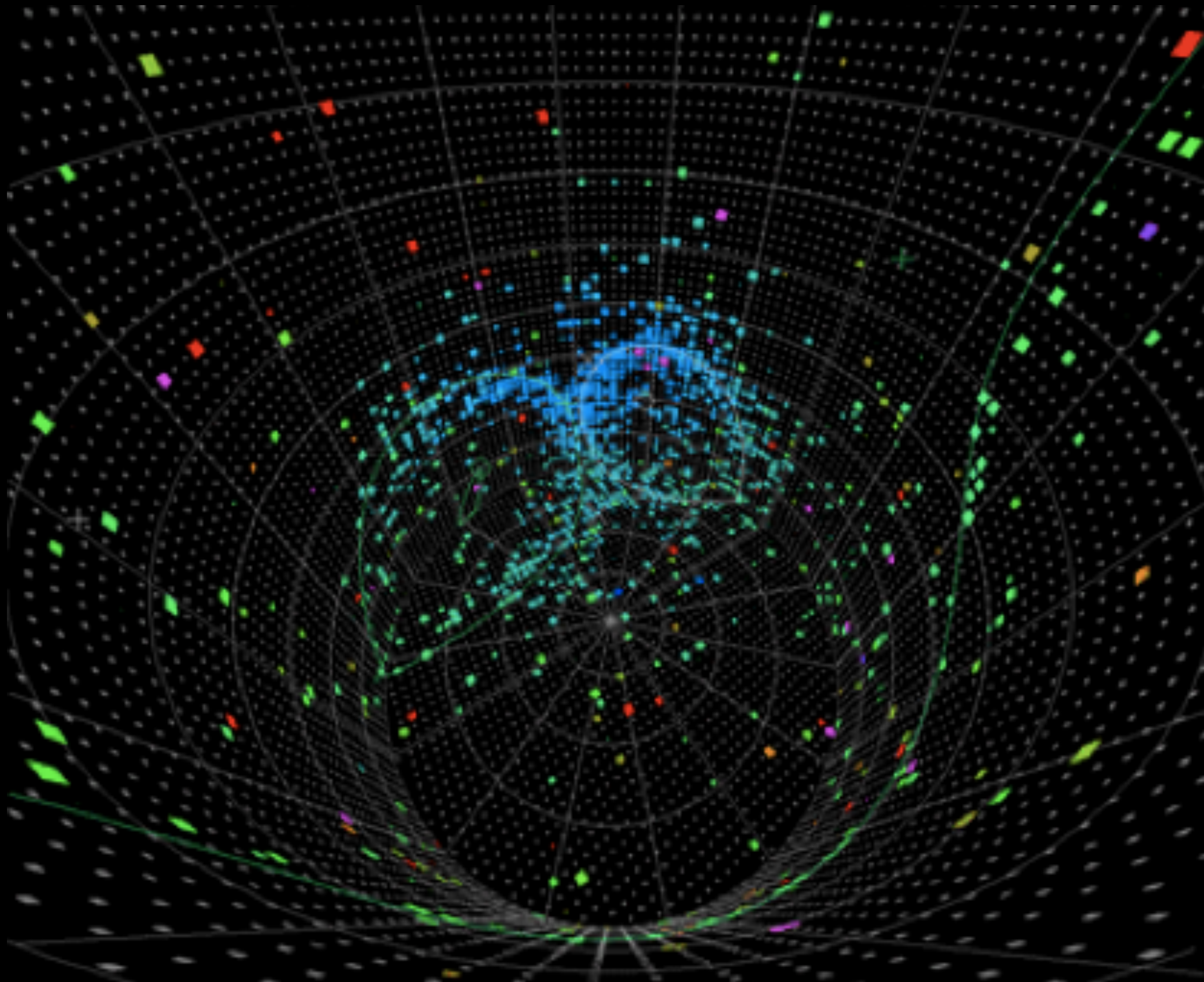
Recent Results from T2K

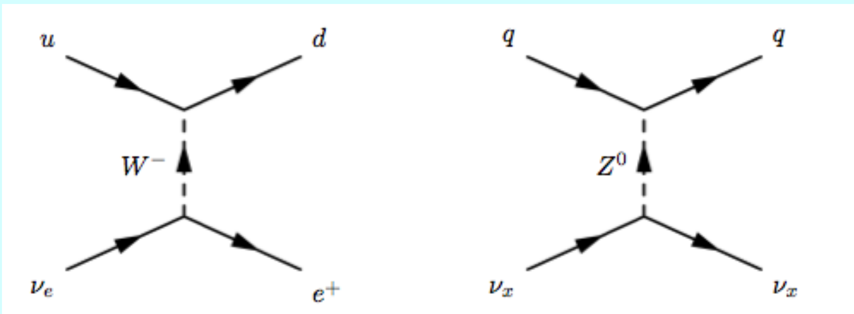


Kate Scholberg, Duke University
SMU, March 2012

Standard Three-Flavor Neutrino Picture

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

neutral partners
to the charged leptons



Charged and neutral
current interactions

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in
weak interactions

eigenstates of free
Hamiltonian

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*} |\nu_i\rangle$$

Parameterize mixing matrix U as

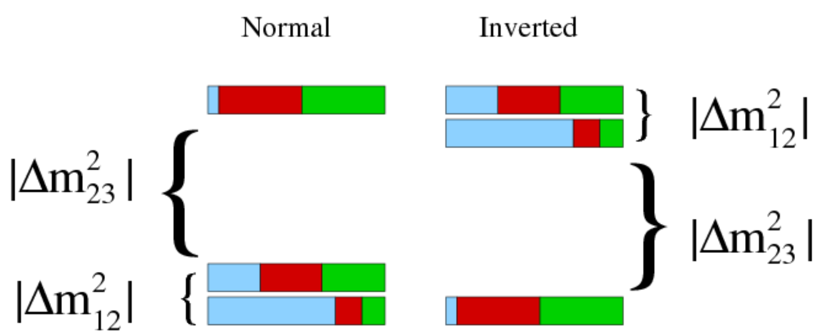
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter



Consequence of this framework:

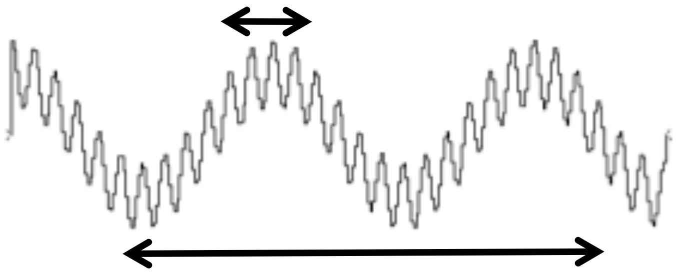
Flavor transitions as neutrinos propagate

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \qquad \text{(L in km, E in GeV, m in eV)}$$

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{j>i} \mathrm{Re}(U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*})\sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$
$$\pm 2\sum_{j>i} \mathrm{Im}(U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*})\sin^2(2.54\Delta m_{ij}^2 L/E_\nu)$$

oscillatory behavior in L and E



$$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$$ ➔ **two frequency scales**

For appropriate L/E (and U_{ij}), oscillations "decouple", and flavor change probability can be described by:

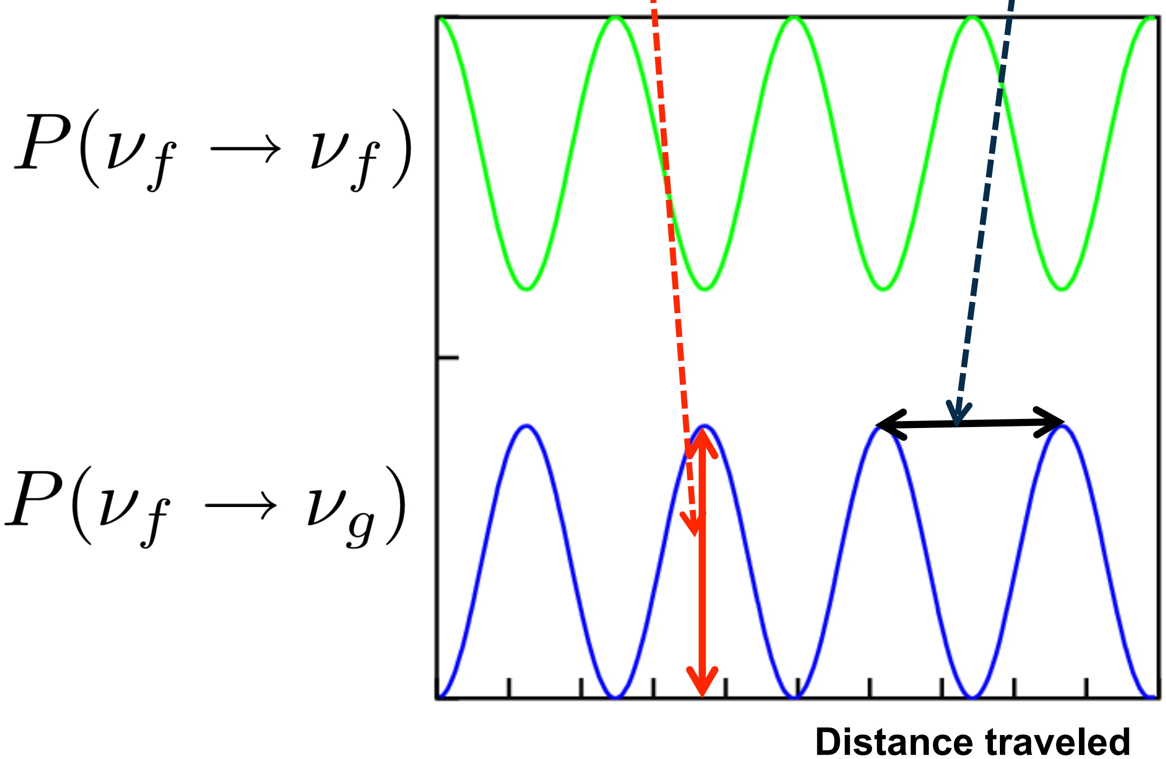
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

In 2-flavor approximation:

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

amplitude

wavelength= $\pi E/(1.27\Delta m^2)$



Measure disappearance of an expected flavor, or appearance of a new one

e.g. $\nu_e \rightarrow \nu_\mu$ at ~MeV

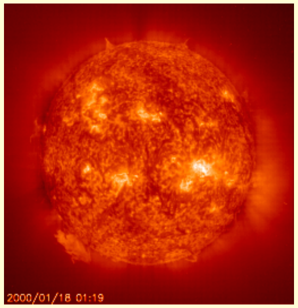
e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV

We now know neutrinos change flavor!

In each case, first measurement with ‘wild’ ν’s was confirmed and improved with ‘tame’ ones

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

SOLAR NEUTRINOS



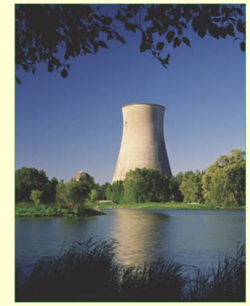
Cl, Ga, SK, SNO, Borexino

Electron neutrinos from the Sun are *disappearing*...

$$\nu_e \longrightarrow \nu_\mu, \nu_\tau$$

$$\bar{\nu}_e \longrightarrow \nu_x$$

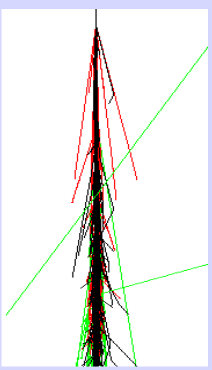
... now confirmed by a reactor ν’s



KamLAND

Described by θ_{12}, Δm^2_{12}

ATMOSPHERIC NEUTRINOS

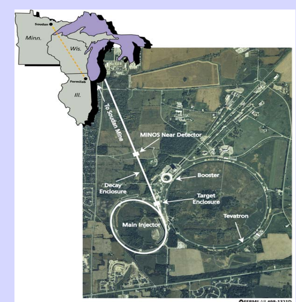


iMB, Kam, Soudan, MACRO, SK, MINOS, IceCube

Muon neutrinos created in cosmic ray showers are *disappearing* on their way through the Earth

$$\nu_\mu \longrightarrow \nu_\tau$$

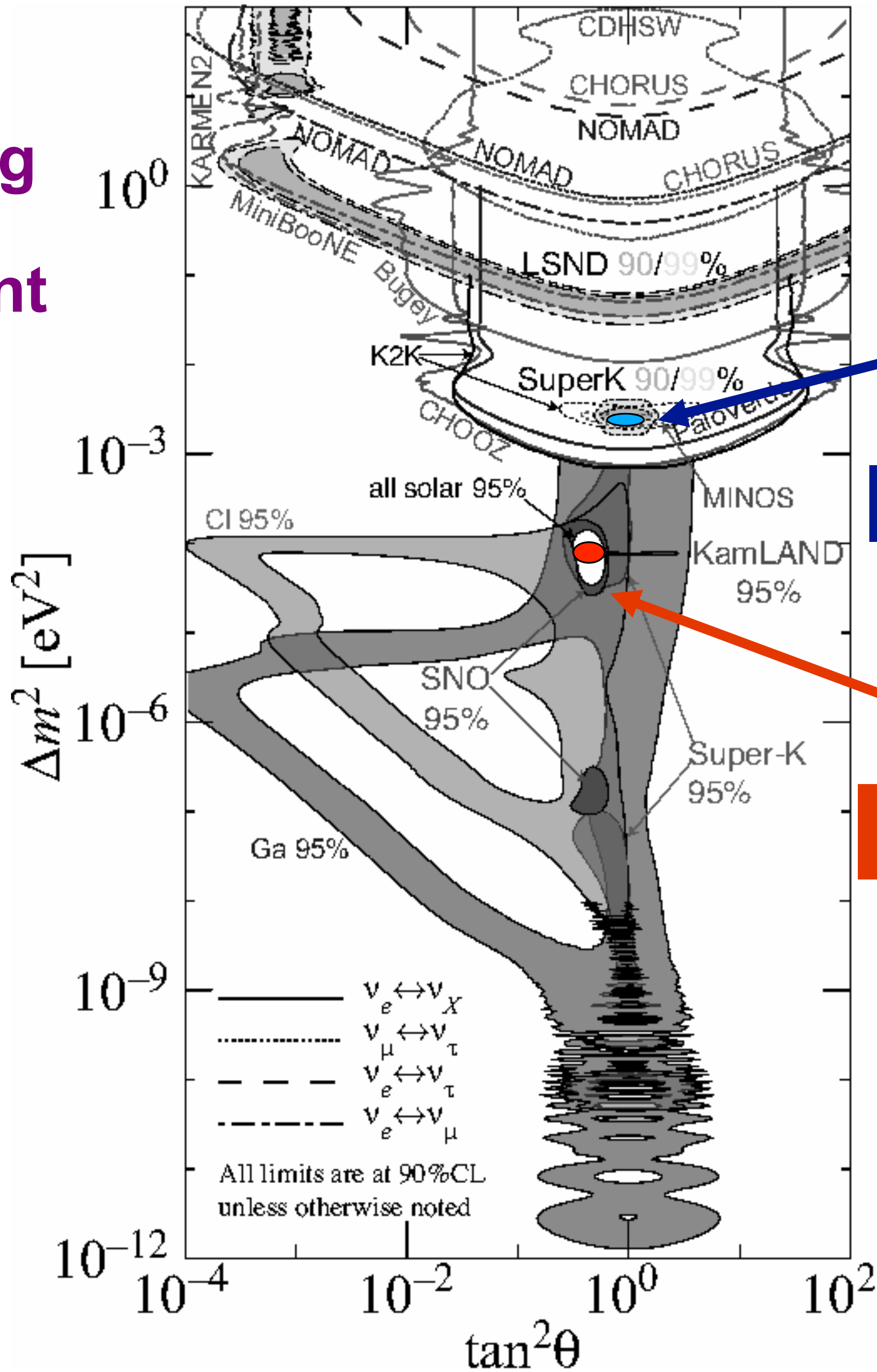
...now confirmed by beam experiments



K2K, MINOS, T2K, OPERA, Icarus

Described by θ_{23}, Δm^2_{23}

Now entering precision measurement era for two-flavor oscillations



atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

Described by θ_{12}, Δm^2_{12}

Next:
3 flavor
picture

After 15 years of oscillation measurements, remaining unknowns in the 3-flavor picture:

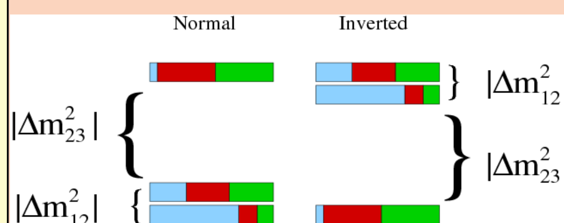
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric/beam ? solar/reactor

Masses

$$m_1,\ m_2,\ m_3 \leftrightarrow \Delta m^2_{12}, |\Delta m^2_{23}|, sign(\Delta m^2_{23}), m_i$$

✓ ✓ ? ?



Angles

(plus Majorana phases)

$$\theta_{12},\ \theta_{23},\ \theta_{13},\ \delta$$

✓ ✓ small ?

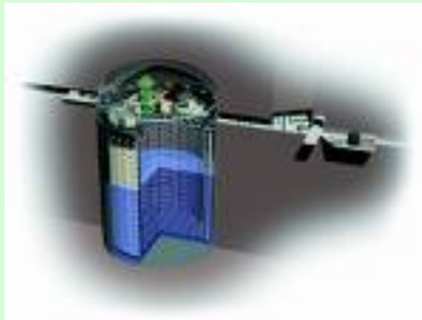
maximal?
octant?

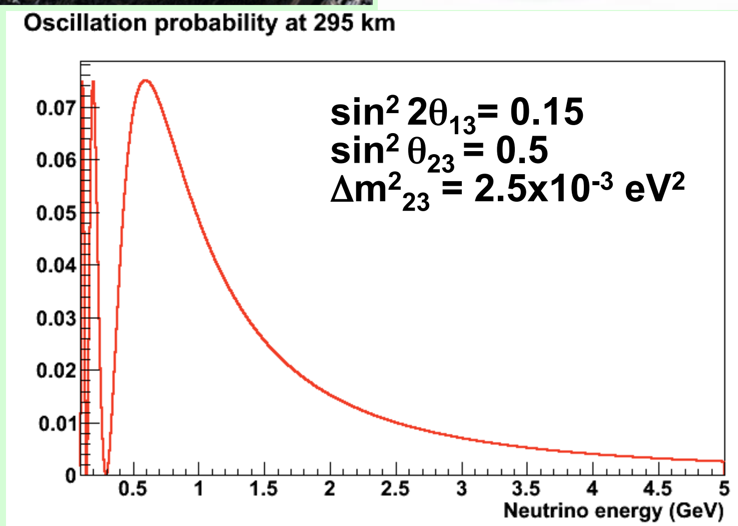
Measuring these parameters will constrain mass models, leptogenesis, etc.; but it's not just about measuring numbers

➔ we need to test the 3-flavor paradigm in multiple ways ... new physics?

Strategies for determining θ_{13}

Beams

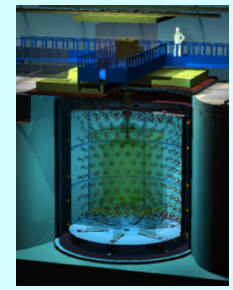


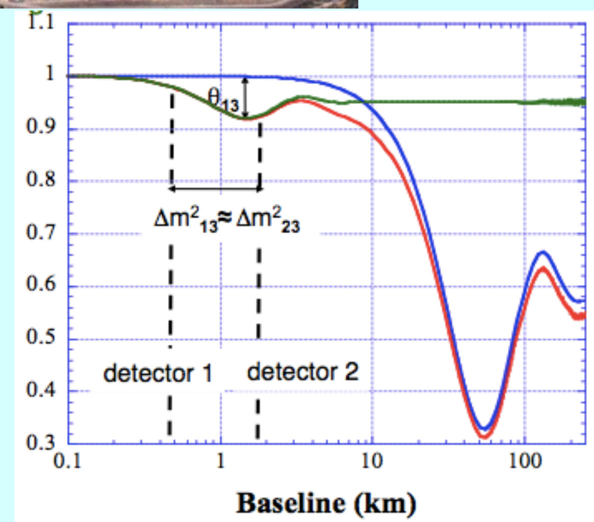


Look for *appearance* of ~GeV ν_e in ν_μ beam on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors

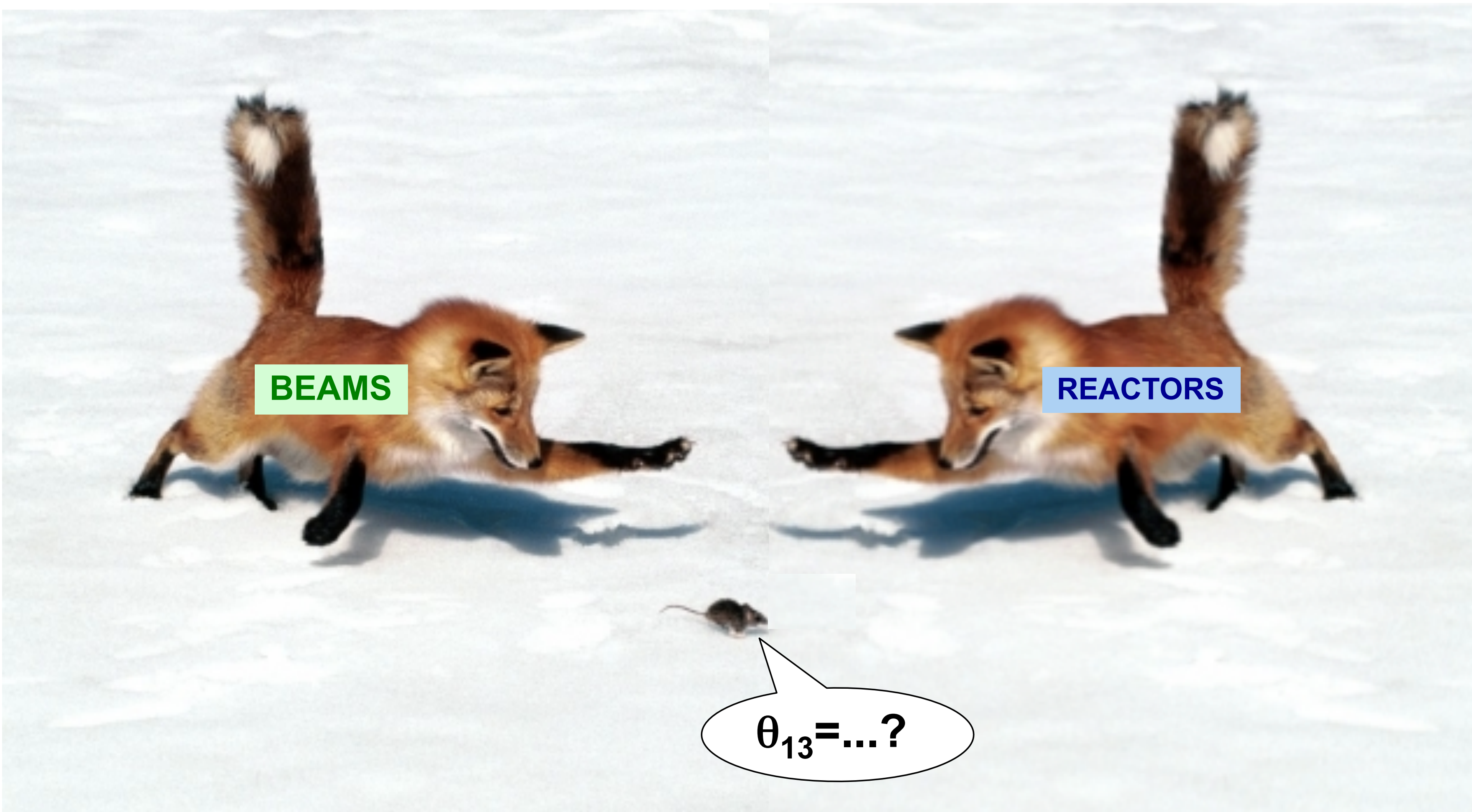




Look for *disappearance* of ~few MeV $\bar{\nu}_e$ on ~km distance scale

CHOOZ, Double Chooz, Daya Bay, RENO

We’re closing in on the answer...

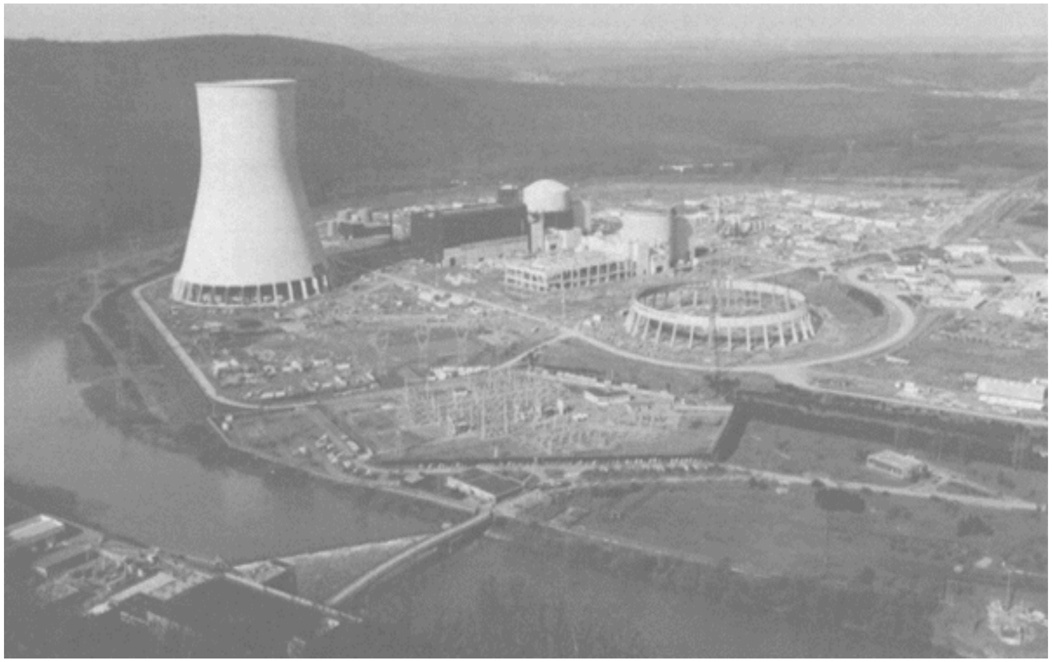


Getting at θ_{13} experimentally: look for disappearance of reactor $\bar{\nu}_e$

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)$$

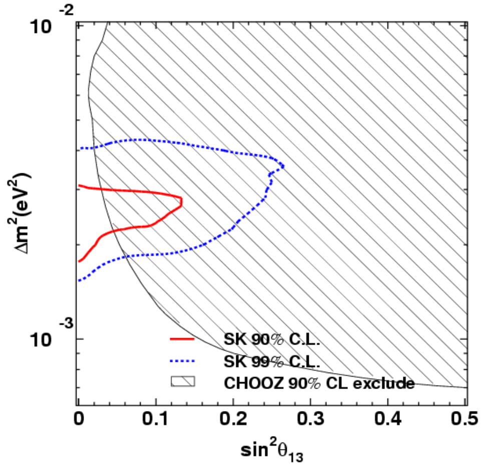
(few MeV, ~ km)

Current best limits for θ_{13} from CHOOZ



$$\bar{\nu}_e \longrightarrow \nu_x$$

$\Rightarrow$ disappearance amplitude < 5-10%

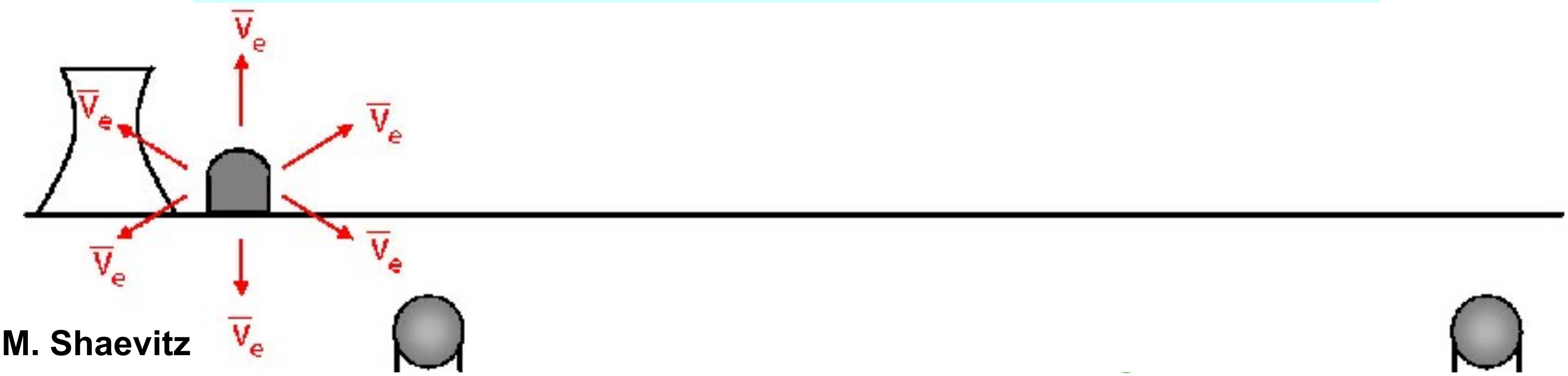


Current generation of proposed experiments: improved reactor disappearance search

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{13} L}{4E} \right)$$

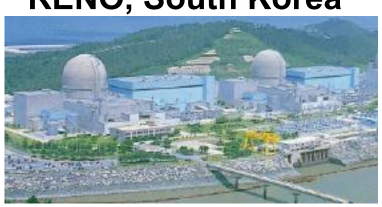
Need <1% systematics!

Cancel systematics w/ 2 detectors



M. Shaevitz

RENO, South Korea



Double CHOOZ, France

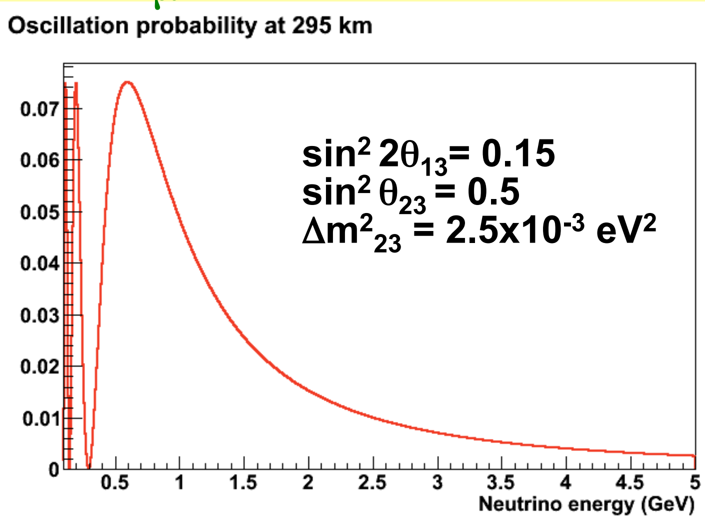
Daya Bay, China

The long-baseline beam approach:

θ_{13} signature: look for *small* ν_e *appearance* in a ν_μ beam

$\nu_\mu \rightarrow \nu_{\mu,\tau}$

$\nu_\mu \dashrightarrow \nu_e$



atmospheric-like wiggling

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{23} L}{4E} \right)$$

small modulation ($\sin^2 2\theta_{13}$)

$\sim 1/2$ ($\sin^2 \theta_{23}$)

for $\Delta m_{23}^2 >> \Delta m_{12}^2$ and $E_\nu \sim L\Delta m_{23}^2$ (in vacuum), δ=0

Hard to measure... known from the CHOOZ reactor experiment that it's a *small* modulation!
Need good statistics, clean sample

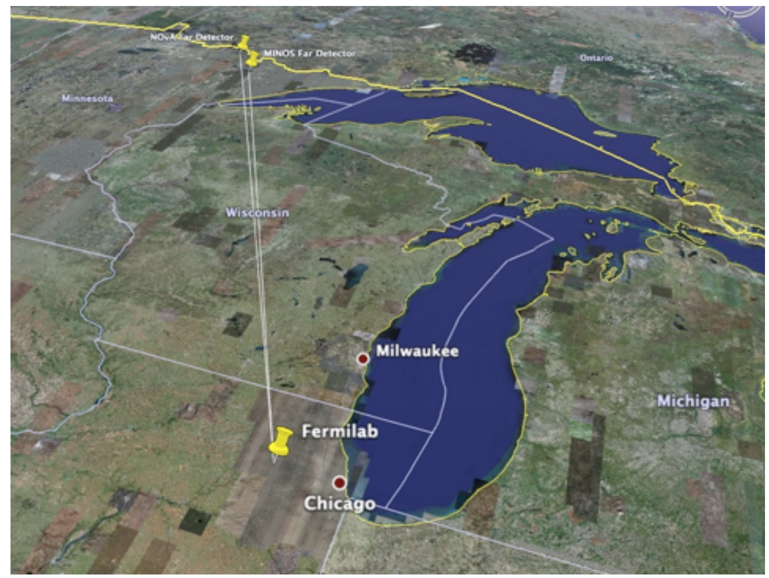
Current Long Baseline Beam Projects

Physics goals : precision 2-3 mixing, non-zero θ_{13} search

T2K: "Tokai to Kamioka"

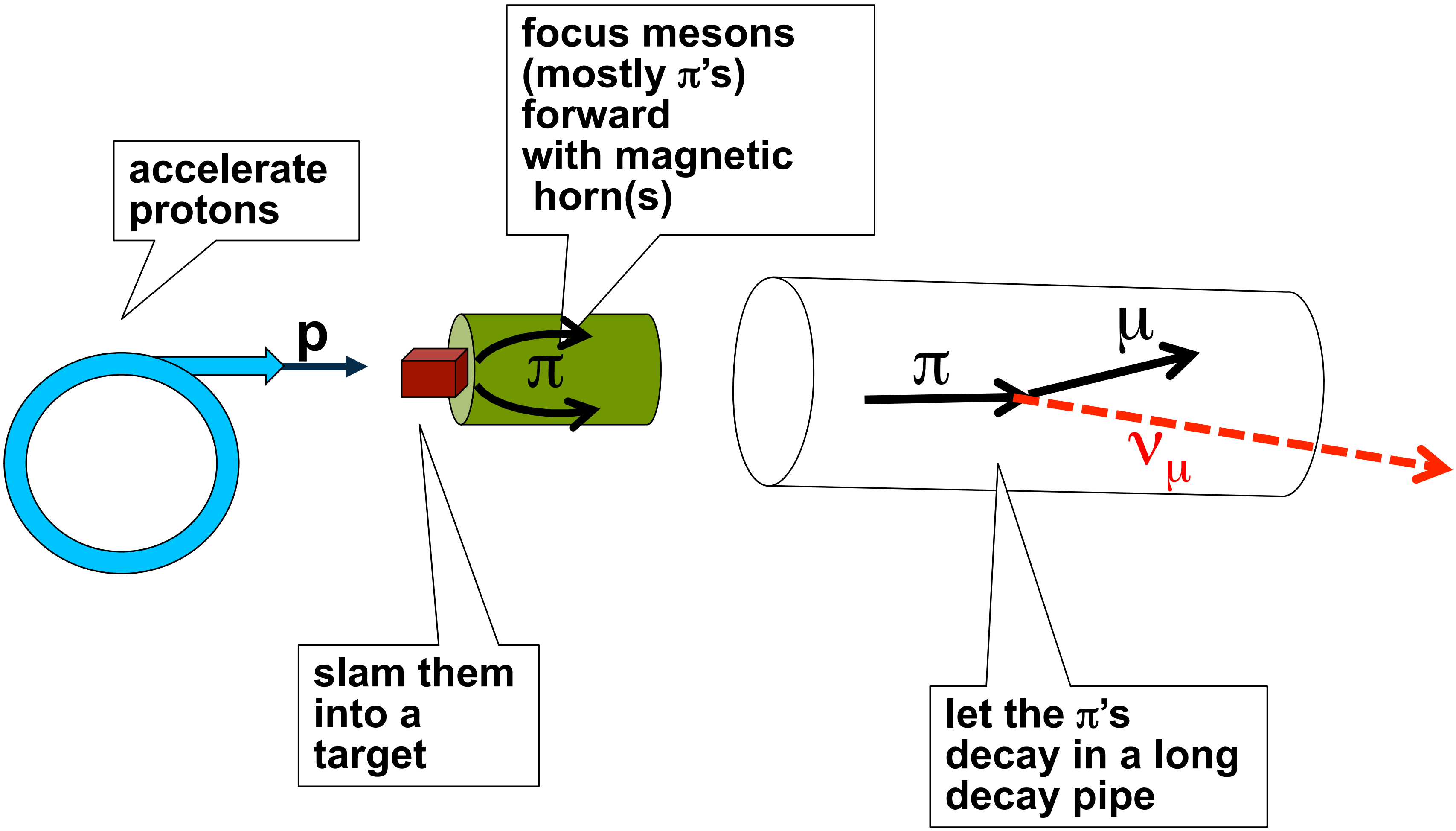
Pre-existing detector: Super-K
New beam from J-PARC (~750 kW)
295 km baseline
Water Cherenkov detector

NOνA at NuMi

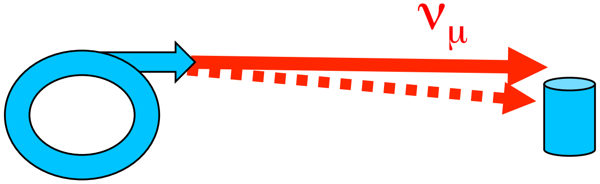


Pre-existing beam:
Fermilab NuMi upgrade
810 km baseline
Scintillator tracking detector

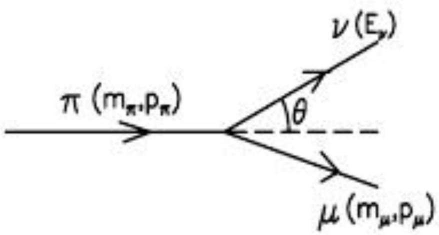
How To Make a Neutrino Beam



Off-axis beams



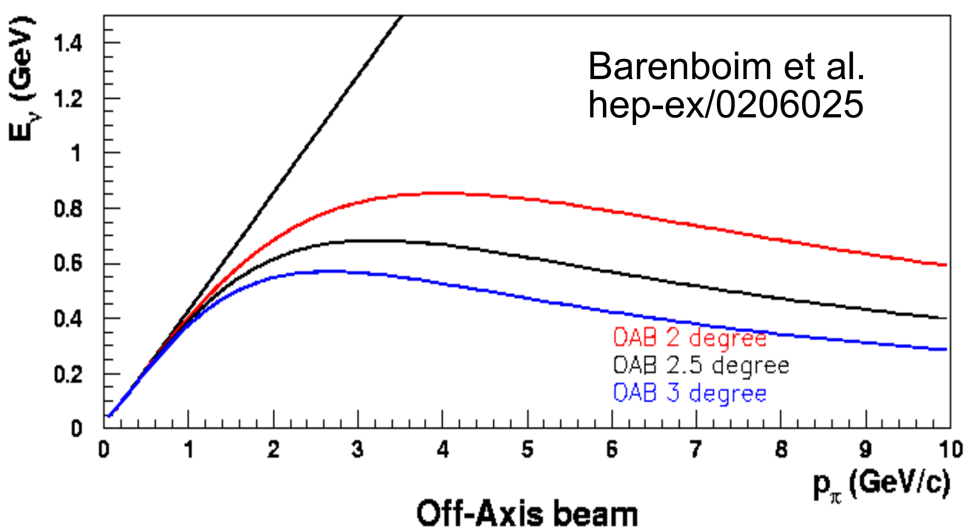
2-body pion decay kinematics

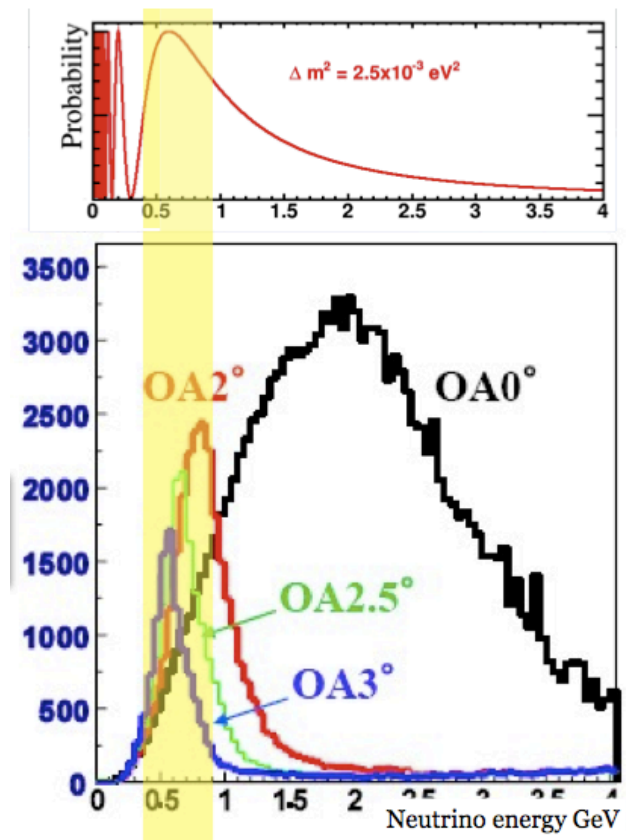


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

Off-axis, ν energy becomes relatively independent of π energy

Get *more sharply peaked* ν energies, and more flux at the oscillation minimum
➔ good for background reduction and oscillation fits





The T2K (Tokai to Kamioka) Experiment

Super-K

J-PARC

- second generation long baseline experiment
  (following K2K, MINOS)

- high-intensity (750 kW) 2.5^{o} off-axis ν_μ beam from J-PARC
  295 km to Super-K, a large water Cherenkov detector

The T2K Collaboration

Canada
TRIUMF
U of Alberta
U of B Columbia
U of Regina
U of Toronto
U of Victoria
U Winnipeg
York U

Switzerland
Bern
ETH Zurich
U of Geneva

Poland
NCBJ
IFJ PAN
T U Warsaw
U of Silesia
Warsaw U
Wroclaw U

Russia
INR

Korea
Chonnam Nat'l U
Dongshin U
Seoul Nat'l U

Italy
INFN Bari
INFN Roma
Napoli U
Padova U

France
CEA Saclay
IPN Lyon
LLR E Poly
LPNHE-Paris

Spain
IFIC, Valencia
IFAE, Barcelona

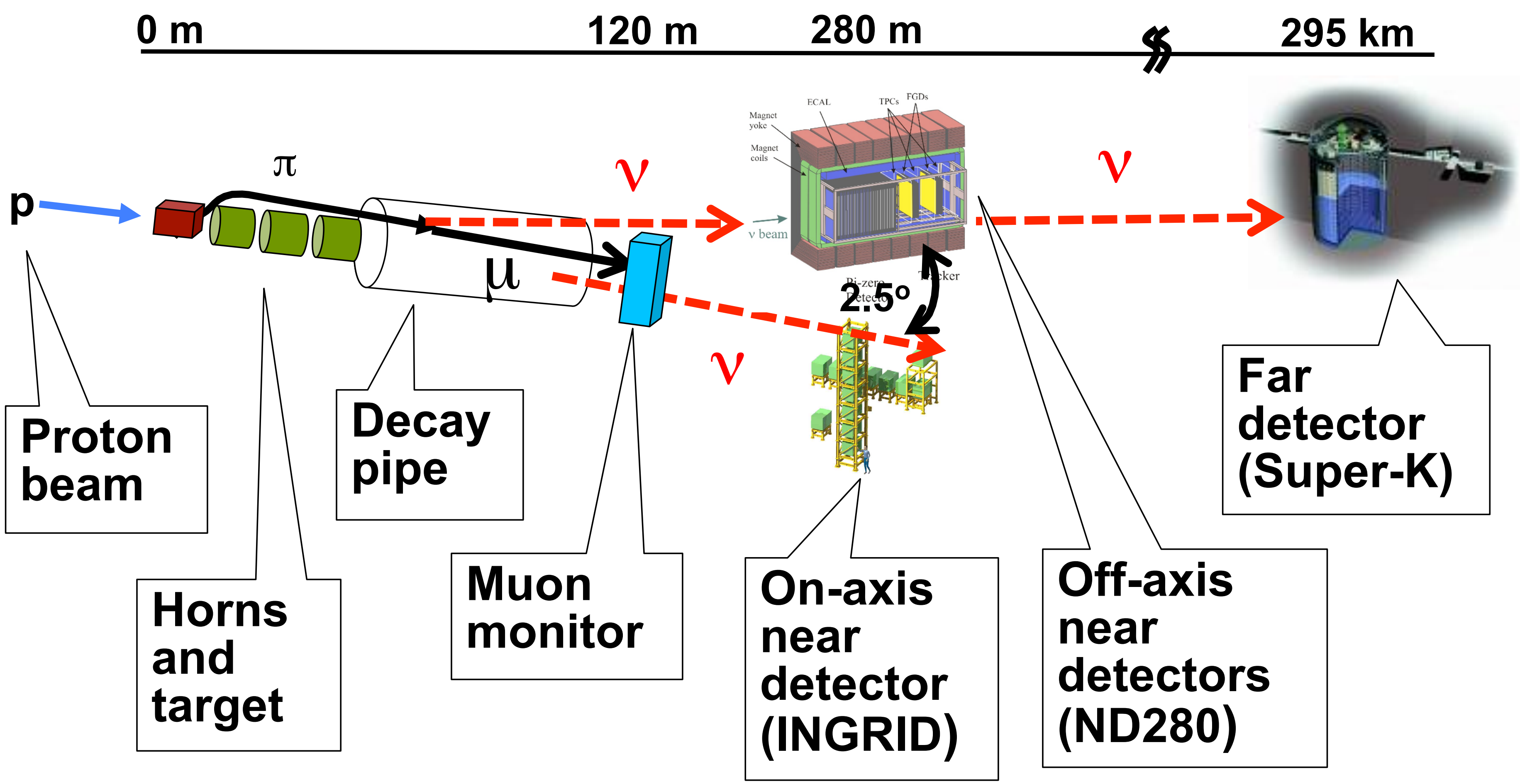
Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U
Kyoto U
Miyagi U of Ed
Osaka City U
U of Tokyo

USA
Boston U
Colorado State U
Duke U
Louisiana State U
Stony Brook U
U of California, Irvine
U of Colorado
U of Pittsburgh
U of Rochester
U of Washington

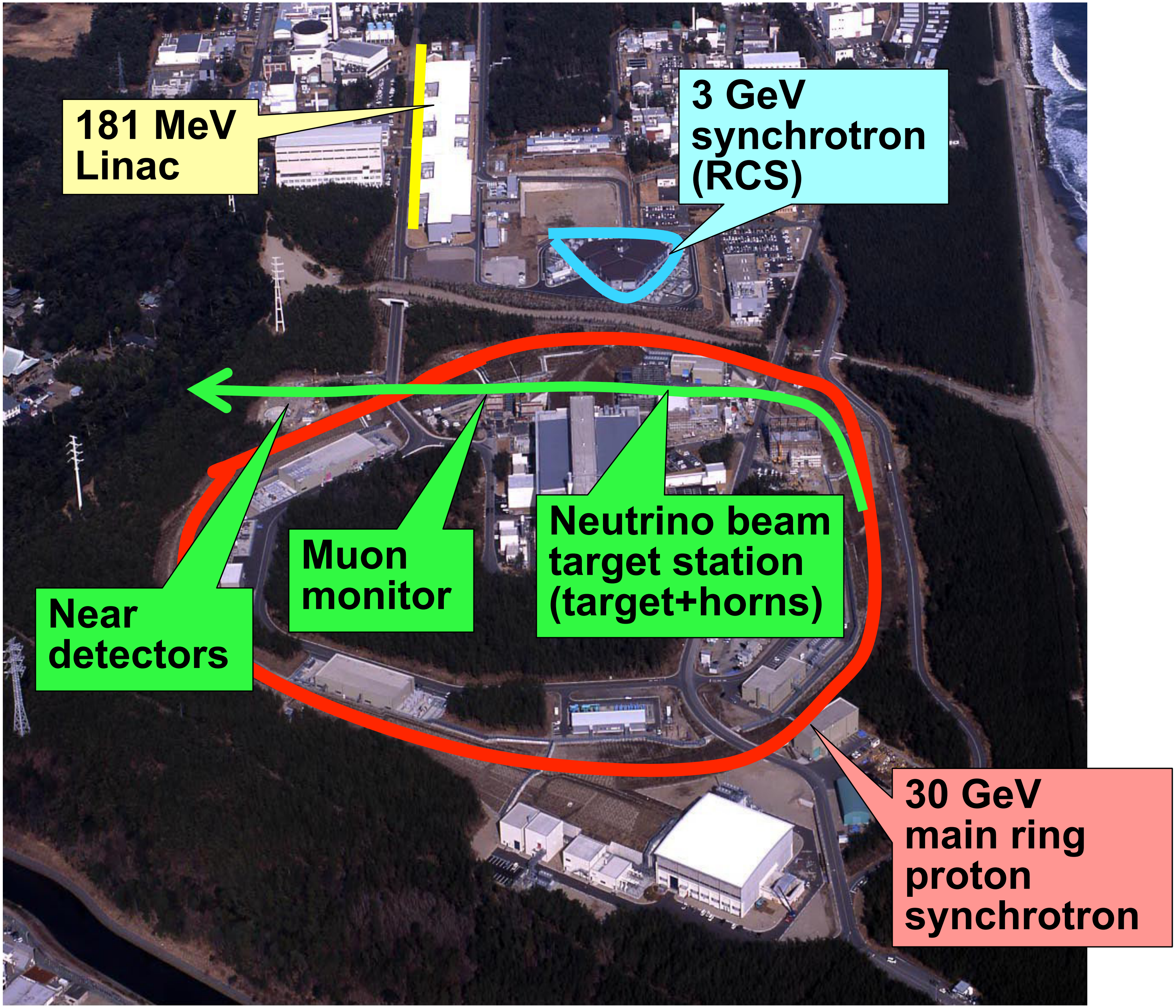
UK
U of Oxford
Imperial C London
Lancaster U
Queen Mary U of L
Sheffield U
STFC/RAL
STFC/Daresbury
U of Liverpool
U of Warwick

Germany
RWTH Aachen U

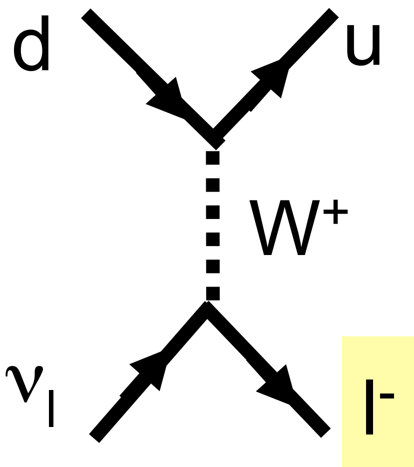
T2K Experiment Overall Design



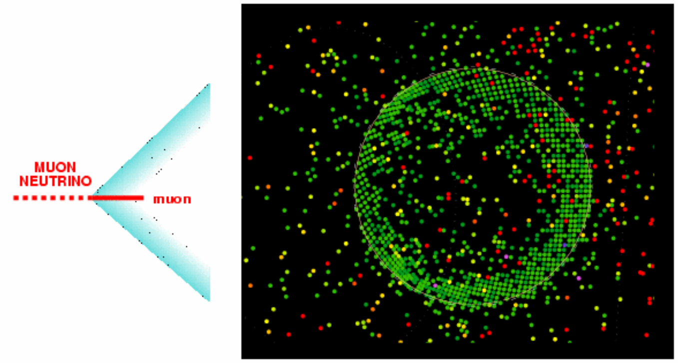
Near detector suite at 280 m for beam characterization
➔ predict flux/spectrum at SK for oscillation measurement

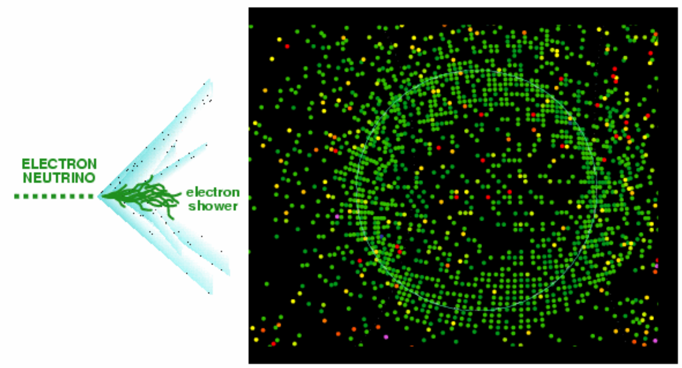

181 MeV Linac
3 GeV synchrotron (RCS)
Neutrino beam target station (target+horns)
Muon monitor
Near detectors
30 GeV main ring proton synchrotron

Signature of non-zero θ_{13} at far detector

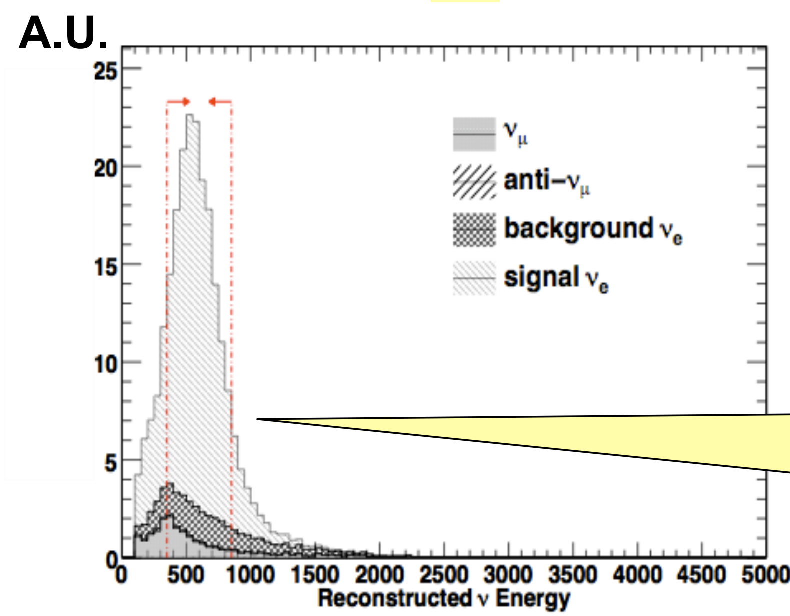


select charged-current quasi-elastic events (~single ring);
vertex, energy, direction from Cherenkov light



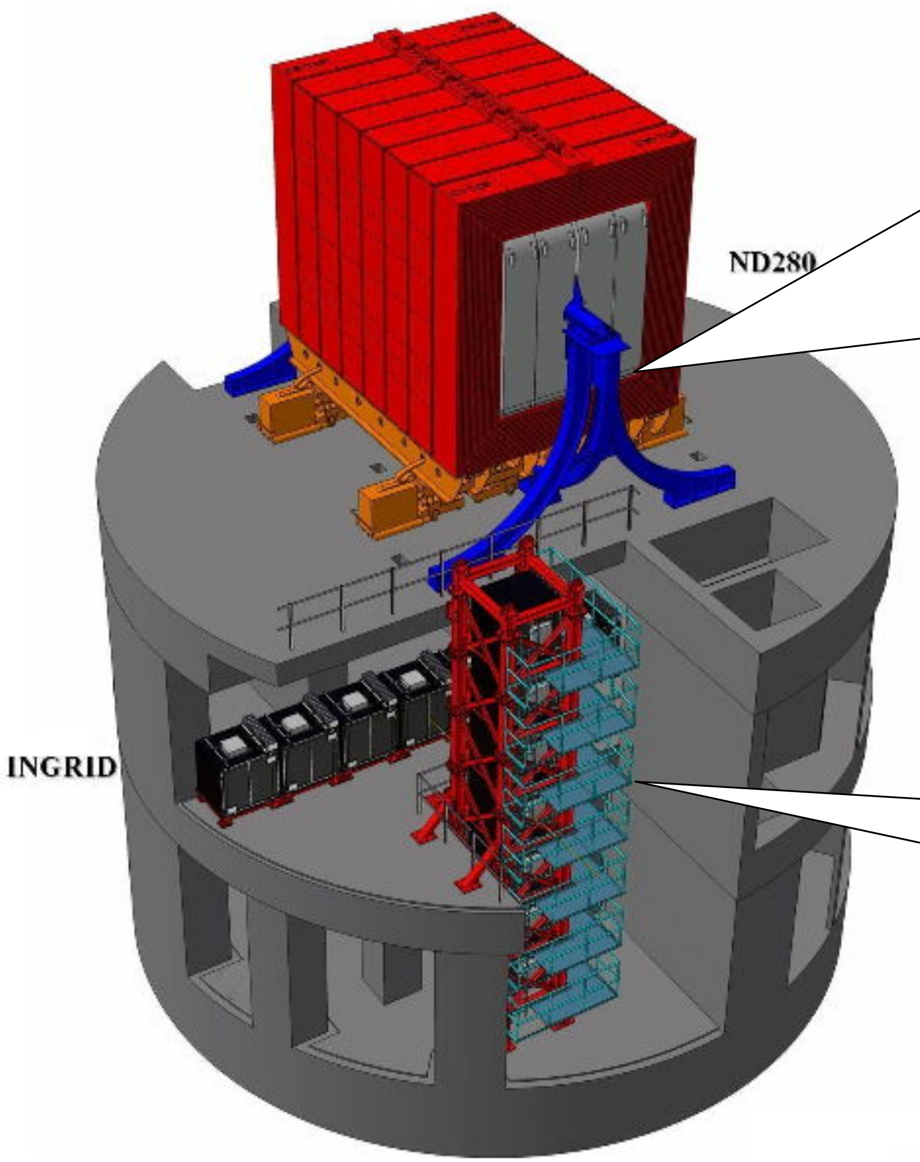


$$\nu_l + N \rightarrow l^{\pm} + N'$$



Look for electron appearance:
single fuzzy rings excess on top of background, with expected spectrum

Near detectors at 280 m



Off-axis detector complex

- fine-grain trackers
- 0.2 T magnetic field (old UA1/NOMAD magnet)
- normalization/ background characterization for oscillation physics
- cross-section studies

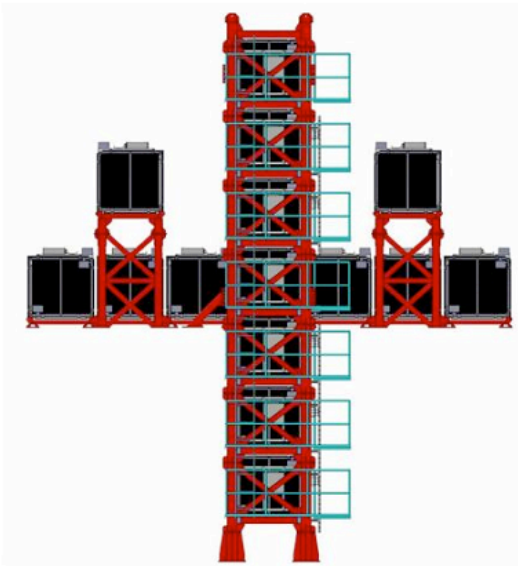
On-axis: INGRID

- iron+scintillator
- beam profile monitoring

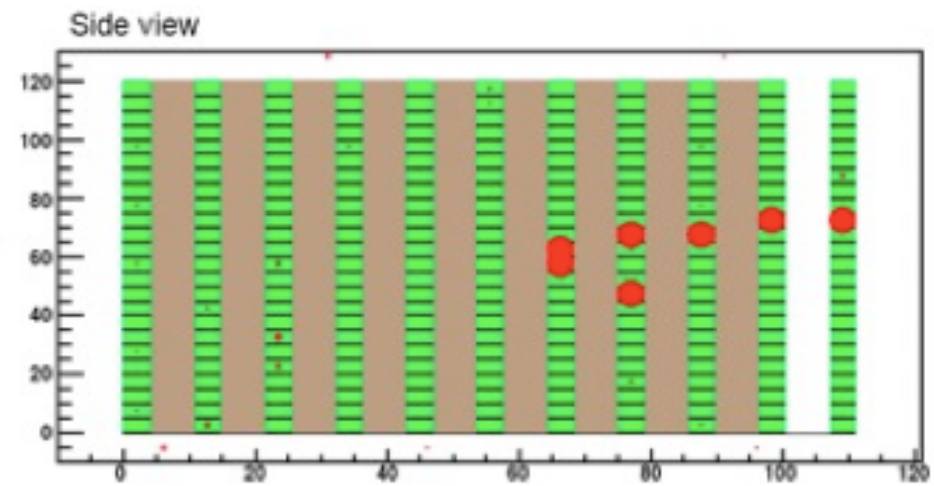
INGRID

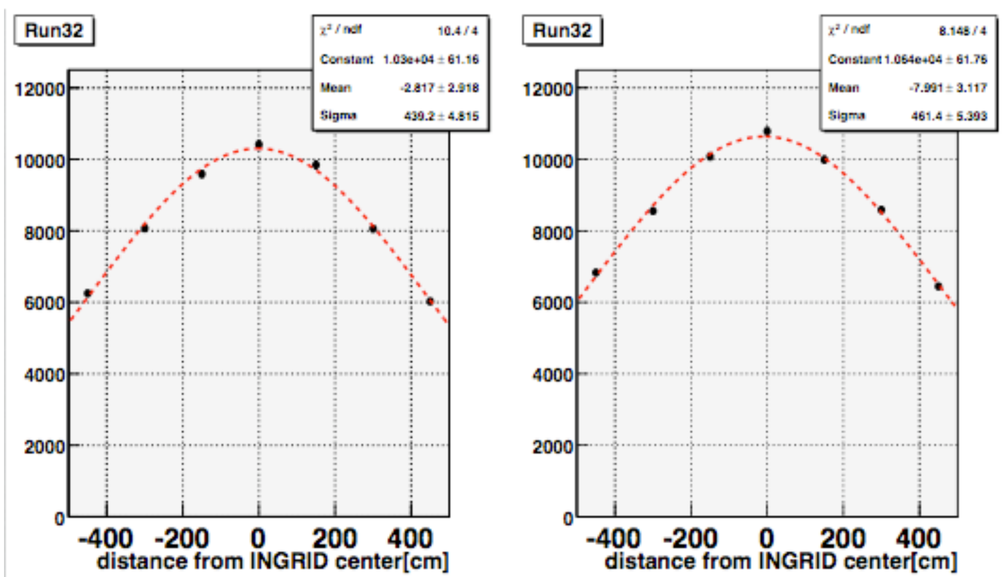
on-axis neutrino beam monitoring

~10K interactions/day at full power



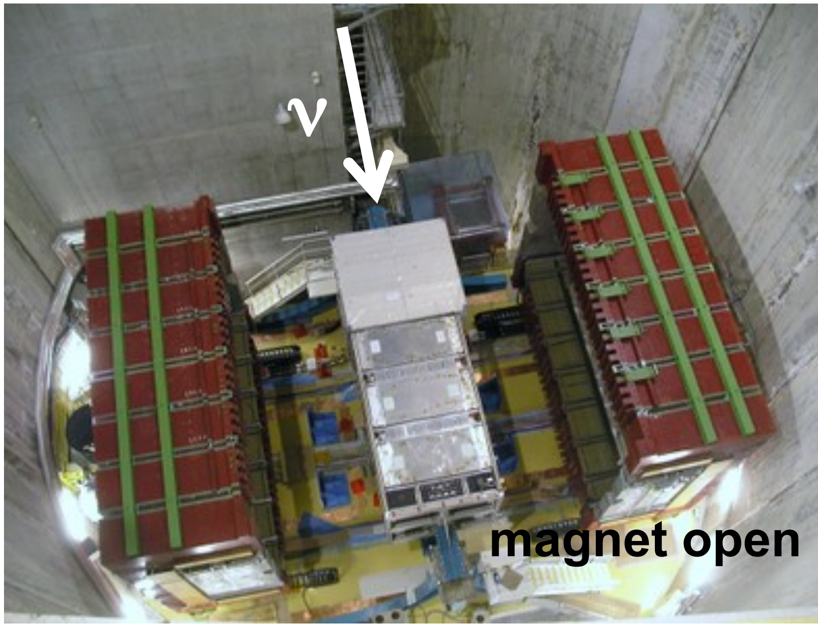
ν beam →

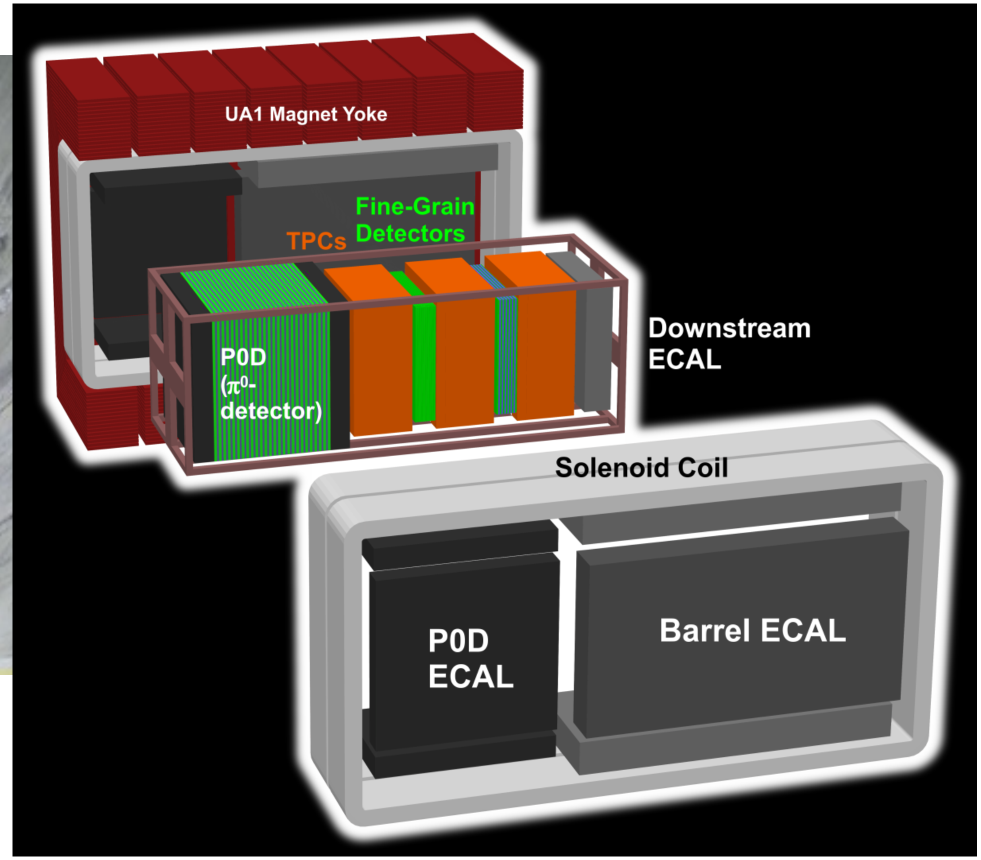




measured beam profile; ~7 cm resolution

ND280 complex

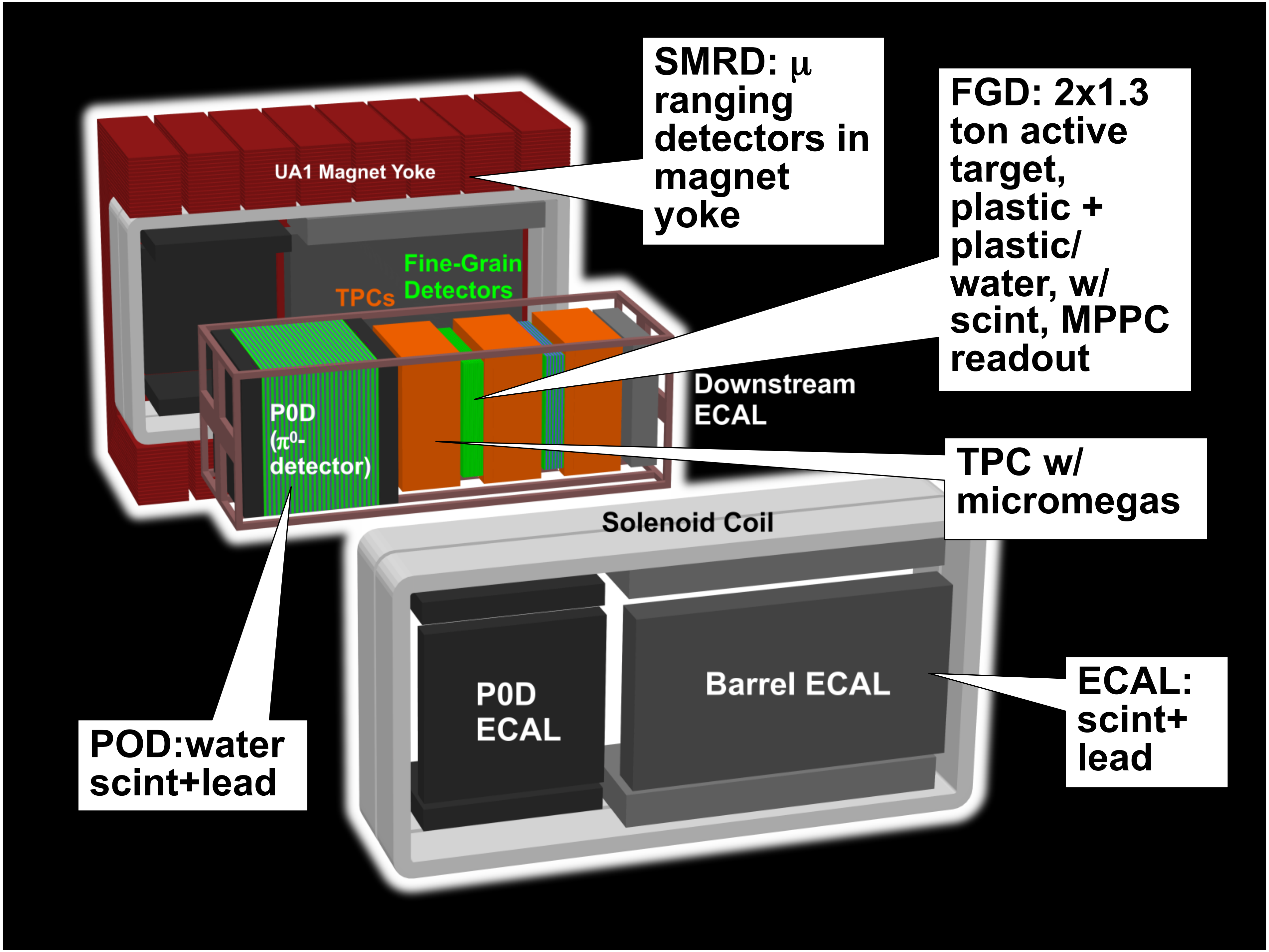




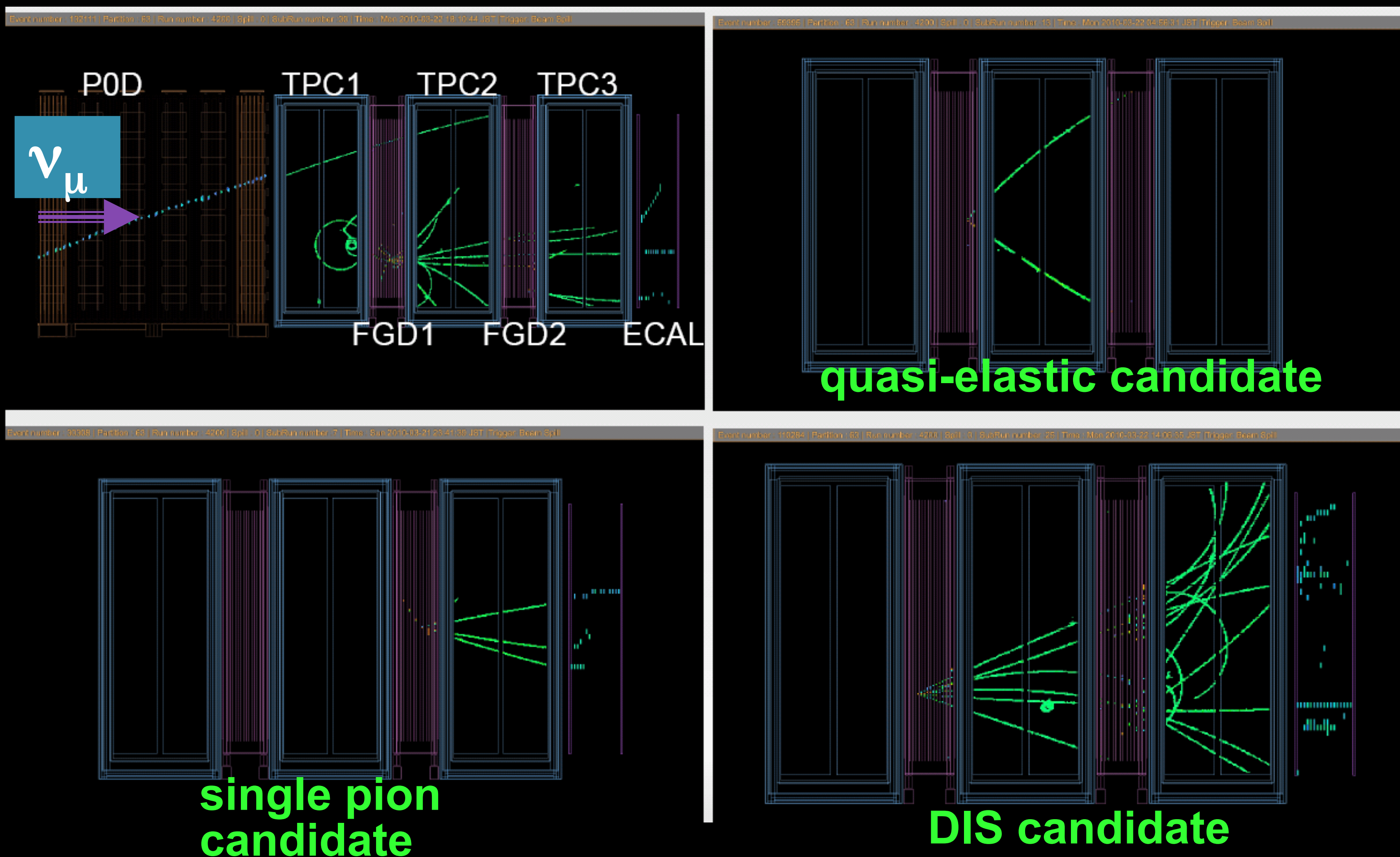
- ν_μ and ν_e flux and spectrum for extrapolation to SK
- CC cross-sections, for signal and bg

} FGD, TPC

- π^0 production cross-sections ➡ POD, FGD, ECAL

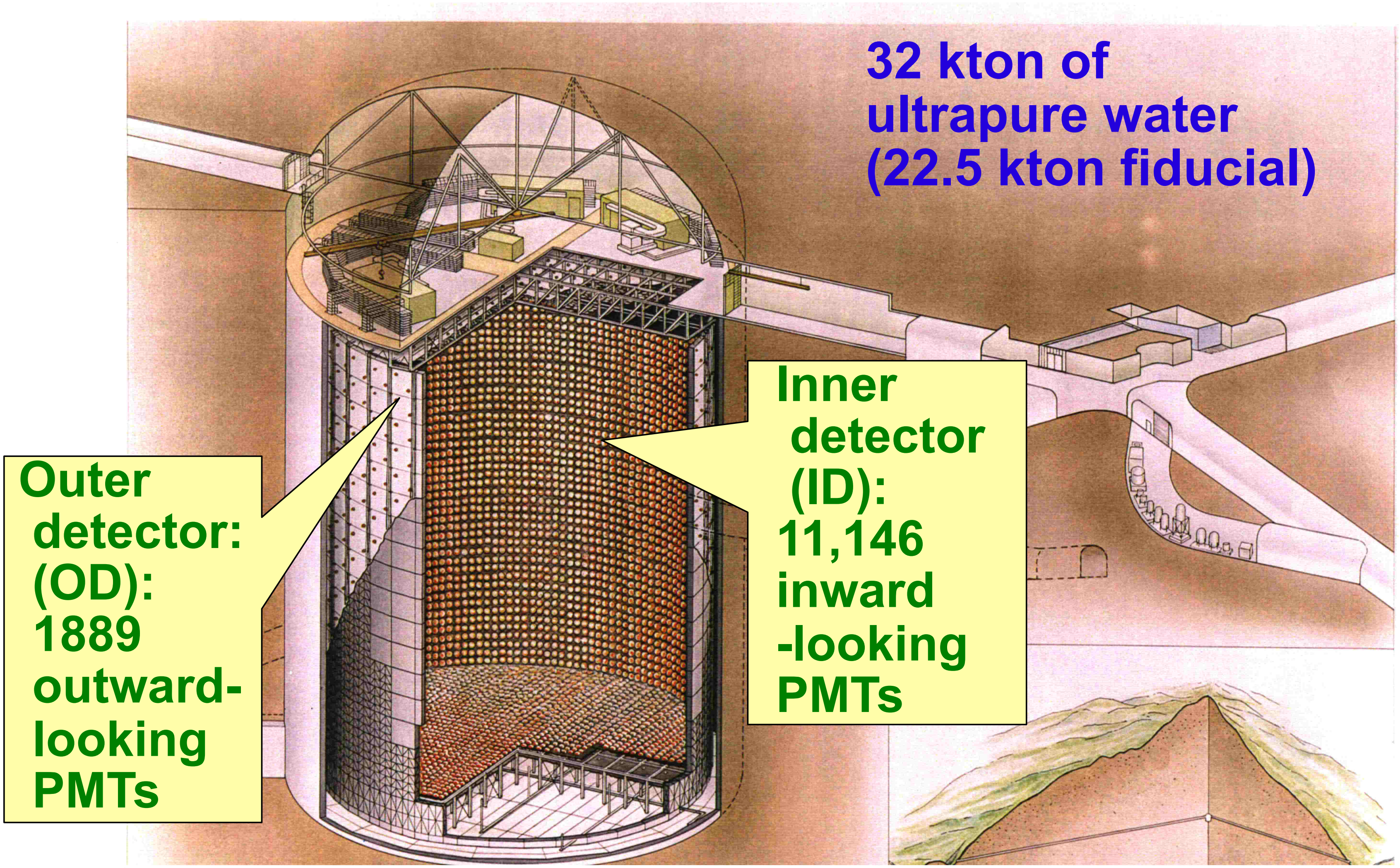

SMRD: μ ranging detectors in magnet yoke
UA1 Magnet Yoke
FGD: 2x1.3 ton active target, plastic + plastic/ water, w/ scint, MPPC readout
Fine-Grain Detectors
TPCs
Downstream ECAL
P0D (π0-detector)
TPC w/ micromegas
Solenoid Coil
P0D ECAL
Barrel ECAL
ECAL: scint+ lead
POD:water scint+lead

Sample ND280 event displays



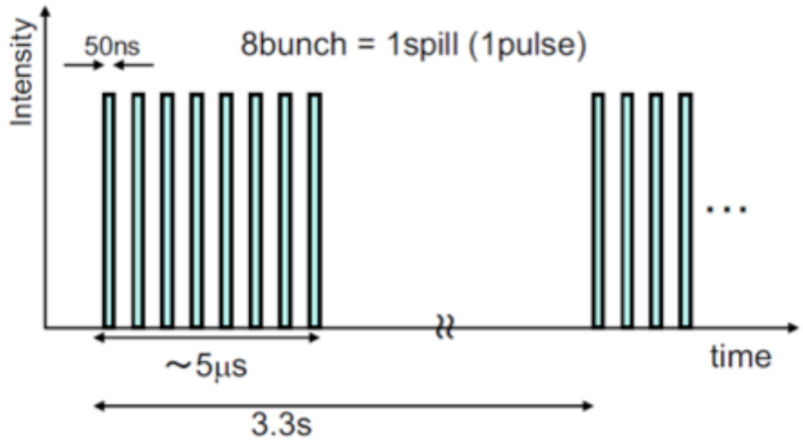
Super-Kamiokande

Water Cherenkov detector in Mozumi, Japan



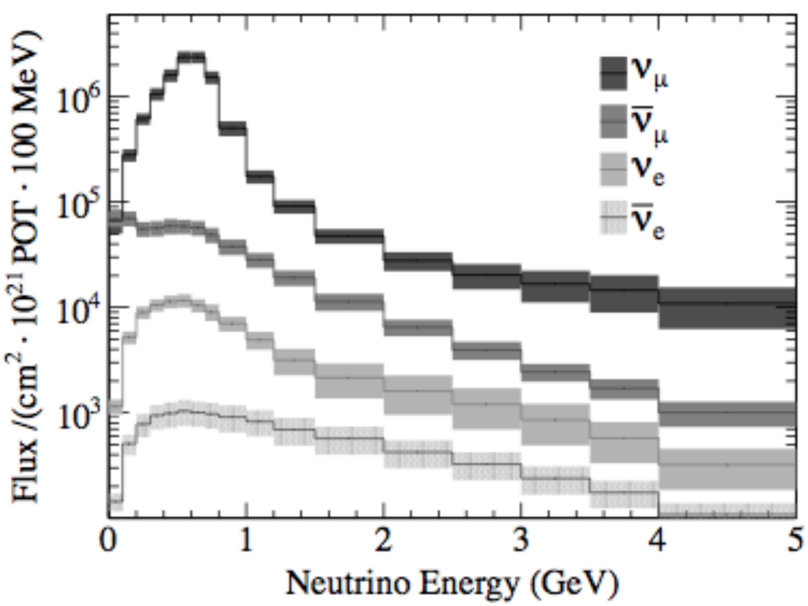
Refurbished in 2008 with new electronics; now running as 'Super-K IV'

Neutrino beam properties



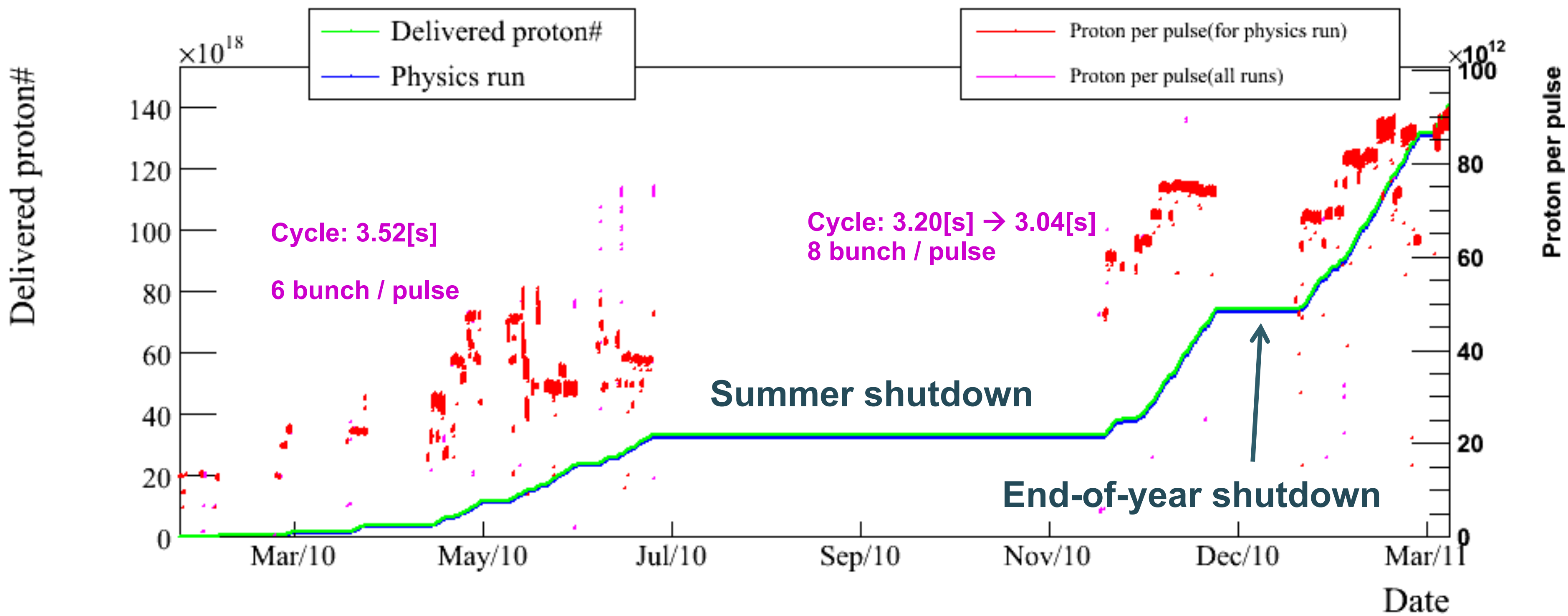
8 bunches
(6 for first running period)

Spills matched to events by GPS timing at Super-K



Beam peaked at ~600 MeV
(optimized for oscillation physics)

T2K neutrino beam history

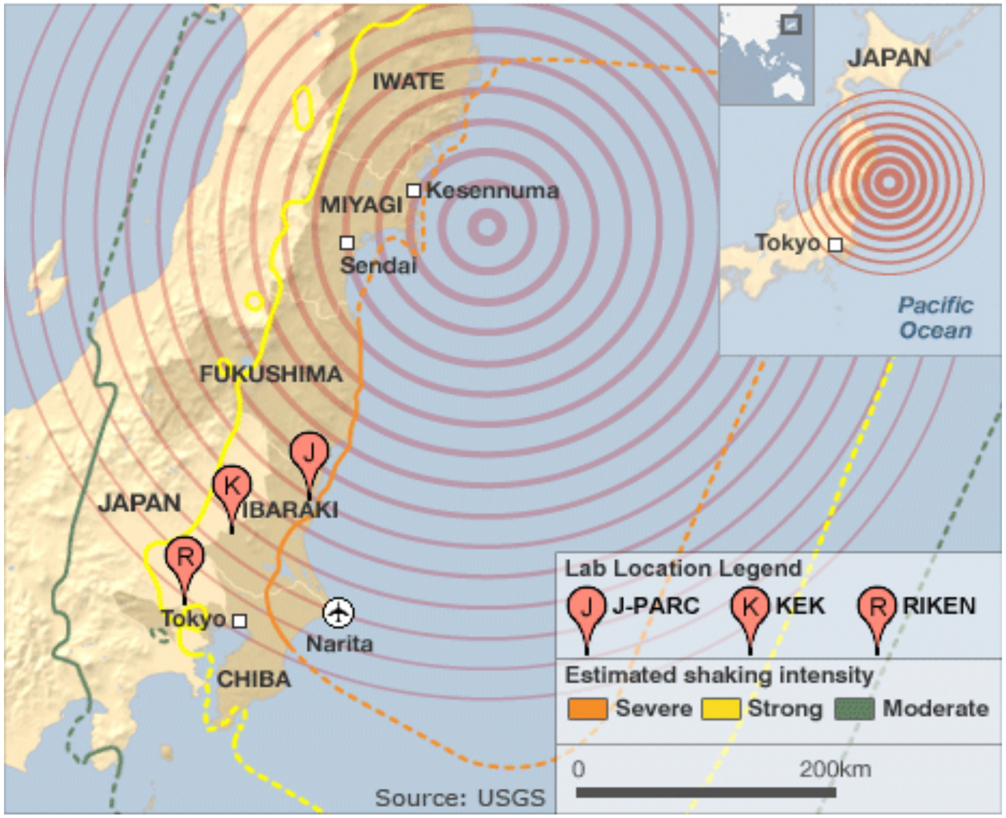


1.43×10^{20} pot by March 11, 2011

(~2% of eventual goal)

Great East Japan Earthquake

- magnitude 9 on Richter scale, >6 at J-PARC
- tsunami did not reach J-PARC (thanks to barrier)
- no reported injuries to any J-PARC or T2K personnel
- no effect at all on SK

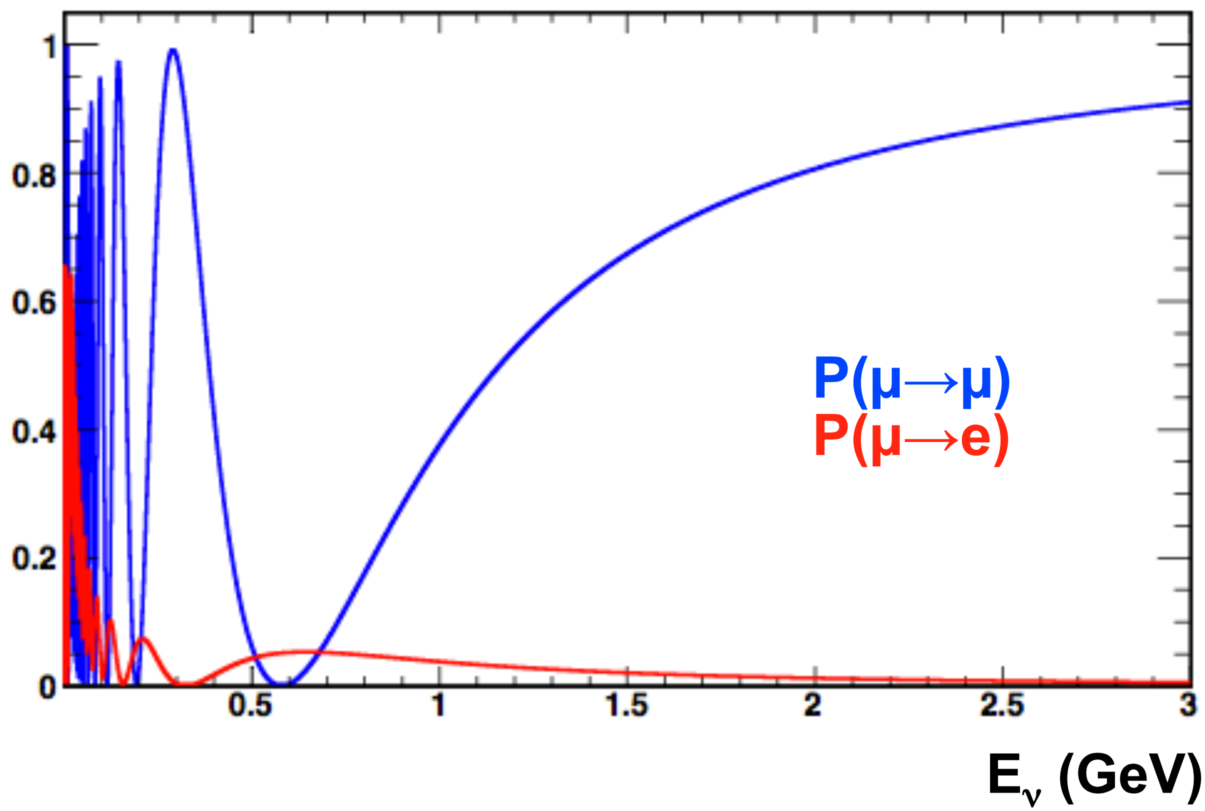


- damage to J-PARC infrastructure and accelerator has been repaired
- near detectors required only minor repairs, now complete
- first beam in late Dec 2011 (no horn)
- T2K run scheduled for ~4 months prior to summer 2012 shutdown

T2K Physics Results So Far

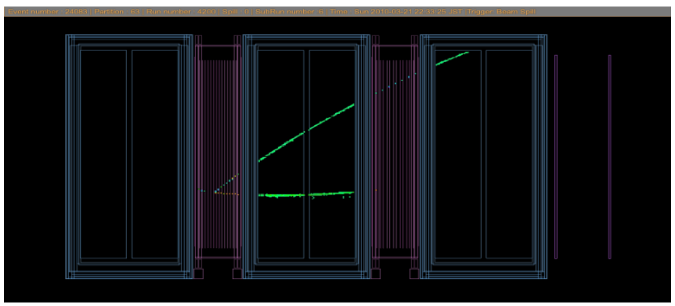
ν_e **appearance:** search for non-zero θ_{13}

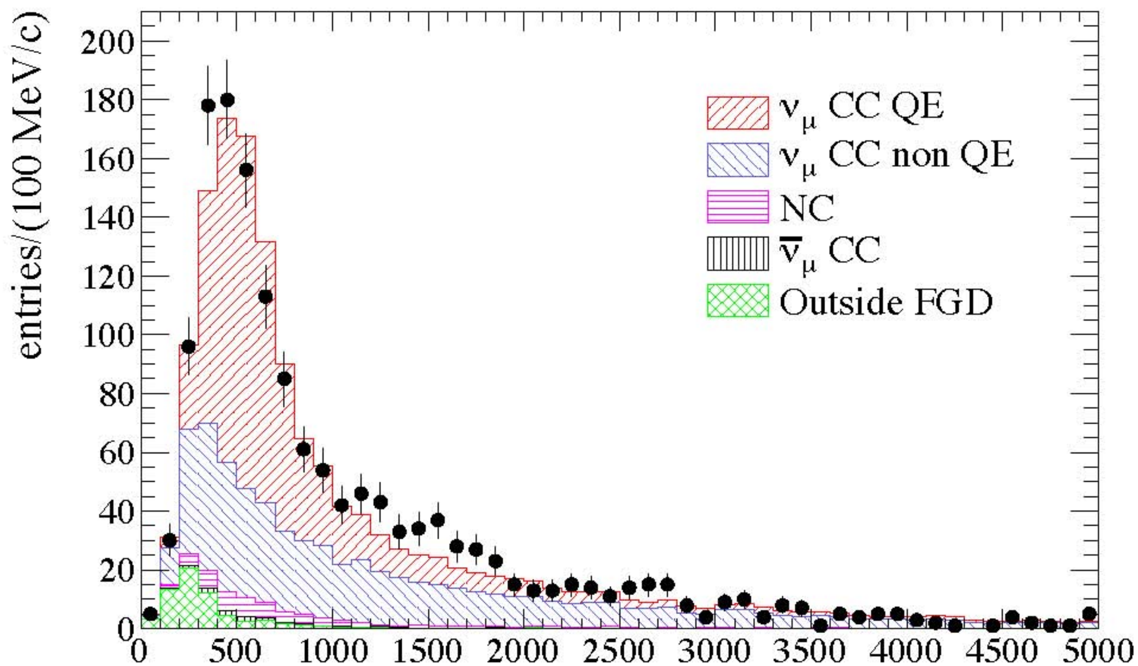
ν_μ **disappearance:** (eventually) precision 2-3 parameters



ND280 off-axis analysis

Charged current inclusive muon event generated in FGD1 or FGD2 are selected; event rate and momentum distribution are compared with MC





$R_{data/MC}$ = 1.036 ± 0.028(stat.) $^{+0.044}_{-0.037}$ (det. syst.) ± 0.038 (phys. model)

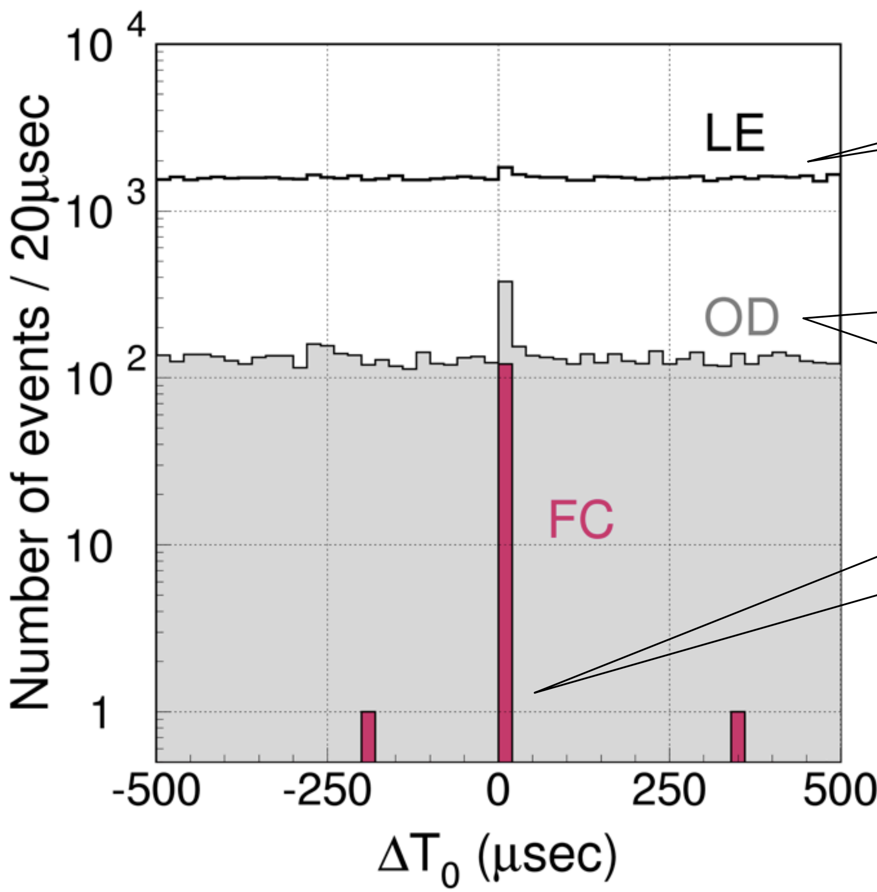
- Only normalization is used in the present analysis
- More ND280 work in progress

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

T2K Event Selection in SK

ΔT_0 : relative event timing to the spill timing

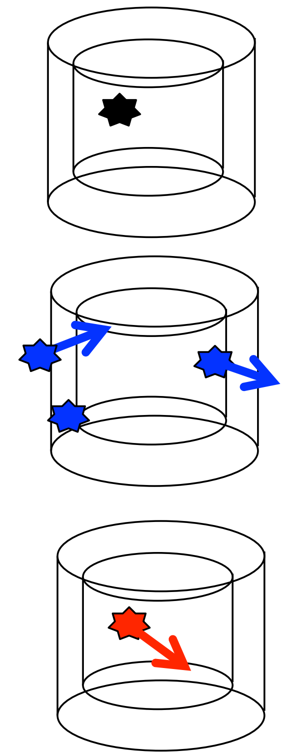
ΔT_0 : -500 ~ +500 μsec



Low energy: for NC γ excitation search

Outer detector light: entering, exiting or contained in OD

Fully contained: light in ID only FV: 2 m from wall



Off-timing
OD/LE rate is flat.
2 off-timing FC events

T2K FC event selection in Super-K

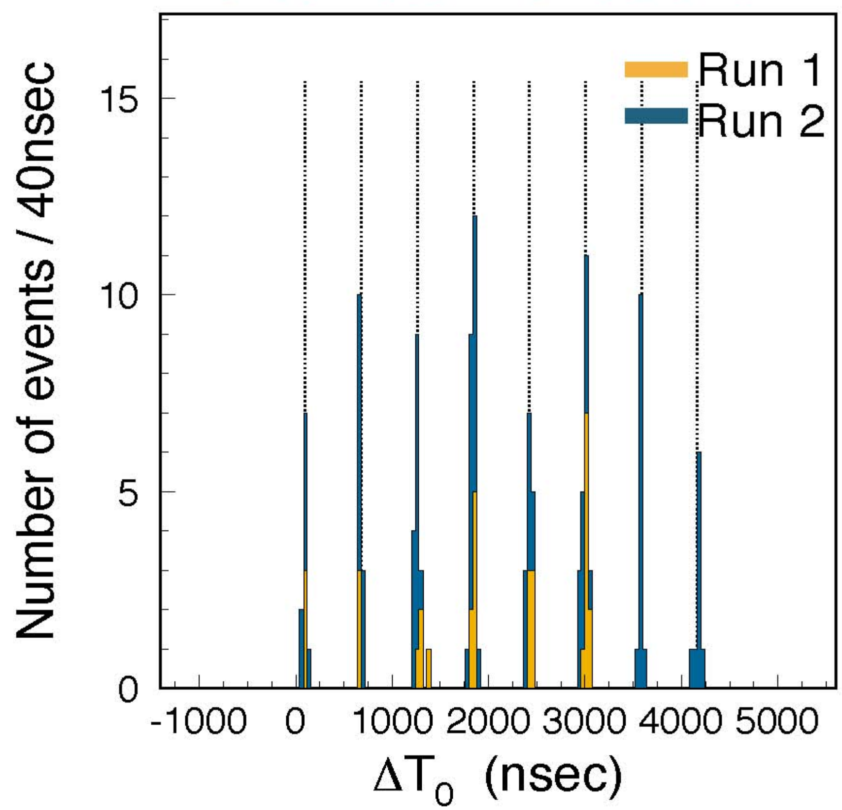
1. Total energy deposit in the inner counter is >30 MeV
2. No outer counter activity or pre-activity
3. Time correlation with the neutrino beam

Final FC selected events:

33 events in Jan 2010 - Jun 2010

121 events in Jan 2010 - Mar 2011 (88 in FV)

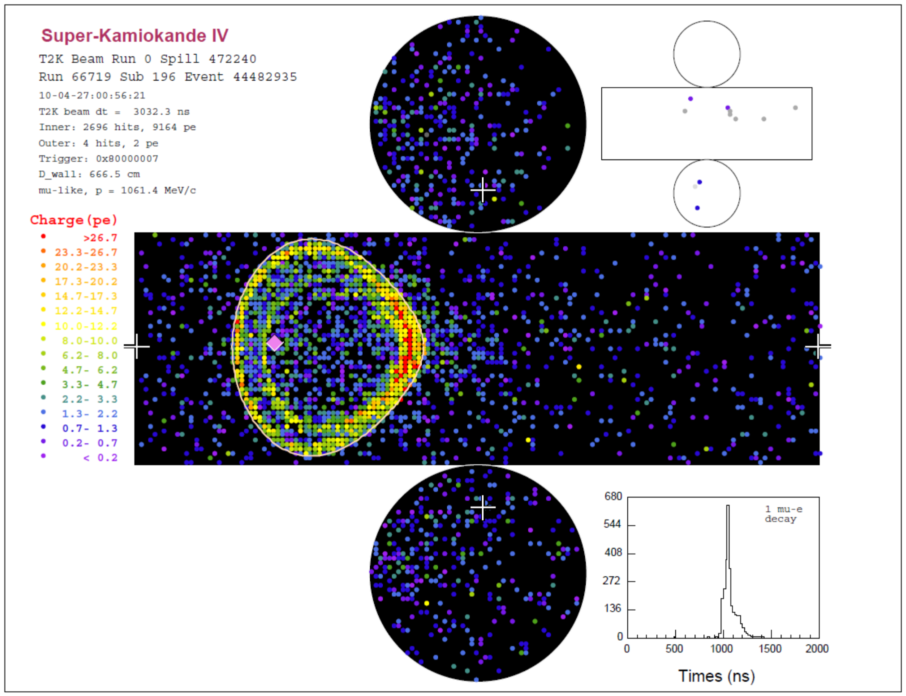
(atmospheric bg: 0.003 events)

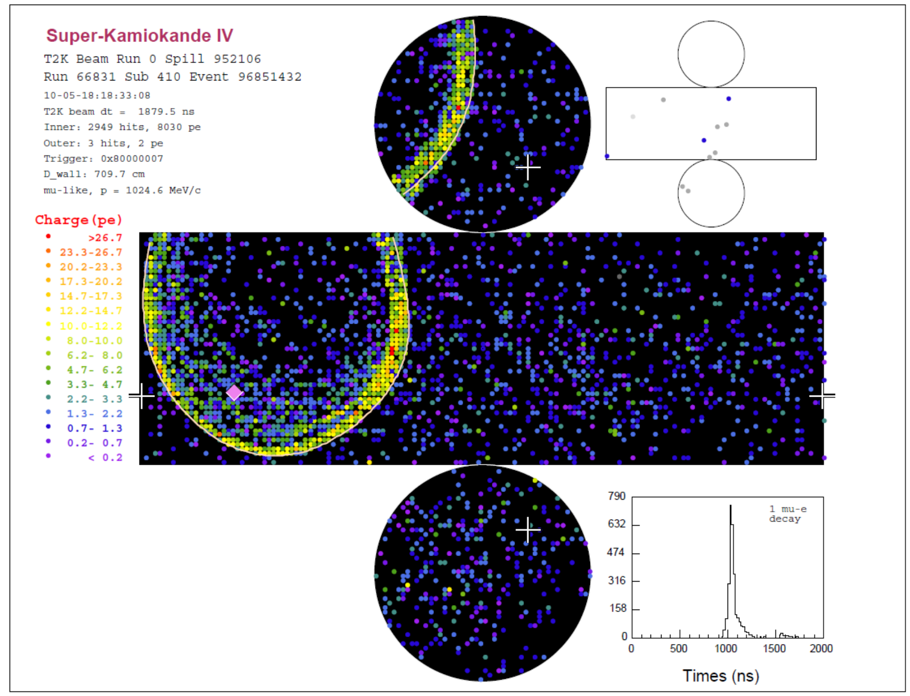


Number of Super-K events observed in the T2K, 1.431×10^{20} POT

	Data	MC		BG
		No oscillation	2-flavor osc. $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	BG ($12\mu s$ window)
Fully-Contained	**121**	246	109	0.023
Fiducial Volume, $E_{vis} > 30MeV$	**88**	166	74.1	0.0028
Single-ring μ-like (P_μ>200MeV/c)	**33 (33)**	112 (111 ± 16)	32.0 (31.8 ± 5.3)	-
Single-ring e-like (P_e>100MeV/c)	**8 (7)**	8.5 (6.8 ± 3.0)	6.7 (5.8 ± 2.2)	-
Multi-ring	**47**	45.3	35.4	-

Event displays (single-ring μ-like events)





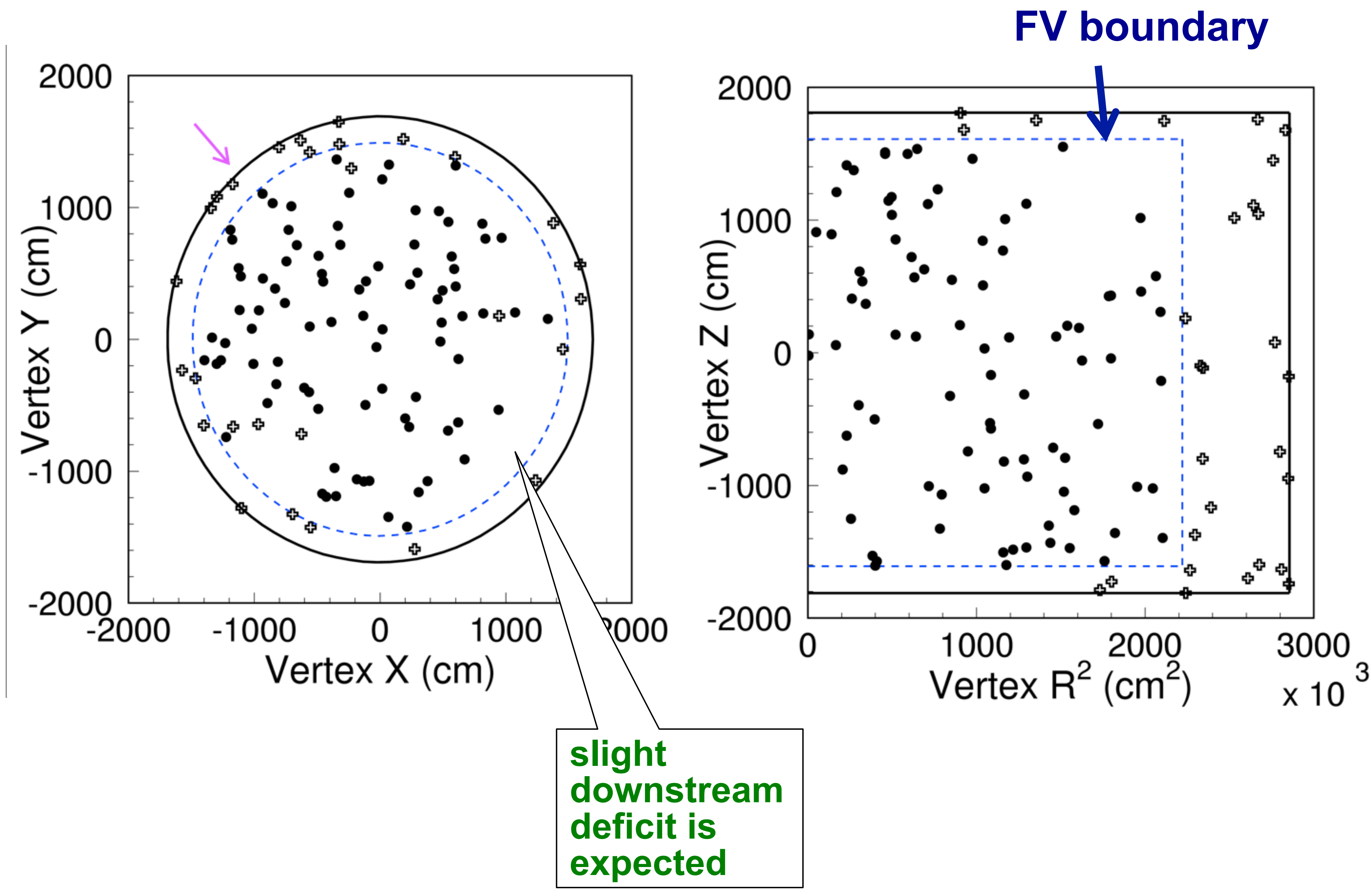
Pμ = 1061 MeV/c

1 decay-e

Pμ = 1025 MeV/c

1 decay-e

Vertex distributions for FC events



Backgrounds to electron neutrino appearance

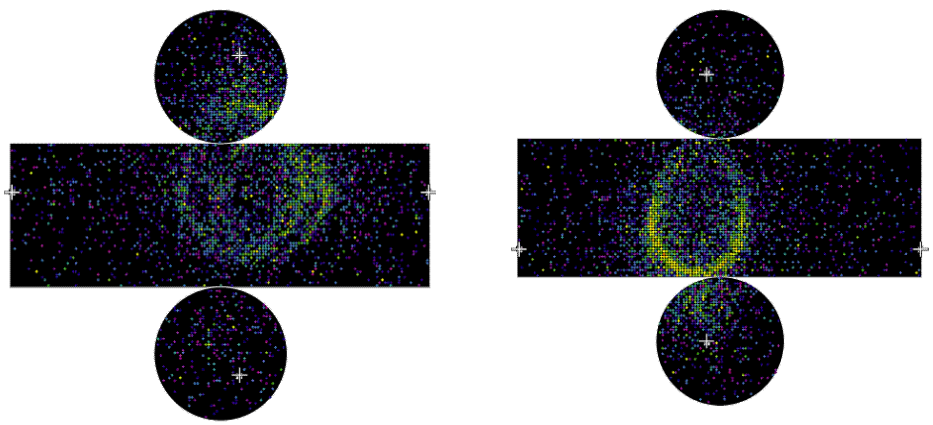
$\pi^+ \rightarrow \mu^+ \nu_\mu$
$\quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

$K^0_L \rightarrow \pi^+ e^- \nu_e$

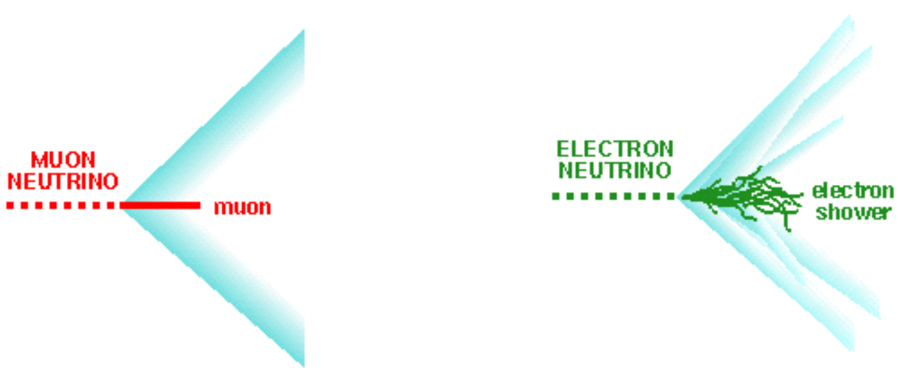
DECAY PIPE

Intrinsic beam ν_e contamination



NC single pions
$\pi^0 \rightarrow \gamma\gamma$

- -asymmetric decay
- -both γ boosted forward
- -one γ near wall



ν_μ mis-id

Electron neutrino selection cuts

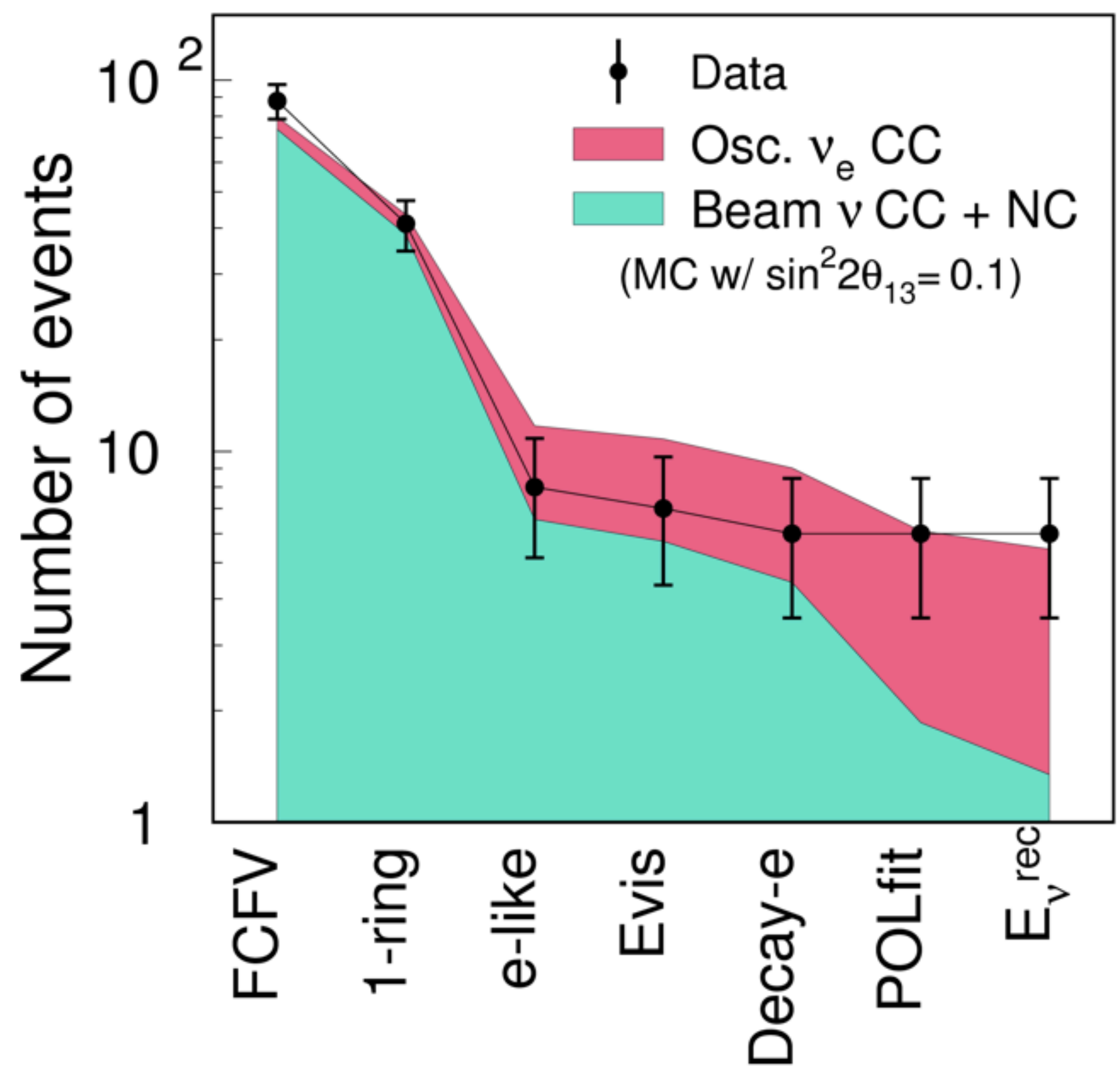
(predefined cuts)

0. Fully contained in SK
1. In fiducial volume (200 cm from wall)
2. Single ring
3. e-like
4. Visible energy > 100 MeV
5. No decay electron
6. Reconstructed invariant mass < 105 MeV/c^2 (specialized π^0 fitter)
7. Reconstructed energy < 1250 MeV

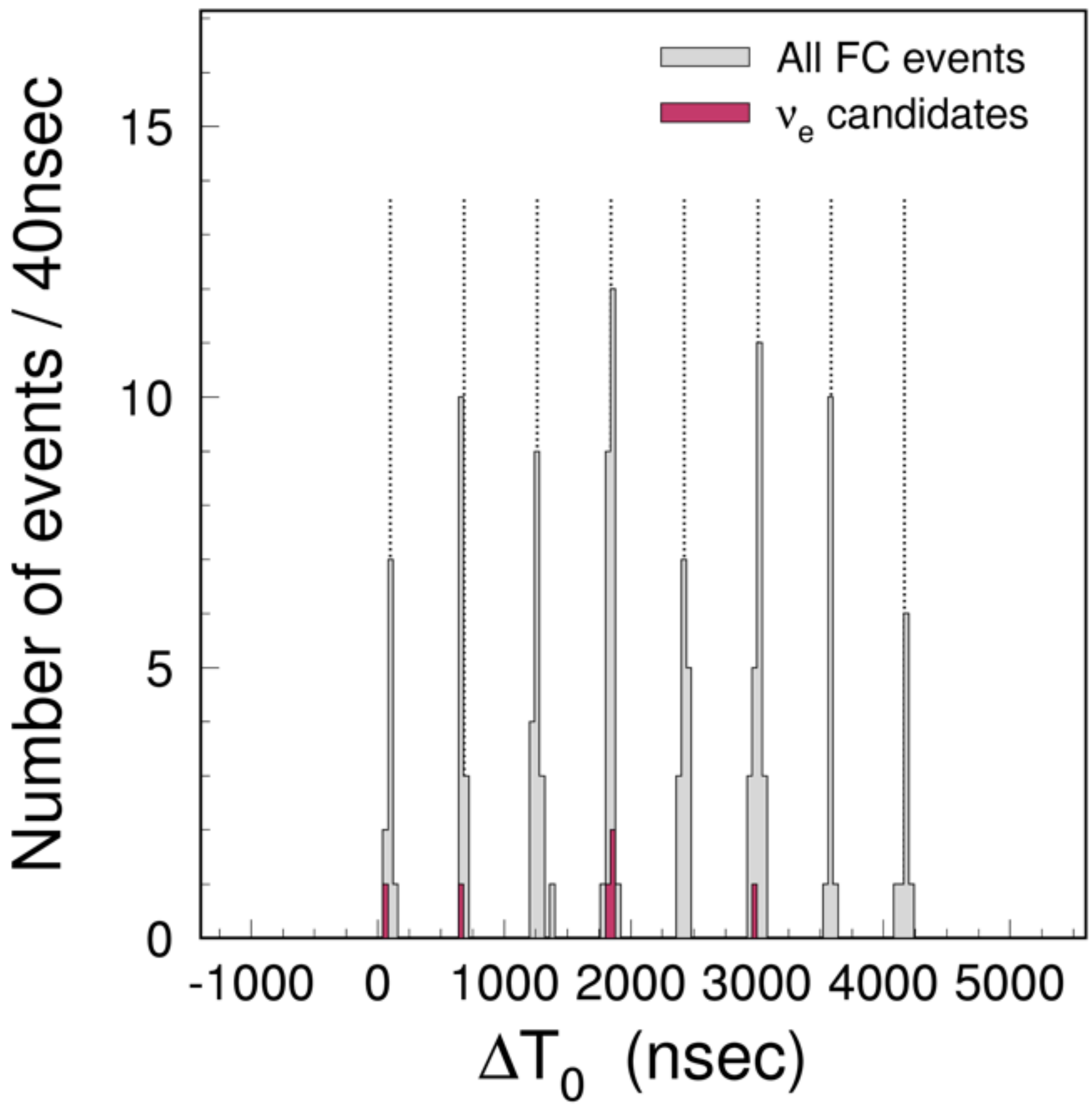
	Data	ν_μCC	ν_eCC	NC	$\nu_\mu \to \nu_e$CC
(0) interaction in FV	n/a	67.2	3.1	71.0	6.2
(1) fully-contained FV	88	52.4	2.9	18.3	6.0
(2) single ring	41	30.8	1.8	5.7	5.2
(3) *e*-like	8	1.0	1.8	3.7	5.2
(4) E_{vis} > 100 MeV	7	0.7	1.8	3.2	5.1
(5) no delayed electron	6	0.1	1.5	2.8	4.6
(6) non-π^0-like	6	0.04	1.1	0.8	4.2
(7) E_ν^{rec} < 1250 MeV	6	0.03	0.7	0.6	4.1

6 events pass ν_e cuts

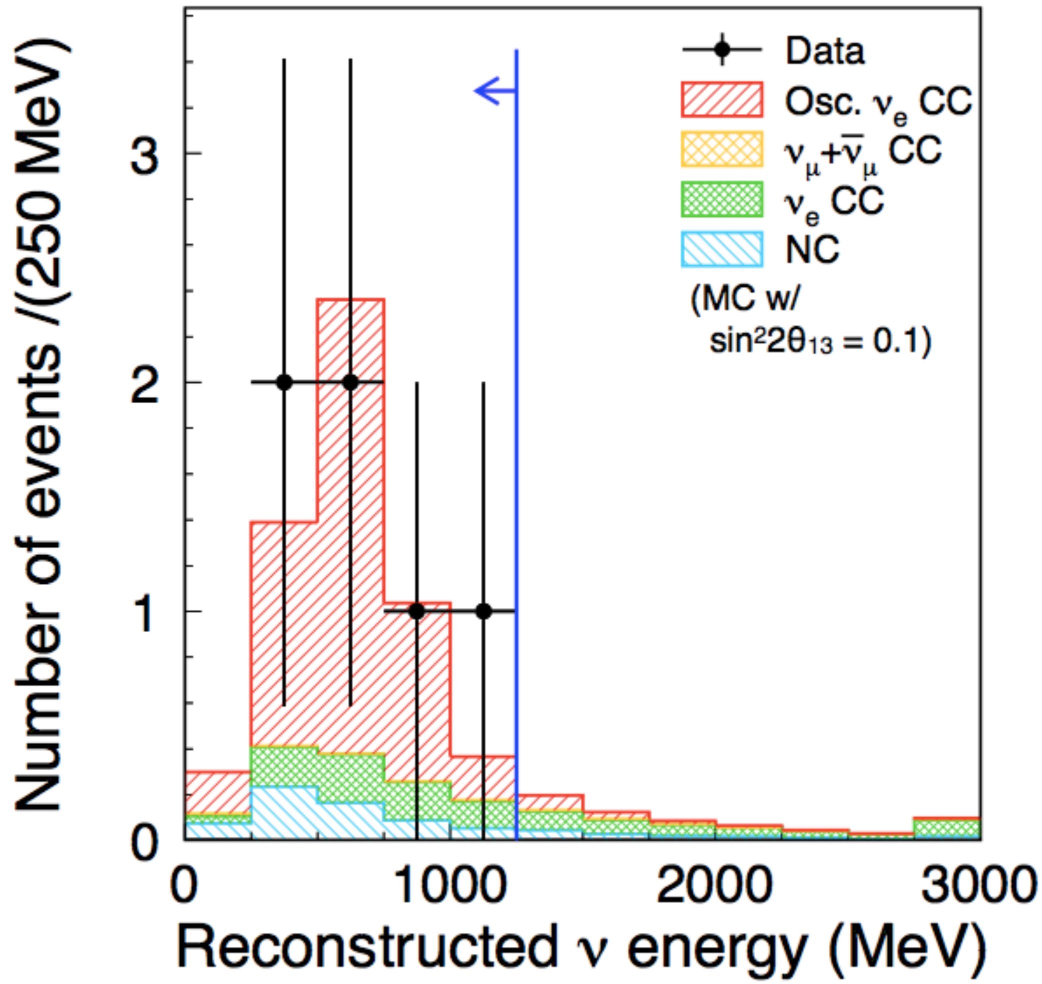
Events as a function of ν_e selection cut

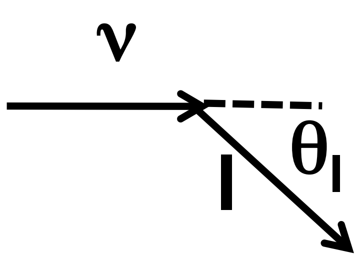


Distribution of ν_e candidate times wrt beam bunch



Reconstructed energies after all ν_e cuts





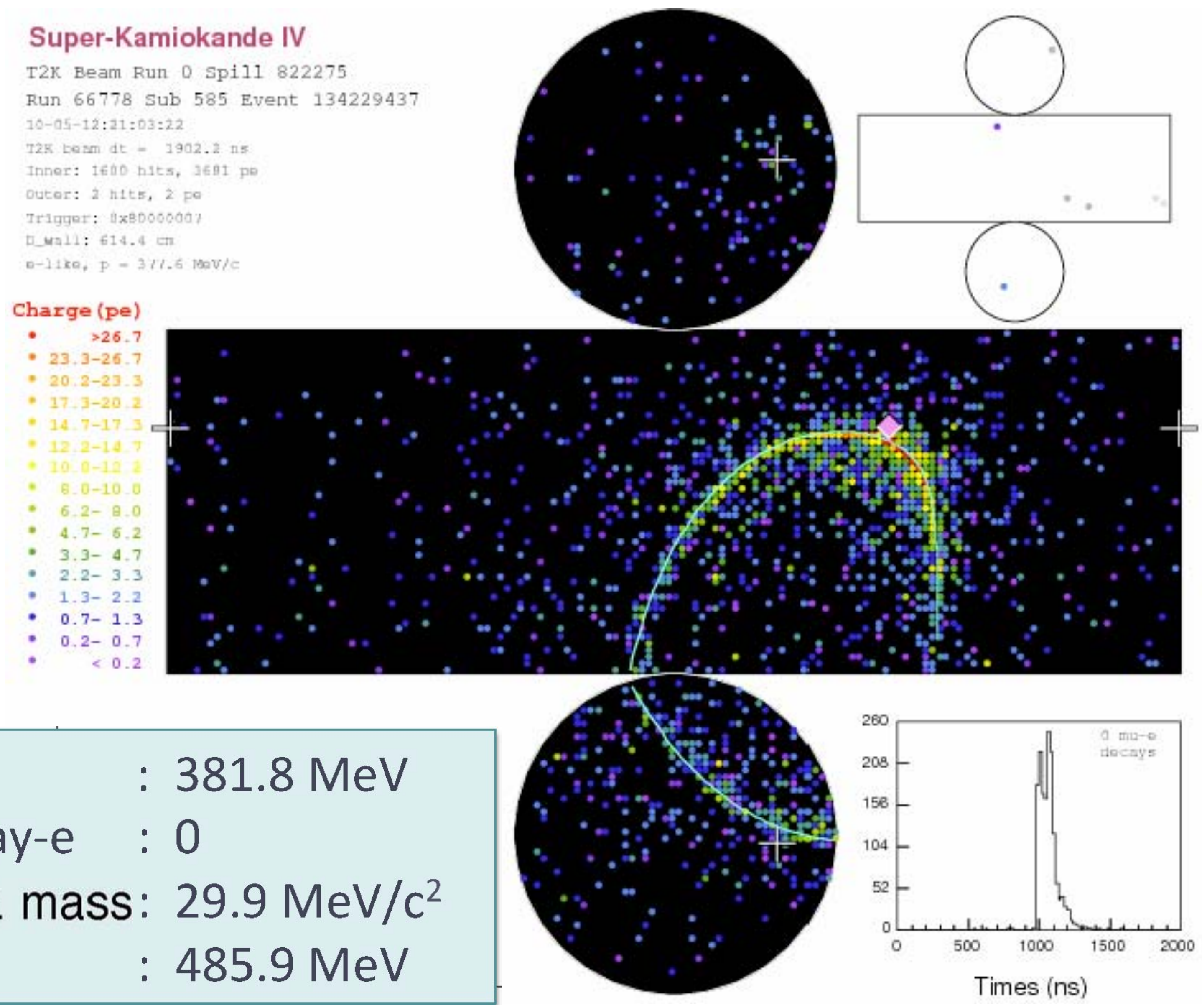
Reconstruct neutrino energy from measured energy and angle wrt beam

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

Results after ν_e selection cuts

Jan. 2010 – Mar. 2011 1.43×10^{20} POT	Data	Expected B.G.
Single Ring e-like (before add. ν_e cut)	7	
Single Ring e-like (after add. ν_e cut)	6	1.5 ± 0.3
Beam ν_e Background		0.8
Neutral Current interactions		0.6
Oscillated ν_μ-ν_e with solar term		0.1

Electron neutrino candidate(1)



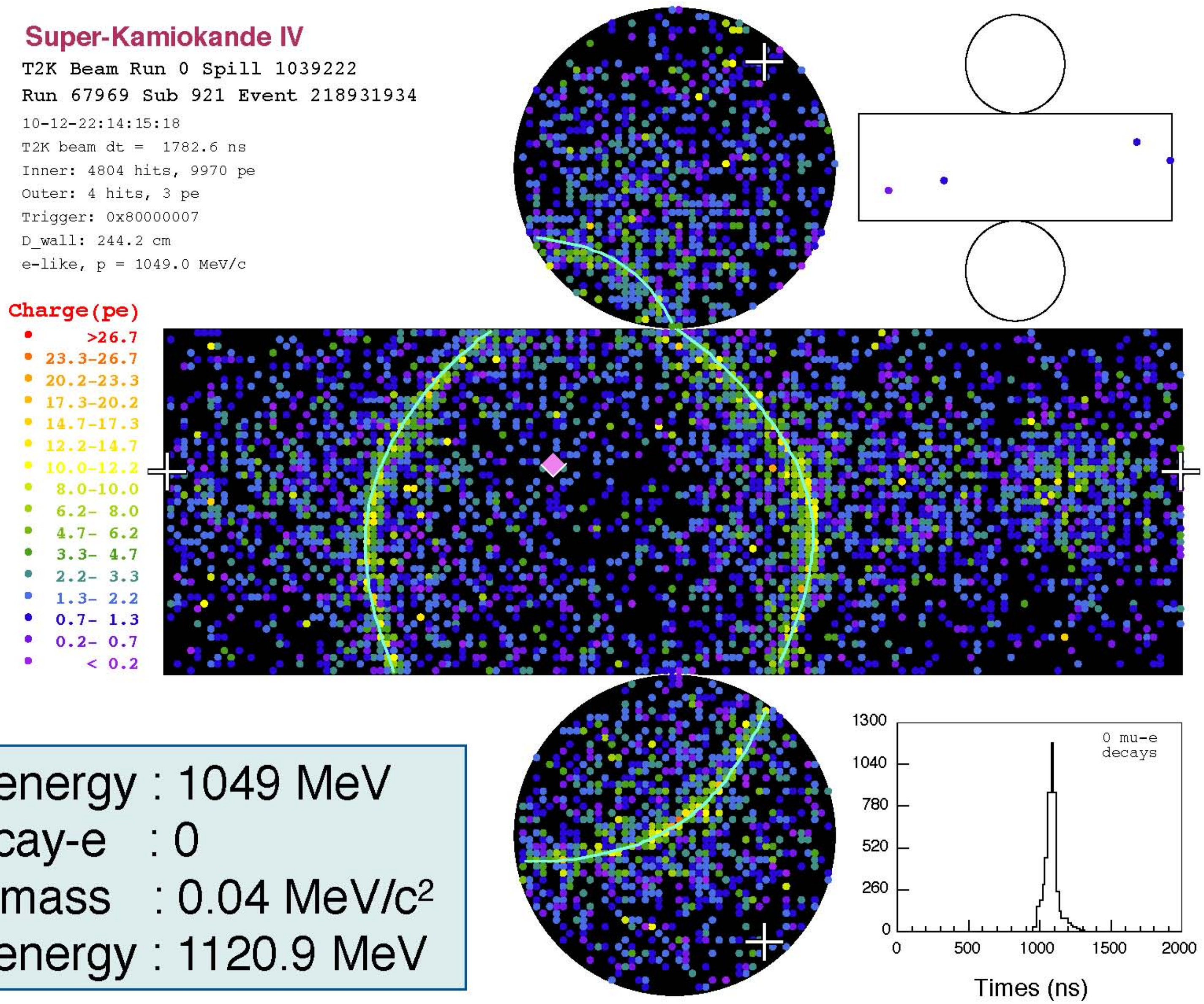
Evis : 381.8 MeV

Ndecay-e : 0

2γ Inv. mass : 29.9 MeV/c^2

E_ν^{rec} : 485.9 MeV

Electron neutrino candidate(2)



visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
recon. energy : 1120.9 MeV

Systematic uncertainty for ν_e appearance search

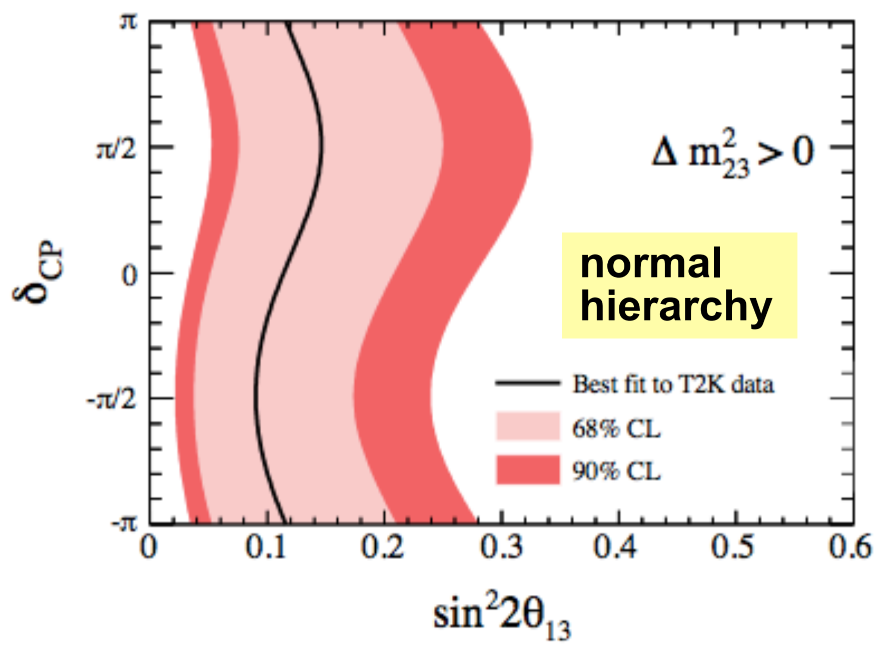
Systematic uncertainty for number of background events at Super-Kamiokande in the ν_e appearance search

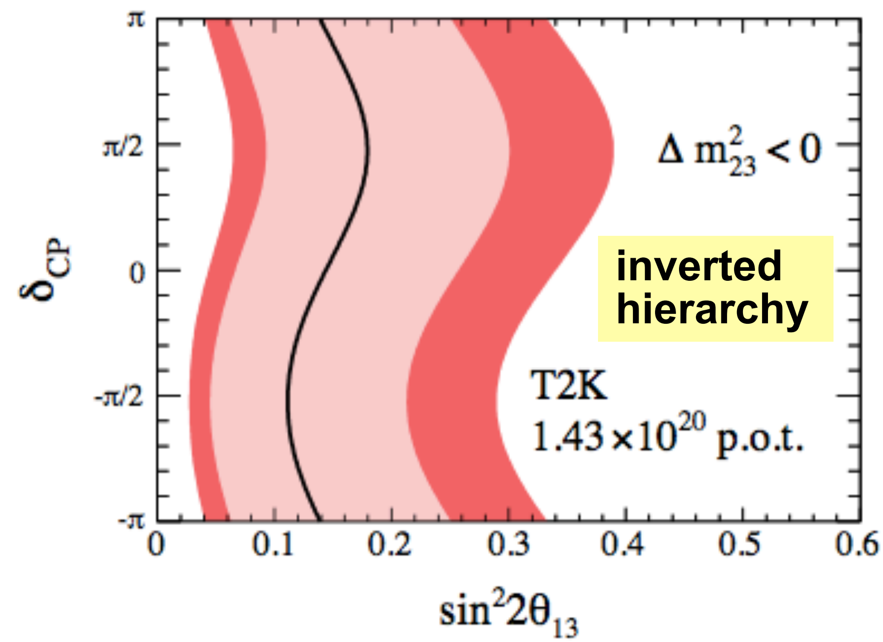
error source	syst. error
(1) ν flux	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$
(5) Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

$\sin^2 2\theta_{13} = 0$

Allowed values of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)



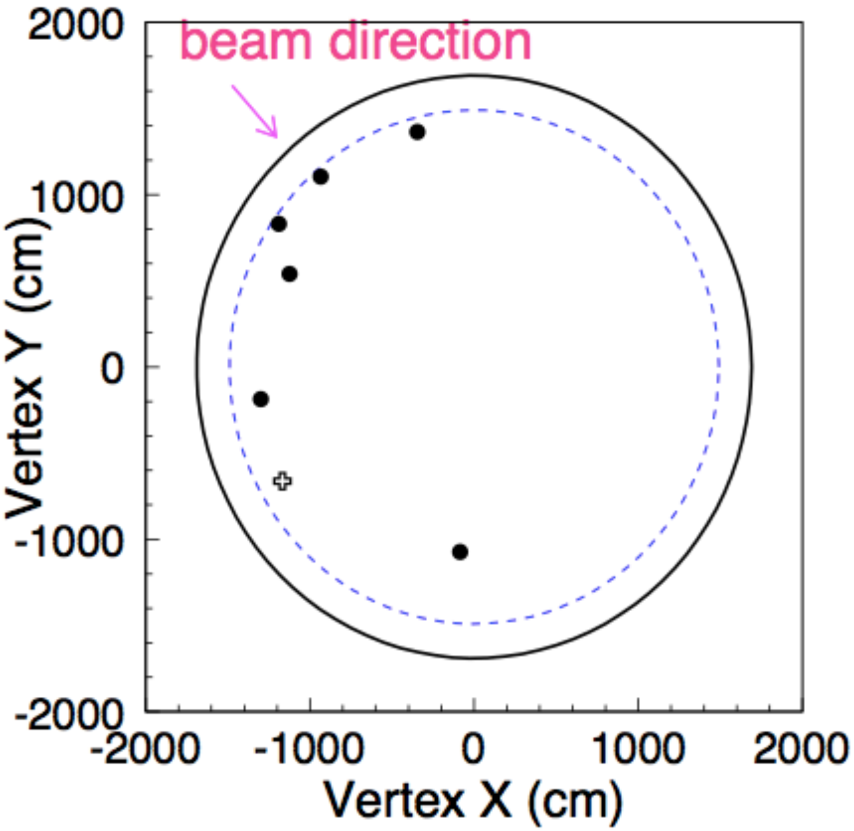


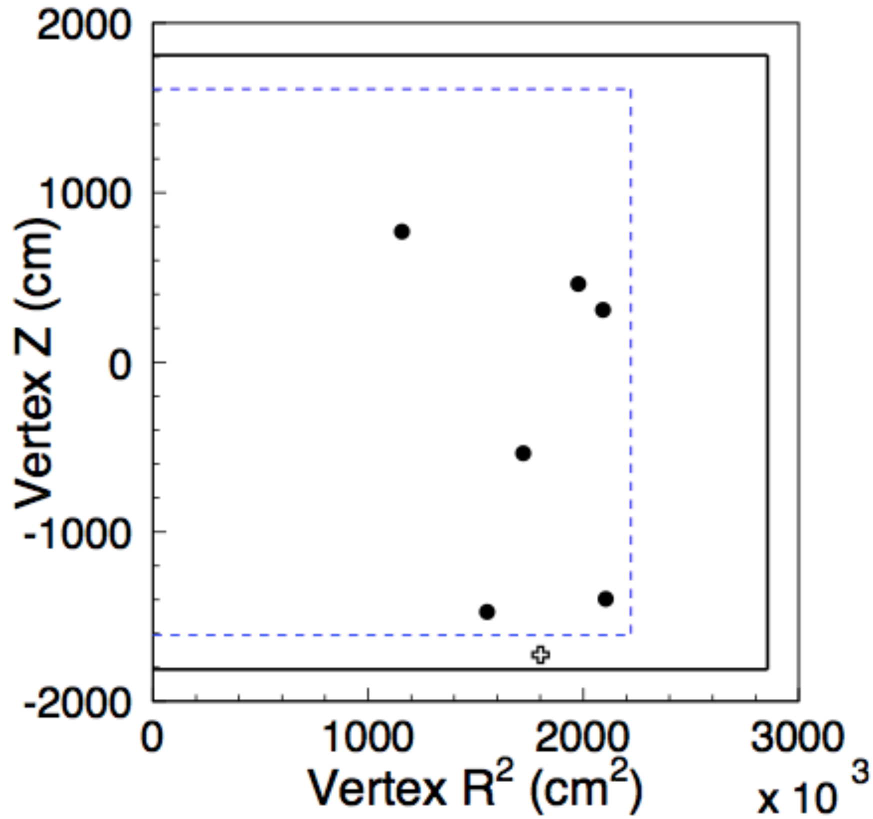
90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$ | $0.04 < \sin^2 2\theta_{13} < 0.34$

$\sin^2 2\theta_{13} = 0.11$ | $\sin^2 2\theta_{13} = 0.14$

Vertex distribution of all ν_e candidates

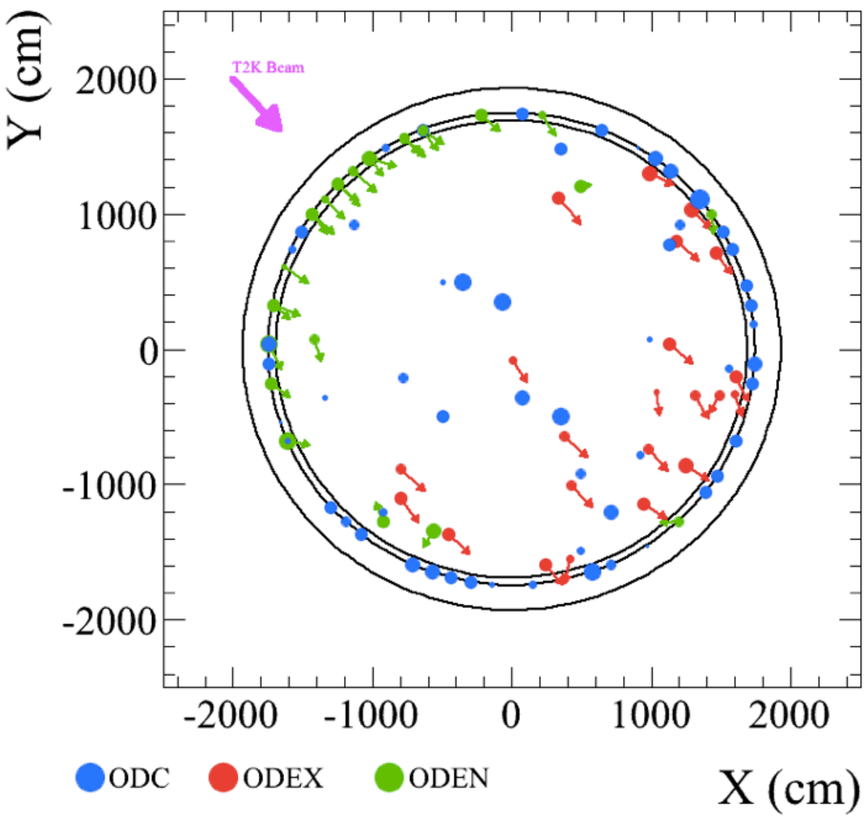


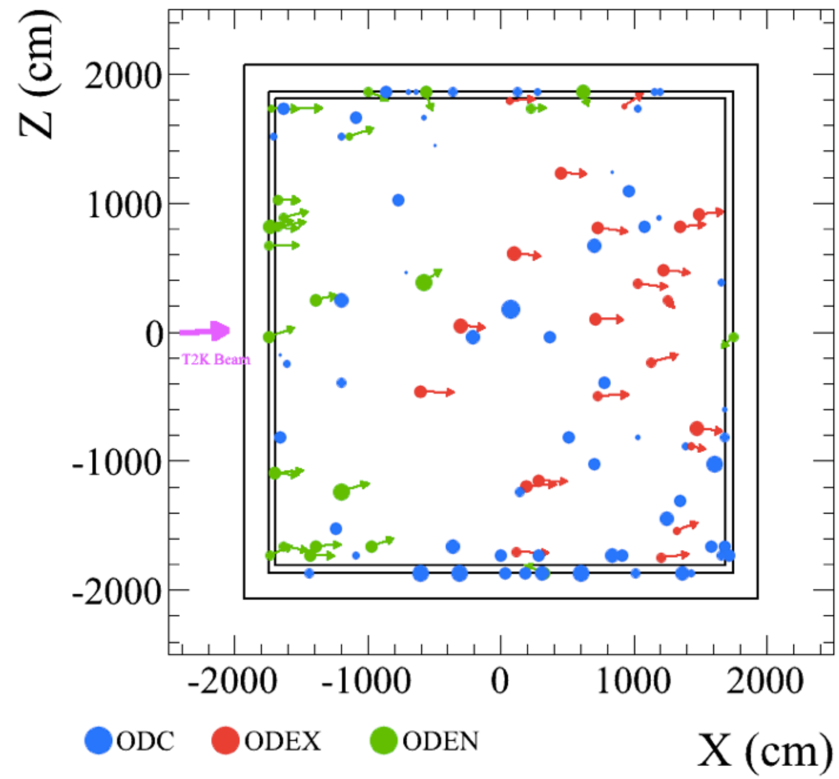


Many checks done:

- probability ~ few %   (trials factor hard...)
- entering contamination should be negligible according to MC
- OD events look fine
- atmospheric neutrino vertices look fine

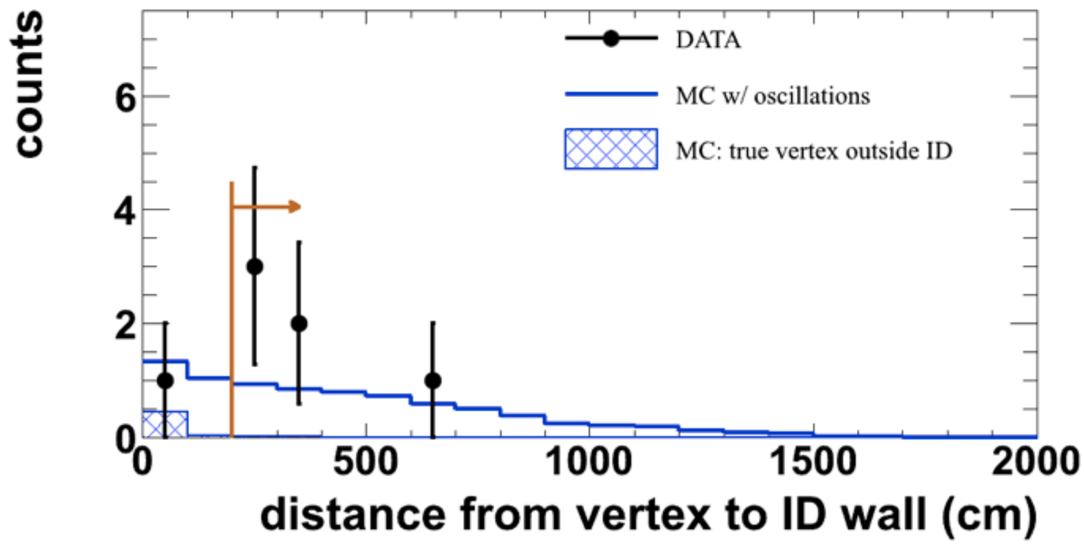
Vertex distribution of events with light in the OD

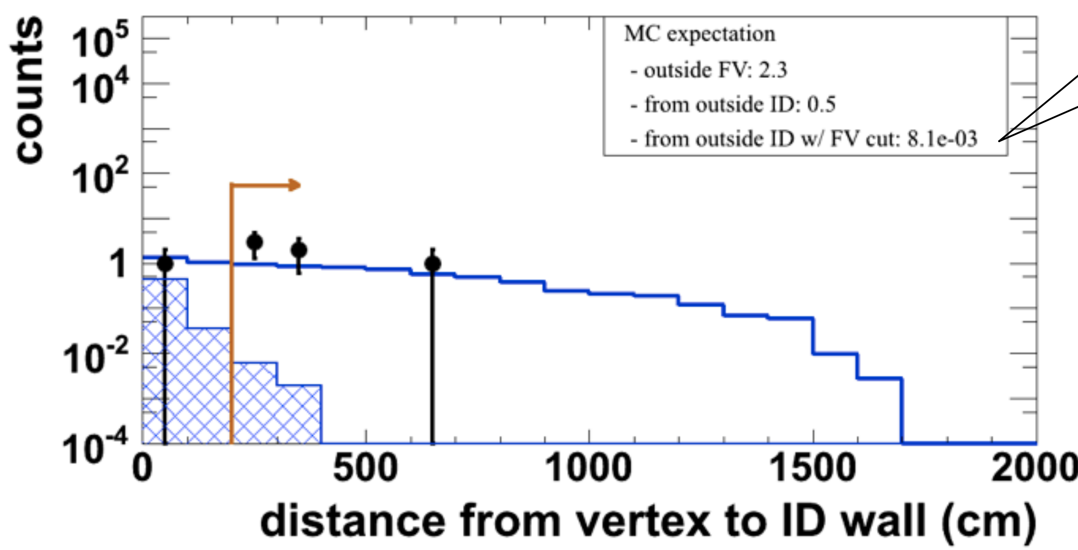




No anomalies...

Study of possible entering contamination

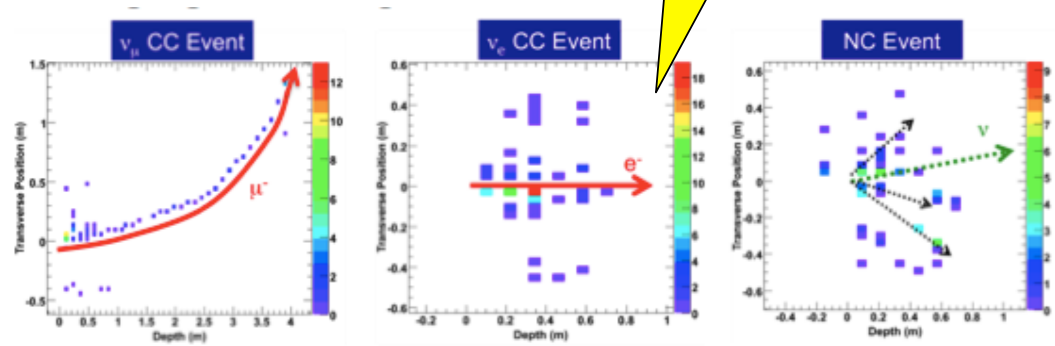




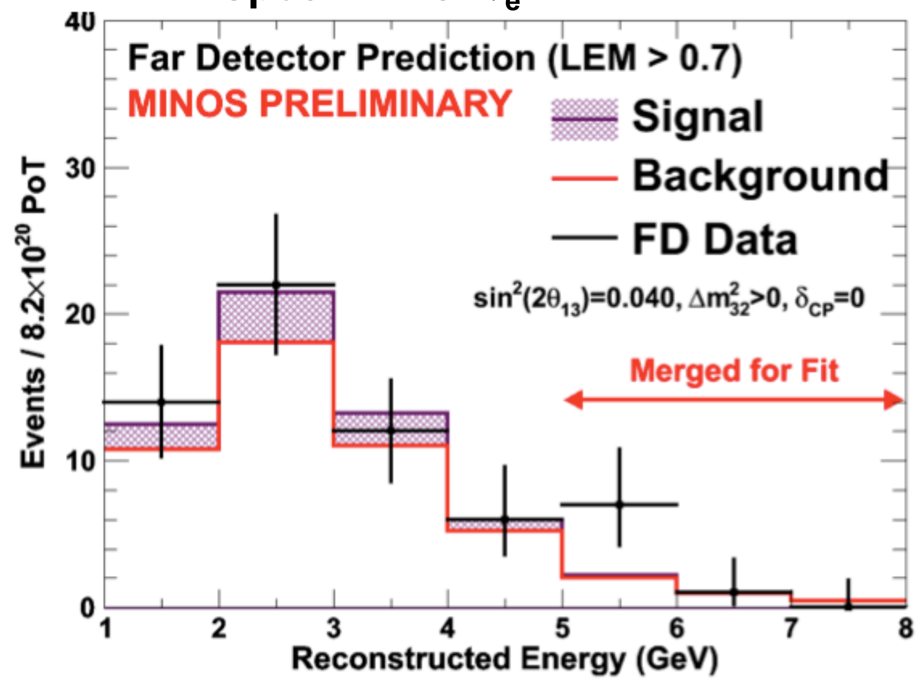
expect only tiny entering event fraction

ν_e appearance results from MINOS are consistent

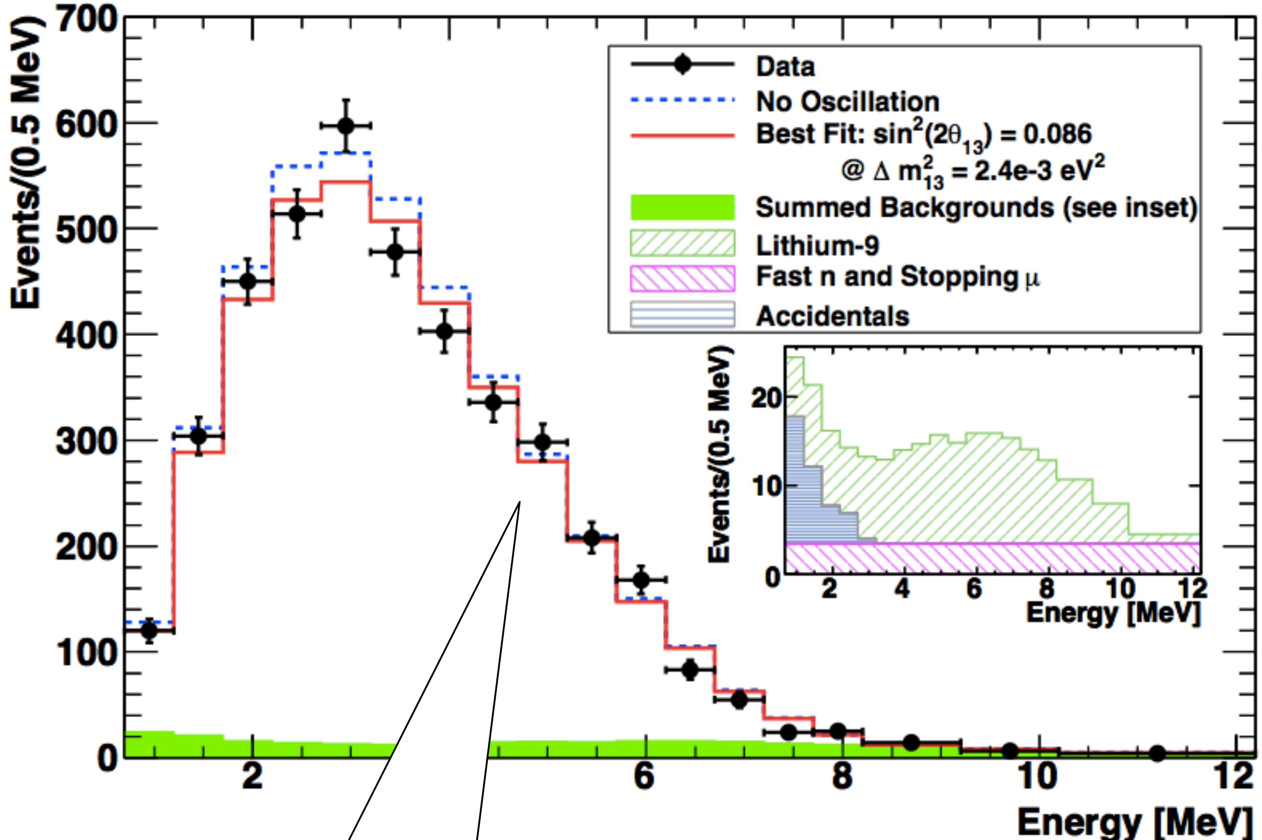
look for these



Spectrum of ν_e -like events



First Double Chooz θ_{13} Results



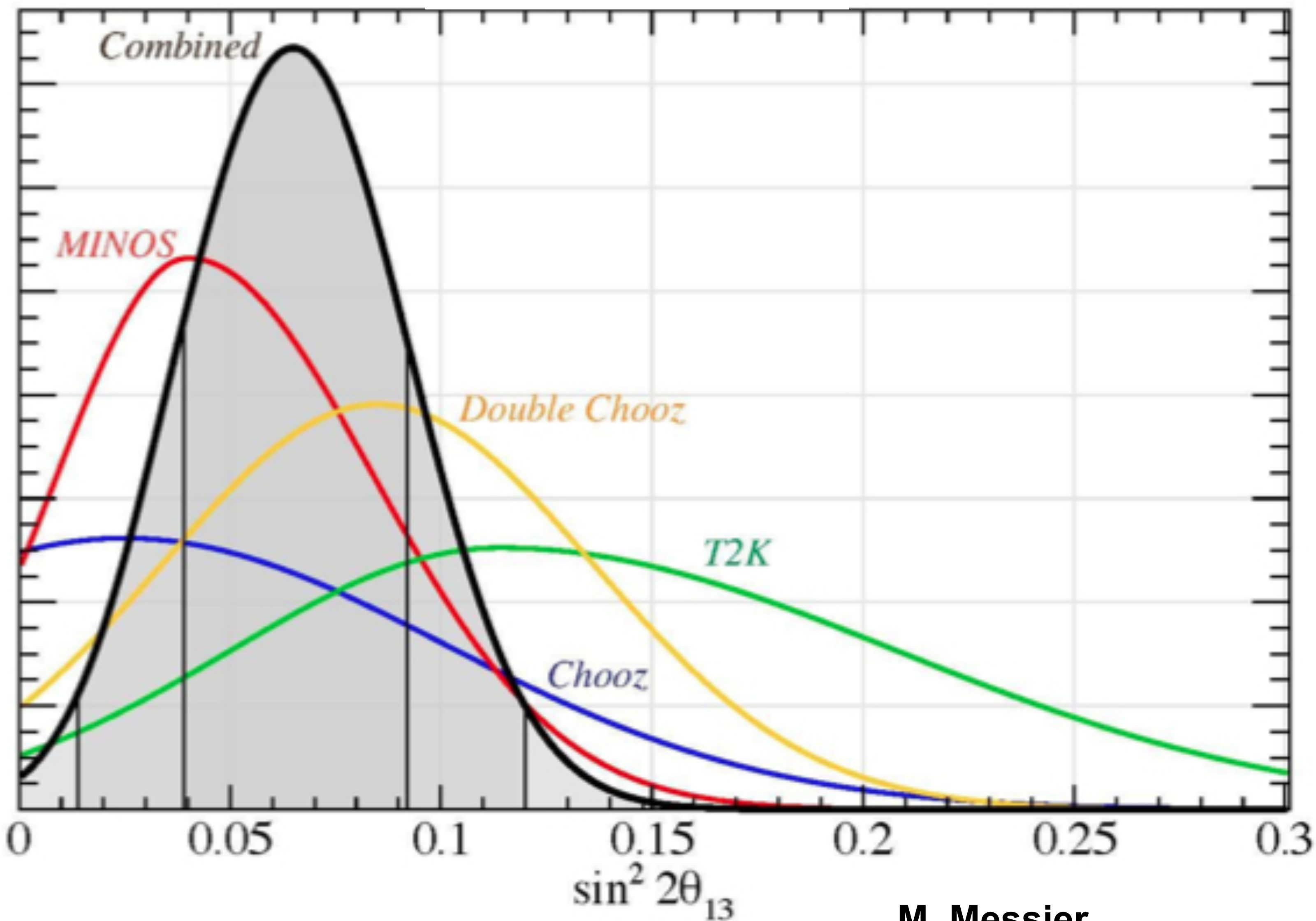
101 days of data w/far detector

Electron antineutrino deficit and spectral distortion consistent with non-zero θ_{13}

Rate + shape analysis, arXiv:1112.6353

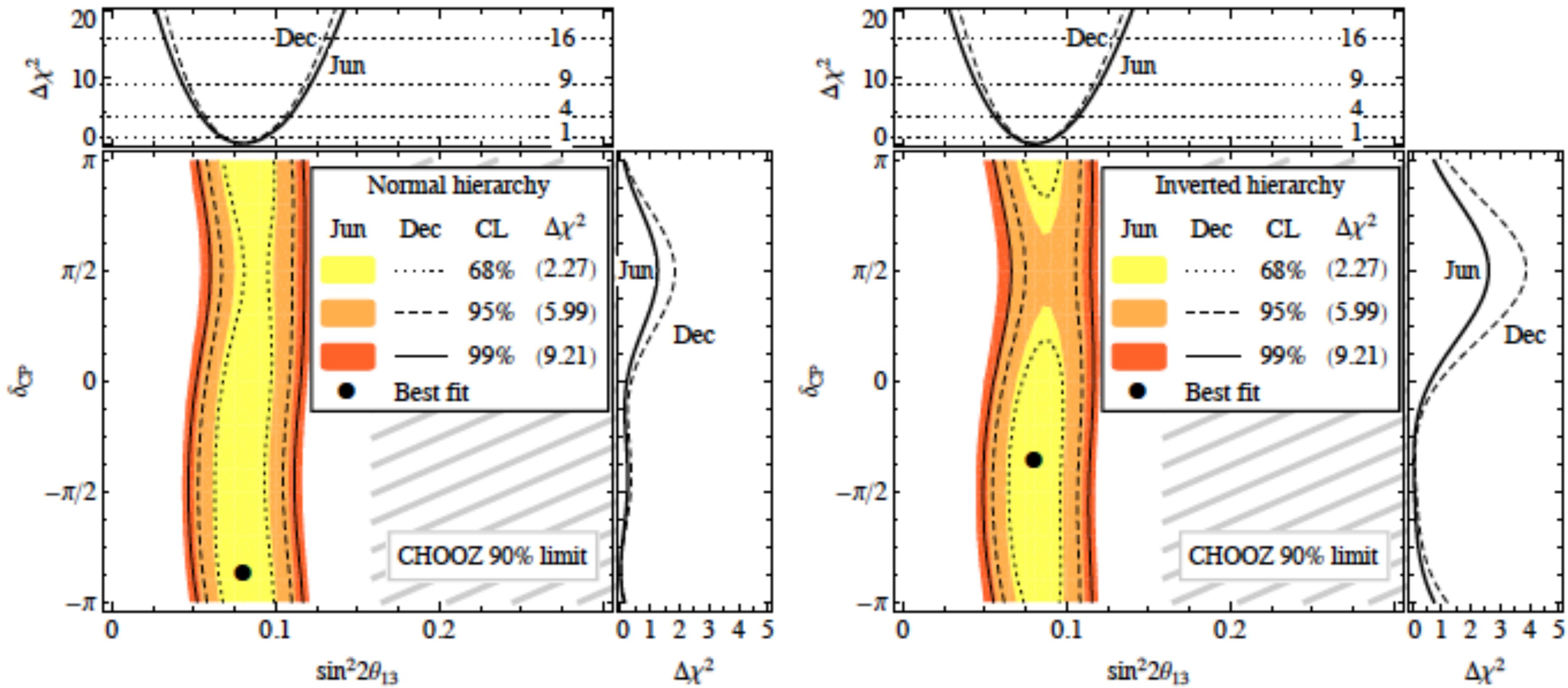
$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{sys})$

Summary of latest θ_{13} measurements



M. Messier

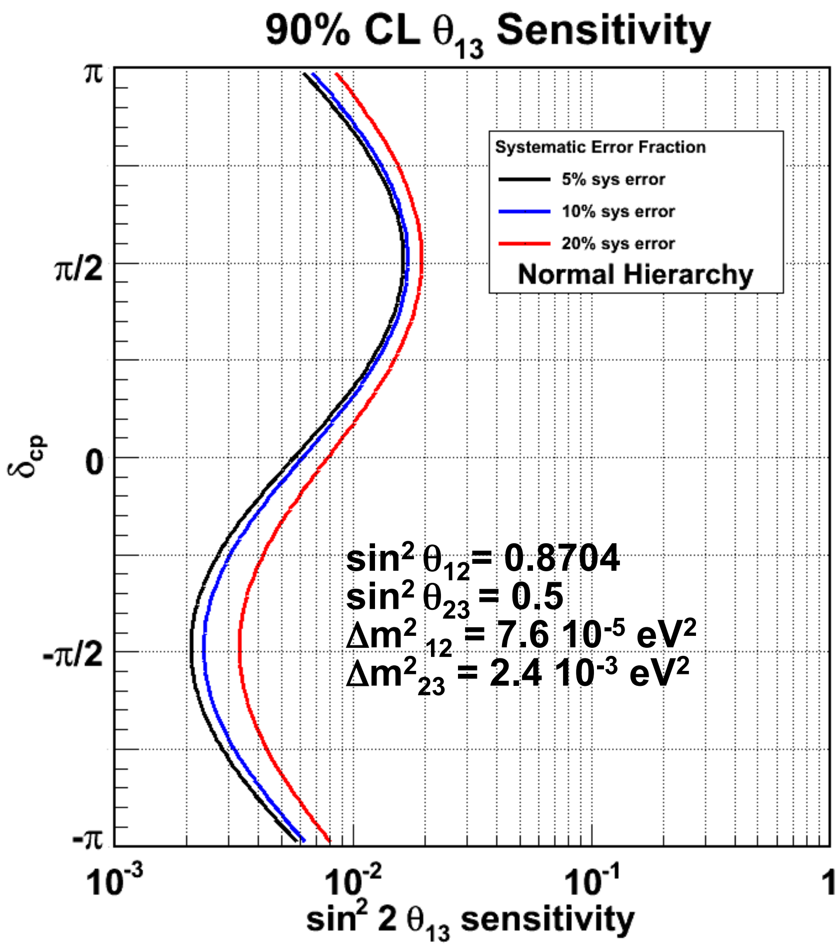
Assuming current best-fit values are the true ones, how well will we know θ_{13} by the end of 2012?

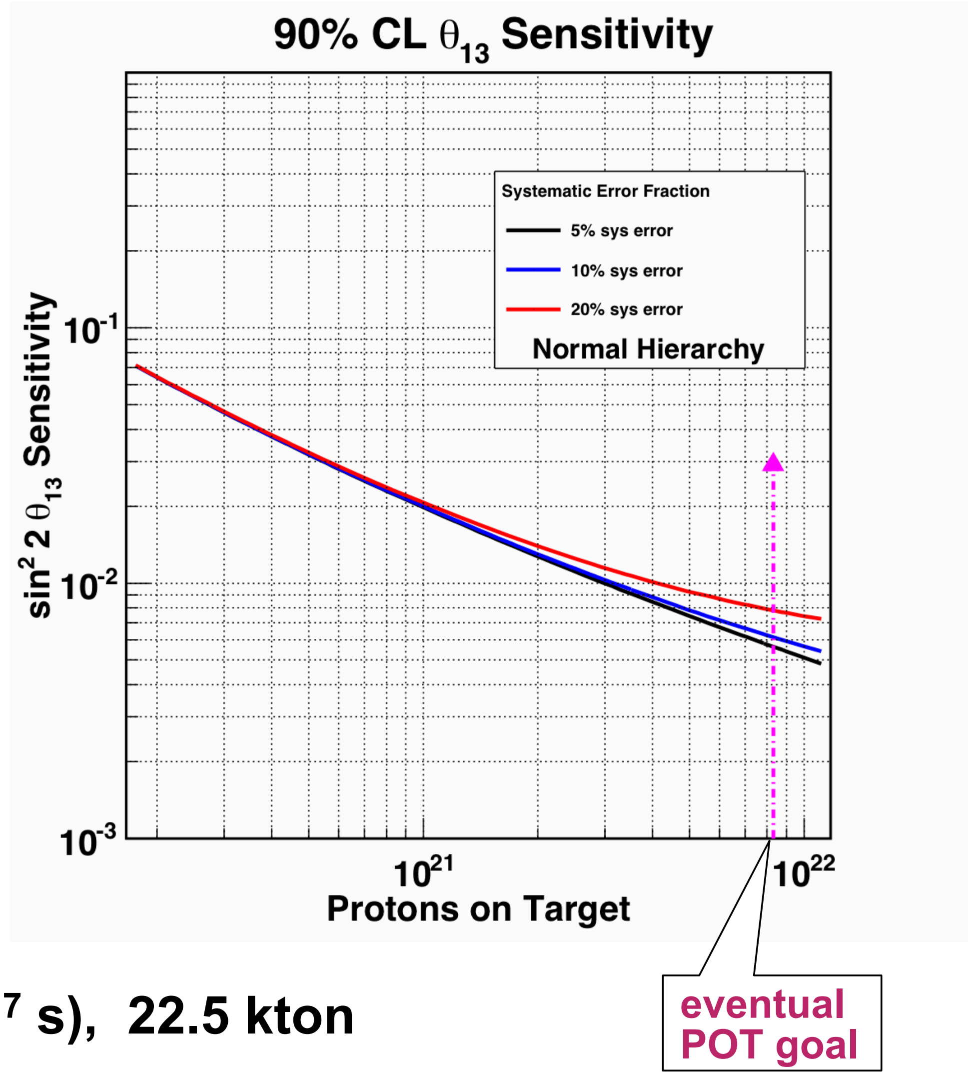


Daya Bay not included in this work

Machado et al.
arXiv:1111.3330

Future T2K sensitivity in $\sin^2 2\theta_{13}$-CP δ space

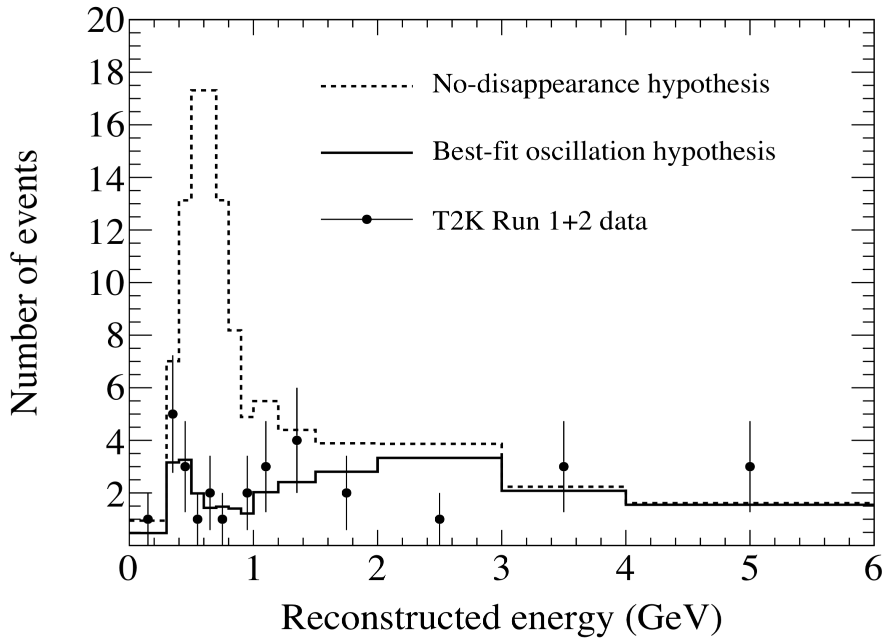


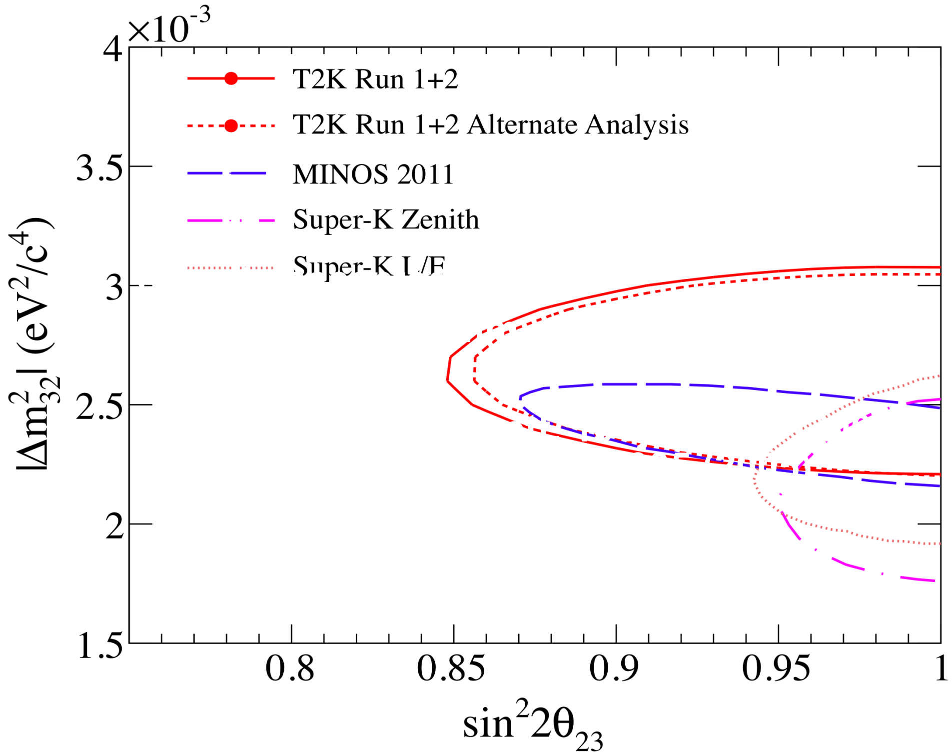


90% C.L. 750 kW x (5 x 10^7 s), 22.5 kton

ν_μ disappearance results

$$P(\nu_\mu \rightarrow \nu_{x\neq\mu}) \cong \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



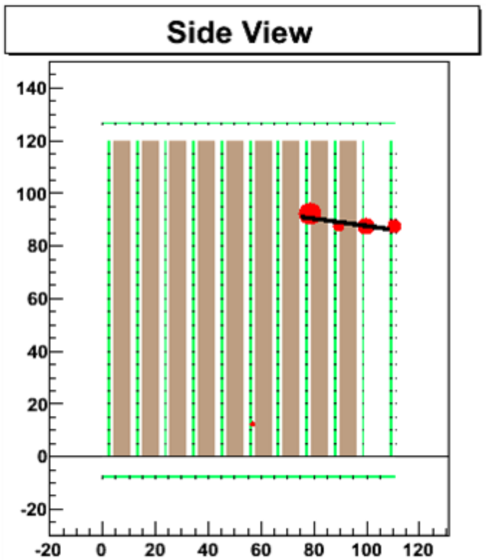


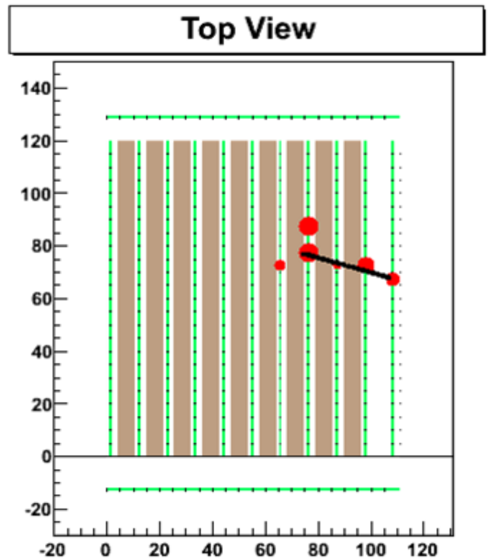
- 31 events pass ν_μ selection cuts
- $103.6^{+13.8}_{-13.4}$ expected for no osc, excluded at 4.5σ

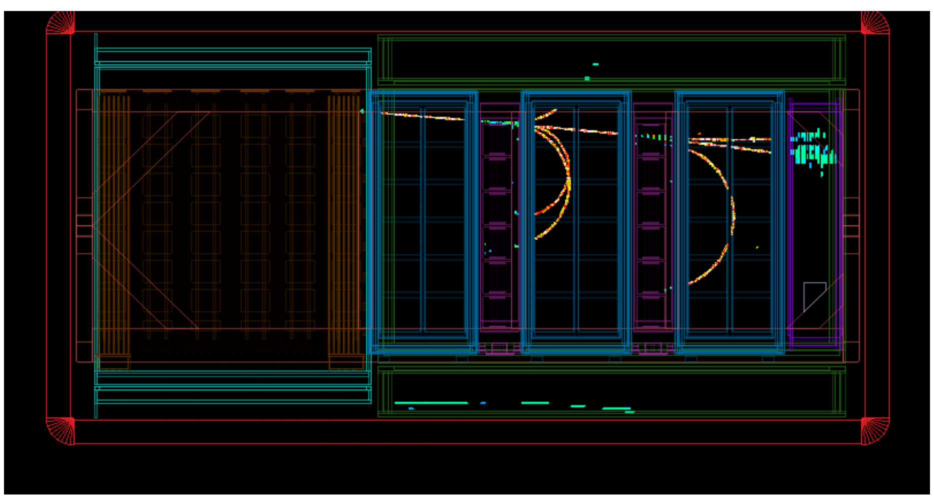
Best fit: $|\Delta m^2_{32}| = 2.65 \times 10^{-3}\ \mathrm{eV}^2$

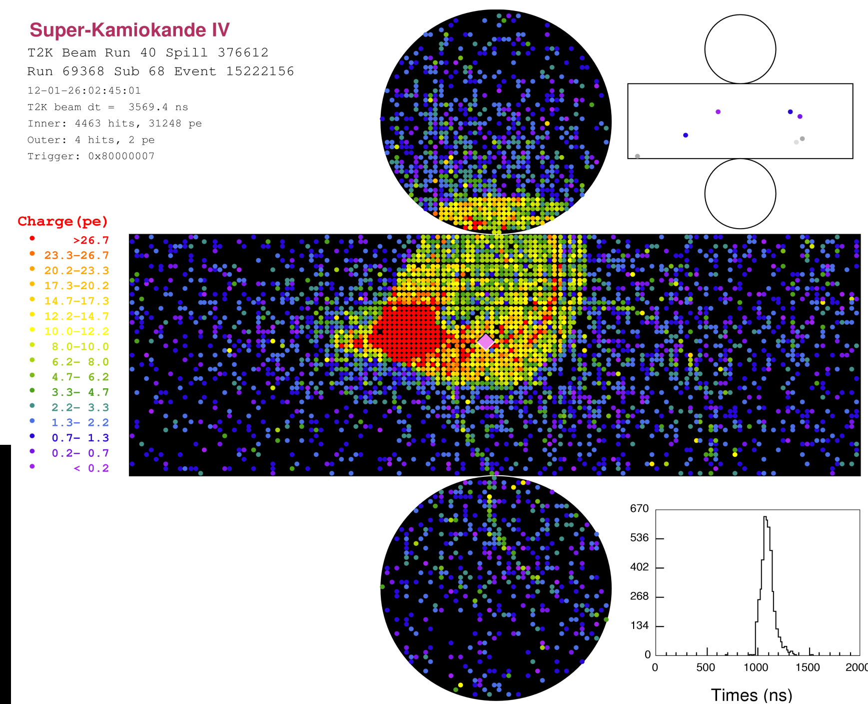
$\sin^2 2\theta_{23} = 0.98$

First post-earthquake neutrinos

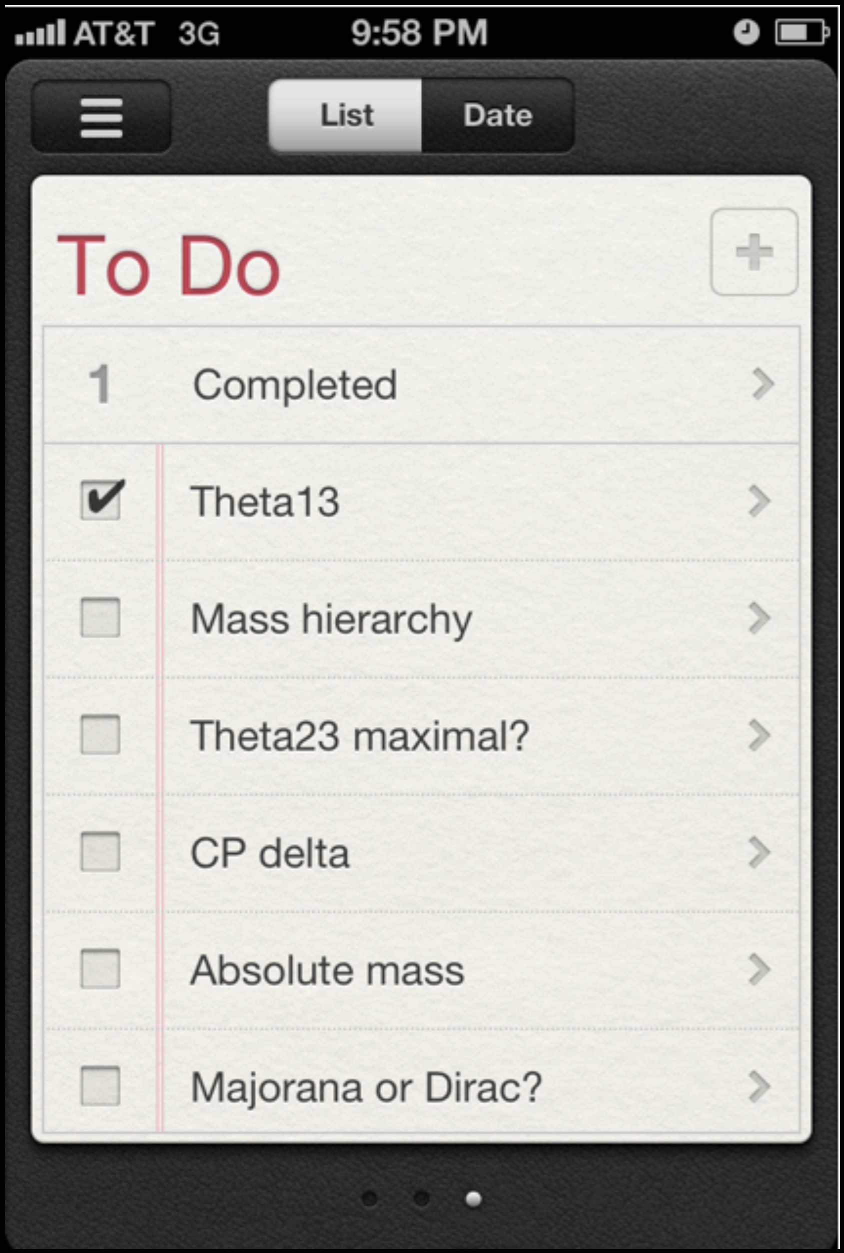








Next on the list...



Summary

With 1.43 x 10^{20} pot, observed 6 ν_e candidates, expect 1.5 ± 0.3 background (2.5 σ)

The constraints on $\sin^2 2\theta_{13}$ are:

$\sin^2 2\theta_{13} = 0.11$ (best fit) and $0.03 < \sin^2 2\theta_{13} < 0.28$ (90% C.L.)
for normal hierarchy, $\delta_{CP}=0$

$\sin^2 2\theta_{13} = 0.14$ (best fit) and $0.04 < \sin^2 2\theta_{13} < 0.34$ (90% C.L.)
for inverted hierarchy, $\delta_{CP}=0$

($\Delta m^2_{23}=2.4\times10^{-3}\mathrm{eV}^2$, $\sin^2 2\theta_{23}=1.0$)

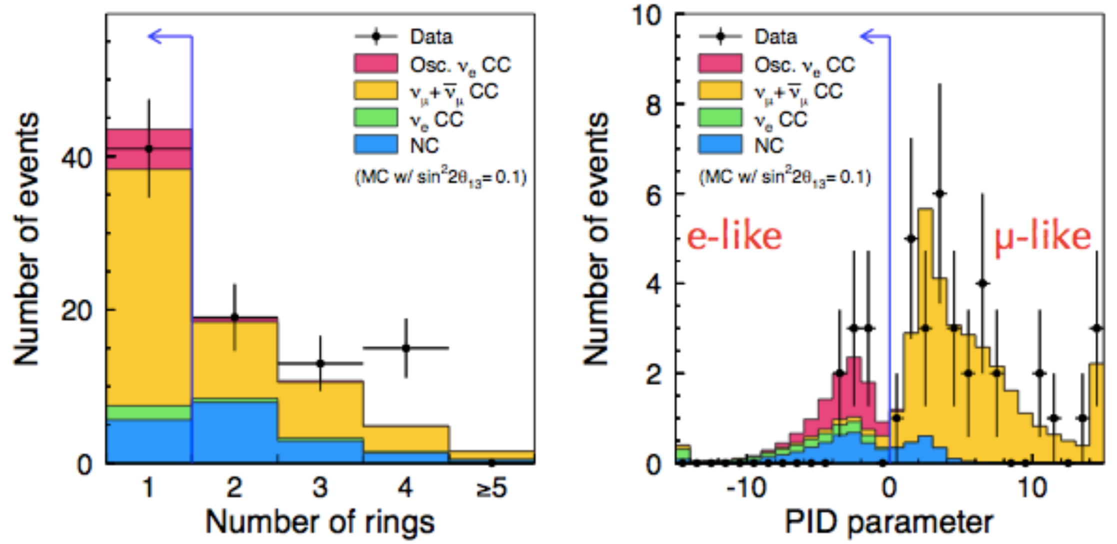
First off-axis beam ν_μ disappearance result

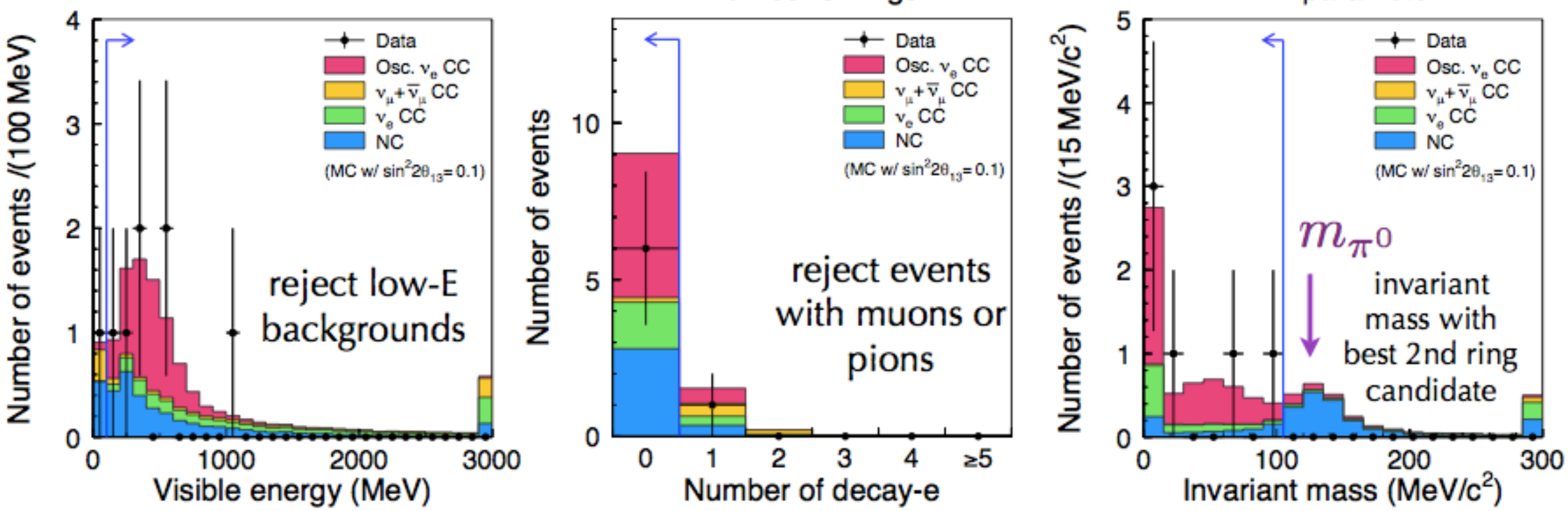
Running has resumed: expect more by summer!

ν_e Appearance

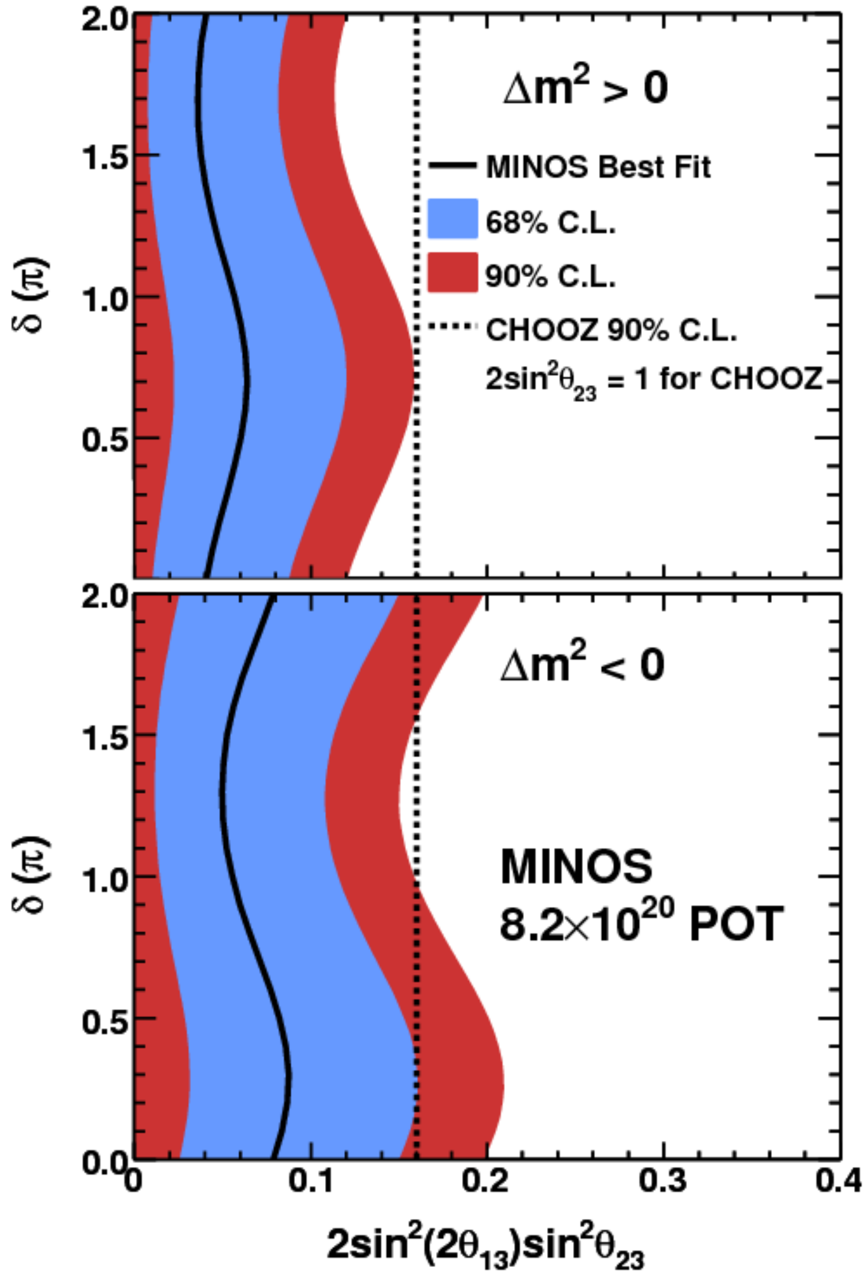
- Fully Contained
- Fiducial Volume
- Single Ring
- e-like
- $E_{visible} > 100$ MeV
- $N_{decay} = 0$
- $m_\pi < 105$ MeV

Data: 6 Events...





ν_e appearance results from MINOS are consistent



And now: getting at CP Violation

Observed for quarks; how about leptons?
... helpful for understanding matter-antimatter asymmetry

phase δ in mixing matrix

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

Compare transition probabilities for
$\nu_\mu \longrightarrow \nu_e$ **and** $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

But not simple to extract CP violating phase δ...
transition rates depend on all
mixing matrix parameters, plus matter effects...

CP Violating Observables

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

Non-CP terms

Changes sign for antineutrinos

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$

CP violating

$$+\tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \ A = \sqrt{2} G_F N_e$$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

A. Cervera et al., Nuclear Physics B 579 (2000)

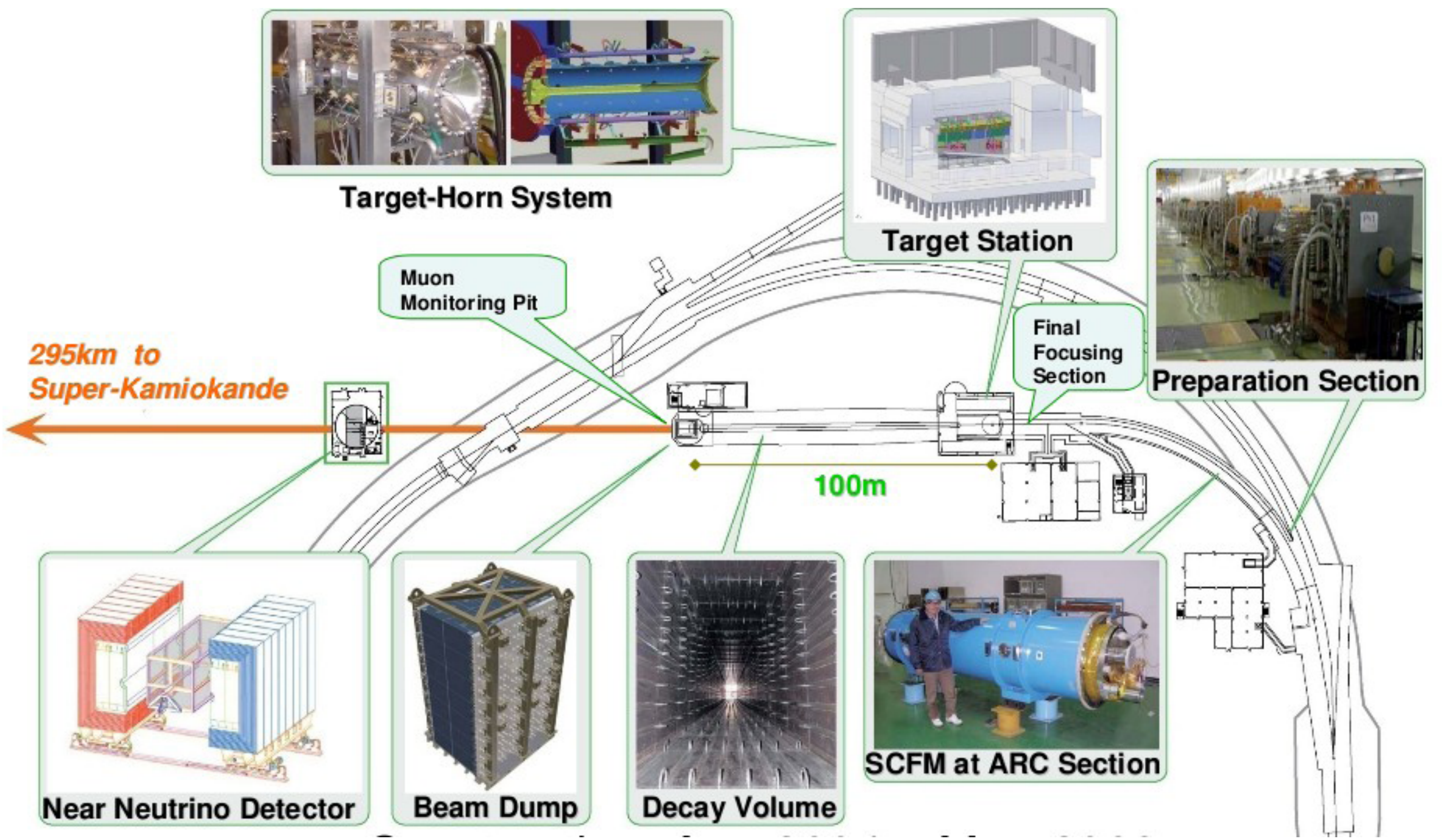
More complicated...

Mass hierarchy affects nu/nubar via matter effects (need long L)

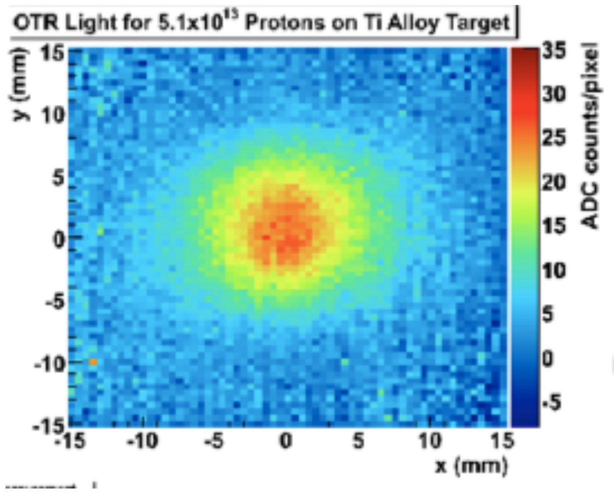
Need precision measurements of parameters....

***Multiple measurements* (ν's and $\bar{\nu}$'s) at different L, E needed to resolve intrinsic ambiguities**

Neutrino beam line

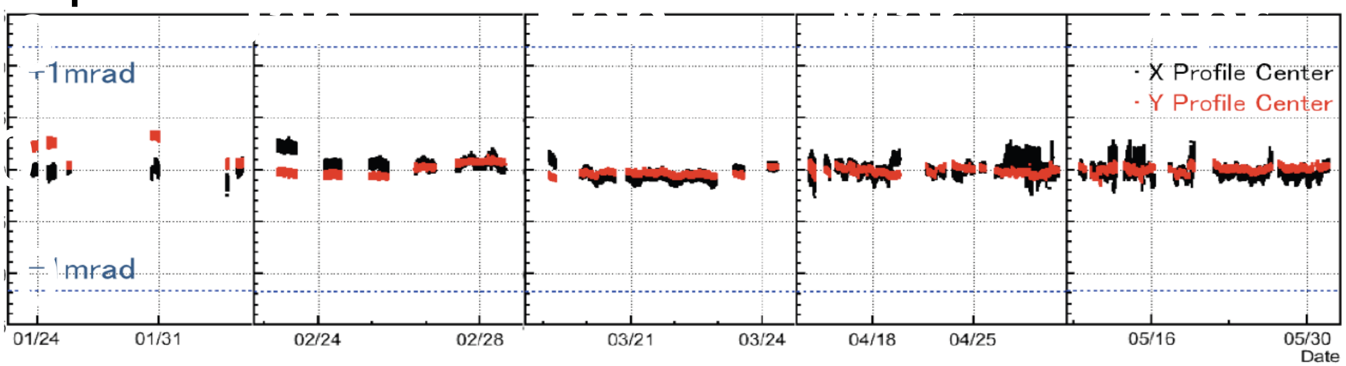


Beam monitors

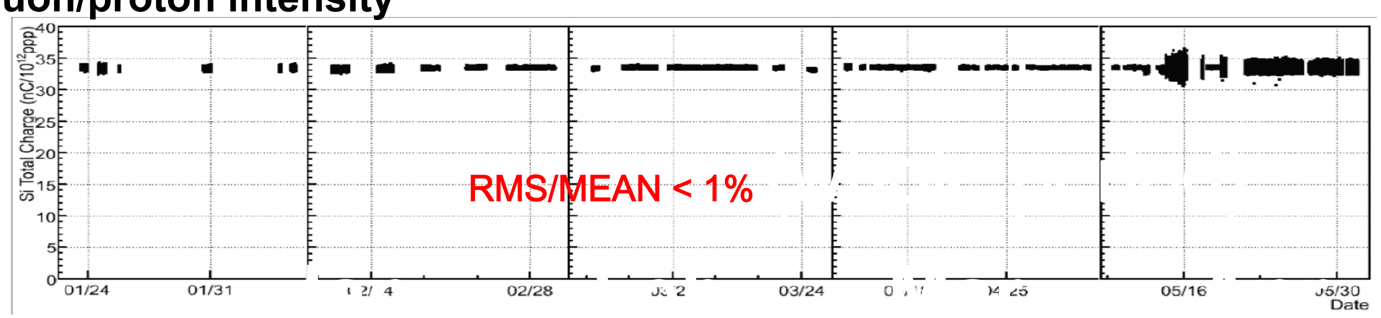


Optical Transition Radiation monitor just upstream of target, to monitor proton beam position

Beam profile center

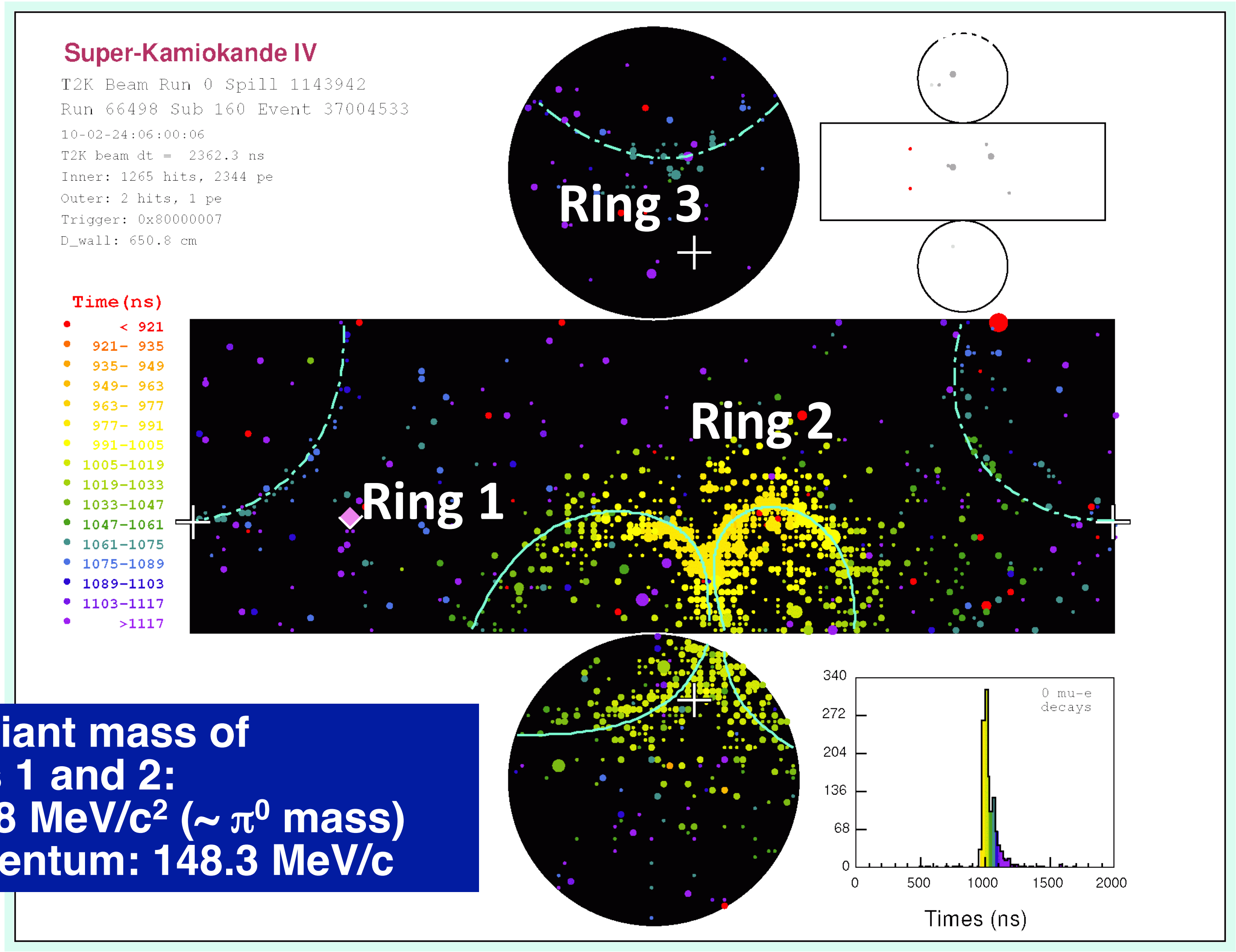


Muon/proton intensity



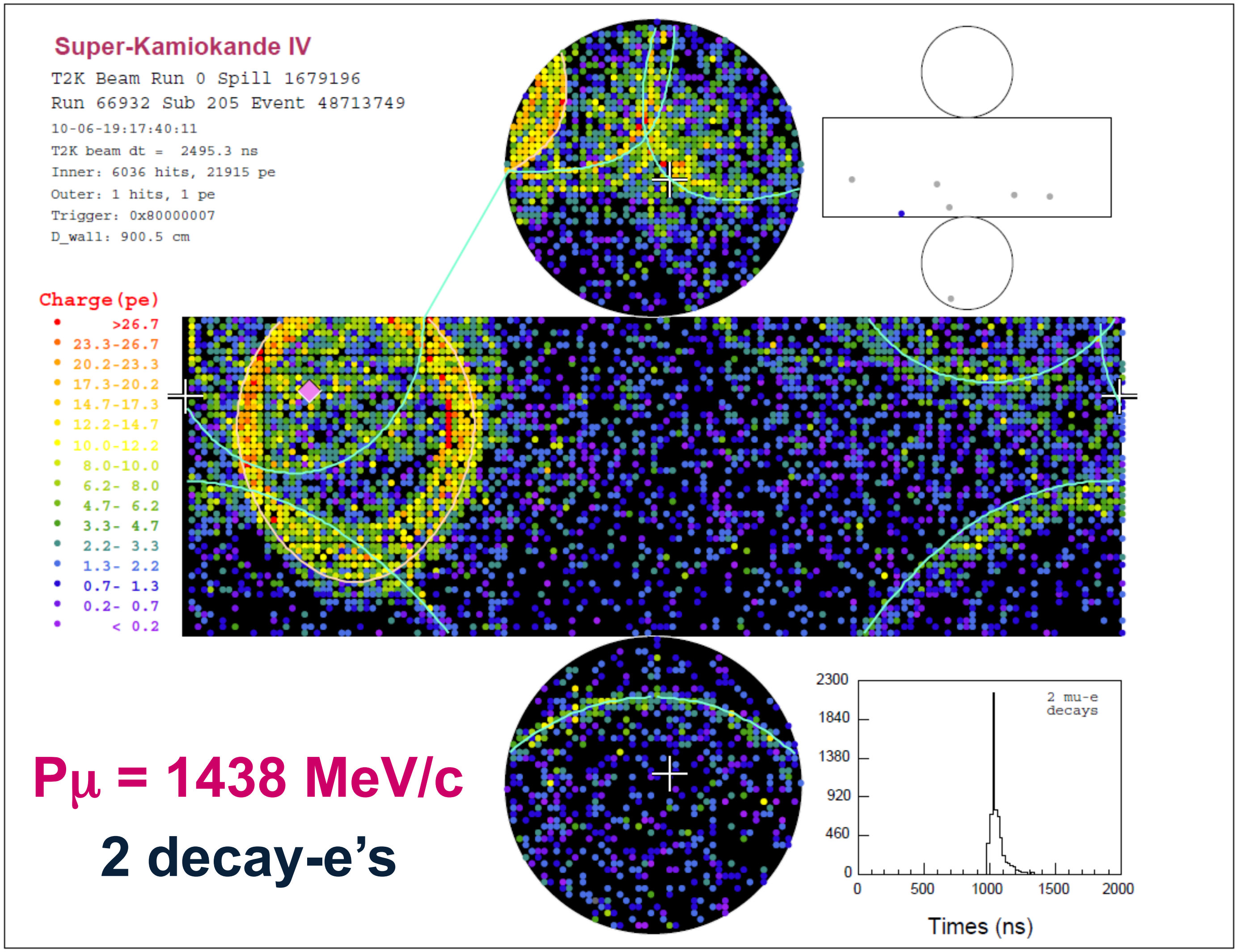
Muon monitor: stable within <1 mrad, intensity (normalized) stable within 1%

First Super-K event from the T2K beam

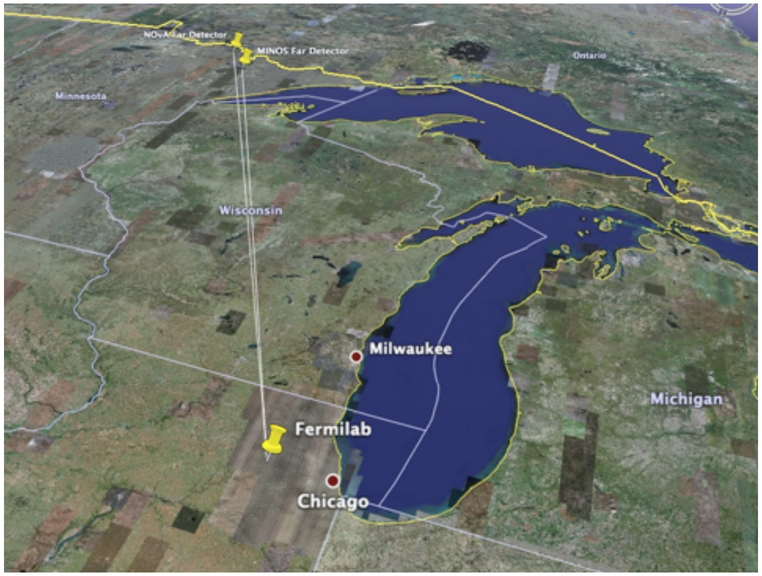


Invariant mass of rings 1 and 2:
133.8 MeV/c^2 (~ π^0 mass)
Momentum: 148.3 MeV/c

Event display (multi-ring μ-like event)

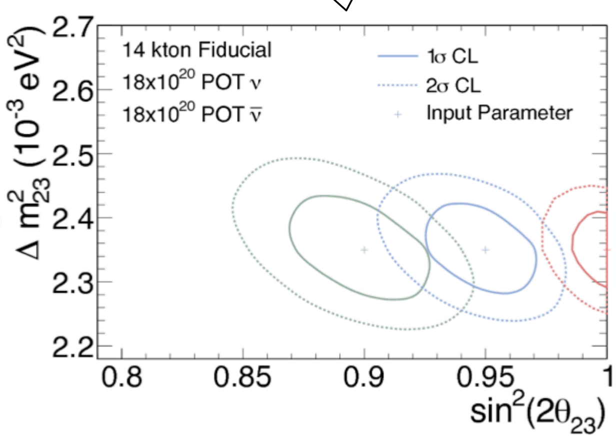


Next in the U.S.: NOνA

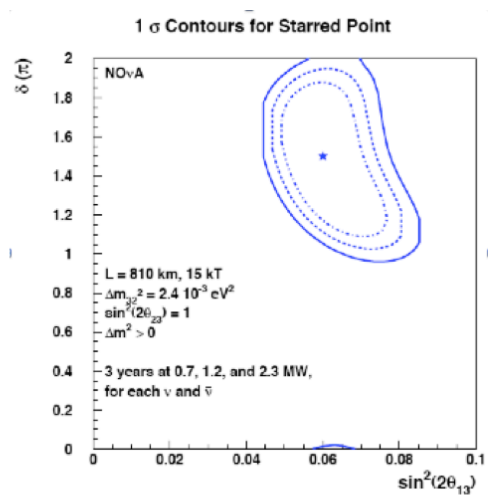


Scintillator tracking detector
NuMI 700 kW upgrade (2012)
810 km baseline
Lab in Ash River complete
Far detector by end of 2013

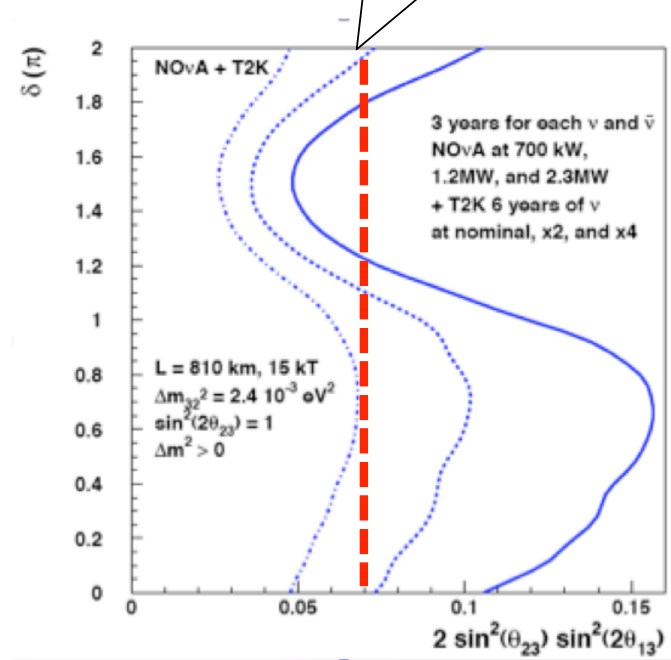
θ_{23} amplitude: maximal?



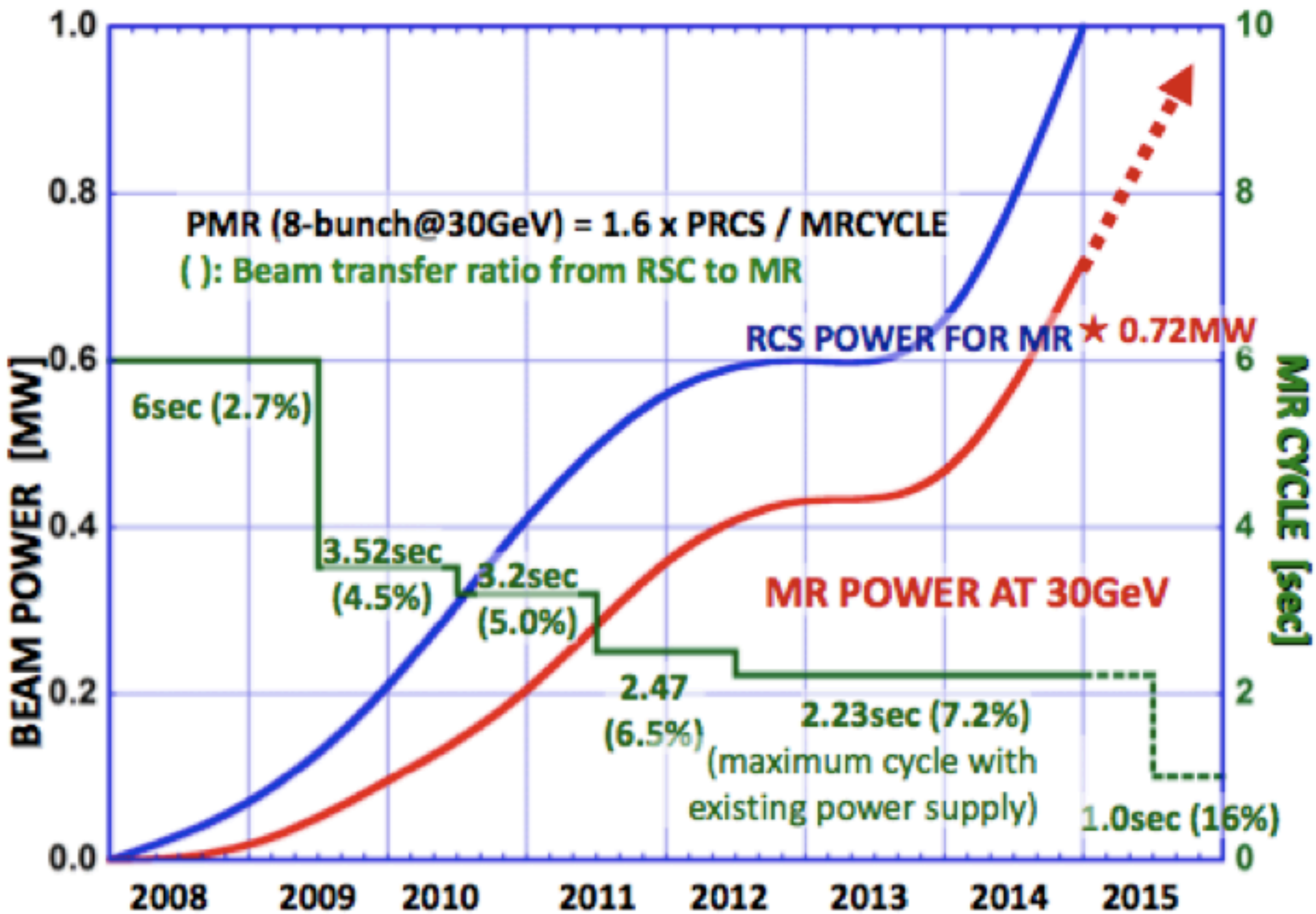
CP δ



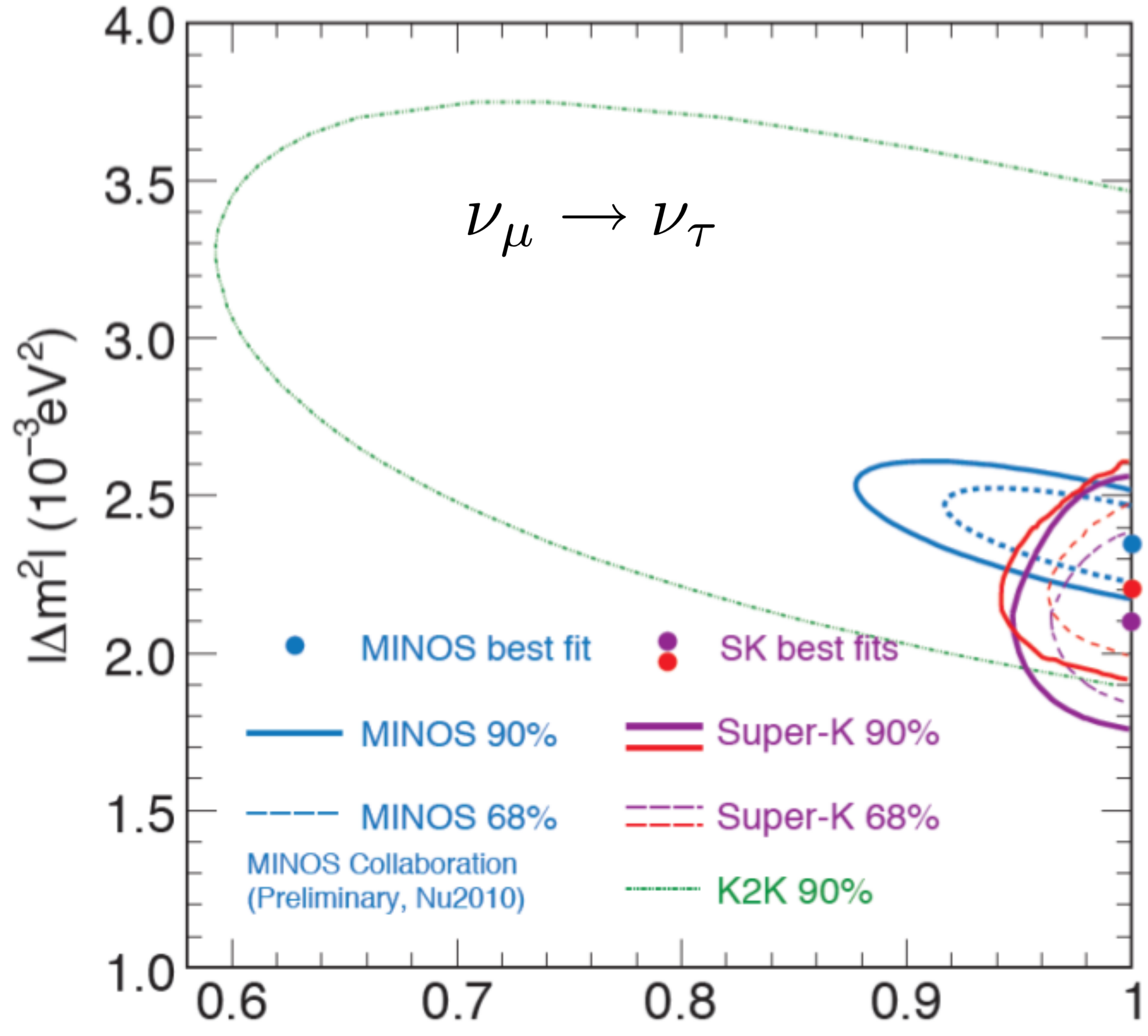
A crack at the mass hierarchy, thanks to longer baseline



Future beam power



Atmospheric neutrino two-flavor parameter space

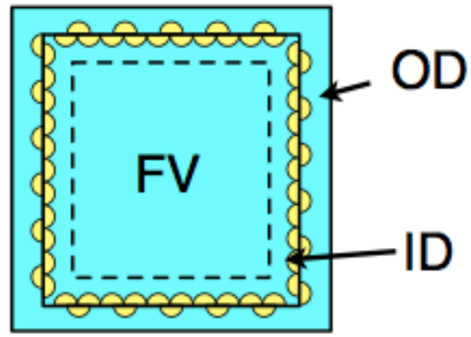


Y. Takeuchi, Nu2010

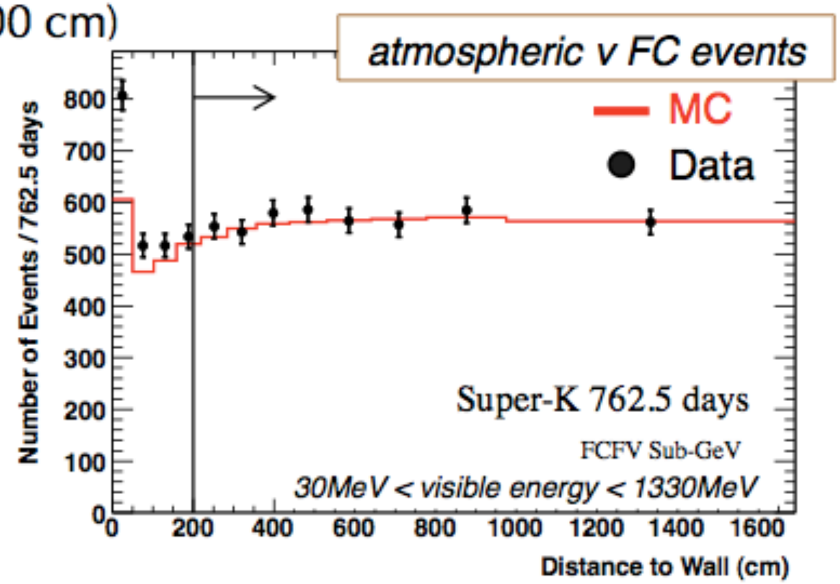
K. Sakashita

7 selection cuts

1. T2K beam timing & Fully contained (FC)
   (synchronized with the beam timing,
   no activities in the OD)



2. In fiducial volume (FV)
   (distance btw recon. vertex and wall > 200 cm)



* Events too close to the wall are difficult to accurately reconstruct vertex

* Reject events which are originated outside the ID

* Define FV 22.5kton

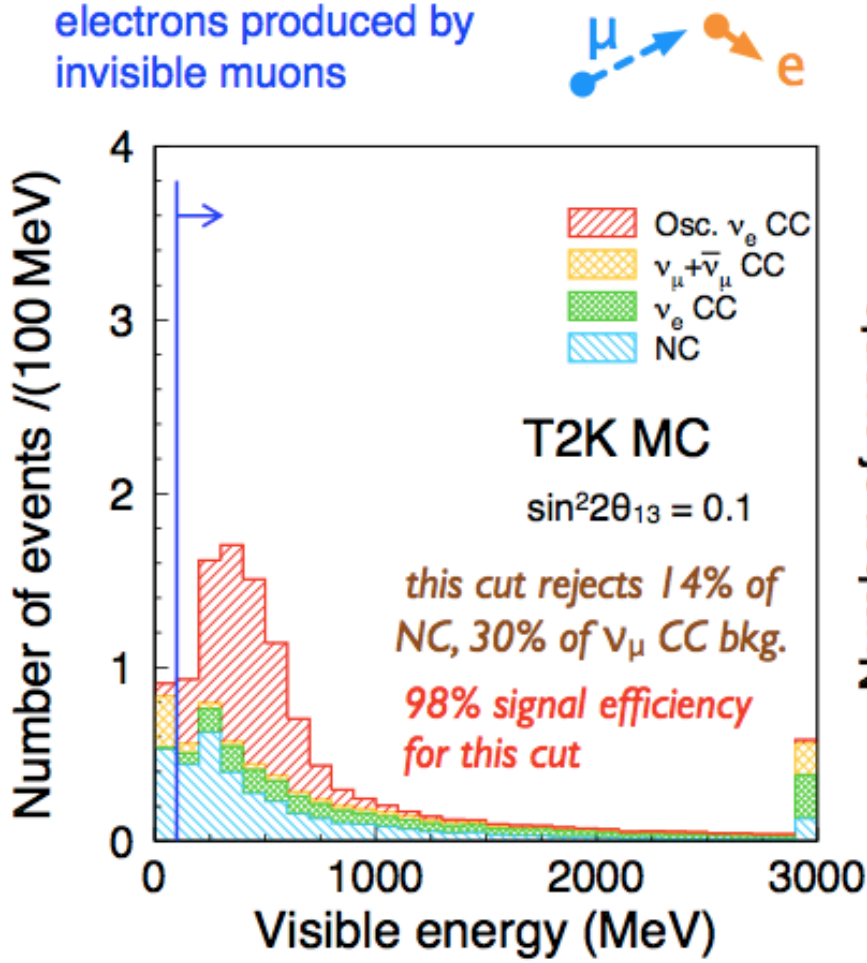
3. Single electron
   (# of ring is one & e-like)

K. Sakashita

4. Visible energy > 100 MeV

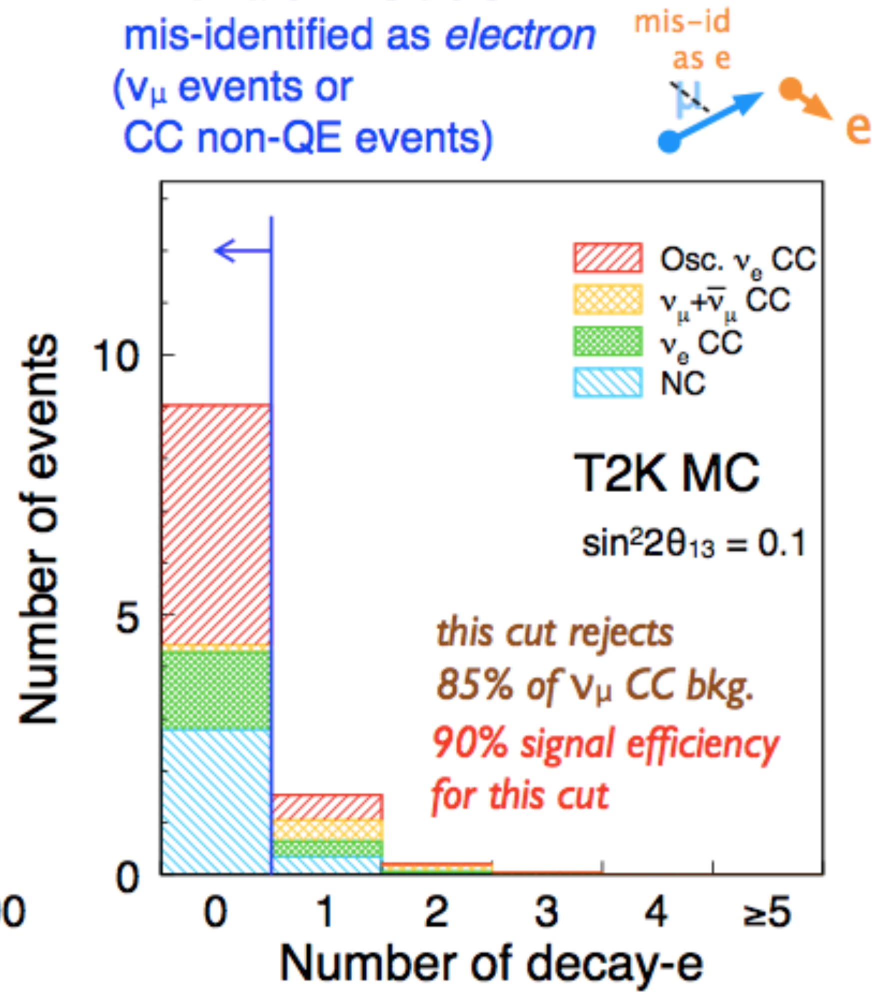
(visible energy = electron energy deposited in ID)

* Reject low energy events, such as NC background and decay electrons produced by invisible muons



5. No decay electron observed (no delayed electron signal)

* Reject events with muons or pions which are invisible or mis-identified as *electron* (ν_μ events or CC non-QE events)



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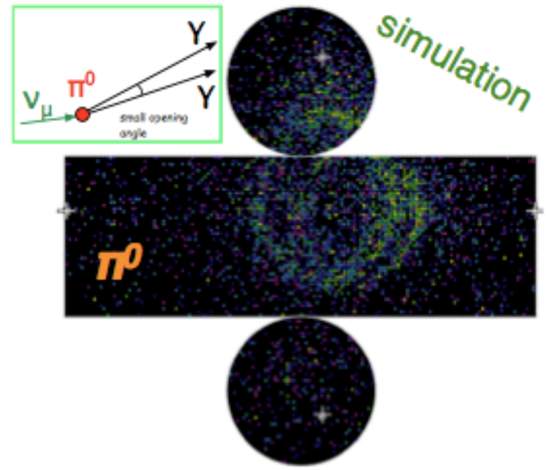
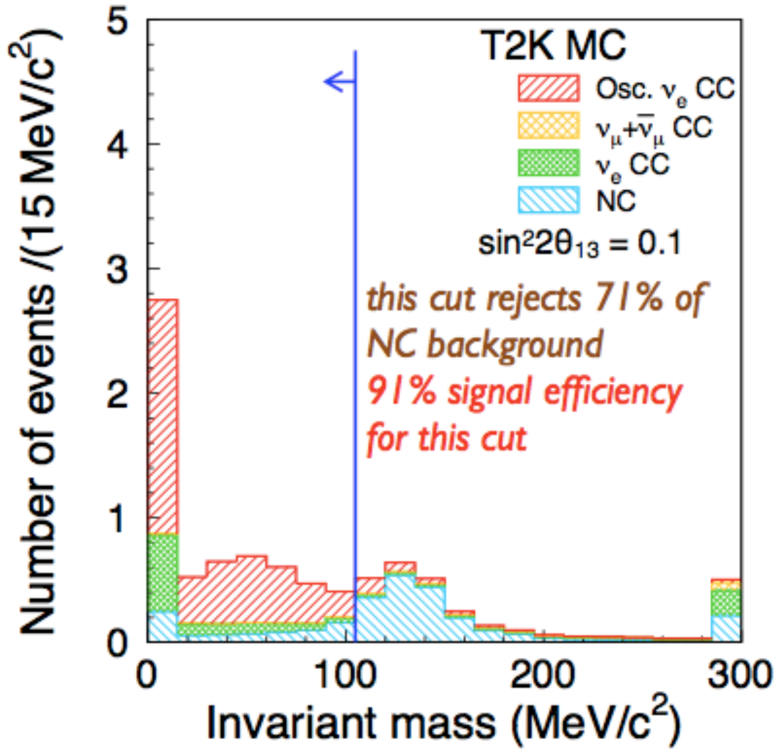
6. Reconstructed
   invariant mass (M_{inv}) < 105 MeV/c^2

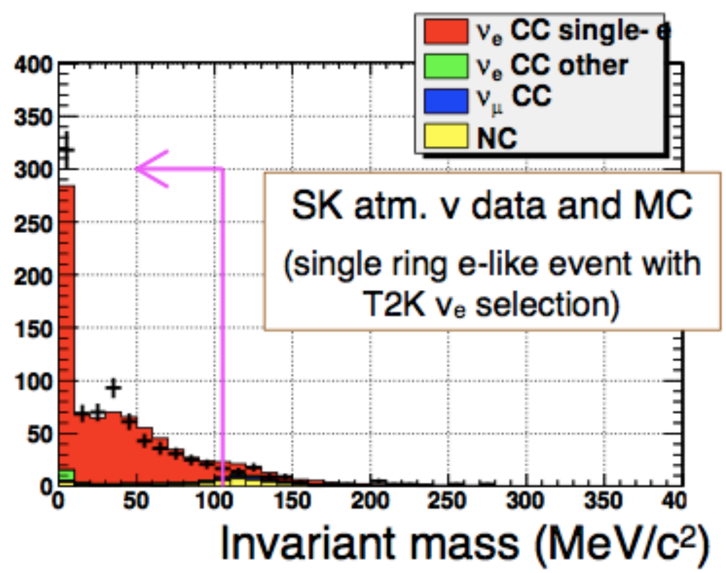
* Suppress NC π^0 background

Find 2nd e-like ring by forcing to fit light pattern under the 2 e-like rings assumption, and then reconstruct invariant mass of these 2 e-like rings



demonstrate to reconstruct invariant mass using atmospheric ν data

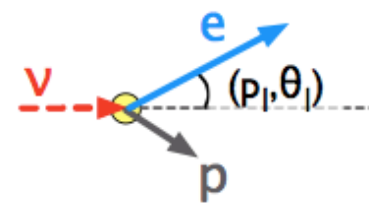




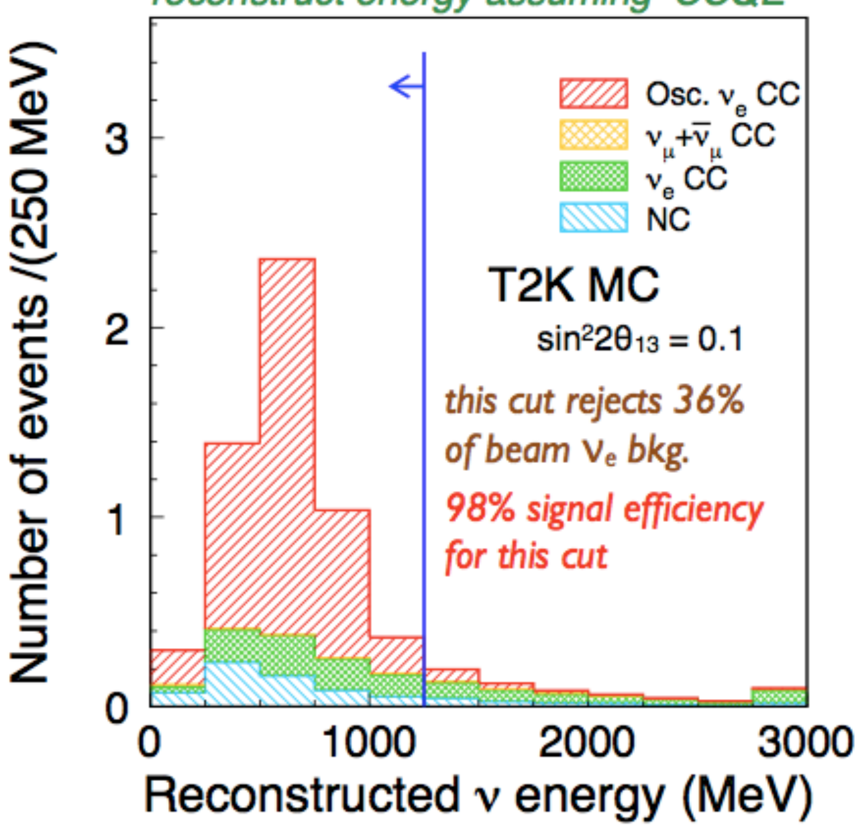
K. Sakashita

7. Reconstructed energy (E_{rec}) < 1250 MeV

- * Reject intrinsic beam ν_e backgrounds at high energy
- * Signal ($\nu_\mu \rightarrow \nu_e$) has a sharp peak at E~600MeV



reconstruct energy assuming CCQE



$$E_{rec} = \frac{m_n E_l - m_l^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_l + p_l \cos\theta_l}$$

(with correcting nuclear potential)

After all the selection criteria
background rejection :
77 % for beam ν_e,
99 % for NC
signal efficiency : 66 %
for the number of events in FV