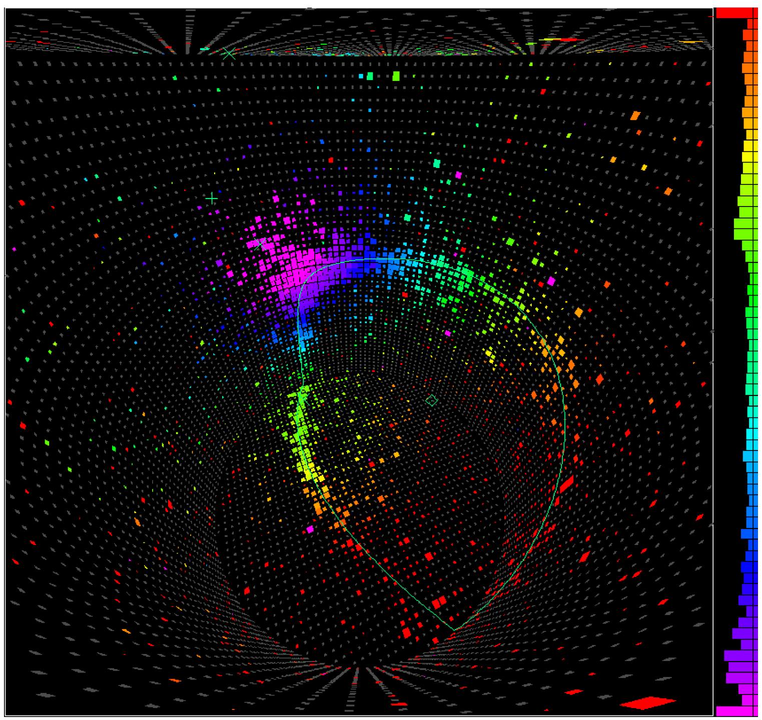
T2K ν_e appearance search



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@東大宇宙線研

Three flavor neutrino oscillation

Situation before T2K

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- 6 oscillation parameters

ignoring Majorana phases

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

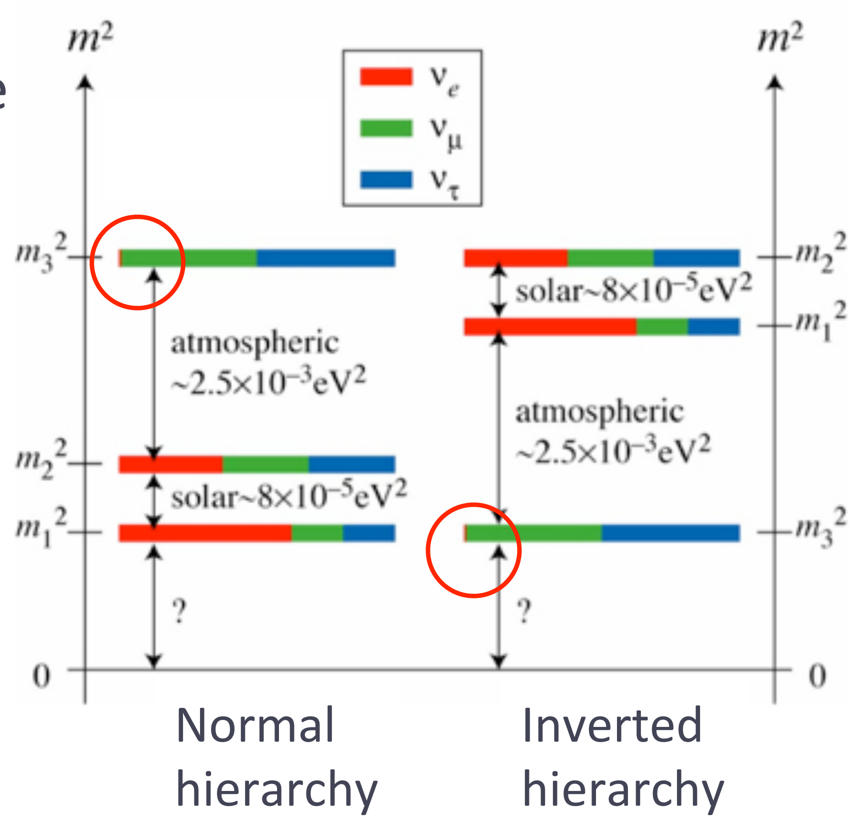
+ 2 mass differences (Δm^2_{12}, Δm^2_{23})

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

Only upper limit on θ_{13} → $\theta_{13}=0$? $\neq 0$? unknown.

Why θ_{13} ?

- The last unknown mixing angle
- Non-zero θ_{13} will open possibility to discover the CP violation in the lepton sector and also reveal the neutrino mass hierarchy



Non-zero θ_{13} hunting around the world

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

- Accelerator neutrino experiments : ν_e appearance

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

$$+ \; 8C^2_{13}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\cdot\sin\Phi_{31}\cdot\sin\Phi_{21} \quad \text{CPC}$$

$$- \; 8C^2_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\cdot\sin\Phi_{31}\cdot\sin\Phi_{21} \quad \text{CPV}$$

$$+ \; 4S^2_{12}C^2_{13}(C^2_{12}C^2_{23} + S^2_{12}S^2_{23}S^2_{13} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21} \quad \text{solar}$$

$$- \; 8C^2_{13}S^2_{13}S^2_{23}(1-2S^2_{13})\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31}. \quad \text{matter effect}$$

→ Sensitive to δ_{CP} and mass hierarchy

- 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

T2K (Tokai-to-Kamioka) experiment

Intense ν_μ beam from J-PARC toward Super-Kamiokande

~500 members from 58 institutes, 12 nations

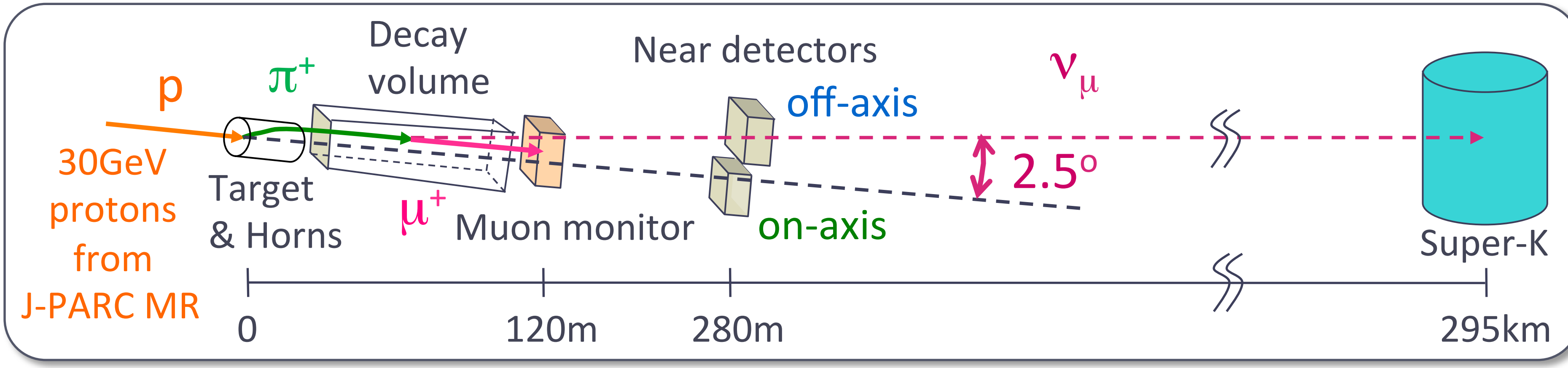
Primary goals :

- Discovery of ν_e appearance by $\theta_{13}\neq 0$

  Sensitivity >10 times better than CHOOZ limit

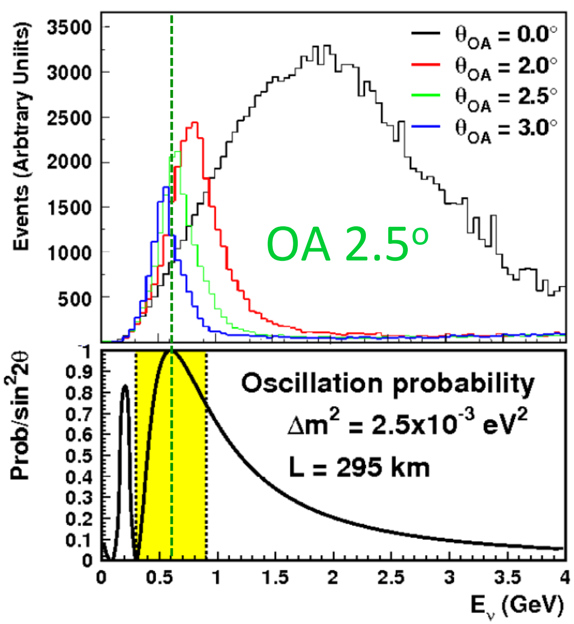
- Precision measurement of ν_μ disappearance

  $\delta(\Delta m^2_{23})\sim 1\text{x}10^{-4}\ \text{eV}^2$, $\delta(\sin^2 2\theta_{23})\sim 0.01$



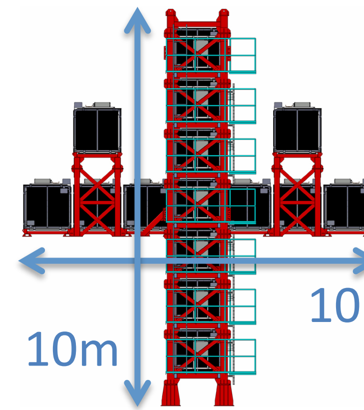
Off-axis ν beam

- Intense narrow-band @ osc. max. (~0.6GeV)
- Reduce high energy tail which creates BG



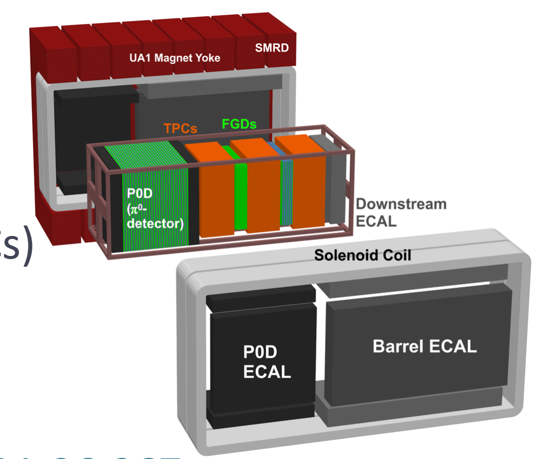
On-axis detector (INGRID)

- 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)

- measure ν flux/spectrum before oscillations
- 2 Fine Grained Detectors (FGDs)
- 3 Time Projection Chambers (TPCs) PID by dE/dx in gas
- P0D (π^0 detector), ECAL, SMRD



http://dx.doi.org/10.1016/j.nima.2011.06.067

Far detector : Super-Kamiokande

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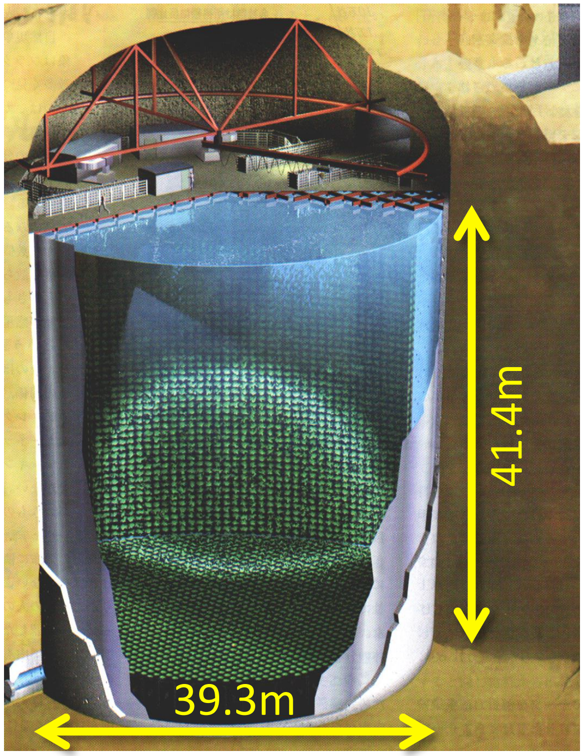
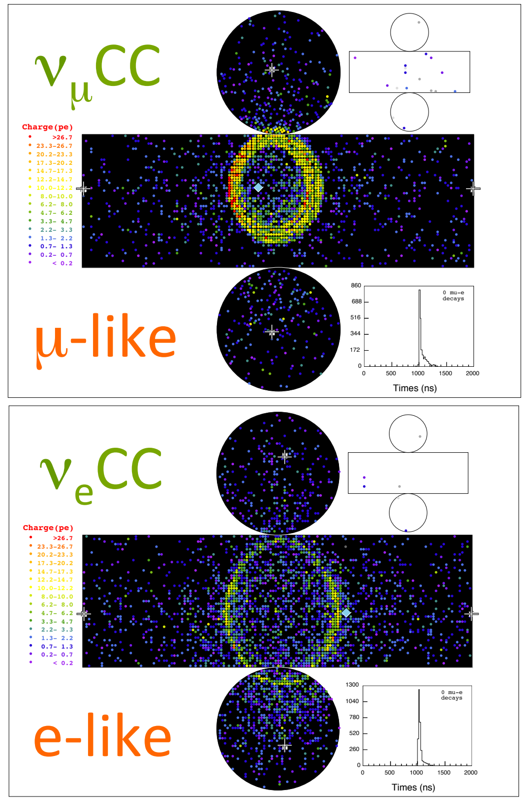
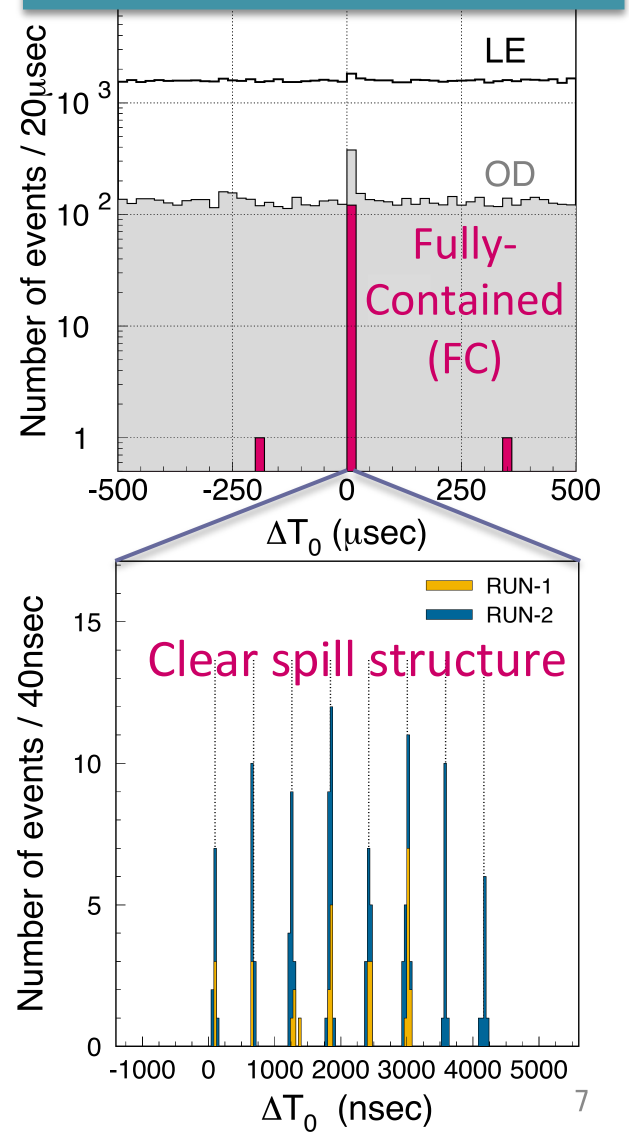


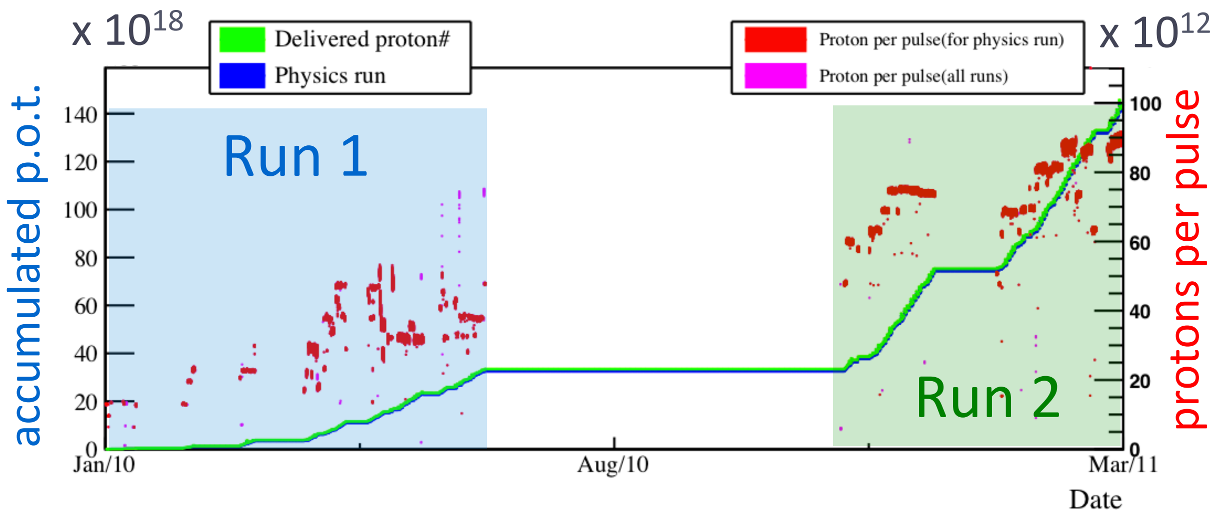


Observed SK event timing
(relative to beam arrival time)



- Water Cherenkov detector, 22.5kton fiducial mass
- Excellent μ/e PID using ring-shape & opening angle (mis-ID probability ~1%)
- T2K: Realtime recording of all PMT hits within ±500μsec of beam arrival time by using GPS

Beam data used in the published results



Run 1 (2010 Jan - 2010 Jun)

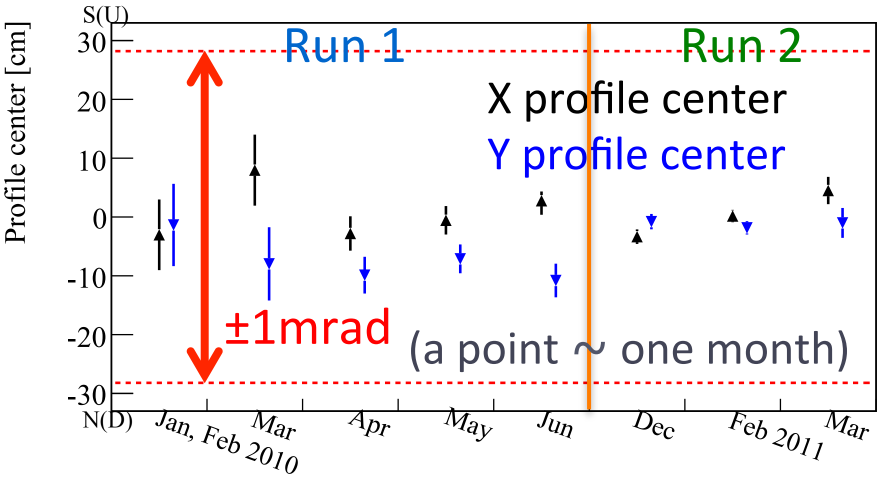
50kW stable operation

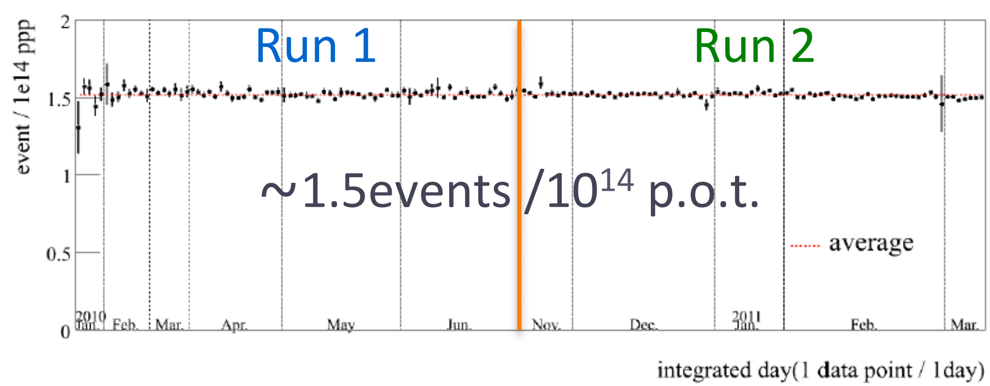
Run 2 (2010 Nov - 2011 Mar)

reached 145kW

Total p.o.t. : 1.43×10^{20}

~2% of T2K final goal





ν beam center measured by INGRID well within ±1mrad (δE<<2%@SK)

INGRID interaction rate stable for Run 1 & 2

(Beam direction & intensity also monitored by Muon Monitor spill-by-spill)

Oscillation analysis

Super-K Measurements :

- ν_e appearance
  → counting analysis
- ν_μ disappearance
  → rate & spectrum shape

ND280 Measurements :

- Inclusive ν_μCC measurement
- ν_e measurement as cross-check

Normalize SK MC prediction by ND ν_μCC rate

$$N_{SK}^{exp} = \frac{R_{ND}^{\mu,Data}}{R_{ND}^{\mu,MC}} \times N_{SK}^{MC}$$

Observation/Expectation comparison to extract oscillation parameters

Far/Near sys. error cancellation

ND280 / Super-K MC simulations

Neutrino Flux :
Detailed MC simulation of beamline with input from proton beam monitors & external hadron data

Neutrino Interaction :
Model (NEUT) tuned/constrained with external data

→ Detector simulations

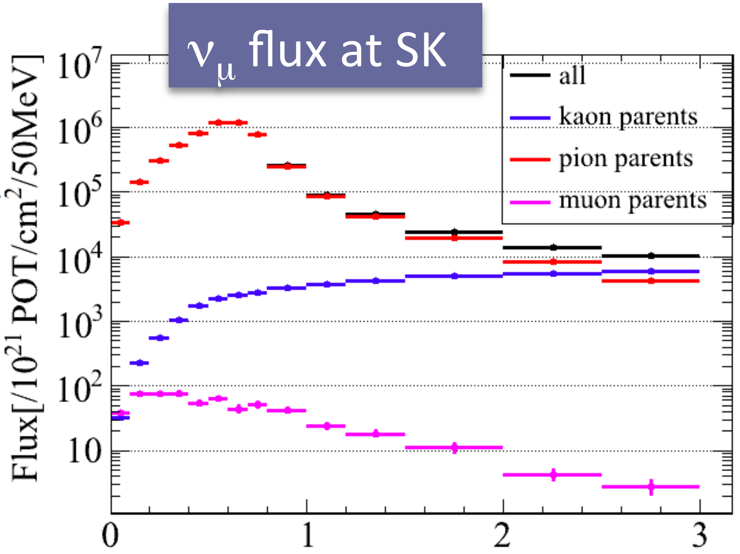
Neutrino flux prediction

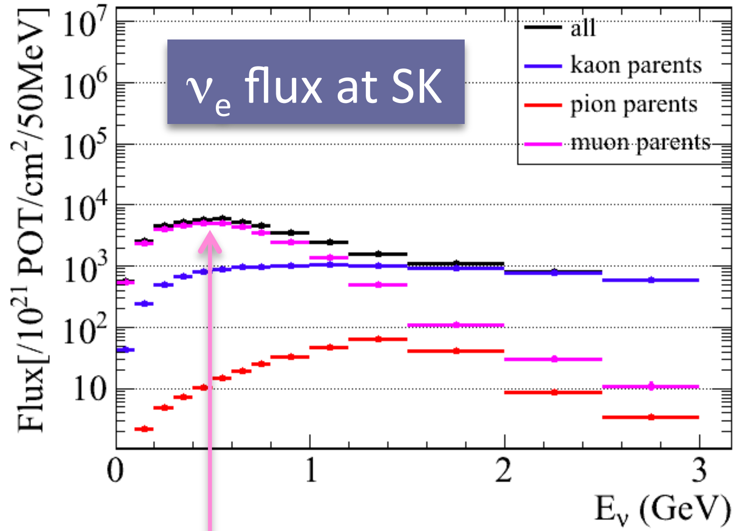
T2K beam simulation based on hadron production measurements

- NA61/SHINE (@CERN) measured hadron production in (p, θ) using 30GeV protons and graphite target
- π outside NA61 acceptance and K production modeled with FLUKA

Error source (ν_e analysis)	$R^{\mu,\,MC}_{ND}$	N^{MC}_{SK}	$\frac{N^{MC}_{SK}}{R^{\mu,\,MC}_{ND}}$
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Nucleon production	5.9%	6.6%	1.4%
Production x-section	7.7%	6.9%	0.7%
Proton beam position/profile	2.2%	0.0%	2.2%
Beam direction measurement	2.7%	2.0%	0.7%
Target alignment	0.3%	0.0%	0.2%
Horn alignment	0.6%	0.5%	0.1%
Horn abs. current	0.5%	0.7%	0.3%
Total	15.4%	16.1%	8.5%

Partial error cancellation after ND correction





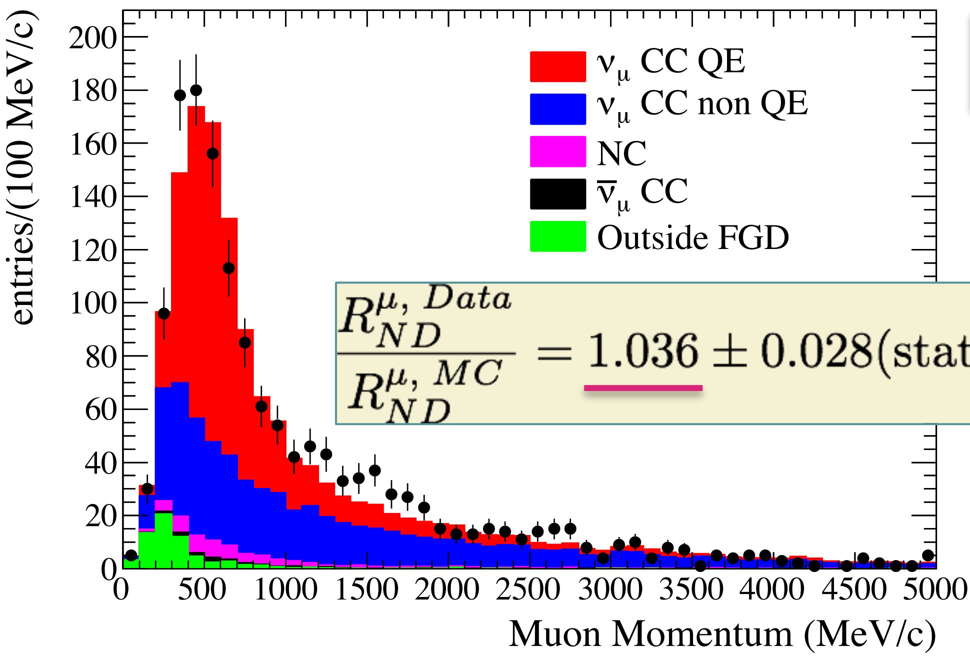
μ decay is dominated at low E_ν

$$\pi^+ \to \mu^+ \nu_\mu\ ,\ \ \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

→ can accurately be predicted by NA61 π measurement

ND280 measurements

Using Run 1 data (2.9×10^{19} p.o.t.)



Inclusive ν_μCC measurement

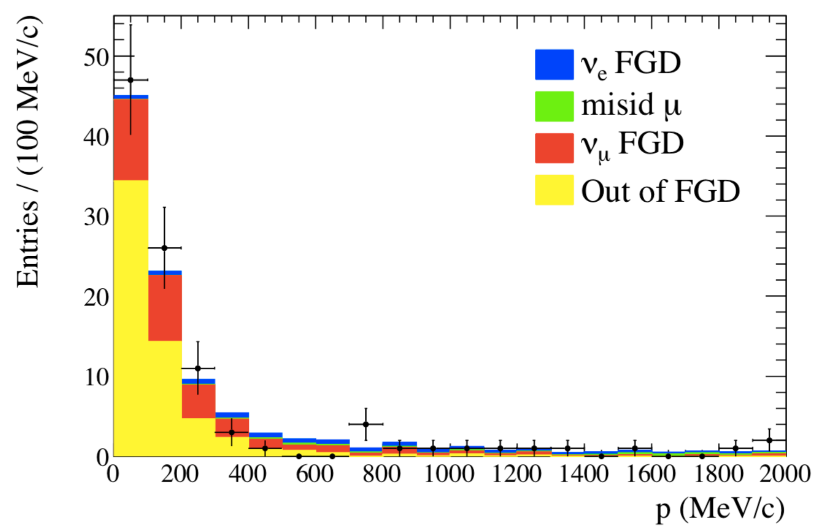
Tracks starting in FGD and identified as μ by TPC dE/dx and curvature

$$\frac{R_{ND}^{\mu,\ Data}}{R_{ND}^{\mu,\ MC}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

Intrinsic beam ν_e measurement

TPC dE/dx to select electron tracks

$R(\nu_e/\nu_\mu) = 1.0 \pm 0.7(\text{stat.}) \pm 0.3(\text{sys.})$ %



Data consistent with MC based on NA61 data and ν interaction simulation

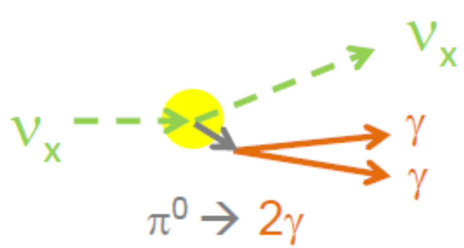
T2K ν_e event selection

Number of remaining events after each cut

Signals : Single-electron events by osc. ν_e CCQE

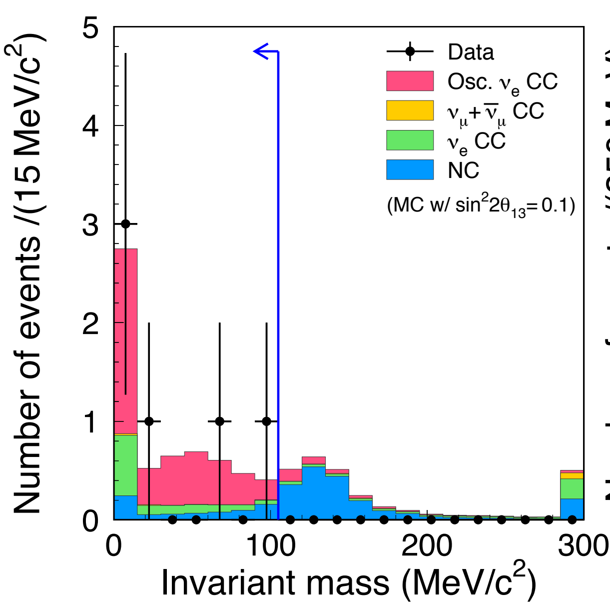
Backgrounds :

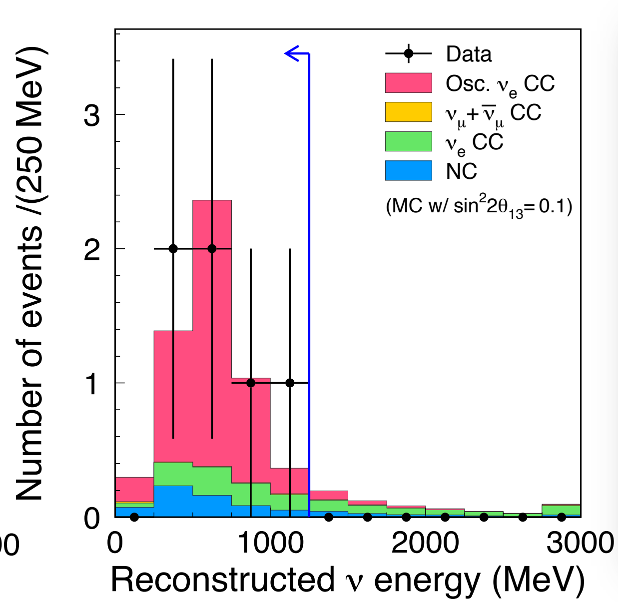
- ✓ Intrinsic beam ν_e
- ✓ NC π^0 events
  - overlap of 2 γ rings
  - asymmetric decay

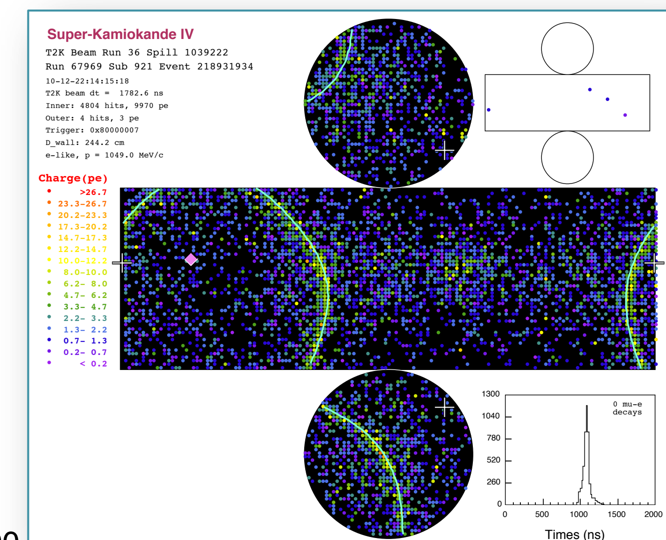


- Beam timing, FC, fiducial (88)
- Single-ring electron-like (8)
- Visible energy > 100MeV (7)
- No delayed electron signal (6)
- Invariant mass < 105MeV/c^2 (6)
- Rec. ν energy < 1250MeV (6)

→ 6 events observed



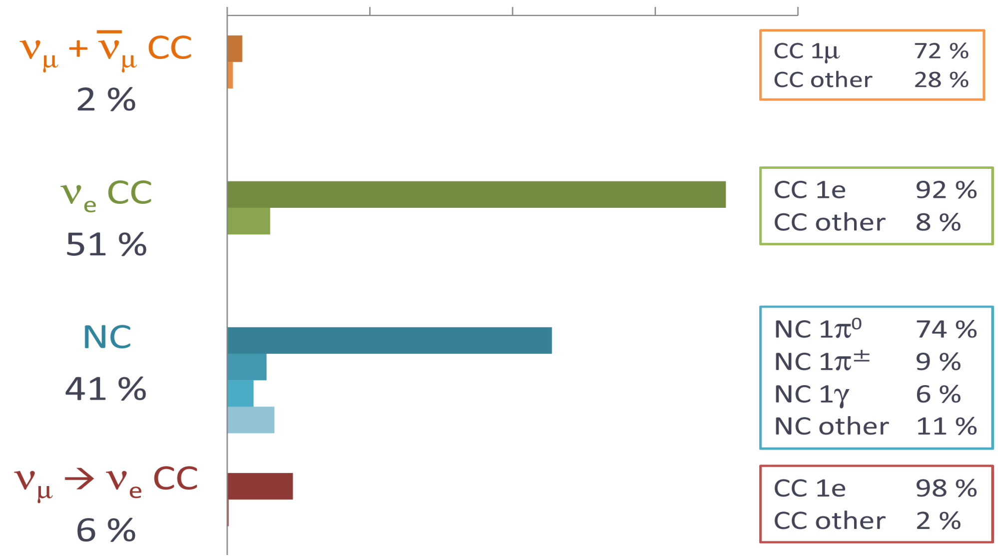




Expected number of ν_e events (θ_{13}=0)

(Δm^2_{23}=2.4x10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0)

Source	N_{SK}^{exp} (events)
Beam ν_μ CC	0.03
Beam ν_e CC	0.8
NC	0.6
Solar $\nu_\mu \rightarrow \nu_e$	0.1
Total	**1.5**



error source	syst. error
ν flux	$\pm 8.5\%$
ν int. cross section	$\pm 14.0\%$
Near detector	$^{+5.6}_{-5.2}\%$
Far detector	$\pm 14.7\%$
Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

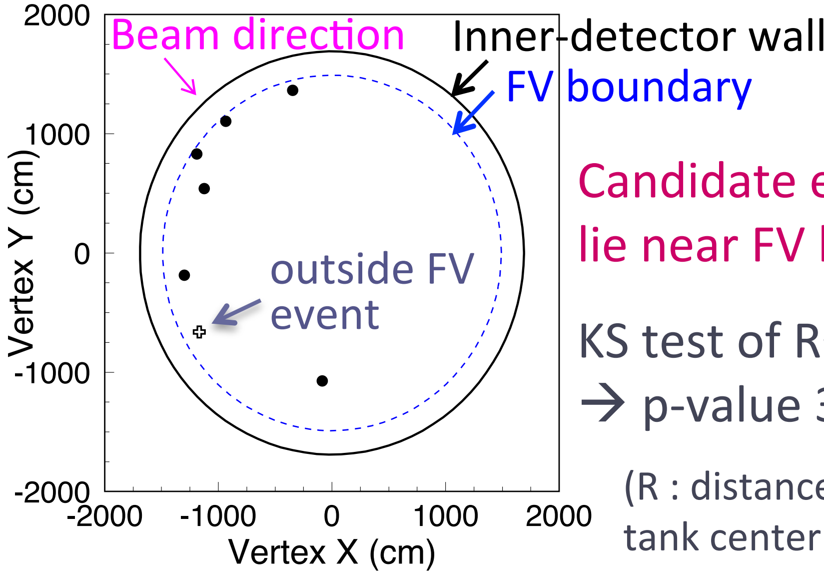
Dominated by hadron production uncertainties

Dominated by FSI and NC1π^0 cross-section uncertainties

Dominated by ring-counting, PID and invariant mass cut uncertainties

Expected number of events for θ_{13}=0 : 1.5 ± 0.3 (sys.) events

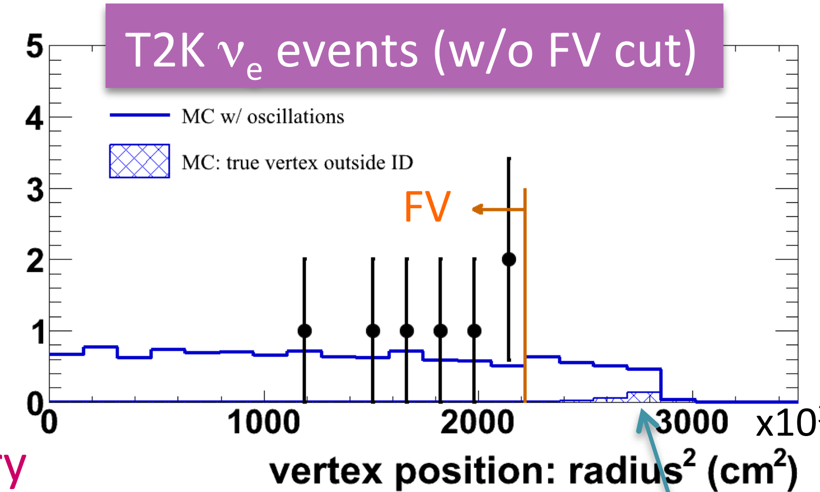
Vertex distribution

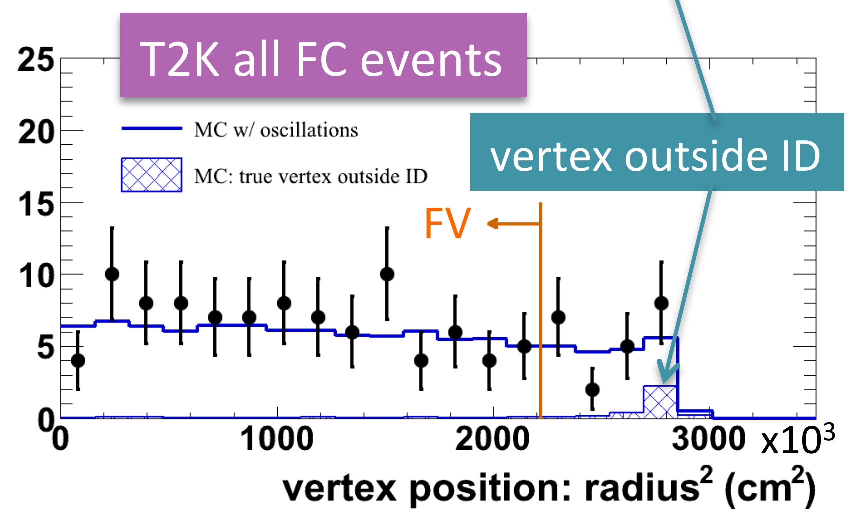


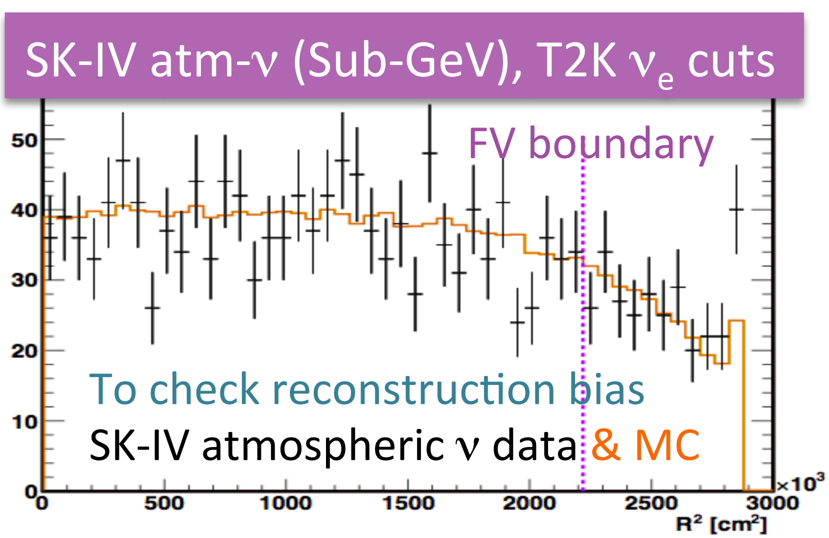
Candidate events lie near FV boundary

KS test of R^2 dist.
→ p-value 3%

(R : distance from tank center axis)







→ *Nice agreement both inside/outside FV*

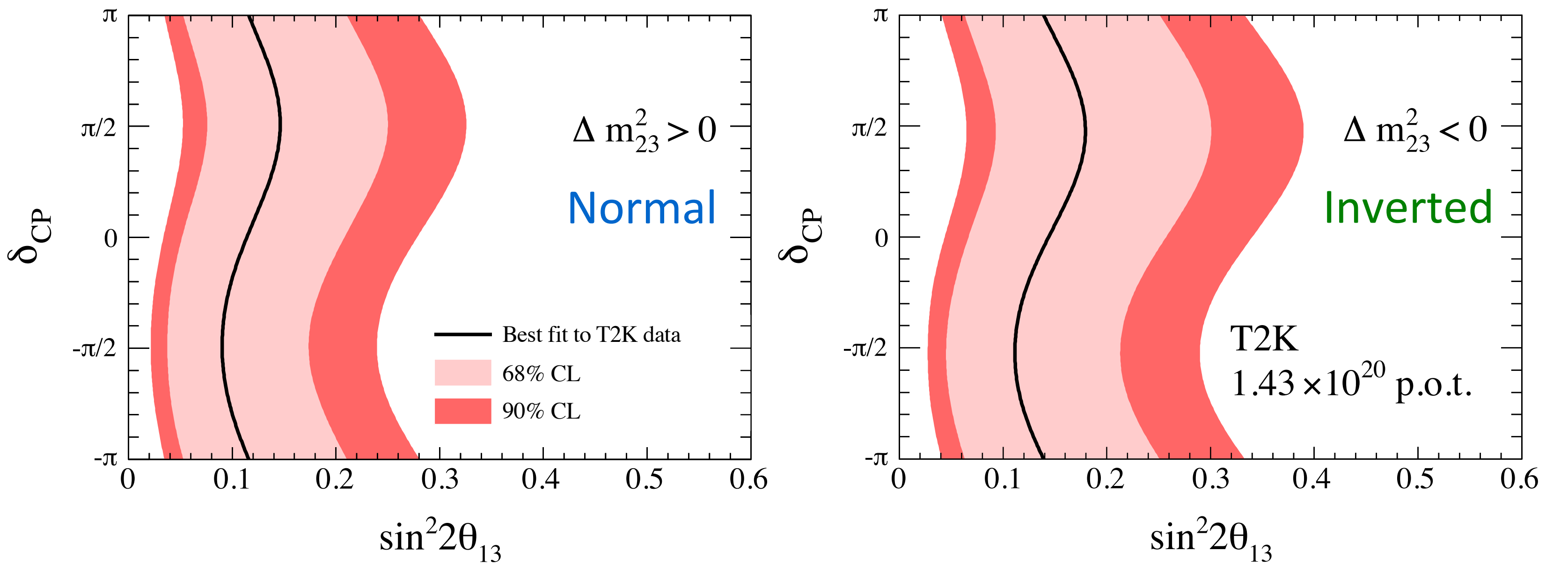
Outside FV / Outer-detector events
→ *No anomalies near edge of FV*

Simulation study of beam-induced BG by mis-ID μ, n, K, etc. from outside
→ *Very few ($3x10^{-3}$) events in FV*

ν_e appearance search result with 1.43×10^{20} p.o.t. data

Prob. of observing ≥6 events if $\theta_{13}=0$ → 0.7% (2.5σ)

First indication of ν_e appearance via non-zero θ_{13}



(Feldman-Cousins method used to produce the confidence intervals)

Normal hierarchy, $\delta=0$: $\sin^2 2\theta_{13}$ = 0.11 (best fit), 0.03-0.28 (90% C.L.)

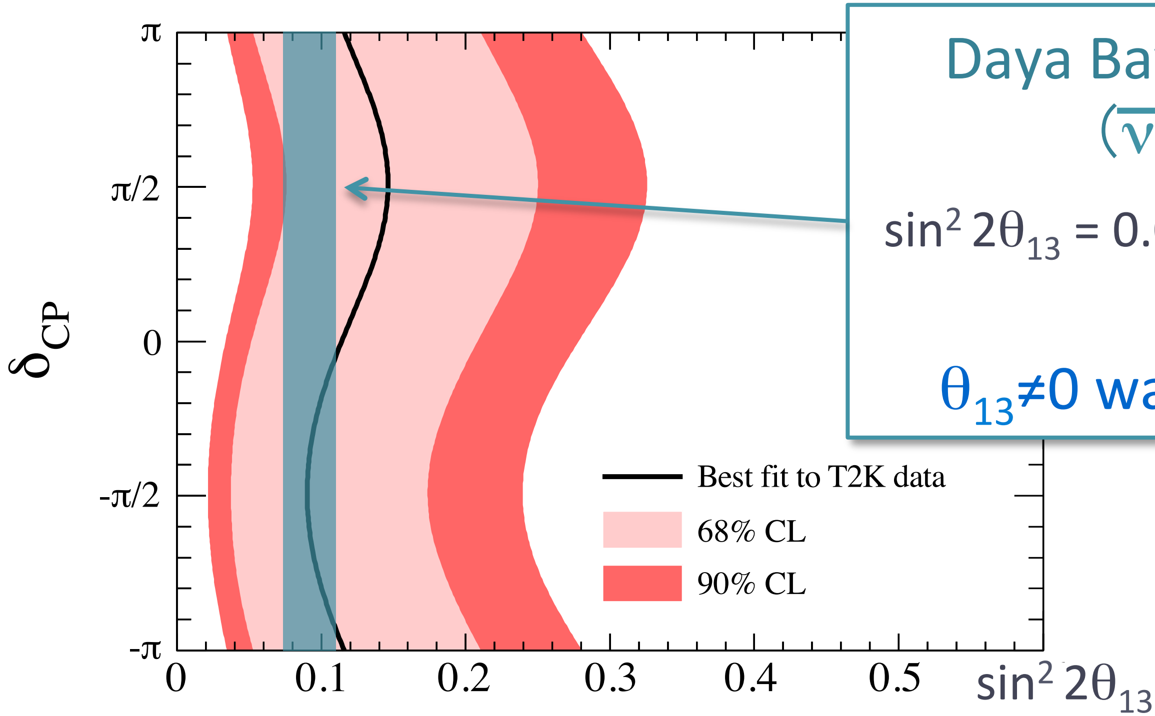
Inverted hierarchy, $\delta=0$: $\sin^2 2\theta_{13}$ = 0.14 (best fit), 0.04-0.34 (90% C.L.)

Published in Phys. Rev. Lett. 107, 041801 (2011)

Recovery after the EQ and commissioning

- Primary beamline (proton beam)
  - Equipment → No fatal damages due to the EQ
  - Re-aligned all the super-conducting magnets
  - → Became ready before December
- Secondary beamline (the target and downstream)
  - Equipment → No fatal damages due to the EQ
  - → Became ready in mid-December after a careful inspection
- During the commissioning
  - The magnetic horn power-supply broke in late-December
  - → Decided to re-use an old horn power-supply
  - Resumed physics runs in early-March with 250kA horn current
  - → A device in the horn PS broke and was replaced with a spare
  - → Resumed the experiment with 200kA horn current for safety

The Daya Bay result, and then …



Daya Bay reactor ν experiment
($\overline{\nu}_e$ disappearance)

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
(arXiv:1203.1669)

$\theta_{13} \neq 0$ was established with $>5\sigma$

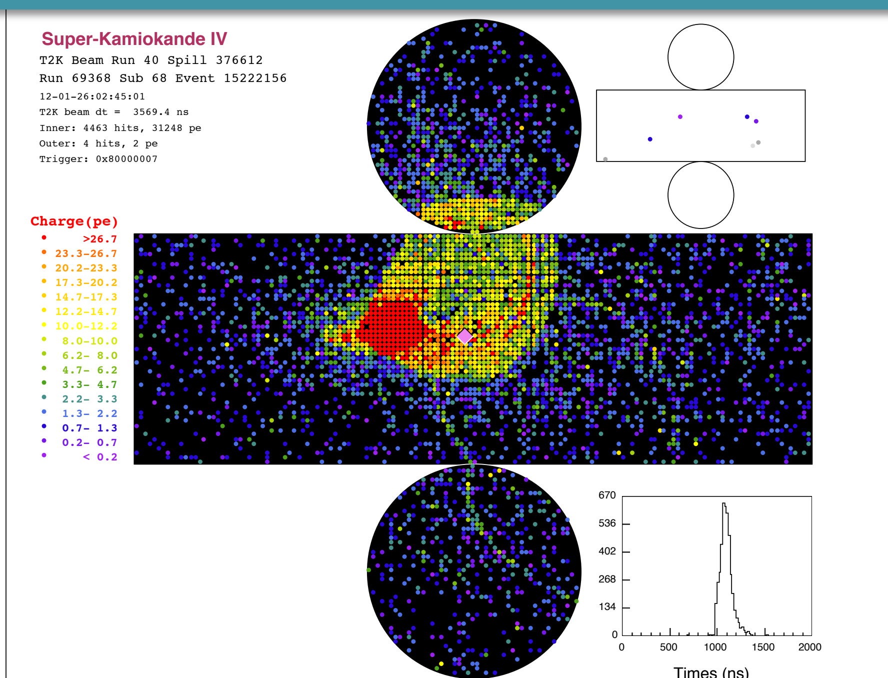
Our aim does not change.

- Discover ν_e appearance first ($>3\sigma$).
- Then measure ν_e appearance probability precisely

T2K current status and plan

- Physics data-taking started on March 8th
  - 2.92 sec repetition cycle (3.02 sec before the EQ)
  - 150kW beam power (145kW max. before the EQ)
  - 200kA horn current (250kA before the EQ)

The first T2K beam event at SK after the EQ



By this summer, T2K will

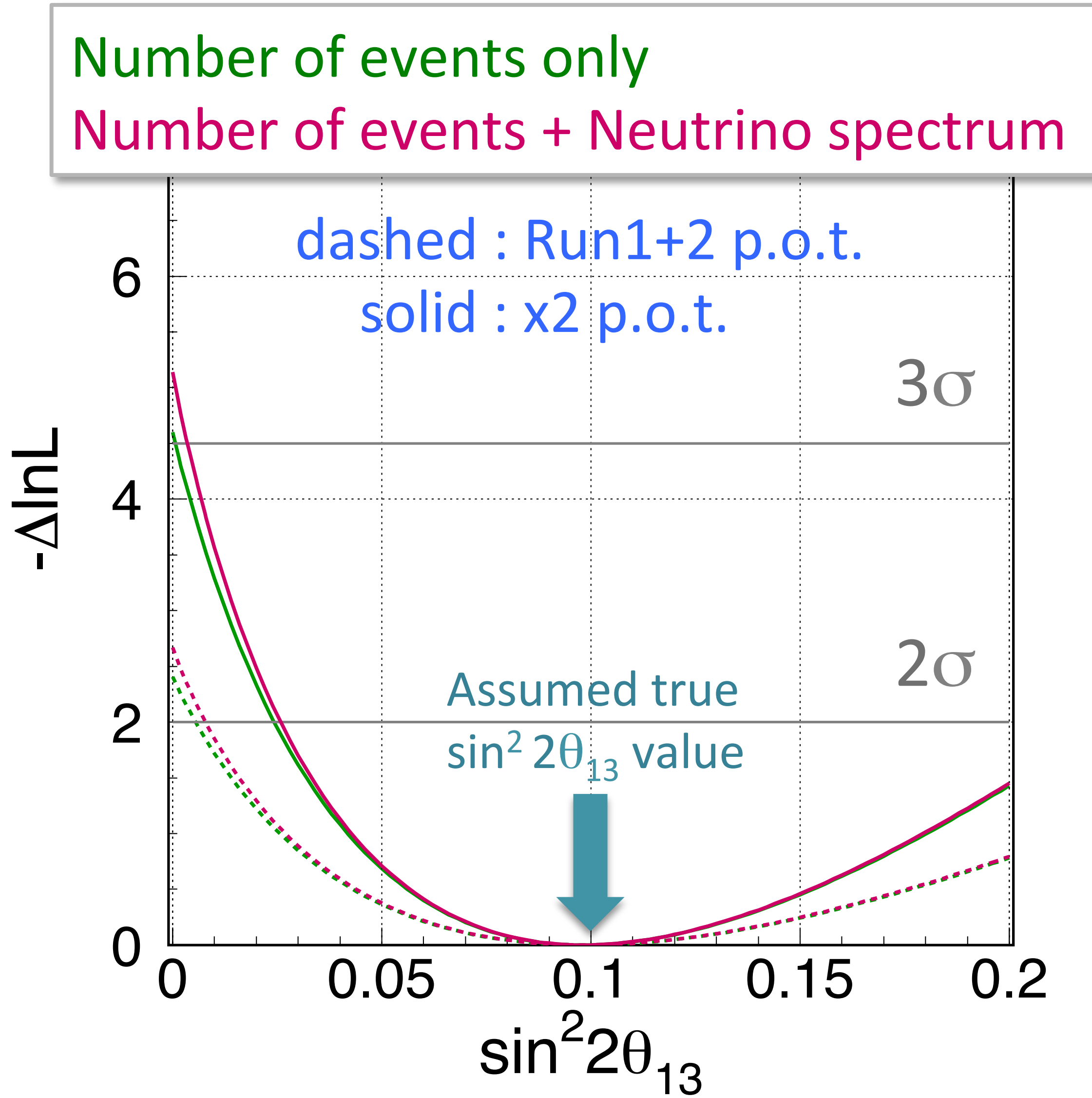
- Double the statistics
- Improve the analysis

Exclude "no ν_e appearance" hypothesis with $>3\sigma$

Analysis improvement is going on

- Neutrino flux model
  - Based additionally on the experimental data of K production (by NA61@CERN using the same proton beam energy and target as T2K)
- Neutrino interaction model
  - Using recent experimental data (MiniBooNE, K2K, …)
- Near detector data analysis
  - ν_μCC inclusive # of events → Distribution of CCQE/CCnonQE samples
- SK detector systematic error
  - Improved error estimation for sub-dominant components
- ν_e appearance analysis using the shape information
  - Reconstructed ν energy, electron momentum vs. direction, …

An example of sensitivity study (MC)



±1σ region of $\sin^2 2\theta_{13}$

Run1+2	p.o.t.	0.04-0.18
x2	p.o.t.	0.06-0.15

Significance @θ_{13}=0

Run1+2	# events	2.2σ
x2	# events	3.0σ
x2	+Spectrum	3.2σ

Summary

- ν_e appearance result from the first off-axis long-baseline ν experiment using 1.43×10^{20} p.o.t. data

- Indication of ν_e appearance via non-zero θ_{13}
  - 6 candidate events observed, while 1.5±0.3 expected if $\theta_{13}=0$

    → probability = 0.7 % (2.5σ significance)

    Phys. Rev. Lett. 107, 041801 (2011)

- Physics data-taking was resumed in early-March
  - would like to double the statistics and discover the ν_e appearance with >3σ by this summer

  → Toward a precise measurement of ν_e appearance probability

Supplement