Premiers résultats d'oscillation des neutrinos avec T2K

Marco Zito

21 mars 2011

- Situation à JPARC
- L'expérience T2K
- La prise de données
- Premiers résultats
- Perspectives

Message from KEK

Japan experienced very severe earthquake on March 11th 2011 at 14:46 JST. J-PARC facility suffered damages for some extent. There are no reports of casualties and all staff, graduate students, and foreign visitors have been located and as of evening Sunday March 13th all T2K members have been evacuated from Tokai area.

Fortunately enough, the Tsunami tidal wave did not hit J-PARC. We will start the investigation of the facilities. We will update the announcement as we learn the detail of the entire damage.

Our present priority is to restore life-supporting infrastructure such as electricity, water supply and gas at J-PARC. It may take some time, but we promise the full recovery of the J-PARC accelerator and T2K experiment in the near future.

I thank you for the messages of solidarity and sympathy.

Director of the Institute of Particle and Nuclear Studies, KEK
Koichiro Nishikawa

Spokesperson of the T2K experiment
Takashi Kobayashi

Le groupe T2K à l'IRFU

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- SPP permanents : O. Besida, S. Emery, E. Mazzucato, G. Vasseur, M. Zito
- SPP Etudiants F. Blaszczyk, C. Ferchichi, M. Macaire
- Experts : P. Colas, I. Giomataris

T2K : le projet de Jacques et François

K2K-> T2K-> Violation de CP

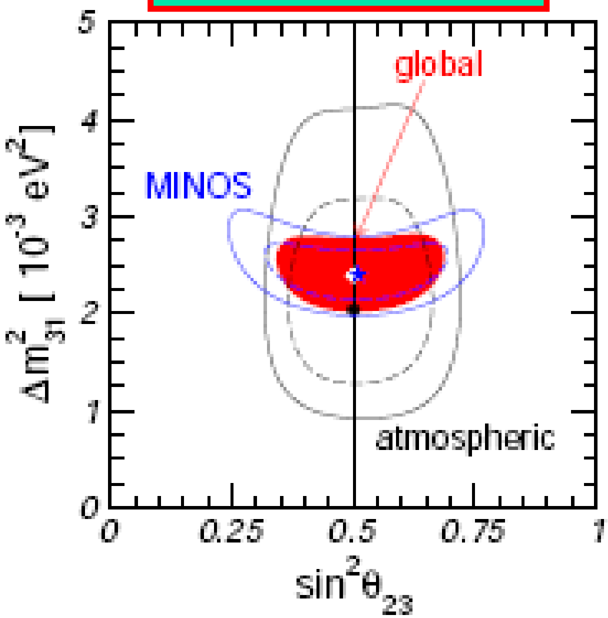
Current status of neutrino mass and mixings

"Atmospheric" "Solar"

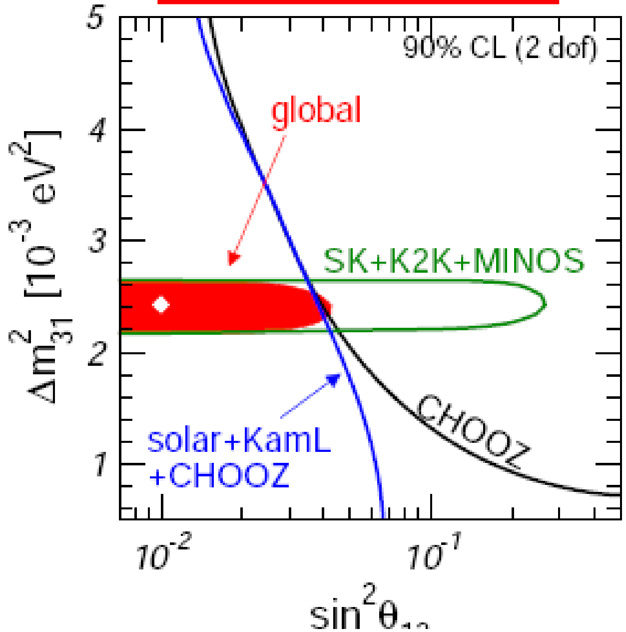
$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3 mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$)
1 CPV phase (δ)
2 (indep.) mass differences ($\Delta m^2_{ij}=m_i^2-m_j^2$)
Additional phases if Majorana neutrinos

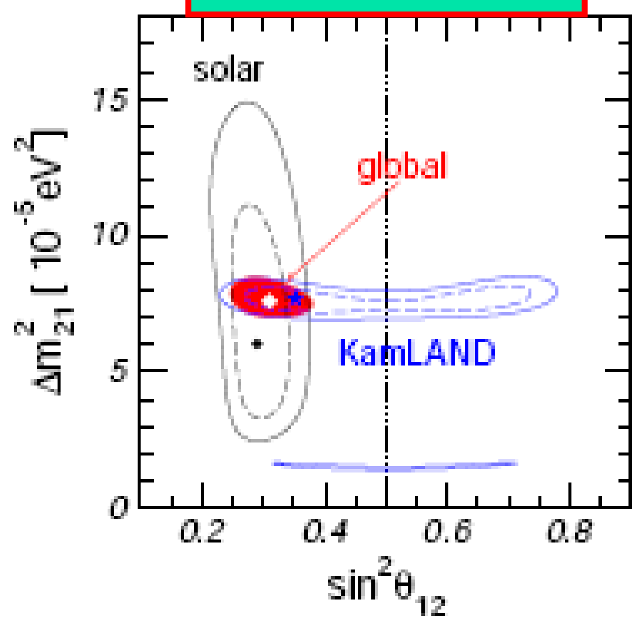
$\theta_{23}, \Delta m_{32}^2$



$\theta_{13}, \Delta m_{31}^2$



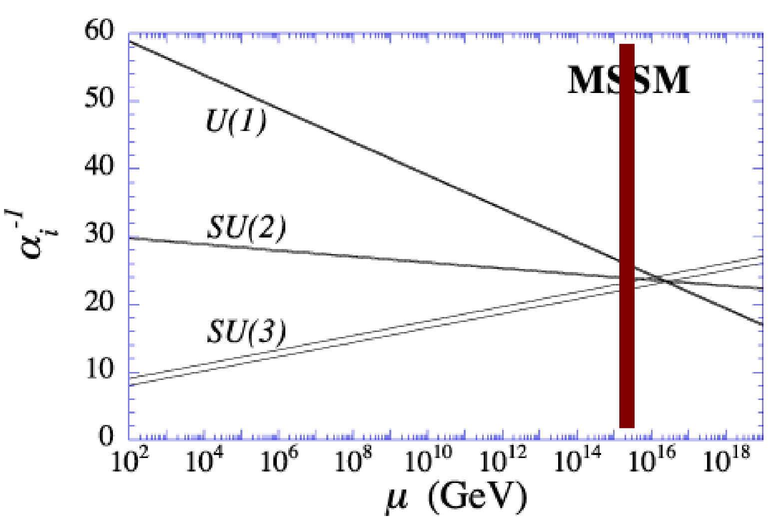
$\theta_{12}, \Delta m_{21}^2$

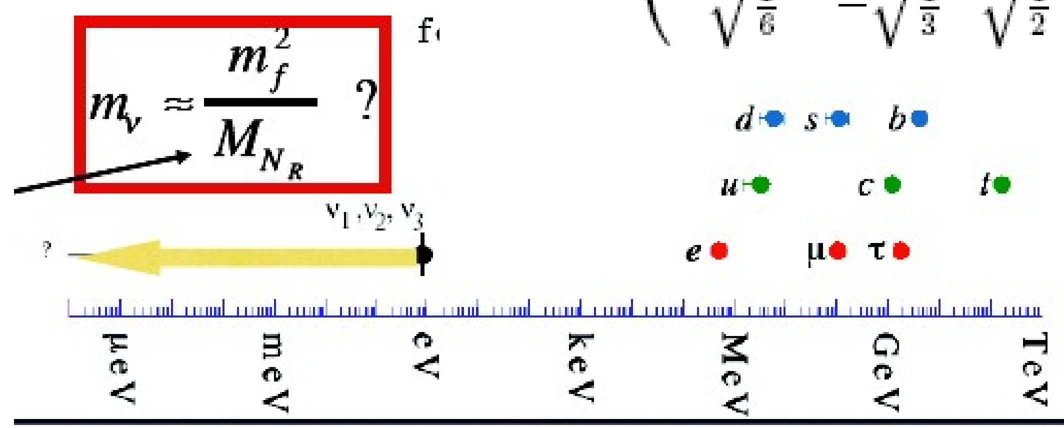


Neutrino masses and new physics

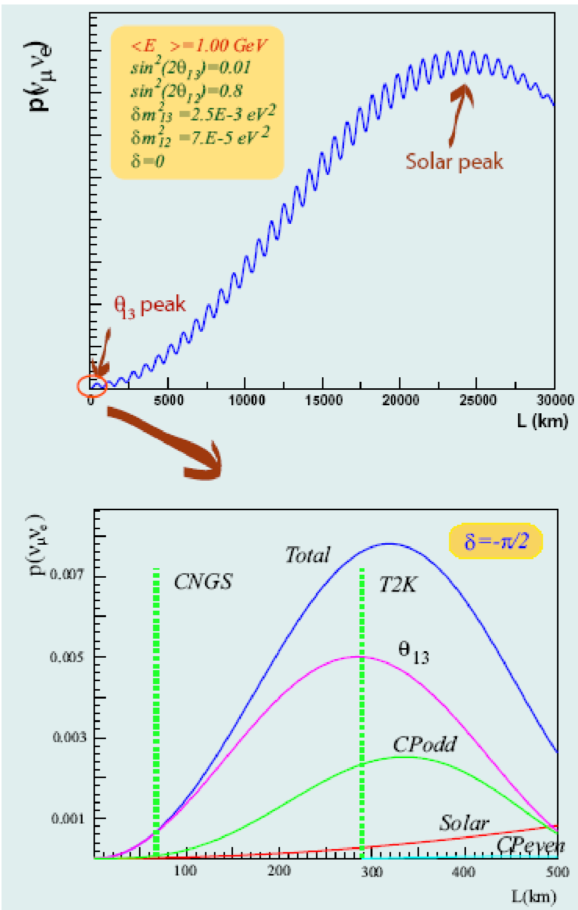
- Non vanishing neutrino masses : clear indication of physics beyond the Standard Model
- Goal: Discovery of CP violation. Supporting evidence for leptogenesis (why matter antimatter asymmetry ?)
- Is θ23 mixing maximal ? Is θ13 different from zero ? Is there leptonic CP violation ? Normal or inverted hierarchy ? Dirac or Majorana ? → 4/5 questions can be answered by ν oscillation physics

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$





ν_μ to ν_e oscillations



$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\,\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\,\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

$$P(\nu_\mu\to\nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23} L}{4E_\nu}$$

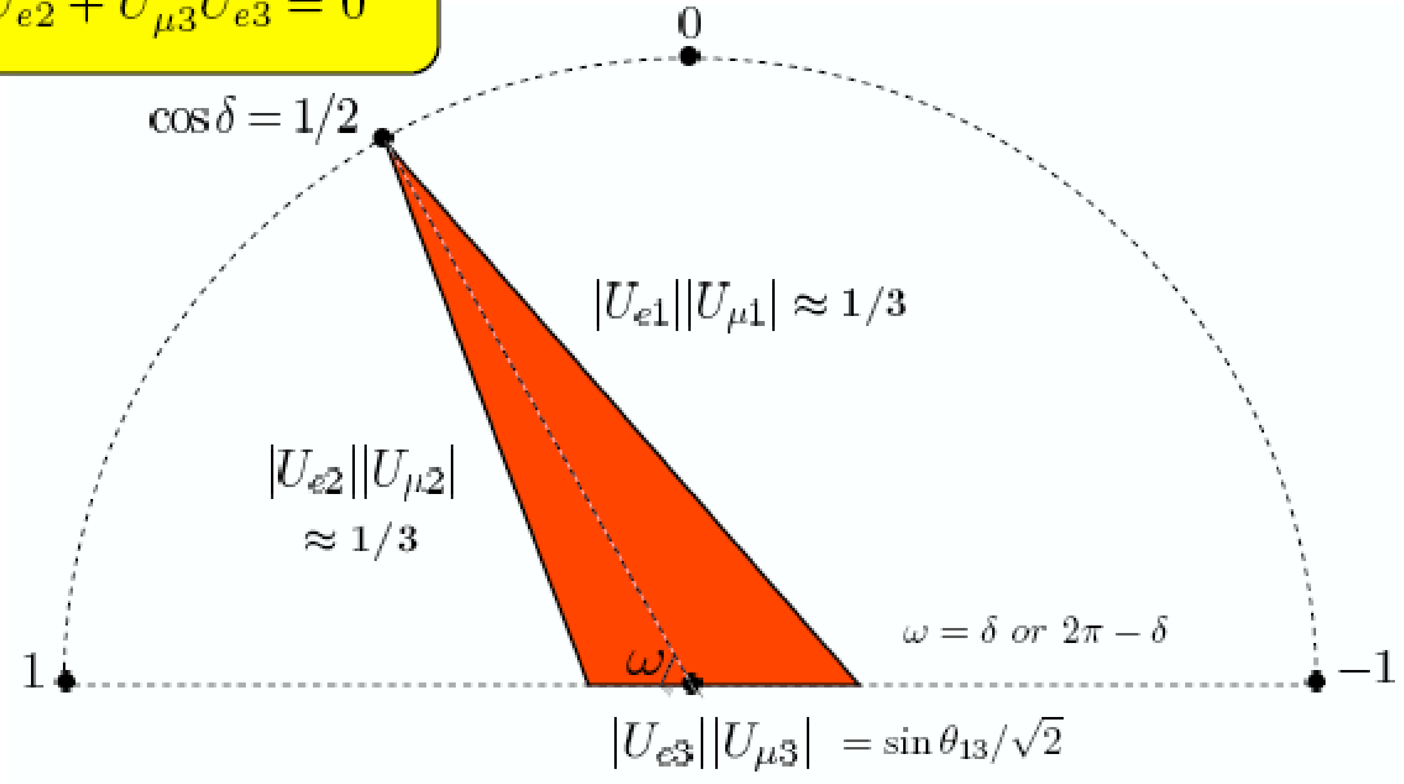
$$P(\nu_\mu\to\nu_\mu) \approx 1-\sin^2 2\theta_{23}\sin^2\frac{\Delta m^2_{23} L}{4E_\nu}$$

M. Mezzetto, Taup 05, Zaragoza, 13 september 2005, 2

L=300 km, E= 600 MeV

Unitarity Triangle:

$$U_{\mu 1}^* U_{e1} + U_{\mu 2}^* U_{e2} + U_{\mu 3}^* U_{e3} = 0$$



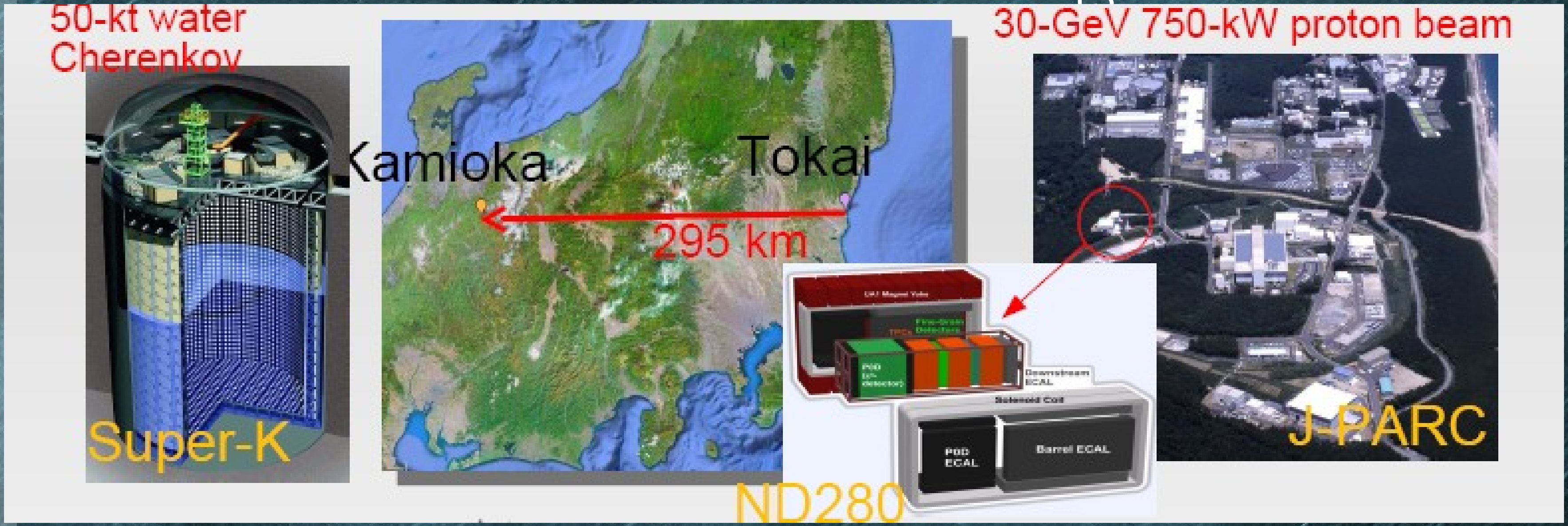
$$|J| = 2 \times Area$$

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta$$

L'expérience T2K

T2K: Tokai to Kamioka experiment

First experiment dedicated to θ_{13} measurement

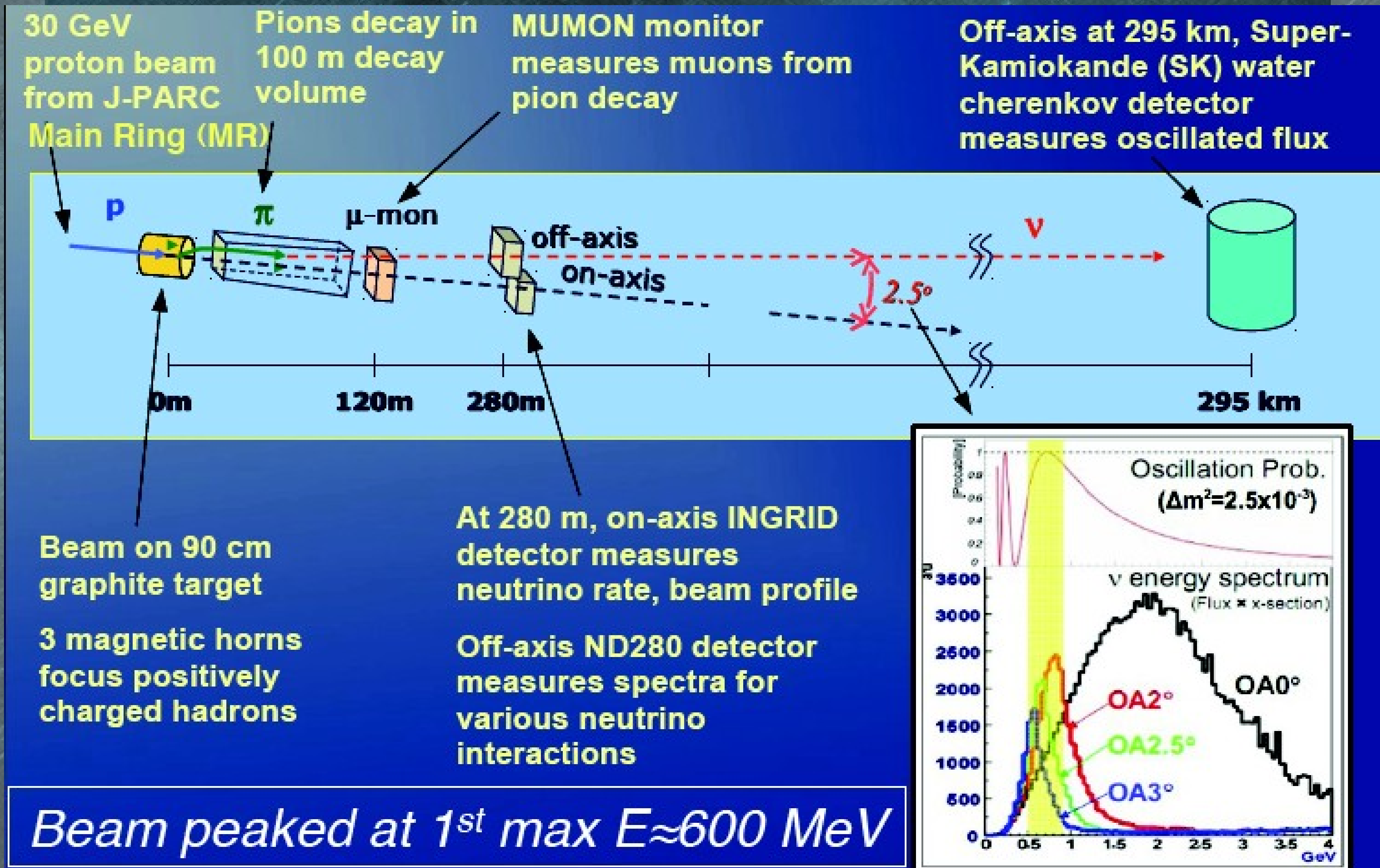


High intensity ν_μ beam from JPARC to SuperKamiokande

Discover ν_e appearance->determine θ_{13}

Precision measurement of ν_μ disappearance -> measure Δm^2_{23} and θ_{23}

T2K: scheme of the experiment



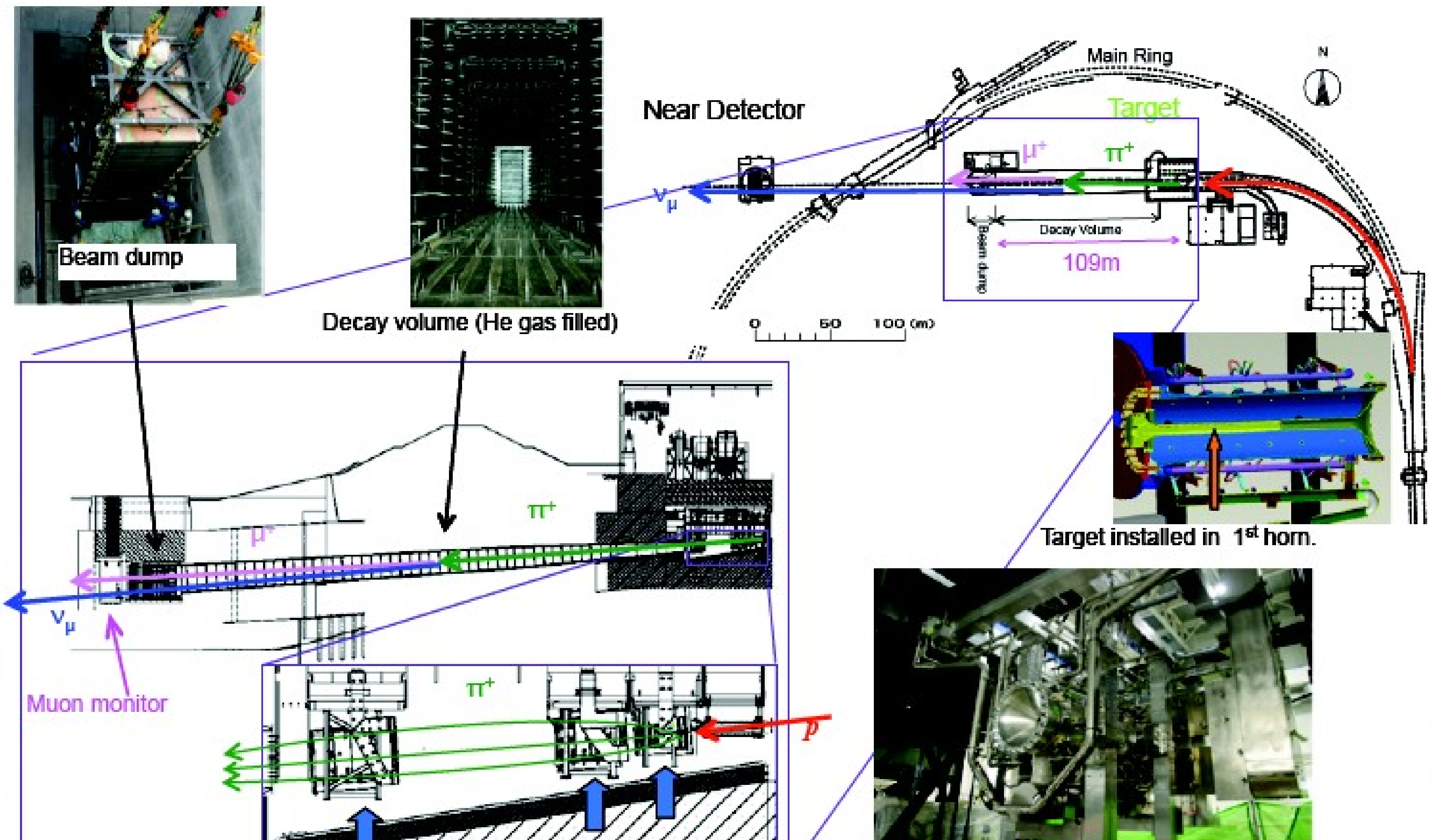
Dates

- JPARC: construction/commissioning 2001-2009
- ND280: construction 2005-2009
- 3 TPC installées : décembre 2009
- 1er neutrino à SK: février 2010
- Run de physique (2010a): janv-juin 2010
- Run de physique 2: nov 2010-juin 2011

Rôle de l'Irfu/SPP

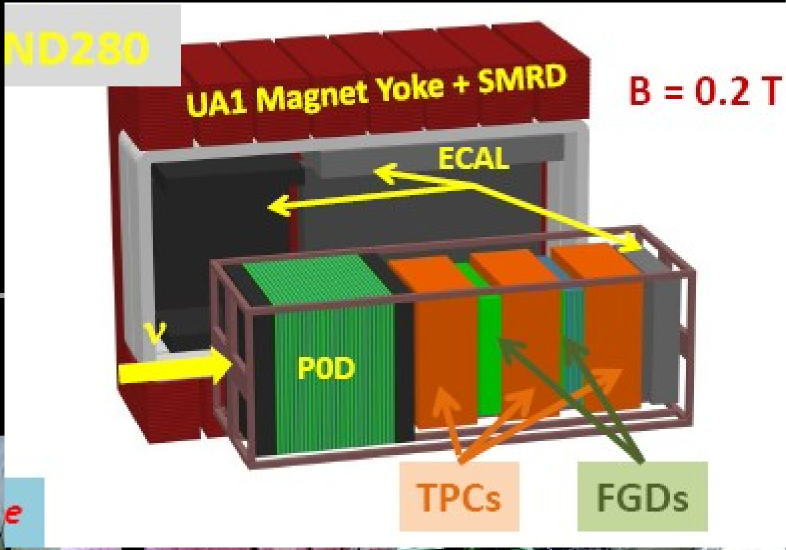
- Design de la TPC
- TPC tests au CERN 2005 et 2006
- TPC tests à TRIUMF 2008-2009
- Installation à JPARC
- Simulation de la TPC
- Mesure de l'ionisation (PID)
- Analyses des données

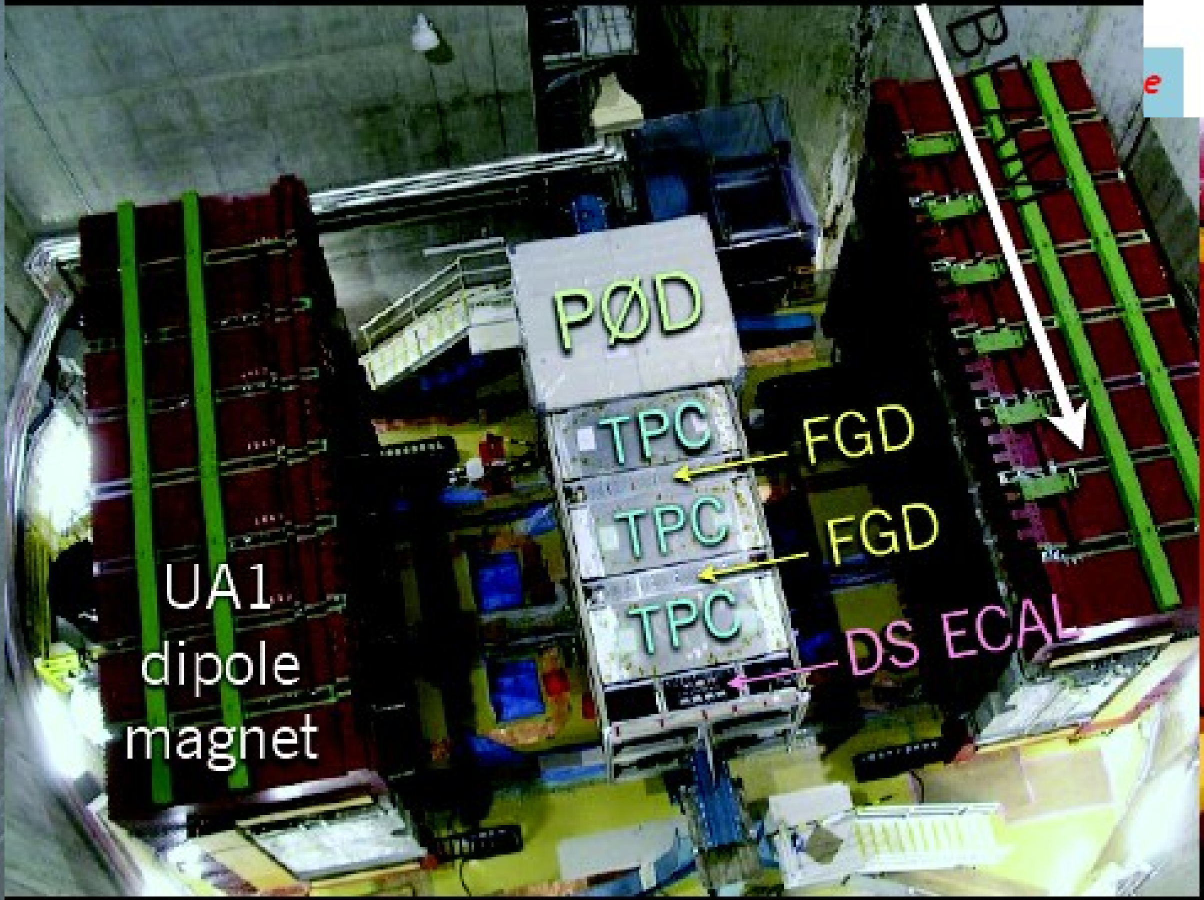
J-PARC neutrino beamline overview



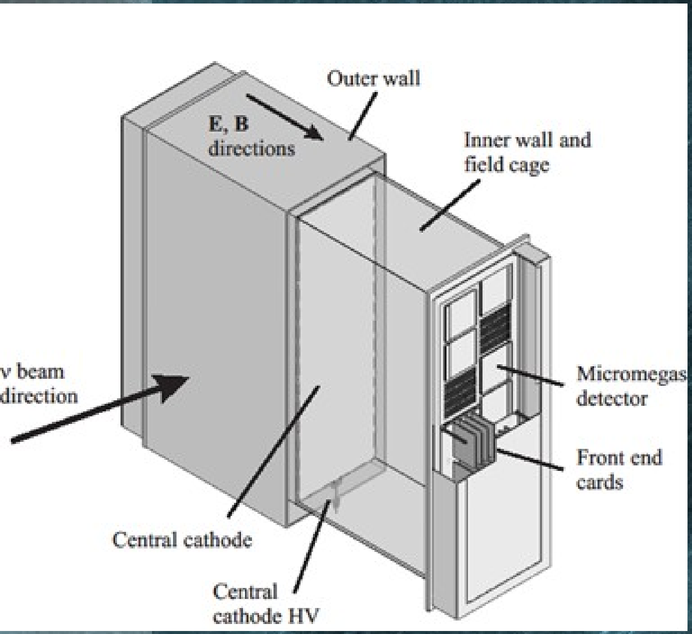
Pions are focused by
3 electromagnetic Horns.

Off-axis Near Detector

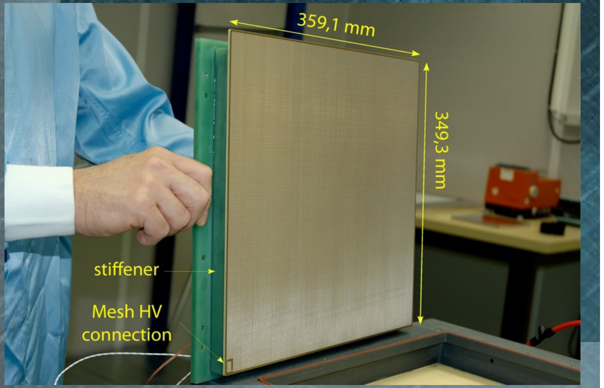


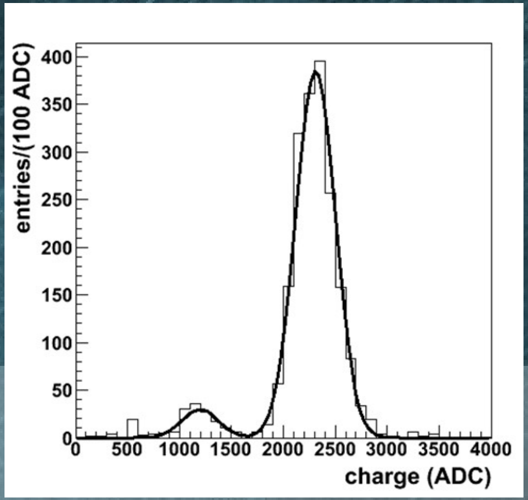


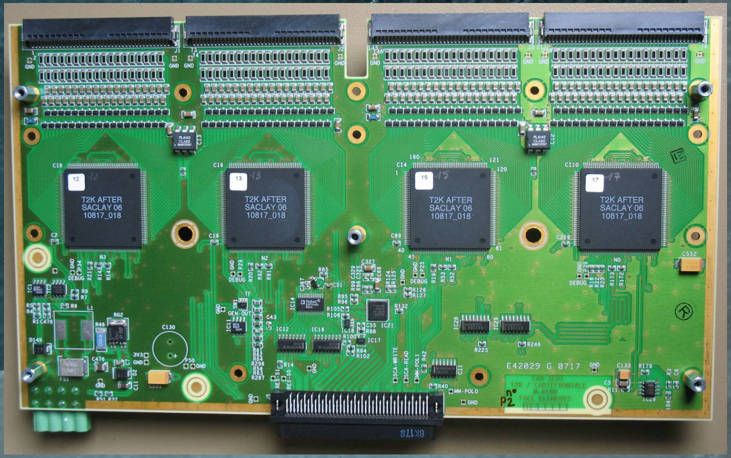
The ND280 TPC



- First large TPC with micro-pattern gas detectors
- IRFU 72 bulk micromegas
- IRFU: full frontend electronics, 1 ASIC chip, 124k channels
- 3D images of a neutrino interaction
- The TPC plays a key role in ND280 analyses

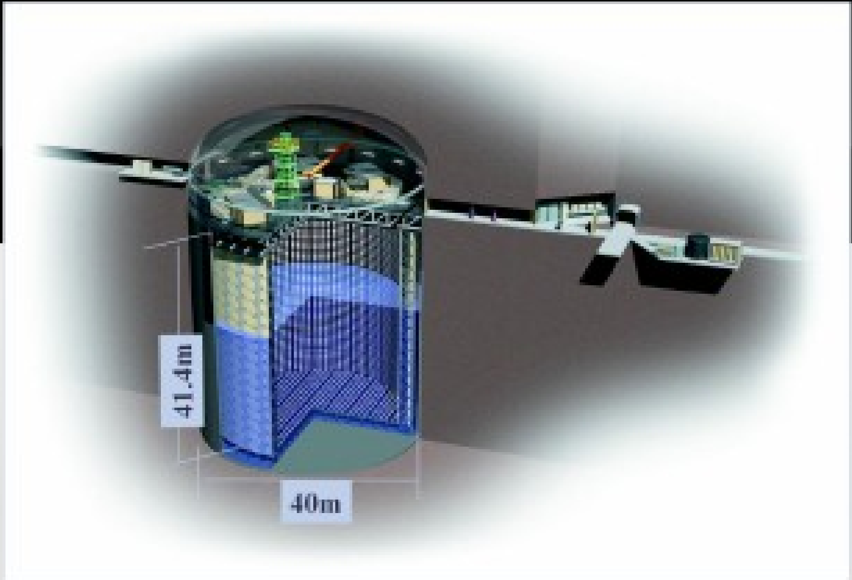


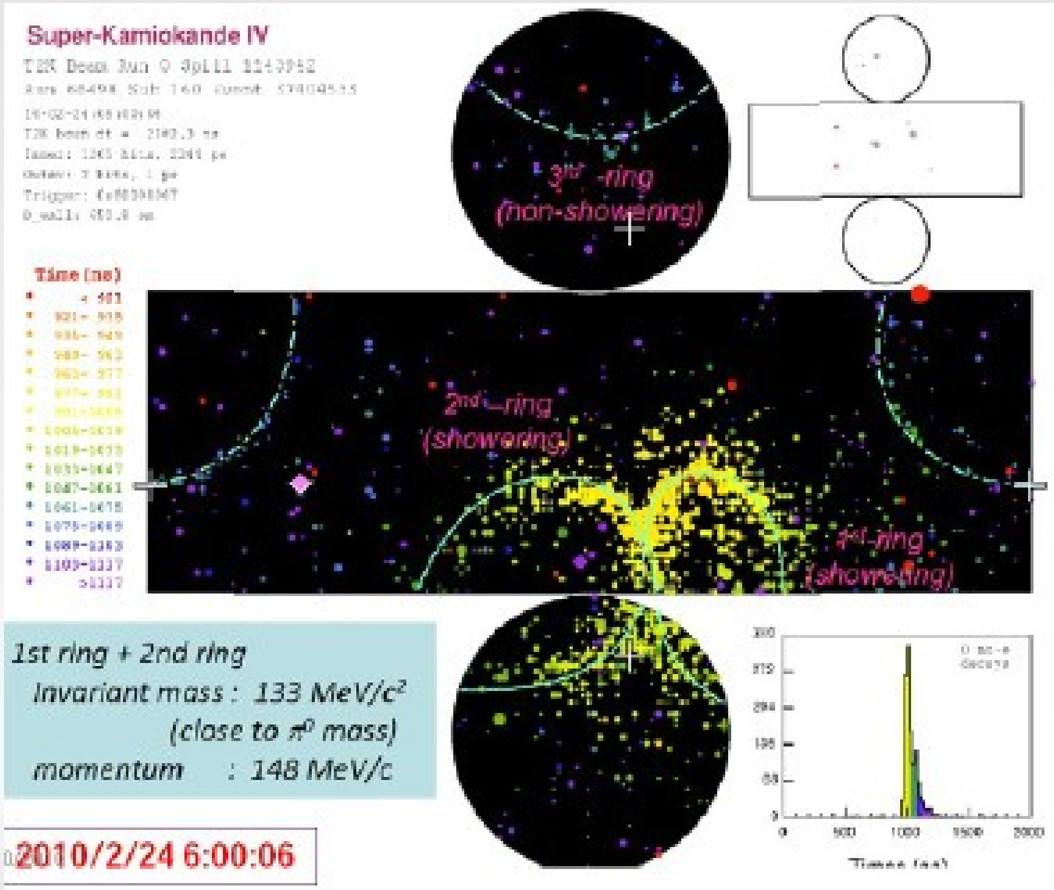




SuperKamiokande IV

- 50 kT water Cerenkov detector (22.5 kT of fiducial volume)
- Stably working since 1996, new readout electronics since 2008
- T2K related events selected by event timing using GPS system
- First T2K related neutrino interaction observed 24th February 2010

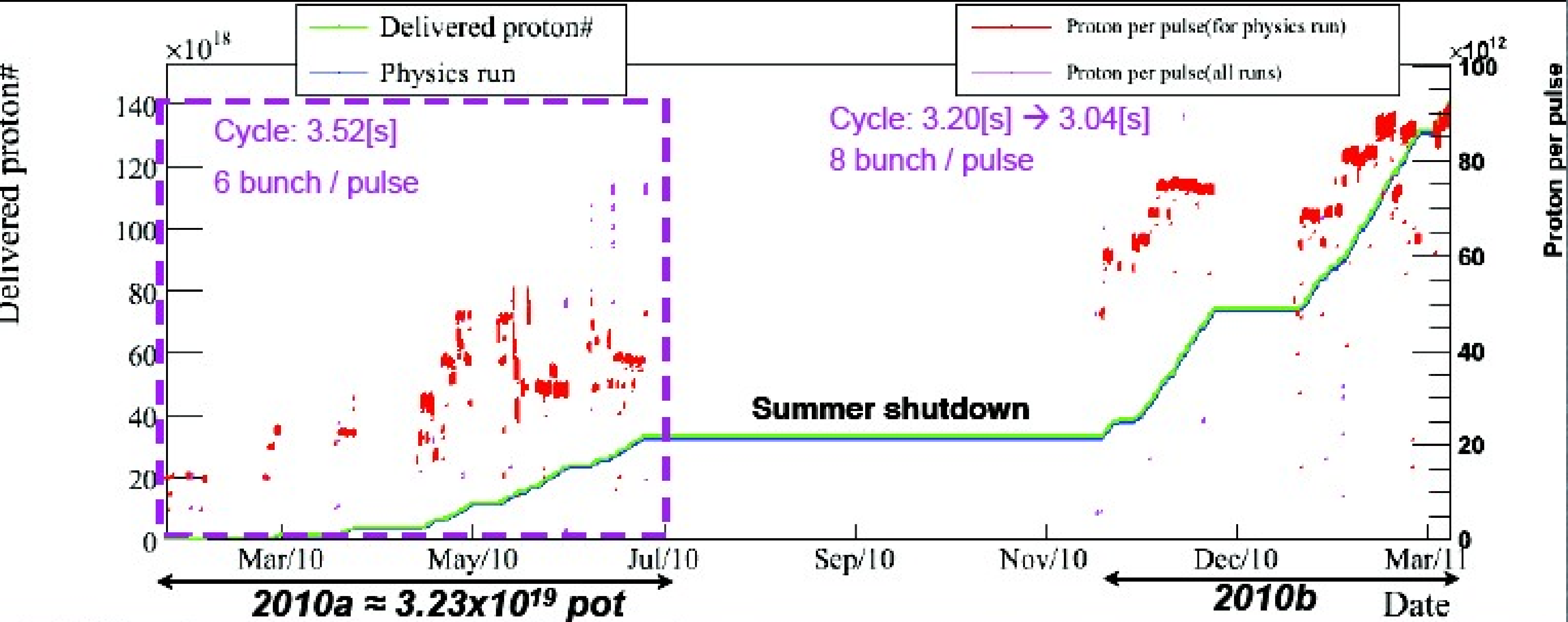




Main backgrounds for ν_e appearance

- Intrinsic ν_e component in the beam (~1%)
  - From mu decays (low energy) and kaon semileptonic decays (high energy)
  - To be measured at ND and controlled with hadroproduction measurements
- NC π^0 production : a photon looks like an electron in a Water Cherenkov detector
  - Will be measured at ND
  - Can be reduced and checked at SK
- **S/B~ 3 (MINOS S/B<<1) (pour theta_13 à la limite actuelle)**

MR protons# delivered



Run 2010a (Jan-Jun 2010)

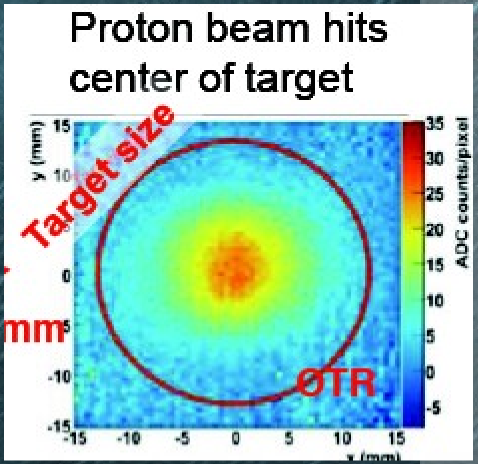
- 6 bunches/spill, cycle: 3.52 sec
- **3.23×10^{19} p.o.t** for T2K analysis
- 50kW stable beam operation (trials at 100 kW)
- Super-K live time >99%

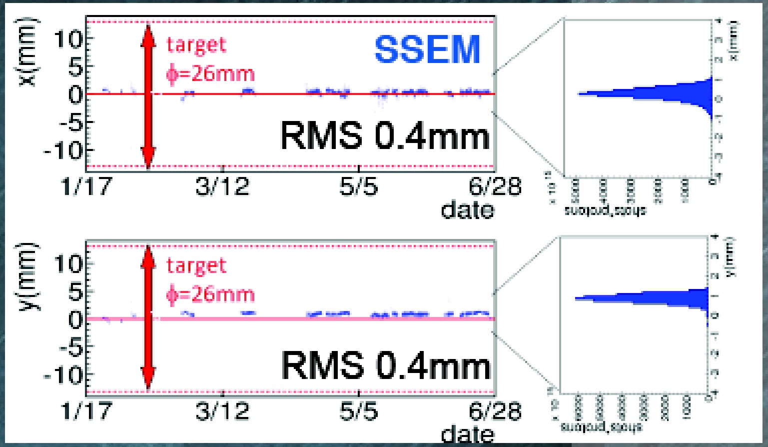
Run 2010b (Nov 2010-??? 2011)

- 8 bunches/spill, **9×10^{13} ppp**
- cycle: 3.52 sec → **3.04 sec**
- 135kW → **145 kW beam power**
- **1.46×10^{20} p.o.t** accumulated so far
- MR intensity limited by losses

T2K Beam monitoring

- Beam position on target within 1 mm
- Muon monitor : beam direction within 1 mrad, intensity stable (<1%)
- Neutrino beam





● ν Beam direction measured by INGRID from 2010 Jan. ~ Jun.

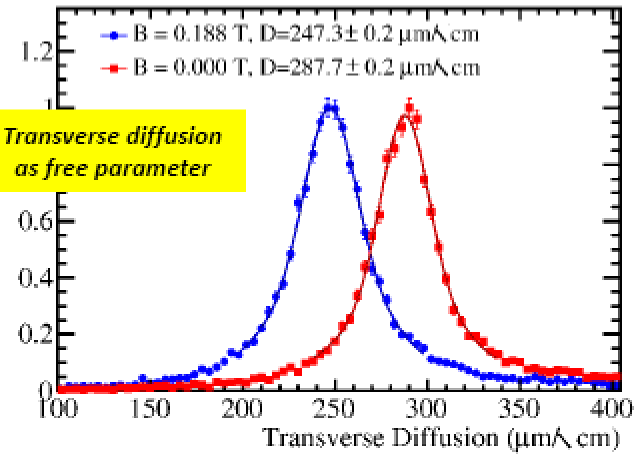
- Horizontal: +0.01±0.05(stat.)±0.33(syst.) mrad
- Vertical : -0.24±0.05(stat.)±0.37(syst.) mrad

•Time Projection Chambers for the T2K Near Detectors 1012.0865 subm. to NIM

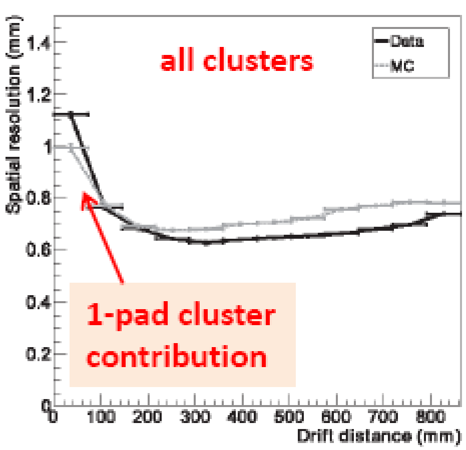
TPC performance : spatial resolution

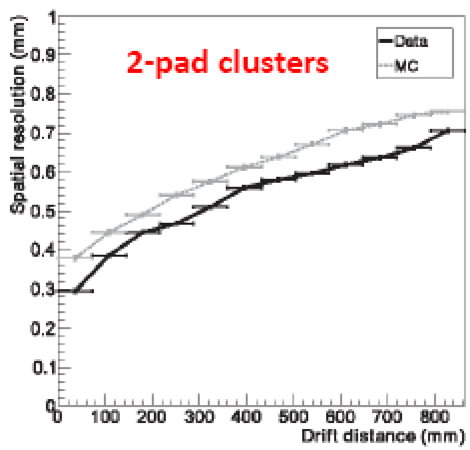
Spatial resolution

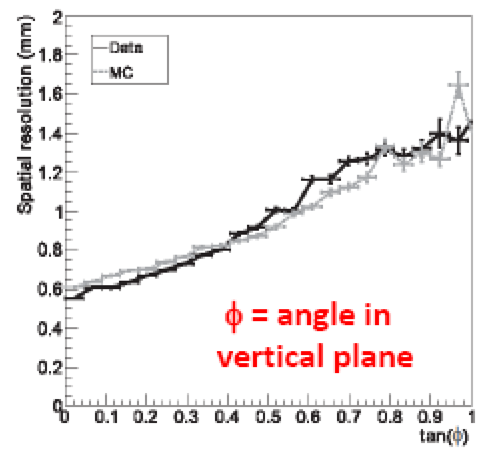
- Clusters formed by neighboring pads within a column (~ horizontal tracks) or within a row (~ vertical tracks)
- Track parameters and ionization width obtained by maximizing the likelihood of observed charge sharing between pads



Spatial resolution: compare transverse coordinate from track fit with single cluster fit:





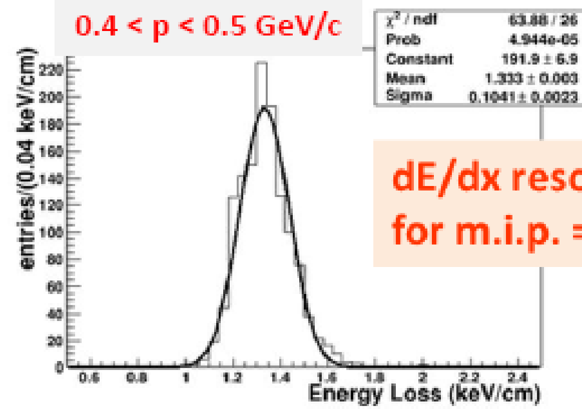


TPC performance: PID

Particle Identification

dE/dx : truncated mean method

- Linear charge density of a track estimated for each cluster
- Lowest 70% of the values used to compute the mean energy loss (C_T)
- T and P corrections applied

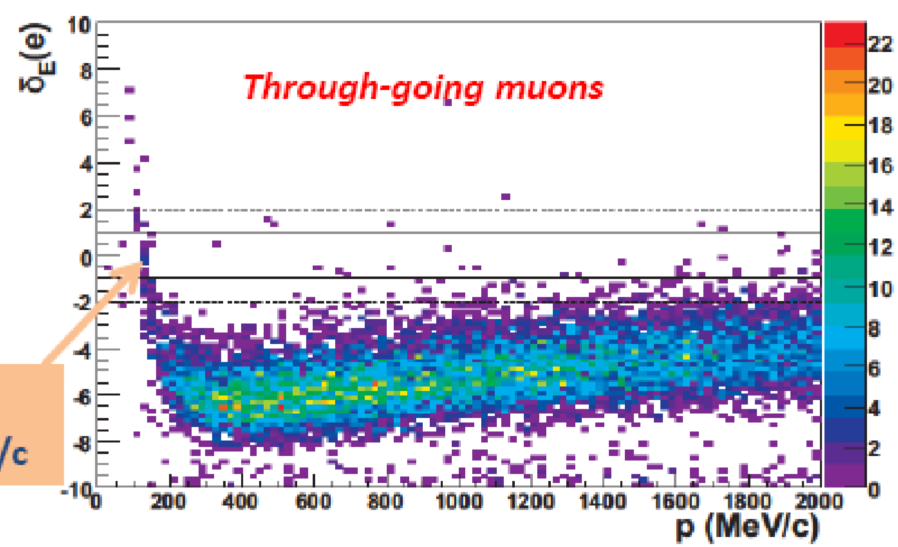


dE/dx resolution for m.i.p. = 7.8%

PID using « pull » variable:

$$\delta_E(i) = \frac{C_T - CE}{\sigma(i)} \quad (i = e, \mu, \pi, K, p)$$

C_E: expected energy loss value

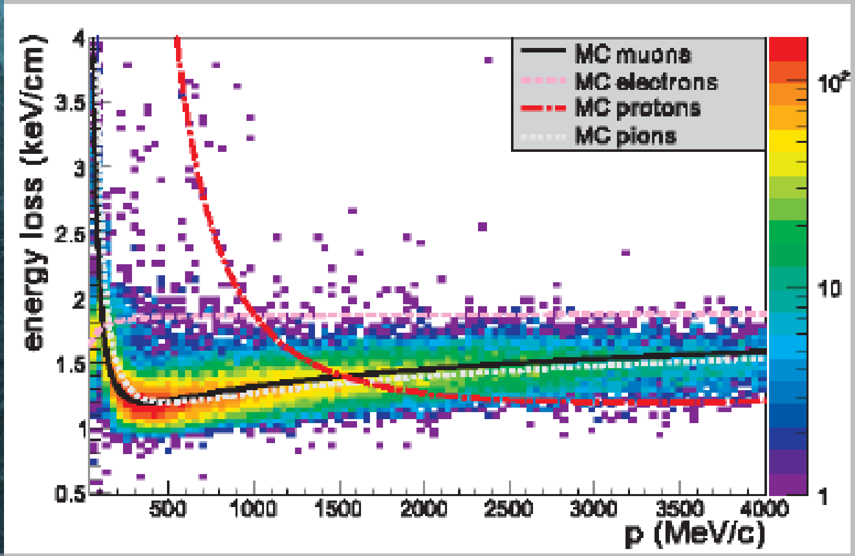


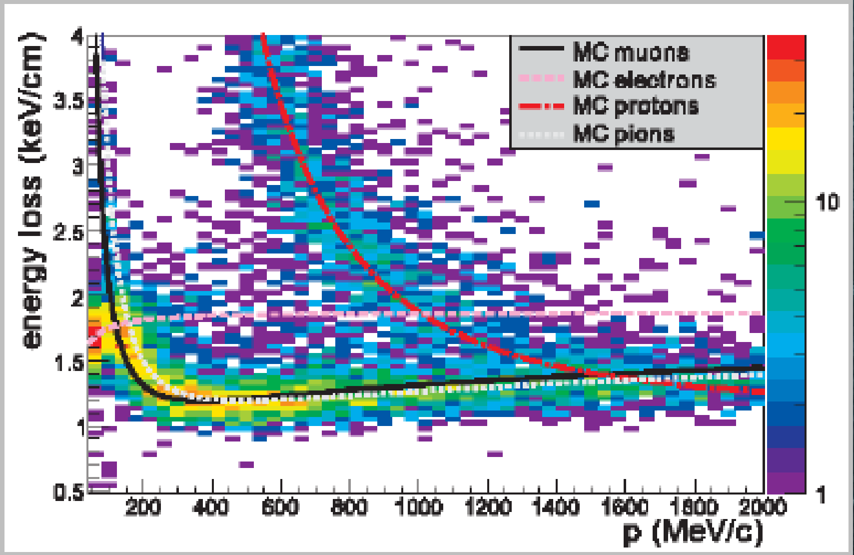
-1 < δ_E (e) < 2 cut gives 0.2% probability of identifying a muon as an electron for p < 1 GeV/c

TPC performance: PID for beam spill events

Particle Identification: dE/dx

Through-going muons and neutrino interactions in ND280

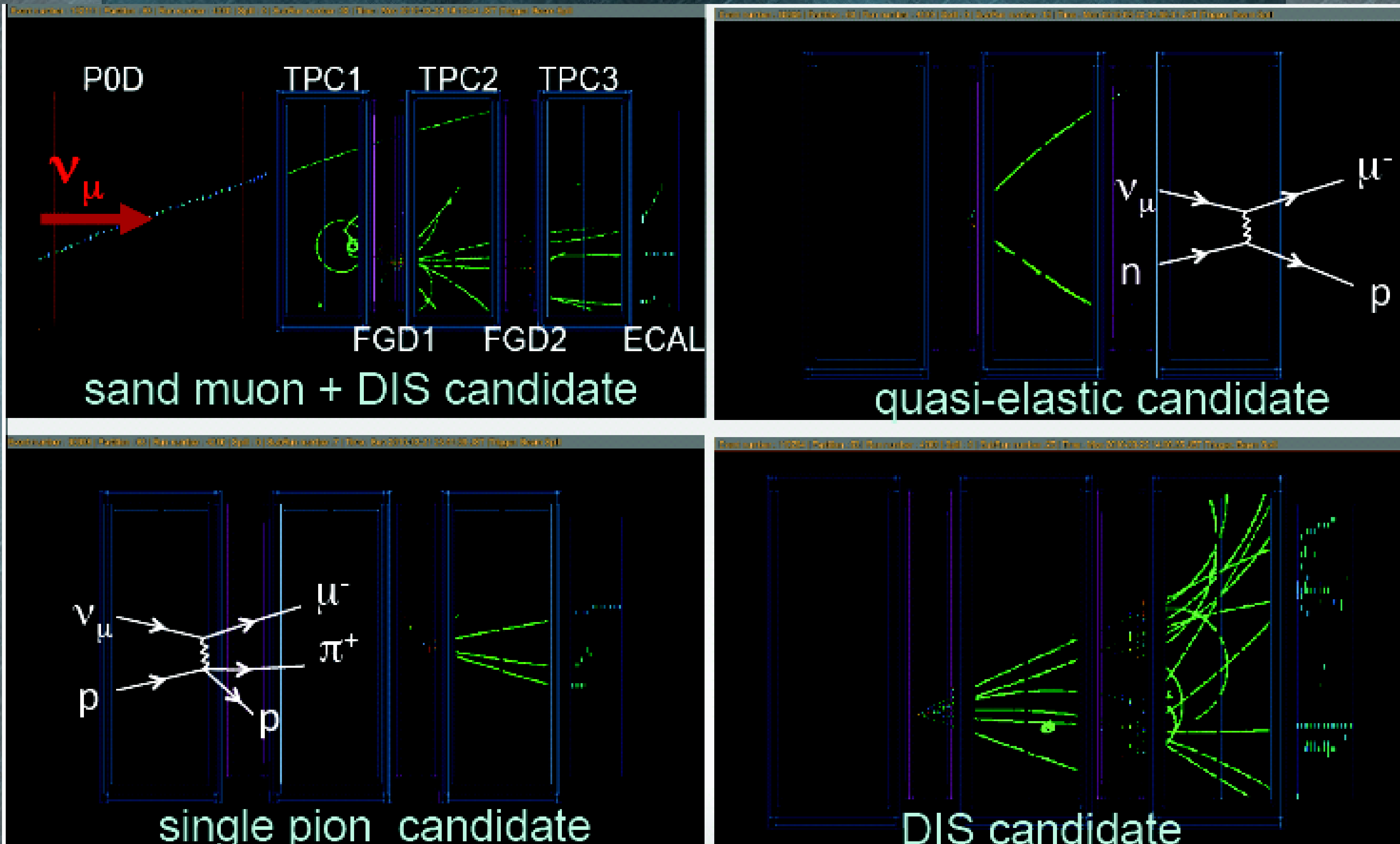




Negative tracks: μ^-, e^-

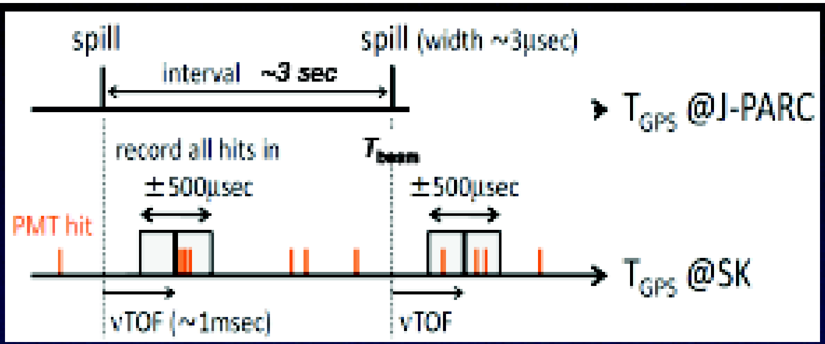
Positive tracks: p, π^+, e^+

Neutrino interactions in ND280

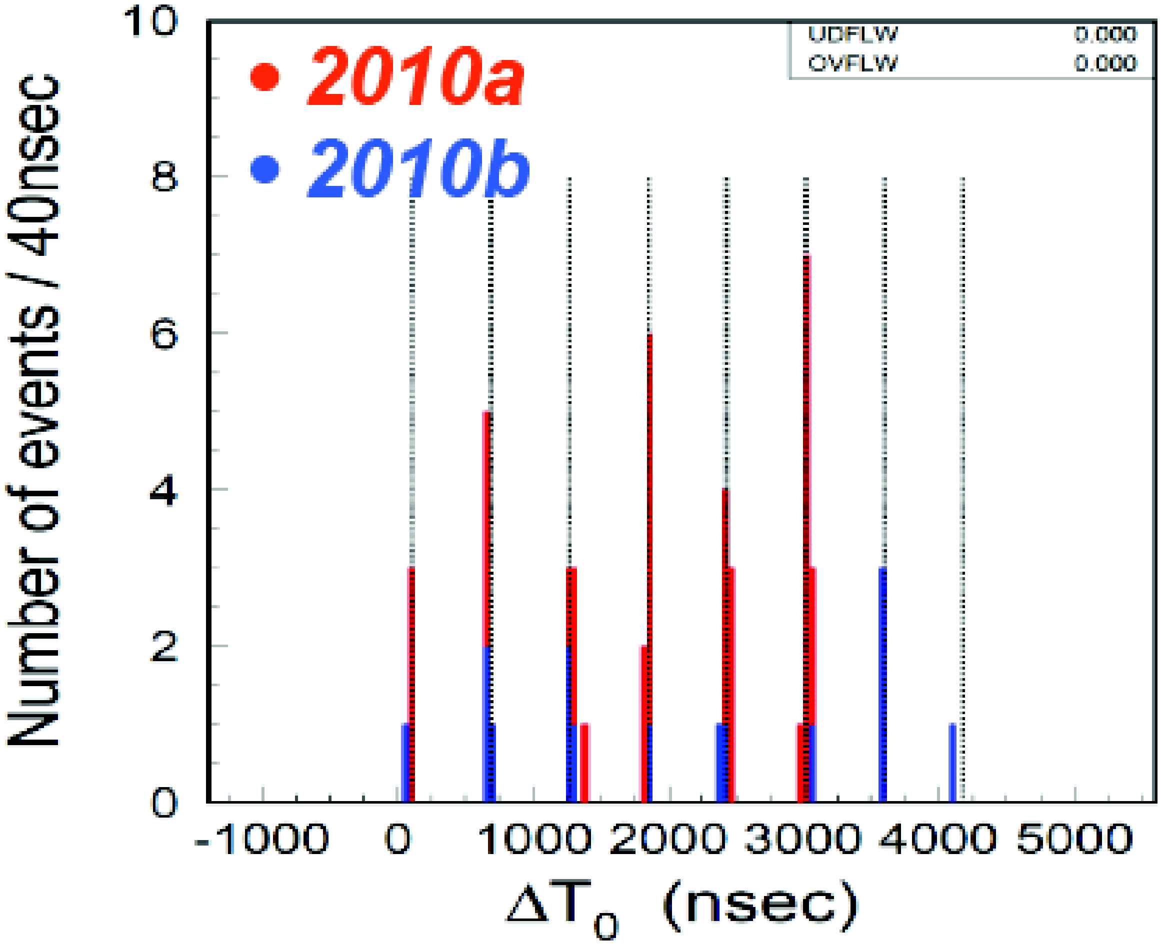


SK-spill synchronization

- **Baseline measurement (Survey)**
  - $L = 295{,}335 \pm 7$ m
    → ToF of ν = 985.132 ± 0.02 μsec (≡ νTOF)
  - Expected event timing @ SK (≡T_{SK})
    = Spill timing @ Tokai (≡T_{beam}) + νTOF.
- **DAQ synchronization**
  - SK signals in ±500μs timing window are recorded as "T2K beam events".
  - Stability of GPS is checked by comparing 2 GPS hardware and atomic clock.
    → Require |GPS1-GPS2| < 200nsec

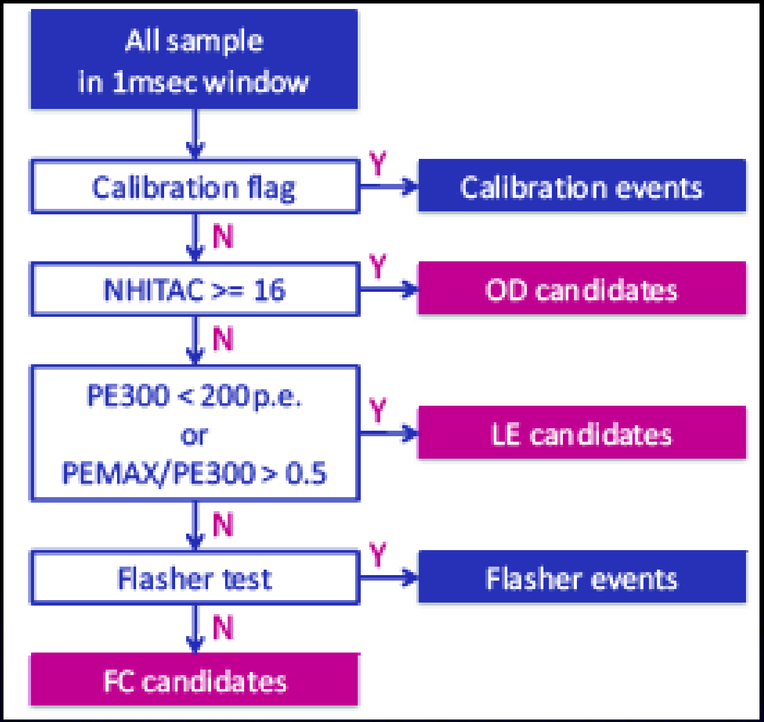


Event timing

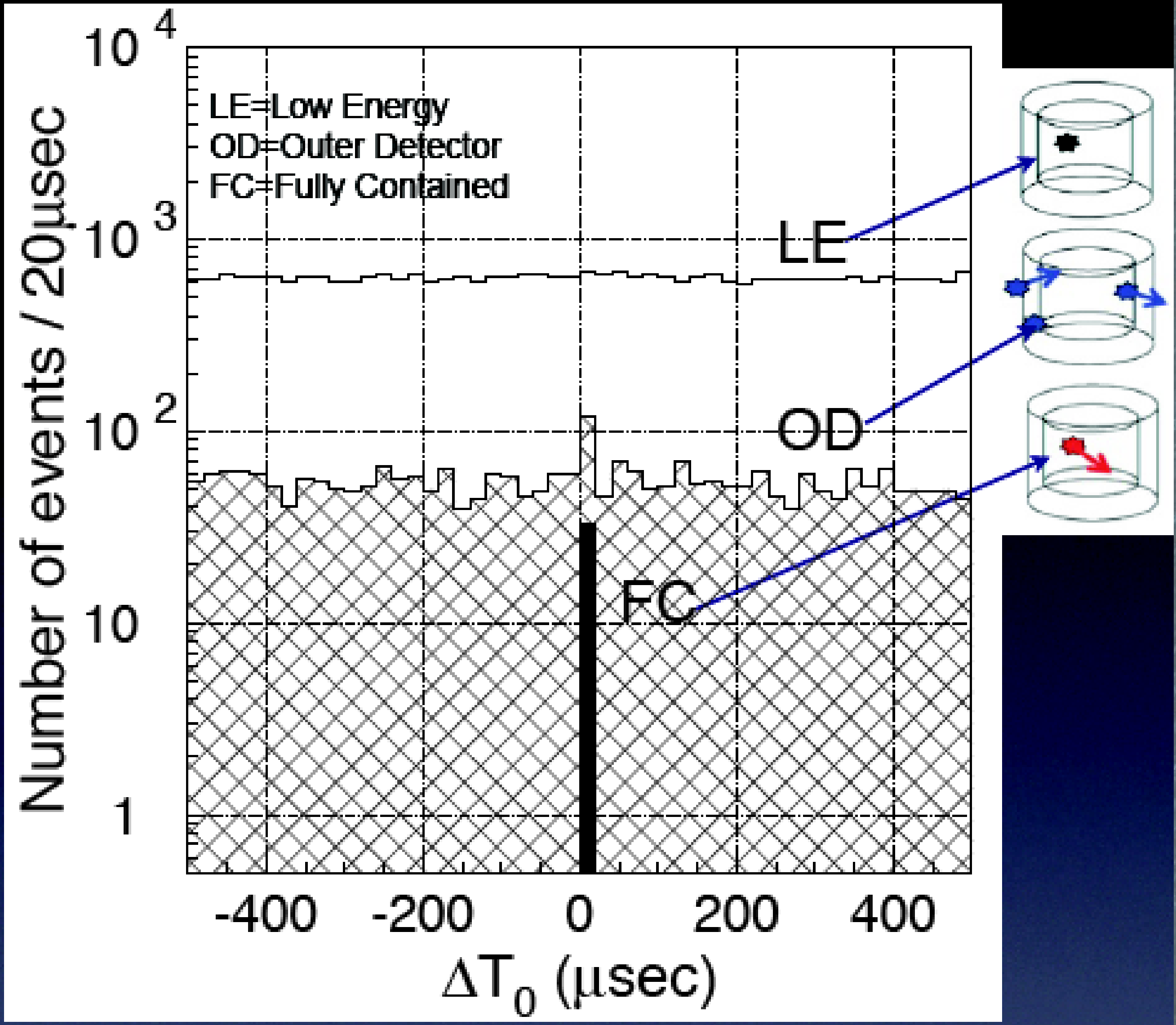


T2K-SK event reduction (2010a)

Reduction of sample collected in ±500μs window around T2K spill

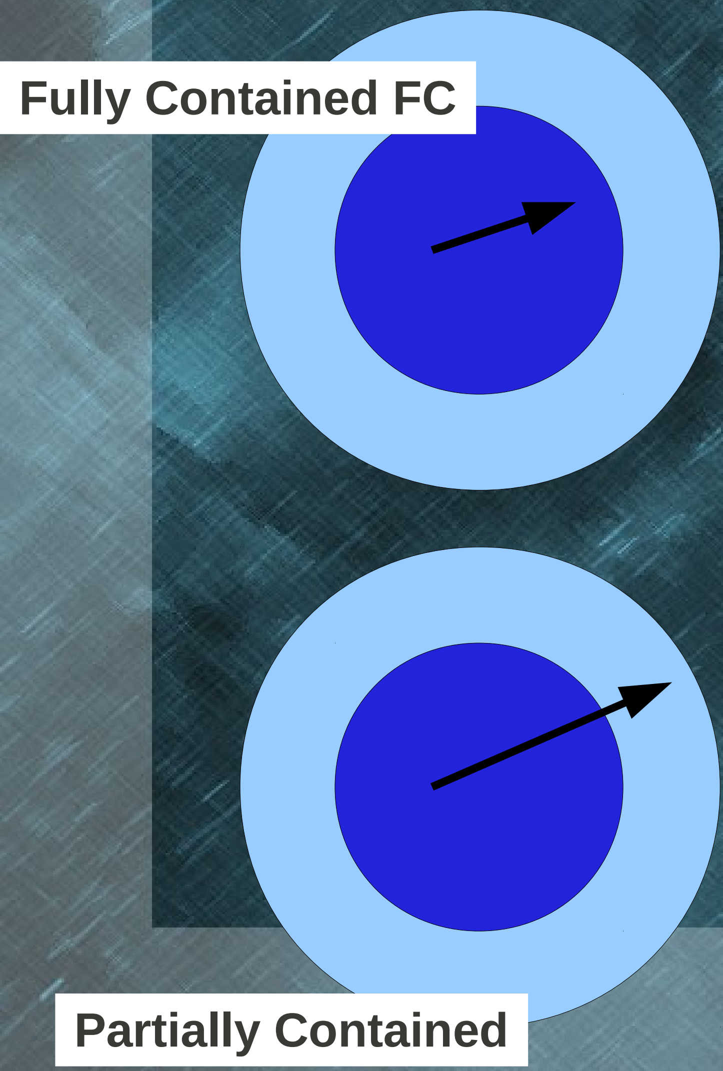


PE300 = sum ID-PMT (p.e.) in 300ns window
PEMAX = maximum charge (p.e.) in a single ID-PMT hit



Number of neutrino candidates observed in SK:
Fully Contained (FC) = 33
Flasher events = 2
Accidental background = 0.0094±0.0067(stat)

SuperKamiokande data



Avec les données de SK on peut classer les données sur la base de :

- Single Ring ou Multi Ring
- mu-like ou e-like
- Fully Contained (FC, on peut mesurer l'énergie) ou pas
- Dans le volume fiduciel (FV)

Les analyses sont basées sur les évt:
Single Ring mu-like FV pour la disparition de nu_mu
Single Ring e-like FV pour l'apparition de nu_e

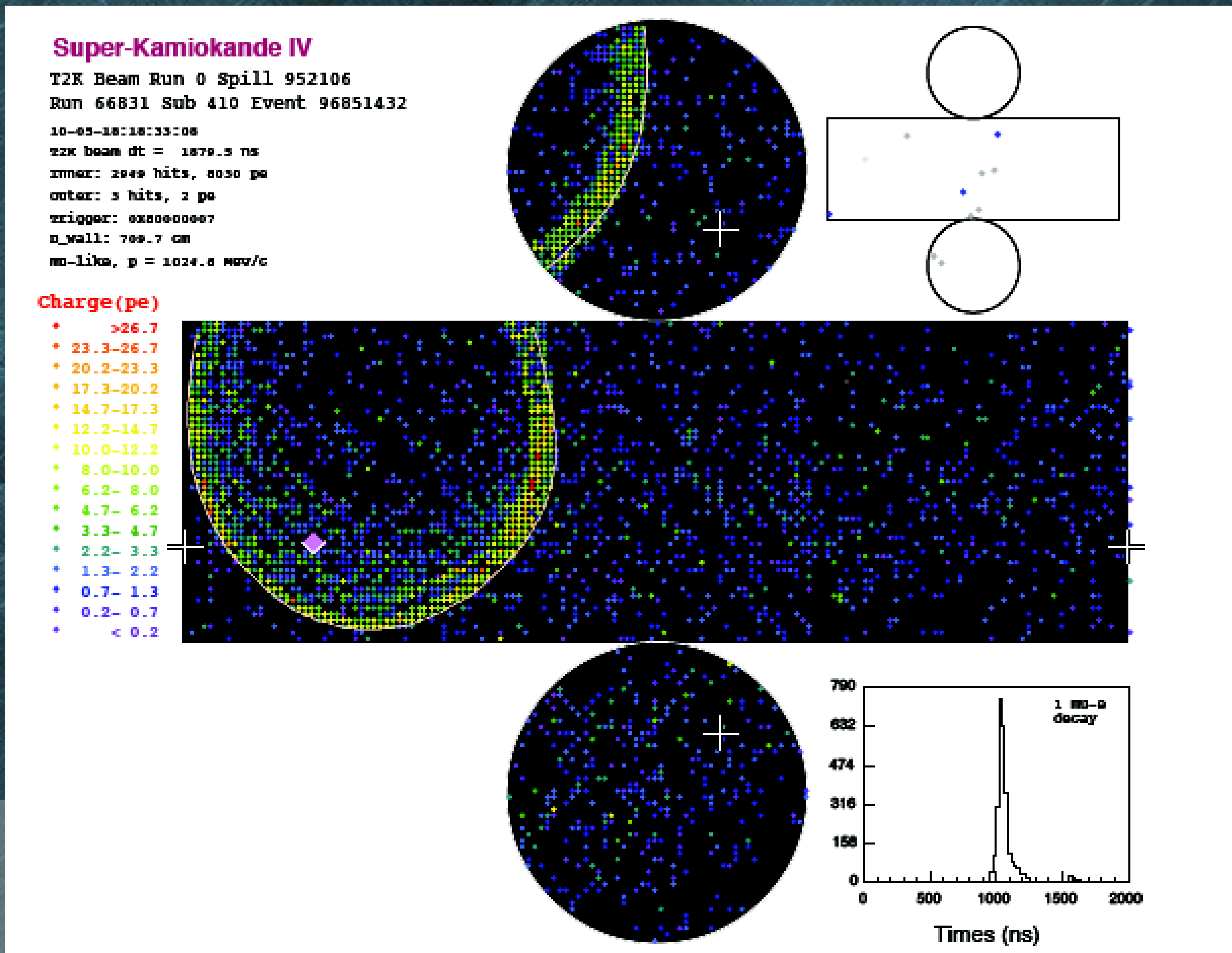
T2K-SK event reduction (2010a)

T2K

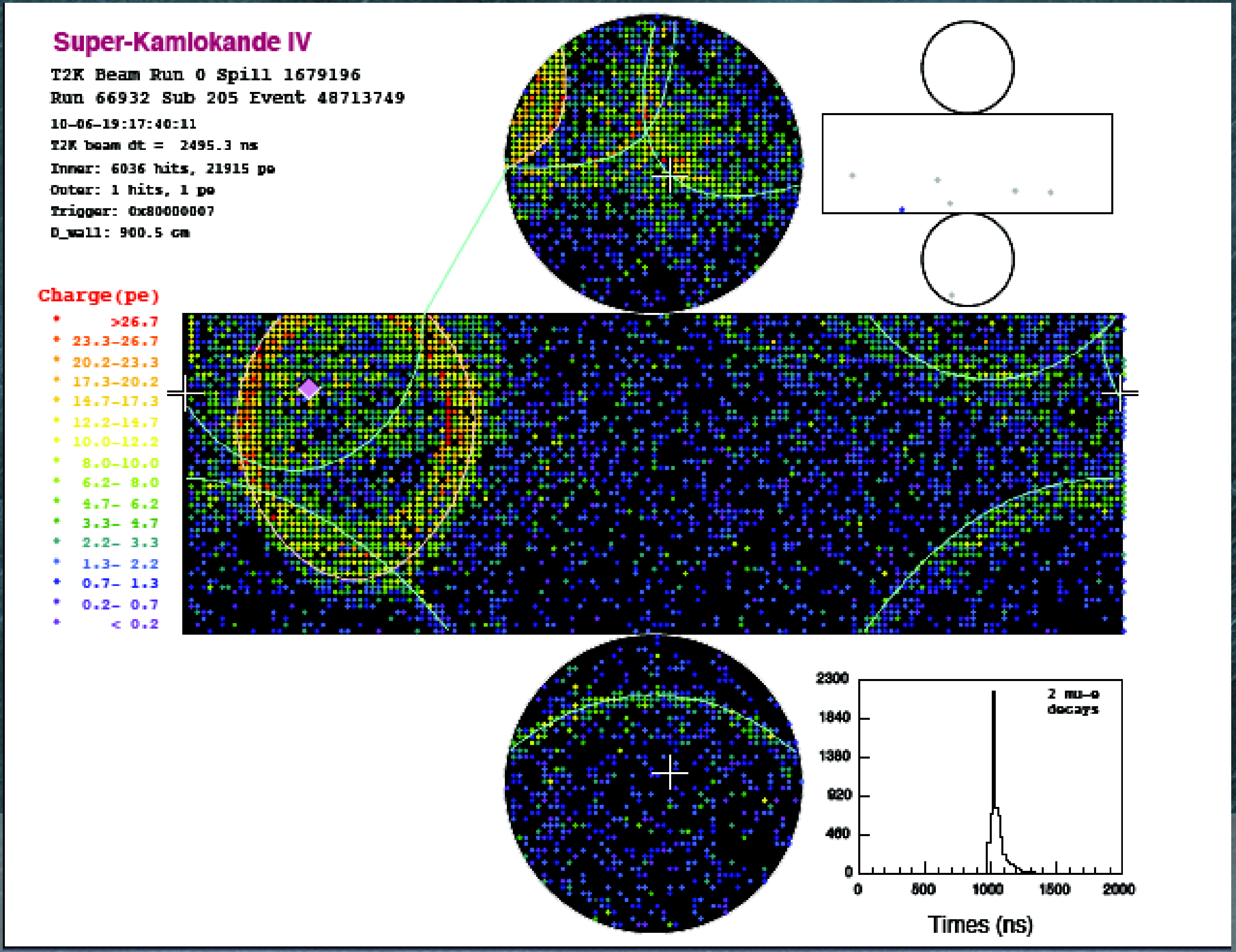
Fully contained, fiducial volume (FCFV) selection, ring counting and 1-ring PID classification

T2K-SK events Fiducial cut: D_{wall} > 200 cm, total fiducial target = 22.5 kton	Data
Fully-Contained	**33**
Fiducial Volume, E_{vis} > 30MeV	**23**
Single-ring μ-like (P_{μ}>200MeV/c)	**8**
Single-ring e-like (P_e>100MeV/c)	**2**
Multi-ring	**13**

SK 1 ring mu-like



SK multi-ring mu-like



Analyse

Analysis strategies (2010a)

(A) ν_μ disappearance analysis:

- *T2K-SK data reduction 1-ring μ-like*
- *Prediction of expected events under two hypotheses:*
  1. *null oscillation*
  2. *oscillations with* $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=1.0$
- *Comparison observed with expectation*

(B) ν_e appearance analysis:

- *T2K-SK data reduction 1-ring e-like*
- *Additional cuts for background suppression*
- *Prediction of expected events under two hypotheses:*
  1. *"background only" = oscillations with* $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=1.0$, *and* $\theta_{13}\equiv0$
  2. *"signal+background" = same as 1. but with* $\sin^2 2\theta_{13}=0.1$
- *Oscillation parameters fit*

Analysis flow (2010a)

T2K

Neutrino flux prediction
- Proton beam data
- Hadron production data

ND280 (near) Detector Measurements
- ν_μ CC inclusive selection
- Measure: $R_{Data/MC} = \frac{N^{Data}_{\mu CC,ND280}}{N^{MC}_{\mu CC,ND280}}$

Neutrino cross-sections
- Tuning to external data
- Interaction models and parameters variation

SK (far) Detector Measurements
- Data reduction and classification
- Compute signal and background expectations (counting)

$$N^{MC}_{signal} = \int dE_\nu \underbrace{\Phi_\mu(E_\nu)}_{\text{flux}} \times \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \times \underbrace{\varepsilon(E_\nu)}_{\text{efficiency}} \times \underbrace{P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})}_{\text{oscillation}}$$

- Correct normalization using ND280 measurement

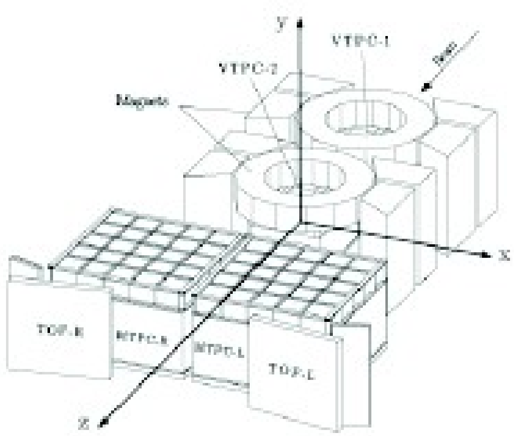
$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg}\right)$$

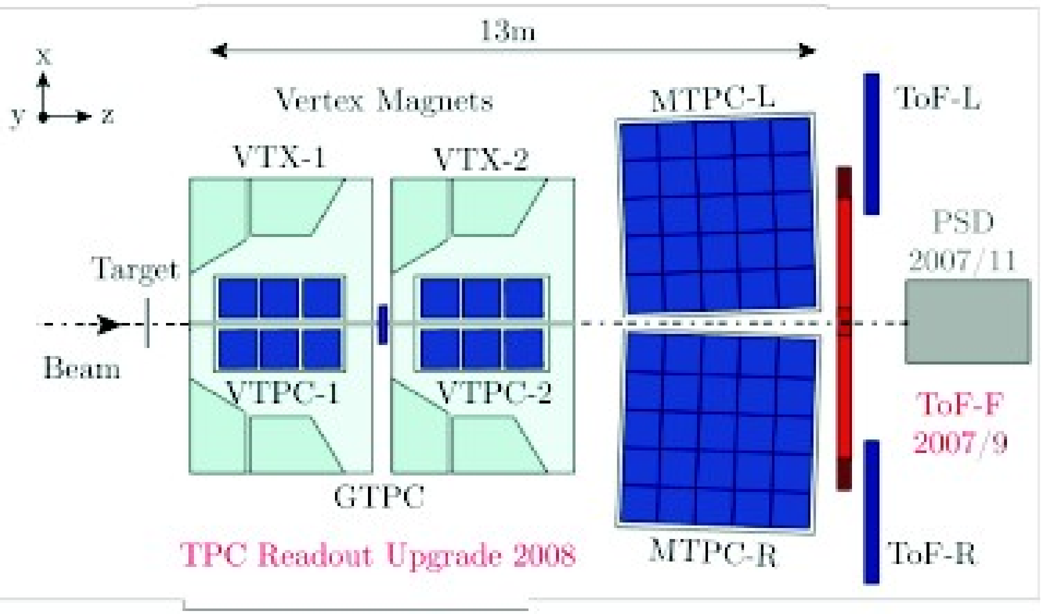
- Evaluate systematic errors
- Extract oscillation parameters

[In the current analyses we do not use the measured near spectrum and the near/far ratio.]

CERN NA61 measurements

Evaluation of Particle Yields in 30 GeV p+C Inelastic Interactions and in the T2K replica target





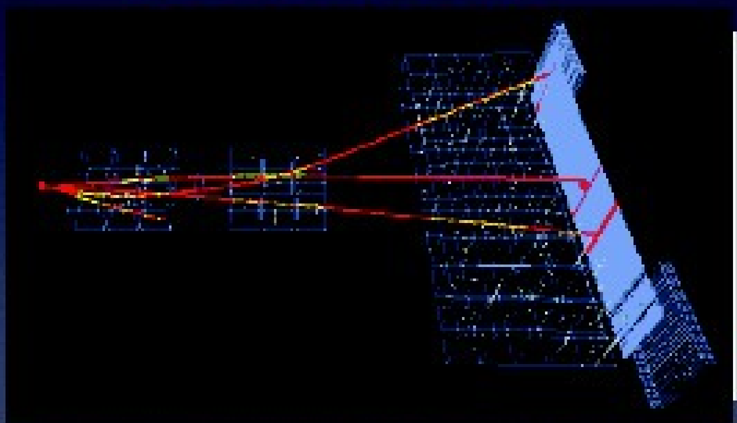
Large acceptance spectrometer:

5 TPCs
2 dipole magnets
$\sigma(p)/p^2 \approx 10^{-4}\ (\mathrm{GeV}/c)^{-1}$
$\sigma(dE/dx)/<dE/dx> \approx 0.04$

3 ToFs
σ(ToF-F) = 120 ps
σ(ToF-L/R) = 60 ps

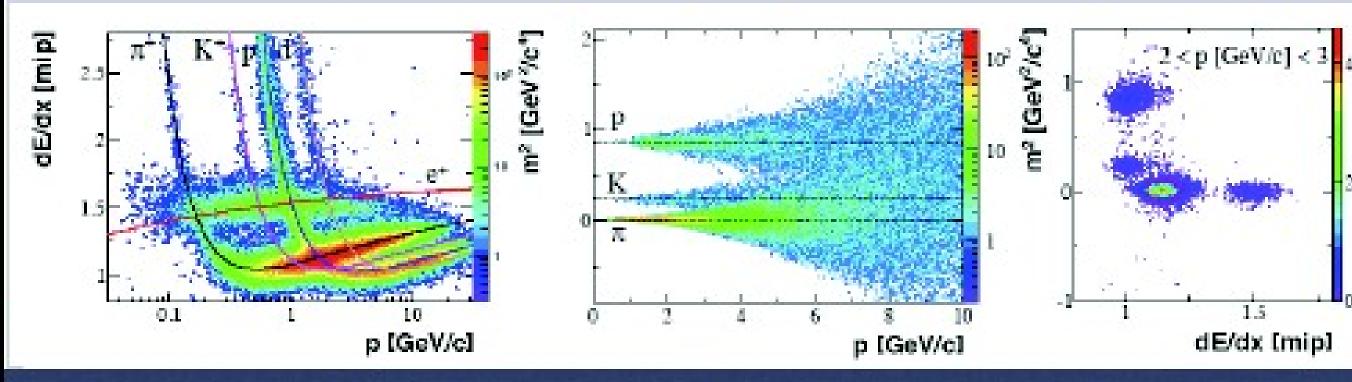
Full Coverage of T2K phase space

p+C @ 31 GeV/c



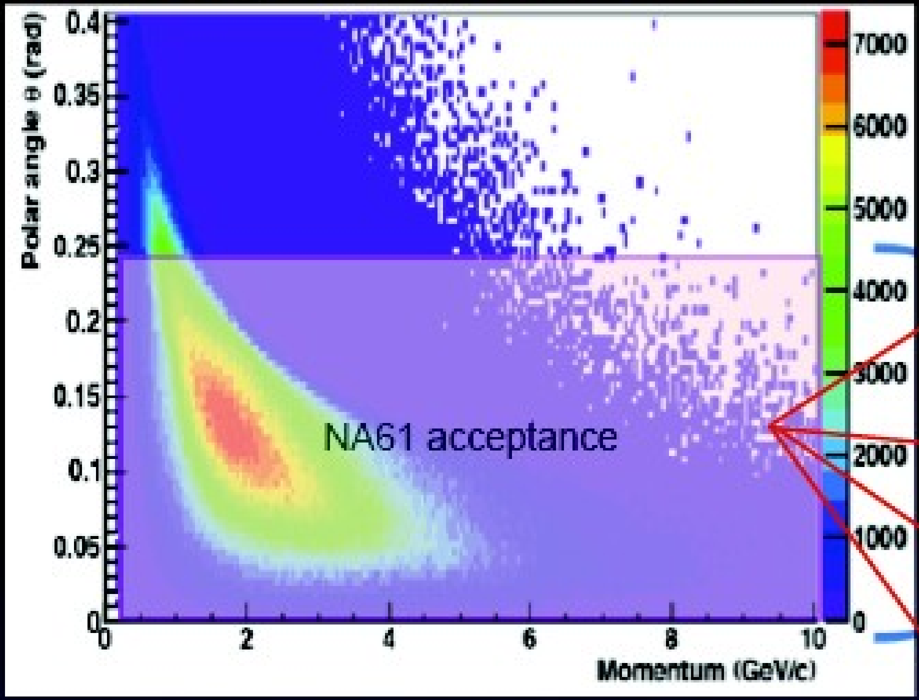
Particle ID methods used:

1) dE/dx (p < 1 GeV/c, p > 4 GeV/c)
2) Combined dE/dx + ToF (1 < p [GeV/c] < 4)
3) Negatively charged hadron h- analysis (π- only)

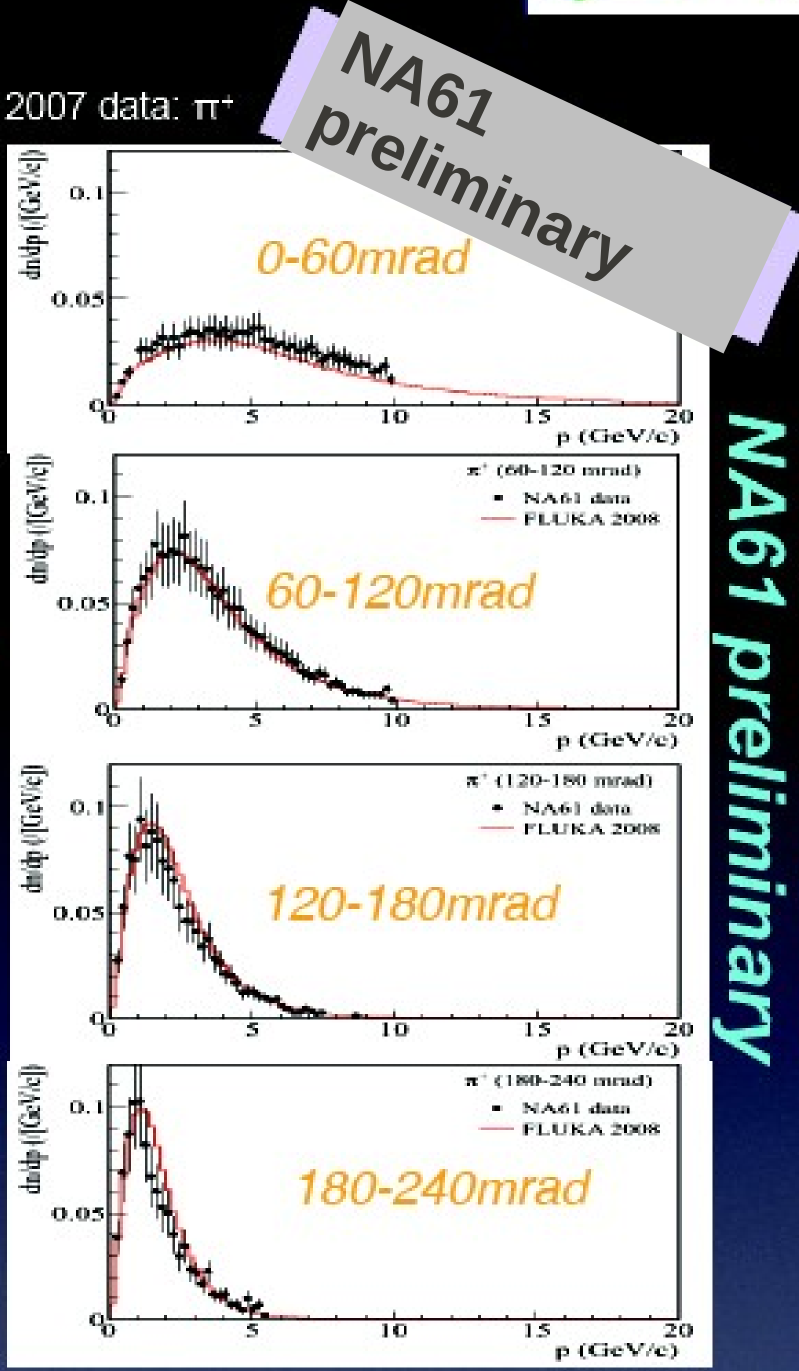


Inclusion of NA61 preliminary measurements

Pion phase space weighted by probability of neutrino interacting at SK



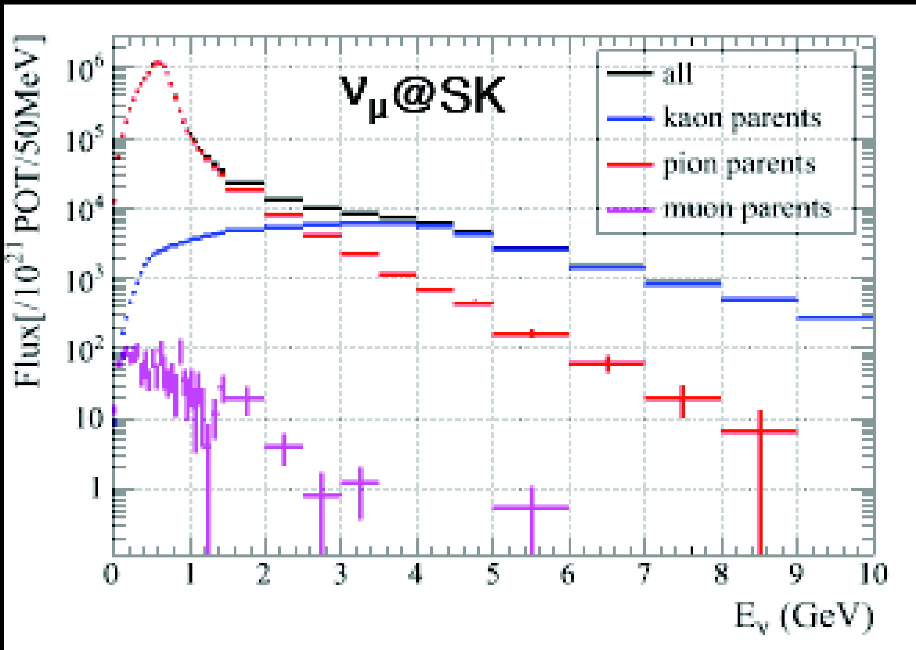
NA61 2007 data: π^+

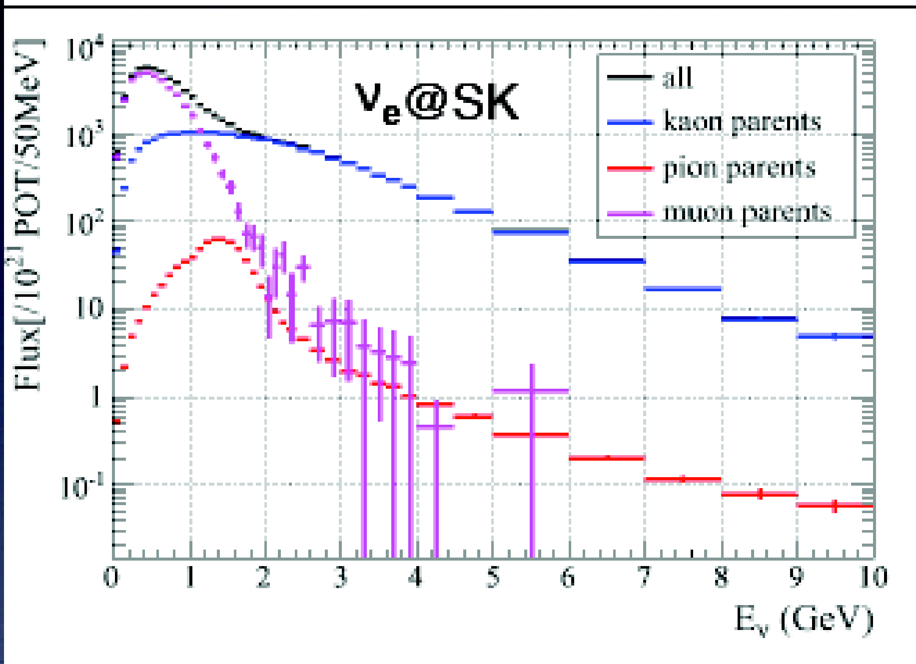


- Analyzed data was taken in 2007
  - p (30GeV) + C (target thin:2cm / thick: 90cm)
- $\pi^{\pm}$ production model in T2K-MC is corrected by NA61 preliminary results which was released in Dec. 2009.
- Conservative systematic uncertainties
  - ±10% : Inelastic p + C cross section
  - ±20% uncorrelated on each bin: Pion multiplicity

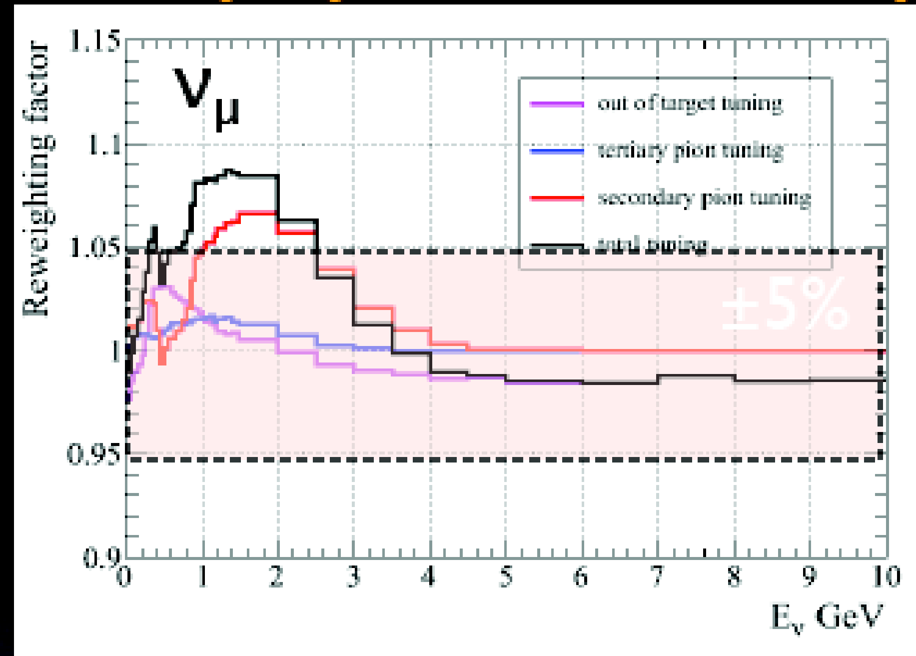
Tuned SK neutrino fluxes

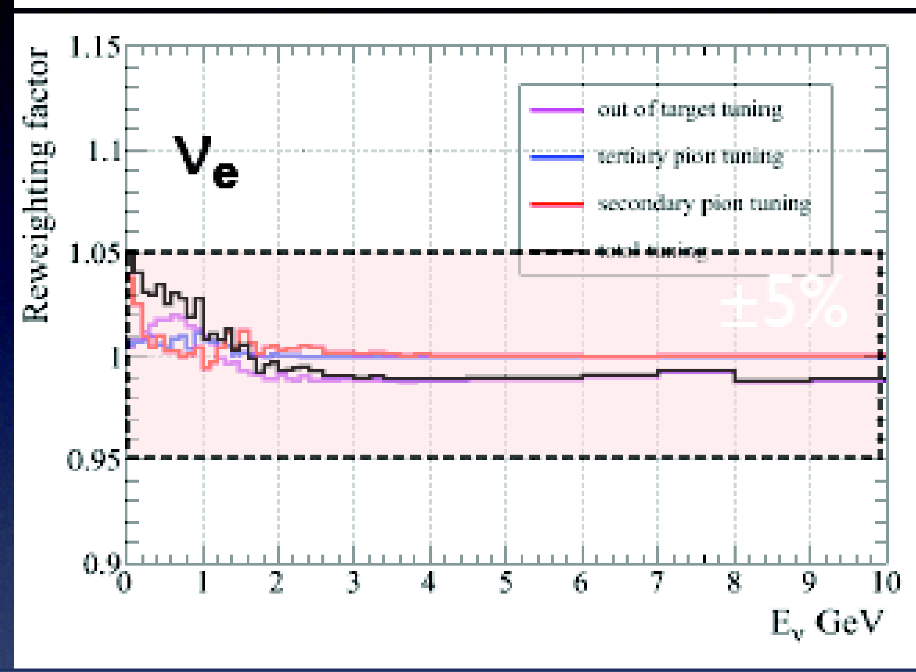
Final neutrino fluxes at SK





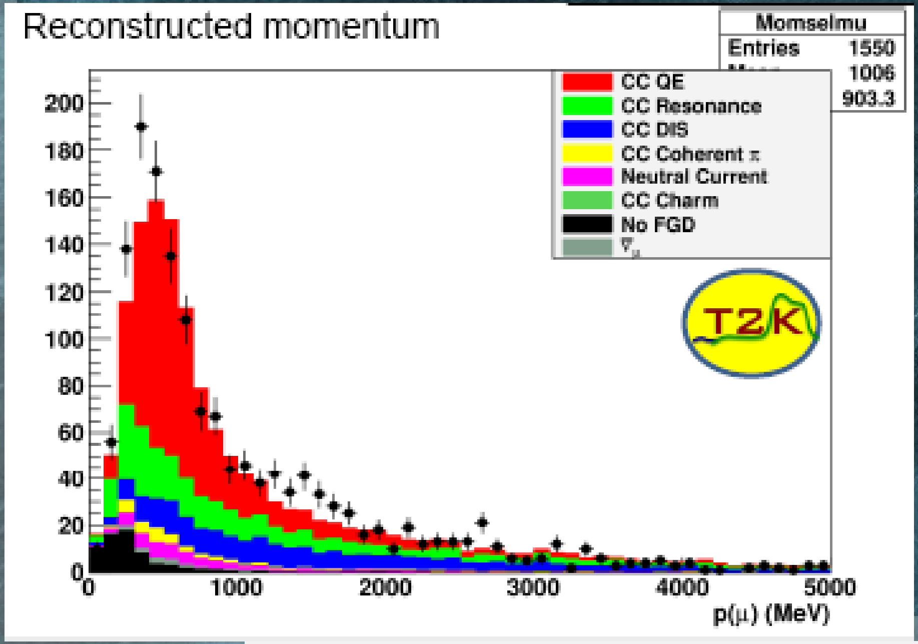
MC reweighting factors vs neutrino energy





Analyses : ν_μ in ND280

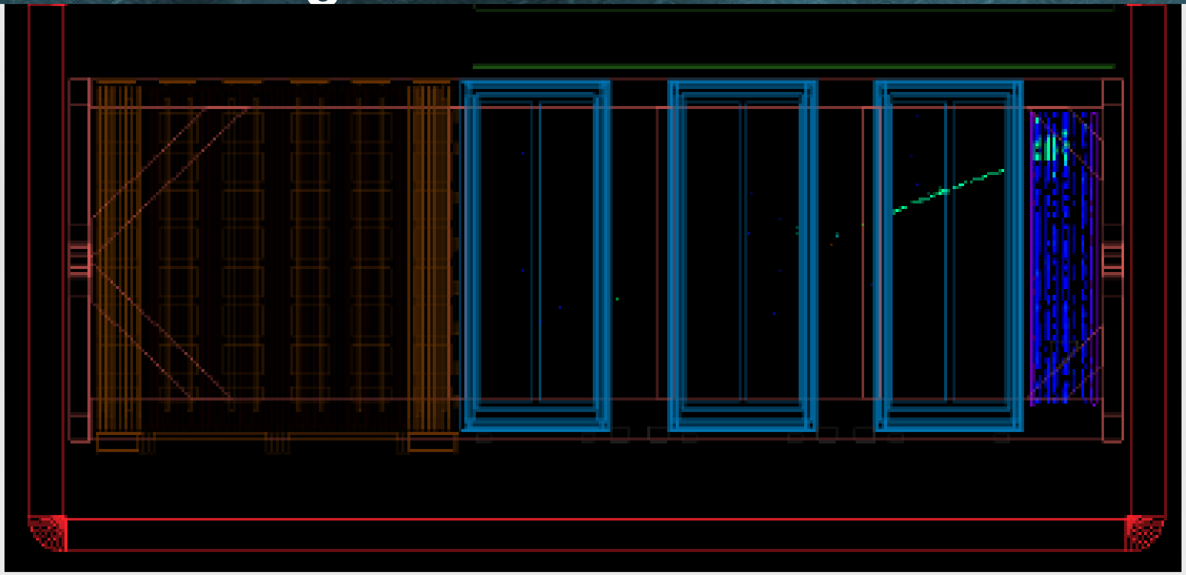
- Analyse de Saclay (C. Giganti, A. Longhin, MZ)
- Choisie pour le premier papier de T2K
- 1550 ev. (interactions dans FGD +trace(s) dans la TPC)
- 90% CC

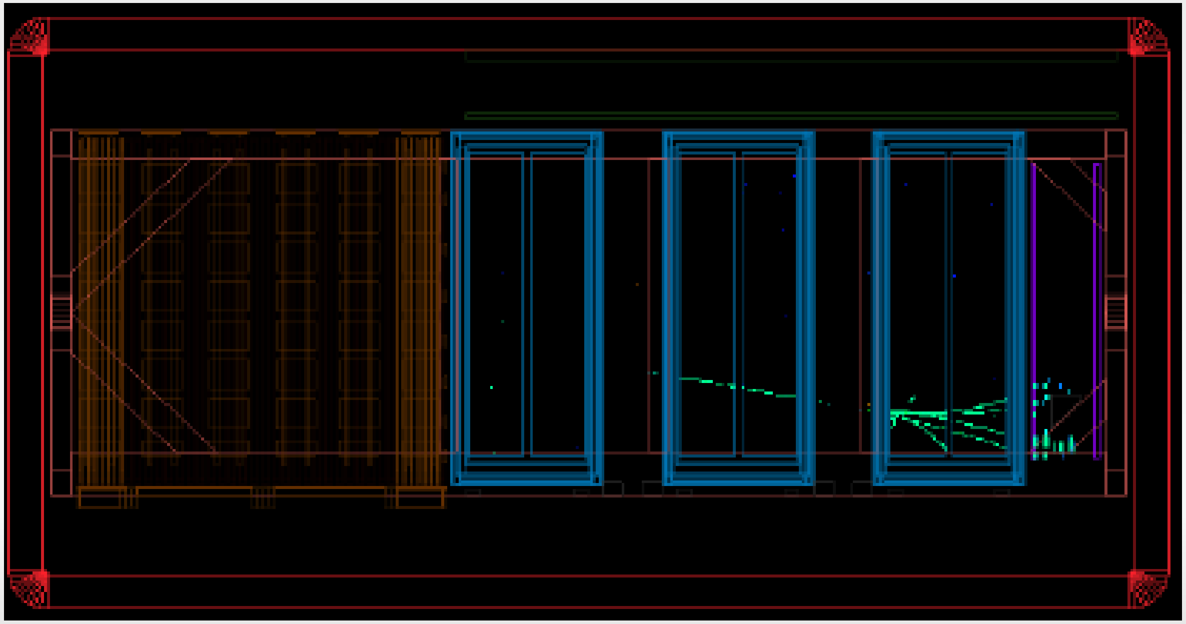


Source	Section	err. sys. +	err sys -
TPC1 veto	7.1	0.01	0.01
TPC eff	7.2	/	0.034
TPC ch misid	7.3	0.01	0.01
TPC-FGD match	7.4	0.021	0.021
FV	7.5	/	/
T_0	7.6	0.001	/
highest mom tk	7.7	/	/
PID pull width	7.8.1	0.030	/
Low gain MM	7.8.2	0.004	0.004
pile-up	7.9	0.009	0.009
cosmics	8.1	/	0.004
Out of FGD	8.3	0.008	0.008
Total		**0.042**	**0.044**

$$R^{rew}_{data/MC} = 1.067 \pm 0.027\,(stat)^{+0.042}_{-0.044}\,(syst\ det) \pm 0.034\,(syst\ model)$$

Beam ν_e candidates in ND

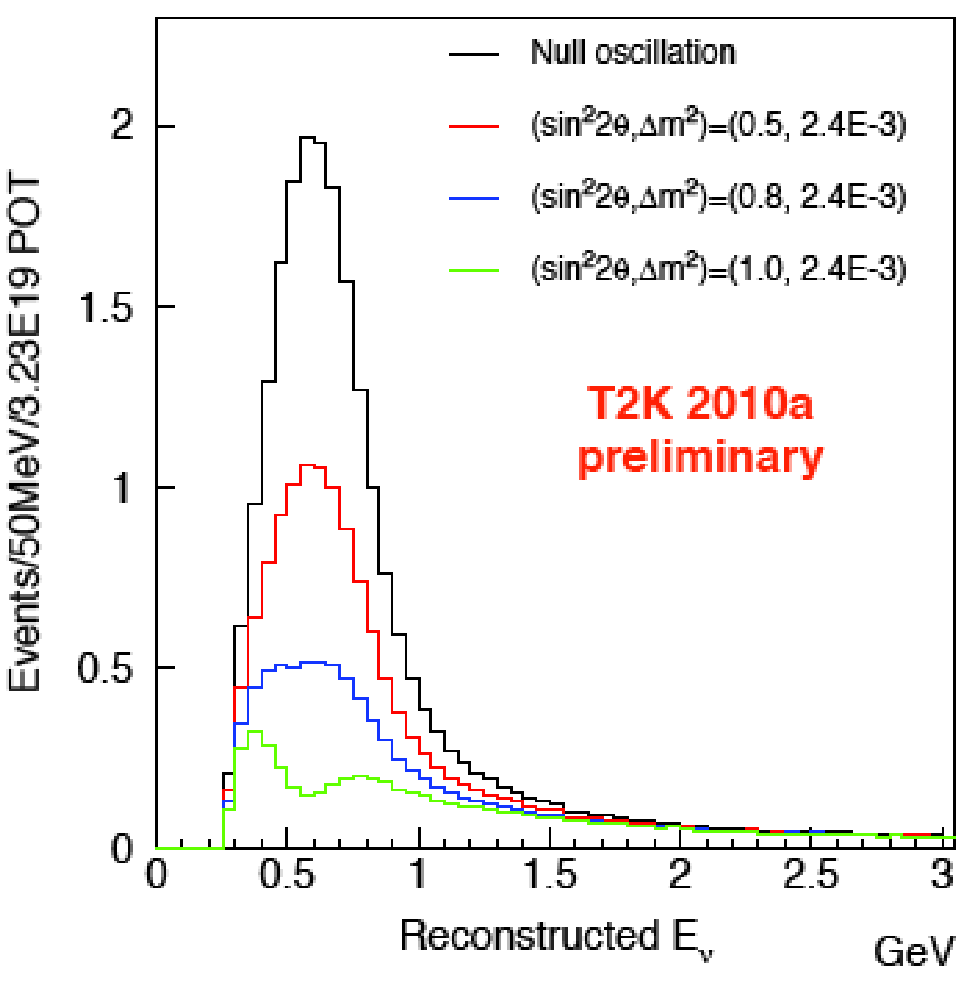


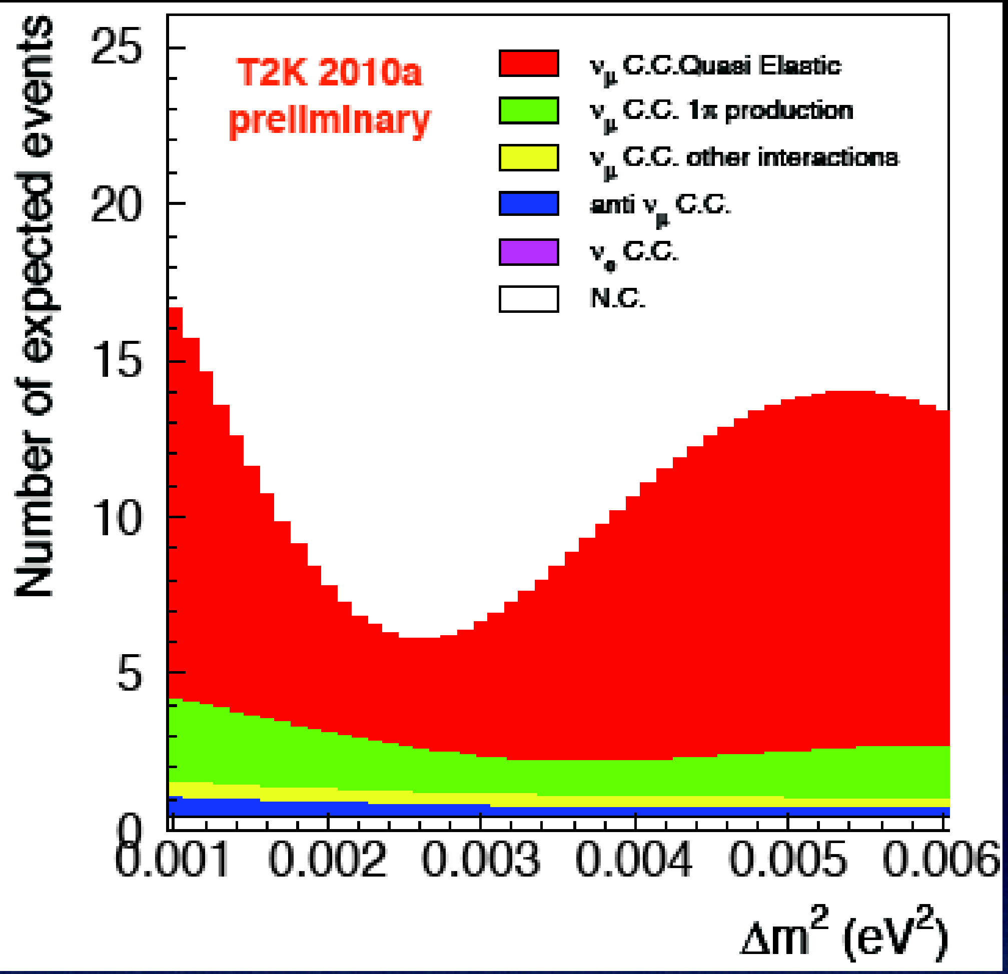


ν_μ disappearance analysis

Aimed at precise measurement of 23-sector

Expected spectrum for different oscillation parameter hypothesis





T2K off-axis configuration ➠ strong dependence on oscillation parameters in region of interest

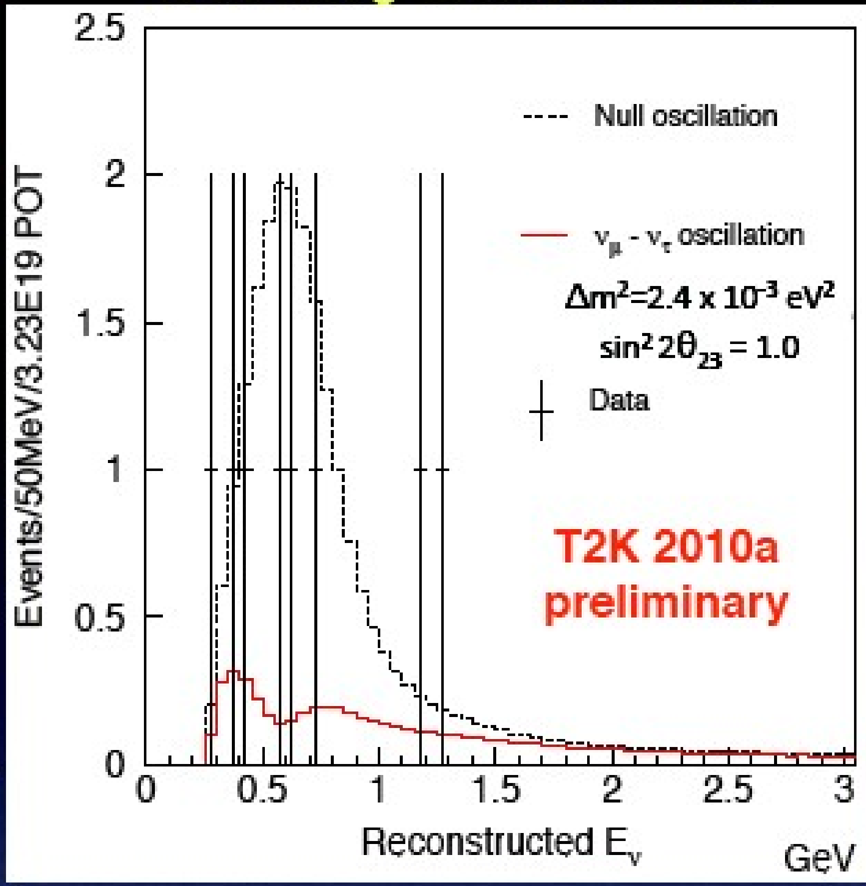
ν_μ disappearance analysis

Event selection for muon disappearance measurement

T2K-SK events	Data	MC		Acc.BG (12μs window)
		No oscillation	W/ oscillation	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring μ-like P_μ>200MeV/c	**8**	24.5±3.9	7.1±1.3	-
+ number decay-e <=1 & Erec<10 GeV	**8**	22.8±3.2	6.3±1.0	-

W/ oscillation: $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1.0$

Reconstructed energy assuming QE kinematics



- Consistent with oscillation parameters measured by MINOS / SK / K2K
- Parameter fitting underway – T2K plans to release result in the near future

ν_e appearance analysis

T2K

Event selection for electron appearance search

T2K-SK events	Data	MC		Acc. BG (12μs window)
		No oscillation	With oscillation and θ_{13}=0	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring e-like P_e>100MeV/c	**2**	1.5±0.7	1.3±0.6	-

Assumed oscillation parameters: Δm^2=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$ = 1.0 and θ_{13} = 0

Apply additional background reduction cuts:

- # of decay electron ($\mu \rightarrow e+\nu_e$) =0
- Reconstructed invariant mass assuming 2γ rings exist <105MeV
- Reconstructed ν energy < 1250 MeV

Cut criteria were frozen before data collection to avoid bias

After all cuts: 65.9% signal efficiency

Combined systematic errors

T2K

Estimated combined total systematic error from each source group on electron events in SK, constrained by ND280 normalization

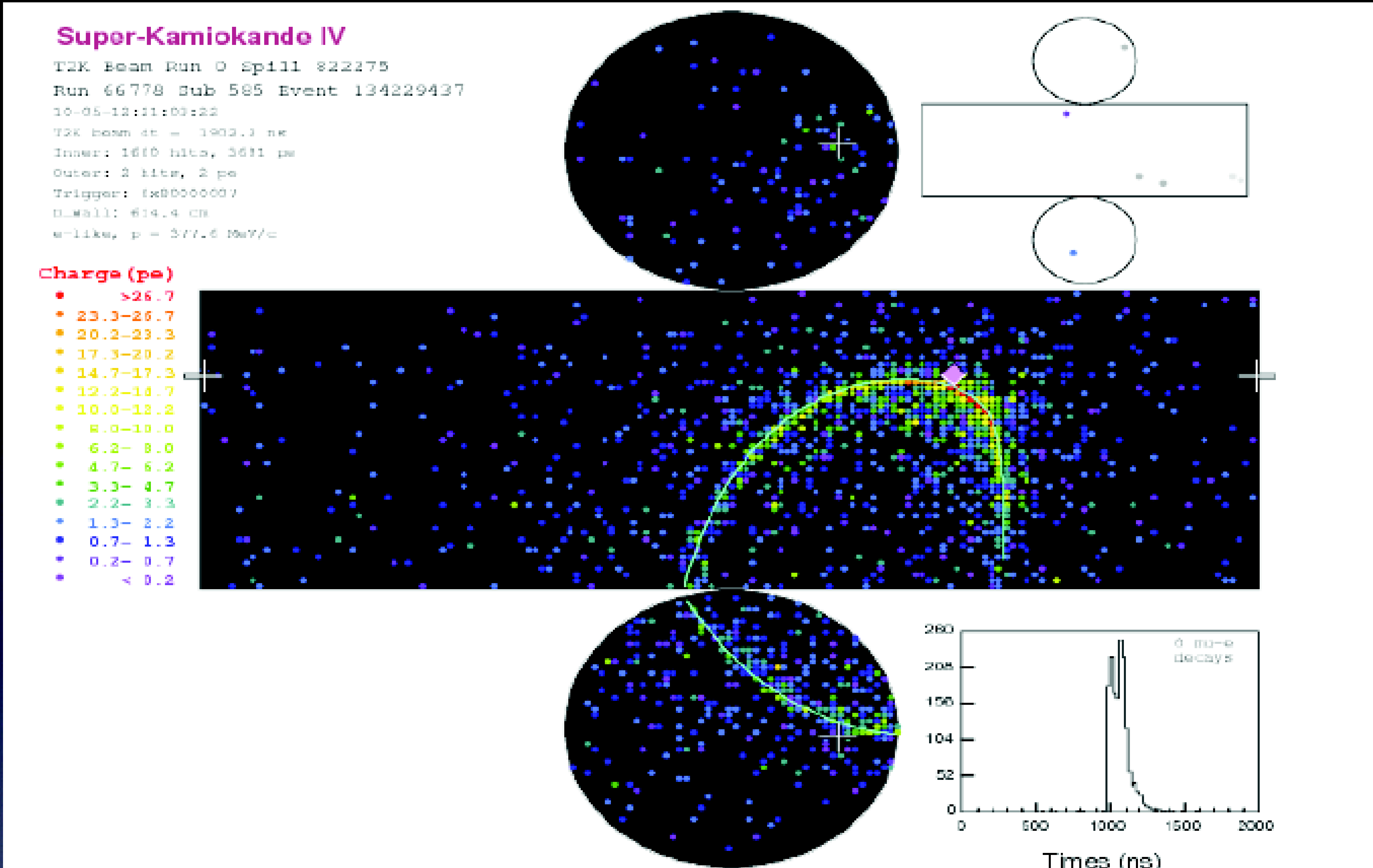
Error source	N_{SK}^{sig}	N_{SK}^{bkg}	N_{SK}^{s+b}	N_{ND}	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Efficiency	$\pm$ 7.6	$\pm$ 15.8	$\pm$ 9.5		$\pm$ 15.8	$\pm$ 9.5
Cross section	$\pm$ 9.7	$\pm$ 13.9	$\pm$ 9.9	$\pm$ 8.4	$\pm$ 14.3	$\pm$ 10.6
Beam Flux	$\pm$ 22.0	$\pm$ 18.1	$\pm$ 20.5	$\pm$ 19.8	$\pm$ 8.9	$\pm$ 11.9
ND Efficiency				$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm.					$\pm$ 2.7	$\pm$ 2.7
Total	$\pm$ 25.2%	$\pm$ 27.8%	$\pm$ 24.7%	$^{+22.2}_{-22.1}$%	$^{+23.9}_{-23.8}$%	$^{+19.5}_{-19.4}$%

★ ~24% total systematic error for background only hypothesis

★ ~20% total systematic error for signal + background hypothesis

Δm^2_{23}=2.4·10^{-3}eV^2
$\sin^2 2\theta_{23}$=1.0, $\sin^2 2\theta_{13}$=0.1
δ_{CP} = 0

Signal candidate event passing all cuts

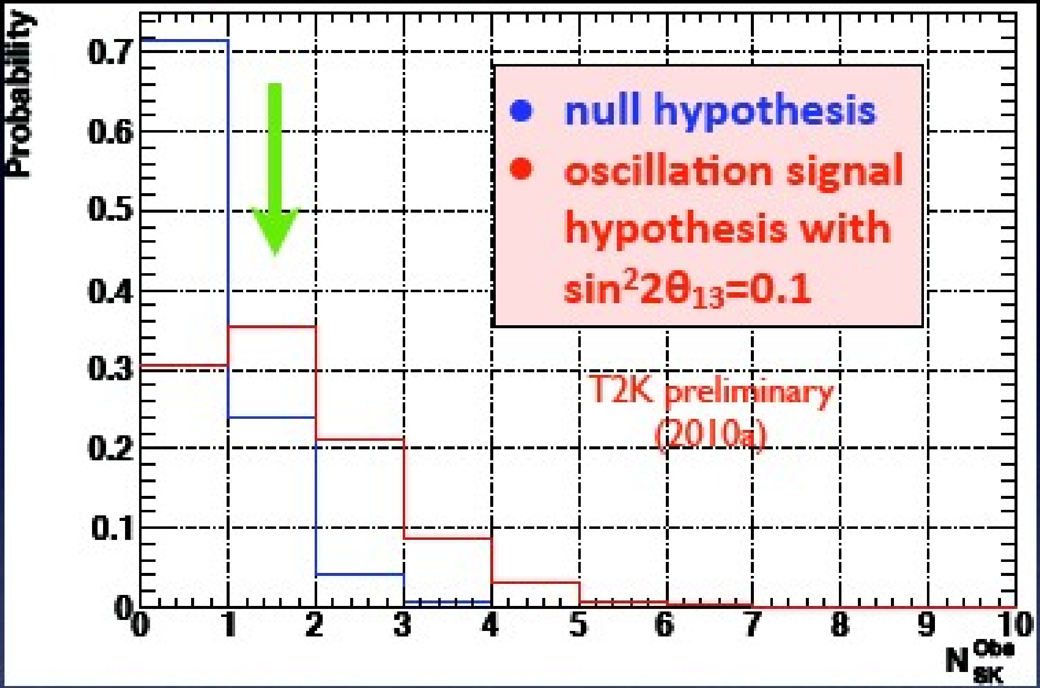


Expected #SK events

Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\bar{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	0.30 ± 0.07 (syst.)
Total sig.+background	1.20 ± 0.23 (syst.)

- #events normalized to p.o.t. and corrected for ND280 ν_μ CC measured normalization
- Assumed oscillation parameters for signal:

$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP}=0$



T2K preliminary
(2010a)

~29% probability to observe >=1 event when expected average = 0.3 event

1 data candidate!

$N_{SK}^{obs} = 1$

T2K appearance upper limit results

Two independent statistical procedures

T2K preliminary
(2010a)

Assuming $\Delta m^2_{23}=2.4\cdot 10^{-3}eV^2$ and $\sin^2 2\theta_{23}=1.0$, $\delta_{CP}=0$:

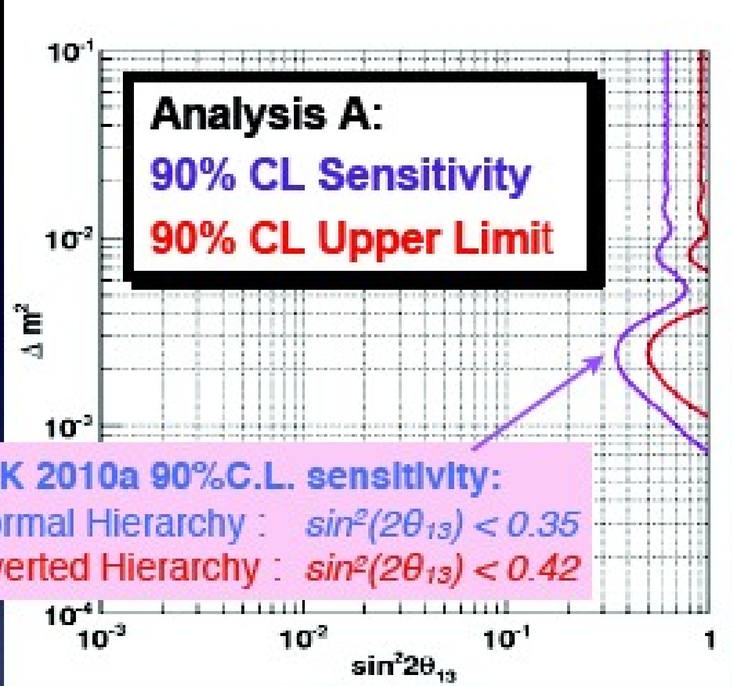
(A) Feldman-Cousins

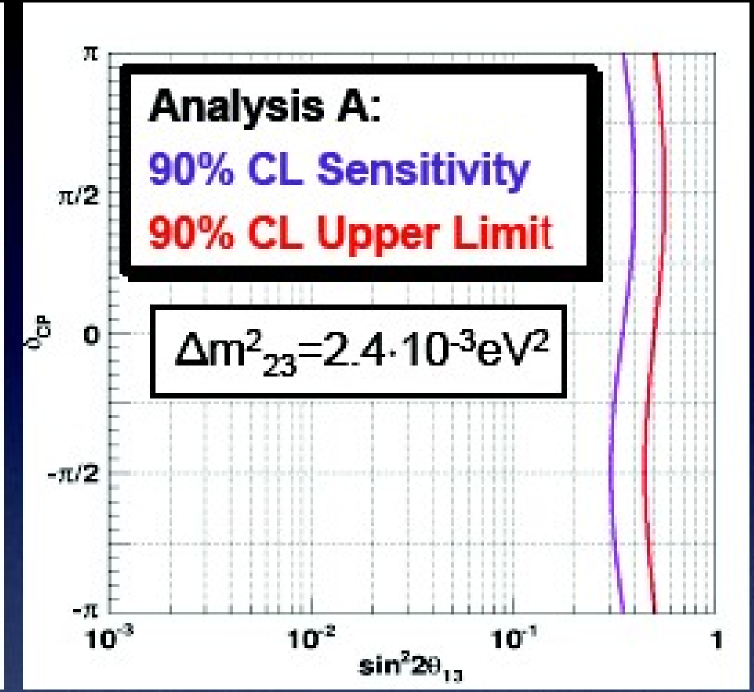
Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.50$ (90%C.L.)
Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.59$ (90%C.L.)

(B) Classical one-sided

Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.44$ (90%C.L.)
Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.53$ (90%C.L.)

- More collected data on tape
- Analyses underway

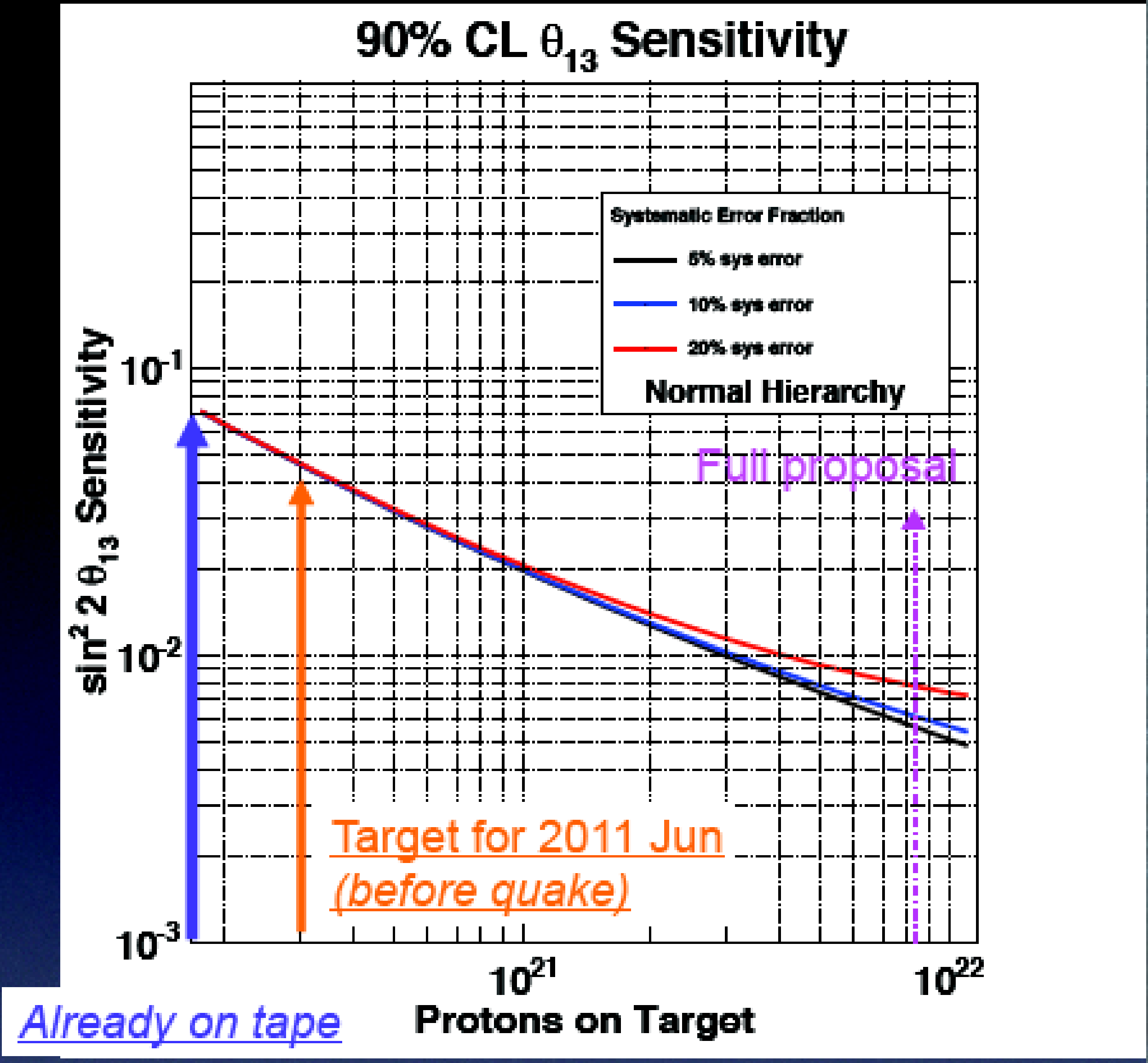




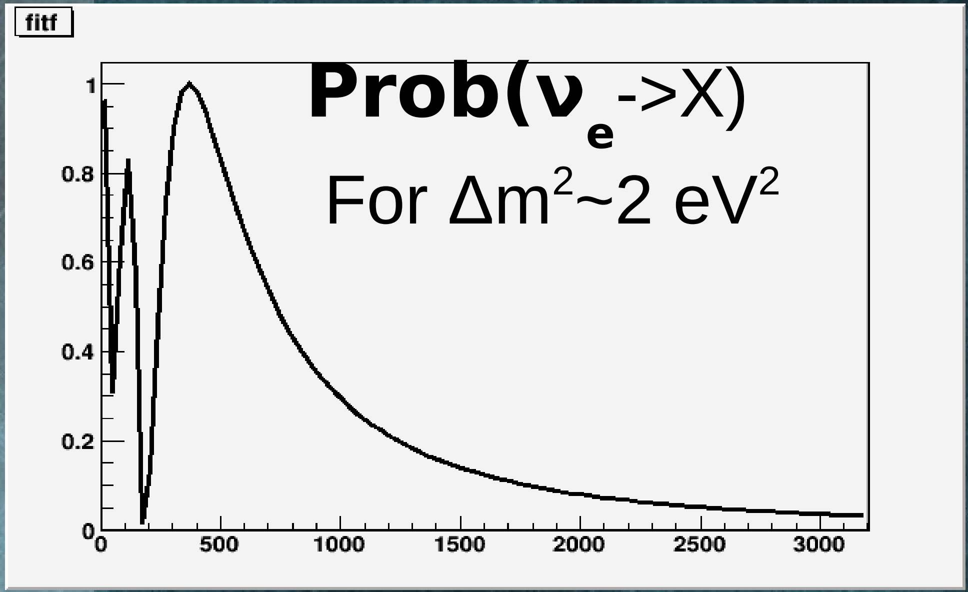
Prospects for updated results

- 1.45×10^{20} p.o.t. on tape = 73kW*1e7 s = 4.5x(2010a)
- Aim at 3×10^{20} p.o.t. = 150kW*1e7 s by July 2011 (quake→??)
- Analysis improvements underway
  - New NA61 results → Systematic error uncertainty from hadron production will be reduced.
  - Spectrum measurement in ND and near/far ratio to reduce model dependence

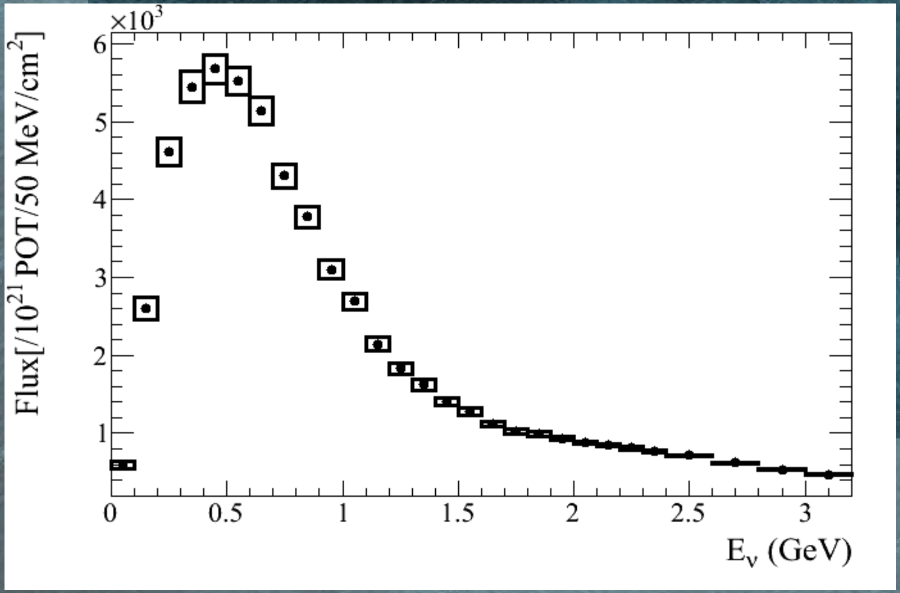
Signal sensitivity vs p.o.t.

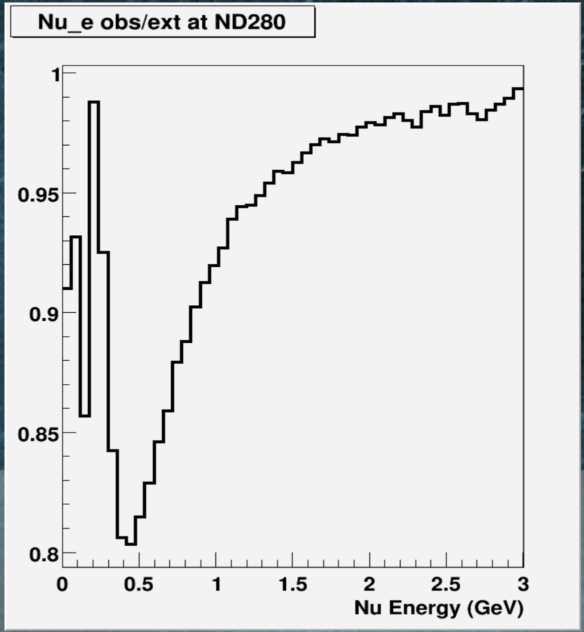


Can T2K ND280 probe $\nu_e \rightarrow$ sterile oscillation ?



- ν_e spectrum peaked at 500 MeV
- ND280 is sensitive to ν_e->X oscillation with Δm^2~2 eV^2
- ν_e flux is ~ 1% of total
- Need to control other backgrounds
- Current data set (2010+2011): ~ 50 ν_e at ND
- This study will continue: beam ν_e meas. is one important contribution by ND to the T2K progr





Conclusions

- T2K started physics running in Jan 2010
- ND280 TPC ; excellent performances for the 1st TPC with MPGD
- First $\nu_\mu \to \nu_e$ oscillation analysis with 3.23 10^{19} POT: 1 evt selected, exp. Bck 0.30+-0.07
- Observed ν_μ CC candidates consistent with neutrino oscillation parameters
- Total sample: 1.45 10^{20} being analyzed. Expected sensitivity better than CHOOZ
- Full impact of the earthquake being assessed