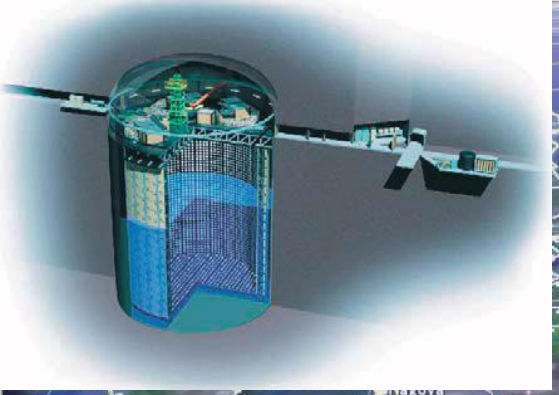


Results from T2K

September 23, NPB2012

Atsumu Suzuki (鈴木　州)

Kobe University

(for T2K collaboration)

T2K Collaboration

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

France
CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu
Osaka City U.
U. Tokyo

Poland
IFJ PAN, Cracow
U Silesia, Katowice
NCBJ, Warsaw
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

S Korea
Chonnam N. U.
Dongshin U.
Seoul N. U..

Spain
IFIC, Valencia
IFAE,. Barcelona

Switzerland
ETH Zurich
U. Bern
U. Geneva

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

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

Host Institutions: KEK, ICRR

12	Countries
59	Institutions
~500	Members

Outline

1. Introduction
2. T2K Experiment
   - Overview
   - Collected Data
   - Near Detector(ND280)
   - Far Detector(SK)
3. Recent Results
   - Electron Neutrino Appearance
   - Muon Neutrino Disappearance
4. Summary

1.Introduction

Motivation

3-flavor mixing describes (almost) all neutrino oscillation phenomena
(3 mixing angles, 2 independent mass differences, 1 CPV phase)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \boxed{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

<u>Atmospheric & accelerator:</u>
$\theta_{23} \sim 45^o$
$(\Delta m_{23})^2 \sim 2.4\times10^{-3}$ eV^2

<u>Interference:</u>
$\theta_{13} \sim 9^o$ and δ_{CP}=??

<u>Solar & reactor:</u>
$\theta_{12} \sim 34^o$
$(\Delta m_{12})^2 \sim 8\times10^{-5}$ eV^2

Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$):

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$
$$+ \text{(CPV term)} + \text{(matter term)} \ldots$$

Sensitive to θ_{13}, δ_{CP}, θ_{23}, Δm^2_{13}

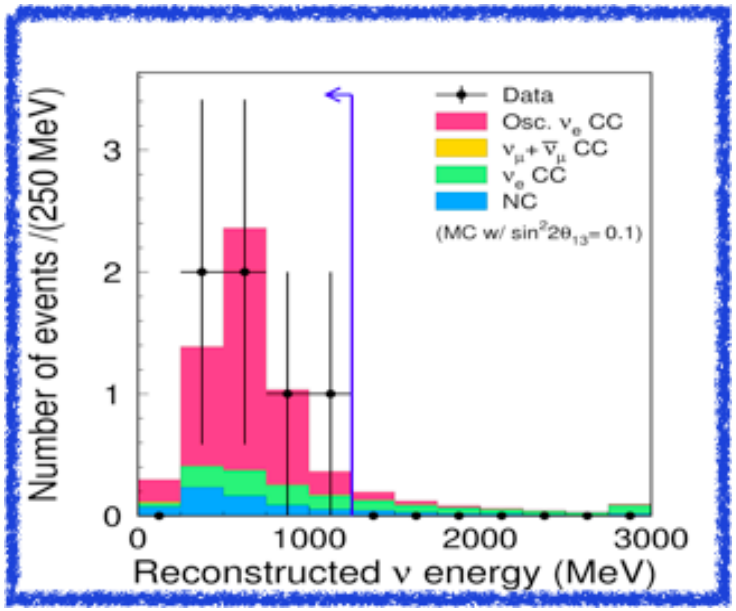
ν_e appearance indicated by T2K in 2011

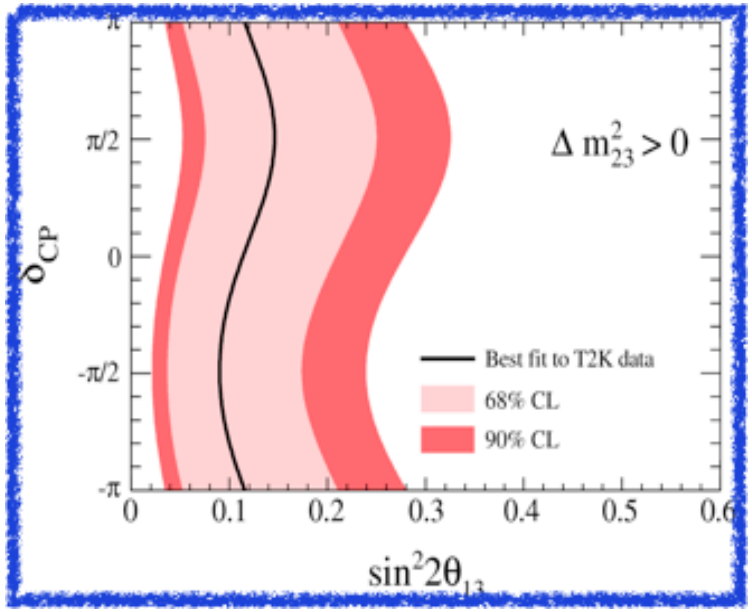
Phys.Rev.Lett. 107, 041801, 2011

Appearance Signal

6 electron neutrino events observed with 1.5±0.3 BG events. → **$\theta_{13} \neq 0$**

p-value=0.007 (2.5σ)



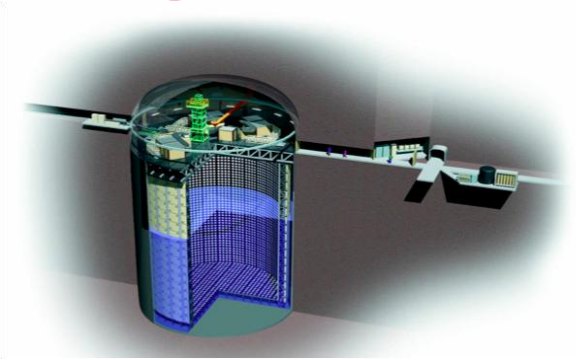


Further measurement is needed for CPV and Mass hierarchy.

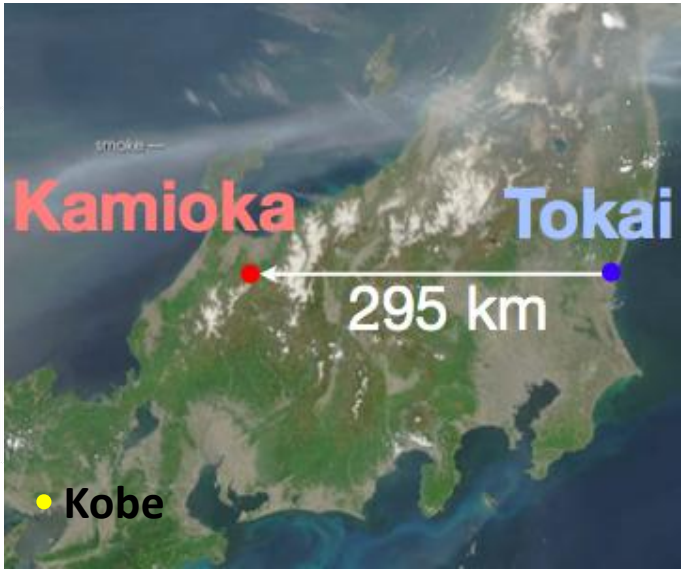
2.T2K Experiment

Overview

SK@Kamioka



Huge
Far detector



J-PARC @Tokai

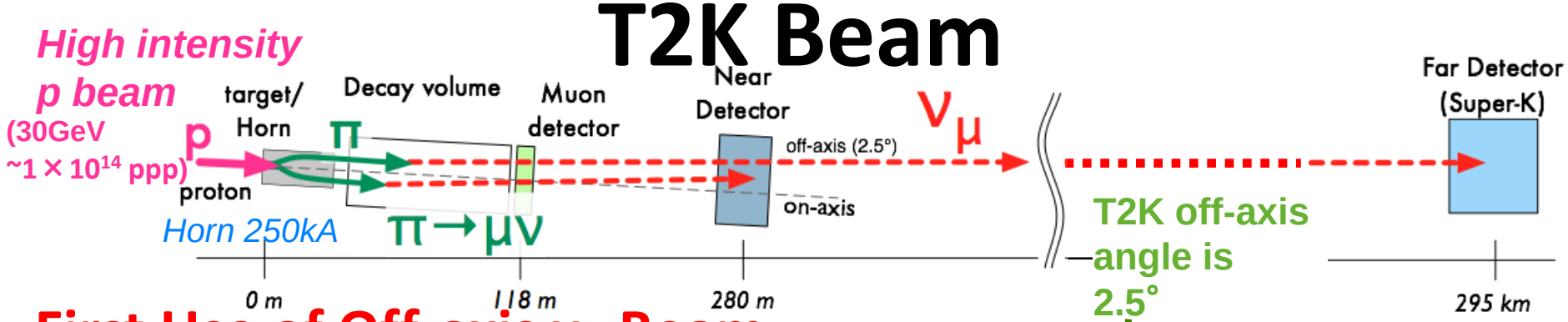
Intense beam

T2K Main Goals:

★ Observation of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

★ Precision measurement of ν_μ disappearance

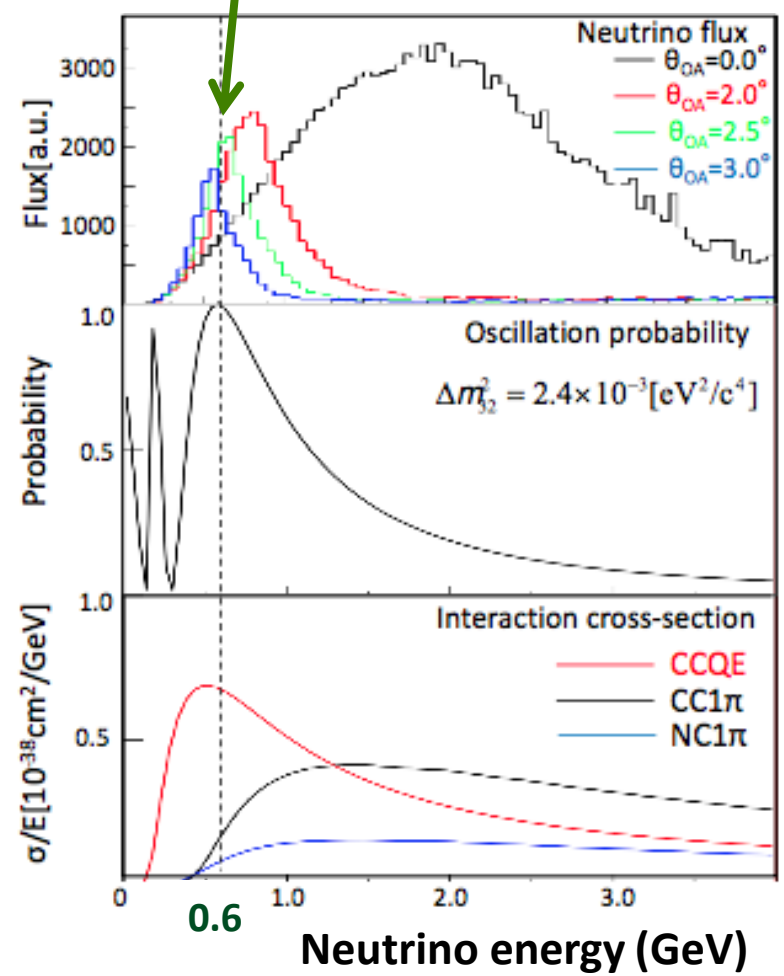
T2K Beam



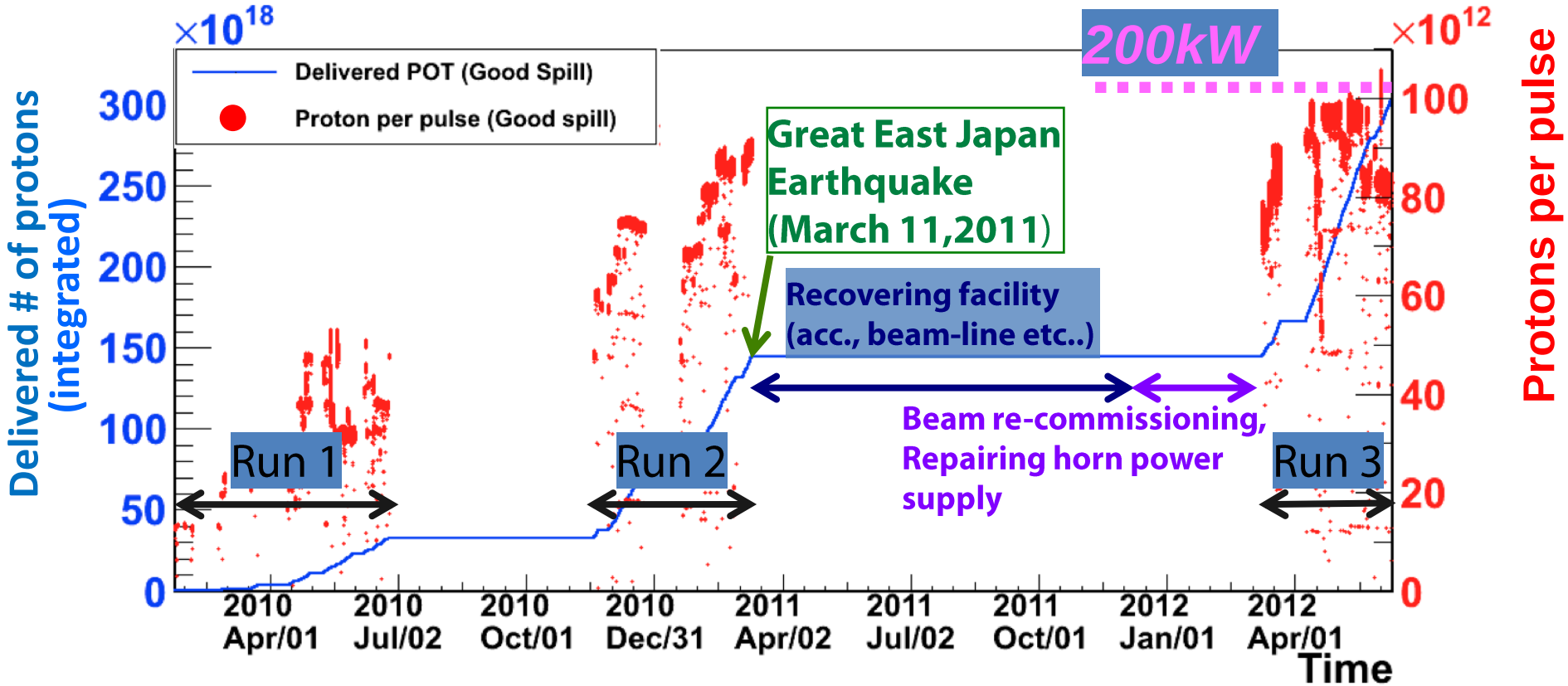
T2K off-axis angle is 2.5°

First Use of Off-axis ν_μ Beam:

- Low energy narrow band beam
- E_ν peak around oscillation maximum (~0.6GeV)
- Small high energy tail → reduces background events (e.g. NC π^0 production)
- Intense & high quality beam (Beam direction stability < 1mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak



Data collected and analyzed



Run1 + 2 (2010-2011)
1.43 x 10^{20} p.o.t.

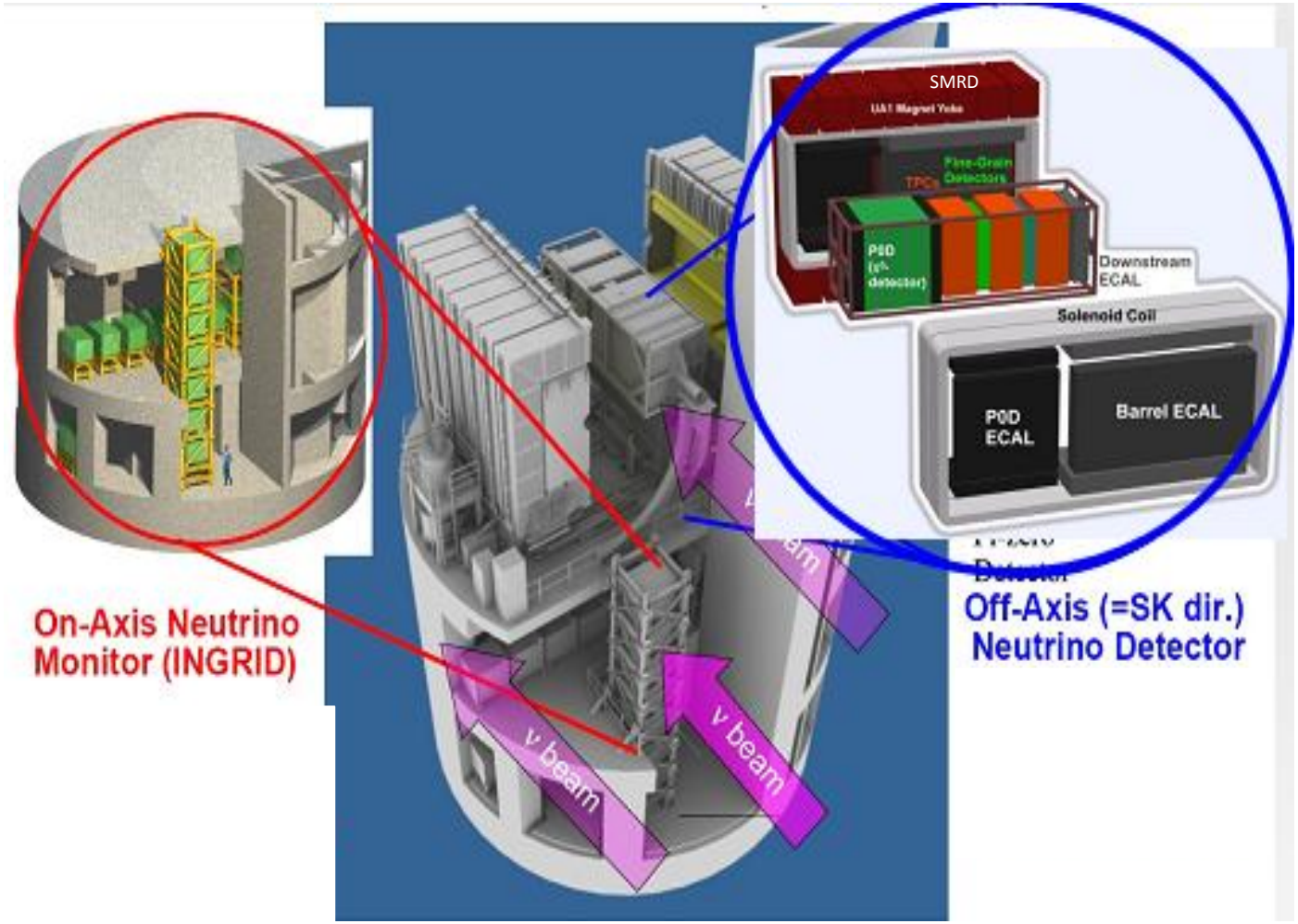
* ND280 Run1+2 data is used for oscillation analysis

Run3 (2012) : 1.58 x 10^{20} p.o.t

- including 0.21 x 10^{20} p.o.t. with 200kA horn operation (13% flux reduction at peak) (250kA horn current for nominal operation)
- ND280 Run3 data is checked and consistent with Run1+2

Today's talk for ν_e appearance :3.01 x 10^{20} p.o.t. (full data),
for ν_μ disappearance : 1.43 x 10^{20} p.o.t.(Run1+2)

Near Detectors



On-Axis Detector (INGRID) monitors ν:

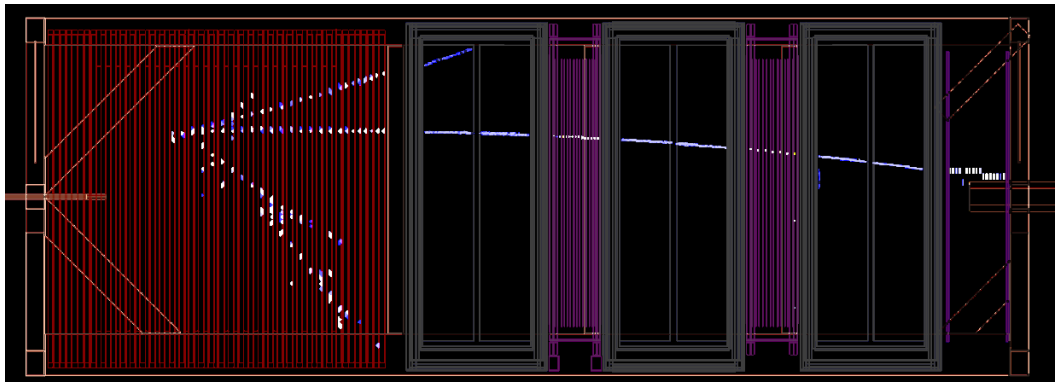
- **Beam direction**
- **Beam Intensity**

Off-Axis Detector (ND280):

- **In SK direction**
- **measures:**
  - **ν flux**
  - **Cross sections using water targets to reduce systematic errors**

Near Detectors:Performance

Good tracking by ND280

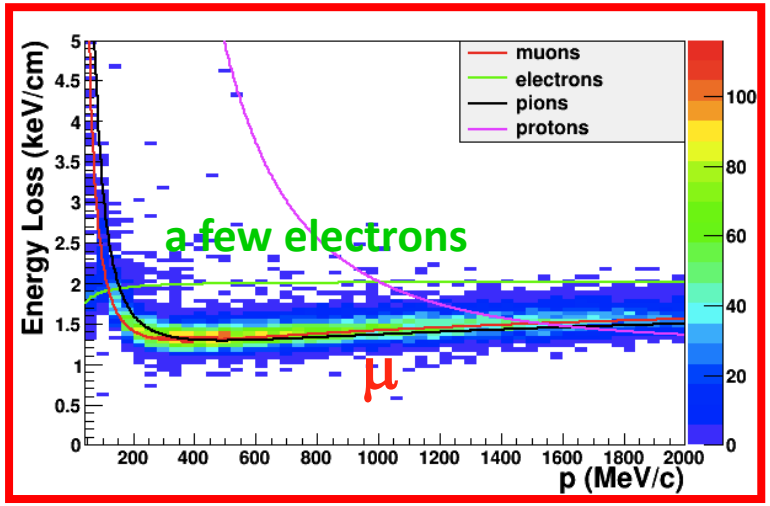


P0D TPC FGD TPC FGD TPC ECal

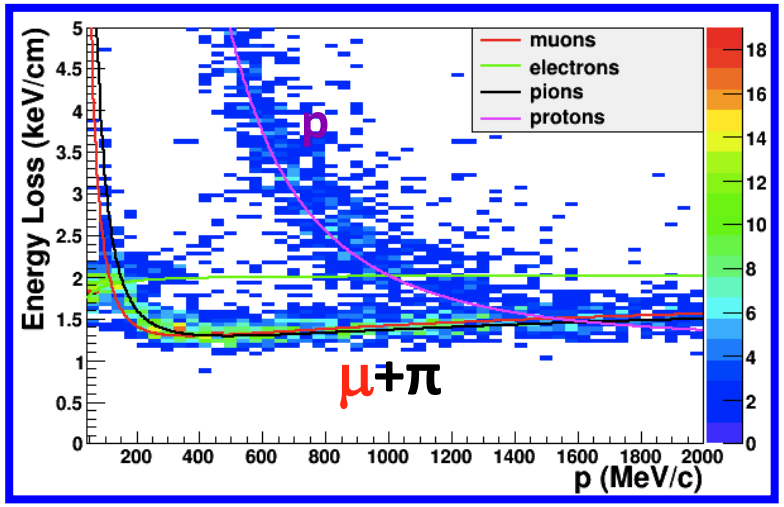
These detectors are inside the UA1 magnet (0.2 T)

Good PID by ND280

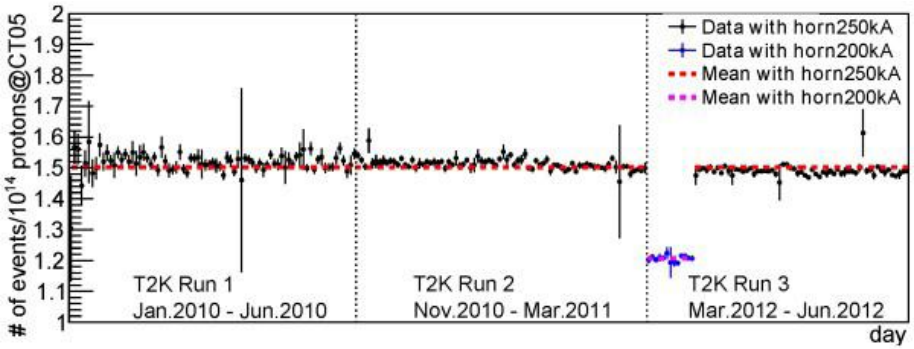
TPC dE/dX (negative tracks)



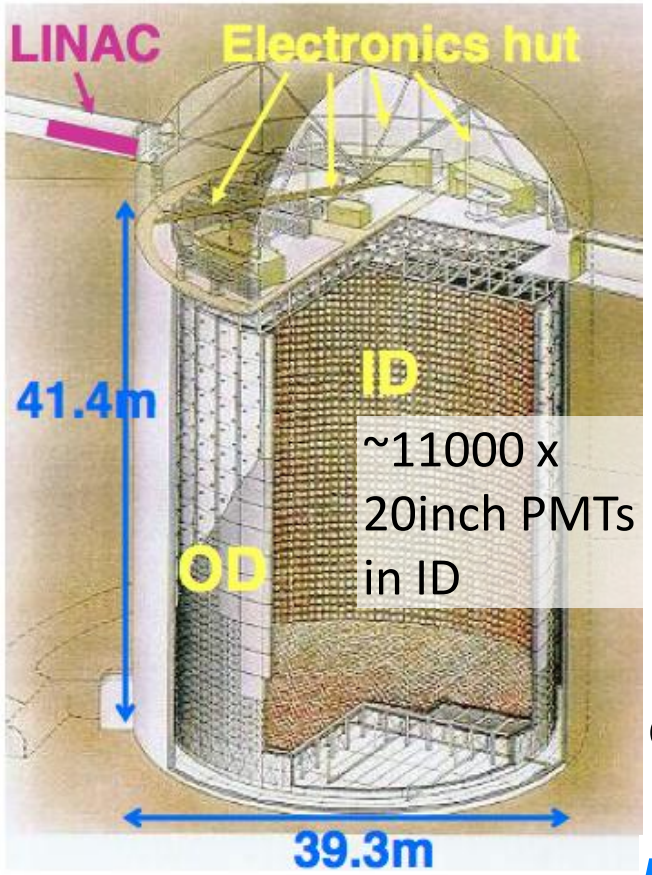
TPC dE/dX (positive tracks)



ν event rate stability by INGRID

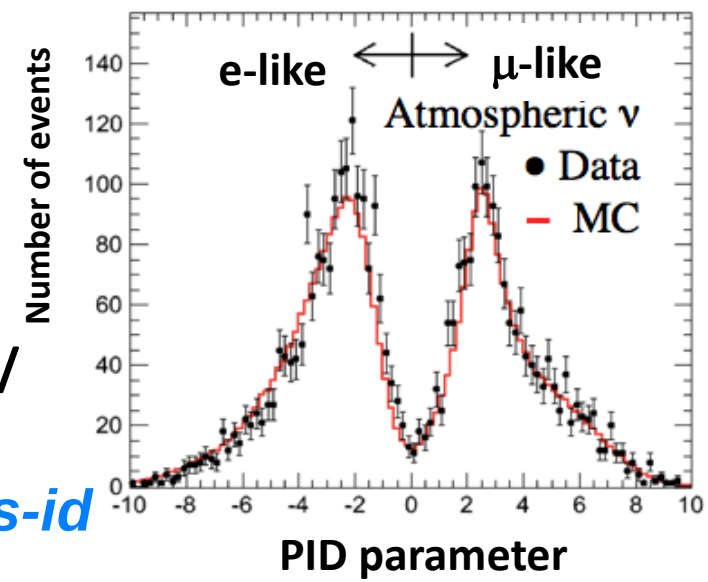


Far detector (Super-K)

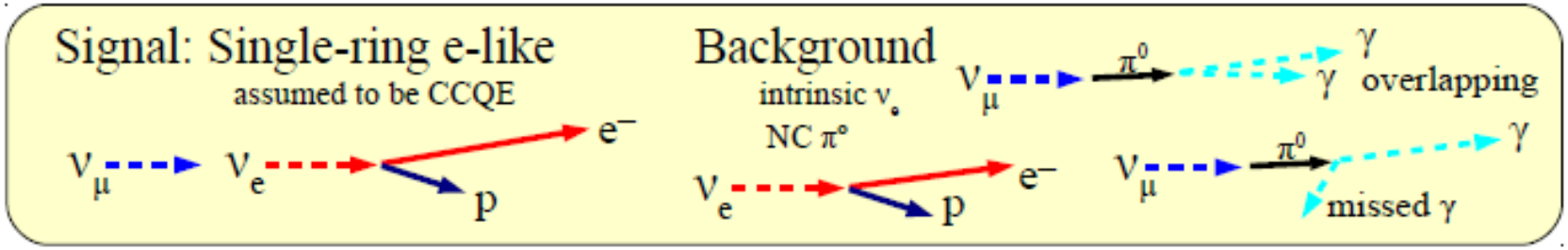


- **Water Cherenkov detector w/ fiducial mass 22.5 kton**
- **Record all the hit PMTs within ±500 μsec centered at the beam arrival time**
- **Detector performance is very good for Sub GeV**

Good e-like (shower ing) / μ-like separation



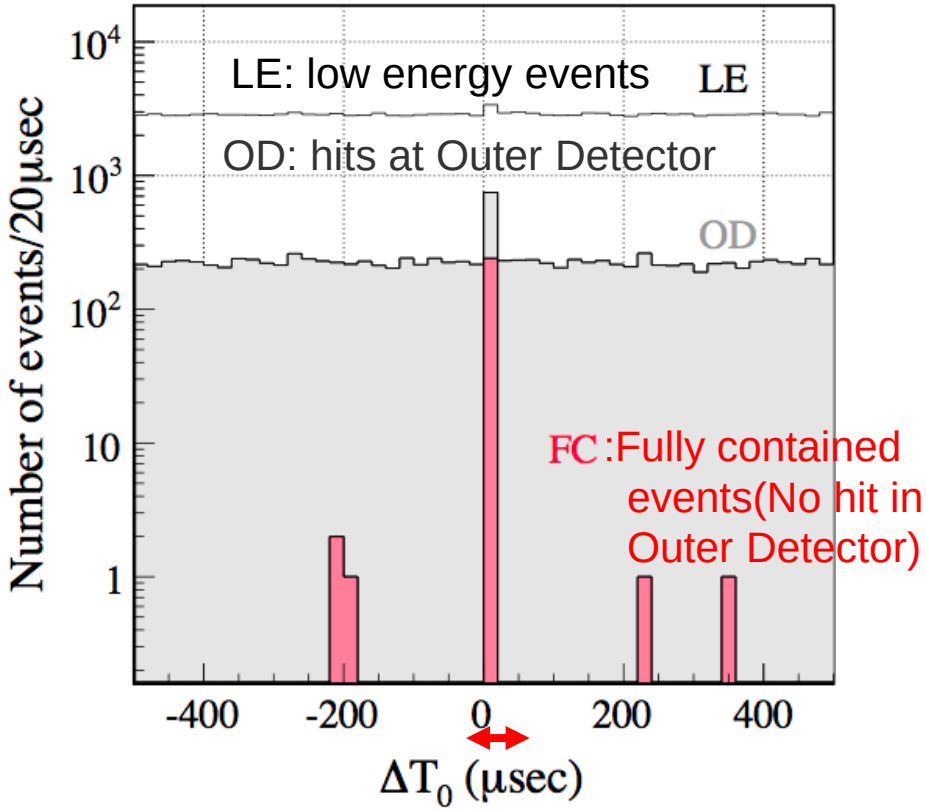
Probability that μ is mis-id as electron is ~1%



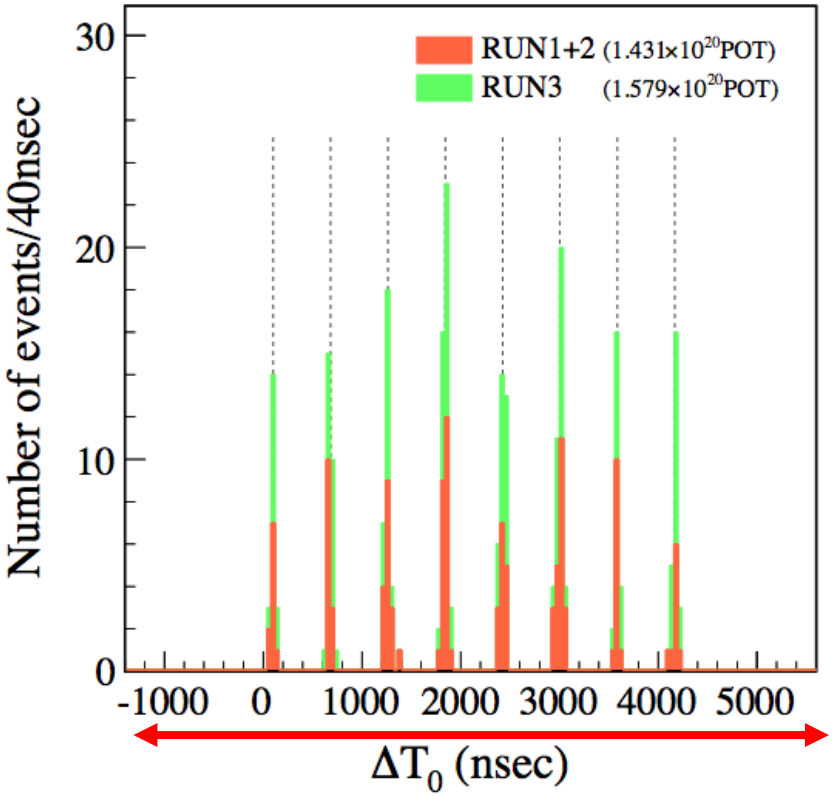
Far Detector: Event Timing

- **Events at the T2K beam timing synchronized by GPS**

Relative event timing to the spill timing



Clear bunch structure !



$\Delta T_0 = T_{GPS}$@SK - T_{GPS}@J-PARC - TOF(~985μsec)

3.Recent Results

ν_e Appearance: Analysis method

Flux prediction

w/ hadron production measurement (CERN NA61)

(Phys.Rev.C84:034604(2011), Phys.Rev.C85:035210(2012))

ND280 ν_μ measurements in CCQE and nonQE samples

detector uncertainties

Flux & ν int. cross section *fit*

to constrain flux and ν int. cross section uncertainties

ν int. cross section model & uncertainties

NEUT + uncertainties set from external data

fit result (flux & ν int. cross section information) is extrapolated to oscillation parameter fit

ν_e candidate events

Oscillation parameter *fit*

to extract $\sin^2 2\theta_{13}$ (δ_{CP} is scanned)

Other ν int. cross section uncertainties

Far detector uncertainties

from atm.-ν & π^0 control sample

ND280 ν_μ measurements

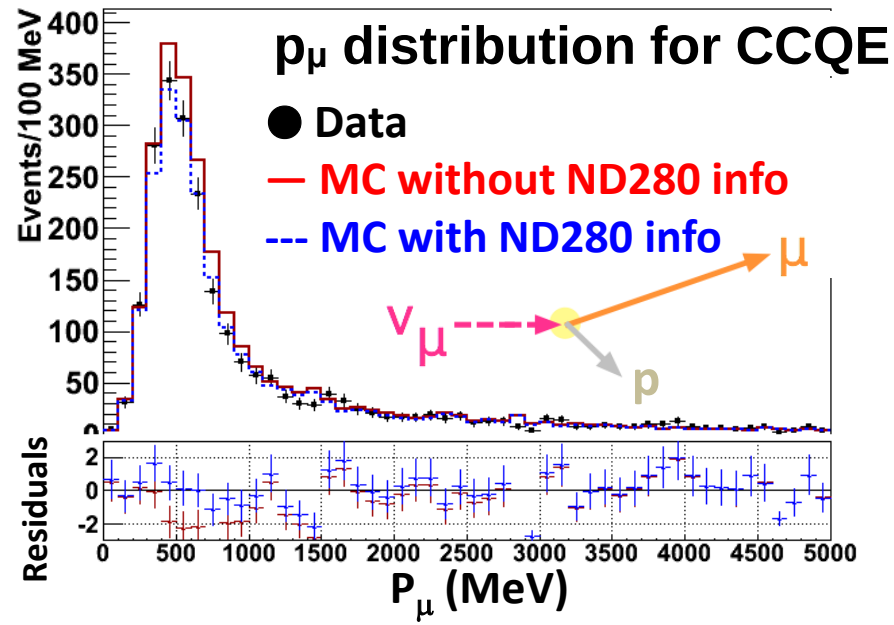
(P_μ, θ_μ) distribution of CCQE and CCnQE enhanced samples are fitted to constrain the flux and ν cross sections (MC predictions at ND280 and SK).

- Good negative track in FV.
- Upstream TPC veto
- μ ID by TPC for CCQE
- 1 FGD-TPC track
- No decay-e in FGD

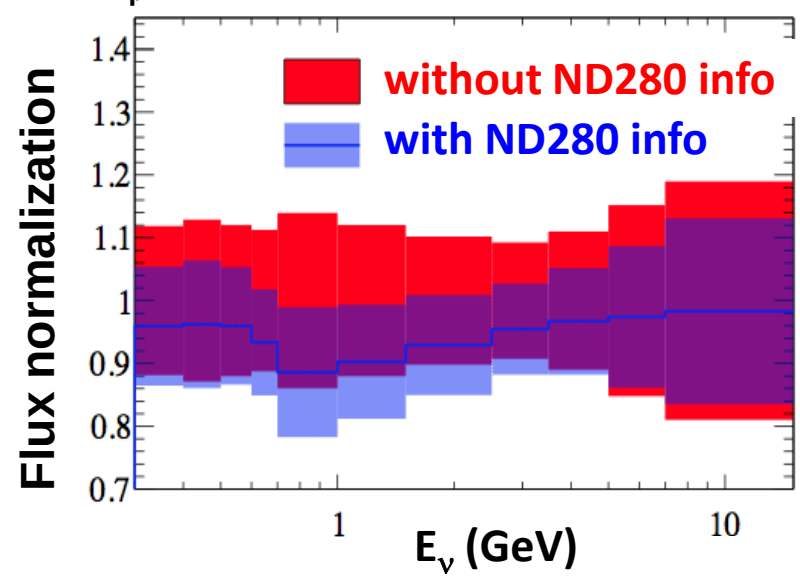
For CCQE selection, 40% eff. w/ 72% purity

Fit results are extrapolated to the prediction at the far detector.

Systematic errors are improved!



Far ν_μ flux normalization & uncertainties



The predicted number of events and systematic uncertainties

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

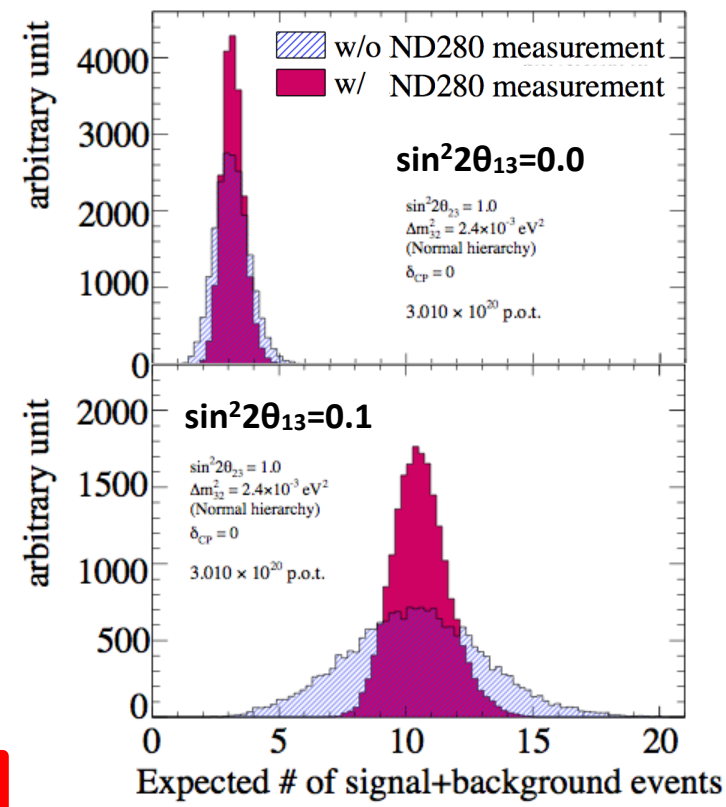
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background(mainly NCπ^0)	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

Big improvement !

the predicted # of event distribution

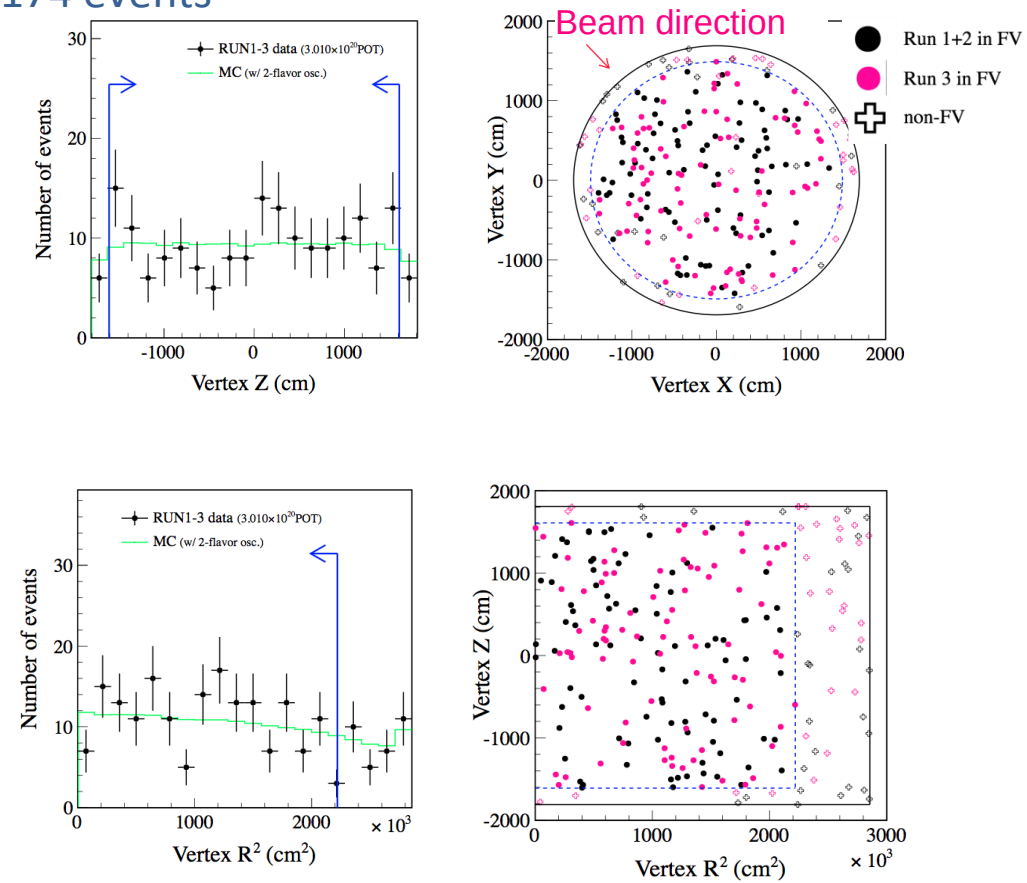


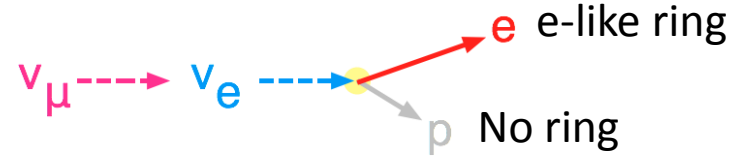
Uncertainties are reduced using ND280 measurement

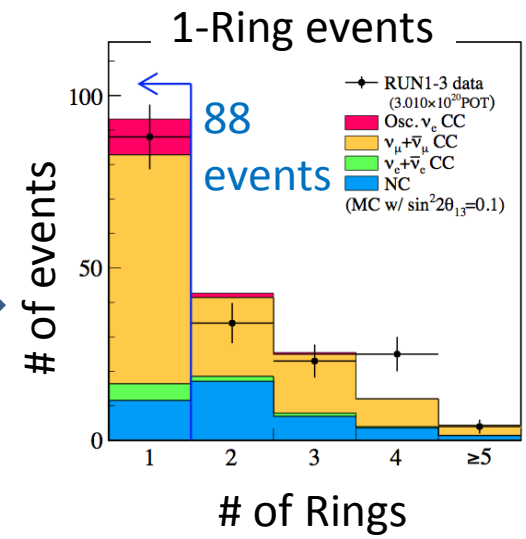
ν_e Event Selection

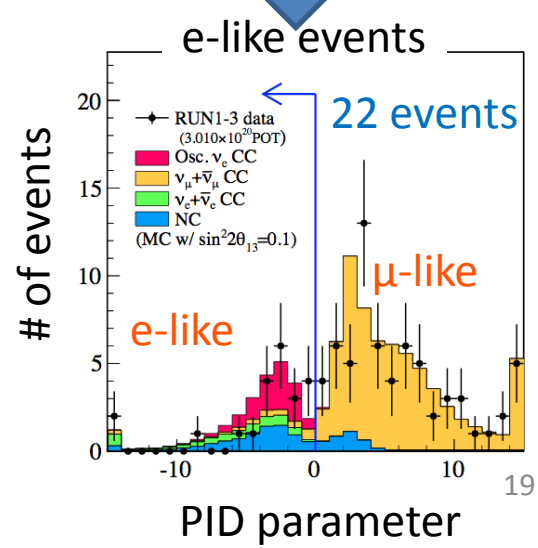
Fiducial volume cut
(distance between recon. vertex and wall > 200cm)

174 events



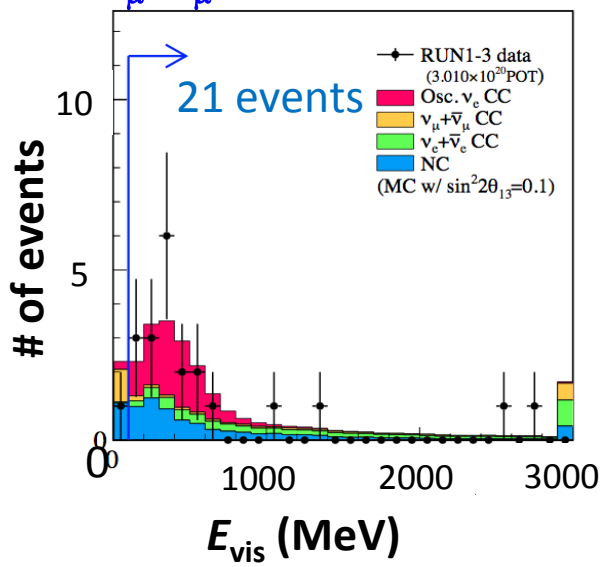




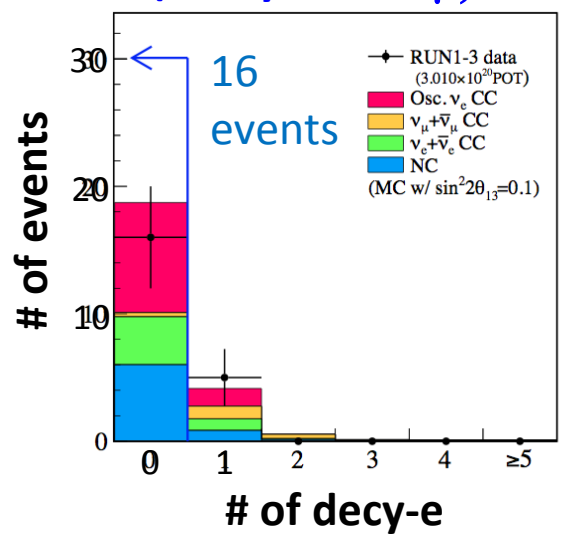


ν_e Event Selection

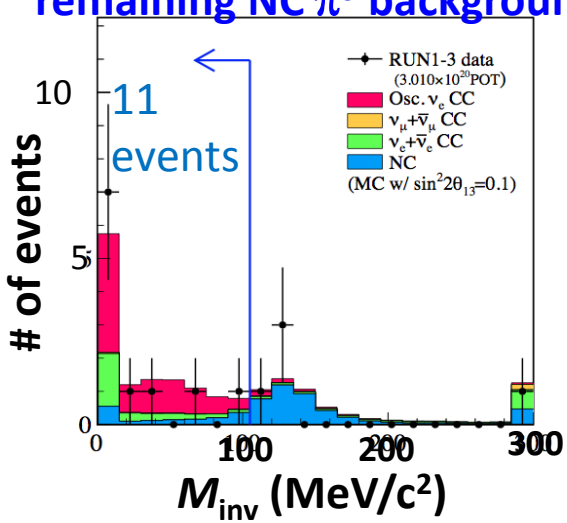
E_{vis} > 100 MeV(to reject $\nu_\mu+\bar{\nu}_\mu$ CC & NC background)



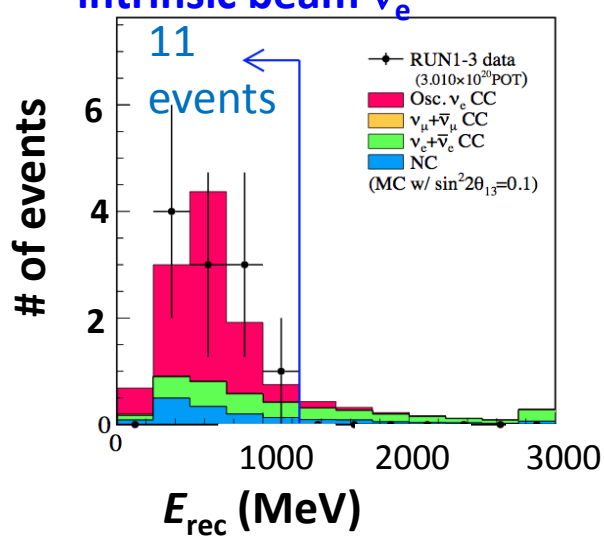
No decay-electron (decay *e* from μ)



M_{inv} < 105 MeV/c² to reject remaining NC π^0 background

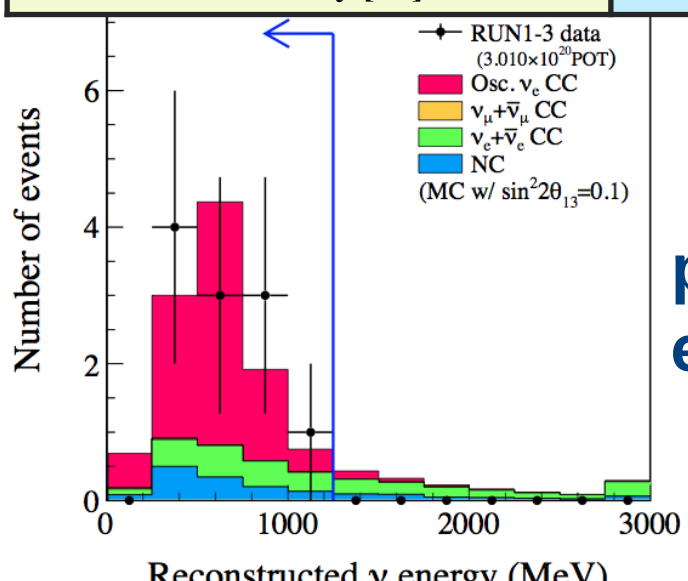


E_{rec} < 1250 MeV to reject intrinsic beam ν_e



ν_e candidate event selection

RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}=0.1$				
		Signal $\nu_\mu\rightarrow\nu_e$	BG total	CC ($\nu_\mu+\bar{\nu}_\mu$)	CC($\nu_e+\bar{\nu}_e$)	NC
Fully contained FV at beam timing	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}>100MeV	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 cut	11	8.05	4.32	0.09	2.60	1.64
E_ν^{rec} < 1250 MeV (MC $\sin^2 2\theta_{13}=0$ case)	11	7.81 (0.18)	2.92 (3.04)	0.06 (0.06)	1.61 (1.73)	1.25 (1.25)
Efficiency [%]		60.7	1.0	0.0	20.0	0.9



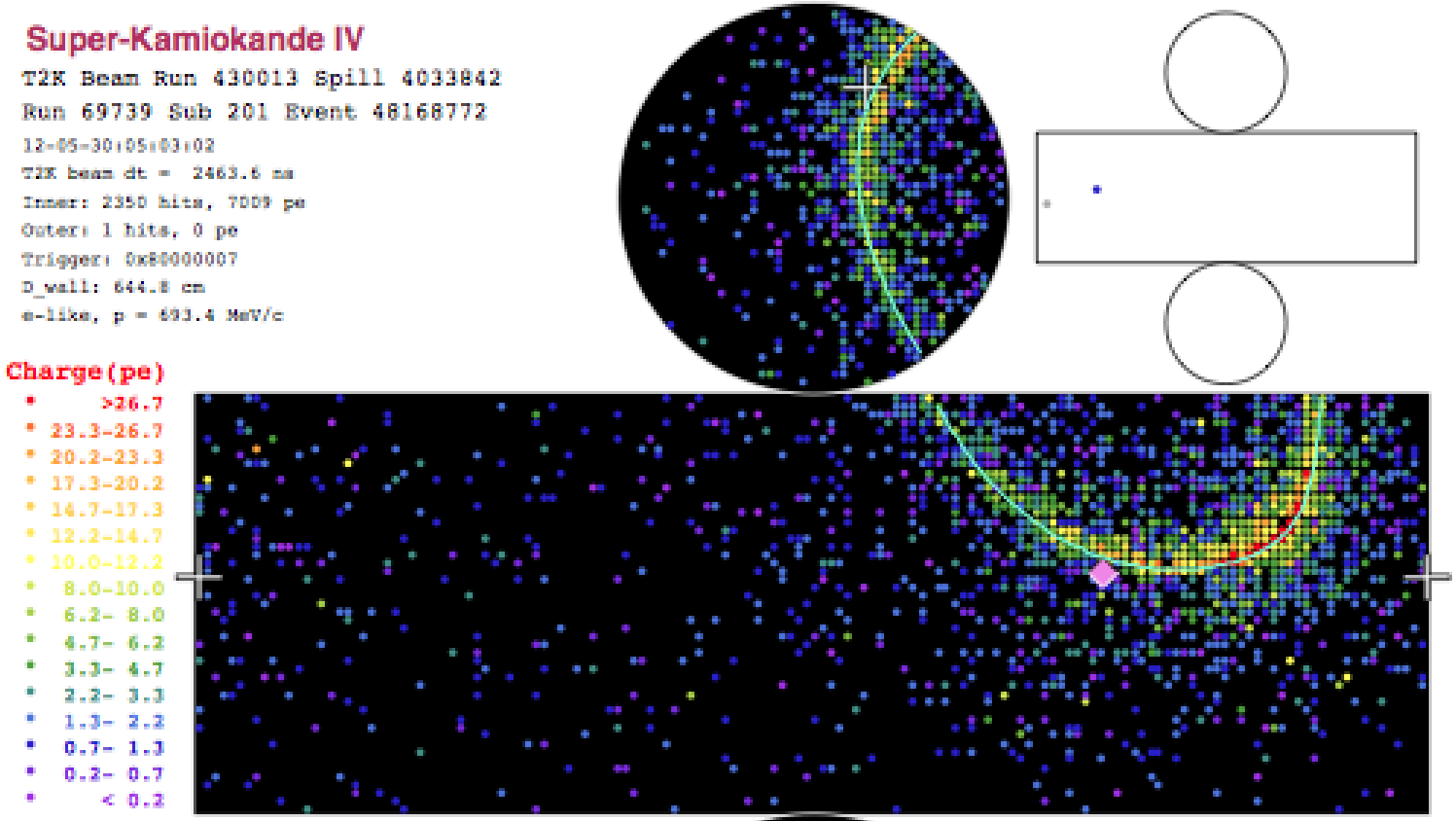
11 events observed

(N_{exp}=3.22±0.43 for $\sin^2 2\theta_{13}$=0)

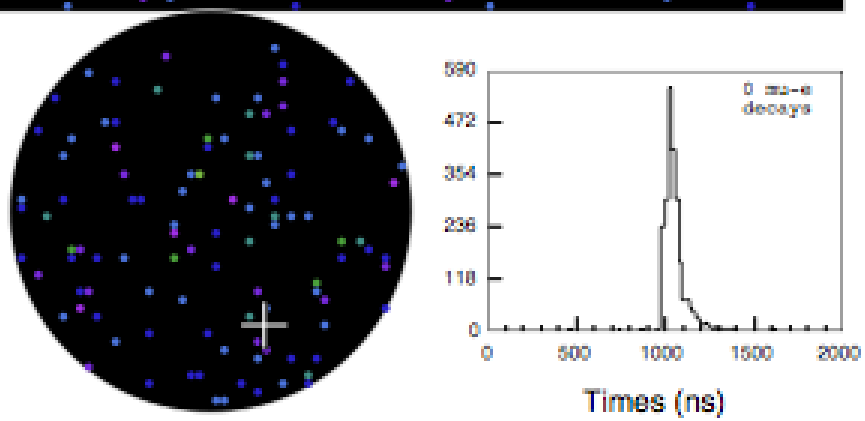
p-value to observe 11 or more events with θ_{13}=0 is 0.08% (3.2σ)

Evidence of ν_e appearance !

Latest ν_e candidate event (Run3)



visible energy : 693.4 MeV
# of decay-e : 0
2γ Inv. mass : 1.2 MeV/c^2
recon. energy : 943.1 MeV



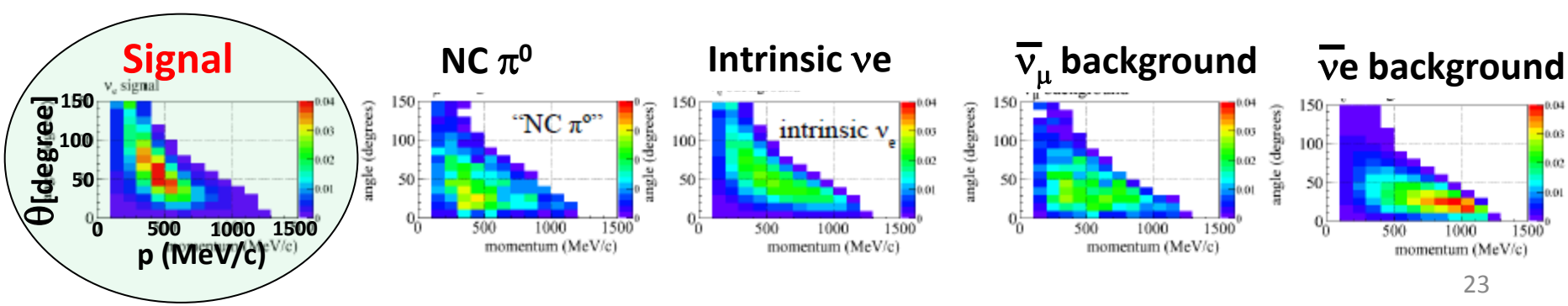
Oscillation parameter fit

Three analysis methods used:

- **Maximum likelihood fit using 2D-distributions of electron momentum & angle → presented here**
- Maximum likelihood fit using reconstructed neutrino energy distribution
- "Rate Only" analysis → Single energy bin using Feldman-Cousins technique

  → All three methods result in consistent values

Difference in p_e-θ_e distribution gives good discrimination of signals from backgrounds:



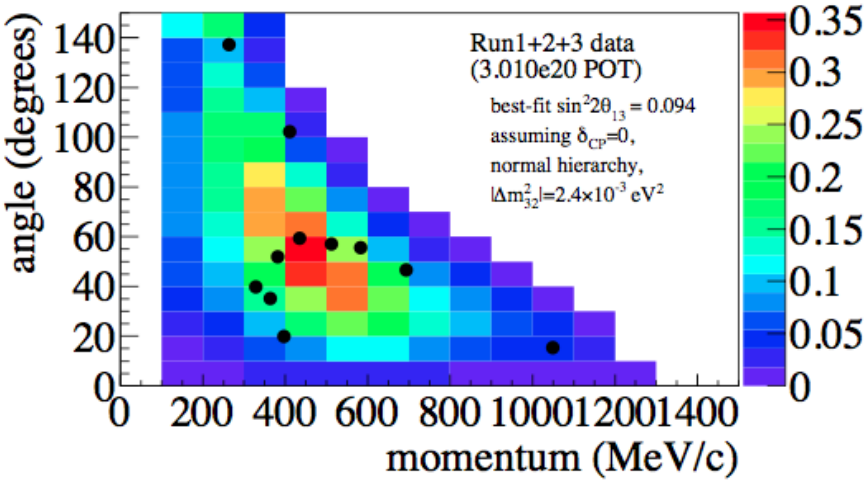
Fit Results: Using Extended Likelihood

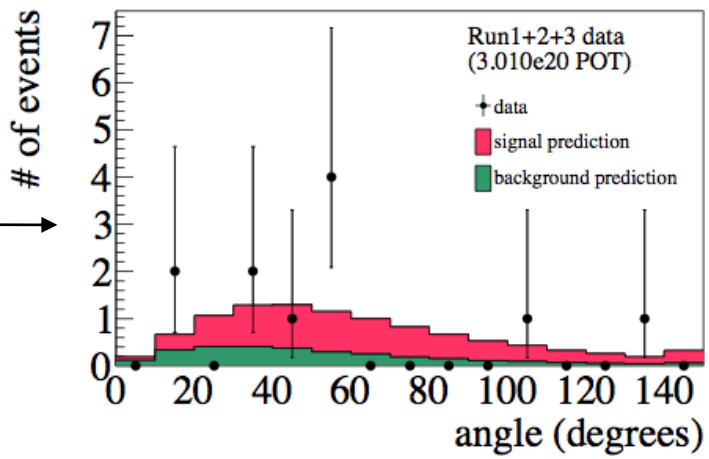
$$\mathcal{L}(\underline{N_{obs.}}, \underline{x}; o, f) = \mathcal{L}_{norm}(N_{obs.}; \underline{o}, f) \times \mathcal{L}_{shape}(x; o, f) \times \mathcal{L}_{syst.}(\underline{f})$$

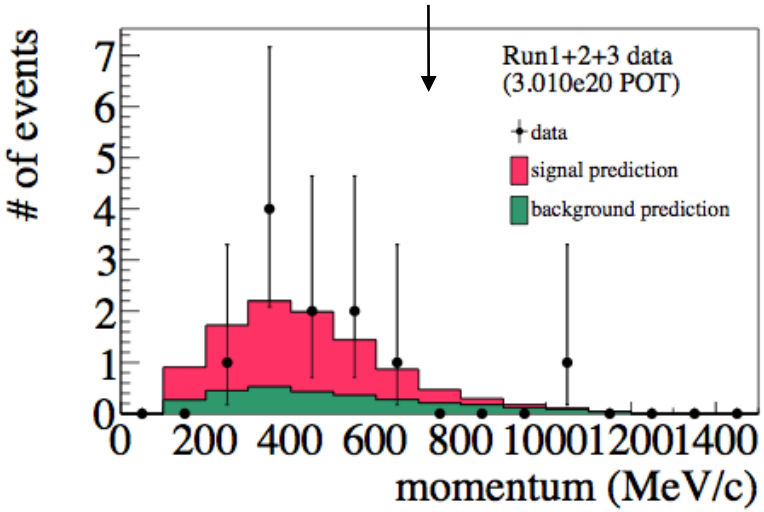
measurement variables

oscillation parameter

systematic parameters (prior: ND280 results)







Assuming : Normal Hierarchy ,

$\delta_{cp} = 0$,

$|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2 , and

$\sin^2 2\theta_{23} = 1$

→ Best Fit: $\sin^2 2\theta_{13} = 0.094$

→ 68% C.L. $0.054 < \sin^2 2\theta_{13} < 0.147$

→ 90% C.L. $0.033 < \sin^2 2\theta_{13} < 0.188$

Results: θ_{13} vs δ_{CP} Scan

Best fit w/ 68% CL errors assuming δ_{CP}=0:

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

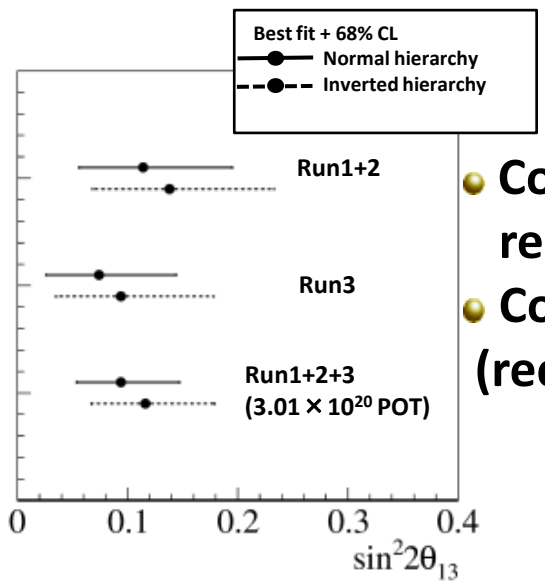
Fixed oscillation parameters

$\Delta m^2_{12}=7.6\times10^{-5}$ eV^2

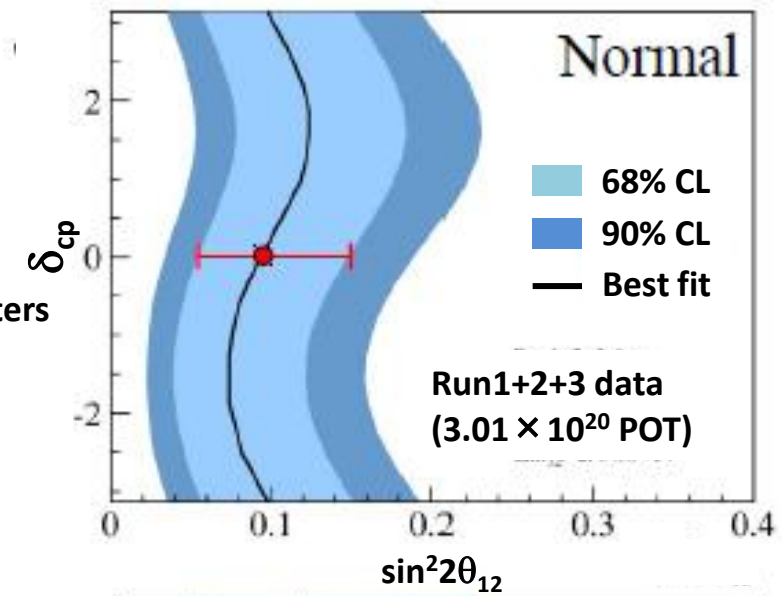
$\Delta m^2_{32}=\pm2.4\times10^{-3}$ eV^2

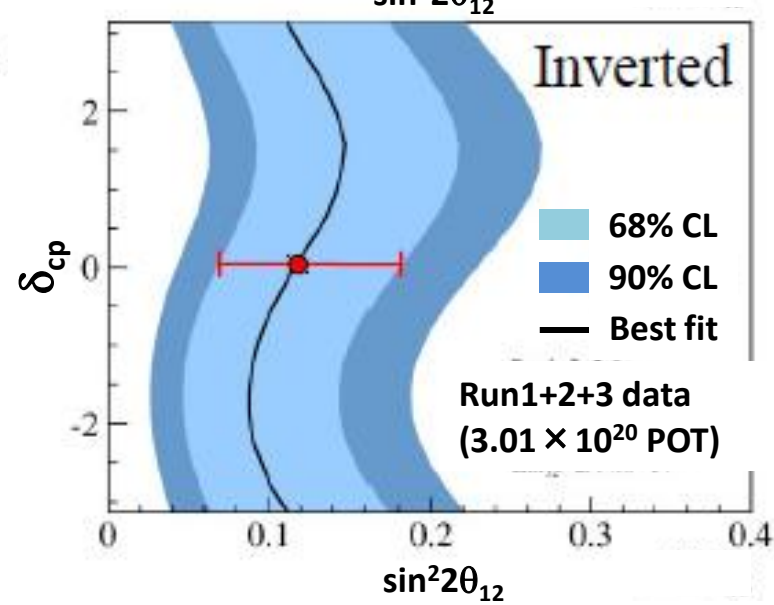
$\sin^2 2\theta_{12}=0.8704$

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



- **Consistent Run 1+2 & Run 3 results**
- **Consistent with rate+shape (rec. E_ν) and rate only method**





ν_μ Disappearance (Run1+2)

31 ν_μ candidate events using 1.43×10^{20} POT

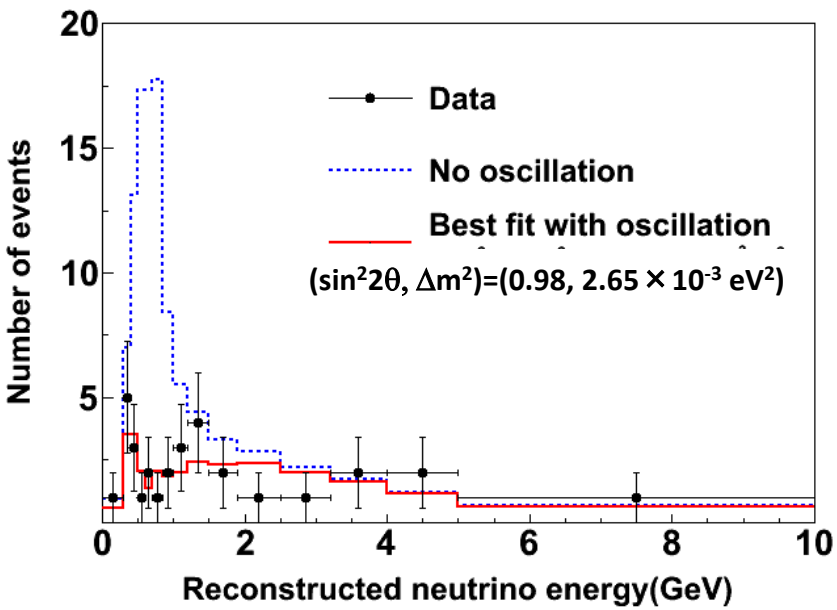
103.6 events expected w/ no oscillation

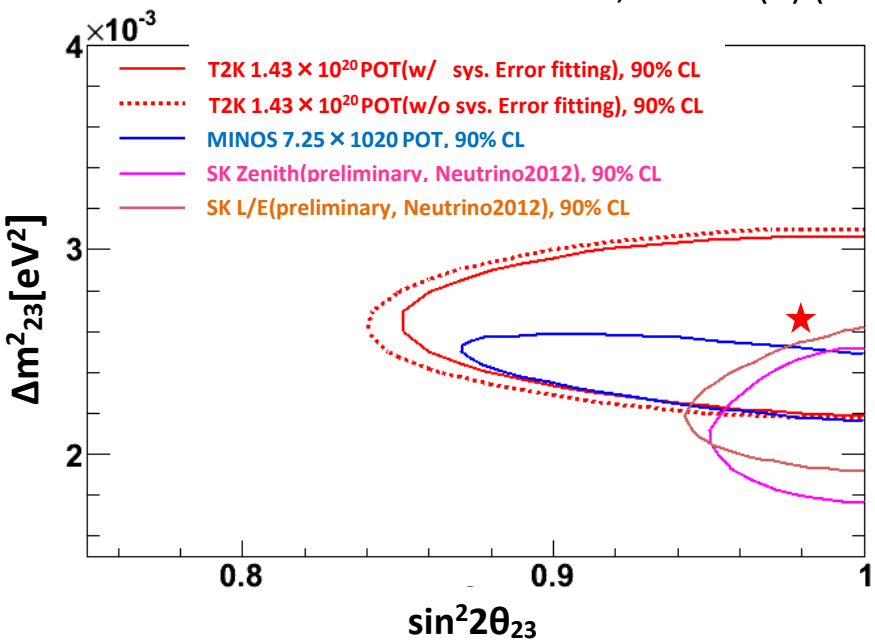
(Event selection: 1-ring, μ-like, $p_\mu > 200$ MeV/c, & # of decay-e < 2)

Best Fit: $\sin^2 2\theta_{23} = 0.98$

$\Delta m^2_{23} = 2.65 \times 10^{-3}$ eV^2

PHYSICAL REVIEW D 85, 031103(R) (2012)





Result with all data(Run1+2+3) is coming soon.

4. Summay

Summary

- ν_e appearance result using 3.01 x 10^{20} POT(~4% of proposed exposure)
  - 11 candidate events observed
  - P-Value is 0.0008 (equivalent to 3.2σ for excluding θ_{13}=0)
    - Confirms previous result: 6 events with 1.5±0.3 expected for 1.43 × 10^{20} POT [PRL 107, 041801, 2011]

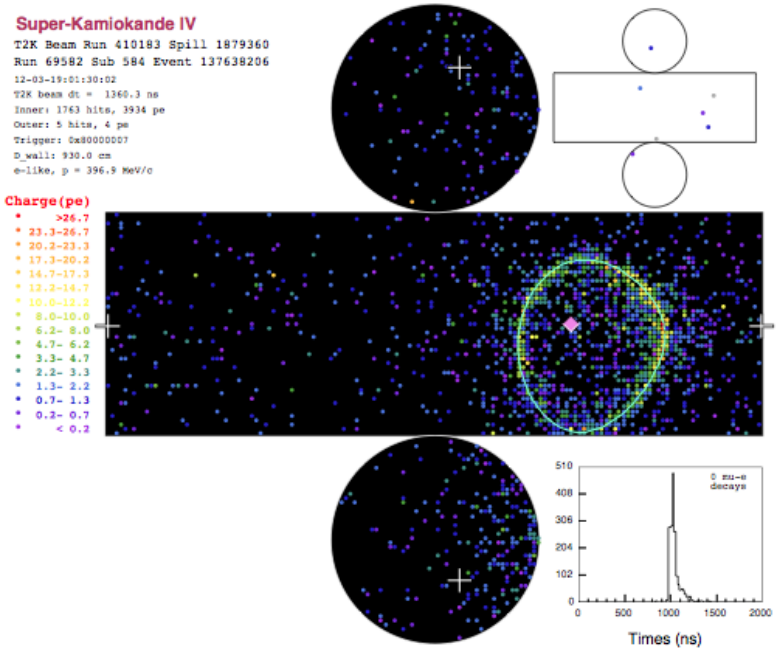
- ν_μ disappearance is observed based on 1.43 x 10^{20} POT
  - Consistent with other experiments
  - Updated ν_μ disappearance measurement soon
  - Important input to:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$
$$+ (\text{CPV term}) + (\text{matter term}) \ldots$$

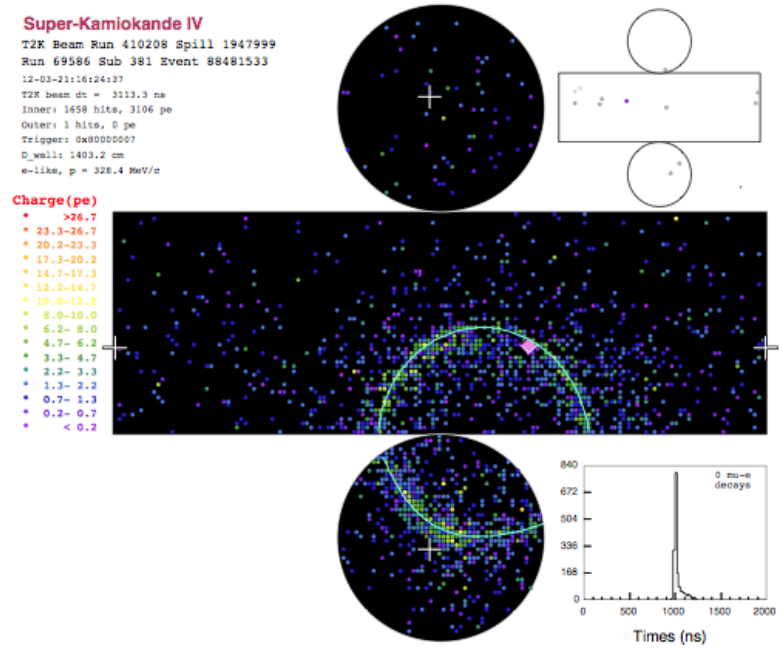
- Future high power runs are planned:
  - 8 × 10^{20} POT (2013) → 12 × 10^{20} POT (2014) →18 × 10^{20} POT (2015)

ν_e candidate events (Run3)

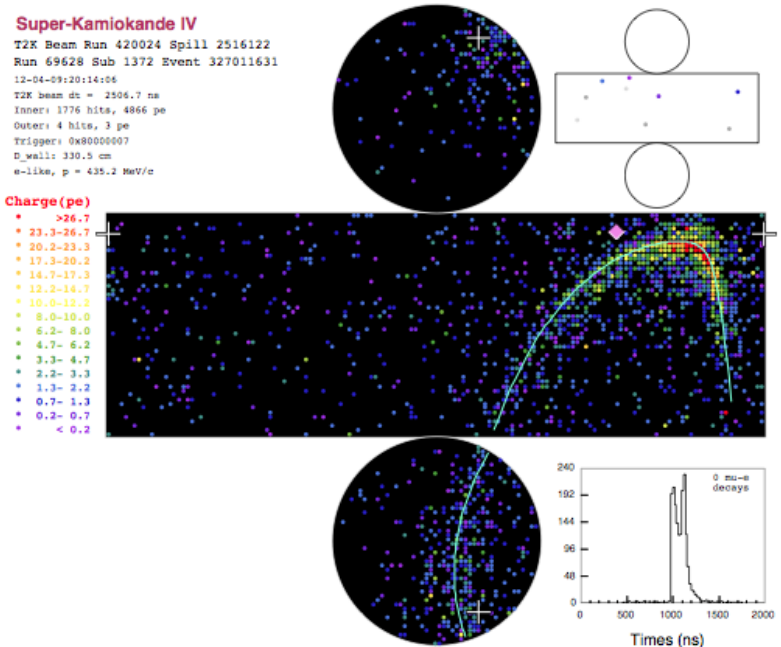
#7



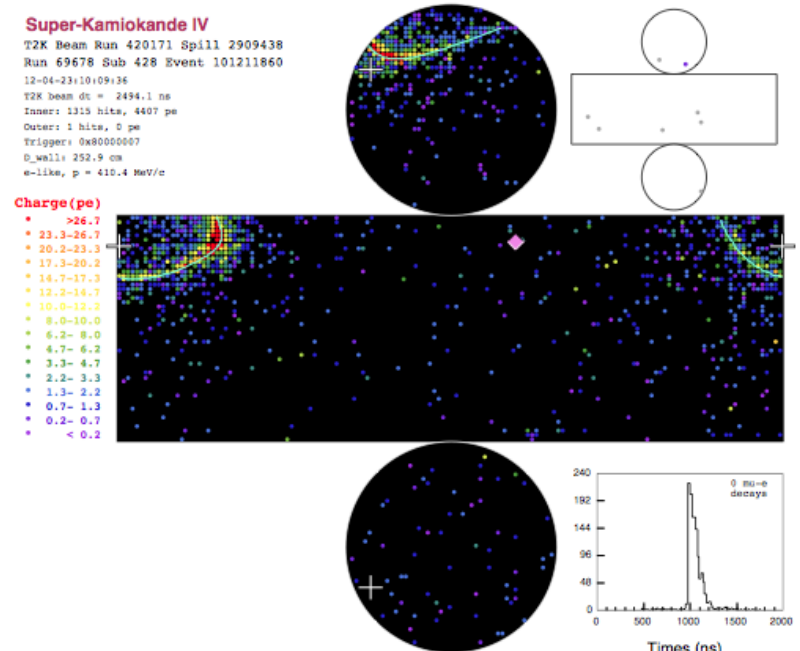
#8



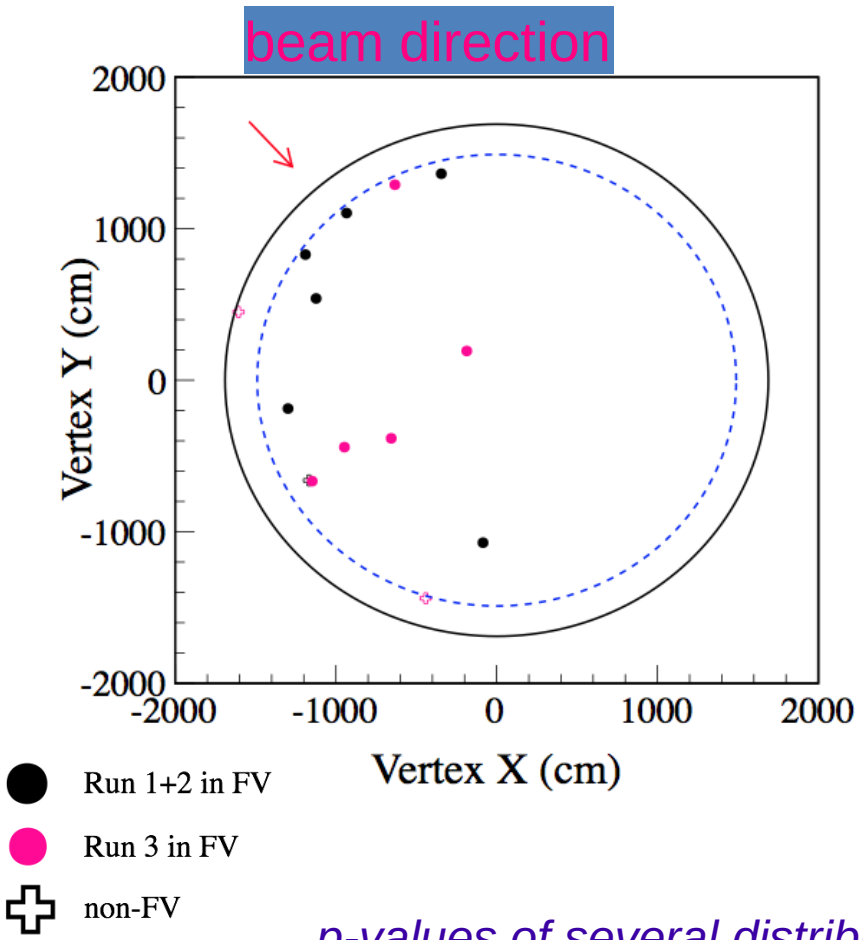
#9

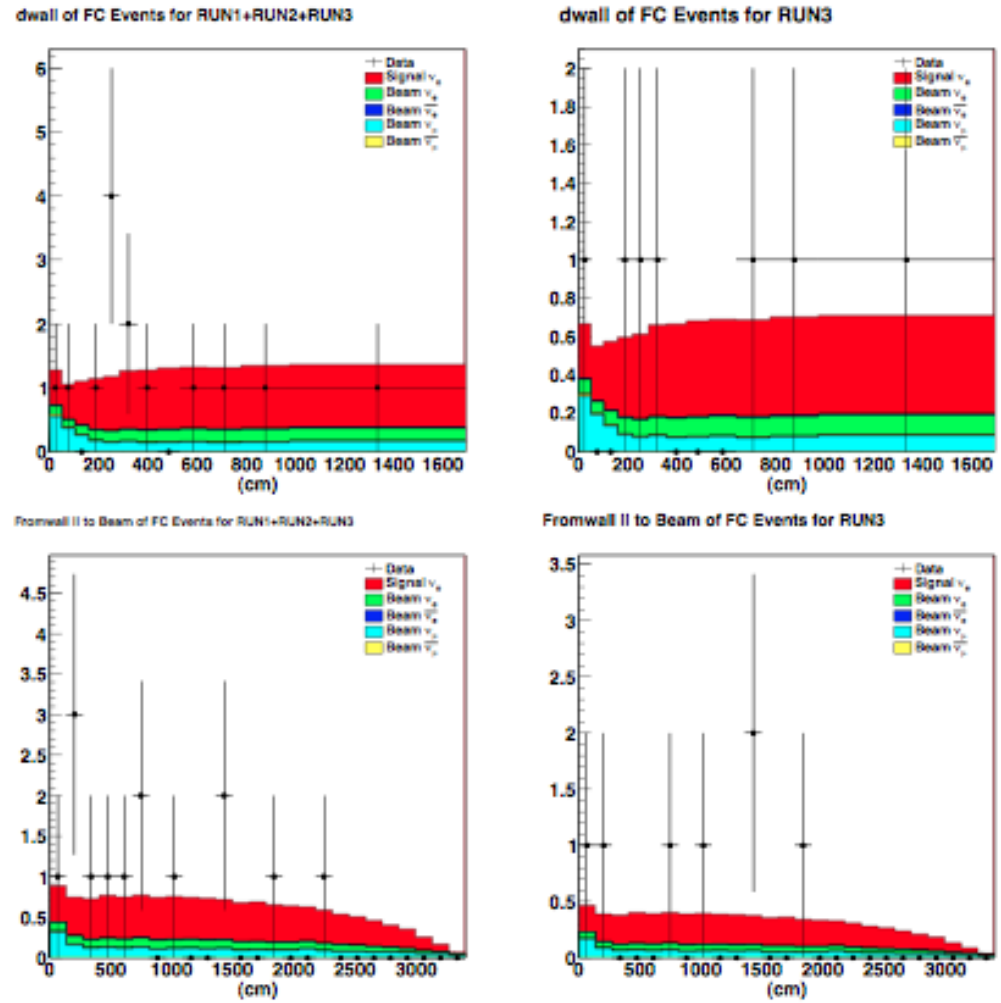


#10



Vertex distribution

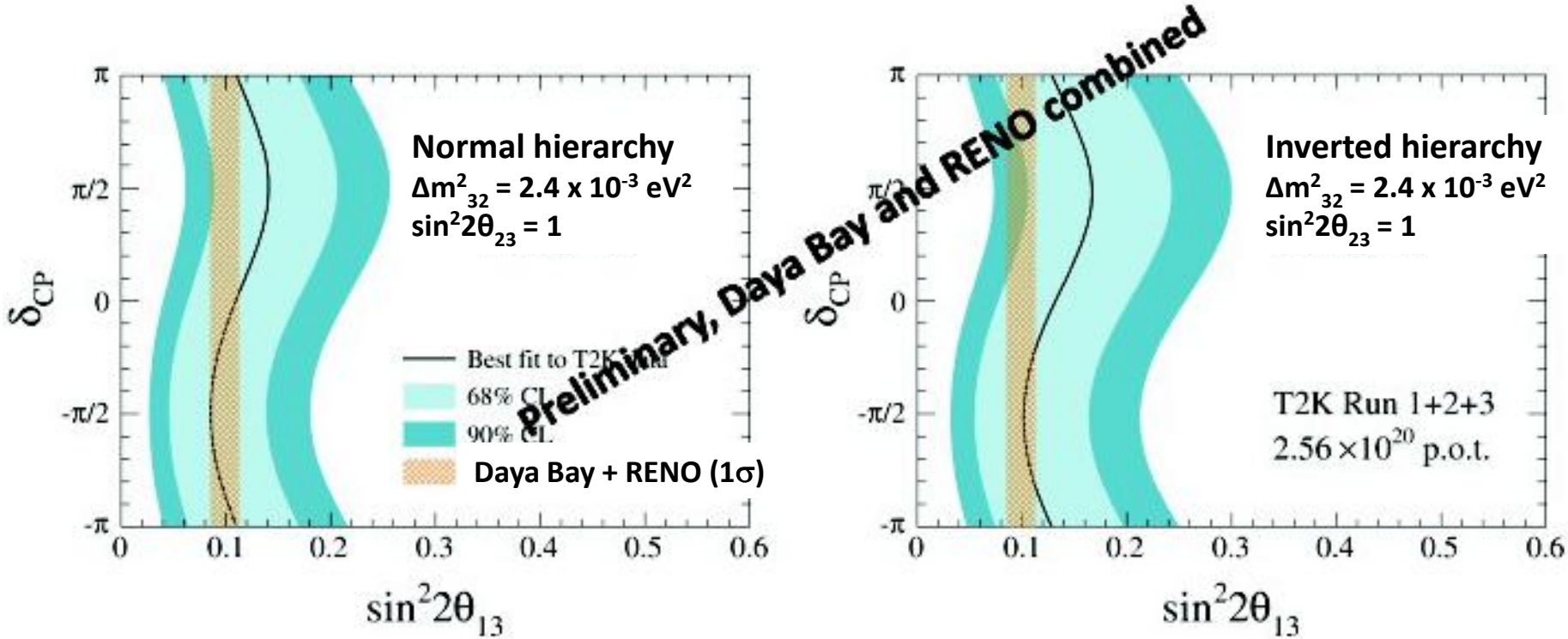




p-values of several distribution are calculated w/ toy MC

	RUN1+2	RUN3	RUN1+2+3
$Dwall$	22.9%	94.7%	39.4%
$Fromwall\ \mathrm{beam}_{\parallel}$	1.34%	35.2%	6.05%
$R^2 + Z$	10.5%	74.6%	32.4%

T2K and (Daya Bay + RENO)

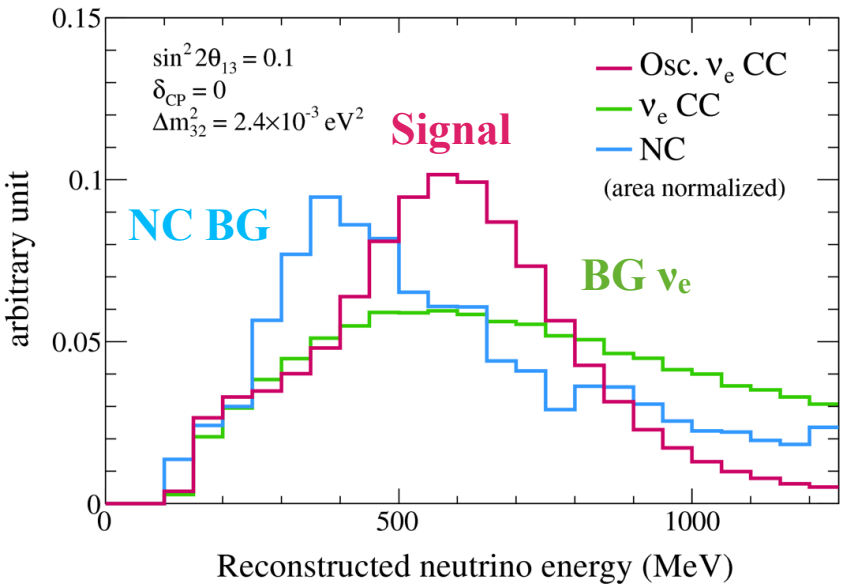


Daya Bay: arXiv:1203:1669
RENO: arXiv: 1204:0626

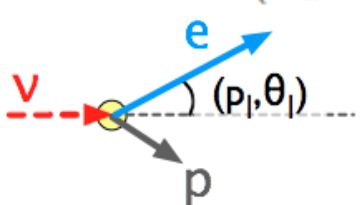
Oscillation fit

Method 2 : Rate + reconstructed Ev shape (1D)

Fit data to the reconstructed energy distribution

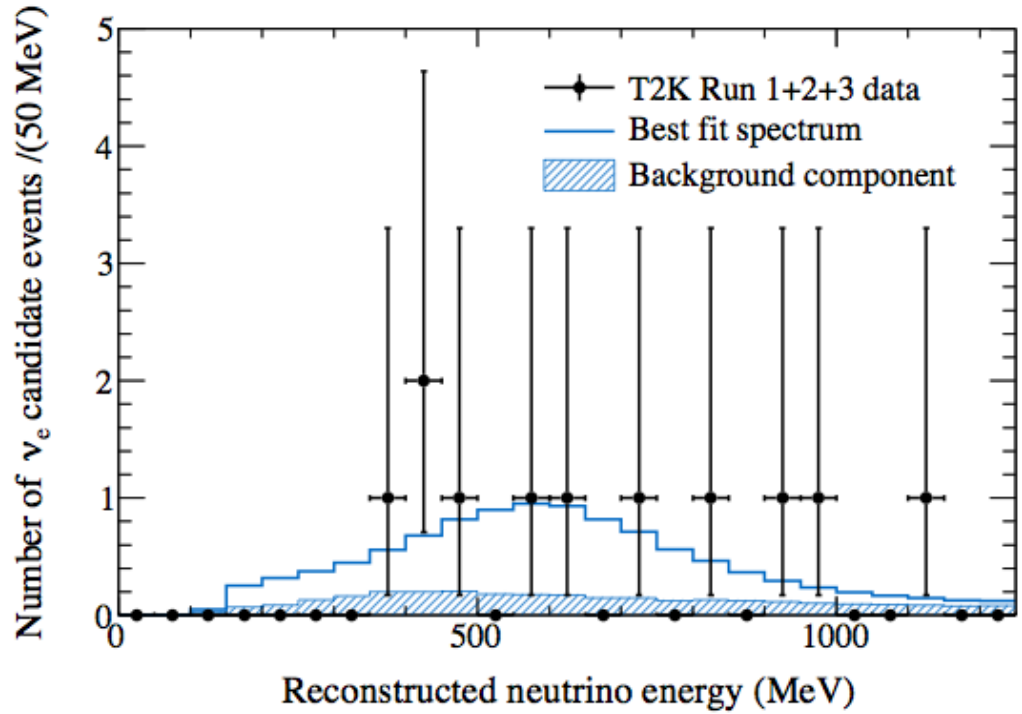


$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$



Fit result

assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$,
Normal hierarchy



best fit w/ 68% CL error

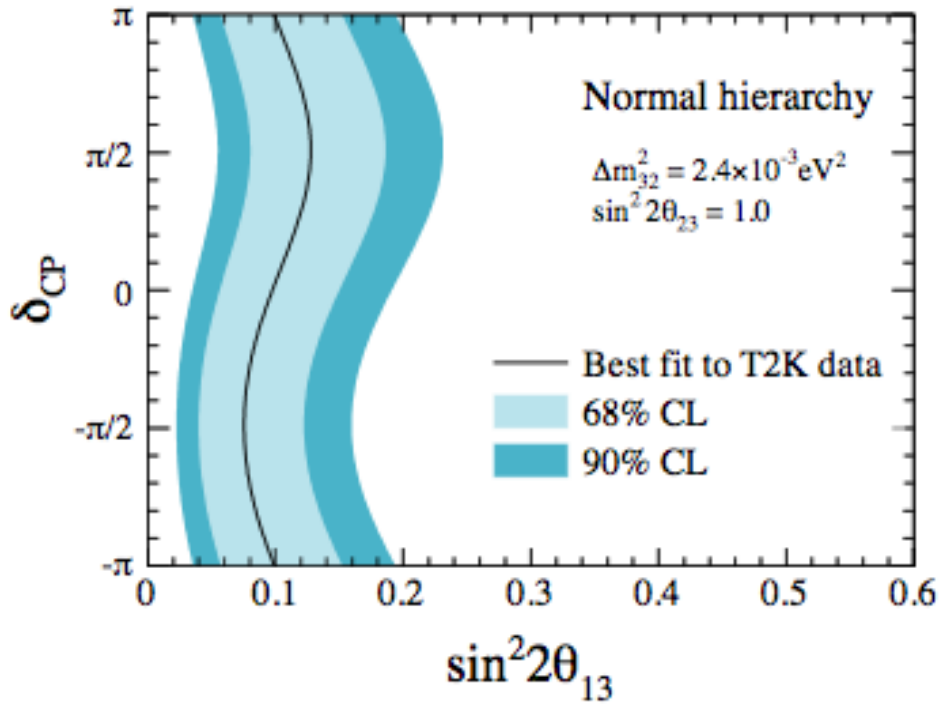
$$\sin^2 2\theta_{13} = 0.098^{+0.052}_{-0.042}$$

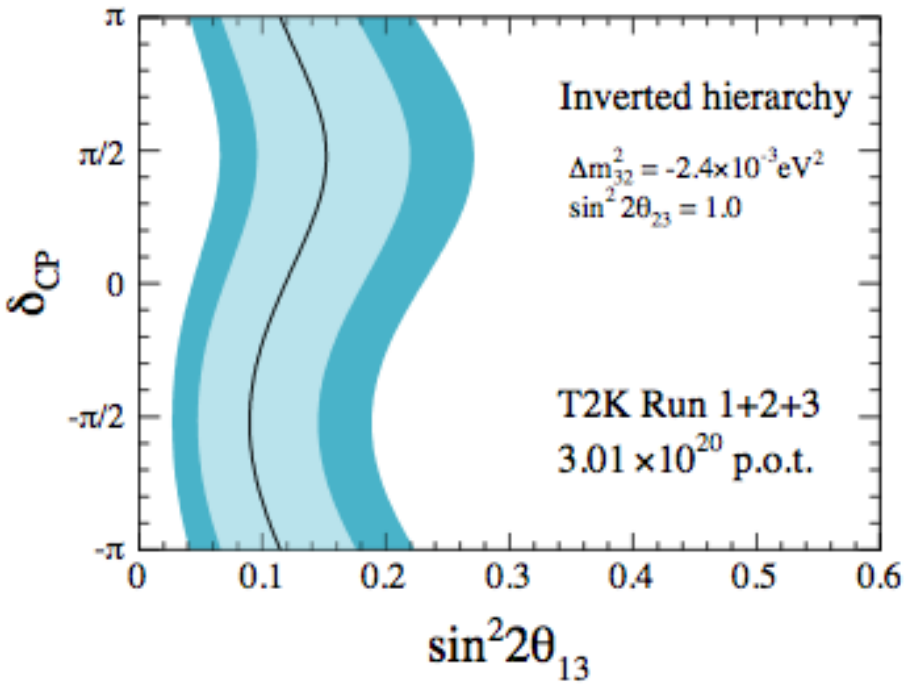
Oscillation fit results

assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23}=1$

Method 2 : Rate + reconstructed Ev shape (1D)

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}





best fit w/ 68% CL error @δ_{CP}=0

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.098^{+0.052}_{-0.042}$$

inverted hierarchy:

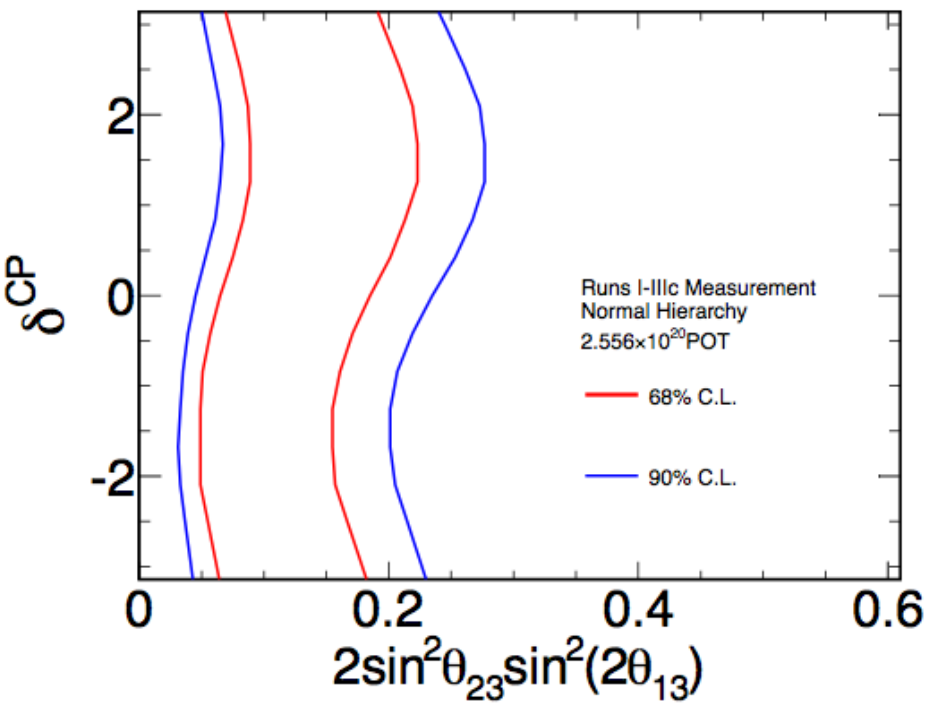
$$\sin^2 2\theta_{13} = 0.118^{+0.063}_{-0.049}$$

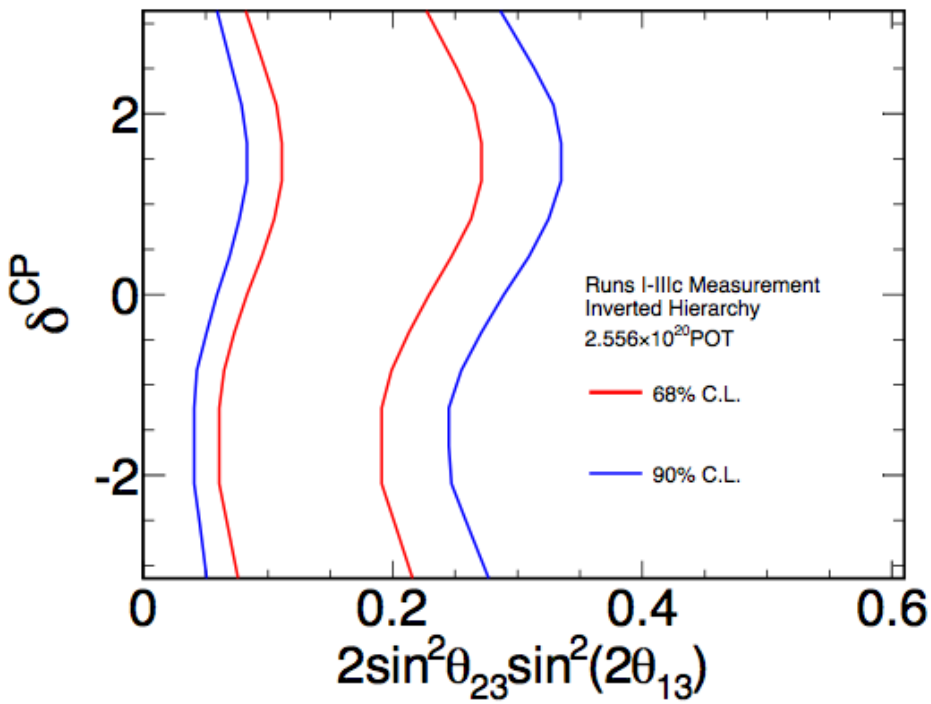
Oscillation fit

Method 3 : Rate only (Feldman & Cousins method)

assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23}=1$

w/ 2.56×10^{20} p.o.t.



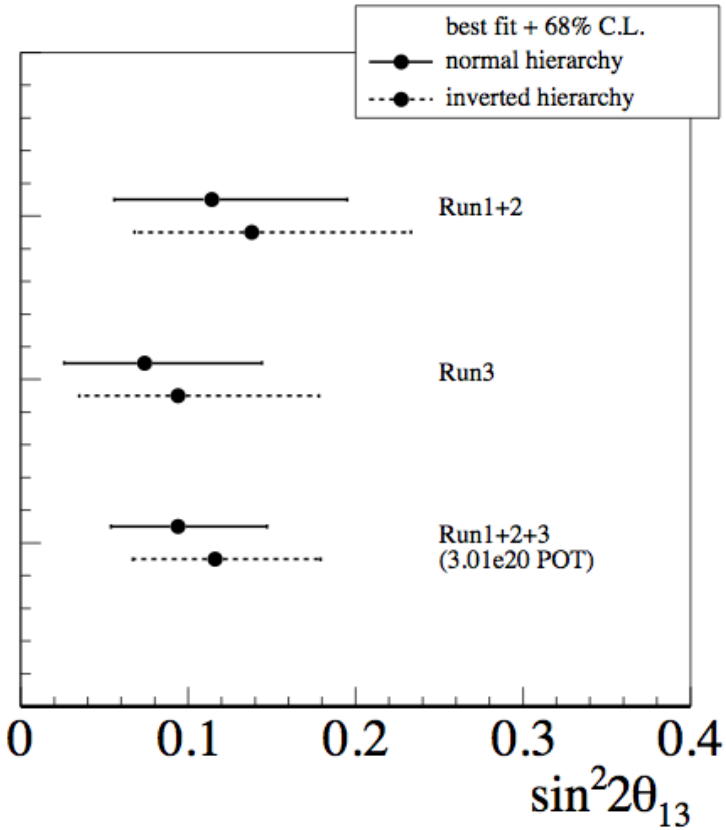


Results obtained from all the three analysis are consistent

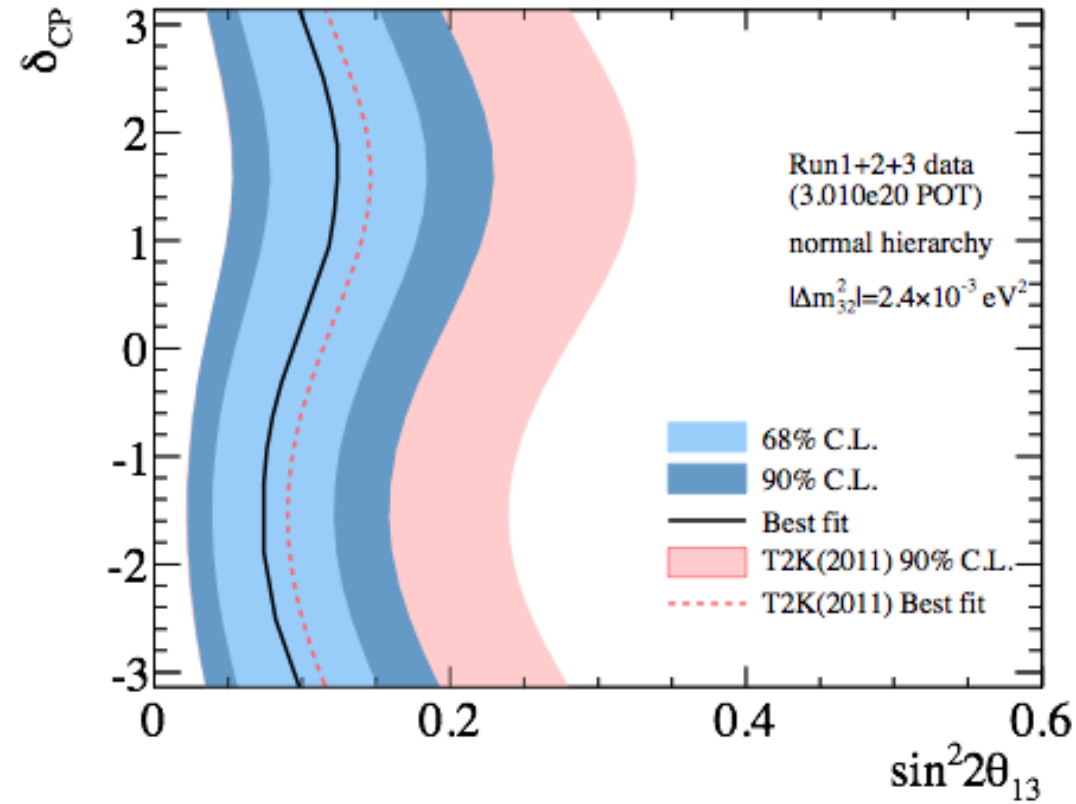
assuming $\sin^2 2\theta_{23}=1$

Comparison w/ 2011 results

Best-fit + 68% C.L. error for individual run period



Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}



Results w/ Run3 only are consistent with Run1+2

This result is consistent w/ the 2011(Run1+2) results and is improved