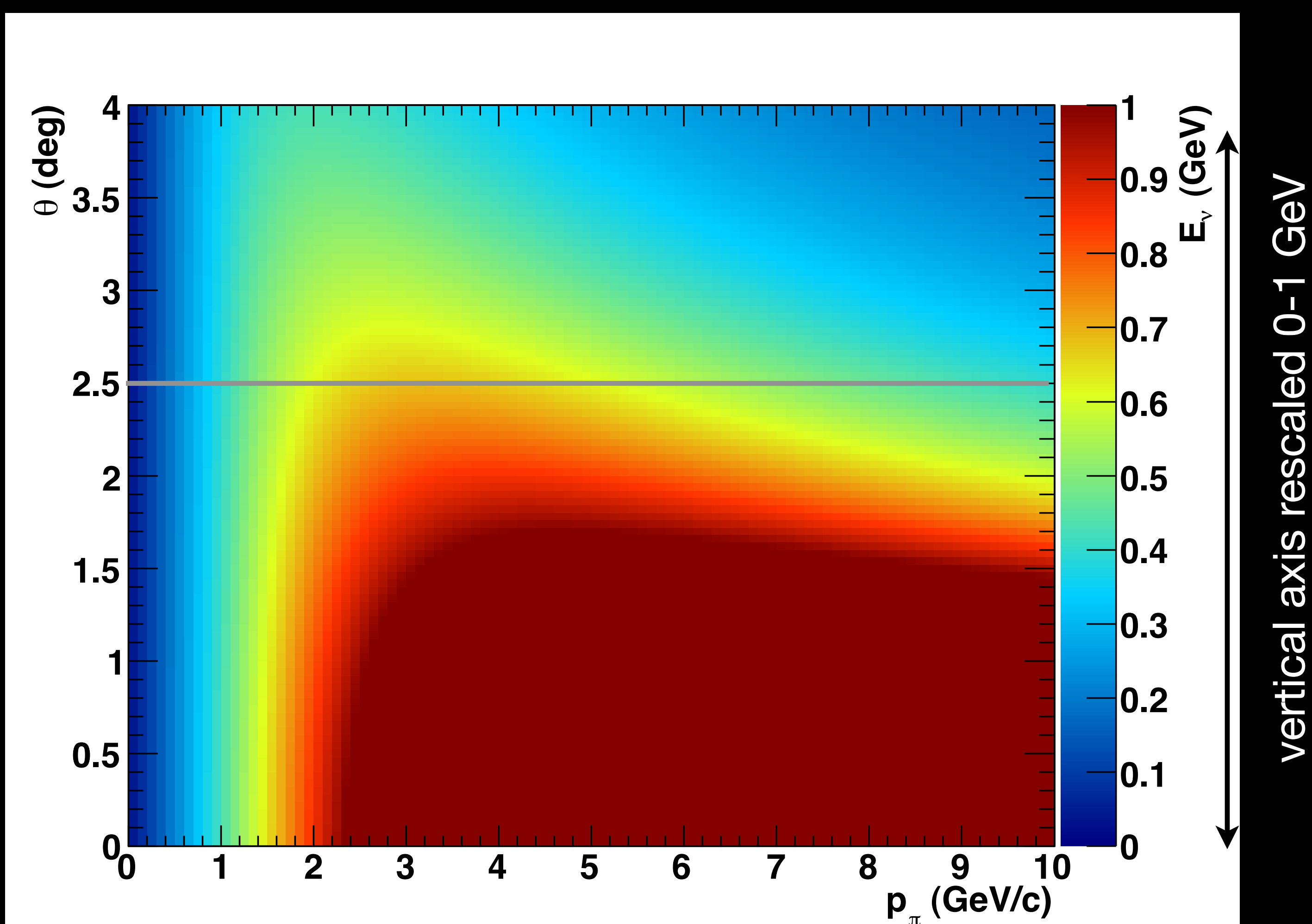

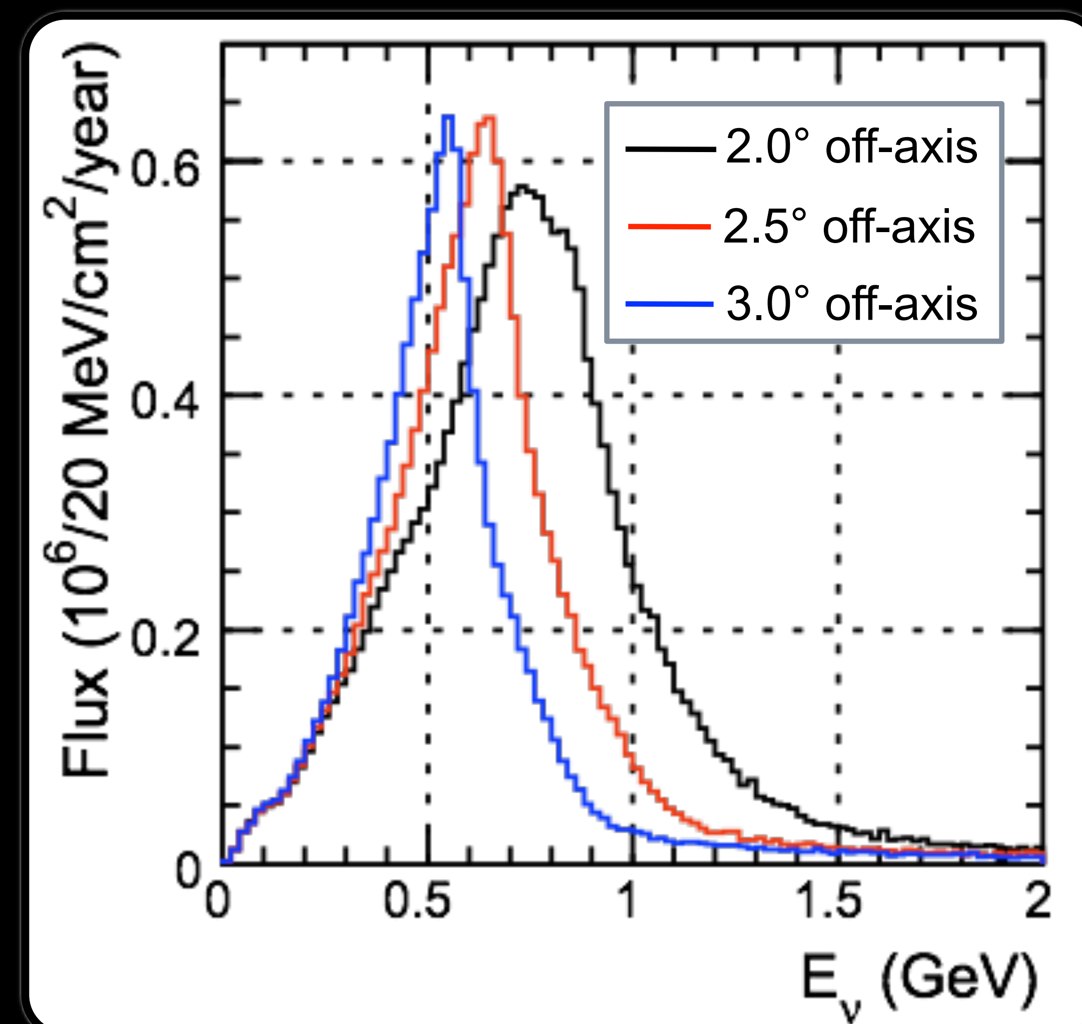

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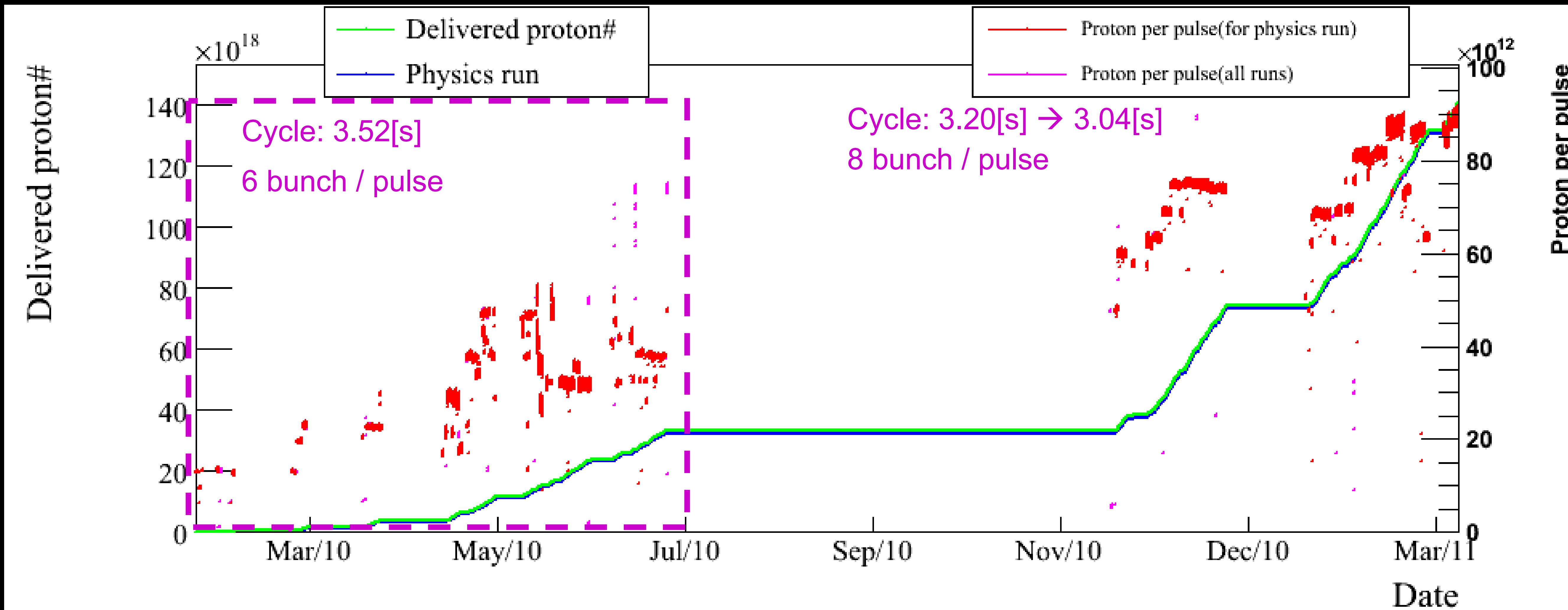
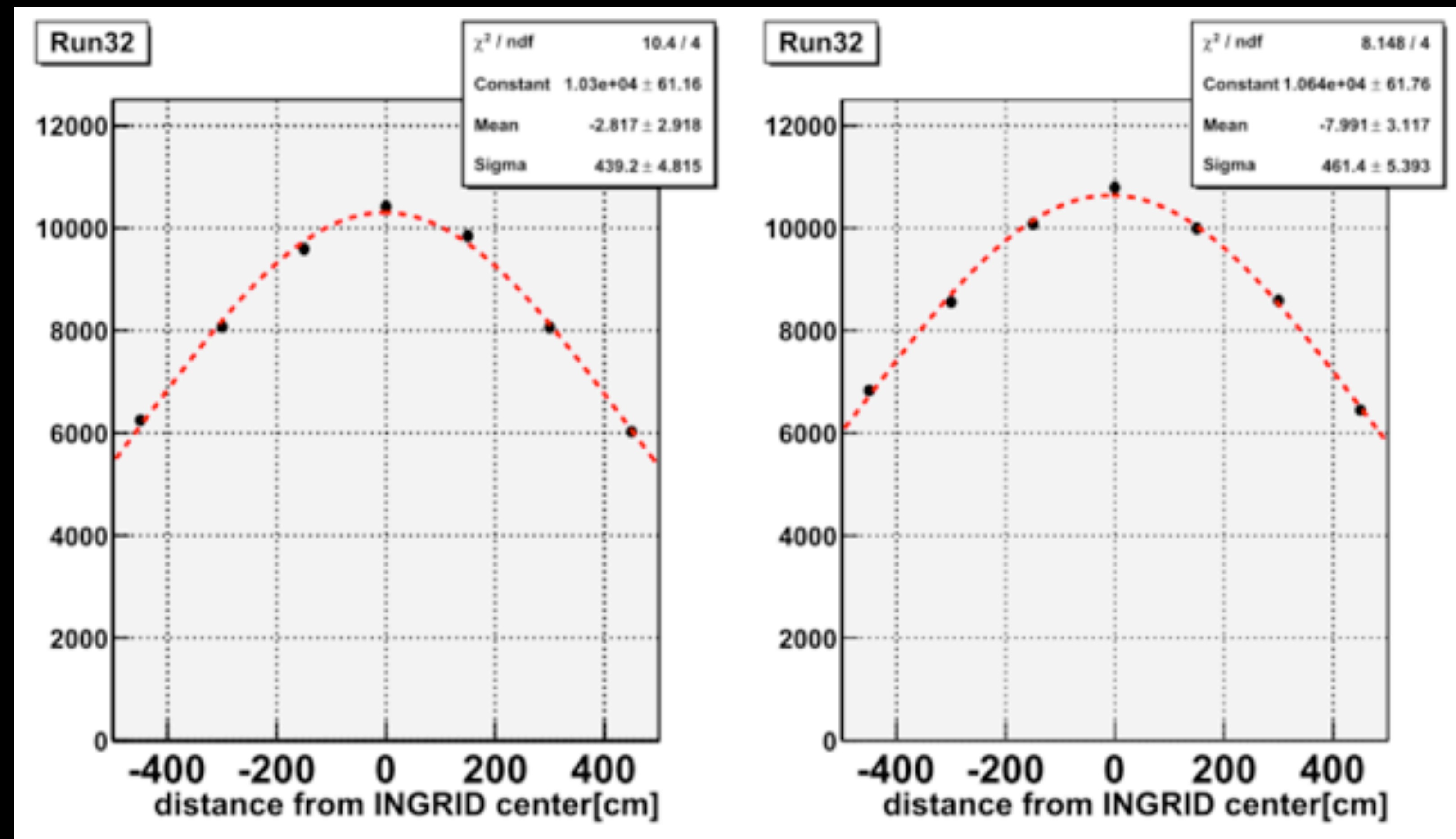
Current Status



- Design: 750 kW, (145 kW achieved thus far)
- Accumulated 1.43x10^{20} POT till March 2011
  - accelerator operations expected resume at end of the year

On-axis: (INGRID)

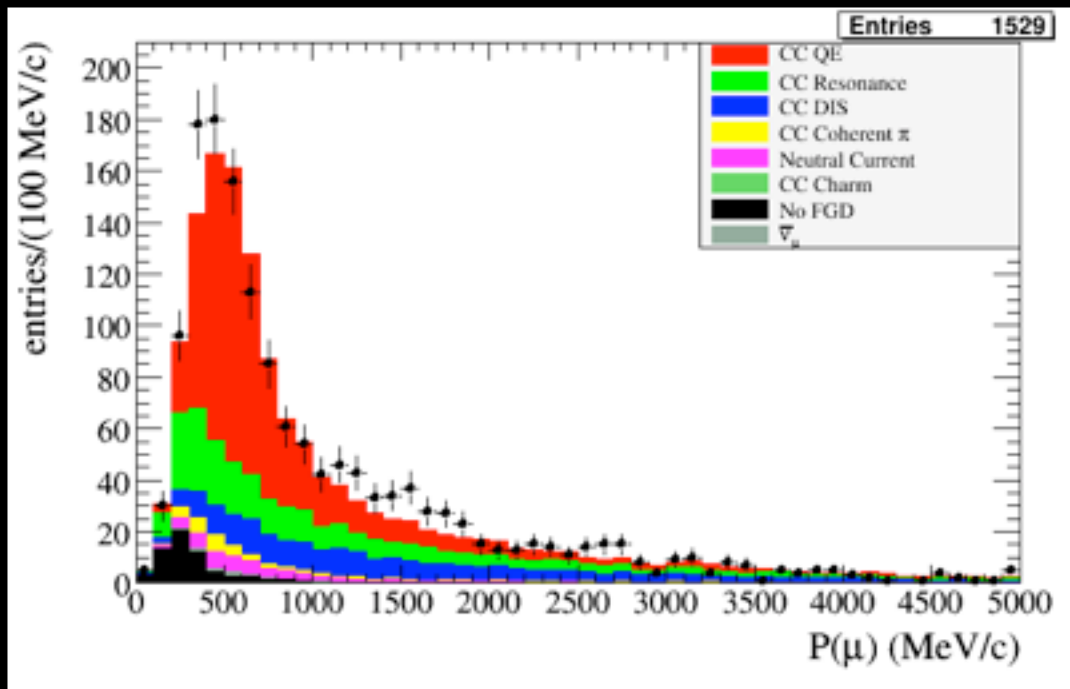


“GRID” of neutrino detectors:

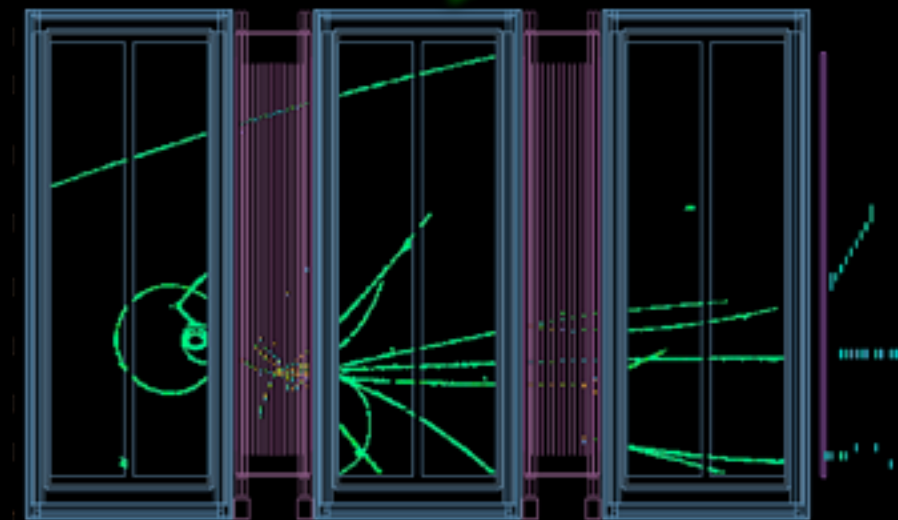
- Fe/Scintillator trackers
- event rate allows ~daily monitor of profile

- Measure center of beam with profile of interaction rate module-to-module
- Beam axis is within 1 mrad of nominal

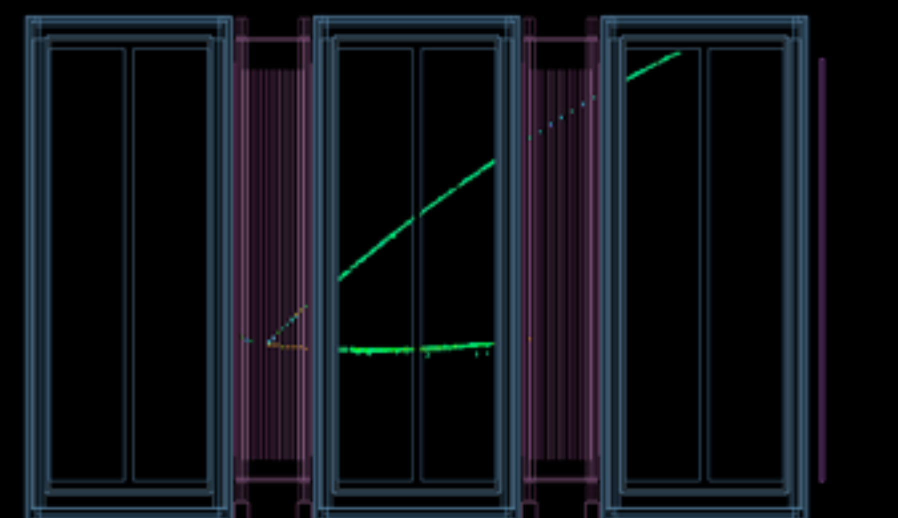
ν_μ CC interactions

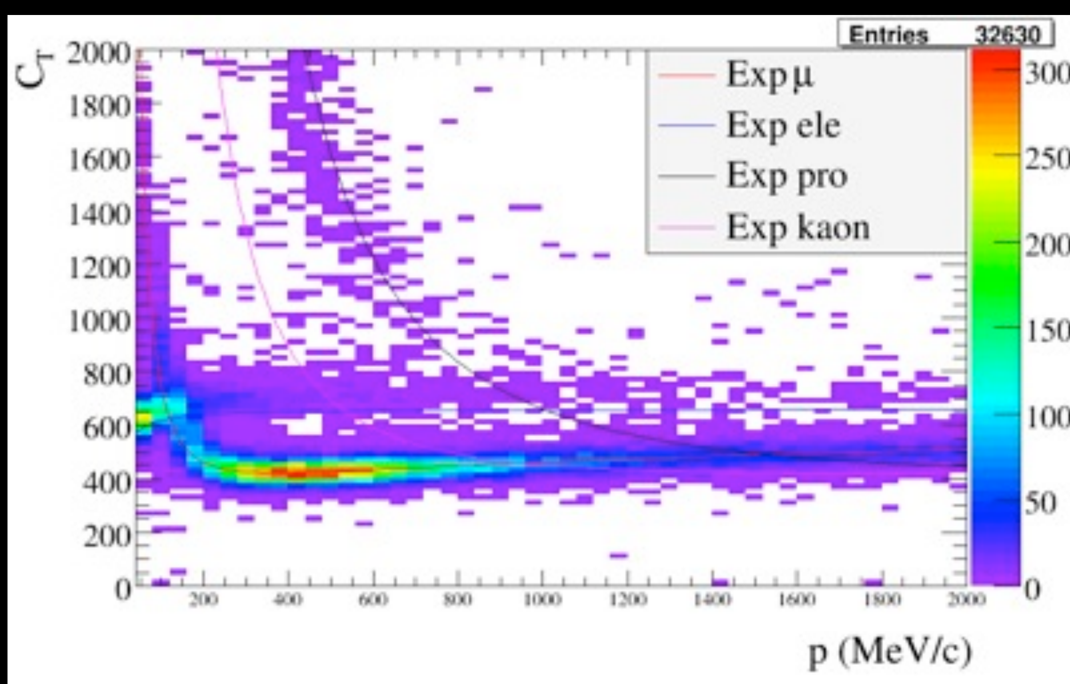


DIS candidate (rejected by upstream veto)



ν_μ CC candidate



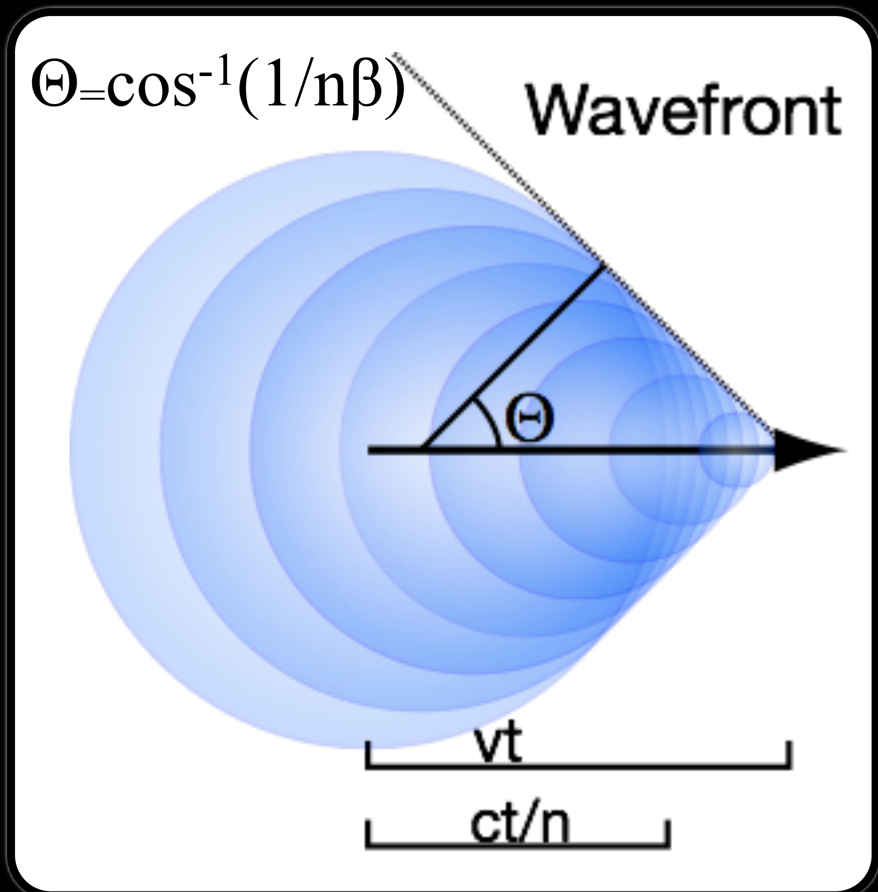


- “inclusive” ν_μ CC selection
  - negative muon in TPC
  - match to FGD to determine vertex

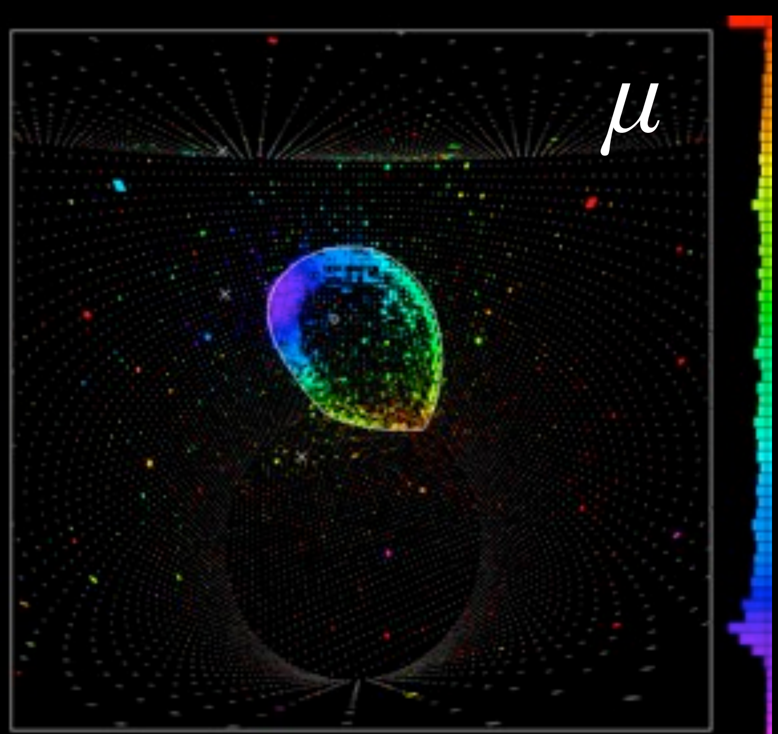
Observed rate relative to expectation is

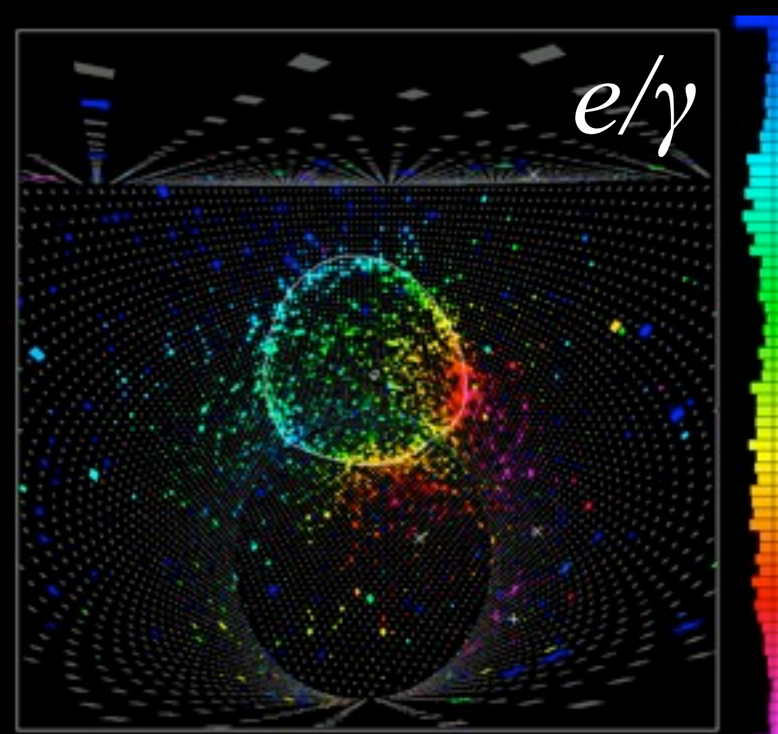
$$R = 1.036 \pm 0.028(\text{stat})^{+0.044}_{-0.037}(\text{det. sys.}) \pm 0.039(\text{phys. model})$$

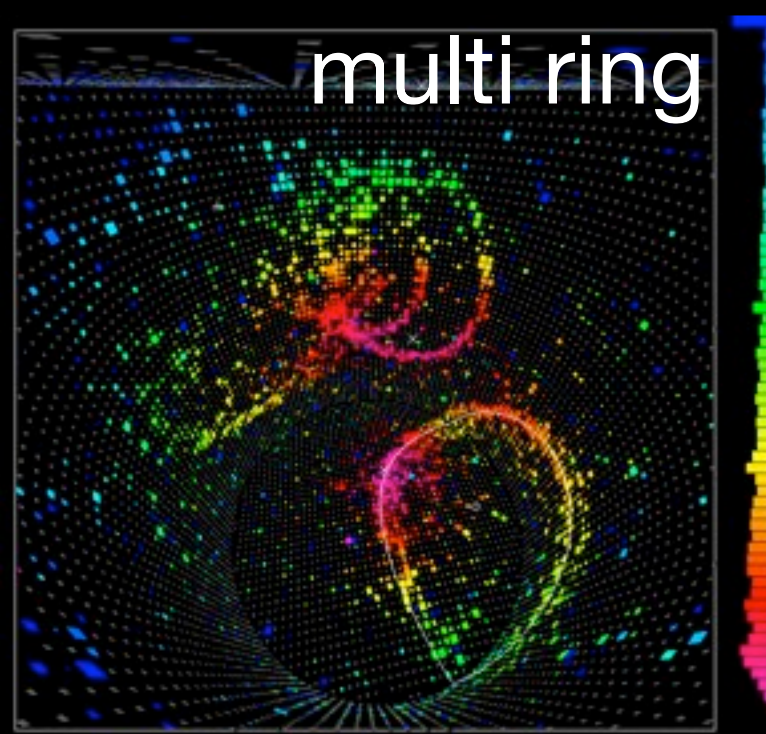
Super Kamiokande



- EM radiation by charged particles with v > c_n
- ~11K photomultiplier tubes
  - 22.5 kiloton fiducial volume
  - sensitive to single photons (40% coverage)
- Particle can be identified by ring profile
  - "muon" vs. e/γ (EM shower)
  - e/π^0 separation by ring search







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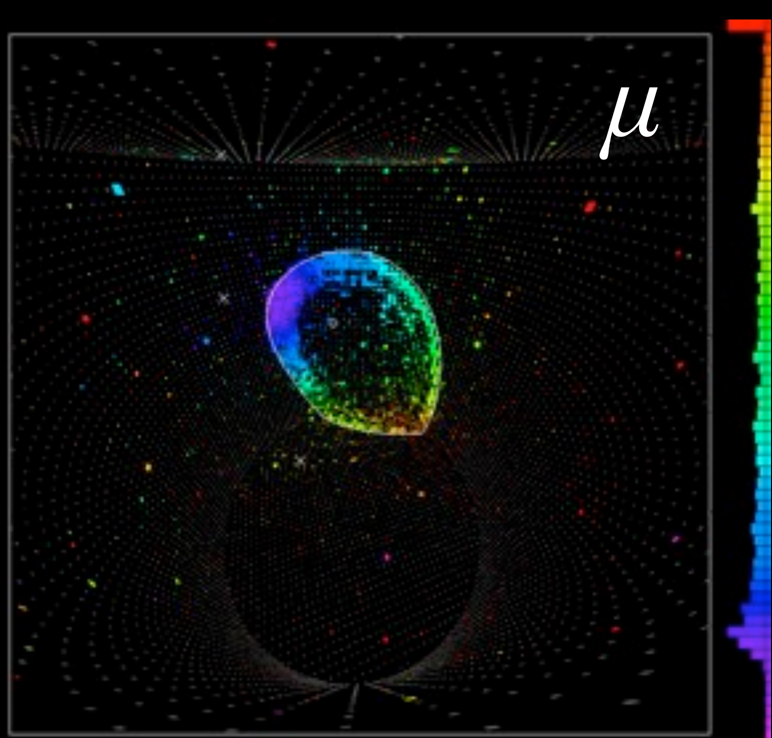

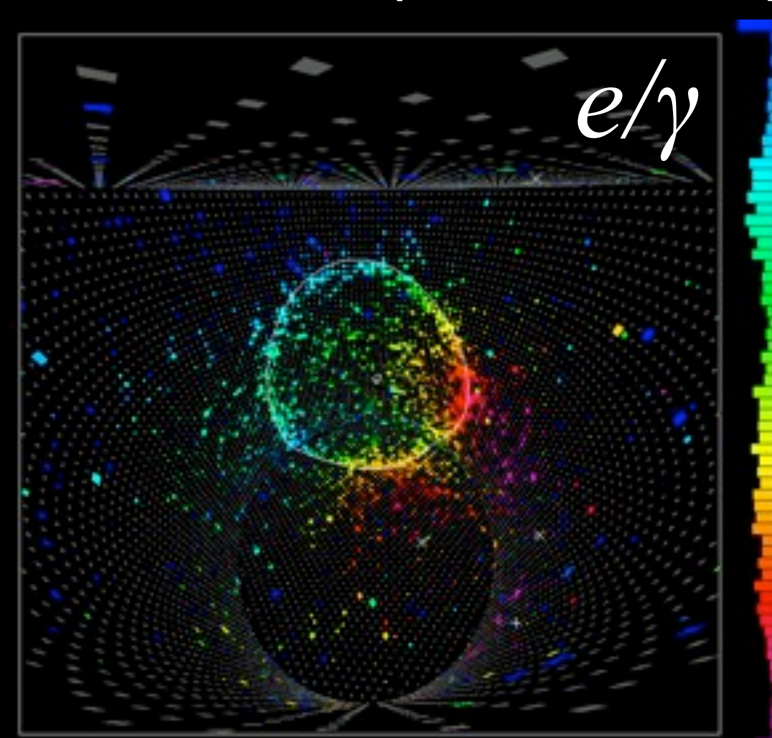

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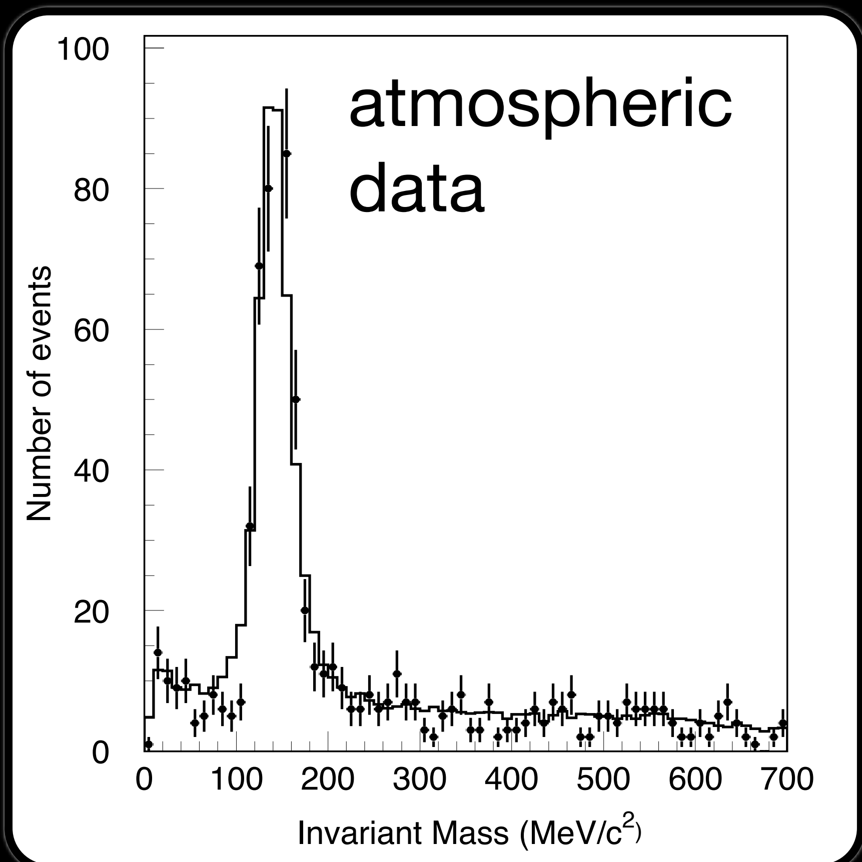

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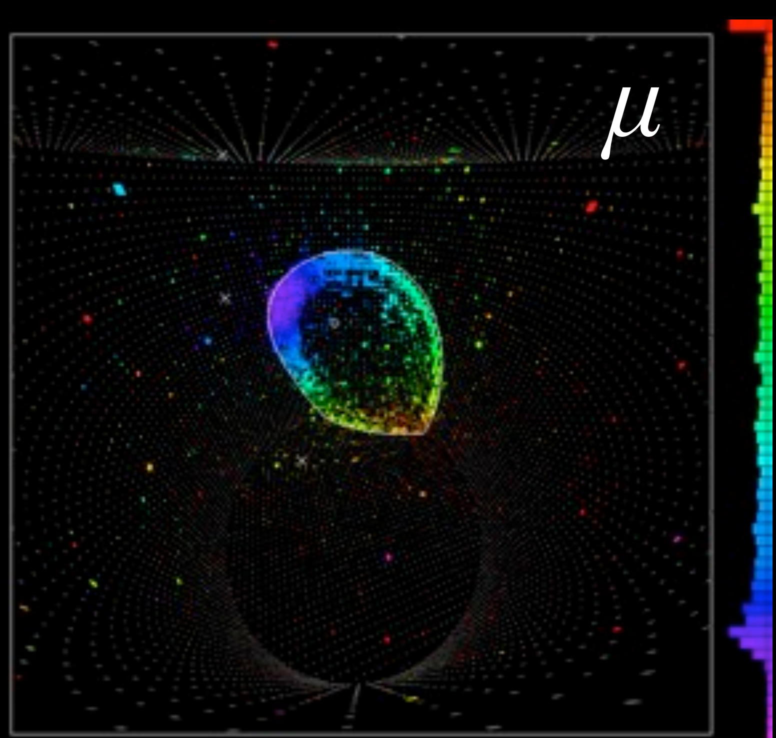
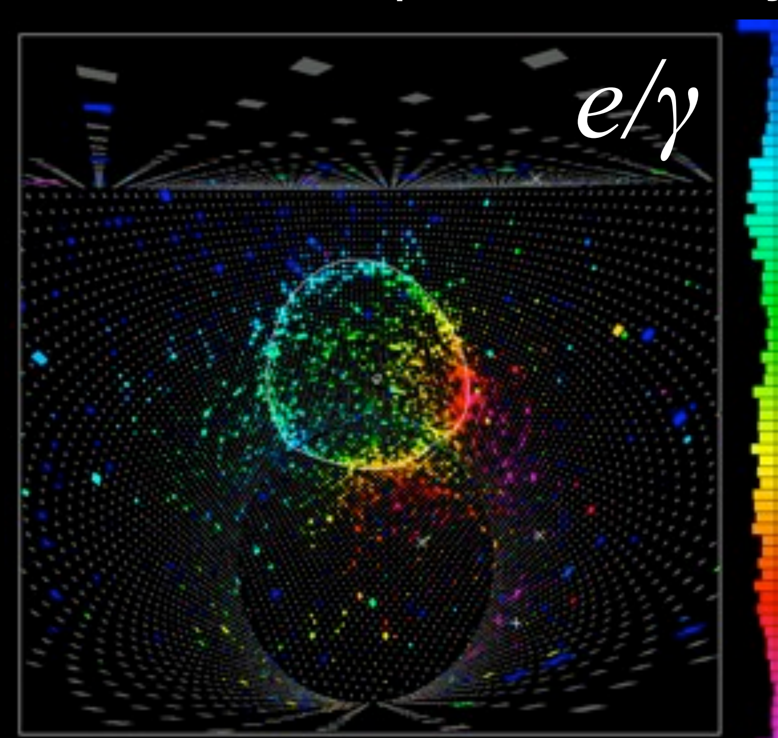
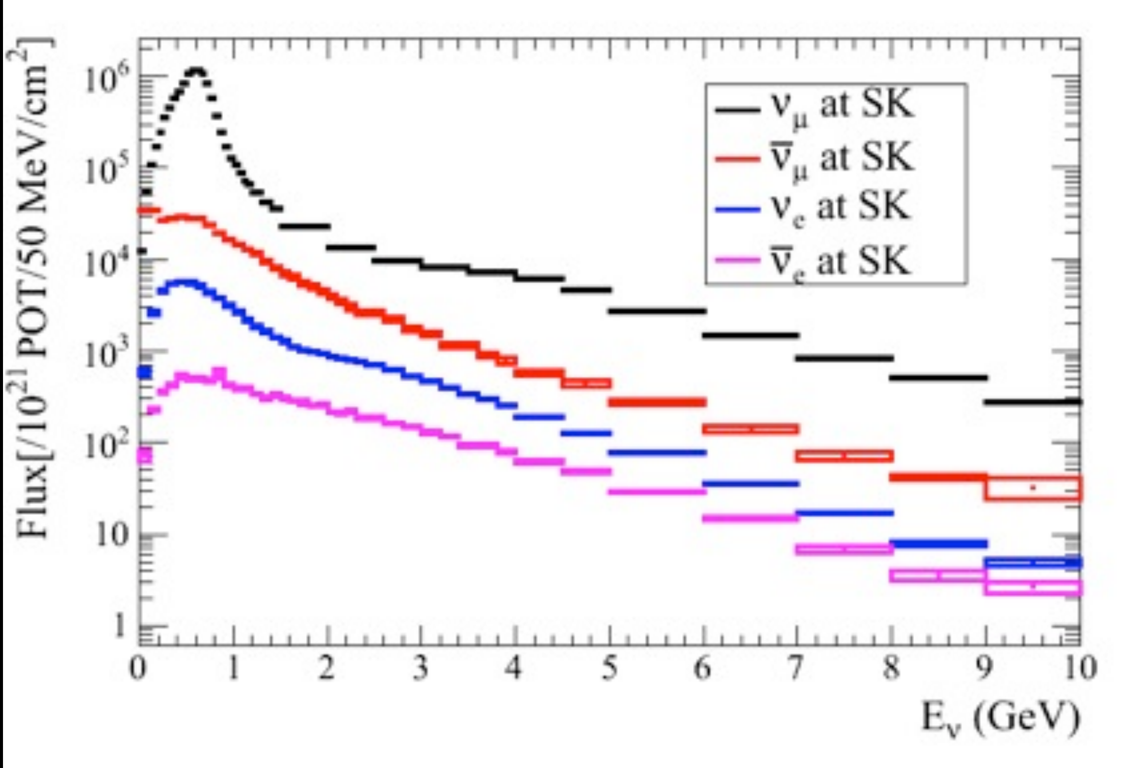




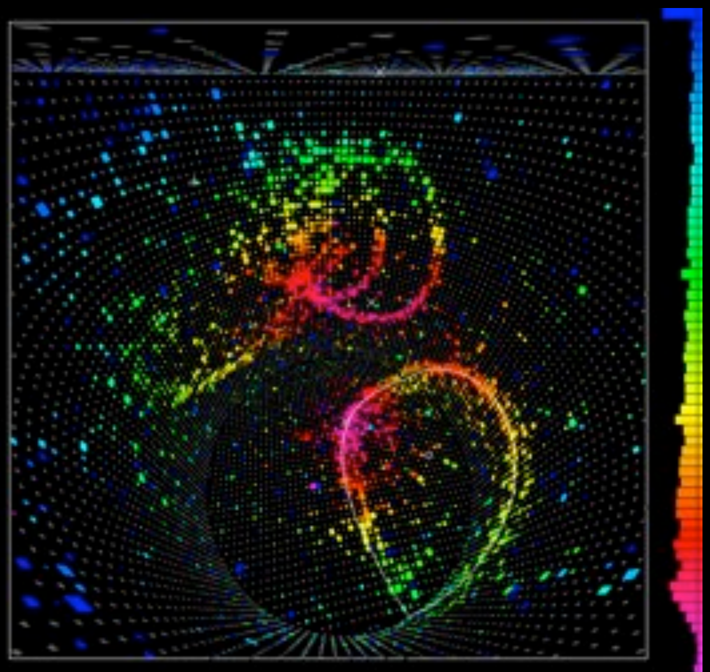
Analysis:



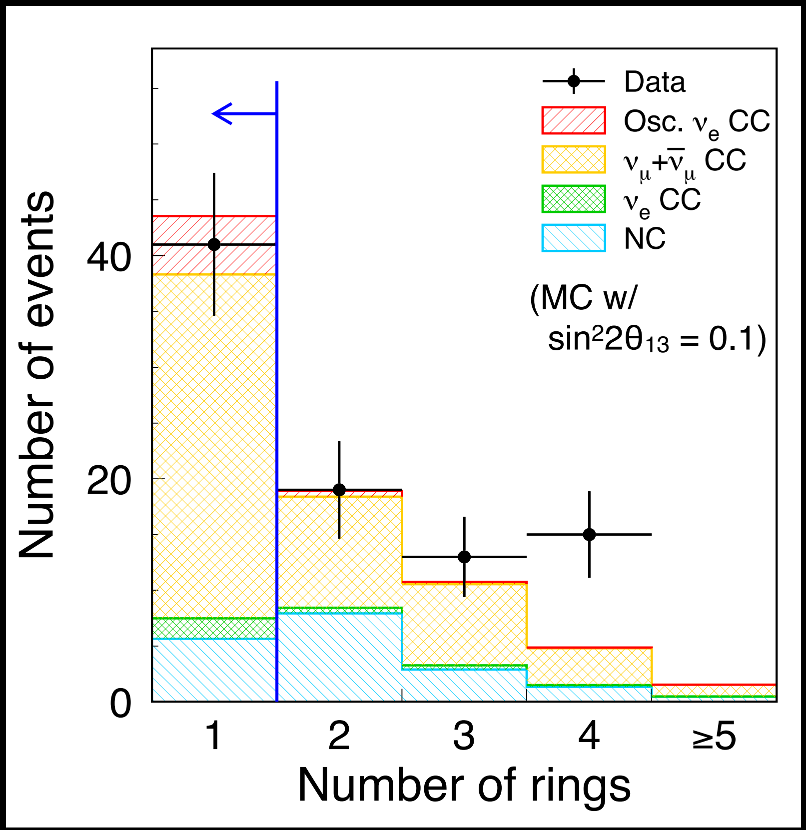
Error Source	Error (%)
Neutrino flux	±8.5
Neutrino interaction	±14.0
Near detector	+5.6/-5.2
Far detector	±14.7
ND statistics	±2.7
Total	+22.8/-22.7

- Flux predicted using MC tuned with
  - beam monitors
  - particle production (e.g. NA61)
  - secondary interactions
- Detailed neutrino interaction generator predicts event rates/final states
- Observed neutrino rate at near detector scales prediction
  - Extrapolation to far detector incorporates uncertainties in near/ far flux and neutrino interactions
  - Some cancellation of uncertainties.

ν_e Selection



reject multi ring events



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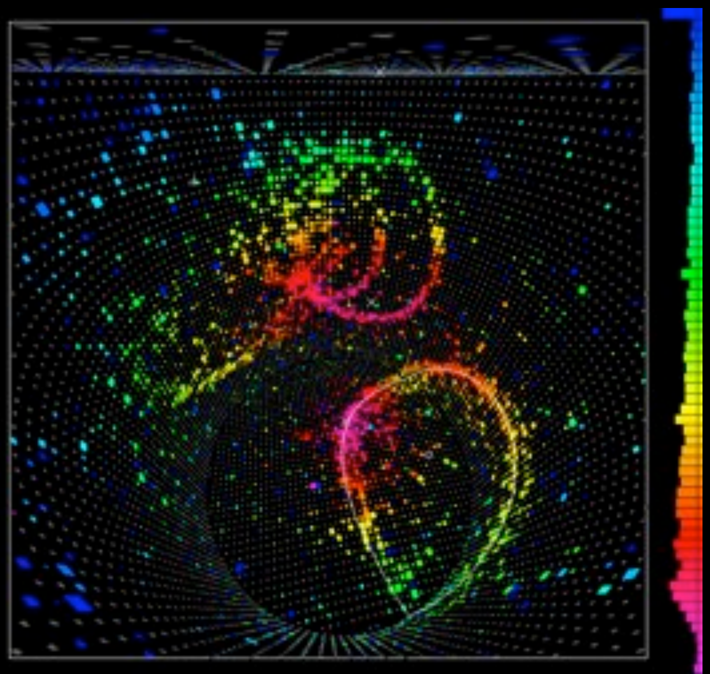
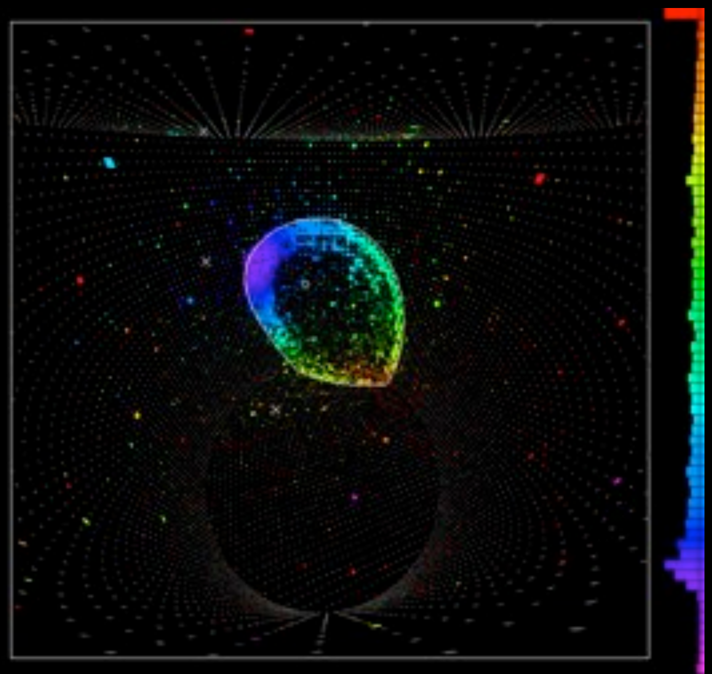
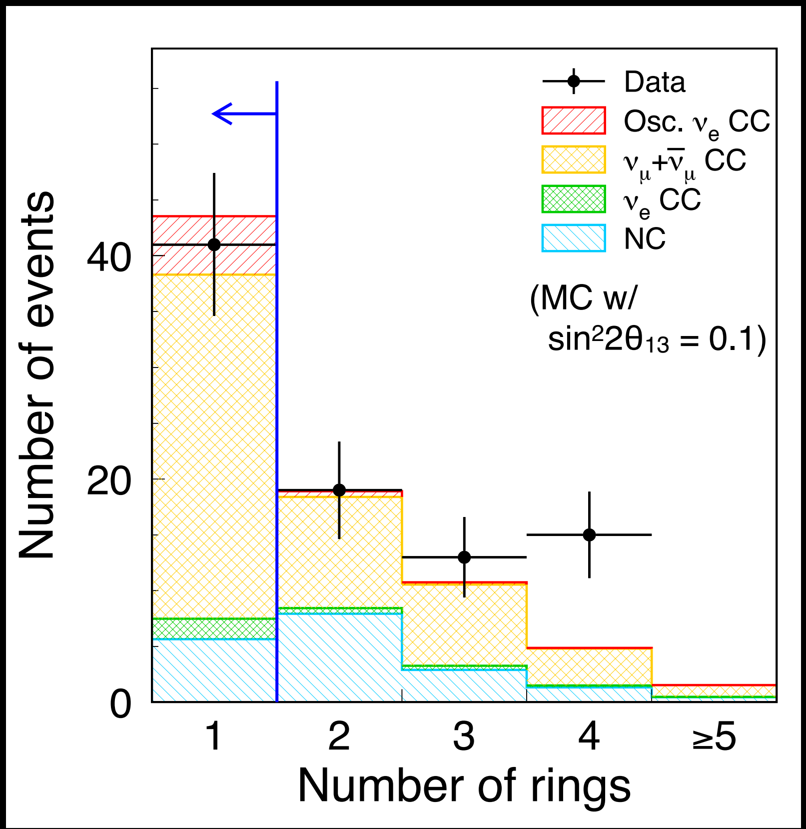
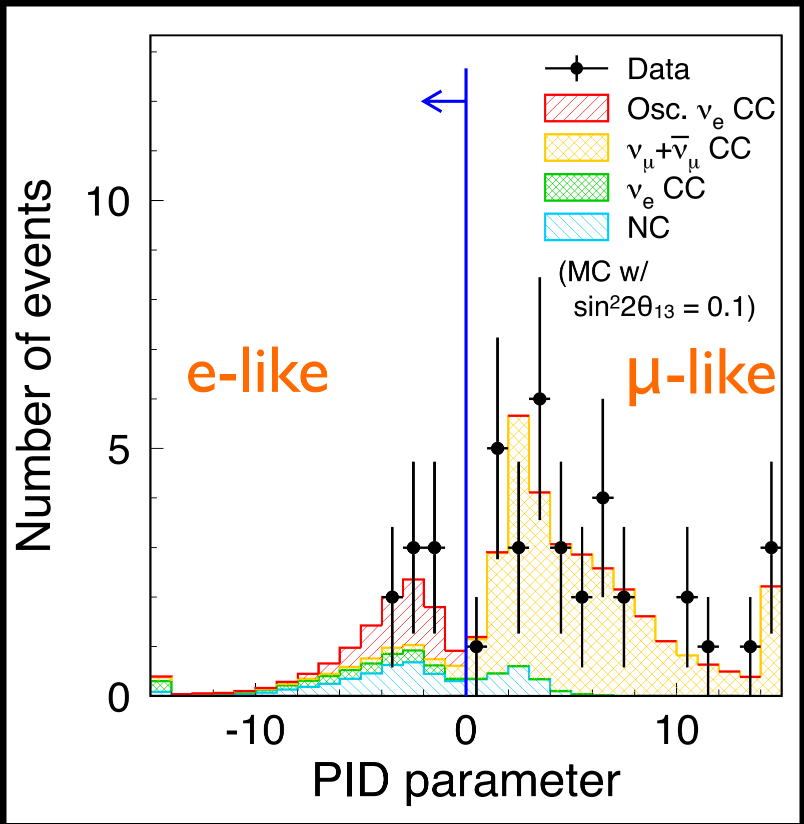




reject multi ring events

reject μ-ring events, μ decay electrons





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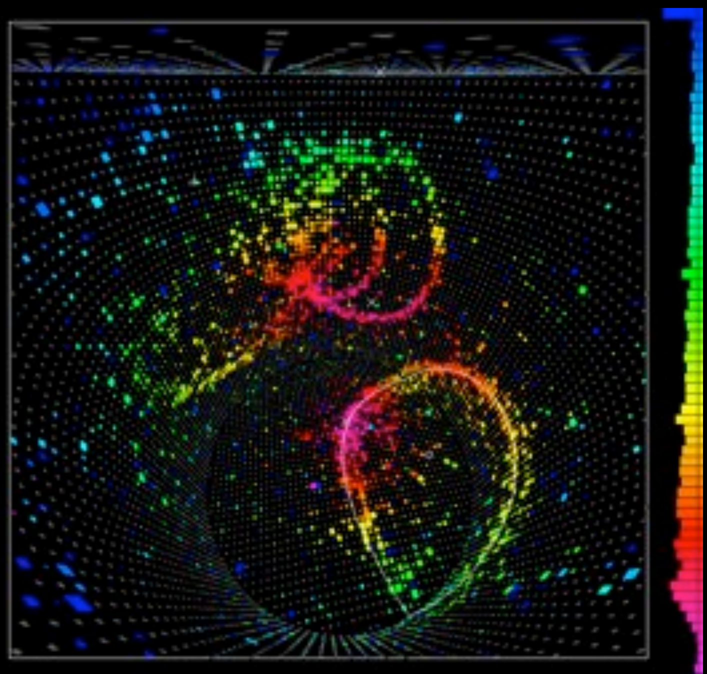

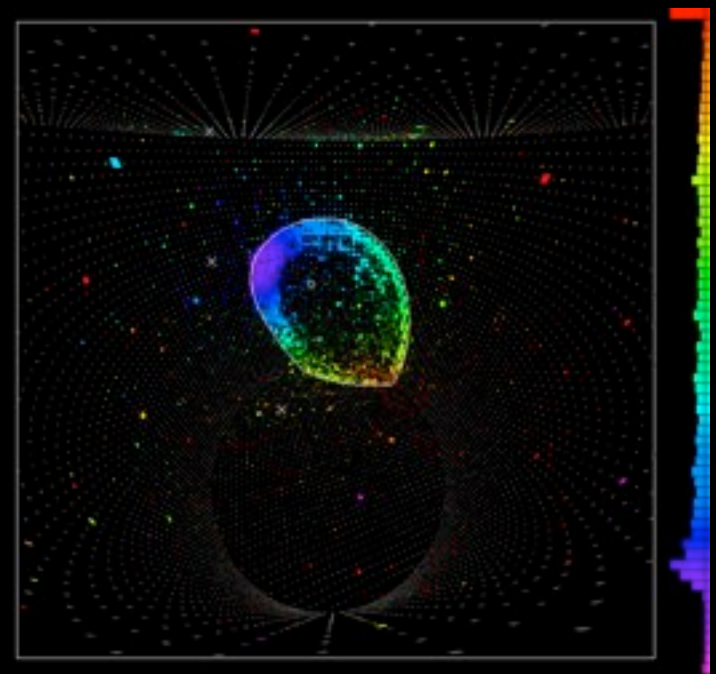

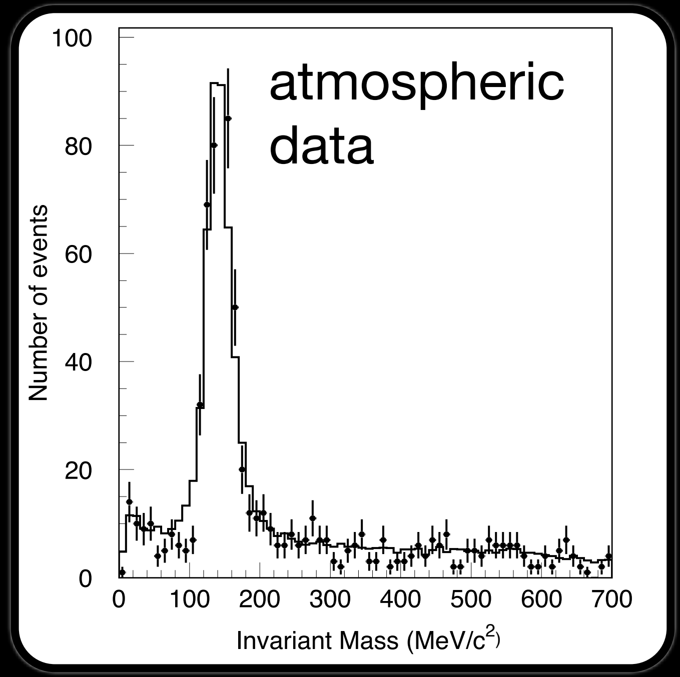

reject multi ring events

reject μ-ring events,
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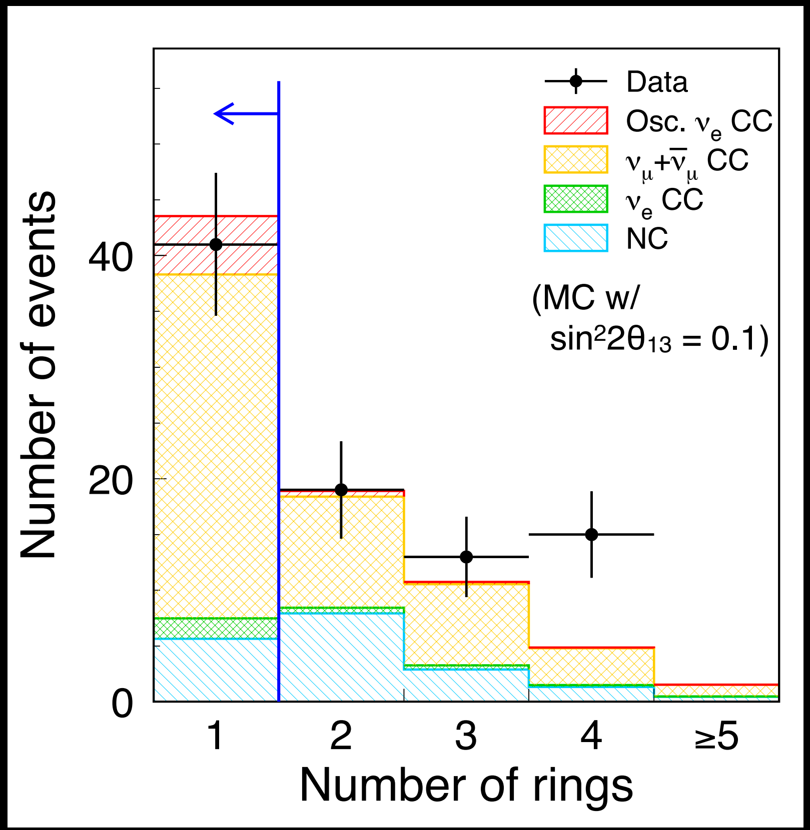
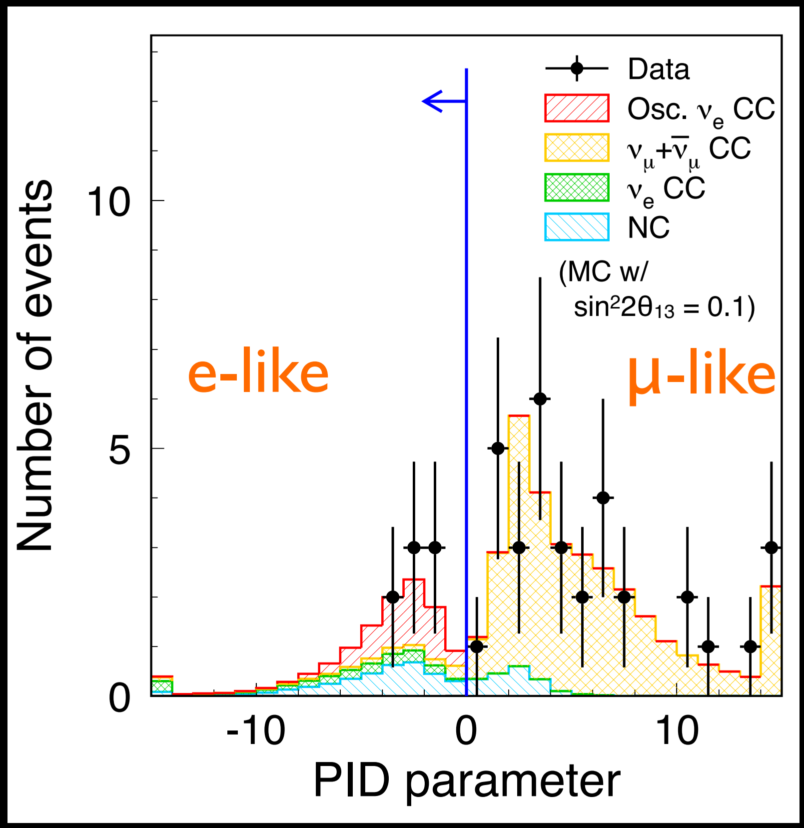
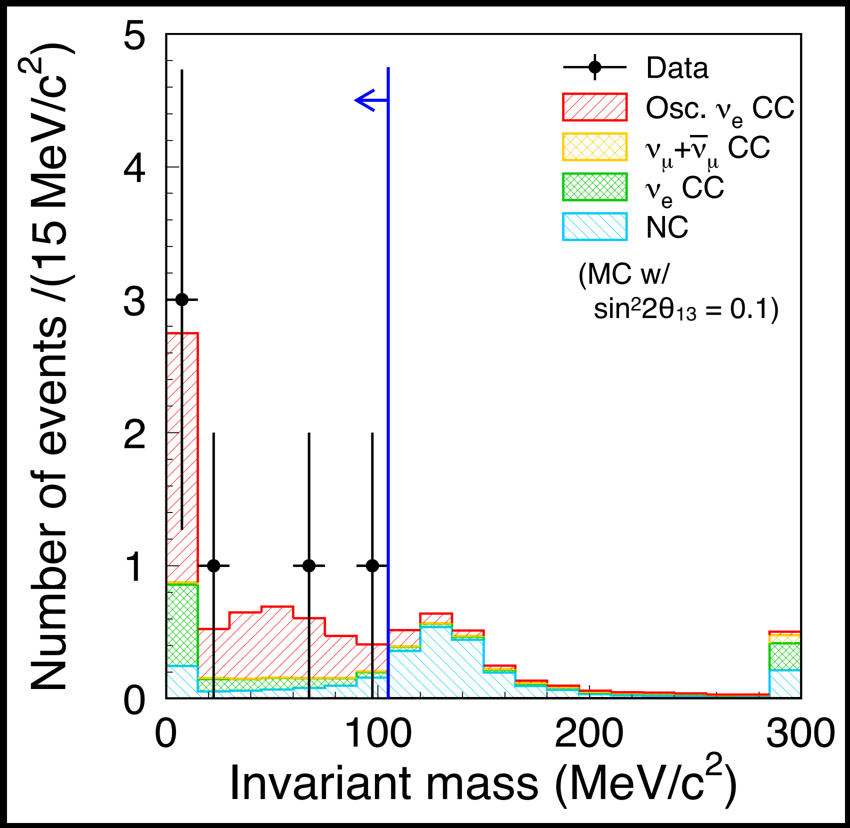
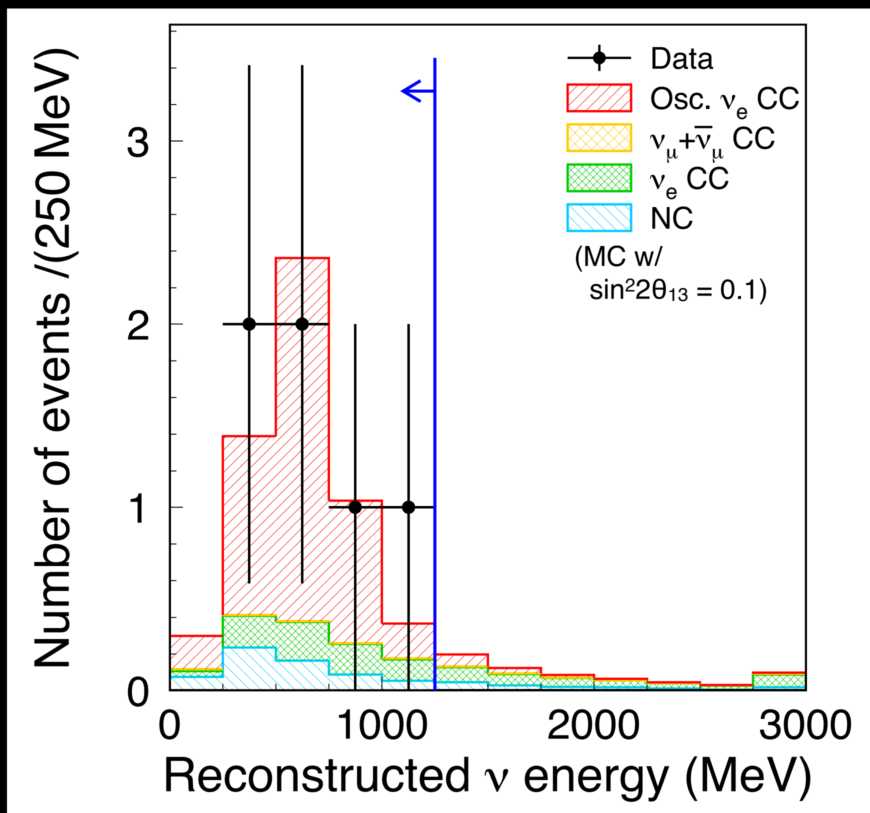
reject π^0 events



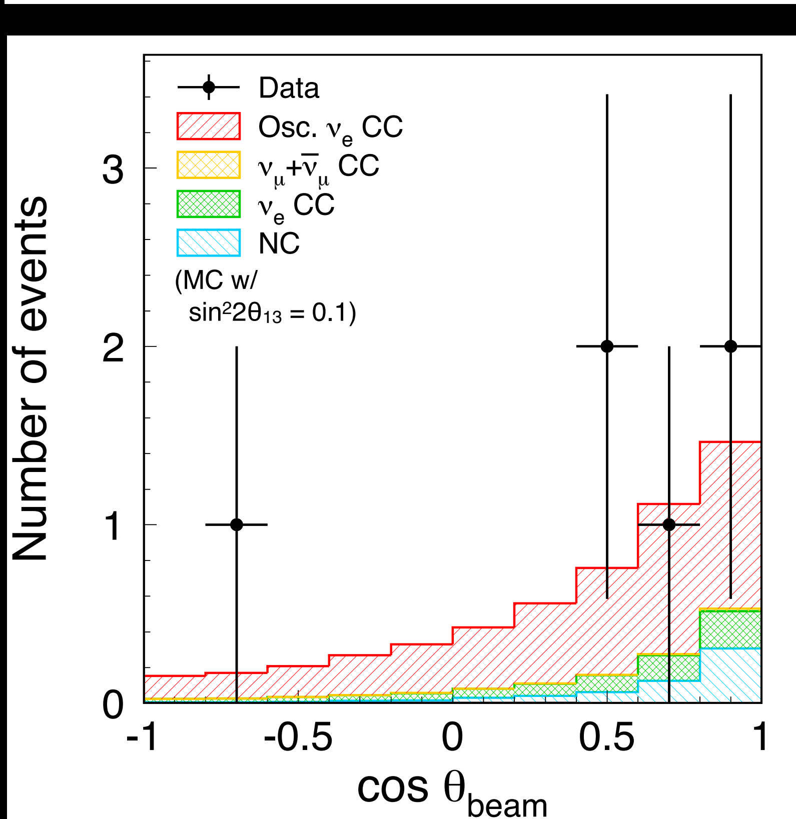


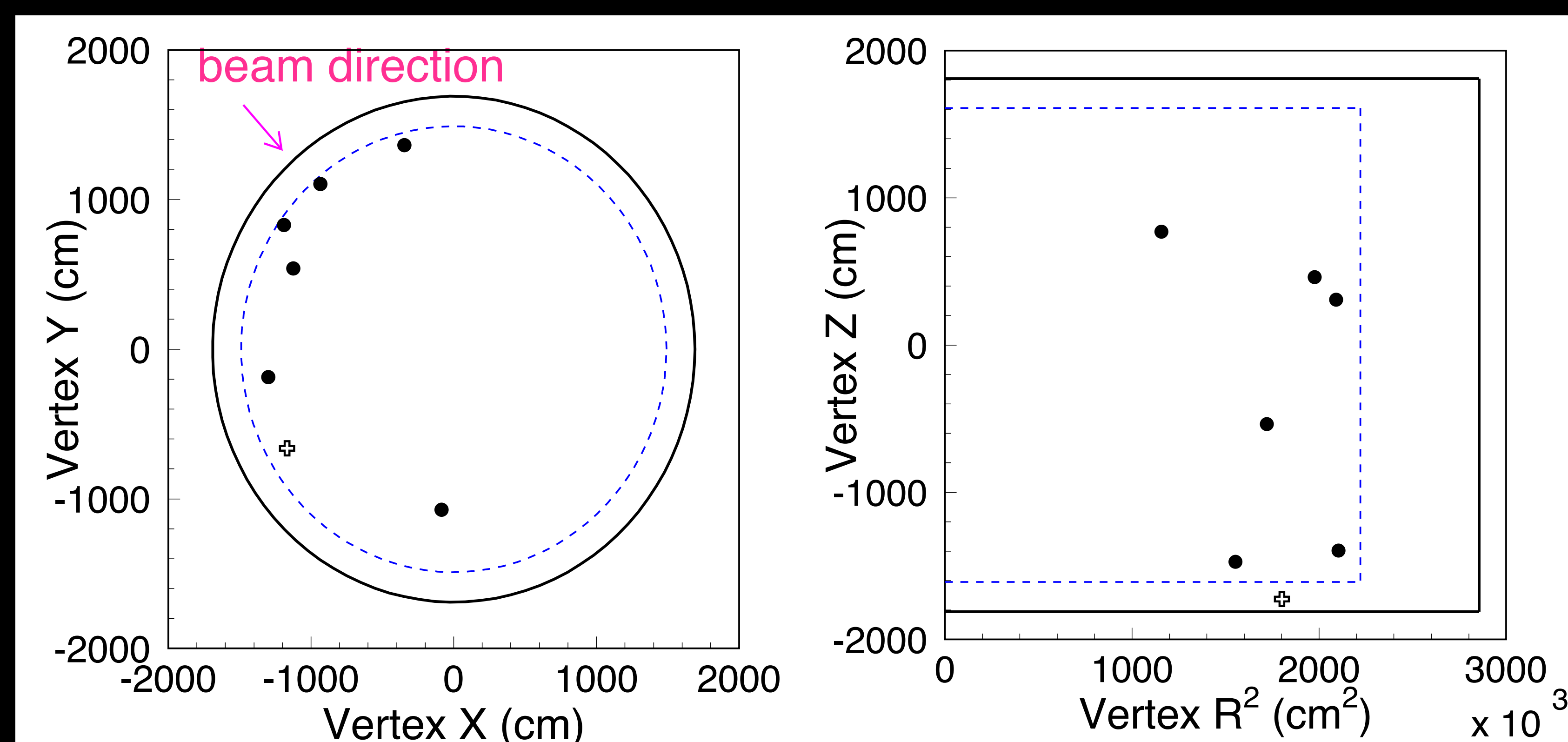


Final Event Sample:

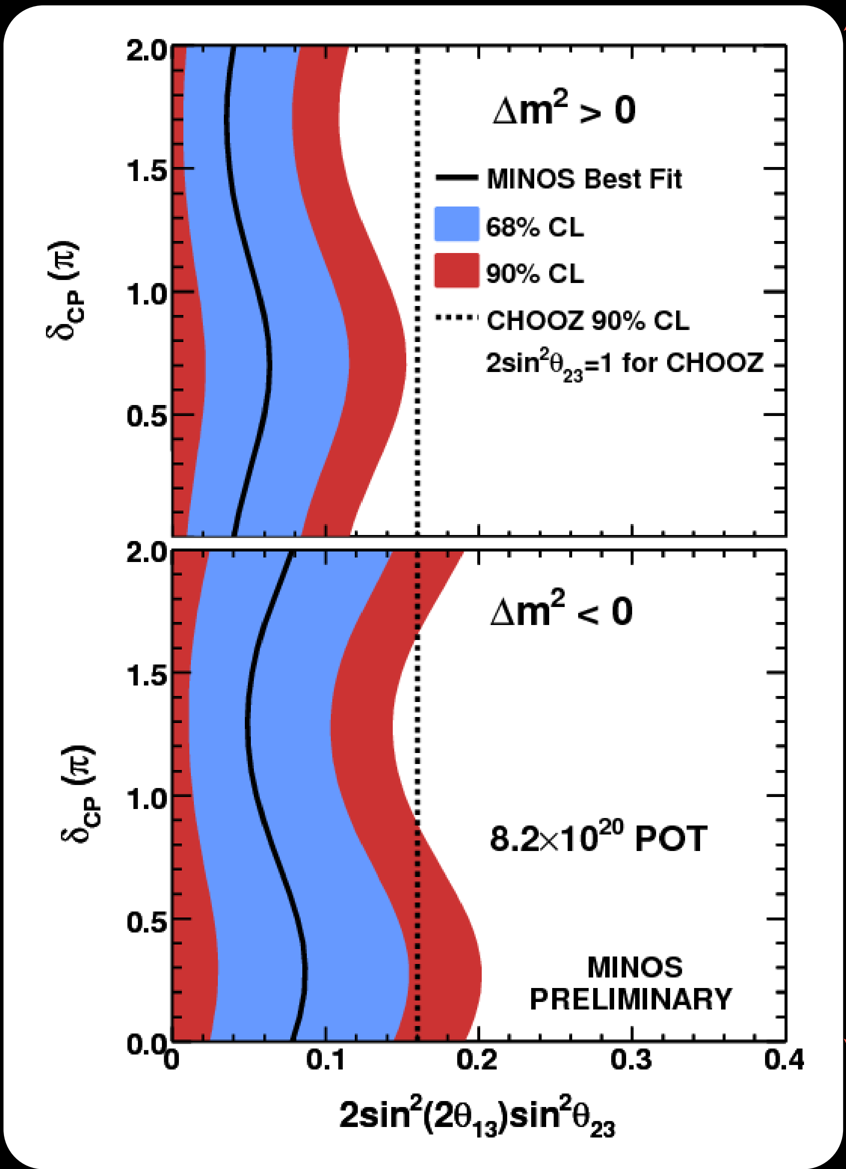


- 6 ν_e candidates observed
- 1.5±0.3 events expected for background
- 0.7% probability for background to fluctuate to 6 or more events (2.5σ)
  - (submitted to/accepted by PRL)

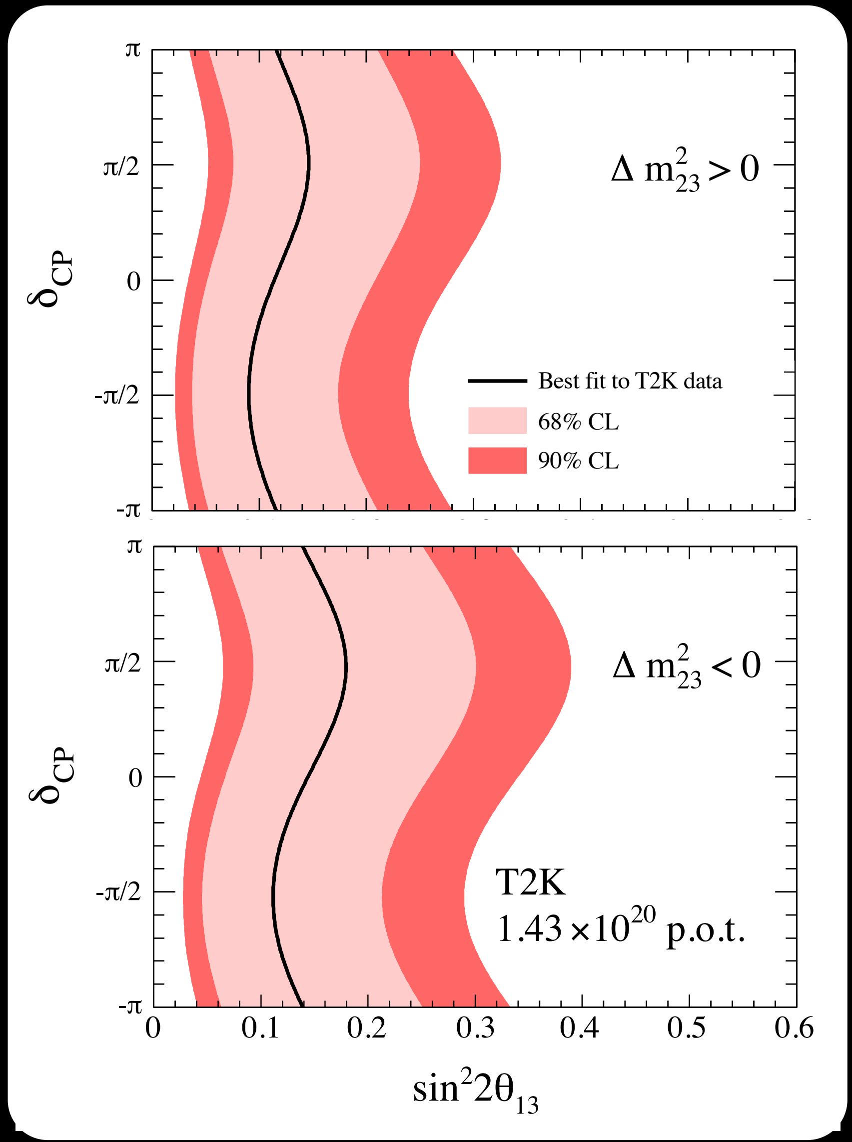




Comparison of Results



Note different axis convention



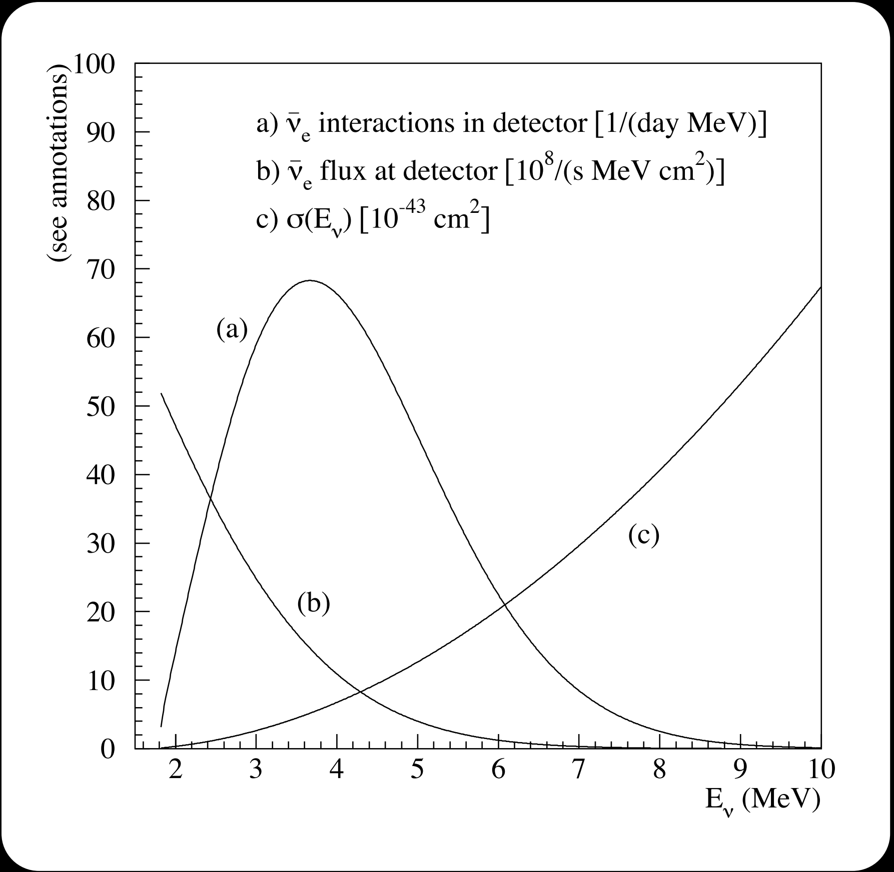
Oscillation probability depends on unknown

- mass hierarchy
- CP violation phase

Both experiments report an excess of events consistent with $\theta_{13}>0$

- MINOS: $\theta_{13}=0$ outside of 89% confidence level region
- T2K: P=0.7% for background ($\theta_{13}=0$) to fluctuate to 6 or more events

Reactor Experiments

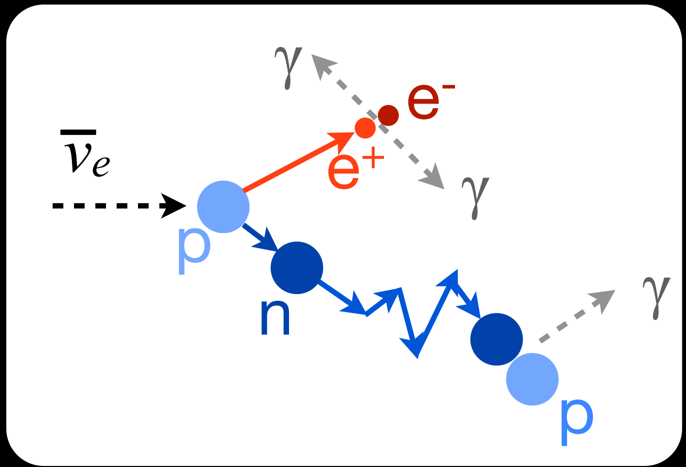


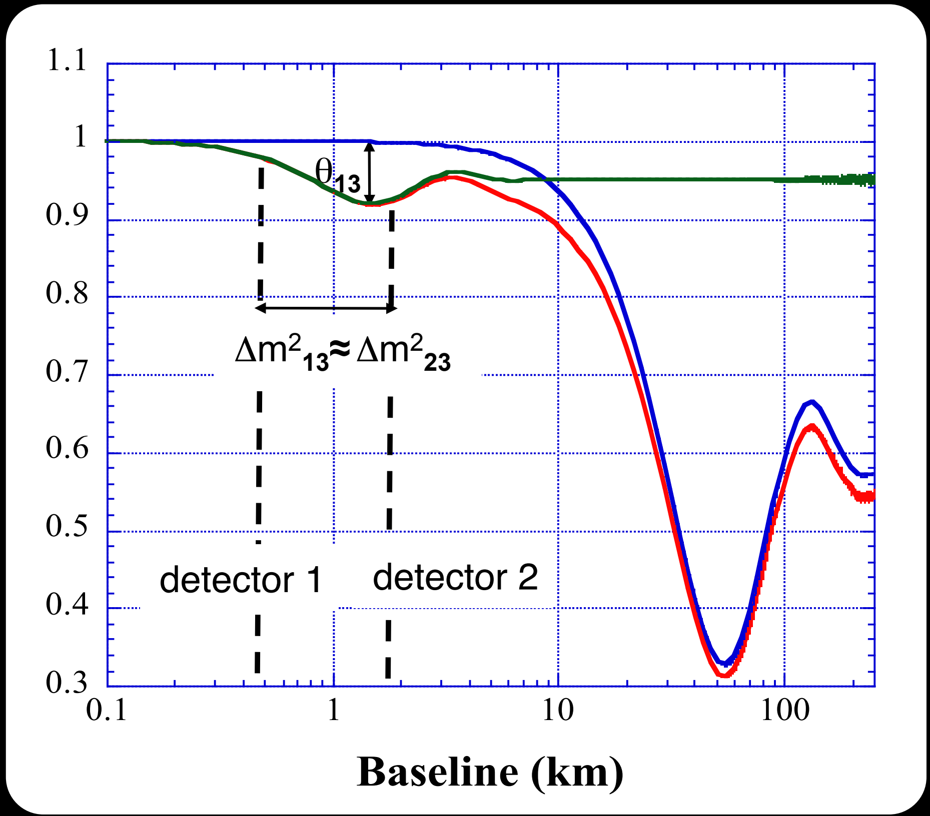
from Bempograd, Gratta, Vogel

Reactor anti-neutrinos:

- Intense source of $\overline{\nu}_e$ from multi-GW nuclear reactors (U/Pu decay chain)
- θ_{13} based on disappearance measurement

$$P(\nu_e \to \nu_e) \quad \sim \quad 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta^2_{31} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin \frac{\Delta^2_{21} L}{4E}$$





- Large scintillator detectors
  - detection via inverse β decay/n capture
  - near/far detectors to cancel uncertainties
- Extraction of θ_{13} with disappearance measurement

*table courtesy of K. Heeger

Reactor Experiments

Double Chooz

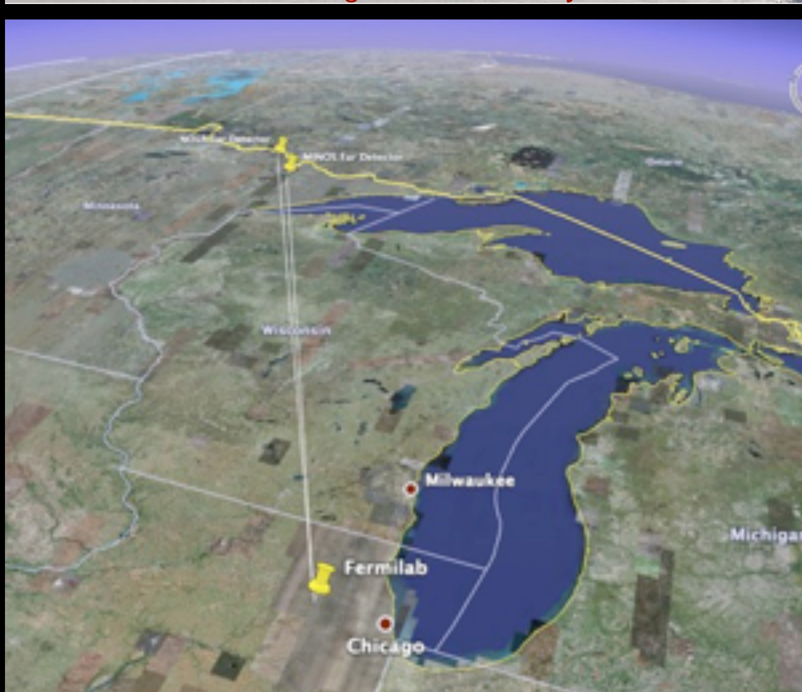
Daya Bay

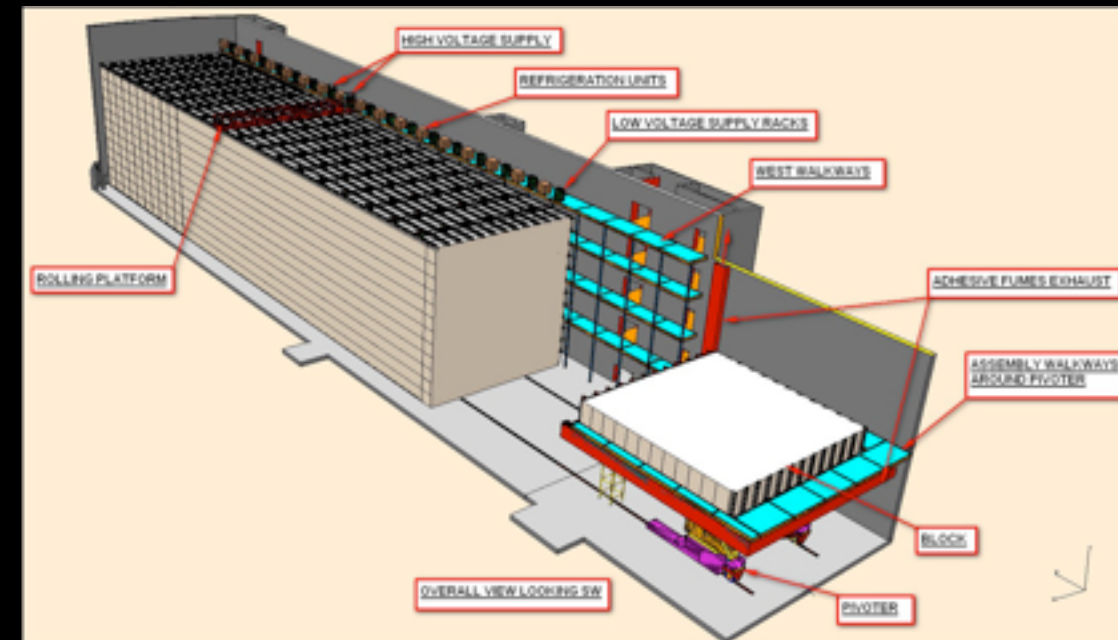
RENO

Experiment*	Thermal Power (GW)	L (near/far) (meters)	Depth (meters)	Target mass (tons)	Start (year)	90% CL (3 years)
Double Chooz	8.6	410/1050	115/300	8.8/8.8	2012/2011	0.03
RENO	17.3	290/1380	120/450	20/20	2011/2011	0.02
Daya Bay	17.4	(353/481)/(1985/1613)	260/910	40x2/80	2011/2012	0.008

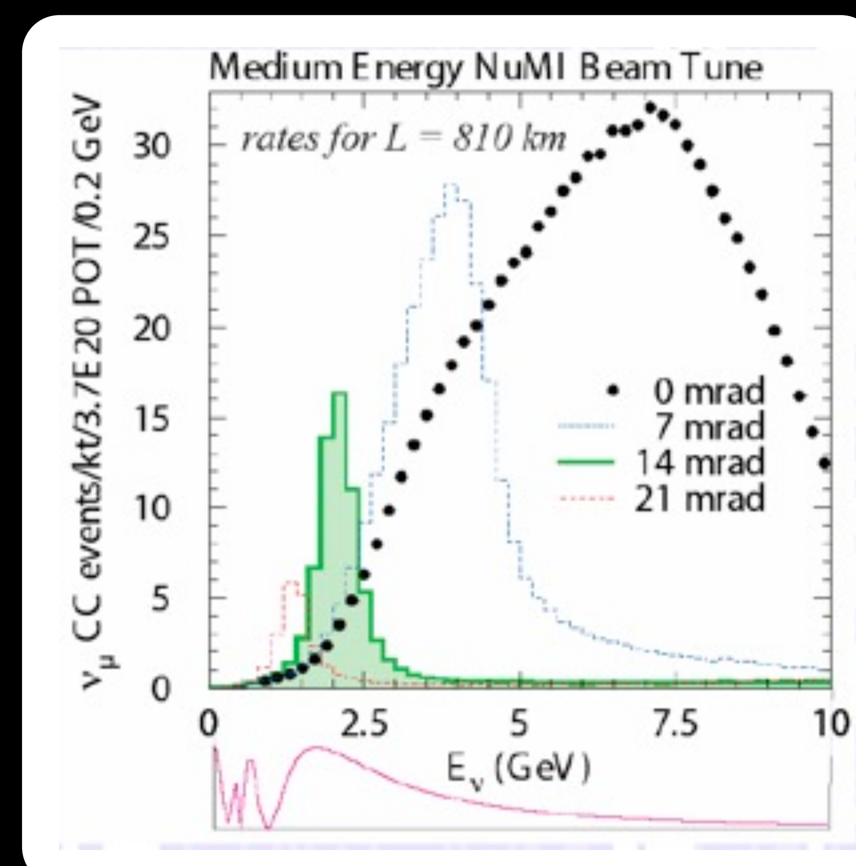
NOνA


Far Detector Building, Ash River, MN - Jan 24, 2011





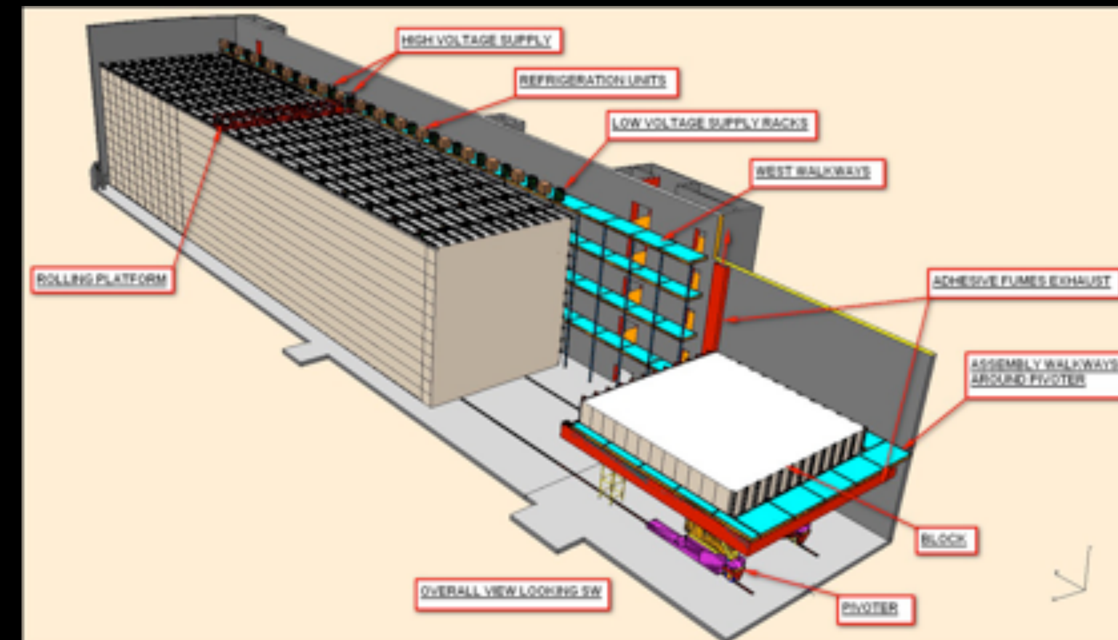
- 15.7 m-long extruded PVC cells filled with liquid scintillator (+WLS/APD) to make 15 kt detector
- 14 mrad off-axis with NuMI: E_ν~2 GeV, L=810 km



- Higher energy gives greater sensitivity to matter effects (~30% vs. ~10% at T2K)
- Allows determination of mass hierarchy
- NDOS operational, far detector under construction.
  - Far detector operation starts 2013

NOνA

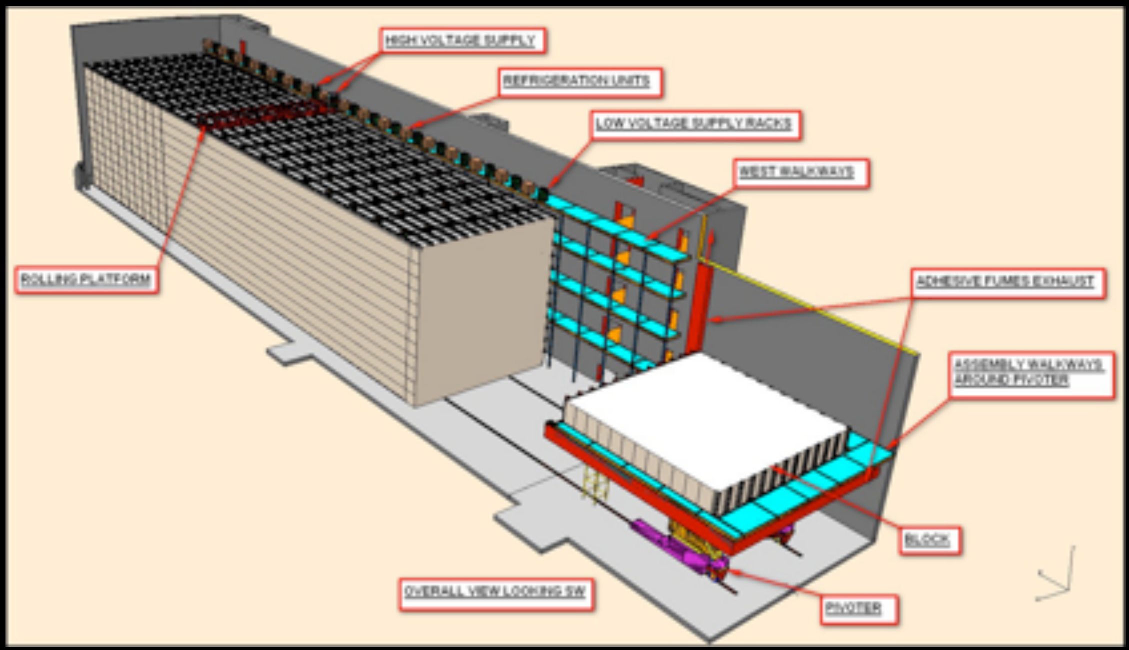

Far Detector Building, Ash River, MN - Jan 24, 2011



- 15.7 m-long extruded PVC cells filled with liquid scintillator (+WLS/APD) to make 15 kt detector
- 14 mrad off-axis with NuMI: E_ν~2 GeV, L=810 km

- Higher energy gives greater sensitivity to matter effects (~30% vs. ~10% at T2K)
- Allows determination of mass hierarchy
- NDOS operational, far detector under construction.
  - Far detector operation starts 2013

NOνA



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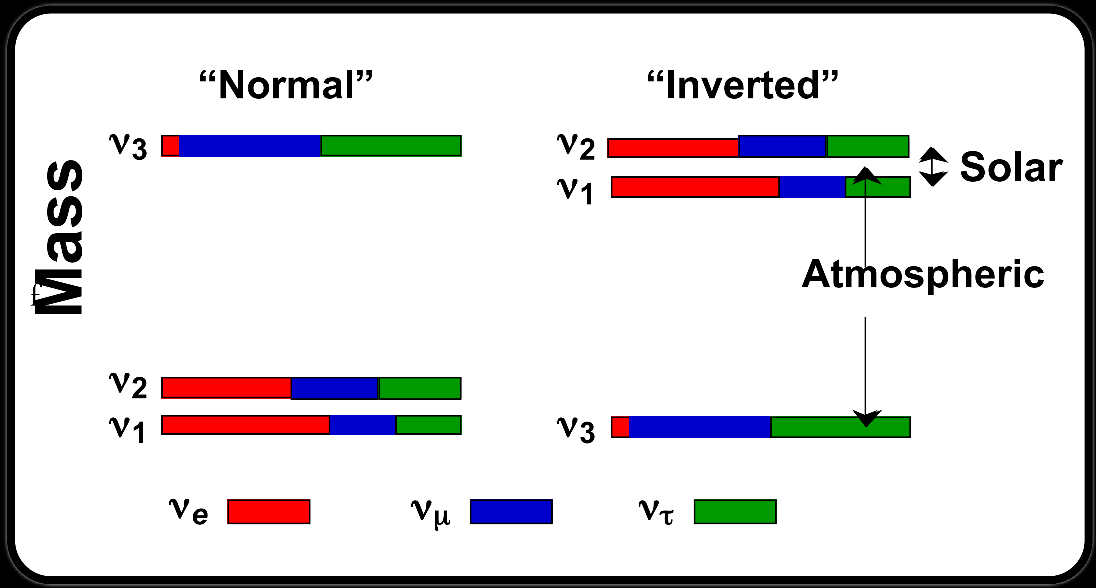
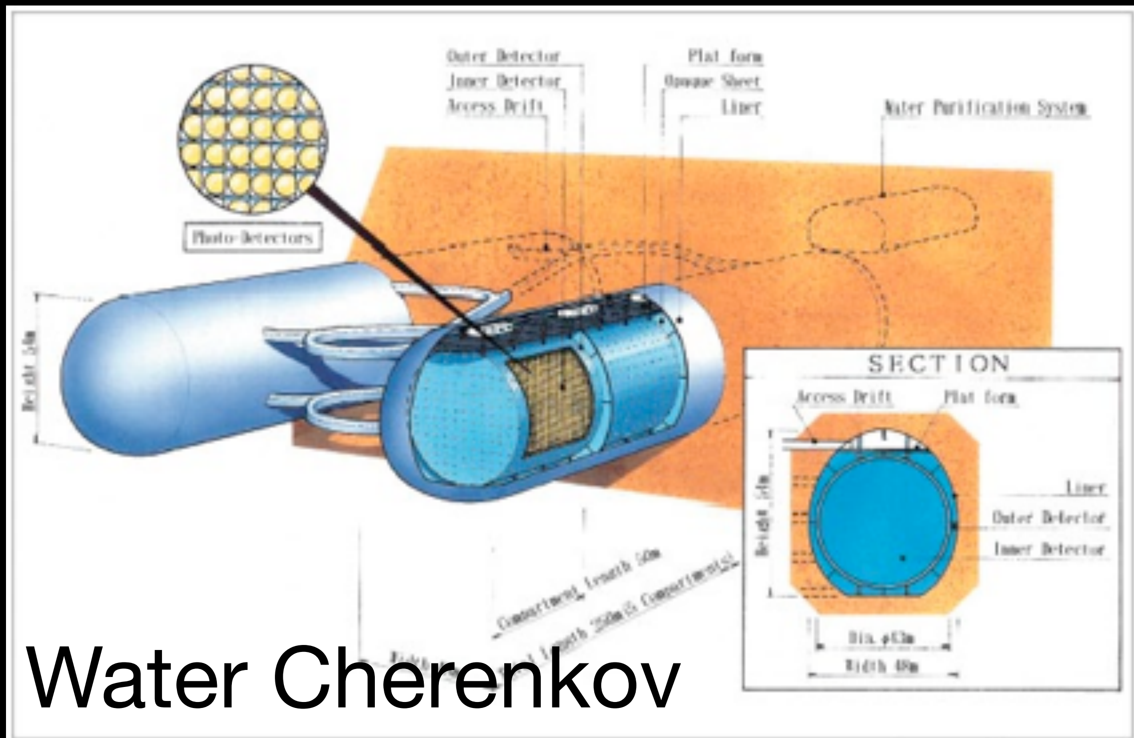
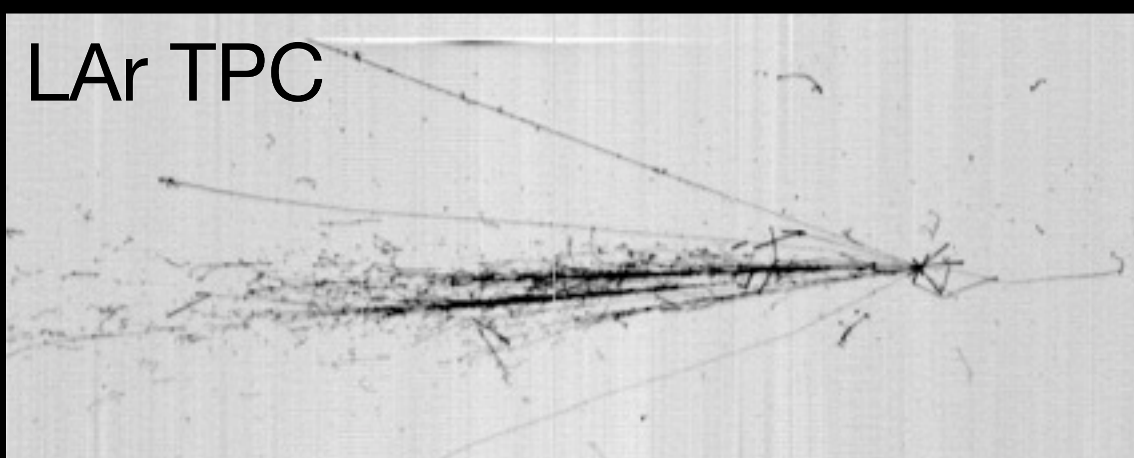


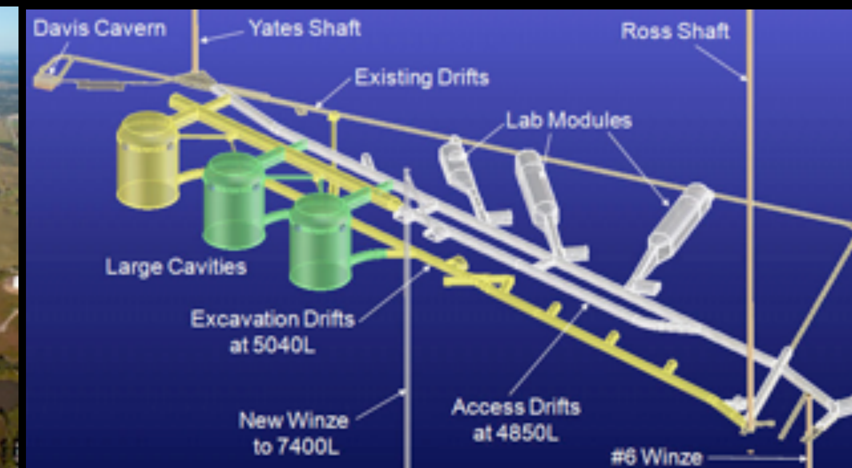
Towards CP Violation:



Water Cherenkov

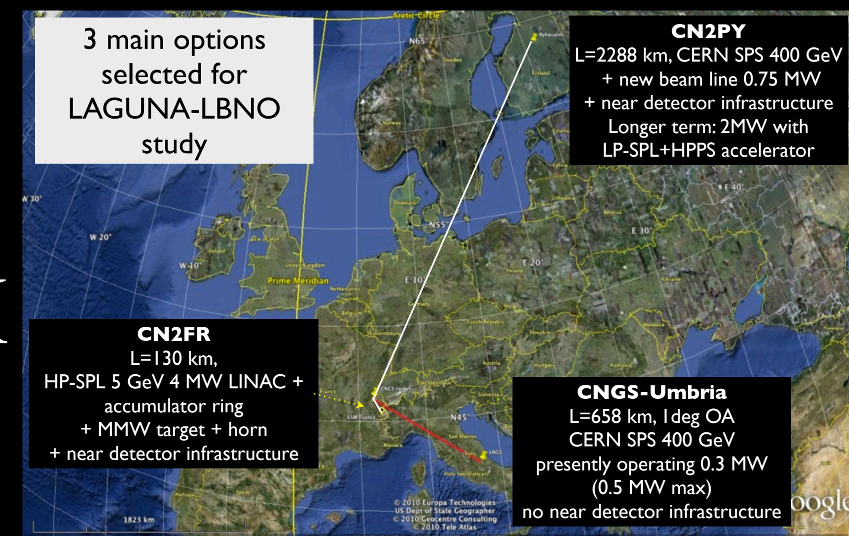


LAr TPC

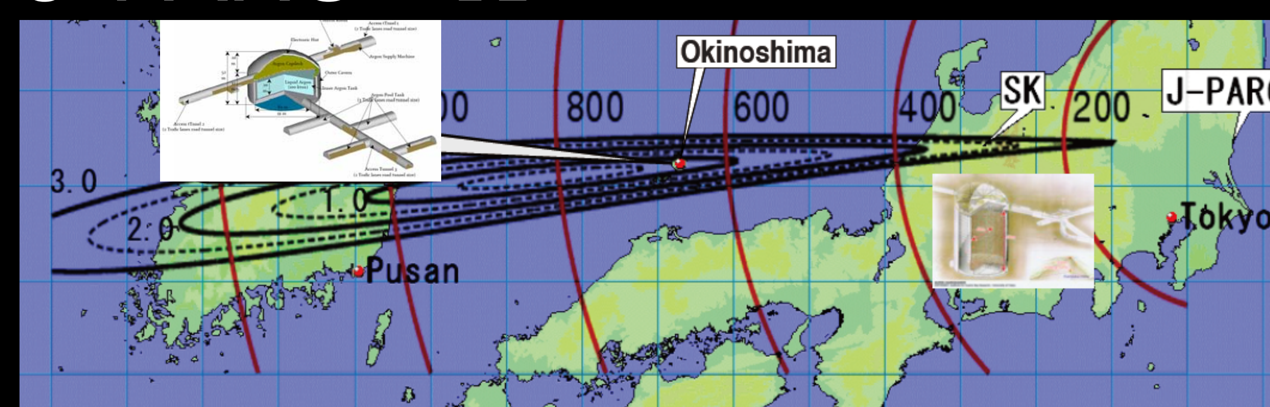


LBNE: FNAL→Homestake

LAGUNA: CERN→X



J-PARC→X



Future options look to

- O(Megawatt) proton accelerators
- O(Megaton) detectors

Outlook

There is much to learn about neutrinos!

- Neutrinos oscillations allow us to study:
  - what are their mixing parameters? Is θ_{23} maximal, $\theta_{13} \neq 0$?
    - θ_{23} precision will increase with NOvA and T2K
    - are we seeing the first indications of $\theta_{13}>0$?
  - Is there CP violation in the lepton sector? ($\theta_{13,}$ $\delta \neq 0$)
- We also hope to learn
  - what are their masses (as opposed to mass differences)?
  - are they there their own antiparticles (are they Majorana)?
- This may in turn shed light on:
  - what determines the mixing/mass structure of quarks and leptons?
  - why is the universe matter dominated?

Expect a leap forward in the coming years!