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UNIVERSITY



***Initial probe of  $\delta_{CP}$  by T2K with  
combined electron neutrino appearance  
and muon neutrino disappearance***

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On behalf of the T2K collaboration

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# Oscillation probability



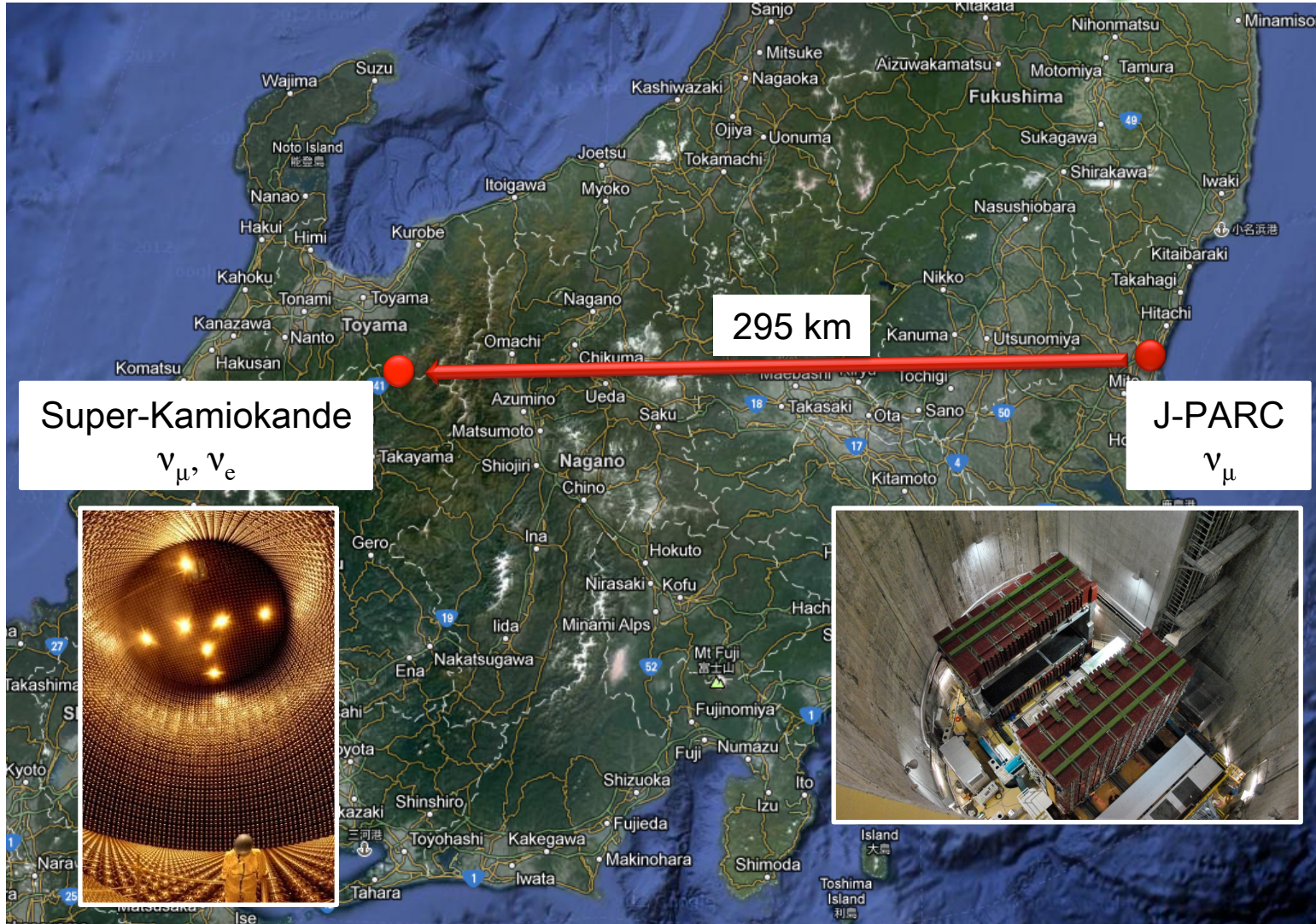
## Muon neutrino disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2(\theta_{13}) \sin^2(\theta_{23}) [1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})] \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

## Electron neutrino appearance

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \frac{\Delta m_{21}^2 L}{4E} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \delta_{\text{CP}} + (\text{CP even term, solar term, matter effect term})$$

# The T2K experiment



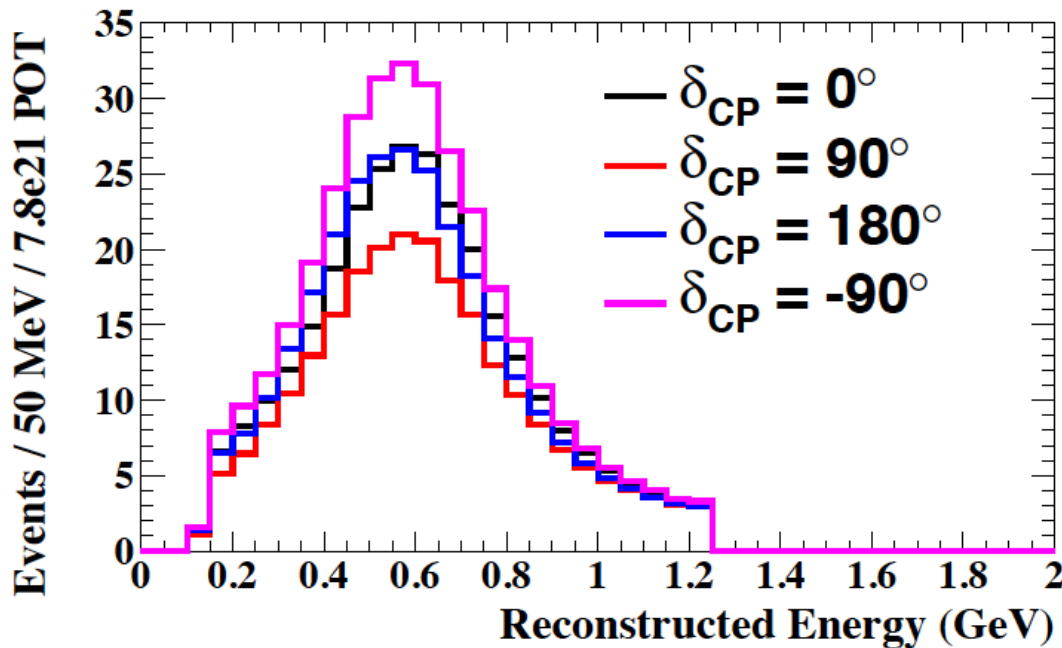
# Neutrino oscillations and $\delta_{CP}$



*T2K is optimized for both appearance and disappearance*

$\nu_{\mu}$  disappearance probability is **INSENSITIVE** to  $\delta_{CP}$

$\nu_e$  appearance probability is **SENSITIVE** to  $\delta_{CP}$



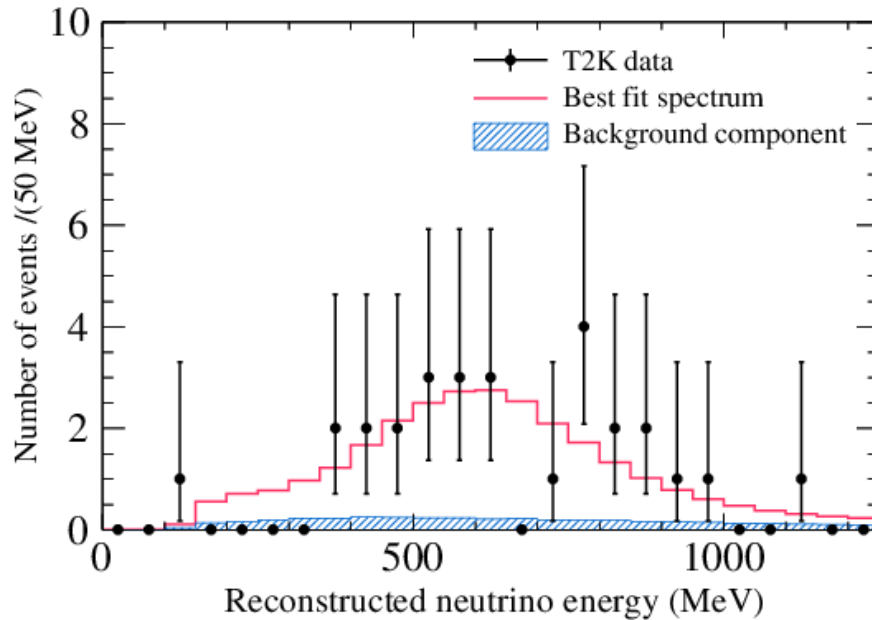
Appearance reconstructed energy spectrum at the far detector assuming  $7.8 \times 10^{21}$  POT at various true values of  $\delta_{CP}$

*Look for  $\nu_e$  appearance at the far detector*



# Observation of $\nu_e$ appearance

PRL 112 061802 (2014)



## For the existing T2K data

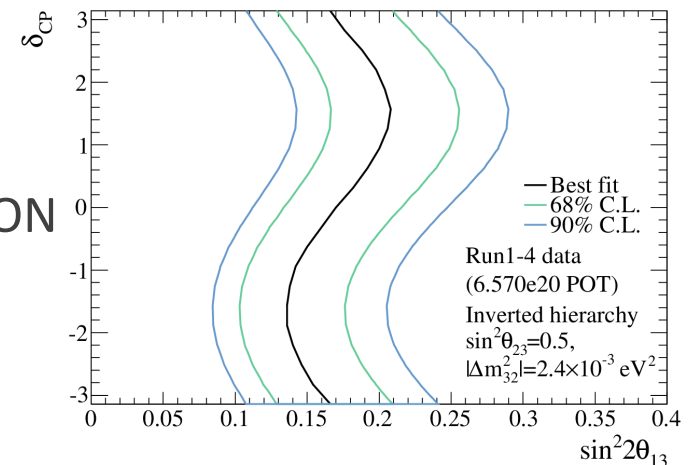
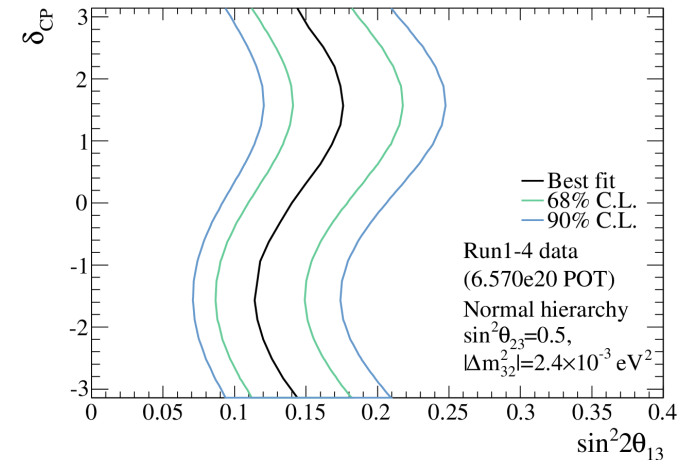
Expect  $4.92 \pm 0.55$   $\nu_e$ -like events with NO OSCILLATION

Observed 28 events

21.6 events predicted for  $\sin^2 2\theta_{13} = 0.1$ ,  $\delta_{CP} = 0$  and

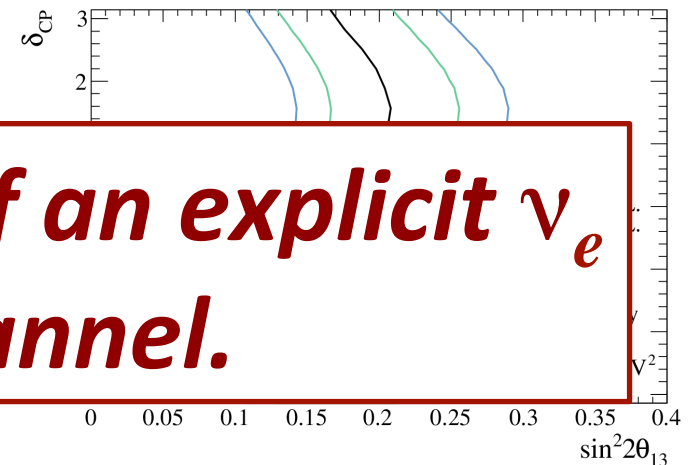
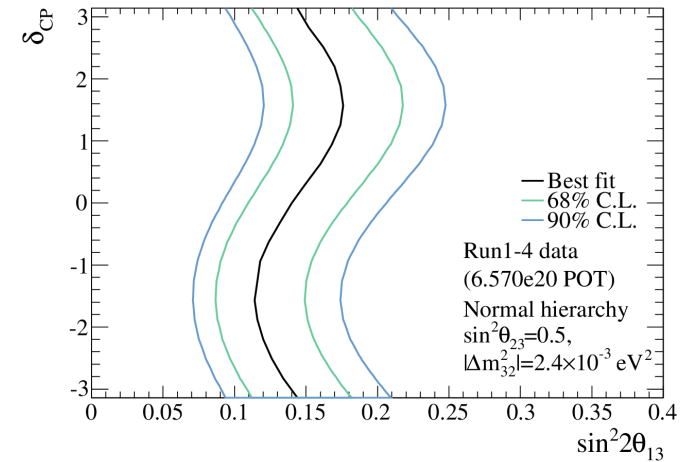
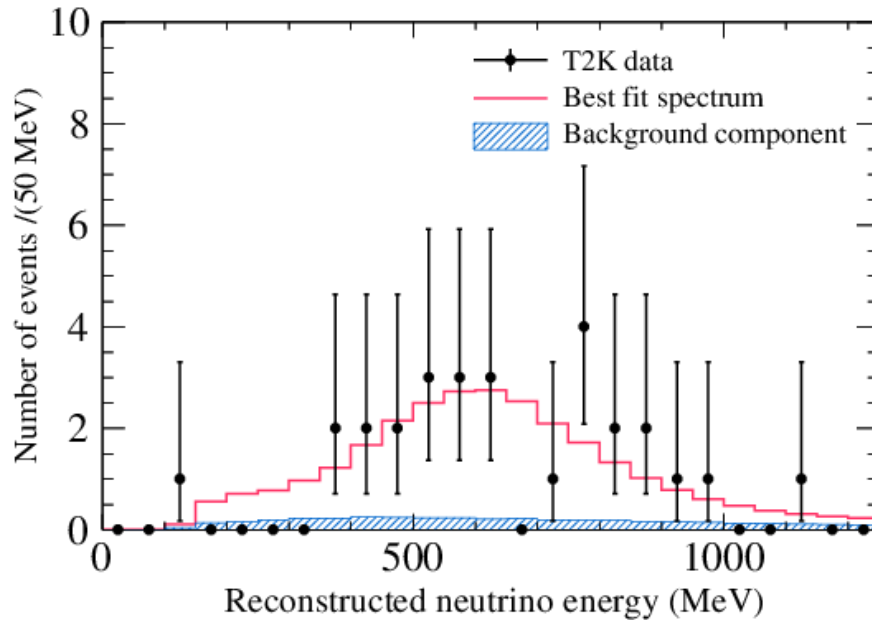
$\sin^2 \theta_{23} = 0.5$

**7.3 $\sigma$  significance for non-zero  $\theta_{13}$**



# Observation of $\nu_e$ appearance

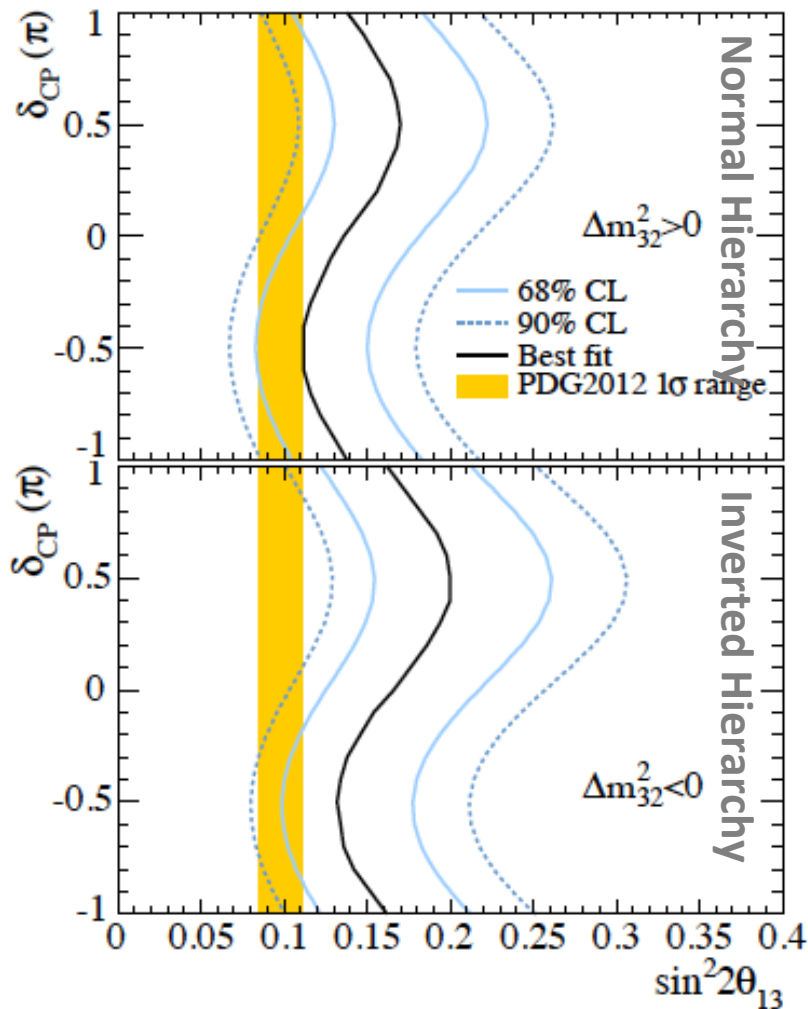
PRL 112 061802 (2014)



**First ever observation of an explicit  $\nu_e$  appearance channel.**

**7.3 $\sigma$  significance for non-zero  $\theta_{13}$**

# Comparison with PDG $\theta_{13}$



Black curve is for T2K-only best fit values of

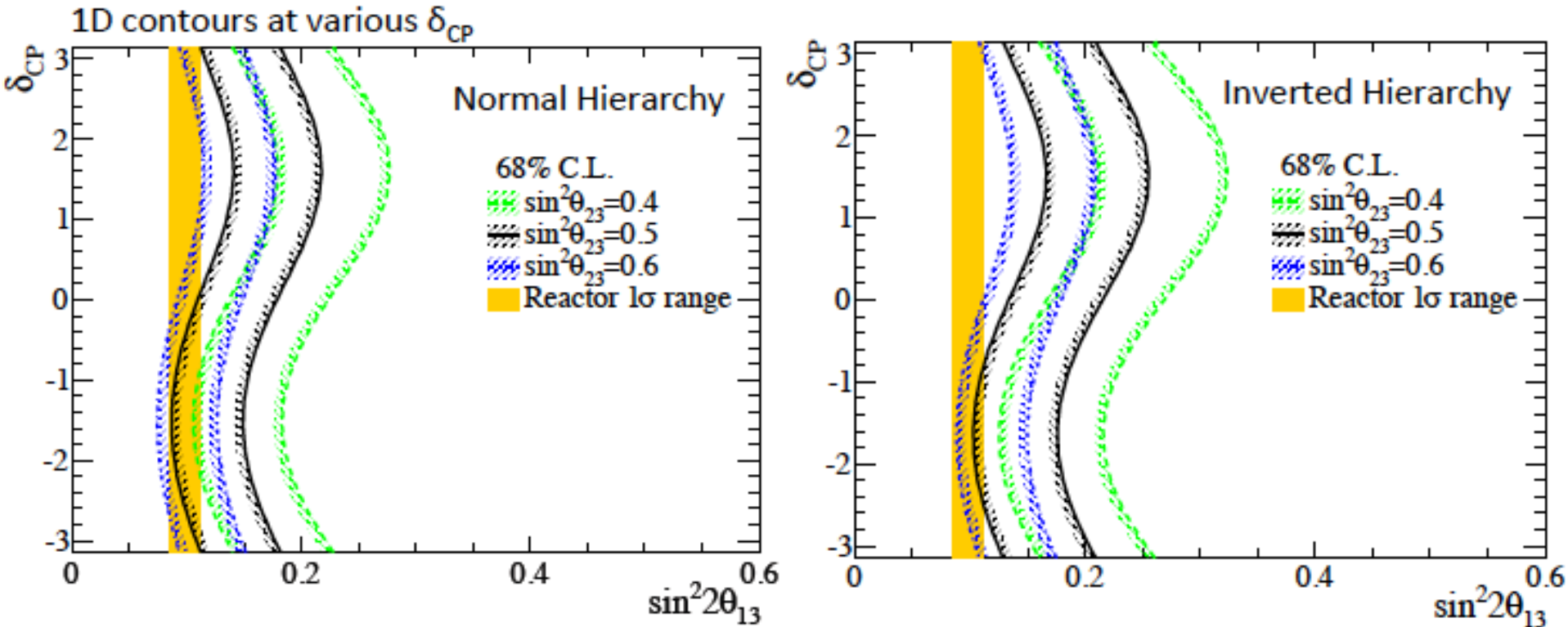
$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032} \text{ (Normal Hierarchy)}$$

$$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037} \text{ (Inverted Hierarchy)}$$

(Best fit point assumes  $\delta_{CP} = 0$ )

Results from T2K are consistent with PDG value for  $\theta_{13}$

# Joint $\nu_\mu$ and $\nu_e$ analysis (2014)



Contours have  $\theta_{23}$  dependence  $\rightarrow$  Joint fit

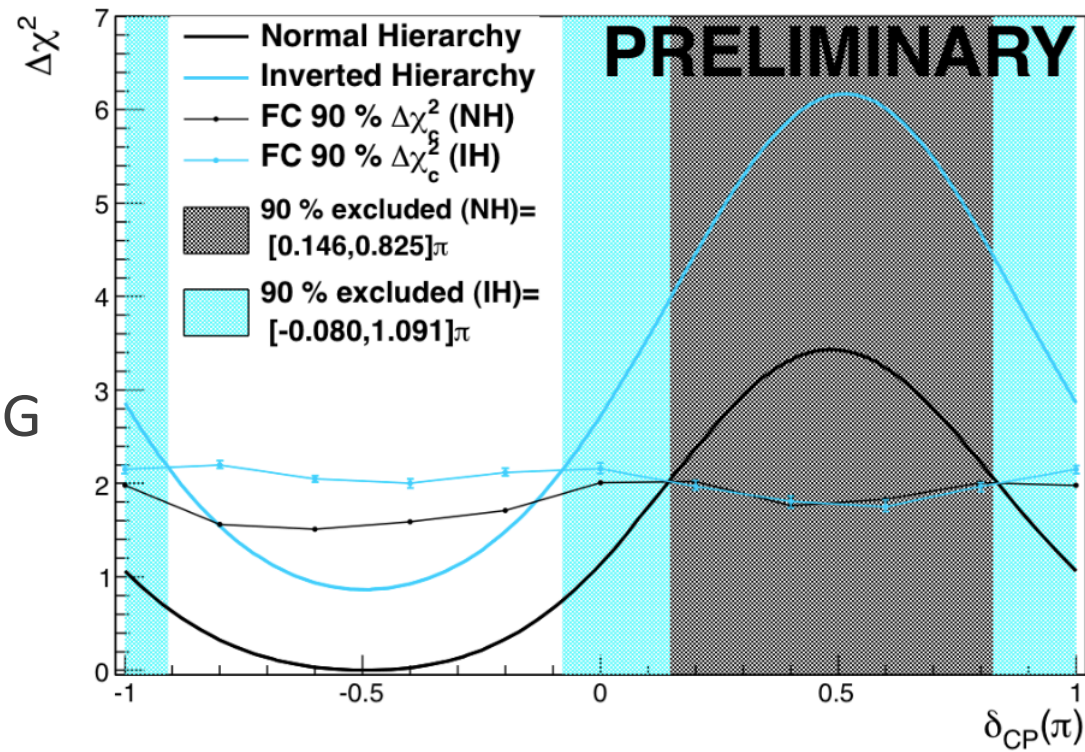


# Joint $\nu_\mu$ and $\nu_e$ analysis (2014)

## Frequentist confidence level



- Combined likelihood ratio fit to  $\nu_\mu$  and  $\nu_e$  samples
- Account for correlations in parameter space
- Include constraint from PDG 2013  $\theta_{13}$



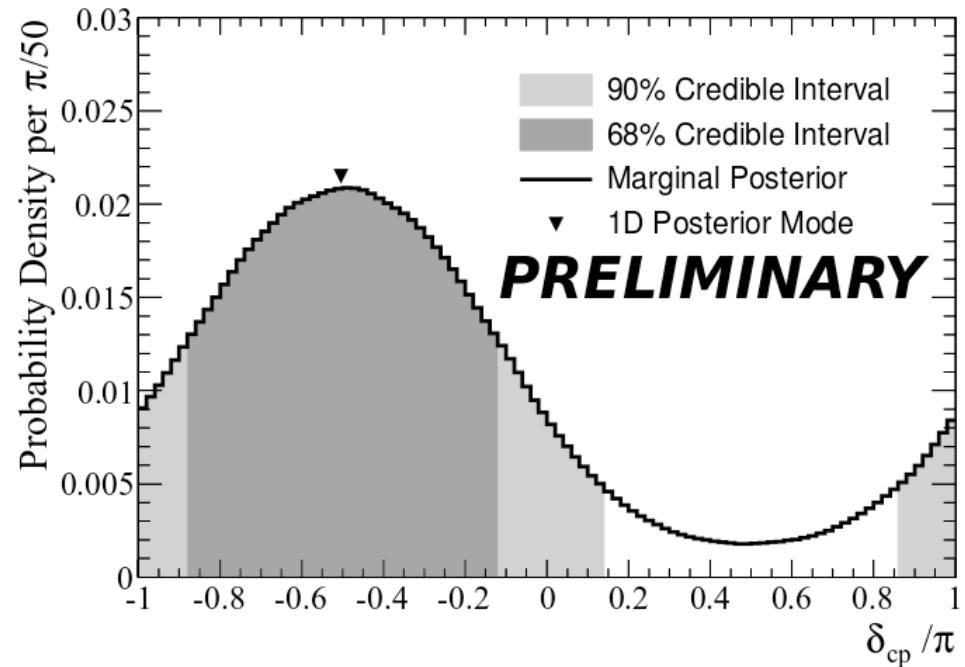
***T2K hints toward  $\delta_{CP} \approx -\pi/2$***

# Joint $\nu_\mu$ and $\nu_e$ analysis (2014)

## Bayesian Credible Interval



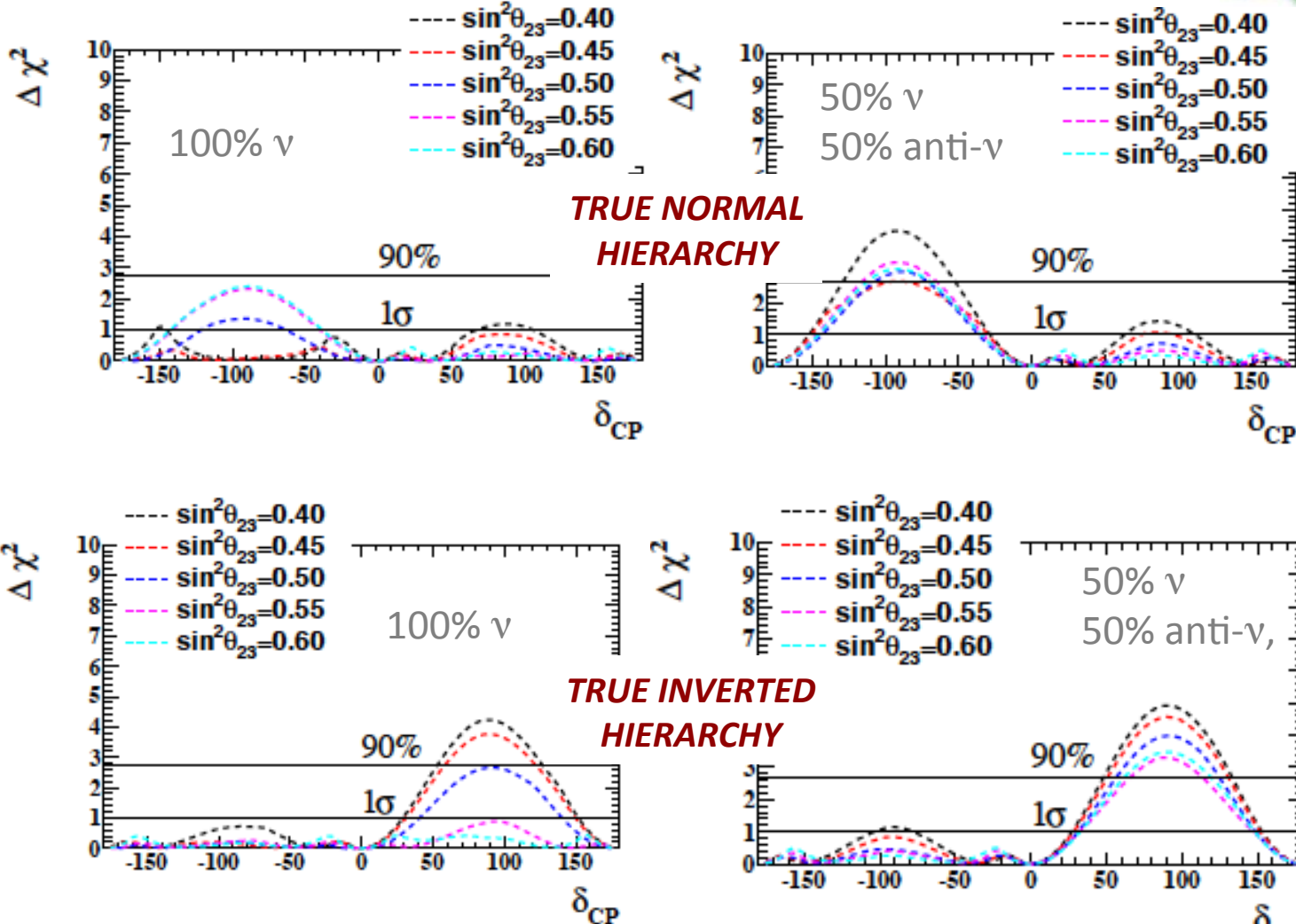
- Markov Chain Monte Carlo (MCMC) using both far detector  $\nu_\mu$  and  $\nu_e$  samples and ND280 samples
- Can marginalize easily
- Compare probabilities for each hierarchy and  $\theta_{23}$  combination



	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%	

# Future sensitivity

## Combined T2K and reactor data



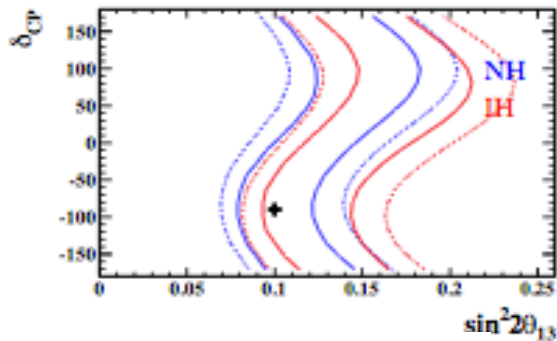
**Assumptions**

- $7.8 \times 10^{21}$  POT
- 2012 Systematic errors
- $\sin^2 2\theta_{13} = 0.1$ ,
- $\delta(\sin^2\theta_{13}) = 0.005$
- $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$

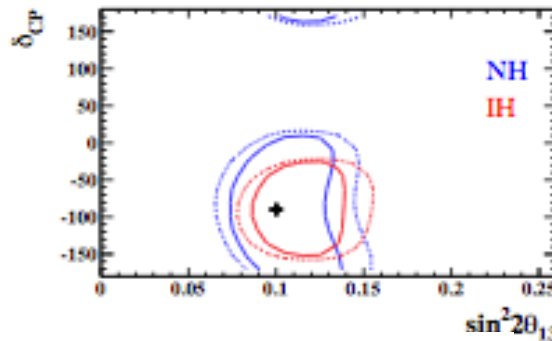
**For full statistics, running with anti-ν improves sensitivity to  $\delta_{CP}$**

# Future sensitivity

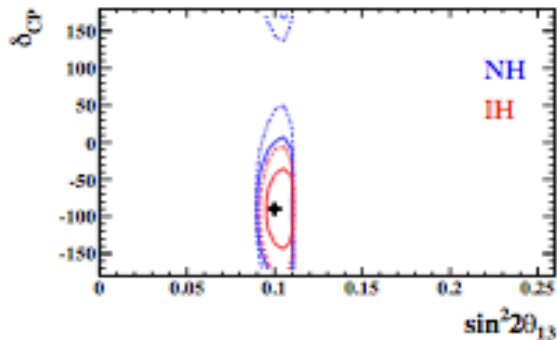
## Combined T2K and reactor data



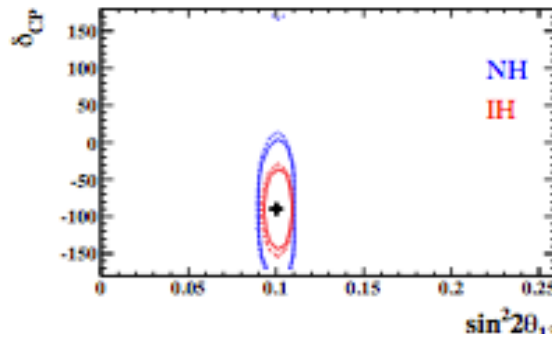
100%  $\nu$ , NH



50%  $\nu$  50% anti- $\nu$ , NH



100%  $\nu$ , NH, reactor constraint



50%  $\nu$  50% anti- $\nu$ , NH, reactor constraint

90% CL allowed regions for  $7.8 \times 10^{21}$  POT

### Assumptions

$$\sin^2 2\theta_{13} = 0.1$$

$$\delta_{CP} = -90^\circ \text{ (test point)}$$

$$\sin^2 \theta_{23} = 0.5$$

$$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

Solid lines = Statistical errors only  
Dashed lines = 5% signal error, 10% background error

Blue curves = fitted with correct MH

Red curves = fitted with incorrect MH

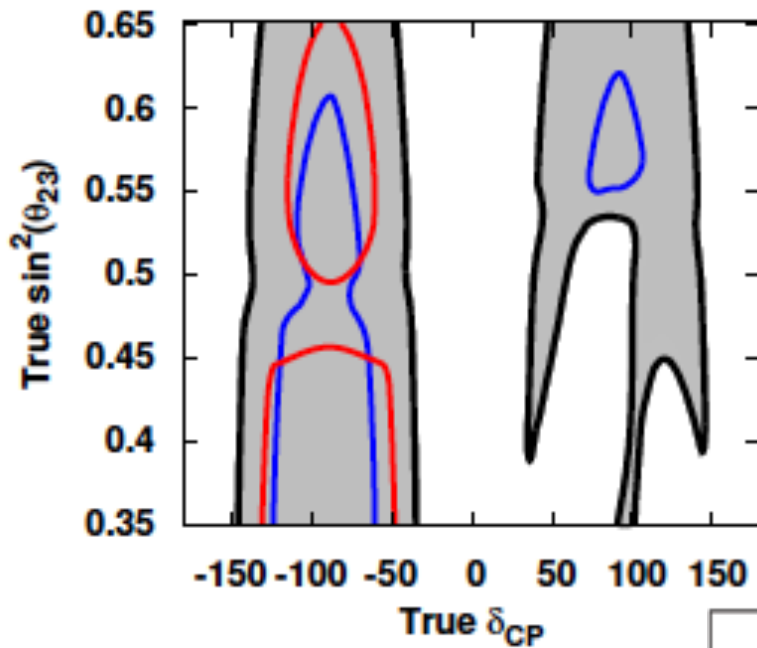
**T2K studies indicate that best sensitivity is achieved with 50%  $\nu$  and 50% anti- $\nu$  running for full expected statistics**

# Future sensitivity

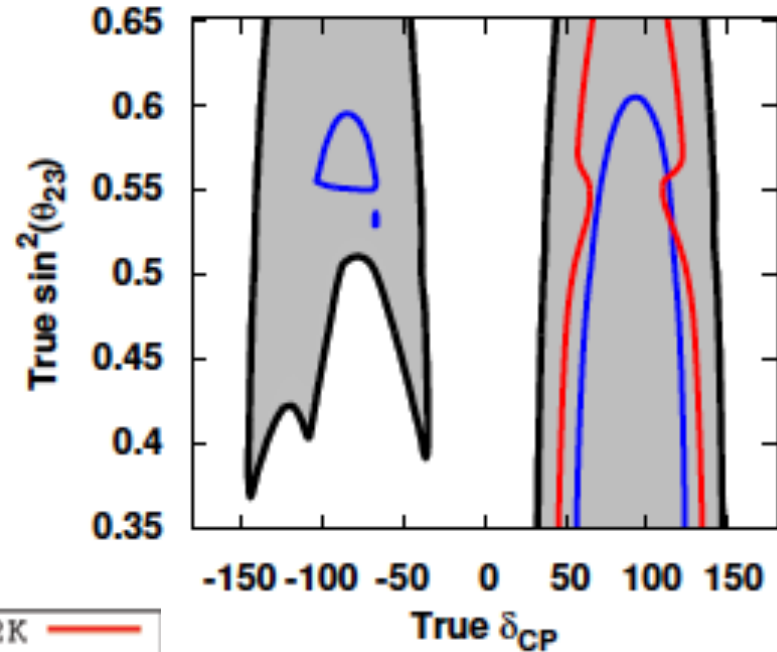
Combined T2K, NOvA and reactor data



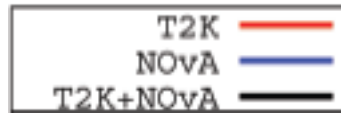
50%  $\nu_\mu$  and 50% anti- $\nu_\mu$



True Normal hierarchy



True Inverted hierarchy



## Assumptions

$$\sin^2 2\theta_{13} = 0.1,$$

$$\delta(\sin^2 \theta_{13}) = 0.005$$

$$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

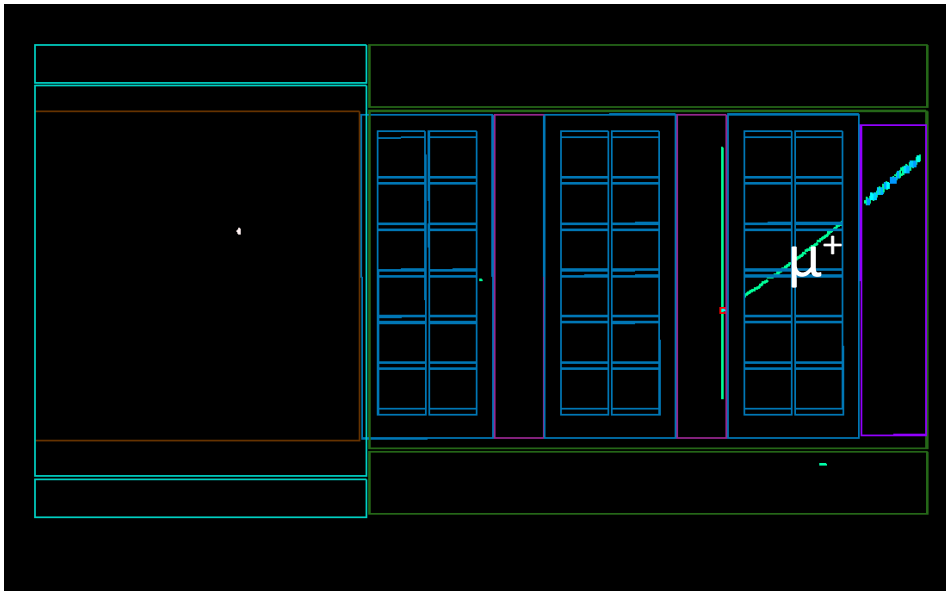
Simple normalization errors



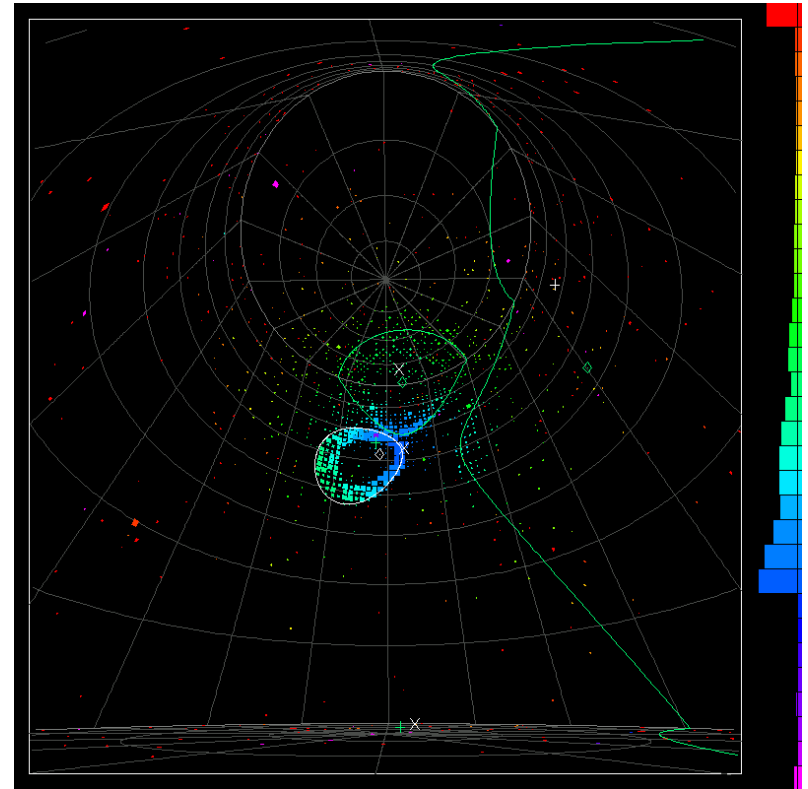
# Anti- $\nu$ running



*First anti- $\nu$  event(s) from test run in May 2014*



*Off-axis near detector*



*Far detector*

**Full anti- $\nu$  analysis is currently in progress**

# Conclusions



- Only 8% of design goal POT
  - World leading results!
  - ***7.3 $\sigma$  significance for non-zero  $\theta_{13}$***
  - Tighter constraints on oscillation parameters
- Hints at  $\delta_{CP}$  from T2K analysis with PDG constraint
  - Consistent with  $\delta_{CP} = -\pi/2$
  - Some values excluded at 90% CL
- Current experiments are becoming sensitive to CPV effect
  - Comparison between PDG/reactor and T2K results
  - Strong indication CPV will be within reach of next-generation experiments