Results from T2K

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2012/July/5, ICHEP 2012

1. Introduction
2. ν_e appearance analysis

   We report an updated analysis of ν_e appearance using the full data set collected

3. Summary

Physics Motivation

★ Discovery of $\nu_\mu \rightarrow \nu_e$

Direct detection of neutrino flavor mixing in "appearance" mode

ν_μ to ν_e plays an important role to study CPV, mass hierarchy

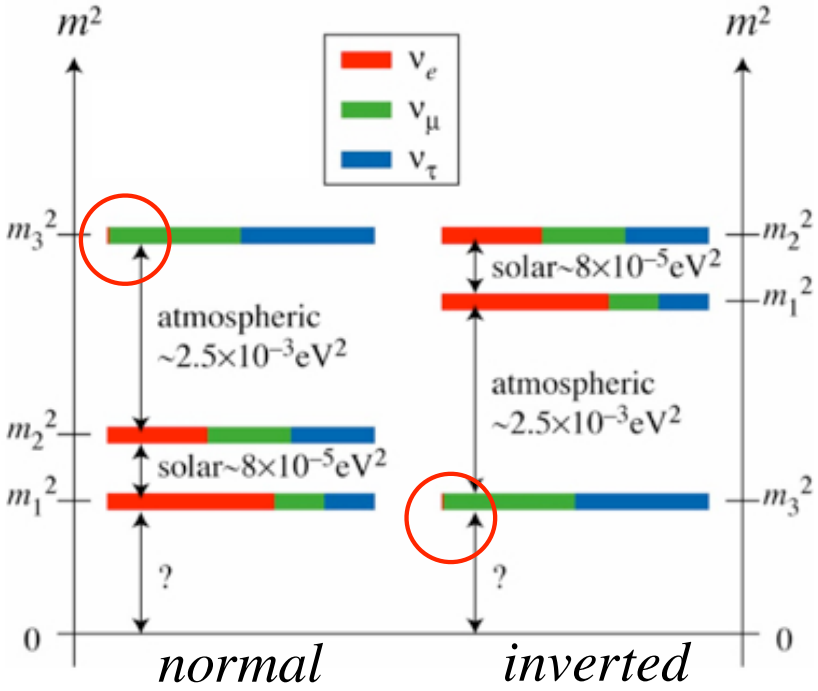
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$

$$+ (\text{CPV term}) + (\text{matter term}) \ldots$$

open a possibility to measure CP violation in lepton sector

CPV term in $P(\nu_\mu \rightarrow \nu_e) \propto \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

Neutrino mass & three flavor mixing



Mixing angle: θ_{12}, θ_{23}, θ_{13}

$\theta_{12} = 34° \pm 3°$ $\theta_{23} = 45° \pm 5°$

θ_{13} measurement

$\sin^2 2\theta_{13} = 0.11\ ^{+0.10}_{-0.06}$ (T2K 2011)

(assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$, $\Delta m^2_{32}=2.4 \times 10^{-3}$ (NH))

p-value for $\theta_{13}=0$ was 0.007 (2.5σ)

First indication of non-zero θ_{13}

Phys.Rev.Lett. 107, 041801, 2011

T2K (Tokai-to-Kamioka) experiment

Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

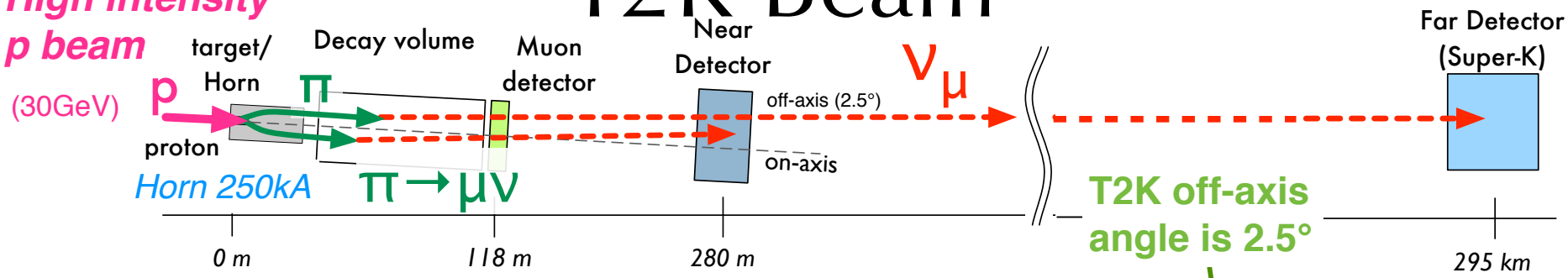
T2K Main Goals:

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

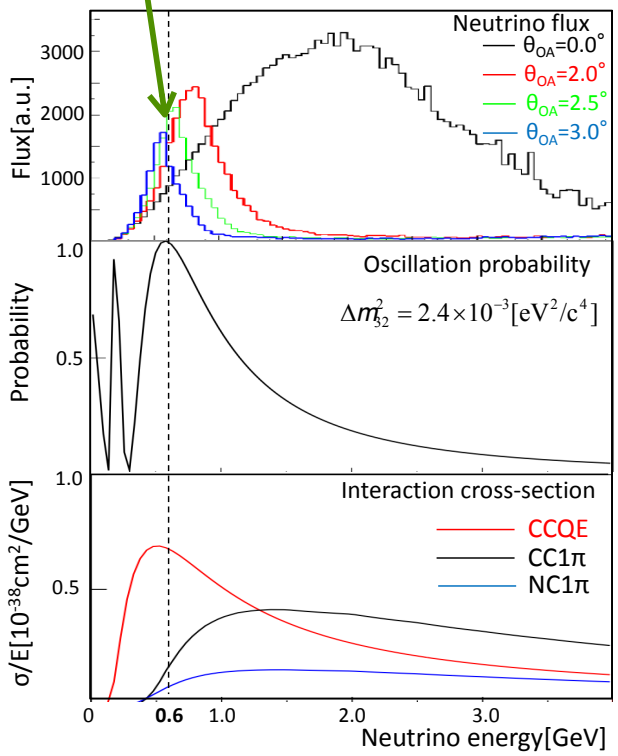
★ Precision measurement of ν_μ disappearance

2011 ν_μ results : Phys.Rev. D 85, 031103(R), 2012

T2K Beam



T2K off-axis angle is 2.5°



Intense & high quality beam

* Off-axis ν_μ beam

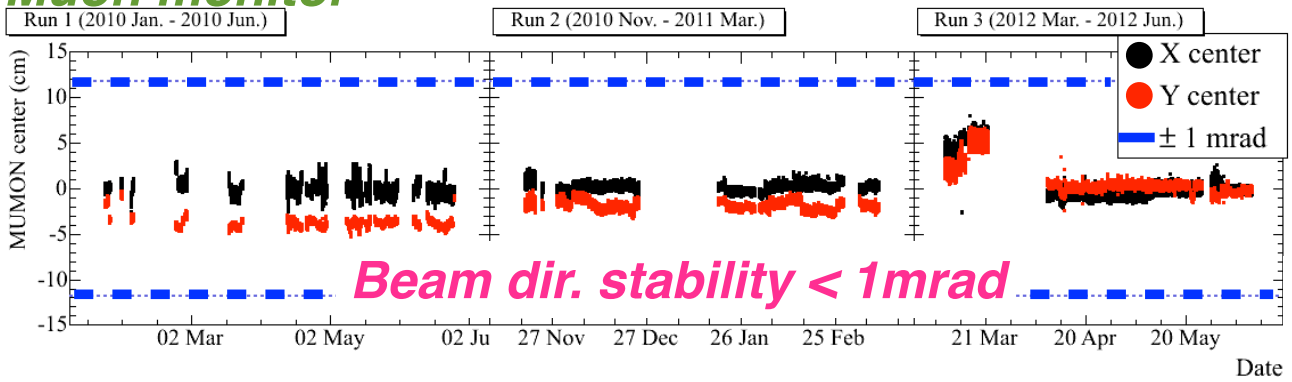
- Low energy narrow band beam
- E_ν peak around oscillation maximum (~0.6GeV)
- Small high energy tail → reduce background events in T2K
  (e.g. NC1π^0 is one of ν_e background)

* Small intrinsic ν_e contamination (~1%) from μ,K decays

π, K production is measured in CERN NA61 exp.

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

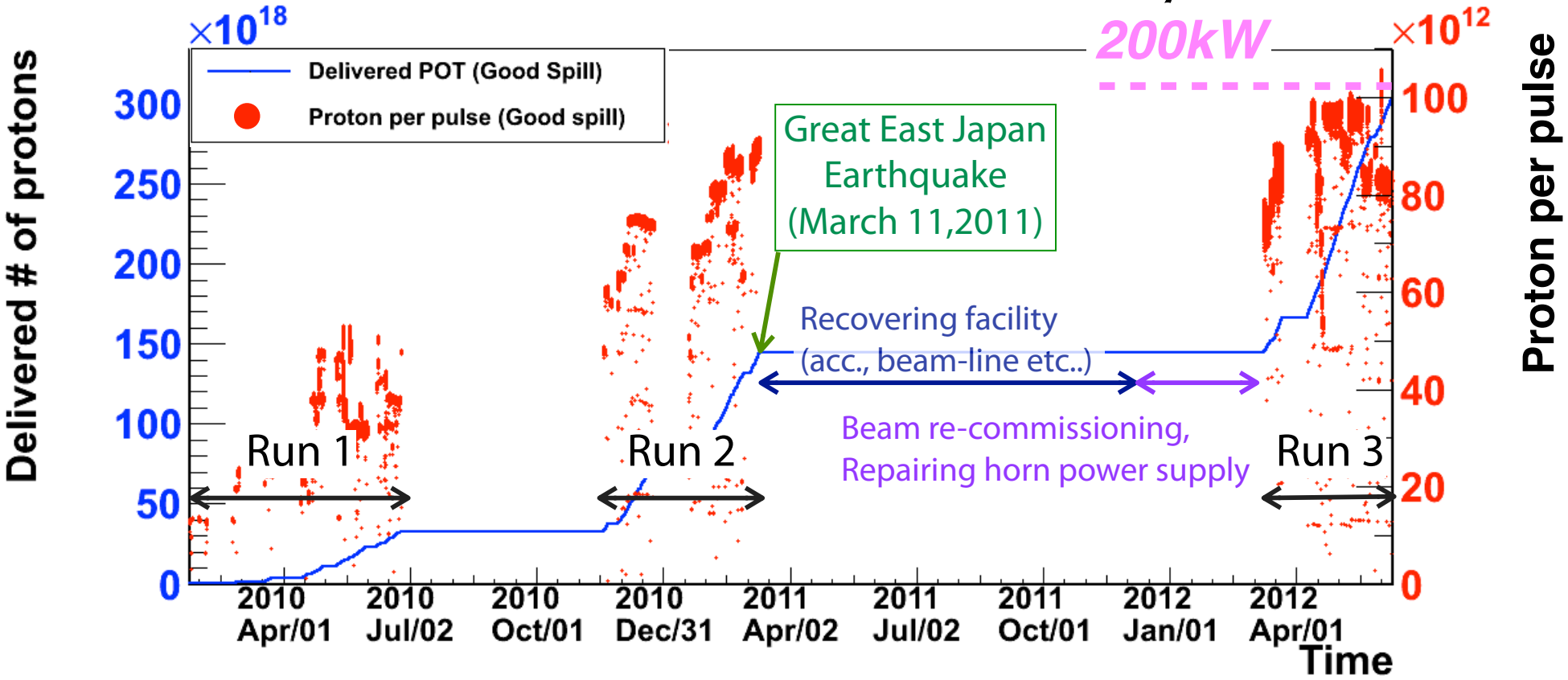
Muon monitor



Important to keep beam direction stable

(requirement) < 1mrad direction shift
→ < ~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

Data for today's talk (full data set up to now) = 3.01 x 10^{20} p.o.t.
(18% of increase from Neutrino2012)

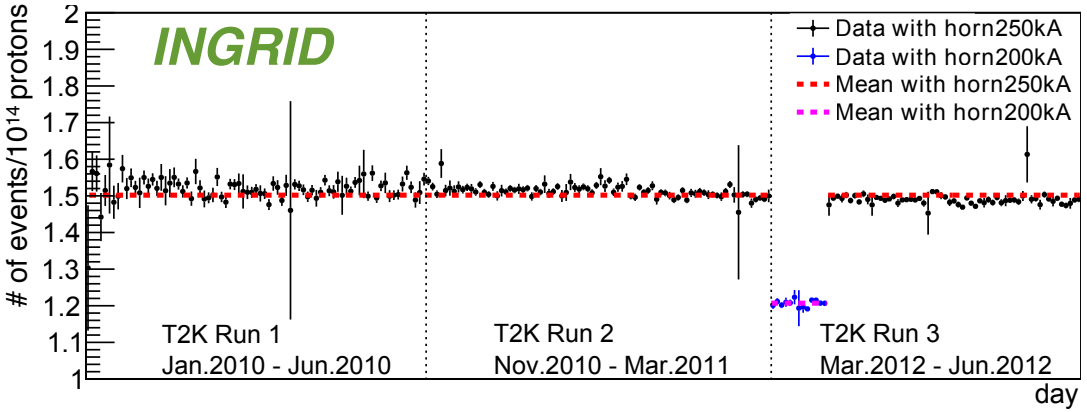
Near detector measurements

@280m from target

On-axis detector (INGRID)

v beam monitor
(rate, direction and their stability)

Off-axis detector (ND280)

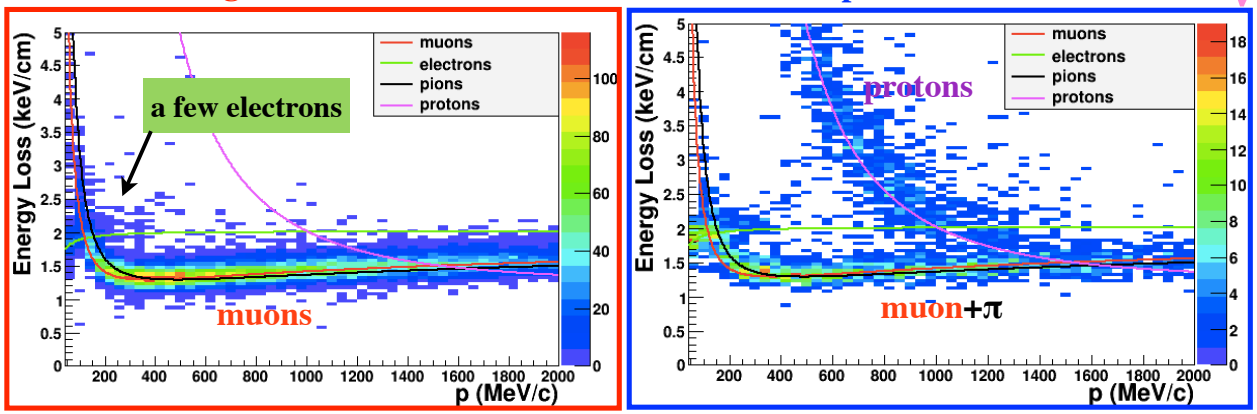


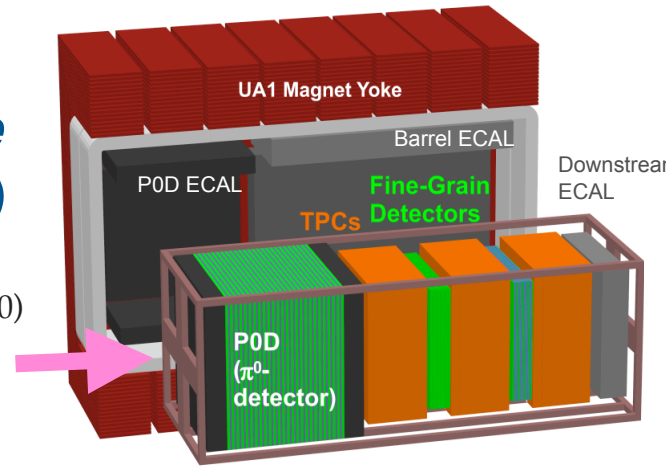
ν_μ CC event measurements is used in oscillation analysis (M.Ravonel's talk)

ν_e CC event and NCπ^0 event measurements are checked (background events for ν_e appearance)

(G.Lopez's talk)

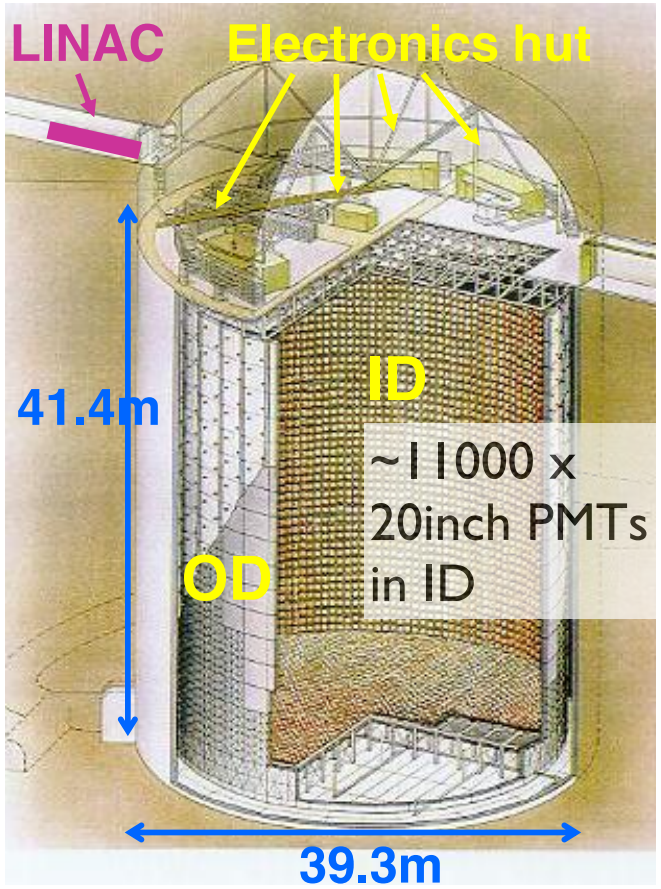
(Poster: Measurement of the electron neutrino component of the T2K beam at ND280)





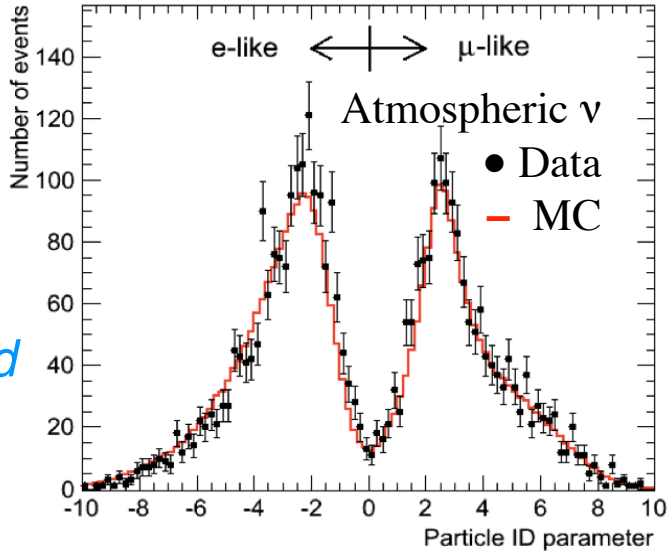
- Dipole magnet w/ 0.2T
- **P0D:** π^0 Detector
- **FGD+TPC:** Target + Particle tracking
- **EM calorimeter**
- **Side-Muon-Range Detector**

Far detector (Super-K) measurements

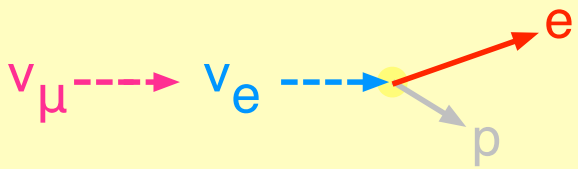


- Water Cherenkov detector w/ fiducial volume 22.5kton
- Record all the hit PMTs within ±500μsec centered at the beam arrival time
- Detector performance is well-matched at sub GeV
  - Good e-like (shower ring) / μ-like separation

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



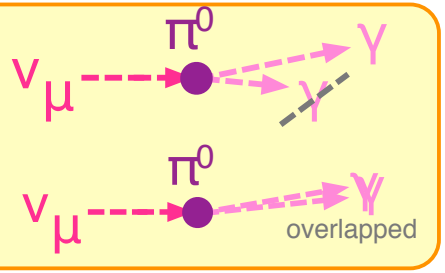
Signal: single ring electron



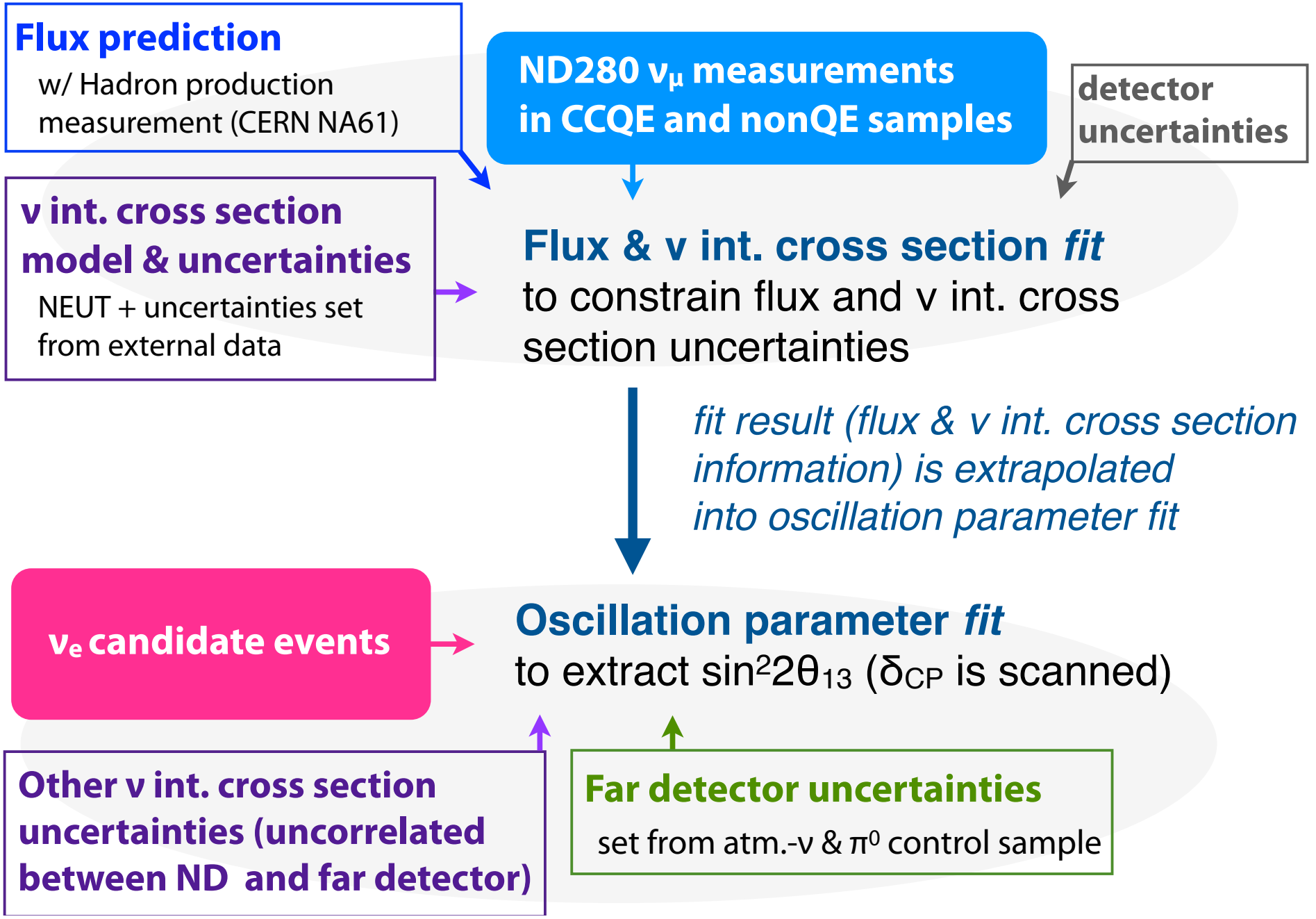
Background:

intrinsic ν_e in beam

π^0 from NC interaction



Oscillation analysis method

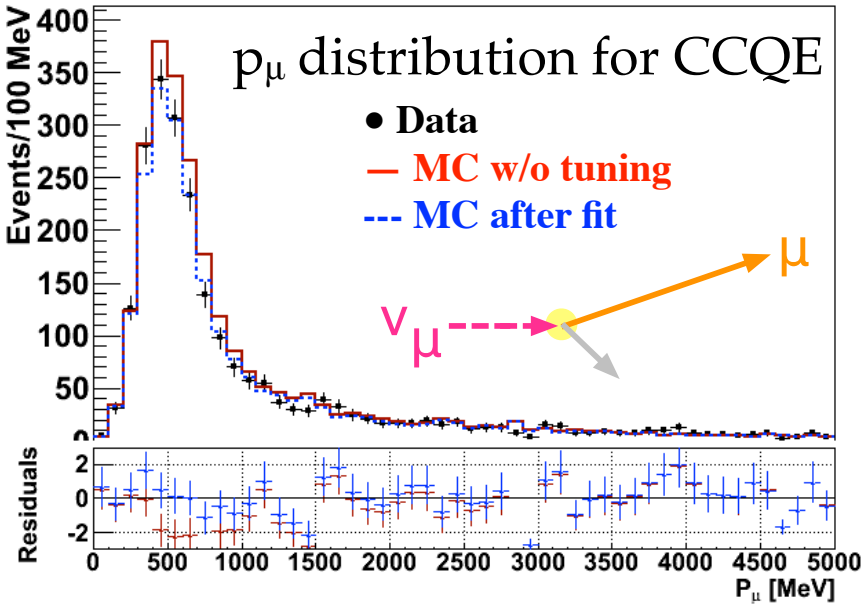


Flux & ν int. cross section fit w/ ND measurement

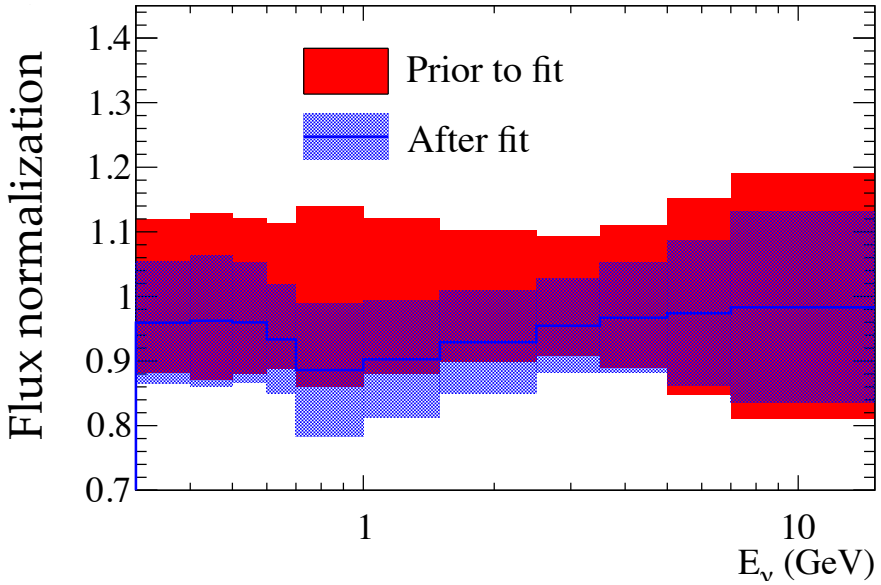
(see also M.Ravonel's talk)

Fit (p_μ, θ_μ) distribution for CCQE and nonQE enhanced samples

- Flux energy dependent errors w/ full correlations among ν types and between detectors (ND280, SK) are taken into account in prior of the fit



T2K far ν_μ flux normalization & uncertainties



Fit results are extrapolated to the prediction at far detector

the predicted event rate is corrected based on the fit results

improved constraint on the systematic errors with ND280 measurement

The predicted number of events and systematic uncertainties

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

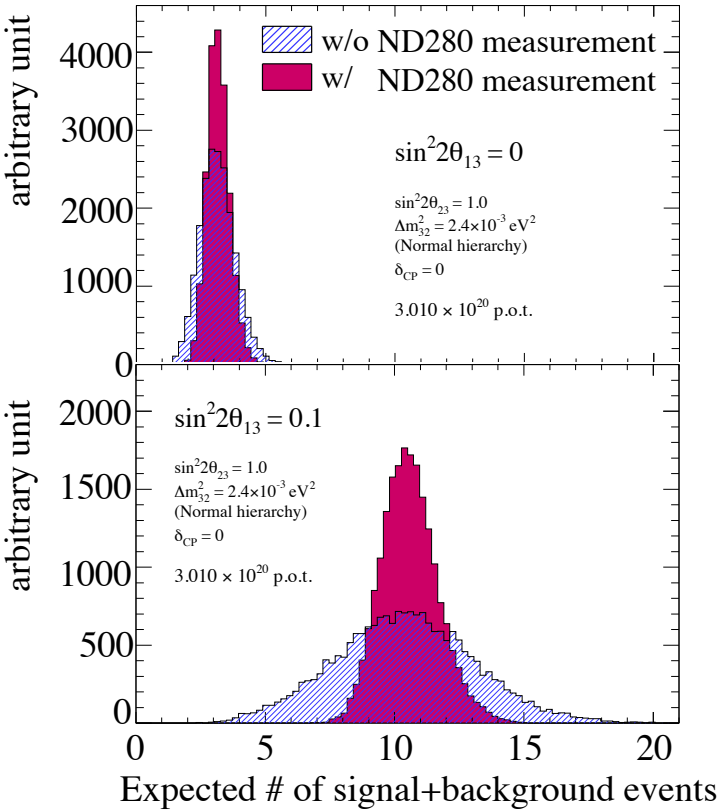
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ^0)	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

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 from the T2K 2011 results

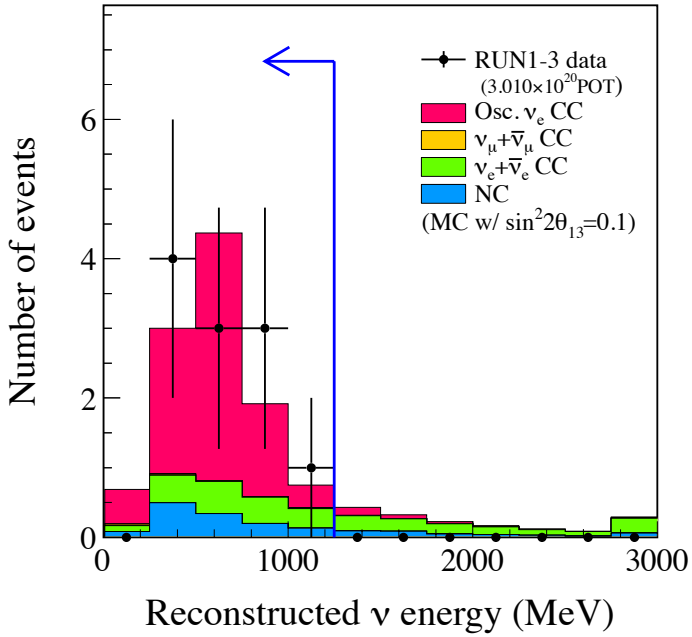
the predicted # of event distribution



Uncertainties are reduced using ND280 measurement

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
$E_\nu^{rec}<1250$ 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 candidate events are observed

$N_{exp}=3.22\pm0.43$ for $\sin^2 2\theta_{13}=0$

The probability (p-value) to observe 11 or more events with $\theta_{13}=0$ is 0.08% (3.2σ)

Evidence of ν_e appearance

Oscillation parameter fit

Performing an extended maximum likelihood fit to extract $\sin^2 2\theta_{13}$

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

measurement variables

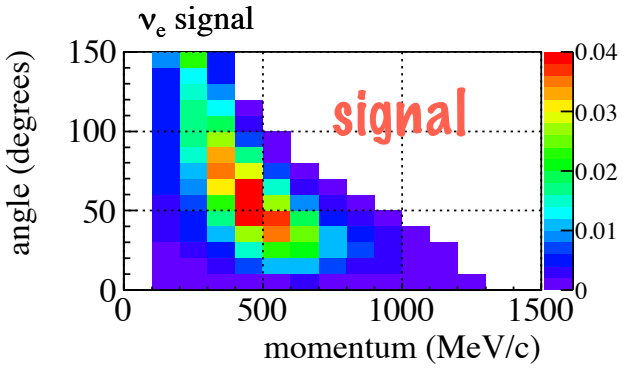
oscillation parameter

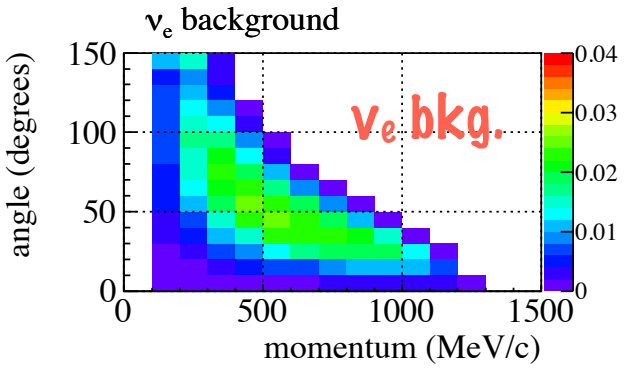
systematic parameters (prior: ND280 results)

ν oscillation parameters fixed:

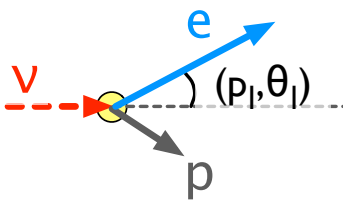
- $\Delta m_{21}^2 = 7.6\times10^{-5}\ \mathrm{eV}^2$
- $\Delta m_{32}^2 = \pm 2.4\times10^{-3}\ \mathrm{eV}^2$
- $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$

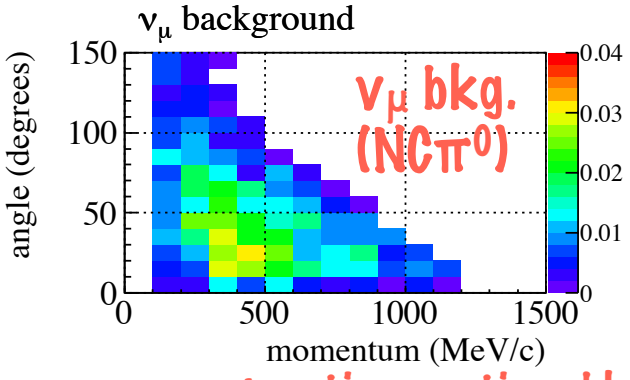
Fit data with rate + (p_e, θ_e) shape (2 dimensional) (method1)





differences in p_e-θ_e distribution allow to have a better discrimination of signal events from backgrounds





+ anti-ν_e, anti-ν_μ bkg.

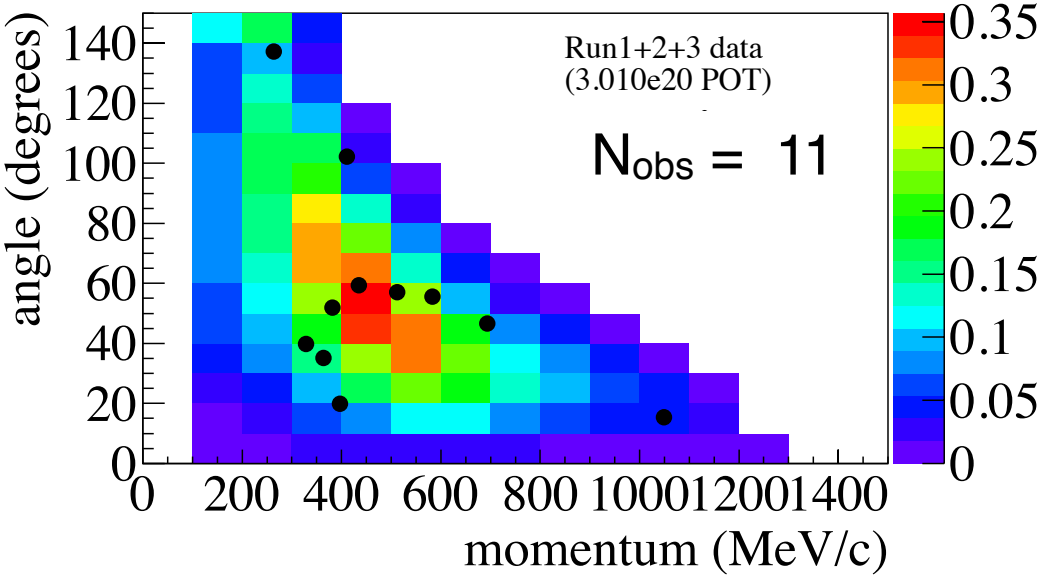
We performed three independent fits

Method2: Rate + reconstructed E_ν shape

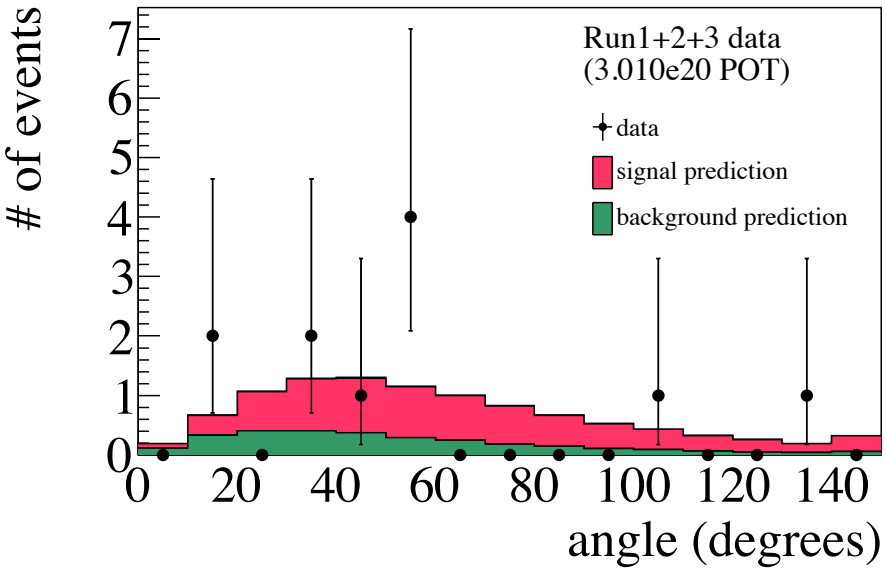
Method3: Rate only (Feldman &Cousins)

Results

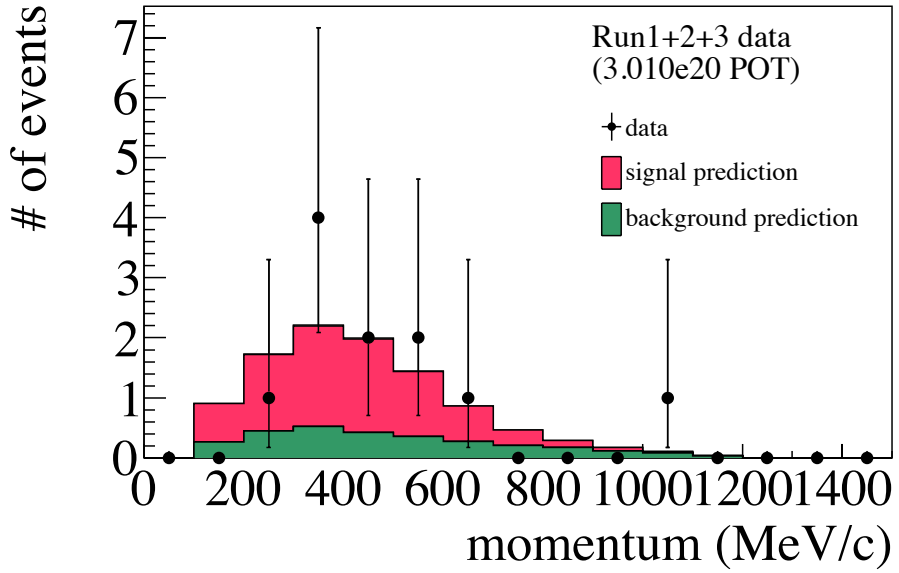
assuming $\delta_{CP}=0$, normal hierarchy
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$



(prediction histograms are based with best-fit $\sin^2 2\theta_{13}$)



preliminary



best fit w/ 68% CL error:

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

90% C.L. arrowed region:

$$0.033 < \sin^2 2\theta_{13} < 0.188$$

$N_{best\text{-}fit}$ = 10.18

Results

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:

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

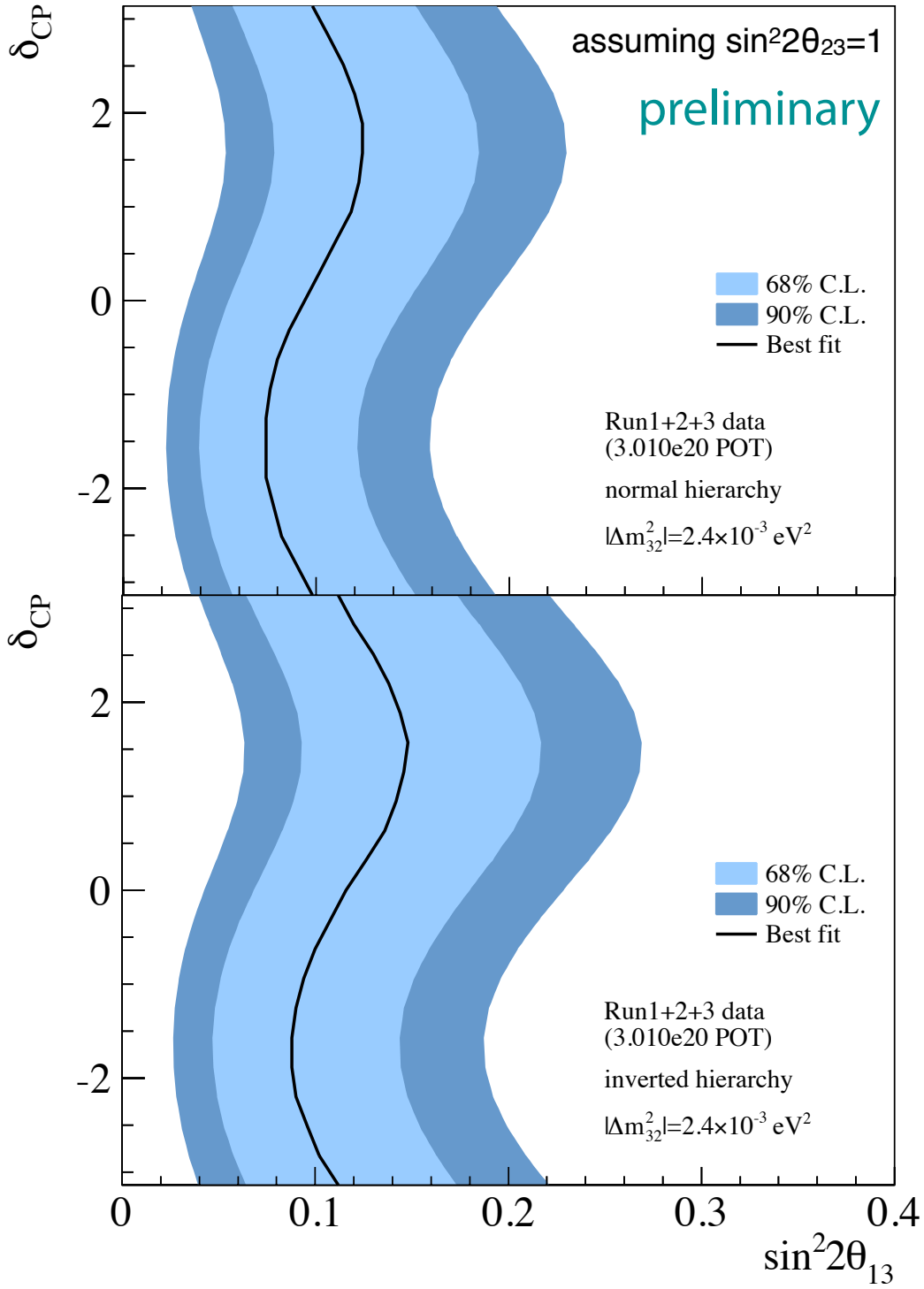
inverted hierarchy:

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

This result is consistent with rate+shape (rec. E_ν) method and rate only method

c.f 2011 result for normal (inverted) hierarchy

$$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06}\ (0.14^{+0.12}_{-0.07})$$



Summary & Outlook

- **We report new results on ν_e appearance analysis based on 3.01 x 10^{20} p.o.t. (~4% exposure of T2K's goal)**
  - 11 candidate events are observed
  - p-value is 0.08% (equivalent to 3.2σ)
  - $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$
    for Δm^2_{32} = 2.4 x 10^{-3} eV^2(NH), δ_{CP}=0, $\sin^2 2\theta_{23}$=1

Evidence of ν_e appearance → open a possibility to measure CP violation in lepton sector

- **We plan to take more data with new runs at higher beam power toward a more precise measurement of ν_e appearance**
  - **~8x10^{20} p.o.t (2013) → ~1.2x10^{21} p.o.t (2014) → ~1.8x10^{21} p.o.t. (2015)**
- **Updated results on ν_μ disappearance coming soon**
  - precise measurement of θ_{23}