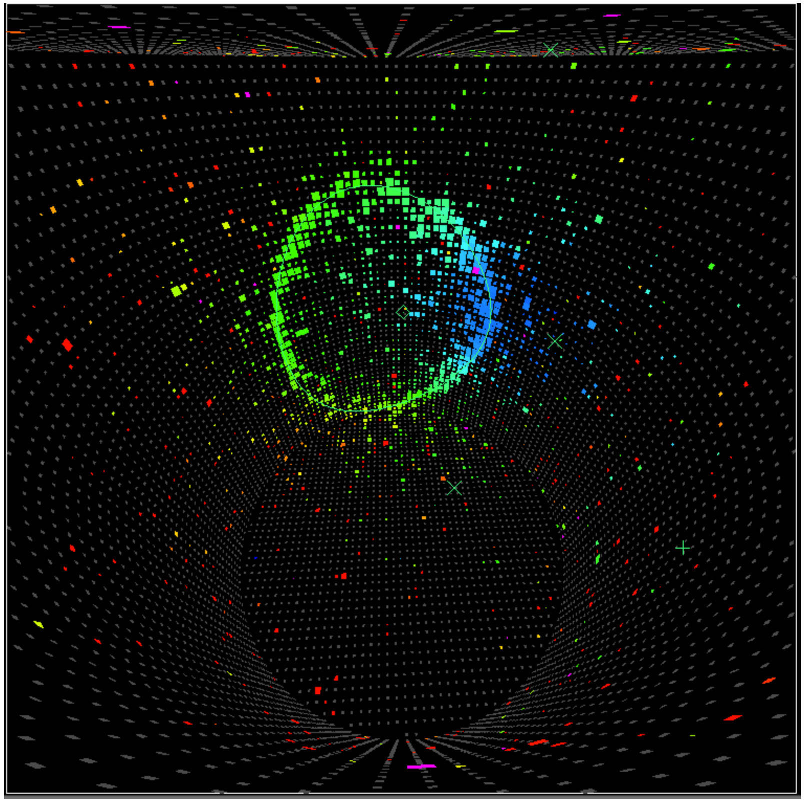
Latest results from T2K



Shoei Nakayama (ICRR)

for the T2K collaboration

August 24, 2012

@ ICRR seminar

Introduction

Neutrino oscillation

- Flavor eigenstate (ν_e, ν_μ, ν_τ) ≠ Mass eigenstate (ν_1, ν_2, ν_3)

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

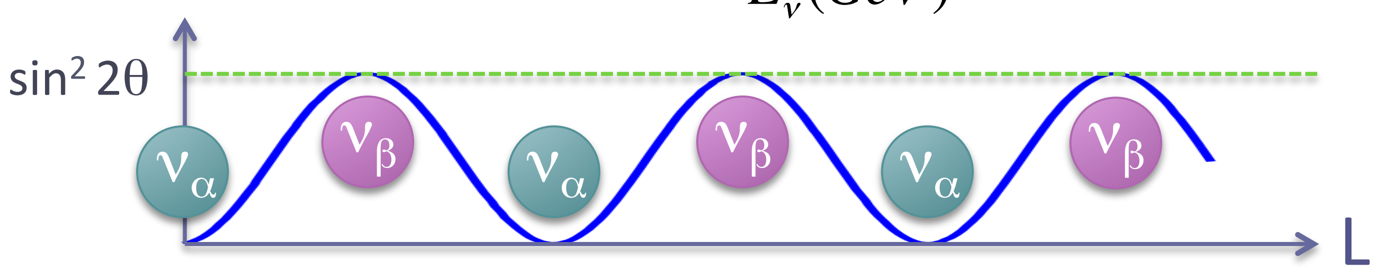
Two-flavor case

α, β = Flavor states
1, 2 = Mass states

- Probability that a neutrino originally generated as ν_α will later be observed as ν_β after traveling a distance of L :

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right)$$

$\Delta m^2 = m_2^2 - m_1^2$



ν oscillation experiments
- measure the disappearance of ν_α
- measure the appearance of ν_β

Neutrino flavor detection

(in case of interactions with a nucleon)

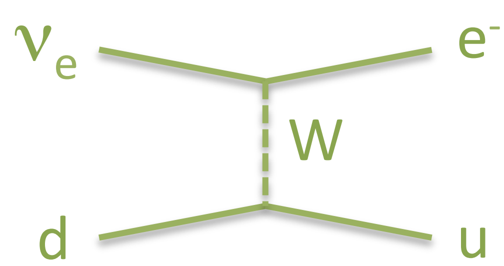
- ## Charged Current (CC) interaction

ex.) CC quasi-elastic scattering (CCQE)

$$\nu_e + n \rightarrow e^- + p$$

$$\nu_\mu + n \rightarrow \mu^- + p$$

Charged lepton w/ the same flavor



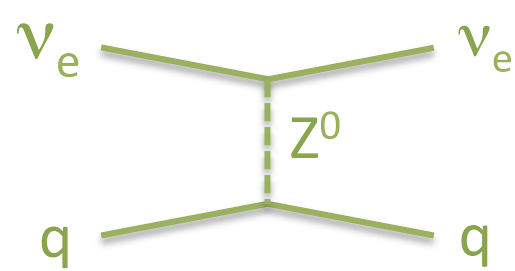
- ## Neutral Current (NC) interaction

ex.) NC elastic scattering

$$\nu_e + p \rightarrow \nu_e + p$$

$$\nu_\mu + p \rightarrow \nu_\mu + p$$

No difference in the visible particles



Identification of the outgoing lepton from CC interactions

→ Flavor of the parent neutrino

Three flavor neutrino mixing

Situation before T2K

$$s_{ij} = \sin\theta_{ij}\,,\ c_{ij} = \cos\theta_{ij}$$

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

ignoring Majorana phases

6 neutrino oscillation parameters

3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 CP phase (δ)

+ 2 mass differences (Δm^2_{21}, Δm^2_{32})

$\theta_{23} \sim 45^o$ $\lvert\Delta m^2_{32}\rvert \sim 2.5 \times 10^{-3}$ (eV^2) atmospheric/accelerator ν	$\theta_{13} < 11^o$ ($\sin^2 2\theta_{13} < 0.15$) reactor/accelerator ν	$\theta_{12} \sim 34^o$ $\Delta m^2_{21} \sim 8 \times 10^{-5}$ (eV^2) solar/reactor ν

Only upper limit on θ_{13} (θ_{13}=0? or ≠0?)

→ Non-zero θ_{13} hunting around the world

θ_{13} measurements (other than solar-ν and atm-ν)

- Reactor neutrino experiments : $\overline{\nu}_e$ disappearance

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \underline{\sin^2(2\theta_{13})} \sin^2\left(\frac{1.27 \Delta m^2_{31} L(m)}{E_\nu (MeV)}\right)$$

pure θ_{13} measurement

- Accelerator neutrino experiments : ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \underline{\sin^2(2\theta_{13})} \sin^2\theta_{23} \sin^2\left(\frac{1.27 \Delta m^2_{31} L(km)}{E_\nu (GeV)}\right)$$

leading term

sub-leading terms

$$\begin{aligned}
&+ \; 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21} && \text{CPC} \\
&- \; 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21} && \text{CPV} \\
&+ \; 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21} && \text{solar} \\
&- \; 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31}. && \text{matter effect}
\end{aligned}$$

δ → -δ
a → -a
for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

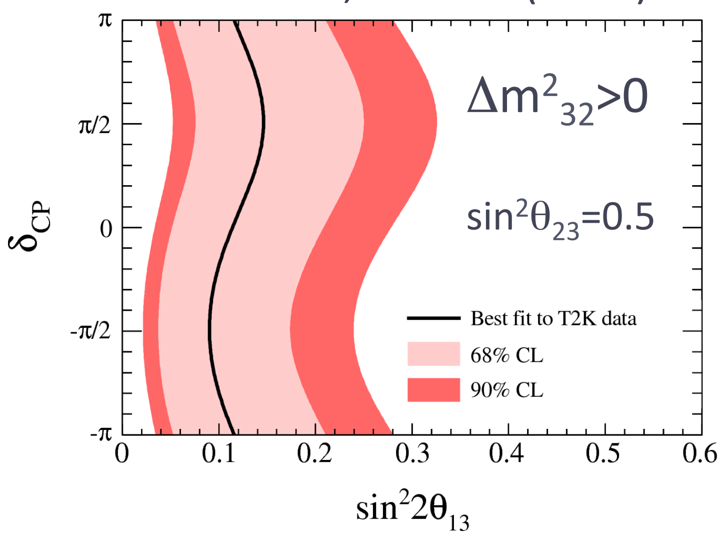
ν_e appearance : sensitive to δ and the mass hierarchy

→ Non-zero θ_{13} opens the possibility to probe the CP violation in the lepton sector !

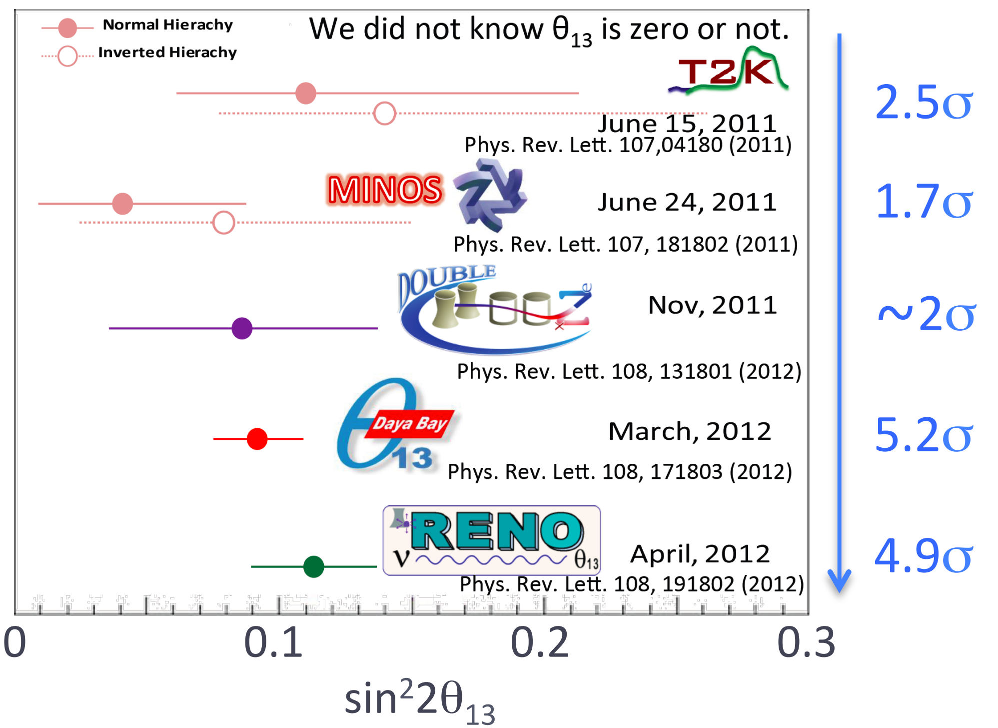
Breakthrough of non-zero θ_{13} search (2011~)

- In 2011 June, T2K reported the first indication of $\theta_{13} \neq 0$ (2.5σ) using the data before the earthquake.

PRL 107, 041801 (2011)



1σ confidence intervals (before Neutrino2012)

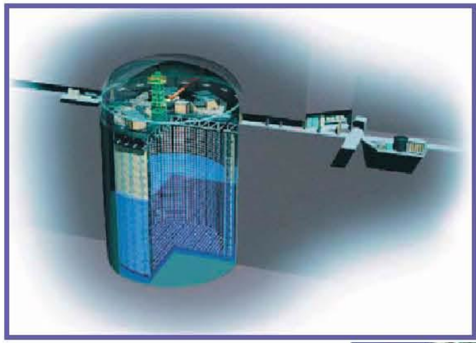


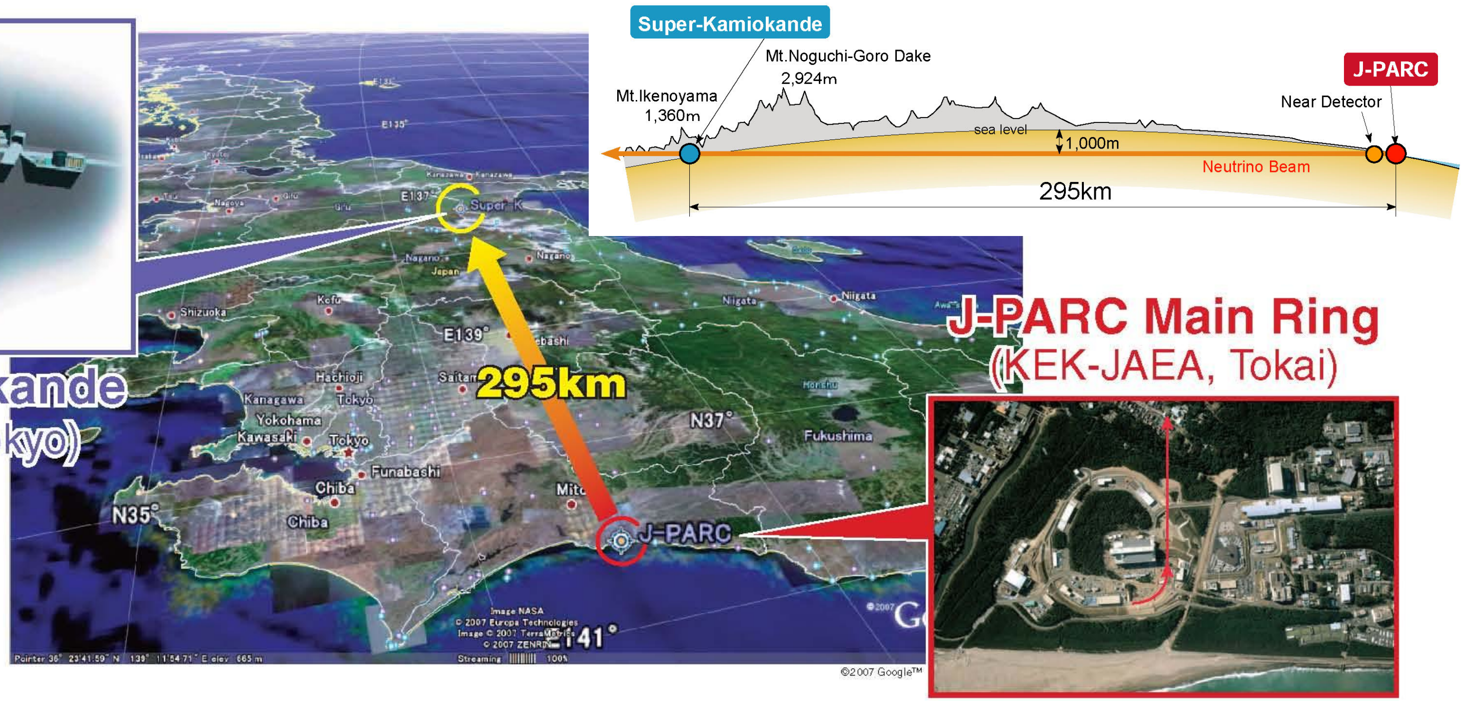
- In 2012, solid confirmation by reactor experiments.

This talk : Updated ν_e appearance analysis using the full T2K data set

T2K experiment

T2K (Tokai-to-Kamioka) experiment





abbreviations :

SK, Super-K

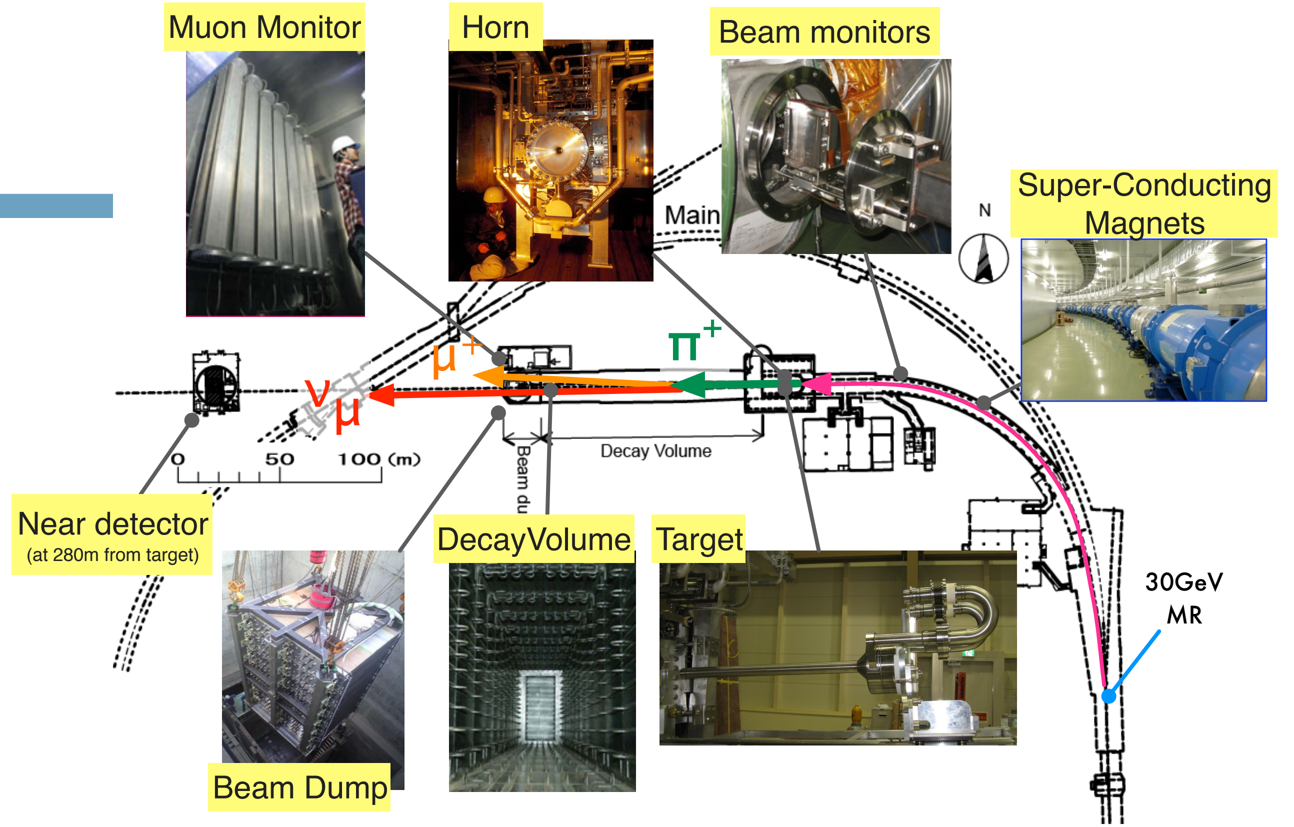
Main goals

- Discovery of ν_e appearance ($\nu_\mu \rightarrow \nu_e$ oscillation)
  - → Measure θ_{13}
- Precision measurement of ν_μ disappearance
  - → $\delta(\Delta m^2_{23}) \sim 1\text{x}10^{-4}\ \text{eV}^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.01$

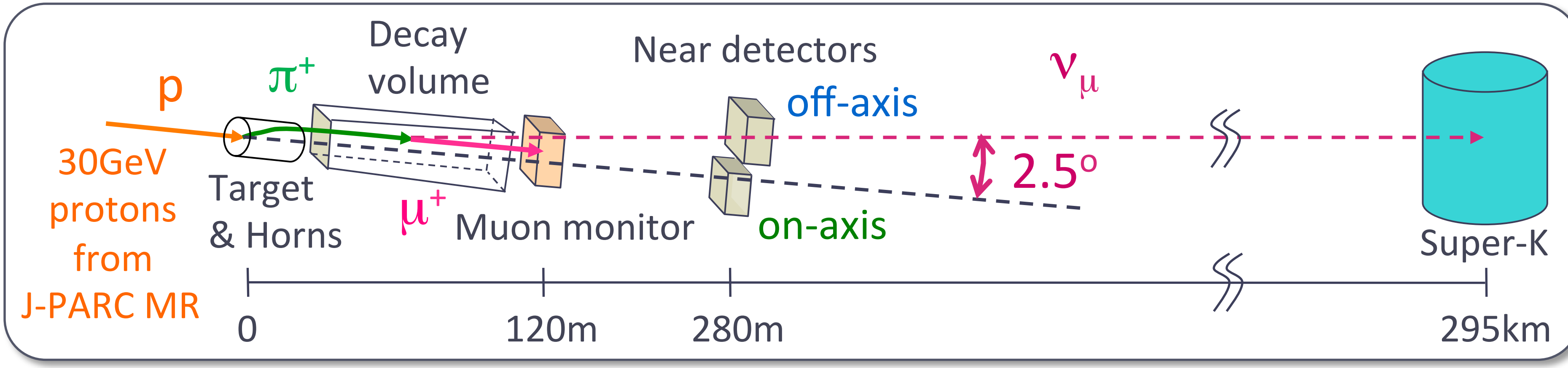
T2K Collaboration

International collaboration
(~500 members from 12 countries)

Beam-line



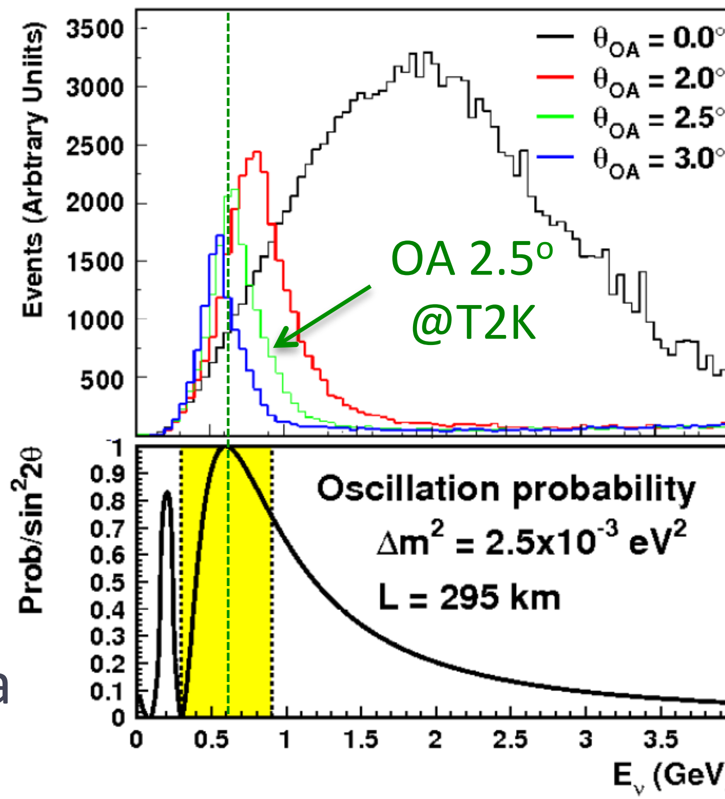
- 30GeV ~10^{14} protons extracted every 2.5~3sec. Spill duration ~5μsec.
- Proton beam impinges the graphite target (φ26mm x 914mm).
- Secondary π^+ (and K^+) focused by 3 magnetic horns (250kA).
- 96m long decay volume.
  - ν_μ mostly from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (ν_e in the beam from μ and K decay)
- Muon monitors : beam direction and intensity, spill-by-spill.



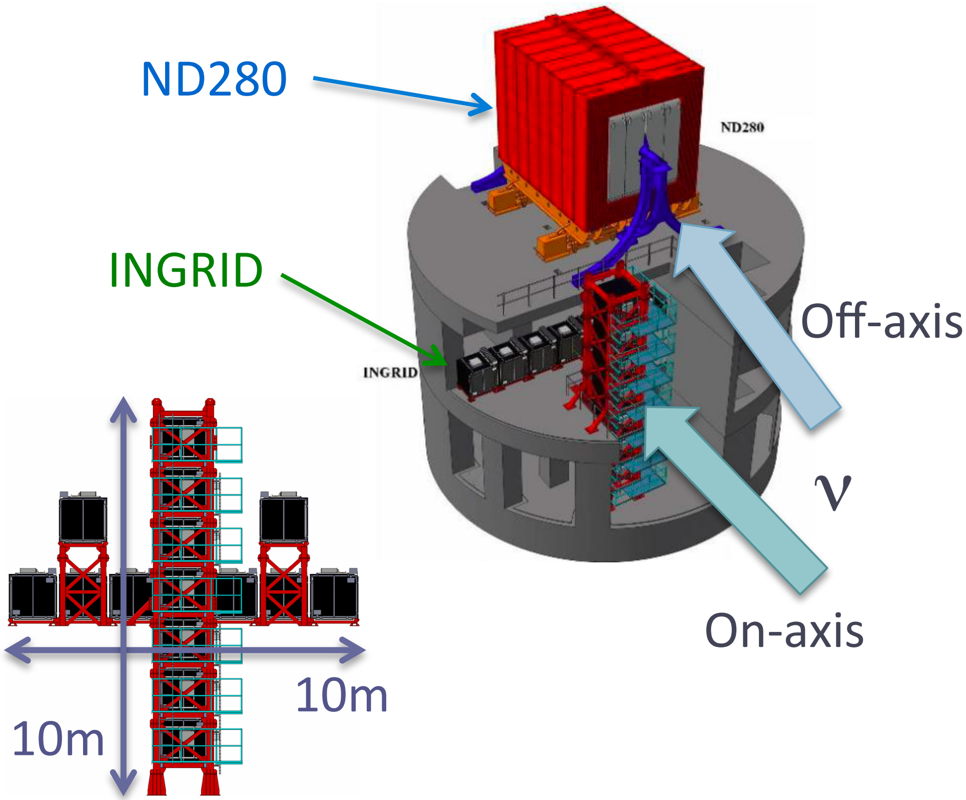
Off-axis neutrino beam

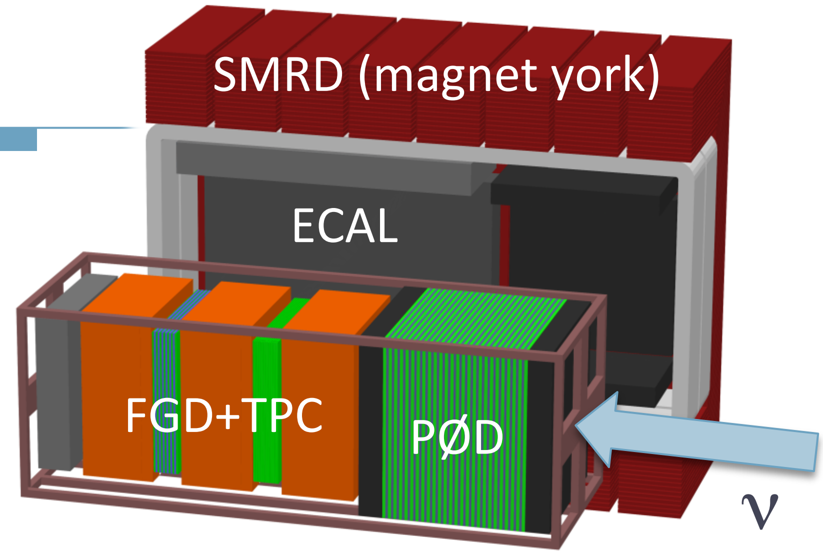
(Ref. : BNL-E889 proposal)

- Intense, low energy narrow-band
- E_ν peak tuned at oscillation maximum (~0.6GeV)
- Small high energy tail, which creates background events
- T2K : 1st experiment to use this idea
- Important to keep the beam direction stable (1mrad direction shift → 2% E_ν shift at peak)



Near neutrino detectors
(@280m downstream)





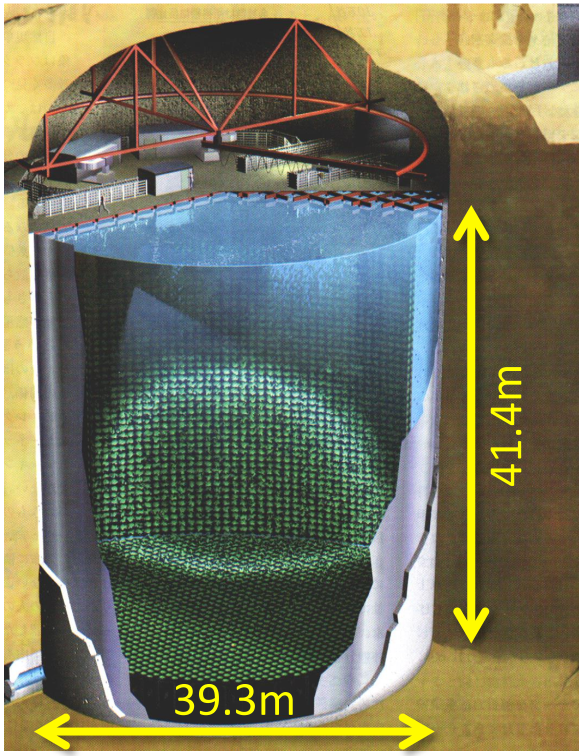
On-axis detector (INGRID)

- direct ν beam day-by-day monitoring (direction, intensity and profile)
- 16 cubic modules. Sandwich of iron plates and scintillator planes

Off-axis detector (ND280)

- measures ν flux/spectrum before oscillations @2.5° off-axis angle
- 0.2T dipole magnet
- Fine Grained Detectors (FGDs) x2
  1.6ton fiducial mass target + tracking
- Time Projection Chambers (TPCs) x3
  PID by dE/dx in gas, resolution <10%
- PØD (π^0 detector)
  ECAL (Electromagnetic calorimeters)
  SMRD (Side Muon Range Detector)

Far neutrino detector : Super-Kamiokande
(@295km from J-PARC)



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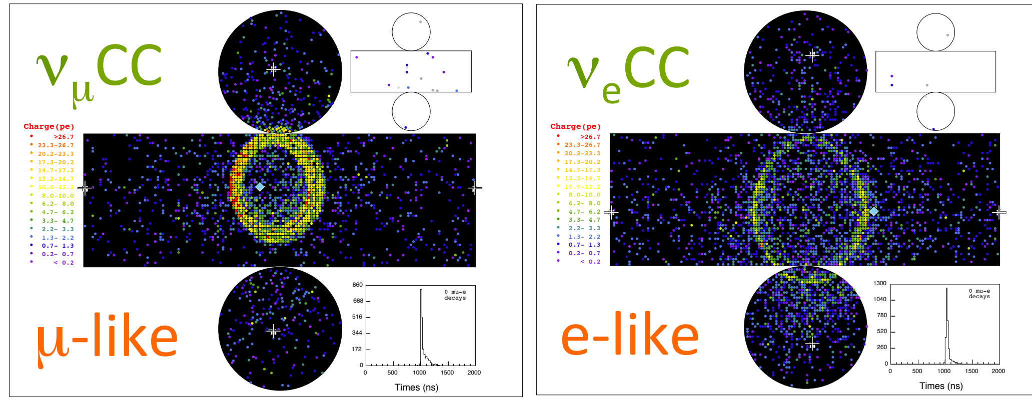
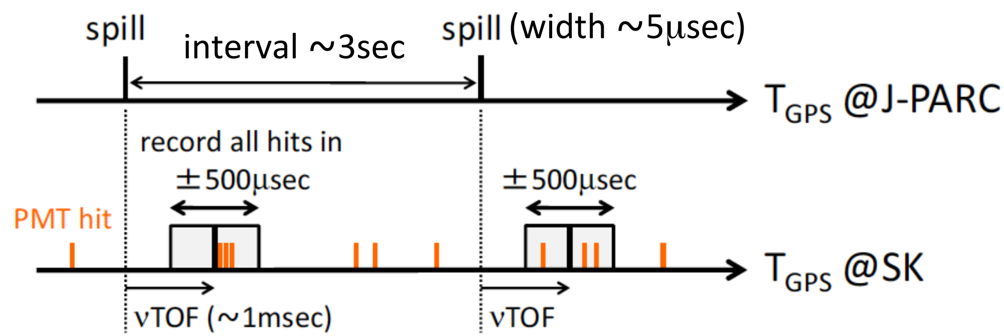
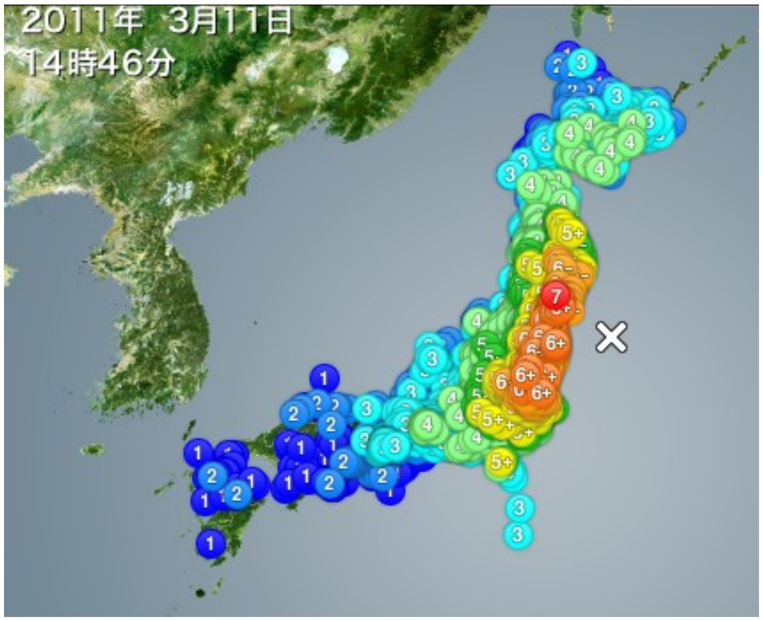




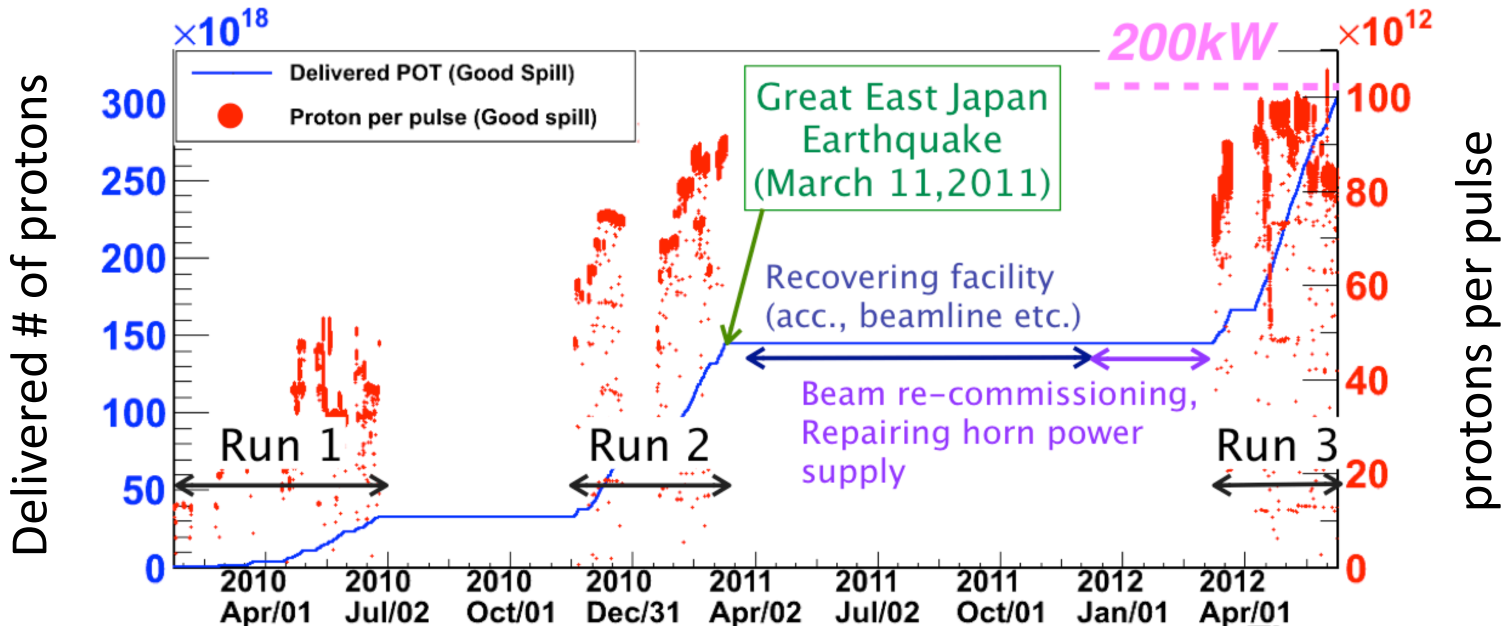
- Water Cherenkov detector, 1000m underground, 22.5kton fiducial mass
- Excellent μ/e PID using ring-shape & opening angle (mis-ID probability ~1%)
- T2K: recording PMT hits within ±500μsec of beam arrival time using GPS
- Atmospheric ν samples to study detector performance

Recovery after the 3.11 earthquake



- December 9, 2011 : J-PARC LINAC operation restarted.
- December 24, 2011 : Neutrino events observed at T2K ND280.
- March 8, 2012 : T2K physics run restarted within 1 year after the earthquake.

Data collected and analyzed

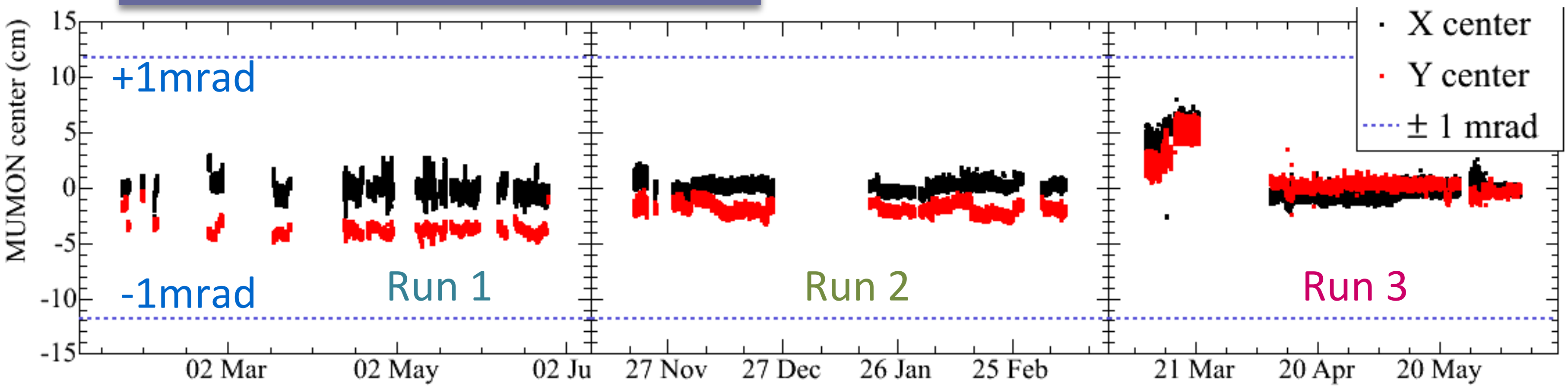


- Run 1+2 (2010-2011) : 1.43 x 10^{20} p.o.t. → data set for the published results
  - ND280 Run1+2 data is used for oscillation analysis shown today
- Run 3 (2012) : 1.58 x 10^{20} p.o.t.
  - including 0.21 x 10^{20} p.o.t. with 200kA horn operation (13% flux reduction @peak)
  - ND280 Run3 data is checked and consistent with Run1+2

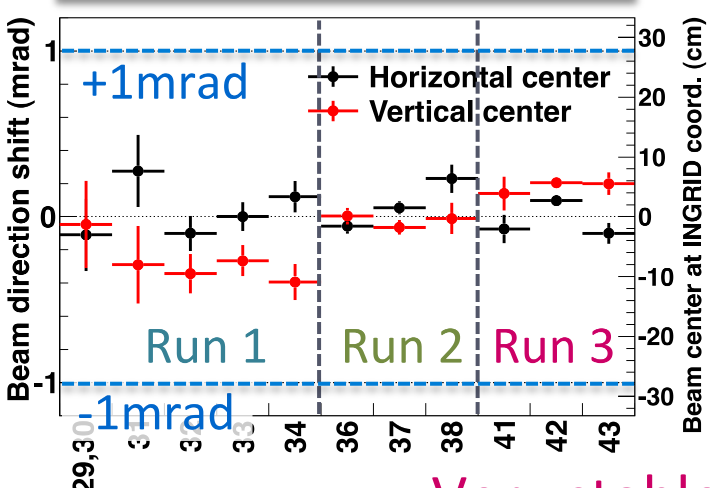
Data in this talk = 3.01 x 10^{20} p.o.t. (whole Run1+2+3 data)

Beam stability

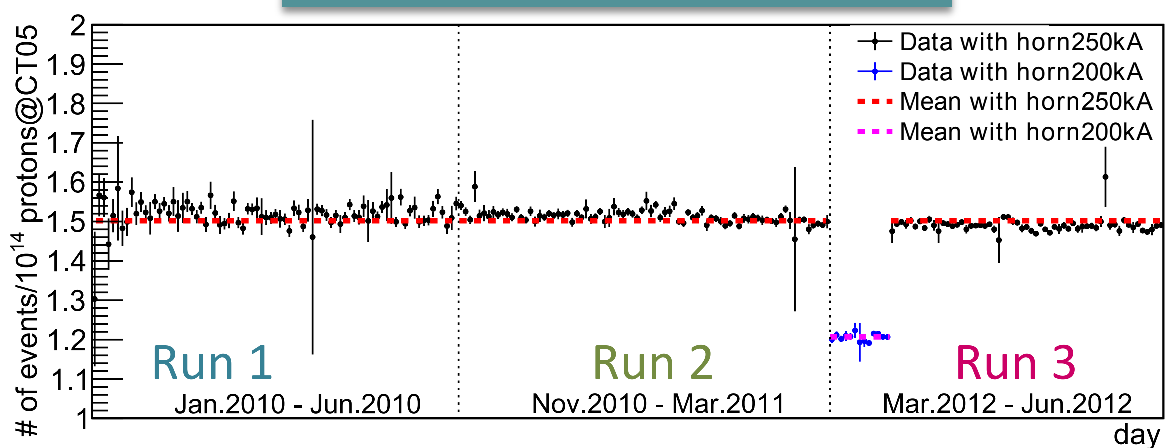
Muon monitor : Beam direction



INGRID : Beam direction



INGRID : Neutrino event rate



Very stable during the whole run period

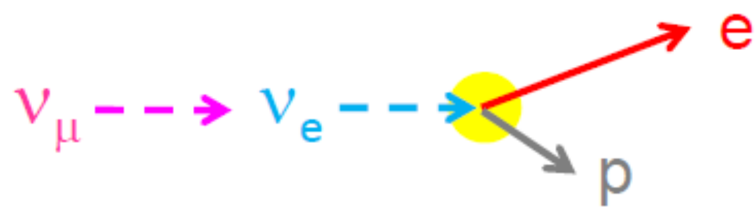
T2K ν_e appearance analysis

Signal and BG for T2K ν_e appearance search

- Signals

Single electron event by CC interaction of ν_e oscillated from ν_μ

- Mainly CCQE : $\nu_e + n \rightarrow e^- + p$
- Protons mostly have momenta below Cherenkov threshold

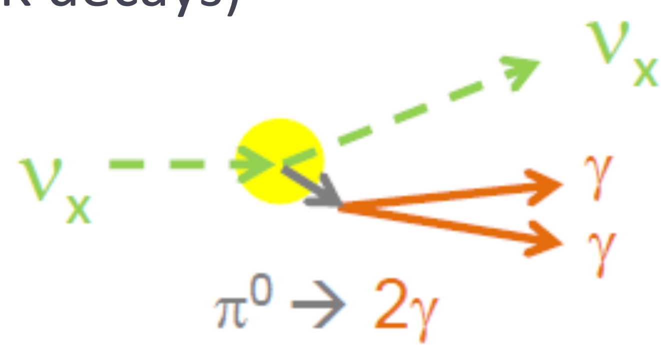


- Backgrounds

(1) intrinsic ν_e in the beam (from μ, K decays)

(2) NC single π^0 events

- overlap of 2 γ rings
- asymmetric decay (one of the γ has very low energy)



Oscillation analysis method

Flux prediction
w/ Hadron production measurement (CERN NA61)

ND280 ν_μ measurements in CCQE and nonQE samples

detector uncertainties

ν int. cross section model & uncertainties
NEUT + uncertainties set from external data

Flux & ν int. cross section *fit*
to constrain flux and ν int. cross section uncertainties

fit result (flux & ν int. cross section information) is extrapolated into 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 (uncorrelated between ND and far detector)

Far detector uncertainties
set from atm.-ν & π^0 control sample

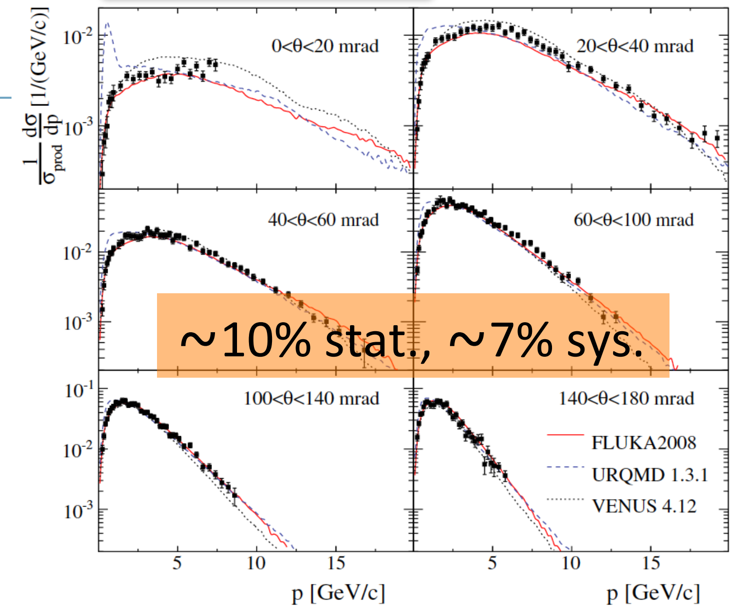
Neutrino flux prediction

Beam simulation based on measurements

- T2K proton beam profile measured by beam monitors input into the simulation
- π, K production cross section tuned mainly by NA61/SHINE(@CERN) measurements with 30GeV protons and a graphite target

NA61 π^+ data

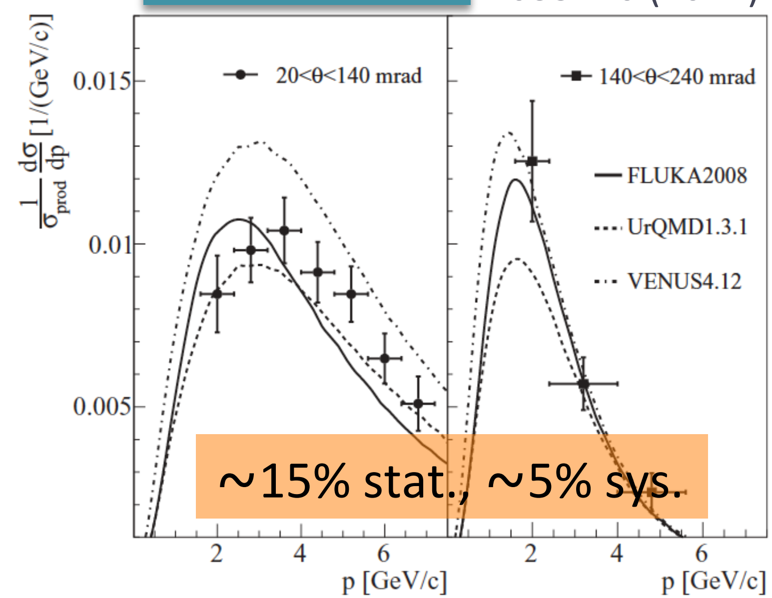
Phys.Rev.C 84, 034604 (2011)



~10% stat., ~7% sys.

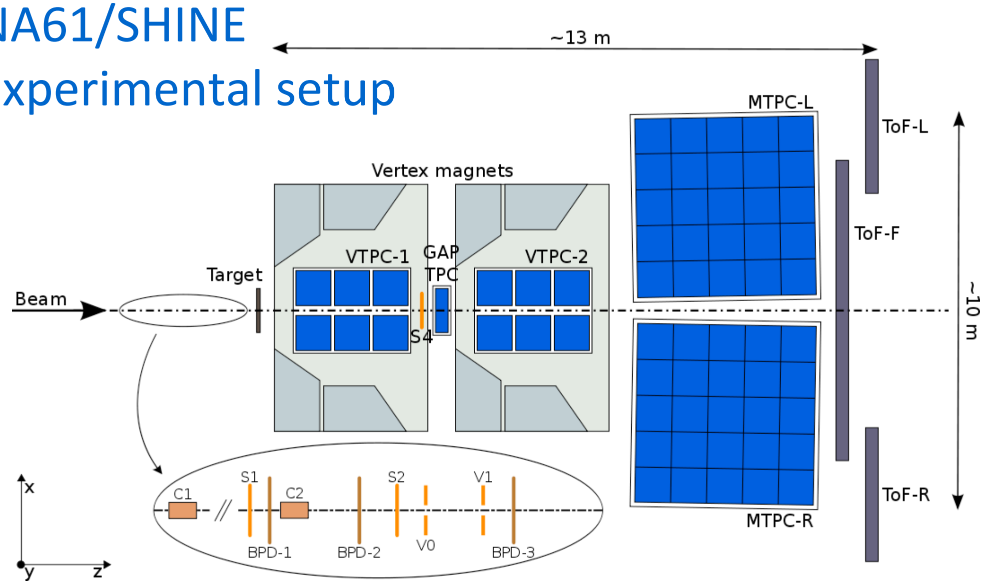
NA61 K^+ data

Phys.Rev.C 85, 035210 (2012)



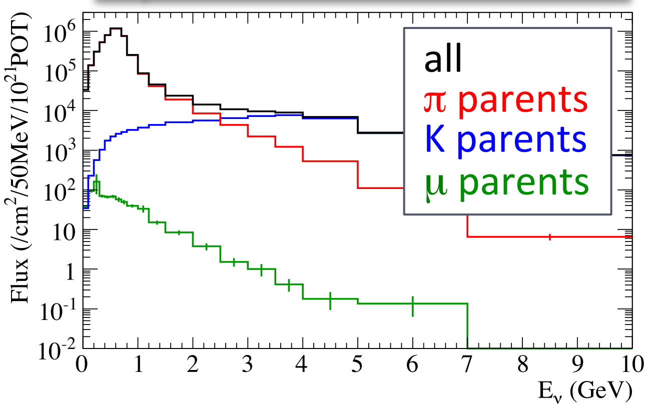
~15% stat., ~5% sys.

NA61/SHINE experimental setup

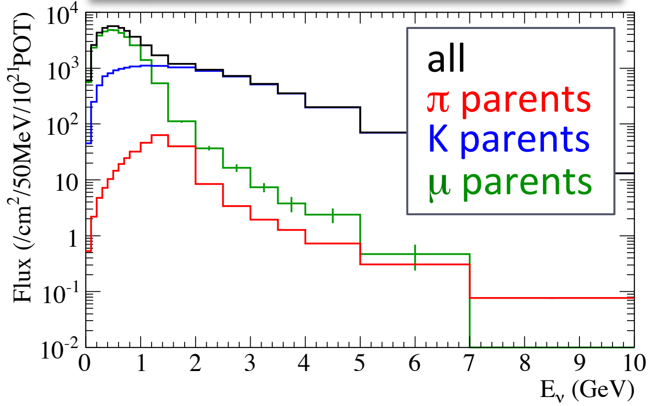


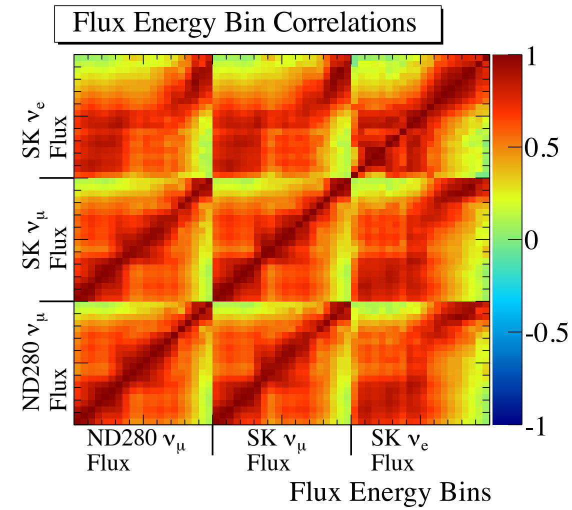
Predicted neutrino flux

ν_μ flux @SK (w/o osc.)

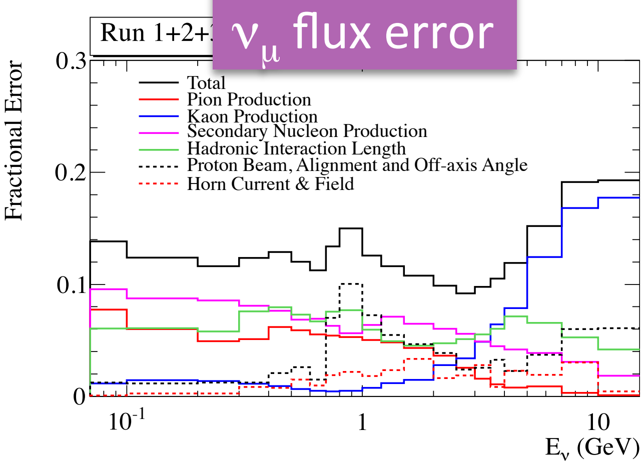


ν_e flux @SK (w/o osc.)

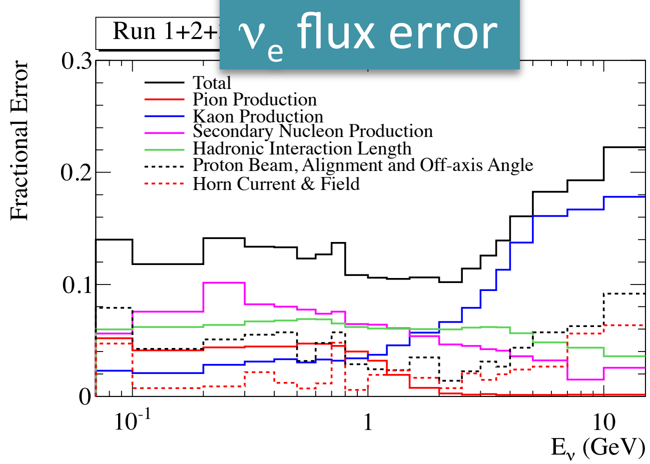




ν_μ flux error



ν_e flux error

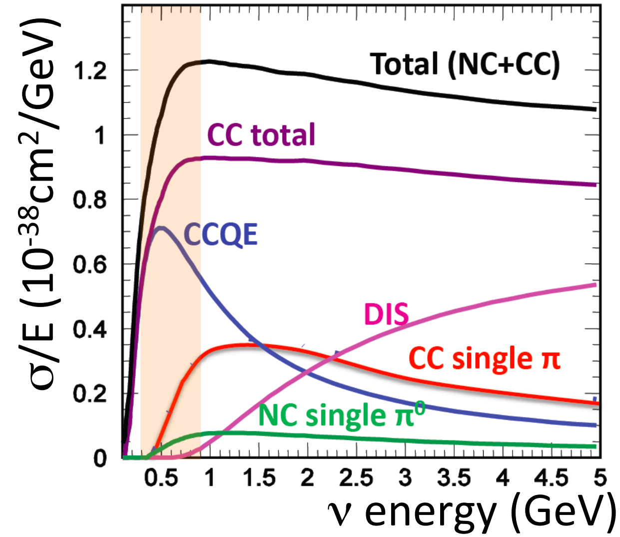


Eν-dependent errors with full correlations among ν flavors at ND280 and SK are taken into account.

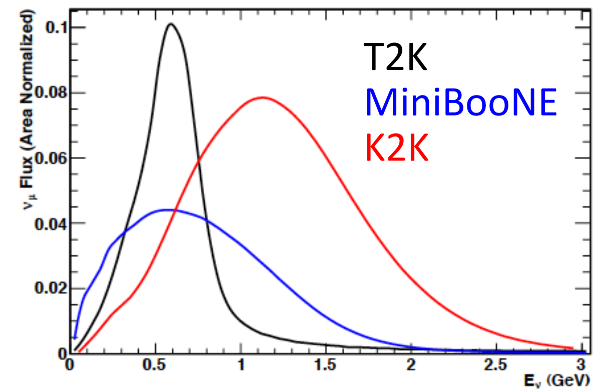
Total flux error 10～15 %

Neutrino interactions at T2K

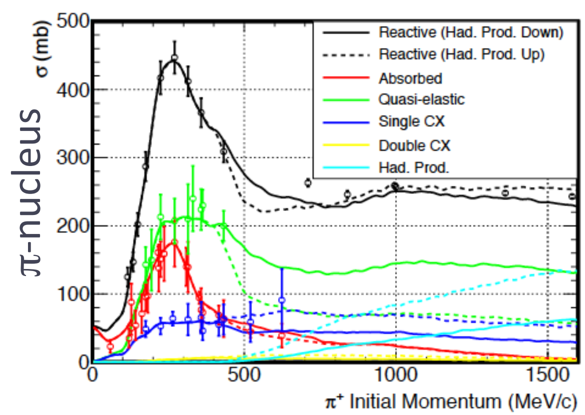
- Dominant interactions are CCQE
- Additional interactions important for analysis are CC1π and NC1π^0 (single pion production)



- Cross sections not yet measured at T2K ND
- Cross section model (NEUT) uncertainties set from fits to MiniBooNE data
  - Similar ν energy, multiple differential cross-section
  - K2K, SciBooNE data sets used as cross check

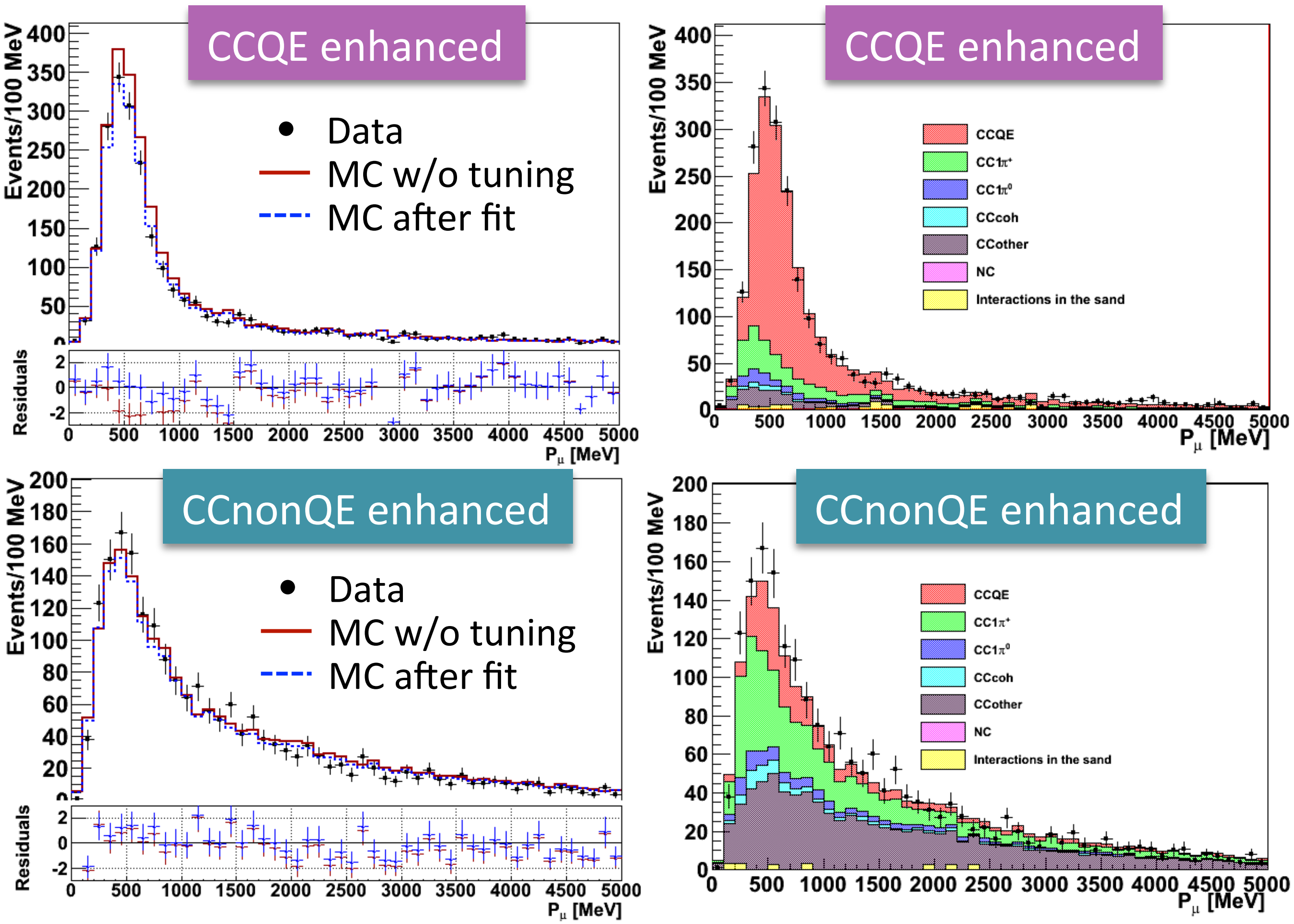


- Final state interaction (FSI)
  - Semi-classical cascade model
  - Choose several parameter sets to cover data uncertainties → propagate in analysis



Near detector ν_μ measurement (Run 1+2 data)

(p_μ , θ_μ) distributions of CCQE and CCnonQE enhanced samples are fit to constrain ν flux and cross sections



Basic selection

- negative track in FV
- upstream TPC veto
- muon ID by TPC

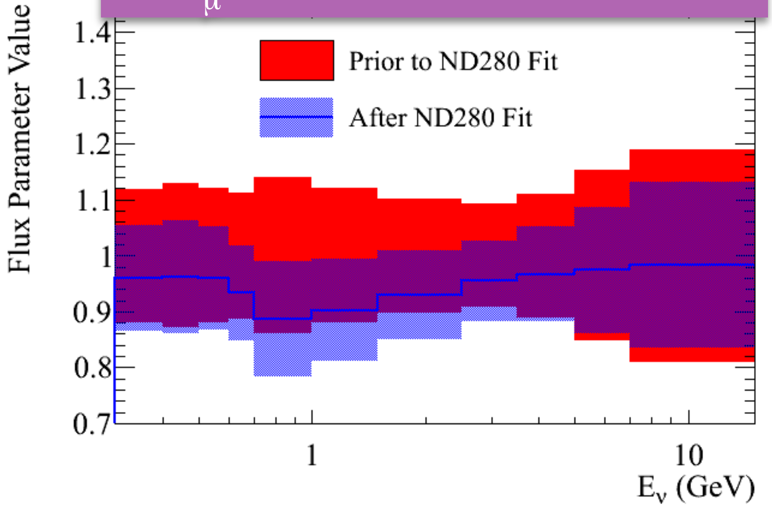
CCQE selection

- 1 FGD+TPC track
- No decay-e in FGD
- 40% efficiency w/ 72% purity

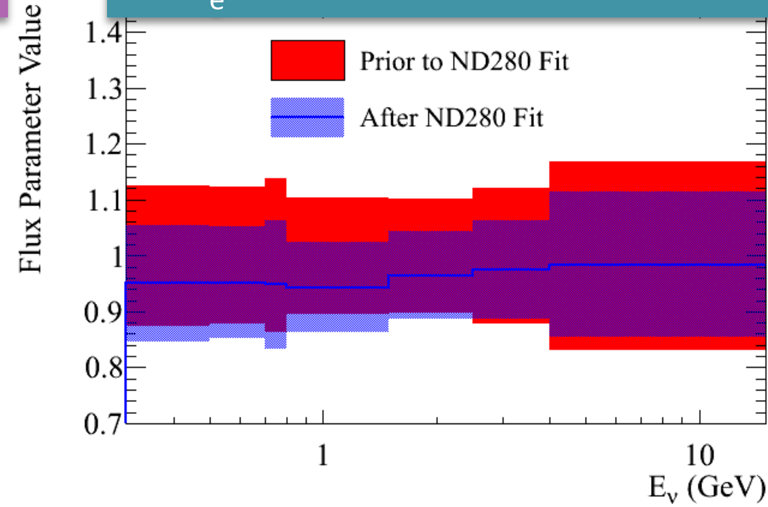
Flux and cross section fit output

Results of the ND280 ν_μ data fit are extrapolated to the prediction at SK

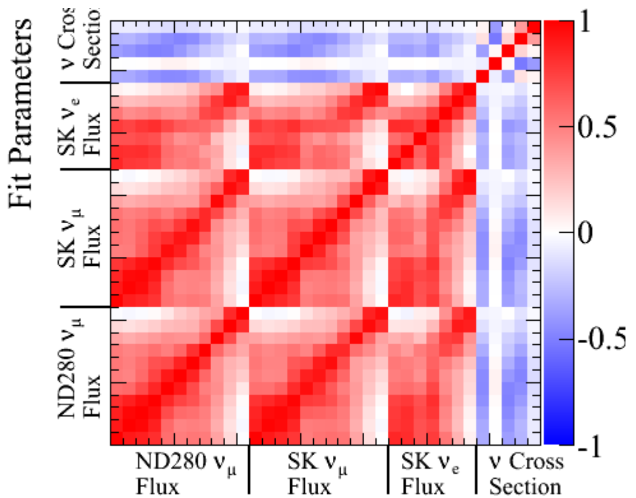
SK ν_μ flux norm. & uncertainties



SK ν_e flux norm. & uncertainties



Improved constraint by ND data fit



Parameter correlations

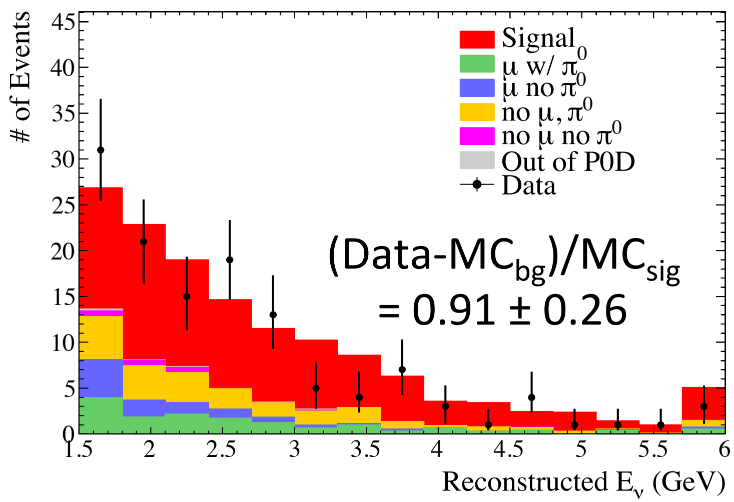
Cross section param. & uncertainties

	Prior Value and Uncertainty	Fitted Value and Uncertainty
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CC1π Norm. 0-2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
NC1π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40

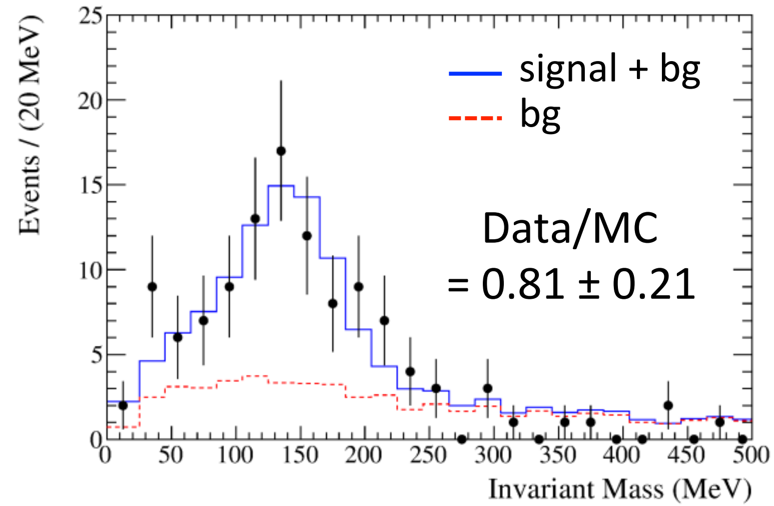
Prior value and uncertainty from fit to MiniBooNE single pion samples

ND280 ν_eCC and NC π^0 checks

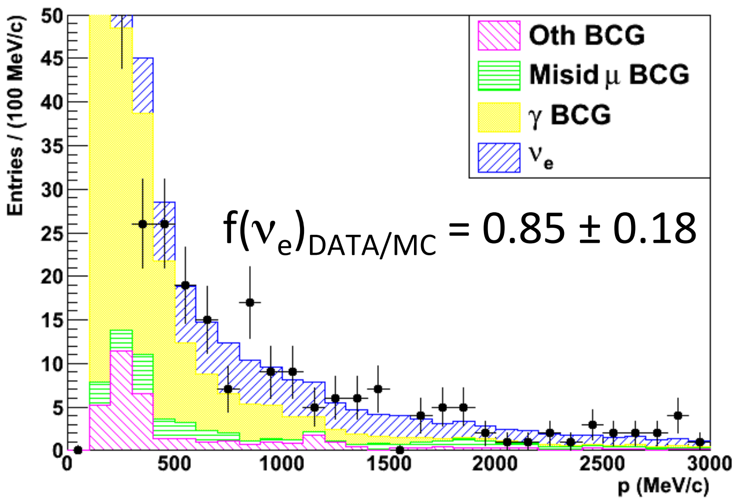
High energy ν_e events (PØD)



NC π^0 events (PØD)



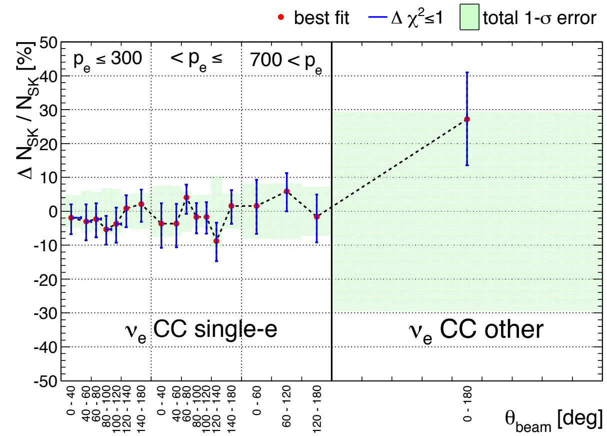
Enhanced ν_e events (Tracker)

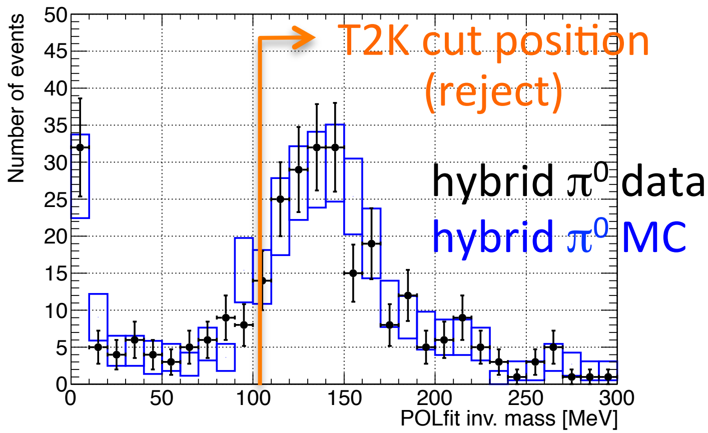


- Dominant BG for ν_e appearance search are measured at ND280
  - Intrinsic beam ν_eCC
  - NC π^0
- Data consistent with MC prediction

Far detector (Super-K) systematics

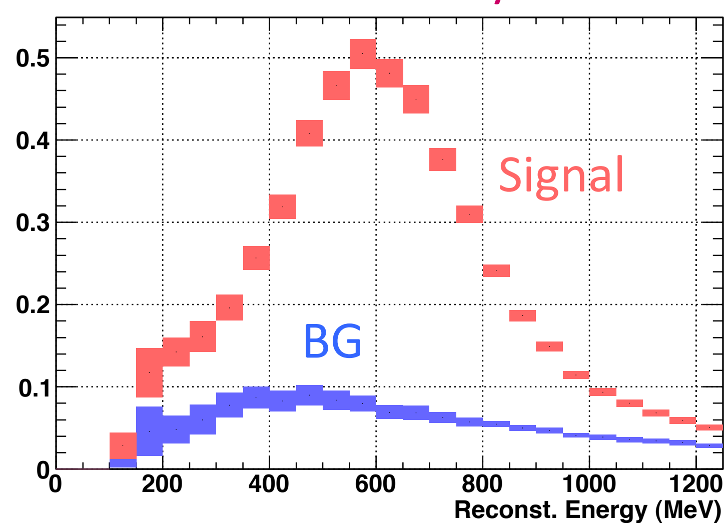
- Dominant error coming from the ring-counting, PID, π^0 mass cuts
- Error for ν_eCC components :
  - Number of events in each (p_e , θ_e) in the atmospheric ν control sample is fit to evaluate the systematic error on efficiency by above cuts
- Error for π^0 BG components :
  - π^0 topological control sample combining one data electron and one simulated γ (hybrid π^0)





π^0 mass (2γ assumption)

Total SK efficiency error



Predicted number of ν_e candidate events

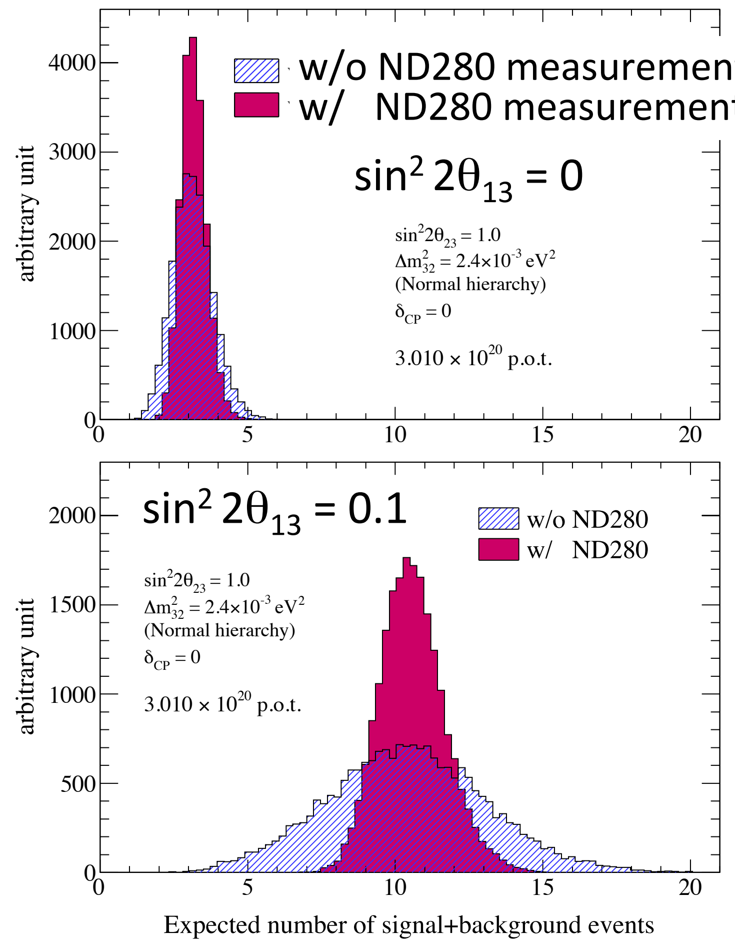
Predicted # of events w/ 3.01 x 10^{20} p.o.t.

Category	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22 ± 0.43	10.71 ± 1.10
ν_e signal	0.18	7.79
ν_e BG	1.67	1.56
ν_μ BG	1.21	1.21
$\bar{\nu}_\mu+\bar{\nu}_e$ BG	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 %

Predicted # of events w/ sys. error

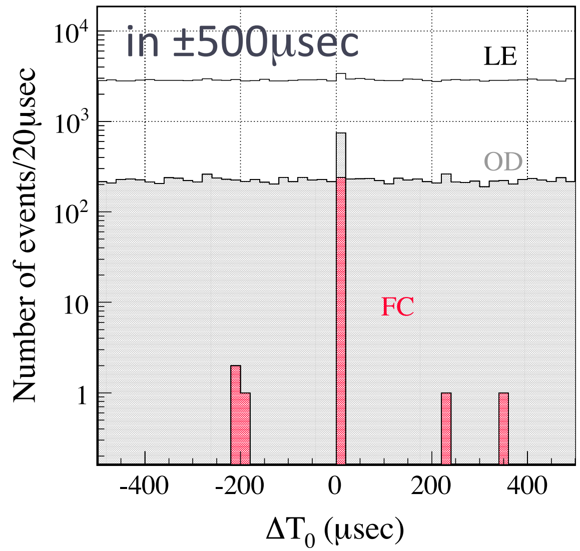


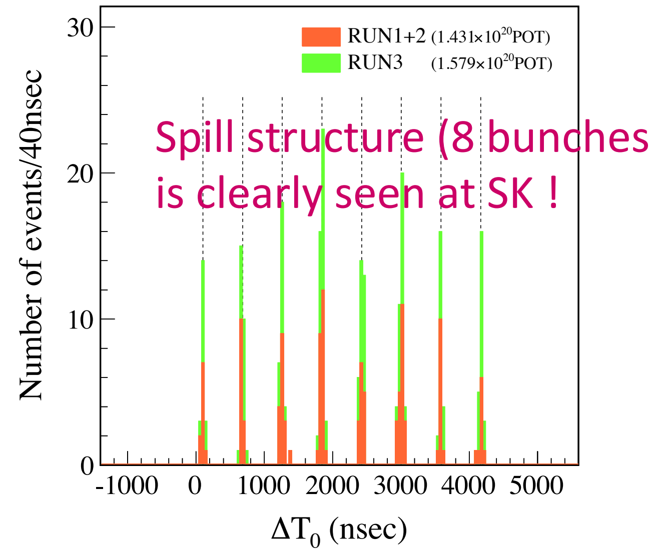
Uncertainty reduced much by the ND280 measurement

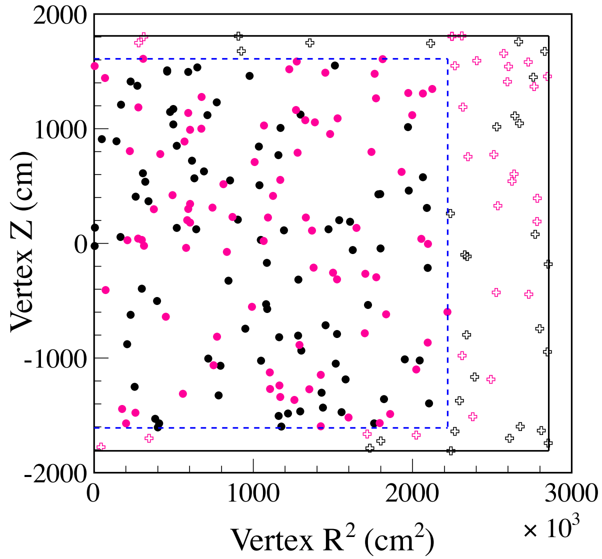
T2K event selection at Super-K

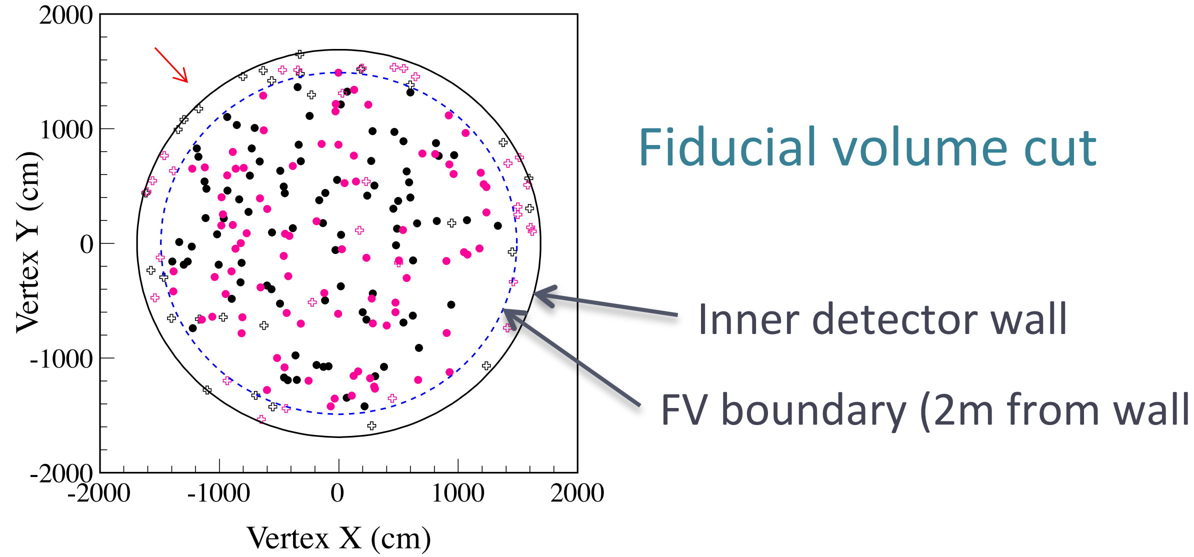
Event timing relative to the beam arrival timing

FC = Fully-Contained events









Fiducial volume cut

T2K ν_e event selection at Super-K

1. Number of rings = 1

   88 events

2. Electron-like PID

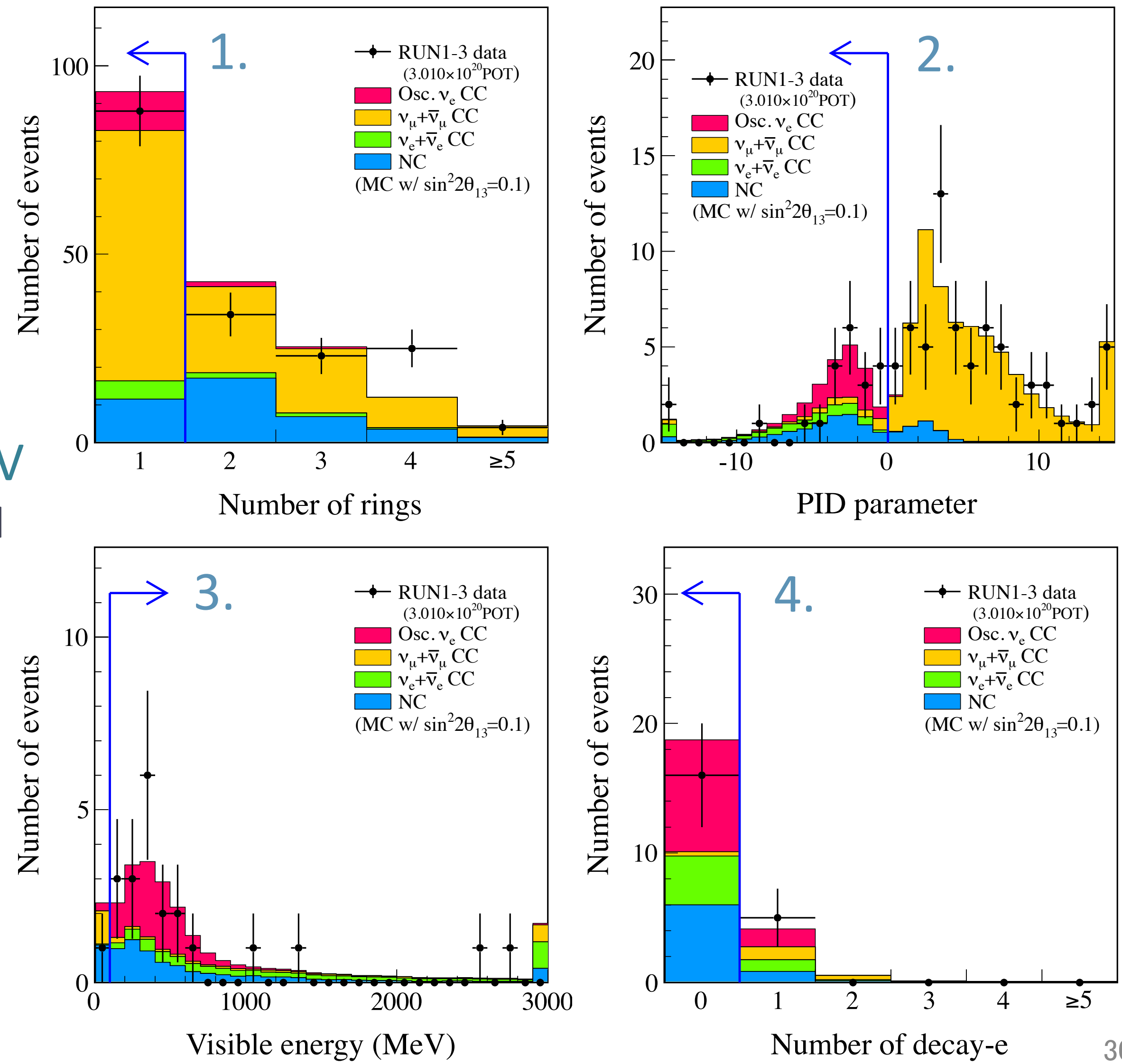
   22 events

3. Visible energy >100MeV
   (rejects low-E NC events end electron from invisible μ, π)

   21 events

4. No μ decay electron
   (rejects events with invisible μ, π)

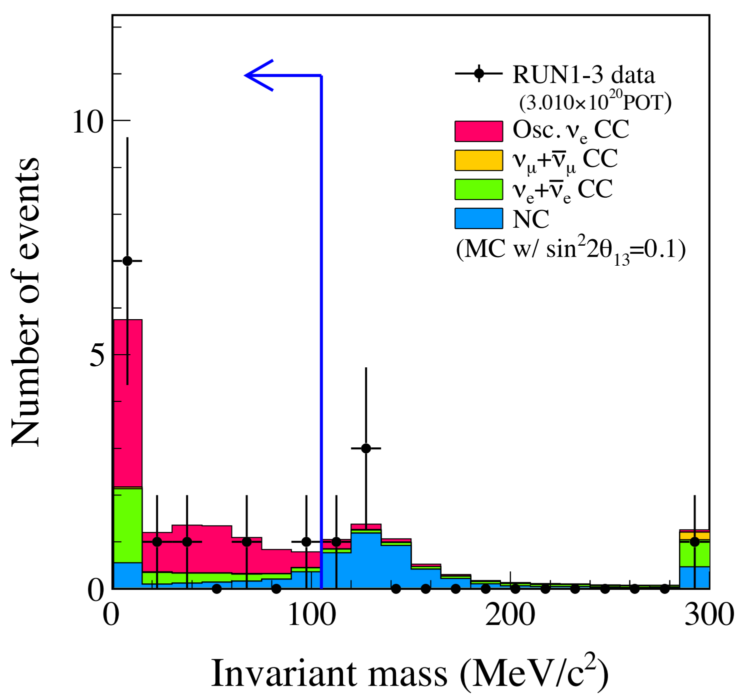
   16 events



T2K ν_e event selection at Super-K (cont'd)

5. 2γ invariant mass <105 MeV/c^2

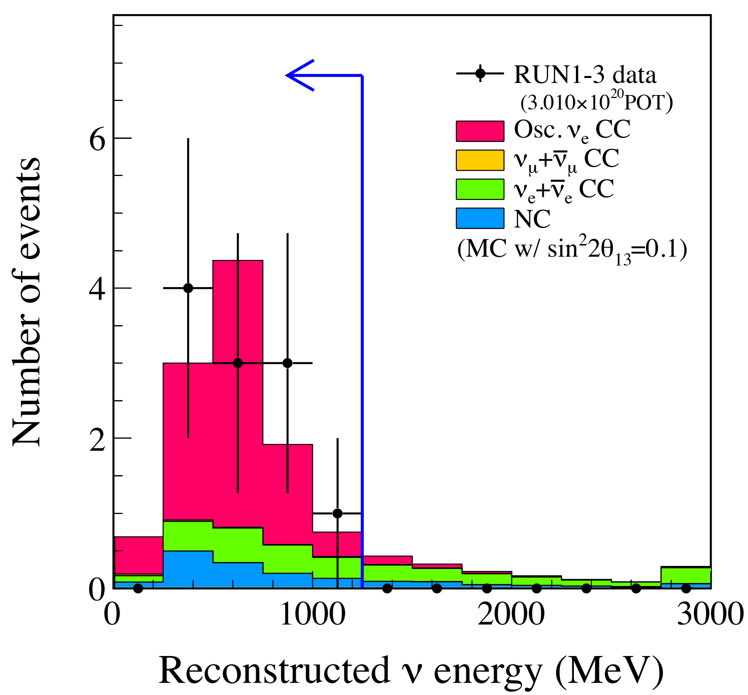
   Every event is forced to be reconstructed with the assumption of two showers to reject events w/ π^0



11 events

6. Reconstructed Eν <1.25 GeV

   Reject intrinsic ν_e in the beam (high energy ν_e mainly from K)



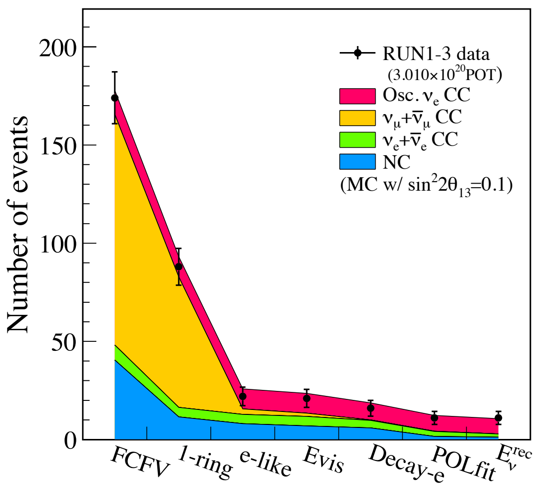
11 events after all cuts

T2K ν_e event selection summary

	MC prediction w/ $\sin^2 2\theta_{13}=0.1$					Data
	$\nu\mu$CC	νeCC	NC	BG all	Signal	
True FV	155	8.0	133	295	12.9	-
FCFV	117	7.7	40.5	165	12.4	174
1 ring	66.4	4.8	11.6	82.8	10.4	88
e-like	2.7	4.8	8.1	15.6	10.3	22
Evis>100MeV	1.8	4.8	7.0	13.5	10.0	21
No decay-e	0.3	3.8	6.0	10.1	8.6	16
π^0 mass	0.09	2.6	1.6	4.3	8.1	11
E_ν^{rec}<1.25GeV	0.06	1.6	1.3	2.9	7.8	11
(efficiency)	<0.1%	20%	<1%	1%	61%	-
	0.06	1.7	1.3	3.0	0.2	11

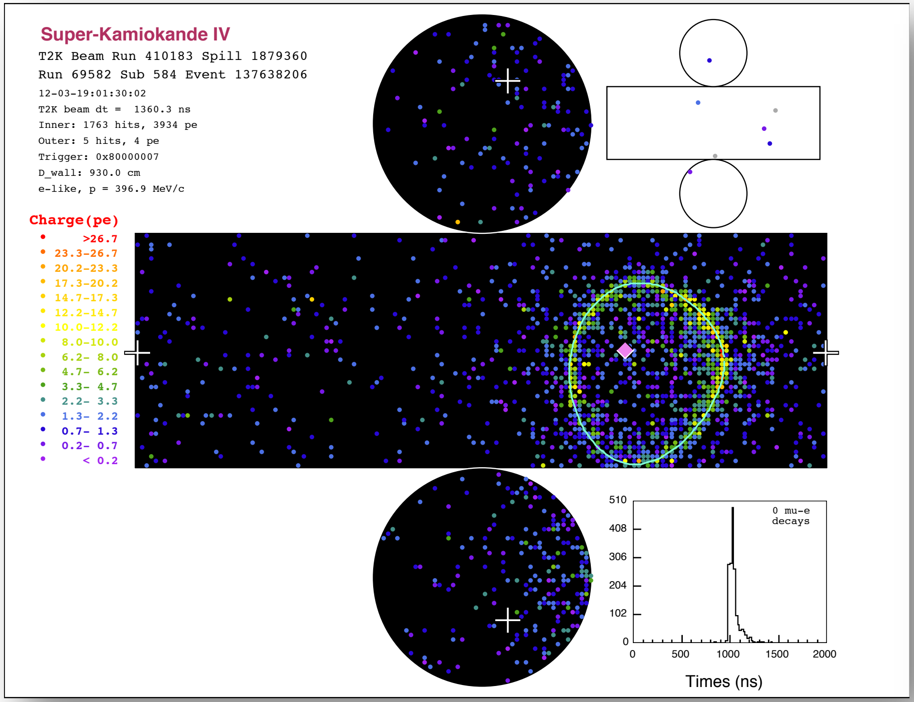
$\sin^2 2\theta_{13}=0.1$

$\sin^2 2\theta_{13}=0$

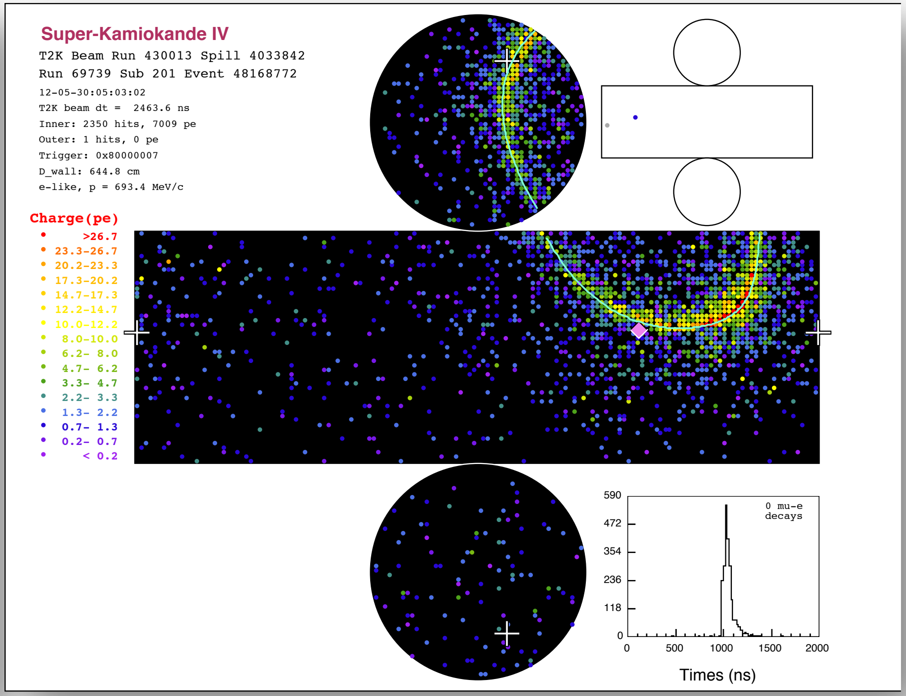


Observed ν_e candidate events

March 19, 2012



May 30, 2012



Preliminary

Significance

ν_e candidate events (3.01x10^{20} p.o.t.) :

Observed : 11 events

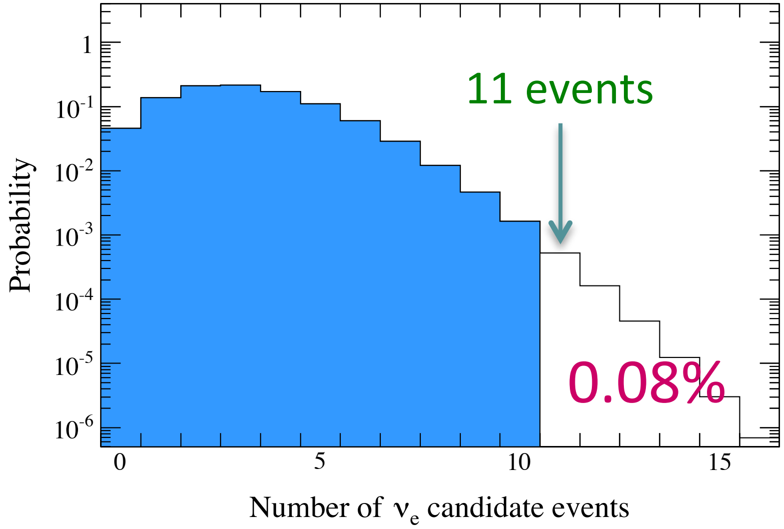
Expected w/ $\sin^2 2\theta_{13}$=0 : 3.22 ± 0.43 events

Under the $\sin^2 2\theta_{13}$=0 hypothesis, the probability to observe 11 or more candidate events is 0.08%.

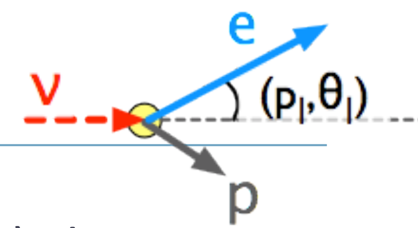
→ 3.2σ significance

Evidence of ν_e appearance !

Number of ν_e candidate events over 1x10^8 toy MCs w/ θ_{13}=0



Oscillation parameter fits



- Method 1 : Maximum likelihood fit w/ Rate + (p_e , θ_e) shape
- Method 2 : Maximum likelihood fir w/ Rate + reconstructed E_ν
- Method 3 : Feldman&Cousins for rate only

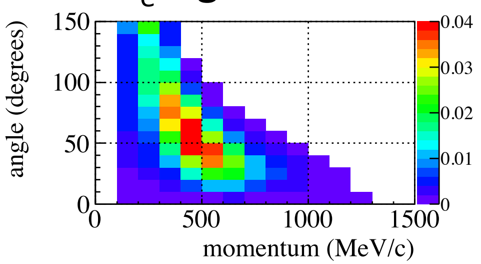
Likelihood in Method-1&2

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

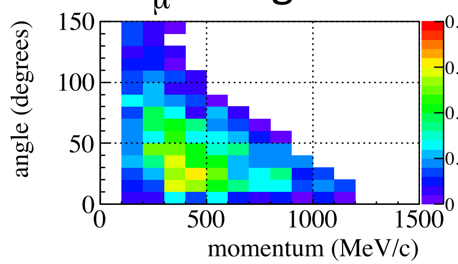
measurement variables — oscillation parameter — systematic parameters (prior: ND280 results)

Method 1

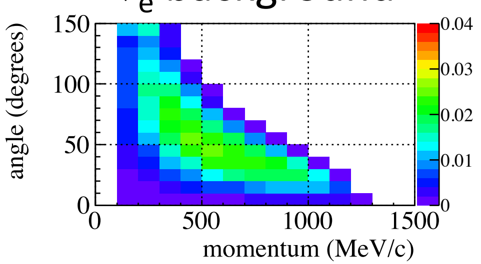
ν_e signal



ν_μ background

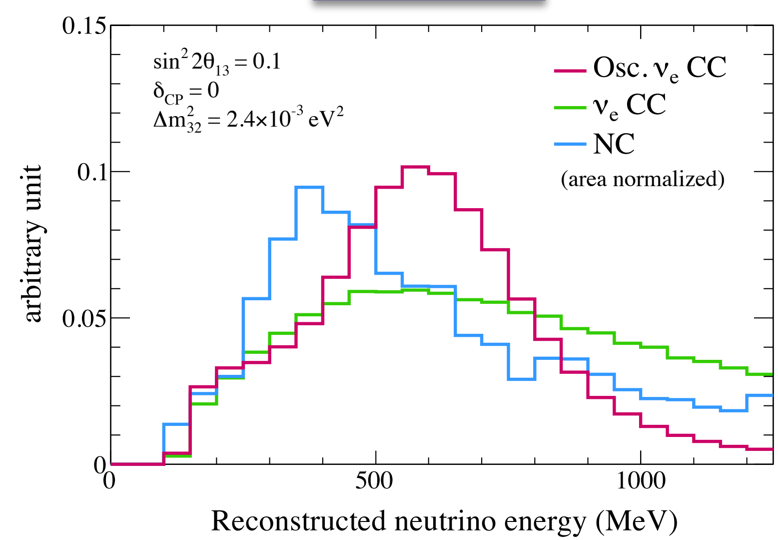


ν_e background



Shape difference allows to have a better discrimination of signal events from background

Method 2



Preliminary

Results (Method 2)

Best fit with 1σ errors

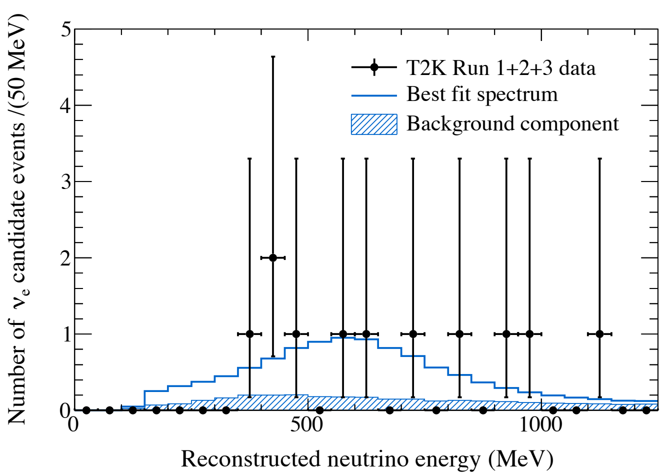
Normal hierarchy

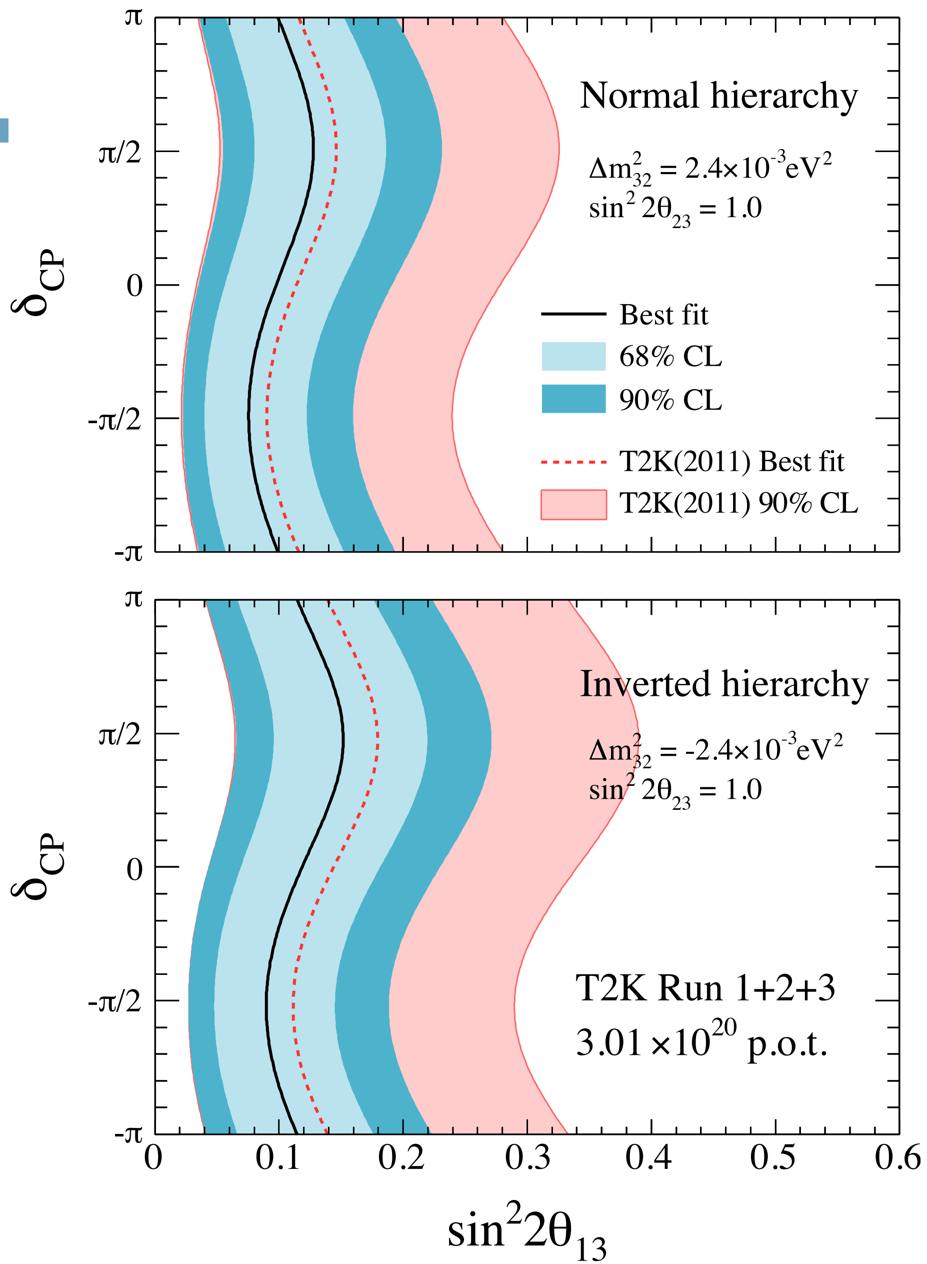
$$\sin^2 2\theta_{13} = 0.098^{+0.052}_{-0.042}$$

Inverted hierarchy

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

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





Preliminary

Results (Method 1)

Best fit with 1σ errors

Normal hierarchy

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

Inverted hierarchy

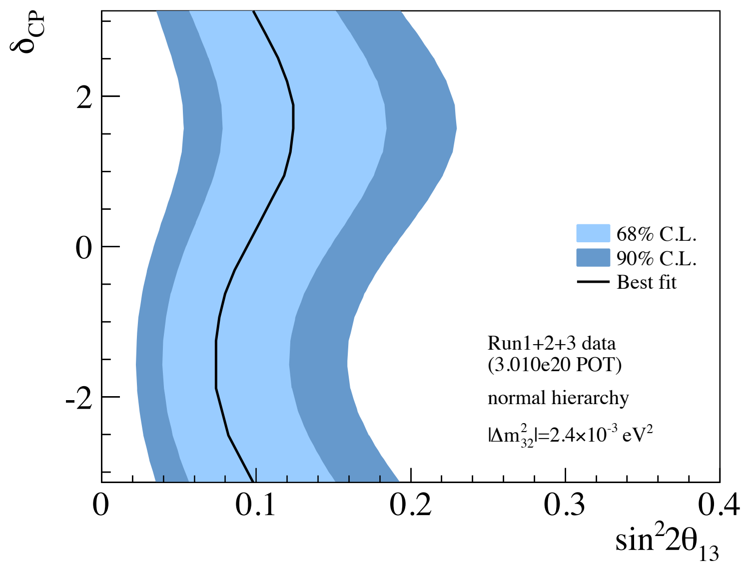
$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

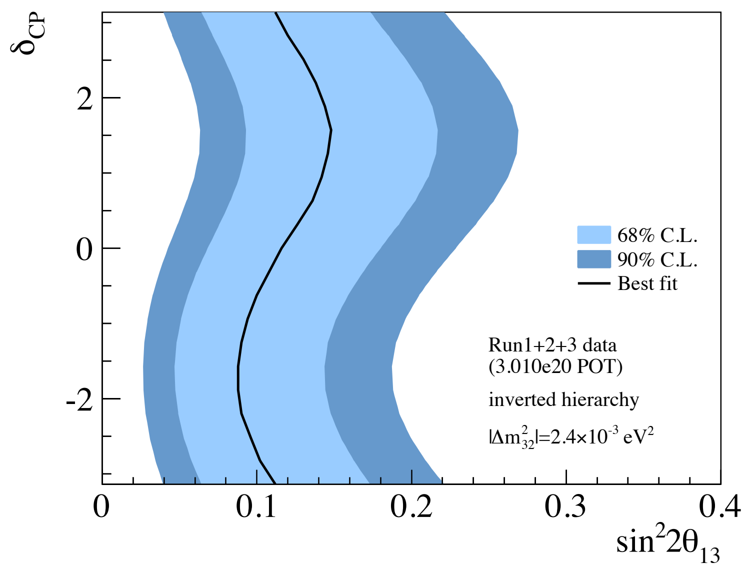
for δ_{CP}=0, $\sin^2\theta_{23}$=0.5

Results from the 3 methods are very consistent

cf. Daya Bay result (@Neutrino2012)

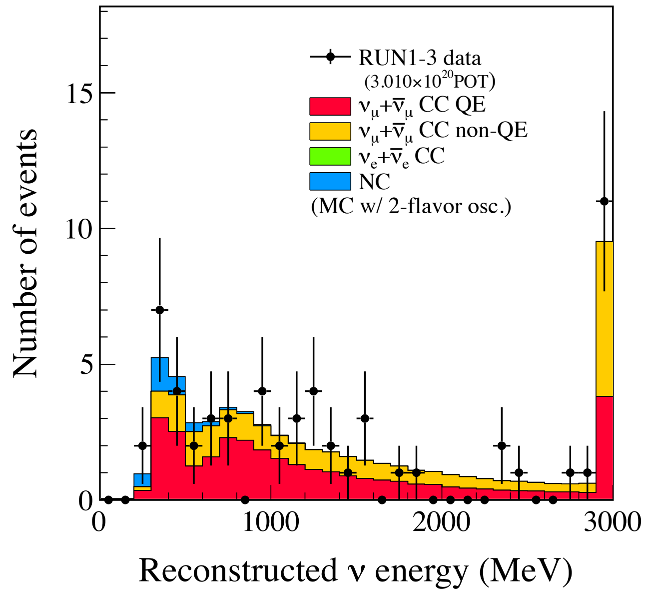
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010(stat.) ± 0.005(sys.)



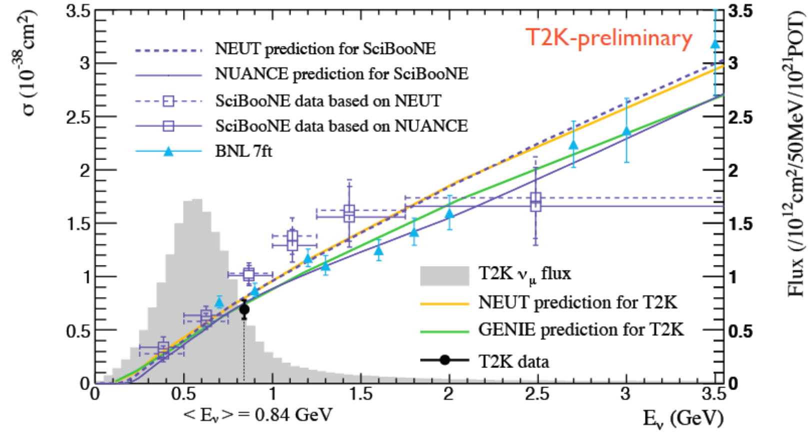


Other studies

- ν_μ disappearance analysis
  - Results w/ Run1+2 data published.
    Phys. Rev. D85, 031103(R) (2011)
  - Finalizing analysis w/ Run1+2+3 data. Results coming soon.



- Cross section measurements
  - Preliminary results from the flux averaged ν_μCC inclusive cross section measurement



- Sterile neutrino search at T2K using NC nuclear de-excitation γ-rays
  - Preliminary results w/ Run1+2 data

and more …

Summary and outlook

- Updated results from the T2K ν_e appearance analysis with 3.01 x 10^{20} p.o.t. data (~4% of the approved T2K exposure)
  - 11 ν_e candidates observed (3.22 ± 0.43 events expected under θ_{13}=0) p-value is 0.08%, equivalent to 3.2σ

    Evidence of ν_e appearance ! → opens the possibility to probe CP violation in the lepton sector

  - For δ_{CP}=0, $\sin^2\theta_{23}$=0.5,

    $$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040} \text{ (NH)}, \quad \sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049} \text{ (IH)}$$

- Will take more data with new high power runs
  - 8x10^{20} p.o.t. (2013) → 12x10^{20} p.o.t. (2014) → 18x10^{20} p.o.t. (2015)
  - more precise measurement of ν_e appearance

- An updated ν_μ disappearance measurement is coming soon.

Next …

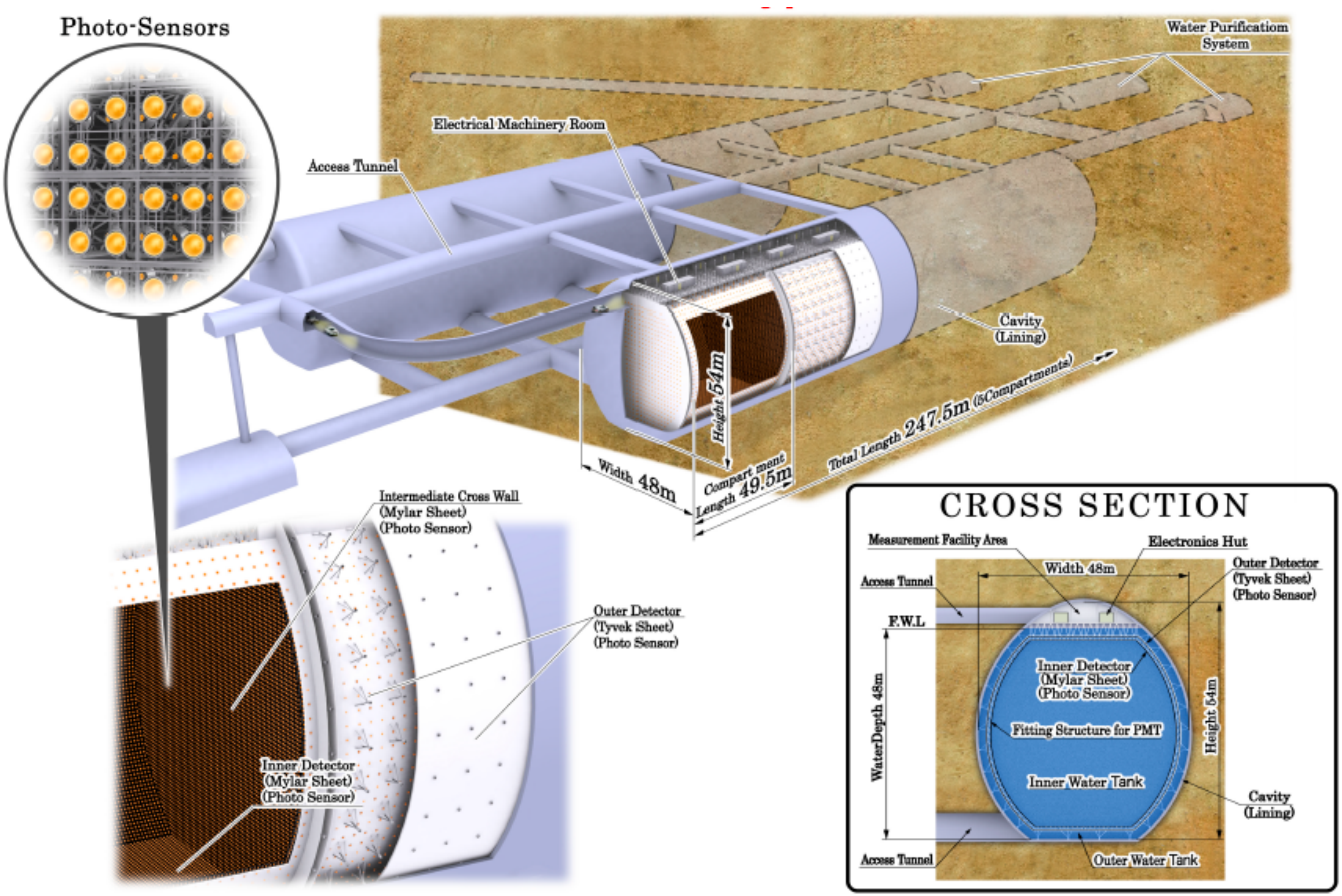
- Non-zero θ_{13} is established (>5σ)
  ν_e appearance is discovered (>3σ)

→ Time to start building the next experiments
to measure the CP violation in the lepton sector

Hyper-Kamiokande

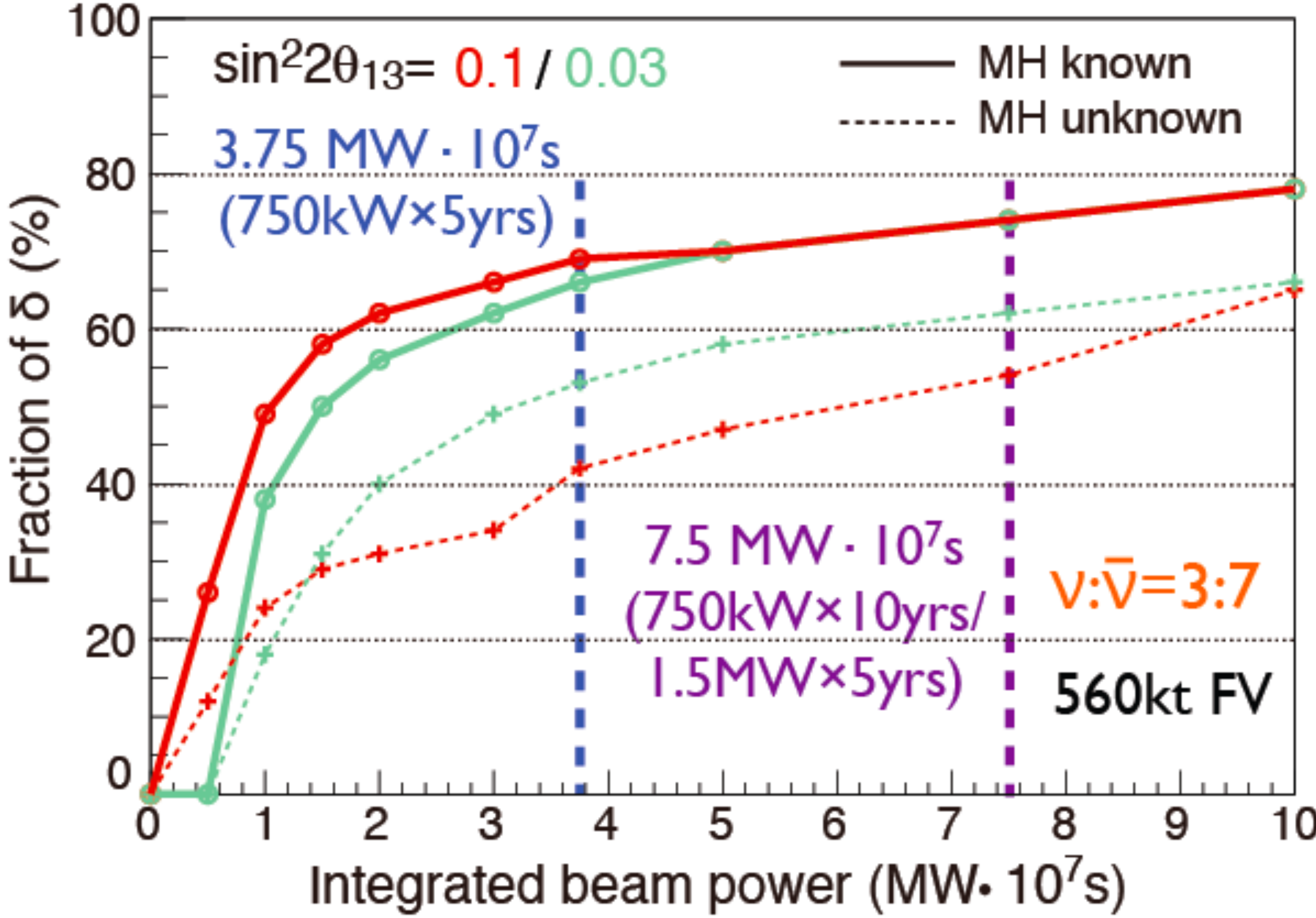
1Mt Water Cherenkov

Fiducial Volume = 25 x Super-K



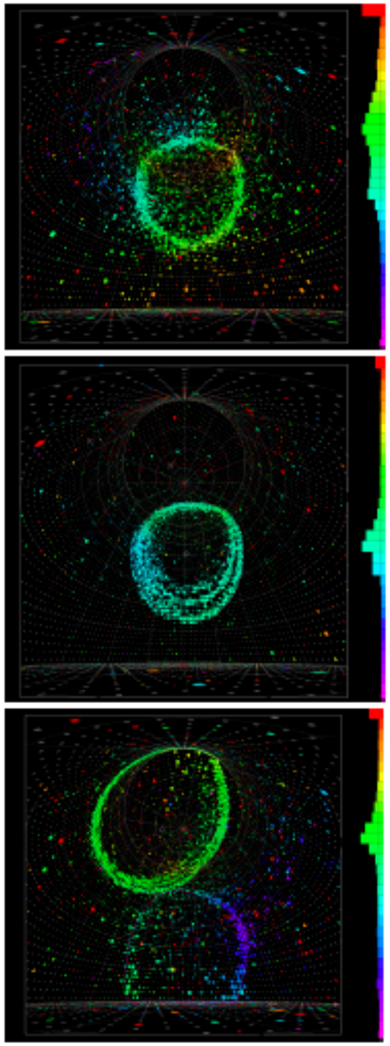
Sensitivity to *CP* violation (HK)

Fraction of true δ possible to observe CPV with >3σ



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

Integ. power (MW× 10⁷s)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%



- Water Cherenkov detector technology
  - Well-proven technology, with excellent performance
  - Scalability (can make big one)

- Rich physics topics (discovery potentials)
  - Discovery potential of CPV, ν mass hierarchy, precise measurements of ν parameters
  - World best sensitivity for nucleon decay searches, direct test of grand unification picture
  - Supernova ν observatory for astronomy and particle physics
  - Other astronomical objects

- Good reason to do it in Japan
  - Existing accelerator J-PARC and its upgrade plan
  - Long, good experience of detector construction, operation, analyses (Super-K)

We had the first open international meeting for this project this week.

~100 physicists participated.

Supplement