Results from the T2K experiment

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9ème rencontre IPhT - SPP

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Outline :

- Neutrino oscillation
- The T2K experiment
- ν_e appearance analysis
- ν_μ disappearance analysis
- T2K near future

More details

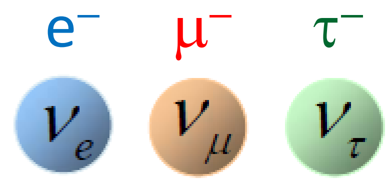
- Michael Macaire, apéro du SPP, 25/11/2011 (ν_μ disappearance)
- Marco Zito, apéro du SPP, 24/06/2011 (ν_e appearance)
- Marco Zito, séminaire du SPP, 21/03/2011

« **Premiers resultats d'oscillation des neutrinos avec T2K** »

- Public T2K web page : http://t2k-experiment.org

- Papers:
  - T2K experiment : NIM-A 659, issue 1, pages 106–135 (December 2011)
  -
  - ν_e appearance : Phys. Rev. Lett. 107, 041801 (2011)
  - ν_μ disappearance: arXiv:1201.1386 submitted to PRL

About neutrinos



- Neutrinos are neutral leptons in three families and they only interact through weak interaction

- In 1998, observation of neutrino oscillation (by the Super-Kamiokande detector) gave an experimental proof that neutrinos are massive particles – indication of physics beyond the standard model

- Oscillations come from : flavor eigenstates (e, μ, τ) ≠ mass eigenstates (1, 2, 3)
  How these eigenstates mix is given by the PMNS matrix

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

U $_{\mathbf{PMNS}}$:
Pontecorvo-Maki-Nakagawa-Sakata matrix

- Neutrinos raise many other questions : What is their absolute mass ? Are they Dirac or Majorana particles ? CP leptonic violation ? Faster than light ?

Neutrino mixing

- The PMNS matrix can be parameterized as follow :

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +C_{23} & +S_{23} \\ 0 & -S_{23} & +C_{23} \end{pmatrix} \cdot \begin{pmatrix} +C_{13} & 0 & S_{13} \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13} \cdot e^{-i\delta} & 0 & +C_{23} \end{pmatrix} \cdot \begin{pmatrix} +C_{12} & +S_{12} & 0 \\ -S_{12} & +C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"Atmospheric" "Solar"

Can be studied with accelerator experiments

Where $C_{ij} = \cos\theta_{ij}$
and $S_{ij} = \sin\theta_{ij}$

- **6 parameters** govern the oscillations **:**

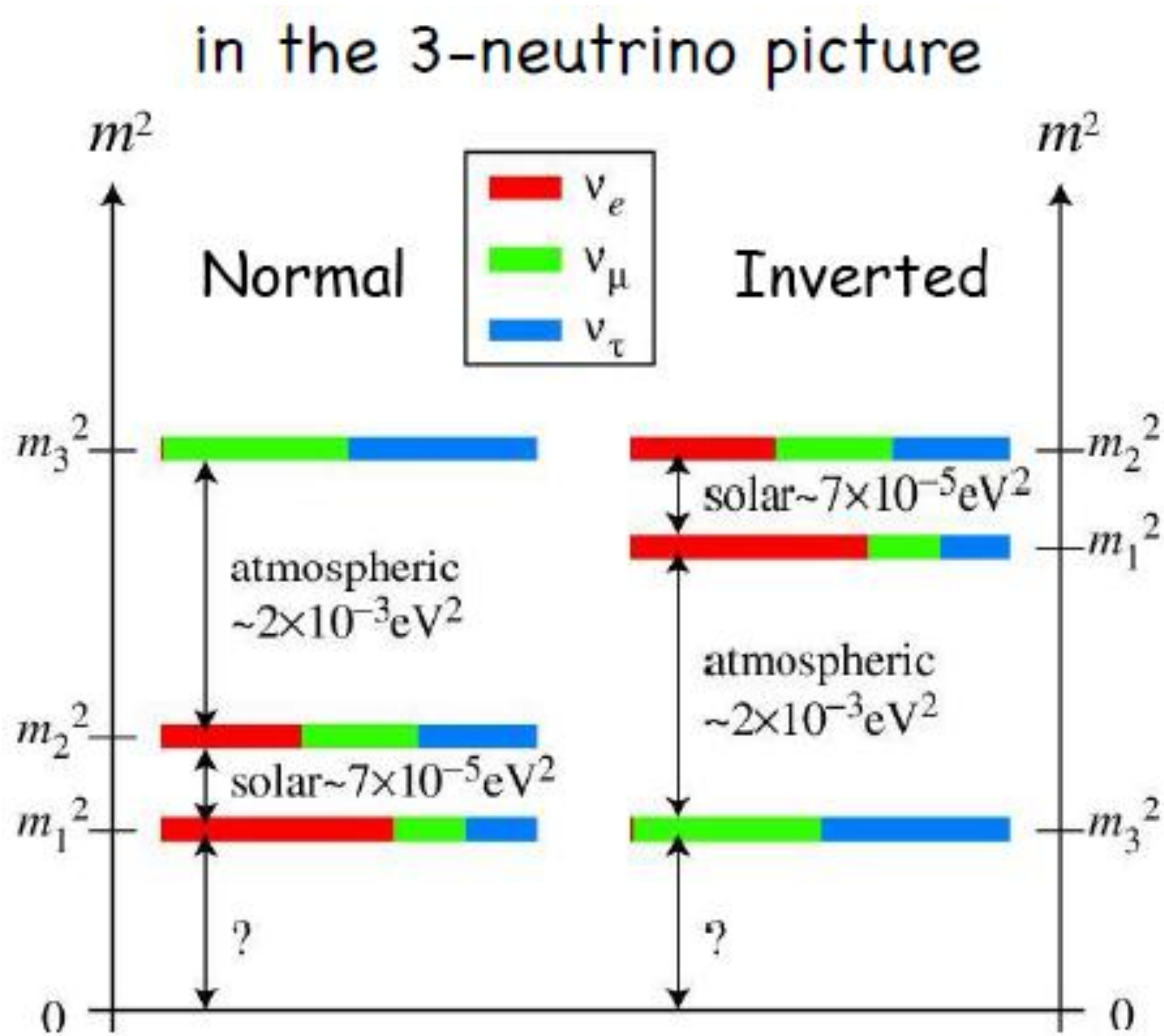
θ_{12}, θ_{23}, θ_{13}, δ (CP violation) and Δm^2_{12} , Δm^2_{23} (mass differences : $\Delta m^2_{ij} = m^2_j - m^2_i$)

$2.3\text{x}10^{-3}$ eV² < $|\Delta m^2_{23}|$ < $7.8\text{x}10^{-3}$ eV²
0.92 < $\sin^2(2\theta_{23}) \leq 1.0$ *(90% CL)*
(SK, K2K, MINOS)

$7.38\text{x}10^{-5}$ eV² < Δm^2_{12} < $7.8\text{x}10^{-5}$ eV²
0.84 < $\sin^2(2\theta_{12})$ < 0.89 *(90% CL)*
(SNO, KAMLAND)

For $\Delta m^2_{23} = 2.4\text{x}10^{-3}$ eV² and $\sin^2(2\,\theta_{23}) = 1$: normal (inverted) mass hierarchy
$\sin^2(2\theta_{13})$ < 0.15 *(90% CL CHOOZ 1999)* ; < 0.12 (0.20) *(90% CL MINOS 2010)*
$\sin^2(2\theta_{13})$ = 0.085±0.029(stat)±0.042(syst) *(68% CL DOUBLE CHOOZ 2011)*
$\sin^2(2\theta_{13})$ > 0.03 (0.04) *(at 2.5σ T2K 2011)*

Mass hierarchy



$\Delta m^2_{12} << |\Delta m^2_{23}|$

$\Delta m^2_{13} \sim \Delta m^2_{23}$

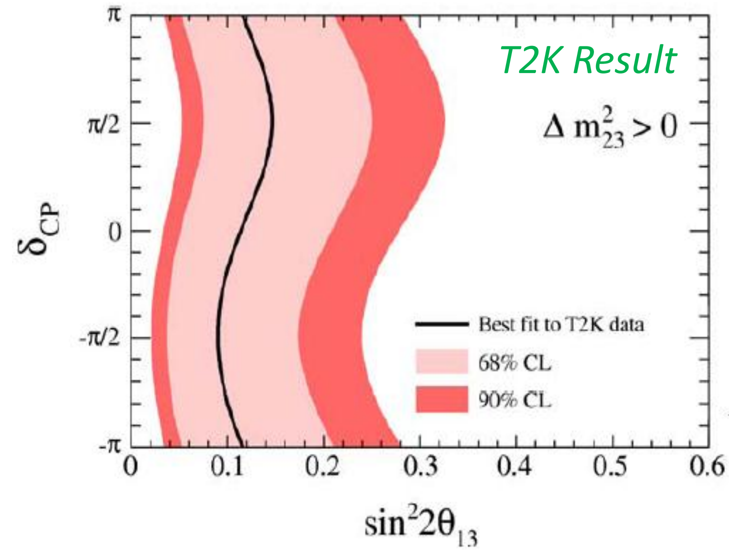
T2K physics

Neutrino oscillation with the T2K ν_μ beam, from Tokai to Kamiokande (295 km)
(Presented results with only 2% of the statistics for T2K proposal goal)

- **Search for $\nu_\mu \rightarrow \nu_e$ oscillations (measurement of θ_{13})**
- **ν_e appearance analysis**

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

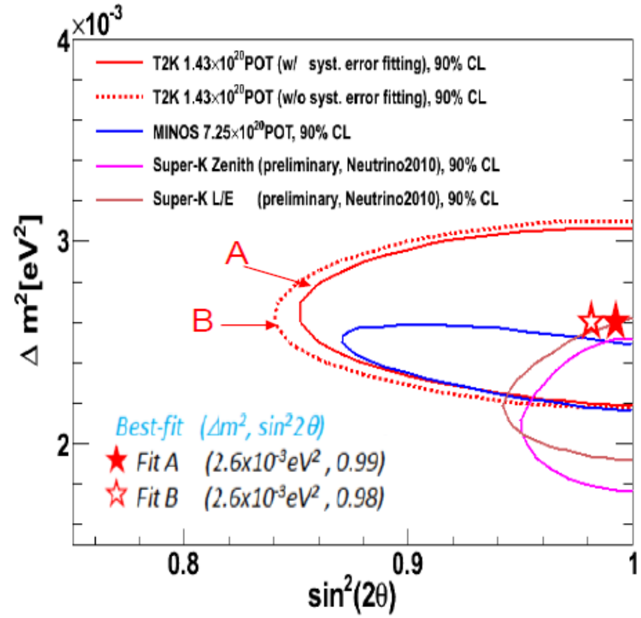
  - **T2K publication** : *Abe et al. , PRL, 107 041801 (2011)*
  - 6 ν_e events observed from ν_μ beam (1.5 bkg expected)
    $\rightarrow$ Null oscillation excluded at 2.5σ
  - Non null θ_{13} opens research for leptonic CP violation



- **Precise measurement of Δm^2_{23} and $\sin^2(2\theta_{23})$ via ν_μ disappearance analysis**
- **Most $\nu_\mu \rightarrow \nu_\tau$, but τ (m~1.8 GeV/c²) not produced at E(ν_τ) ~ 600 MeV, so ν_τ are not detected**

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

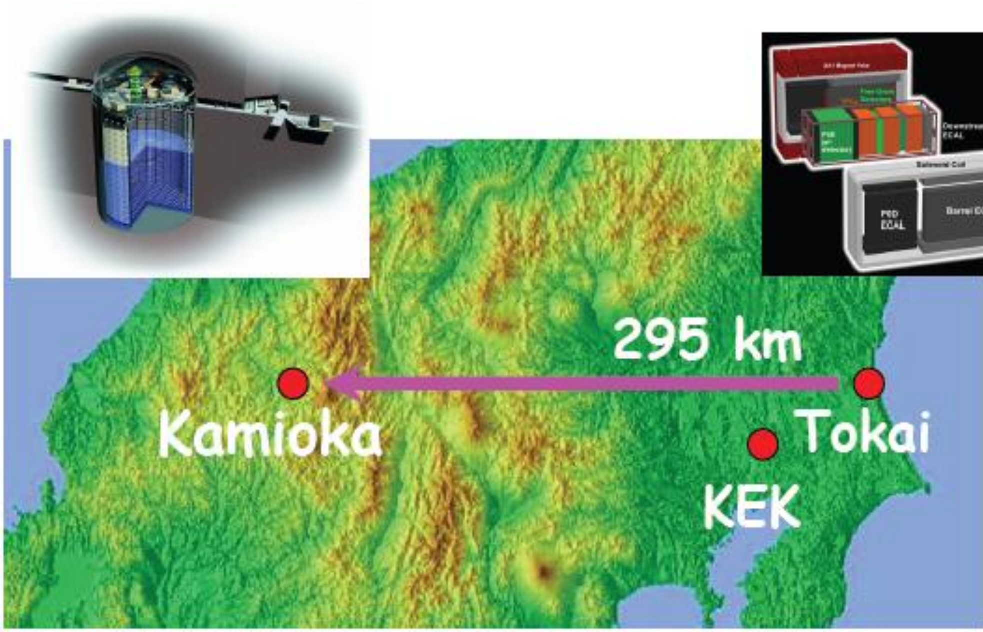
T2K publication : arXiv:1201.1386 submitted to PRL

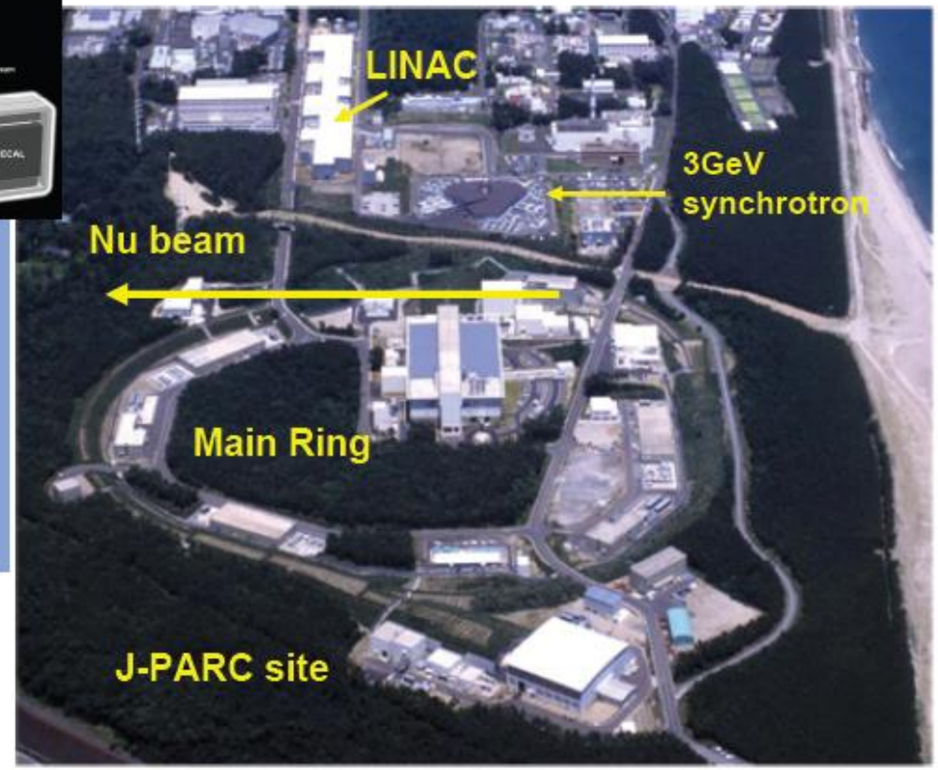


The T2K collaboration

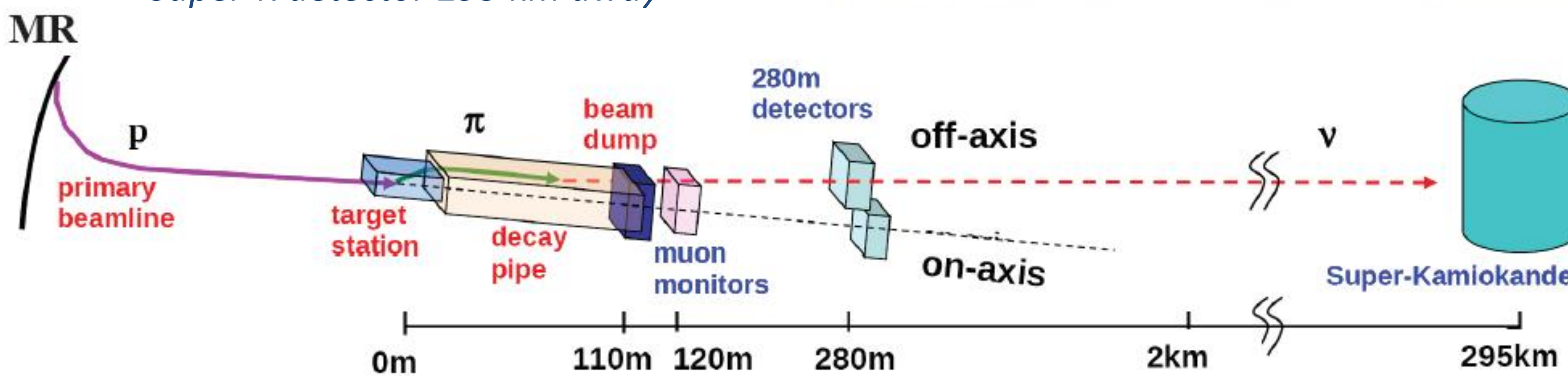
~ 500 members, 58 national institutes, 12 countries

Tokai-to-Kamioka



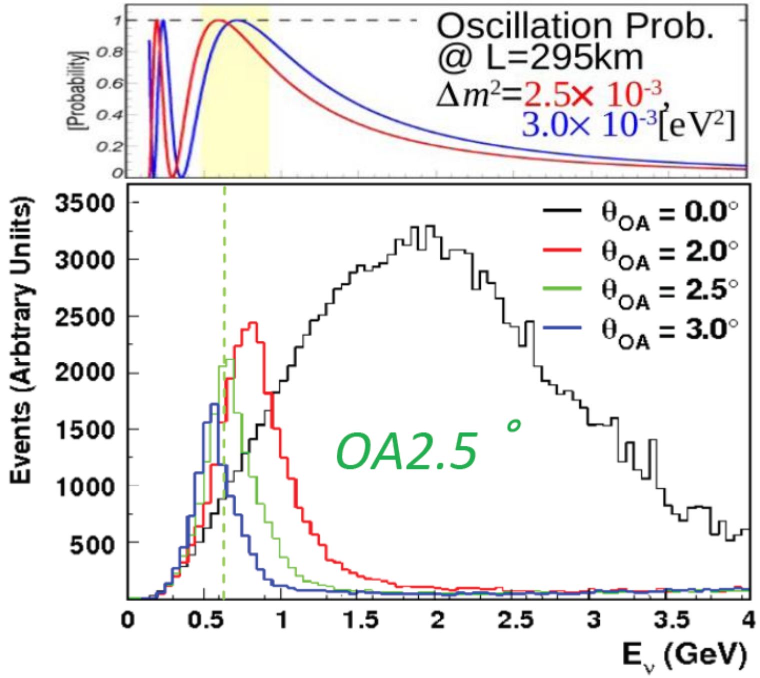


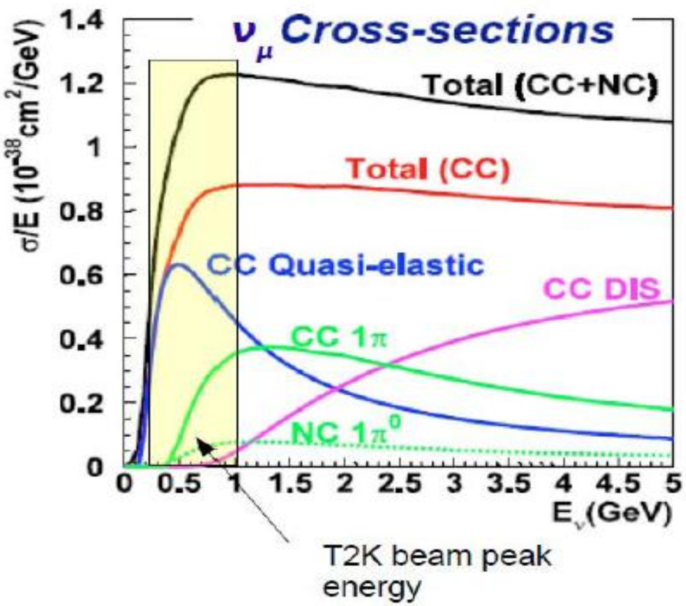
High intensity muon neutrino (ν_μ) beam from the J-PARC 30 GeV proton accelerator to the Super-K detector 295 km away



An off-axis experiment

- The T2K detectors are not located on the beam axis but shifted by 2.5° (first off-axis long baseline experiment)
- Off-axis technique gives a narrow measured spectrum peaked at ~600 MeV
(and reduces ν_e background in the beam)
- Optimized spectrum for maximal oscillation probability





- At the T2K energy, charged current interactions are dominated by quasi-elastic processes **(CCQE)**

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

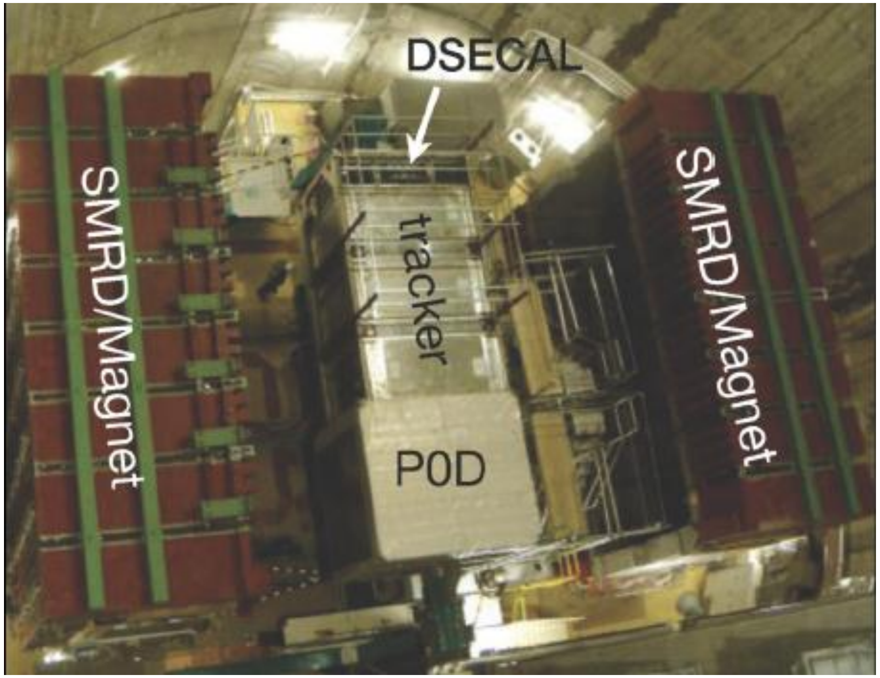
$$(\nu_e + n \rightarrow p + e^-)$$

Muons (electrons) from neutrino interaction are detected

- With CCQE, the neutrino energy can be reconstructed

$$E_\nu^{CCQE} = \frac{m_p^2 - m_\mu^2 - m_n^2 + 2m_n E_\mu}{2(m_n - E_\mu + p_\mu \cos\theta)}$$

The near detector



•The off-axis near detector (ND280)'s goal is to characterize the beam before oscillation, to reduce the beam uncertainty at the far detector

• ND280 ν_μ measurement is made with the tracker

➢ **TPCs** (time projection chambers) : with bulk MicroMegas technology from Saclay for tracking and PID

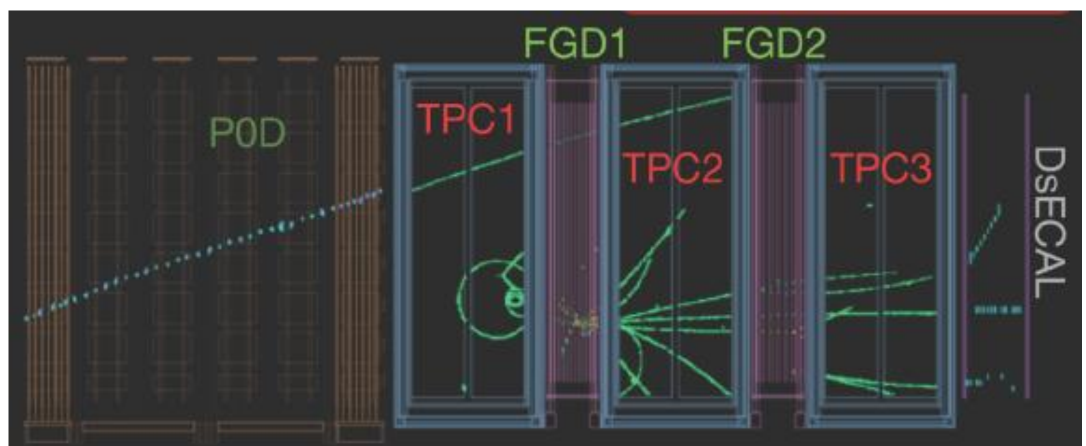
➢ **FGDs** (fine grained detectors) : 1 ton of scintillators layers

➢**Ecal** : Donwstream and Barrel calorimeters are surrounding the inner detectors

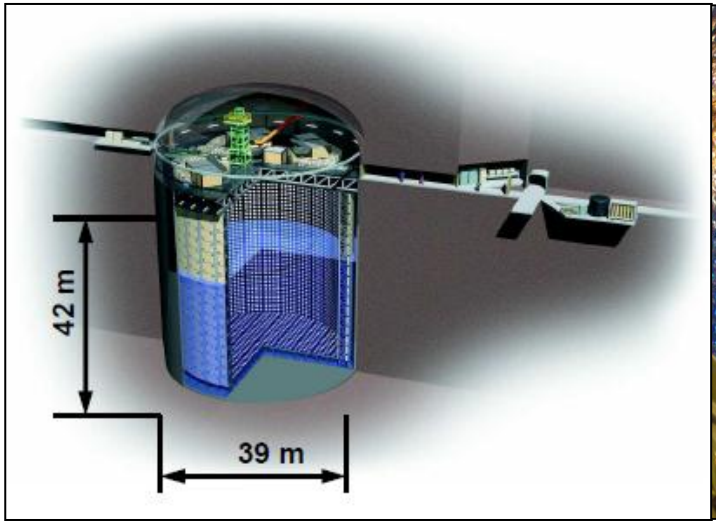
• **Other detectors** : (not used in this analysis)

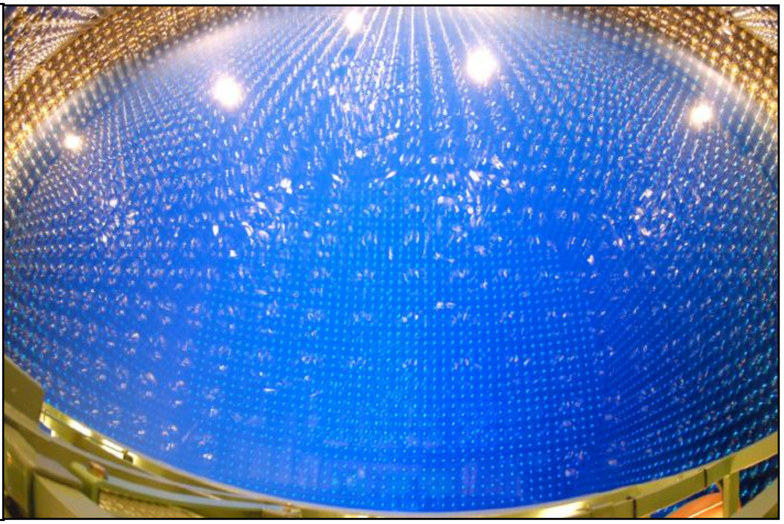
- P0D (π0 detector)
- SMRD (side muon range detectors)

• All detectors embedded in the refurbished UA1 magnet



The Super-Kamiokande detector





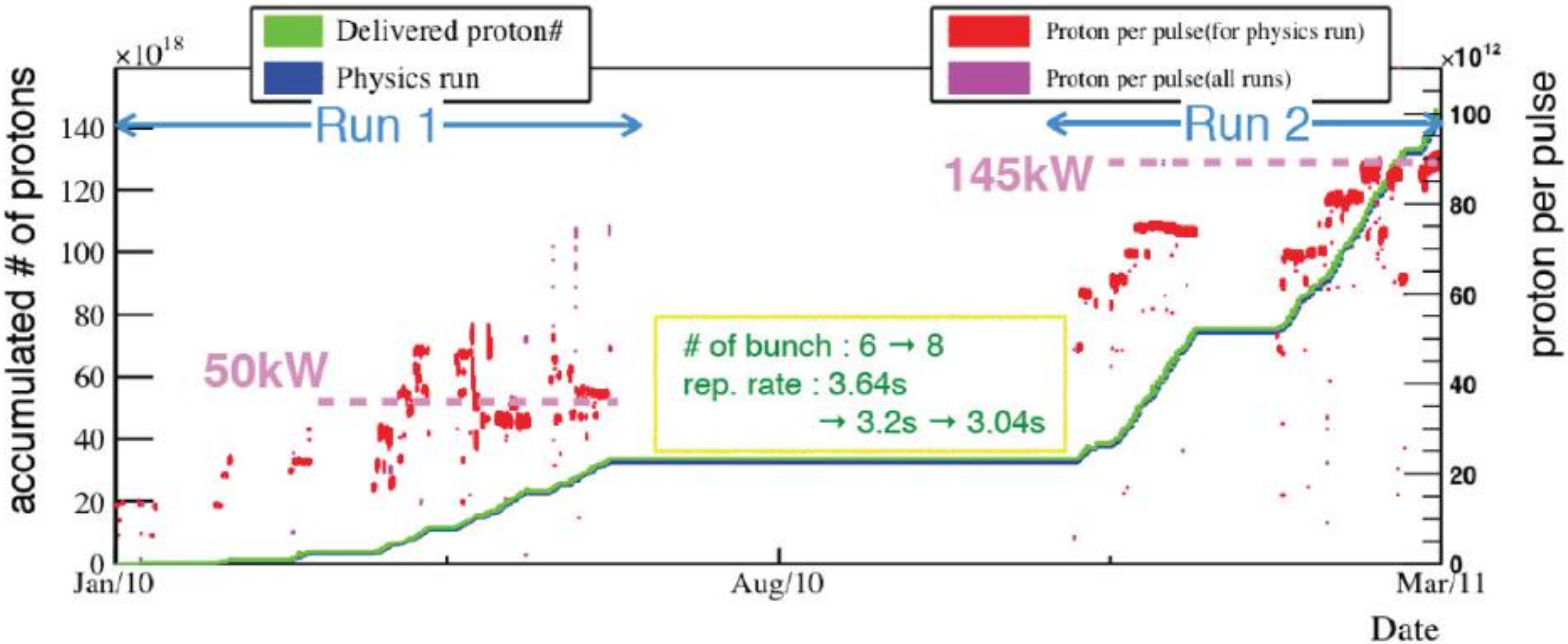
• Located 295km away from Tokai in the Kamioka mine (1000m underground)

• 50 kT water Cherenkov detector (22.5 kT of fiducial volume) w/ ~11000 PMTs

• Very good μ/e separation because of shape and opening angle of the cherenkov ring

The μ/e misidentification probability is less than 1%

Data taking



- Physics data taking started in January 2010 – ended on March 11th 2011
- At the end of Run 2, stable operation at 145 kW was achieved
- Run1 + Run 2 total dataset : **1.43×10^{20} POT** (protons on target)
  This amount of data represents 2% of T2K's proposal goal
- All physics dataset is used in ν_e appearance and ν_μ disappearance analyses

Oscillation analysis strategy

Compute the number of expected events at the far detector

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

SK events by MC simulation

- Calculated based on flux prediction

From simulation tuned using NA61 (Shine) data

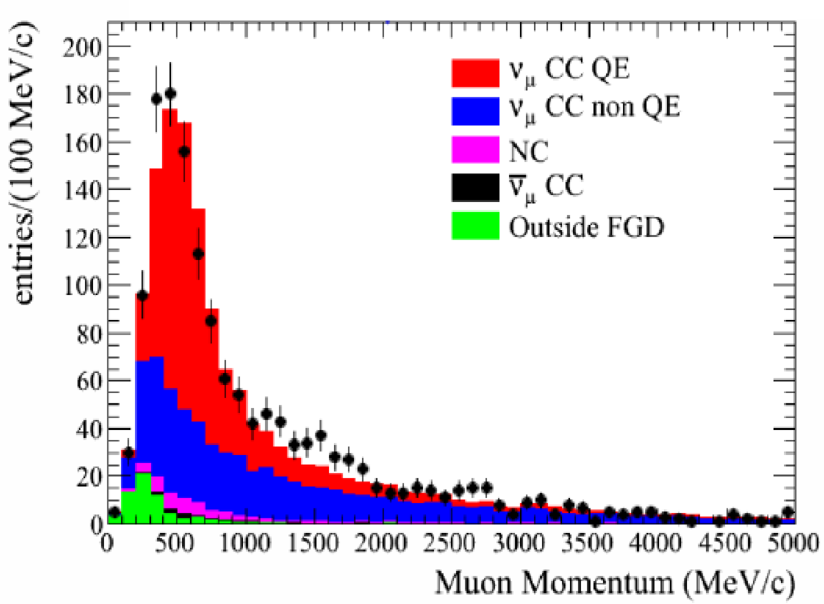
- Depends on the cross sections predictions, detector efficiencies, and given oscillation parameters

Normalization by ND

- Data/MC ratio evaluated on the measurement of ν_μ inclusive CC interactions in ND280 tracker

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

- Normalization reduces uncertainties on the far detector expectations

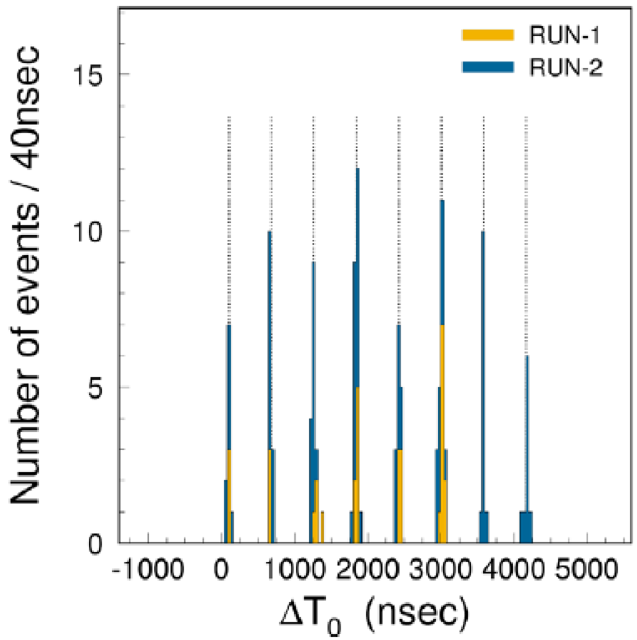


$\nu_{\mu,e}$ event selection at Super Kamiokande

T2K selection cuts were predefined before the analysis using MC and atmospheric data

- **Timing selection** : -2 +10 μs window on GPS time, synchronized between J-PARC and SK
- Select **fully contained** (FC) events in the **fiducial volume** (FV)

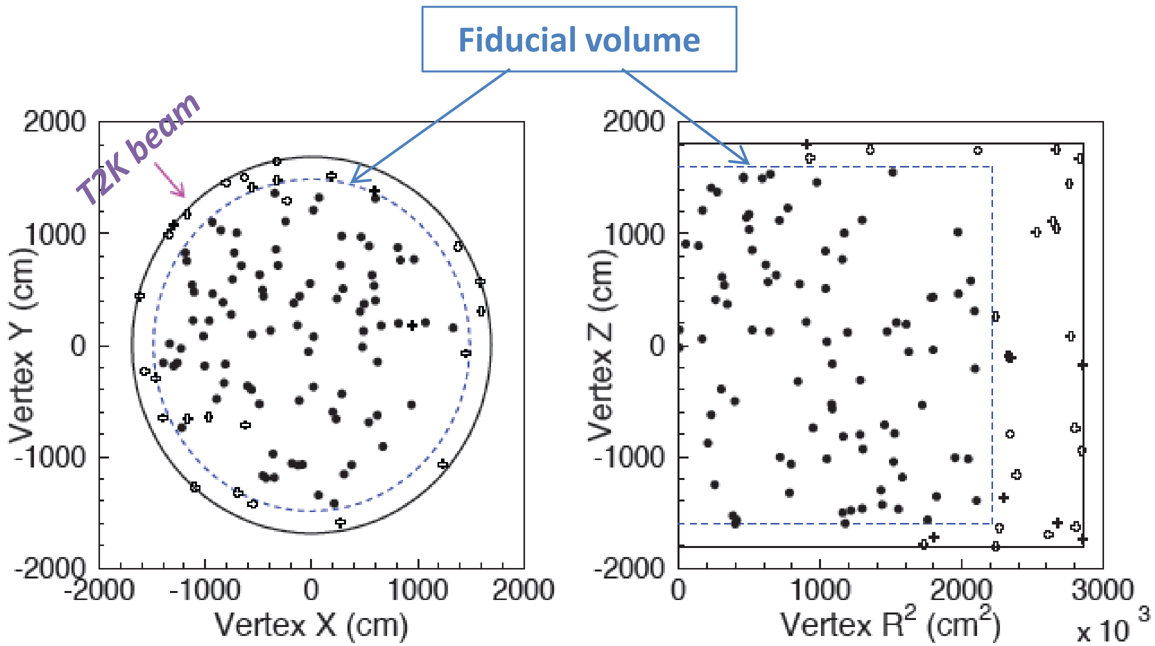
121 on-time FC events



Clear bunch structure

$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

Event distribution



88 selected FC FV events

41 Single Ring events

ν_e appearance

Ring e_like + additional cuts to reduce bacgrounds

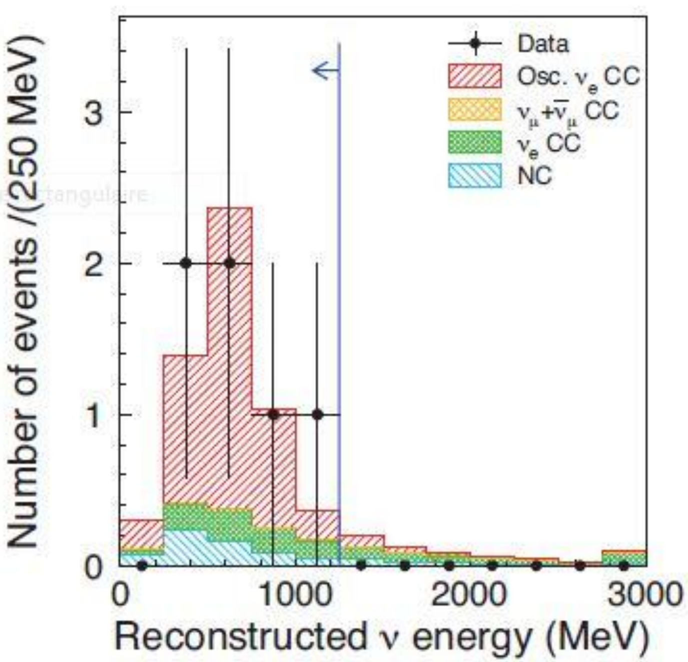
6 /41 candidate events pass cuts

1/2 intrinsic ν_e in beam

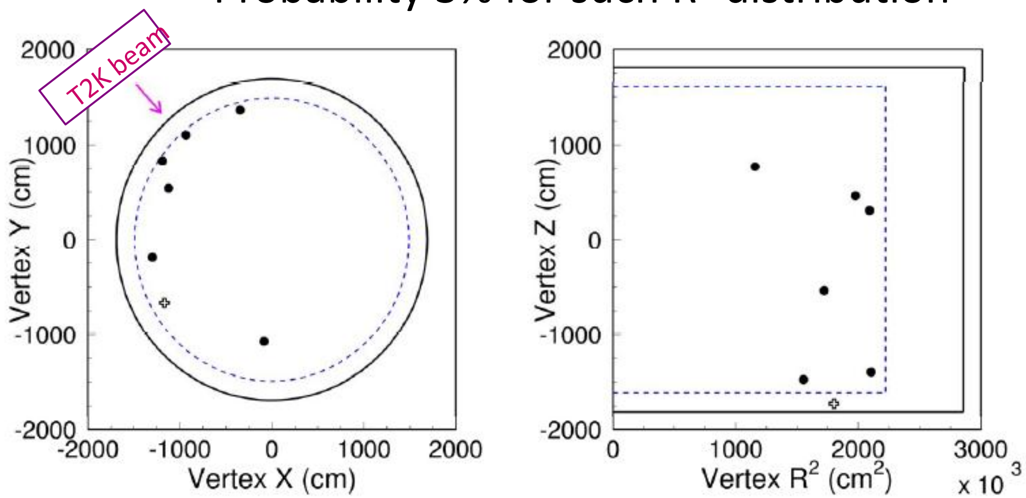
1/2 ν_μ neutral current interaction with π^0

Expected number of events for $sin^2 2\theta_{13} = 0$

$$N_{SK} = 1.5 \pm 0.3 \text{ (syst) events}$$

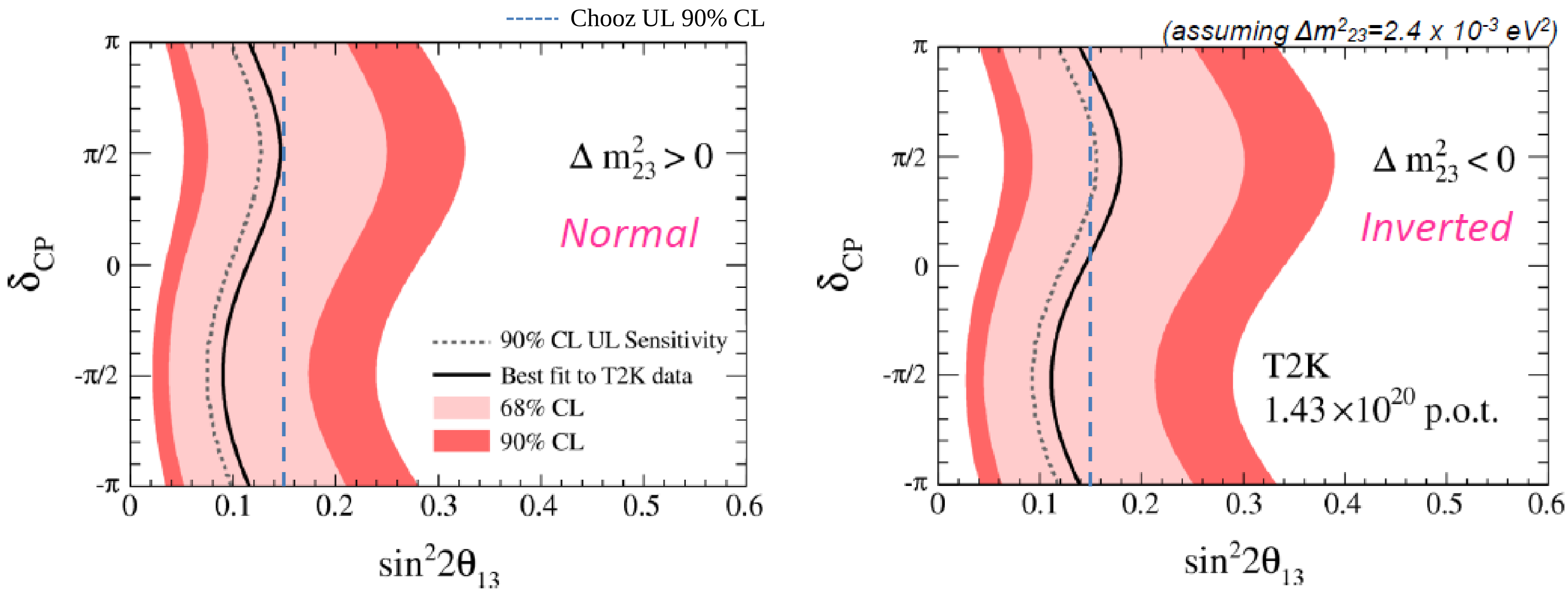


Probability 3% for such R^2 distribution



ν_e *appearance results*

- Results on appearance published in **Phys. Rev. Lett. :** ***PRL, 107 041801 (2011)***
- 6 ν_e events were observed when null oscillation (θ_{13} = 0) gives 1.5±0.3 expected events
- Fluctuation probability p-value = 0.7% , **null oscillation disfavored at 2.5σ**



90% C.L. (Feldman-Cousins method) intervals and best fit values
(for Δm^2_{23} = 2.4x10-3 eV², $\sin^2(2\theta_{23})$ = 1 and δ_{CP} = 0)

$0.03 < \sin^2(2\theta_{13}) < 0.28$
$\sin^2(2\theta_{13}) = 0.11$

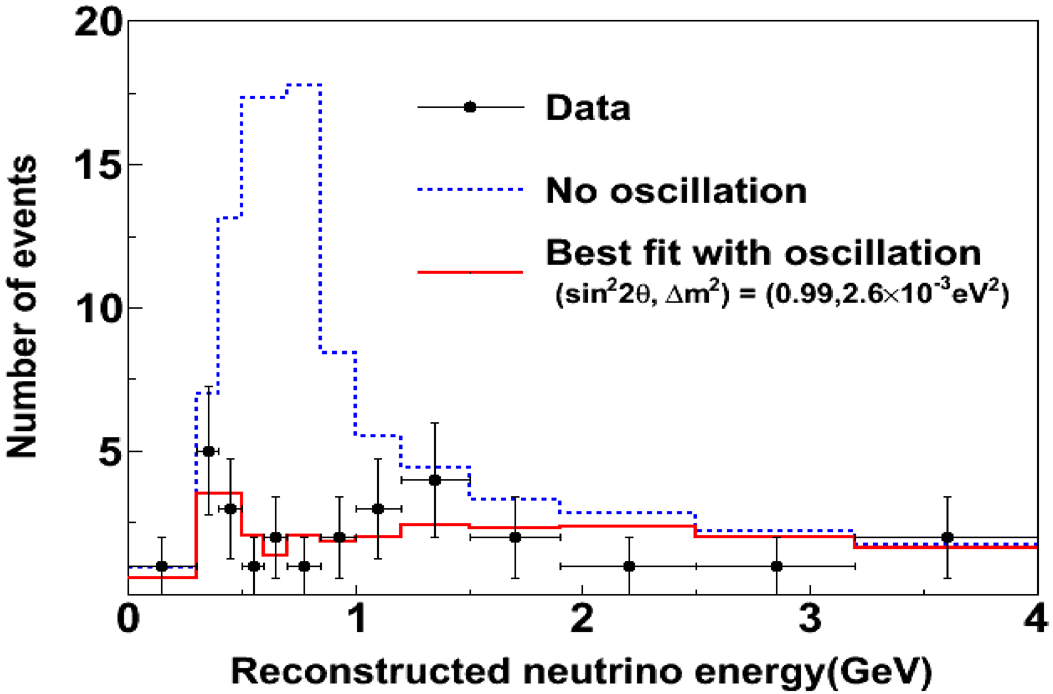
$0.04 < \sin^2(2\theta_{13}) < 0.34$
$\sin^2(2\theta_{13}) = 0.14$

ν_μ disappearance

ν_μ selection

Ring μ_like + additional cuts to reduce bacgrounds

31 /41 events
(FCFV, single ring) pass cuts



$N_{SK} = 103.6 \pm 10.2$ (stat) $^{+13.8}_{-13.4}$ (syst) events

expected without oscillation

No oscillation excluded at 4.5σ

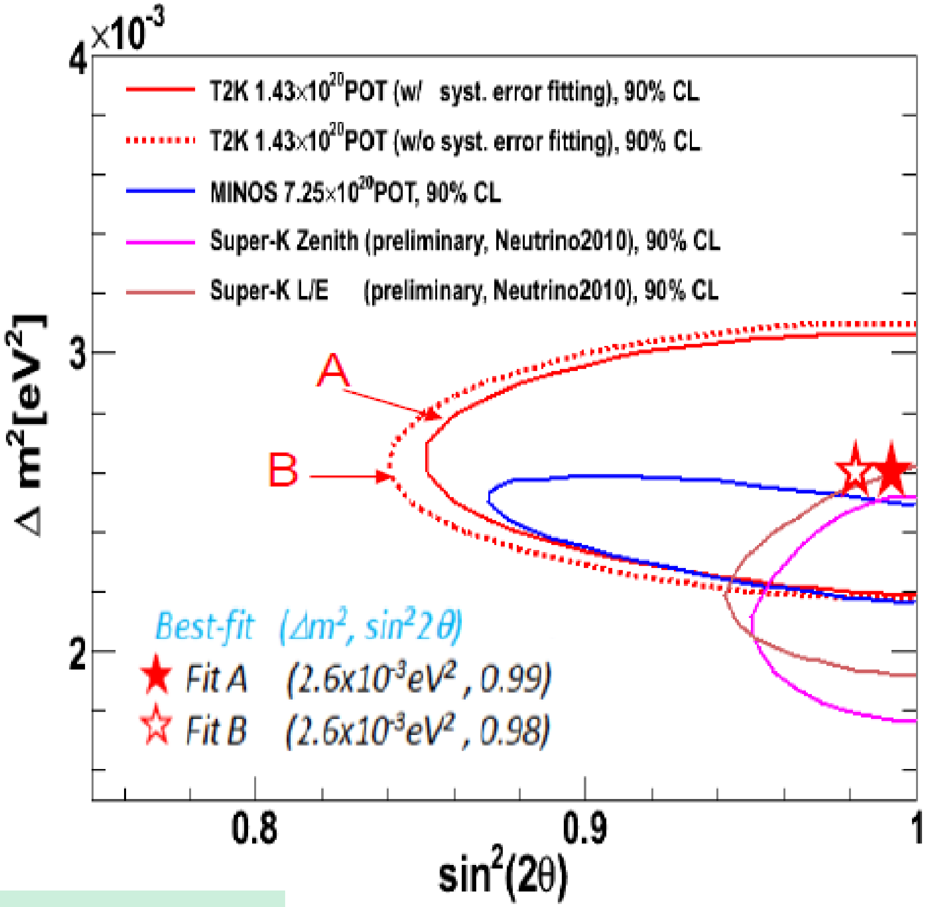
Disappearance results

Two independent analyses were performed to cross check the results

The Feldman-Cousins method was used to produce the confidence intervals

Method A :
Un-binned maximum likelihood with systematic error parameter fitting

Method B :
Likelihood ratio of binned spectrum without systematic parameter fitting



The two methods are consistent with SK (atmospheric) and MINOS (accelerator – 7.25x10^{20} POT) results

Paper arXiv:1201.1386 submitted to PRL

Near future

- The March 11th earthquake didn't cause strong damages on the accelerator

- Accelerator status :
    - Magnets and monitors are re-aligned
    - Accelerator commissioned in December

- Near detector : all subdetectors tested successfully

- SK was not damaged by the earthquake

- Beginning of january : problem with the horn power supply
(magnetic horns focus charged pions produced from the proton beam interaction on the target. Pions then decay yielding ν_μ) =>Neutrino beam not focused.

- Restart of physics data taking scheduled around march 2nd (instead of end of january)

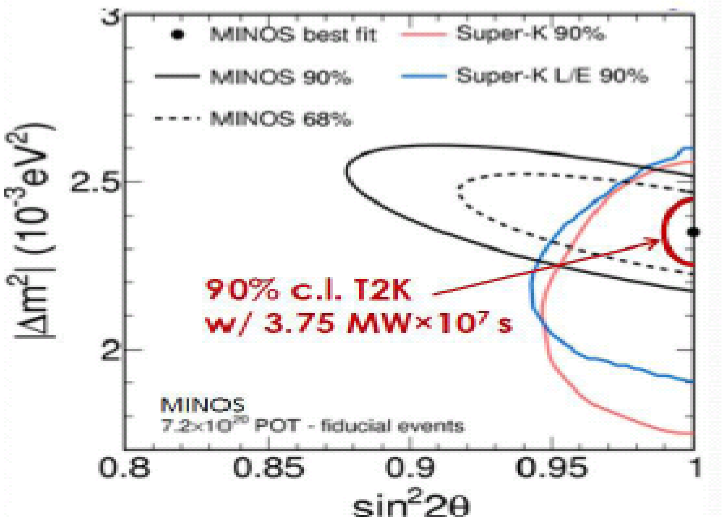
Milestone : 10^{21} POT by summer 2013
Exclusion of $\theta_{13} = 0$ at 5σ with the T2K best fit value of $\sin^2(2\theta_{13}) = 0.11$

The main goal remains the discovery of a non-zero θ_{13} !

Also improve accuracy on so-called « atmospheric » parameters

- Expected sensitivity with full T2K proposal statistics (3,75 MW x 10^7 s)

$\delta(\Delta m^2_{23})$ ~ 1×10^{-4} eV² and **$\delta(\sin^2 2\theta_{23})$ ~ 1%**



Thank you for your attention

Back-up slides

After several month of recovery work since the earthquake we succeeded to take the proton beam from Dec.24,2011 as scheduled and confirmed the functionality of the beam line components and the reproducibility of the neutrino production, successfully.

However, on Dec.22, during the final operation test, switching devices called IGBTs in the horn power supply were broken. The cause is being identified in detail.

Therefore, the beam operation during December was made without horn operation.

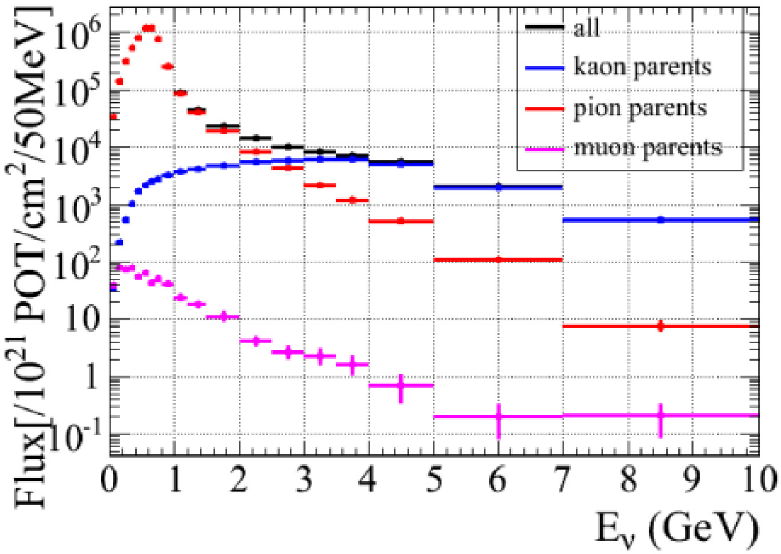
We are working to recover the power supply and aim to restart the full experiment with the horn operation from March.

During January we plan to take beam with the horn off in order to make beam studies for high power operation and various systematic studies using near neutrino detectors.

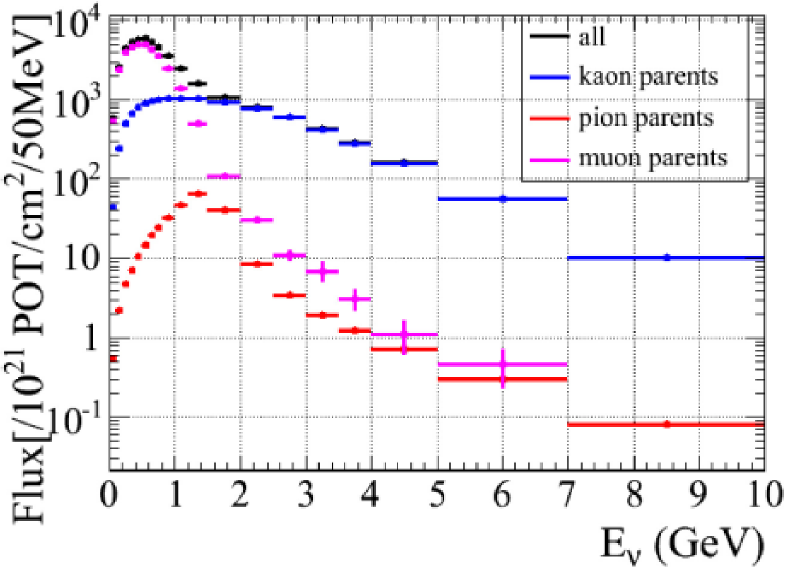
Beam prediction

- The beam prediction is based on the FLUKA MC simulation package
- This model is tuned with **NA61** experiment (CERN) results for pions and kaons production. NA61 operates p+C collisions at the same proton energy as T2K and with a T2K target replica
- Horn focusing, secondary interactions and particles decay are then simulated by GEANT3
- The beam is not completely pure in ν_μ but is composed of an intrinsic ν_e component, expected to be below 2%

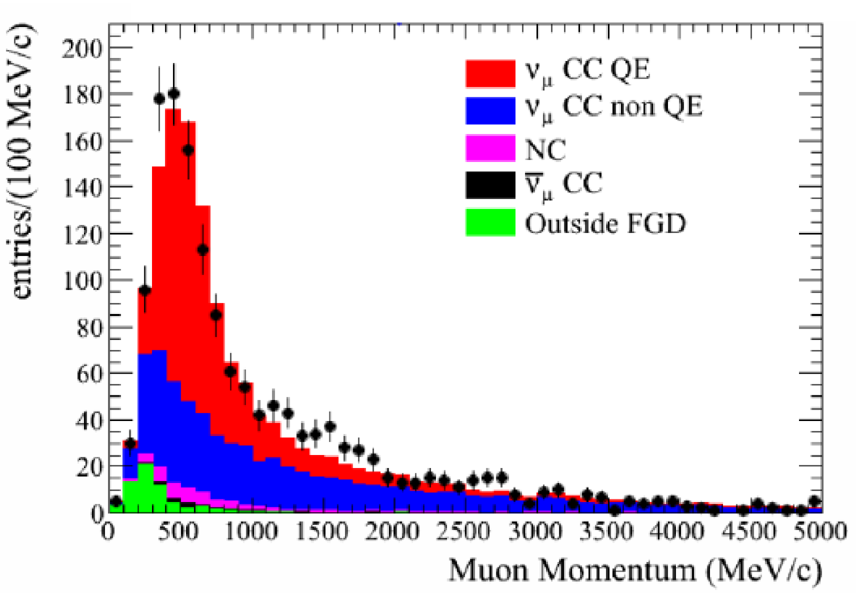
SK ν_μ flux



SK ν_e flux



Near detector ν_μ measurement



- Inclusive CC ν_μ selection for 2.9×10^{19} POT (Run1) with major contribution from the Saclay group

- Selection : Interaction in a FGD with a muon track observed in a TPC (TPC PID) - 38% efficiency, 90% purity are reached

- Consistency between data and MC based on NA61+FLUKA+NEUT (neutrino interactions)

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

- This normalization factor is used to reduce the uncertainty on the beam flux to extrapolate the number of events expected in SK

- The intrinsic ν_e contamination is also analyzed and measured to be < 2% at 90% C.L.

ν_e selection

	Data	Expected N_{SK} for $\sin^2 2\theta_{13}=0.1$				
		BG expectation				Signal
		Total BG	ν_μCC	ν_eCC	NC	$\nu_\mu \to \nu_e$
Interaction in FV	-	**141.3**	67.2	3.1	71.0	**6.2**
FCFV	**88**	**73.6**	52.4	2.9	18.3	**6.0**
Single-ring	**41**	**38.3**	30.8	1.8	5.7	**5.2**
e-like	**8**	**6.6**	1.0	1.8	3.7	**5.2**
E_{vis} > 100 MeV	**7**	**5.7**	0.7	1.8	3.2	**5.1**
No decay-e	**6**	**4.4**	0.1	1.5	2.8	**4.6**
M_{inv} < 105 MeV/c^2	**6**	**1.9**	0.04	1.1	0.8	**4.2**
E_ν^{rec} < 1250 MeV	**6**	**1.3**	0.03	0.7	0.6	**4.1**

6 candidate events pass all cuts

Expected number of events for $\sin^2 2\theta_{13}=0$

$$N_{SK} = 1.5 \pm 0.3\ (syst)\ events$$

ν_μ selection

	Data	MC w/ 2-flavor oscillation					MC w/o osc.
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC	
Interaction in FV	-	141	24.0	43.7	3.2	71.0	243
FCFV	88	74.1	19.0	33.8	3.0	18.3	166
Single-ring	41	38.7	17.9	13.1	1.9	5.7	120
μ-like	33	32.0	17.6	12.4	< 0.1	1.9	112
P_μ > 200 MeV/c	33	31.8	17.5	12.4	< 0.1	1.9	111
N(decay-e) ≤ 1	31	28.4	17.3	9.2	< 0.1	1.8	104

	Data	MC w/o oscillation				
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC
Interaction in FV	-	243.0	96.5	72.3	3.2	71.0
FCFV	88	165.8	88.9	55.5	3.0	18.3
Single-ring	41	120.5	86.3	26.6	1.9	5.7
μ-like	33	111.9	85.2	24.7	< 0.1	1.9
P_μ > 200 MeV/c	33	111.3	84.9	24.5	< 0.1	1.9
N(decay-e) ≤ 1	31	103.6	84.6	17.2	< 0.1	1.8

$N^{SK}_{exp.}$ 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%

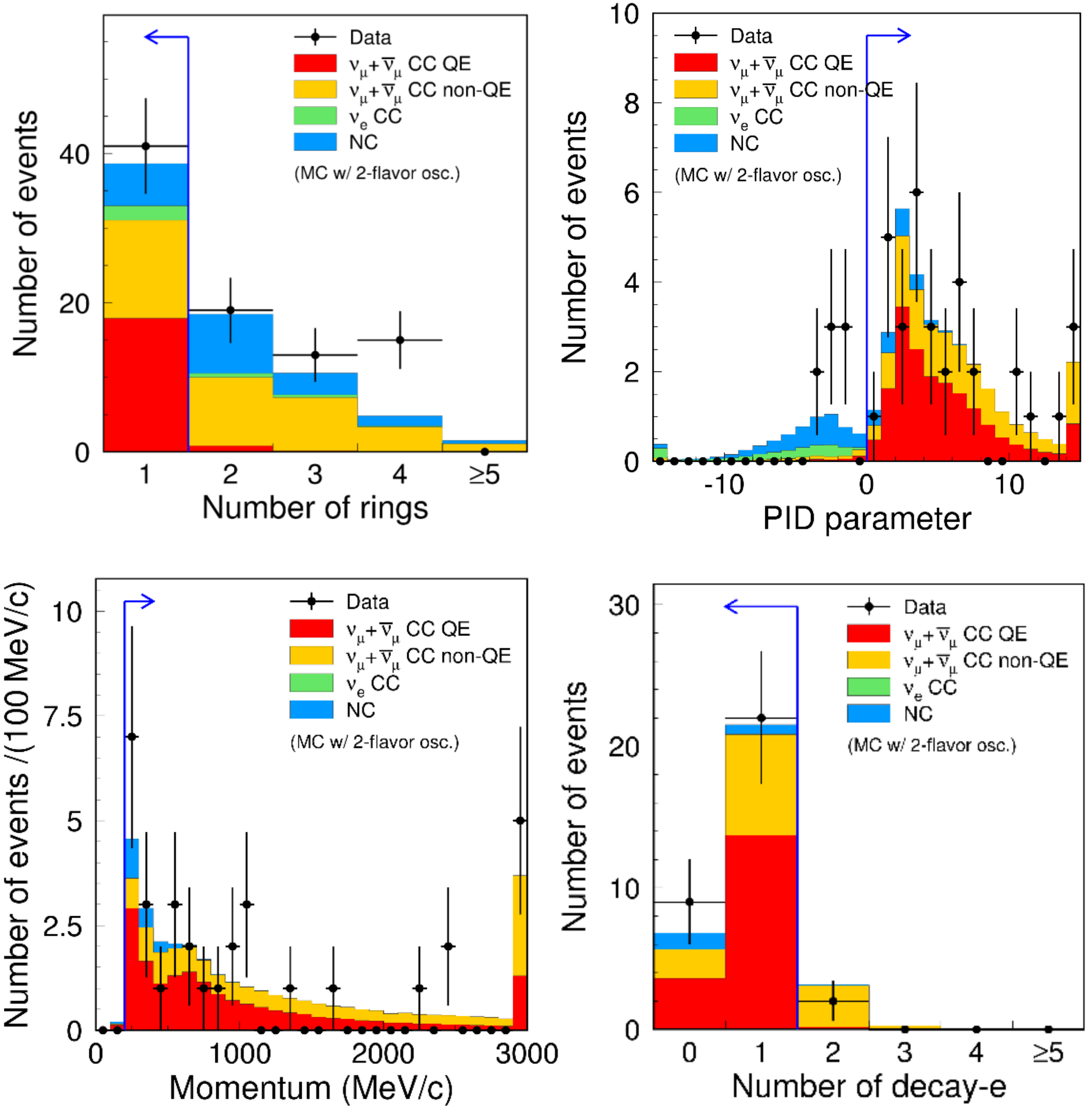
ν_μ event selection at SK (2)

Additionnal cuts :

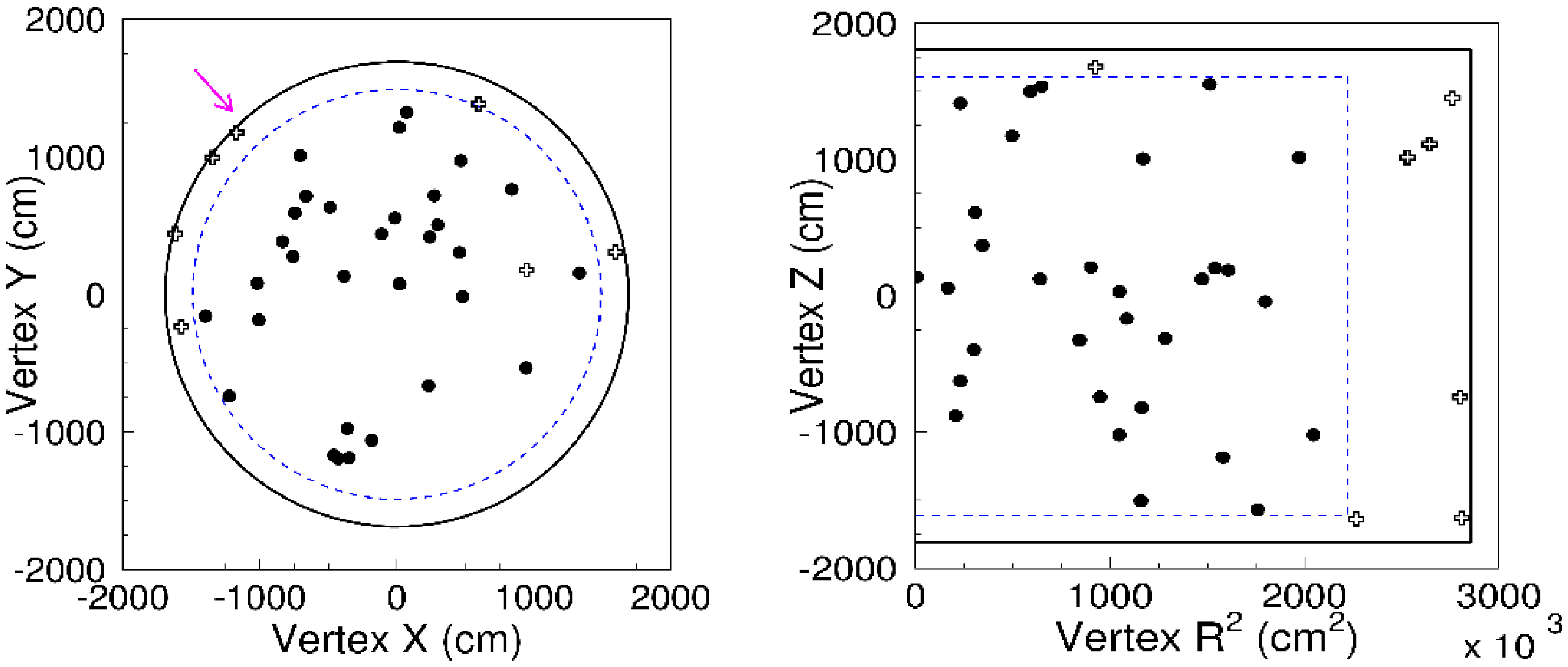
Cut	*Events in data*
FCFV	**88**
Only 1 ring	**41**
μ-like	**33**
P_μ > 200 MeV	**33**
Nb decay e- < 2	**31**

Final ν_μ CCQE purity = 61%
Final ν_μ CCQE efficiency = 72%

31 events remain after all cuts



ν_μ selected events distribution



Far detector expectation

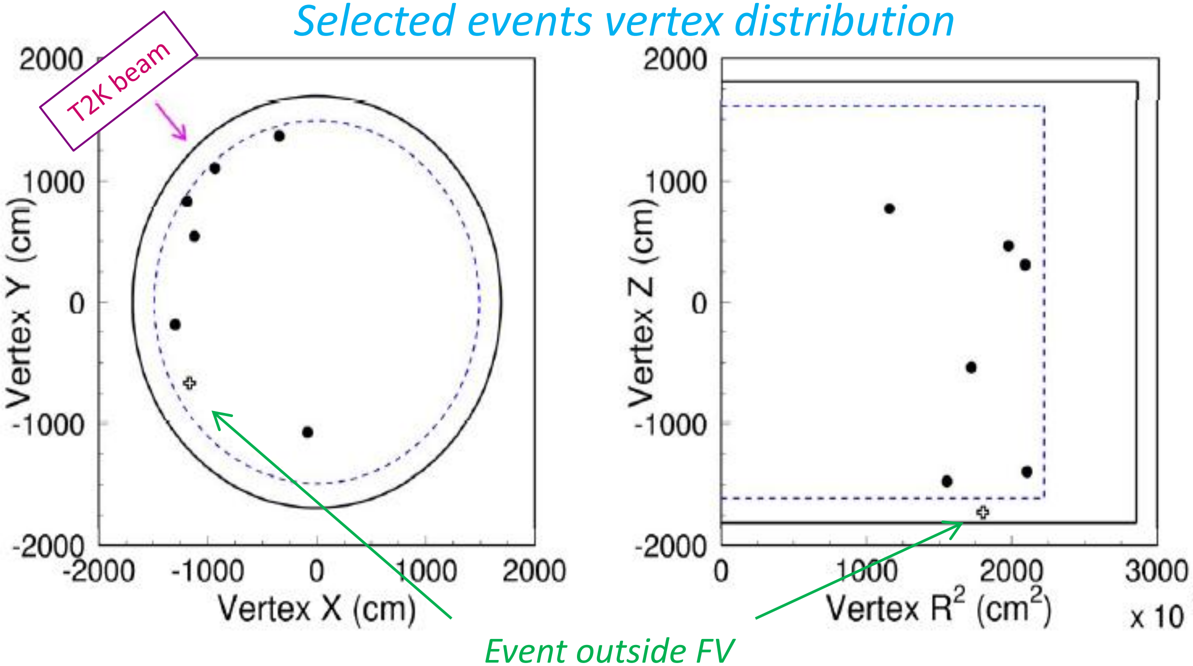
$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

$$\frac{\int \Phi^{\mathrm{SK}}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\; dE_\nu}{\int \Phi^{\mathrm{ND}}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\; dE_\nu}$$

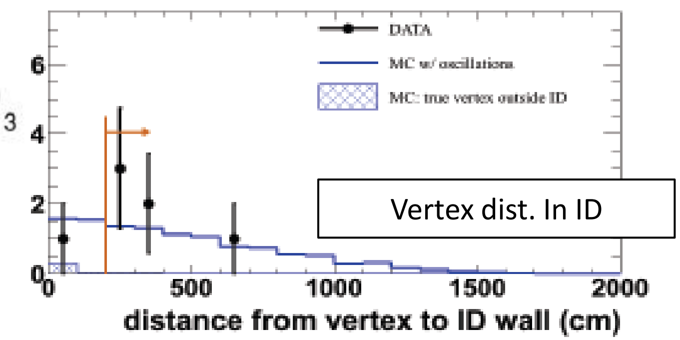
Expected # of events estimated by MC

ν_e event distribution

Selected events vertex distribution

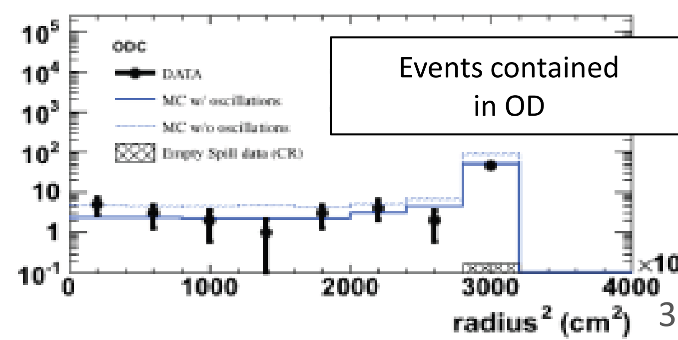


- The selected events are located at large R
- KS test gives 0.03 p-value for such R^2 distribution



Additional checks were performed

- Distribution of events outside FV shows no indication of background contamination
- Distribution of events in OD show no indication of background contamination



T2K ν_μ disappearance analysis methods

- Fit with 2 flavor oscillation scenario

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

- Two independent methods to extract oscillation parameters
- Feldman-Cousins method to produce confidence intervals

- Method A – maximum likelihood

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

  - 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

Disappearance analysis

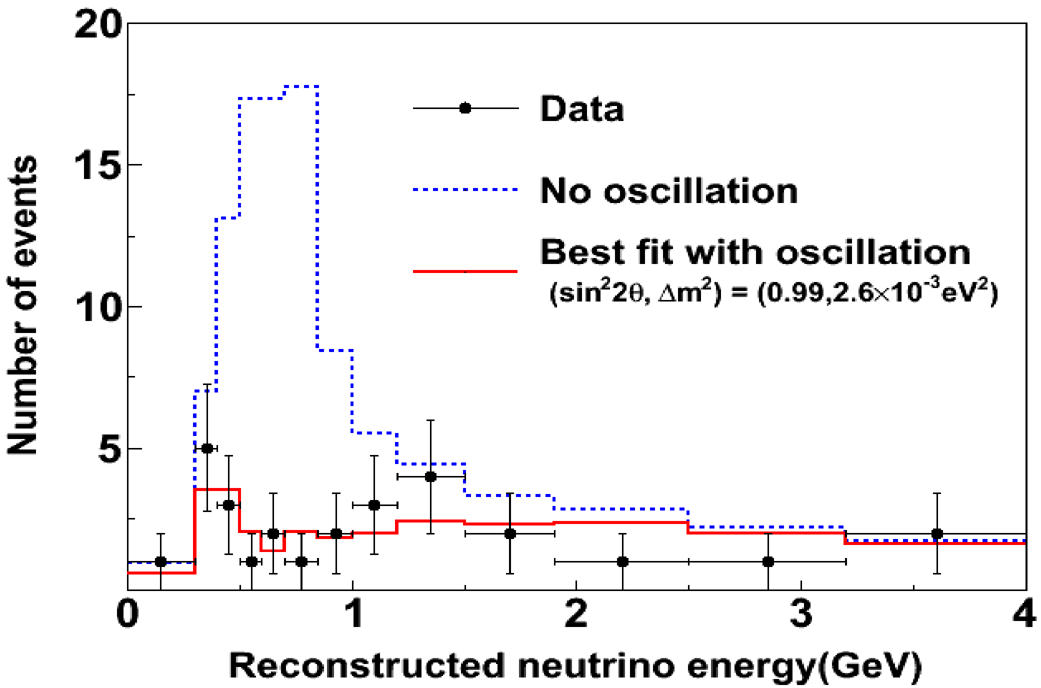
- **With a null oscillation hypothesis**
  103.6 events expected

No oscillation hypothesis excluded at 4.5 σ

- **For $\sin^2(2\theta_{23})=1$ and $\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2**
  28.3 events expected

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

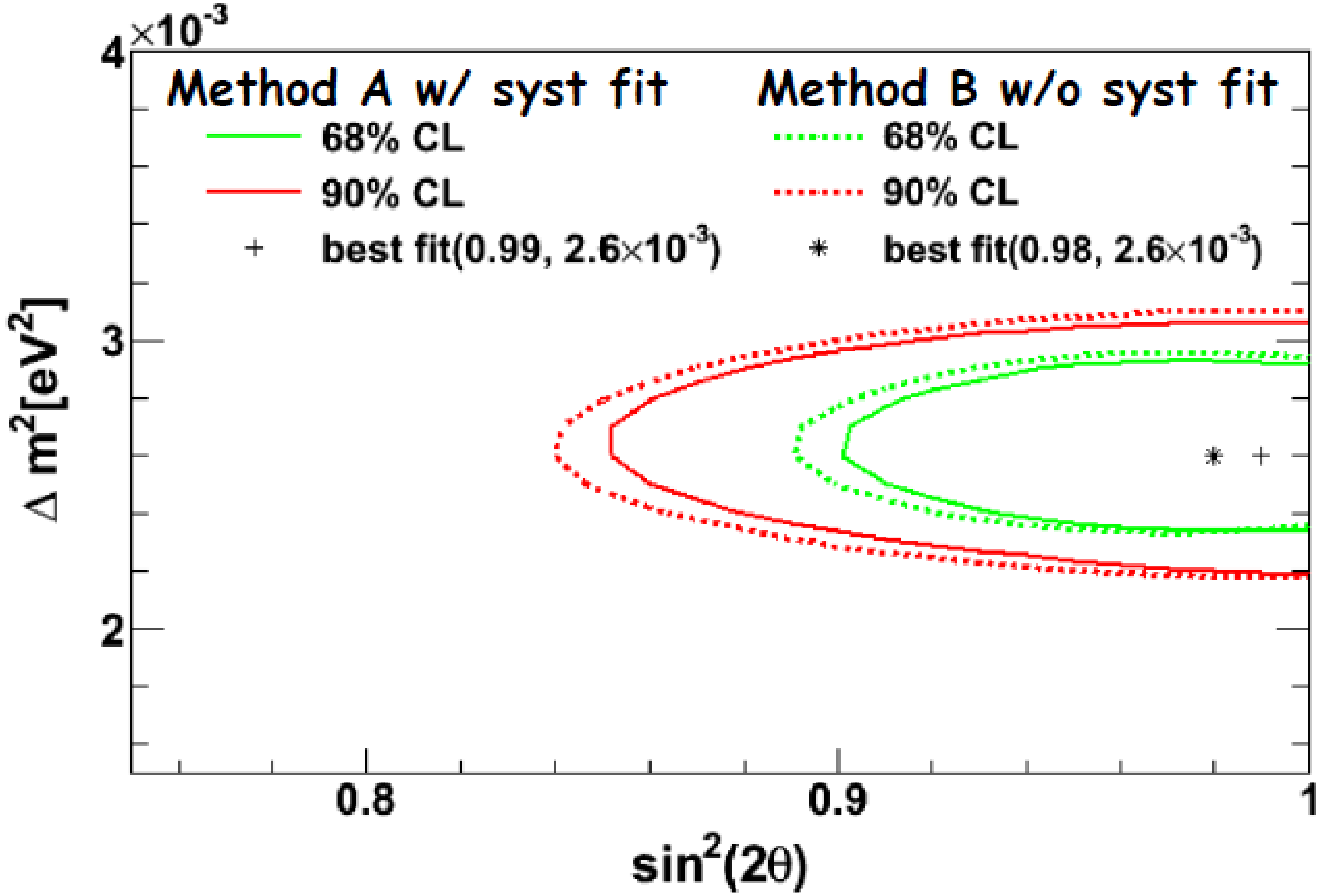
Error source	$\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$	Null Oscillation
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%



Clear disappearance in the energy spectrum

Shows power of off-axis technique!

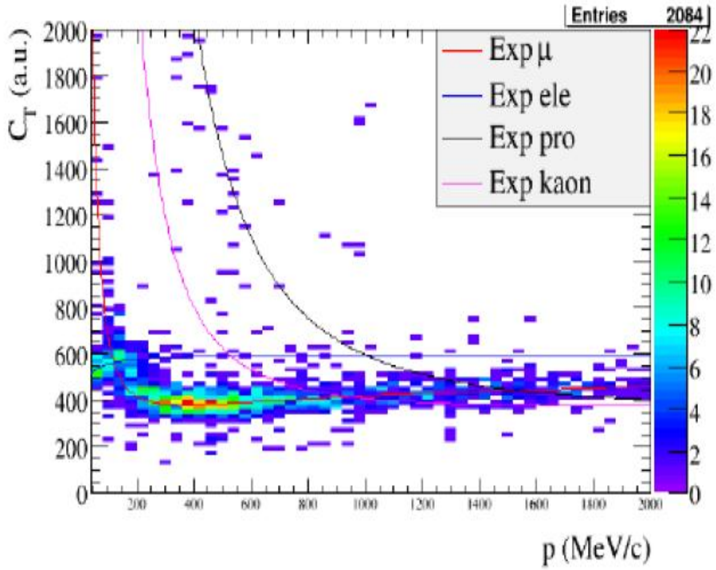
$\sin^2(2\theta_{23})$ contours

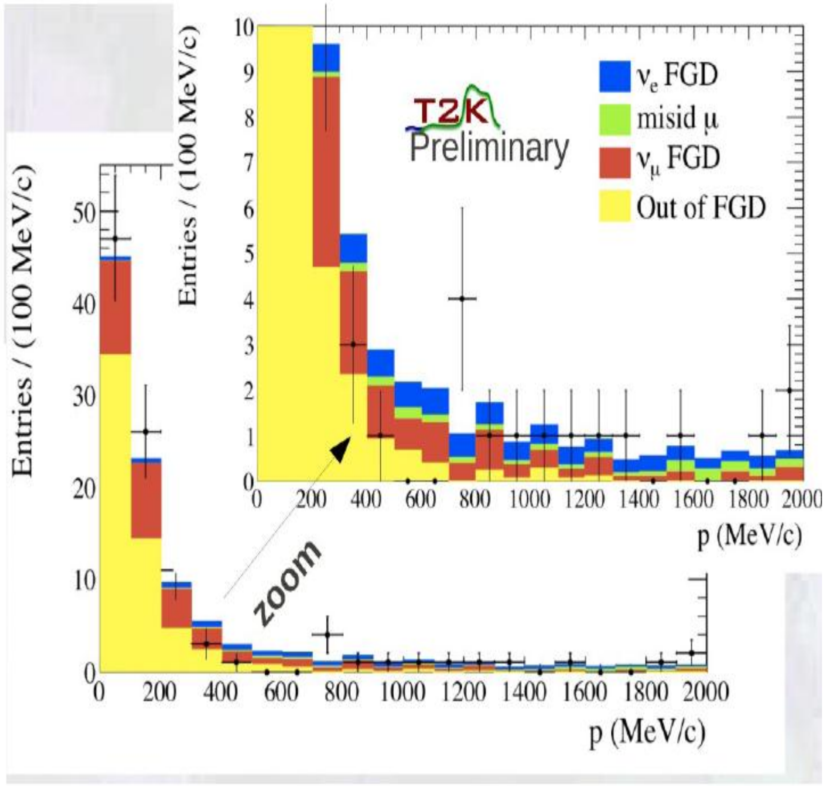


ν_e at the near detector

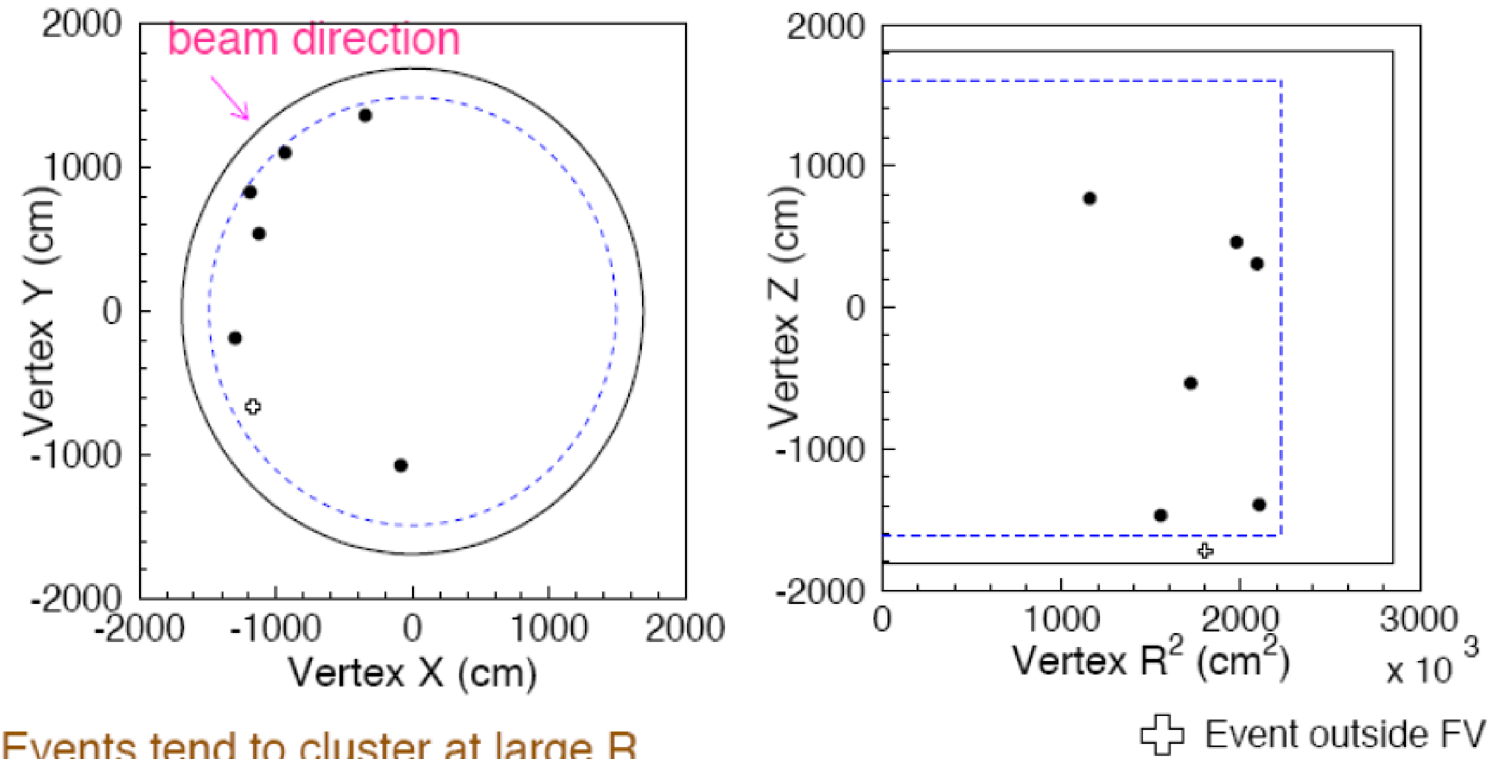
$R_{\nu e/\nu\mu} = (1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}))\%$
$< 2.0\%$ @ 90% C.L.

Main tool:
TPC PID:





Distribution of ν_e events



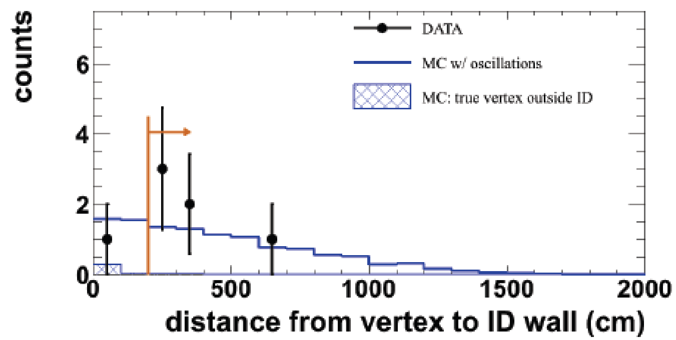
Events tend to cluster at large R

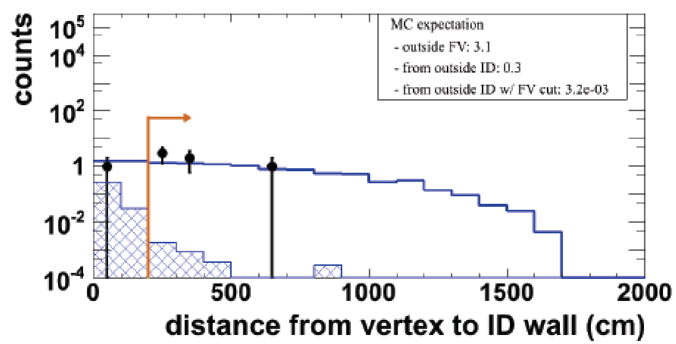
→ Perform several checks. for example

* Check distribution of events outside FV → no indication of BG contamination
* Check distribution of OD events → no indication of BG contamination
* K.S. test on the R^2 distribution yields a p-value of 0.03

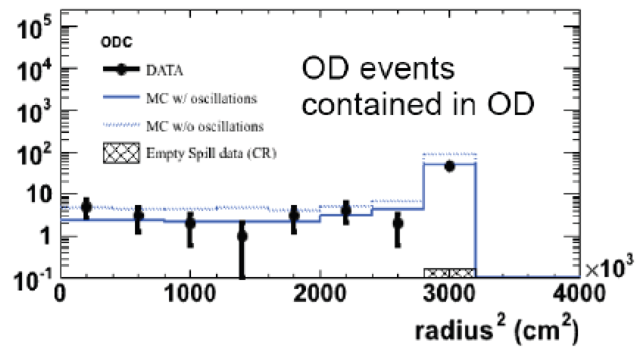
Distribution of ν_e events

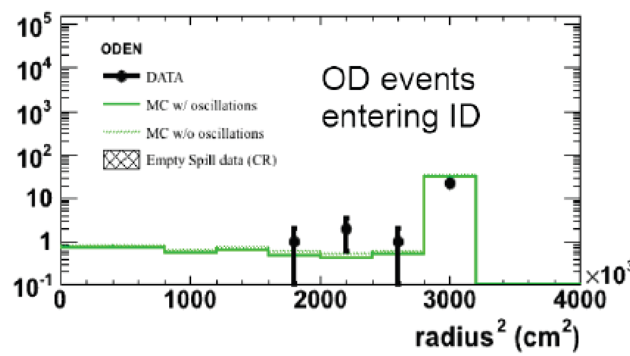
Vertex distribution in ID; MC interactions simulated out to 550 cm from ID wall





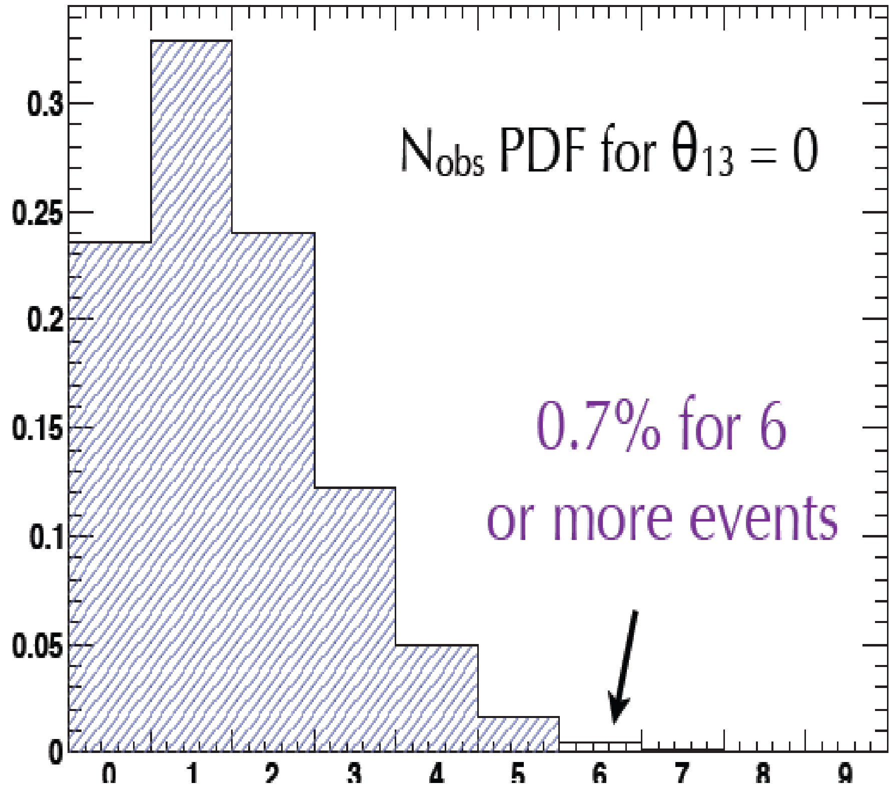
Vertex distribution in Outer Detector





ν_e events – what it means for θ_{13} ?

Observed 6 Events, with 1.5±0.3 events background at $\theta_{13} = 0$

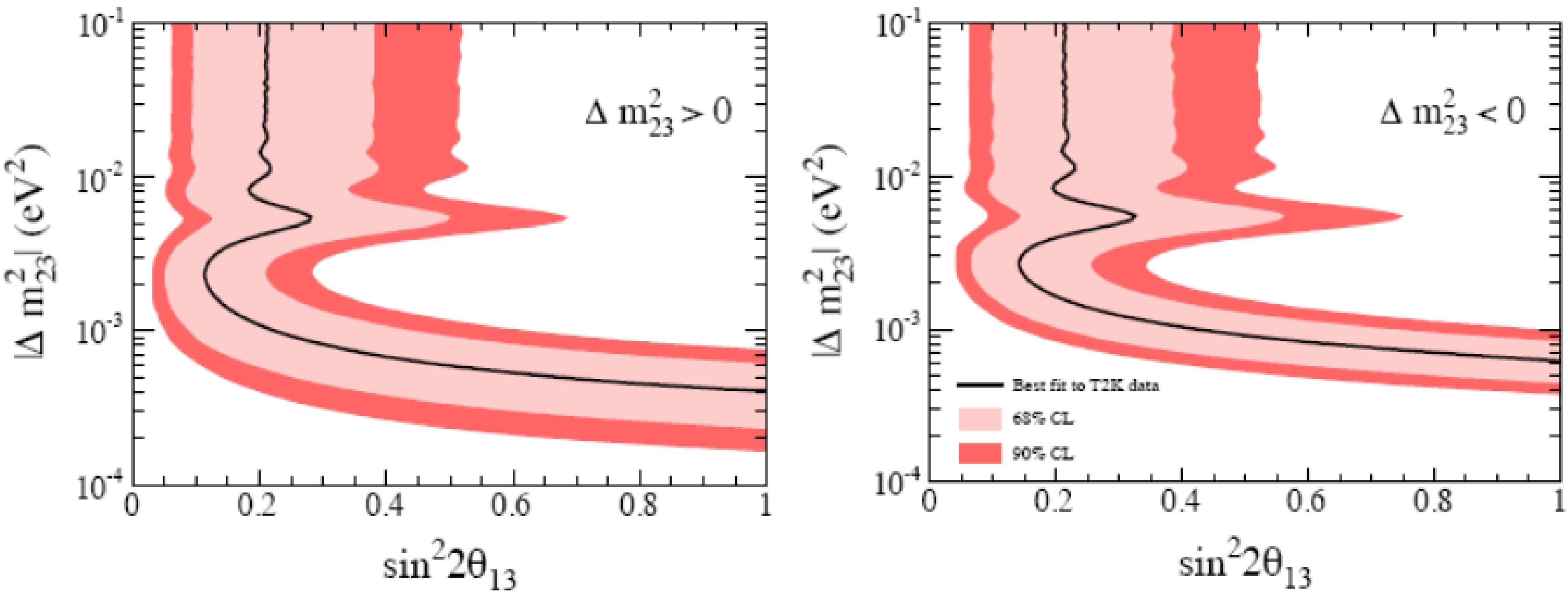


p-value of 0.7%

2.5σ exclusion

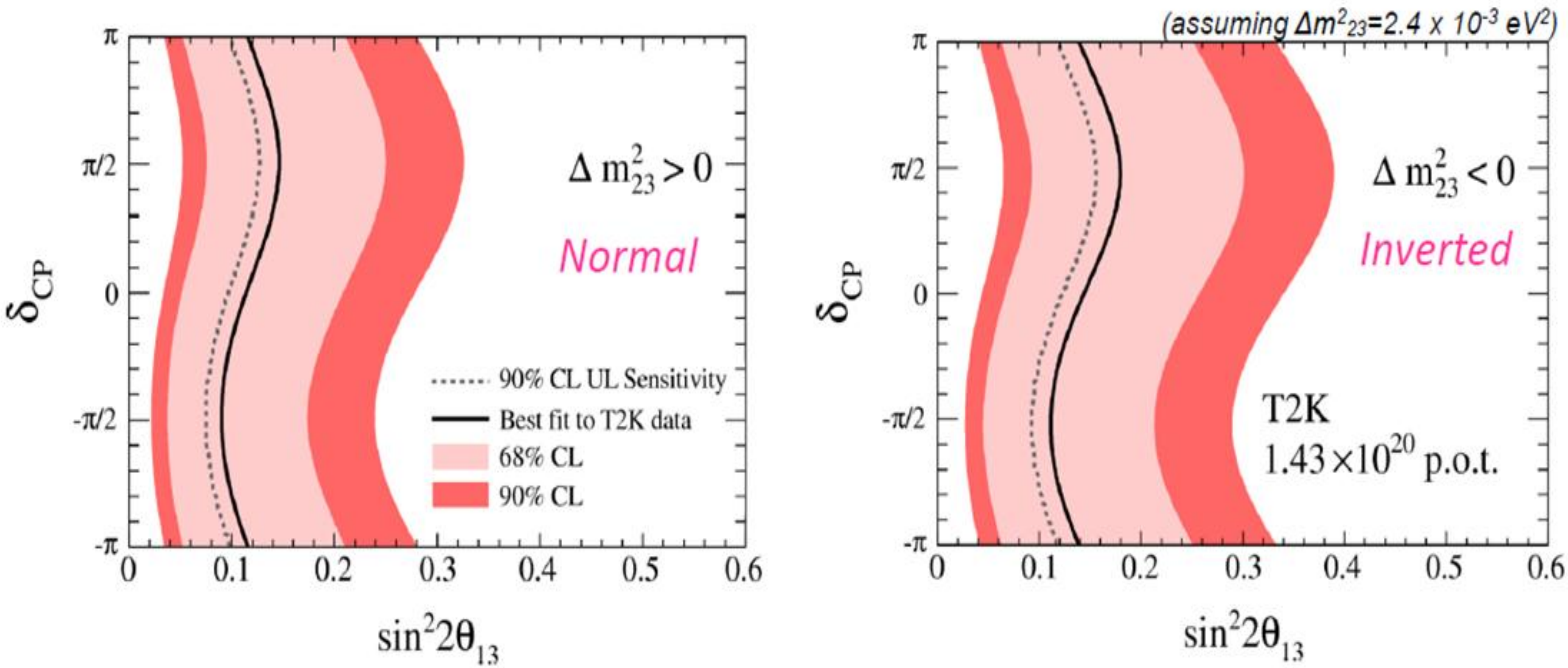
Allowed region of $\sin^2(2\theta_{13})$ as a function of Δm^2_{23}

(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

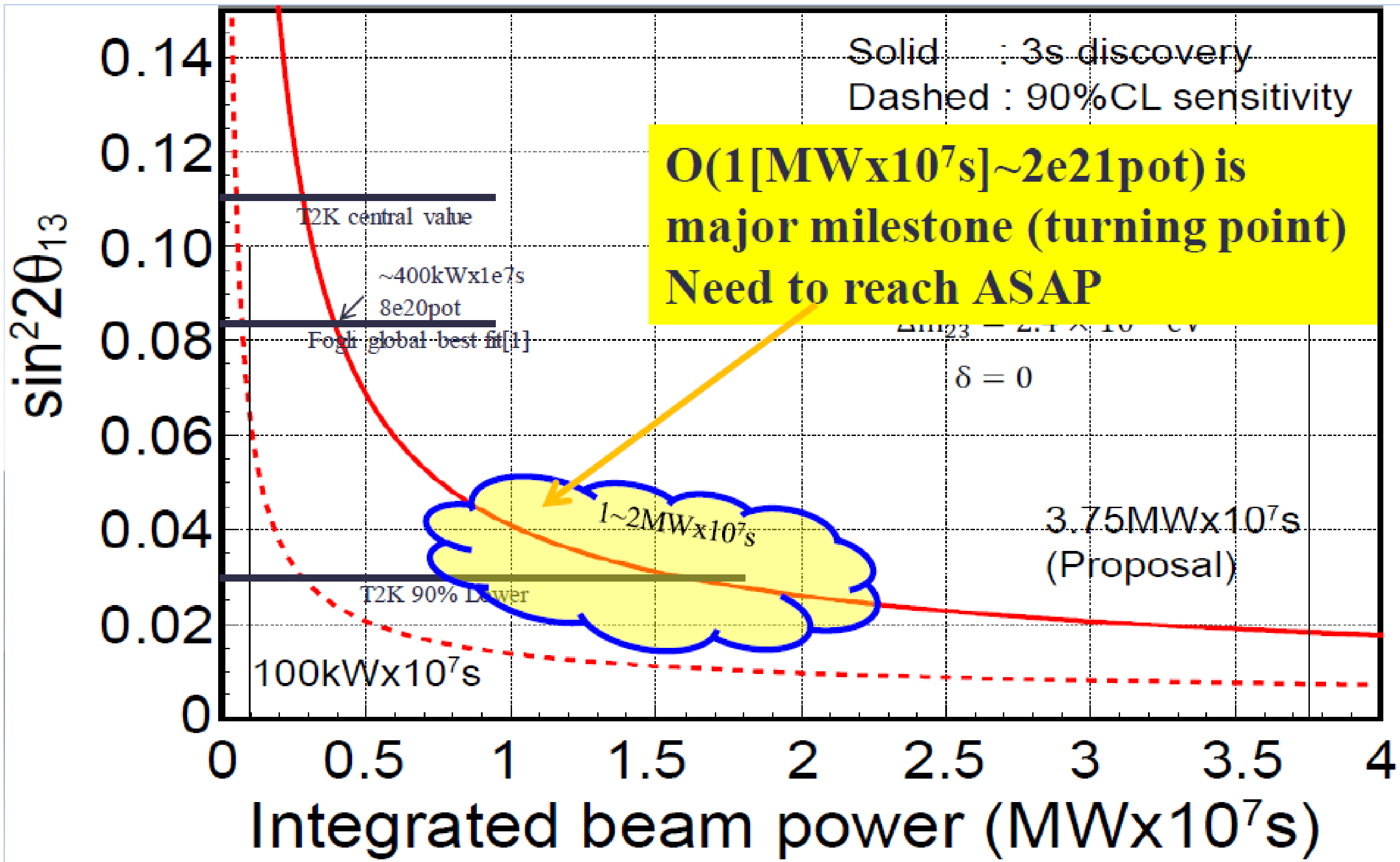


Feldman-Cousins method was used

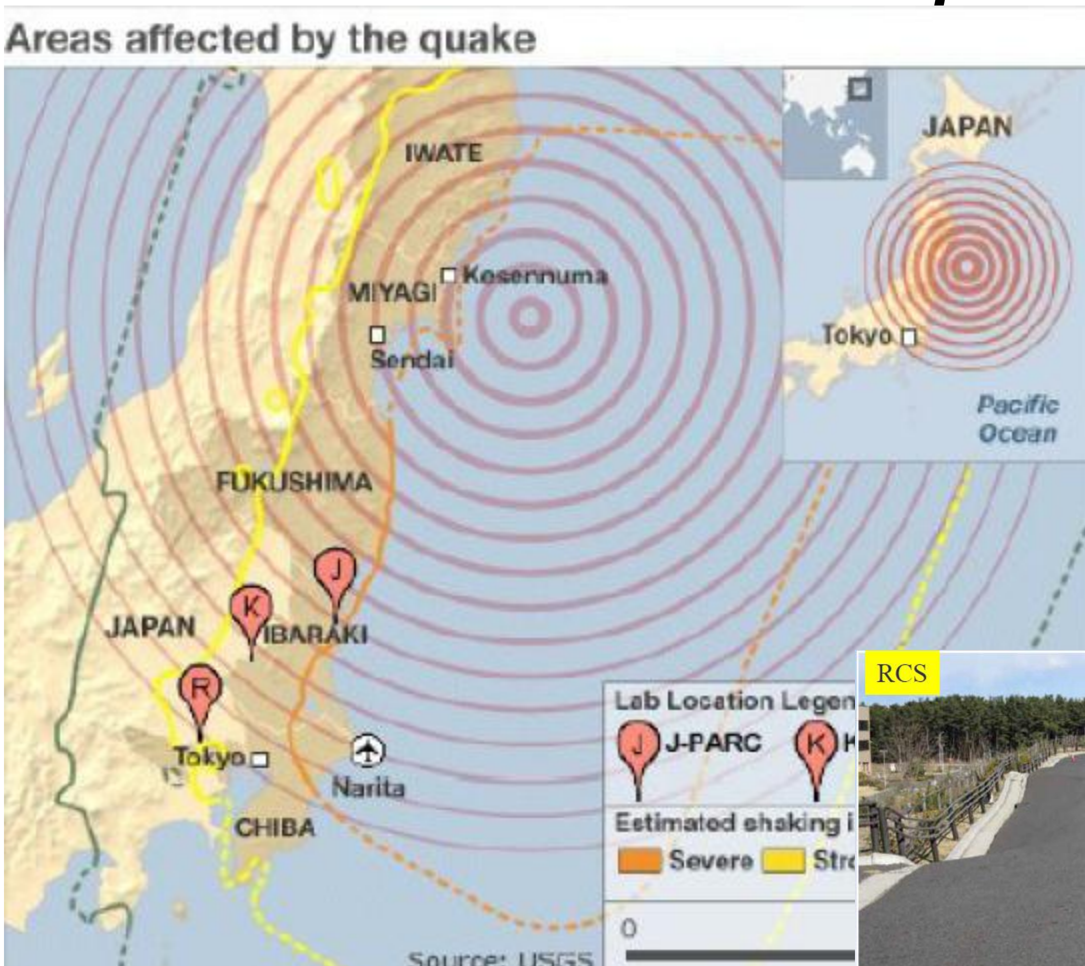
Allowed region of $\sin^2(2\theta_{13})$ as a function of δ_{CP}



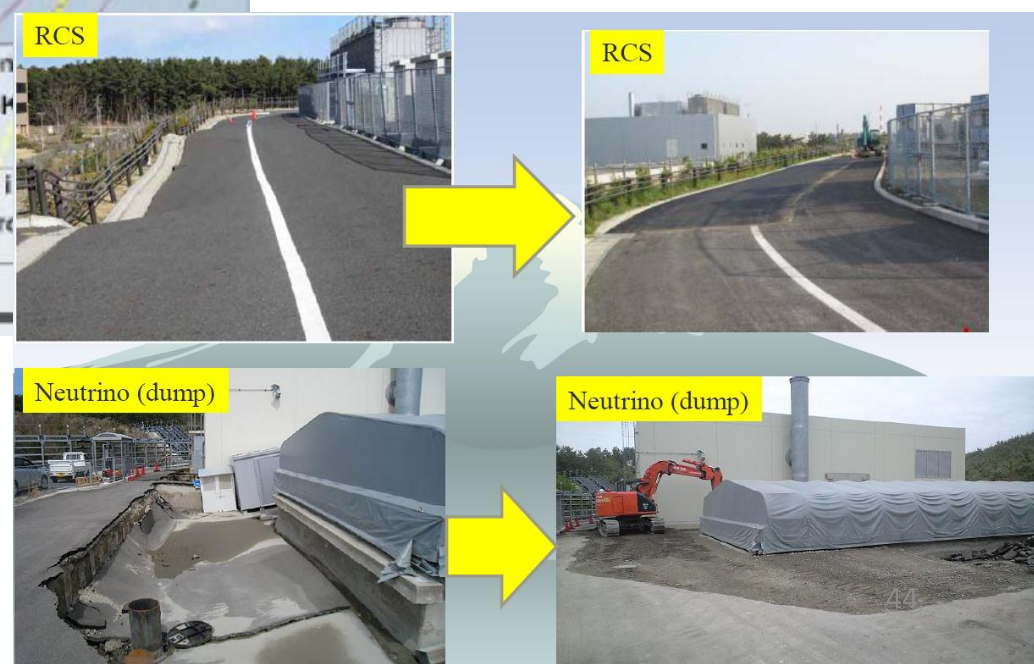
Expected sensitivity



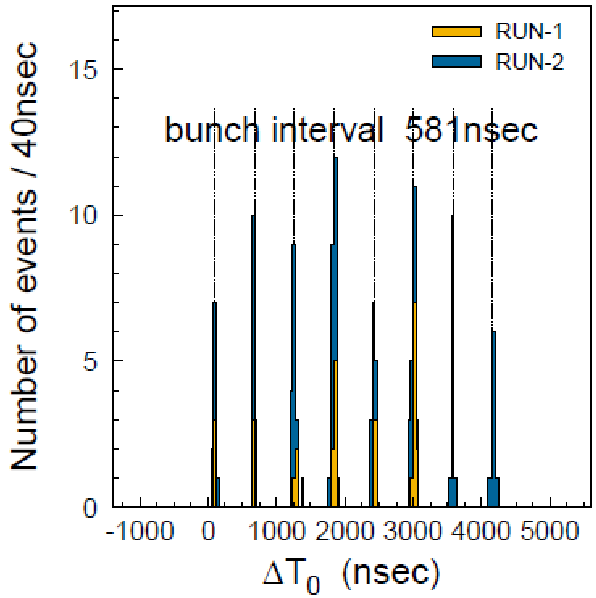
earthquake



Réparations



ν TOF



$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

1) Based on our initial assessment of our capability, at the moment T2K cannot make any definitive statement to verify the Opera measurement of the speed of neutrino (Opera Anomaly).

2) We will assess a possibility to improve our experimental sensitivity for a measurement to cross-check the OPERA anomaly in the future. Such a measurement with an improved system, however, could take a while to achieve.

Spill timing information, synchronized by the Global Positioning System (GPS) with < 150 ns precision, is transferred from J-PARC to SK and triggers the recording of photomultiplier (PMT) hits within 500 μs of the expected neutrino arrival time.