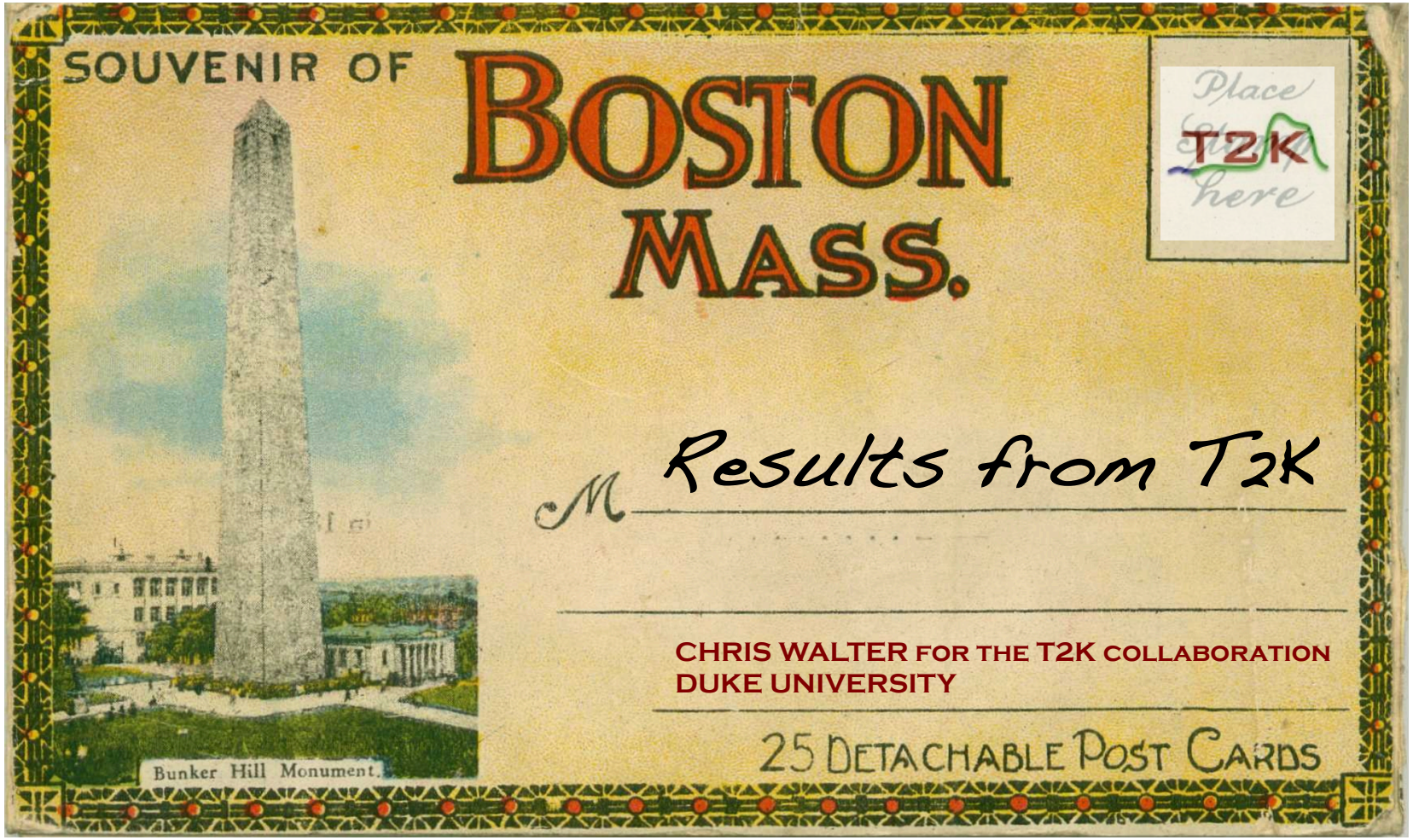


Neutrino 2014
Boston, MA, USA
June 2014

The T2K Experiment

~500 Collaborators / 340 Authors / 59 Institutions / 11 Countries

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

Many T2K Posters you should look at!

#190 Measurement of the nu_e component and plans to measure the nue-bar component in the T2K beam with the ND280 Tracker (L. Southwell)

#186 Electron neutrino cross-section on carbon using the T2K near detector (B. Smith)

#187 A first search for sterile neutrinos with the T2K near detector (J. Caravaca and D. Sgalaberna)

#210 Measurement Of Neutral Current Single pi^0 Production Of Neutrino Interaction On Water Using The T2K Pi-zero Detector (K. Gilje)

#188 Towards Measuring the NuMu Charged Current Quasielastic Cross Section on Water using T2K's Near Detector (T. Yuan)

#341 "The observation of gamma rays after neutral current interactions at Super-Kamiokande by using the T2K neutrino beam" (K. Huang)

#250 "Joint Analysis of nu_mu disappearance and nu_e appearance using MCMC" (A. Kaboth)

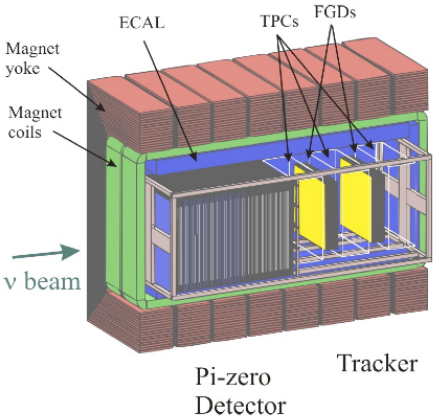
#160 **"**Joint Appearance and Disappearance Analysis for the T2K Long-Baseline Neutrino Experiment" (M. Friend, T. Kikawa, and M. Ikeda)

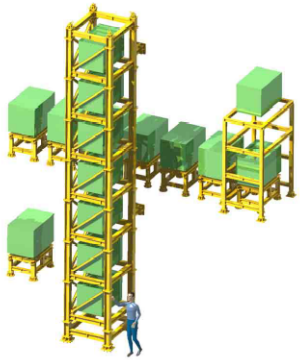
#322 "Upper bound on neutrino mass with T2K" (T. Kutter, O. Perevozchikov)

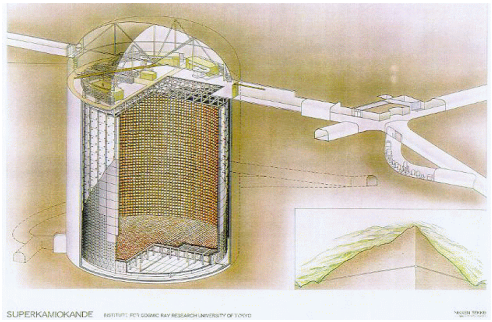
#068 "Measurement of Muon Neutrino Disappearance at T2K" (T. Wongjirad)

The T2K Experiment Overview

Uses the **J-PARC accelerator** complex for the beam.

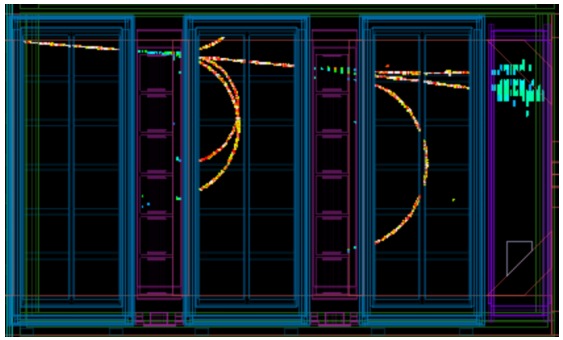






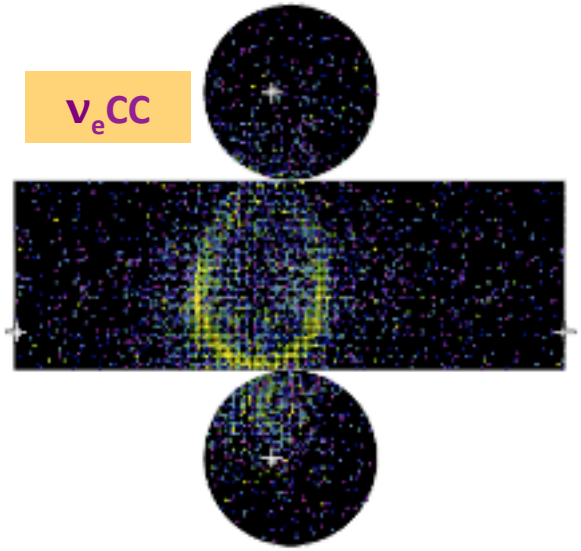
Far detector: Super-K at 295 km.

On and off-axis hybrid **near detectors** at 280m



Use information from hadron production experiment NA61

ν_eCC

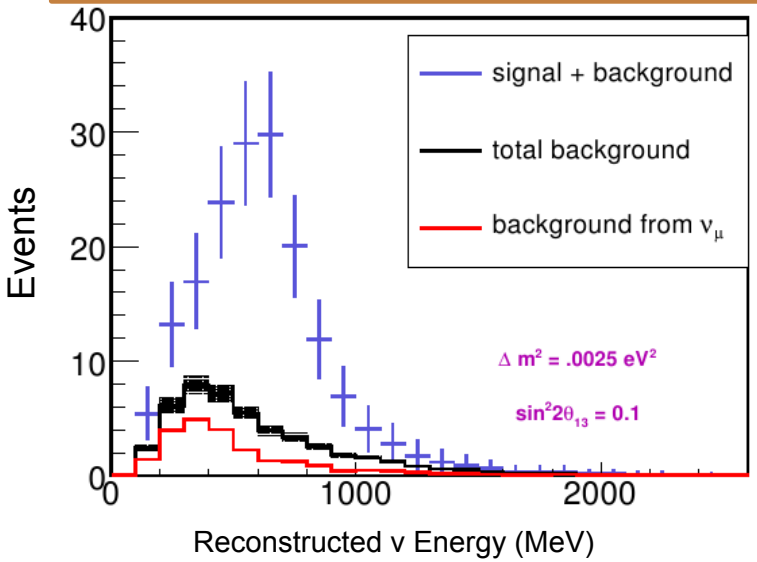


Oscillation searches at T2K

T2K is optimized for both appearance and disappearance searches.

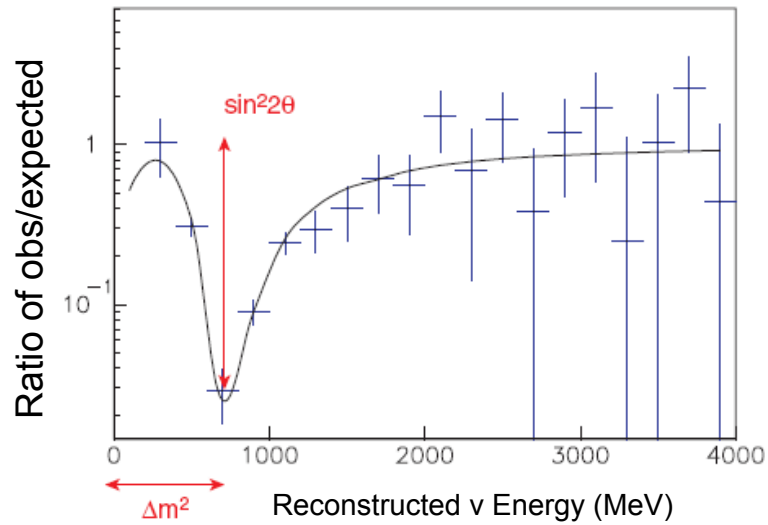
Appearance

ν_e appearance: determine θ_{13} constrain δ_{CP}



Disappearance:

ν_μ disappearance: determine θ_{23} and Δm^2_{32}



For maximum power fit both data samples **jointly**

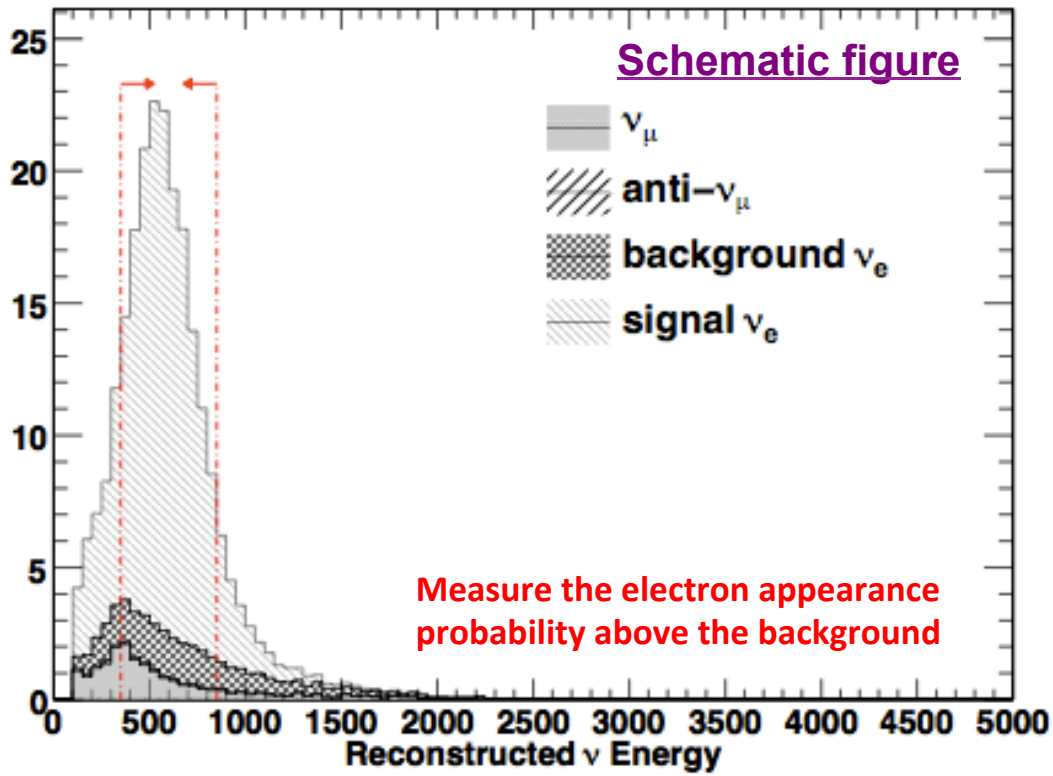
Measuring the ν_e appearance probability

(Octant is here)

$$P(\nu_\mu \to \nu_e) \cong \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\boxed{\sin\delta_{CP}}$$

(sinδ is here)

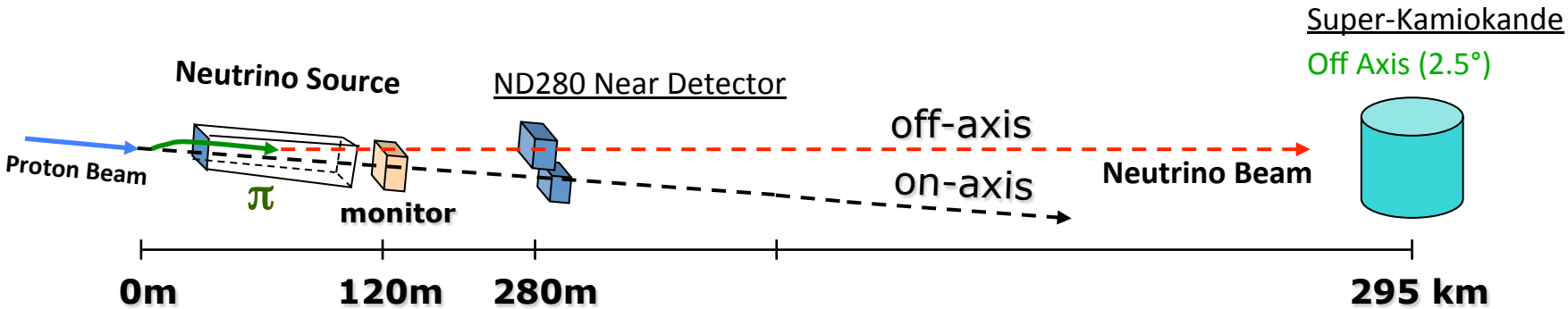
+ (CP even term, solar tem, matter effect term)

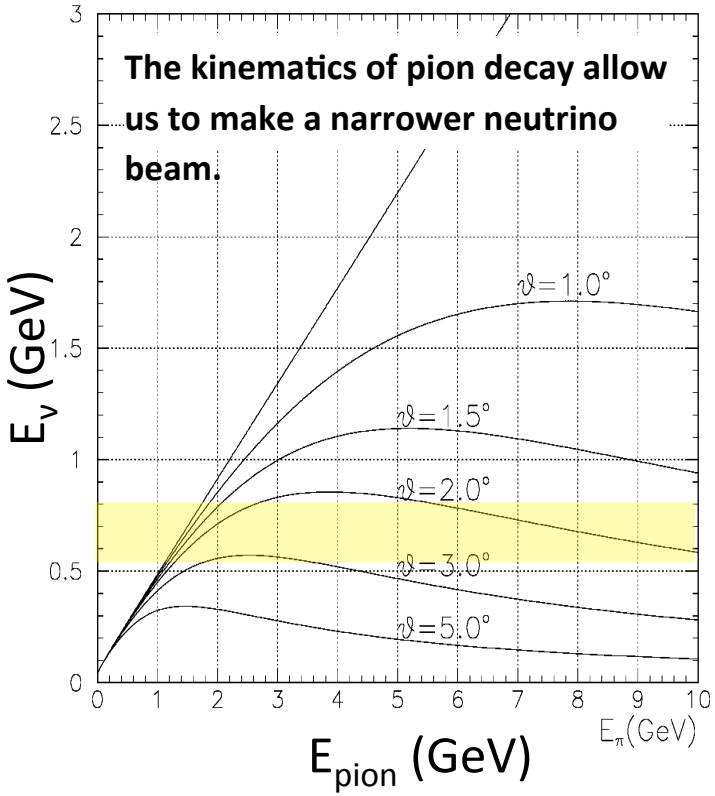


There is more than one parameter that controls the ν_e appearance!

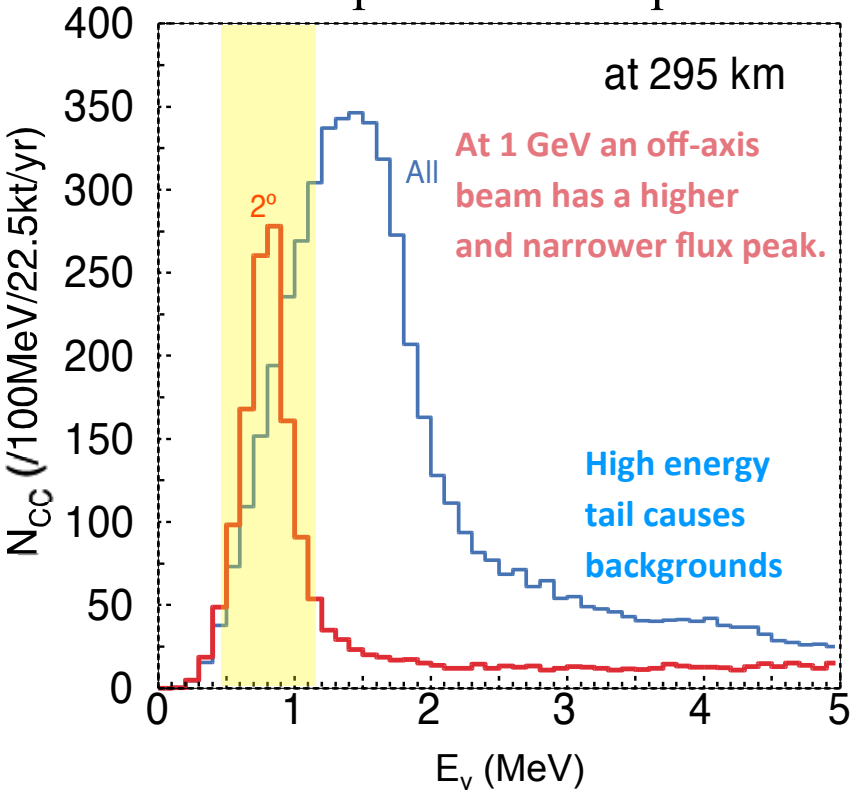
- We need a very high intensity beam and a large target.
- Make a pure neutrino beam and look for electrons to appear.

The T2K Off-Axis Beam

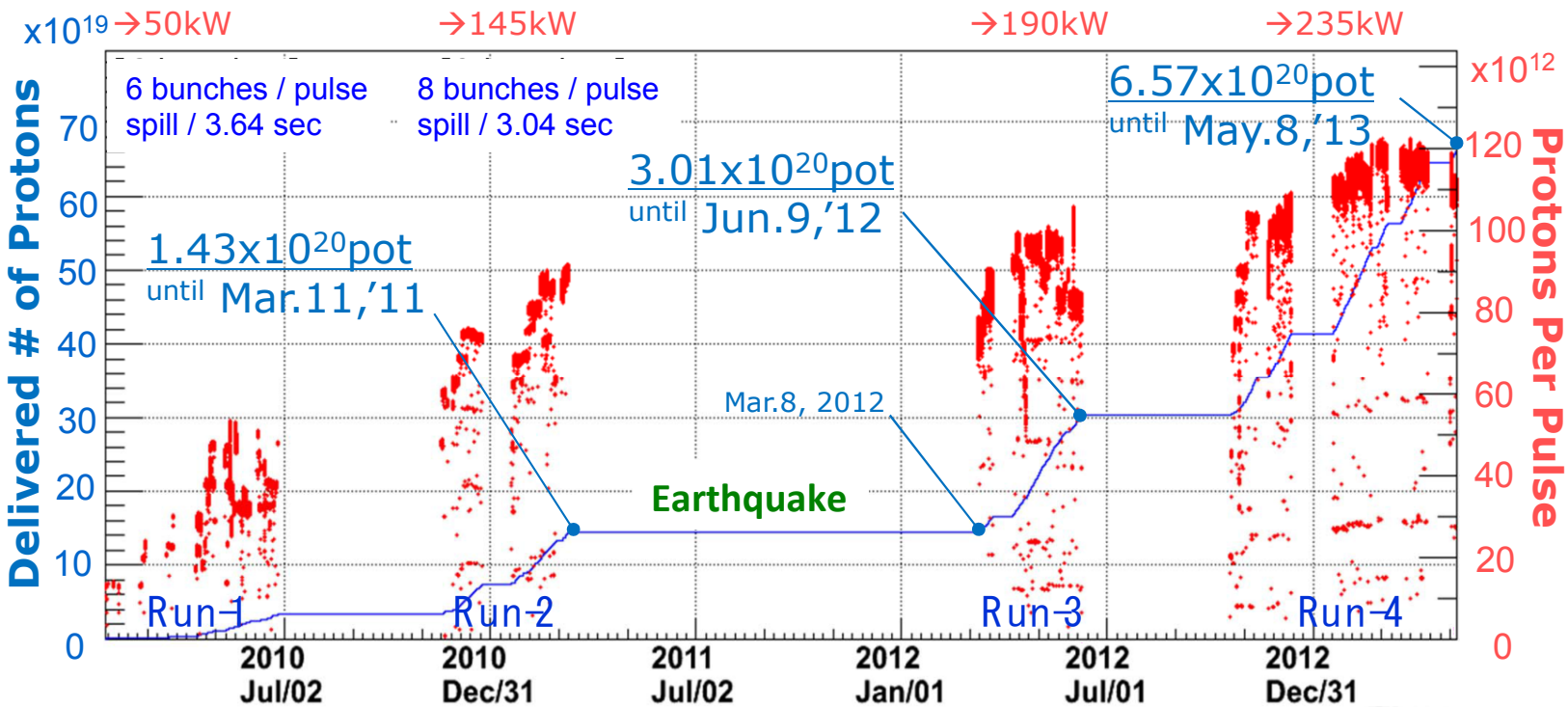




Example Off-axis Spectra



Analysis Data Set

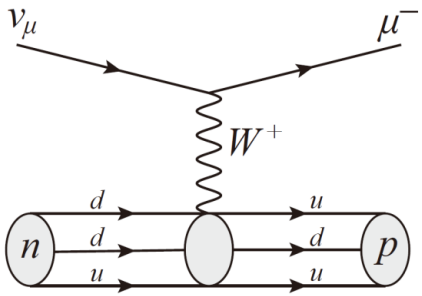


- Data sets contain 6.57 x 10^{20} POT
- Run 1 instantaneous power reached 50 kW
- ➔ Increased # bunches/pulse, protons/bunch, repetition rate
- Run 4 stable power reached **235 kW**

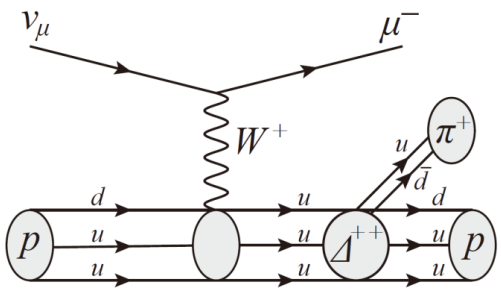
POT ~8% of final design goal

ND280 fit of p_μ-$\cos\theta_\mu$ distributions

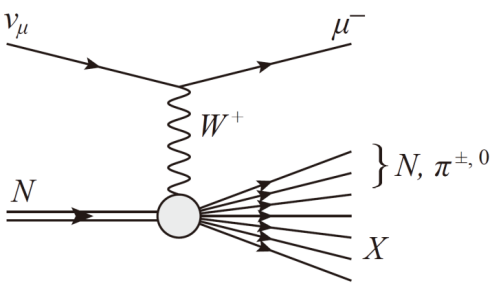
Fit topological samples which constrain flux and cross section



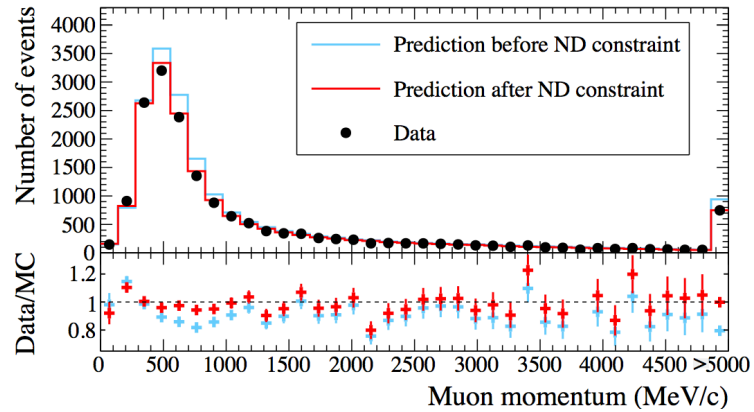
CCQE



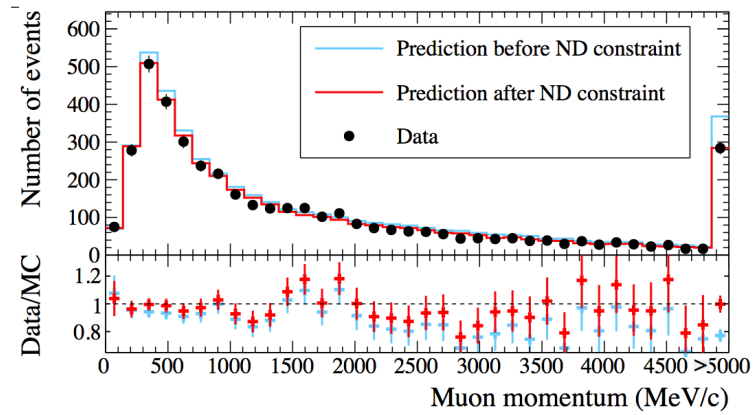
CC Resonance



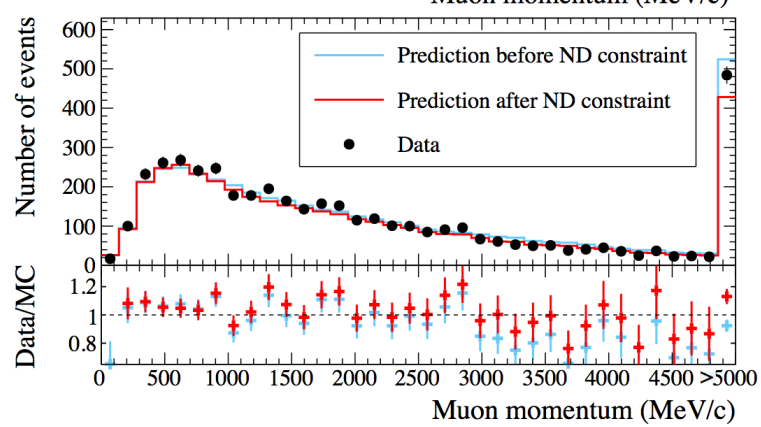
CC DIS



CC 0π
(63% CCQE purity)

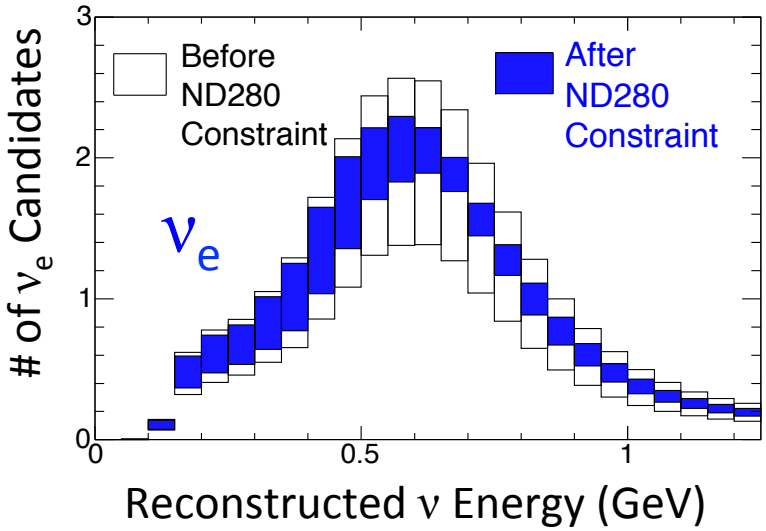


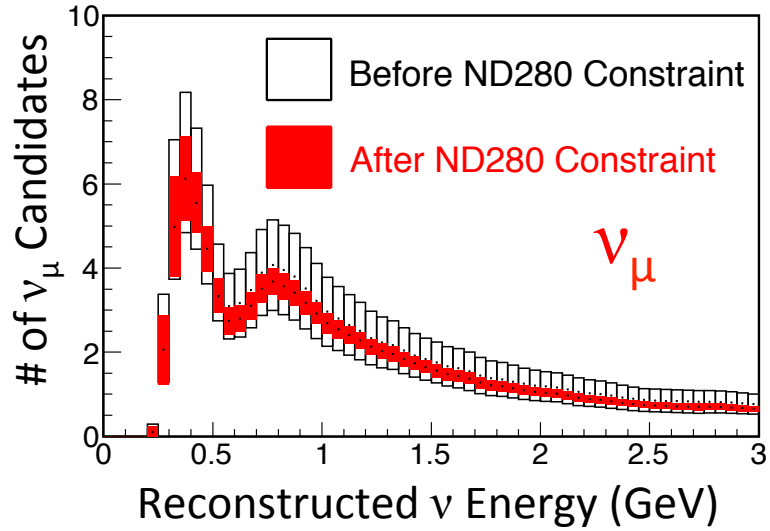
CC $1\pi^+$
(39% CCRES purity)



CC Other
(68% CCDIS purity)

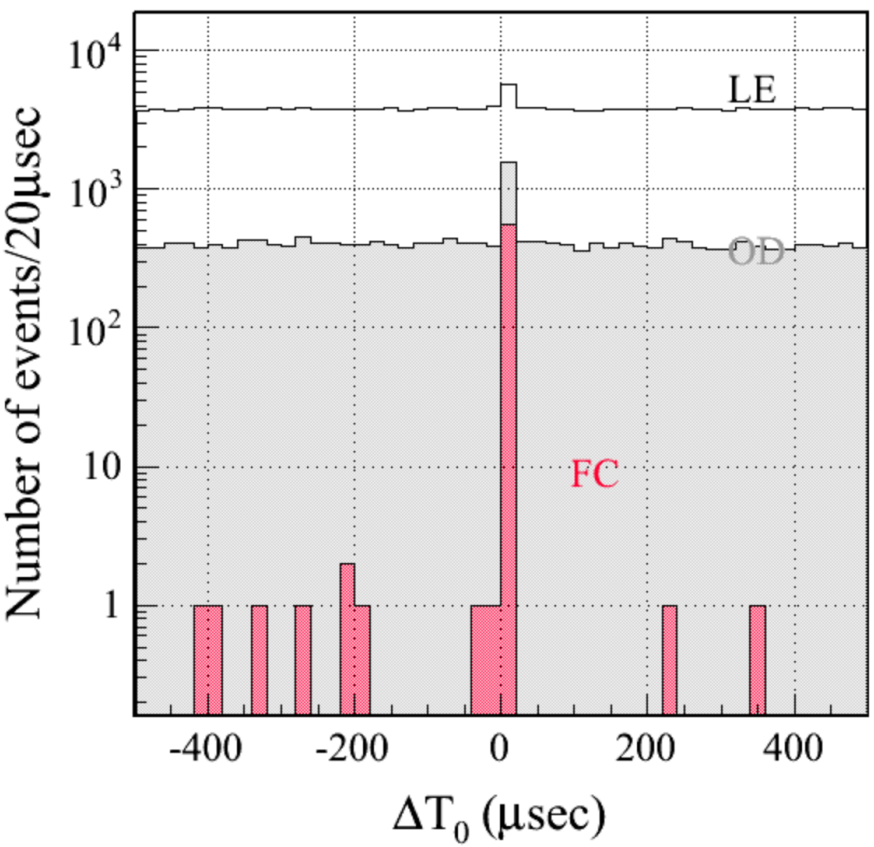
Resulting Systematic Errors

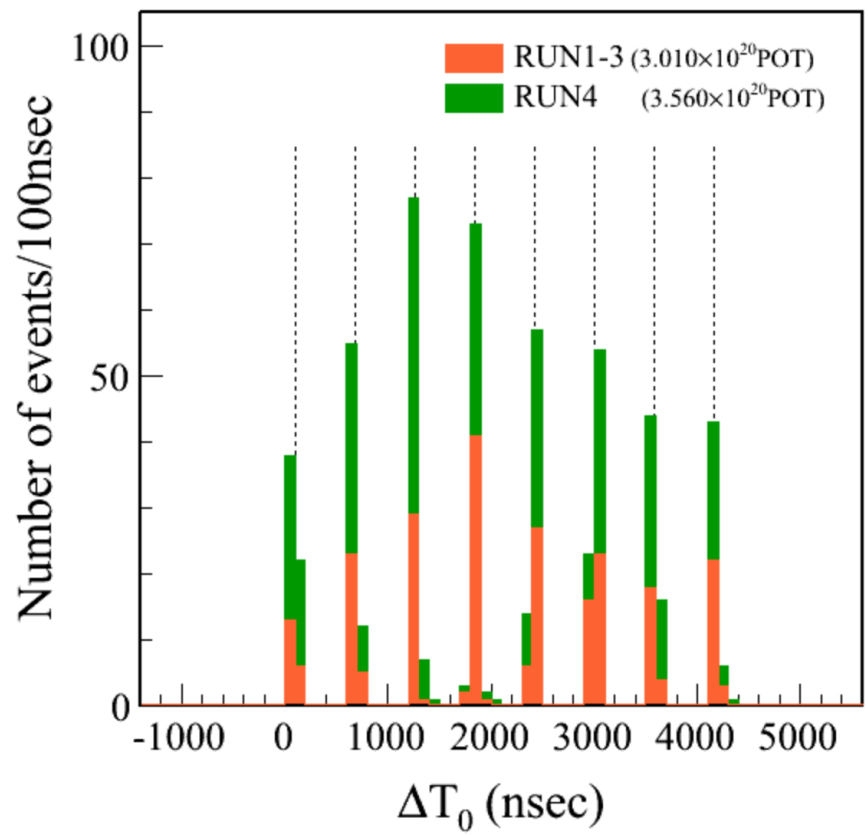




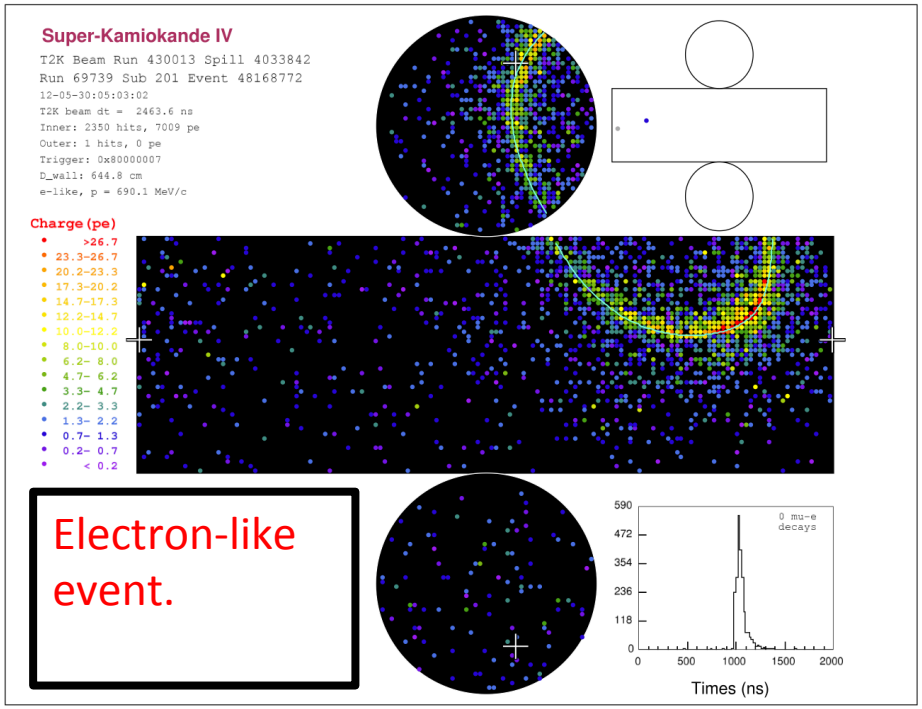
Systematic Source	Relative Uncertainty in # of ν_e Candidates (%)	Relative Uncertainty in # of ν_μ Candidates (%)
Flux + cross section (ND280 constrained)	3.1	2.7
Cross section (ND280-independent)	4.7	5.0
π Hadronic Interactions	2.3	3.5
SK Detector	2.9	3.6
Total	**6.8**	**7.6**

Far Detector Arrival Distributions

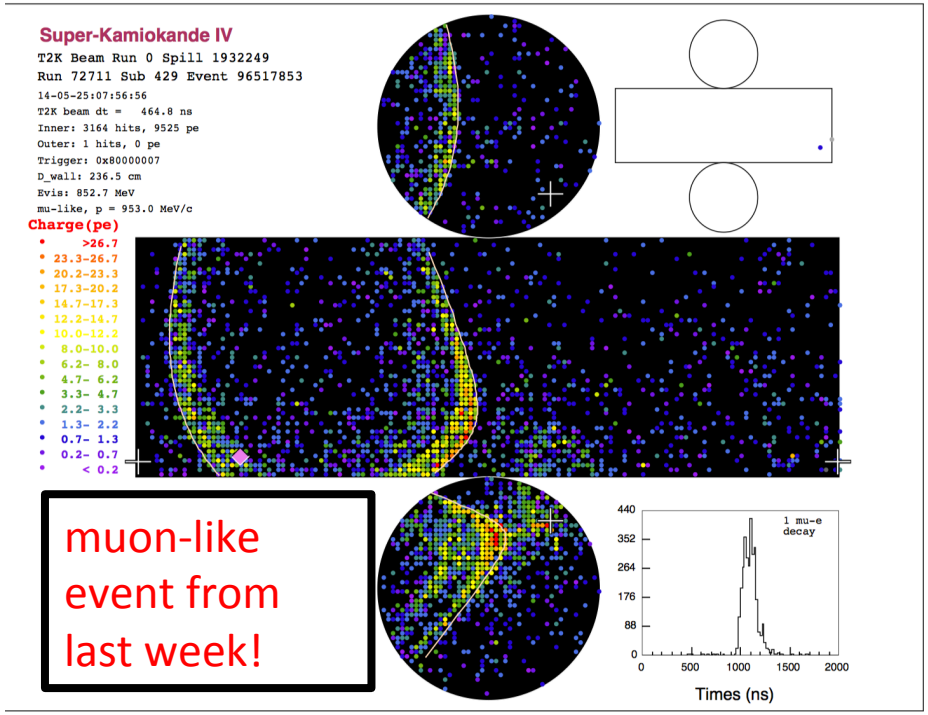




Examples of far detector events



Electron-like event.

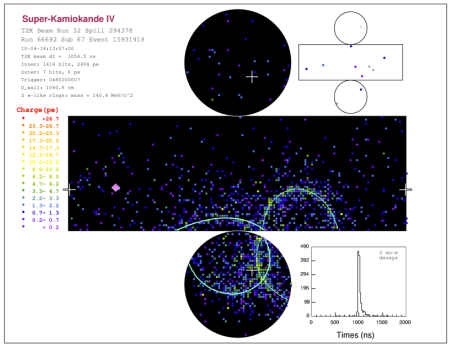


muon-like event from last week!

P_e = 690 MeV/c 0 decay-e

P_μ = 953 MeV/c 1 decay-e

<u>Super-K has excellent particle ID</u>
These events are split into three selected streams: ν_μ, ν_e and low energy events.



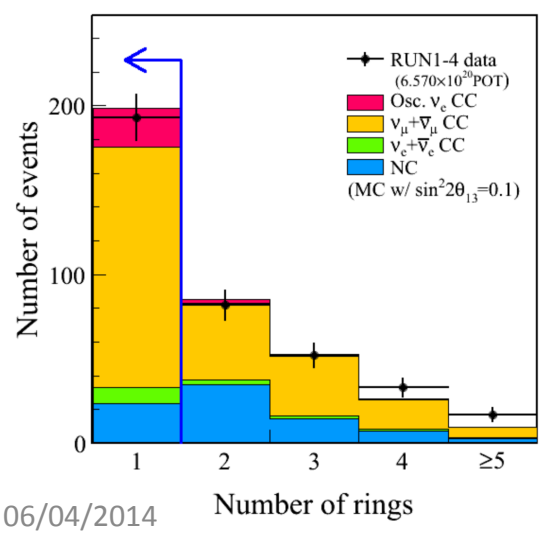
π^0 candidate.
M_{inv}=104 MeV/c^2

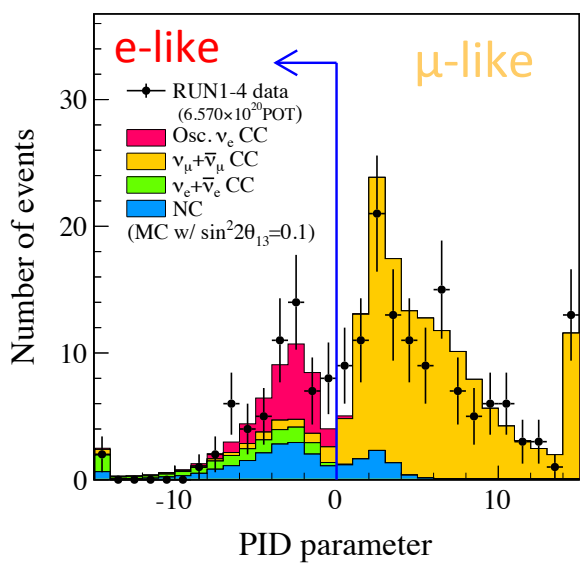
ν_e event selection

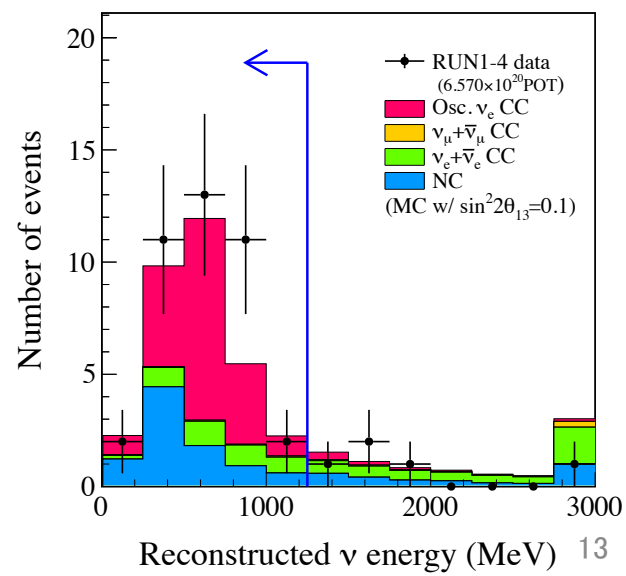
T2K has made improvements in background and error reduction.

- Fully-contained fiducial volume (FCFV) event
- Single-ring e-like event
- $E_{visible} > 100$ MeV
- # of decay electron = 0
- $0 < E_\nu^{rec} < 1250$ MeV
- π^0 cut

28 events
in 6.57×10^{20} POT

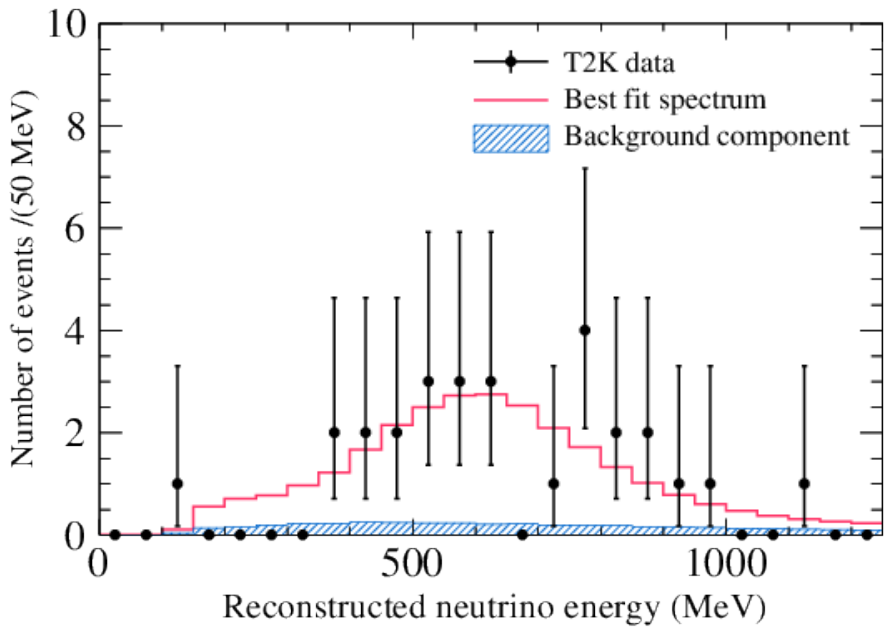


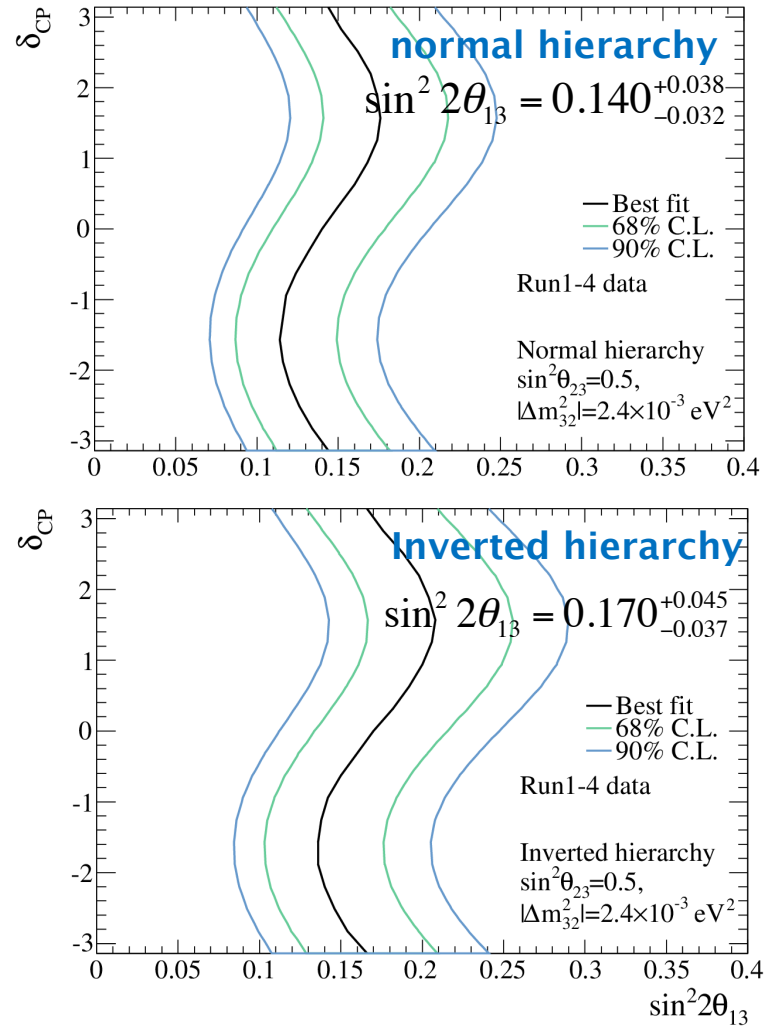




Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13} = 0.1$

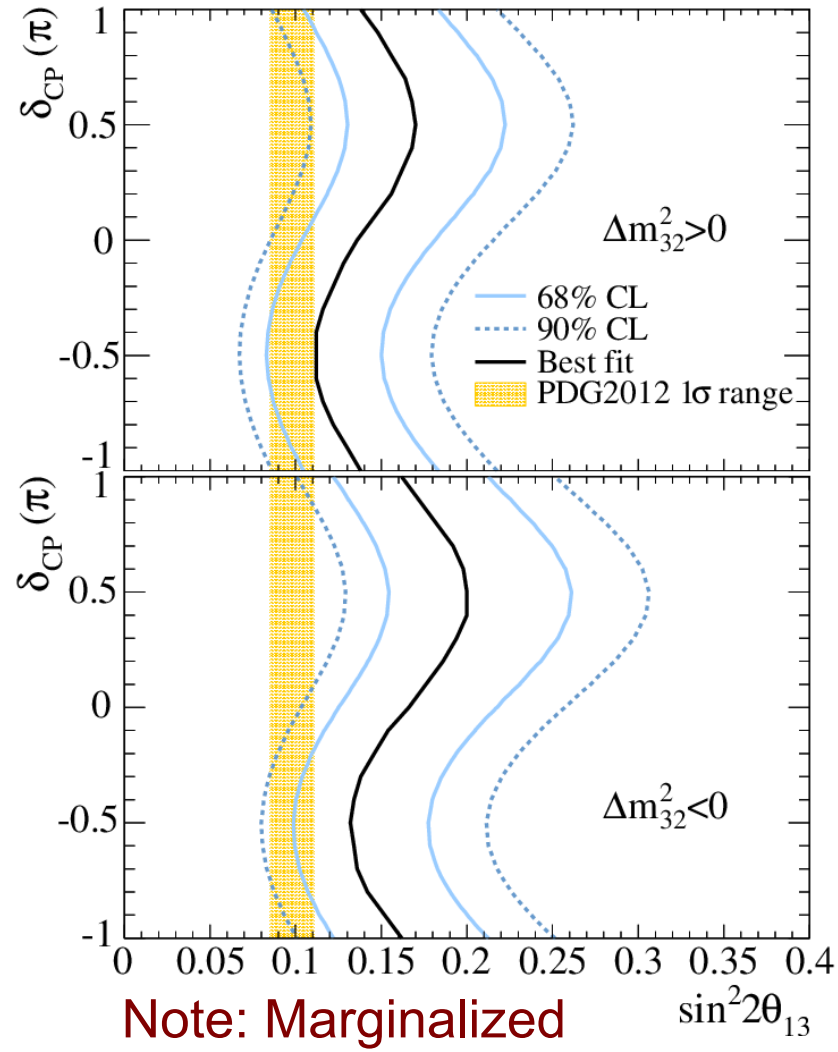
$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

7.3 σ significance for non-zero θ_{13}

<u>First ever observation (>5σ) of an explicit ν appearance channel</u>

Let's think about these regions!

- Comparing with the external reactor constraint the best overlap is for the normal hierarchy with $\delta_{cp}=-\pi/2$.
- This is a **lucky point**!
- You also need to increase the θ_{23} mixing angle to account for the number of observed events.



Note: Marginalized over θ_{23} and Δm^2_{32}

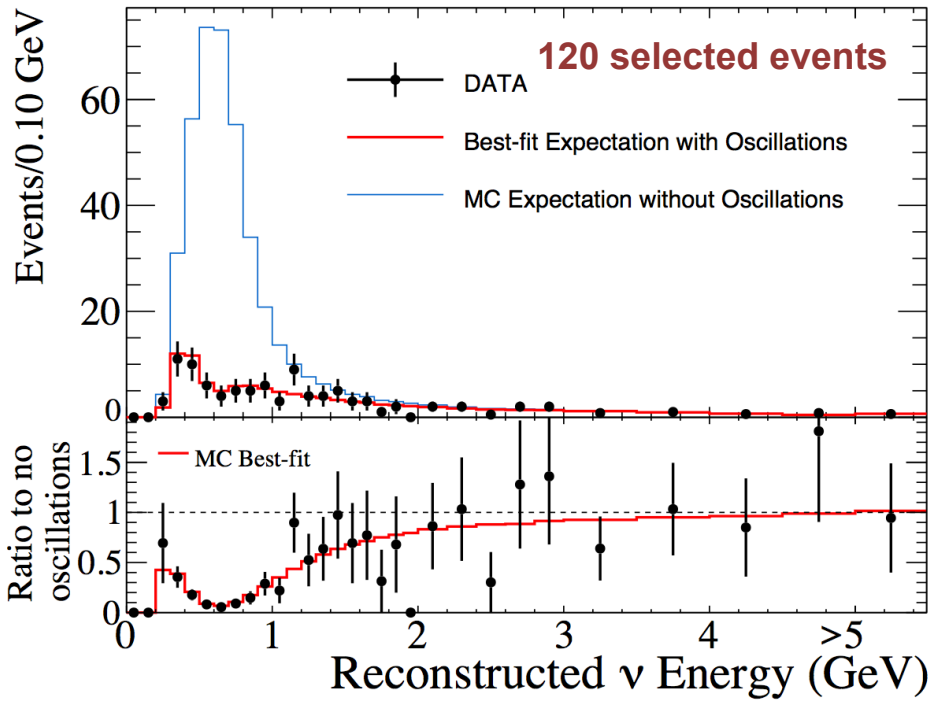
Phys. Rev. Lett. 112, 181801 (2014)

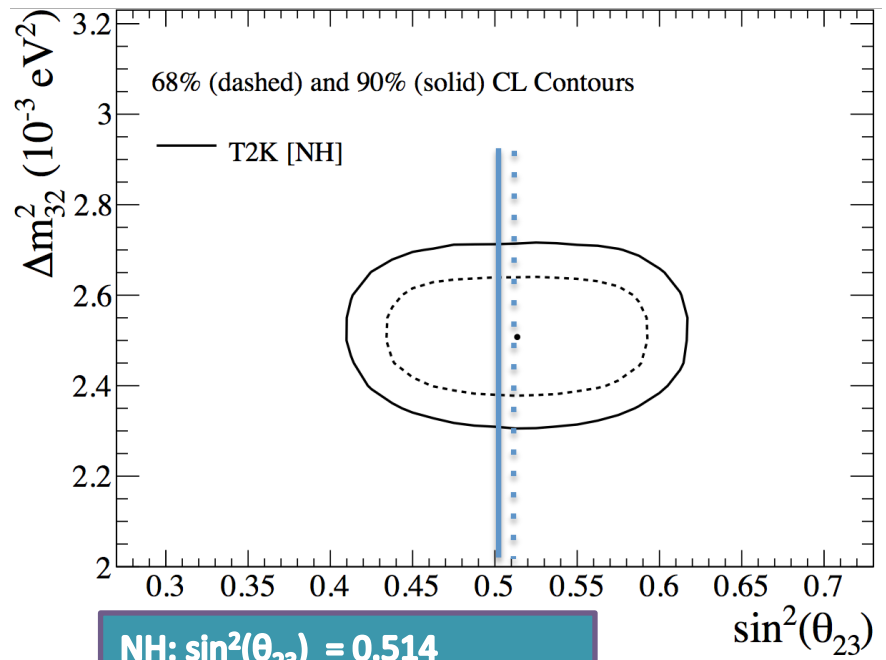
Poster #068!

T2K ν_μ Results

Maximal mixing is not the same as maximum disappearance if θ_{13} is not zero!

Shows the power of the off-axis technique!





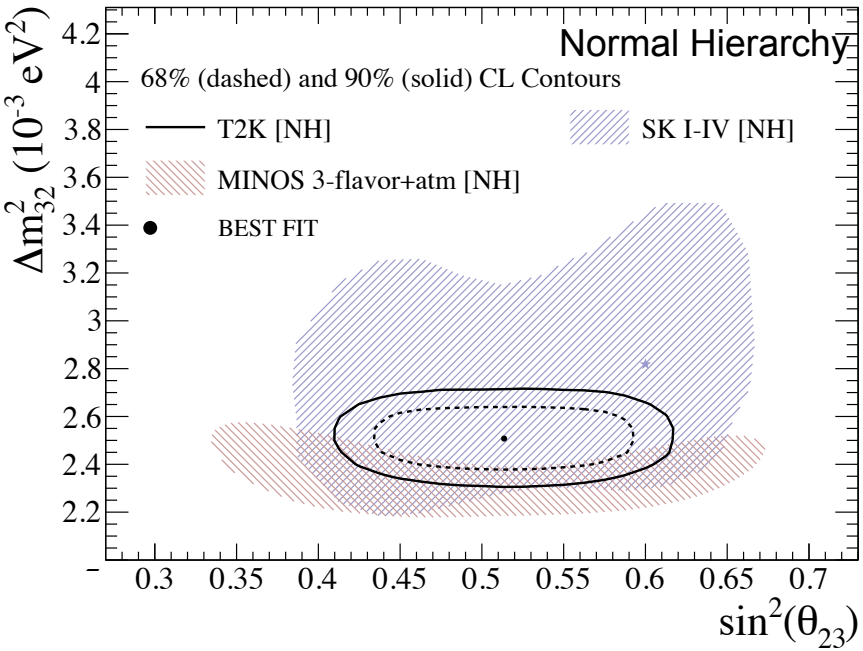
NH: $\sin^2(\theta_{23})$ = 0.514
NH: Δm^2_{32} = 2.51×10^{-3} eV^2

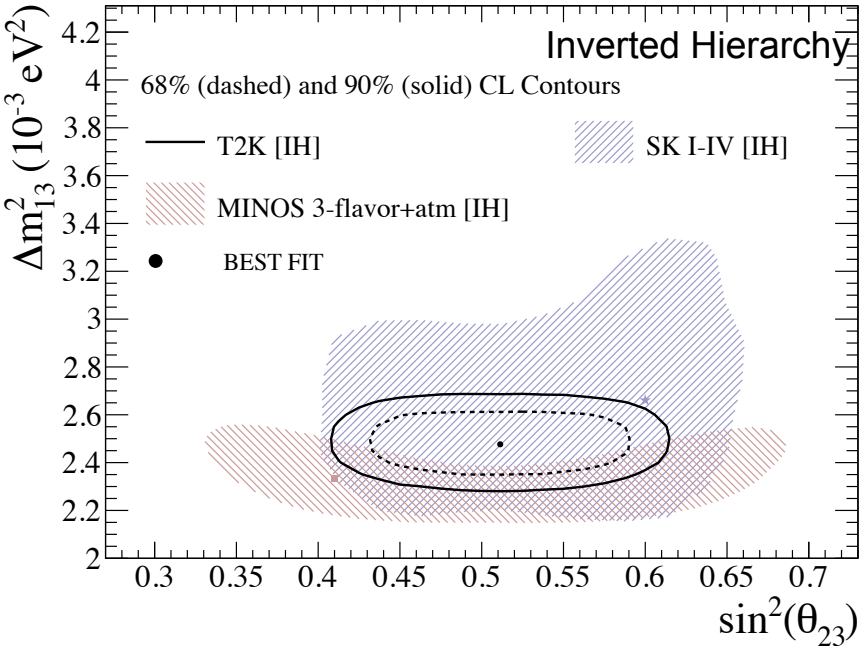
For θ_{13} given by reactor experiments:

$$P_{\mu\to\mu} \approx 1 - \sin^2(\Phi) + \sin^2(\Phi) 4\cos^4\theta_{13}\left(\sin^2\theta_{23} - \frac{1}{2\cos^2\theta_{13}}\right)^2$$

At reactor value: $\frac{1}{2\cos^2\theta_{13}} \approx 0.513$

Compare with other experiments





For the first time, the mixing angle is better constrained by an accelerator experiment than by atmospheric neutrinos!

		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

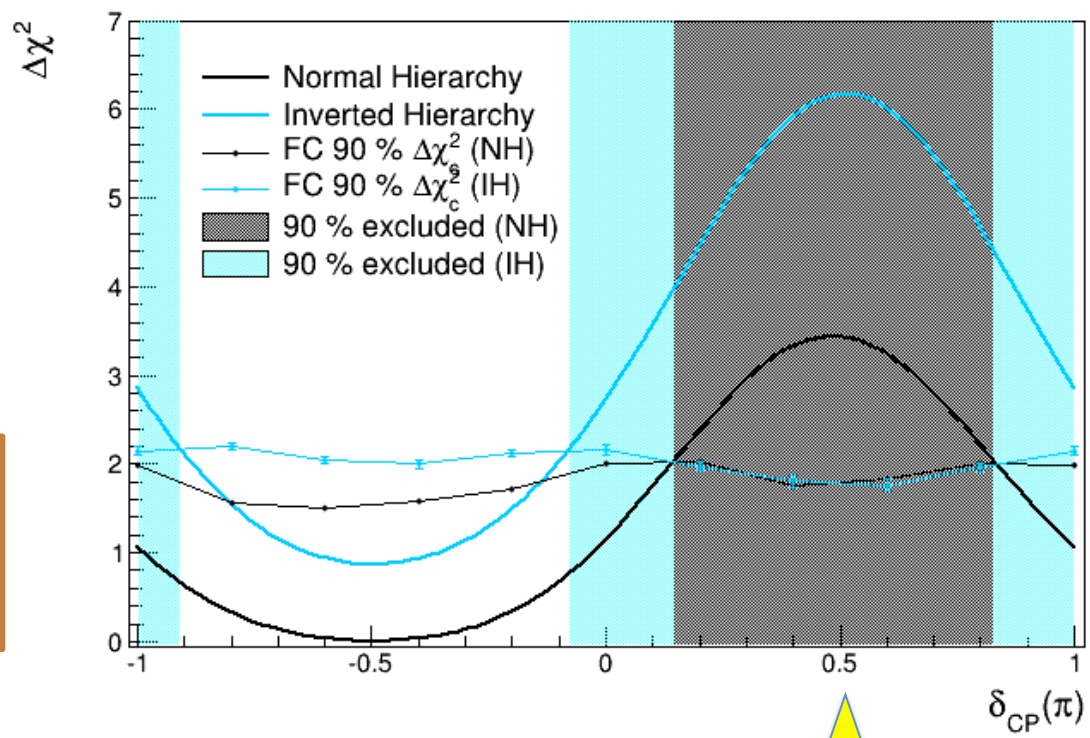
T2K Joint $\nu_\mu + \nu_e$ Analysis: Constraints on δ_{CP}

Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples

Plot includes constraint from reactor experiments as given by PDG 2013.

T2K has a slight hint for the normal hierarchy with a value of δ_{CP} of $-\pi/2$

PRELIMINARY



FUTURE -> Neutrino + Antineutrino running!

Poster #160!

T2K Joint $\nu_\mu + \nu_e$ Bayesian Analysis

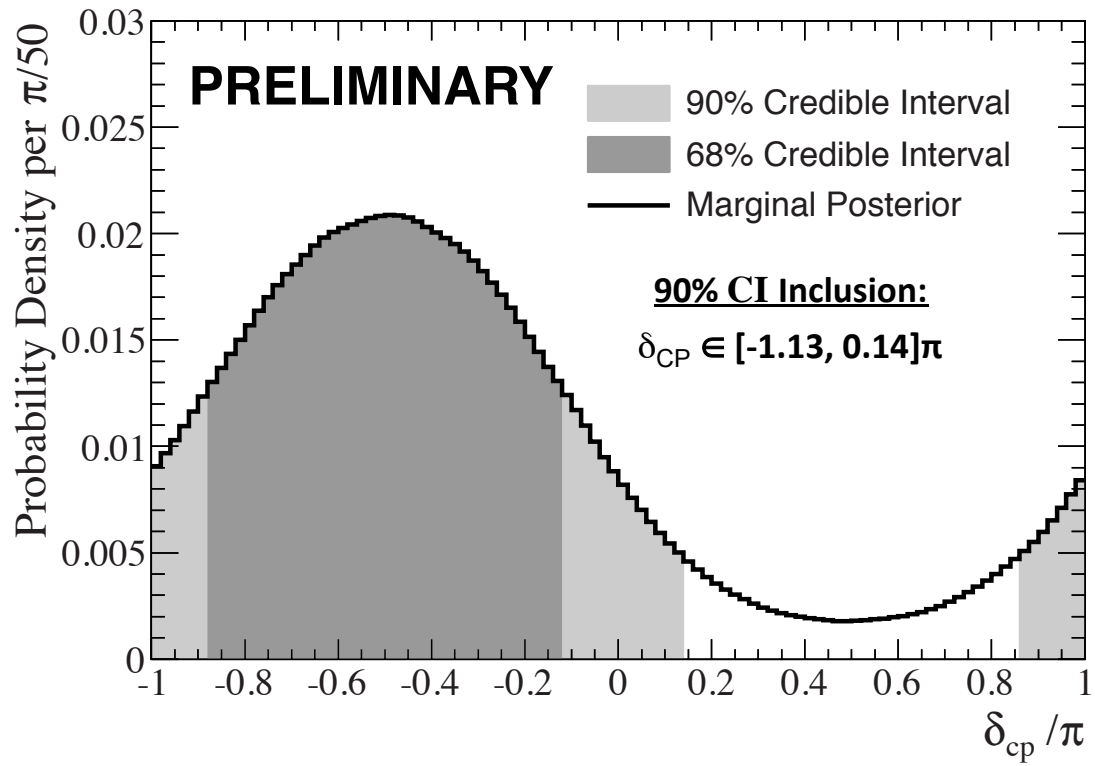
New Result:

Use a Markov Chain Monte Carlo (MCMC) with both T2K-SK $\nu_\mu + \nu_e$ and ND280 samples.

Note: Marginalized over hierarchy.

Poster #250!

Assuming flat priors for $\sin^2\theta_{23}$, $|\Delta m^2_{32}|$; P(NH) = P(IH) 0.5



Can compare the probabilities for each MH and θ_{23} octant combination in the posterior probabilities.

(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26%
$\sin^2\theta_{23} > 0.5$	50	24	74%
Sum	68%	32%	

PRELIMINARY

Lots of non-oscillation physics!

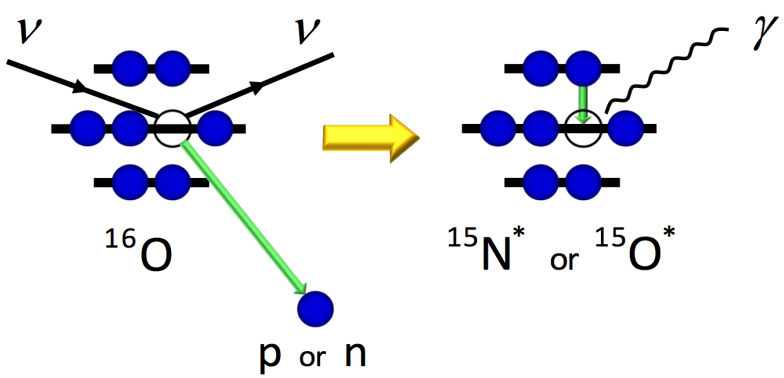
8 talks at NuInt 2014 workshop. See LOTS of posters!

Would like to highlight two interesting results:

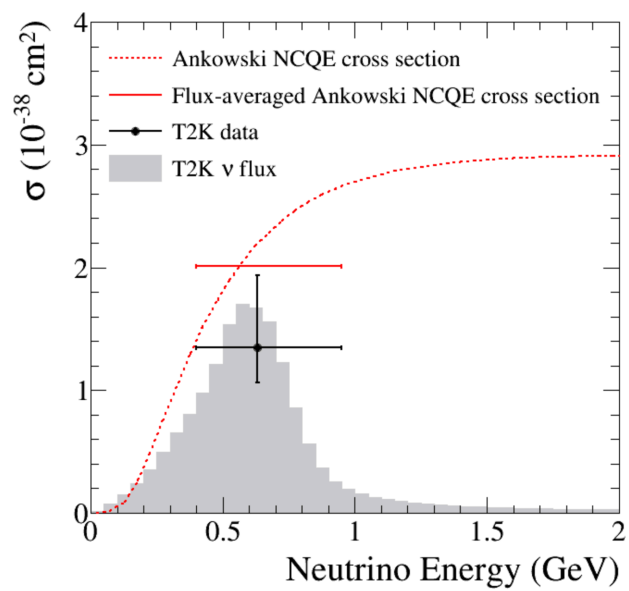
Poster #190!

$$\frac{\text{measured } \nu_e}{\text{predicted } \nu_e} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$$

Poster #187!

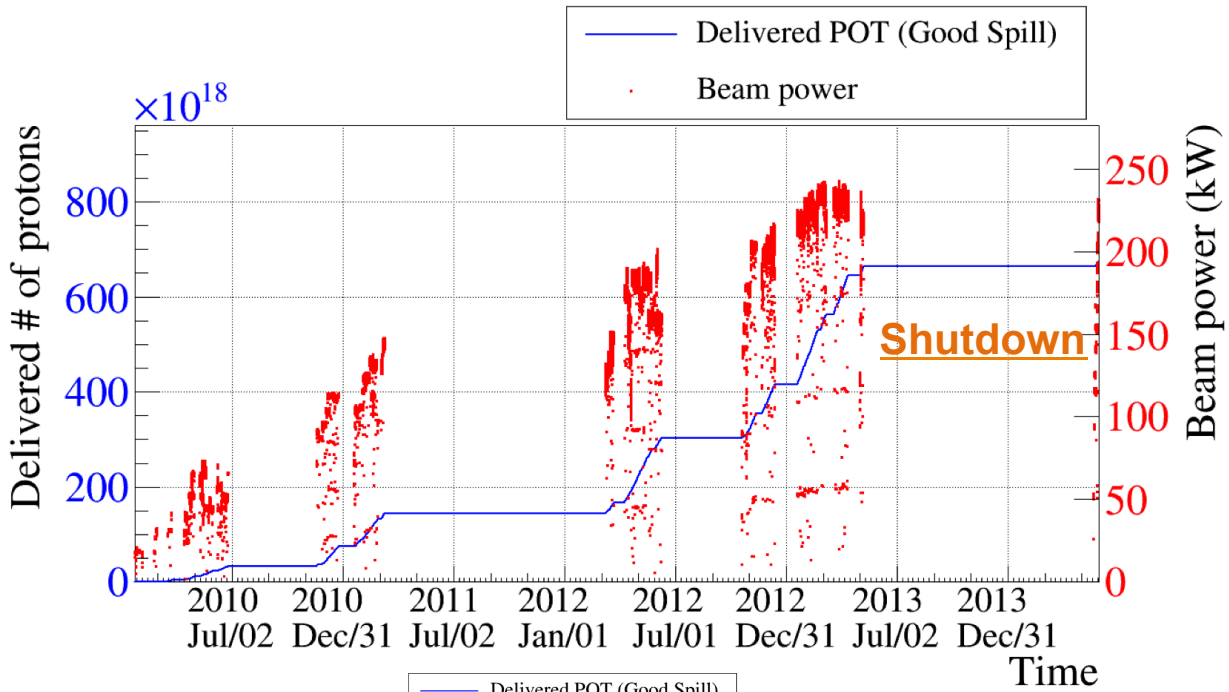


Poster #341!

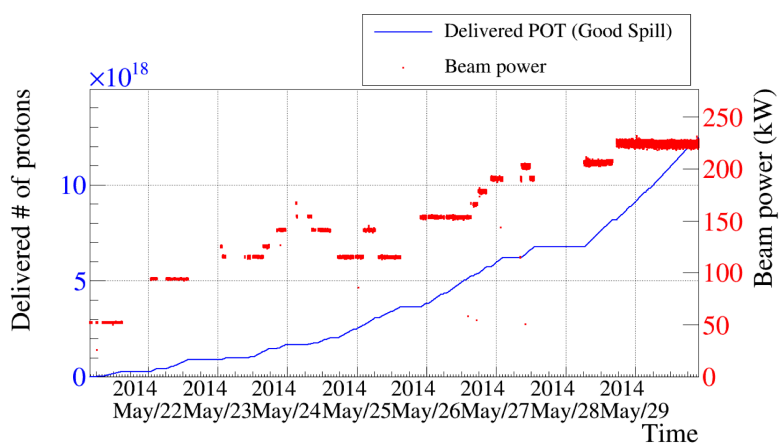


With these events new physics opportunities become available such as the search for dark matter by looking for a time delay.

Current J-PARC accelerator status.



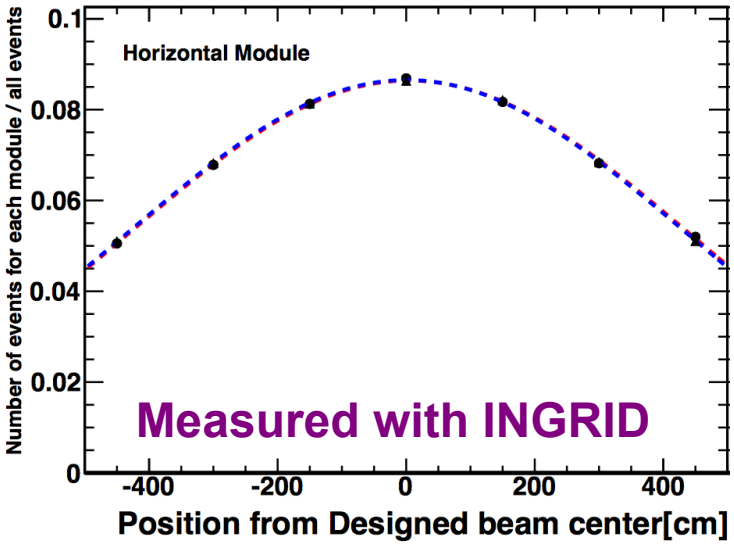
In this shutdown period:
- Linac upgraded to 400 MeV
- 3 horns replaced
- New beam monitors



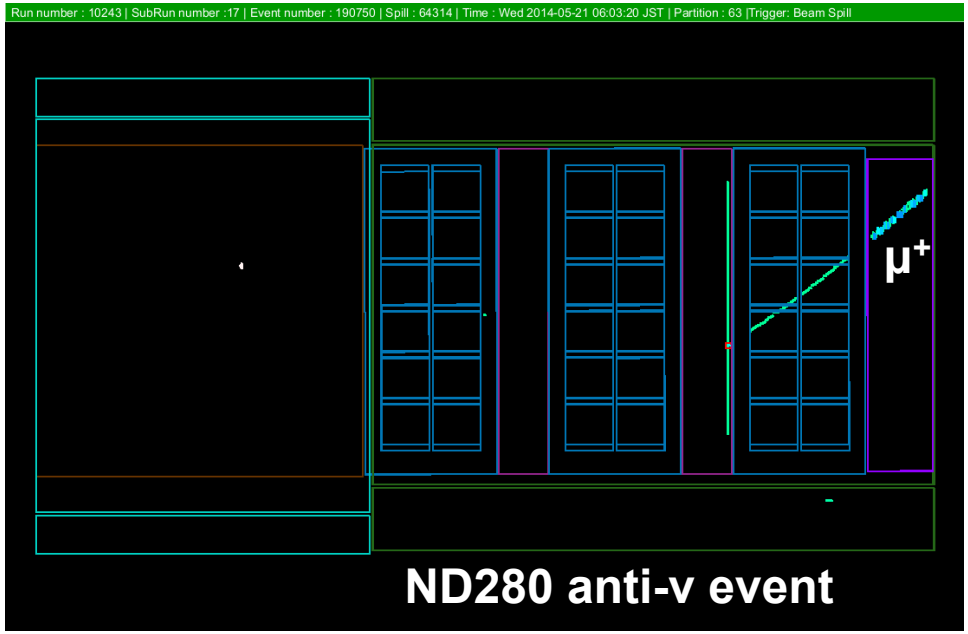
Integrated POT for this period : 1.246 x 10^{19}

Now at same level as power as before shutdown.

Run Status



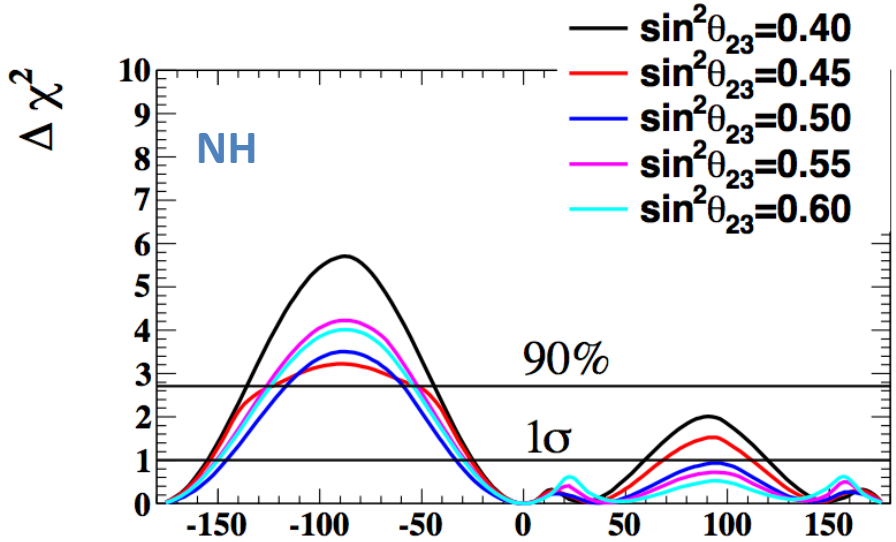
The width of the beam is comparable to the measured Gaussians in the previous runs.



The detectors are all working well.

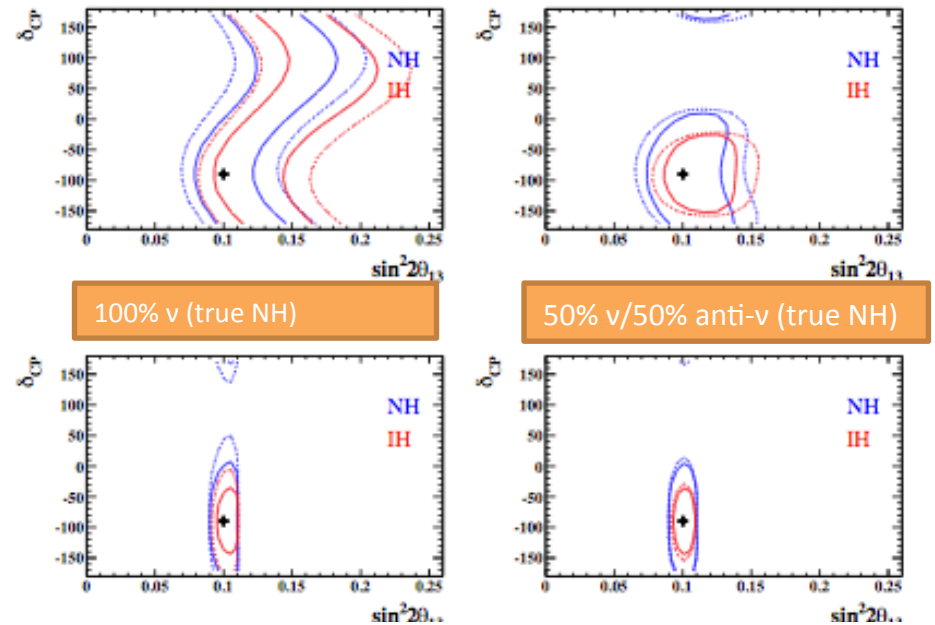
<u>Here is our first identified anti-neutrino event from an anti-neutrino test run!</u>

Future Sensitivity to CPV using T2K



T2K: 50% ν/50% anti-ν

"Lucky! (+: Sin²2θ=0.1, δCP=-90)"



100% ν (true NH)

50% ν/50% anti-ν (true NH)

100% ν (true NH) w/ Reactor constraint

50% ν/50% anti-ν (true NH) w/ Reactor constraint

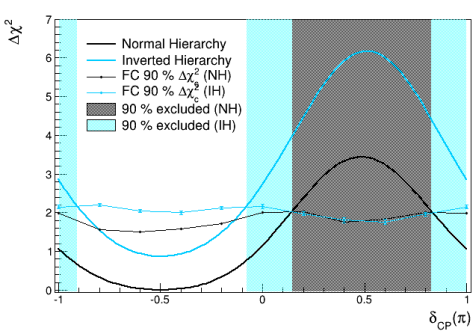
No systematics

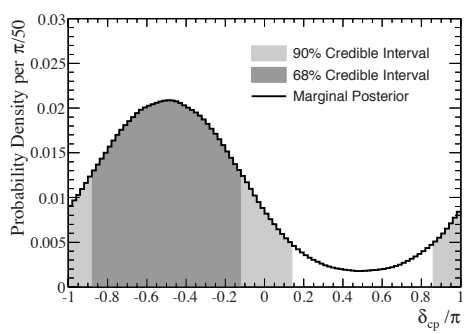
5% error on signal, 10% on background

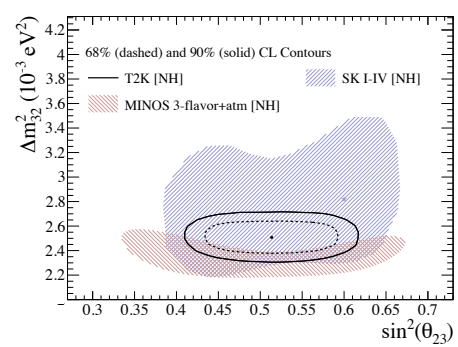
T2K studies indicate our best sensitivity will be for 50% ν/50% anti-ν running. Anti-nu running also opens a large new physics program.

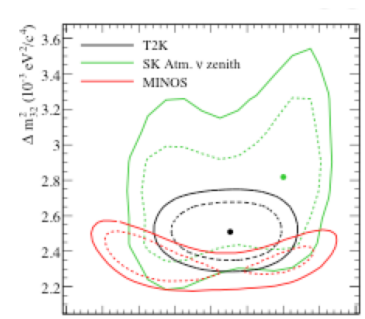
Conclusion

- <u>With only 8% of 7.8×10^{21} POT taken, T2K has achieved world leading results</u>.
  - $\nu_\mu \rightarrow \nu_e$ appearance observation (7.3 sigma)
  - World leading precision on θ_{23} (3° error)
- Our analyses with a reactor constraint give hints that δ_{CP} is consistent with $-\pi/2$.
- The T2K beam has restarted, including anti-neutrino test data. ***More exciting results to come!***









The T2K Collaboration

~500 members (337 authors), 59 Institutes, 11 countries

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U. Regina
U. Toronto
U. Victoria
U. Winnipeg
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Germany
U. Aachen

Italy
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INFN, U. Padova
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