Measurement of θ_{13} with T2K

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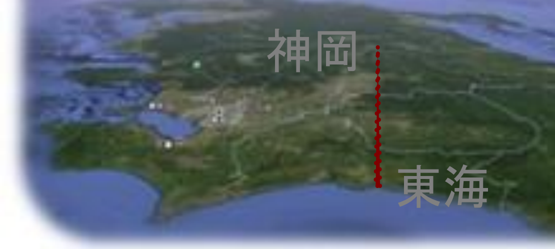
for the T2K collaboration

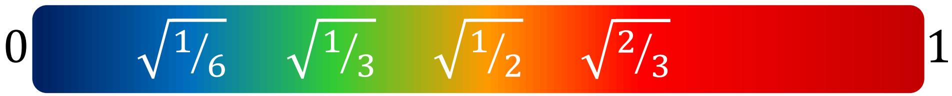
PPC'12, KIAS

Neutrino mixing



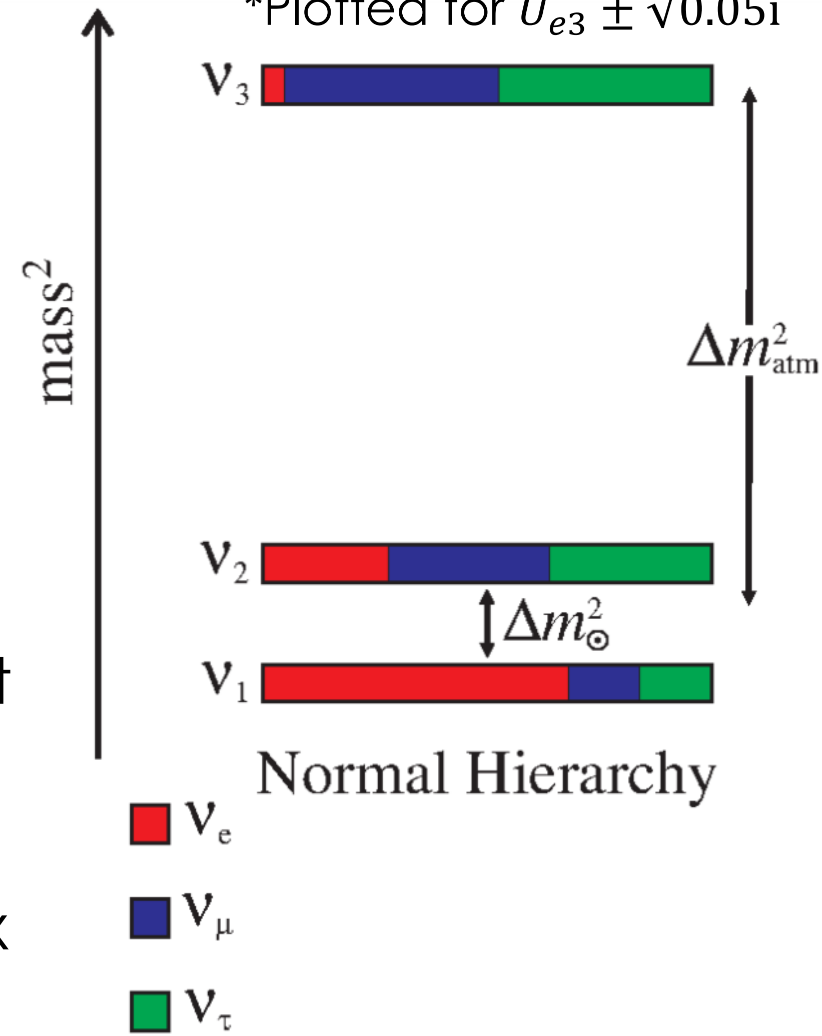
Neutrino mixing (PMNS) matrix is:

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

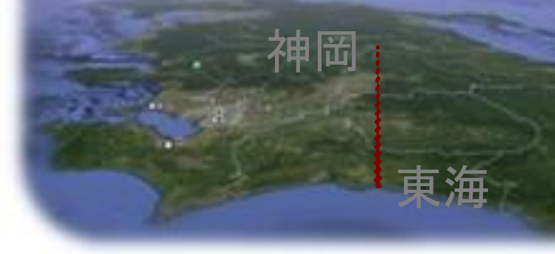


- 8 large elements
- U_{e3} is significant as the smallest element, and the last to be measured (inferred).
- Very different from CKM matrix

*Plotted for $U_{e3} \pm \sqrt{0.05}i$



Angle parameterisation



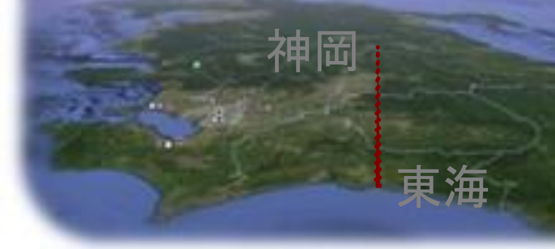
The mixing matrix is commonly parameterised as the product of two rotations and a unitary transformation. Writing $s_{ij} = \sin\theta_{ij}$, and $c_{ij} = \cos\theta_{ij}$:

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

The choice of parameterisation is convenient as the **solar** and **atmospheric** disappearance amplitudes can be approximated as functions of $\boldsymbol{\theta_{12}}$ and $\boldsymbol{\theta_{23}}$, respectively.

This approximation only works to the extent that the third angle $\boldsymbol{\theta_{13}}$ is small.

The role of θ_{13}



In the standard parameterisation, it turns out that

$U_{e3} = \sin\theta_{13}\, e^{-i\delta}$,   and therefore $\sin\theta_{13} = |U_{e3}|$.

The value of $\sin\theta_{13}$ particularly significant because a zero element in the mixing matrix would have eliminated the possibility of (KM-mechanism) leptonic CP violation.

The future program of neutrino physics is strongly dependent on the size of $\boldsymbol{\theta_{13}}$.

To study, need channels involving $\langle \nu_e | \nu_3 \rangle$. The most accessible are $\bar{\nu}_e \to \bar{\nu}_e$ (reactor) and $\boldsymbol{\nu_\mu \to \nu_e}$ **(accelerator)** at first 'atmospheric' maximum (L/km ~ 0.5 × E/MeV)

$\nu_\mu \rightarrow \nu_e$ appearance probability

The ν_e appearance probability can be written approximately as a sum of terms quadratic in the small parameters $\alpha = \Delta m^2_{21}/\Delta m^2_{31} \approx 1/32$, and $\sin 2\theta_{13}$:

$$P(\nu_\mu \rightarrow \nu_e) \approx T_{\theta\theta} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + T_{\alpha\alpha}\alpha^2 \frac{\sin^2(A\Delta)}{A^2}$$
$$+ T_{\alpha\theta}\alpha \sin 2\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

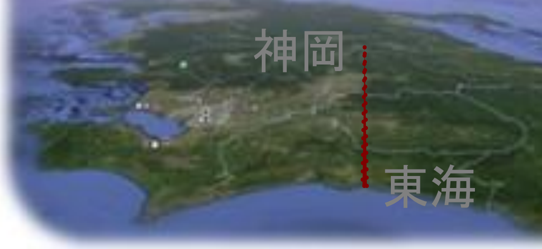
where

$$T_{\theta\theta} = \sin^2\theta_{23}, \qquad T_{\alpha\alpha} = \cos^2\theta_{23} \sin^2 2\theta_{12},$$
$$T_{\alpha\theta} = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

and $\Delta = \frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$ at 1st osc. maximum.

$A(= \pm 2\sqrt{2} G_F n_e E \,/ |\Delta m^2_{31}|)$ is the matter density parameter. For T2K, $|A| \sim 0.07$

Synergies with $\bar{\nu}_e \to \bar{\nu}_e$



For reactor antineutrinos in the earth's crust we can ignore matter effects, and the probability is very simple:

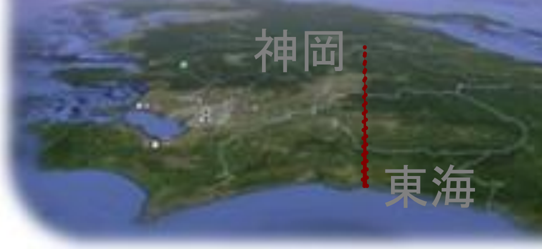
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \alpha\Delta$$

On a ~1km baseline the 3rd solar-scale term is small, so the survival probability measures $\sin^2 2\theta_{13}$ directly.

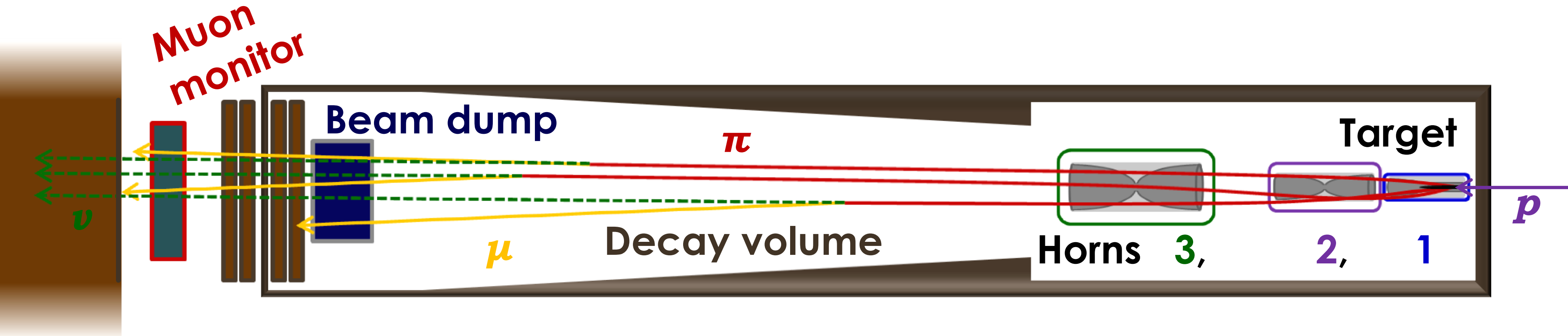
So the role of reactor and LBL experiments will change over time:

- Initially, both are valuable as independent measurements with different systematics.
- Later, LBL can use reactor results as input to understand CP effects and the mass hierarchy.

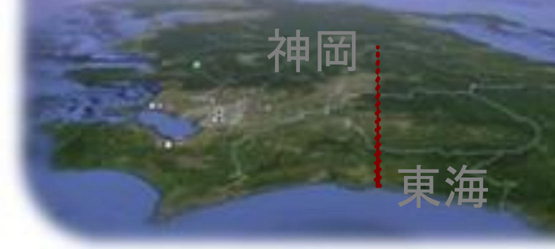
The neutrino beam.



- ν_μ from pion decay.
- Pions produced in proton interactions on a target, and focussed by 3 magnetic horns
- Horn current and geometry most important in determining (on-axis) spectrum
- Wrong sign (anti-ν) and ν_e backgrounds are ~ few %

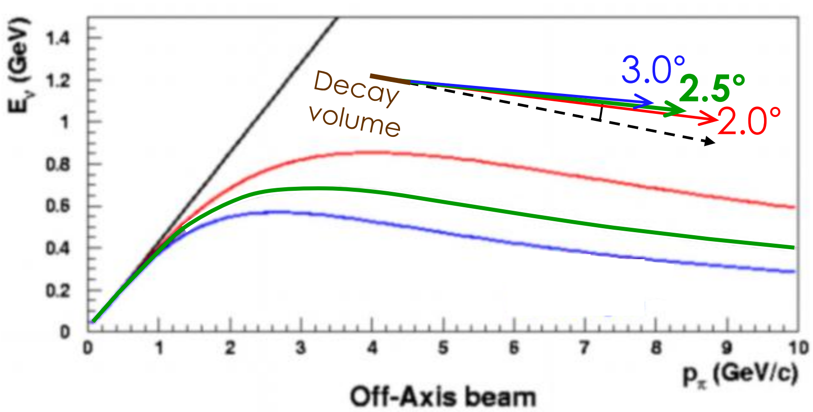


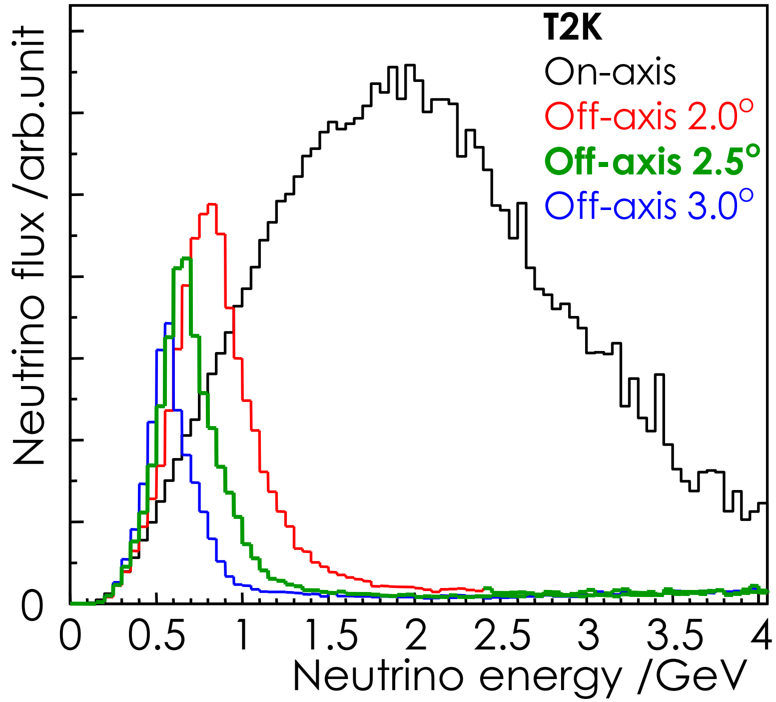
The Off-axis 'trick'



T2K is the first experiment to have its detectors off-axis

Relativistic kinematics → at a small angle to the beam axis, neutrino energy is insensitive to parent pion energy.



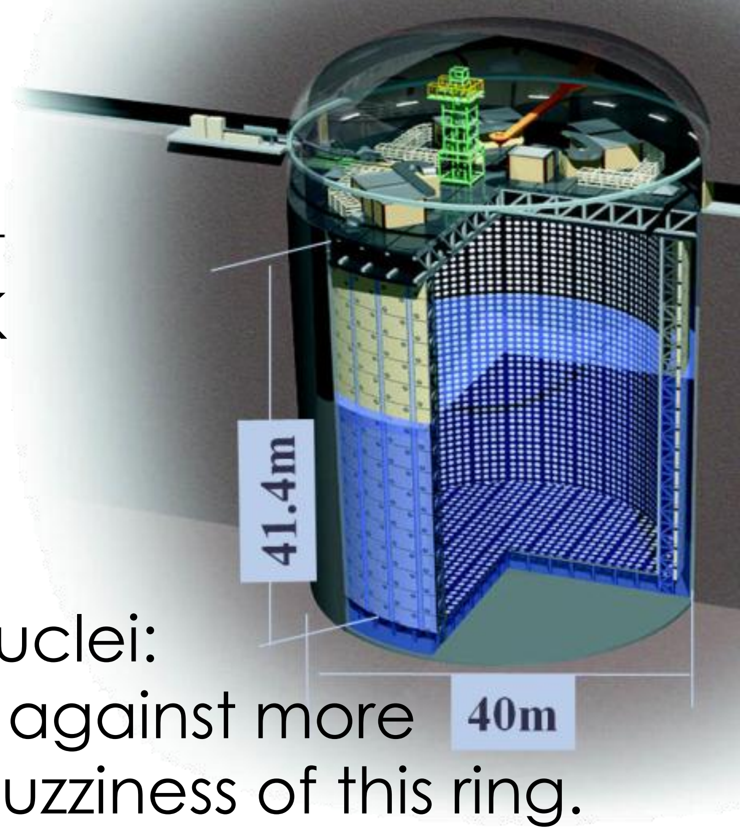


Gives slightly narrower flux peak, and **drastically reduces high energy tail**.

- Ideal for ν_e appearance (much reduced NC BG)

The far detector

T2K uses the 22.5 kt (fiducial) Super-K water Čerenkov detector to look for ν_e appearance.

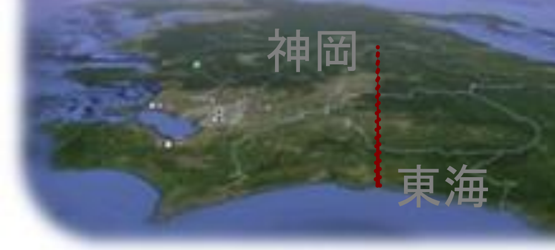


Signal is $\nu, n \rightarrow p, e^-$ (CCQE) on ^{16}O nuclei: Results in a fuzzy Čerenkov ring. PID against more common μ^- events is based on the fuzziness of this ring.

Other important backgrounds from

- Beam ν_e contamination
- NC-π^0 events

T2K uses exclusive channels, so need good understanding of cross-sections → drives design of the Near Detector.



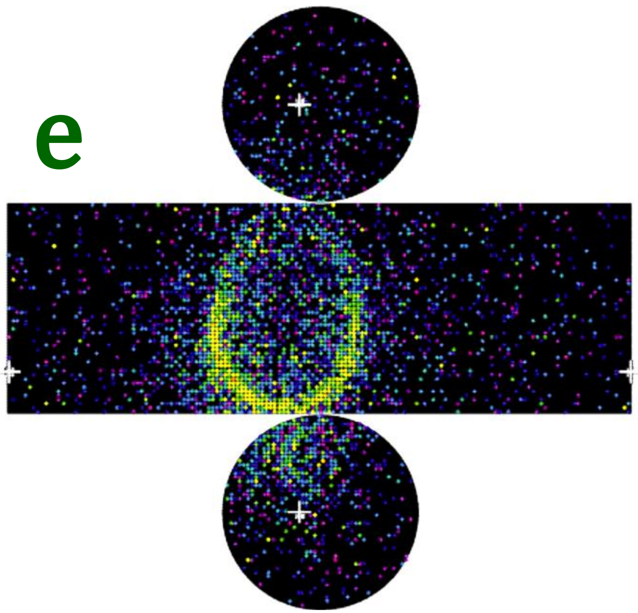
Example event displays

Electrons from ν_e are the signal we are looking for.

Muons from ν_μ are the most common event type.

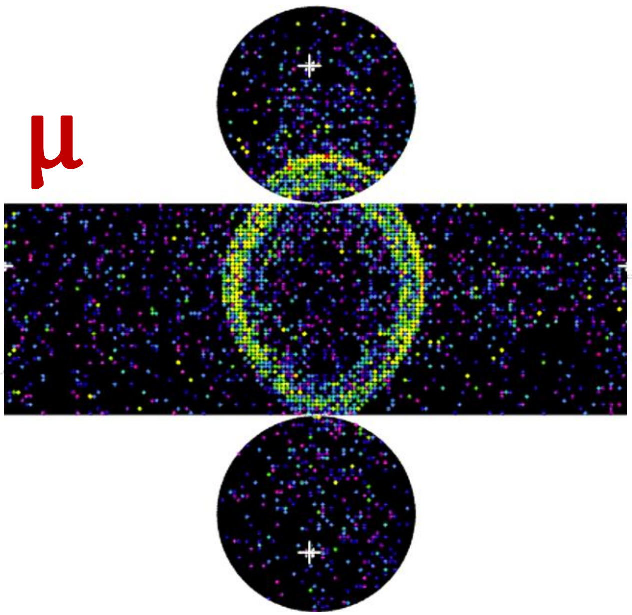
NC-π^0 events are another important background.

e



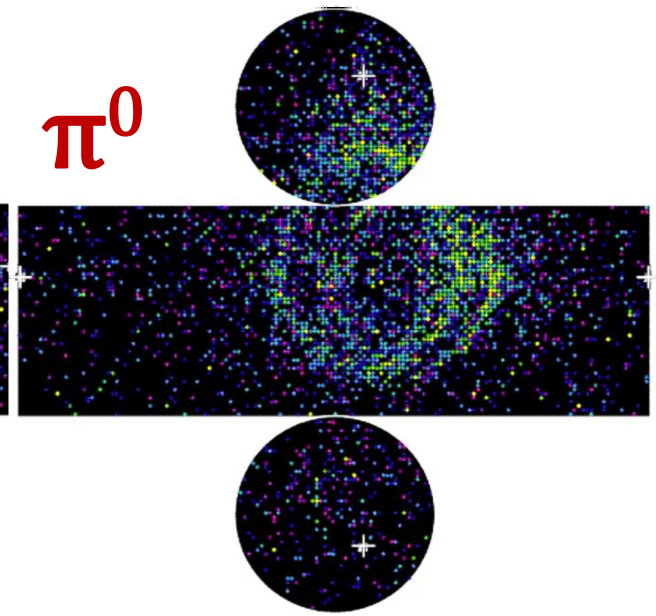
Single fuzzy Čerenkov ring

μ



Čerenkov ring is sharp

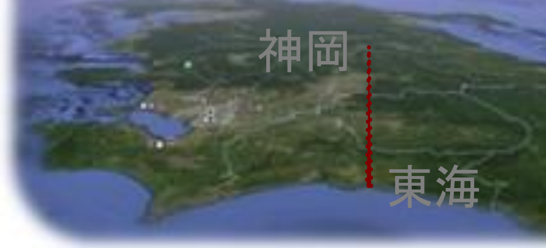
π^0



Mimic electron if one ring is missed

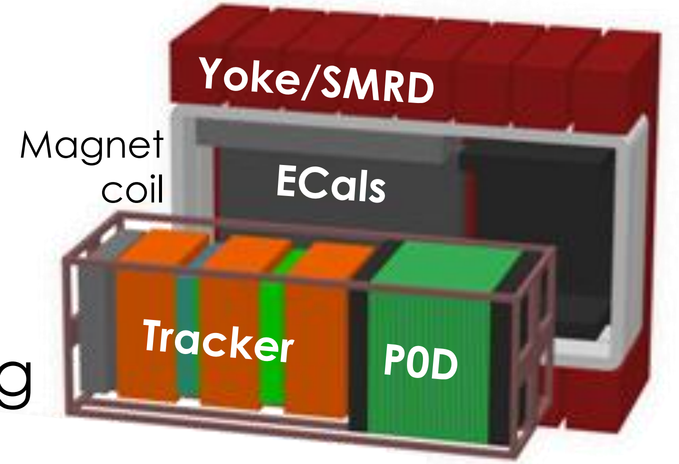
All taken from MC simulation

ND280 near detectors



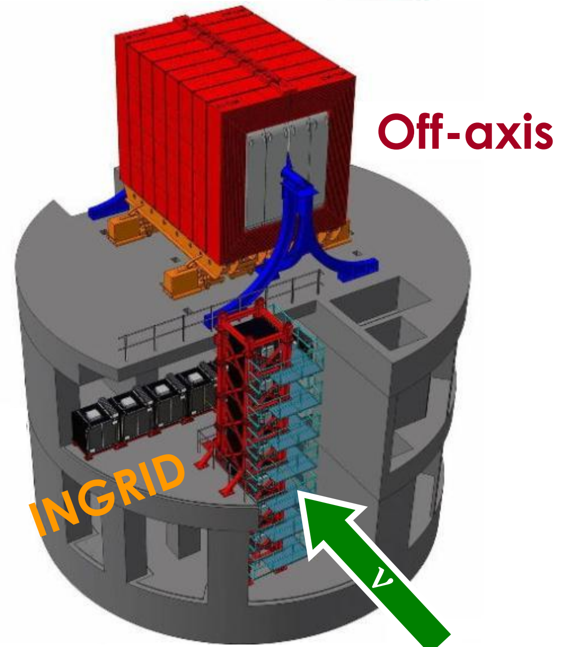
Off-axis detector uses fine-resolution scintillator detectors and TPCs for momentum measurement and PID.

- Much better estimate of interaction rates than using MC dead-reckoning
- Extensive program of cross-section measurements to improve future MCs

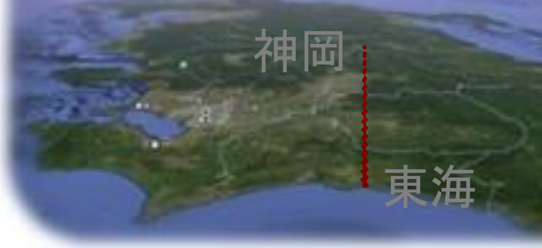


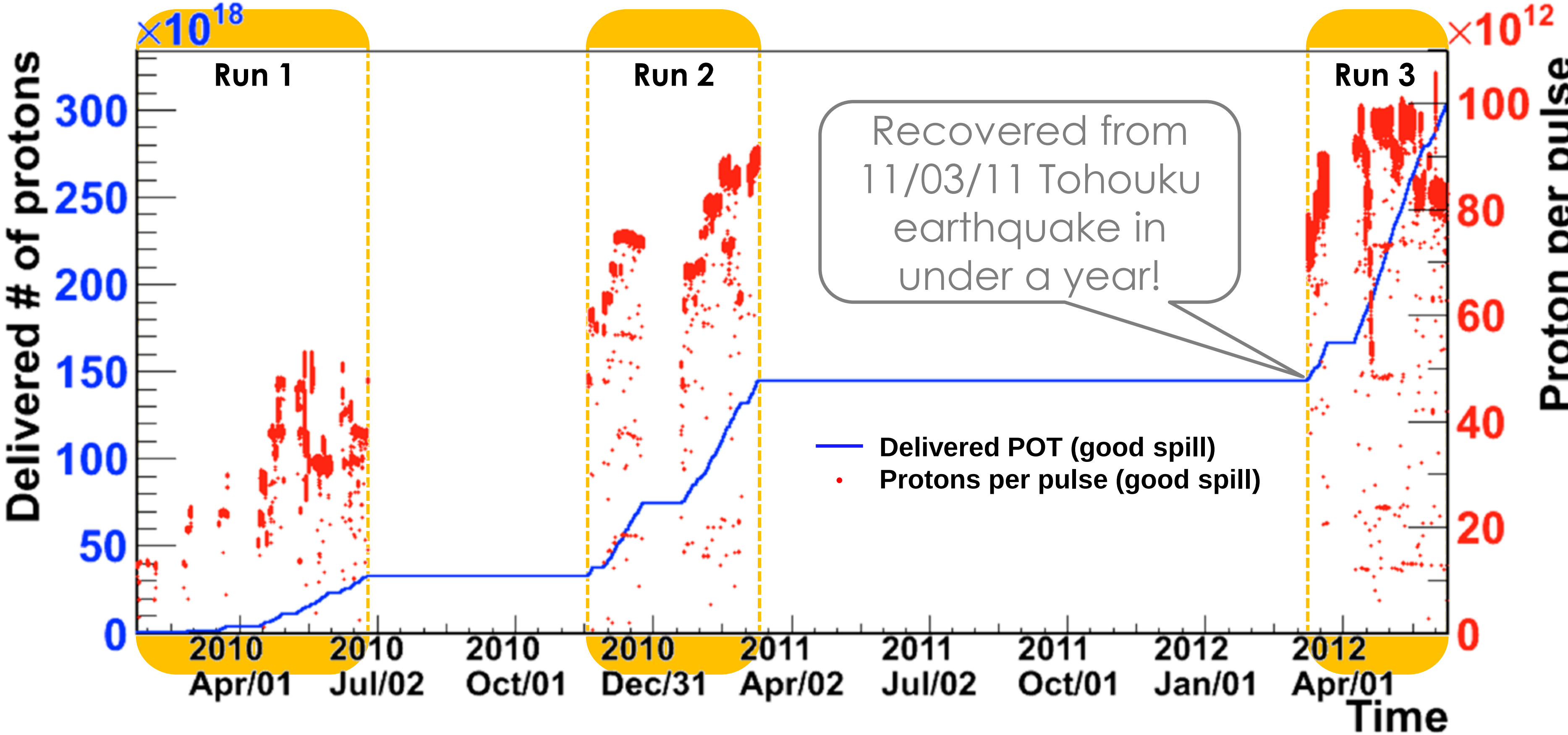
INGRID: A cross arrangement of iron-scintillator detectors, centred on the beam axis, to check beam direction.

- Beam is stable to better than required (1mrad)



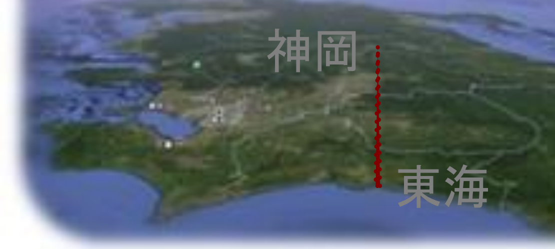
Data set: Runs 1, 2 and 3

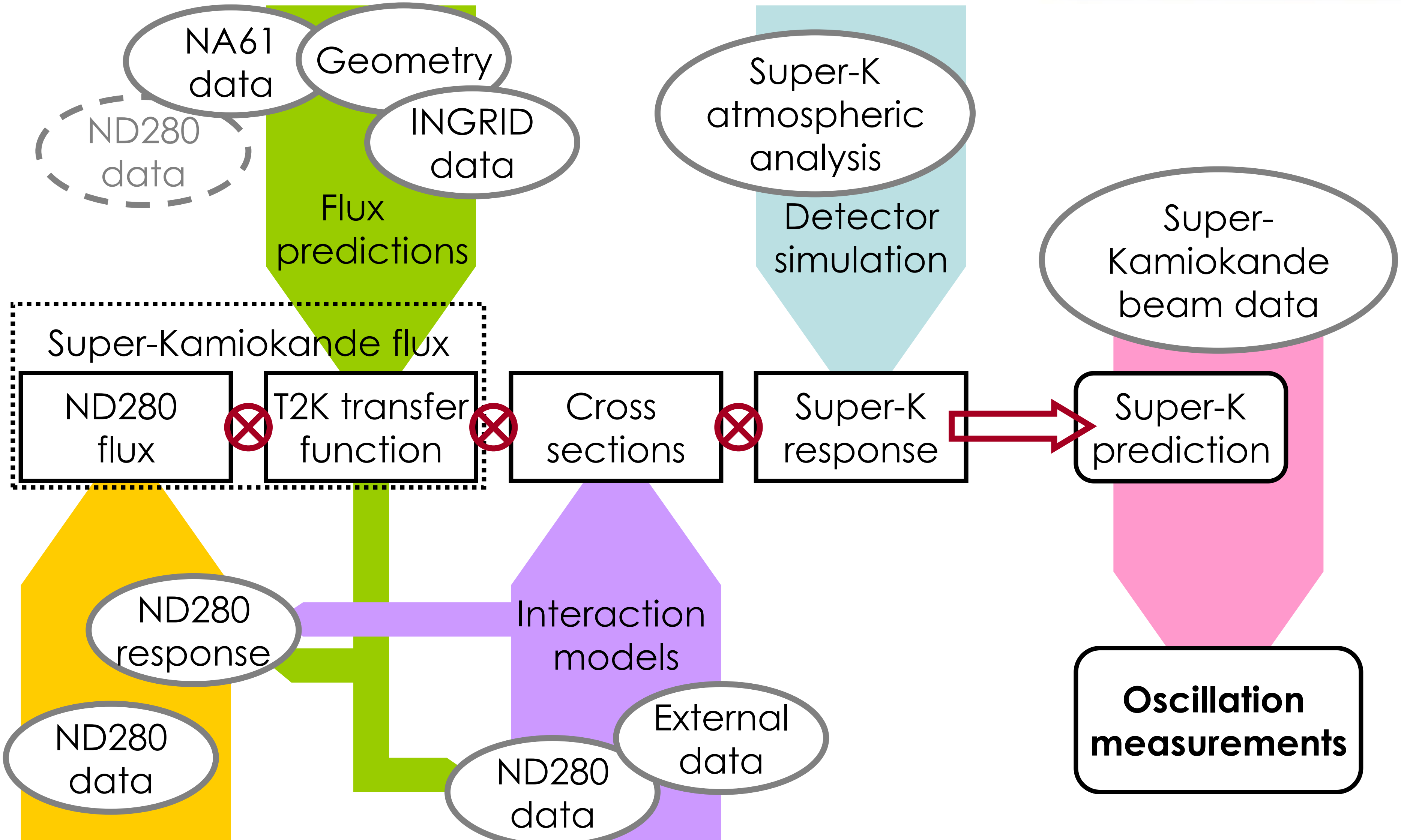




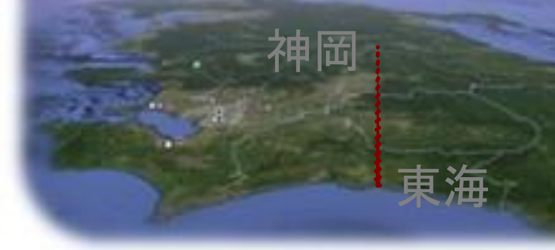
Data set runs up to 2012/06/09 (End of Run 3)
POT used in this analysis: $\mathbf{3.010 \times 10^{20}}$

T2K analysis strategy





Implementing the analysis



'ND280 data' appears in the analysis strategy to constrain both fluxes and cross sections.

- One might reasonably ask **"How can we disentangle these two effects with ND280 data?"**

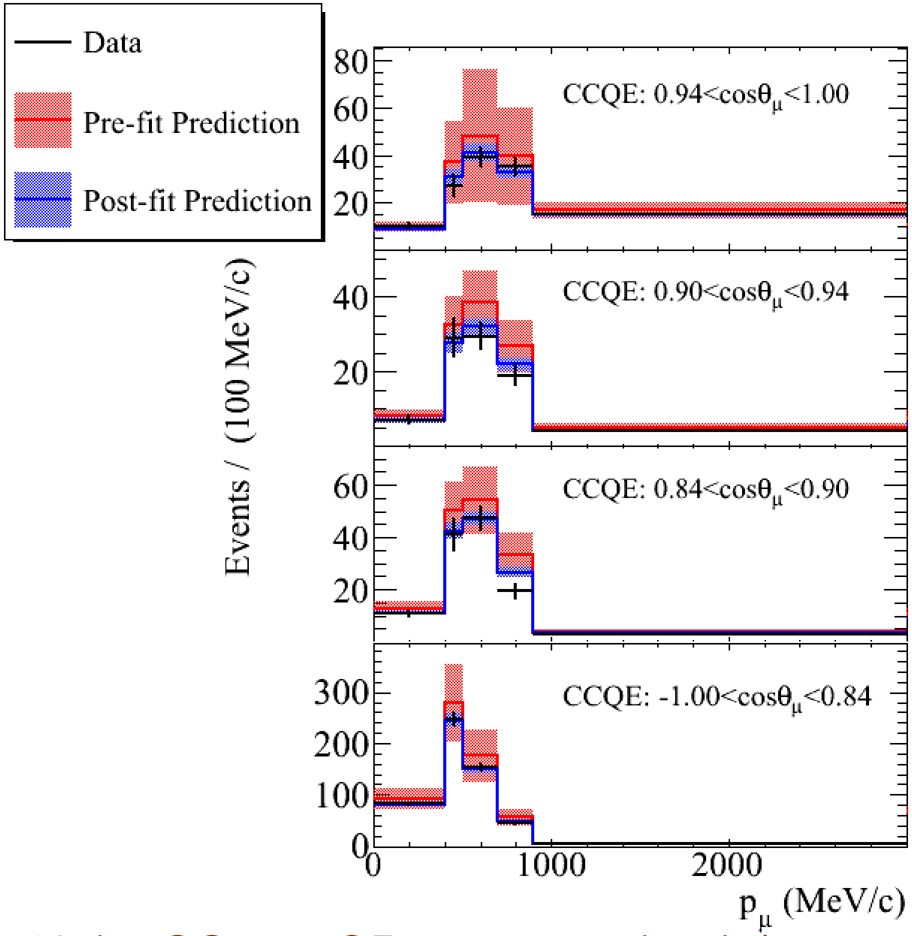
Answer:

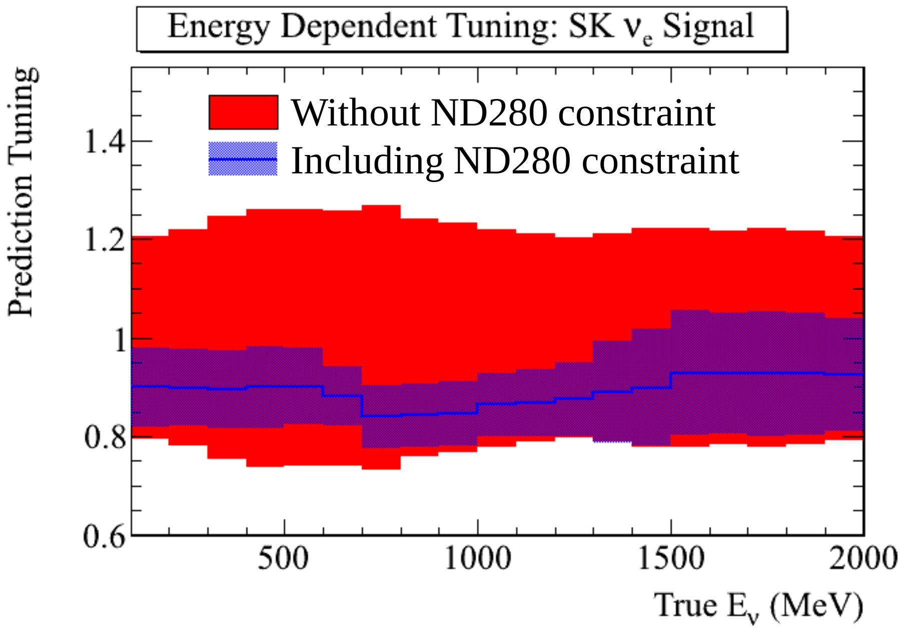
1. Fit the ND280 data for **all systematic uncertainties** (fluxes, cross-sections, detector efficiency), using available external constraints.

2. As well as taking the best fit as input to SK, use the **correlated error matrix** after fitting to supply constraints on SK systematic uncertainties

ND280 fitting

ND280 fit to tracker data ⇨ Effect on T2K ν_e signal uncertainties at SK



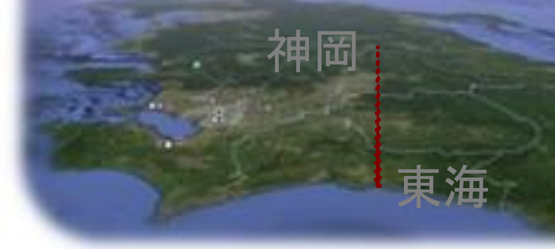


Note: Uncertainties on backgrounds also reduced—see reserves

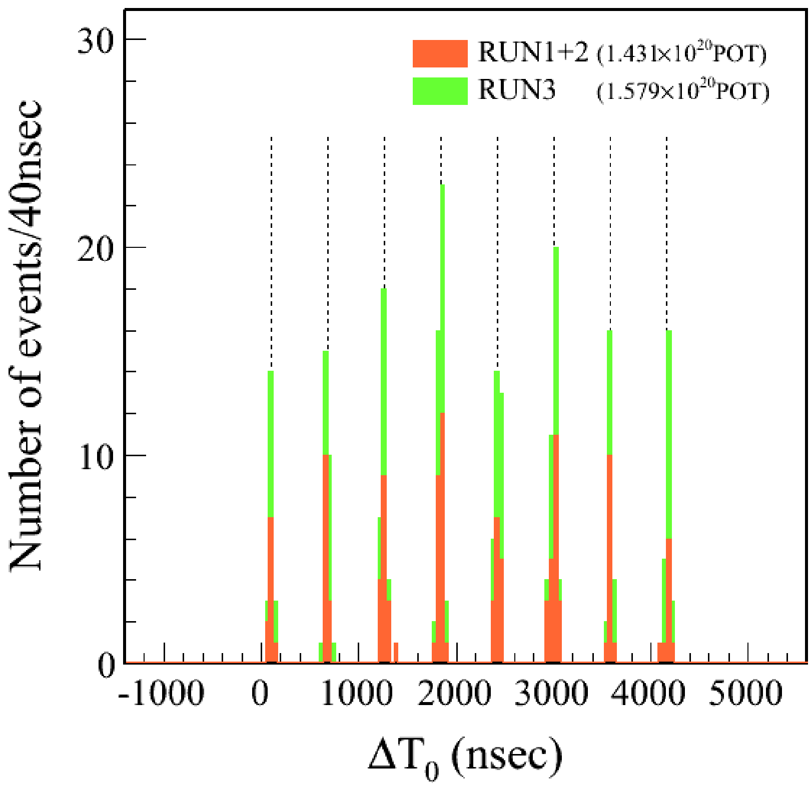
Note: CC non-QE component not shown—see reserves

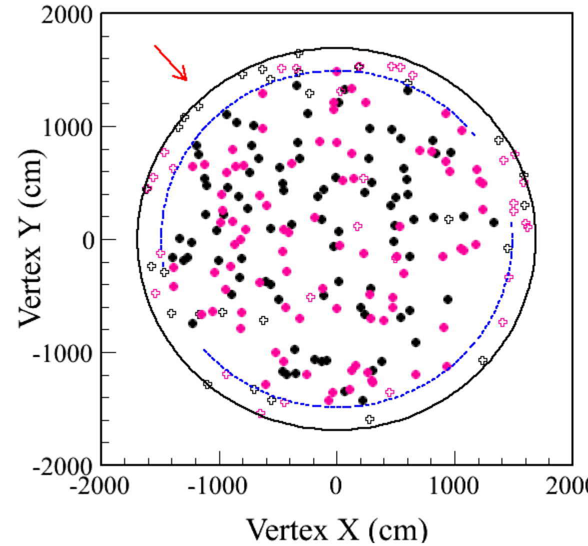
Note: Finer binning and components (post fit) shown in reserves

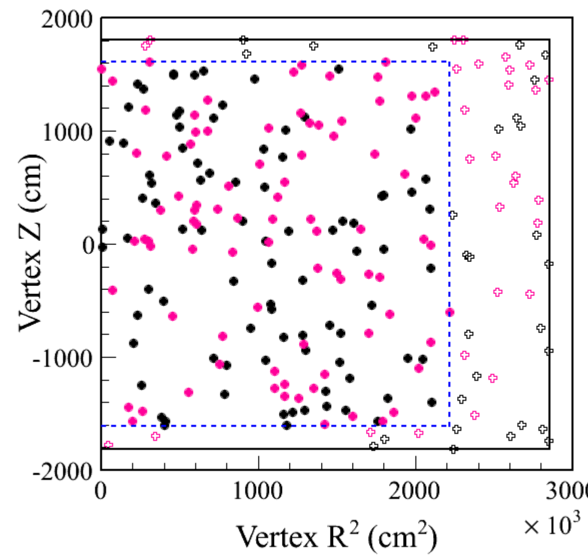
T2K basic selection at SK



Basic selection includes fiducial and timing cuts, as well requiring that events are fully contained.



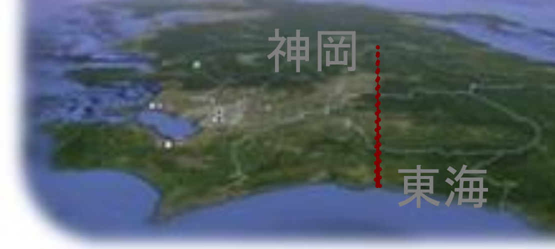


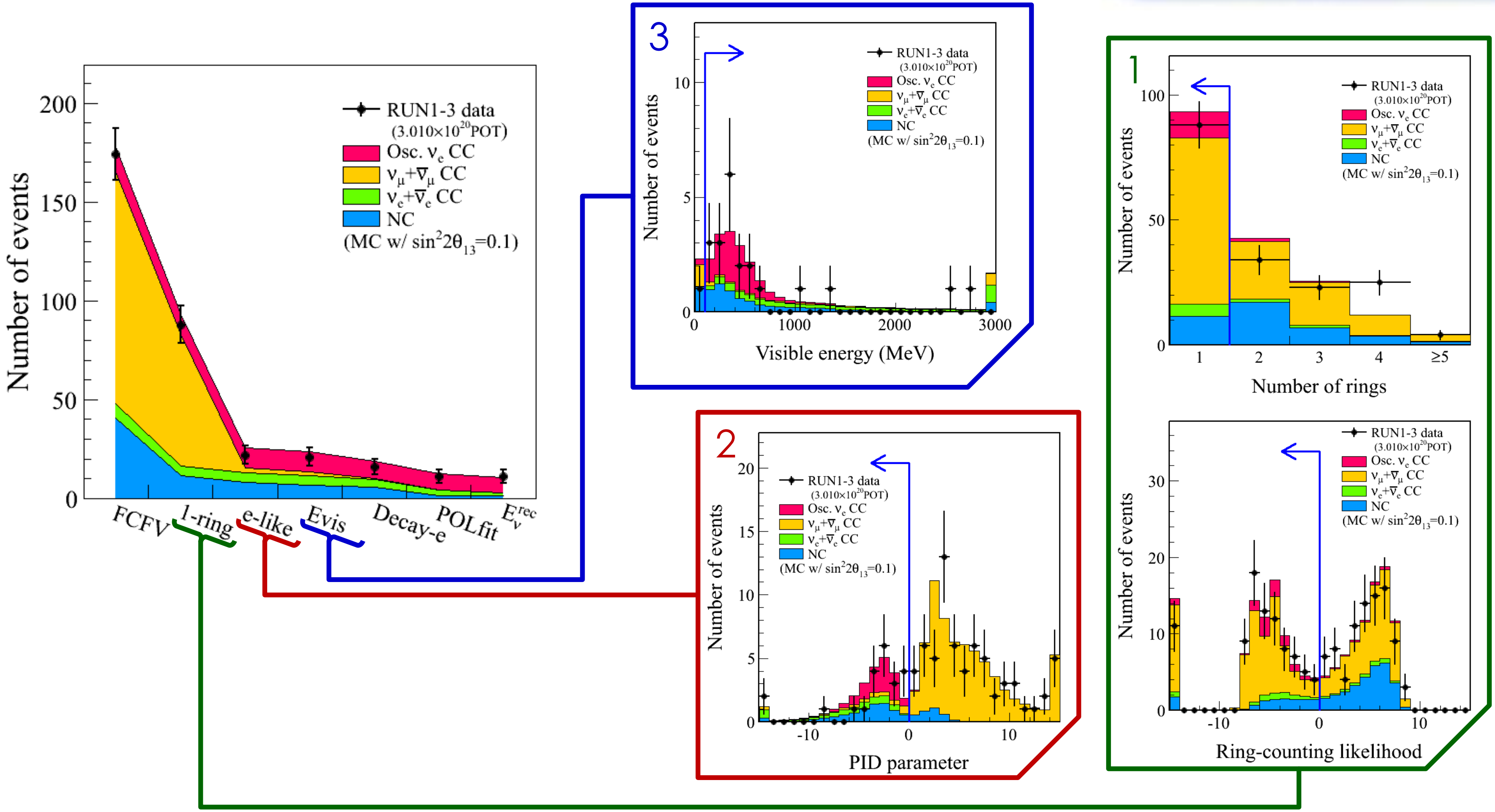


Run1+2
Run 3

Fiducial
Out-of-fiducial

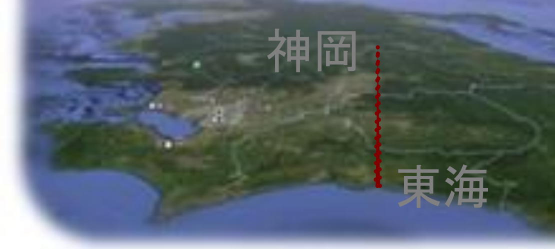
T2K selection of ν_e at SK

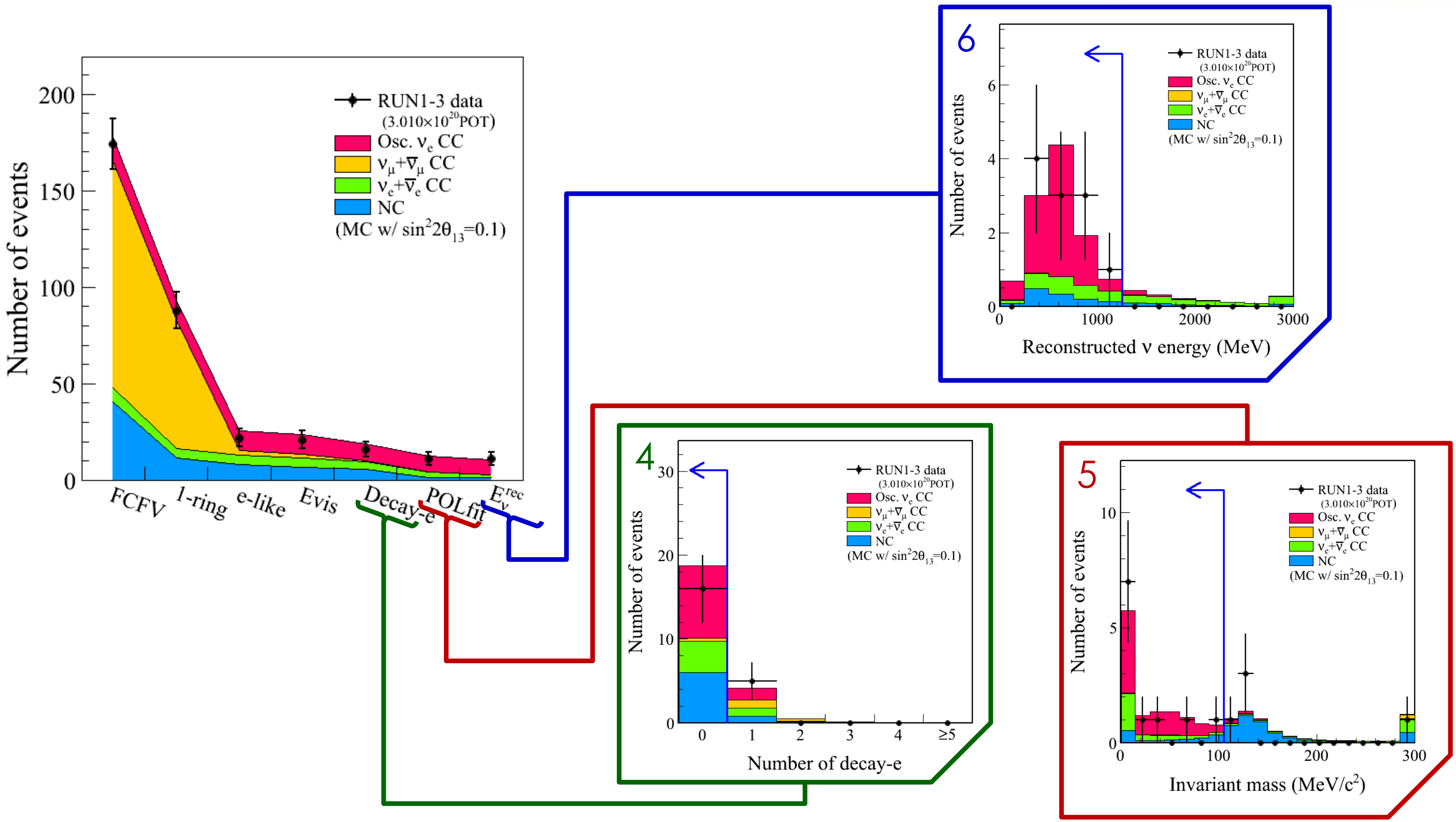




Event selection is by an ordered series of cuts

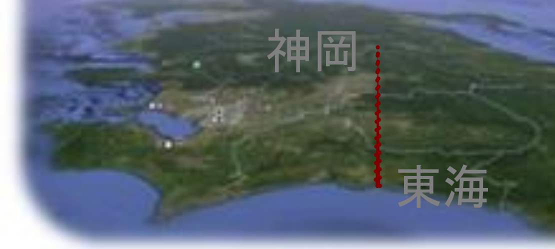
T2K selection of ν_e at SK





11 events are selected as ν_e candidates

ν_e appearance results*

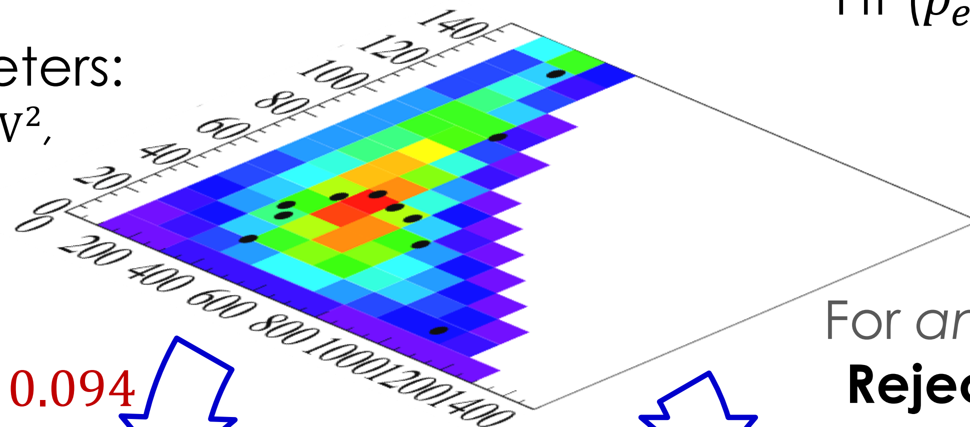


*T2K 3.010×10^{20} POT, first shown at ICHEP 2012

Fit $(p_e, \vartheta_{e,\nu})$ distribution

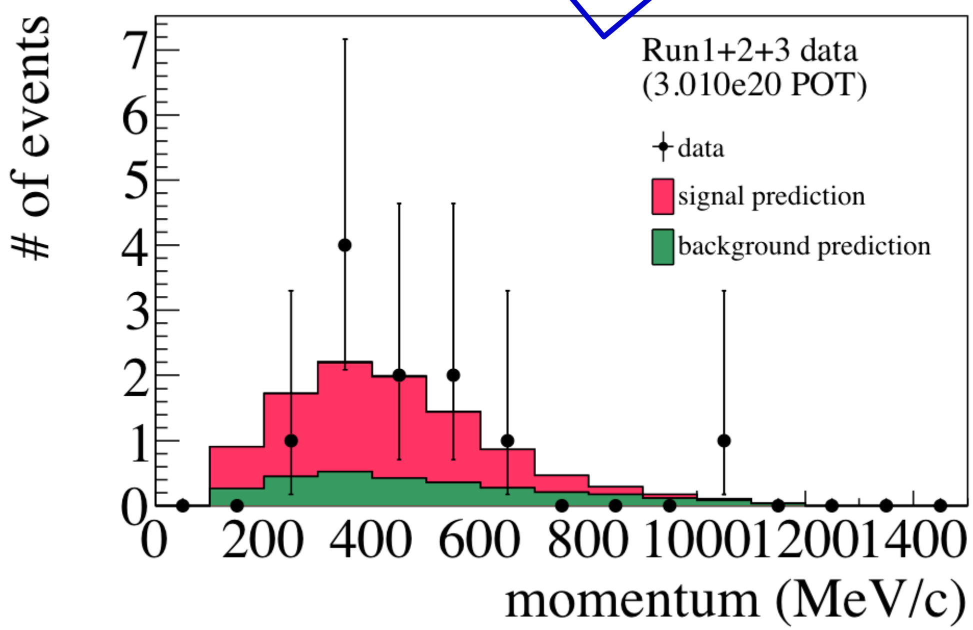
For these parameters:

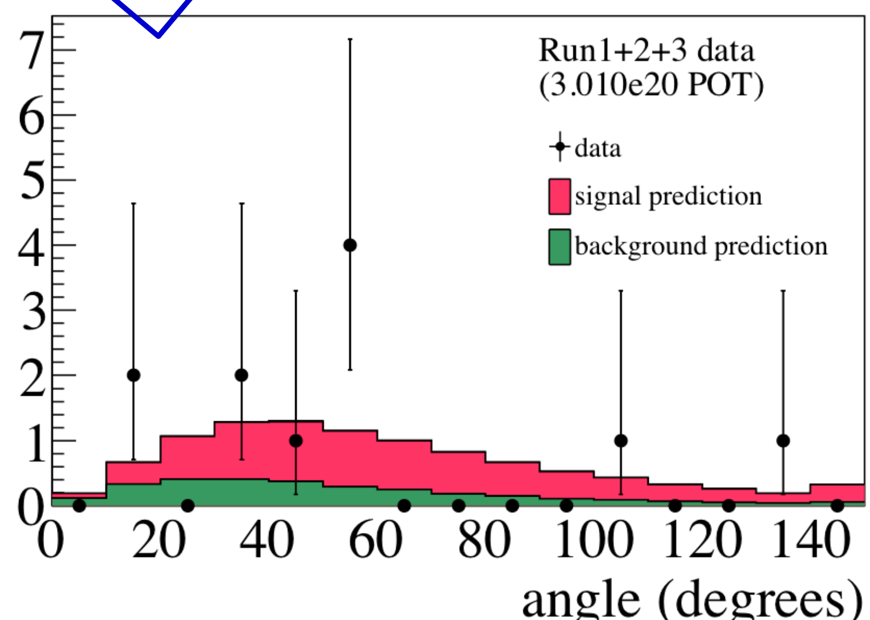
$|\Delta m^2_{32}| = 2.4 \times 10^{-3} \mathrm{eV}^2$,
$\sin^2 2\theta_{23} = 1$,
$\delta = 0$,
Normal hierarchy,



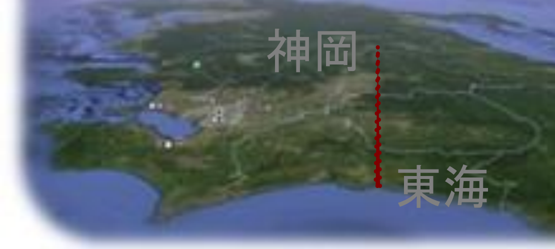
Best fit $\sin^2 2\theta_{13} = 0.094$

For *any* parameters:
Reject $U_{e3} = 0$ at **3.2σ**





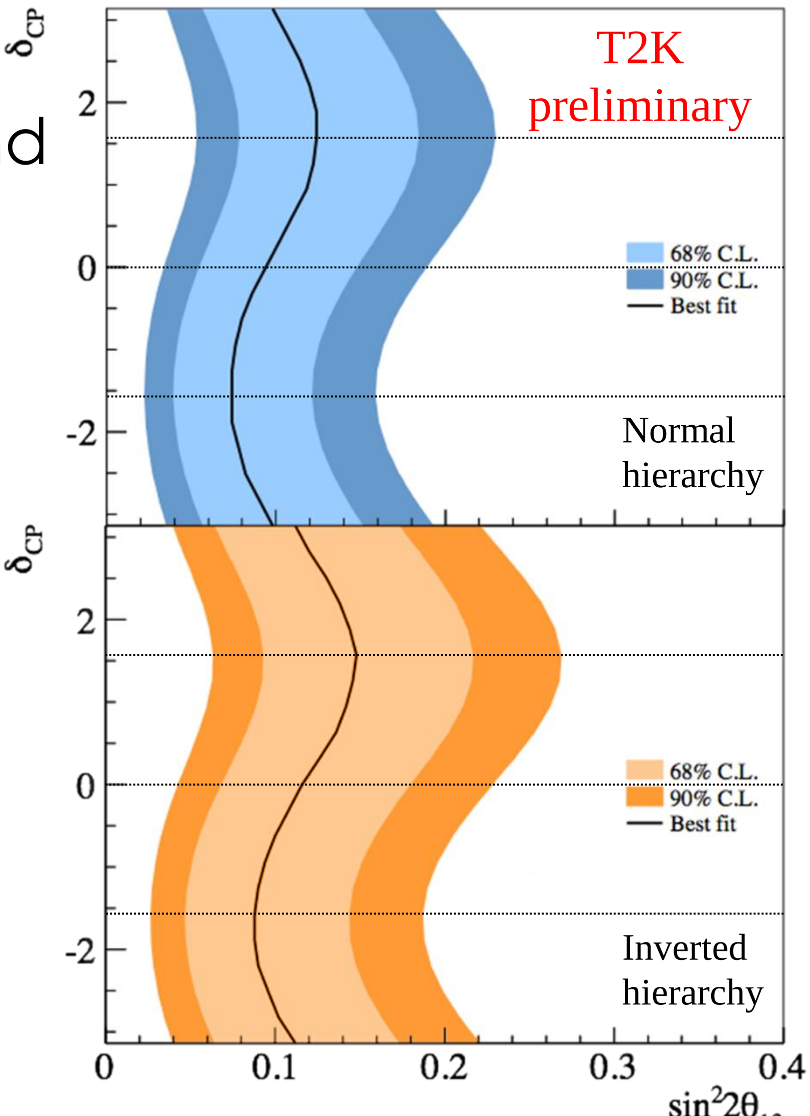
Sensitivity to unknown parameters



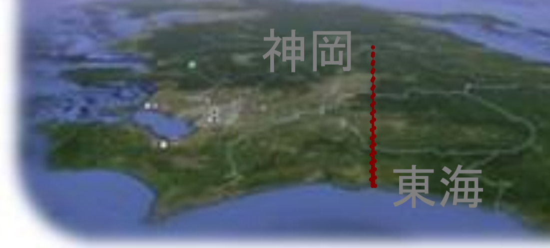
Leave $|\Delta m^2_{32}|$ and θ_{23} fixed, but allow the unknown CP phase and hierarchy to vary.

Plots show allowed regions of $\sin^2 2\theta_{13}$ for each value of CP phase and hierarchy.

(In principle data can already express a preference for a particular hierarchy & CP value, but this is so weak as to be unimportant.)



Results from MINOS*

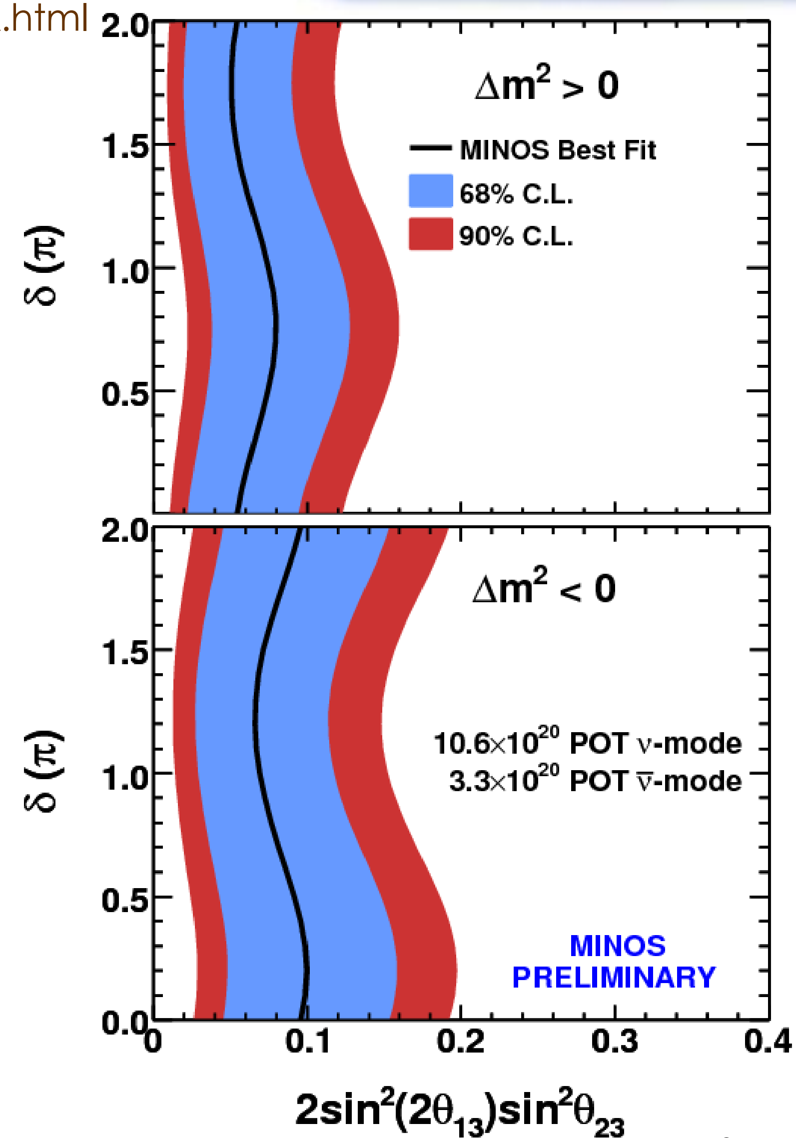


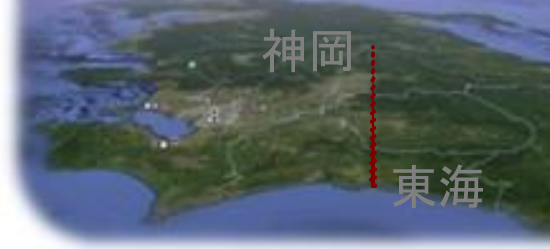
*http://www-numi.fnal.gov/pr_plots/index.html

T2K is not the only long baseline neutrino experiment to see ν_e appearance.

The MINOS experiment at Fermilab has compatible results.

- Different approach leads to different systematic errors.
- Best fit value is slightly lower, resulting in slightly weaker rejection of $\sin^2 2\theta_{13} = 0$
- MINOS data-taking finished 2012/04, *but T2K continues!*

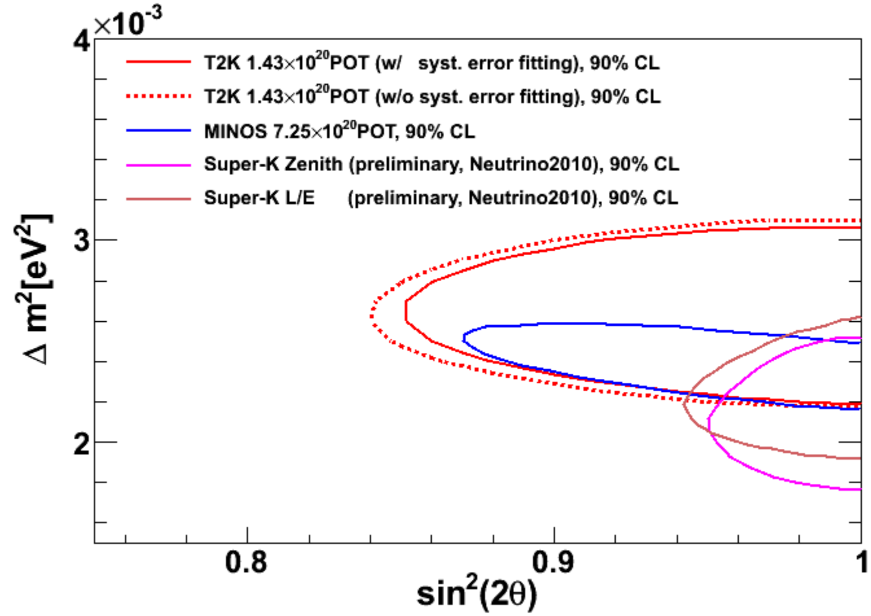


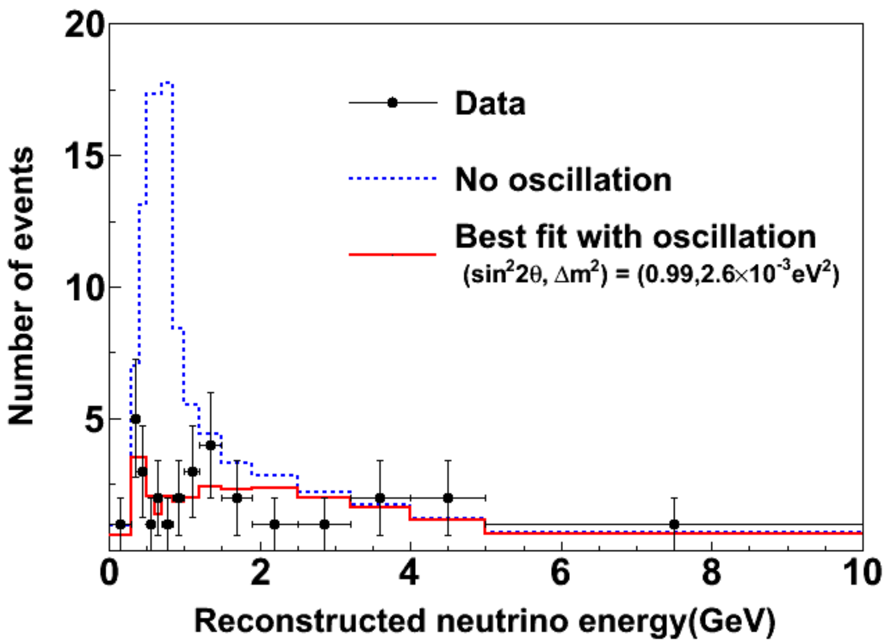


ν_μ disappearance analysis

Use quasi-elastic reaction kinematics to reconstruct neutrino energy.

$$E_\nu = \frac{m_N E_\ell - m_\ell^2/2}{m_N - E_\ell + \boldsymbol{p}_\ell \cdot \hat{\boldsymbol{p}}_\nu}$$





Already comparable to MINOS in $\sin^2 2\theta_{23}$.
This is run 1 & 2 only (about half of data taken so far). Goal is to increase by an order of magnitude.

Summary

T2K is progressing well

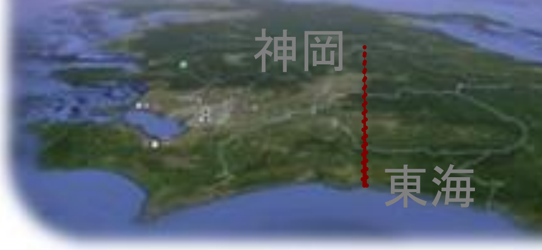
- Earthquake set us back, but still competitive, and now running fine.
  - Data taking in Run 4 (2012~13) started last month.
- Only direct evidence for ν_e appearance at atmospheric scale: **Reject $U_{e3} = 0$ at 3.2σ**
- Will soon have world-leading measurements in disappearance channel ($|\Delta m^2_{\mathrm{atm}}|$, θ_{23})

Future analyses can look into δ_{CP} and $\mathrm{sign}\left[\Delta m^2_{atm}\right]$

Many other analyses not covered here:

- Lorentz violation
- Sterile neutrinos and new mass splittings.
- Neutrino-nucleon cross sections

Notes



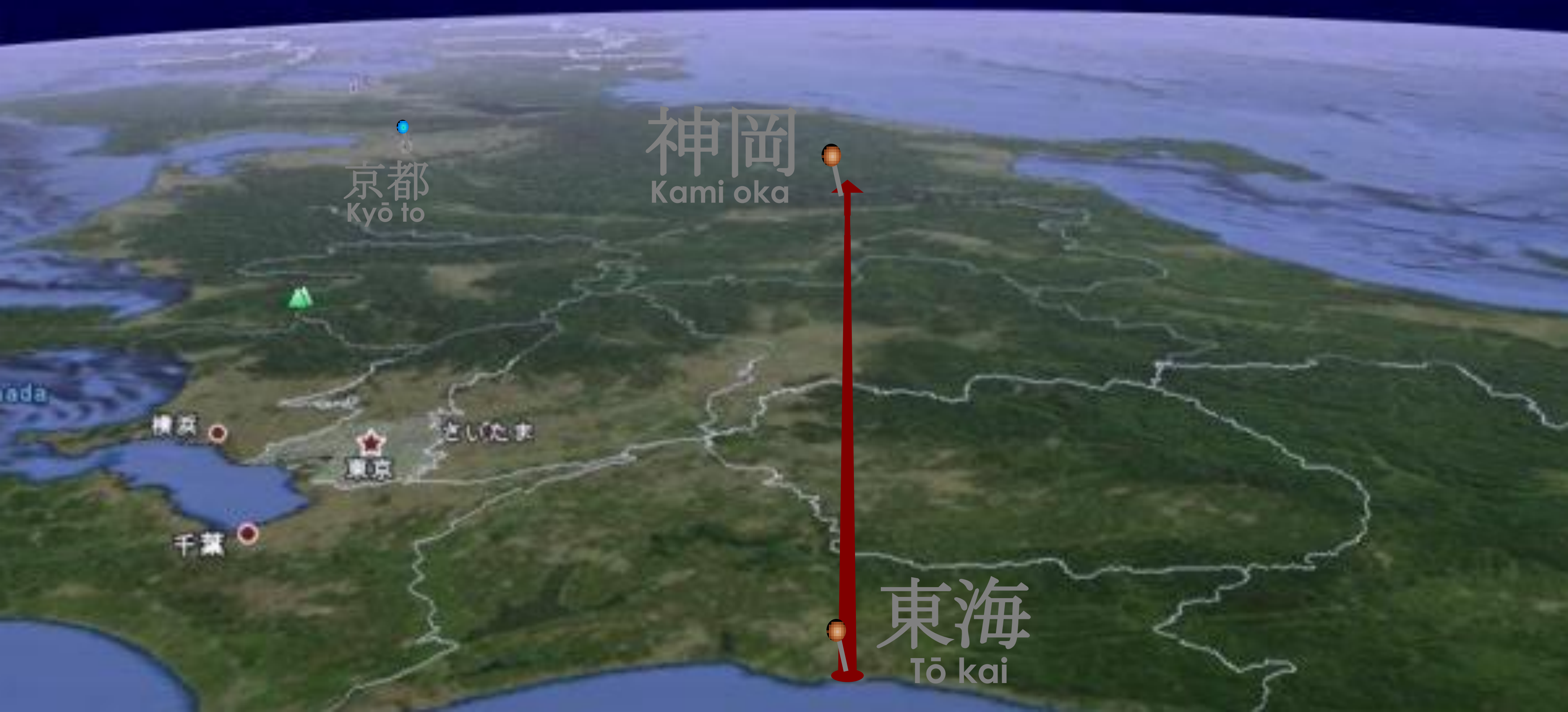
- Preliminary T2K ν_e results, first shown at ICHEP 2012:
  http://indico.cern.ch/contributionDisplay.py?contribId=242&sessionId=68&confId=181298

- Published results based on pre-earthquake data:
  http://arxiv.org/abs/1106.2822

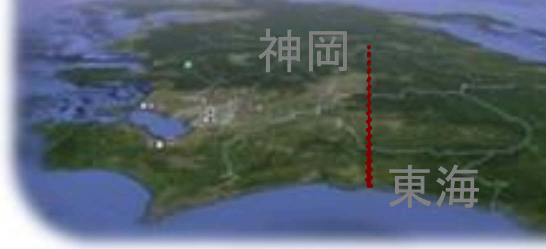
- ν_μ disappearance analysis:
  http://arxiv.org/abs/1201.1386

- Public web page
  http://t2k-experiment.org/for-physicists/

Reserve slides



The T2K collaboration



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Spain
IFIC, Valencia
U. A. Barcelona

Switzerland
ETH Zurich
U. Bern
U. Geneva

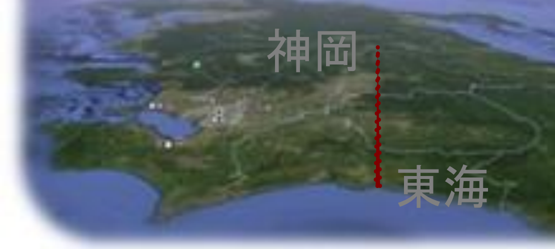
UK
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

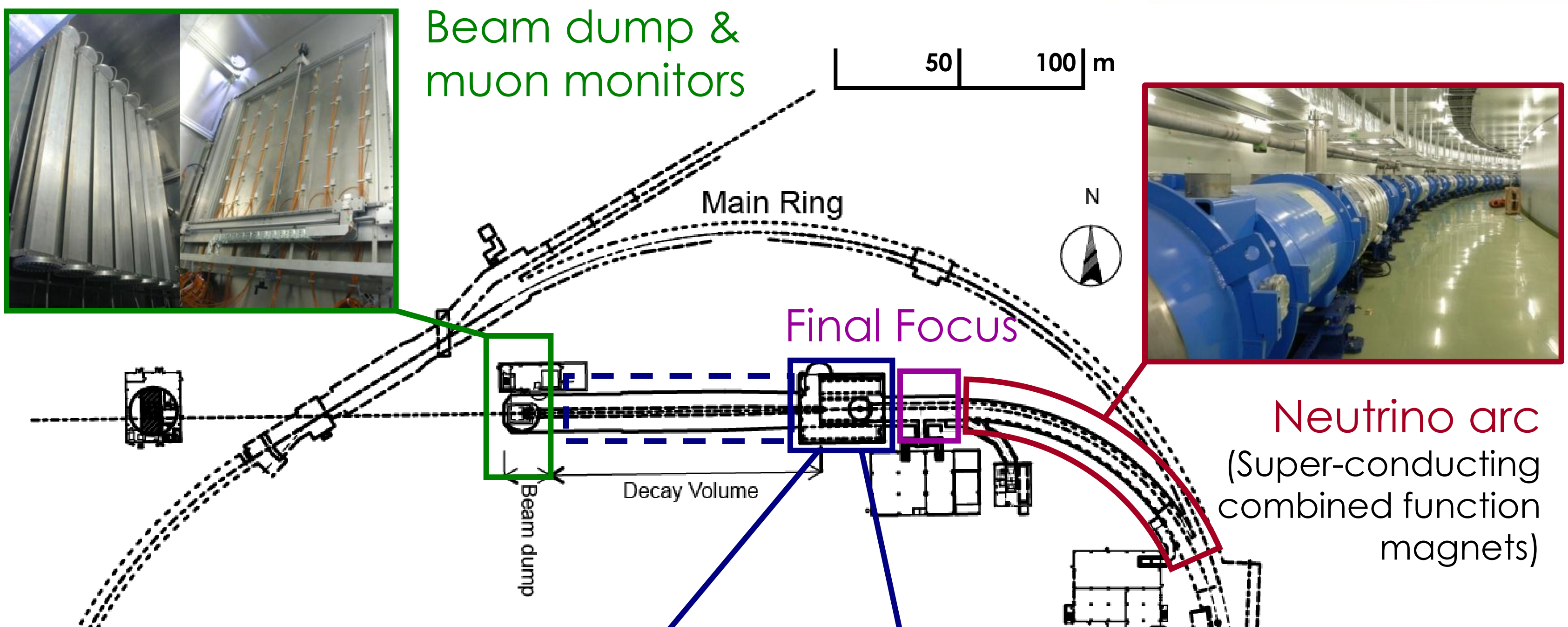
USA
Boston U.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Total:
~500 members
57 institutes
12 countries

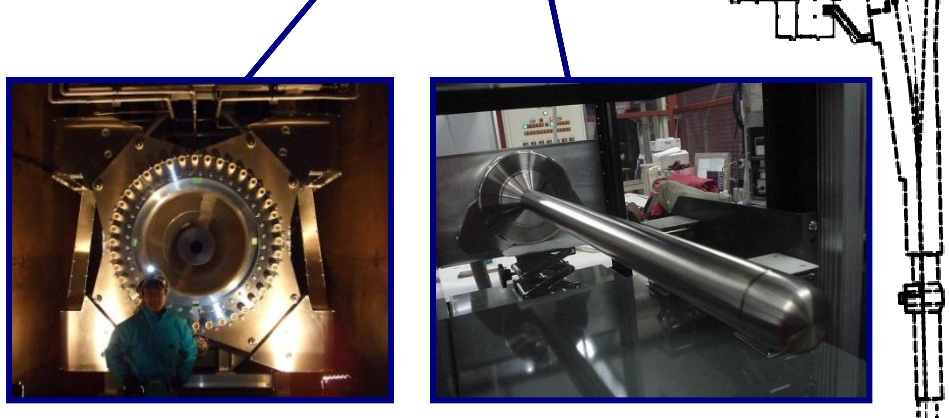
J-PARC facility (KEK/JAEA)

Neutrino beamline



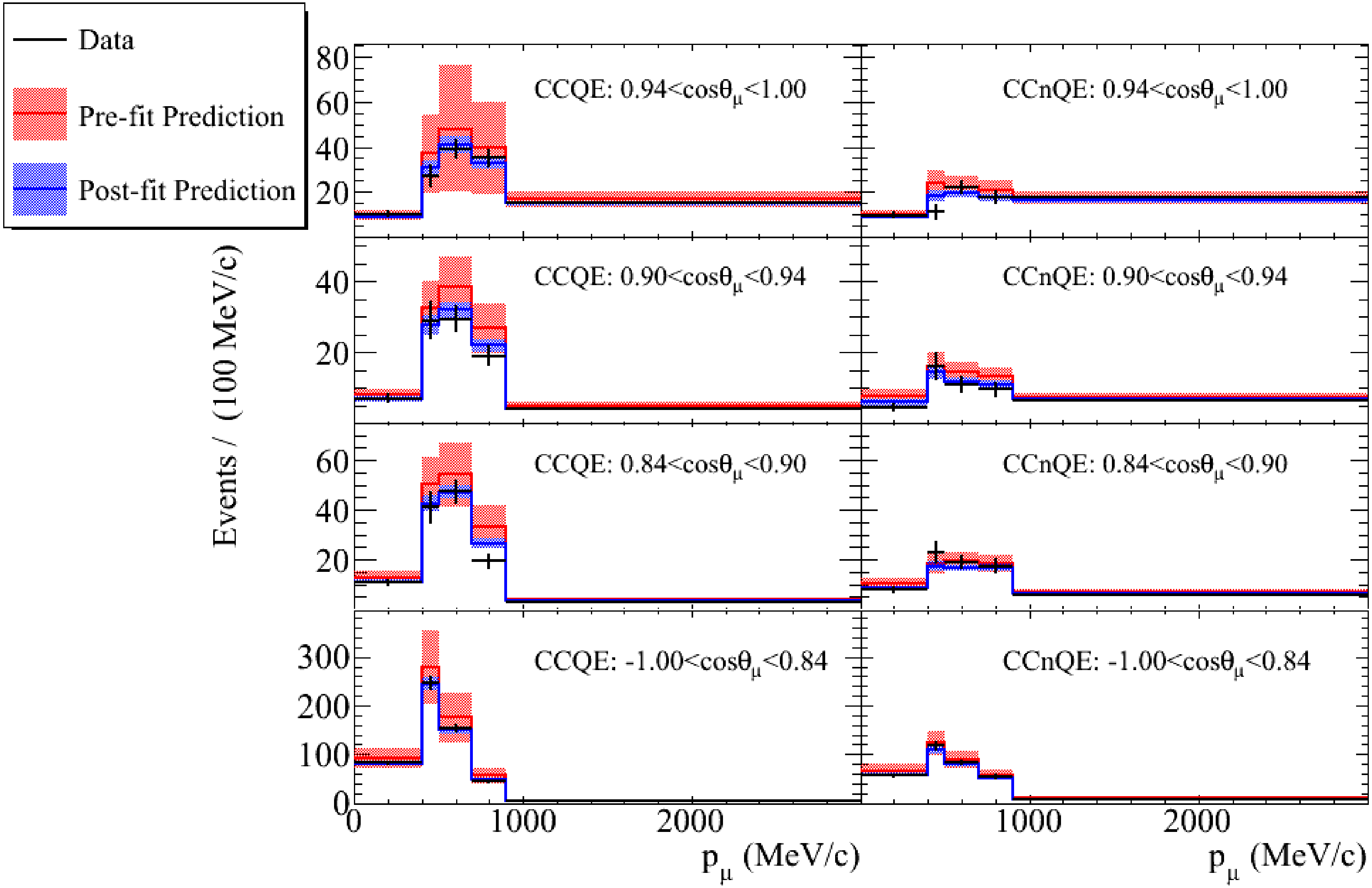


- 8 bunch fast extraction
- ϕ2.6 × 90 cm Helium-cooled graphite target
- Horns at 250 (320)kA

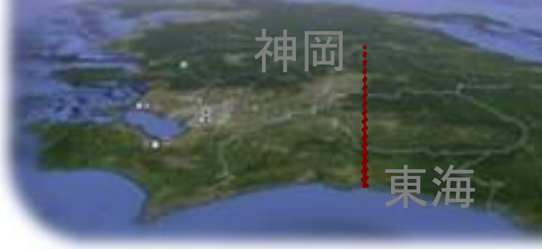


Target and horns(3), decay volume (110m)

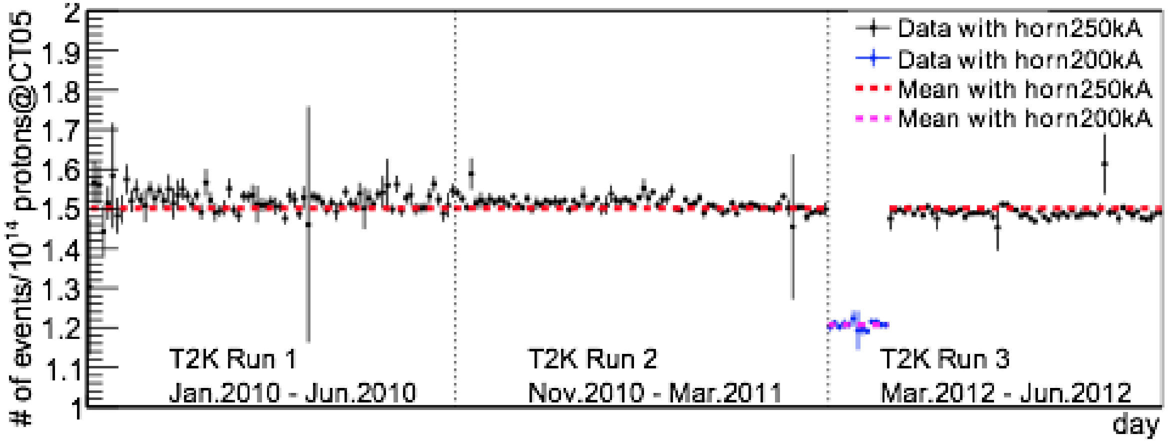
ND280 ν_μ fit, showing non-QE



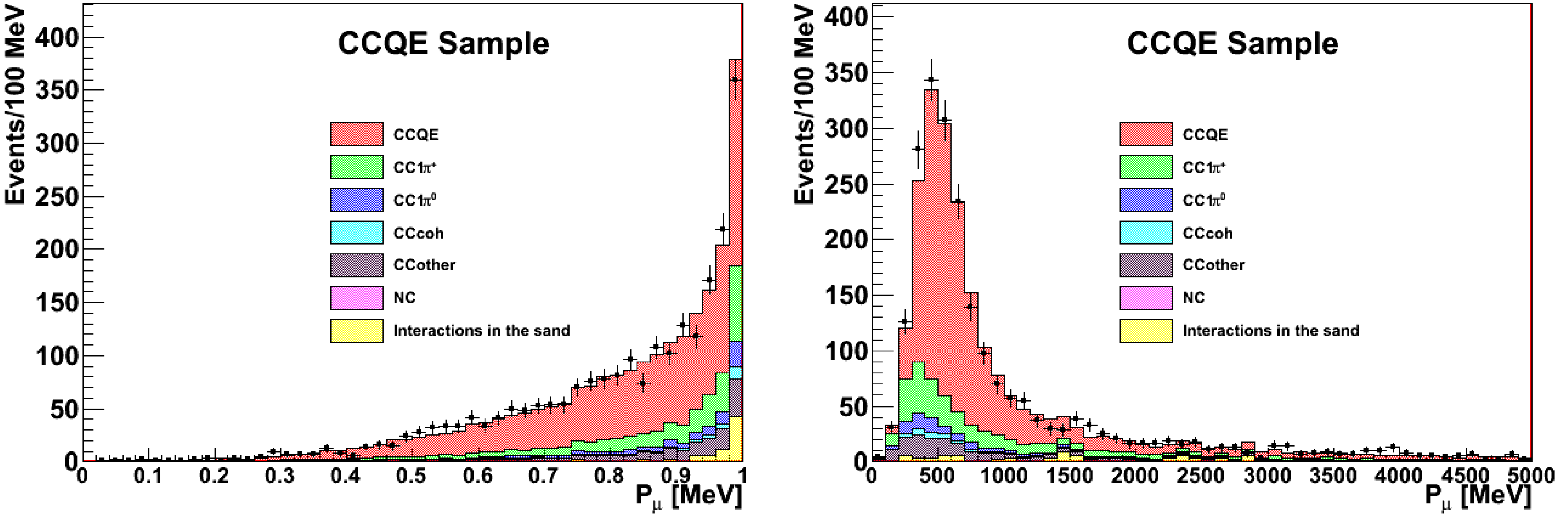
Results from ND280



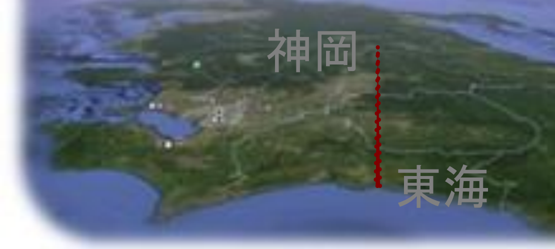
► INGRID results show beam continues to be stable.

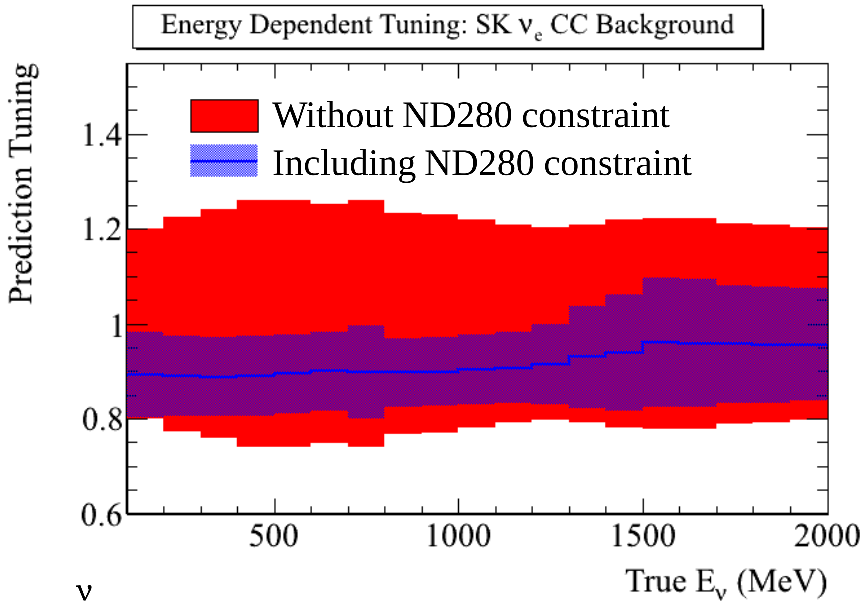


▼ Off axis detector CC-QE selected distributions, after fitting.

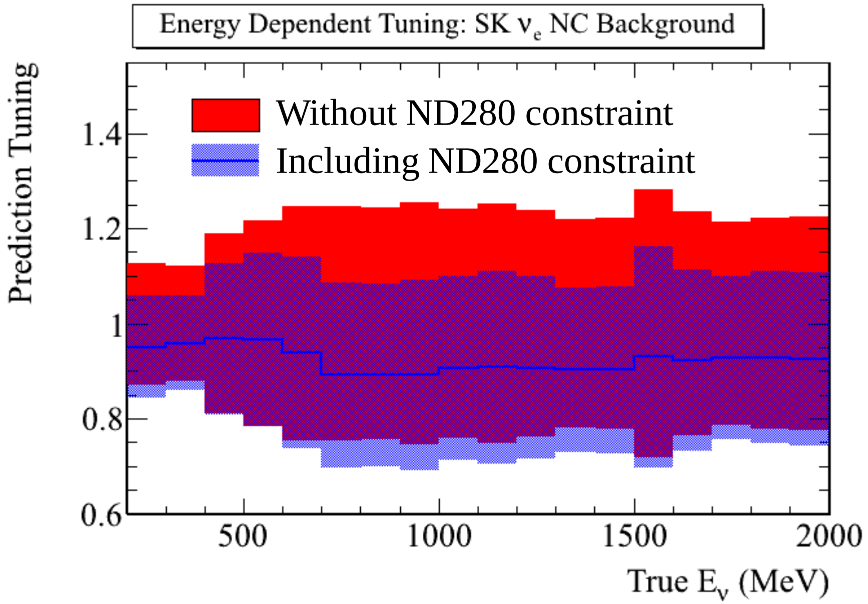


T2K background constraints at SK

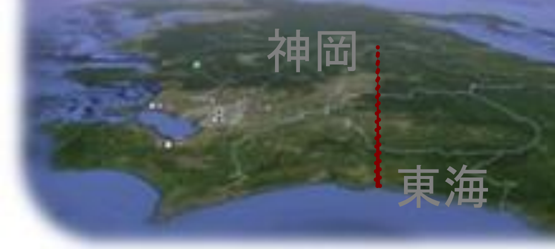




ν



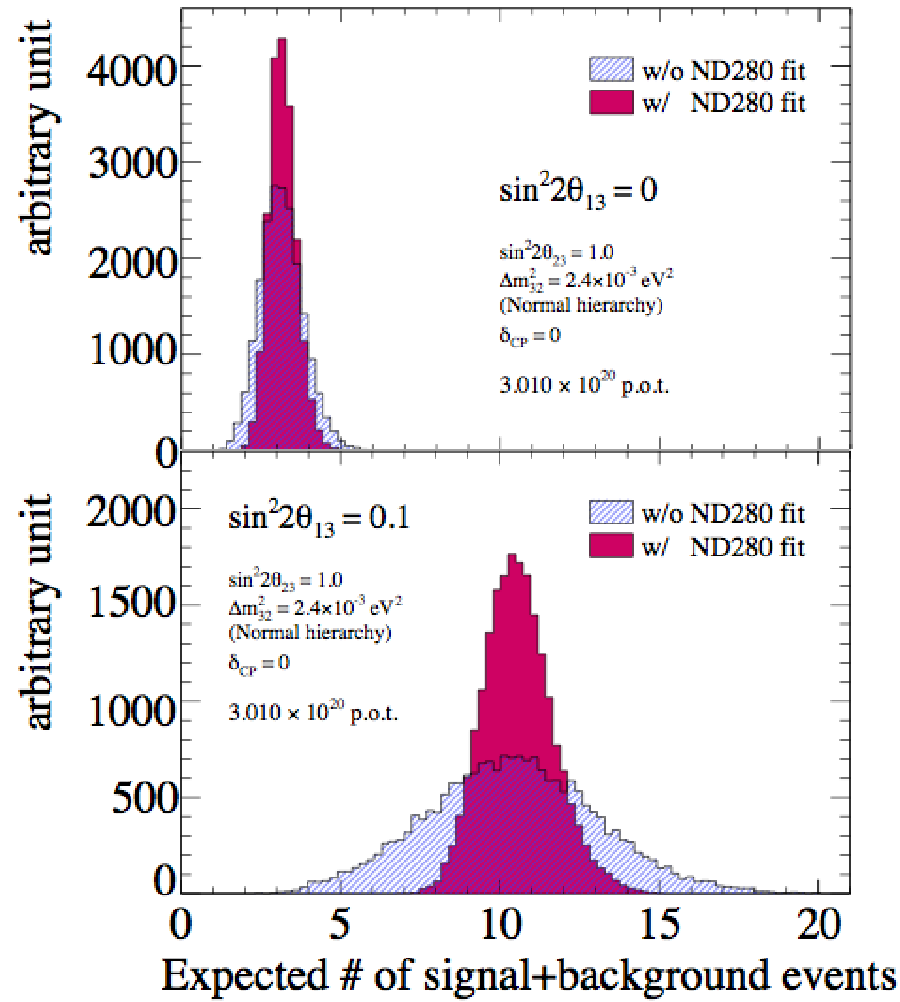
ND280 fitting constrains predictions of SK event rate



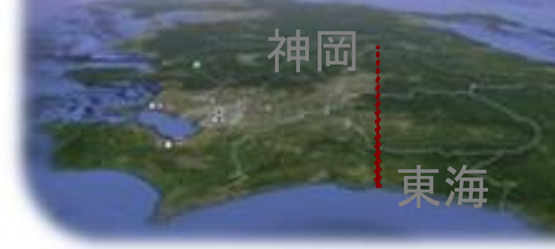
Plots show the effect of the ND280 fitting on the PDF for the *expected* number of events at SK.

This is the prediction uncertainty. It does not represent the (Poisson) statistical fluctuations.

ND280 fitting significantly reduces this uncertainty, particularly for signal.

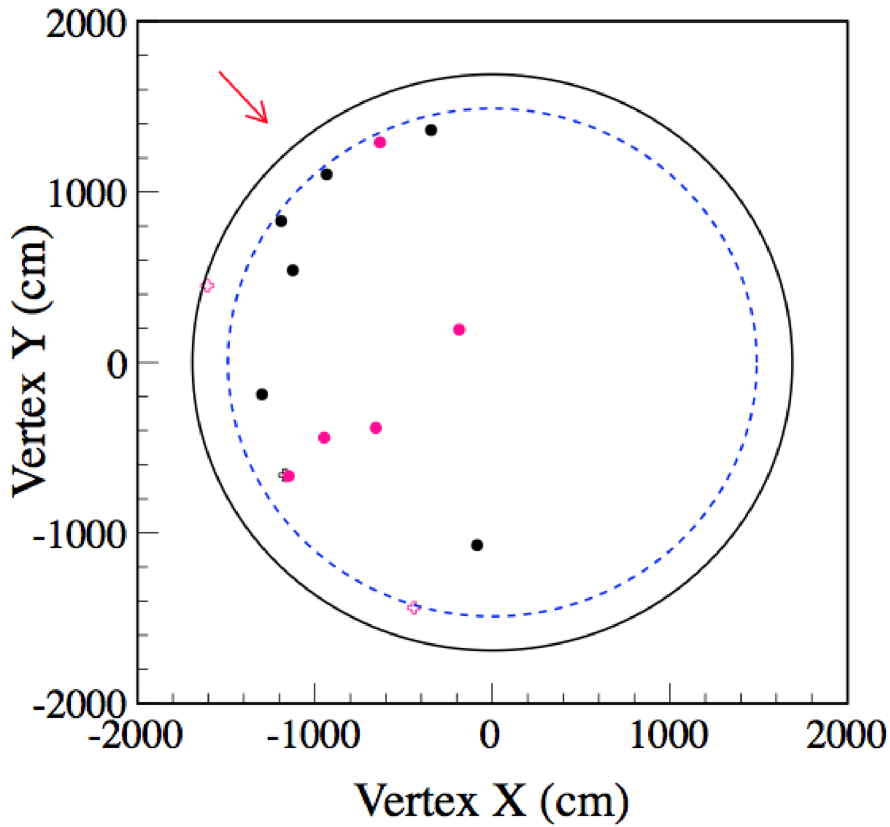


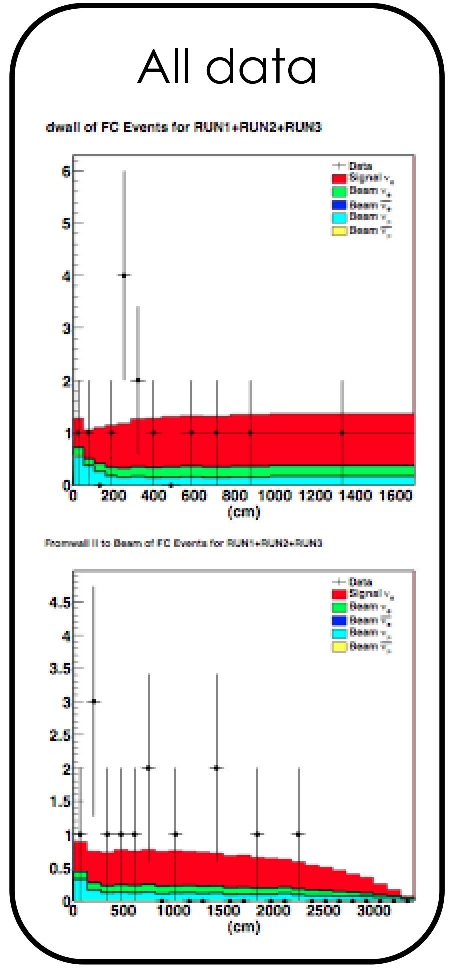
T2K selection of ν_e at SK

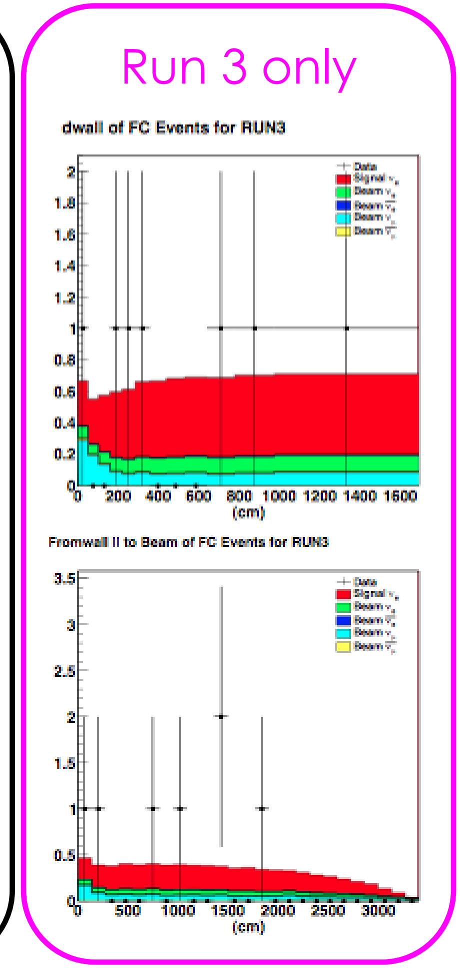


RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13} = 0.1$				
		Signal $\nu_e + \bar{\nu}_e$	BG total	$\nu_\mu + \bar{\nu}_\mu$ CC	Intrinsic $\nu_e + \bar{\nu}_e$	NC
FC FV & in time	174	12.35	165.47	117.33	7.67	40.48
Single ring	88	10.39	82.78	66.41	4.82	11.55
e like	22	10.27	15.60	2.72	4.79	8.10
E_{vis} > 100 MeV	21	10.04	13.53	1.76	4.75	7.01
No decay e	16	8.63	10.09	0.33	3.76	6.00
2γ invariant mass	11	8.05	4.32	0.09	2.60	1.64
E^{reco} < 1250 MeV [$\sin^2 2\theta_{13} = 0$]	11	7.81 [0.18]	2.92 [3.04]	0.06 [0.06]	1.61 [1.73]	1.25 [1.25]
Fraction selected		60.7%	1.0%	0.0%	20.0%	0.9%

Vertex distributions (are fine)







- Test statistics for Run 3 are completely normal.
- Combined data set is reverting to mean.