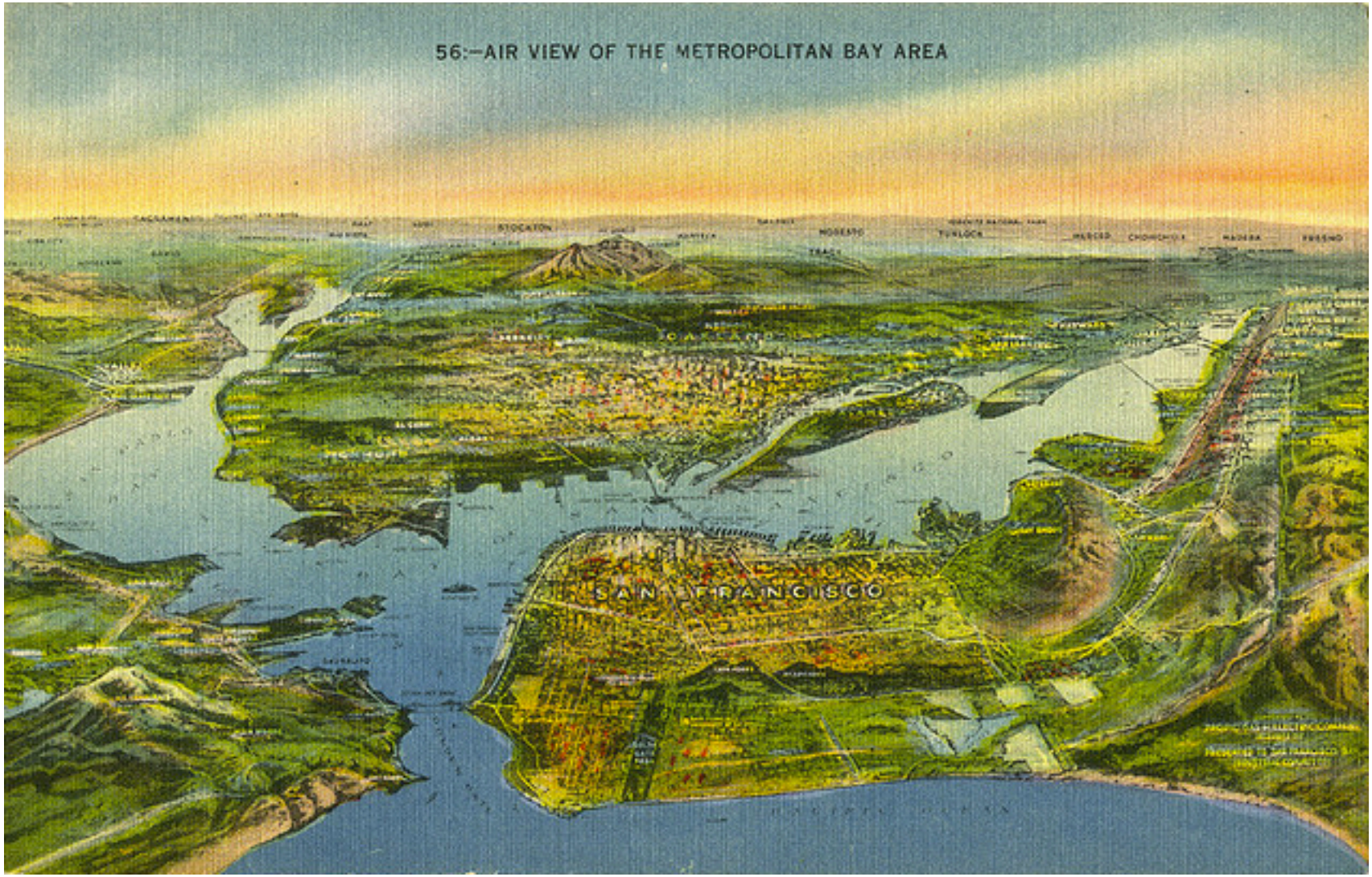
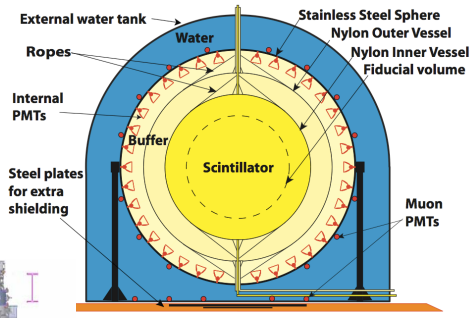
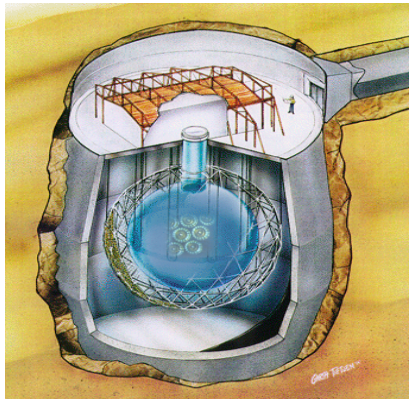
Indication of Electron Neutrino Appearance in the T2K Experiment

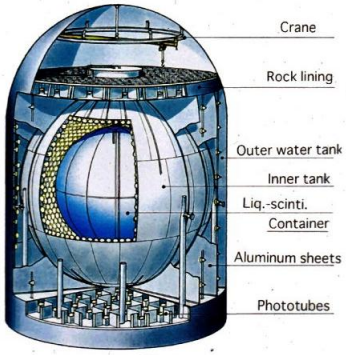


SLAC-LBL Seminars
September 5th-9th 2011

Types of neutrino experiments



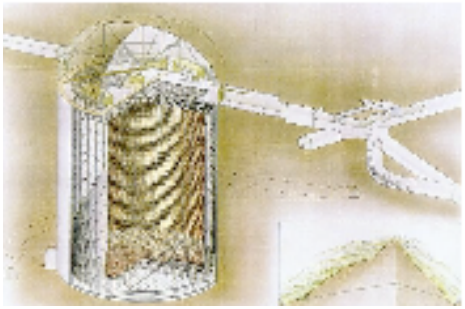




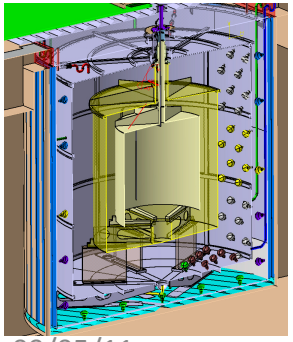
Direct Mass * Double Beta Decay

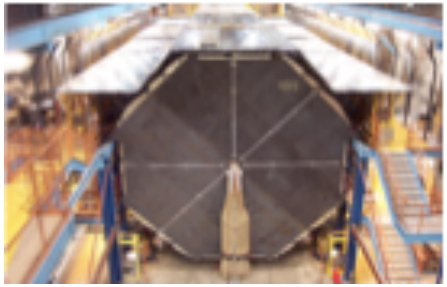
Reactor Experiments * Atmospheric and Solar Neutrinos

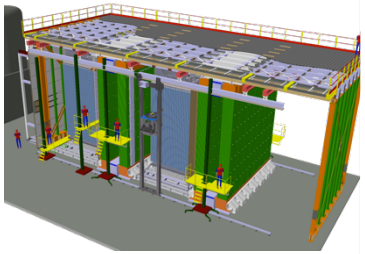
Accelerator Based Oscillation Experiments

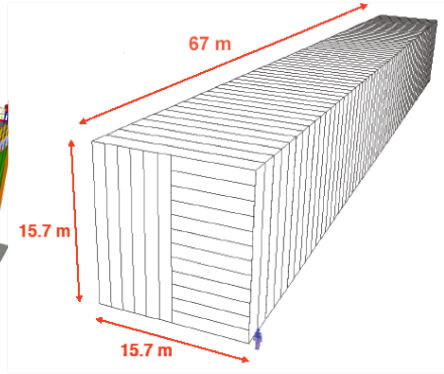


Today





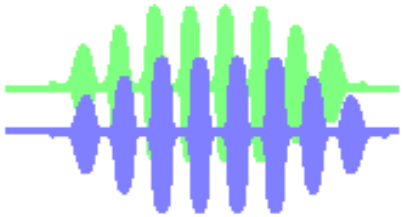




How do they oscillate?

"Flavor" states are mixture of mass states.

$$\begin{aligned}\nu_\mu &= \quad \nu_2 \cos\theta + \nu_3 \sin\theta \\ \nu_\tau &= -\nu_2 \sin\theta + \nu_3 \cos\theta\end{aligned} \qquad \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\left|\nu_\mu(t)\right\rangle = e^{iE_1 t}\left|\nu_1(0)\right\rangle \cos\theta + e^{iE_2 t}\left|\nu_2(0)\right\rangle \sin\theta$$

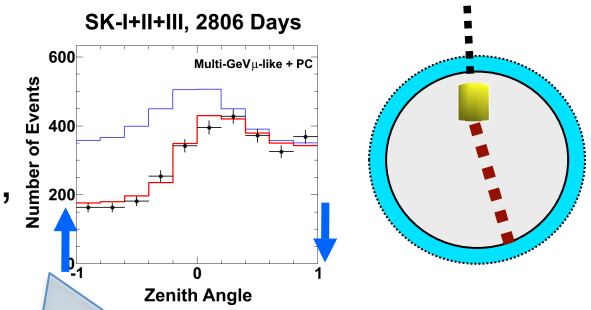
$$P_{\mu\tau} = \sin^2 2\theta \, \sin^2 \frac{1.27\Delta m^2 L}{E}$$

Current information on neutrino oscillations*

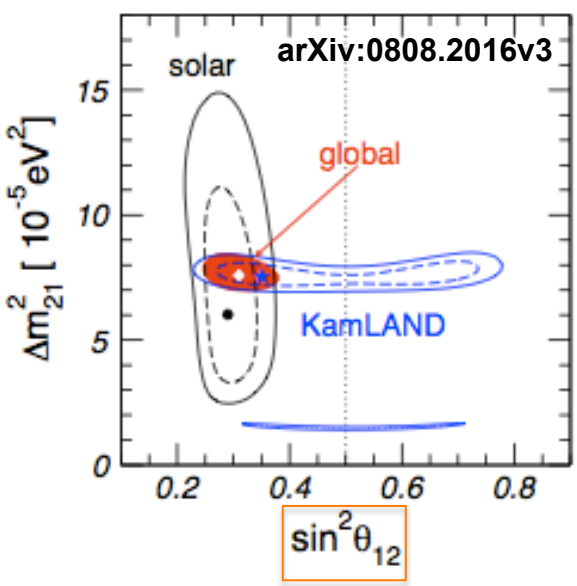
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

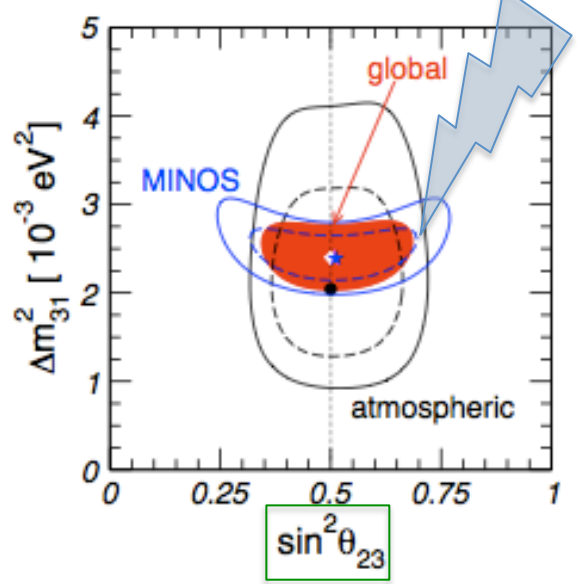
Atmos Oscillations — unknown — Solar Oscillations

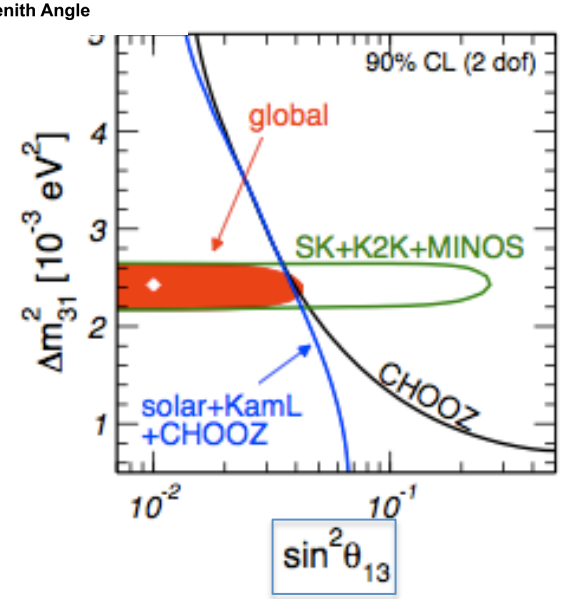
$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & \boxed{s_{23}} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & \boxed{s_{12}} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} c_{23} = \cos\theta_{23} \\ s_{23} = \sin\theta_{23} \end{matrix}$$



Results come from a set of solar, atmospheric, accelerator and reactor experiments



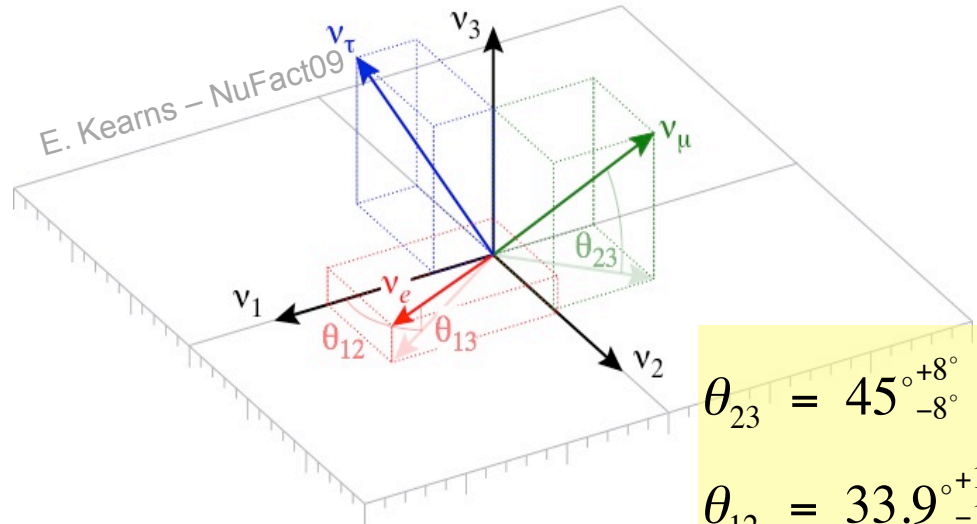




*ignoring some recent very new odd results from MiniBooNE/~~Minos~~

To address in oscillation experiments:

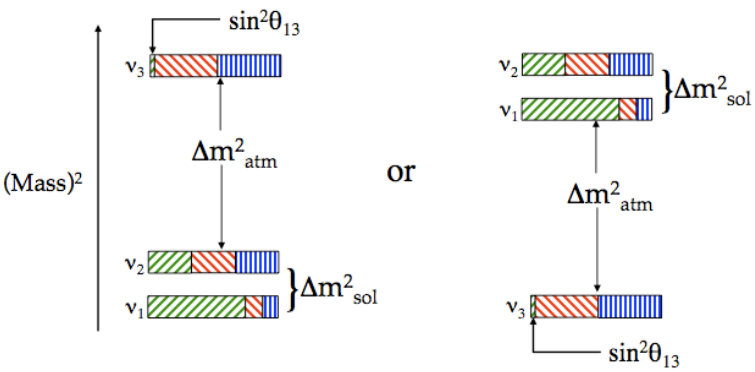
- What is the pattern of neutrino masses?
- Is there CP violation in the neutrino sector? Is it big enough to drive lepto-genesis and is it related to the quark sector?
- What is the value of the final unmeasured mixing angle, and is the atmospheric angle maximal?



$$\theta_{23} = 45^\circ{}^{+8^\circ}_{-8^\circ}$$

$$\theta_{12} = 33.9^\circ{}^{+1.2^\circ}_{-1.2^\circ}$$

$$\theta_{13} < 13^\circ$$



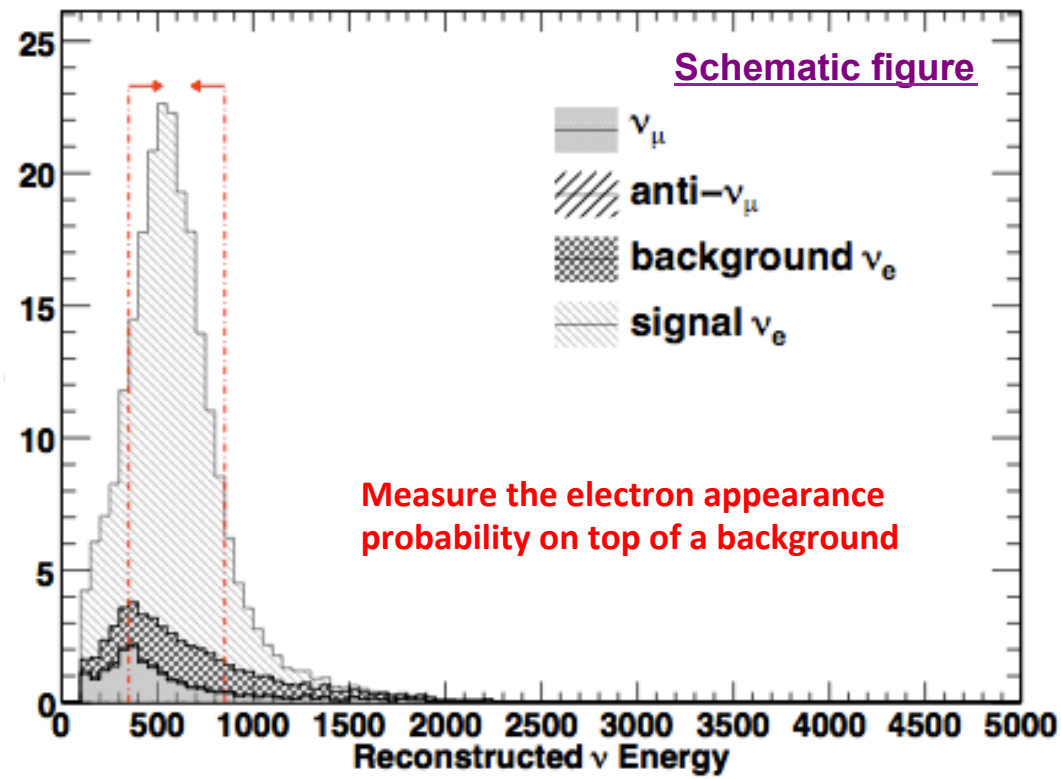
"Normal" "Inverted"

The third angle has only an upper limit. Unless all of the angles are finite we can't measure CP violation in neutrinos.

In a beam experiment, the signal for non-zero θ_{13} is ν_e appearance in a pure ν_μ beam.

How do we measure θ_{13}?

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E_\nu} + sub\text{-}leading\ terms$$

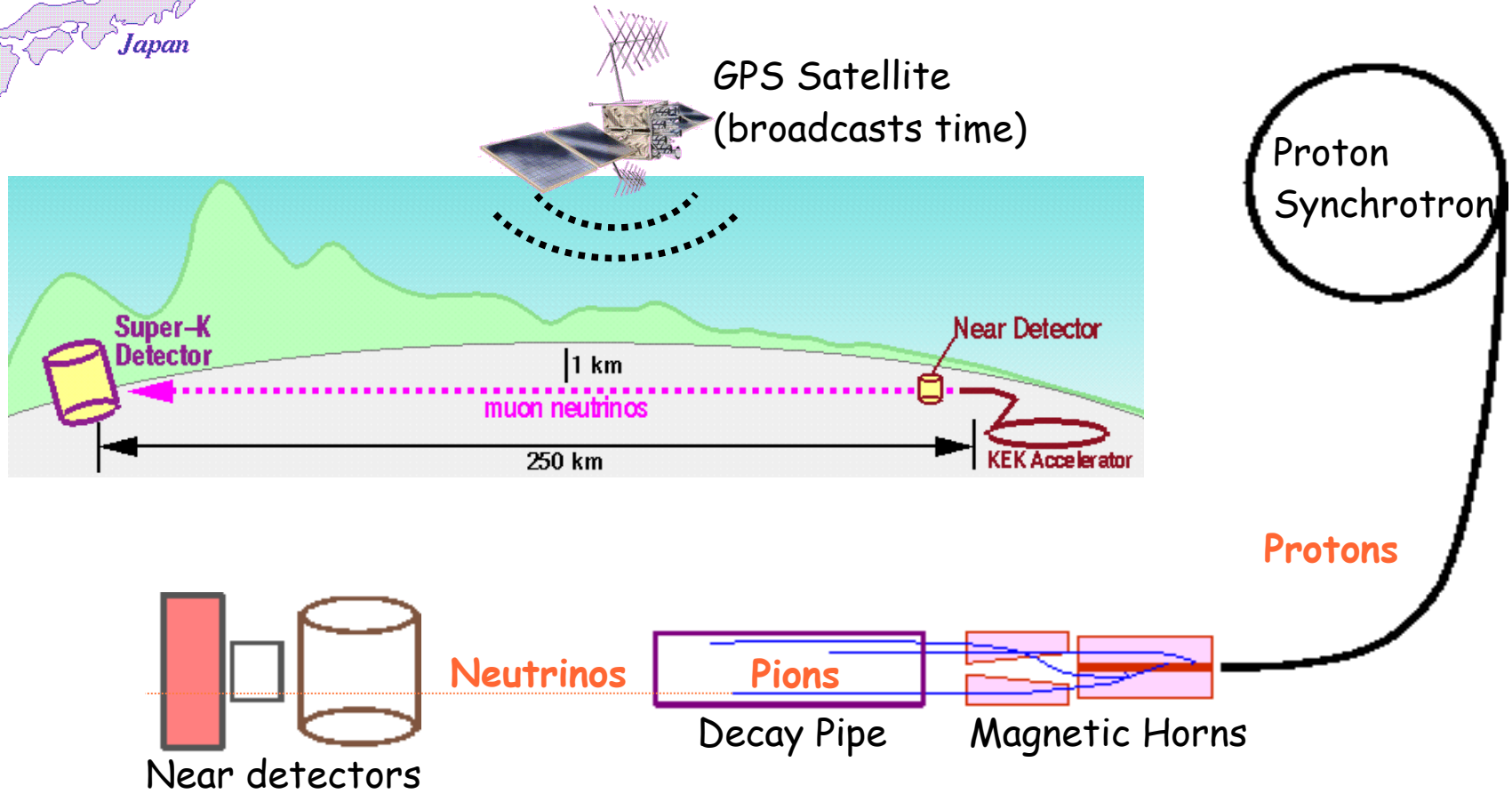


For appearance three main types of background:
intrinsic ν_e, *misidentified* π^0, *mis-identified charged* μ

We need a very high intensity beam and a large target. Make a pure neutrino beam and look for electrons to appear.

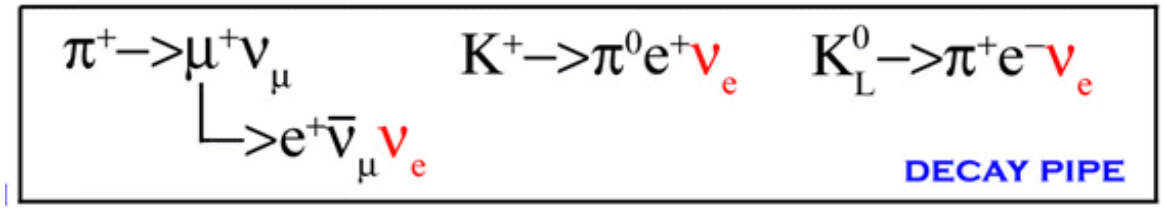
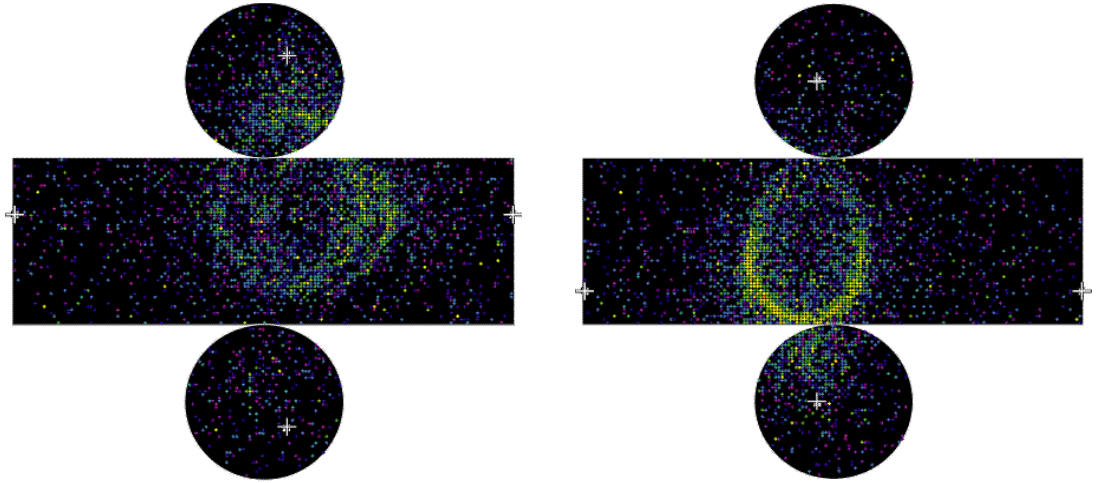
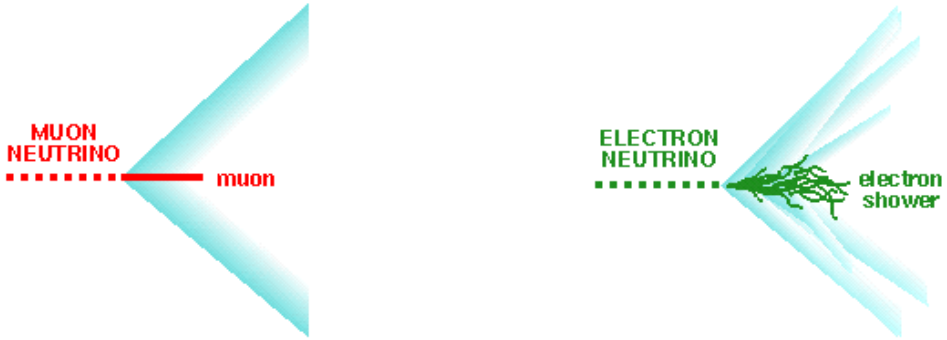
How do you build a long-baseline experiment?

(1st example: K2K -> MINOS -> T2K)



Always the same pattern:
Accelerator -> Target -> Horns -> Decay Pipe -> Near detector -> Far Detector

Main Backgrounds in WC detectors

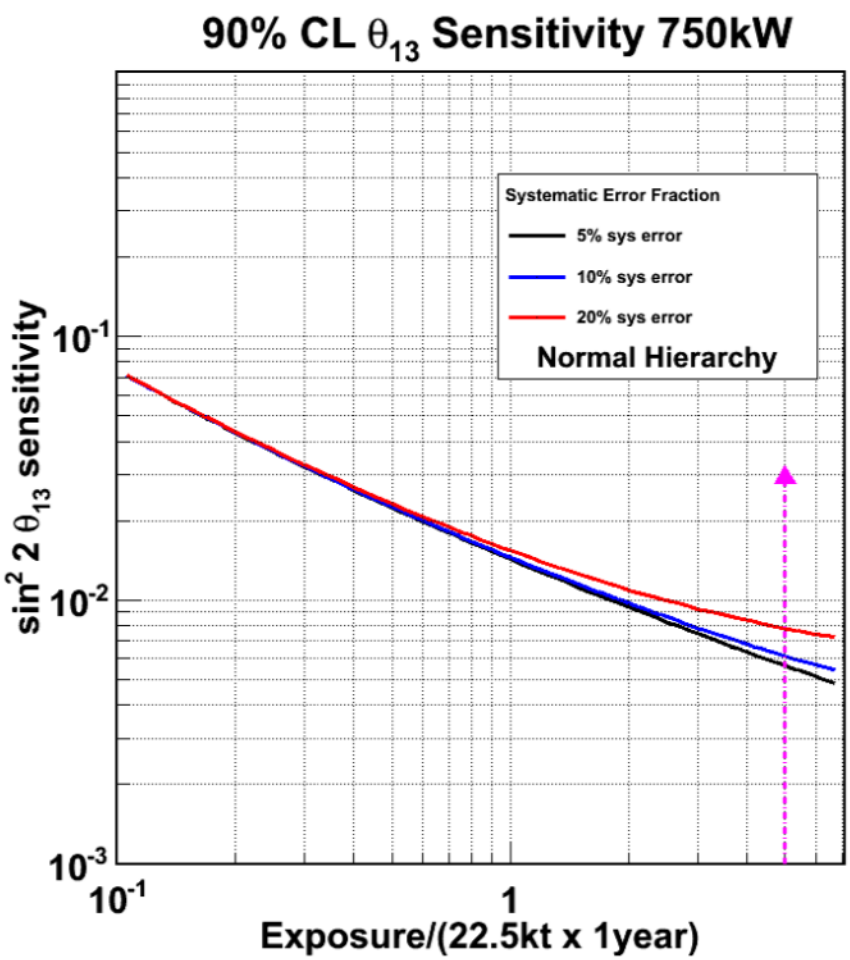
Intrinsic ν_e contamination	
Confuse $\pi^0 \to \gamma\gamma$ with ν_e	
Confuse ν_μ with ν_e	

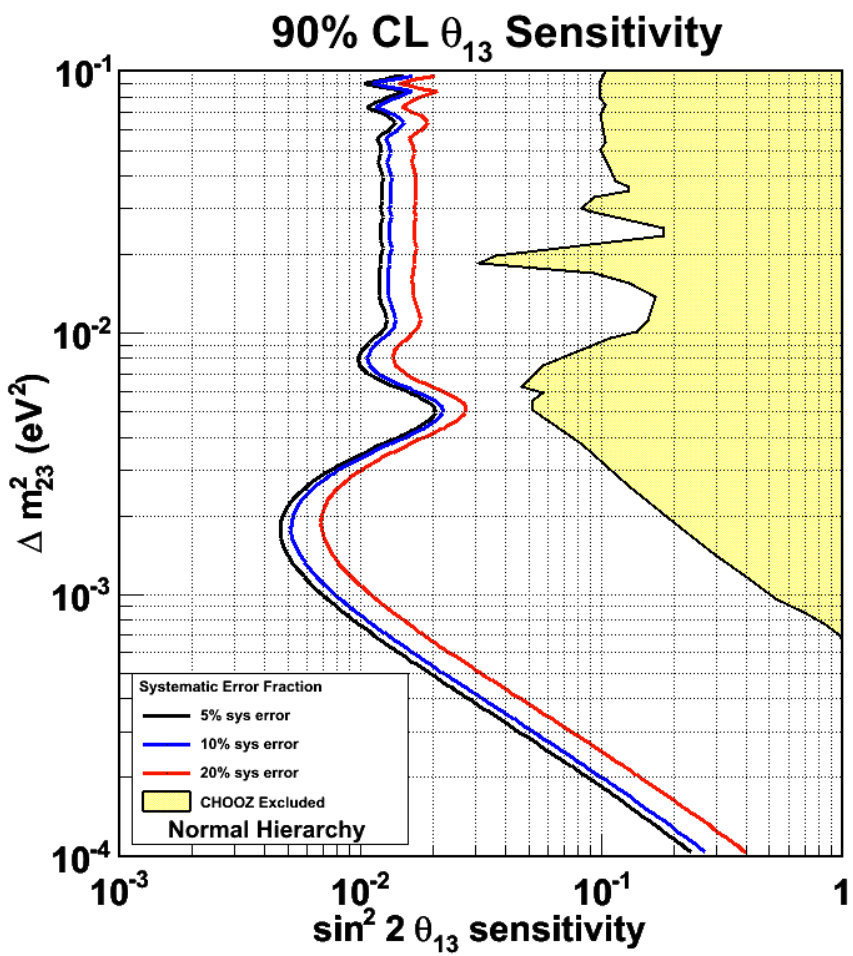
T2K Collaboration

~500 Collaborators / 59 Institutions / 12 Countries

(Canada / France / Germany / Italy / Japan / Poland / Russia / S. Korea / Spain / Switzerland / UK / USA)

Expected sensitivities after 5 year run.

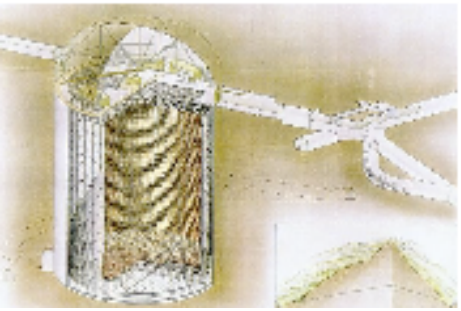




T2K's current exposure is about 70 kw x 10^7 seconds of integrated proton power on target approximately 2% of the final goal.

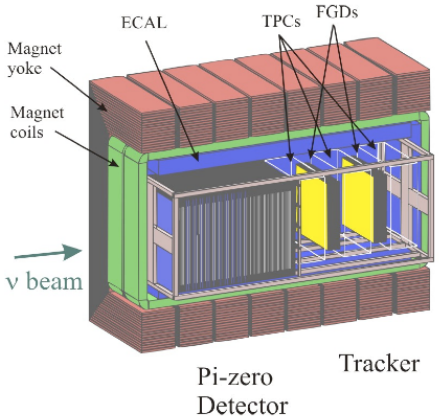
The T2K Experiment

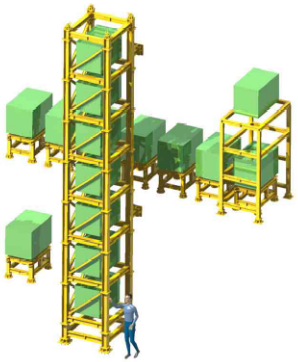
Super-K water Cherenkov Detector as far detector.
Uses the new JPARC accelerator complex

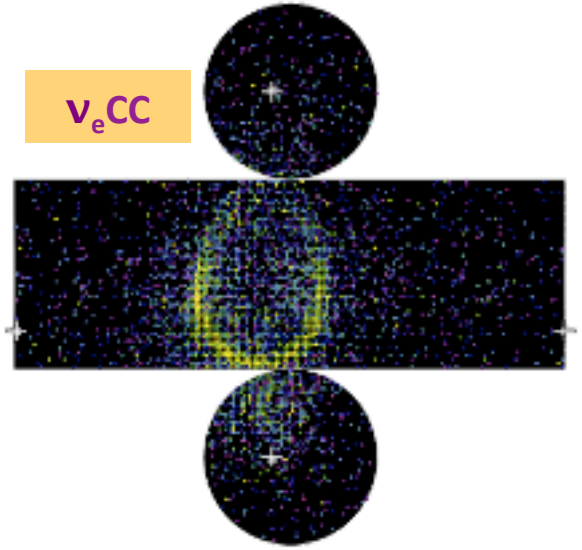


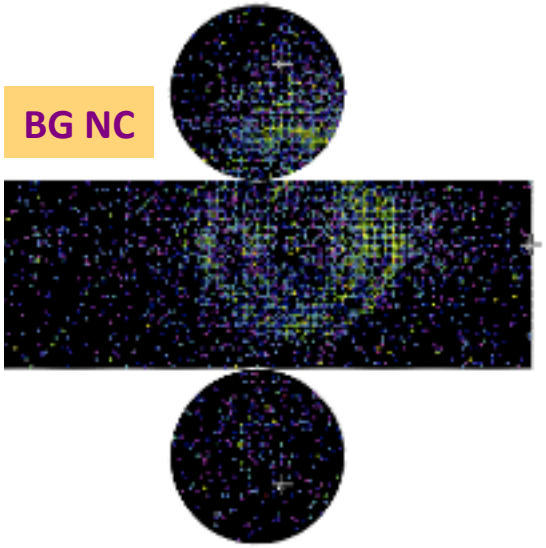
Far detector: Super-K

On and off-axis hybrid near detectors

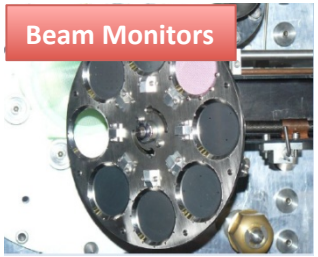


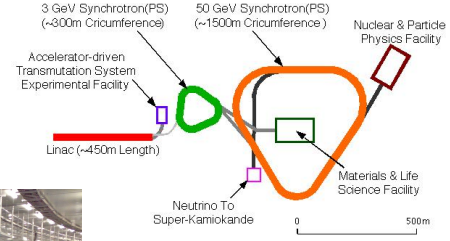




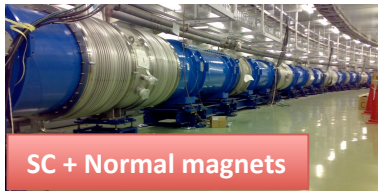


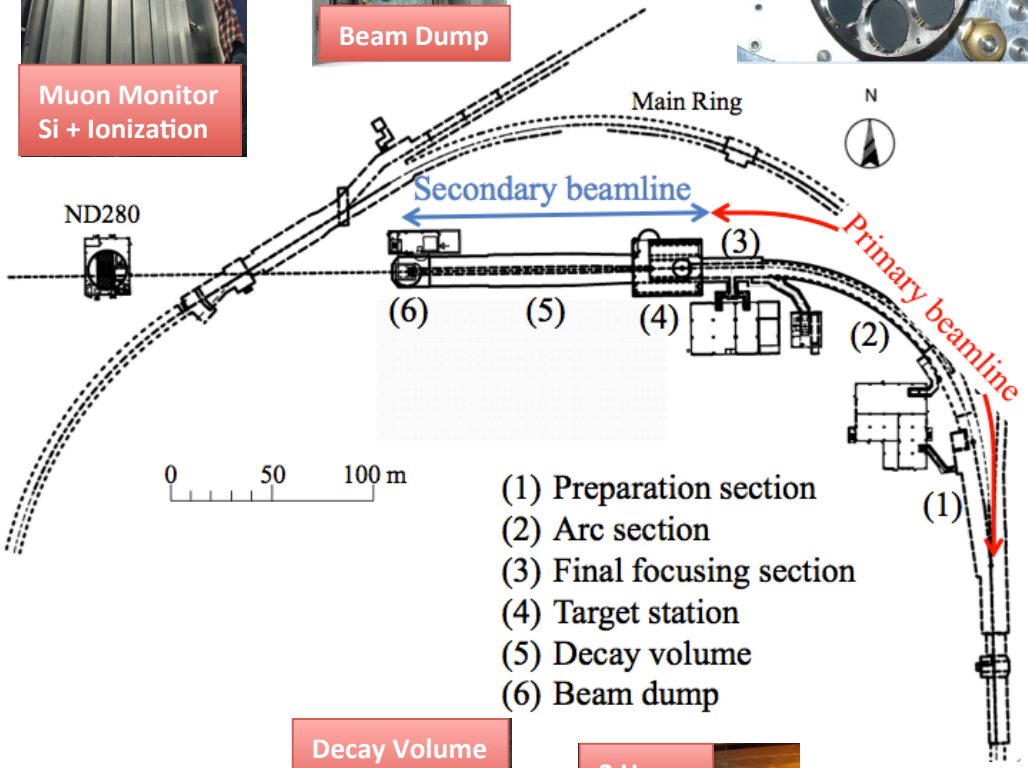
- 50 Kton Water Cherenkov Detector
- >11,000 PMTs read out by QTCs
- Image processing for reconstruction

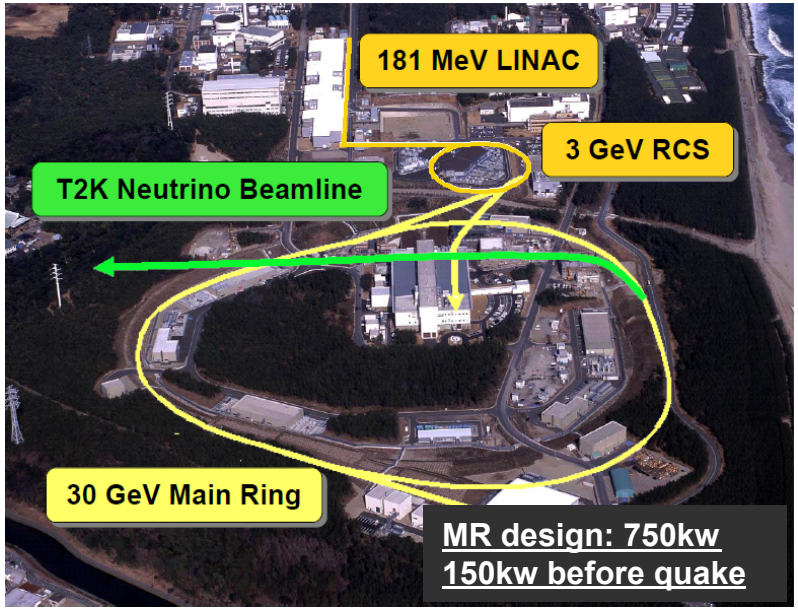


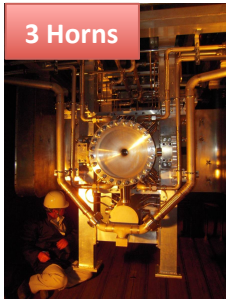


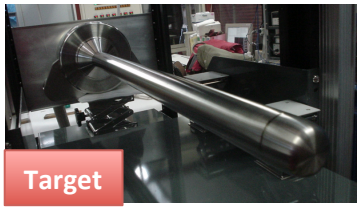
High Intensity Proton Accelerator Project





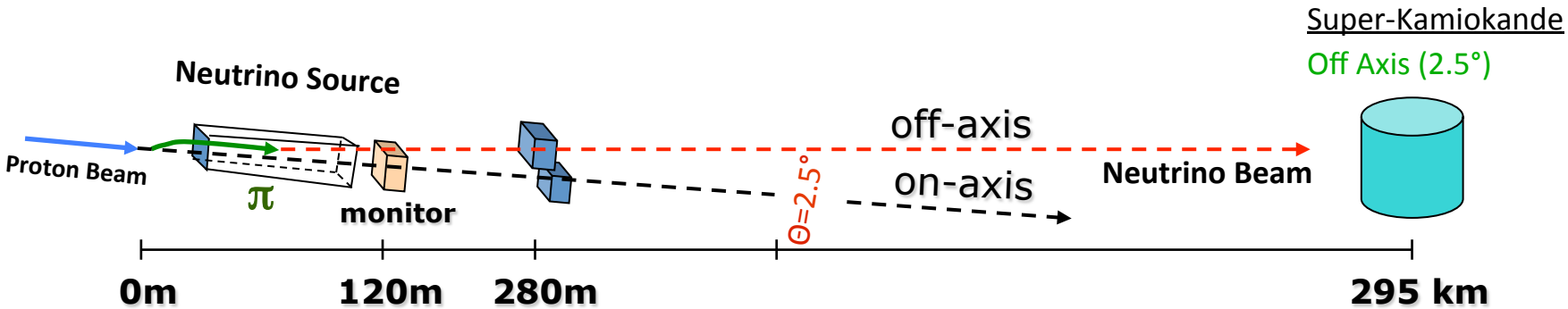


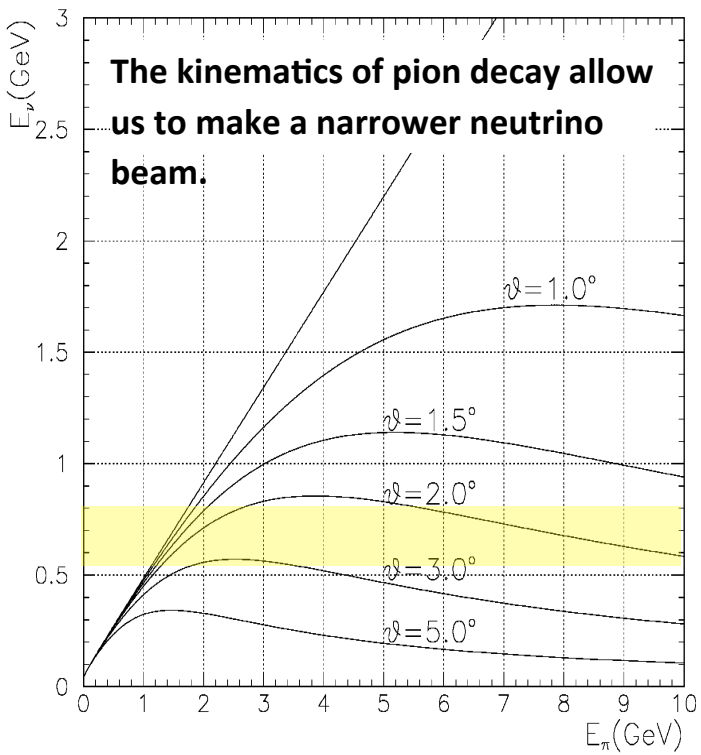


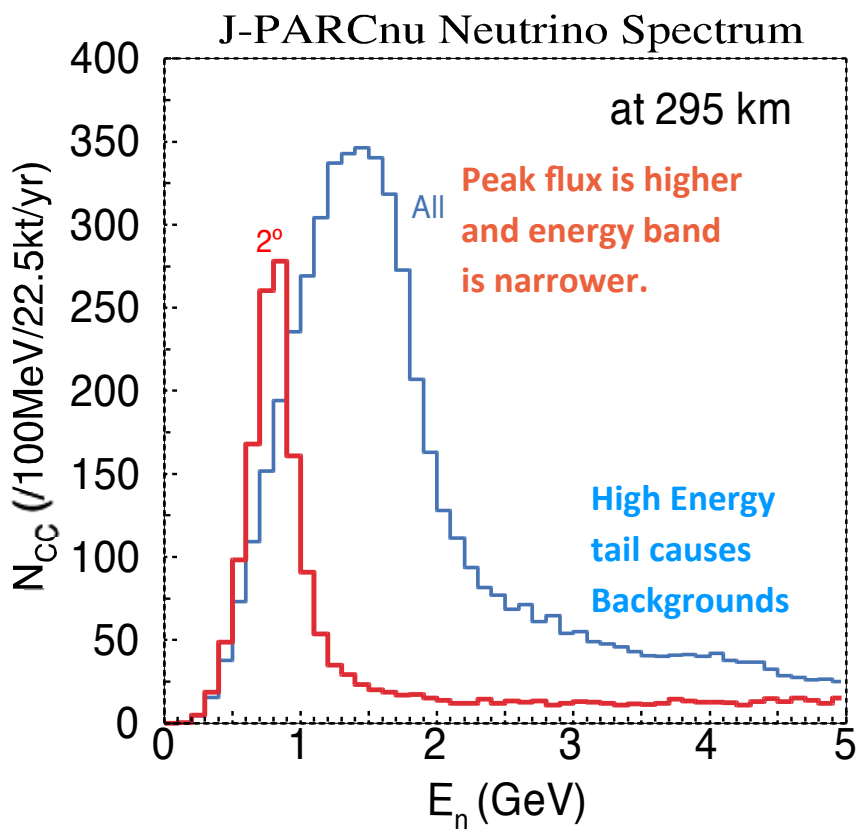


JPARC Site

Off-Axis Beams

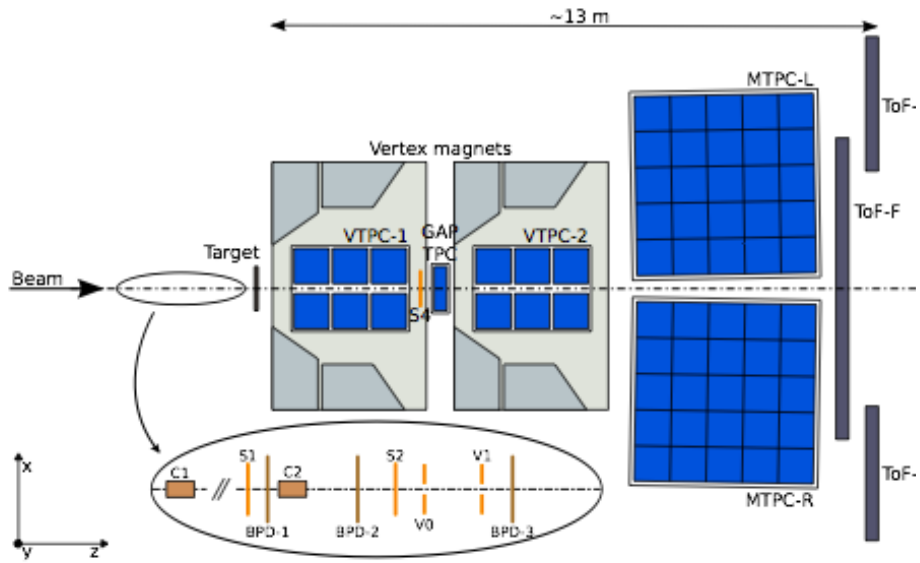




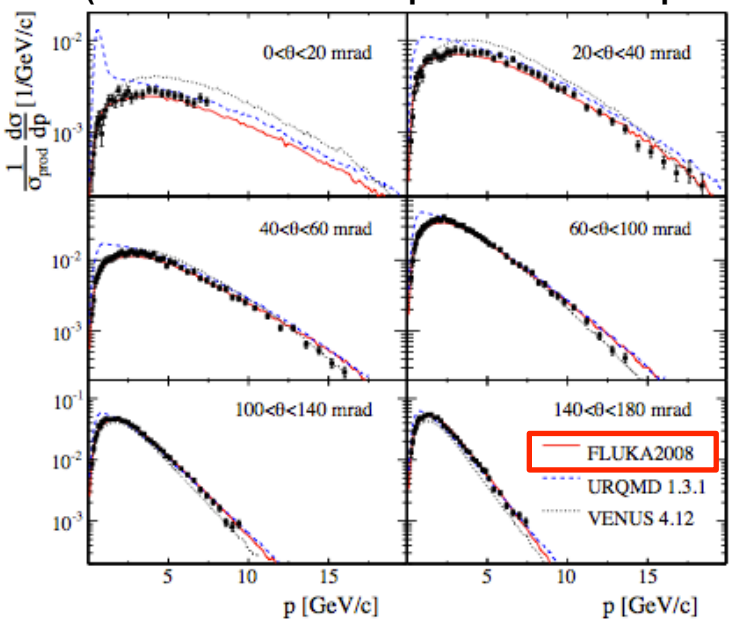


NA61 Experiment at CERN

NA61 is used to tune our neutrino flux



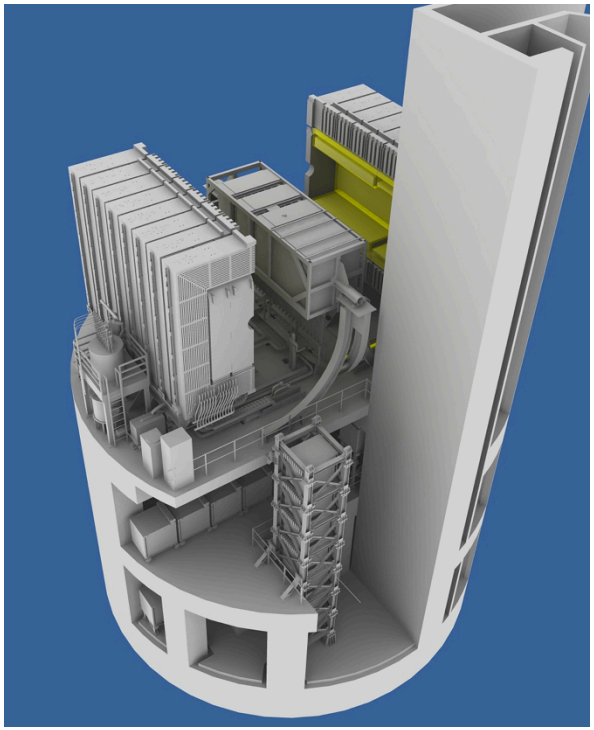
30GeV proton cross-sec on C^{12}
(measure differential production multiplicity)

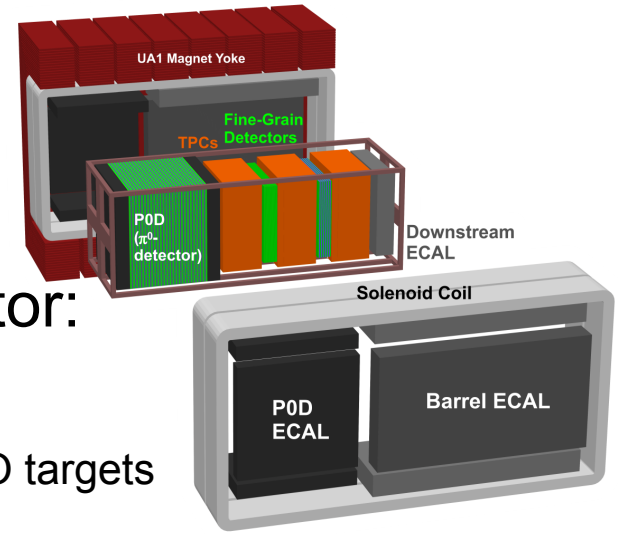


- Large acceptance spectrometer with dE/dx and TOF counters
- 30 GeV proton beam matches T2K.
- Both a "**thin**" .04 λ target and a replica of the T2K target
- Can measure **pion** and kaon production

Today: Pions with thin

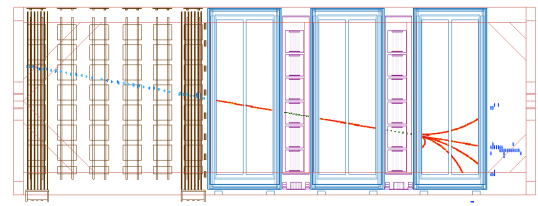
280m Complex





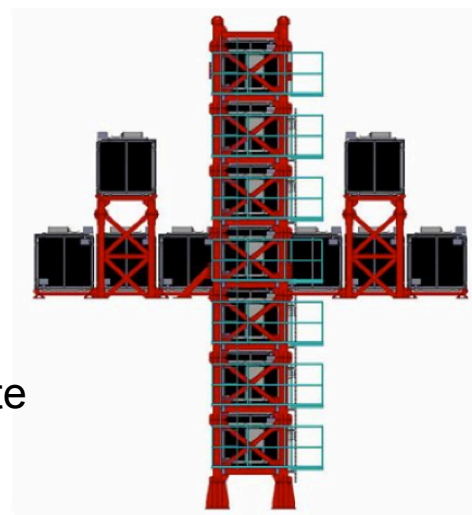
ND280 Off-axis detector:

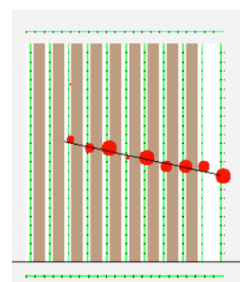
- Off-axis
- 0.2 Tesla UA1 Magnet
- FGDs with scintillator and H_2O targets for mass.
- Followed by TPCs for tracking and dE/dX.
- Ecal for shower measurement
- Scintillator/Water P0D π^0 detector
- Side muon detectors in magnet



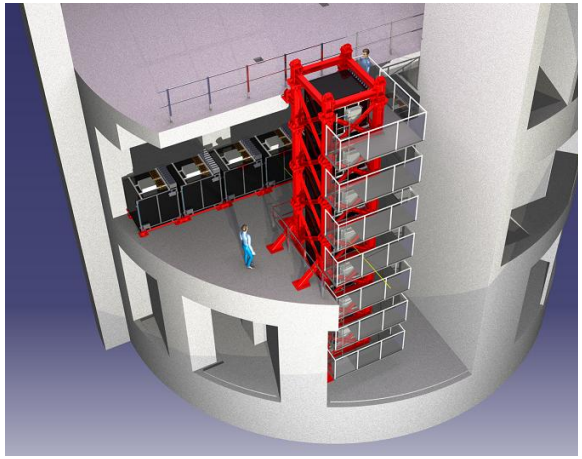
INGRID:

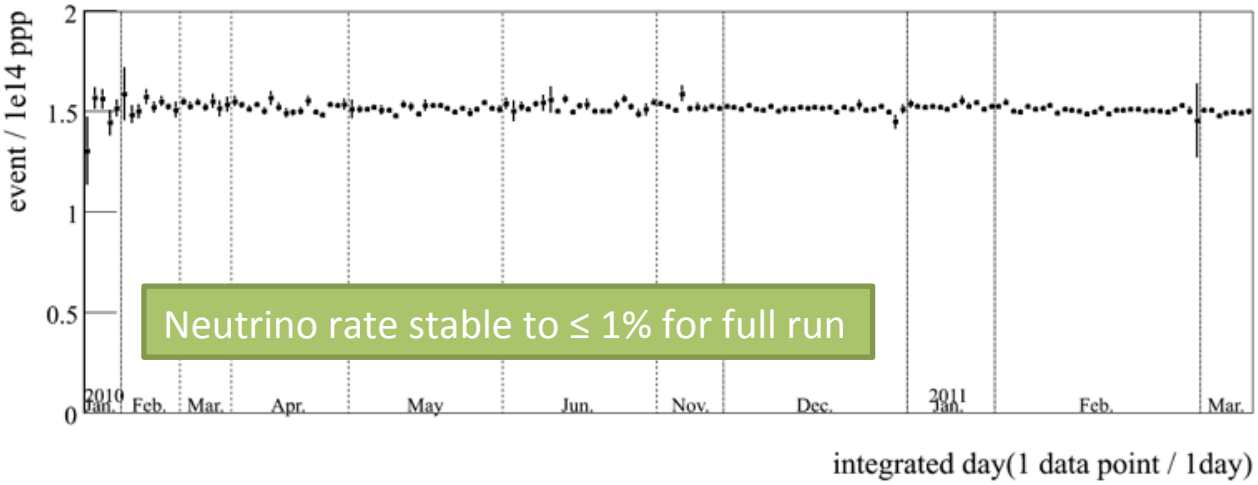
- On-axis
- 16 Modules of Iron and Scintillator
- Measures the beam profile and rate



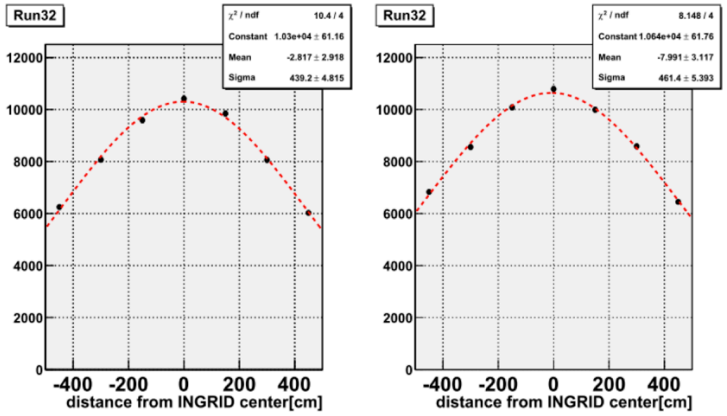


INGRID: Beam is stable/well pointed

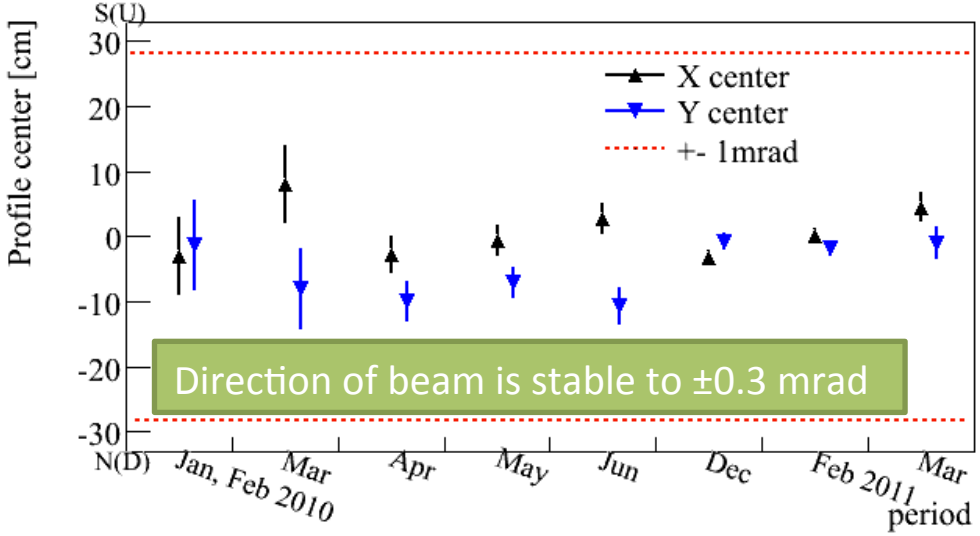




Neutrino rate stable to ≤ 1% for full run

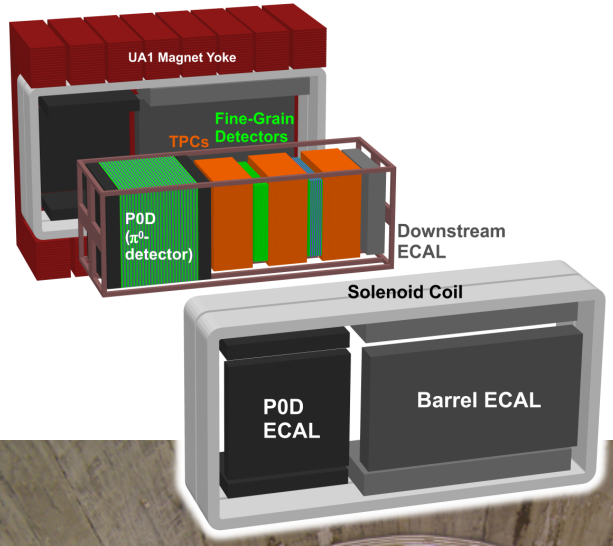


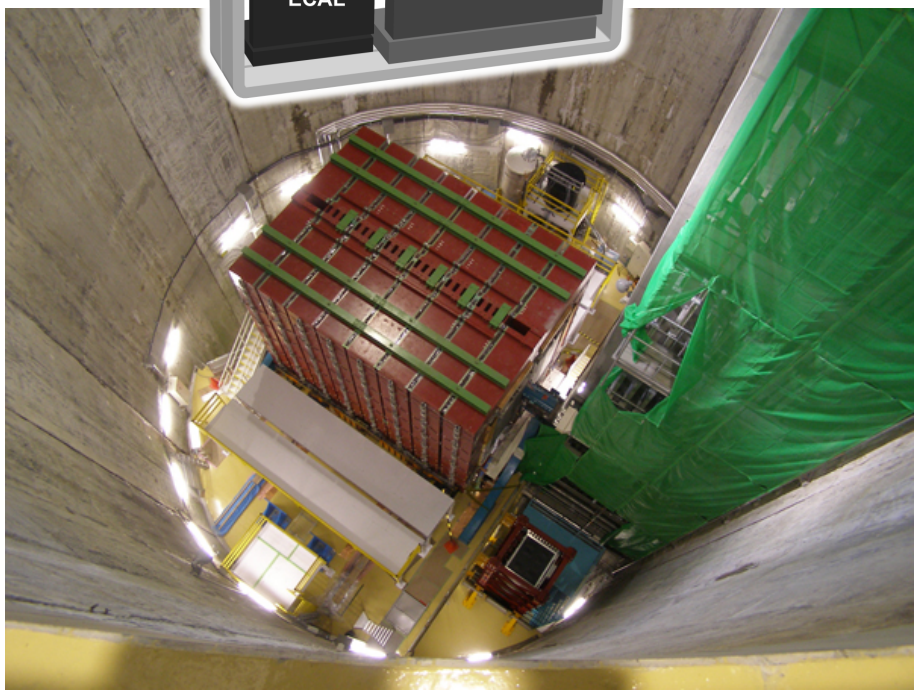
Beam profiles in X and Y

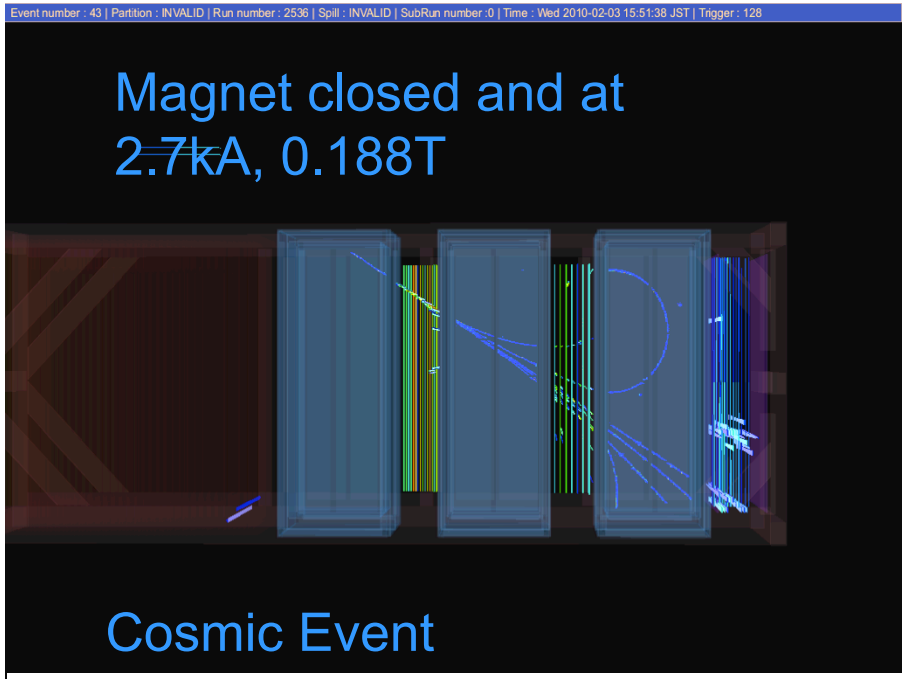


Direction of beam is stable to ±0.3 mrad

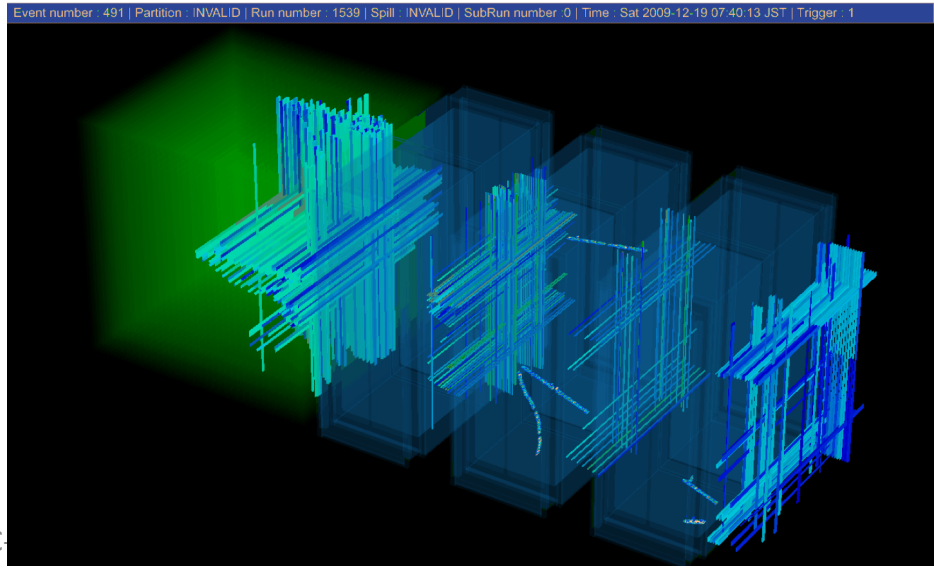
Off-axis detector used for beam normalization



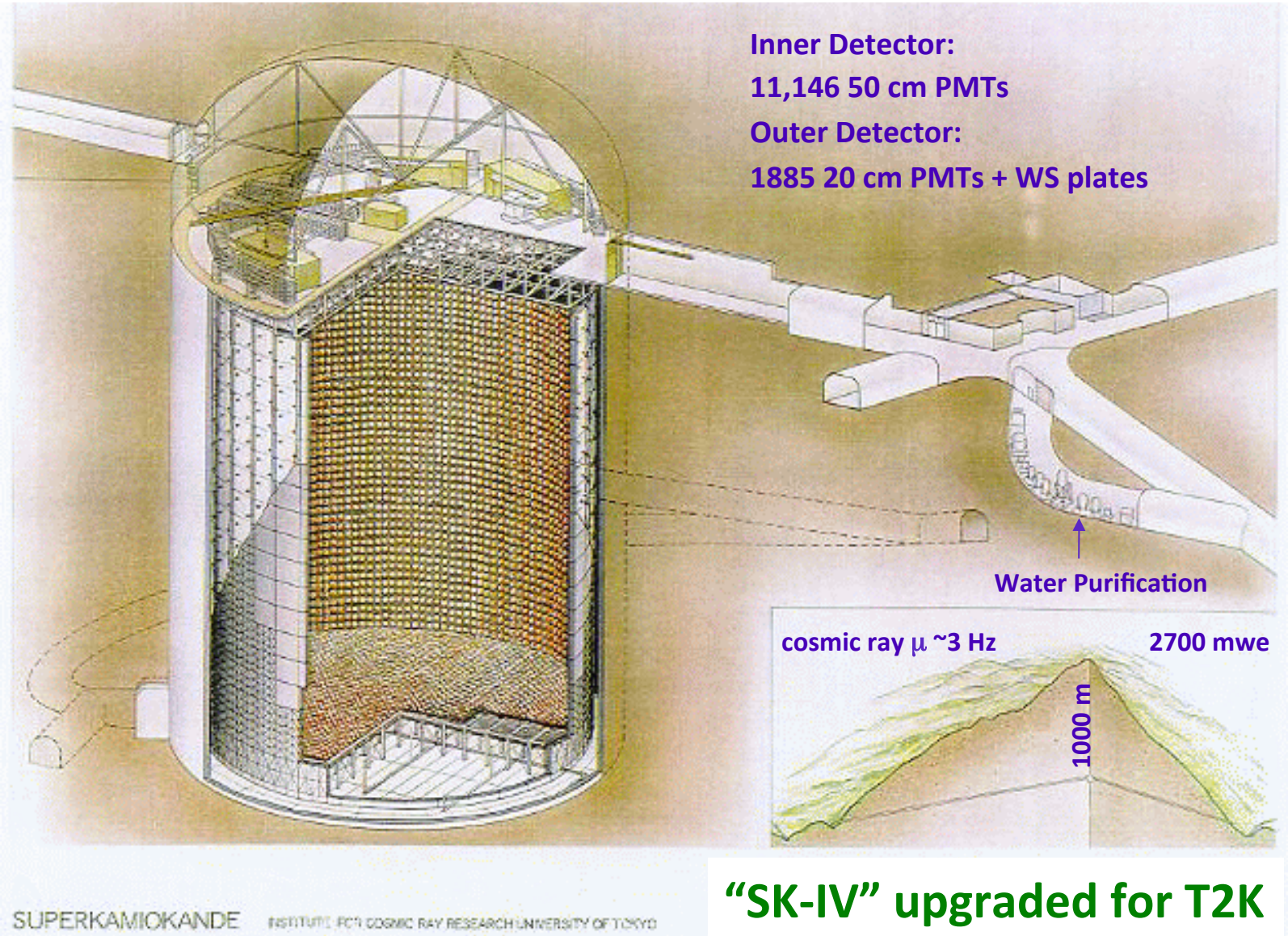




First neutrino interaction in ND280 off axis detector
December 19, 2009



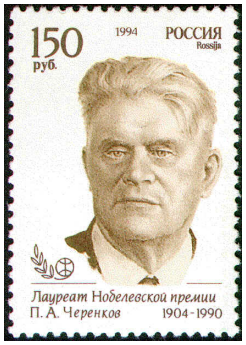
Super Kamiokande Detector: 50,000 Ton Water Cherenkov Detector



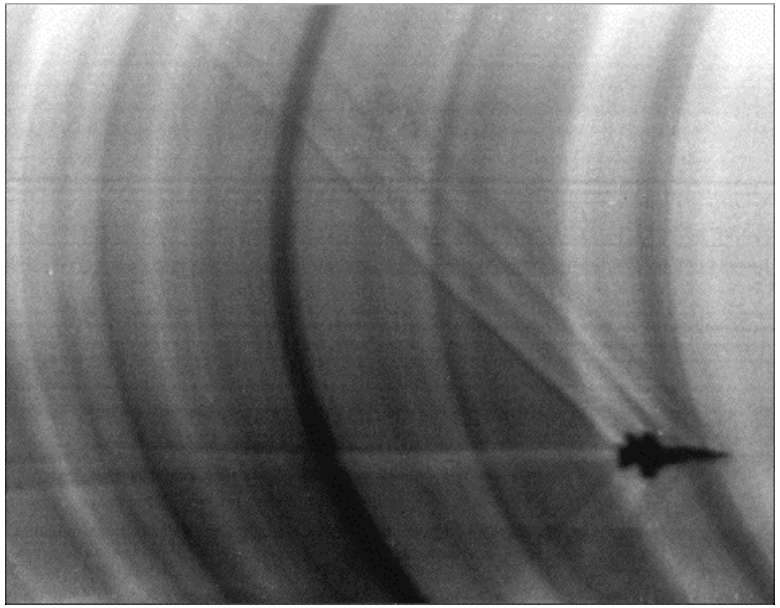
"SK-IV" upgraded for T2K

Cherenkov Radiation

Cherenkov light is emitted when a charged particle, like a muon or an electron goes faster than the speed of light in some medium. The Cherenkov light is emitted like a shockwave, in a cone along the direction of particle motion.

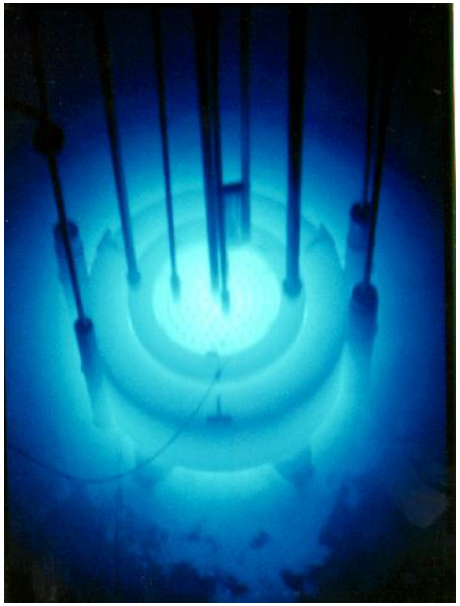


Hypersonic Jet



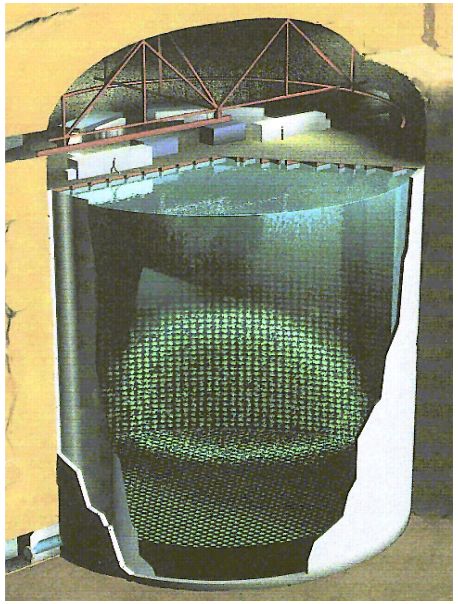
Moving faster than the speed of sound in air makes a sonic boom.

Reactor Core



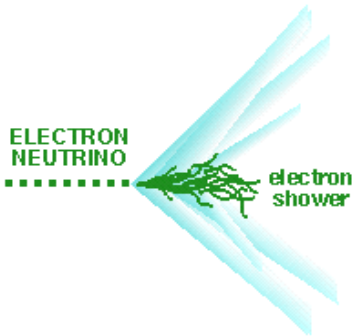
Electrons moving faster than c/n in water make light.

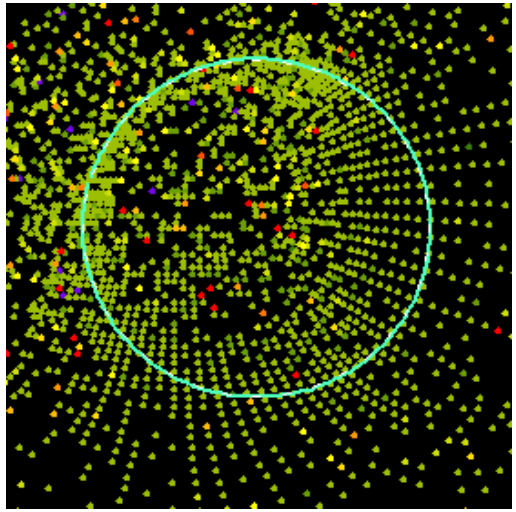
Super-K

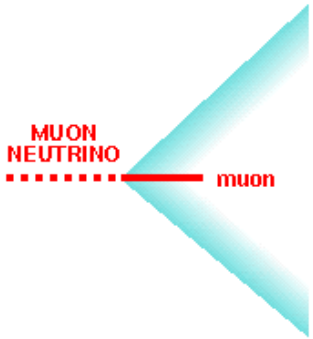


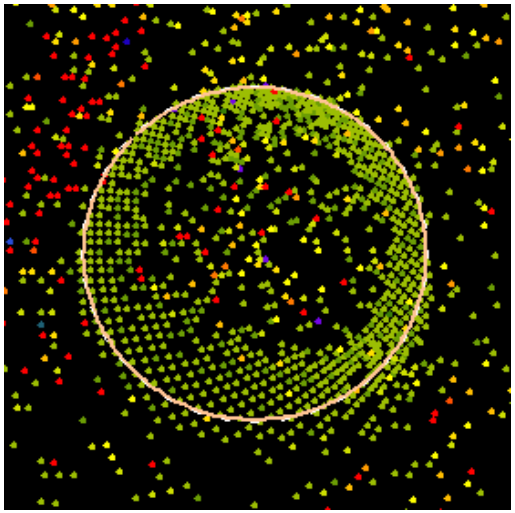
Particles **moving faster than c/n** make cones of light.

Telling Electrons from Muons

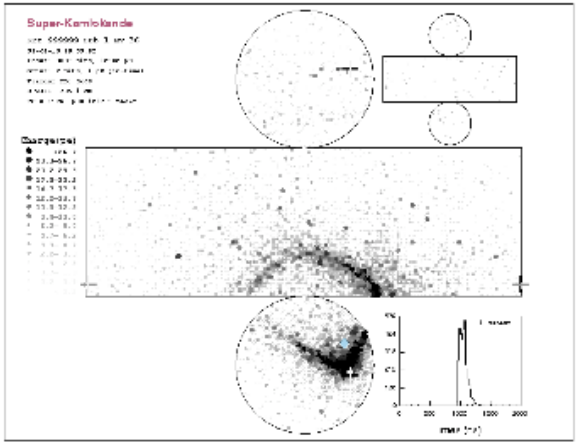


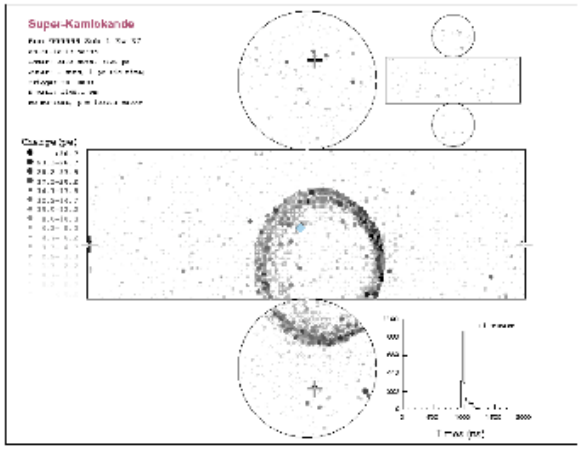






Compare profile of ring against a shape likelihood.



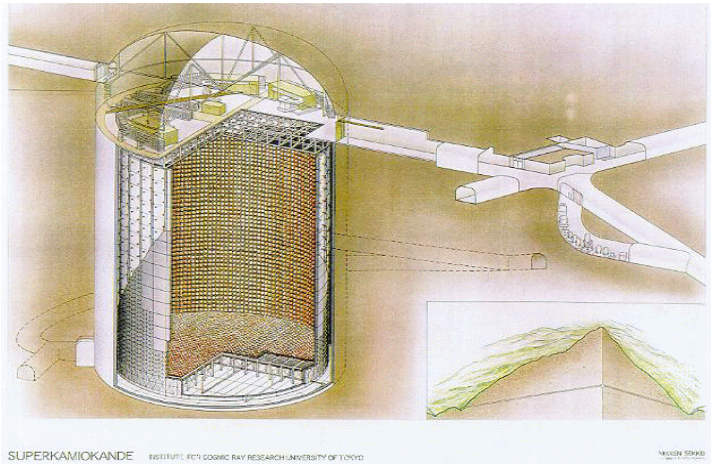


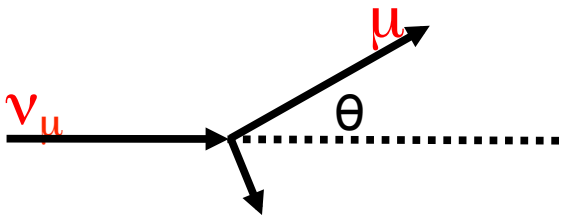
Electrons bremstrahlung and pair produce making many particles each making light.

Thickness gives momentum

Muons move forward producing a single cone of light.

E_ν Reconstruction (assuming QE)





$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}$$

m_N = Neutron Mass
E_μ = Muon Energy
m_μ = Muon mass
p_μ = Muon momentum
θ_μ = Muon angle wrt beam

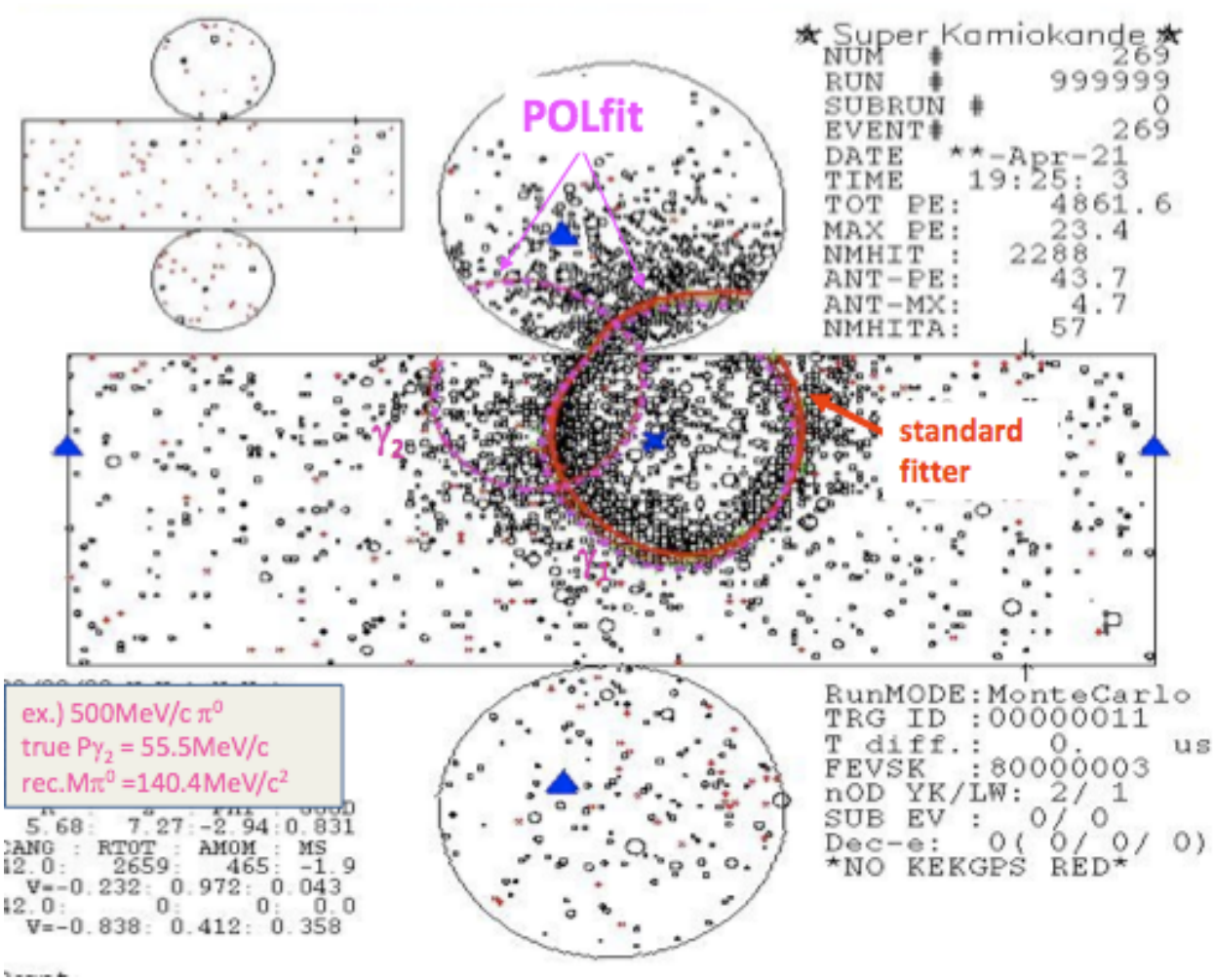
In Water Cherenkov detectors not every particle is above Cherenkov threshold. Luckily, in a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy!
[Case for most events in T2K Energies]

If the interaction is non Quasi-Elastic then the reconstructed energy will be incorrect.

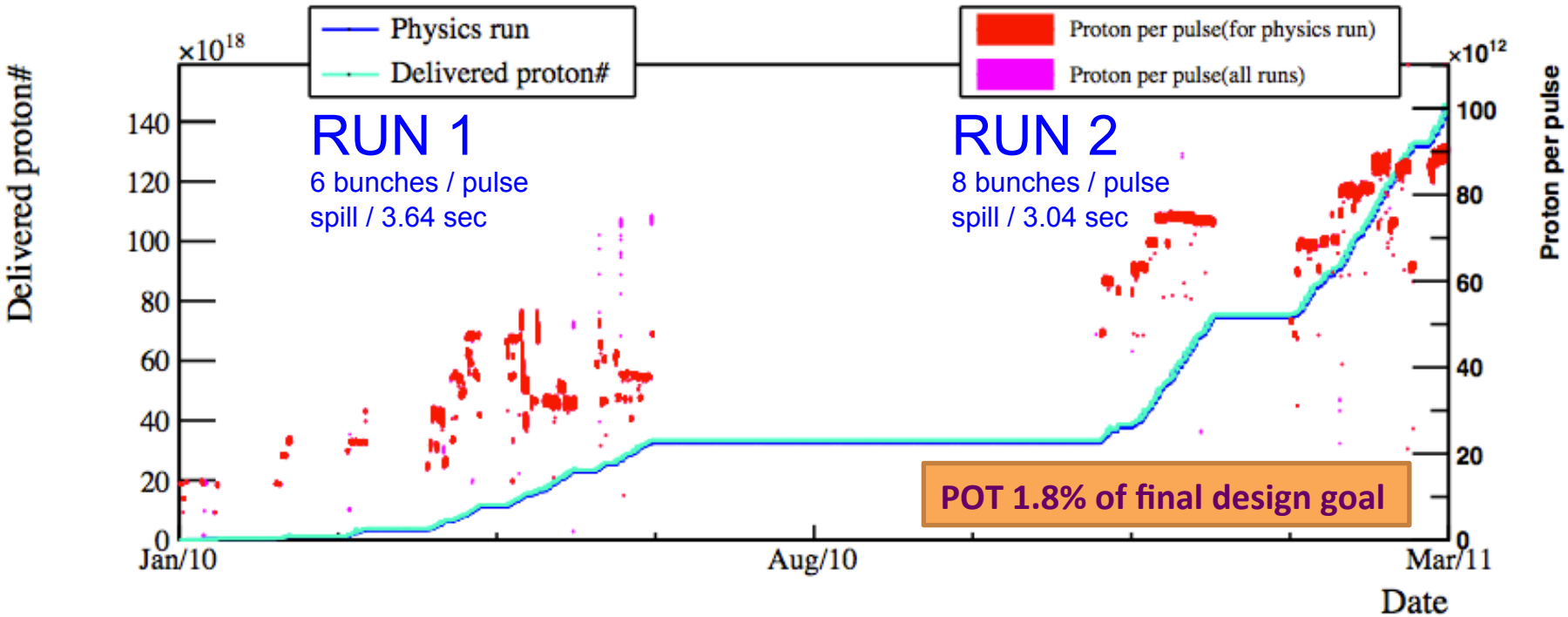
Pattern of Light Fitter

Optimized to find weak 2nd ring from asymmetric decay

- Start from single e-like ring with no decay electrons.
- Assume there is a 2nd ring from a pizero decay somewhere in the event.
- Make a e-like pattern (including scattered light) and move it around until you get the best fit.
- Check the invariant mass of the reconstructed pizero and likelihood and decide whether there was a ring or not.



Analysis Data Set

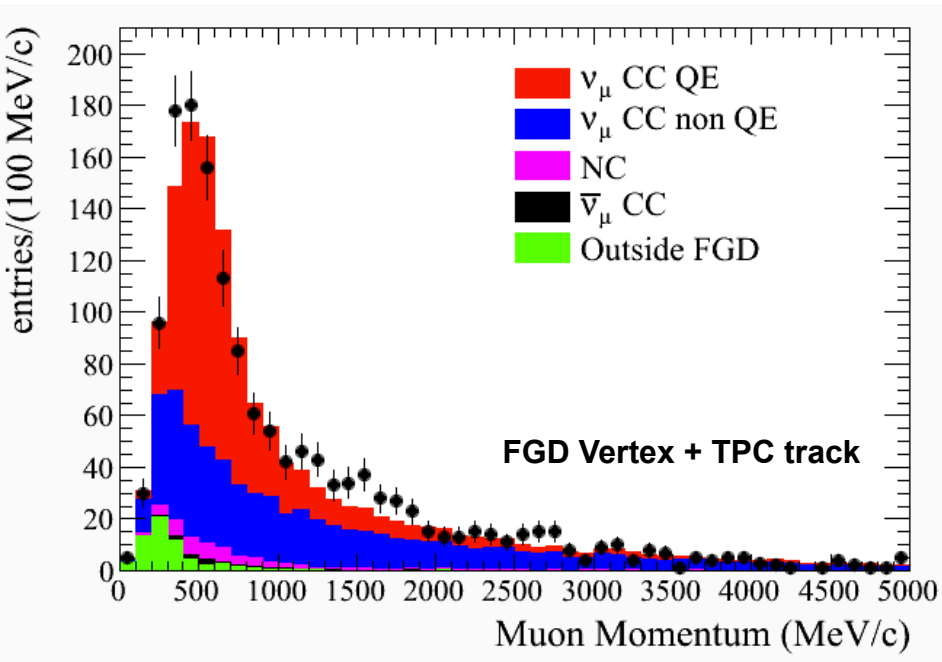


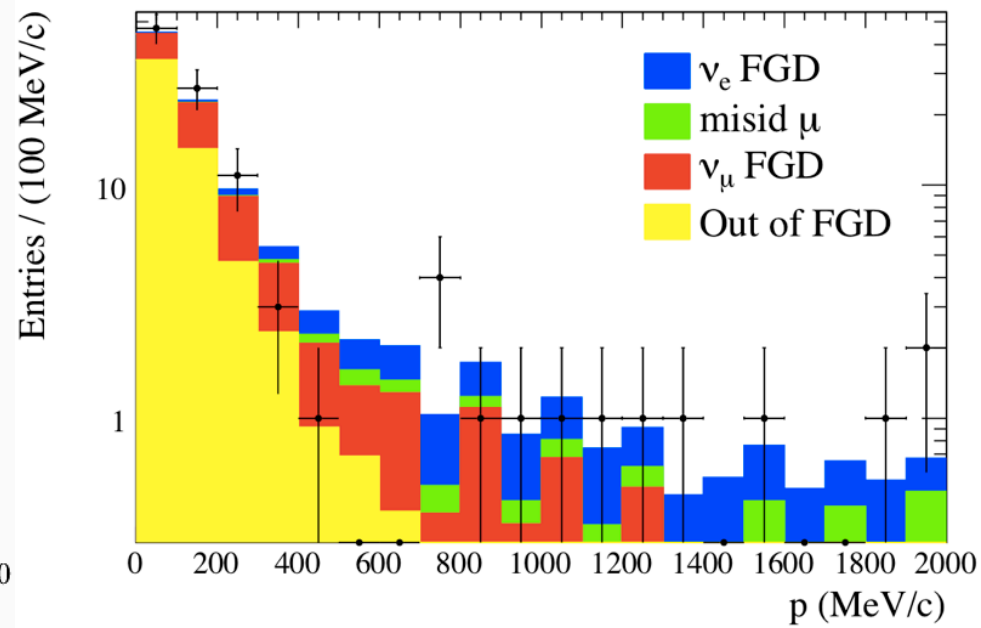
- Run-1 and Run-2 data set contain 1.43 x 10^{20} POT
- Run 1 instantaneous power reached 50 kW
- ➔ Increased # bunches/pulse, protons/bunch, repetition rate
- Run 2 stable power reached **145 kW**

Off-axis normalization measurement

ν_μ inclusive charged current measurement. compares data with normalized MC.

Select nue candidates in TPC using PID for electron neutrino cross-check.

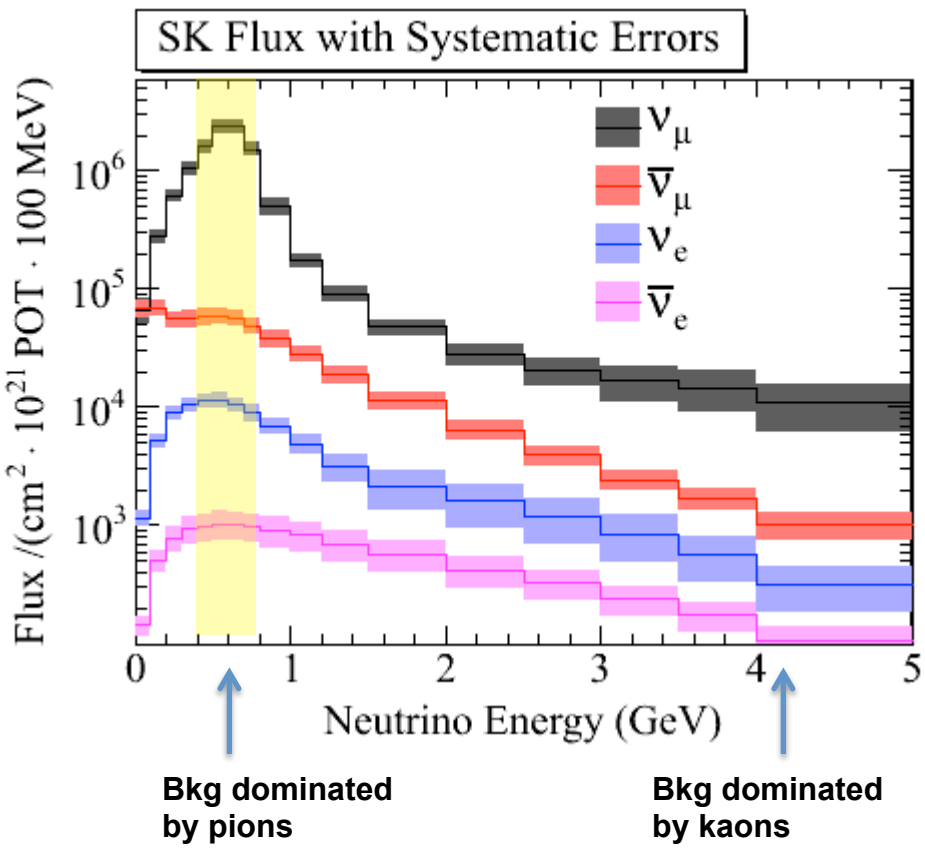


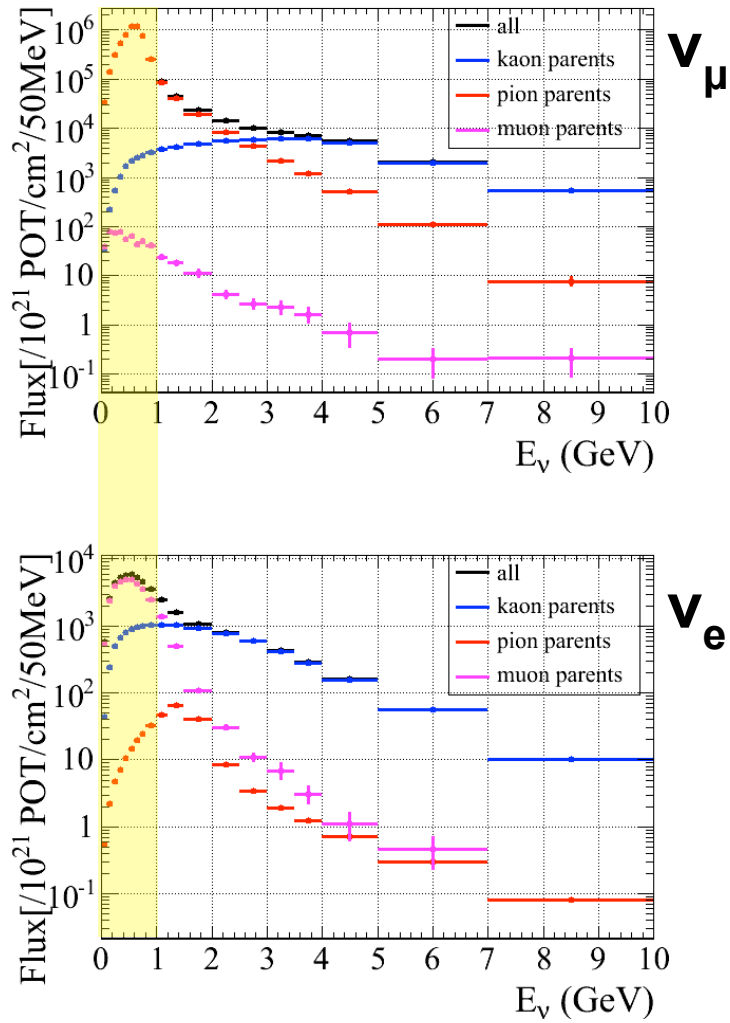


Normalization factor from inclusive CC analysis will be used in oscillation analysis:

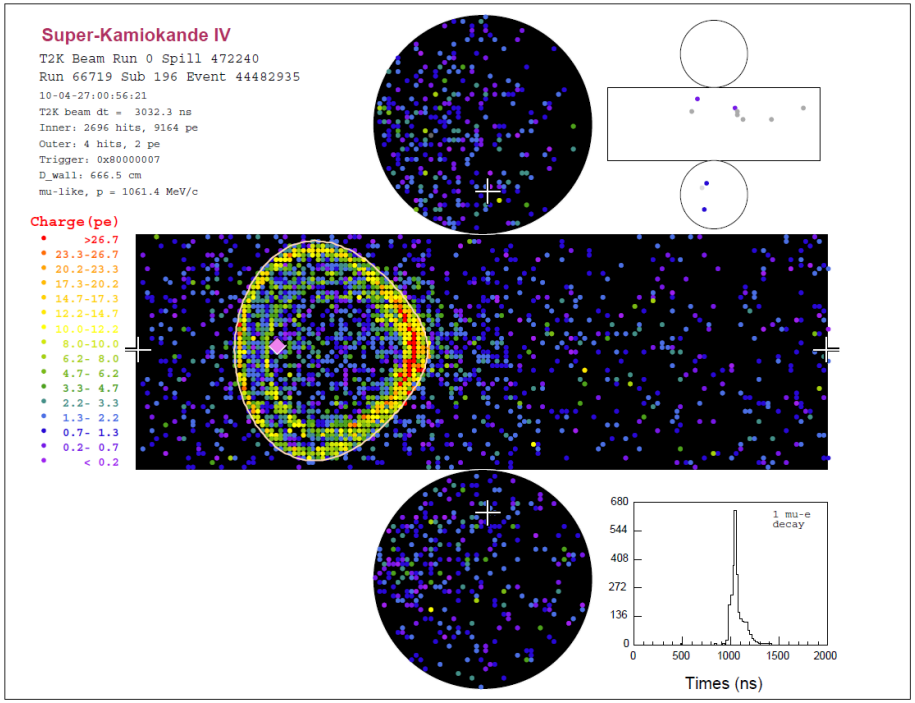
$$\frac{N_{ND}^{obs}}{N_{ND}^{MC}} = 1.036 \pm 0.028_{\text{stat}} \; {}^{+0.044}_{-0.037}{}_{\text{detector}} \pm 0.038_{\substack{\text{interaction}\\ \text{model}}}$$

Expected flux at Super-K



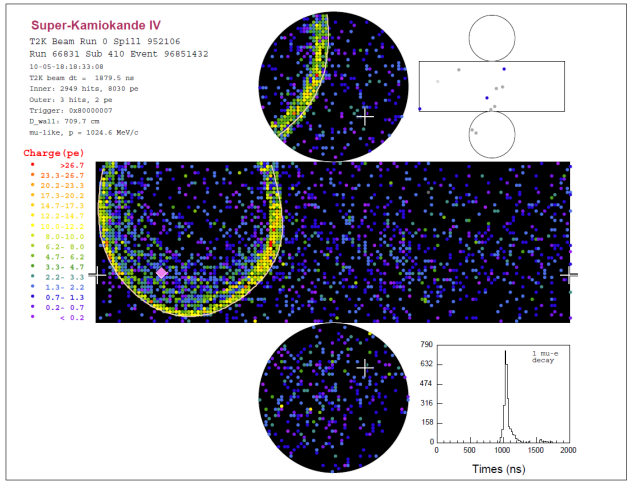


Far detector events!

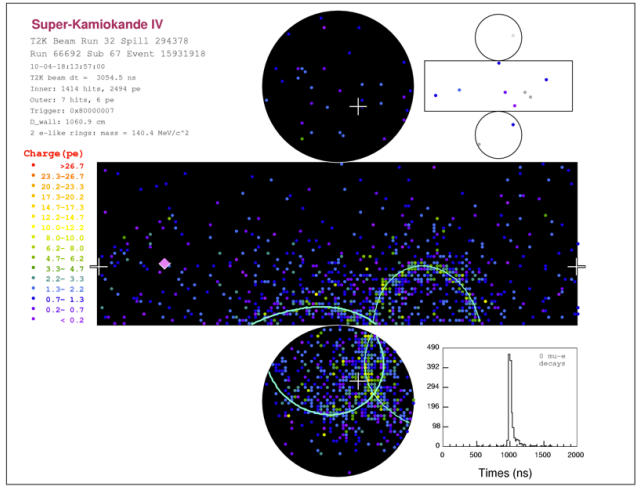


$P\mu$ = 1061 MeV/c

1 decay-e

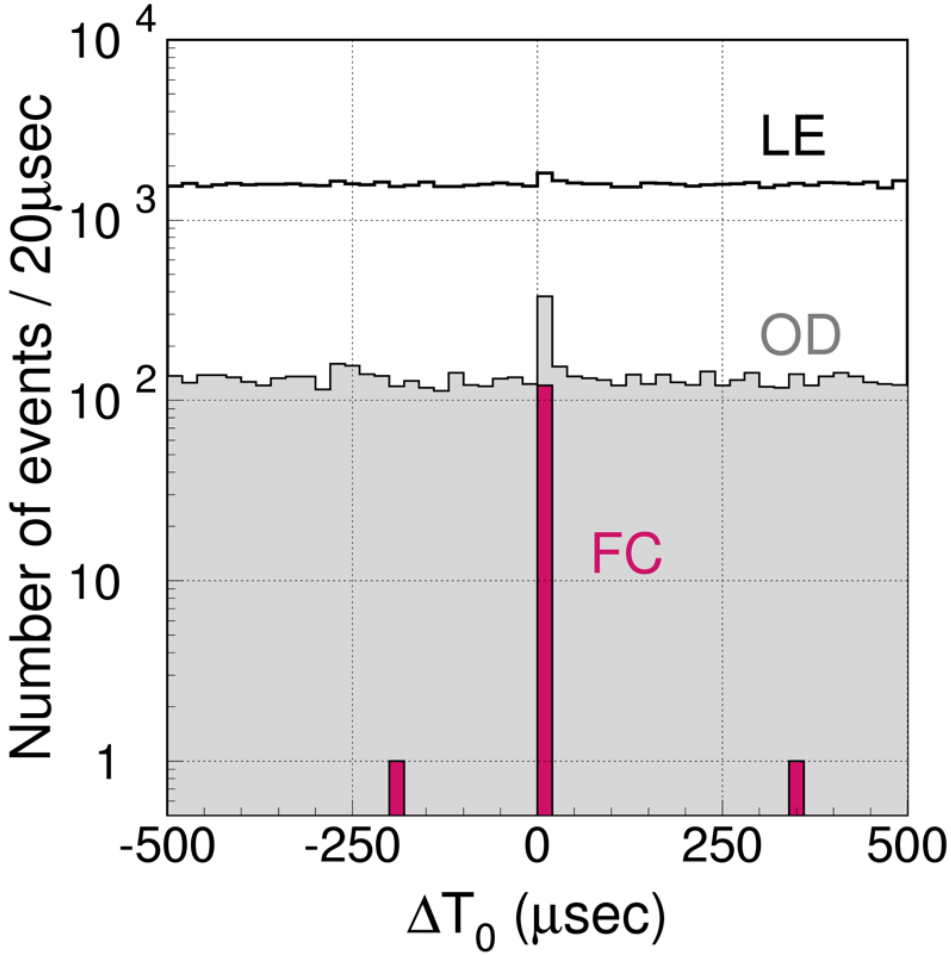


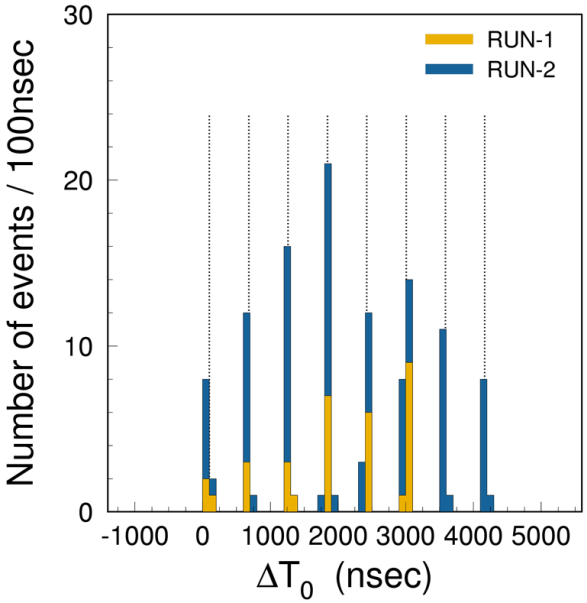
$P\mu$ = 1025 MeV/c 1 decay-e

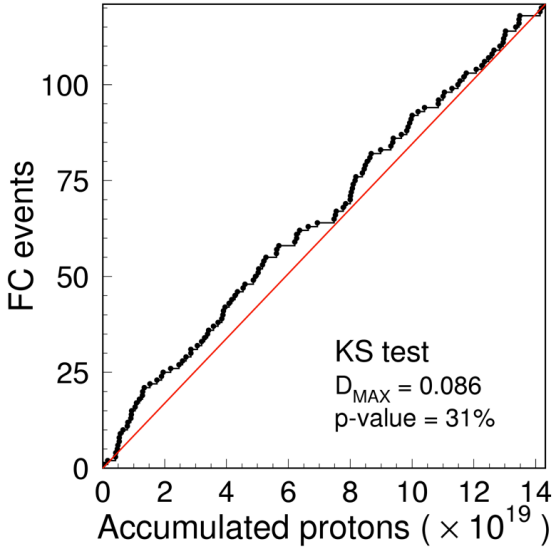


π^0 candidate. M_{inv}=104 MeV/c^2

Arrival Distributions



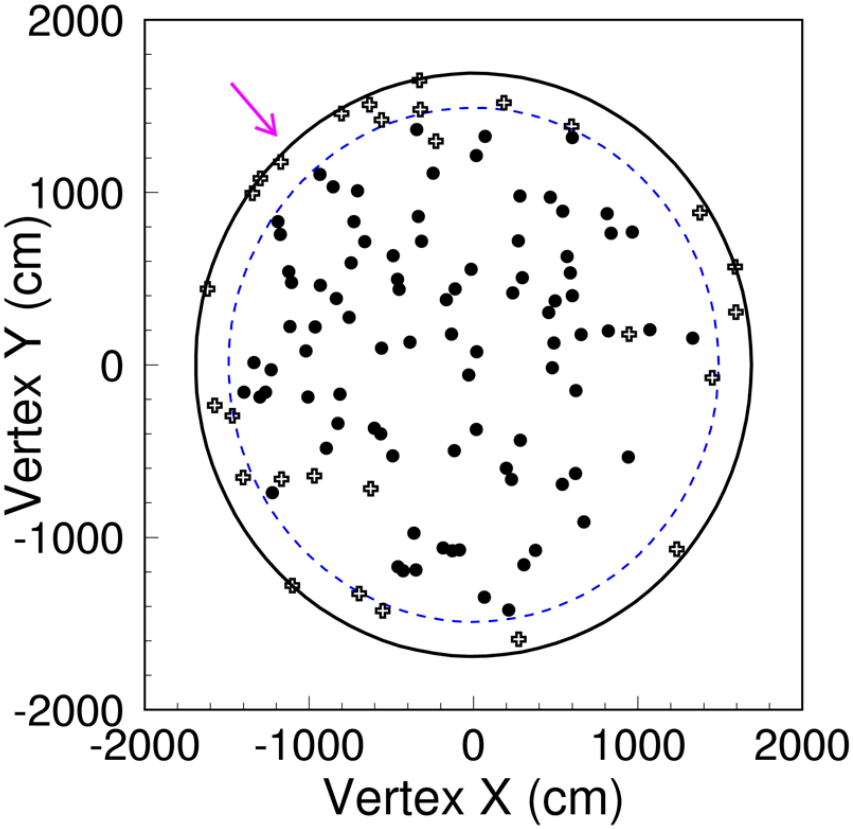


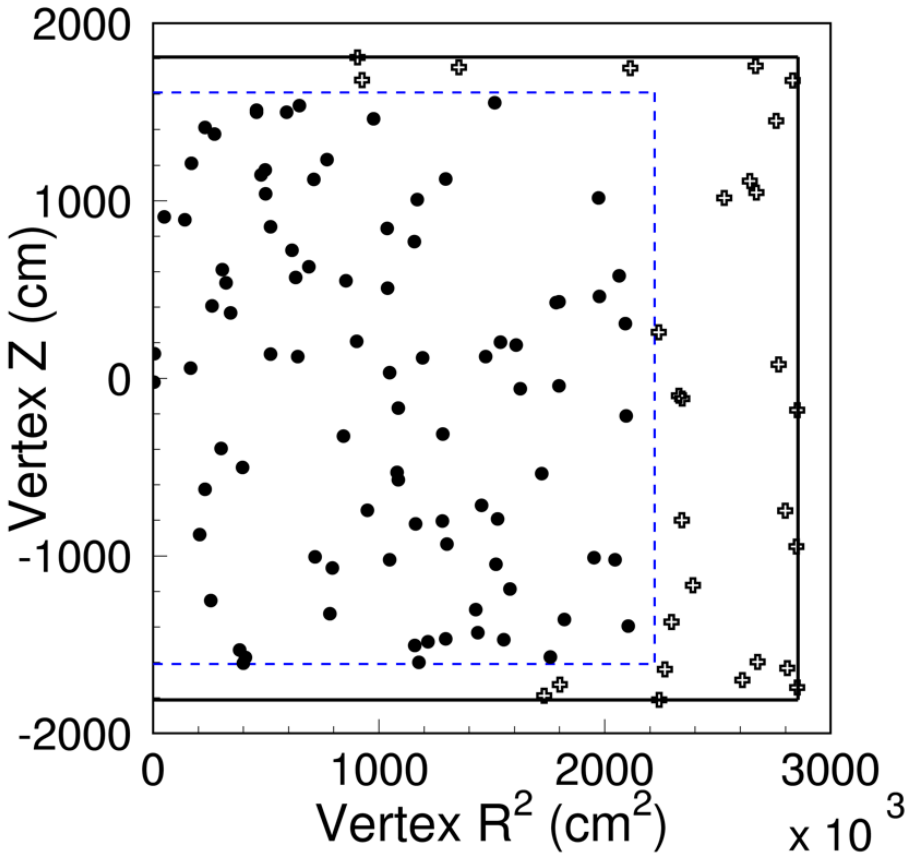


Number of Super-K events observed in the T2K 1.431×10^{20} POT data

	Data	MC		BG (12μs window)
		No oscillation	2-flavor osc. $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	
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	-

Vertex distributions for FC events



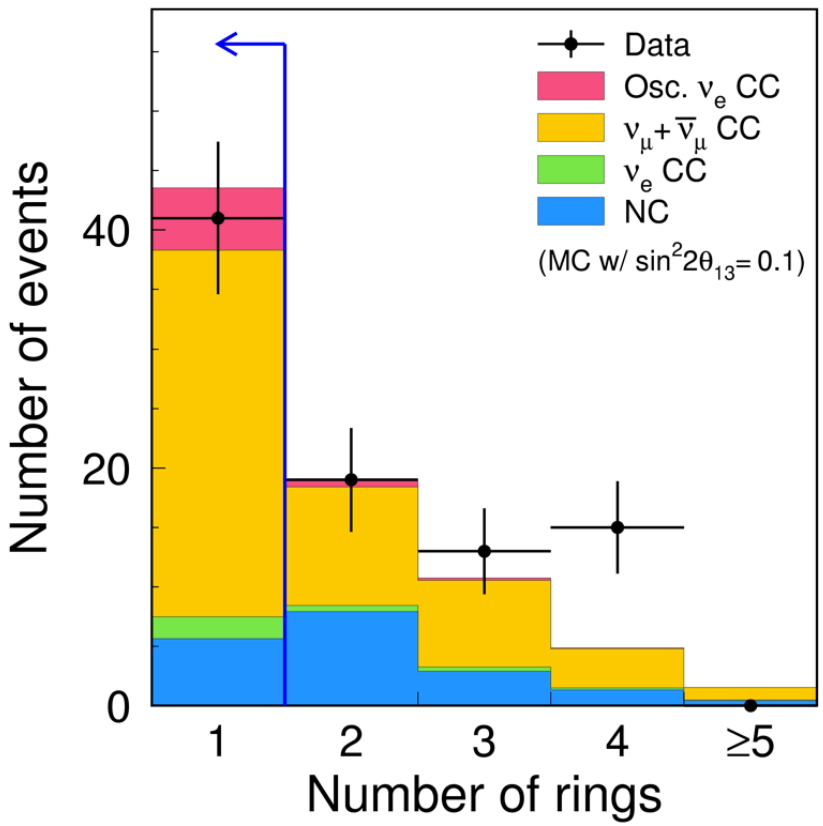


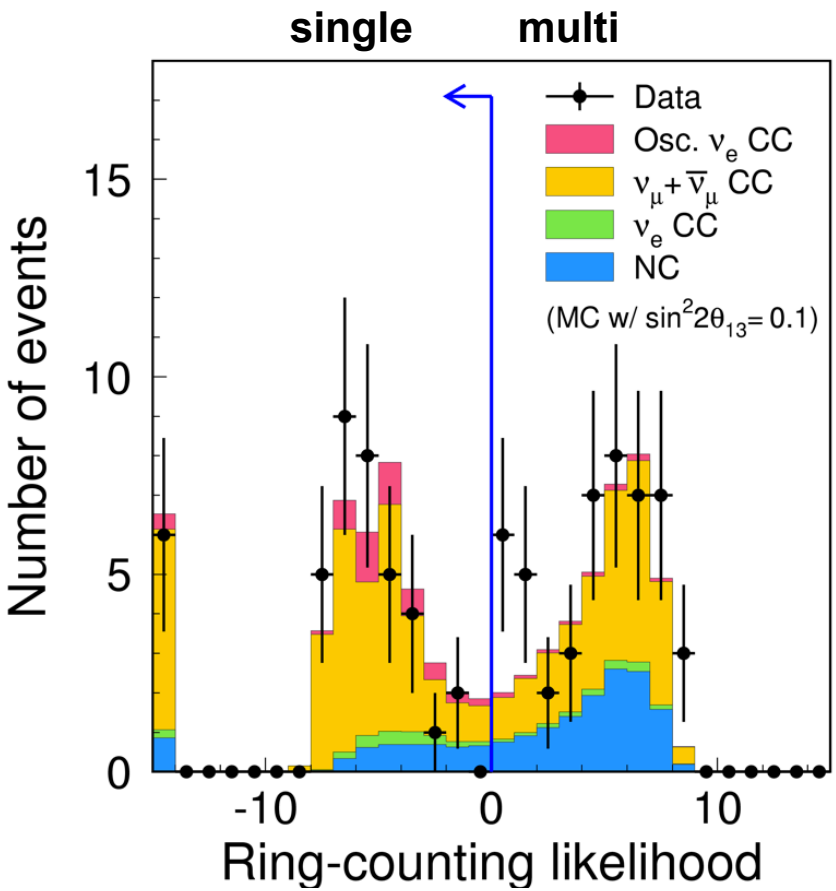
Next we need to select the electron neutrino candidates.

➔ These cuts were set before data taking.

(Need single ring e-like events with no-evidence of other particles)

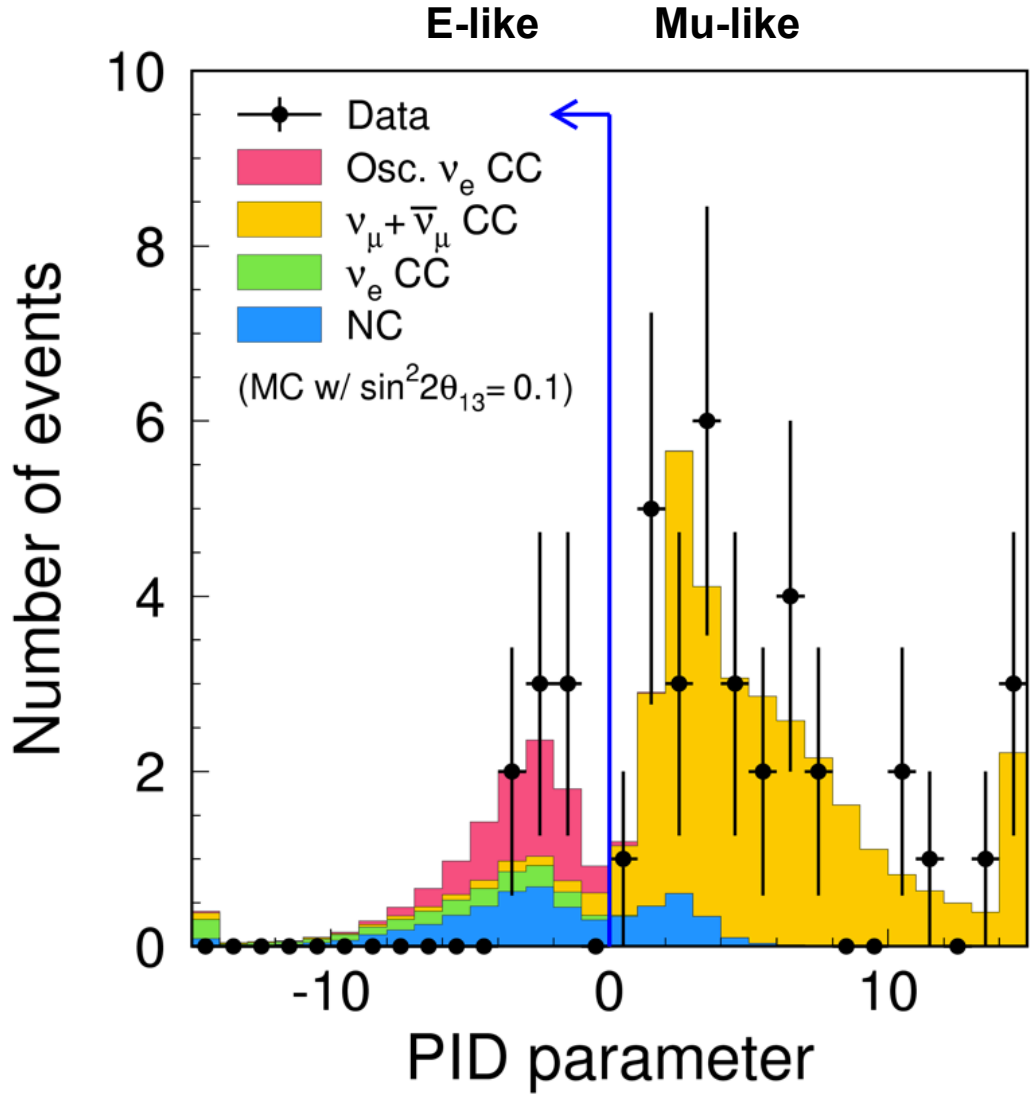
Start with the FV contained events in the time window. Require no OD activity.

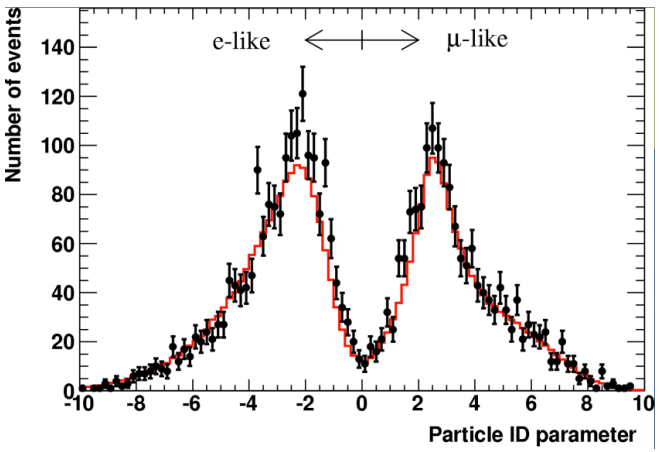




Then select single ring events.

Now choose electron like events

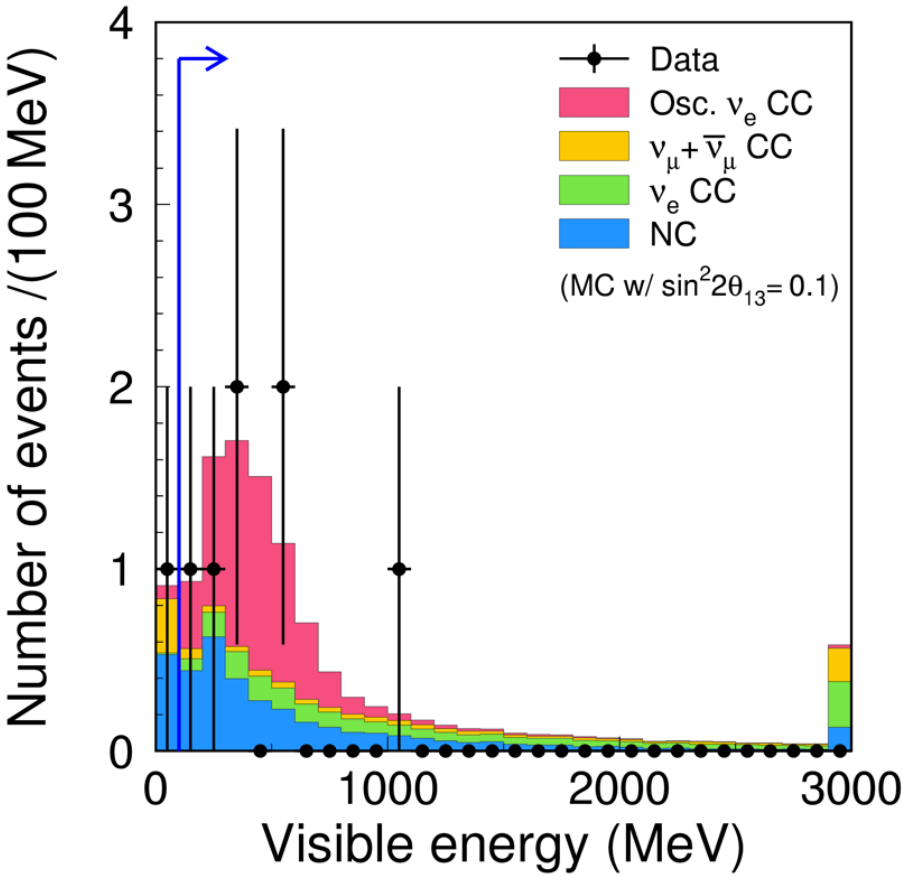




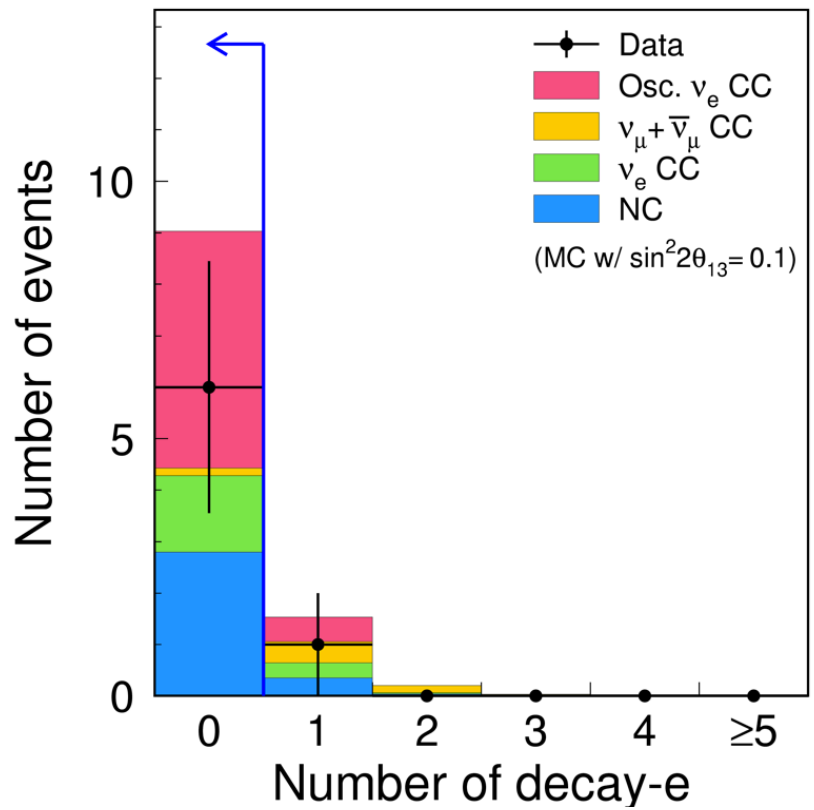
SK-IV atmospheric neutrino data.
mis-id ≤~ 1%

Remove low energy and decay-e events

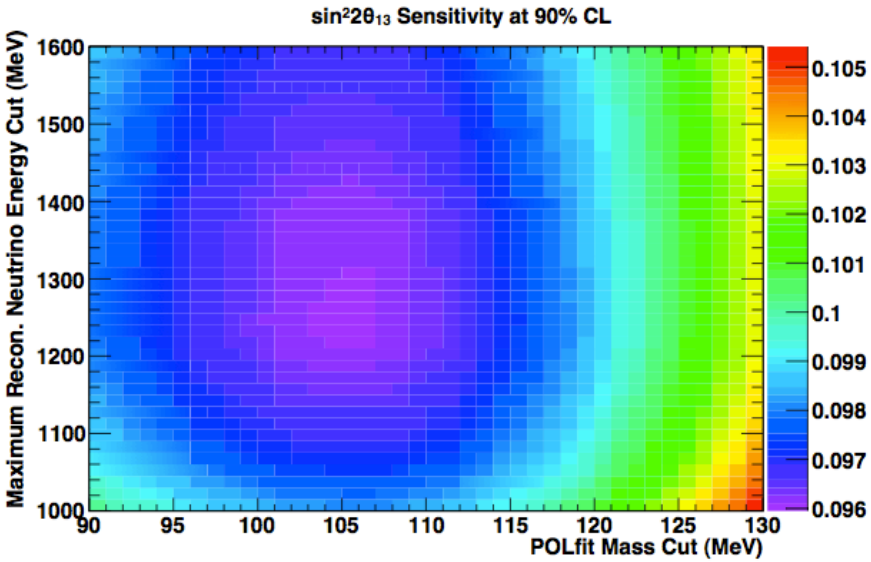
Decay in flight and NC events
➔ very low energy



Sub-threshold pions still have decay electrons.

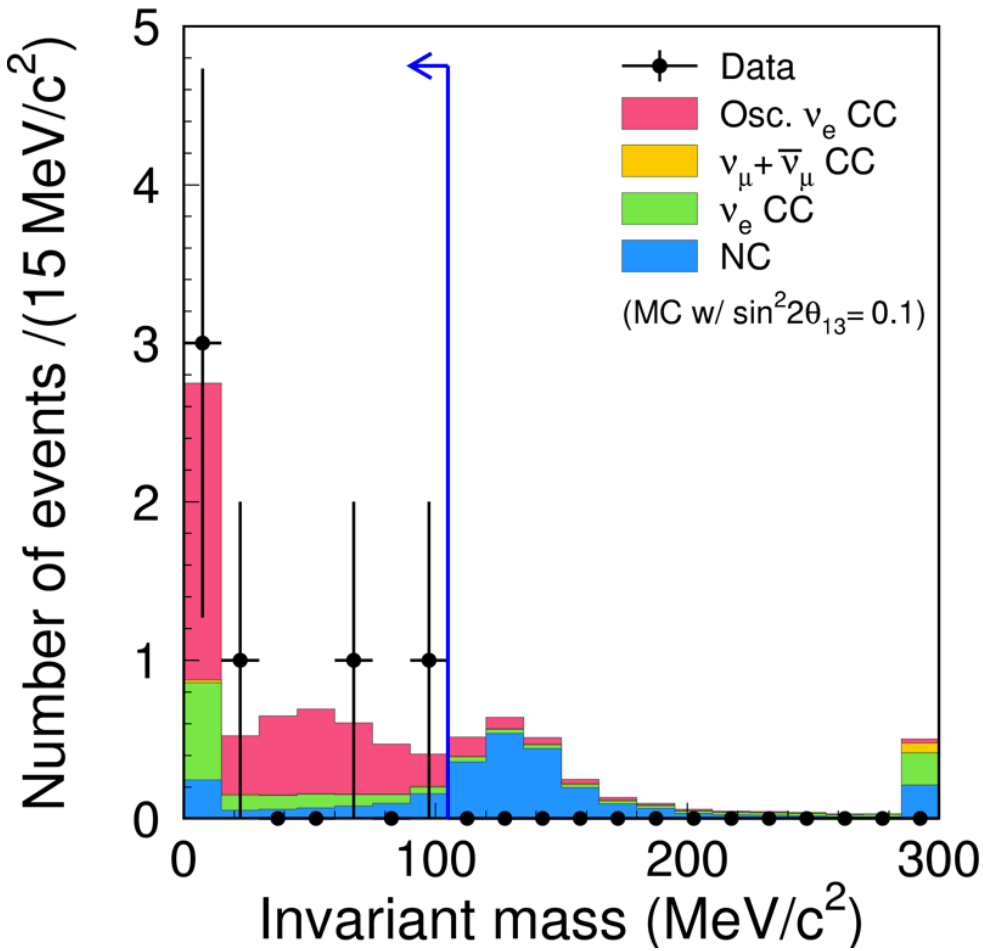


Remove events with likely π^0

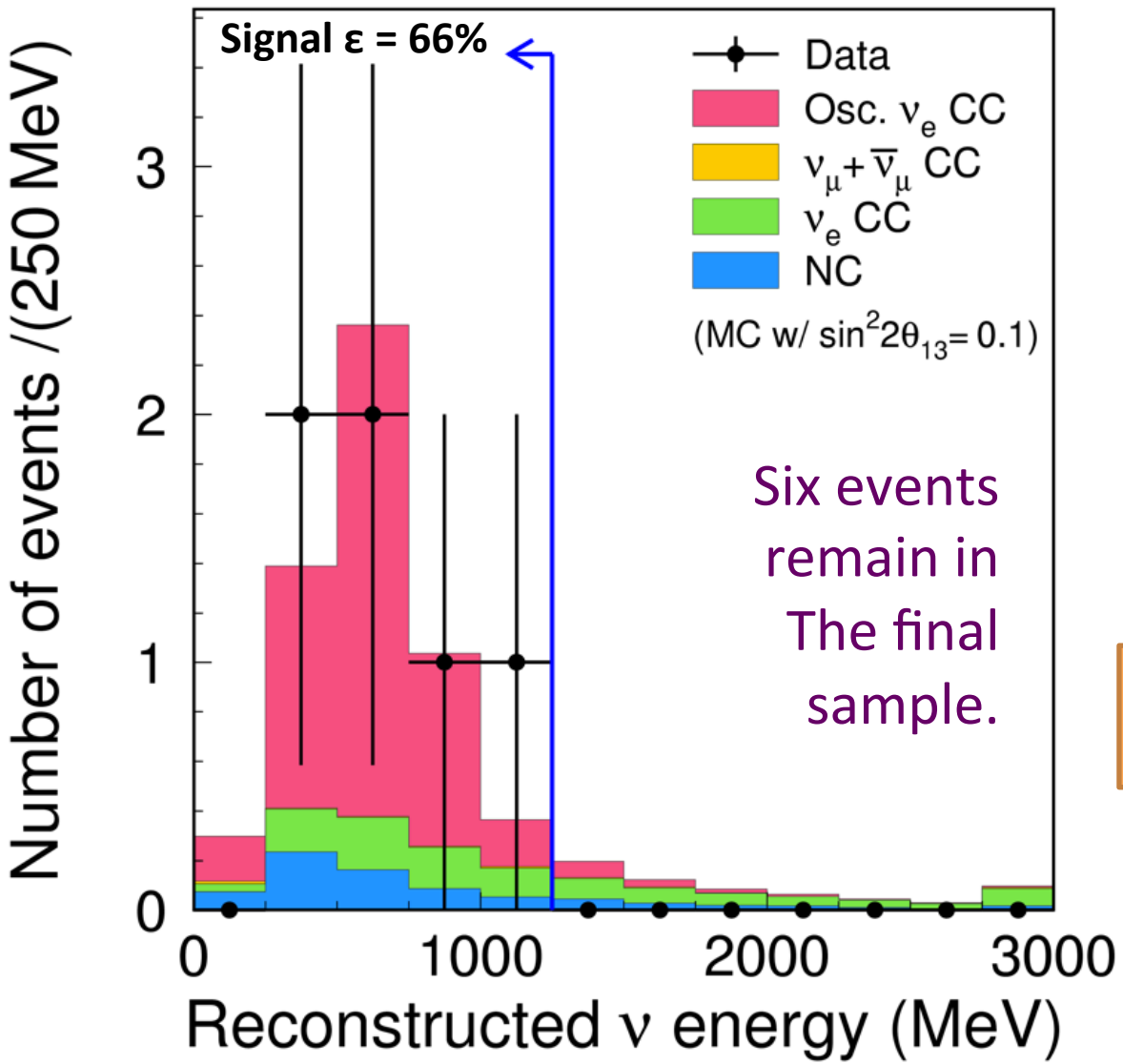


- POLfit mass cut optimized at ~105 MeV
- Energy Window high cut optimized at ~1250 MeV

The polfit cut was optimized for our current low-statistics run.



Choose energy window for final sample



Expected background

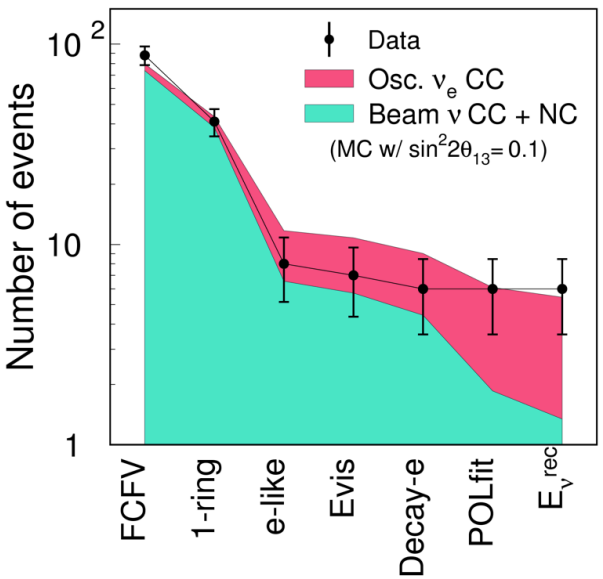
Source	Number
NC bkg	0.6
Beam ν_e bkg	0.8
Solar Term	0.1
ν_μ CC misid	0.03
Total	**1.5 ± 0.3**

Six events were seen
1.5 ± 0.3 were expected

(error due to systematics)

Number of events at each cut step (MC w/ $\sin^2 2\theta_{13} = 0.1$)

	Data	BG expectation				$\nu_\mu \rightarrow \nu_e$ expect.
		Total	ν_μCC	ν_eCC	NC	
Interaction in FV	-	**141.3**	67.2	3.1	71.0	6.2
FCFV	**88**	**73.6**	52.4	2.9	18.3	6.0
Single-ring	**41**	**38.3**	30.8	1.8	5.7	5.2
e-like	**8**	**6.6**	1.0	1.8	3.7	5.2
E_{vis} > 100 MeV	**7**	**5.7**	0.7	1.8	3.2	5.1
No decay-e	**6**	**4.4**	0.1	1.5	2.8	4.6
M_{inv} < 105 MeV/c^2	**6**	**1.9**	0.04	1.1	0.8	4.2
E_ν^{rec} < 1250 MeV	**6**	**1.3**	0.03	0.7	0.6	4.1
Efficiency	-	**1 %**	< 0.1%	23 %	1 %	66 %

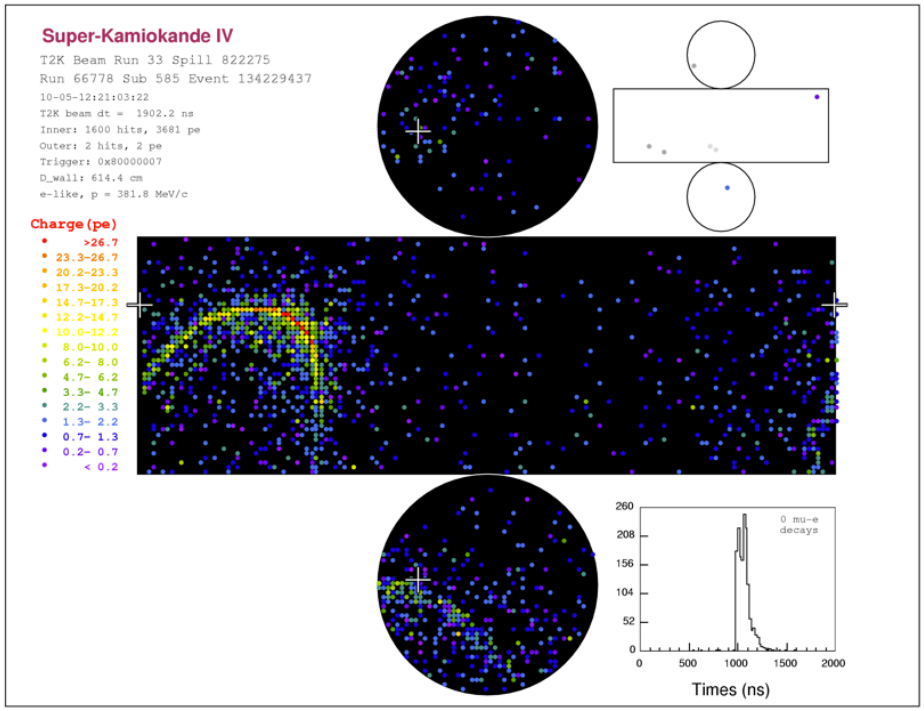


Note: this is only a *counting experiment*. But, the candidate samples look like good events.

See next slides

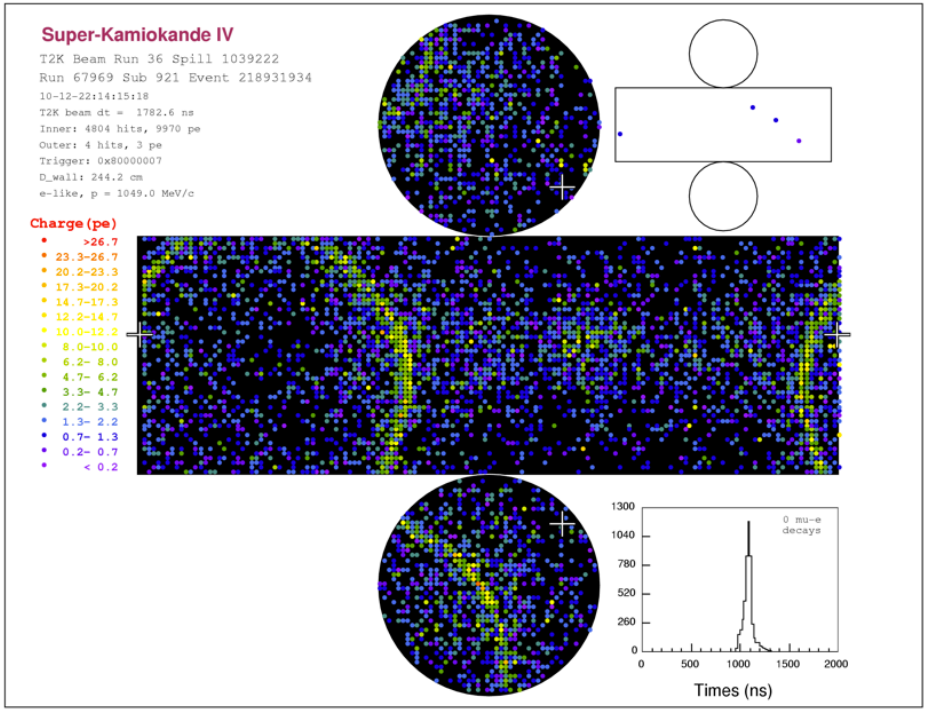
ν_e candidate event displays

Candidate #1



P_e = 318 MeV/c

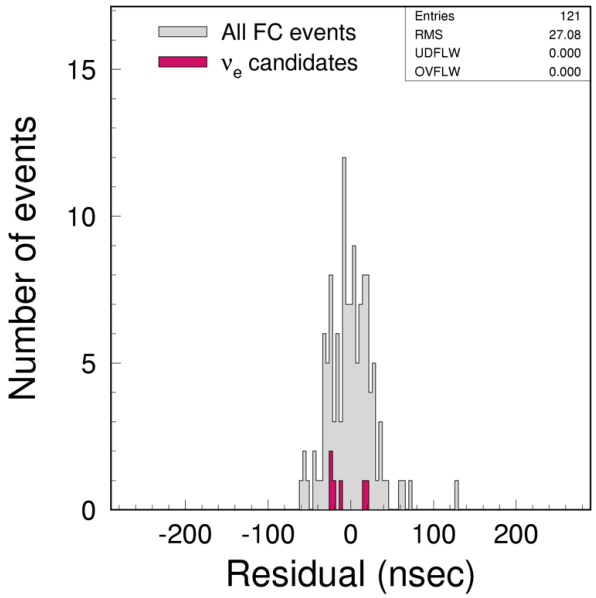
Candidate #4



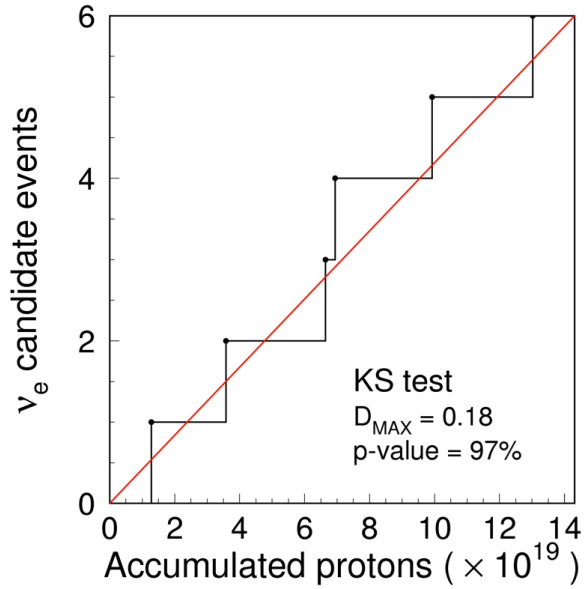
P_e = 1049 MeV/c

Candidate properties

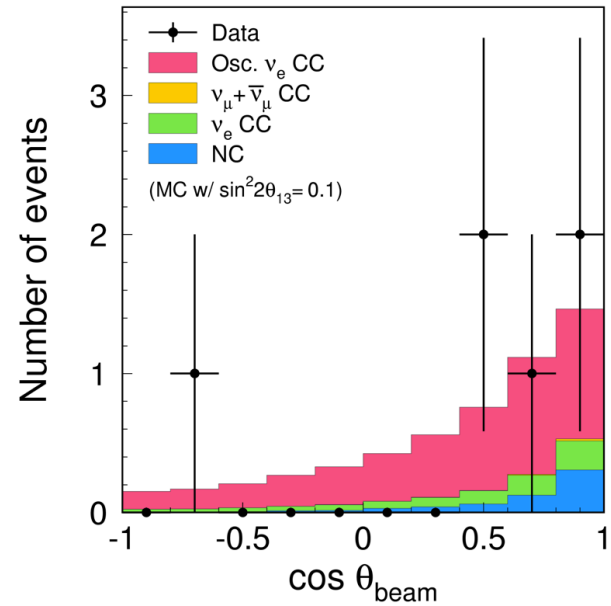
Residual time

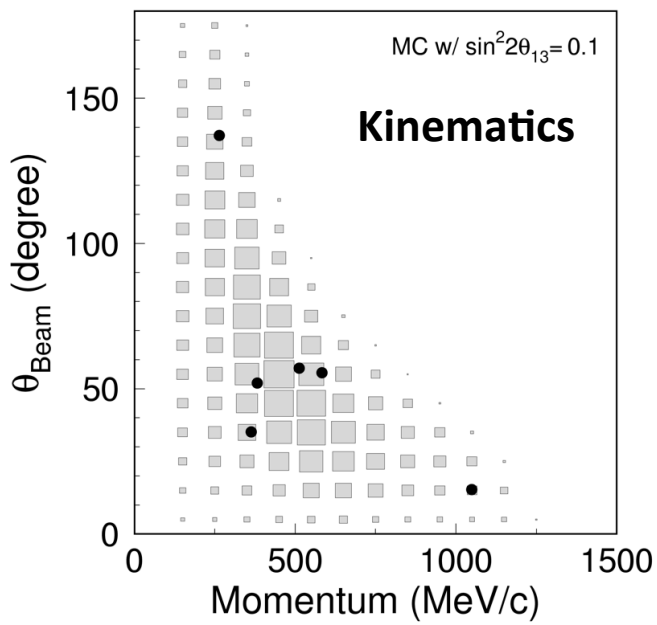


Arrival distribution



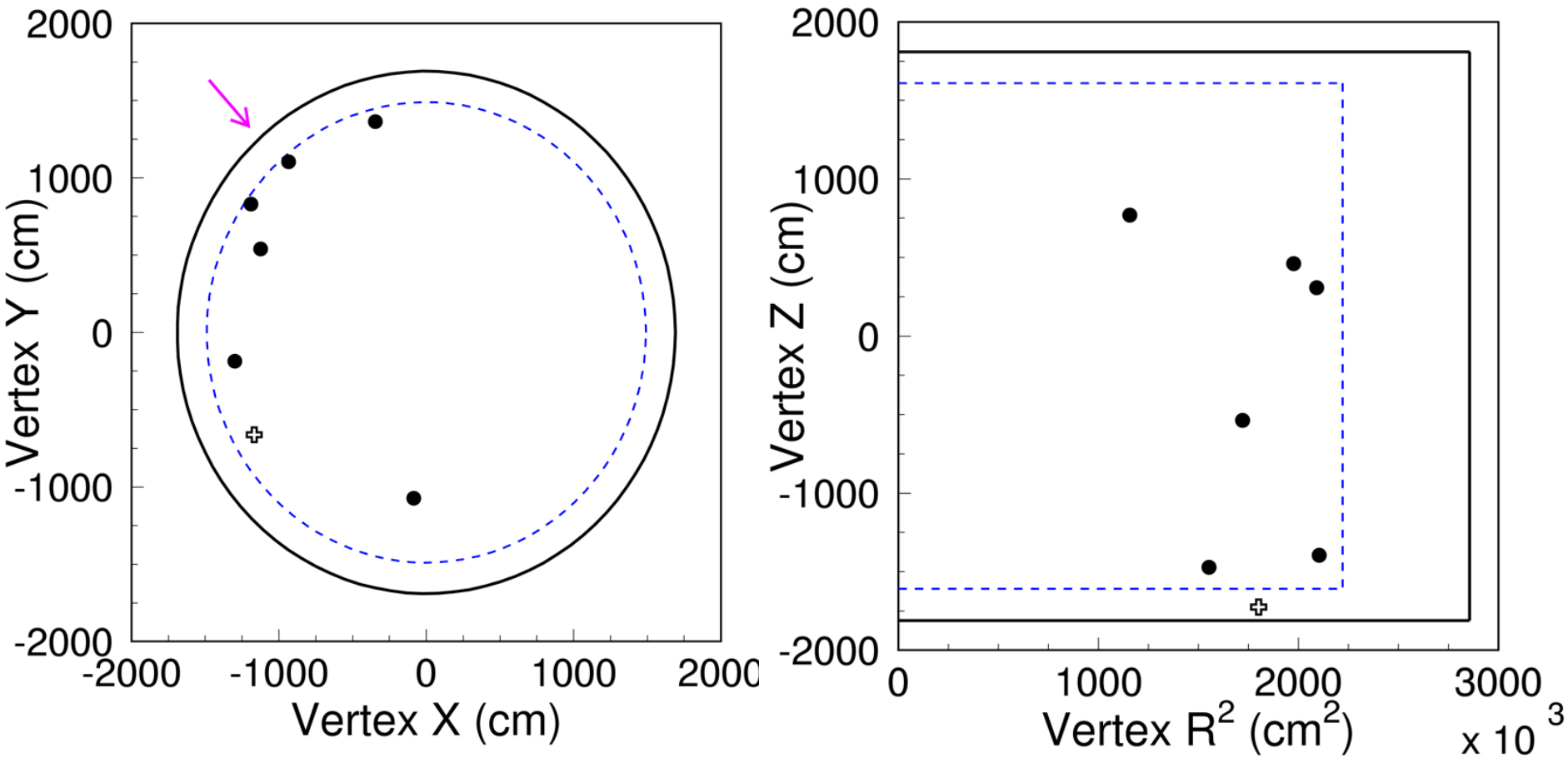
Angular distribution





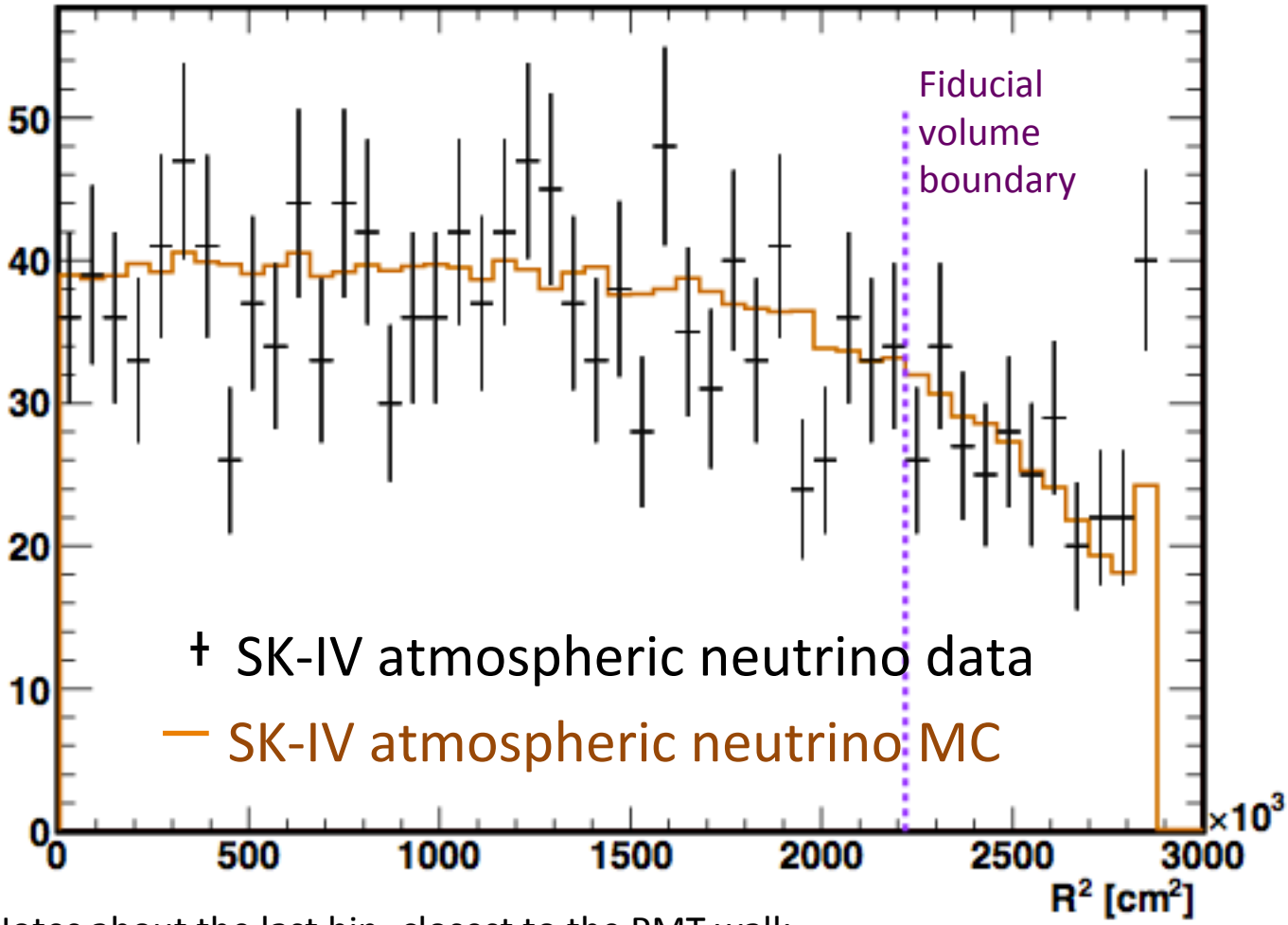
Looks good!

Candidate Vertex Distributions



Is this reasonable? **LOTS** of checks!

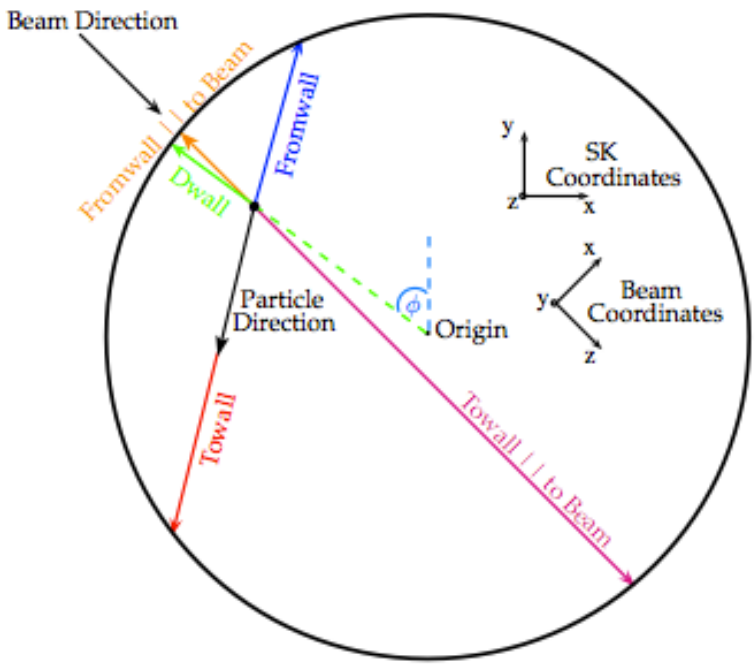
Use atmospheric events to check FV boundary

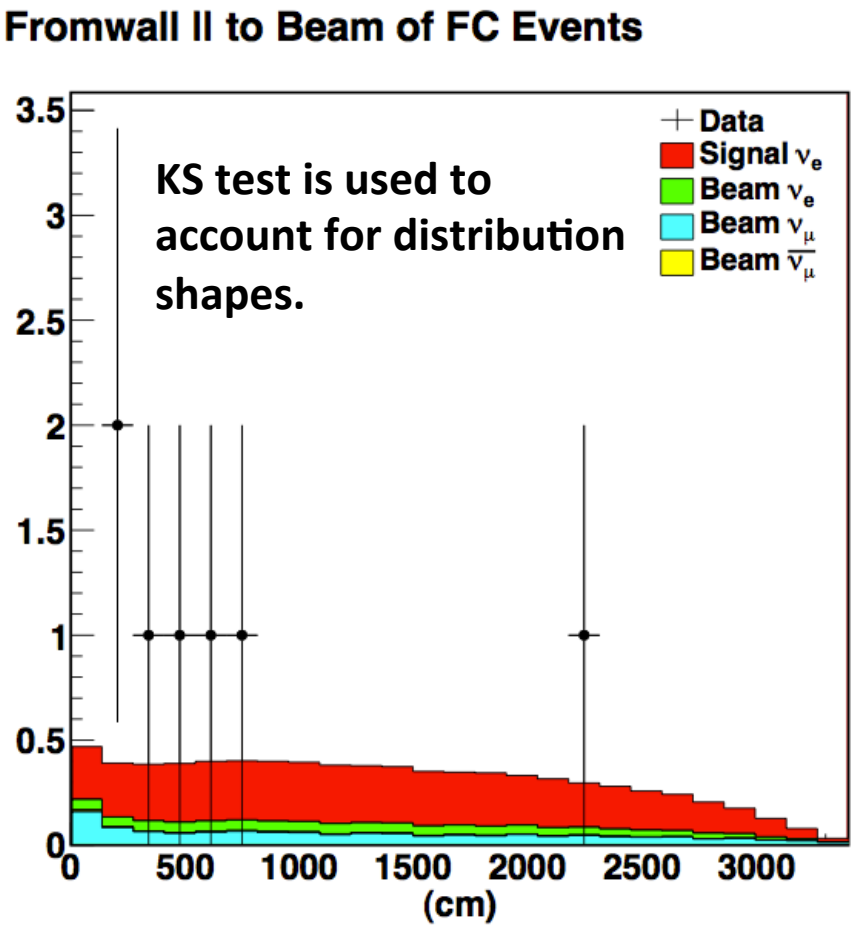


Notes about the last bin- closest to the PMT wall:

- The bin is only 18 cm wide in R.
- The SK vertex fitter is constrained to inside the PMT wall.
- Visual scan shows events with electronic noise that is not modeled in the MC.

Use KS test to check several distributions



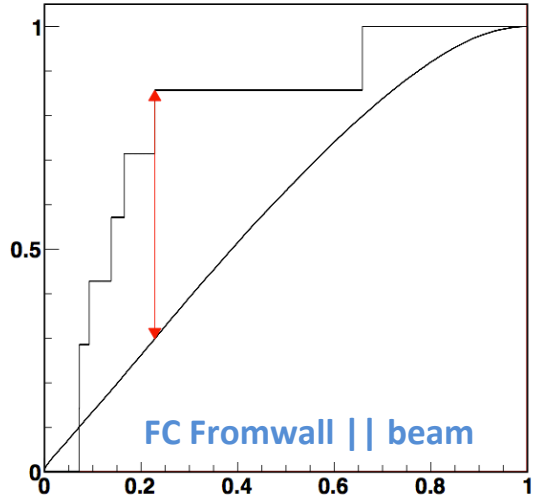


The "natural" variables we usually Check are R^2 and and dwall. We undertook a systematic check of many others. <u>But note: be careful of bias!</u>

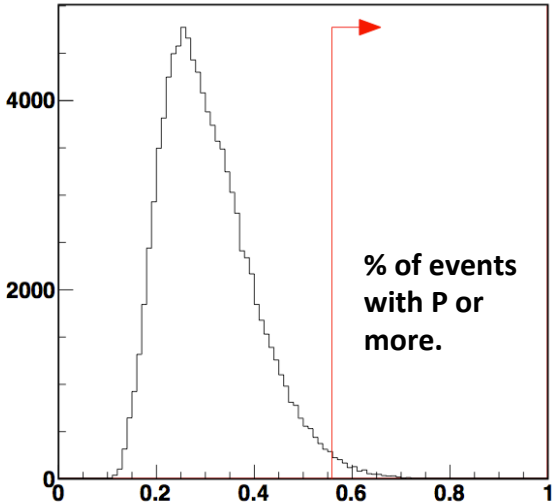
Use toy MC to study probability

Wide range of values. Seems to be a 1-3% effect

Max K-S distance



KS prob of max distance



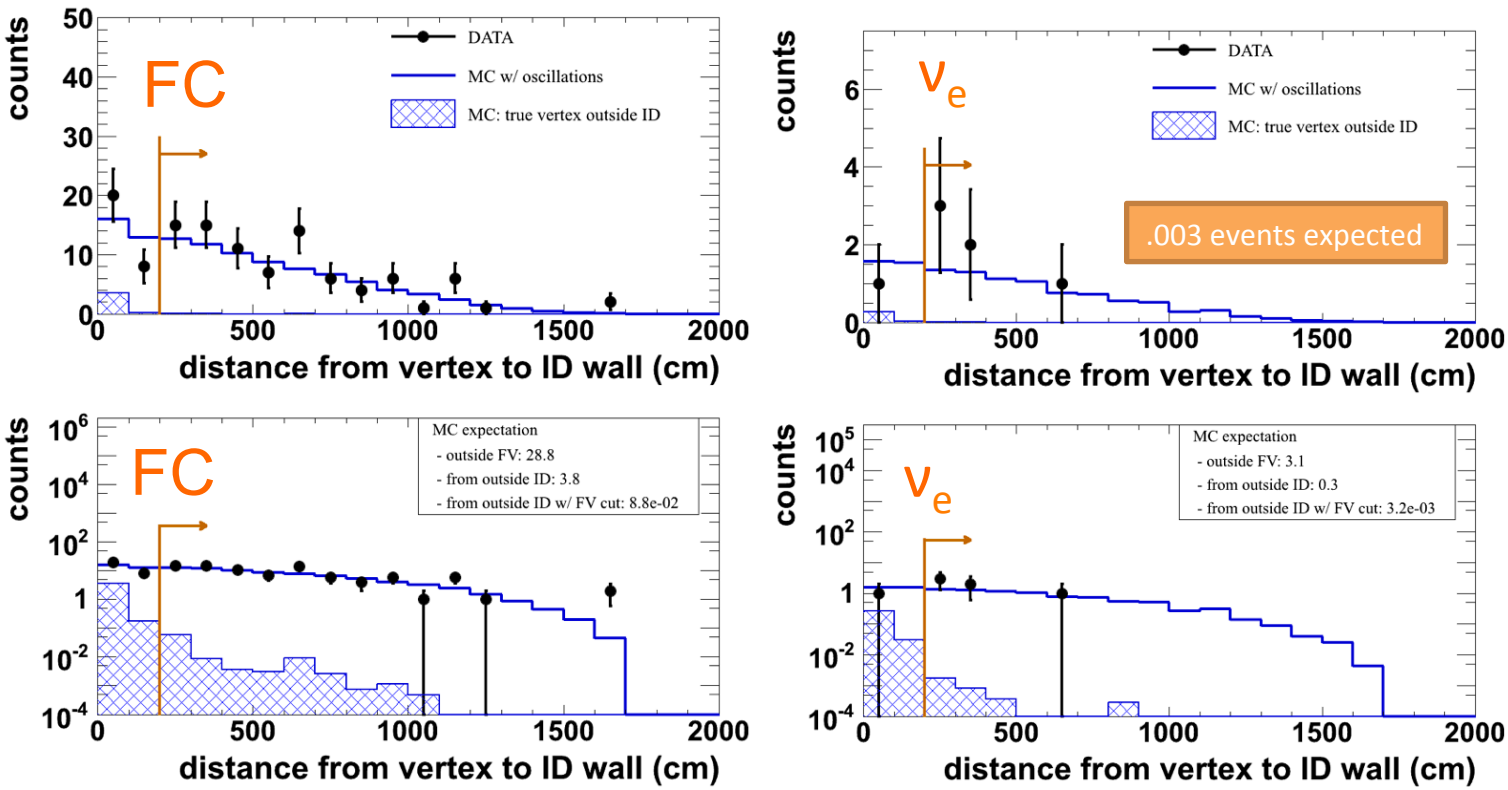
KS Toy MC Probabilities	7 FC events	6 Events in FV
Dwall	20.2%	3.7%
Towall	7.1%	2.0%
Towall || beam	5.3%	1.2%
Fromwall	20.5%	4.9%
Fromwall || beam	1.3%	0.1%
R squared	9.5%	3.1%

USE 7

USE 6

Entering background

MC interactions including the rock was used to evaluate background from outside.



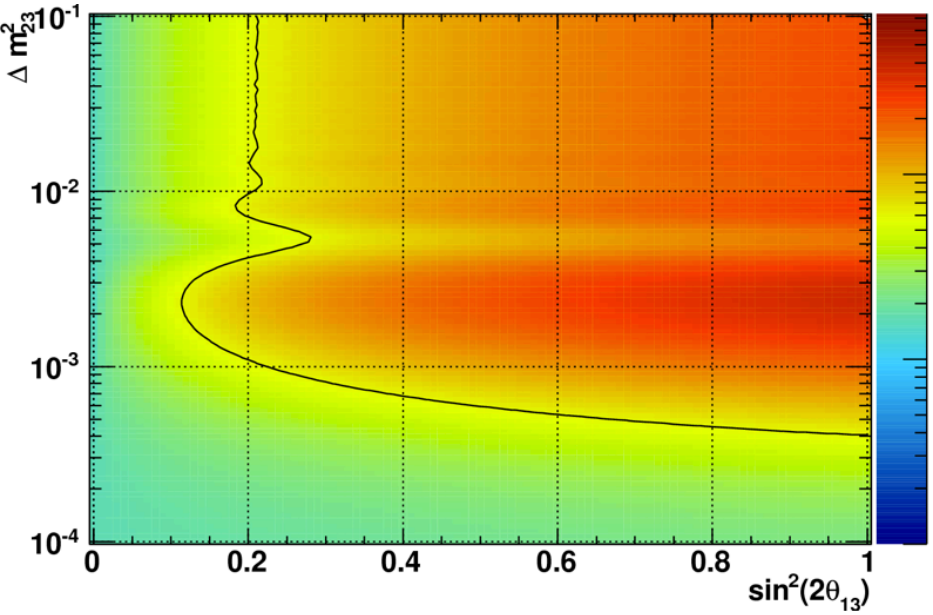
Sources of beam-induced background with True Vertex outside the ID

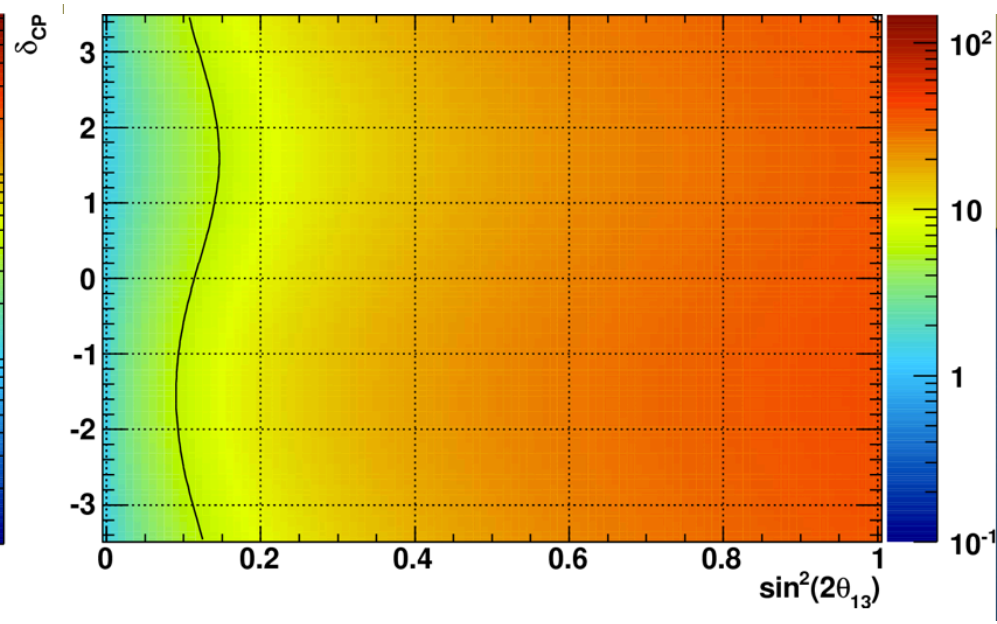
Sample	Expected true vertex outside ID	Source of track, from MC truth*				
		mis-id muon	pi0 photon	neutron	K-long	K-short
Nue Analysis Sample (w/ FV cut)	3.16E-03	9%	78%	11%	0.01%	<0.01%
Nue Analysis Sample (w/o FV cut)	0.30	4%	75%	3%	<0.01%	<0.01%

*percentages do not total to 100% because list here is not exhaustive
Expectation assumes $\sin^2\theta_{13} = 0.1$, $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2.

Θ_{13} and the expected number of events

Line is drawn at six events. This should be the "best fit" of our analysis.





$$\sin^2 2\theta_{12} = 0.8704$$

$$\sin^2 2\theta_{23} = 1.0$$

$$\Delta m^2_{12} = 7.6 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

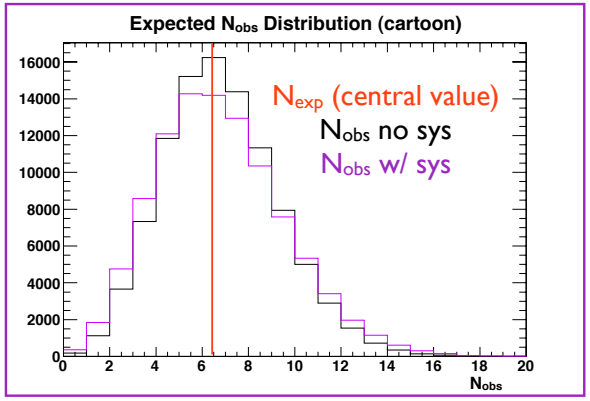
How likely a point is consistent with six events is given by the statistics and systematic errors.

There are errors associated with Super-K / ND280 / ν interactions / flux uncertainties

$$N_{\text{exp}} = \sum_{\text{all MC evts}} \Theta_{\text{cuts}} \times \gamma_{\text{norm}}(x)$$

$\Theta_{\text{cuts}} = 1$ if ν_e cuts are passed, 0 otherwise.
γ_{norm} scales MC to expected data based on SK true FV.
$x = \nu_\mu, \nu_e, \overline{\nu_\mu}, \nu_\mu \to \nu_e$ (ν species)

$$N_{\text{exp}} = \sum_{\text{all MC evts}} \left(\Theta_{\text{cuts}} \times \gamma_{\text{norm}} \times P_{\text{osc}}\left(\theta_{13}, \Delta m^2, \delta_{CP}, E_\nu^{\text{true}}, x\right)\right)$$



Incorporating systematics

$$N_{\text{exp}} = \left(\frac{N_{\text{NDOA1}\mu}^{\text{data}}}{N_{\text{NDOA1}\mu}^{\text{MC}}}\right) \sum_{\text{all MC evts}} \left(\Theta_{\text{cuts}} \times W_{\text{SKMC}}\right)$$

Central Value

$$N_{\text{exp}} = \left(\frac{N_{\text{NDOA1}\mu}^{\text{data}}}{N_{\text{NDOA1}\mu}^{\text{MC}}}\right) \sum_{\text{all MC evts}} \left(\Theta_{\text{cuts}} \times W_{\text{SKMC}} \times \prod_{i=\text{sys error}} \left(1 + \underline{\delta_i\left(E_\nu^{\text{true}}, E_\nu^{\text{rec}}, m, x\right)}\right)\right)$$

$$N_{\text{exp}} = \left(N_{\text{NDOA1}\mu}^{\text{data}} \Big/ \sum_{m,x,E_\nu^{\text{true}}} \left(N_{\text{NDOA1}\mu}^{\text{MC}}\left(m, x, E_\nu^{\text{true}}\right)\right)\right) \sum_{\text{all MC evts}} \left(\Theta_{\text{cuts}} W_{\text{SKMC}} \times \prod_{i=\text{sys error}} \left(1 + \delta_i\right)\right)$$

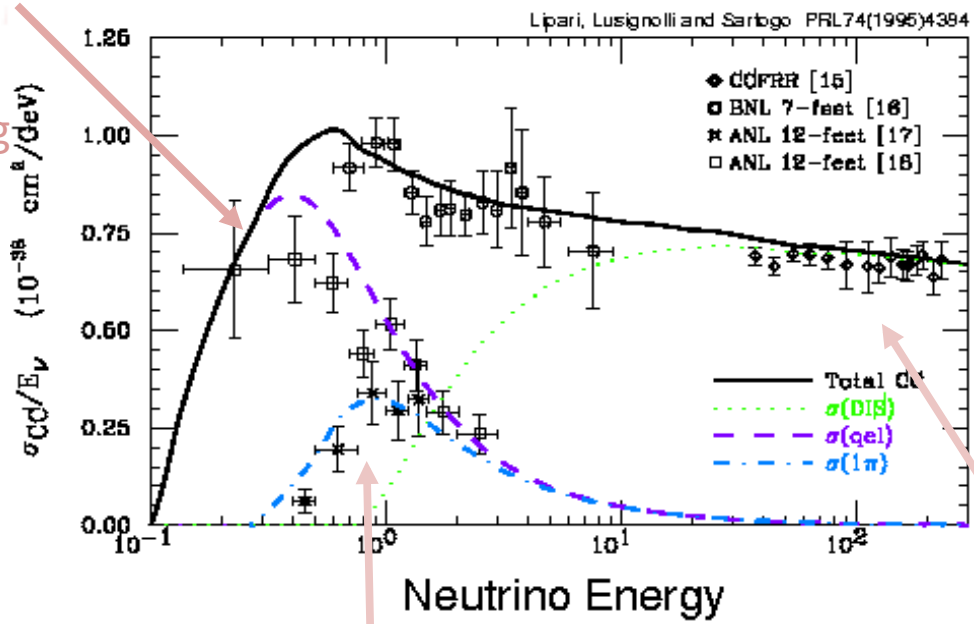
$$N_{\text{exp}} = \left(N_{\text{NDOA1}\mu}^{\text{data}} \Big/ \sum_{m,x,E_\nu^{\text{true}}} \left(\underline{N_{\text{NDOA1}\mu}^{\text{MC}} \prod_{j=\text{sys error}} \left(1 + \delta_j\right)}\right)\right) \sum_{\text{all MC evts}} \left(\Theta_{\text{cuts}} W_{\text{SKMC}} \prod_{i=\text{sys error}} \left(1 + \delta_i\right)\right)$$

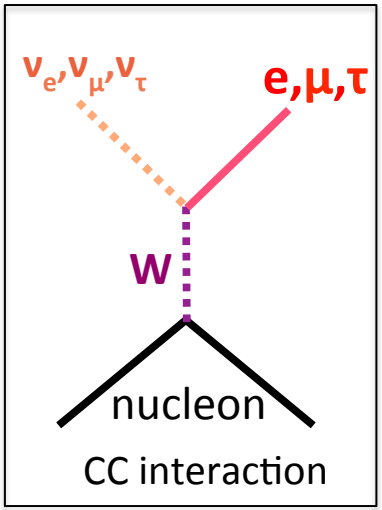
$$N_{\text{exp}} = \underline{\left(1 + \delta_{\text{near/far}}\right)} \left(\frac{N_{\text{NDOA1}\mu}^{\text{data}}}{N_{\text{NDOA1}\mu}^{\text{MC}} \prod \left(1 + \delta_j\right)}\right) \sum_{\text{all MC evts}} \left(\Theta_{\text{cuts}} \times W_{\text{SKMC}} \times \prod_{i=\text{sys error}} \left(1 + \delta_i\right)\right)$$

Example ν cross-sections (a topic of their own!)

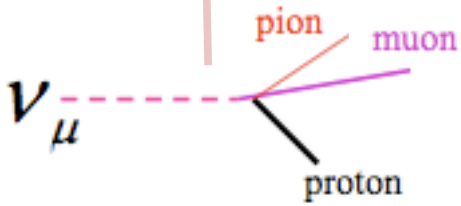
More energy: More Particles!

Quasi-Elastic Scattering
(E <~ GeV)

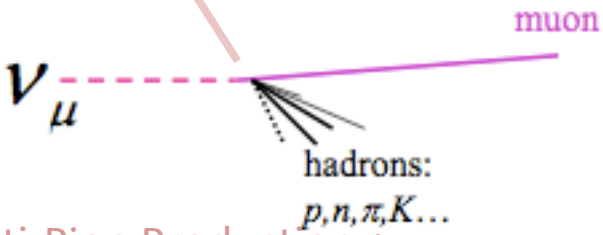




Error Source	N_{SK}(exp)
CCQE Shape	3.1%
CC 1π	2.2%
CC Coherent π	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherent π	2.3%
NC Other	2.3%
$\sigma(\nu_e)$	3.4%
FSI	10.1%
Total	**14%**



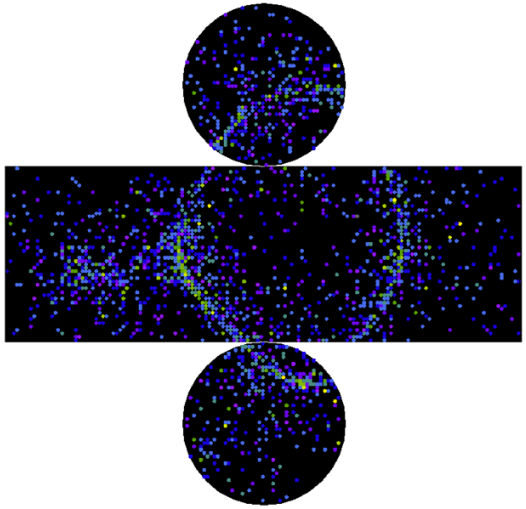
Single Pion Production
E ~ GeV



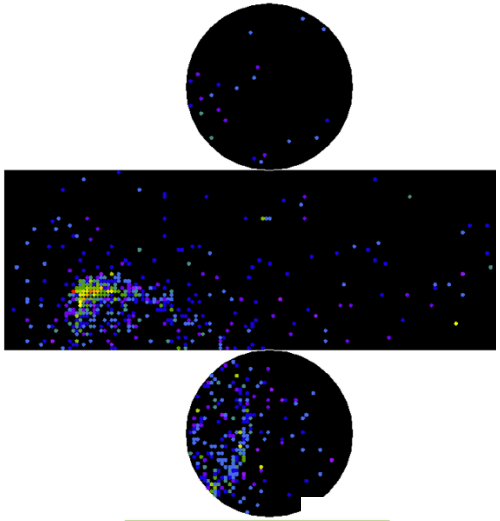
Multi-Pion Production +
Deep inelastic scattering
E > many GeV

Far detector uncertainty

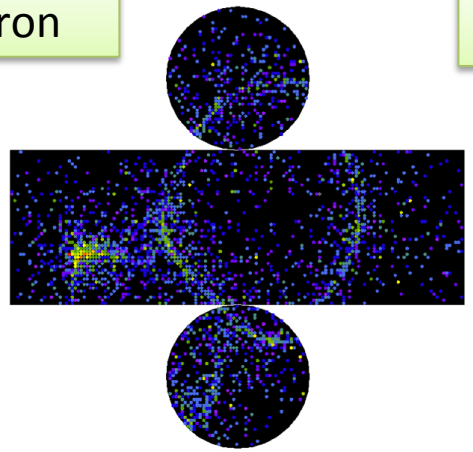
Example: detection efficiency of NC $1\pi^0$ background



Data or MC electron



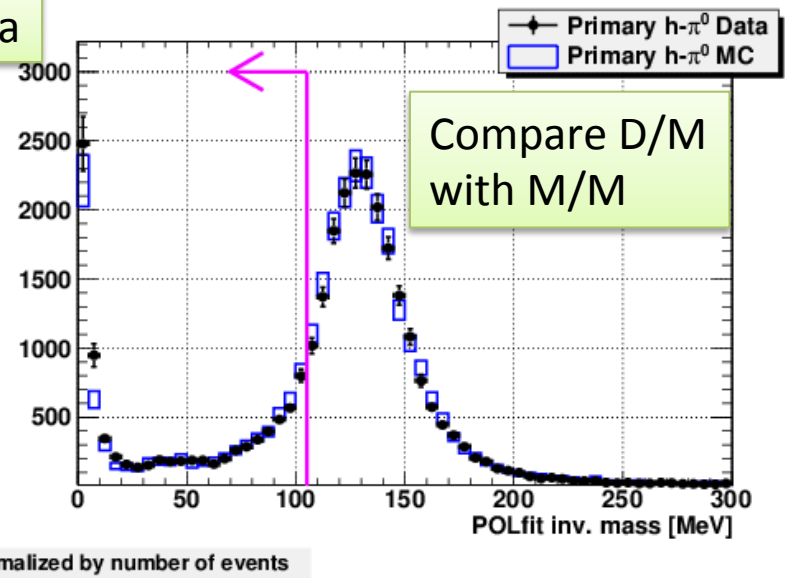
MC gamma



Merged event

Error source	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	**7.6%**	**15%**

atmospheric

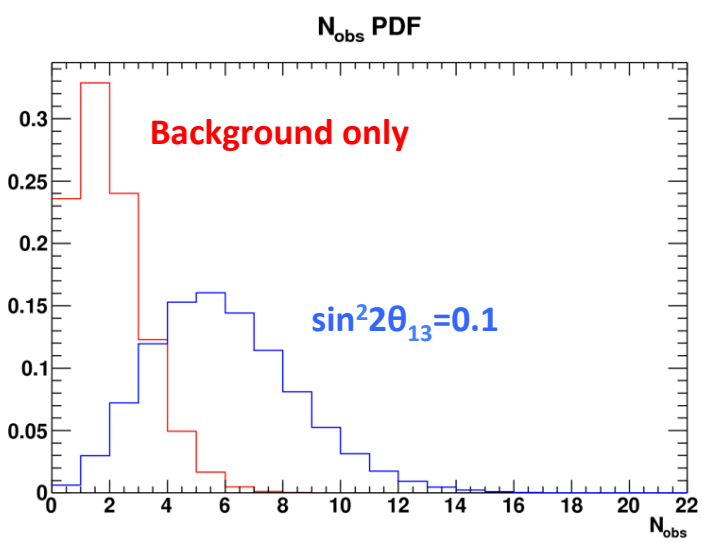


Normalized by number of events

Systematic errors in the analysis

S and B have different errors

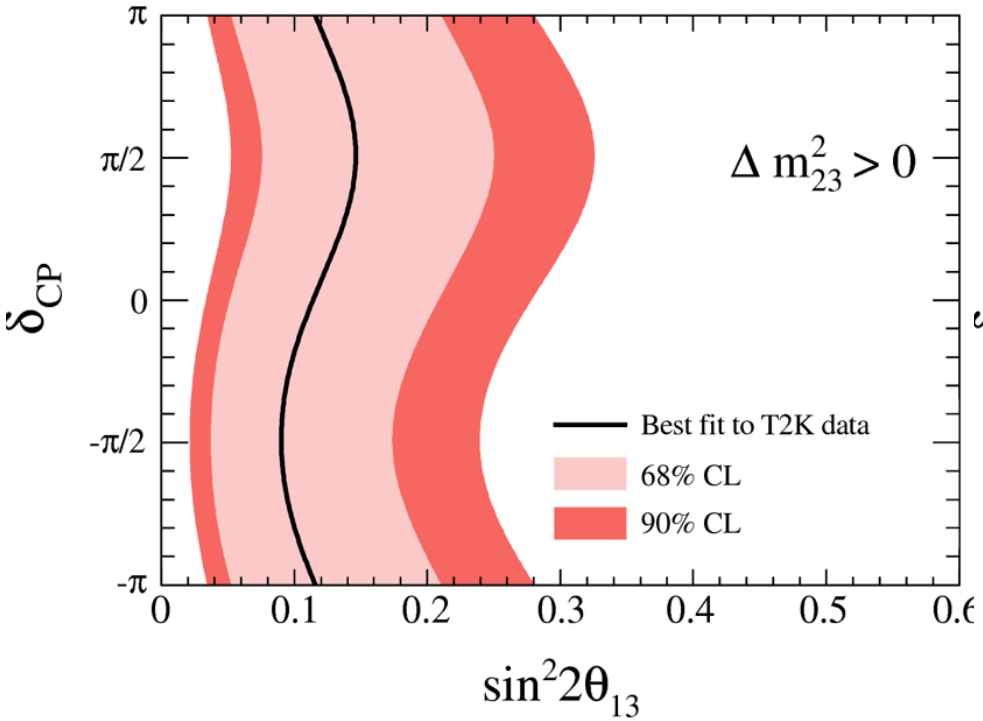
		$\sin^2 2\theta_{13}=0$		$\sin^2 2\theta_{13}=0.1$	
Error source	N_{ND}	N_{SK}	N_{SK}/N_{ND}	N_{SK}	N_{SK}/N_{ND}
SK Efficiency	± 0.0	± 14.7	± 14.7	± 9.4	± 9.4
Cross section	± 8.3	± 13.5	± 14.0	± 9.8	± 10.5
Beam Flux	± 15.4	± 16.1	± 8.5	± 14.9	± 8.5
ND Efficiency	$^{+5.6}_{-5.2}$	± 0.0	$^{+5.6}_{-5.2}$	± 0.0	$^{+5.6}_{-5.2}$
Overall Norm.	± 0.0	± 0.0	± 2.7	± 0.0	± 2.7
Total	± 18.4	± 25.6	$^{+22.8}_{-22.7}$	± 20.2	$^{+17.6}_{-17.5}$

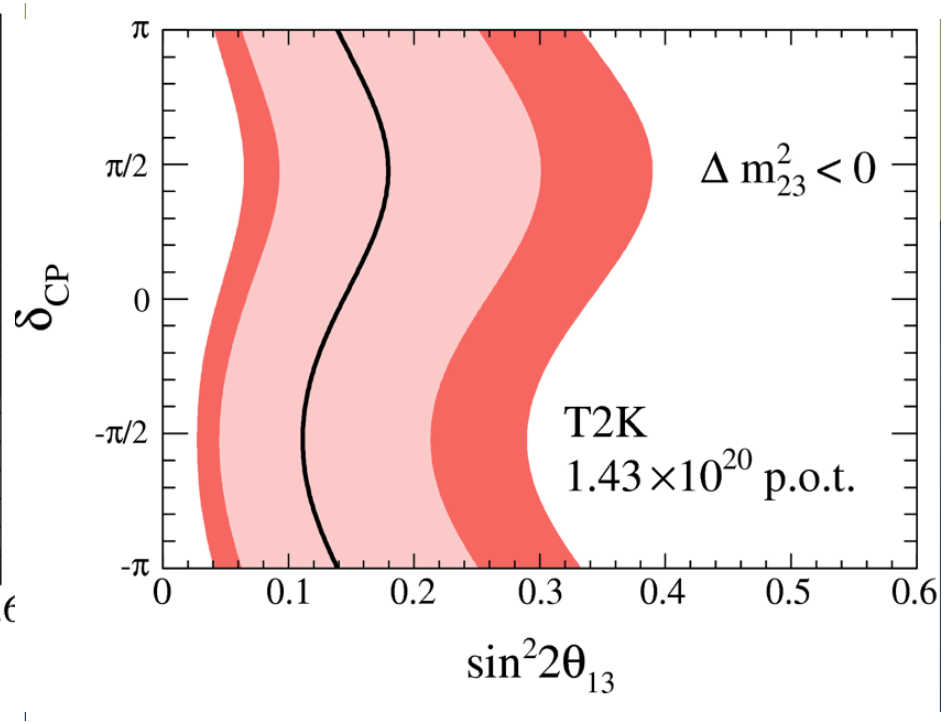


The probability to observe ≥ 6 events is 0.66% which corresponds to a 2.5σ significance.

Produce allowed region with Feldman-Cousins

Values fixed: $\sin^2 2\theta_{23}=1.0$ and $\Delta m^2_{23}= 2.4\times10^{-3}$ eV^2





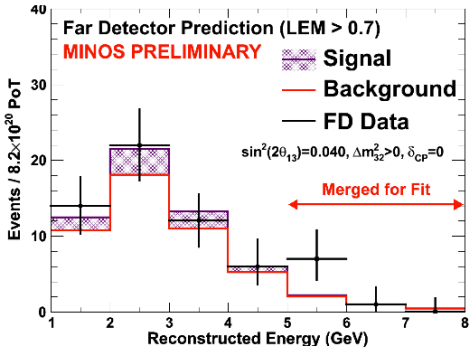
At these values the 90% CL contours enclose:

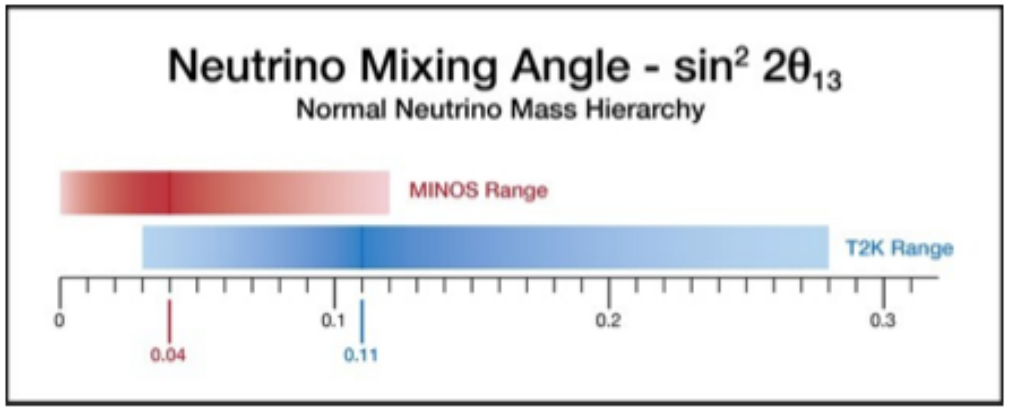
Normal Hierarchy: $0.03 < \sin^2 2\theta_{13} < 0.28$ *(best fit = 0.11)*

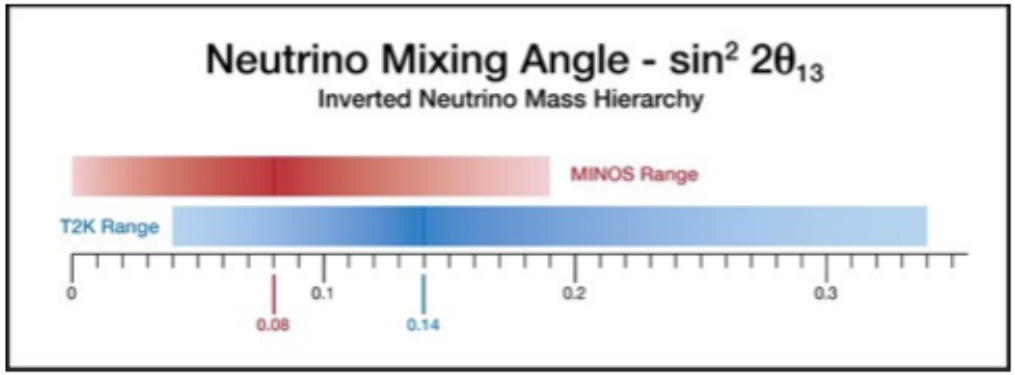
Inverted Hierarchy: $0.04 < \sin^2 2\theta_{13} < 0.34$ *(best fit = 0.14)*

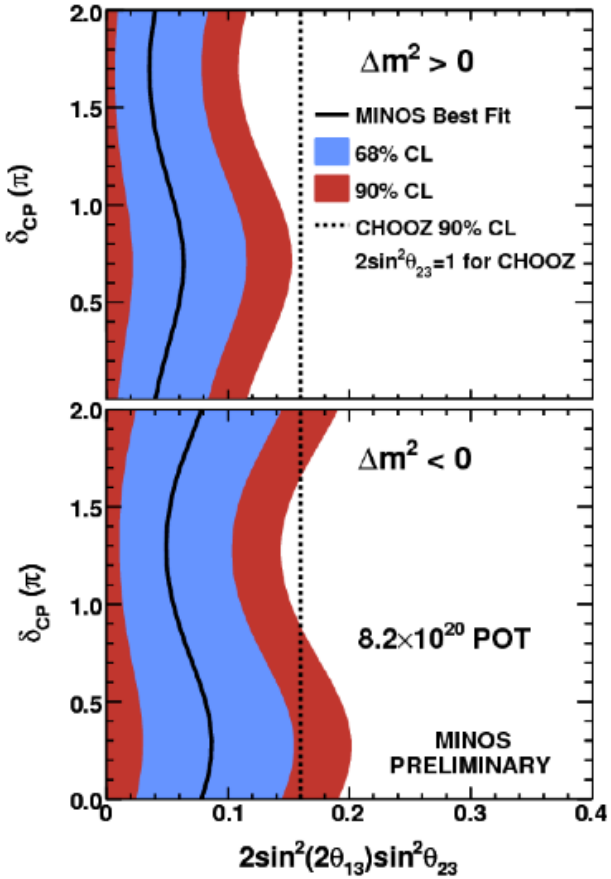
New MINOS results

FNAL Wine & Cheese June 24th
Lisa Whitehead



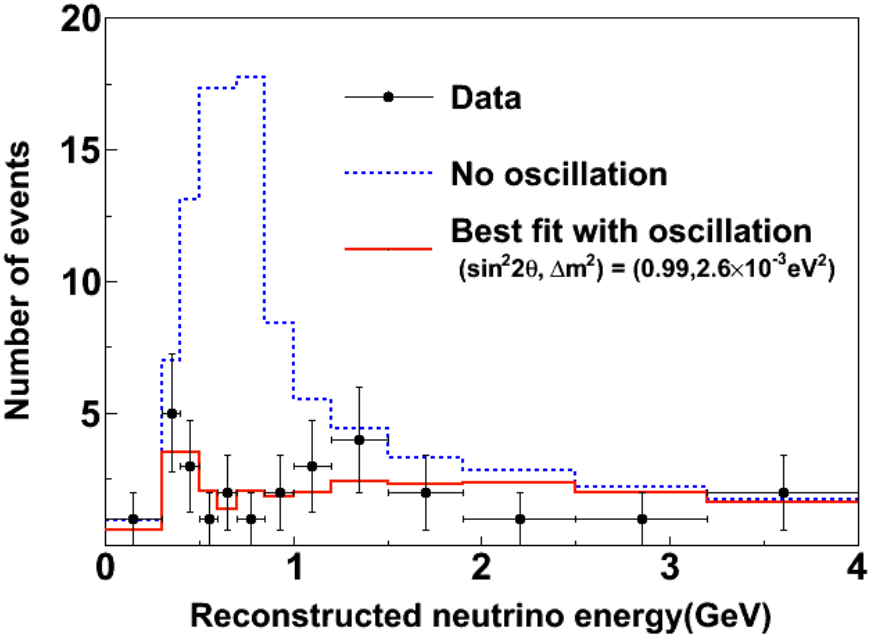


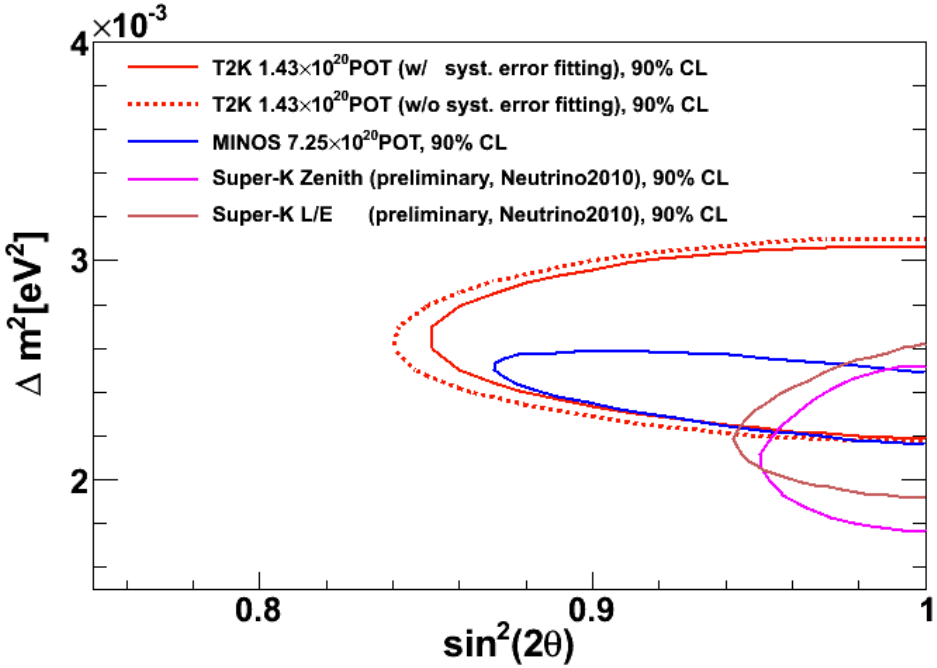




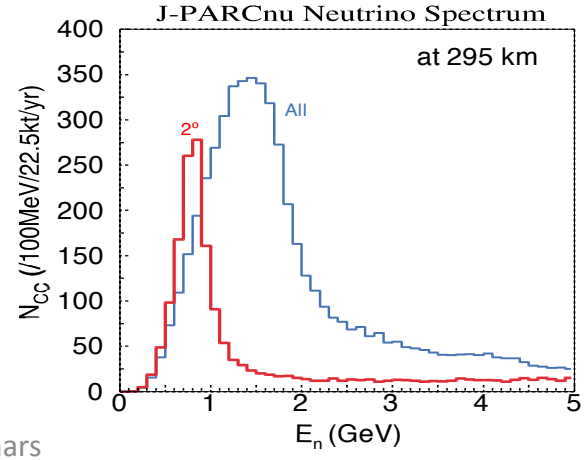
Results are consistent!

New T2K ν_μ results





This result even with limited statistics shows the power of the off-axis technique.



Our Strategy for the future

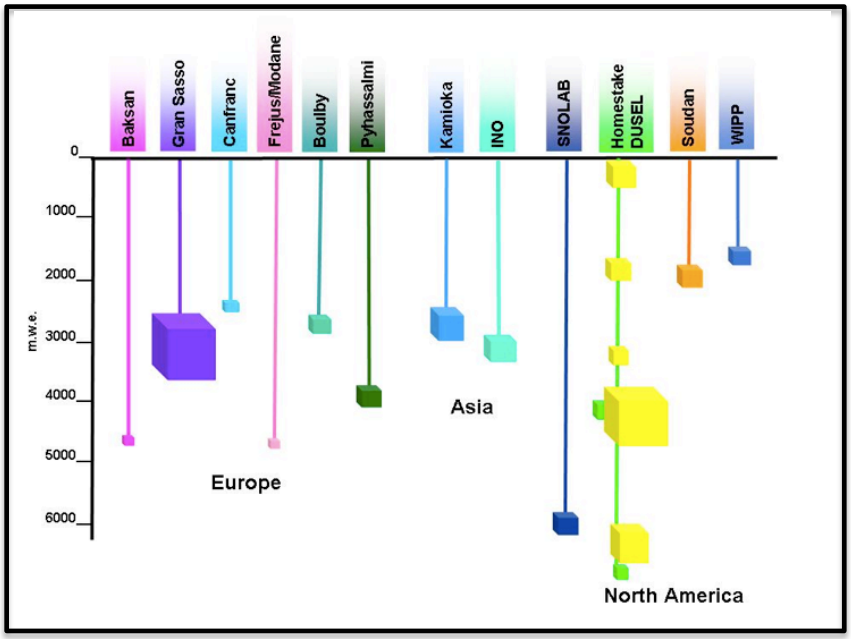
If $\sin^2(2\theta_{13})$ is found to be >~ 0.01 in the next generation of accelerator and reactor experiments we can try to:

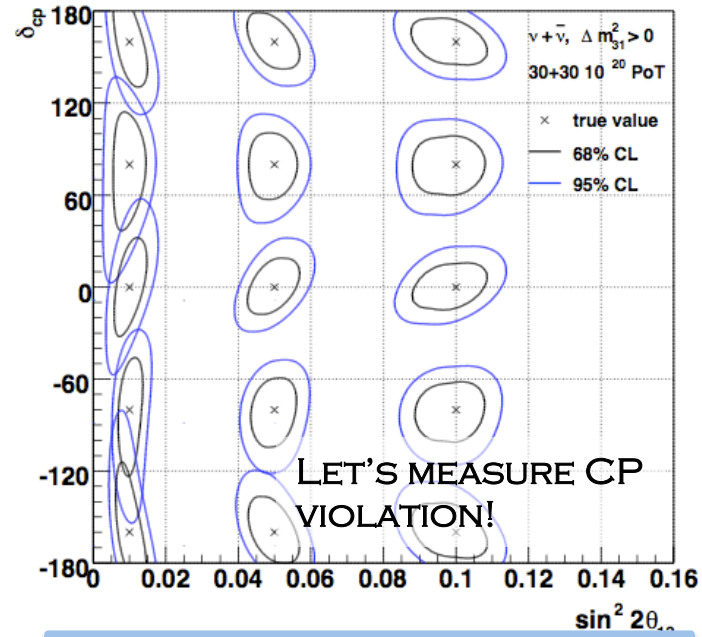
- Measure the phase of δ and observe CP violation
- Determine the mass hierarchy [if not already done]
- Make precision measurements of the atmospheric mixing angles.

To do this we need to <u>both</u> increase the <u>intensity</u> of our Super-beam sources, and increase the <u>mass</u> of our detectors.

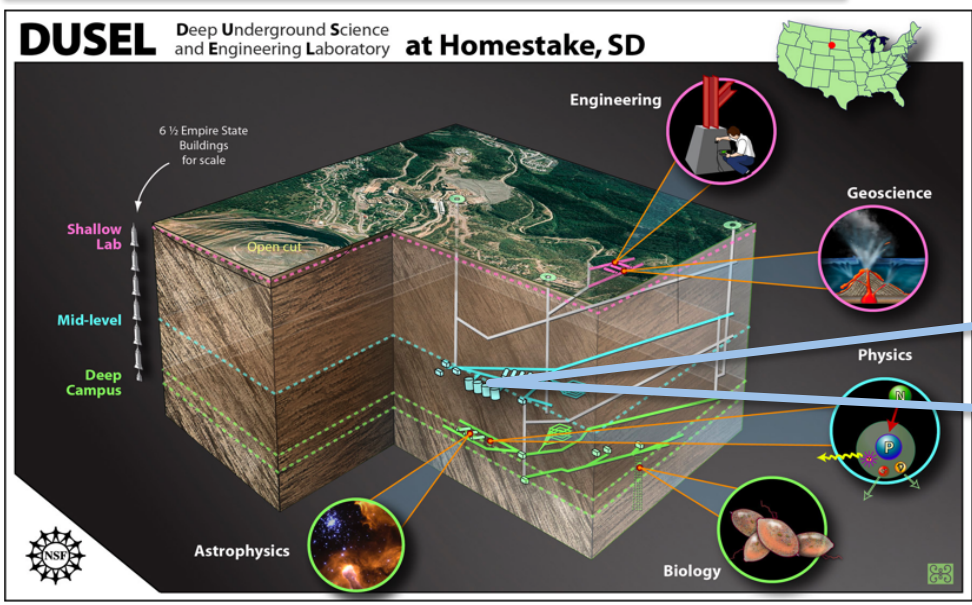
	Now or Soon	Glorious Future
J-PARC	0.75 MW (T2K)	1.7 MW (JPARC II)
FNAL	0.3 MW (NuMI)	2.1 MW (Project-X)
	→	
Water Cherenkov	22.5 kton (SK)	200-500 kton
Fine Grained	15 kton (NOνA)	20-100 kton (LAr)

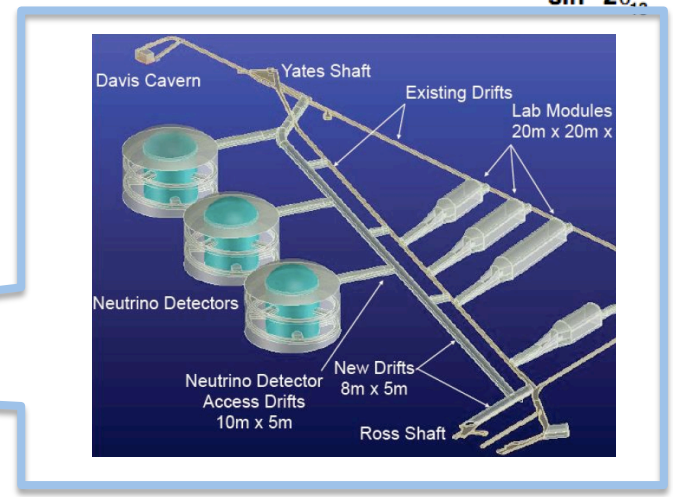
Project-X to DUSEL (LBNE)





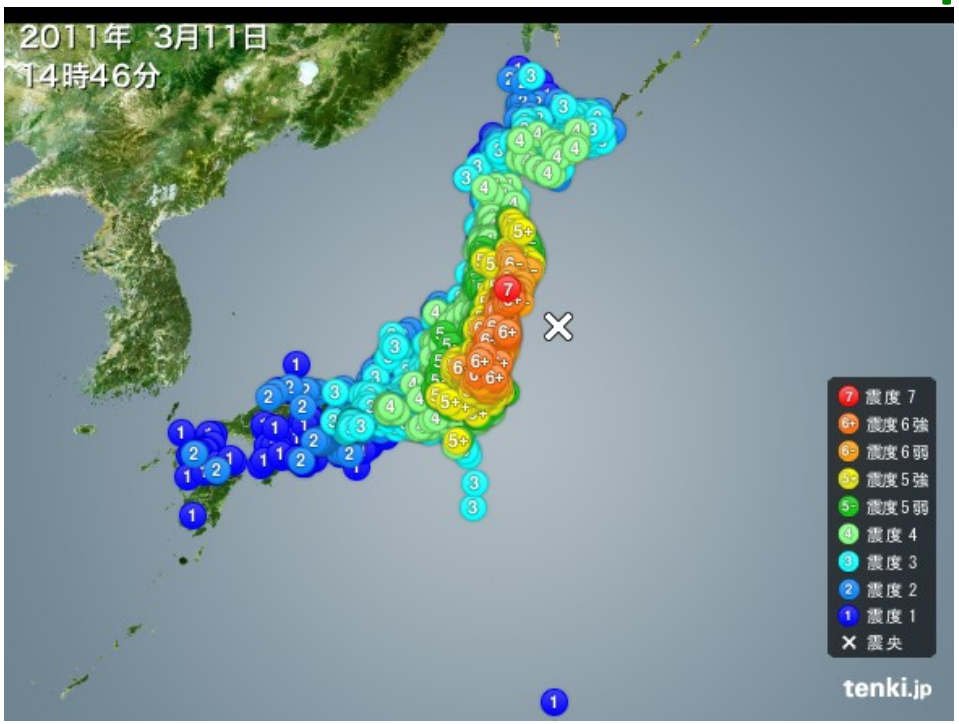
Let's measure CP violation!



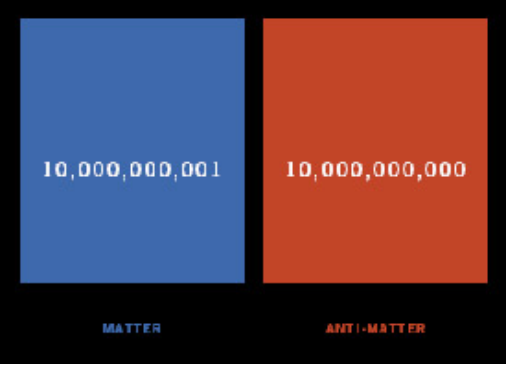


WC And/Or LAr at 4850ft.

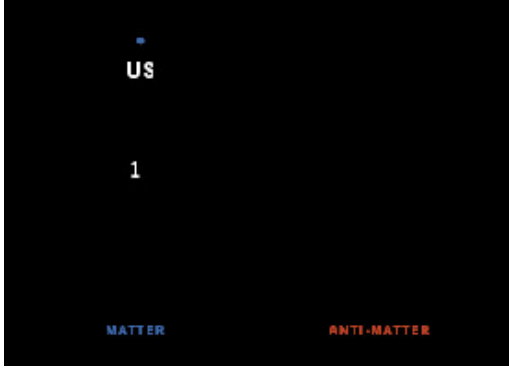
Earthquake



- All collaborators safe, and the tsunami was stopped by sea wall.
- Lots of road damage but no major equipment damage.
- Recovery is underway
- Planning on beam operation at the end of 2011.



Conclusion



- After 2% of our planned running we observed 6 electron neutrino candidates.
- In the $\sin^2 2\theta_{13}=0$ scenario we only expected 1.5±0.3 events. ***This chances of a fluctuation to explain this effect are 0.66% or 2.5σ.***
- At 90% CL we measure an allowed region of $0.03 < \sin^2 2\theta_{13} < 0.28$ for the normal hierarchy.
- We are working to decrease the systematic errors in the flux, interactions, near detector and far detector.
- We hope to <u>start running again in December</u>, so far no major equipment damage has been found. At least 98% of the data yet to come!