The T2K experiment status

Macaire Michaël

GDR neutrino

LAPP, Annecy-le-vieux

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<u>Outline :</u>

- The T2K experiment setup
- ν_e appearance results
- ν_μ disappearance results
- Future plans

T2K physics goals

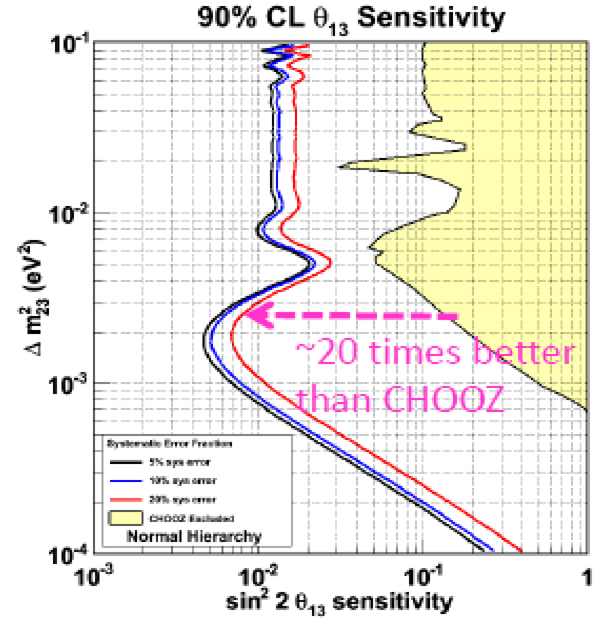
- **Search for $\nu_\mu \rightarrow \nu_e$ oscillations (measurement of θ_{13})**

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

- Expected sensitivity with full T2K proposal statistics (3.75 MW x 10^7 s)

$\sin^2(2\theta_{13}) > 0.008$

- Non-zero θ_{13} is crucial for leptonic CP violation and mass hierarchy measurement in LBL experiments

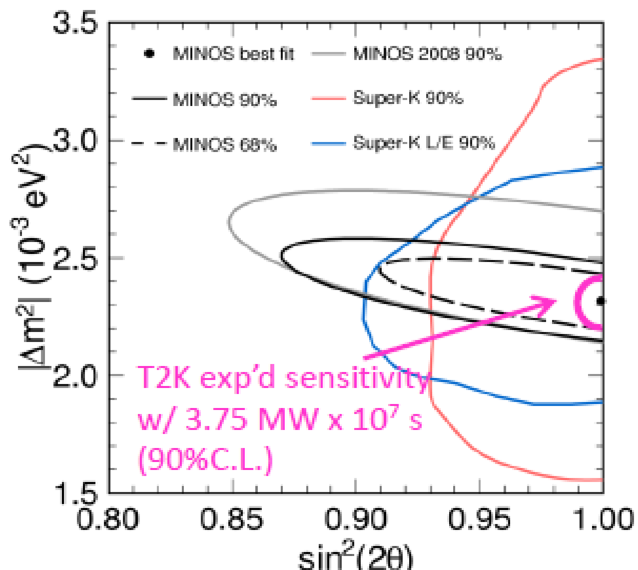


- **Precise measurement of Δm^2_{23} and $\sin^2(2\theta_{23})$ via ν_μ disappearance**

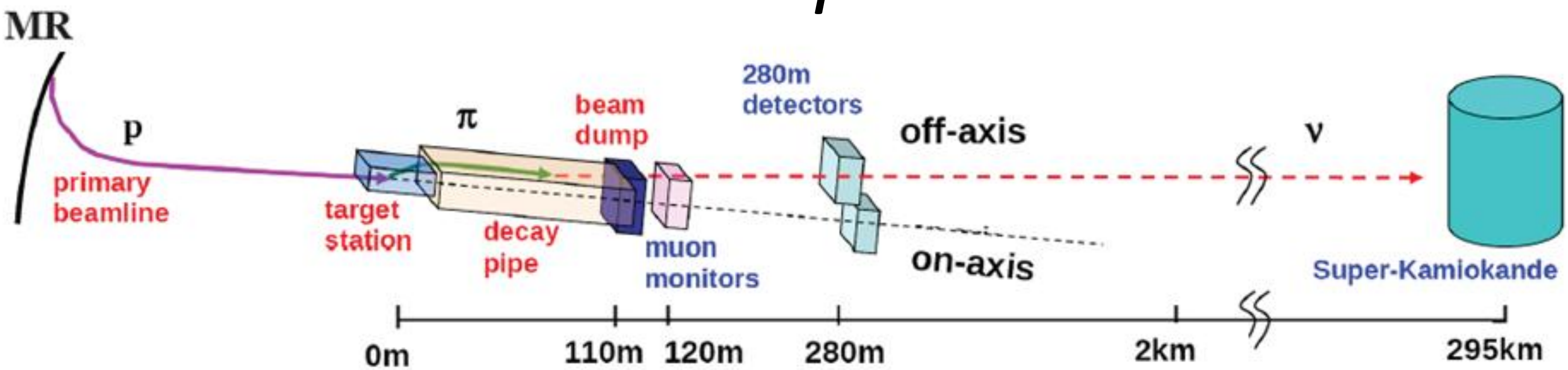
$$P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2_{23}L}{E}\right)$$

- Expected sensitivity with full T2K proposal statistics

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



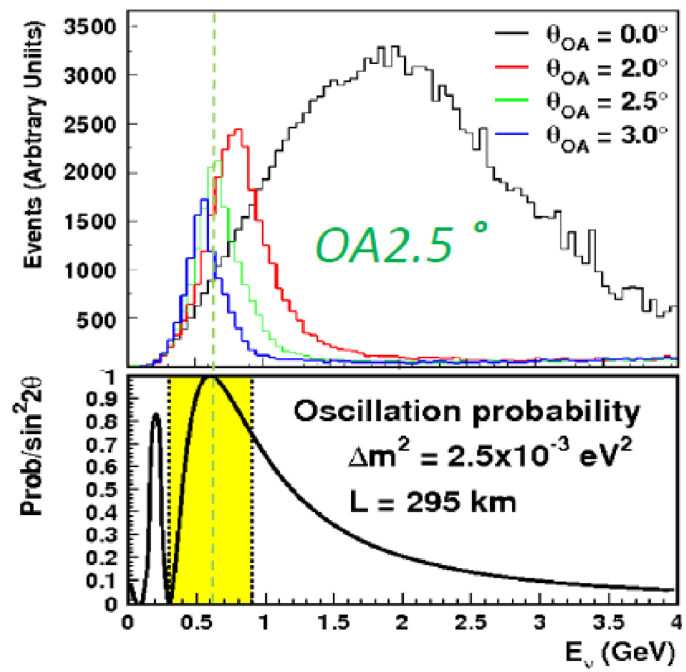
The T2K experiment



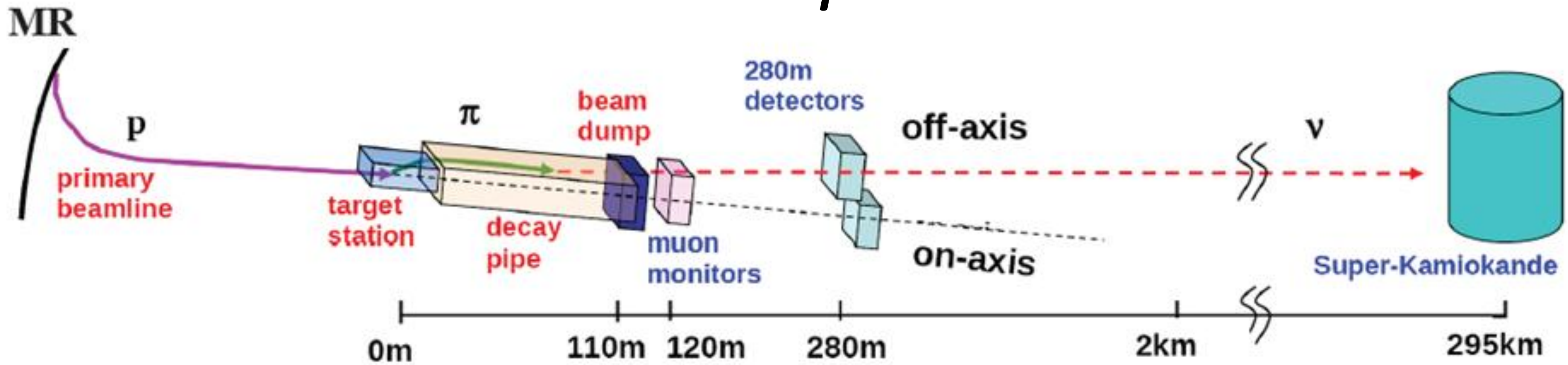
• THE BEAM

- JPARC accelerator delivers 30 GeV protons for collision on carbon target to create conventional ν_μ beam
- First ***OFF-AXIS*** long-baseline experiment
- Narrow spectrum at **~600 MeV** (oscillation maximum)
  - At this energy, interactions are mainly **CCQE** *(clear signal, good approx. of reconstructed E_ν)*
  - High energy background is reduced

Off axis technique



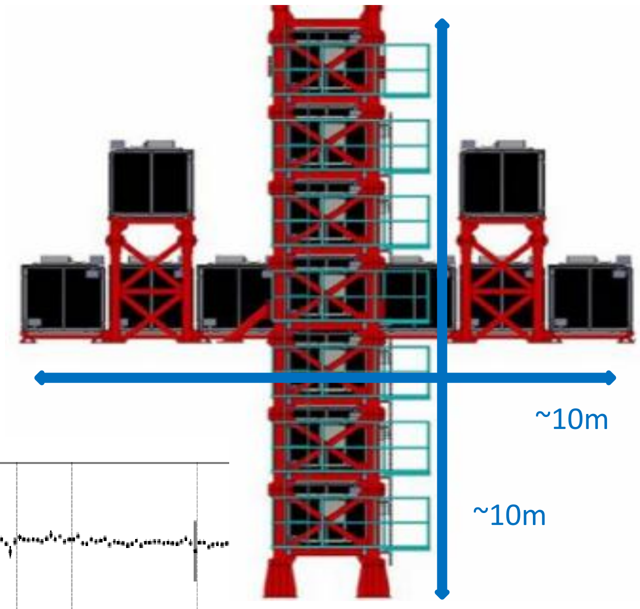
The T2K experiment

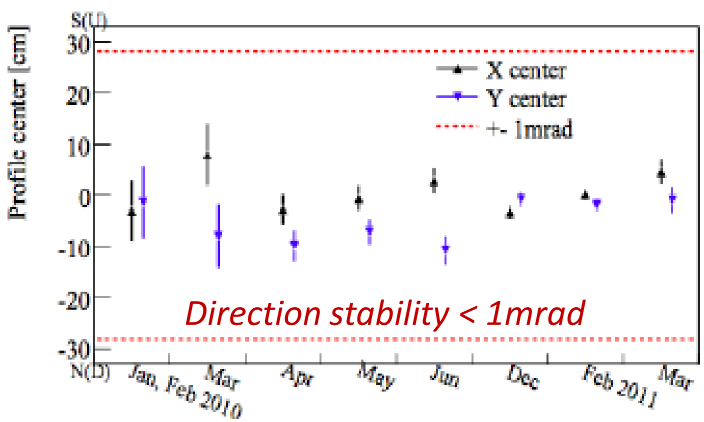


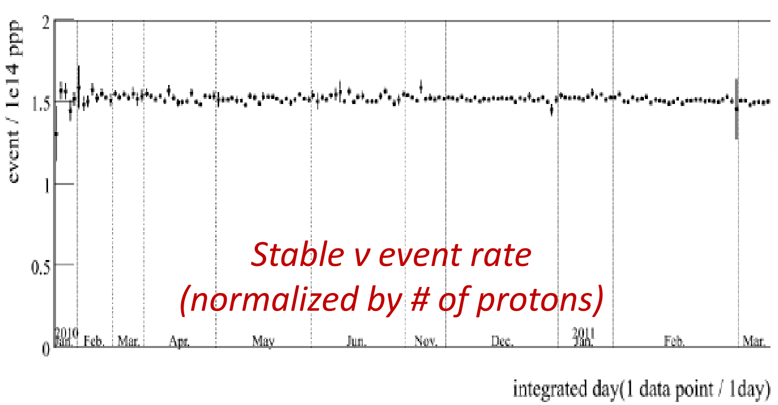
- **THE BEAM**

- **THE NEAR DETECTORS**

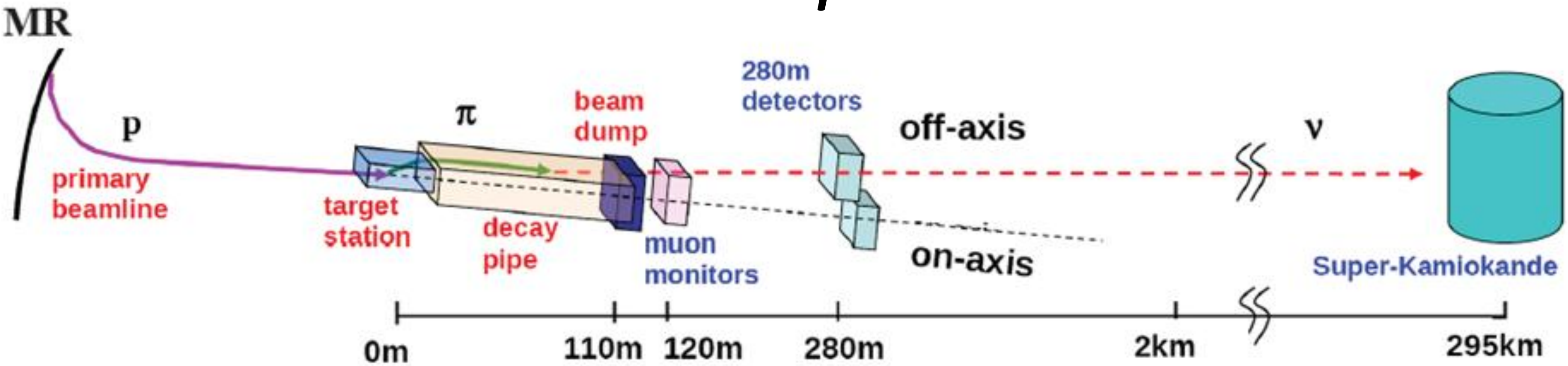
➢ On-Axis **INGRID** :
  - Measure the direction and intensity of the ν_μ beam
  - 16 scintillator/iron modules
  - Requirement for beam stability < 1mrad







The T2K experiment



- ***THE BEAM***

- ***THE NEAR DETECTORS***

➢ On-Axis **INGRID**

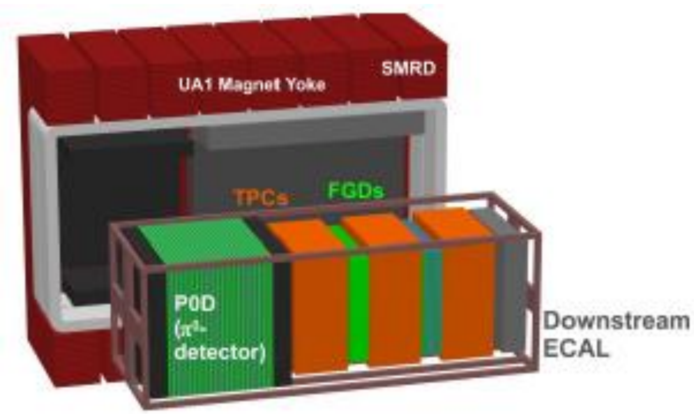
➢ Off-Axis **ND280 :**

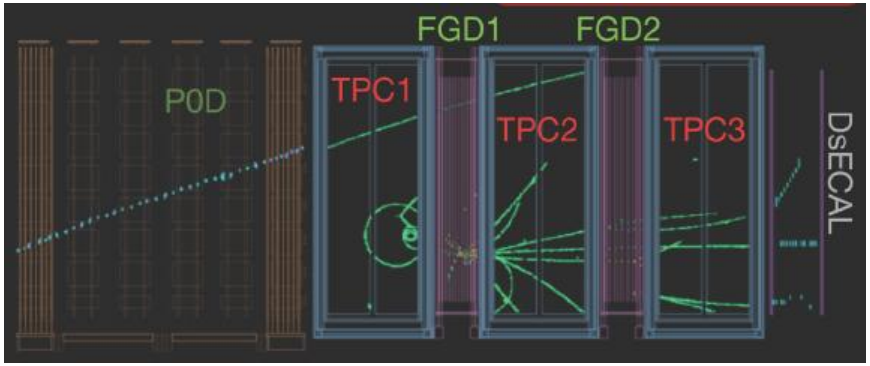
❑ To characterize the beam before oscillation
(flux, spectrum, composition, cross section measurement)

❑ Multiple subdetectors
(P0D+ECal, SMRD, Tracker+ECal)

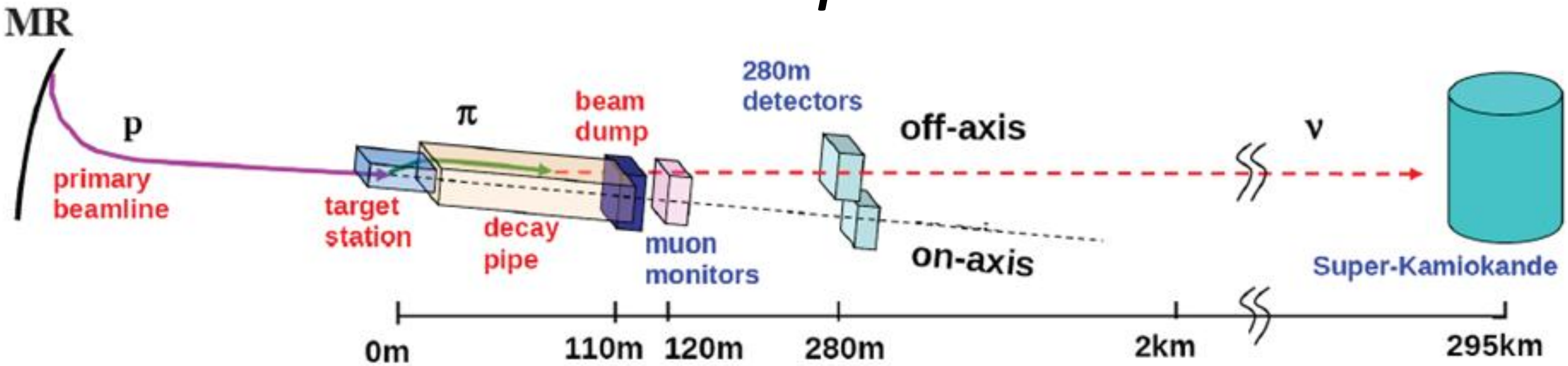
Tracker composed of **2 FGDs** between **3 TPCs** :
provides 1+1 tons of scintillator (+*water*) target and tracking and PID

❑ Subdetectors embedded in UA1 magnet providing a ~0.2 Tesla magnetic field





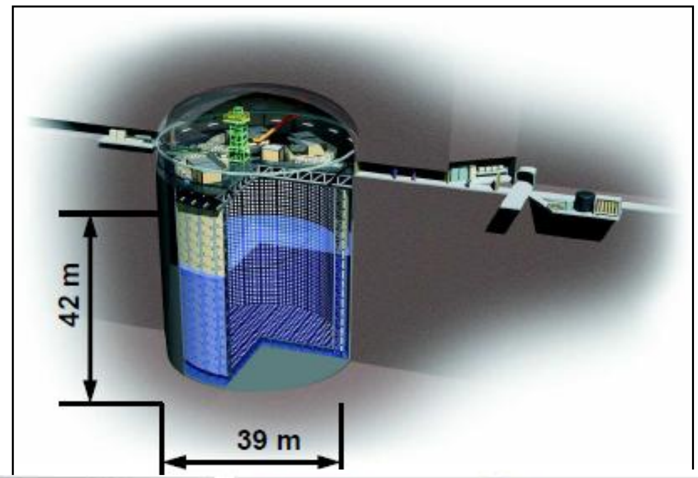
The T2K experiment

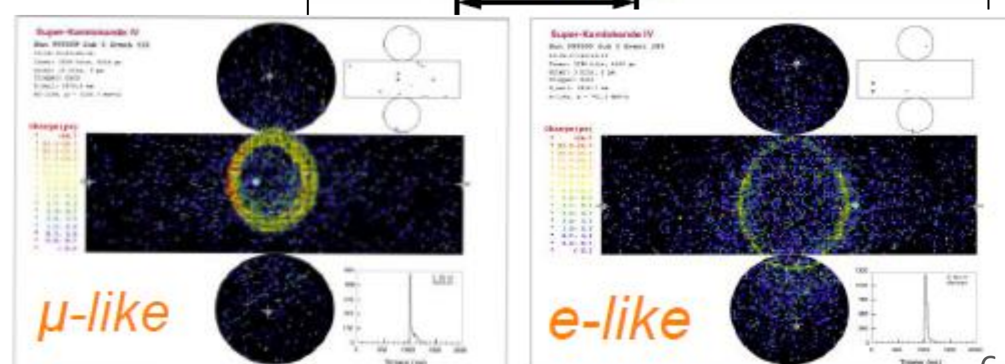


- ***THE BEAM***

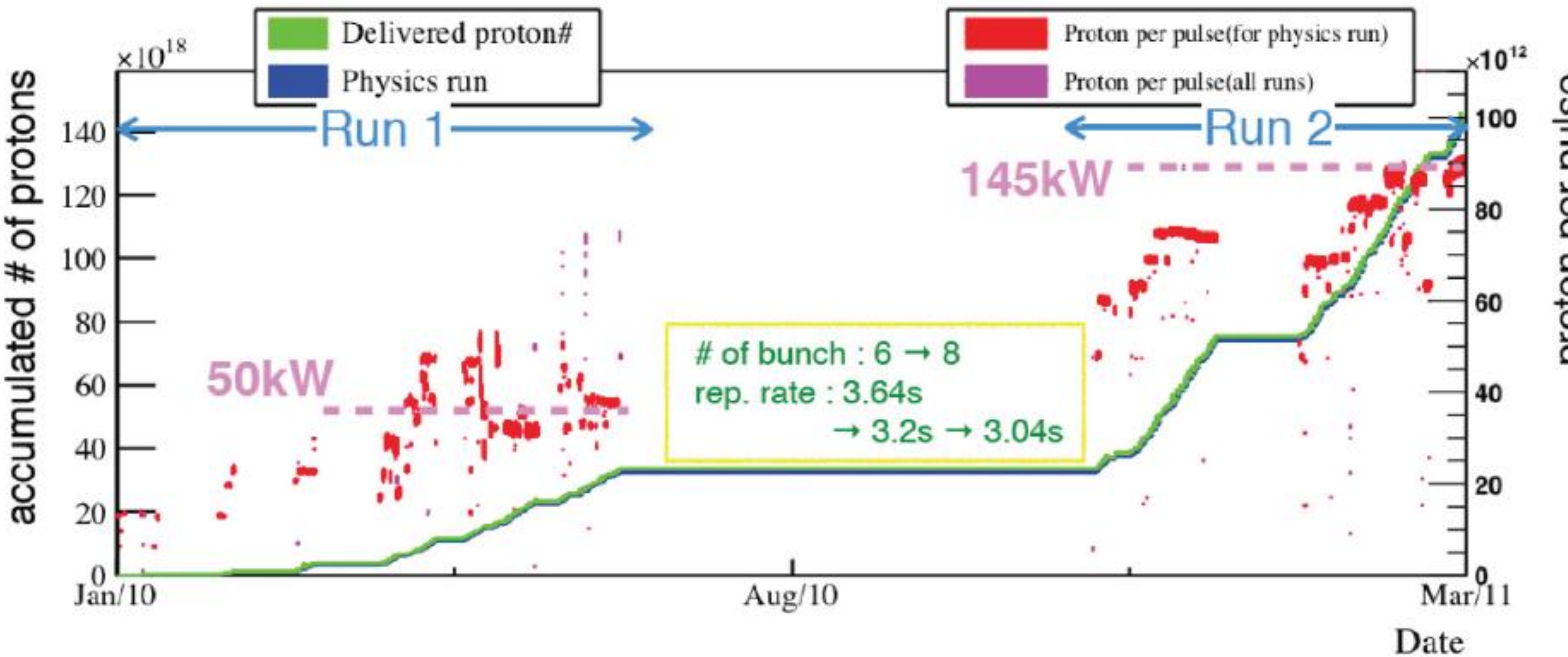
- ***THE NEAR DETECTORS***
  - On-Axis **INGRID**
  - Off-Axis **ND280**

- ***THE FAR DETECTOR***
  - **Super Kamiokande** :
    - 50 kT water Cherenkov detector
    - Excellent e/μ discrimination (mis-id < 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 datasets are used in the analyses

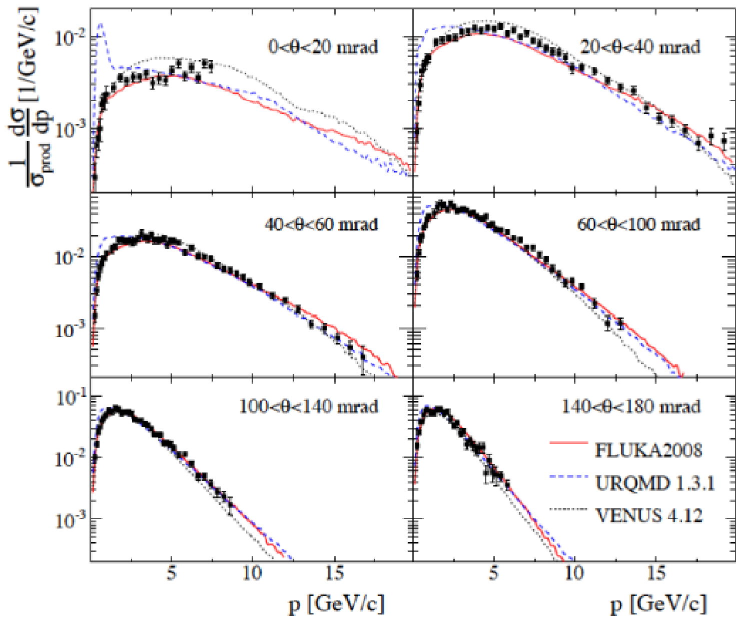
Flux prediction

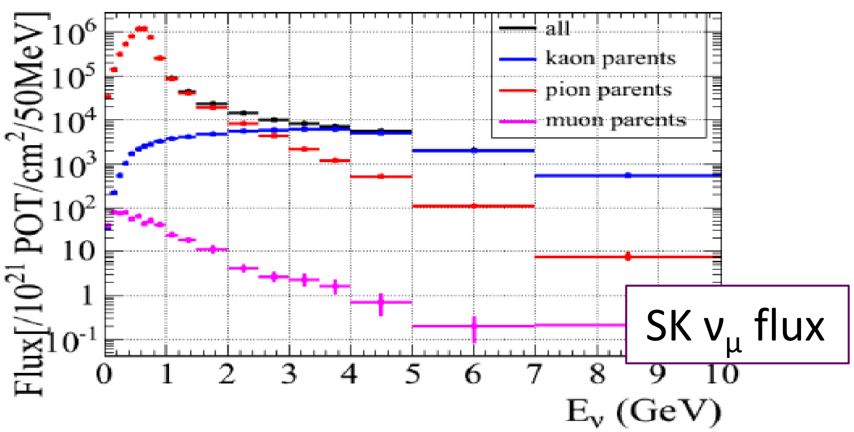
• Beam prediction based on the data of pion production from the ***NA61*** experiment *(CERN)*

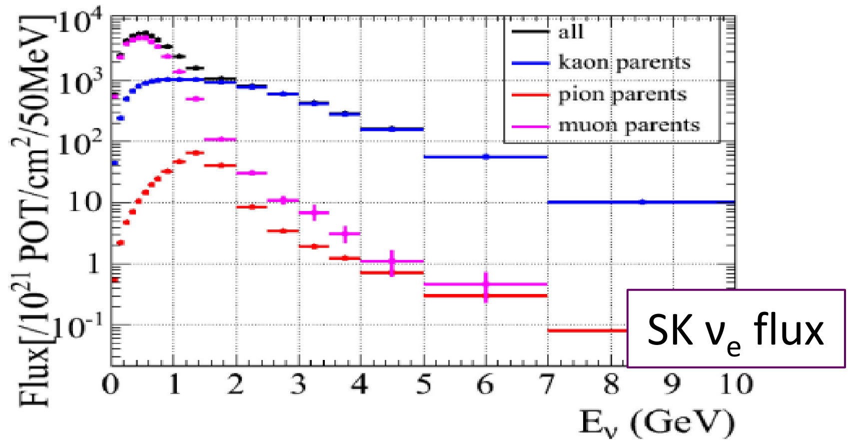
• Systematic uncertainty evaluated in each (p,θ) bin – typically 5-10%

• Kaon production, pions outside the NA61 acceptance, and other target interactions modeled with FLUKA

31 GeV/c protons on carbon target; 2007 data







• Near detector measurement indicates ν_e intrinsic contamination < 2% at 90% CL

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

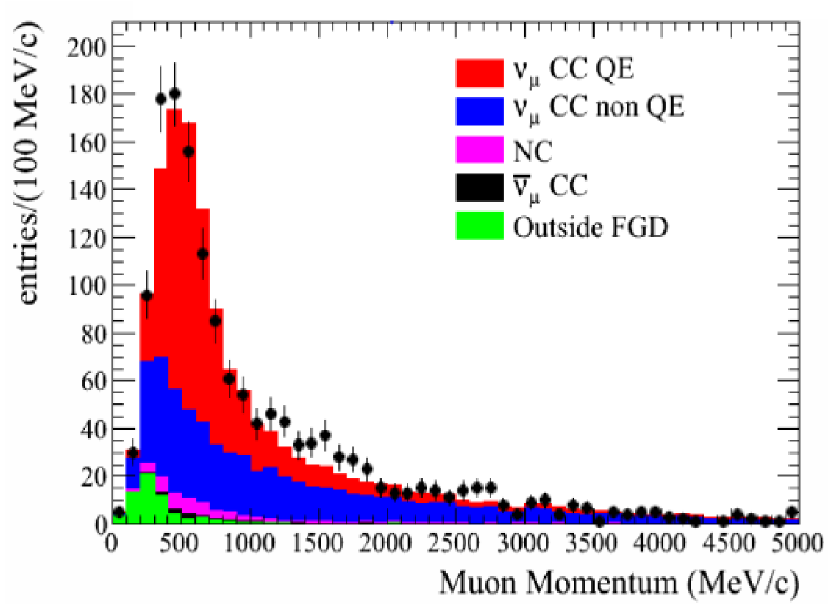
- Calculated based on flux prediction
- Depends on the cross sections predictions, detector efficiencies, and given oscillation parameters

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



ν_e appearance

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	$\nu_\mu \rightarrow \nu_e$
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**

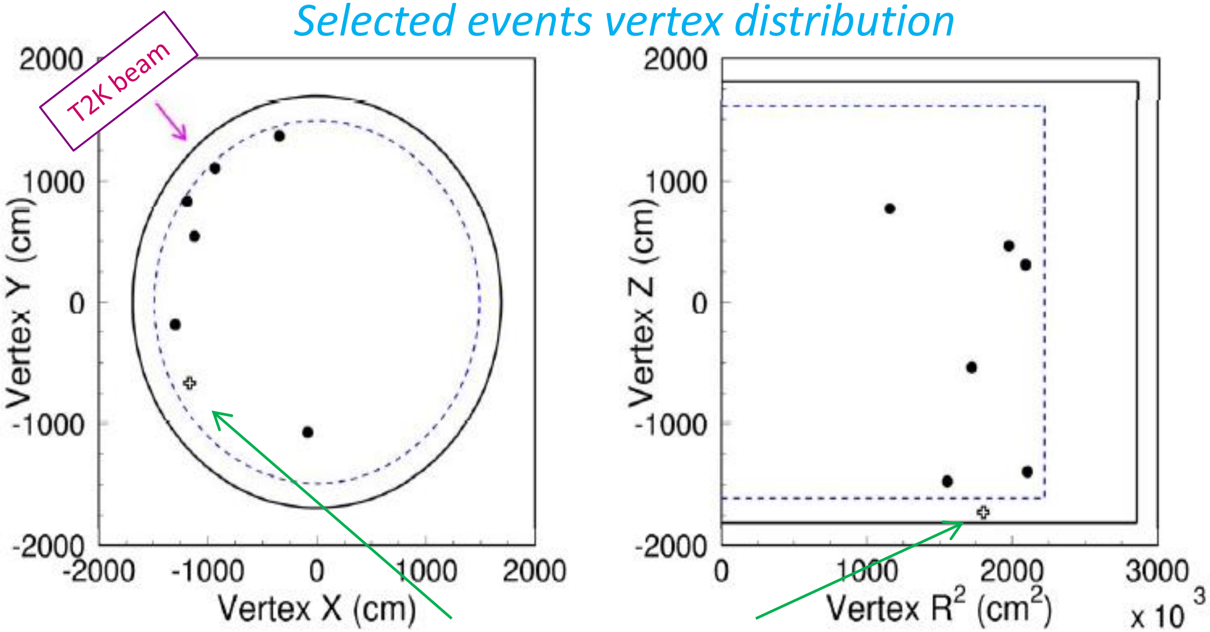
6 candidate events pass all cuts

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

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

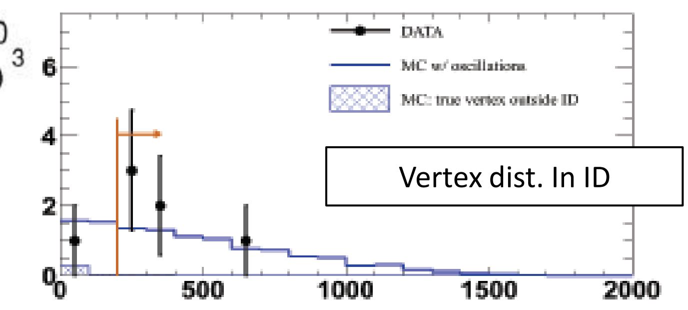
ν_e event distribution

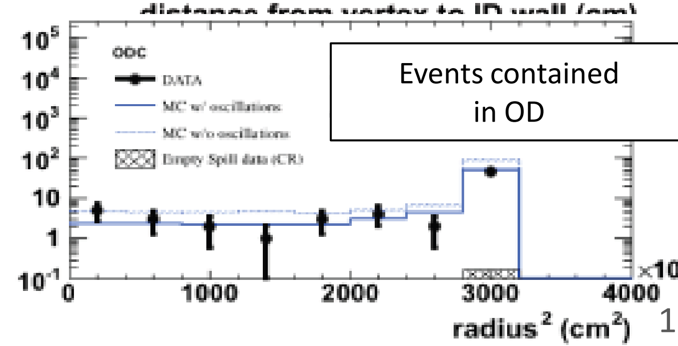
Selected events vertex distribution



Event outside FV

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



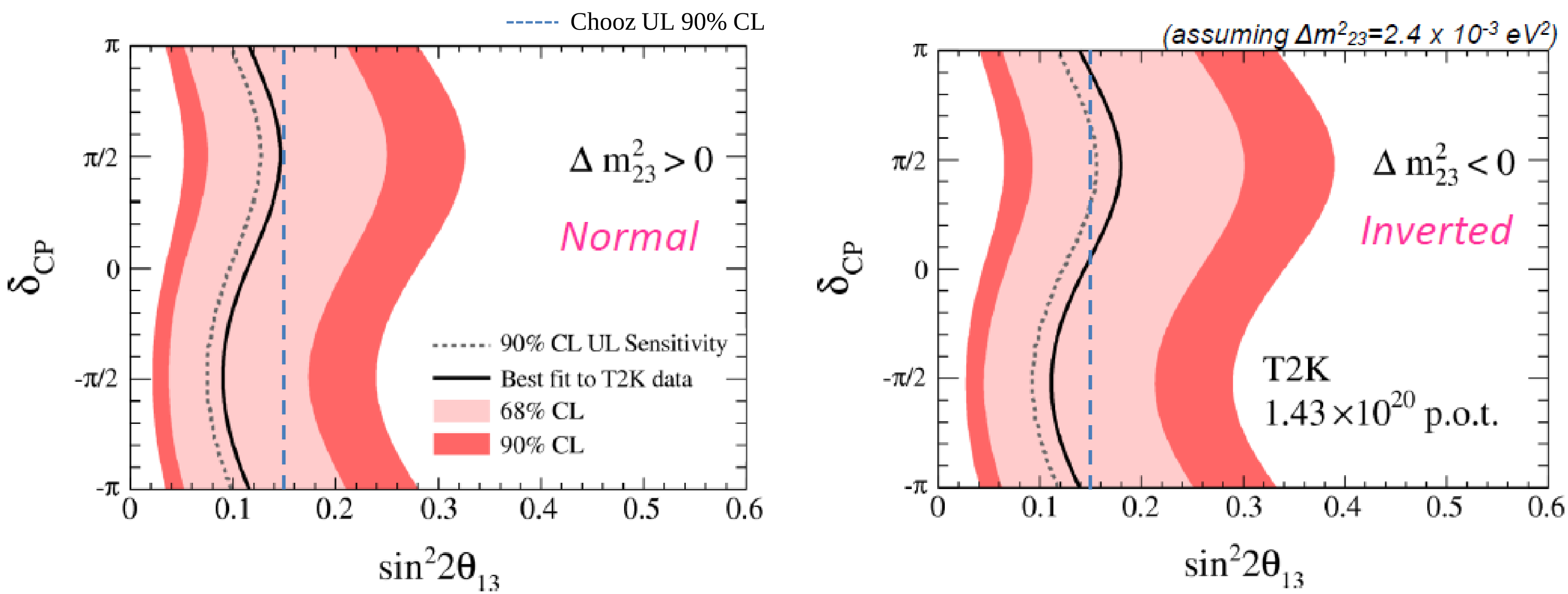


Additionnal checks were performed

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

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

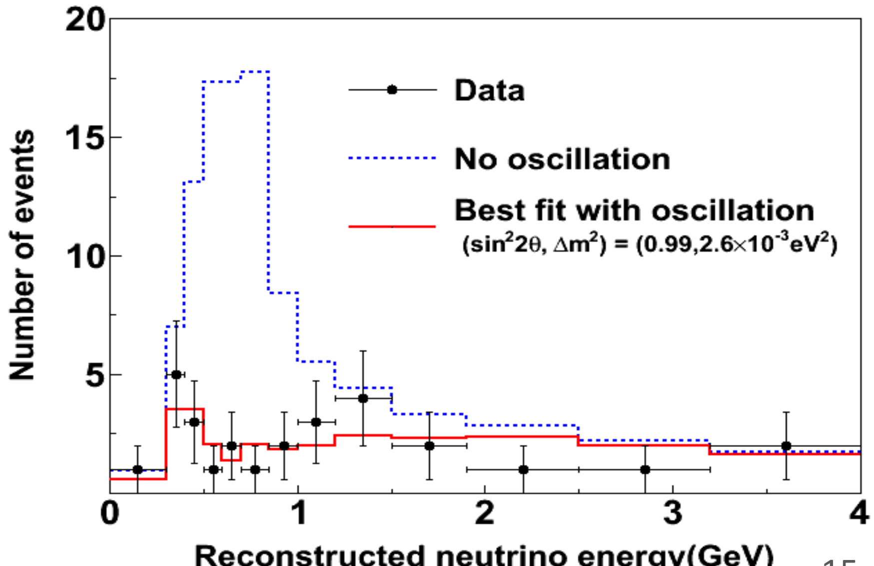
	Data	MC w/o oscillation				
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC
Interaction in FV	-	**243.0**	**96.5**	72.3	3.2	71.0
FCFV	**88**	**165.8**	**88.9**	55.5	3.0	18.3
Single-ring	**41**	**120.5**	**86.3**	26.6	1.9	5.7
μ-like	**33**	**111.9**	**85.2**	24.7	< 0.1	1.9
P_μ > 200 MeV/c	**33**	**111.3**	**84.9**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

31 candidate events pass all cuts

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

expected without oscillation

No oscillation excluded at 4.5σ



ν_μ oscillation fit

- 2 independent methods were used for the fit (in a 2-flavour oscillation assumption)
- Feldman-Cousins method was used to produce the confidence intervals

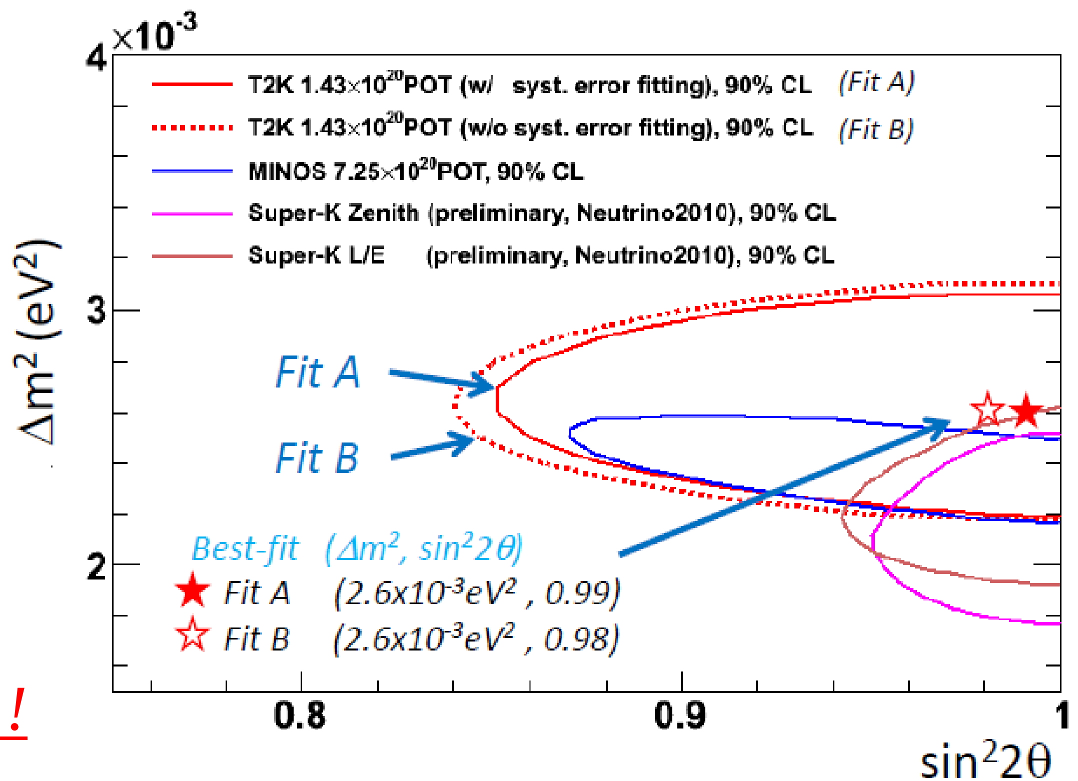
Fit A : Unbinned maximum likelihood
(w/ systematic error fitting)
$$L = L_{norm} \times L_{shape} \times L_{syst}$$

Fit B : Binned likelihood ratio
(w/o systematic error fitting)
$$\chi^2 = 2\Sigma_{bins} [n_i^{obs} . \ln(n_i^{obs}/n_i^{exp}) + n_i^{exp} - n_i^{obs}]$$

90% C.L. allowed

	Δm^2_{23} (eV^2)	$\sin^2(2\theta_{23})$
Fit A	$2.1 - 3.1 \times 10^{-3}$	> 0.85
Fit B	$2.1 - 3.2 \times 10^{-3}$	> 0.84

The results are consistent with SK/MINOS results



Paper in preparation !

T2K near future

✓ The March 11th earthquake didn't cause strong damages to the accelerator and the detectors

✓ Accelerator status :
- Magnets and monitors are re-aligned
- Goal to restart at 100 kW

✓ The near detector is under maintenance at the moment
- All subdetectors have been tested successfully

✓ SK was not damaged by the earthquake

Recommissionning phase

Accelerator recommissioning will start in the middle of December

↓

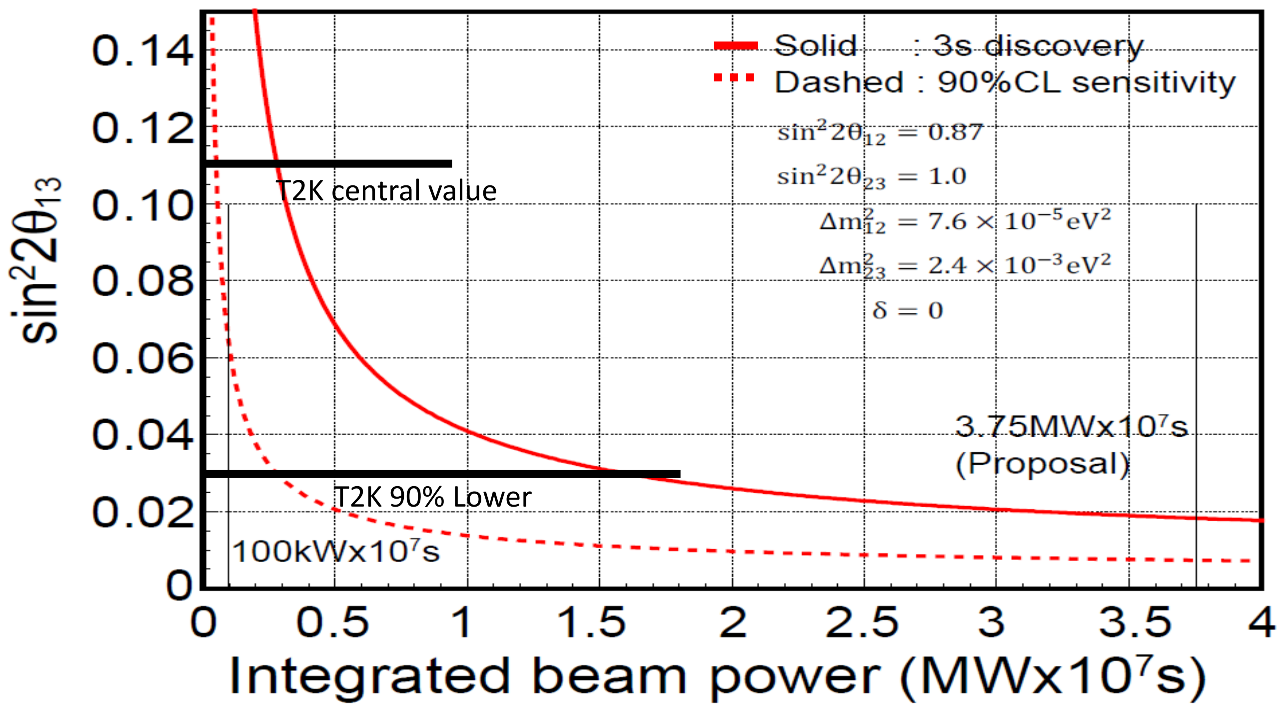
ND recommissioning will start in the beginning of January 2012
Restart of physics data taking soon after

Expected sensitivity

The main goal remains to establish a non-zero θ_{13} !

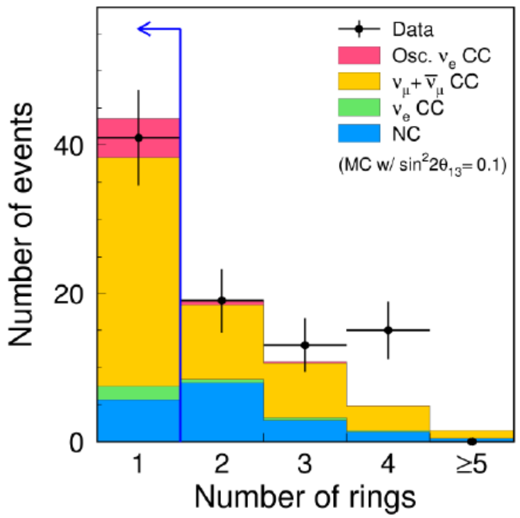
Milestone :
10^{21} POT (~500kW.1e7sec) by summer 2013 (before long shutdown)

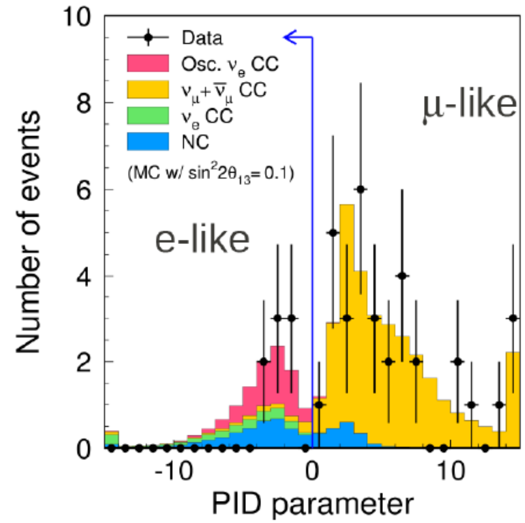
With this statistics, exclusion of θ_{13} = 0 at 5σ at the best fit value $\sin^2(2\theta_{13})$=0.11

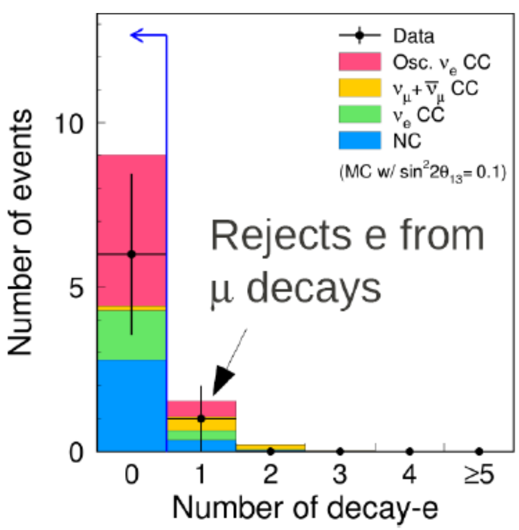


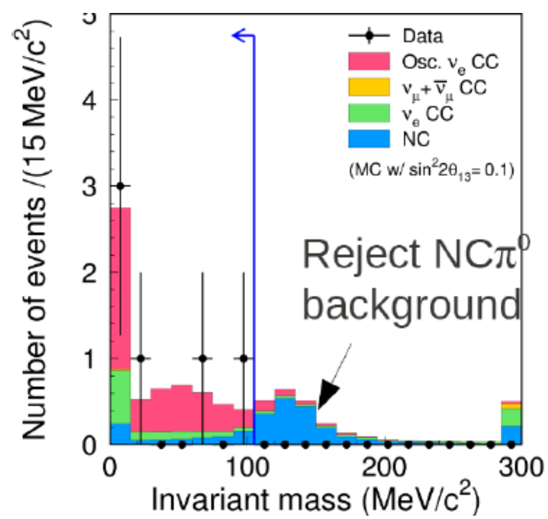
Backups

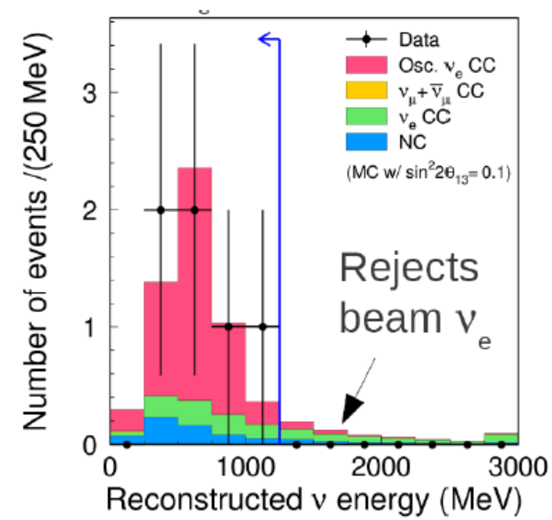
SK ν_e cuts


Data
Osc. νe CC
νμ+ν̄μ CC
νe CC
NC
(MC w/ sin²2θ13= 0.1)
Number of events
Number of rings
0
20
40
1
2
3
4
≥5


Data
Osc. νe CC
νμ+ν̄μ CC
νe CC
NC
(MC w/ sin²2θ13= 0.1)
μ-like
e-like
Number of events
PID parameter
0
2
4
6
8
10
-10
0
10

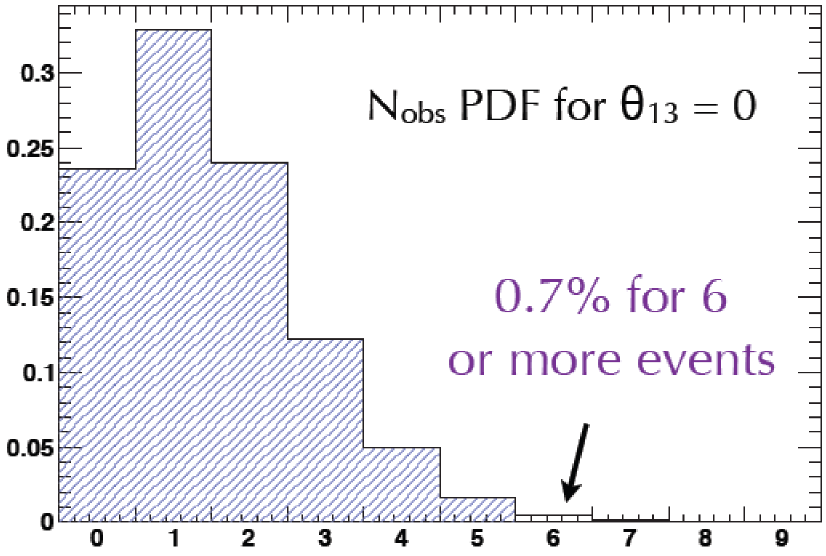

Data
Osc. νe CC
νμ+ν̄μ CC
νe CC
NC
(MC w/ sin²2θ13= 0.1)
Rejects e from μ decays
Number of events
Number of decay-e
0
5
10
0
1
2
3
4
≥5


Data
Osc. νe CC
νμ+ν̄μ CC
νe CC
NC
(MC w/ sin²2θ13= 0.1)
Reject NCπ0 background
Number of events /(15 MeV/c²)
Invariant mass (MeV/c²)
0
1
2
3
4
0
100
200
300


Data
Osc. νe CC
νμ+ν̄μ CC
νe CC
NC
(MC w/ sin²2θ13= 0.1)
Rejects beam νe
Number of events /(250 MeV)
Reconstructed ν energy (MeV)
0
1
2
3
0
1000
2000
3000

6 events - What it means for θ_{13}

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

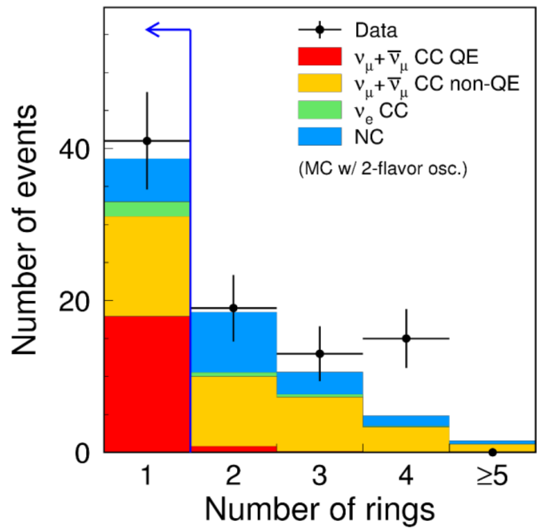


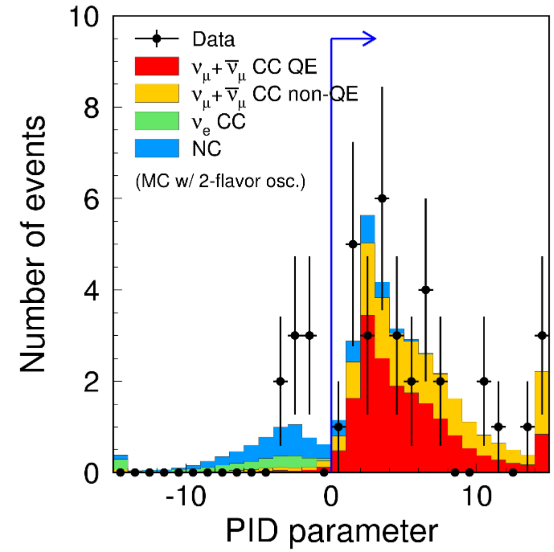
p-value of 0.7%

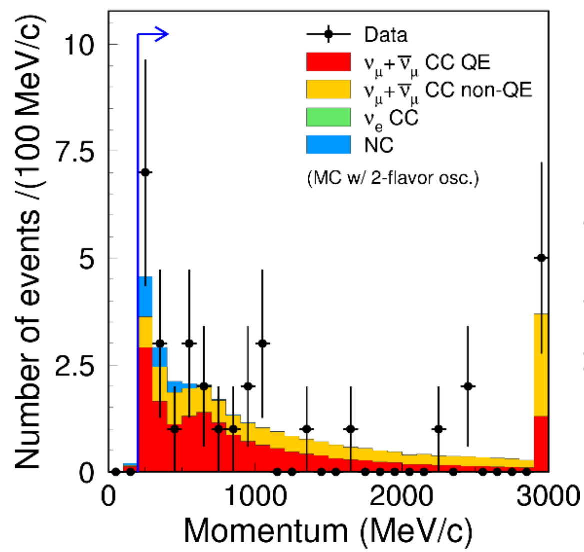
2.5σ exclusion

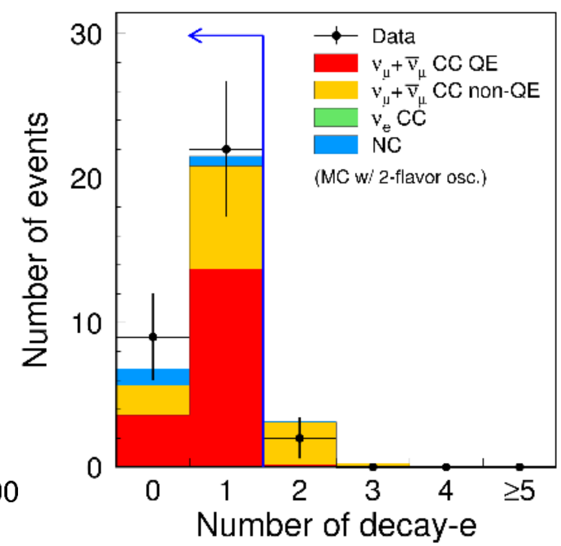
SK ν_μ cuts

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









Beam uncertainty

Summary of Beam flux uncertainties on N^{exp}_{SK} for $\sin^2 2\theta_{13}=0$

$$N^{exp}_{SK} = N^{Data}_{ND} \times \frac{N^{MC}_{SK}}{N^{MC}_{ND}}$$

Source	N^{MC}_{ND}	N^{MC}_{SK}	$\frac{N^{MC}_{SK}}{N^{MC}_{ND}}$	
Pion production	5.7%	5.8%	2.5%	Hadron production & interaction
Kaon production	10.0%	11.0%	7.6%	
Nucleon production	5.9%	6.2%	1.4%	
Production x-section	7.7%	9.4%	0.8%	
Proton beam position	2.2%	0.0%	2.2%	
Beam dir. measurement	2.7%	2.9%	0.7%	
Target alignment	0.3%	0.0%	0.2%	
Horn alignment	0.6%	0.7%	0.1%	
Horn abs. current	0.5%	1.0%	0.3%	
Total	15.4%	16.1%	8.5%	

- NA61 Kaon data will be included and precision is expected to be much better

Neutrino interaction uncertainties

ν int. cross section uncertainty
on N^{exp}_{SK} for $\sin^2 2\theta_{13}=0$

Source	syst. error on N_{SK}^{exp}
CC QE shape	3.1%
CC 1π	2.2%
CC Coherentπ	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherentπ	2.3%
NC Other	2.3%
$\sigma(\nu_e)$	3.4%
FSI	10.1%
Total	14.0%

NSK uncertainty

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

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

NuE

Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Dominated by hadron production uncertainties

ND uncertainties (tracking and efficiency)

Dominated by FSI and NCπ0 x-sec uncertainties

Dominated by ring counting, PID and invariant mass cut uncertainties

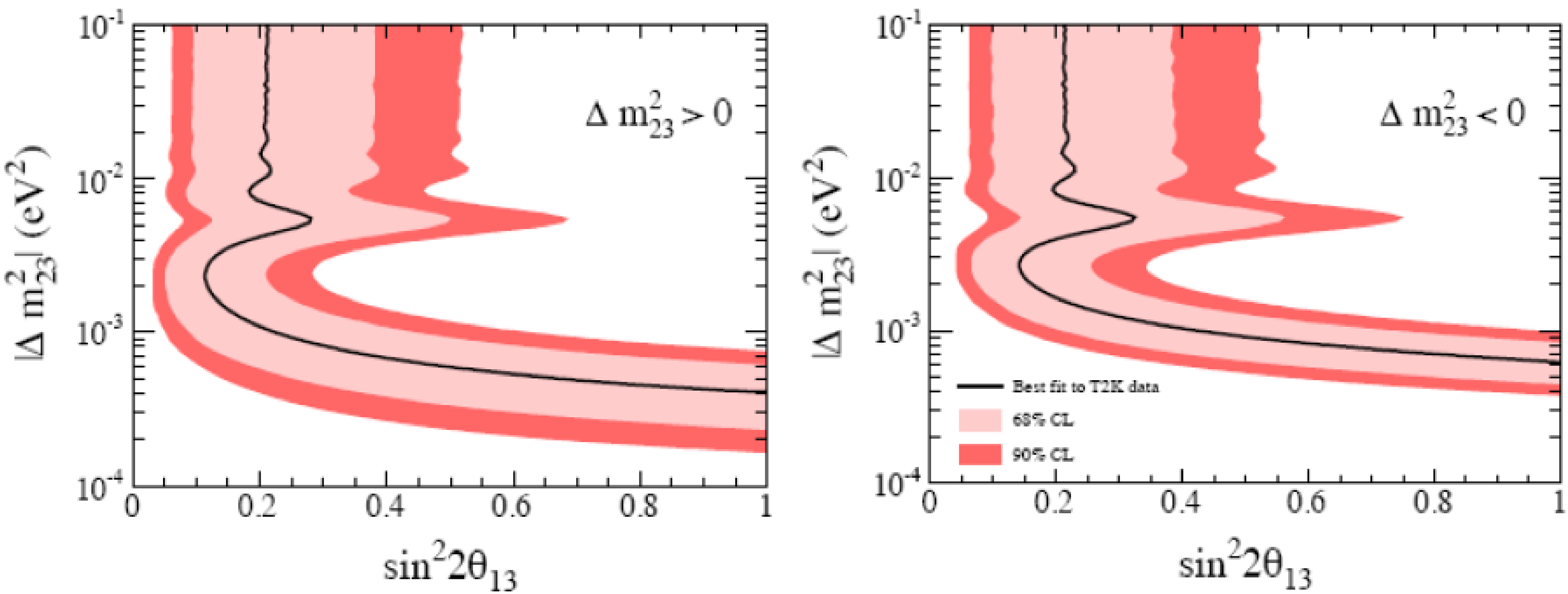
NuMu

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

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

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



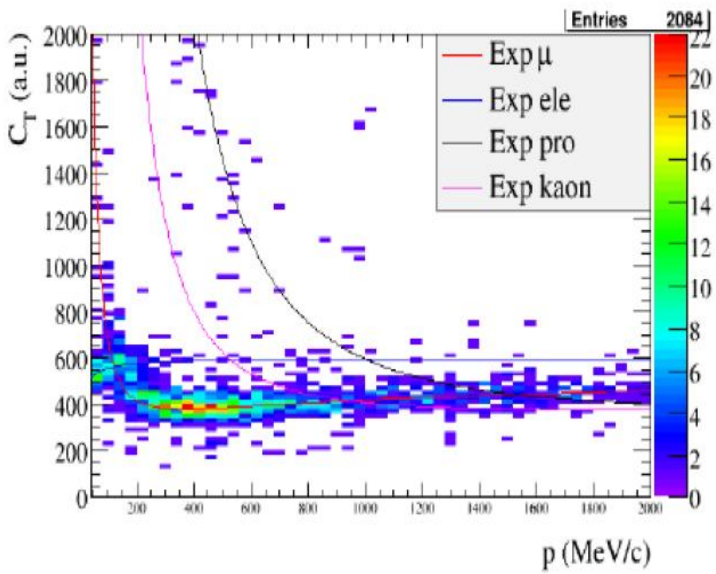
Feldman-Cousins method was used

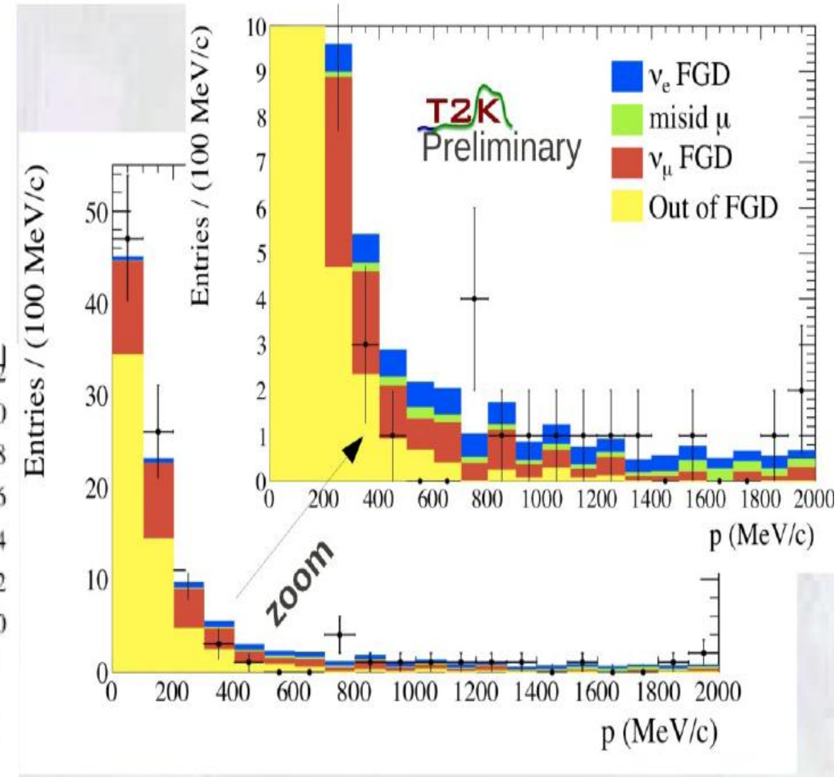
ν_e at the near detector

$R_{\nu e/\nu\mu} = (1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}))\%$

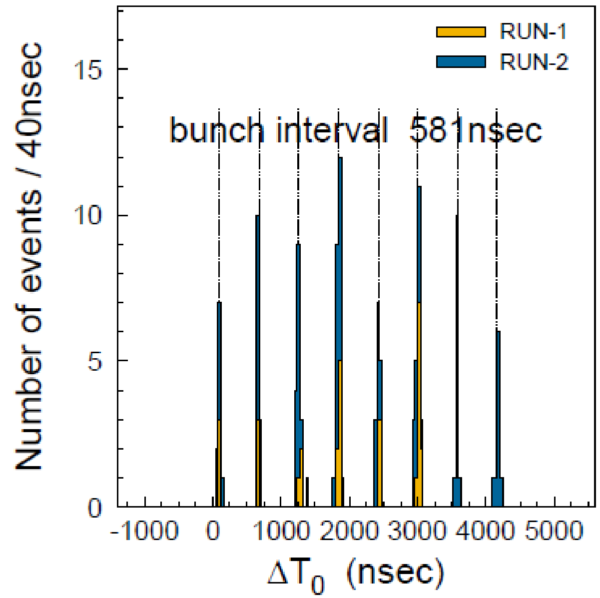
$< 2.0\%$ @ 90% C.L.

Main tool:
TPC PID:





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.