Indication of $\nu_\mu \rightarrow \nu_e$ appearance in the T2K EXPERIMENT

θ_{13}

Alain Blondel – University of Geneva
On behalf of the T2K collaboration

There are today THREE compelling and firmly established observational facts that the Standard Model fails to account for:

-- neutrino masses
-- the existence of dark matter
-- the baryon asymmetry of the universe

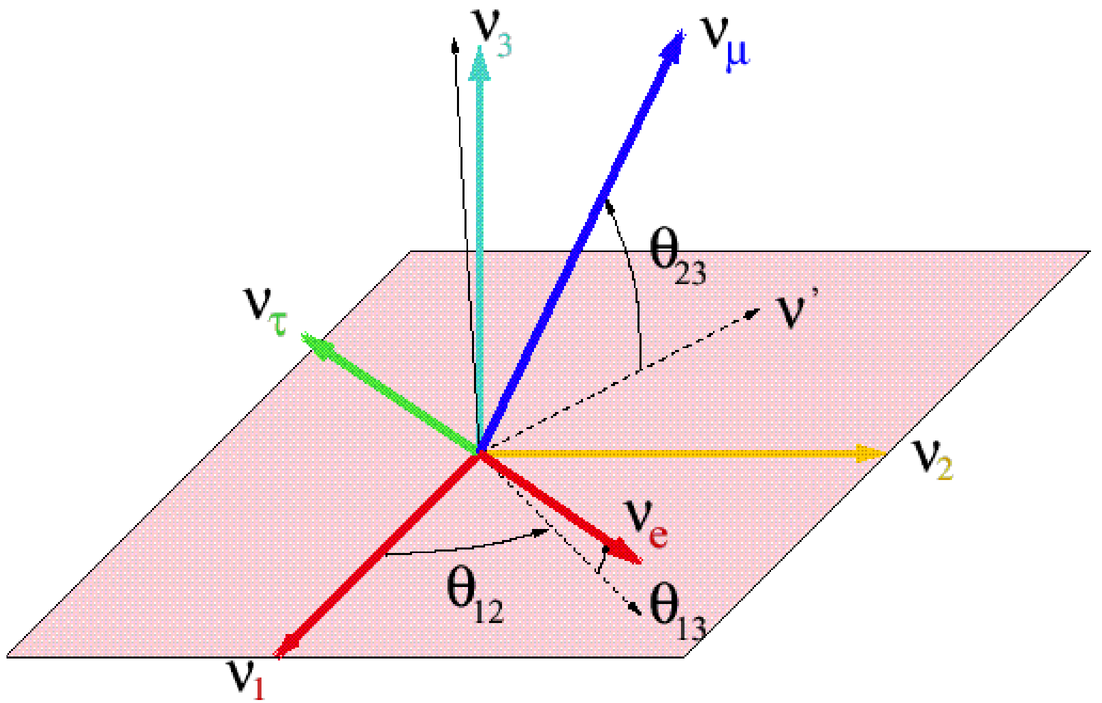
The fact that neutrino have masses and mix is established by neutrino oscillations

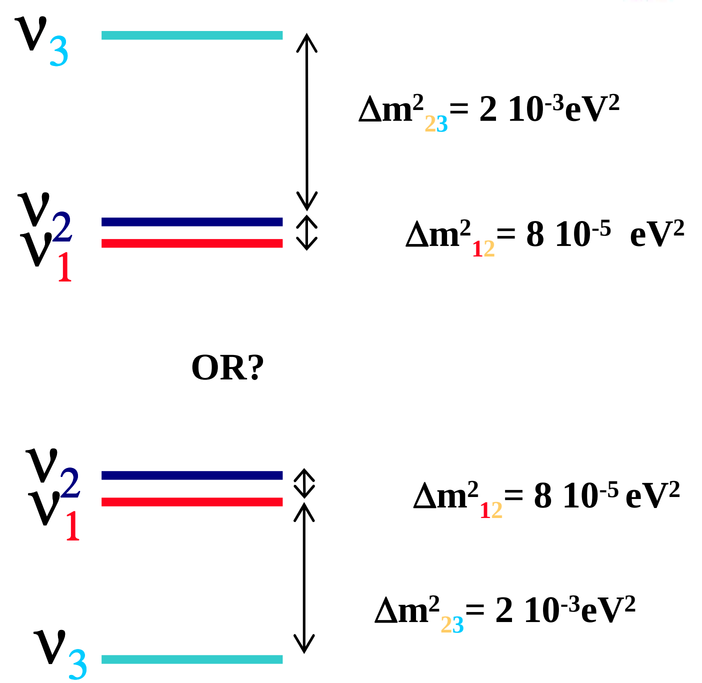
The neutrino masses offer a chance to explain the baryon asymmetry in the most natural way via

***** LEPTOGENESIS *****

by a combination of
-- fermion number violation (authorized by neutrino masses and GUT)
-- three families of neutrinos ==> leptonic CP violation
(authorized by the mixing of three families with large mixing angles)

The neutrino mixing matrix: 3 angles and a phase δ





θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 32^0, θ_{13} (Chooz) < 13^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known
θ_{13}, phase δ, sign of Δm^2_{13}

Ieutrino oscillations: where we are

Updated global 6-parameter fit (including δ_{CP}):

- **Solar**: Cl + Ga + SK-I + **SNO-leta (I+II)** + SNO-III + BX-low + BX-high;
- **Atmospheric**: SK-I + SK-II + **SK-III**;
- **Reactor**: Chooz + KamLAND;
- **Accelerator**: K2K + **Minos-DIS** + **Minos-APP**;

BPS09(GS): best-fit and 1σ (3σ):

$$\theta_{12} = 34.4 \pm 1.0 \left({}^{+3.2}_{-2.9}\right), \quad \Delta m^2_{21} = 7.59 \pm 0.20 \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \left({}^{+10.7}_{-7.3}\right), \quad \Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2, \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2, \end{cases}$$

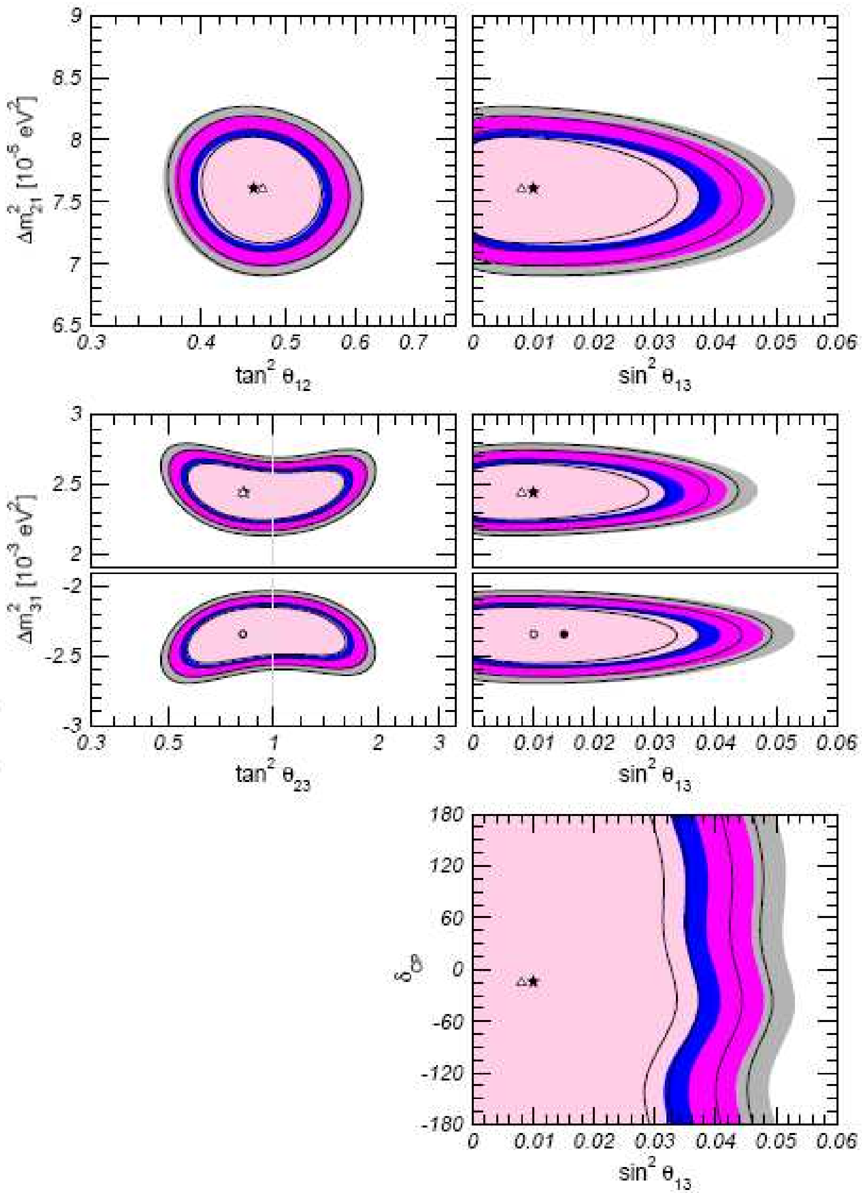
$$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7}\ (\leq 12.5), \quad \delta_{CP} \in [0, 360];$$

BPS09(AGSS): same as above except:

$$\theta_{12} = 34.5 \pm 1.0 \left({}^{+3.2}_{-2.8}\right), \quad \theta_{13} = 5.1\,{}^{+3.0}_{-3.3}\ (\leq 12.0);$$

"$\theta_{13} \neq 0$":

Solar model	Sol+Kam	Global
BPS09(GS)	1.26σ	1.31σ
BPS09(AGSS)	1.05σ	1.17σ



[Gonzalez-Garcia, MM & Salvado, arXiv:1001.4524]

Oscillation maximum $1.27\,\Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.4\ 10^{-3}\ eV^2$ $L = 500$ km @ 1 GeV

Solar $\Delta m^2 = 7.6\ 10^{-5}\ eV^2$ $L = 16000$km @ 1 GeV

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_e$ oscillation at L_{atm}

(acc) $P(\nu_\mu \leftrightarrow \nu_e)_{max}$ =~ ½ $\sin^2 2\theta_{13}$ +… (small)

(reactor) $P(\nu_e \leftrightarrow \nu_e)_{max}$ =~ 1 - $\sin^2 2\theta_{13}$ +…(small)

II There will be CP or T violation

CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

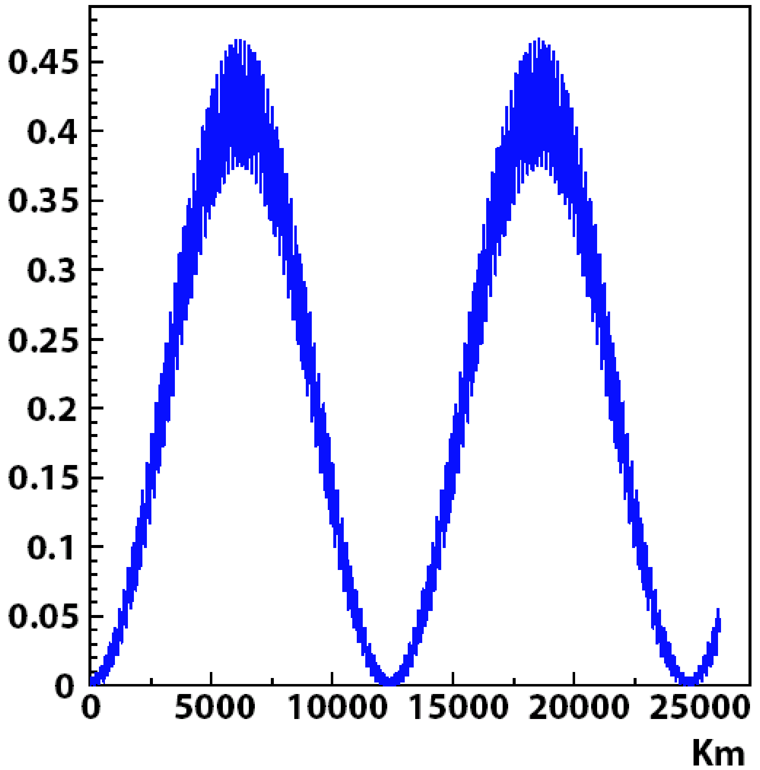
T : $P(\nu_\mu \leftrightarrow \nu_e) \neq P(\nu_e \leftrightarrow \nu_\mu)$

1st maximum ≠ second maximum

III. we do not know if the neutrino ν_1 (which contains more ν_e) is the lightest one (natural?) or not.

Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



$$P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\,\sin\delta$$

$$\bar{P}(\nu_e \bar{\to} \nu_\mu) = |A|^2 + |S|^2 - 2\,A\,S\,\sin\delta$$

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP} \propto \frac{\sin\delta \;\; \sin(\Delta m^2_{12} L/4E) \;\; \sin\theta_{12} \sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}\ldots}$$

… need large values of sin θ_{12}, Δm^2_{12} (LMA-- we have it!) but *not* large $\sin^2\theta_{13}$

… need APPEARANCE … $P(\nu_e \to \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (100%) for suppressed channel (one small angle vs two large)

at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \to \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$

Three family oscillations and $\nu_\mu \rightarrow \nu_e$ oscillation

Mezzetto

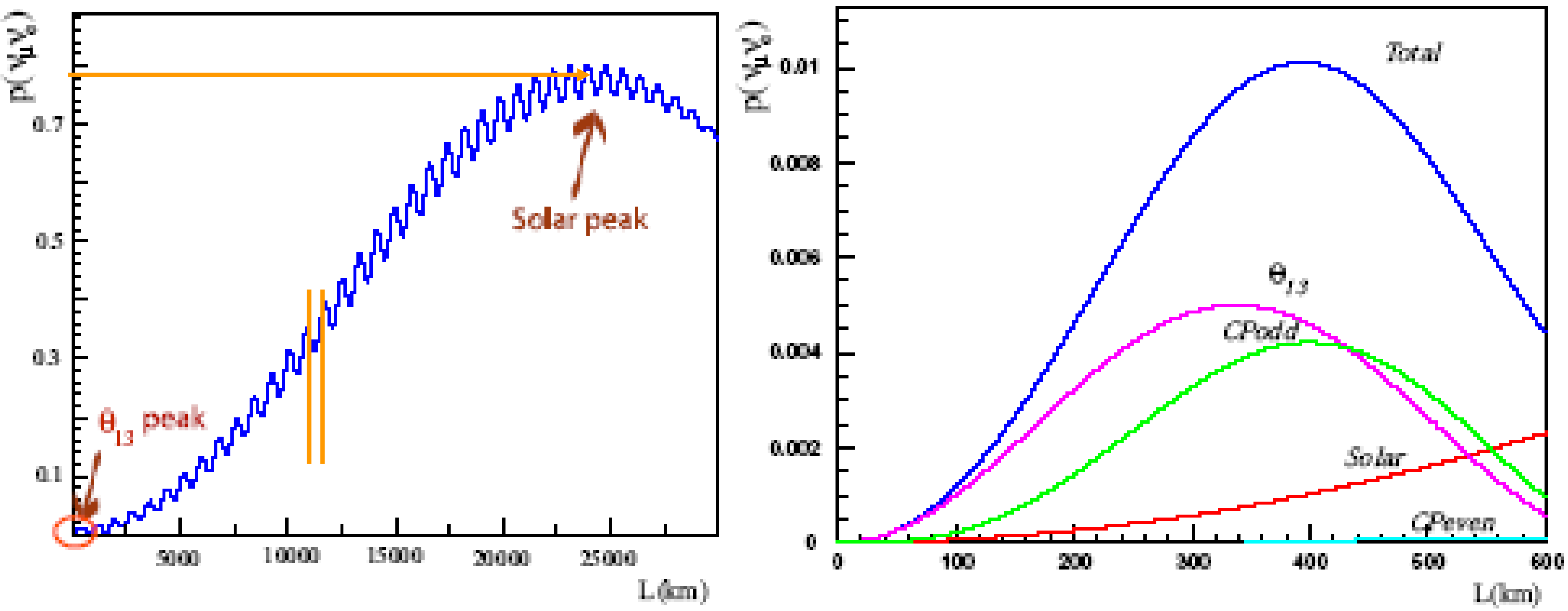


Figure 3: Sketch of $P(\nu_\mu \rightarrow \nu_e)$ as function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for δ_{CP} =0 (left) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (right), where the different terms of eq. 4 are displayed. The following oscillation parameters were used in both cases: $\sin^2 2\theta_{13} = 0.01$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2, $\Delta m^2_{12} = 7 \cdot 10^{-5}$ eV^2.

$$P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\;\sin\delta$$

$$\bar{P}(\nu_e \bar{\to} \nu_\mu) = |A|^2 + |S|^2 - 2\,A\,S\;\sin\delta$$

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP} \;\alpha\; \frac{\sin\delta \;\; \sin(\Delta m^2_{12} L/4E) \;\; \sin\theta_{12} \sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term…}}$$

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at wavelength at which ‘solar’ = ‘atmospheric’ and for $\nu_e \to \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$

NOTES:

Asymmetry can be very large.

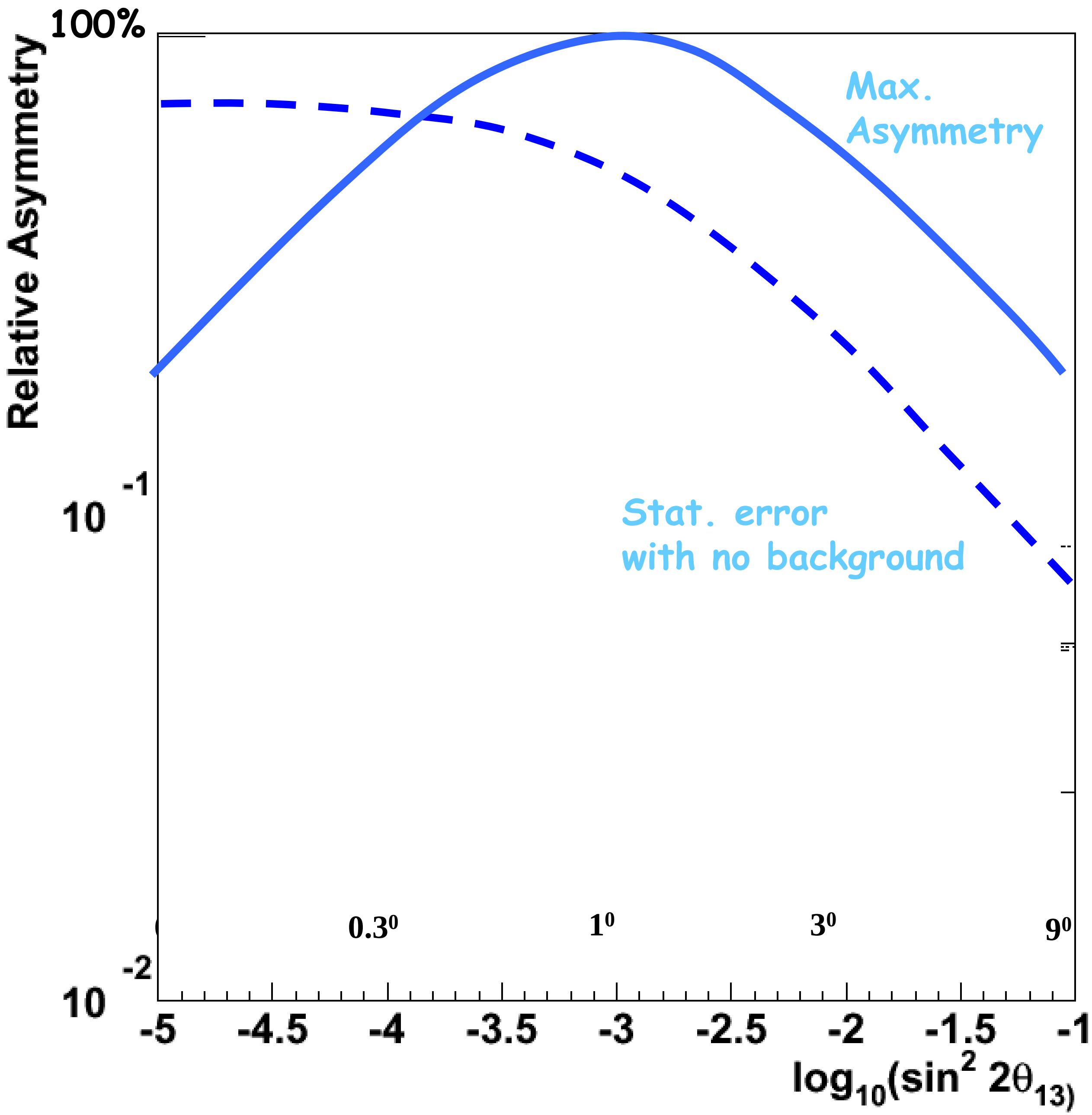
Stat. sensitivity
in absence of bkg
is ~independent of θ_{13}
down to max. asym. point

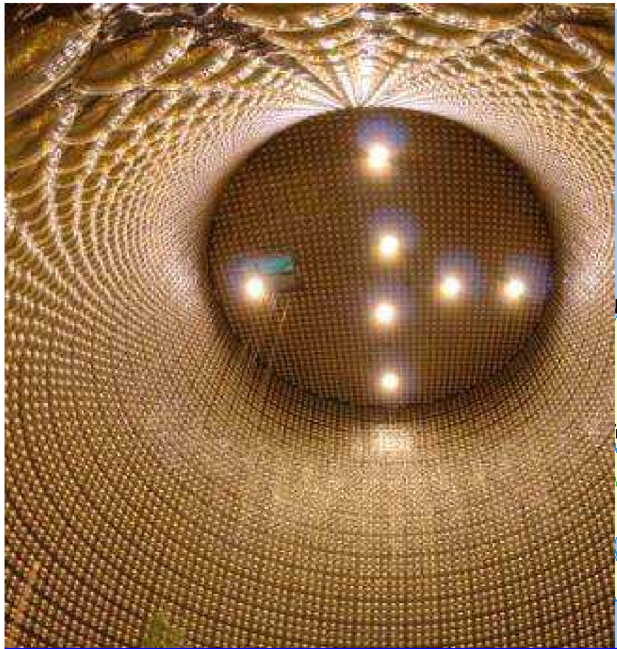
Asymmetry changes sign
from one max. to the next.

Sensitivity at low values
of θ_{13} is better for short
baselines, sensitivity at
large values of θ_{13} is
better for longer baselines
(2d max or 3d max.)

sign of asymmetry changes
with max. number.

T asymmetry for sin $\delta = 1$





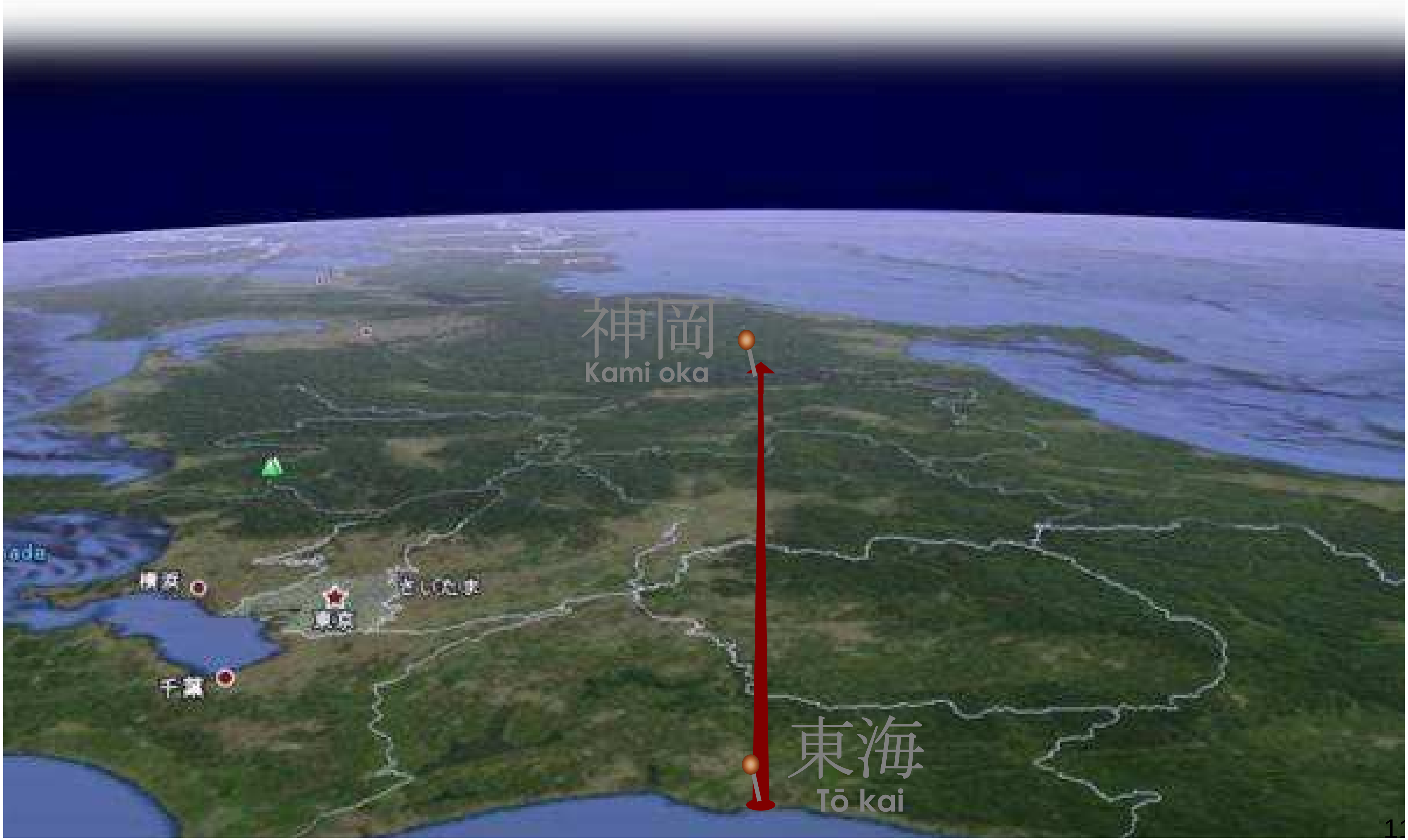
Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)

-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/50GeV Proton Synchrotron

-- baseline 295 km ➔ neutrino energy for first maximum is ~600 MeV achievable by pion-decay beam at 2.5 degrees off-axis

T2K



~500 members, 61 Institutions, 12 countries

Canada
TRIUMF
Univ. Alberta
Univ. Brit. Columbia
Univ. Regina
Univ. Toronto
Univ. Victoria
York Univ.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Univ. Aachen

Italy
INFN, Univ. Rome
INFN, Univ. Naples
INFN, Univ. Padua
INFN, Univ. Bari

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe Univ.
Kyoto Univ.
Miyagi Univ. of Educ.
Osaka City Univ.
Univ. Tokyo

Poland
Soltan Inst., Warsaw
Niewodniczanski Inst., Cracow
Technical Univ. Warsaw
Univ. Silesia, Katowice
Univ. Warsaw
Univ. Wrocław

Russia
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S. Korea
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Warwick Univ.
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Duke Univ.
Louisiana St. Univ.
SUNY-Stony Brook
U. C. Irvine
Univ. Colorado
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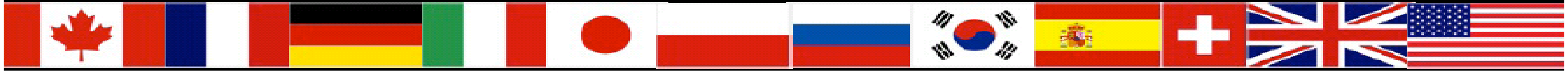
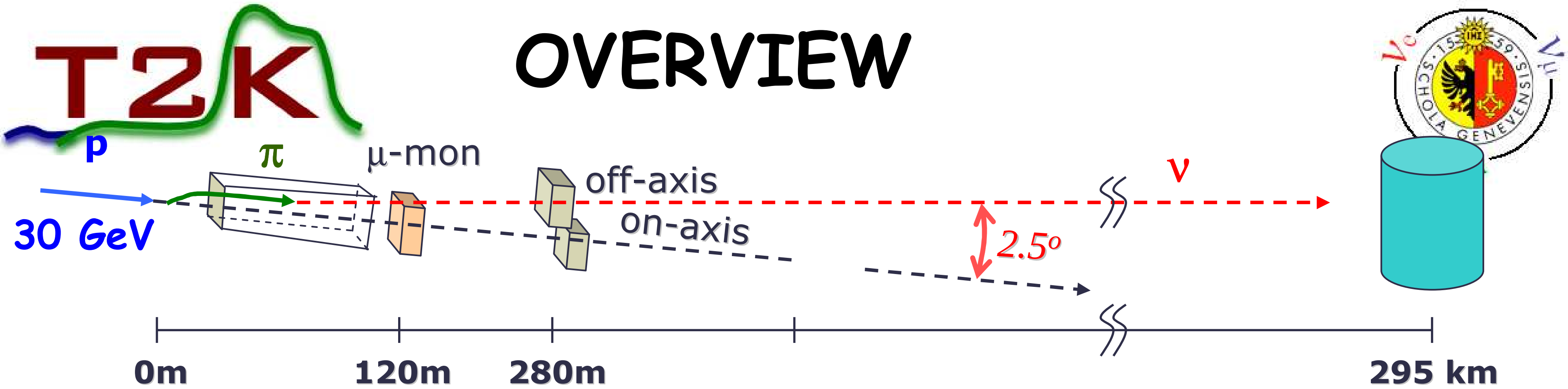
Univ. Rochester
Univ. Washington



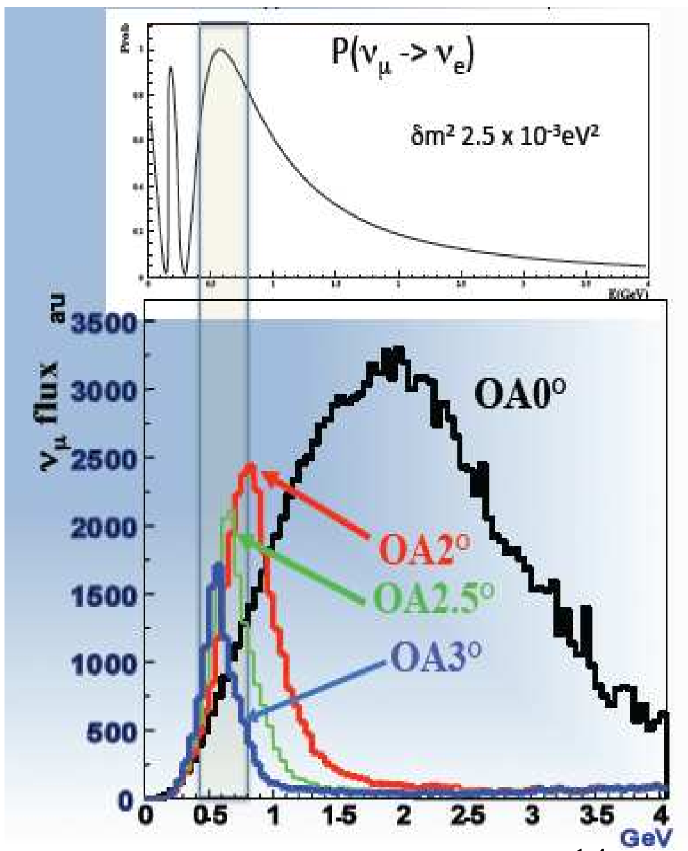
University of Geneva:
N. Abgrall, J. Argyriades, A. Blondel, A. Bravar, F. Dufour, A. Ferrero, A. Haesler, A. Korzenev, S. Murphy, M. Ravonel, G. Wikström

OVERVIEW



- **2.5 degrees off-axis beam**
  - Low energy, narrow band beam tuned at osc. max.
  - Neutrino peak ~600 MeV/c
- **Near detector @ 280 m from target**

⇒ extrapolate ν energy spectrum and flux to SK
  - **INGRID:** on axis to monitor beam direction
  - **ND280:** off axis to measure ν_μ and ν_e interaction rates and backgrounds
- **NA61 at CERN**
  → **hadro-production measurement**
- **Far detector SuperKamiokande @ 295 km**
  - Very large water Cerenkov detector
  - Very good μ/e separation capability for sub-GeV neutrinos



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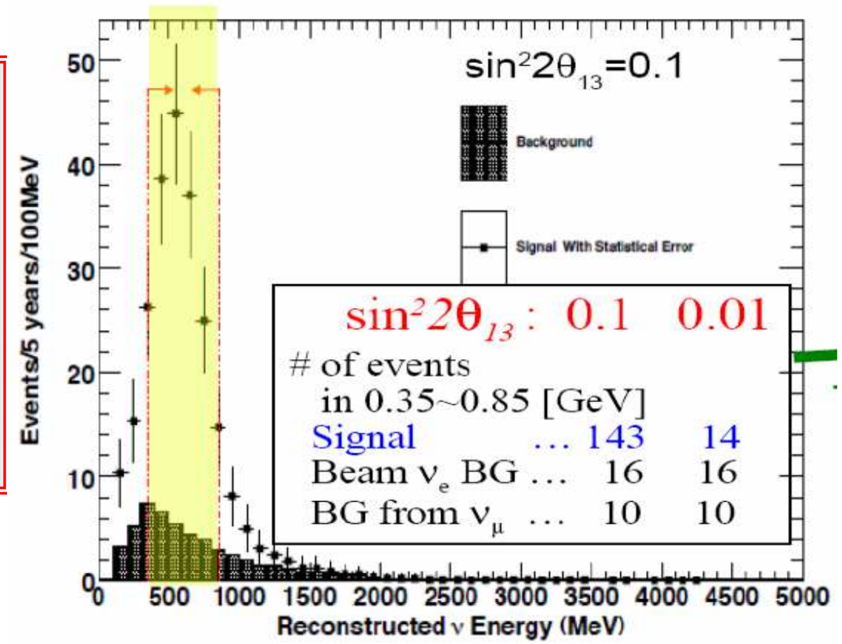
T2K physics goals

Experiment is optimized for the search of

$\nu_\mu \to \nu_e$ oscillation ➔ θ_{13}

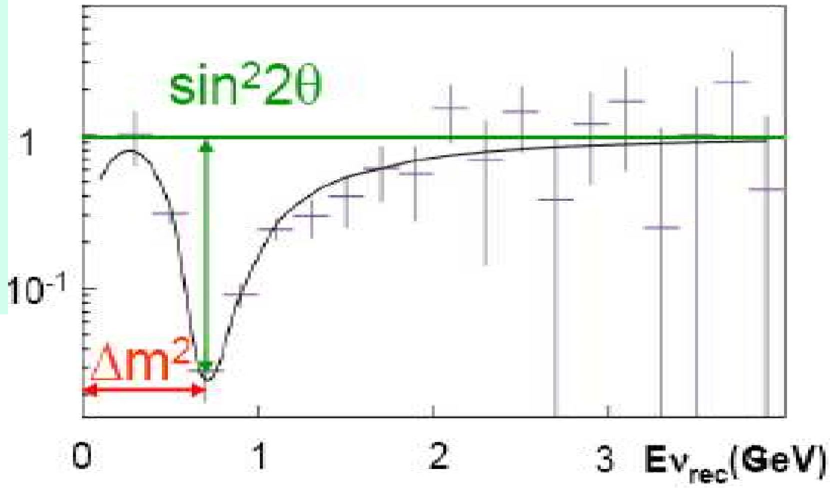
$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin(1.27\ \Delta m^2_{23}\ L/E_\nu)$$



-- is also able of precision measurement of

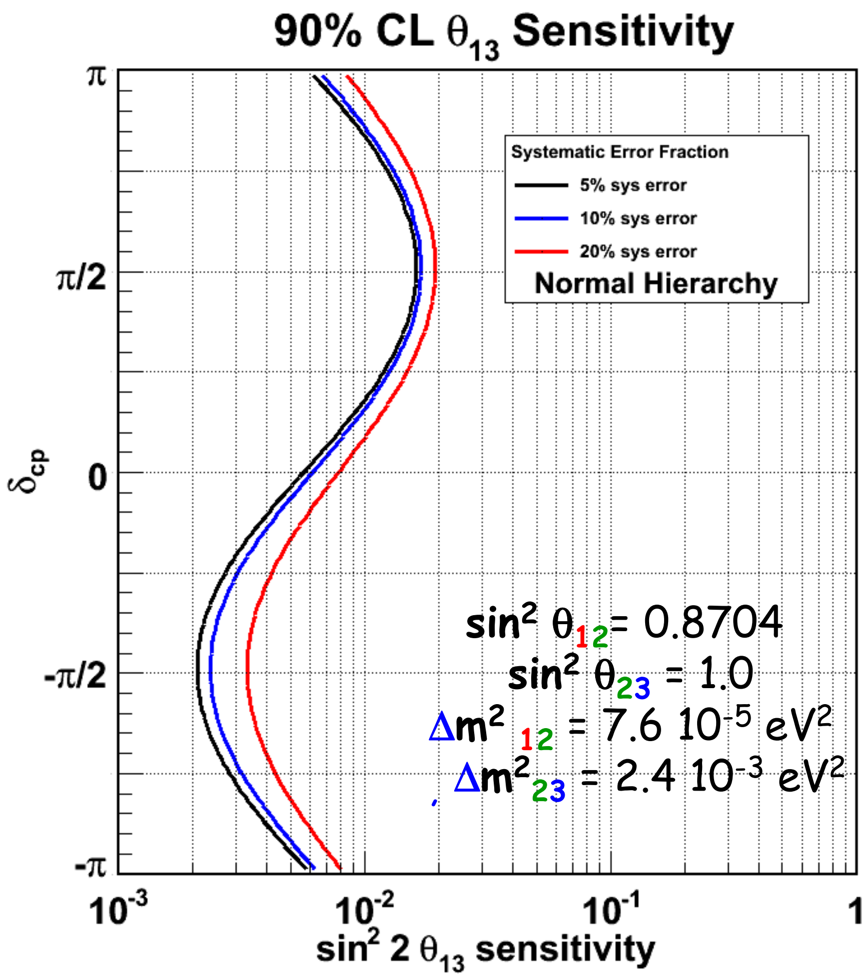
$\nu_\mu \to \nu_\mu$ oscillation ➔ θ_{23}, Δm^2_{23}

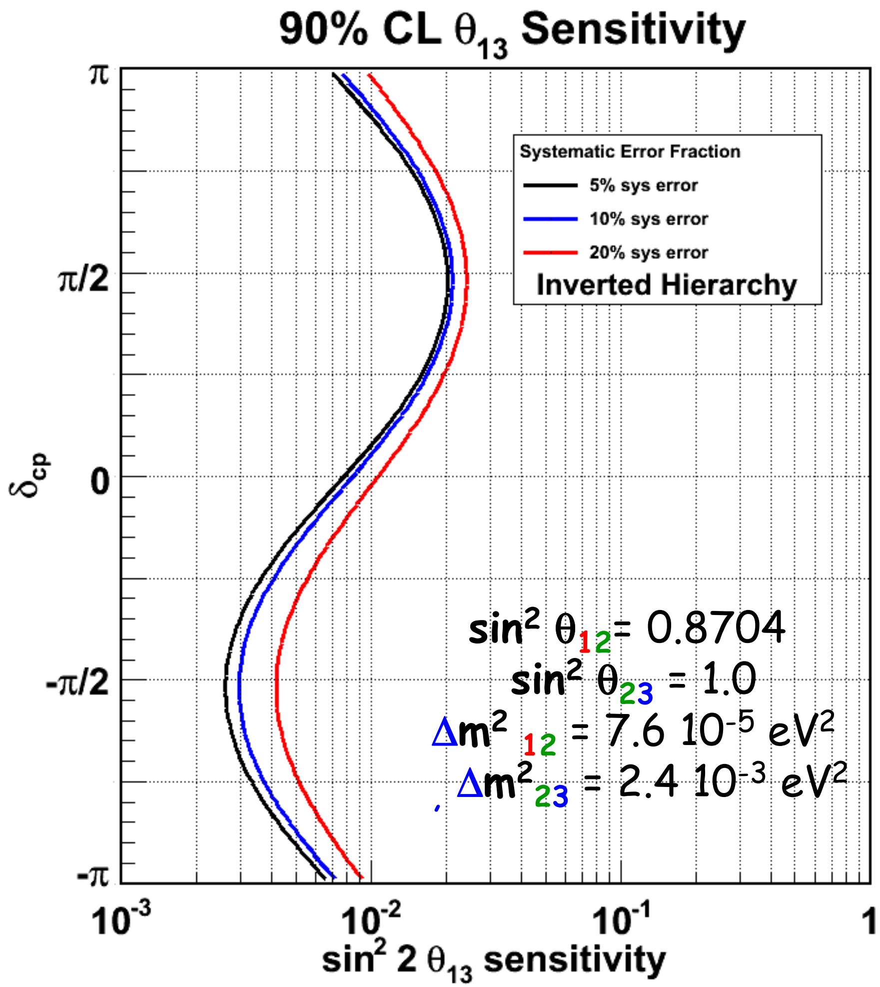
$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin(1.27\ \Delta m^2_{23}\ L/E_\nu)$$



-- and measurements of cross-sections around 600 MeV in the near detector

θ_{13}

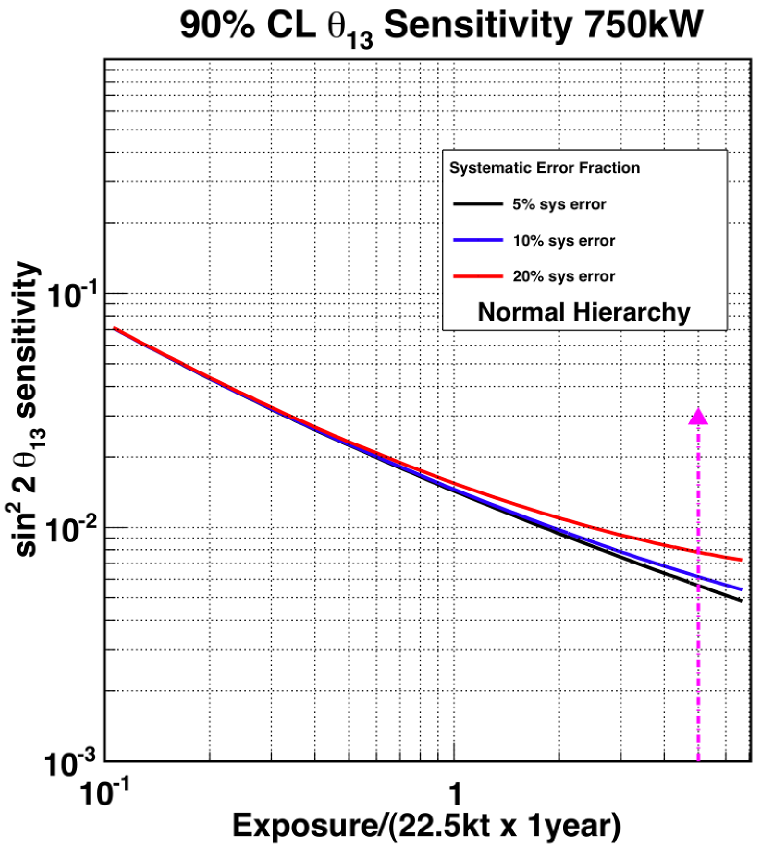




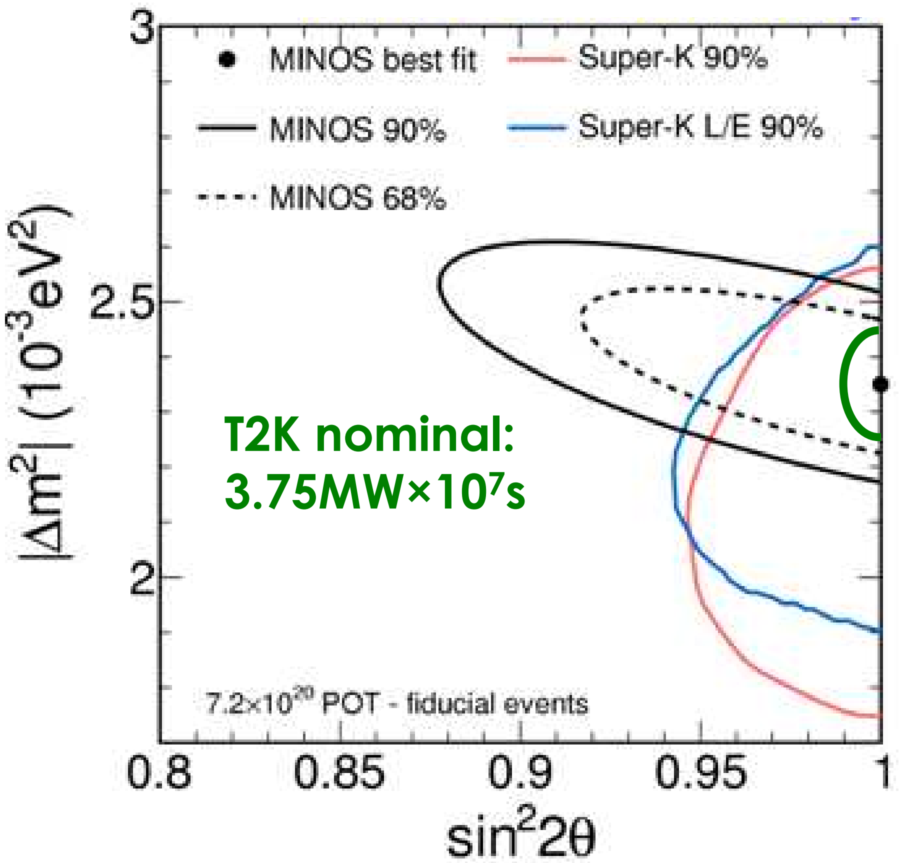
90% C.L. 750kW X 5 years X 22.5 kton fid.

short baseline ➔ little sensitivity to matter effects, but sensitive to δ_{CP}

Appearance: Dis-appearance



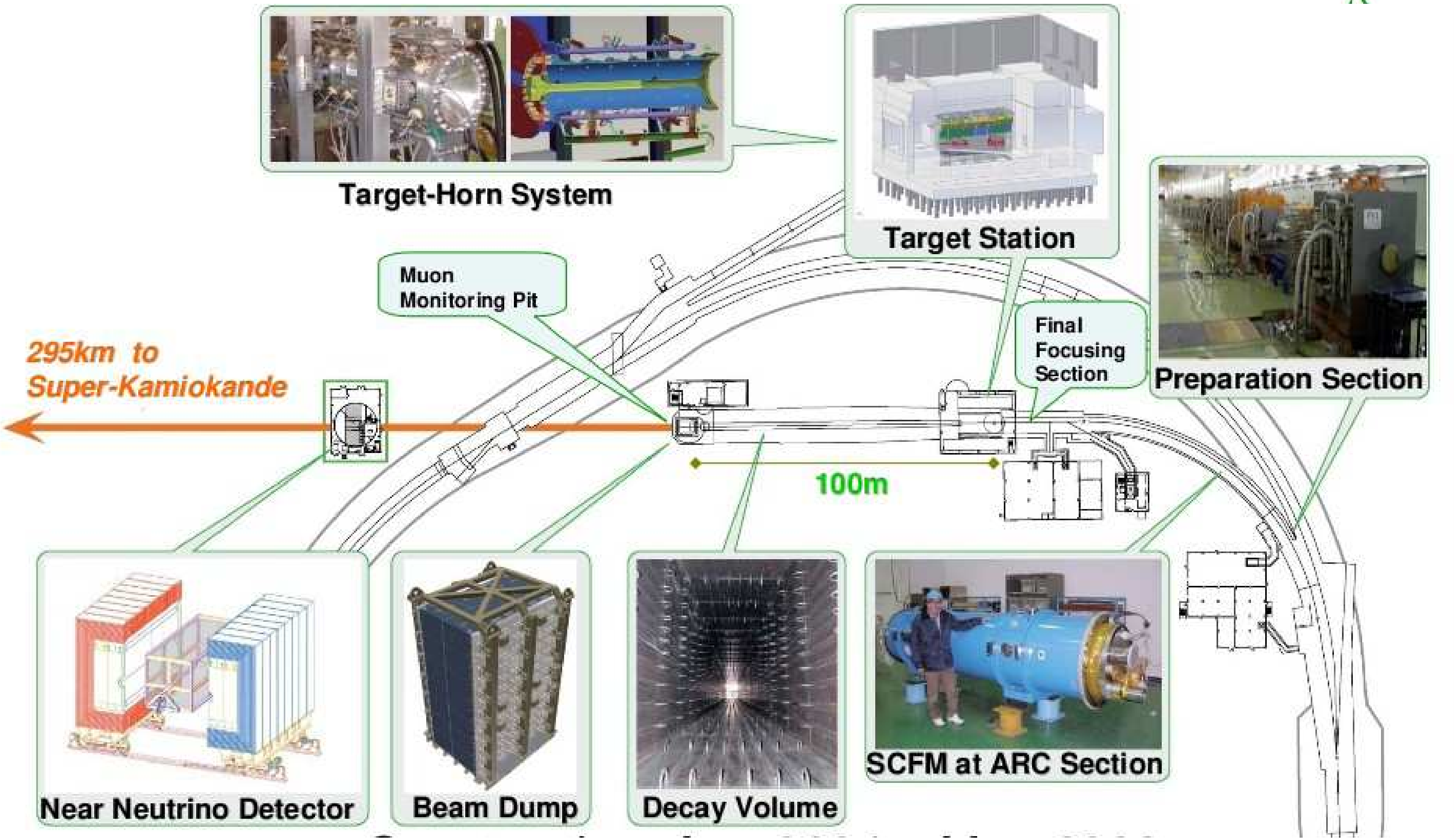
MINOS & Super-K preliminary @ Nu'10



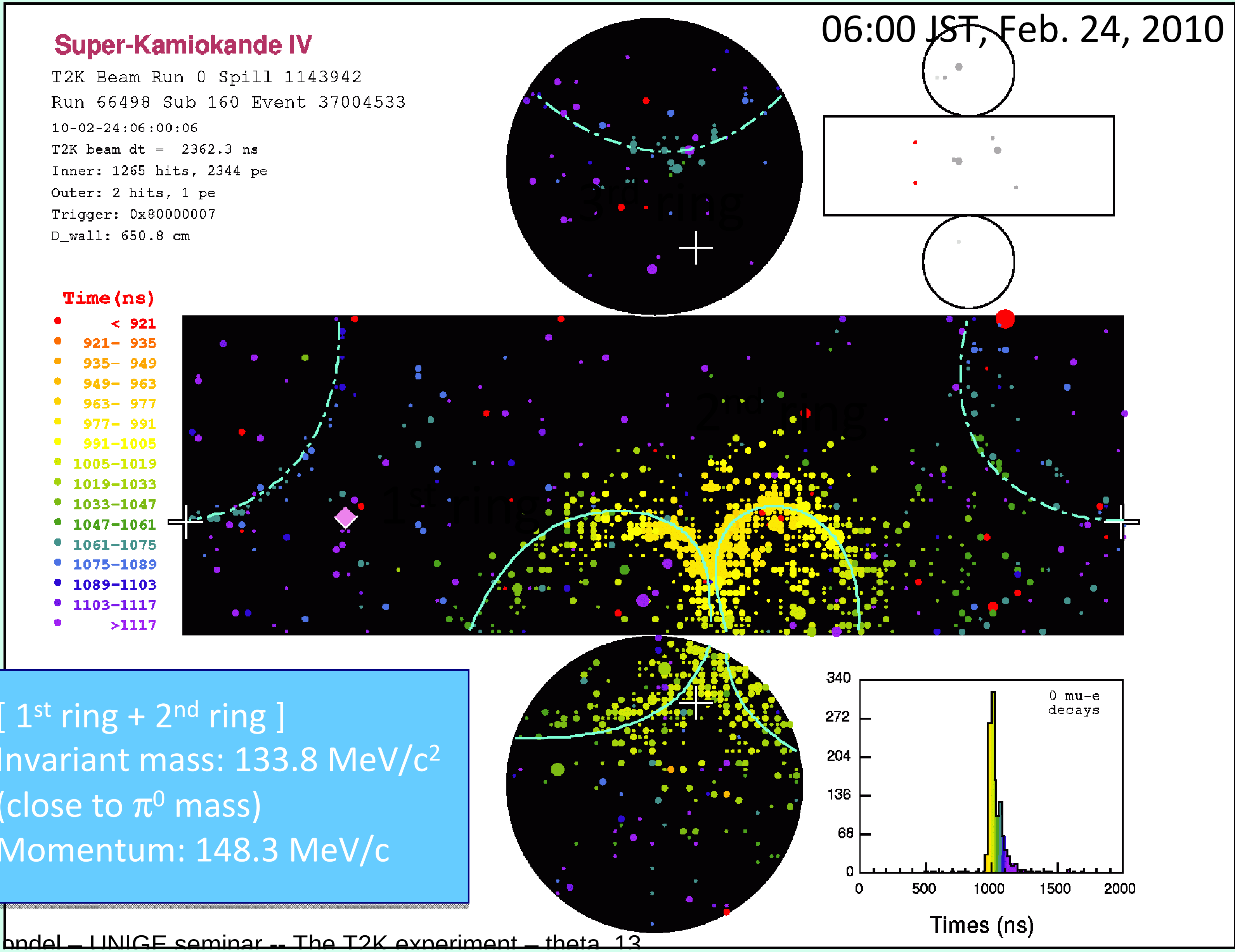
$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)
for 5 years@750kW
= 8.3 10^{21} p.o.t@30 GeV

spectrum centered on oscillation maximum
→very rapidly sensitive to Atm. Params.
$\Delta\sin^2 2\theta_{23} \approx 0.01$
$\Delta m^2_{23} < 1\times10^{-4}$ eV^2

Beam Line


Target-Horn System
Target Station
Preparation Section
Muon
Monitoring Pit
Final
Focusing
Section
295km to
Super-Kamiokande
100m
Near Neutrino Detector
Beam Dump
Decay Volume
SCFM at ARC Section

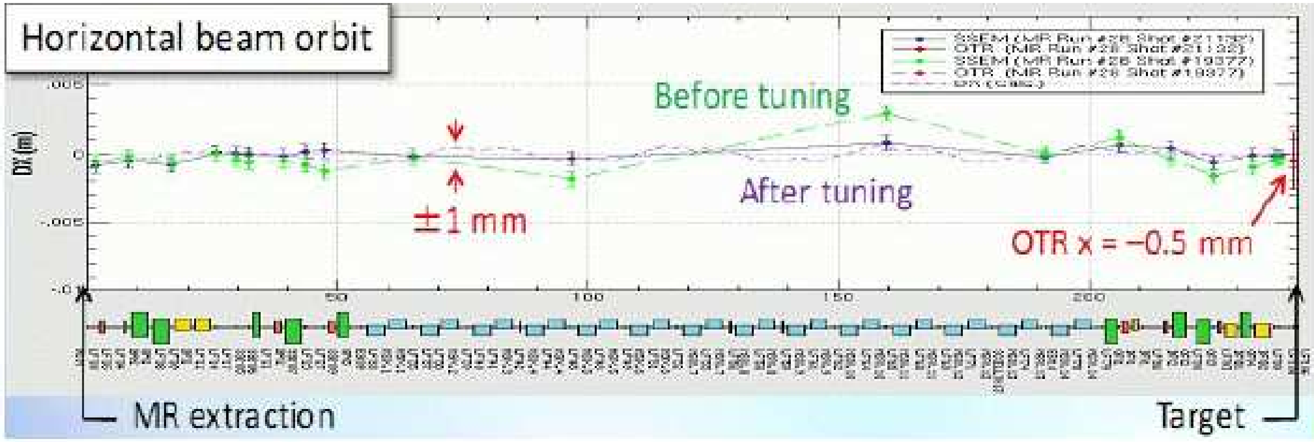
T2K 1st ν event in Super-K

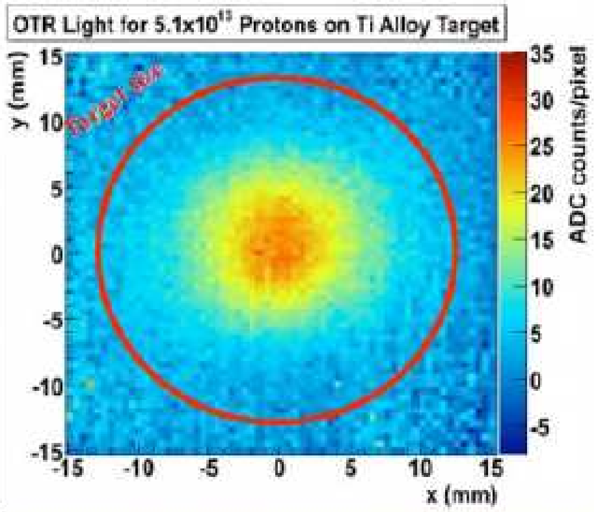


[1^{st} ring + 2^{nd} ring]
Invariant mass: 133.8 MeV/c^2
(close to π^0 mass)
Momentum: 148.3 MeV/c

Beam Monitors

Proton beam precisely tuned (<1mm) to minimize beam loss, and control direction of secondary beam

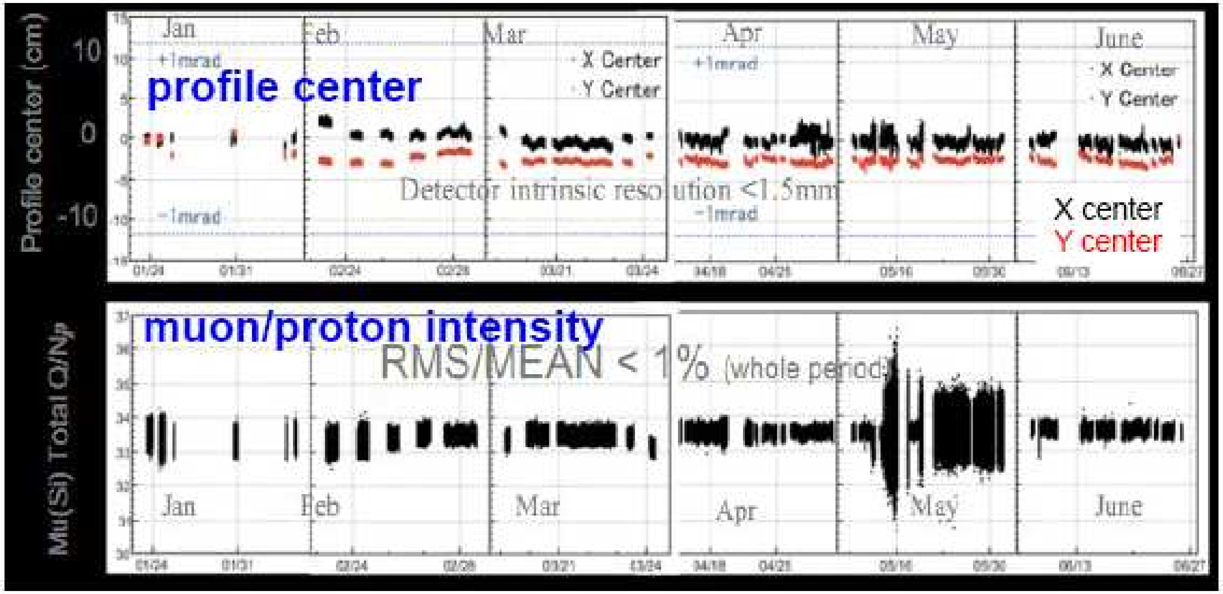




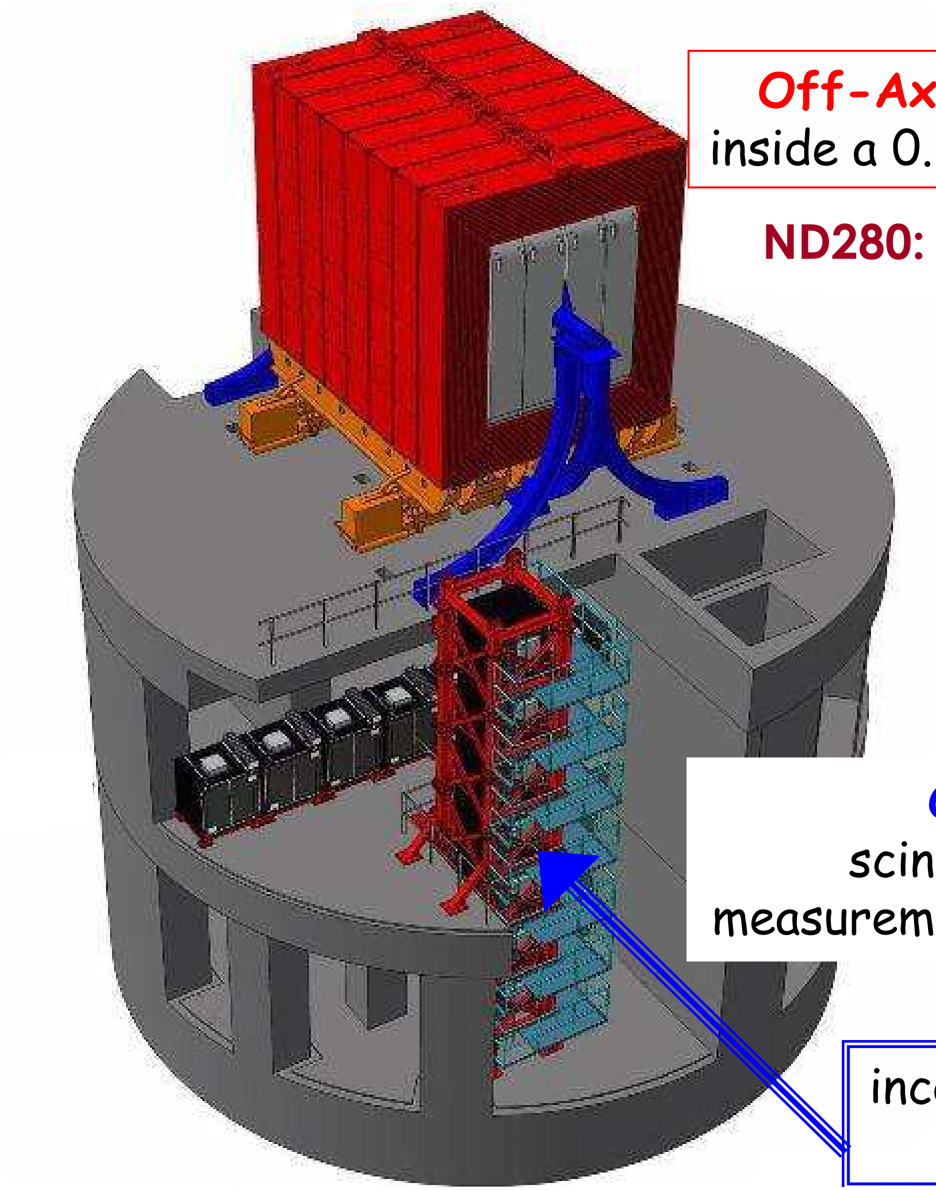
Optical transition radiation detector (OTR) immediately upstream of target:

Muon monitors (SiPIN and ionization chambers):

- measure beam direction and intensity spill-by-spill
- requirement: <1mrad (ΔE_{ν}^{peak} ~ 2%/mrad)



Near Detector Complex ND280



Off-Axis suite of fine grain detectors/tracker inside a 0.2 T magnetic field (UA1/NOMAD magnet)

ND280:

measurements of
-- $CC\nu_\mu$ events
(normalization, disappearance)

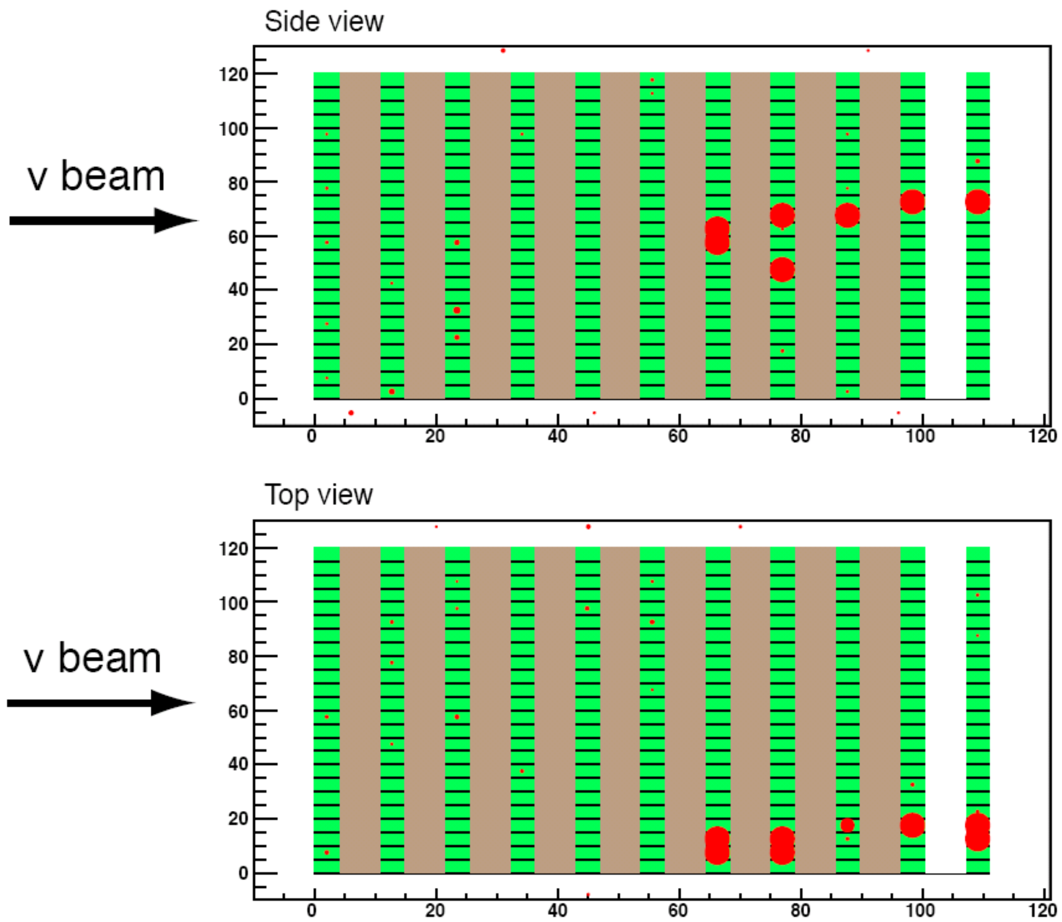
-- $CC\nu_e$ events
-- π^0 events
Backgrounds to $\nu_\mu \rightarrow \nu_e$ search

On-axis INGRID
scintillator-iron detectors
measurement of beam angular profile

incoming neutrino beam

IN GRID

INGRID first neutrino event candidate

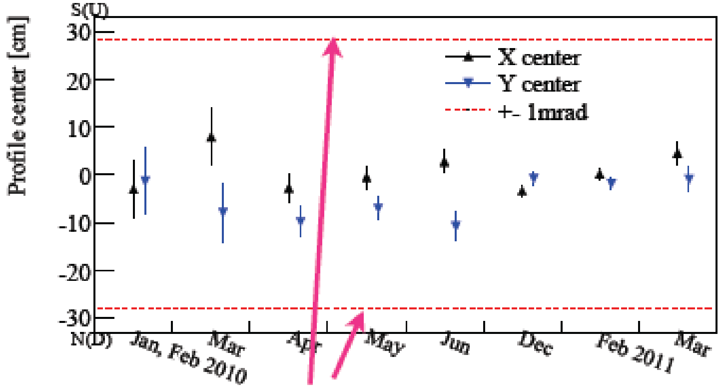


Nov. 22, 2009

MR Shot #19655
T2K Spill# 241792

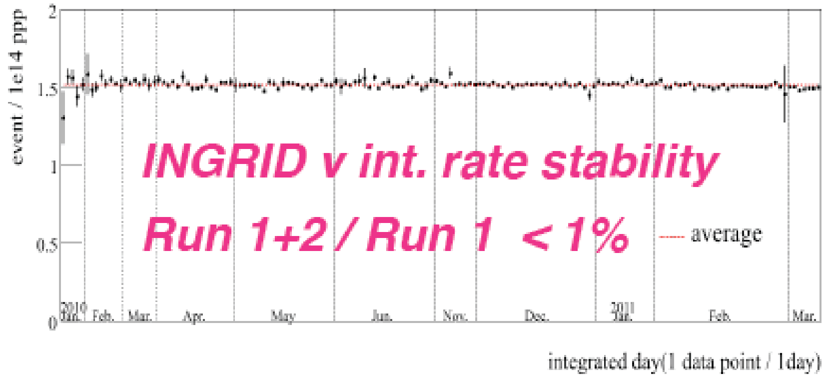
ν beam stability

Stability of ν beam direction (INGRID)



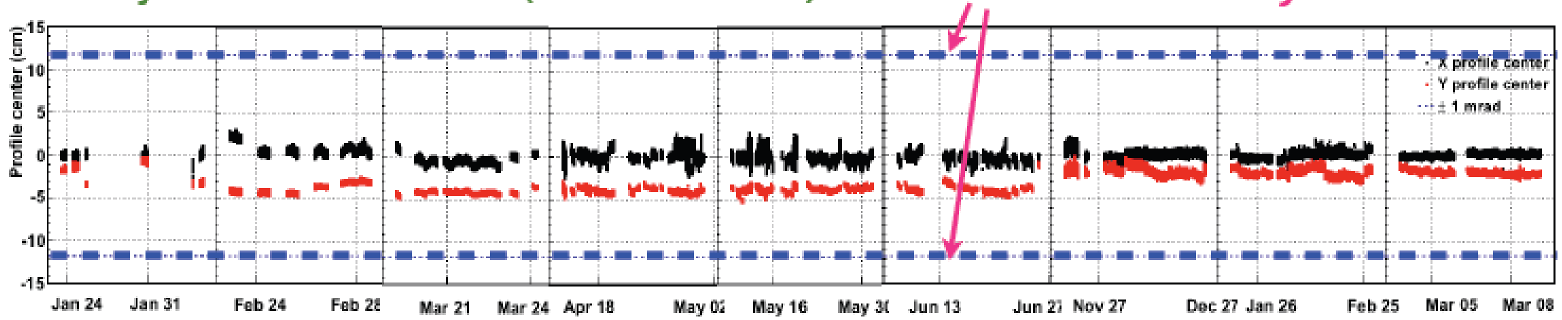
ν beam dir. stability < 1mrad

Stability of ν interaction rate normalized by # of protons (INGRID)



Stability of beam direction (Muon monitor)

Beam dir. stability < 1mrad



Search for $\nu_\mu \rightarrow \nu_e$ appearance

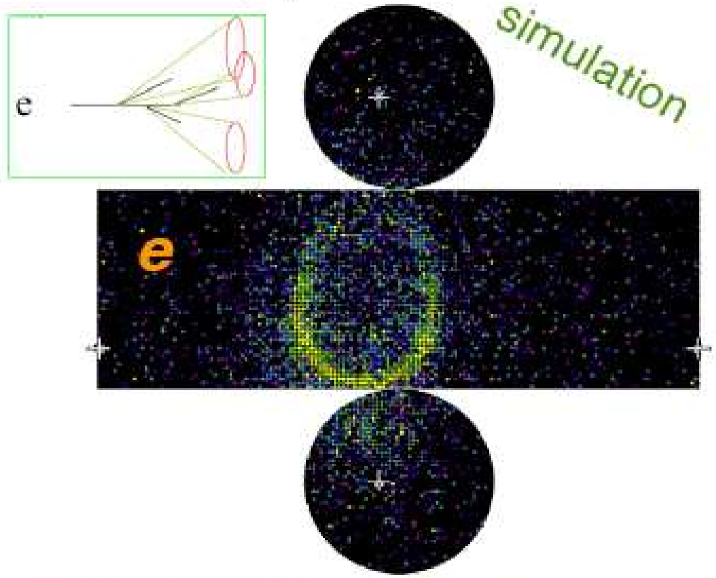
1. Event selection at SK
2. Prediction of number of expected events (oscillation/no oscillation)
3. Systematic errors
4. Open the last three cuts
5. Inspect what you see
6. results

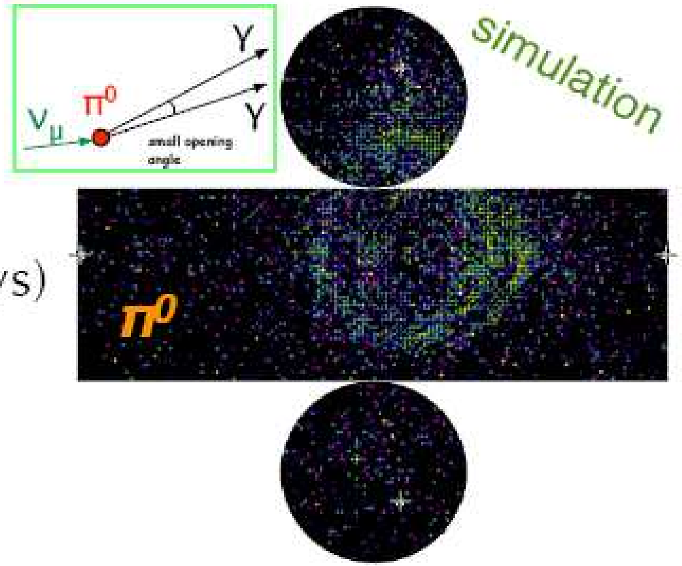
most slides that follow from T2K seminar at KEK, K. Sakashita (KEK)

T2K Signal & Background for ν_e appearance

- Signal = **single electron event**
  - oscillated ν_e interaction :

CCQE : $\nu_e + n \rightarrow e + p$
(dominant process at T2K beam energy)





- Background
  - intrinsic ν_e in the beam (from μ, K decays)
  - π^0 from NC interaction

Unbiased event selection

SK event selection was fixed before run.

➔ Possible because SK is a mature & well understood detector.

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincident w/ beam time (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (Vertex >2m from wall)	
E_{vis} > 30MeV	E_{vis} > 100MeV
nº of rings =1	
μ-like ring	e-like ring
	No decay electron
	Inv. mass w/ forced-found 2nd ring < 105MeV
	E_ν^{rec} < 1250MeV

NB: slide shown at NUFACT10 October 2010

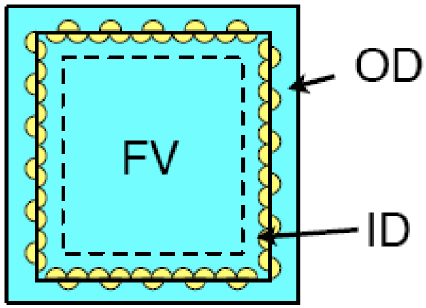
ν_e selection at far detector (SK)

The selection criteria were optimized for initial running condition

The selection criteria were fixed before data taking started to avoid bias

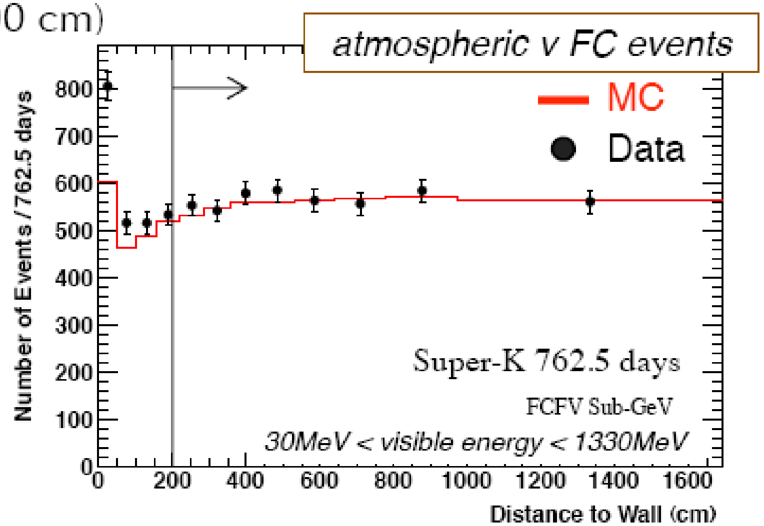
7 selection cuts

1. T2K beam timing & Fully contained (FC)
   (synchronized with the beam timing,
   no activities in the OD)



2. In fiducial volume (FV)
   (distance btw recon. vertex and wall > 200 cm)

* Events too close to the wall are difficult to accurately reconstruct vertex
* Reject events which are originated outside the ID
* Define FV 22.5kton

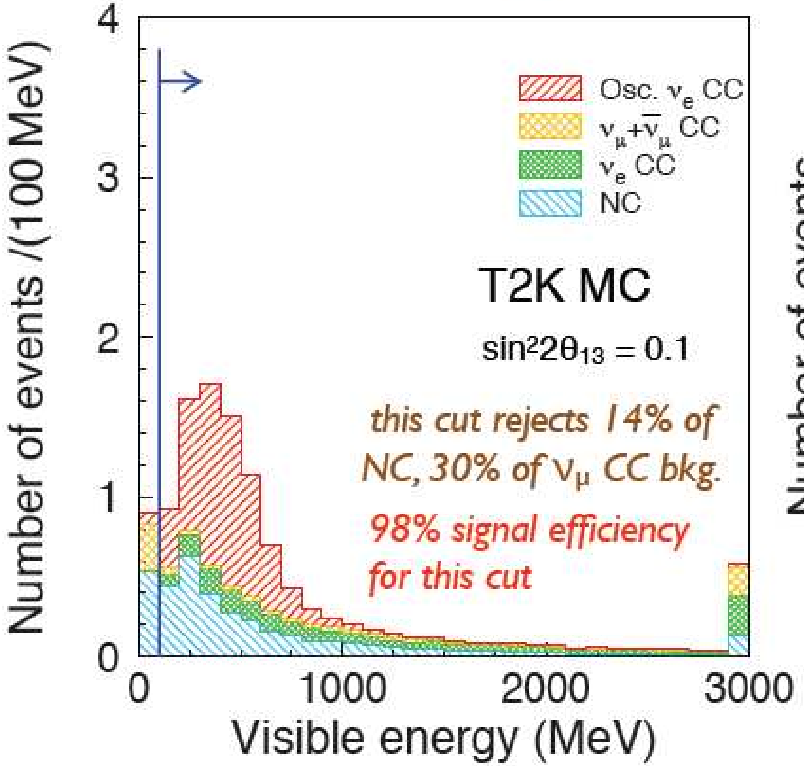


3. Single electron
   (# of ring is one & e-like)

4. Visible energy > 100 MeV

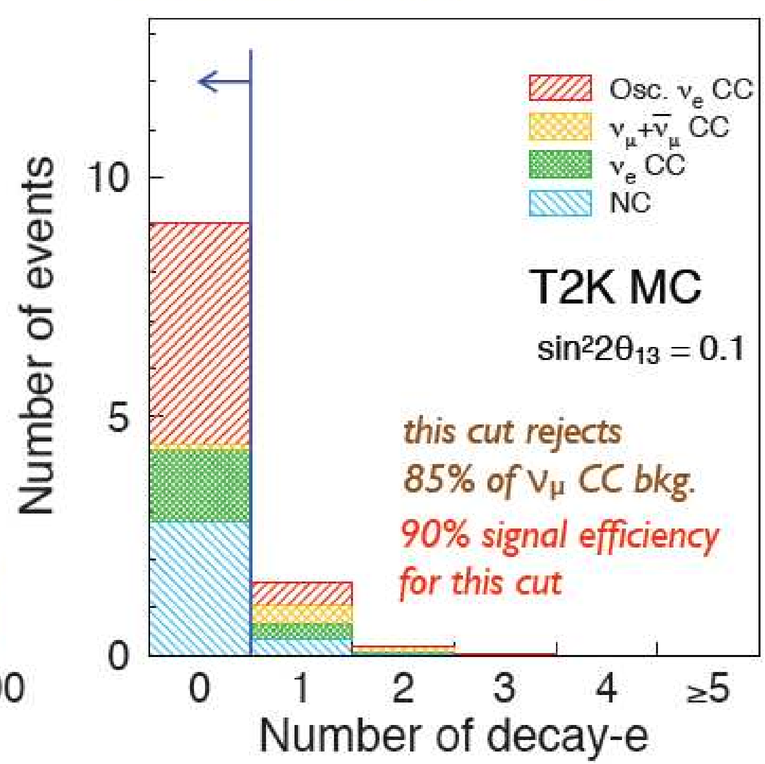
(visible energy = electron energy deposited in ID)

* Reject low energy events, such as NC background and decay electrons produced by invisible muons



5. No decay electron observed (no delayed electron signal)

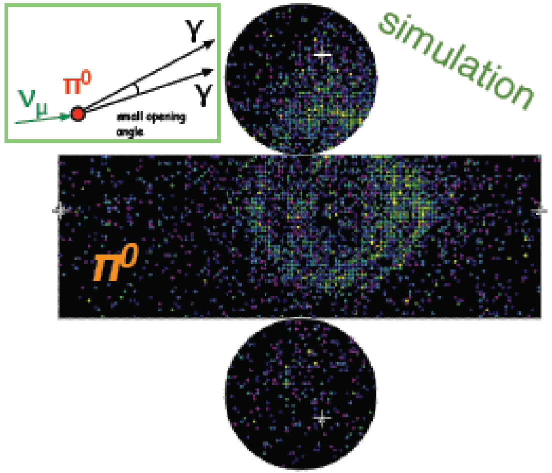
* Reject events with muons or pions which are invisible or mis-identified as *electron* (ν_μ events or CC non-QE events)

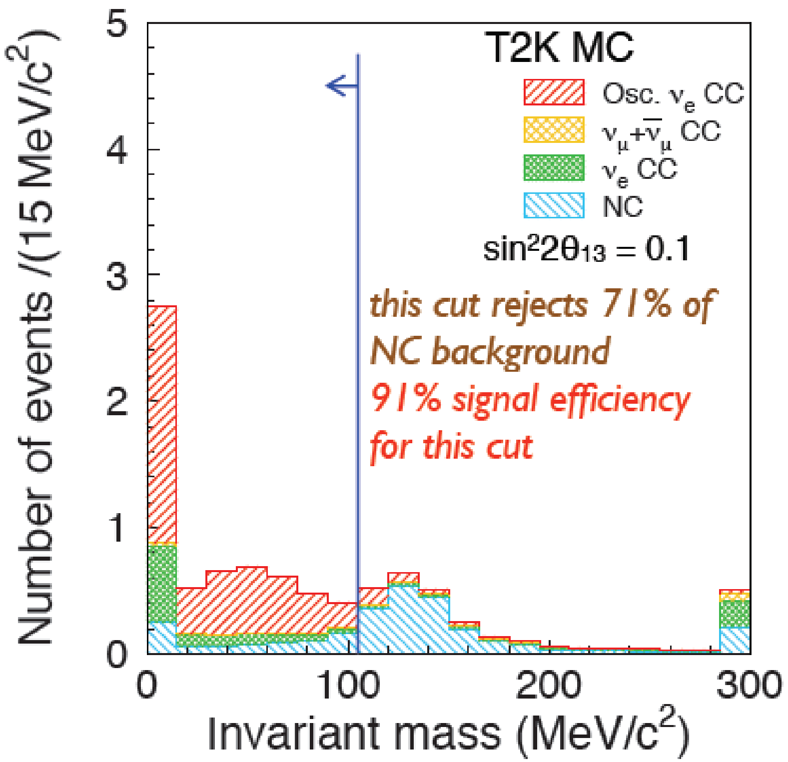


6. Reconstructed invariant mass (M_{inv}) < 105 MeV/c^2

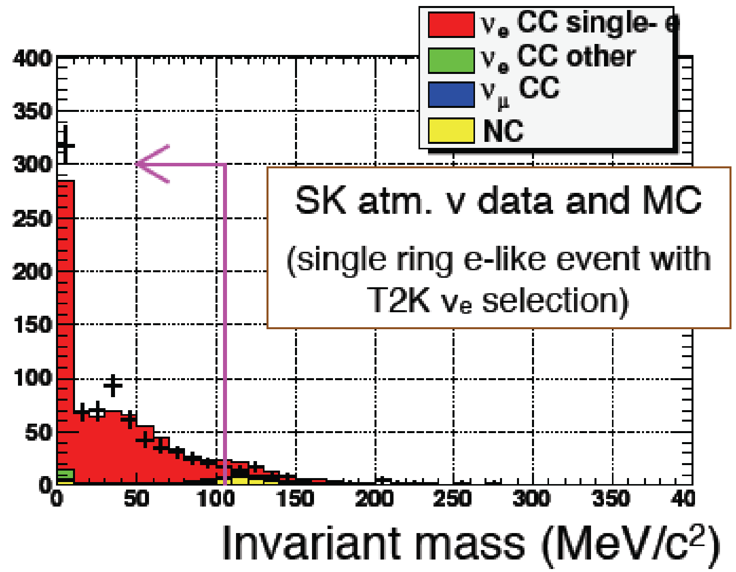
* Suppress NC π^0 background

Find 2nd e-like ring by forcing to fit light pattern under the 2 e-like rings assumption, and then reconstruct invariant mass of these 2 e-like rings





demonstrate to reconstruct invariant mass using atmospheric ν data

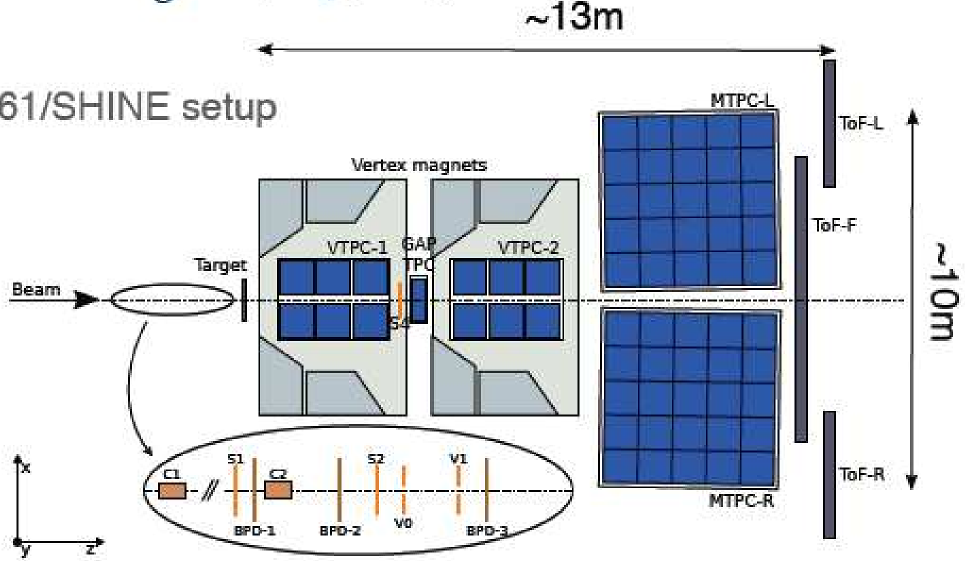


CERN NA61/SHINE measurement

Measure hadron(π, K) yield distribution in
30 GeV p + C inelastic interaction

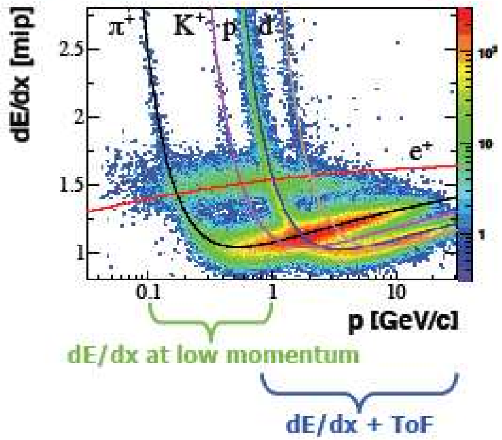
- **thin target 4%λ_I (2cm)**

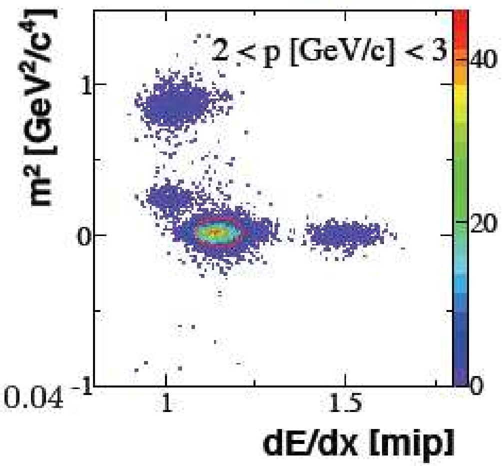
NA61/SHINE setup



Large acceptance spectrometer + TOF

π^+ production: Two analysis for different momentum region





detector performance

$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$ for $p>5,\ p=2,\ p=1$ GeV/c

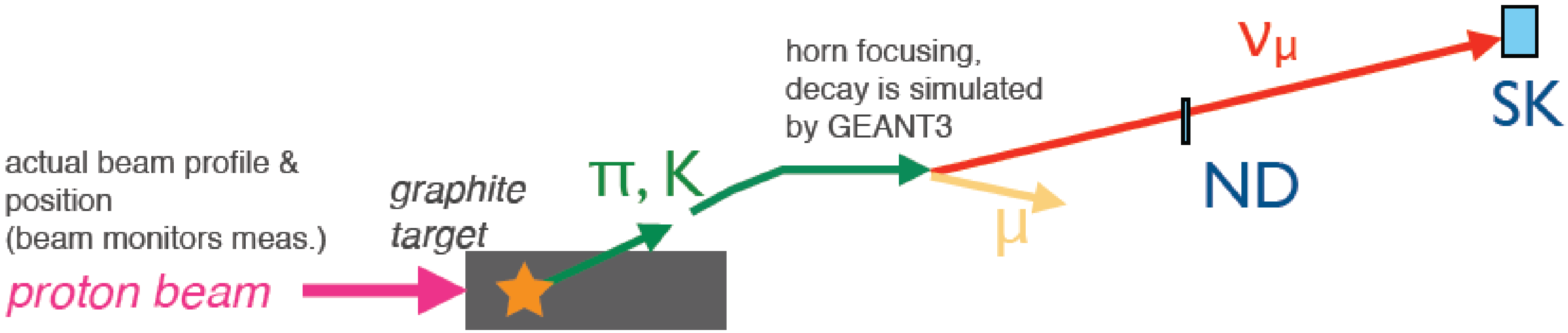
$\sigma(\mathrm{dE/dx})/\langle\mathrm{dE/dx}\rangle \approx 0.04$

$\sigma(\mathrm{TOF\text{-}F}) \approx 115$ ps

Neutrino flux prediction

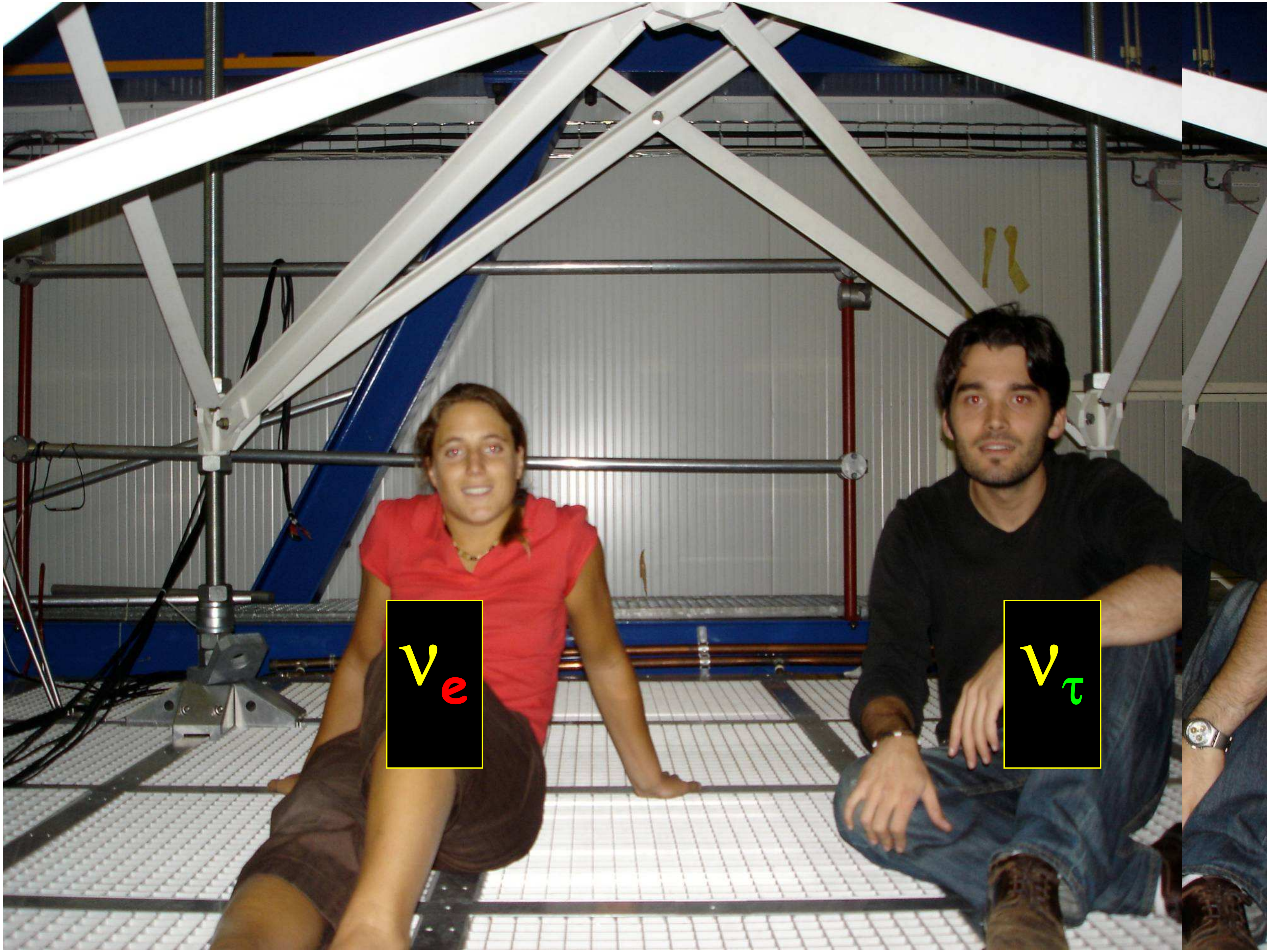
T2K Neutrino beam simulation based on Hadron production measurements

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



Hadron production in 30GeV proton + C

- ***Use CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)***
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*


ν_e
ν_τ

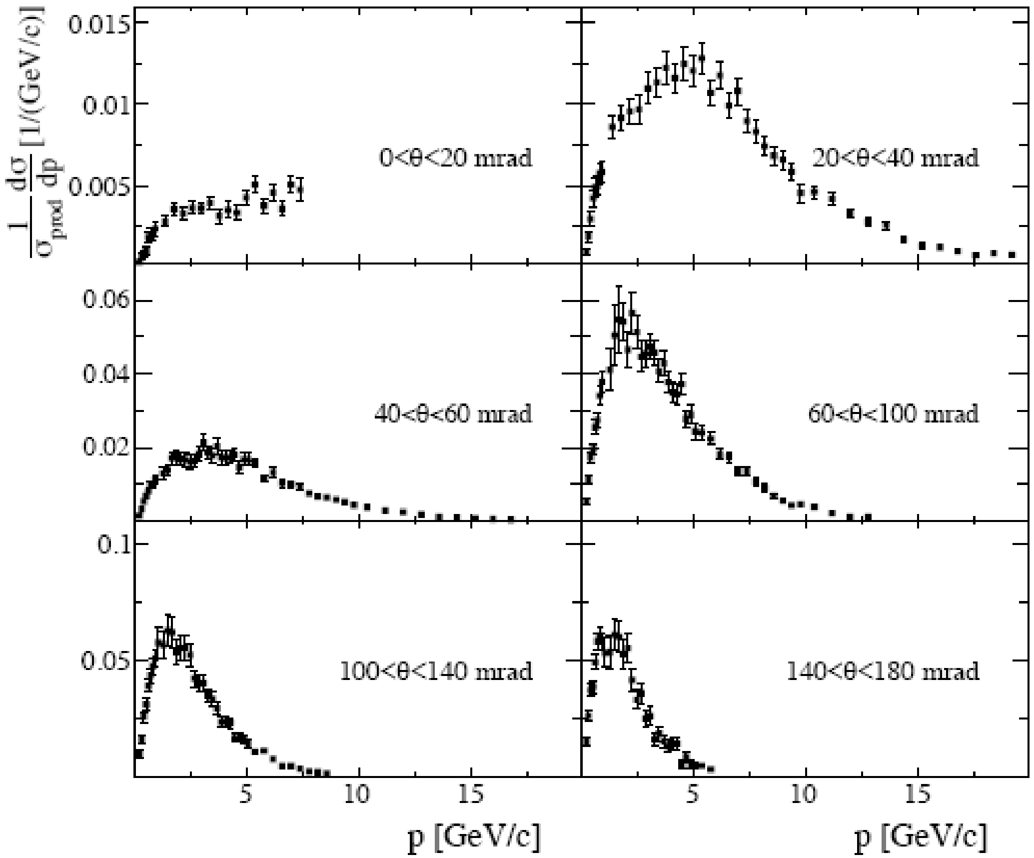
UNIGE: Bravar, Abgrall, Murphy, Ravonel, Argyriades, Korzenev, Haesler

Results of pion production from thin target (2007 data)

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

Differential cross section for π^+ production in 30GeV p+C

Error bars = stat. + syst. in quadrature
no normalization error is shown



Systematic uncertainty was evaluated in each (p,θ) bin

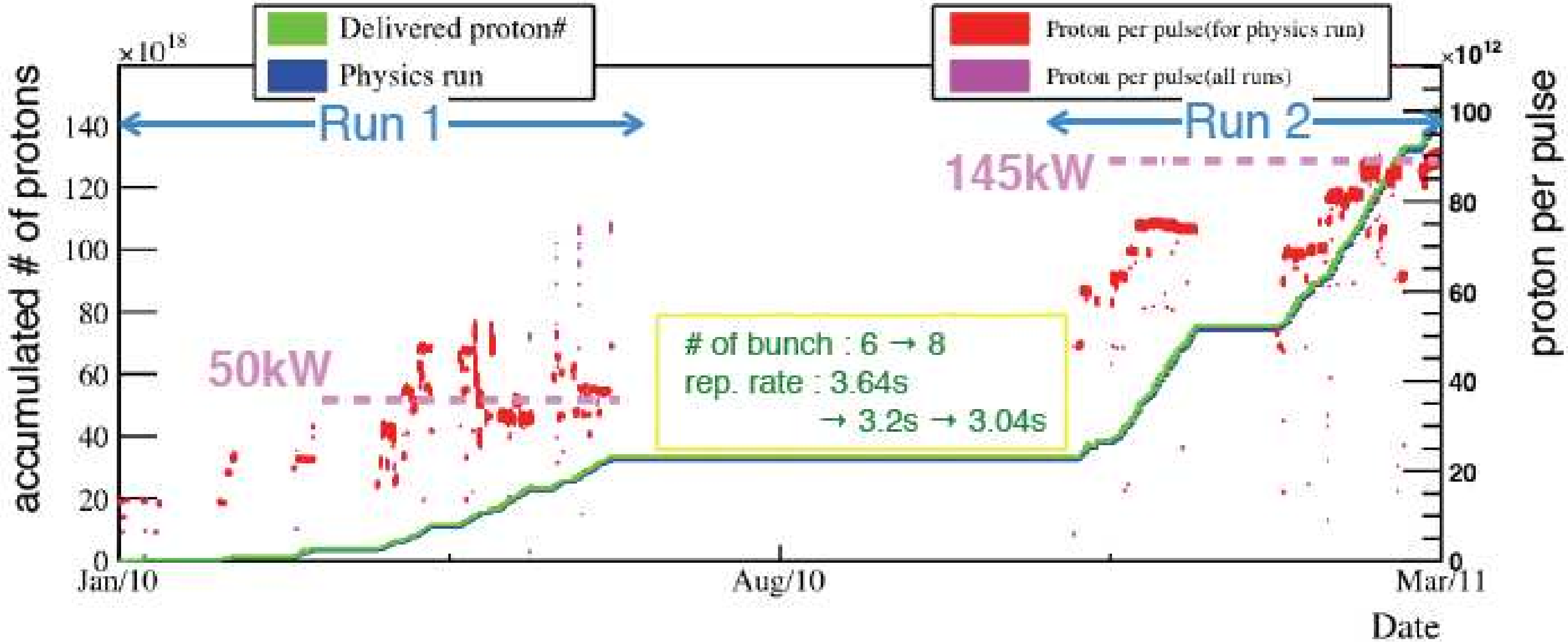
typically 5-10%

The normalization uncertainty is 2.3% on the overall (p,θ)

→ Propagate the systematic uncertainty in each (p,θ) bin into the expected number of events in T2K

→ Input to T2K neutrino beam simulation

Total # of protons used for analysis



Run 1 (Jan. '10 - June '10)

- 3.23×10^{19} p.o.t. for analysis
- 50kW stable beam operation

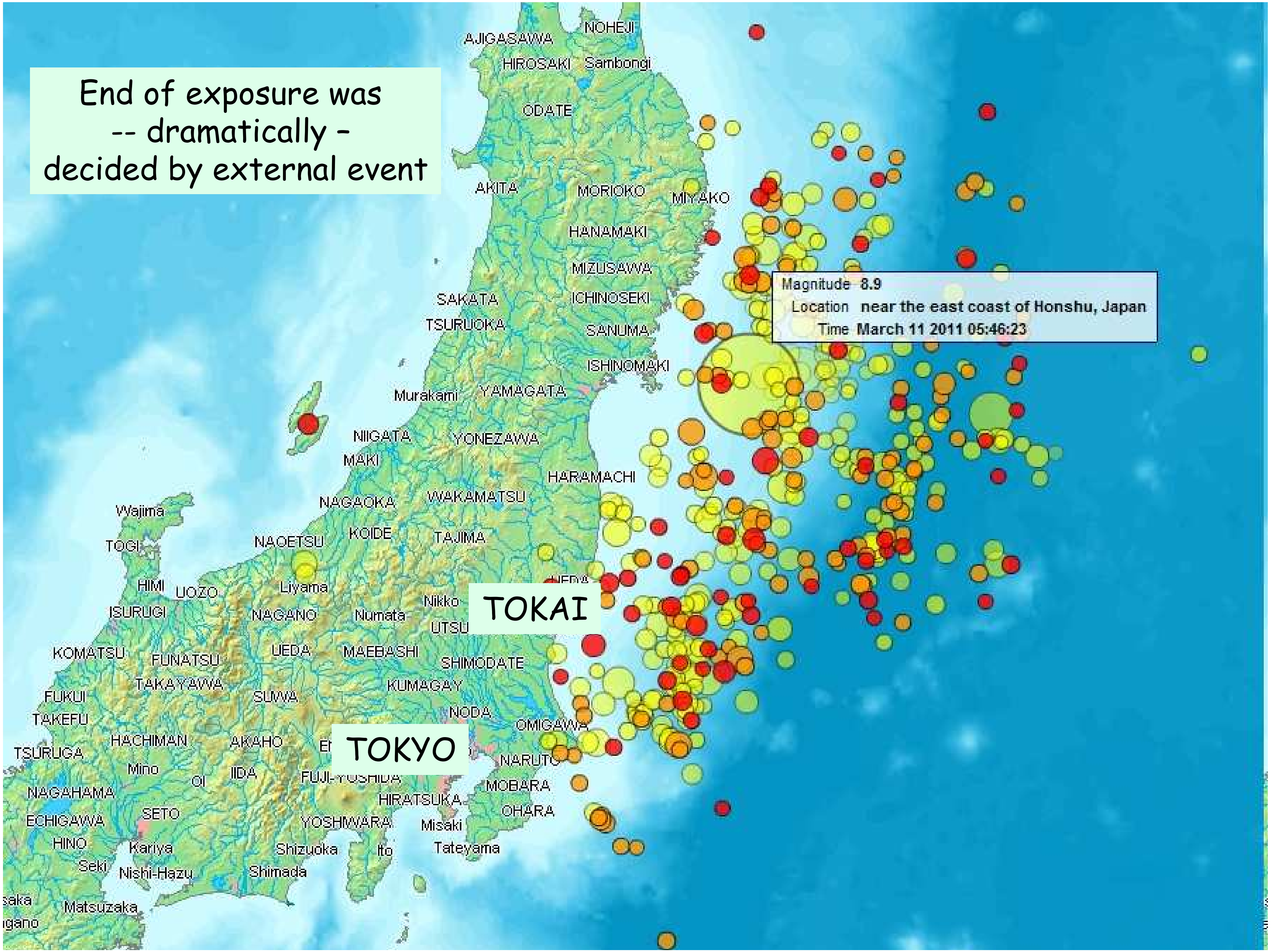
Run 2 (Nov. '10 - Mar. '11)

- 11.08×10^{19} p.o.t. for analysis
- ~145kW beam operation

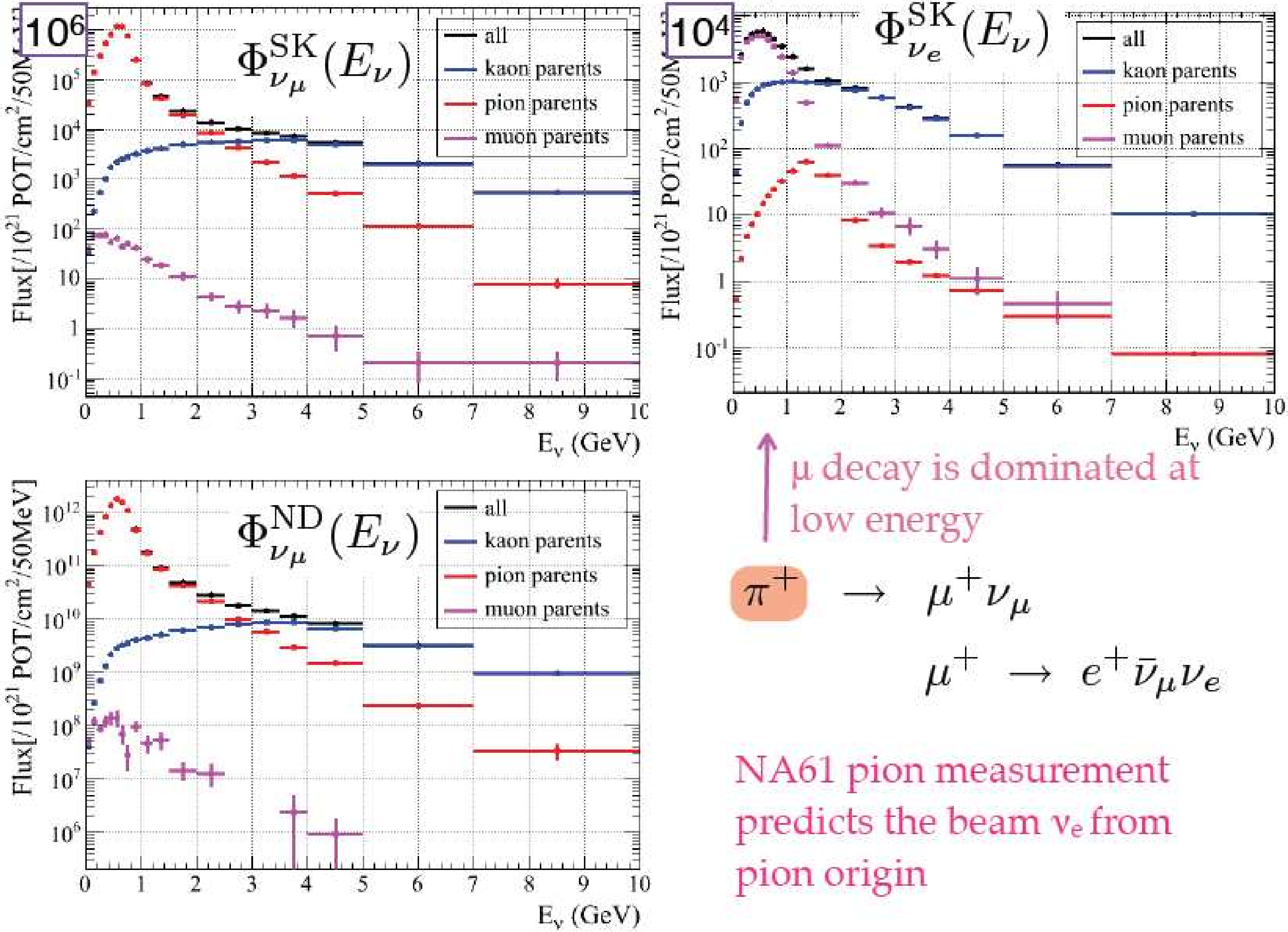
Total # of protons used for this analysis is 1.43×10^{20} pot

2% of T2K's final goal and ~5 times exposure of the previous report

End of exposure was
-- dramatically –
decided by external event



Predicted neutrino flux (center value)



μ decay is dominated at low energy

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

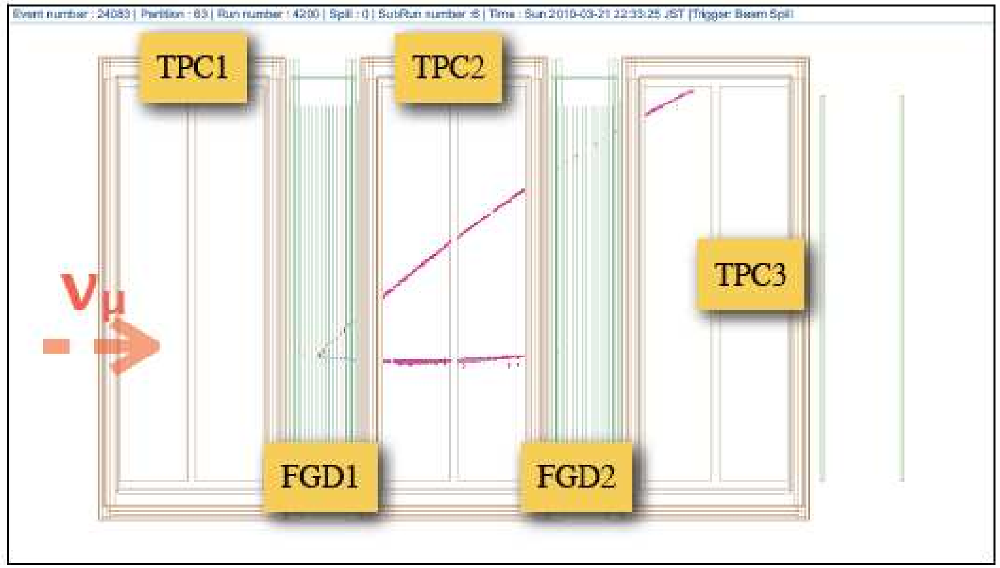
NA61 pion measurement predicts the beam ν_e from pion origin

ν_μ interaction rates at near detector

- Measure # of inclusive ν_μ charged current interaction (N^{Data}_{ND})

Select events which have FGD hits and μ-like tracks reconstructed in single TPC

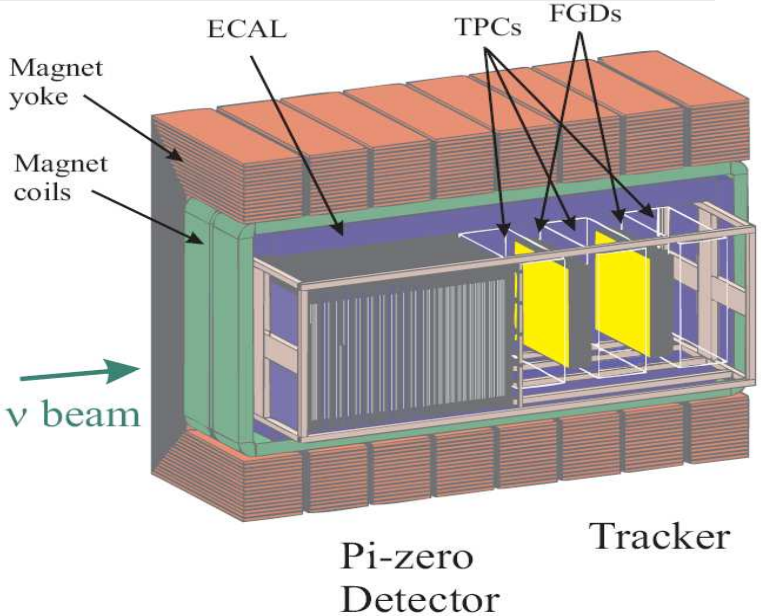
Event display (data)



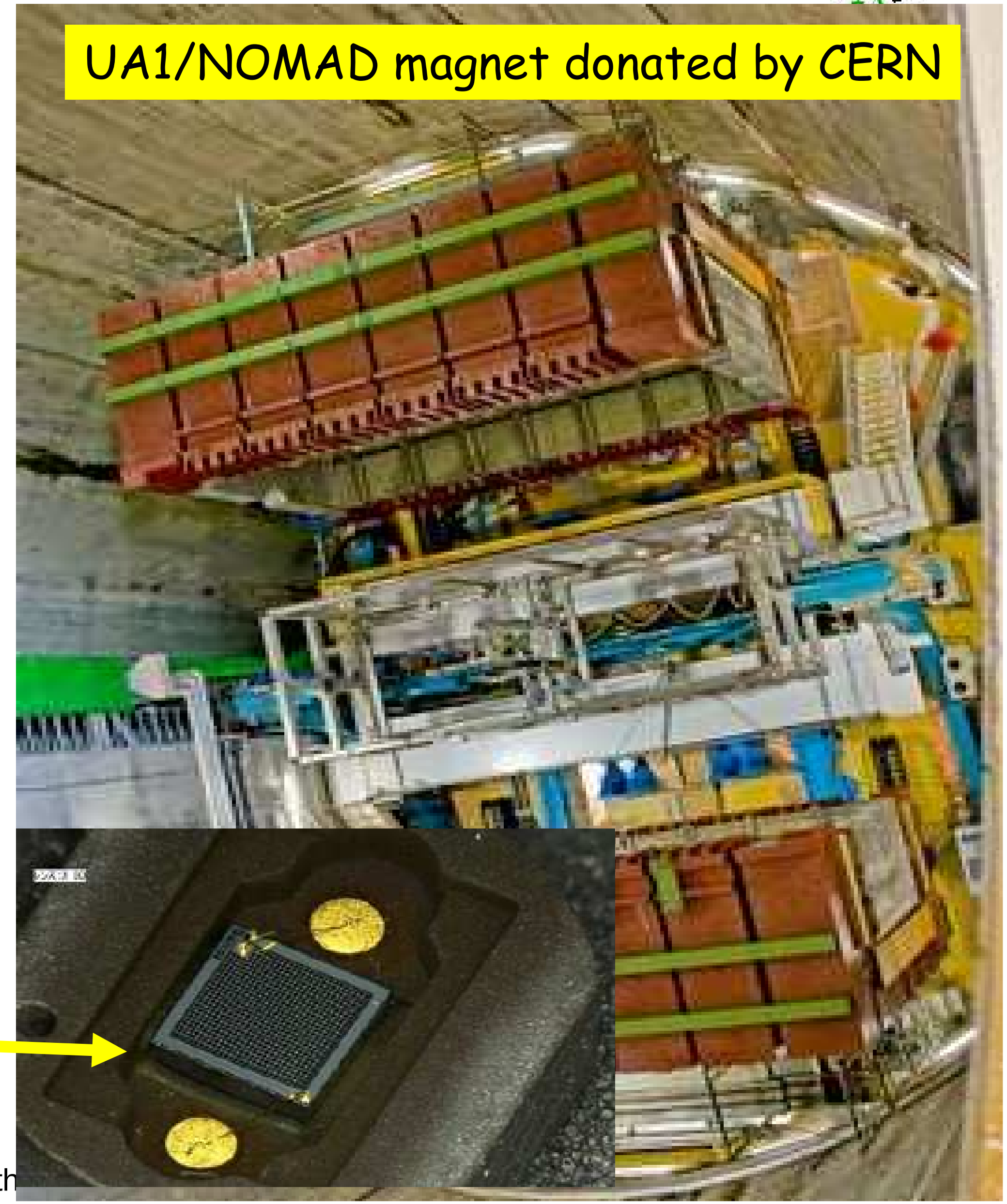
High purity : 90% ν_μ Charged Current int. (50% CCQE)

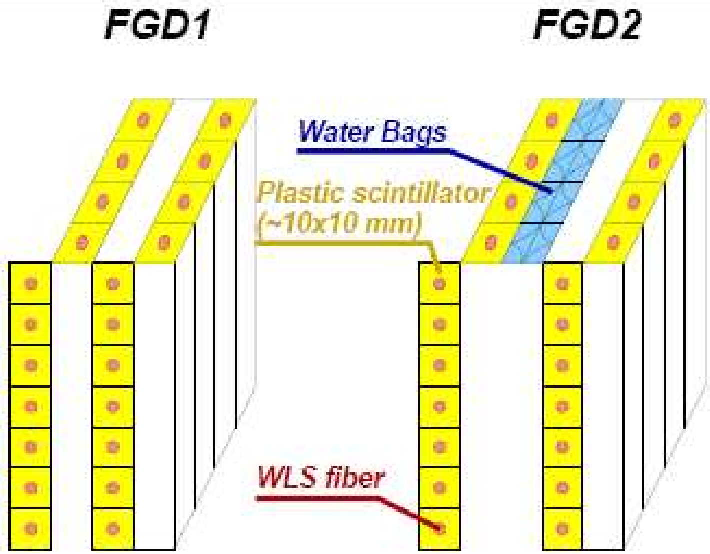
The Off-Axis Near Detector

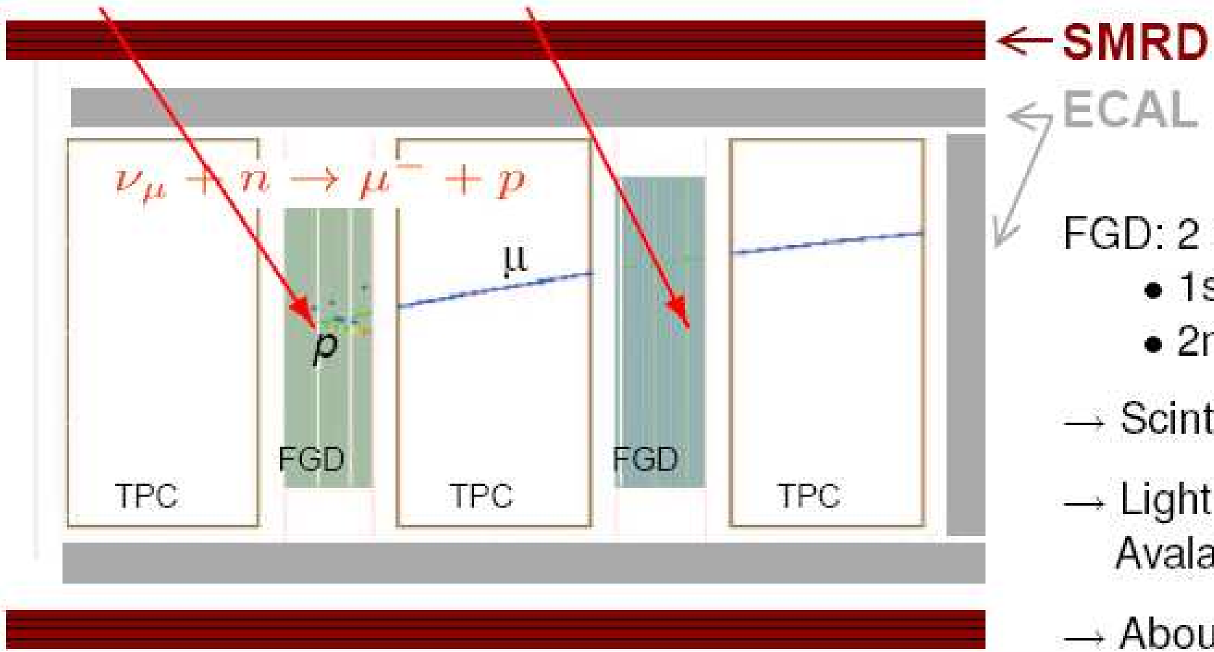
Cannot be Water Cherenkov:
 -- pile-up
-- (worse) granularity of
 small vs large detector

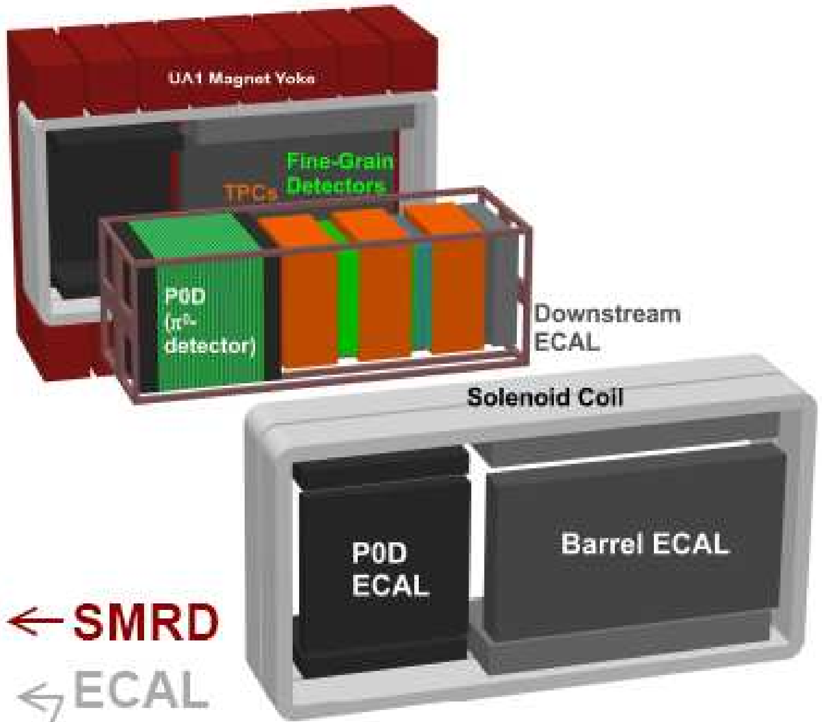


fine grain detector of light material (even water!)
-- Scitillators with MPPC readout
 (60'000 channels!)
-- TPC tracker









FGD: 2 × 1.3 Ton active target

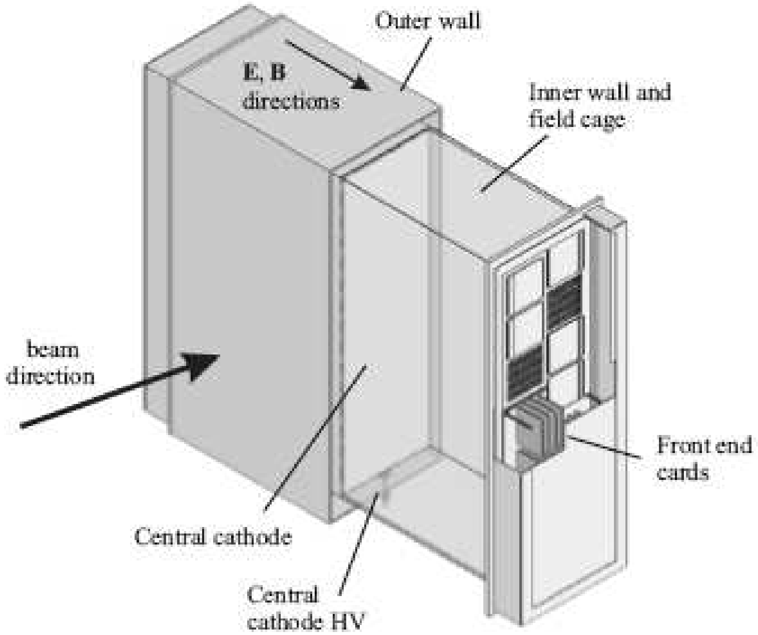
- 1st FGD: plastic only
- 2nd FGD: plastic + water

→ Scintillators similar to K2K SciBar

→ Light detection by Geiger mode Avalanche Photodiodes (MPPC)

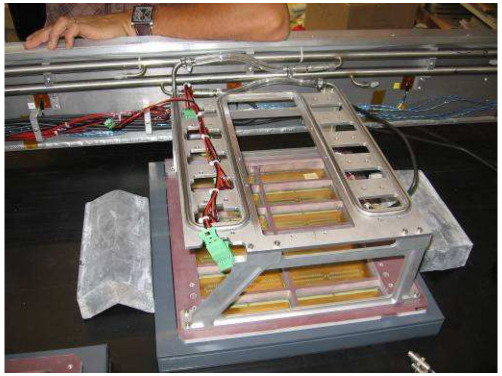
→ About 9500 channels

TPC's

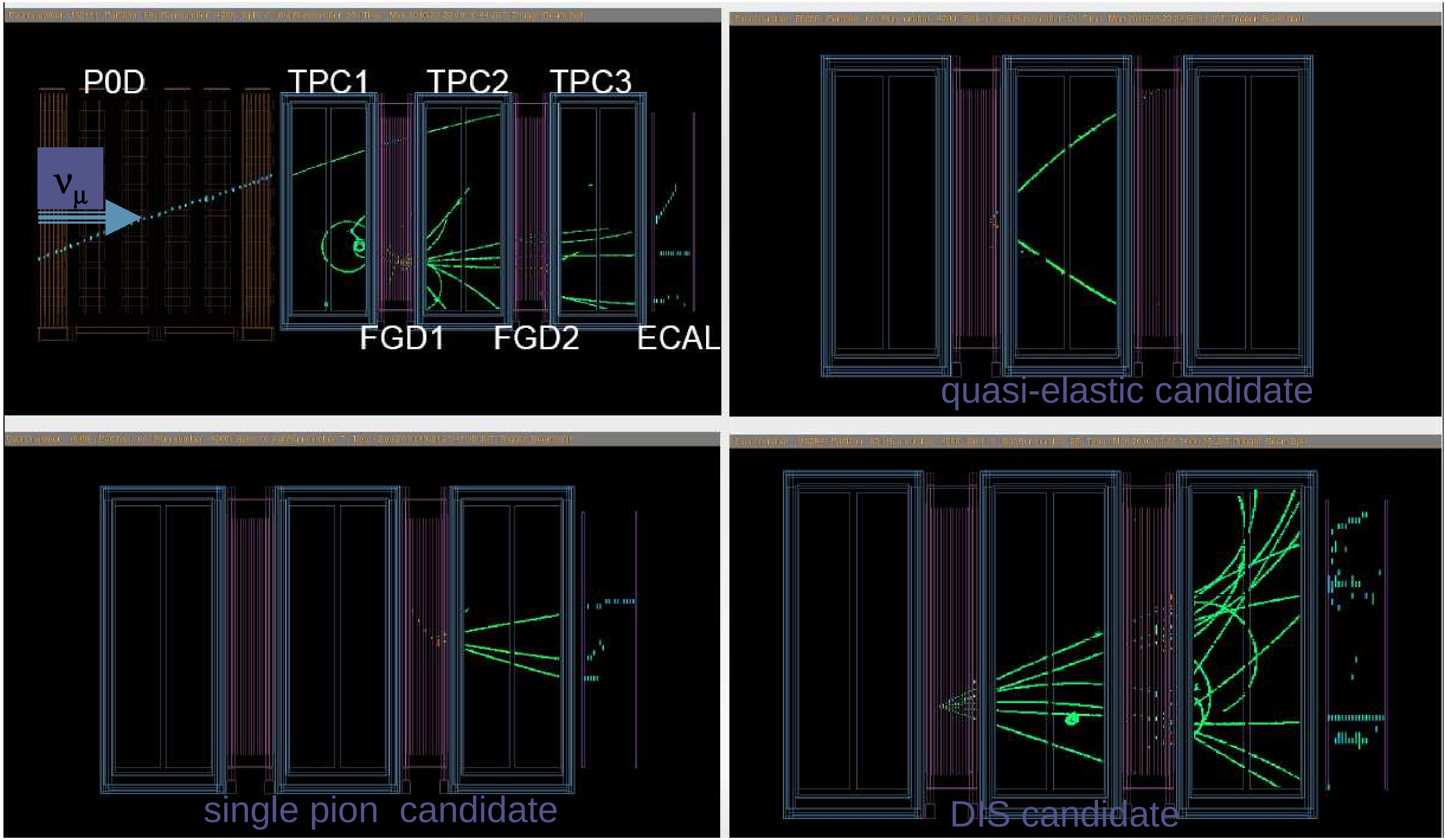


3 TPC's, 1.8 x 2 x 0.70 m^3 sensitive area
World's Largest TPC
with micro-pattern read out (MicroMeGas)

TPC modules built at CERN/UNIGE→



A few ND280 neutrino interaction candidates



Intrinsic Beam ν_e background at Far detector

- **The number of beam ν_e background events at far detector is predicted using the ν beam simulation based on NA61 measurements (pion) and FLUKA (kaon)**
  - ND measurements (μ momentum and event rate) are consistent with MC based on the ν beam simulation

$$N^{exp}_{SK\ beam\ \nu_e\ bkg.} = R^{\mu,\ Data}_{ND} \times \frac{N^{MC}_{SK\ beam\ \nu_e\ bkg.}}{R^{\mu,\ MC}_{ND}}$$

$$\frac{N^{MC}_{SK\ beam\ \nu_e\ bkg.}}{R^{\mu,\ MC}_{ND}} = \frac{\int \Phi^{\rm SK}_{\nu_e}(E_\nu) \cdot P_{\nu_e \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ \ dE_\nu}{\int \Phi^{\rm ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ \ dE_\nu} \cdot \frac{M^{SK}}{M^{ND}} \cdot {\rm POT}^{SK}$$

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

The expected number of events with 1.43 x 10^{20} p.o.t.

$$N^{exp}_{SK\ tot.} = 1.5 \text{ events}$$

	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**

# of NC background is calculated by

$$N^{exp}_{SK\ NC\ bkg.} = R^{\mu,\ Data}_{ND} \times \frac{N^{MC}_{SK\ NC\ bkg.}}{R^{\mu,\ MC}_{ND}}$$

Systematic uncertainty on $N^{exp}{}_{SK}$

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

for $\sin^2 2\theta_{13}=0$

➡ *$N^{exp}{}_{SK}=1.5\pm 0.3$ events*

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

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

Neutrino flux uncertainty

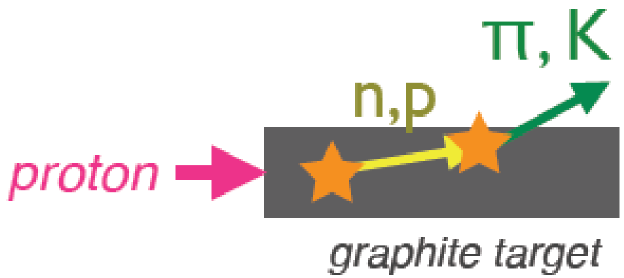
error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

Uncertainties in hadron production and interaction are dominant sources

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

Error source

- Pion production
  - NA61 systematic uncertainty in each pion's (p,θ) bin
- Kaon production
  - Used model (FLUKA) is compared with the data(Eichten et. al.) in each kaon's (p,θ) bin
- Secondary nucleon production
  - Used model (FLUKA) is compared with the experimental data



- Secondary interaction cross section
  - Used model (FLUKA and GCALOR) is compared with the experimental data of interaction x-section (π, K and nucleon)

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

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

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

Hadron production & interaction

The uncertainty on N^{exp}_{SK} due to the beam flux uncertainty is **8.5%**

Error cancellation works for some beam uncertainties (factor 2)

ν int. cross section uncertainty

error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

Evaluate uncertainty on F/N ratio by varying the cross section within its uncertainty

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

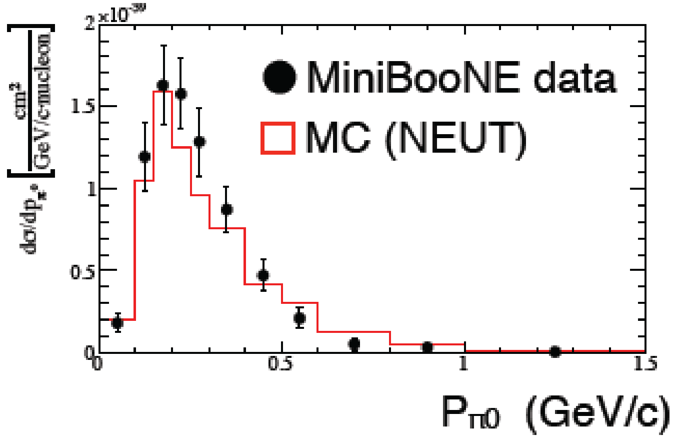
Main ν interaction in each event category

NC background : NC1π^0
Beam ν_e background : ν_e CCQE
Signal : ν_e CCQE
ND CC event : CCQE(50%)
CC1π(23%)

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% (upper limit from [30])
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)

Uncertainty of $\sigma(\nu_e)/\sigma(\nu_\mu) = \pm 6\%$

Cross section uncertainties are estimated by Data/MC comparison, model comparison and parameter variation



error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

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

Error 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%

← *Uncertainty in pion's final state interaction is dominant*

The uncertainty on N^{exp}_{SK} due to the ν x-section uncertainty is **14%** ($\sin^2 2\theta_{13}=0$)

Far detector uncertainty

error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

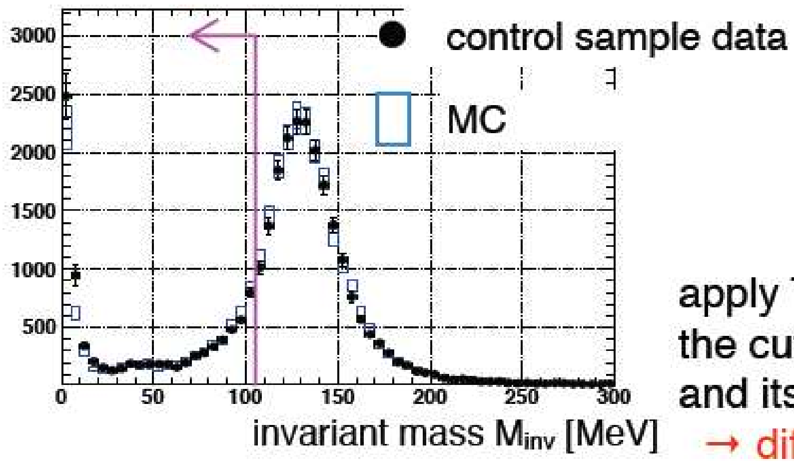
- Uncertainty due to the SK detector uncertainty
- Evaluation using control sample

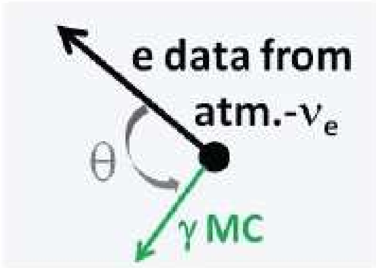
$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu)\cdot P_{osc.}(E_\nu)\cdot \sigma(E_\nu)\cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu)\cdot \sigma(E_\nu)\cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

One of big error sources:

detection efficiency of NC 1π^0 background

control sample with one data electron + one simulated γ





apply T2K ν_e selection and compare the cut efficiency between control sample data and its MC
→ difference is assigned as sys. error

Summary of Far detector systematic uncertainty

Error source	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	**7.6%**	**15%**

Evaluated by atmospheric ν_e enriched data

→ The total uncertainty on $N^{MC}_{SK\ tot.}$ is **14.7 %** ($\sin^2 2\theta_{13}=0$)
(uncertainty on the background + solar term oscillated ν_e)

Total Systematic uncertainties

Summary of systematic uncertainties on $N^{exp}_{SK\ total.}$ for $\sin^2 2\theta_{13}$=0 and 0.1

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	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

(due to small Far det. uncertainty for signal)

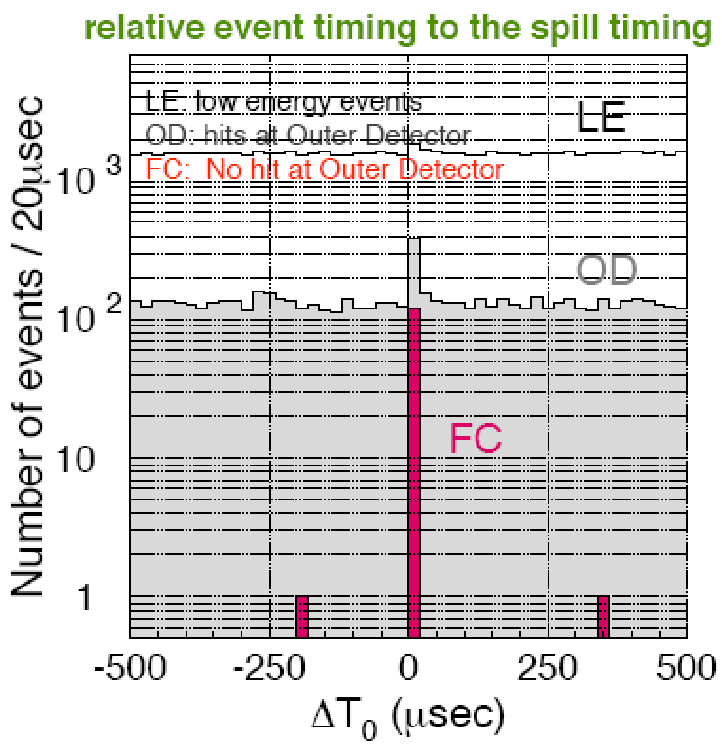
cf.
$\sin^2 2\theta_{13}$=0:
#sig = 0.1 #bkg = 1.4

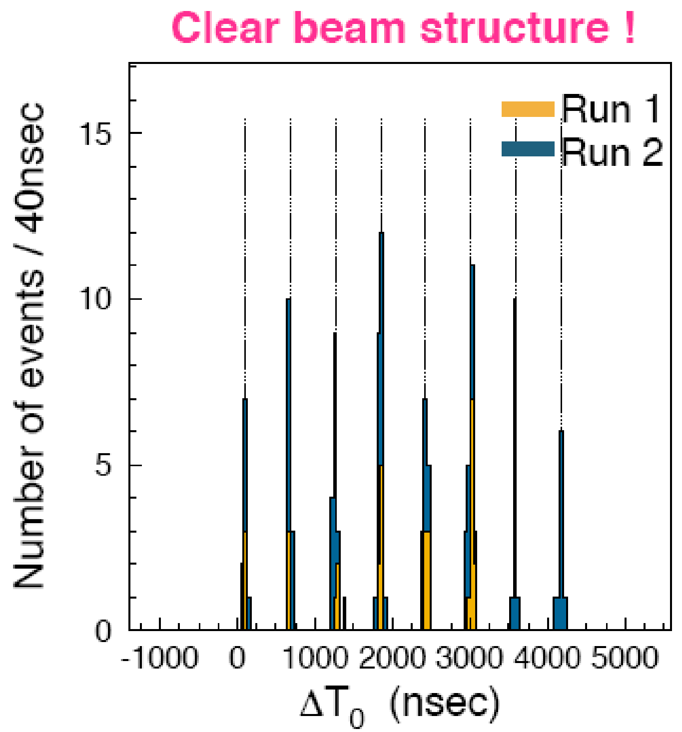
$\sin^2 2\theta_{13}$=0.1:
#sig = 4.1 #bkg = 1.3

$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}$=0

SK events in beam timing

- Events in the T2K beam timing synchronized by GPS





$\Delta T_0 = T_{GPS}$@SK - T_{GPS}@J-PARC - TOF(~985µsec)

Number of T2K events at far detector

Number of events in on-timing windows (-2 ~ +10 μsec)

Class / Beam run	RUN-1	RUN-2	Total	non-beam background
POT (x 10^{19})	3.23	11.08	**14.31**	
Fully-Contained (FC)	33	88	**121**	0.023

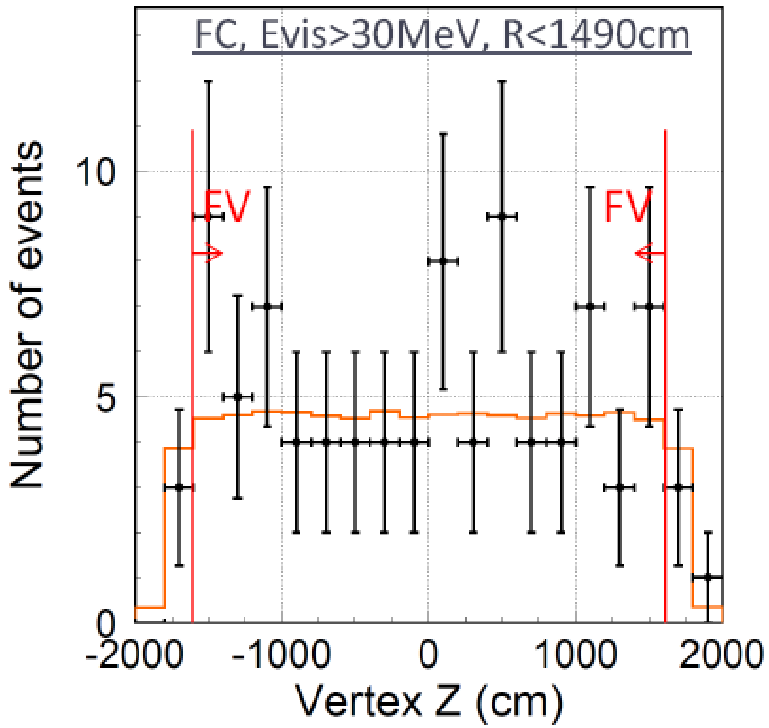
The accidental contamination from atmospheric ν background is estimated using the sideband events to be 0.023

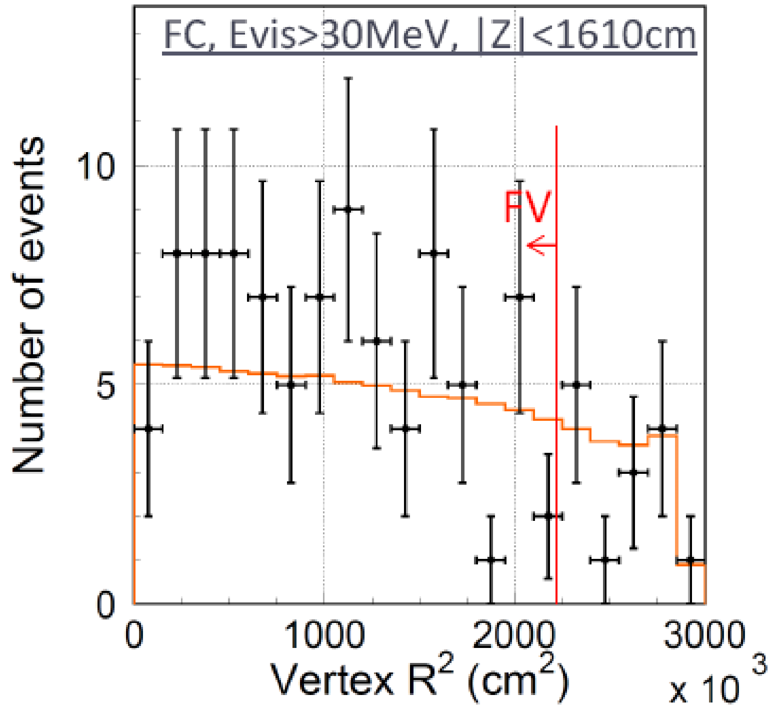
Apply ν_e event selection

defined before the data collection
6 selection cuts in addition FC cut

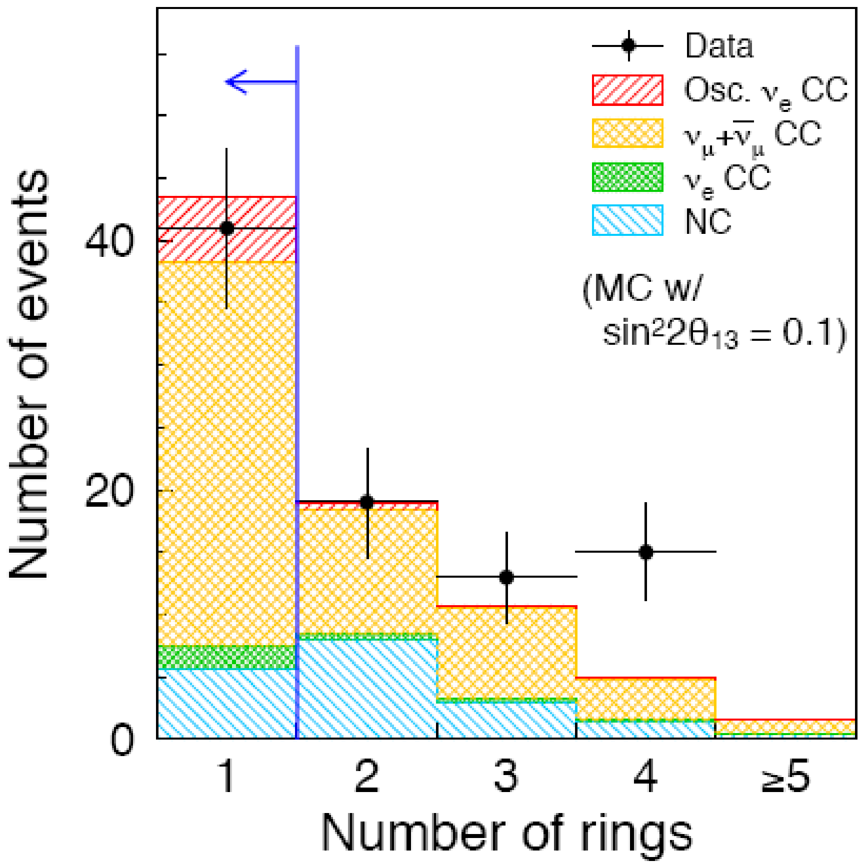
Fiducial volume cut

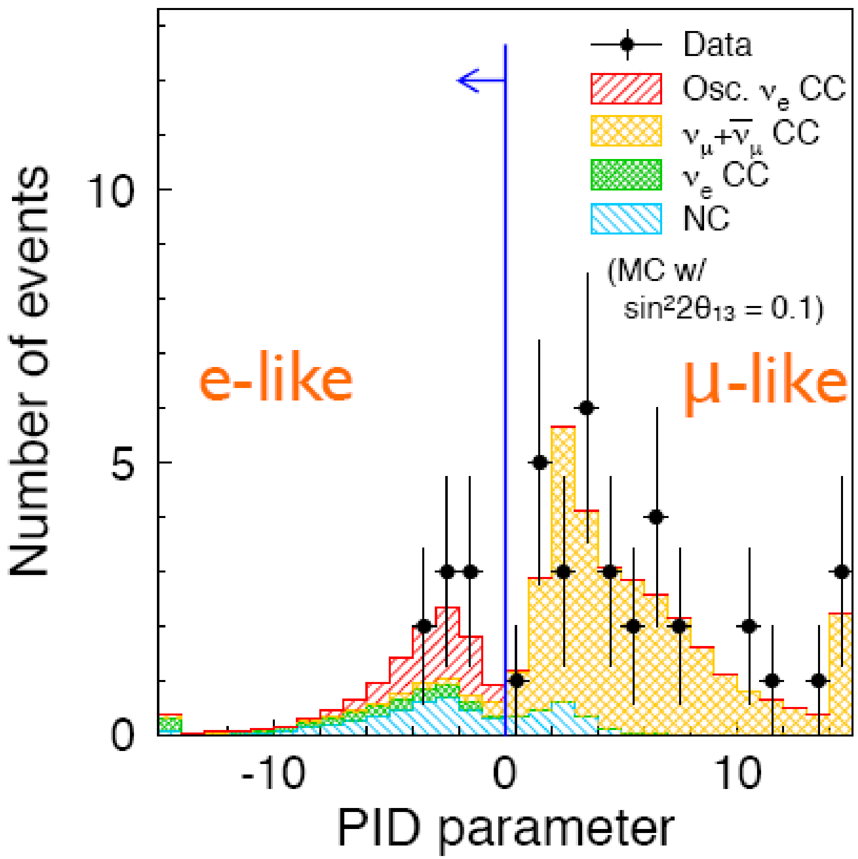
(distance between recon. vertex and wall > 200cm)





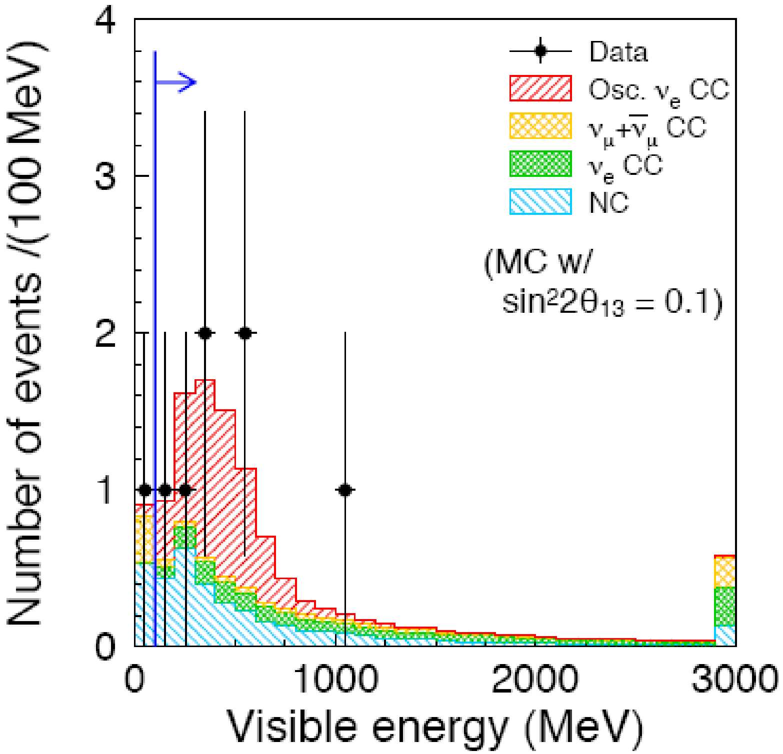
Single electron cut (# of ring is one & e-like)

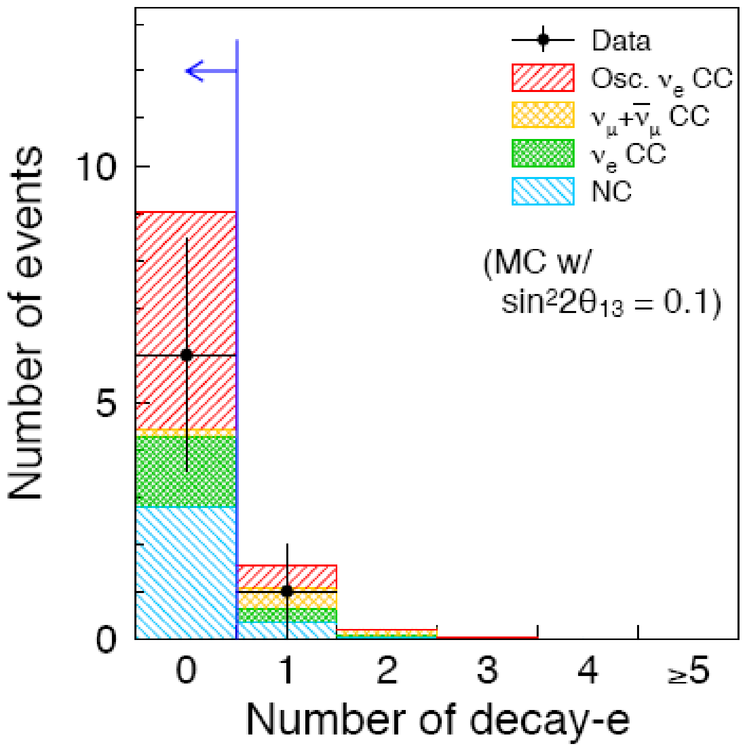




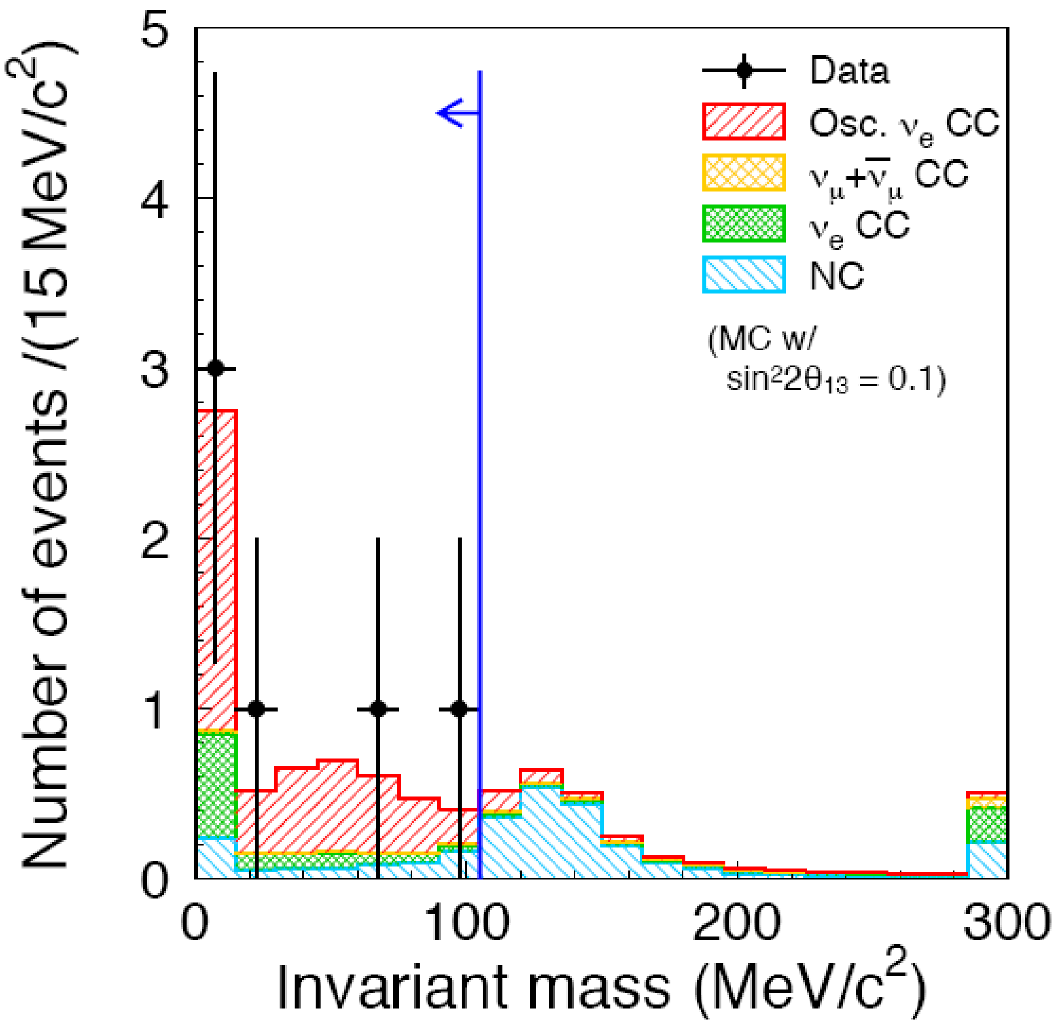
Visible energy > 100 MeV

No decay electron

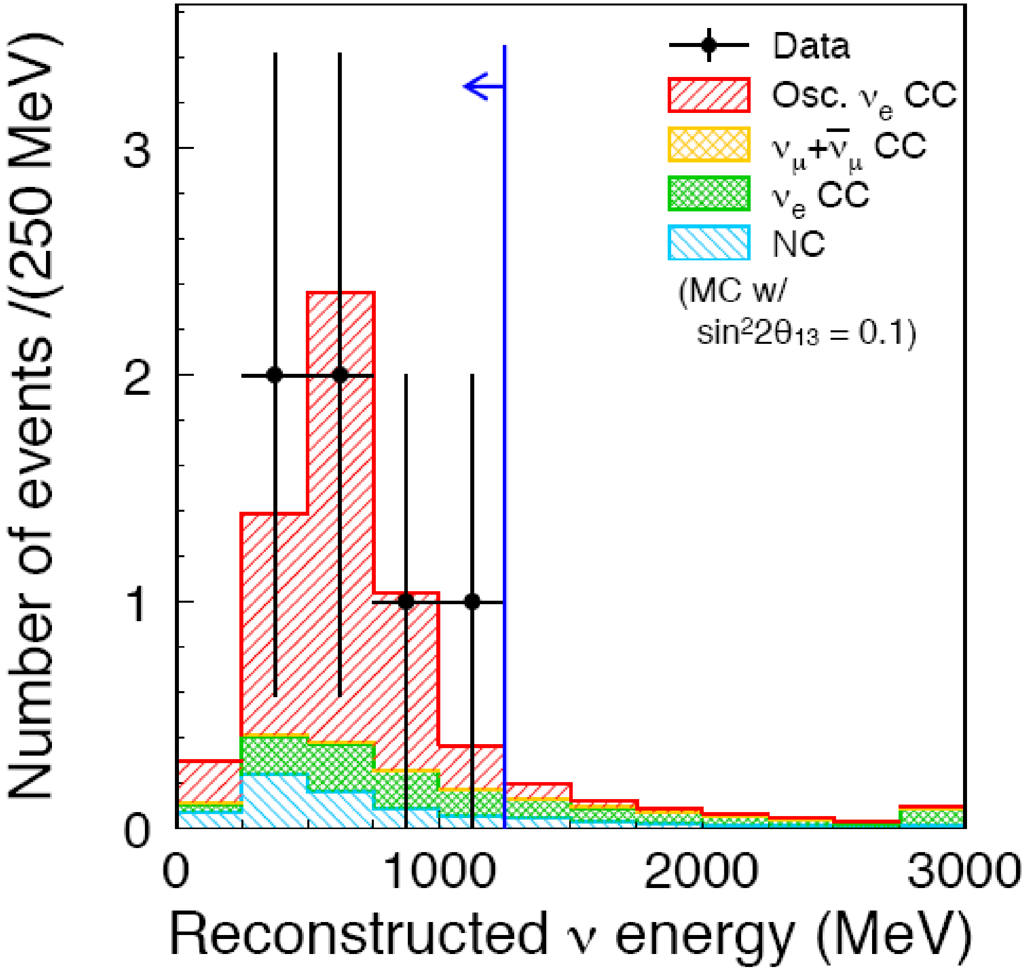




Invariant mass cut (M_{inv} < 105 MeV/c^2)



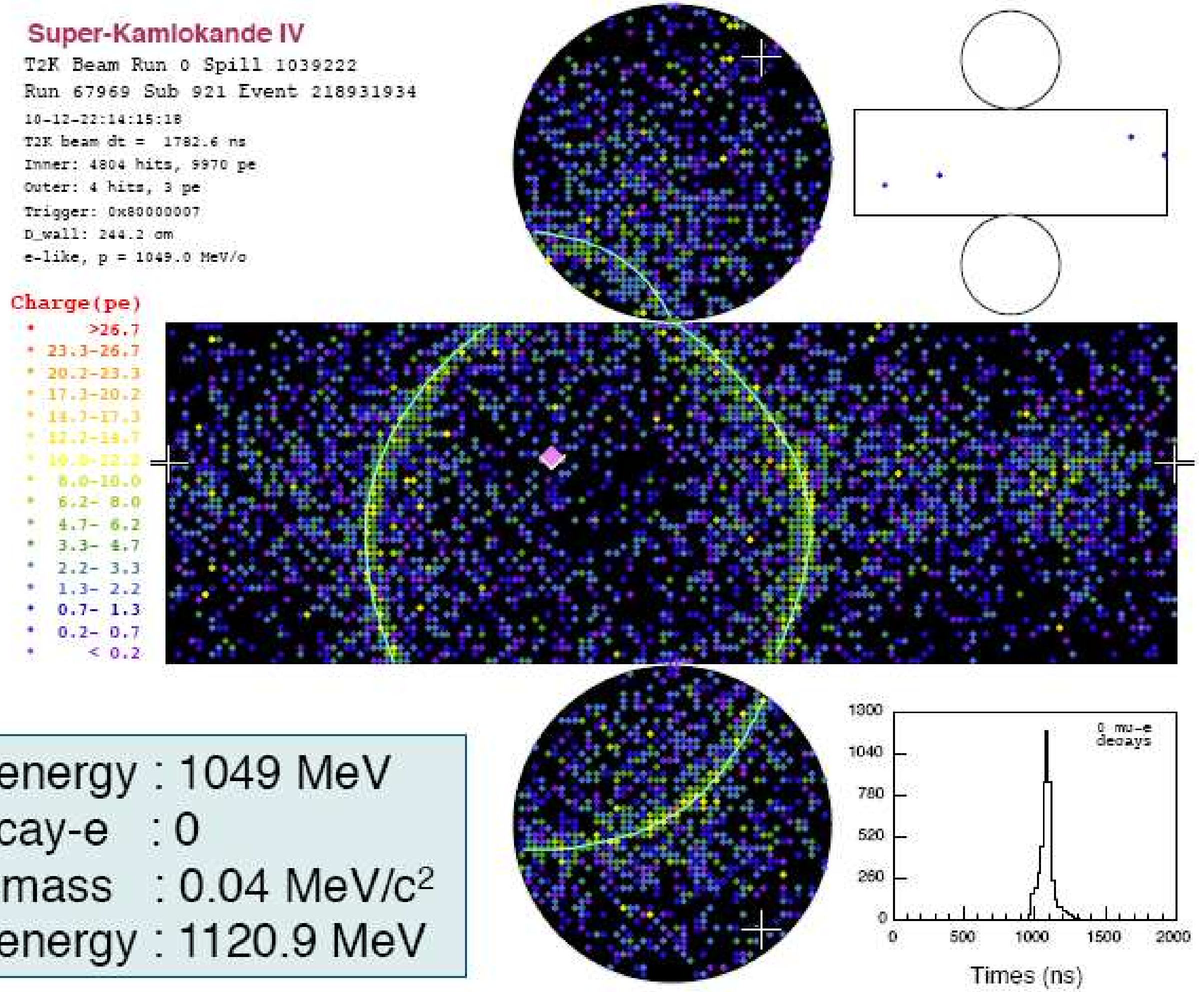
Reconstructed ν energy cut (E_{rec} < 1250 MeV) : *Final cut*



6 candidates after all cuts!

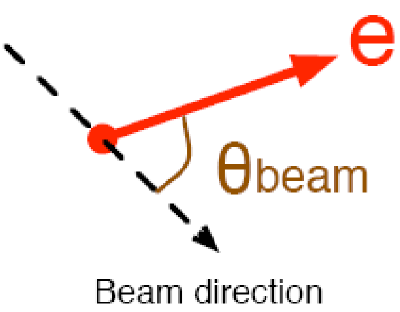
N_{exp}=1.5±0.3 for $\sin^2 2\theta_{13}$=0

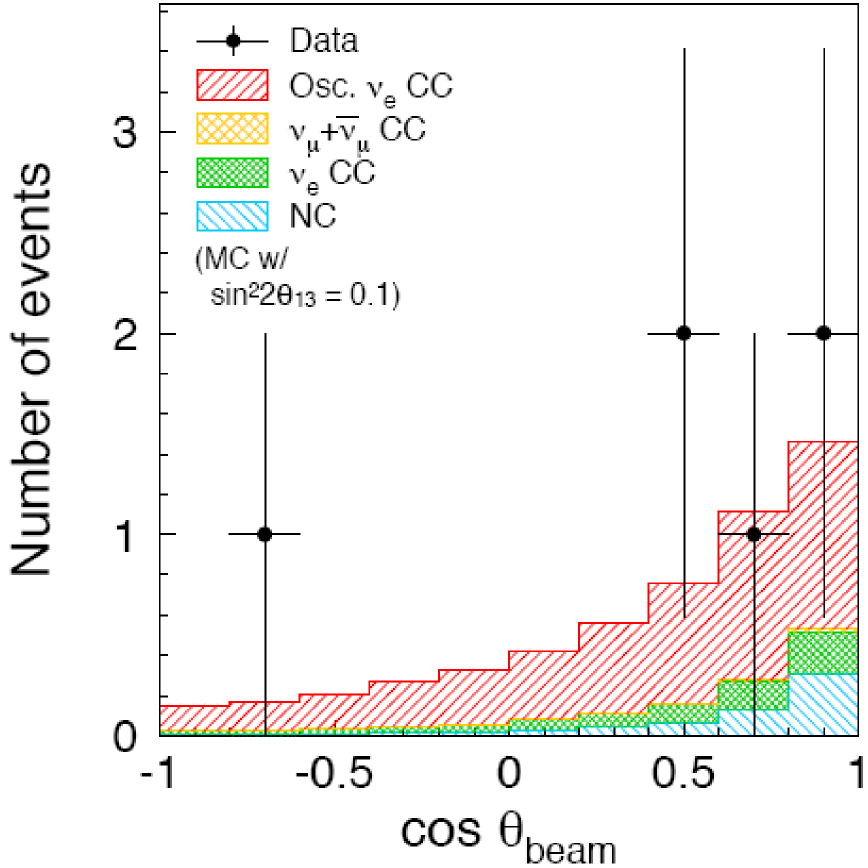
ν_e candidate event



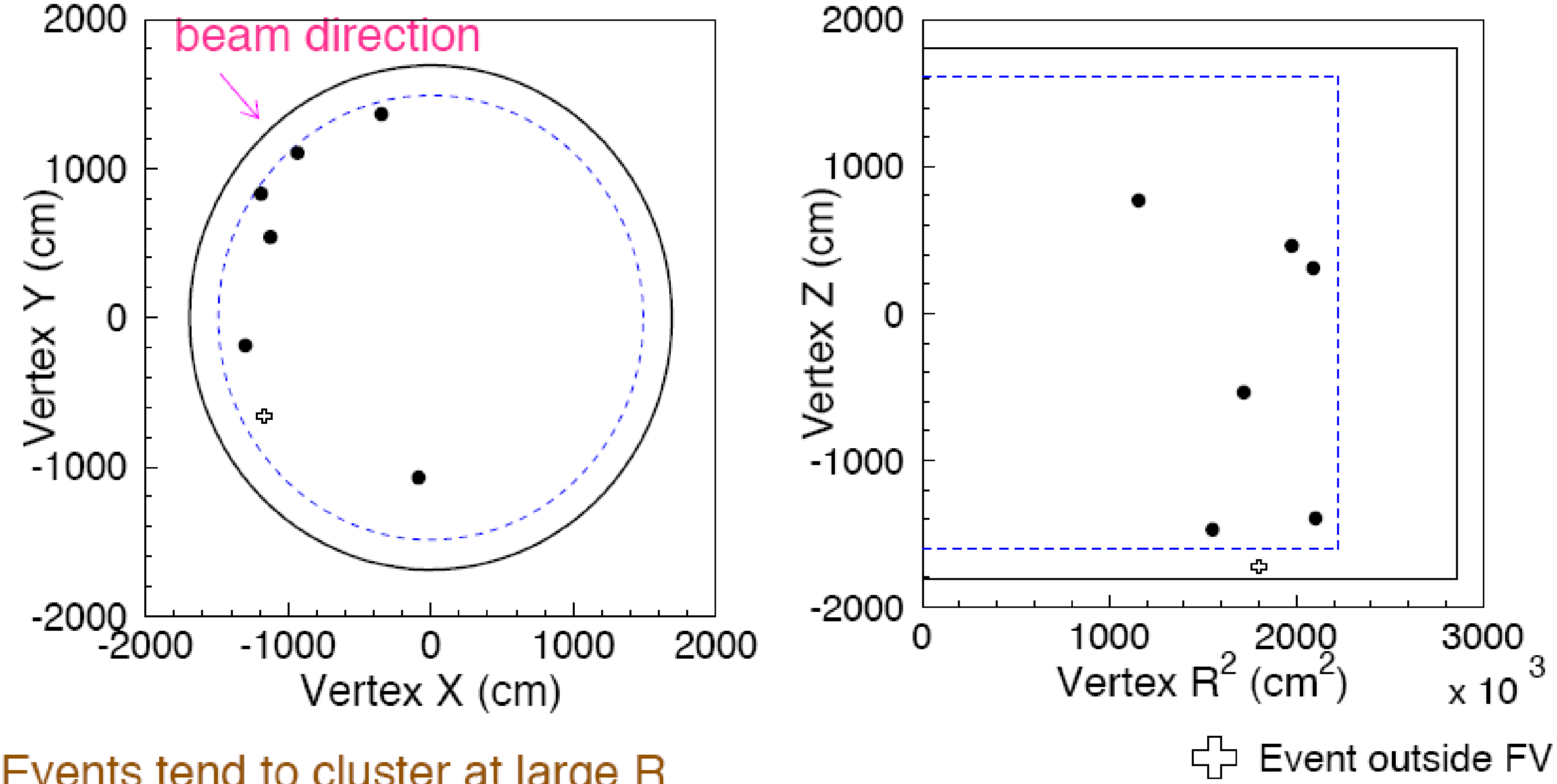
visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
recon. energy : 1120.9 MeV

Look at the events properties


e
θbeam
Beam direction


Data
Osc. ν_e CC
$\nu_\mu+\bar{\nu}_\mu$ CC
ν_e CC
NC
(MC w/
$\sin^2 2\theta_{13} = 0.1$)
Number of events
cos θ_{beam}
0
1
2
3
-1
-0.5
0
0.5
1

Vertex distribution of ν_e candidate 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

hmmmmm....?

Result of the ν_e appearance search with 1.43×10^{20} p.o.t.

The observed number of events is **6**

The expected number of events is **1.5 ± 0.3** *if* $\theta_{13} = 0$

the probability to observe six or more candidate events is 0.007 (equivalent to 2.5σ significance)

We will be eagerly waiting for more data to obtain a larger significance!

Cornell University Library

arXiv.org > hep-ex > arXiv:1106.2822

Search or Article

High Energy Physics - Experiment

Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam

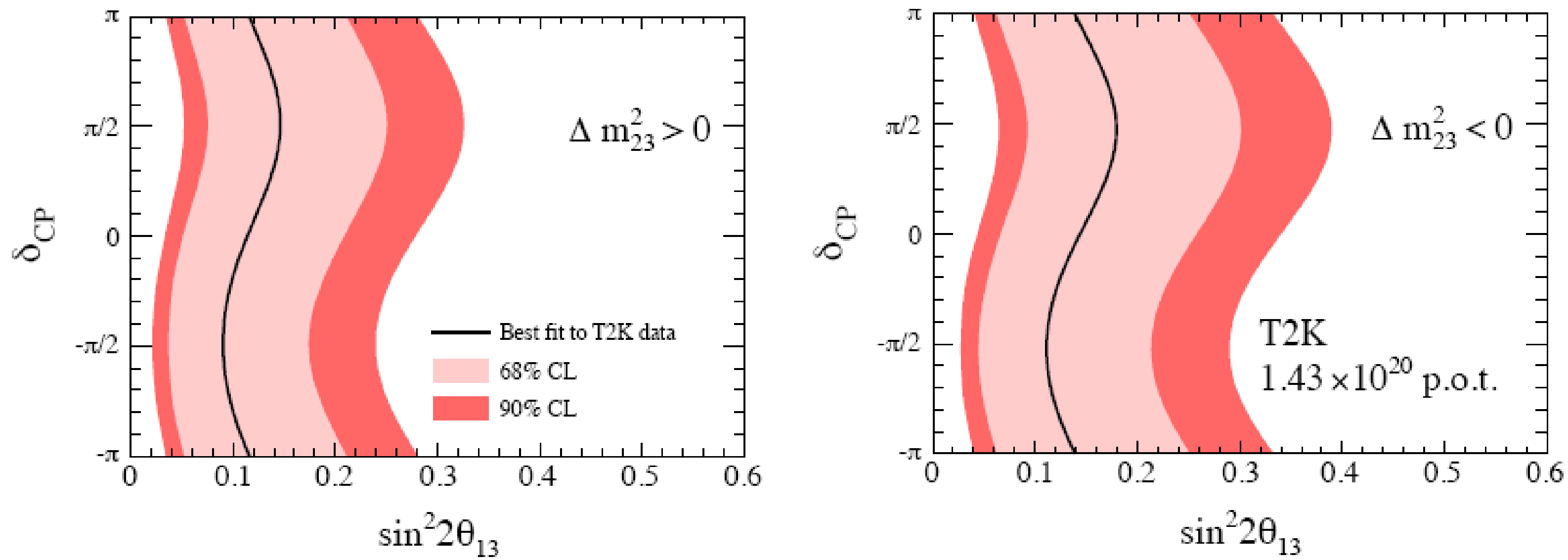
T2K Collaboration: K.Abe (49), N.Abgrall (16), Y.Ajima (18), H.Aihara (48), J.B.Albert (13), C.Andreopoulos (47), B.Andrieu (37), M.D.Anerella (6), S.Aoki (27), O.Araoka (18), J.Argyriades (16), A.Ariga (3), T.Ariga (3), S.Assylbekov (11), D.Autiero (32), A.Badertscher (15), M.Barbi (40), G.J.Barker (56), G.Barr (36), M.Bass (11), F.Bay (3), S.Bentham (29), V.Berardi (22), B.E.Berger (11), I.Bertram (29), M.Besnier (14), J.Beucher (8), D.Beznosko (34), S.Bhadra (59), F.d.M.Blaszczyk (8), A.Blondel (16), C.Bojechko (53), J.Bouchez (8, deceased), S.B.Boyd (56), A.Bravar (16), C.Bronner (14), D.G.Brook-Roberge (5), N.Buchanan (11), H.Budd (41), D.Calvet (8), S.L.Cartwright (44), A.Carver (56), R.Castillo (19), M.G.Catanesi (22), A.Cazes (32), A.Cervera (20), C.Chavez (30), S.Choi (43), G.Christodoulou (30), et al. (364 additional authors not shown)

(Submitted on 14 Jun 2011)

The T2K experiment observes indications of $\nu_\mu\rightarrow \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m_{23}^2|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$ and $\sin^2 2\theta_{13}=0$, the expected number of such events is 1.5$\pm$0.3(syst.). Under this hypothesis, the probability to observe six or more candidate events is 7$\times10^{-3}$, equivalent to 2.5σ significance. At 90% C.L., the data are consistent with 0.03(0.04)$<\sin^2 2\theta_{13}<$ 0.28(0.34) for $\delta_{\rm CP}=0$ and normal (inverted) hierarchy.

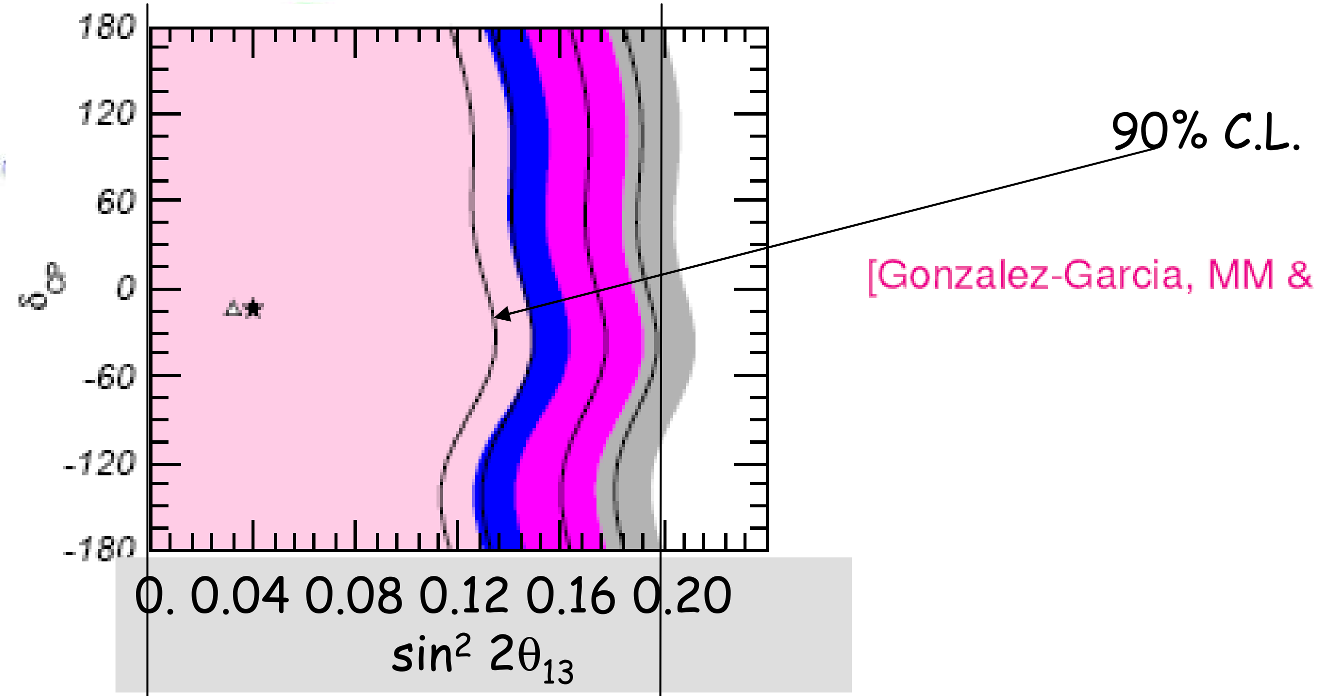
Allowed region of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)

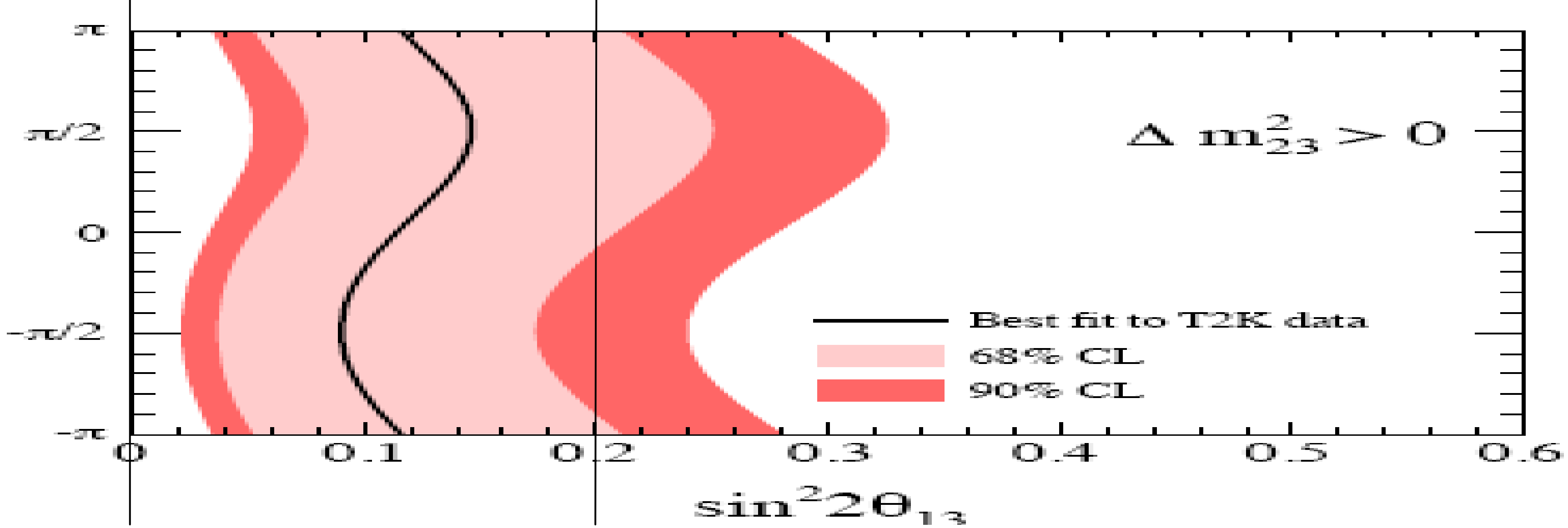


90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**



[Gonzalez-Garcia, MM & Salvado, arXiv:1001.4524]



Final remarks

1. the T2K experiment is working very well !

2. Although the significance is only 2.5 sigma the analysis procedure is such (cuts fixed in advance, sample defined by external events) that a statistical "fabrication" can be completely excluded.

3. T2K is now under reconstruction:
   beam expected to resume (if no bad surprise) in November 2011

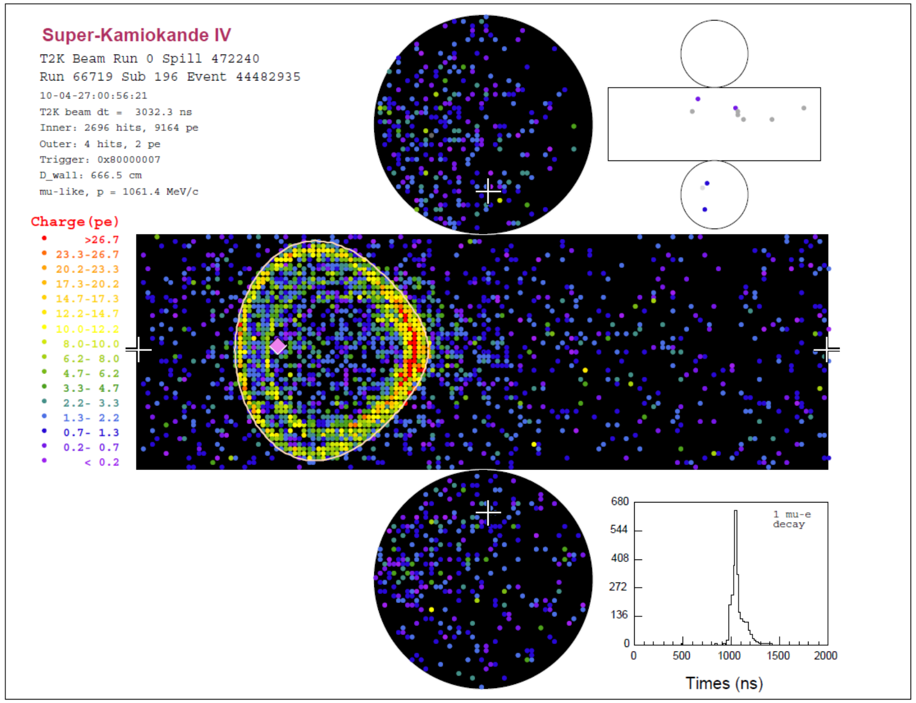
4. if it is confirmed that θ_{13} is "large" this will have consequences on the design of the next generation of experiments (good for NOvA in first instance)

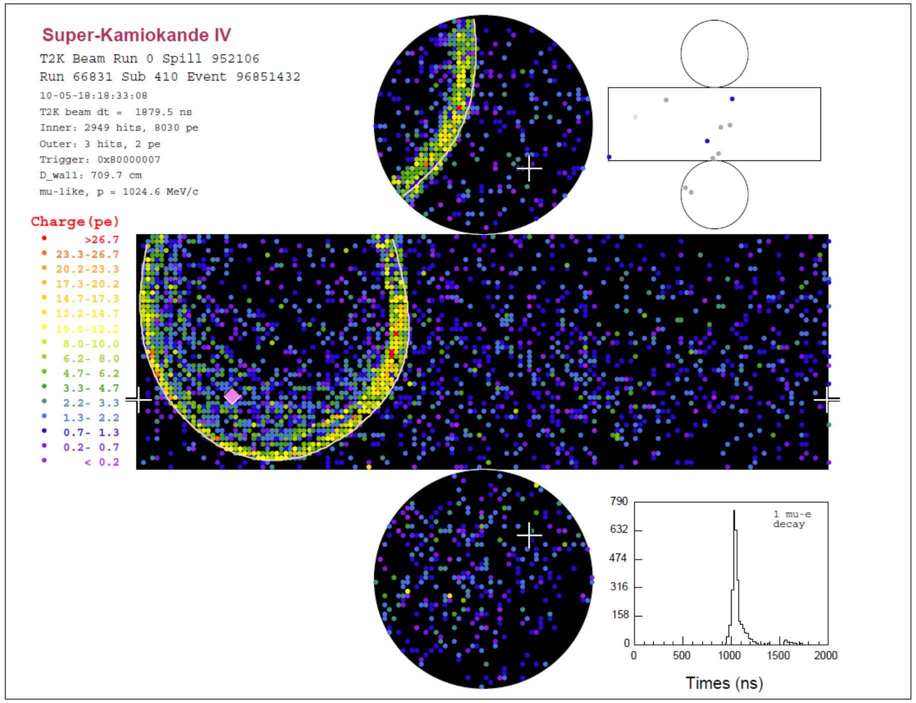
5. this summer will be very exciting on the neutrino front:
   new results from (at least) MINOS, OPERA, DCHOOZ are expected

COME TO NUFACT11 at CERN/GENEVA 1-6 August 2011!
http://nufact11.unige.ch

A few reserve slides

Event display
single-ring μ-like events





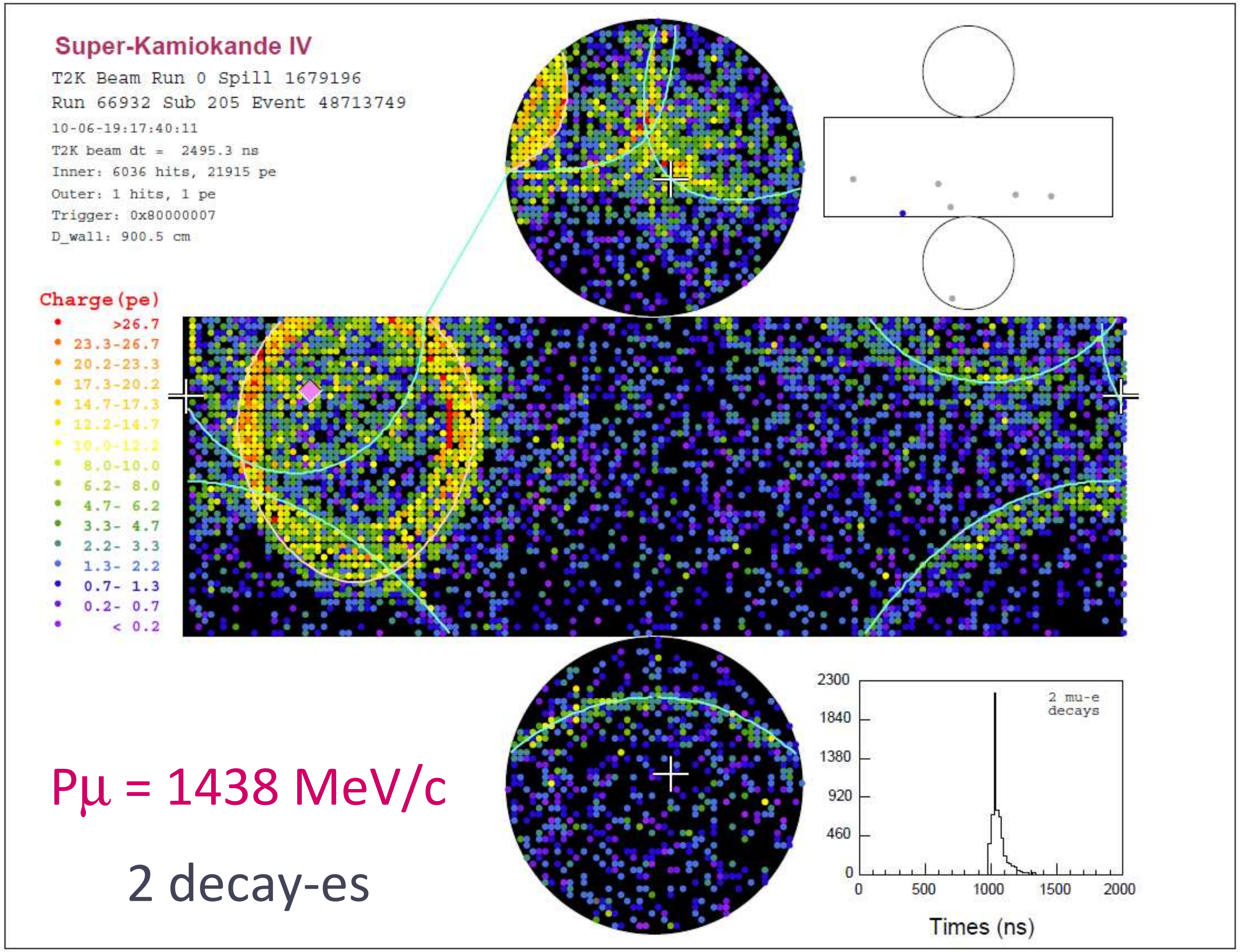
Pμ = 1061 MeV/c

1 decay-e

Pμ = 1025 MeV/c

1 decay-e

Event display
multi-ring μ-like event



$P\mu$ = 1438 MeV/c

2 decay-es

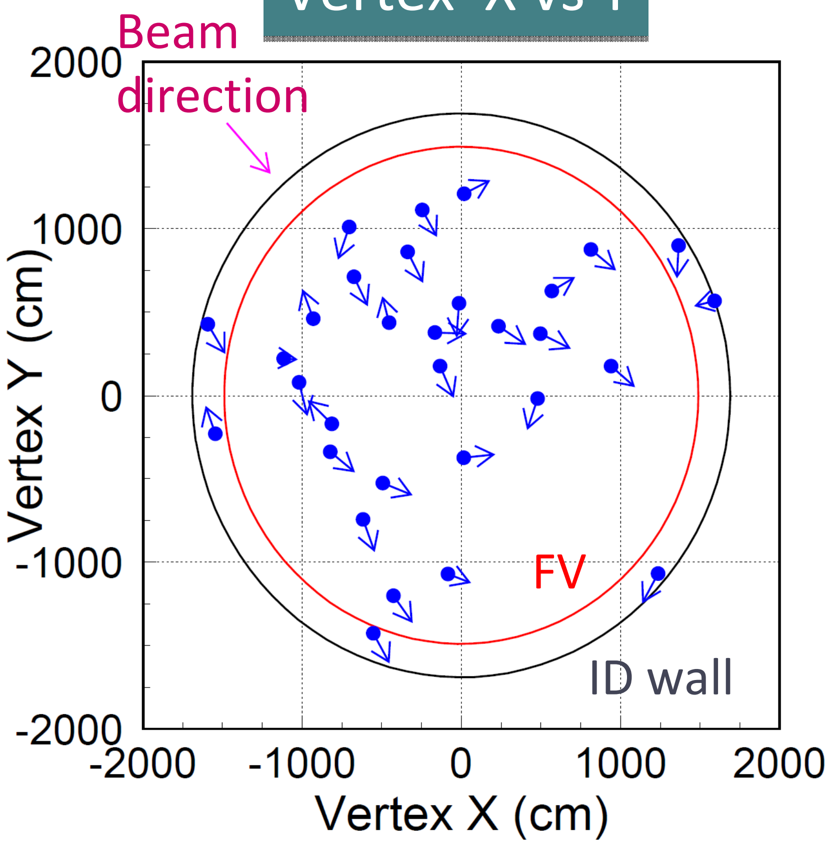
Vertex and direction

(FC, Evis>30MeV)

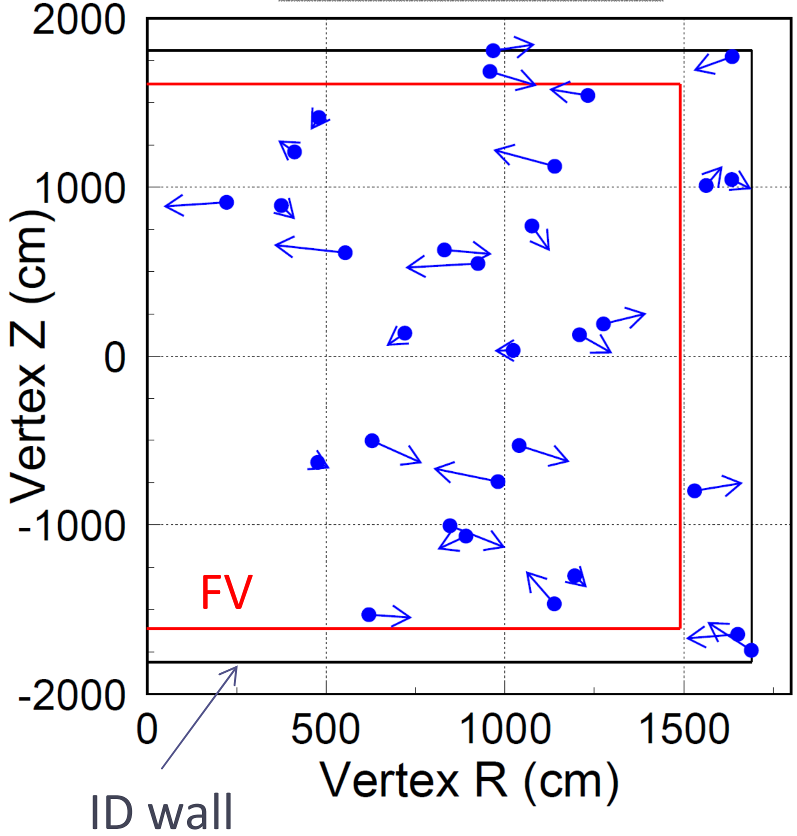
Points : Reconstructed event vertex

Arrow : 1st-ring direction

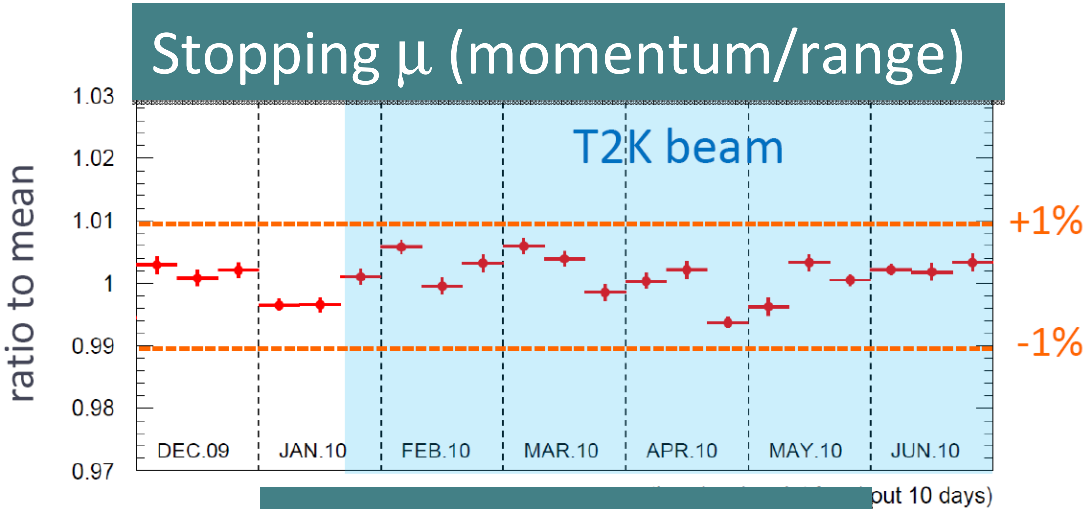
Vertex X vs Y



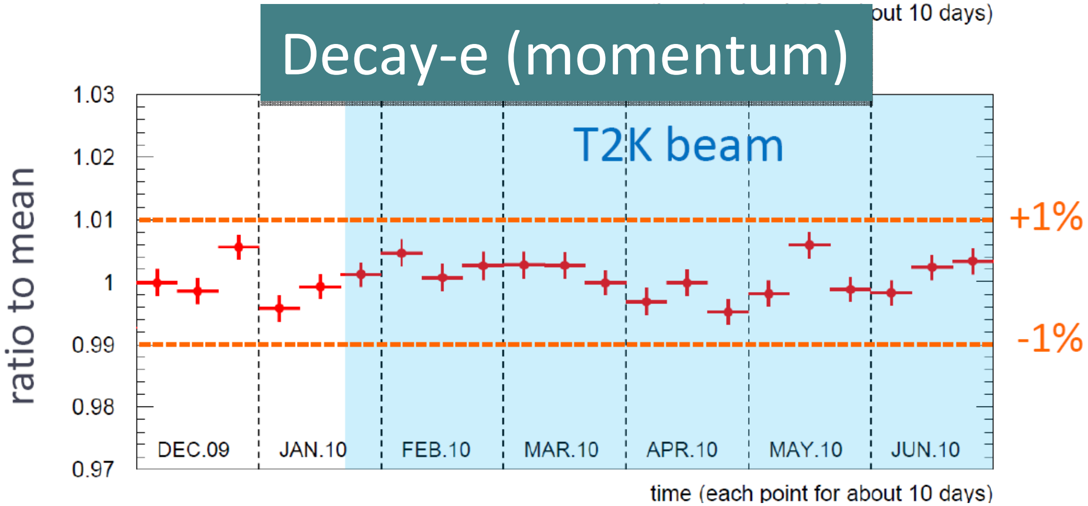
Vertex R vs Z



Super KamiokaNDE
Energy scale stability



RMS/MEAN
T2K period : 0.31%
(SK-IV all : 0.39%)

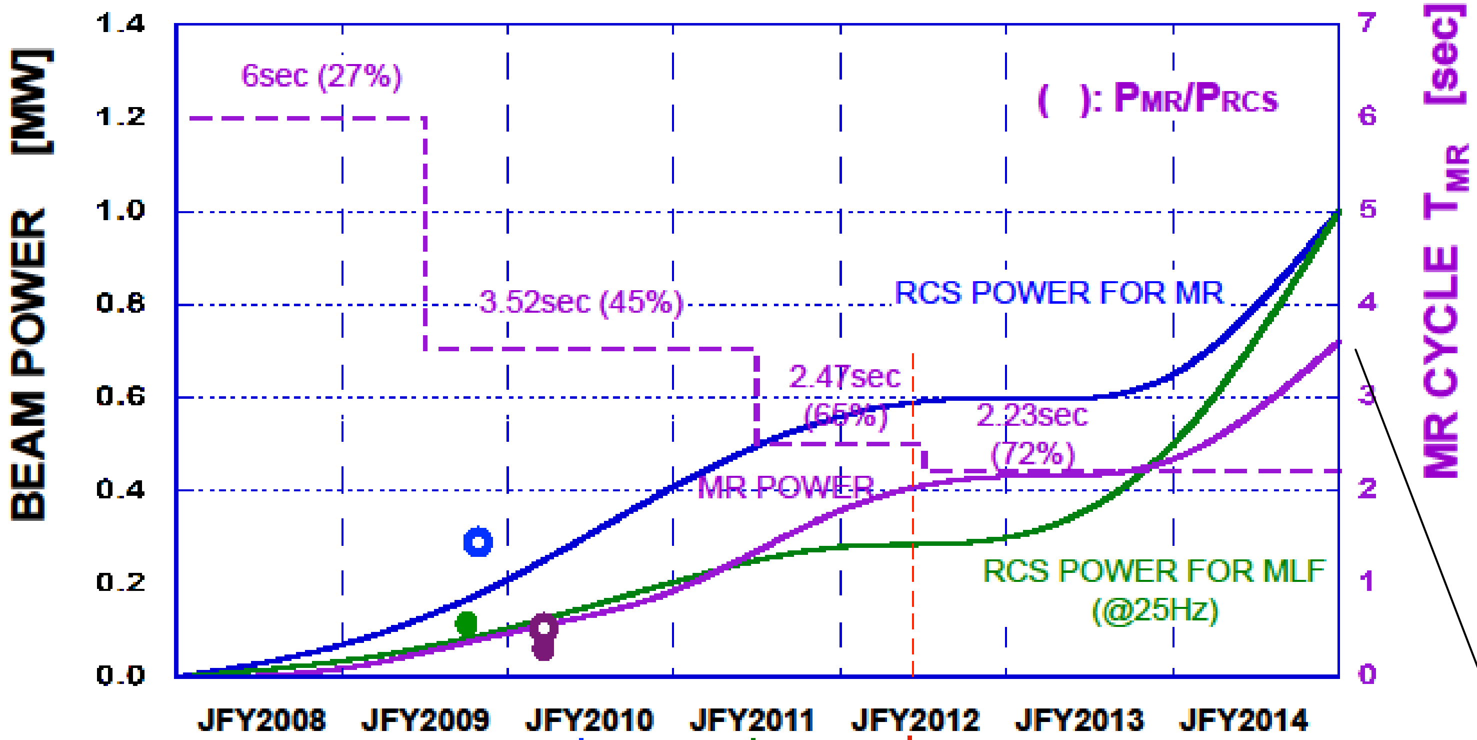


RMS/MEAN
T2K period : 0.28%
(SK-IV all : 0.45%)

Energy scale has been quite stable.

Power upgrade plan of RCS and MR(FX)

For 8 bunches, 30 GeV at MR: $P_{MR}=1.6 \times (P_{RCS}/T_{MR})$



3-50BT collimator shields, RF (1st HH), FX kickers

Ring collimator shields, RF (6th F, 2nd HH), Inj. Sep 1

ACS Installation in JFY2012
400 MeV injection in the RCS

RF (3rd HH), Inj. Sep 2, FX Septa,

750kW in 2014