Первые результаты ускорительного нейтринного эксперимента T2K

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Семинар ОФВЭ ИЯИ РАН, 10 октября 2011 года

Neutrino oscillation parameters and PMNS matrix

Flavor weak eigenstates related to mass eigenstates

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

SK, K2K, MINOS — CHOOZ, MINOS — Solar, KamLAND

Neutrino oscillation parameters: three angles θ_{12}, θ_{23}, θ_{13}; CP-phase δ_{CP};
two mass squared differences $\Delta m^2_{ij}=m^2_j-m^2_i$

PDG, 2010

$7.38 \times 10^{-5}\ eV^2 < \Delta m^2_{12} < 7.80 \times 10^{-5}\ eV^2$

$0.84 < \sin^2 2\theta_{12} < 0.89$

$2.3 \times 10^{-3}\ eV^2 < |\Delta m^2_{23}| < 2.56 \times 10^{-3}\ eV^2$

$0.92 < \sin^2 2\theta_{23} < 1.0$

For $\Delta m^2_{23} = 2.4 \times 10^{-3}\ eV^2$, 90% C.L.

CHOOZ 1999: $0 < \sin^2 2\theta_{13} < 0.15$

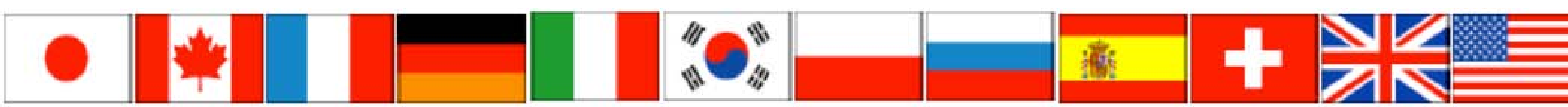
MINOS 2010: for $\sin^2 2\theta_{23}=1.0$ and $\delta_{CP}=0$

$0<\sin^2 2\theta_{13}<0.12(0.20)$ for normal (inverted) mass hierarchy

$$\theta_{13} - ? \qquad \delta_{CP} - ?$$

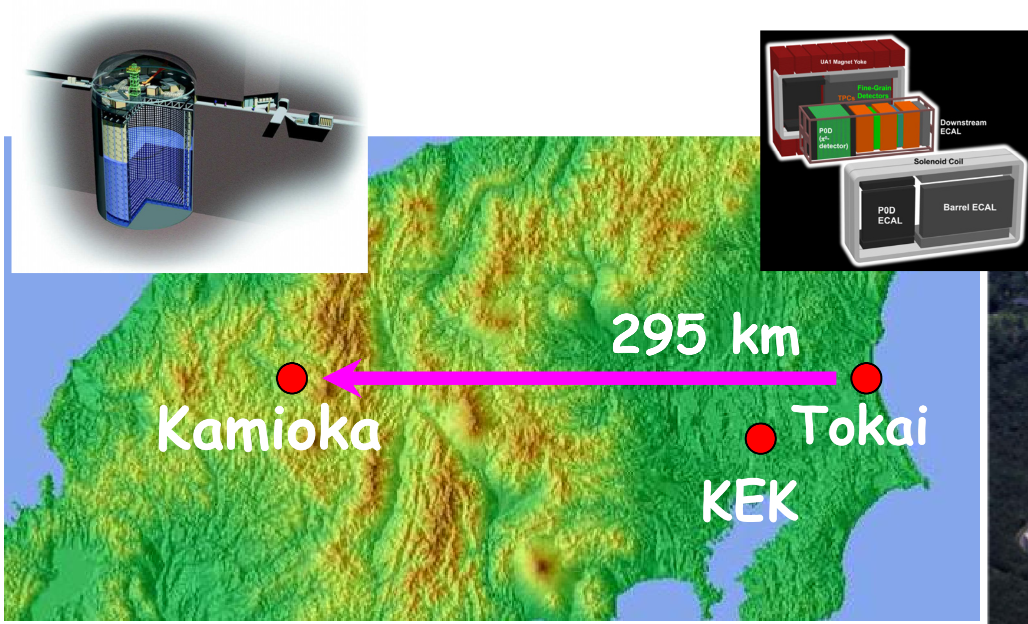
Inverted or normal mass hierarchy?

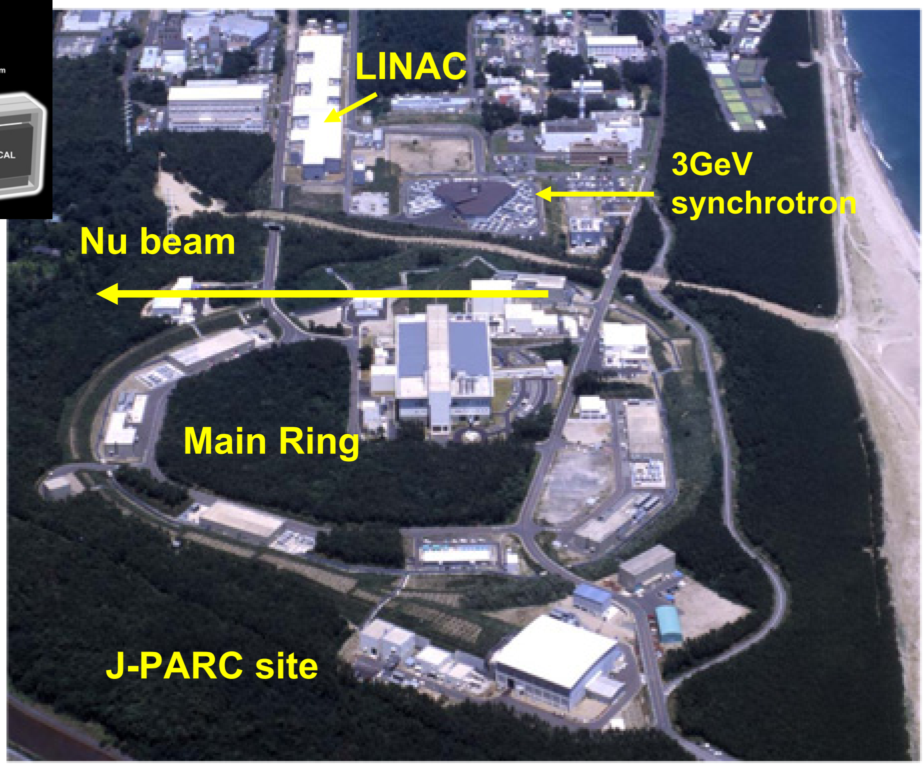
T2K collaboration



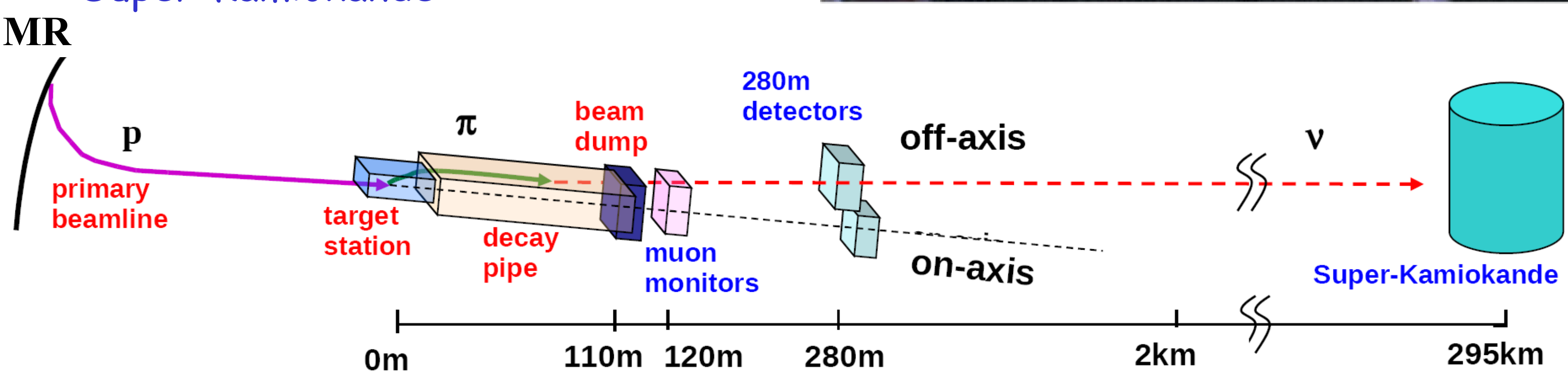
~ 500 members, 58 national institutes, 12 countries

T2K (Tokai-to-Kamioka) experiment





High intensity neutrino beam from J-PARC 30 GeV MR to Super-Kamiokande



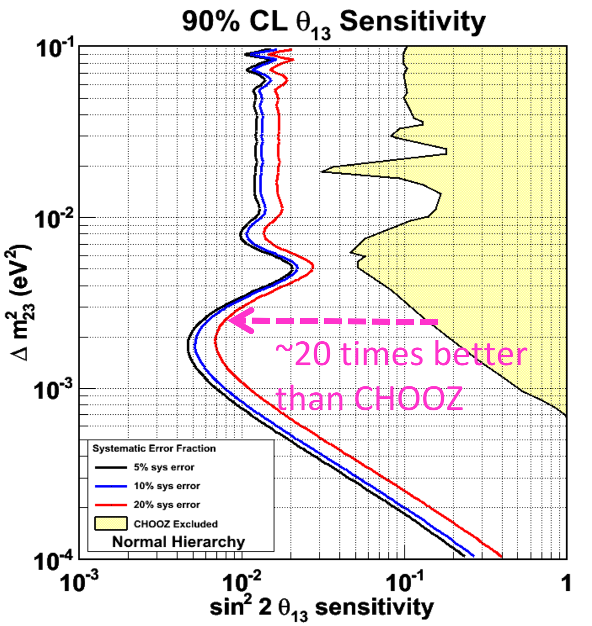
T2K physics goals

Search for $\nu_\mu \rightarrow \nu_e$ oscillations and hence non-zero θ_{13}

$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m_{31}^2 L}{E}\right)$$

- last unknown PMNS mixing angle;
  non-zero θ_{13} is crucial for further lepton CPV and mass hierarchy experimental observations

- expected T2K sensitivity w/full T2K dataset ($8\text{x}10^{21}$ p.o.t.):
  ~20 times better than CHOOZ limit



Precise measurements of Δm^2_{23} and $\sin^2(2\theta_{23})$ in $\nu_\mu \rightarrow \nu_\mu$ channel

$$P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m_{23}^2 L}{E}\right)$$

- expected sensitivity w/ full T2K dataset:

$\delta(\Delta m_{23}^2) \sim 1 \times 10^{-4}\ \text{eV}^2$, $\delta(\sin^2 2\theta_{23}) \sim 1\%$ (90% C.L.)

T2K off-axis conception and neutrino interactions

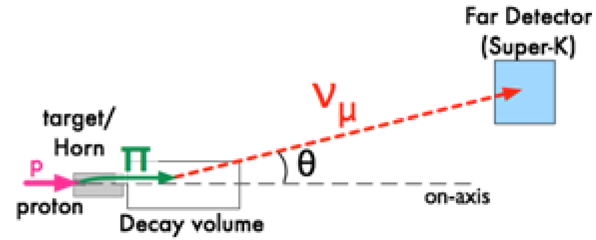
T2K is the first LBL experiment using off-axis neutrino beam conception

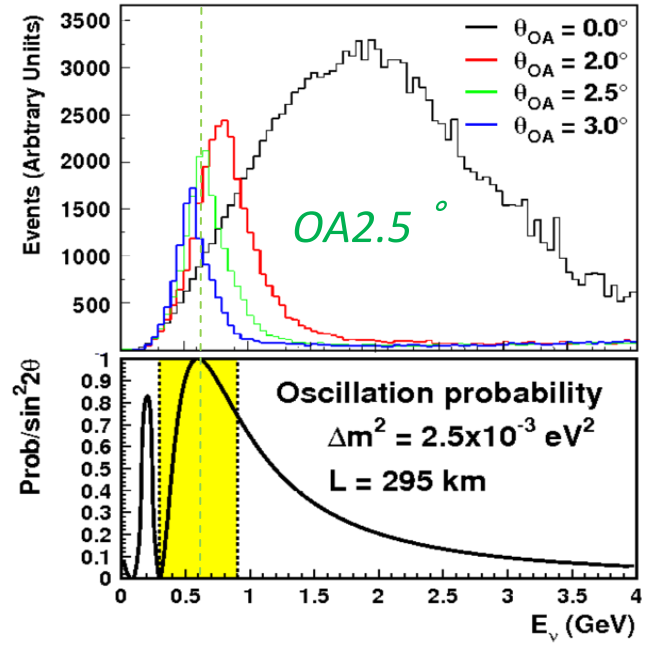
→ T2K utilizes 2.5° off-axis angle

→ optimize beam energy for oscillation max

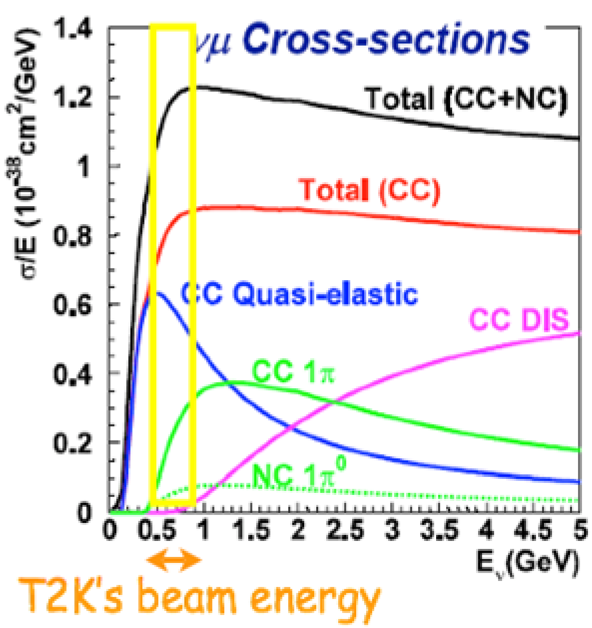
  E_nu ~ 600 MeV

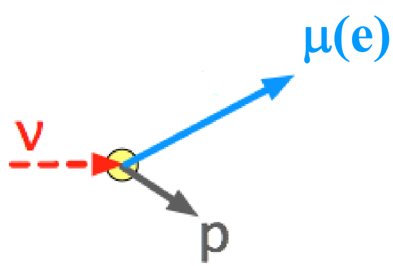
→ small high energy tail





Crucial: accurate beam direction monitoring!



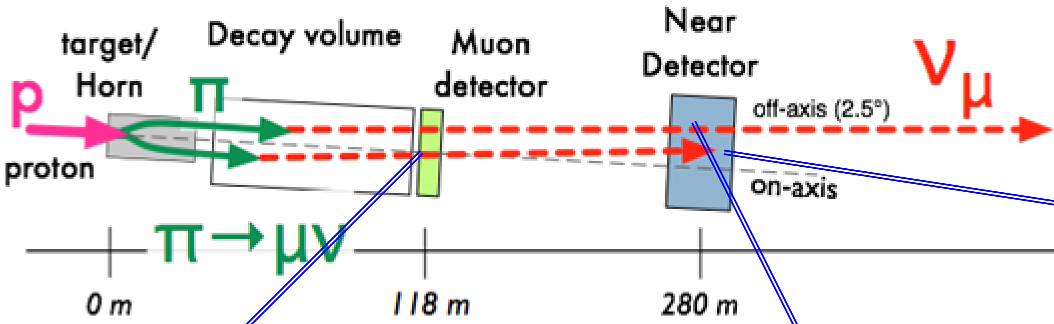


CCQE interactions are dominant at T2K energy → T2K signal

Background increases with energy:
CC1π, NC1π, π`s from DIS, intrinsic ν_e →
<u>reduced due to off-axis beam</u>

“Pre-oscillation” neutrino beam monitoring

K.Abe et al. (T2K collaboration), arXiv:1106.1238 [physics.ins-det] accepted by NIM



Muon monitor (MUMON):

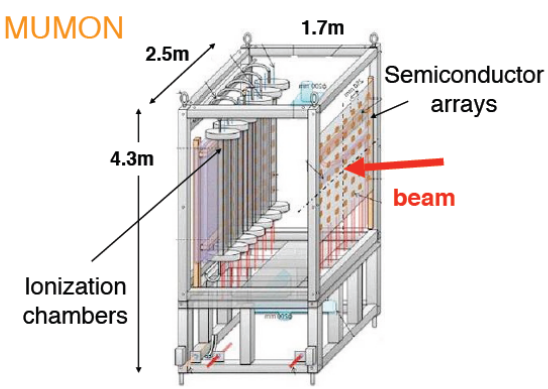
- installed behind the beam-dump
- spill-by-spill monitoring via detecting high energy muons
- muon direction and intensity *monitoring*

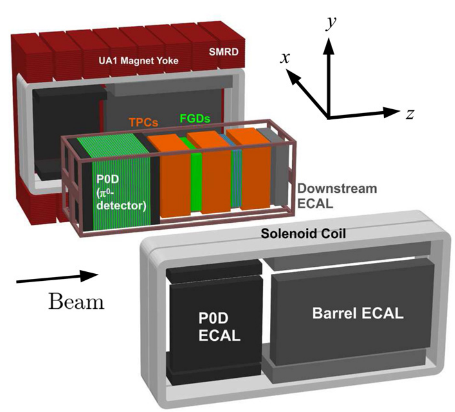
ND280 off-axis detector :

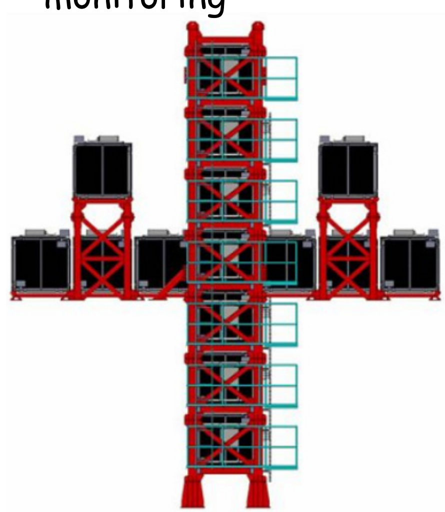
- neutrino spectra measurements before oscillations
- cross-section measurements
- background estimation

ND280 on-axis detector (INGRID):

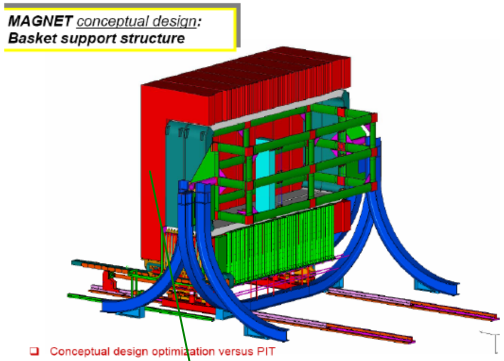
- direct neutrino beam day-by-day monitoring
- beam profile and center position monitoring
- neutrino beam intensity monitoring

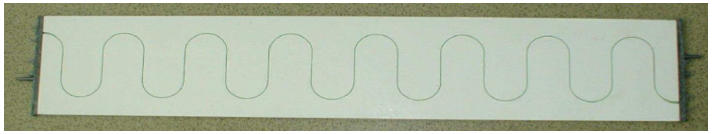


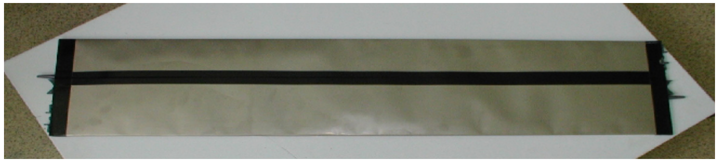


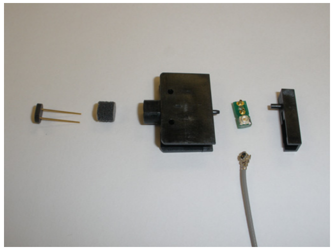


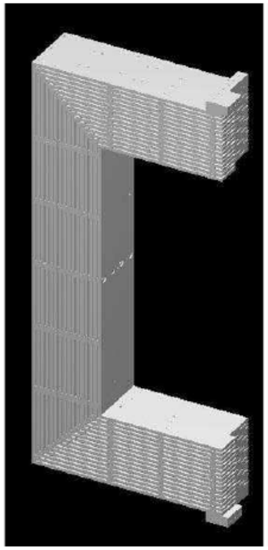
Детектор мюонного пробега SMRD











Задачи и структура SMRD

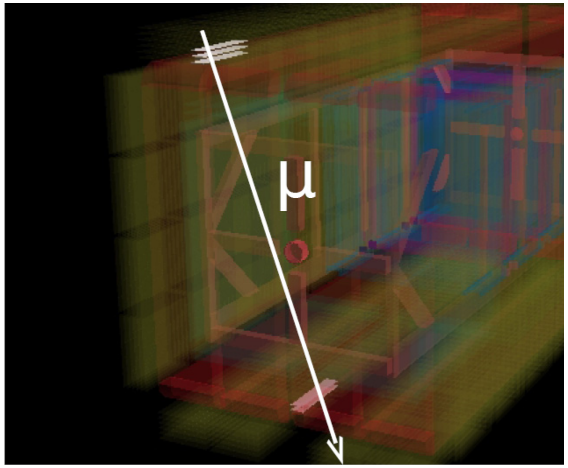
- Регистрация CC-QE мюонов, вылетающих под большими углами к оси нейтринного пучка
- Идентификация фоновых событий
- Калибровка внутренних детекторов
- Воздушные прослойки UA1 магнита, оборудованные сцинтилляционными счетчиками

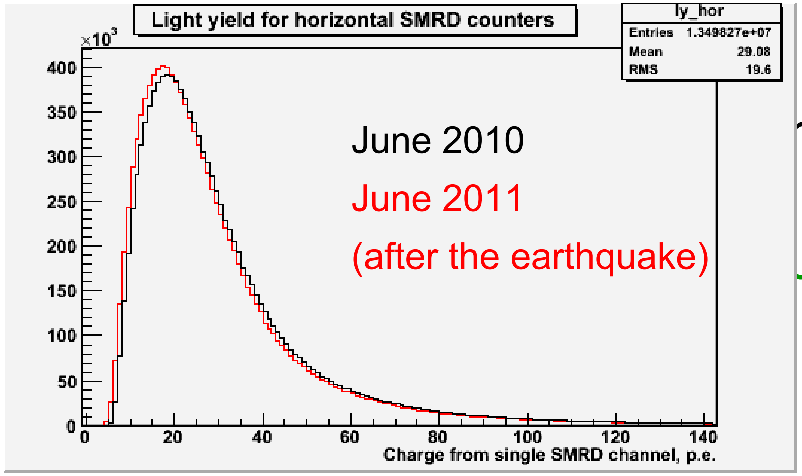
SMRD счетчики разработаны и созданы в ИЯИ РАН

- ~2200 индивидуальных сцинтилляционных счетиков
- светосбор с двух торцов сцинтиллятора: Y11 (d=1мм) WLS оптоволокно S-формы, Hamamatsu MPPC фотодетекторы
- суммарный световыход 25-50 p.e./MIP (~1.5 МэВ) для центра счетчика T=20-22 C
- эффективность регистрации MIP >99.9%
- $\sigma_x < 10$ см; $\sigma_t \sim 1$ нс

SMRD детектор

Космический мюон SMRD



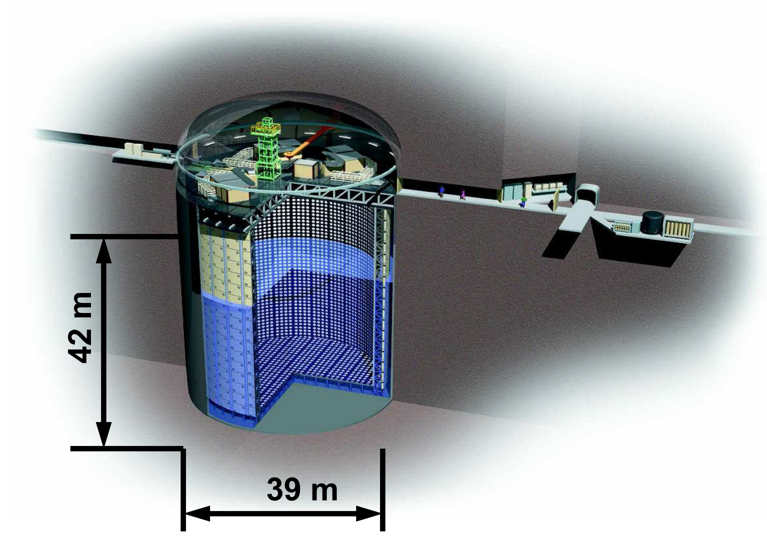


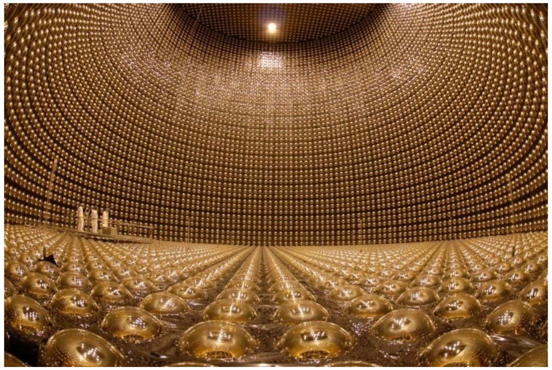
Стабильная работа детектора в течение ~3 лет

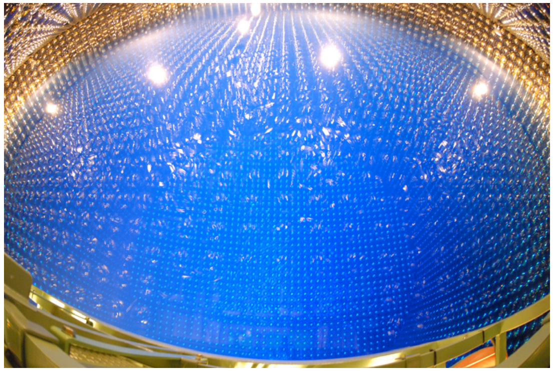
Число «проблемных» каналов ~5 (один полностью мертв)(!) из 4016

Детектор успешно запущен после землетрясения в Японии 11 марта 2011 года

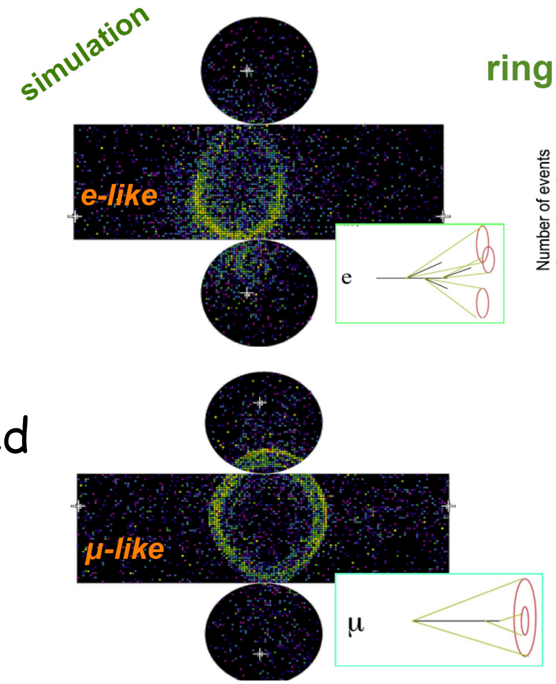
Far Detector Super-Kamiokande (SK)

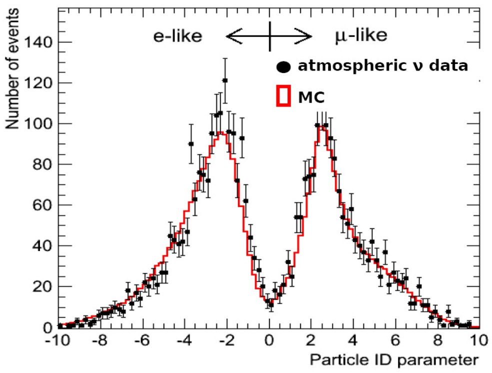






Particle ID using
ring shape & opening angle





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

50 kT water Cherenkov detector

11k PMTs (Inner Detector ID)

Detector performance is well-matched at sub GeV

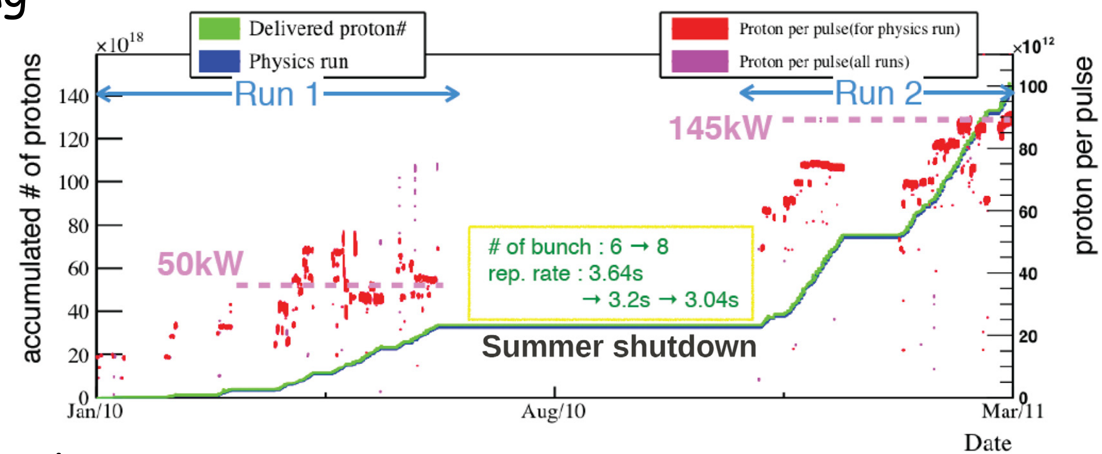
Excellent performance for single particle events

Good e-like ("fuzzy" ring)/μ-like rings separation

Анализ нейтринных осцилляций

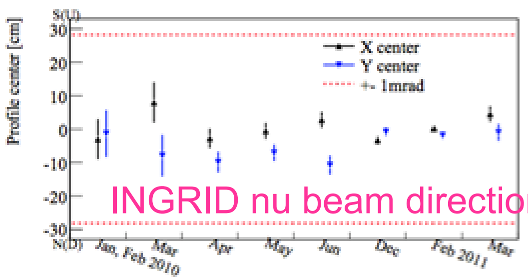
Neutrino beam data used in analysis

- Jan 2010 – start of data taking
- 145 kW stable operation achieved in Run 2
- **Run1 + Run2 total datasets: 1.43×10^{20} p.o.t. (2% of T2K final goal)**

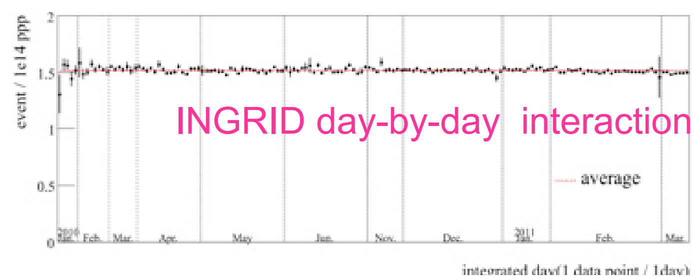


- all collected data used in analysis

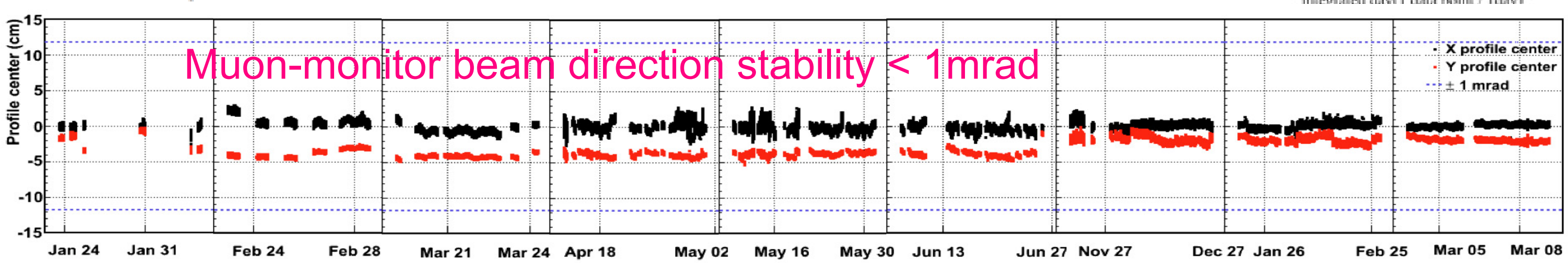
Stable operation of neutrino beam during data collecting
- beam direction stability is well within 1mrad ($\delta E/E<2\%$)



INGRID nu beam direction stability < 1mrad



INGRID day-by-day interaction rate is stable



Muon-monitor beam direction stability < 1mrad

T2K oscillation analysis principles

Flux prediction:
- proton beam measurements
- hadron production data (NA61 CERN)

ND280 measurements:
- inclusive CC ν_μ → $R_\mu^{ND,Data}/R_\mu^{ND,MC}$
- ν_e rate measurement as a cross-check

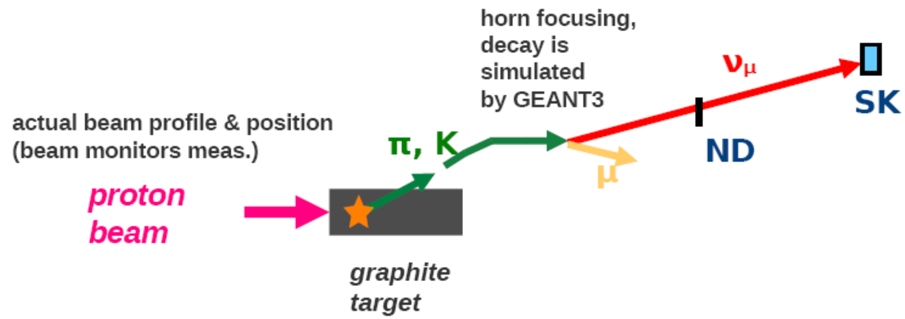
Neutrino interactions:
- ν interactions models
- external cross-section data

Super-K measurements:
- select CCQE ν_μ and ν_e candidates
- compute N_{SK}^{MC} w/o oscillations
- normalize N_{SK}^{MC} using ND280 measurements → $N_{SK}^{exp}=(R_\mu^{ND,Data}/R_\mu^{ND,MC})\times N_{SK}^{MC}$

- evaluate oscillations parameters by comparing with N_{SK}^{obs}
  - ν_e: number of events
  - ν_μ: number of events and E spectra shape combined

T2K neutrino flux prediction

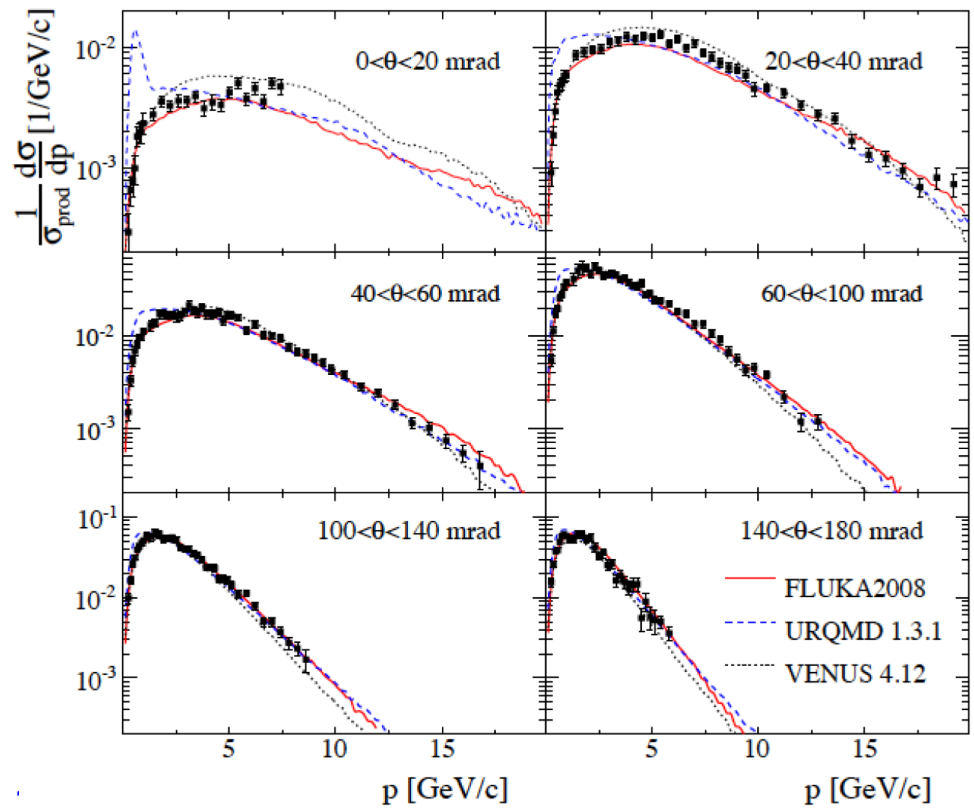
Proton monitors measurements as inputs for actual beam profile and position



Hadron production in T2K target:

- NA61 experiment
  - pions in p+C interactions
  - same as T2K proton energy and target material
  - systematic uncertainty evaluated in each (p,θ) bin, typically 5-10%
  - normalization error 2.3%
- kaon production, pion outside NA61 acceptance, other target interactions modeled with FLUKA

31 GeV/c protons on carbon target; 2007 data



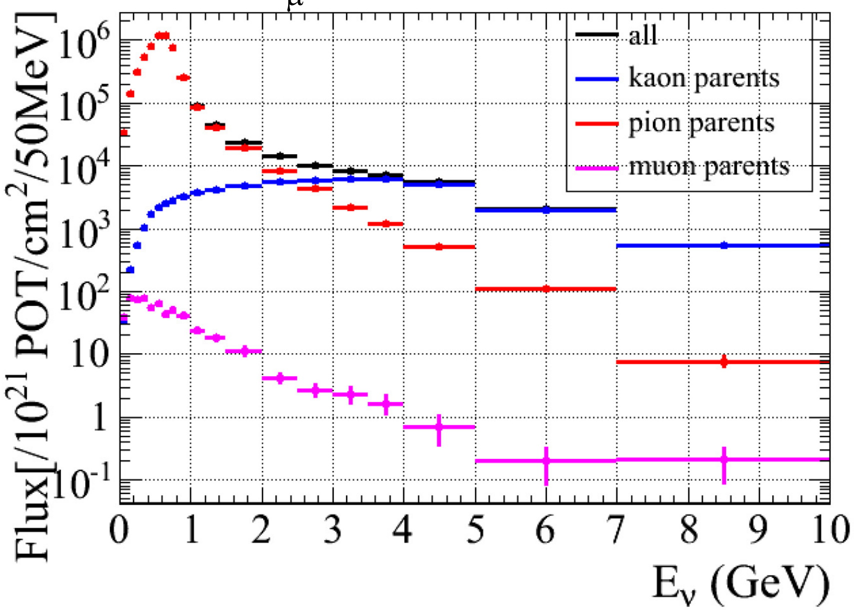
Out of target interactions, horn focusing, secondary interactions, particle decays

- GEANT3 simulation
- interaction cross-sections tuned to existing data

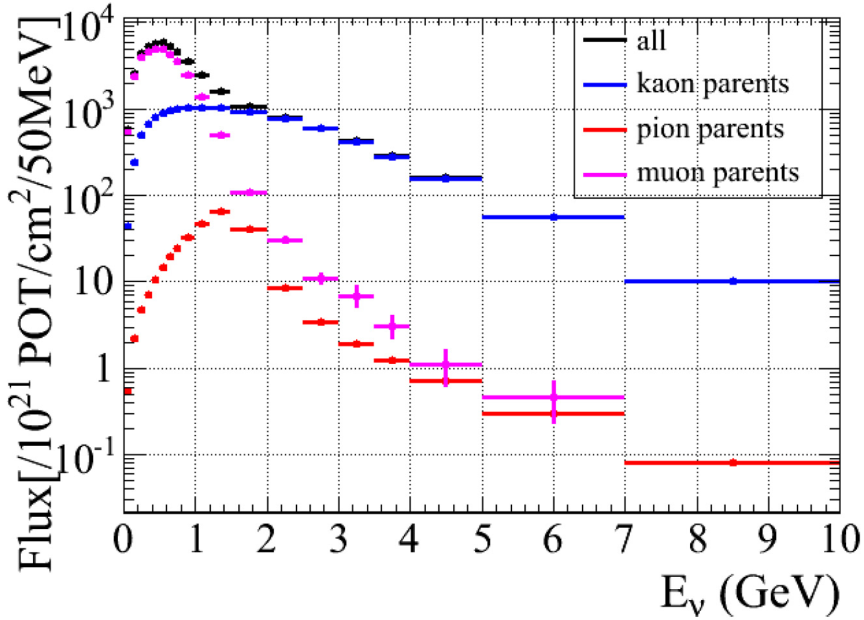
N.Abgrall et al., arXiv:1102.0983 [hep-ex] accepted by Phys.Rev.C (2011)

Flux predictions and uncertainties

SK ν_μ flux



SK ν_e flux



Systematic errors from beam uncertainty (ν_e appearance):

$$\delta N_{ND}^{MC} = 15.4\% \qquad \delta\left(N_{ND}^{MC} \Big/ N_{SK}^{MC} \right) = 8.5\%$$

$$\delta N_{SK}^{MC} = 16.1\%$$

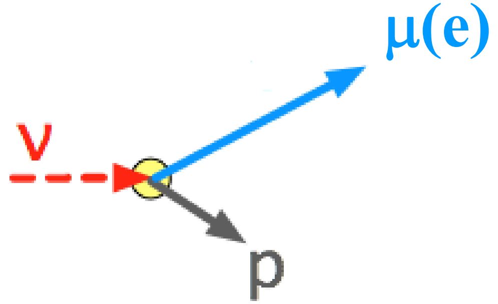
- significant uncertainty reduction when normalizing to near detector (far/near correlation)
- kaon production uncertainty is dominant (7.6% out of 8.5%) to be improved with NA61 kaon measurements

Expected intrinsic beam ν_e contamination ~ 1% in the oscillation region

- mainly comes from muon decays
- NA61 pion data predicts ν_e from pion parents

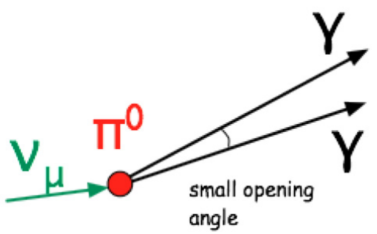
Neutrino interactions uncertainties

SK signal:
CCQE neutrino interactions producing leptons (μ or e)



Background:

- ν_e appearance:
  π^o from NC interactions
  γ misidentified as e at SK
- ν_μ disappearance:
  CC1π interactions



Process	Cross section uncertainty relative to the CCQE total x-section
CCQE	energy dependent ($\sim \pm 7\%$ at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^0	100%
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
Final State Int.	energy dependent ($\sim \pm 10\%$ at 500 MeV)

Neutrino interaction uncertainties come from:

- comparison of models to data: SciBooNE, MiniBooNE, SK atm.
- different models
- parameter variation in models

Total influence on systematics:

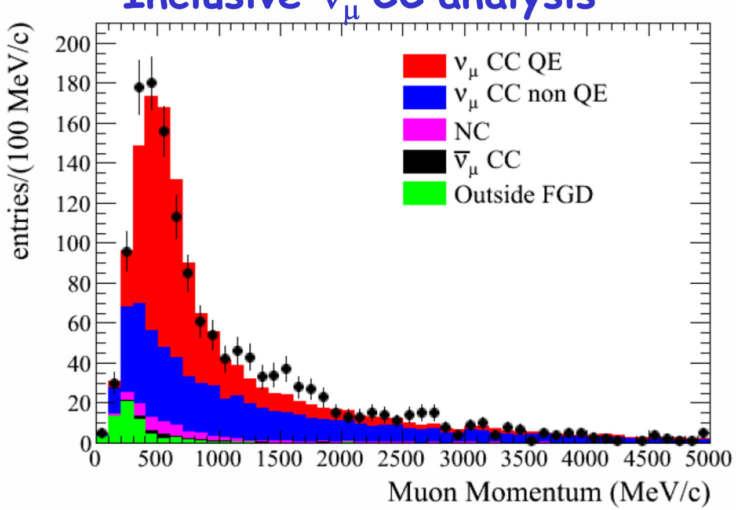
- 14% for ν_e appearance background (w/o osc.)
- 8% for ν_μ disappearance

Cross section ratio ν_e/ν_μ uncertainty is ~6%

ND280 input

- Run I (2.9×10^{19} p.o.t.) used for ND280 analysis
- measure inclusive CC ν_μ and intrinsic beam ν_e
- analysis based on Tracker (FGD+TPC) data
- useTPC PID (dE/dX) to select muons and electrons

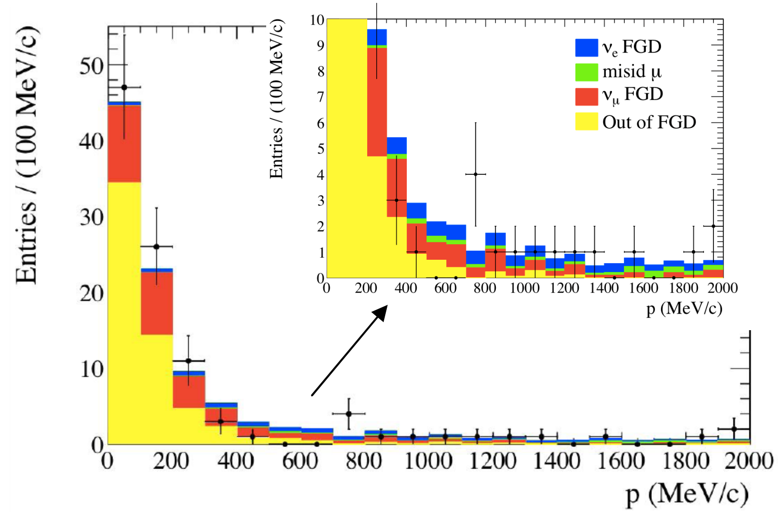
Inclusive ν_μ CC analysis



- 90% purity and 38% efficiency in CC selection
- systematics mainly from tracking efficiency and TPC-FGD matching
- good agreement between Data and MC based on NA61 + FLUKA (flux) and NEUT (neutrino interactions)

$$\frac{N_{ND}^{obs}}{N_{ND}^{MC}} = 1.036 \pm 0.028(\text{stat})^{+0.044}_{-0.037}(\text{det. syst}) \pm 0.038(\text{phys. model})$$

Intrinsic beam ν_e component



- intrinsic beam ν_e form main background for ν_e appearance
- observed ND280 ν_e/ ν_μ ratio is in consistence with MC expectations
- confirms flux predictions

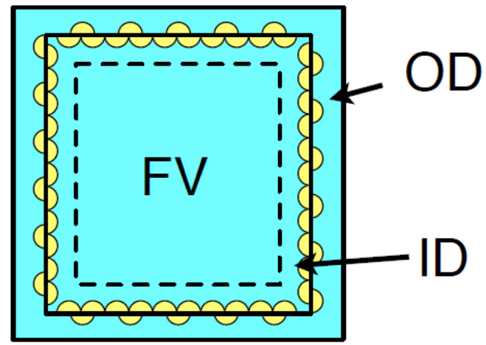
$$R(\nu_e/\nu_\mu) = (1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}))\%$$

$$\frac{N(\nu_e)^{DATA} N(\nu_\mu)^{MC}}{N(\nu_\mu)^{DATA} N(\nu_e)^{MC}} = 0.6 \pm 0.4(stat) \pm 0.2(syst)$$

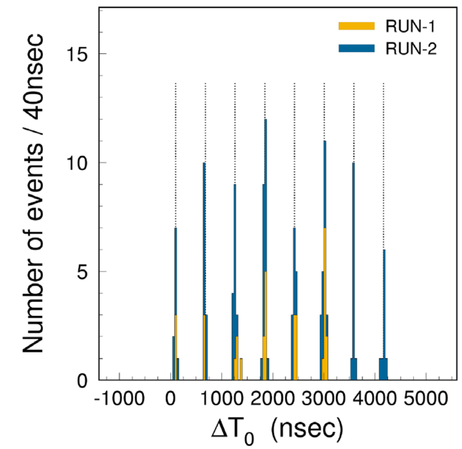
Neutrino events selection in Far Detector

T2K selection cuts predefined and fixed prior to analysis using MC and atmospheric data

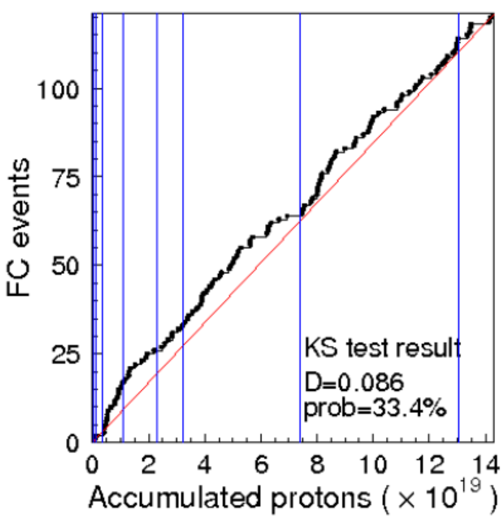
- GPS time synchronization between SK and J-PARC beam: -2~+10 μs on-time window
- Select fully contained (FC) events in ID; <16 PMT clusters in Outer Detector (OD)
- 121 total FC events selected
  expected background (cosmics) 0.023
- Event vertex >200 cm from the ID wall (fiducial volume FV cut) → FCFV events
  - poor reconstruction accuracy for events too close to ID walls
  - reject events outside ID
  - 22.5 kT fiducial volume
- Select events with exactly one ring
- PID based on ring shape to select e`s and μ`s



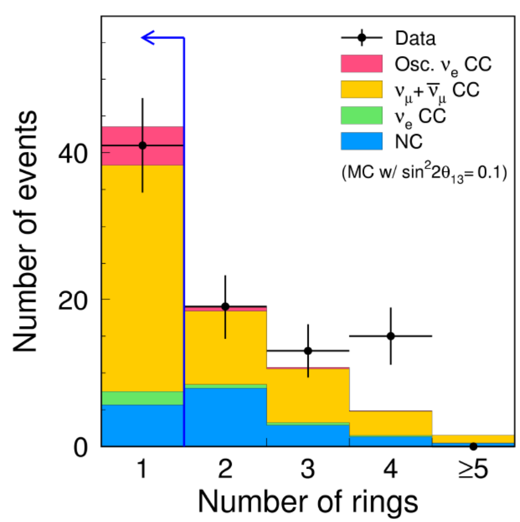
121 FC events



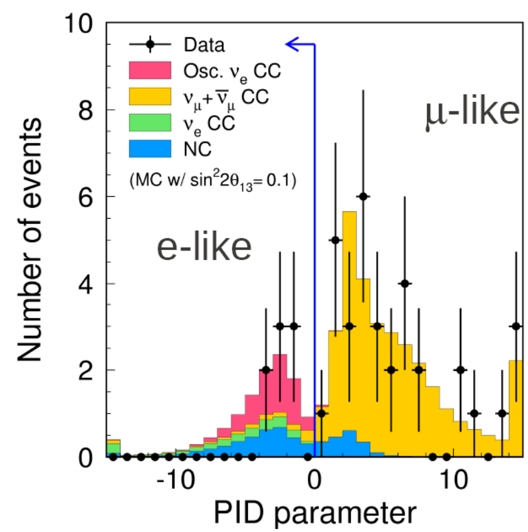
88 FCFV events



41 one-ring FCFV events



33 μ– an 8 e-like events selected



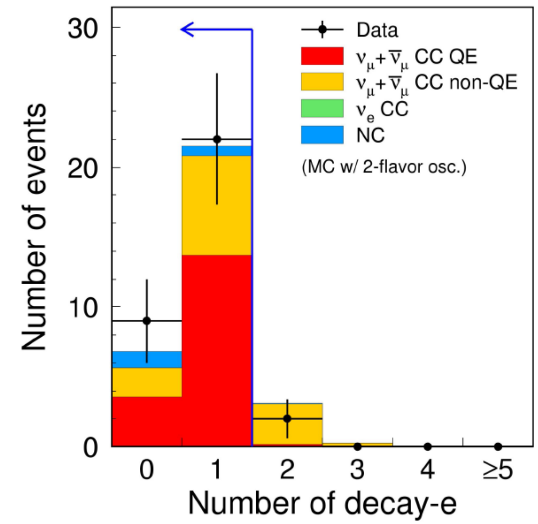
T2K ν_μ disappearance analysis

T2K ν_μ events selection

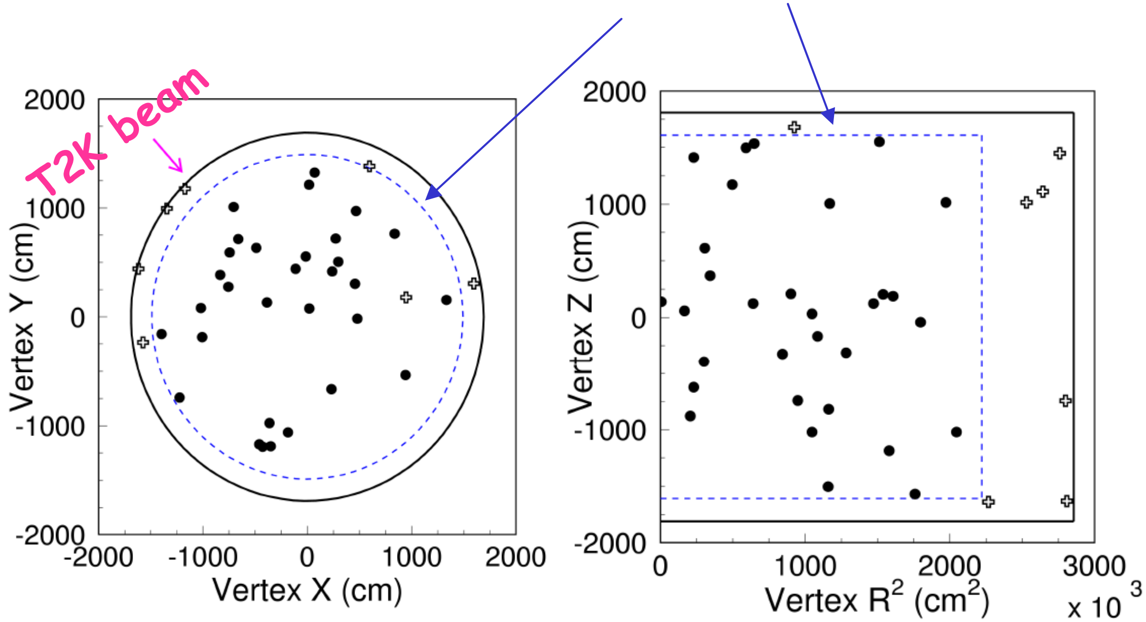
After "basic" selection cuts 33 μ-like event candidates remained

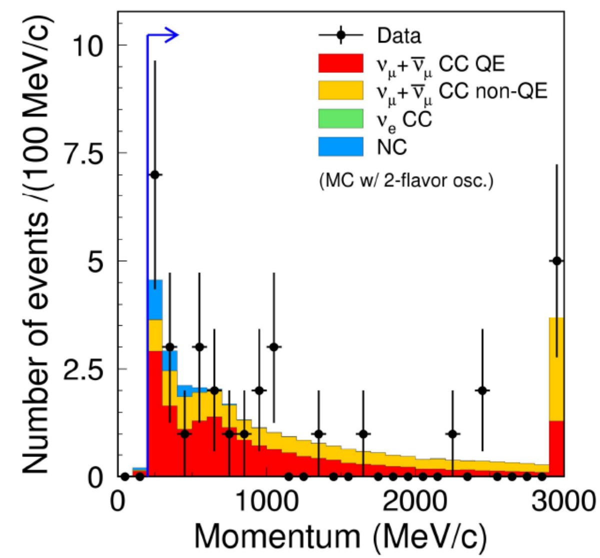
Additional Far Detector cuts applied for remaining events:

- number of reconstructed decay electrons <2
- reconstructed muon momentum > 200 MeV
- 31 events survived all cuts



Vertex distribution   Fiducial volume





MC w/ $\sin^2 2\theta_{23}$=1.0 and Δm^2_{23}=2.4x10^{-3} eV^2

Selected and expected ν_μ events in T2K

31 events remained after selection cuts

No oscillation hypothesis:
103.7 events expected

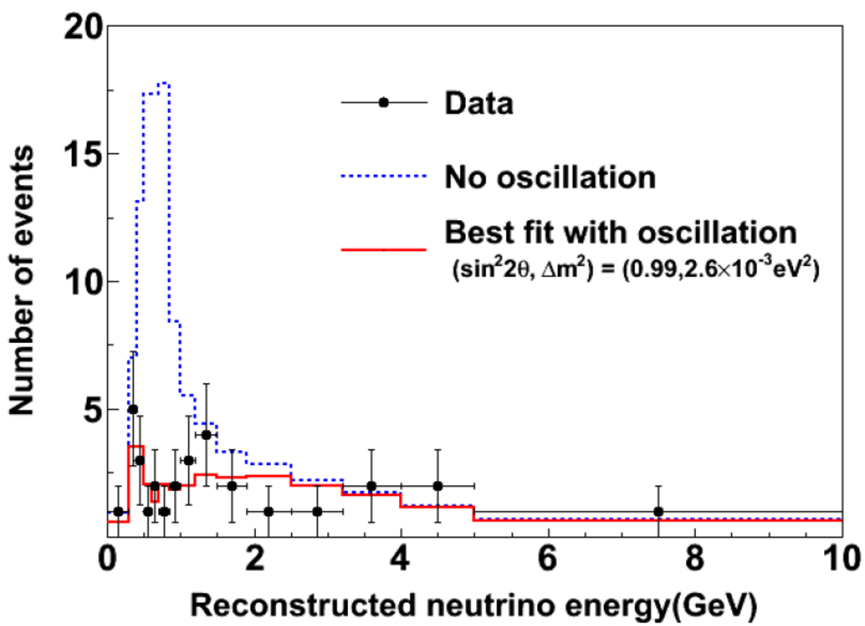
For $\sin^2 2\theta_{23}$=1.0 and Δm^2_{23}=2.4x10^{-3} eV^2:
28.3 events expected

Expected events systematics

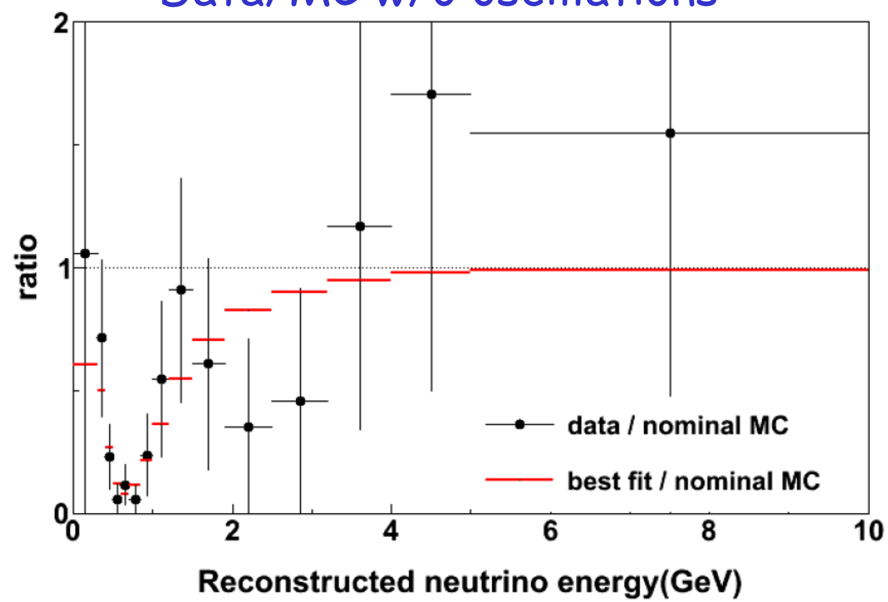
$N^{SK}_{exp.}$ error table

Error source	$\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$	Null Oscillation
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%

Null-oscillation hypothesis is excluded at 4.5 sigma level!



Data/MC w/o oscillations



T2K ν_μ disappearance analysis methods

- Fit with 2 flavor oscillation scenario
- Two independent methods to extract oscillation parameters
- Feldman-Cousins method to produce confidence intervals

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m_{23}^2 L}{E}\right)$$

- Method A – maximum likelihood

$$L(\sin^2 2\theta, \Delta m^2, \vec{f}) = L_{norm}(\sin^2 2\theta, \Delta m^2, \vec{f}) L_{shape}(\sin^2 2\theta, \Delta m^2, \vec{f}) L_{shape}(\vec{f})$$

- L_{norm} – number of the observed events (Poisson distributed)
- L_{shape} – unbinned energy spectrum shape
- $f = f(f_{Flux}, f_{Xsec}, f_{ND}, f_{SK})$ – parameter representing systematic errors

- Method B – likelihood ratio

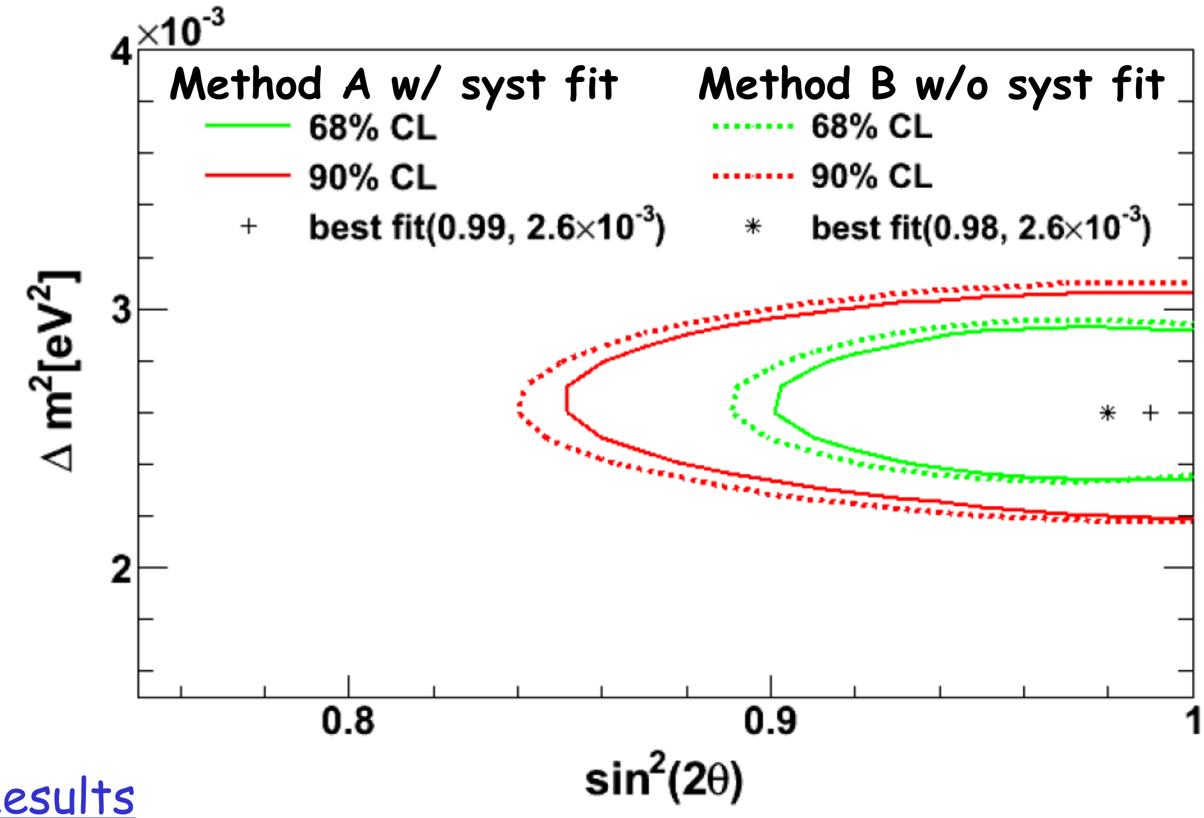
$$\chi^2 = 2\sum_{i=1}^{N_{bin}}\left[n_i^{obs}\cdot\ln\left(\frac{n_i^{obs}}{n_i^{exp}}\right) + n_i^{exp} - n_i^{obs}\right]$$

- i – SK energy bin
- $n_i^{obs(exp)}$ – number of observed (expected) events in particular SK energy bin

- Main difference: systematic parameters fitting in A, no fitting in B

T2K ν_μ disappearance analysis results

Two methods are in a good agreement



Results

Method A

Best fit: $\sin^2 2\theta_{23}=0.99$, $\Delta m^2_{23}=2.6\times10^{-3}\ eV^2$

90% C.L.: $\sin^2 2\theta_{23}>0.85$, $2.1\times10^{-3}\ eV^2<|\Delta m^2_{23}|<3.1\times10^{-3}\ eV^2$

Method B

Best fit: $\sin^2 2\theta_{23}=0.98$, $\Delta m^2_{23}=2.6\times10^{-3}\ eV^2$

90% C.L.: $\sin^2 2\theta_{23}>0.84$, $2.1\times10^{-3}\ eV^2<|\Delta m^2_{23}|<3.2\times10^{-3}\ eV^2$

T2K ν_e appearance analysis

T2K ν_e events selection

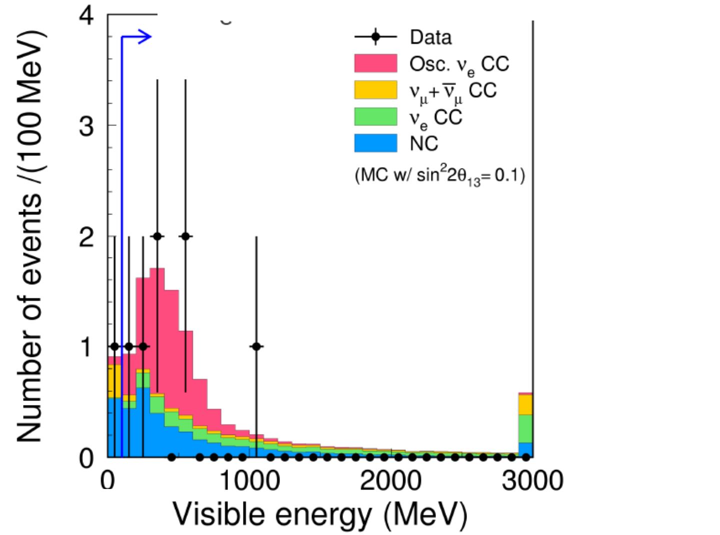
Start from 8 e-like single-ring FCFV events after "basic" T2K selection criteria

T2K ν_e selection cuts in SK optimized for intrinsic beam ν_e and NCπ^o background minimization

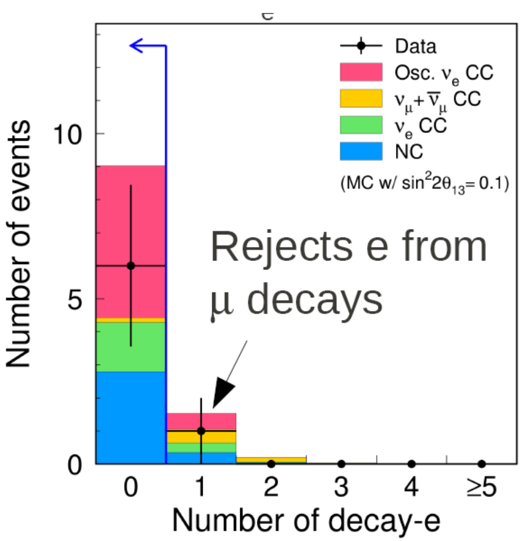
After all cuts:

- signal efficiency 66%
- intrinsic ν_e rejection 77%
- NC background rejection 99%

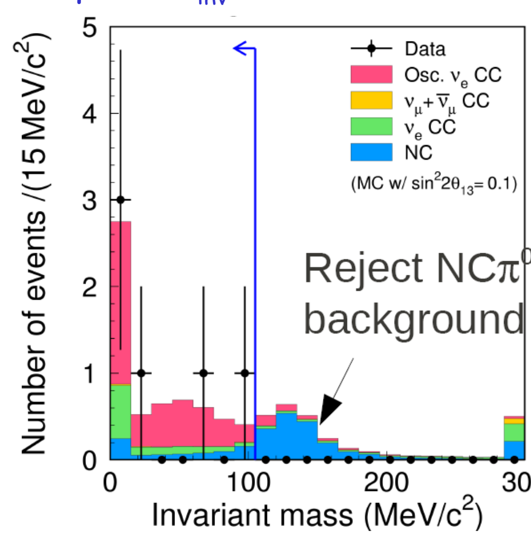
Energy deposited in ID >100 MeV → 7 events



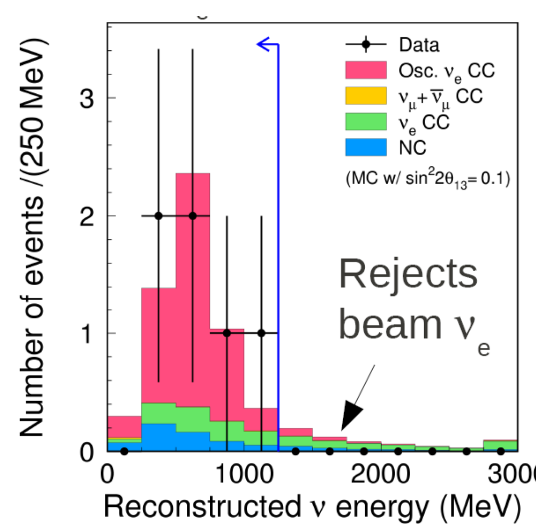
No Michel electrons → 6 events



Force reconstruction to fit light pattern under two e-like rings assumption, require M_{inv}<105 MeV → 6 events



Reconstructed neutrino energy <1250 MeV → 6 events



Expected events in Far Detector

After all cuts 6 final candidate events remained!

1.5 ν_e candidates expected with zero θ_{13} hypothesis

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	0.8	0.6	0.1	1.5

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

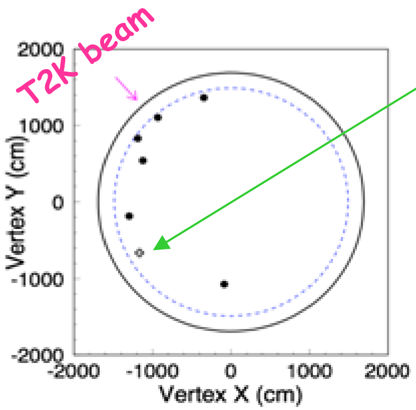
Smaller cross-section and SK uncertainties for signal events

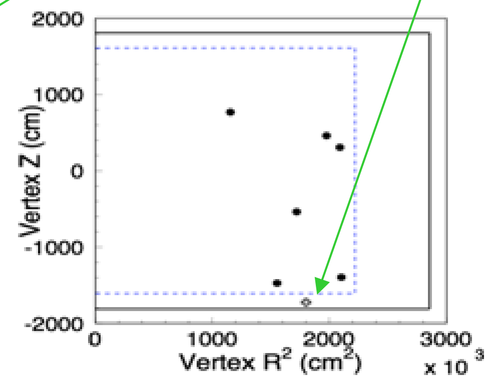
$$N_{SK,total}^{exp} = 1.5 \pm 0.3 \quad (\textit{for accumulated } 1.43 \times 10^{20} \; p.o.t.)$$

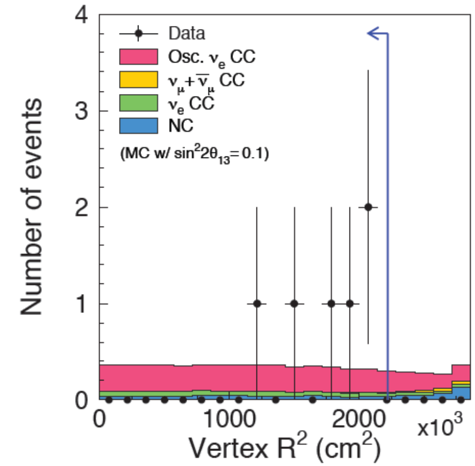
Reconstructed vertex distribution

Selected events clustering at large R
KS test gives 0.03 p-value for such R^2 distribution

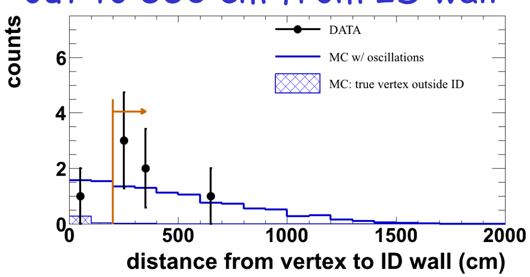
Event outside SK FV

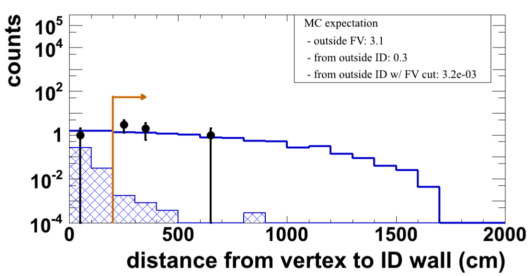




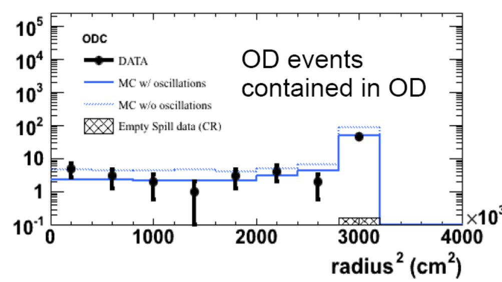


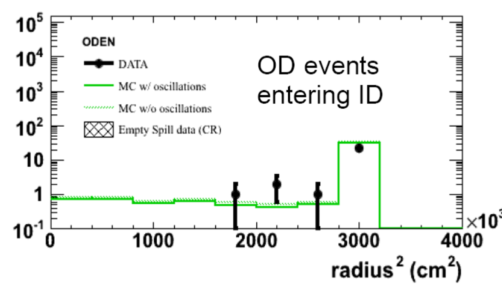
Vertex distribution in ID; MC interactions simulated out to 550 cm from ID wall





Vertex distribution in Outer Detector





More checks of vertex distributions:

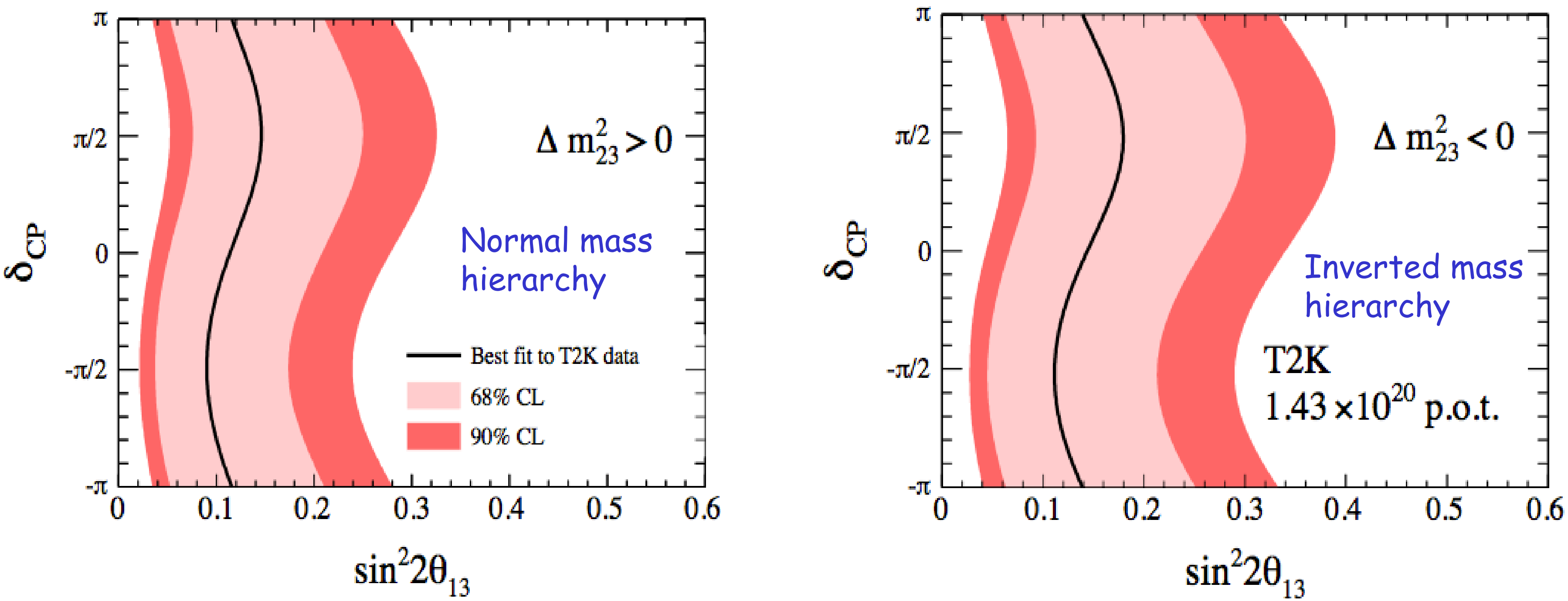
- good Data-MC agreement
- if outside source then expect events excess at large R^2 outside FV
- vertex distributions in OD data sample show no significant data excess

T2K ν_e appearance result

Probability to observe 6 or more events under zero θ_{13} hypothesis is 0.7% (2.5 sigma significance)

Feldman-Cousins method used to produce confidence intervals

For $\sin^2 2\theta_{23}$=1.0 and Δm^2_{23}=2.4x10^{-3} eV^2:



Normal mass hierarchy and δ_{CP}=0:

- best fit: $\sin^2 2\theta_{23}$=0.11
- 0.03<$\sin^2 2\theta_{23}$<0.28 at 90% C.L.

Inverted mass hierarchy and δ_{CP}=0:

- best fit: $\sin^2 2\theta_{23}$=0.14
- 0.04<$\sin^2 2\theta_{23}$<0.34 at 90% C.L.

Conclusion

T2K performed two oscillation analysis based on 1.43×10^{20} p.o.t. dataset (2% of final T2K goal)

ν_μ disappearance analysis results:

- no oscillation hypothesis excluded at 4.5 sigma level
- $\sin^2 2\theta_{23} > 0.85$ and 2.1×10^{-3} eV$^2 < \Delta m^2_{23} < 3.1\times10^{-3}$ eV^2 at 90% C.L.

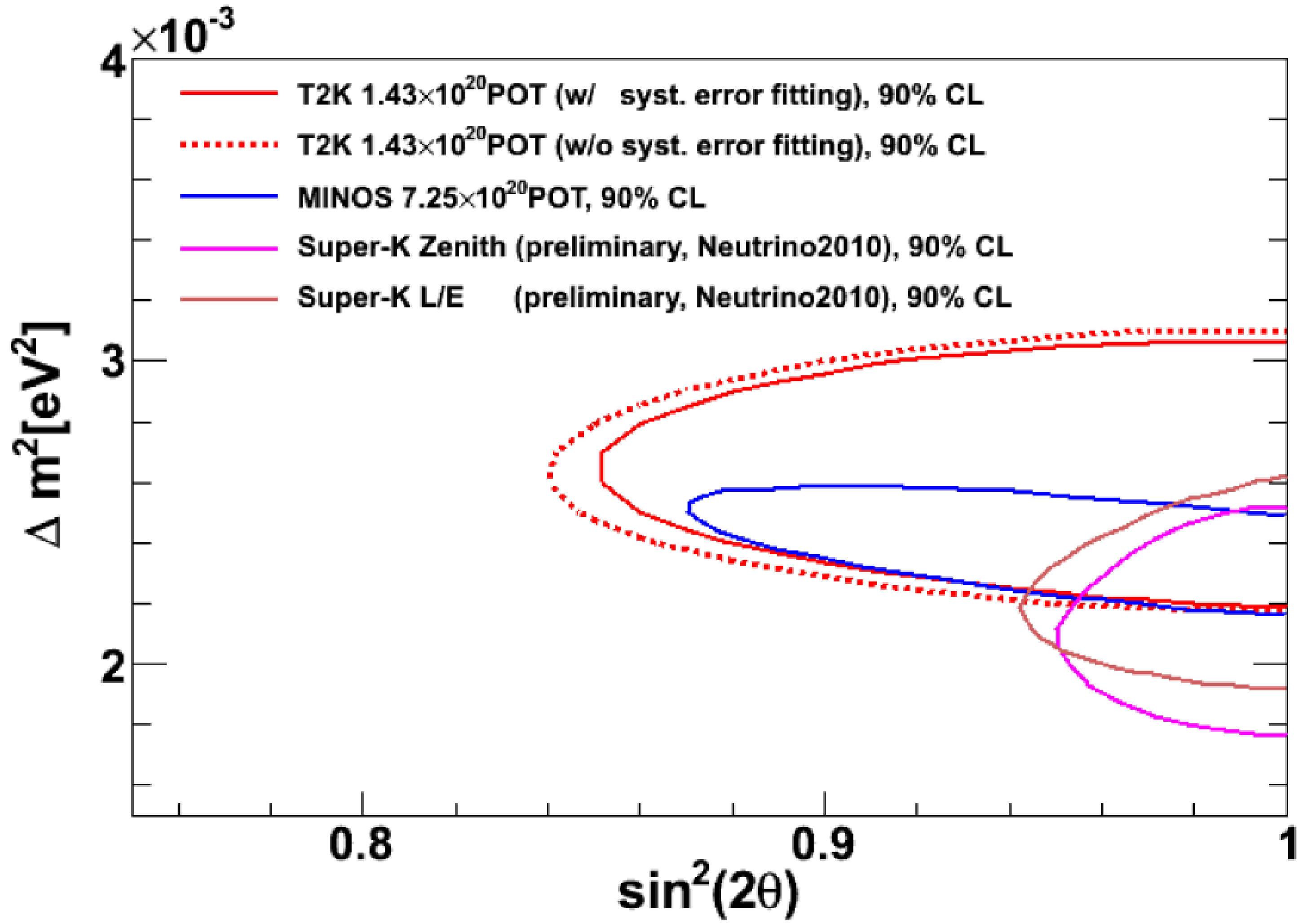
ν_e appearance analysis results:

- 6 events selected with 1.5 ± 0.3 expected w/o oscillations
- probability to observe 6 or more events is 0.7% (2.5 σ significance)
- $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ at 90% C.L. for normal (inverted) mass hierarchy, $\sin^2 2\theta_{23}=1.0$, $\Delta m^2_{23}=2.4\times10^{-3}$ and $\delta_{CP}=0$
- published in PRL, Phys.Rev.Lett.107:041801,2011

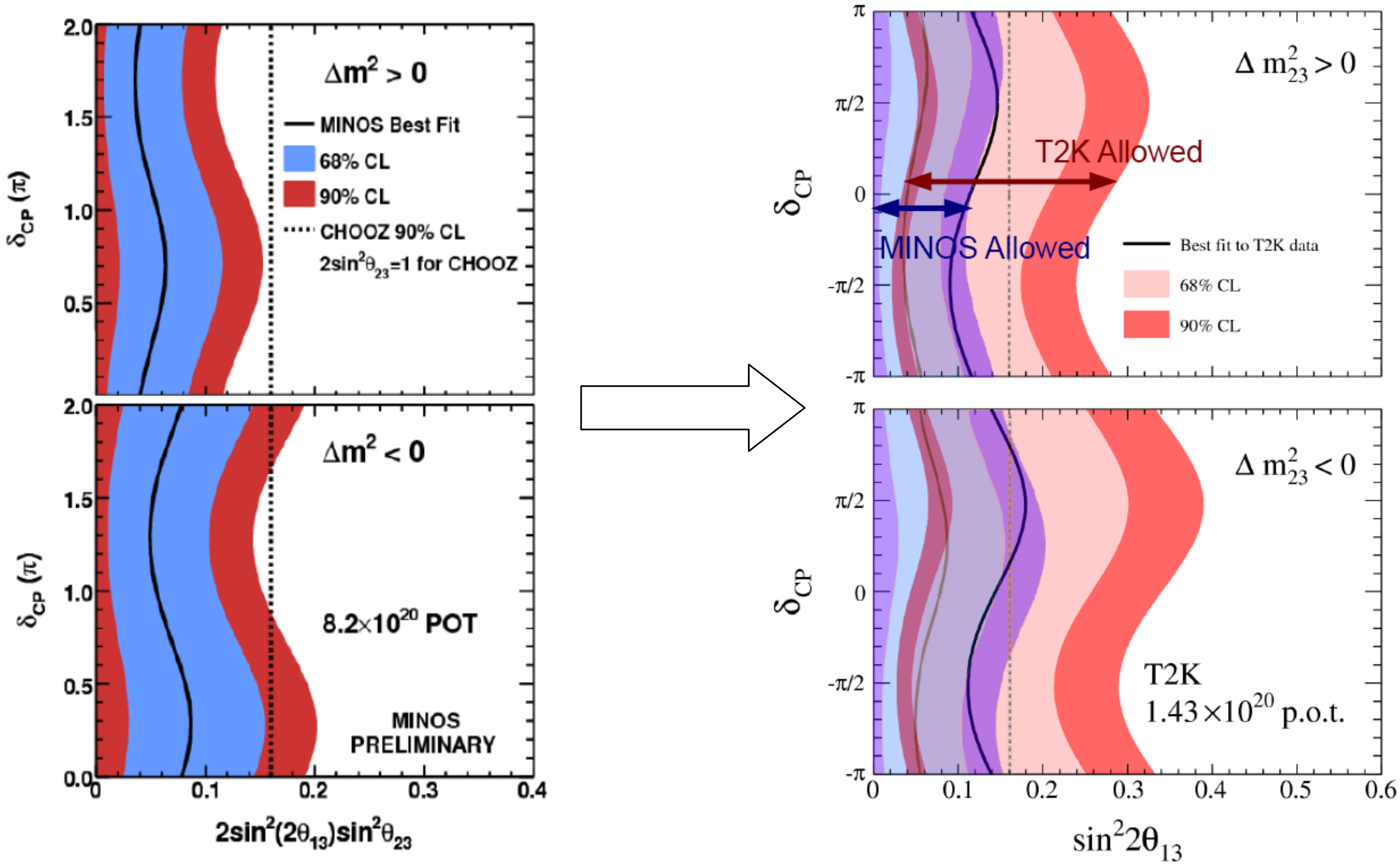
The T2K is now recovering from the March 11th earthquake
Investigations taken so far indicate that all damage is repairable
Plan to restart J-PARC accelerator in December 2011

Backup slides

Comparison of T2K ν_μ disappearance result with SK and MINOS

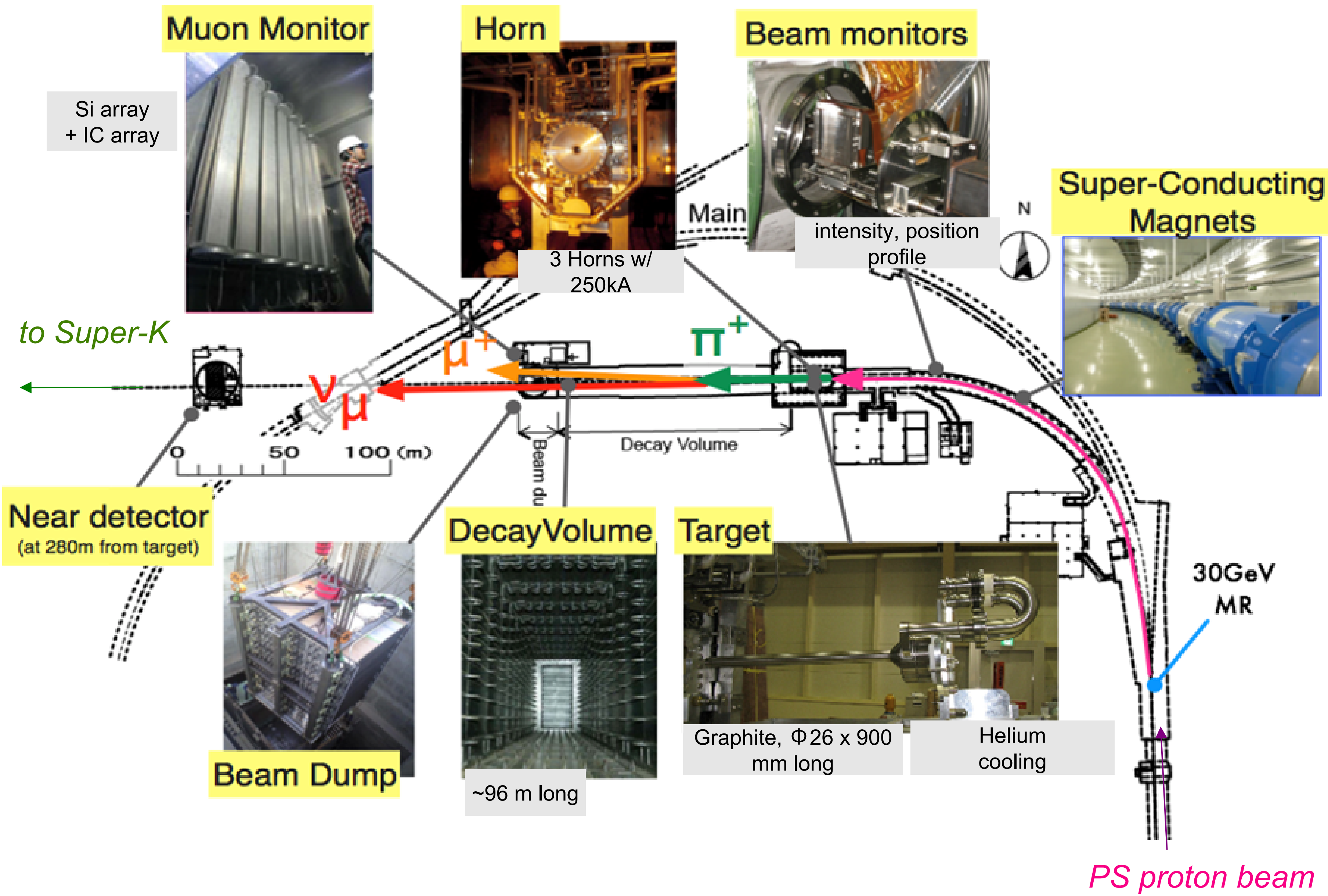


Comparison of T2K ν_e appearance result with recent MINOS results

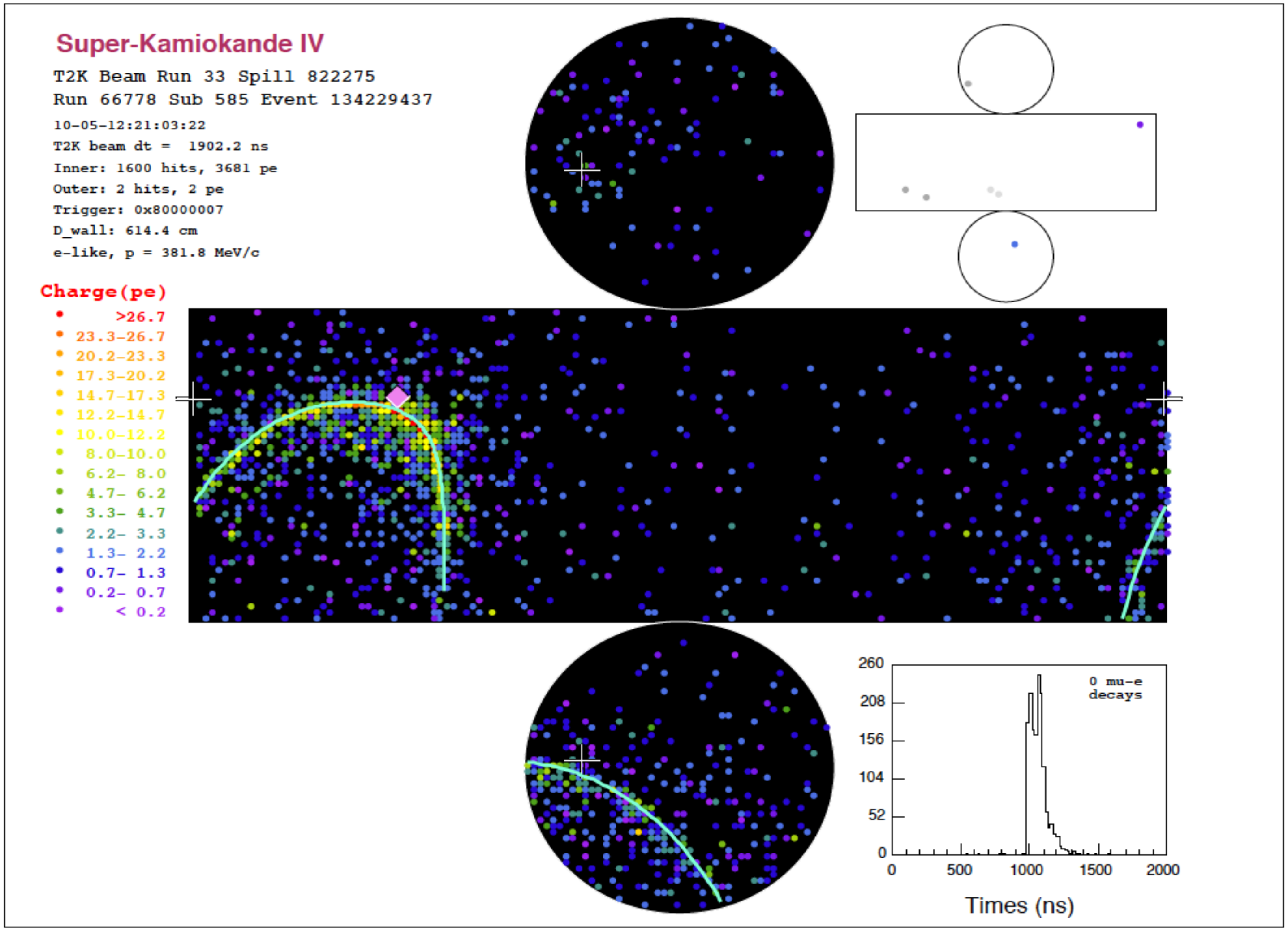


Significant overlap of 90% C.L. allowed regions

J-PARC T2K neutrino beamline

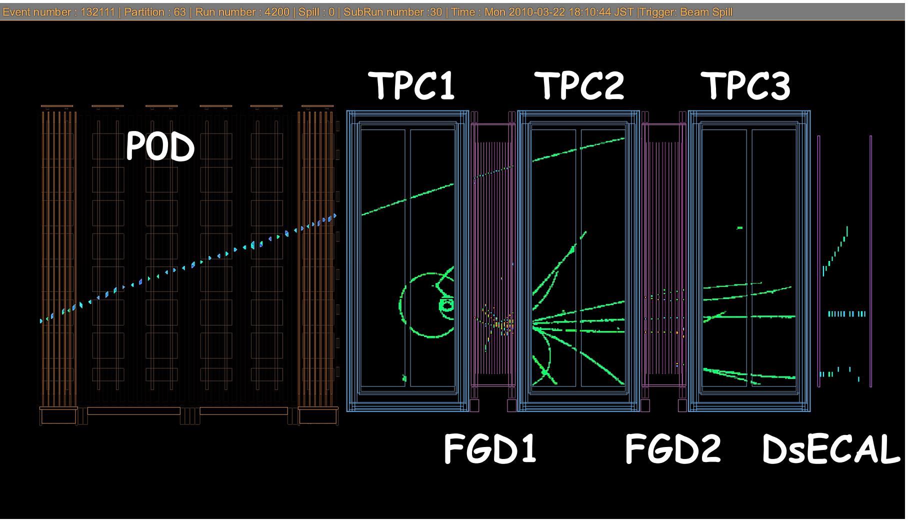


T2K ν_e CCQE event candidate

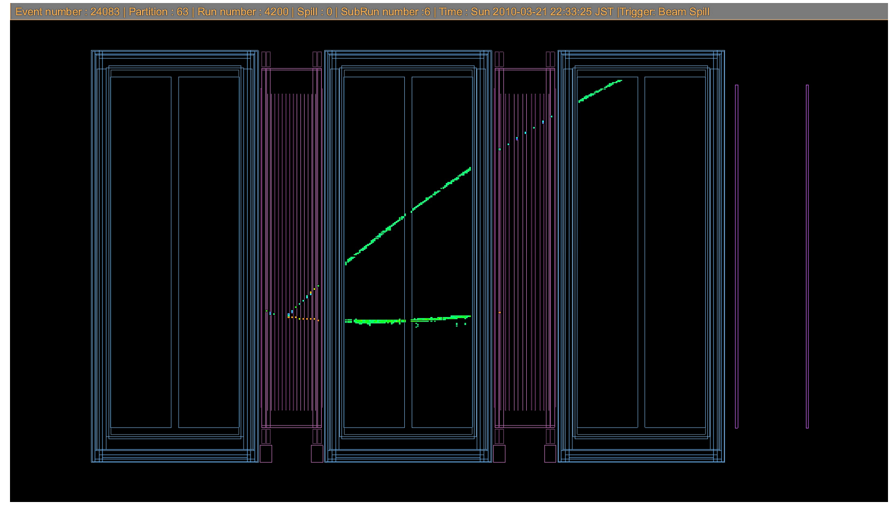


	D_{wall} (cm)	Ring-counting likelihood	PID parameter	E_{vis} (MeV)	POLfit mass (MeV/c^2)	E_ν^{rec} (MeV)
#1	614.4	-5.7	-1.2	381.8	29.9	485.9

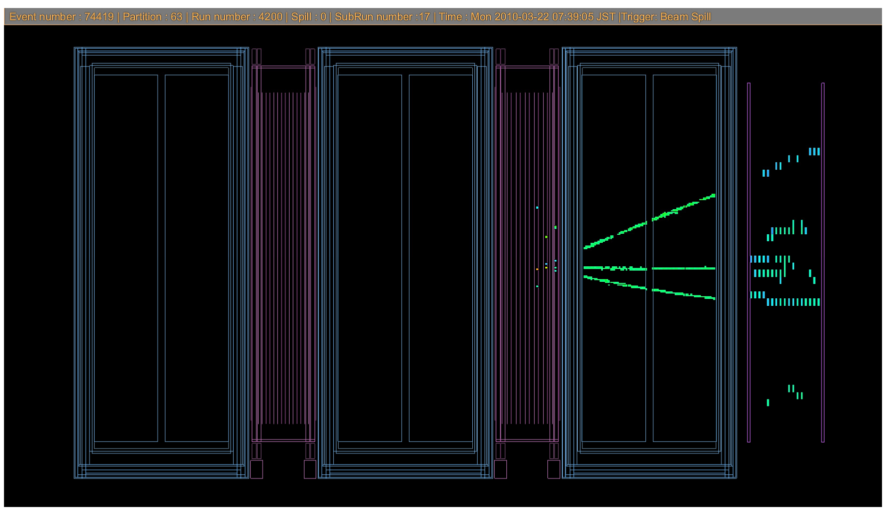
ND280 neutrino events



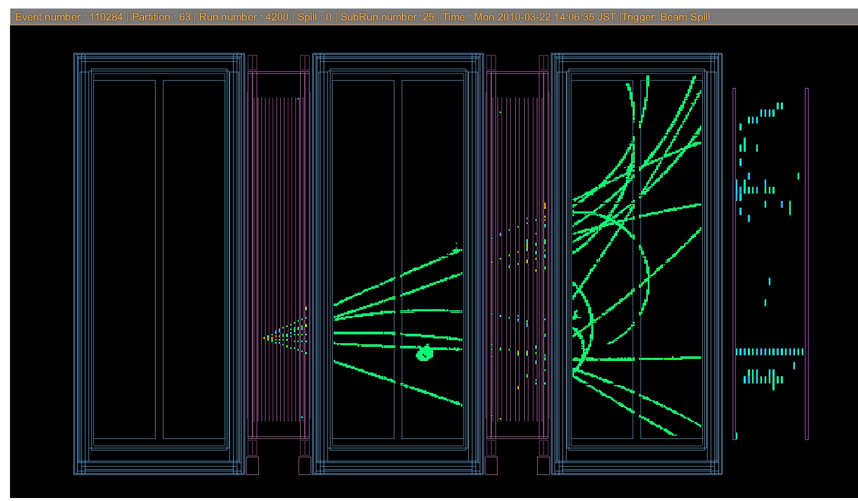
Sand muon + DIS candidate



CCQE candidate



CC1π candidate



DIS candidate

ν_e vertex distribution from SK atmospheric data

T2K-like ν_e selection cuts applied to sub-GeV atmospheric neutrinos