Neutrino oscillations in T2K experiment

first results

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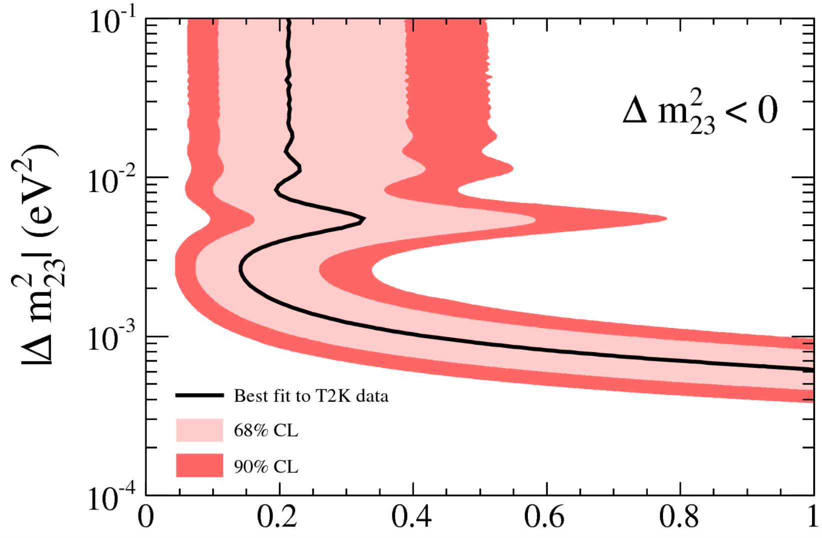
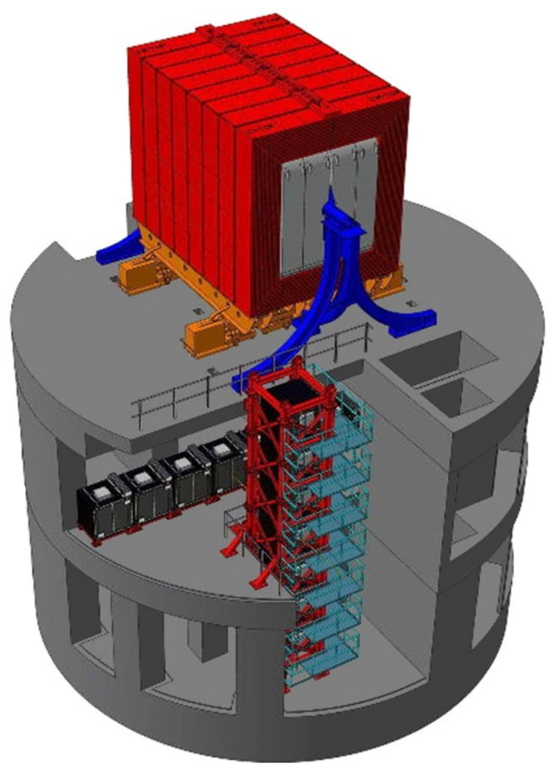
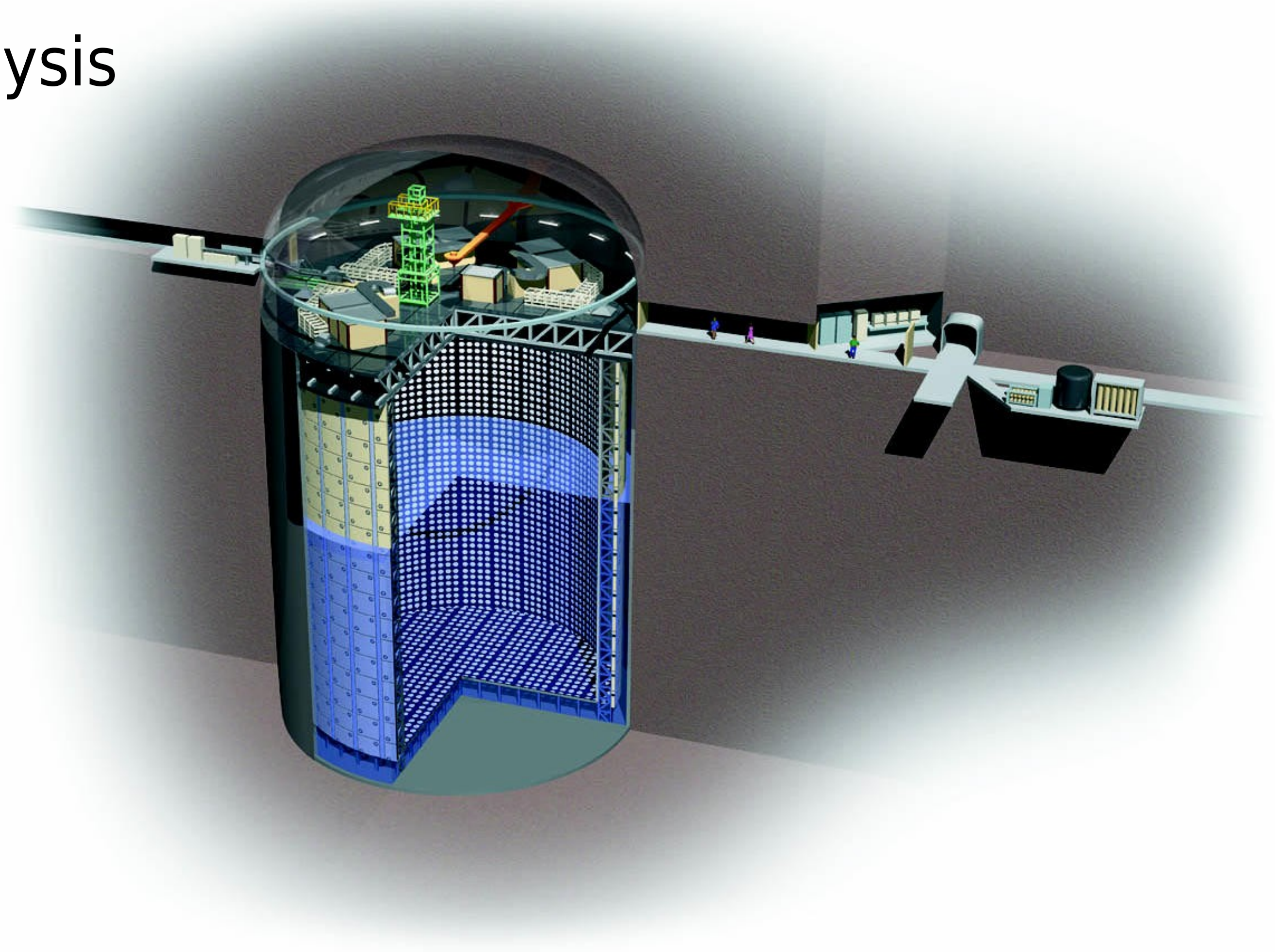
on behalf of the T2K collaboration

Outline

- neutrinos and oscillations
- the T2K experiment
- the analysis method
- ν_e appearance analysis
- ν_μ disappearance analysis
- future plans







The neutrinos

- interactions of neutrinos

charged current (**CC**)

ν_e (ν_μ, ν_τ) — e (μ, τ)

W

neutral current (**NC**)

ν_e (ν_μ, ν_τ) — ν_e (ν_μ, ν_τ)

Z

<u>Hadronic final state</u>

QE: nucleon

RES: resonance → nucleon+pion

DIS: nucleon+pions

\+ Final State Interactions

- flavor eigenstates are the linear combinations of mass eigenstates → Pontecorvo-Maki-Nakagawa-Sakata matrix
  - parametrized by 3 mixing angles and CP-violating phase δ_{CP}

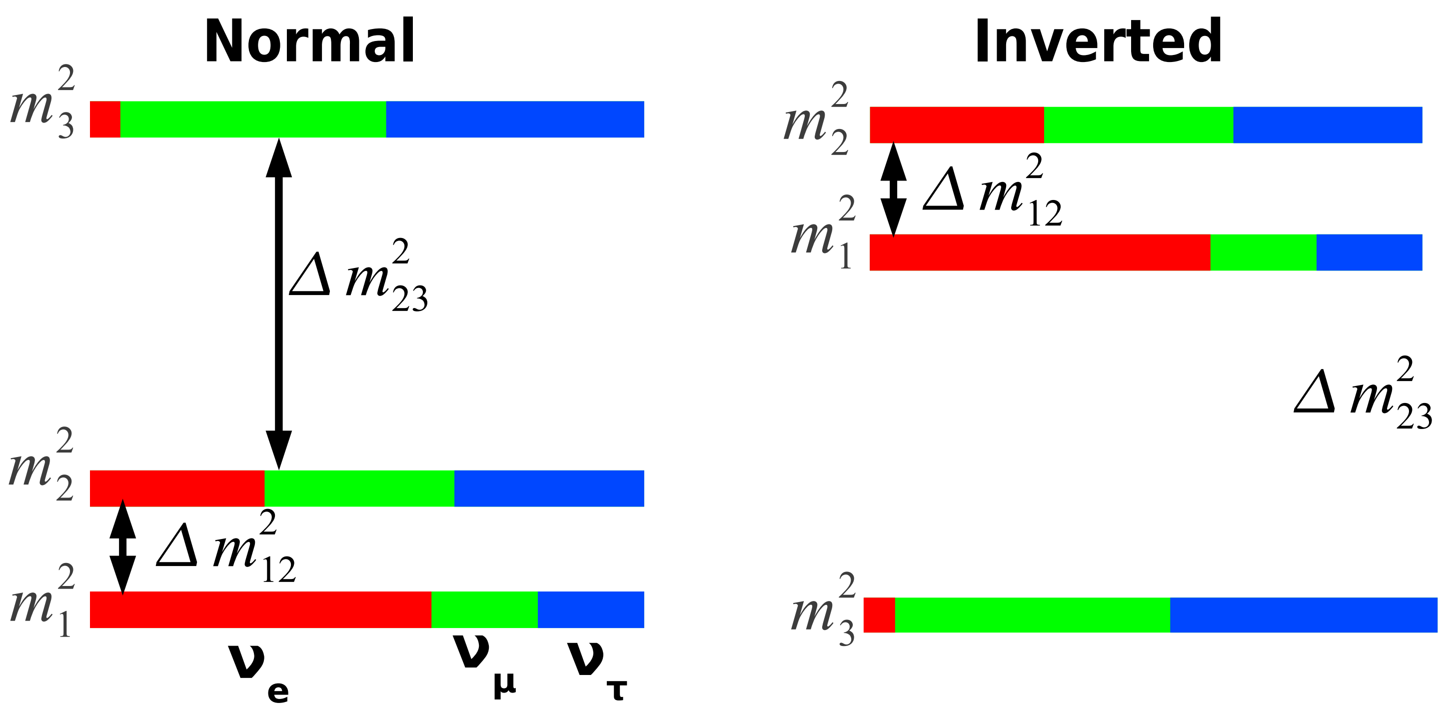
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0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

The oscillation phenomenon

- (two flavours approximation) the oscillation probability depends on mixing angle **θ**, neutrino energy $\mathbf{E_\nu}$, traveled distance **L** and squared mass difference $\mathbf{\Delta m^2}$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4 E_\nu}$$

- 3 neutrinos → 2 independent Δm^2 ("solar" and "atmospheric")
- neutrino mass hierarchy



The oscillation parameters

- θ_{12} – “solar sector”
  - ν_e disappearance (SNO, KamLAND, SuperK and others)
  - $0.84<\sin^2 2\theta_{12}<0.89$, $7.38\cdot10^{-5}<\Delta m^2_{12}(eV^2)<7.80\cdot10^{-5}$
- θ_{23} – “atmospheric sector”
  - ν_μ disappearance (SuperK, K2K, MINOS)
  - ν_τ appearance (OPERA, SuperK)
  - $0.92<\sin^2 2\theta_{23}<1.0$, $2.3\cdot10^{-3}<|\Delta m^2_{23}|(eV^2)<2.56\cdot10^{-3}$
- θ_{13} sector
  - only upper limit known (CHOOZ, MINOS)
  - $\sin^2 2\theta_{13}<0.13$ @ 90% CL (2010)
  - δ_{CP} uknown

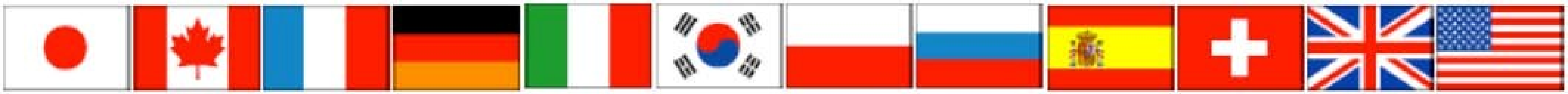
reactor experiments with short base

accelerator experiments with long base

observation of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

The T2K experiment

- long baseline oscillation experiment
- collaboration: ~500 members, 58 institutes, 12 countries

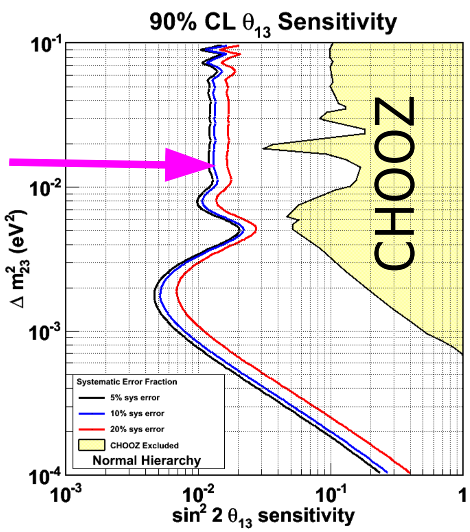


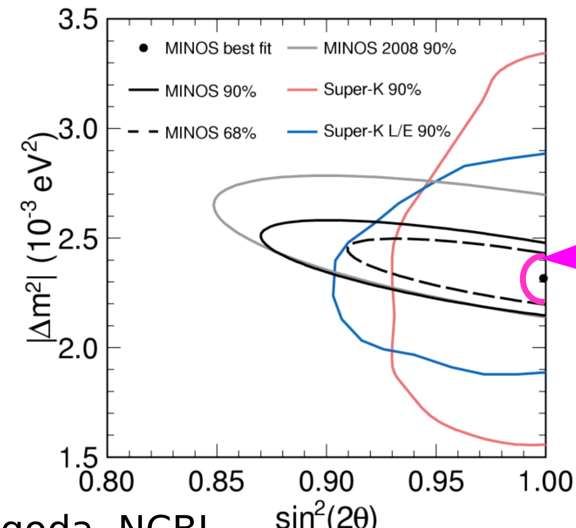
- the main goals:

the measurement of the $\nu_\mu \rightarrow \nu_e$ oscillation

precise measurement of ν_μ disappearance

θ_{13} sensitivity 20 times better than CHOOZ
(with $8 \cdot 10^{21}$ POT)

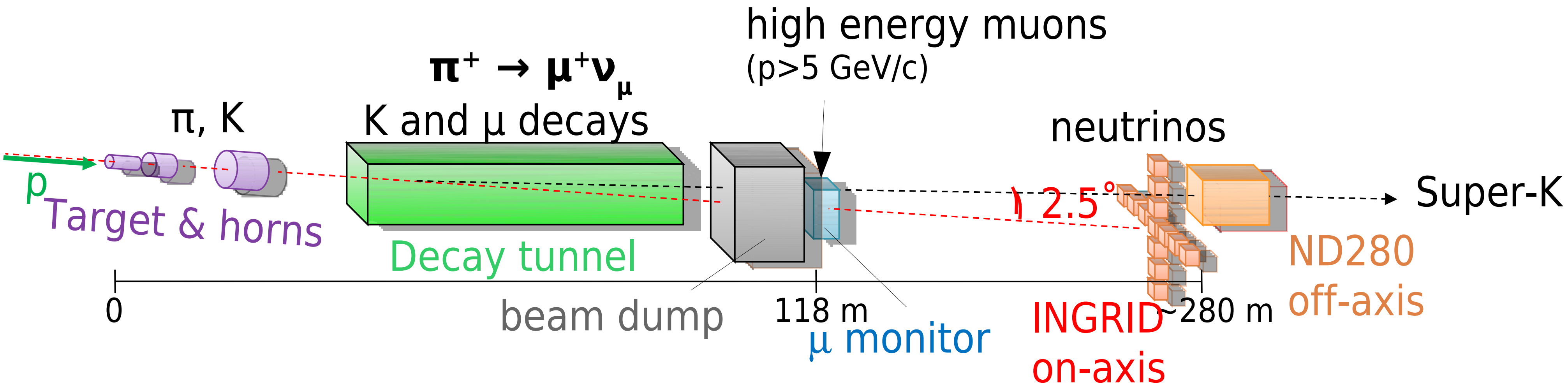




$\delta(\sin^2 2\theta_{23}) \sim 0.01$
$\delta(\Delta m^2) \sim 10^{-4}\,eV^{-2}$

The beam line

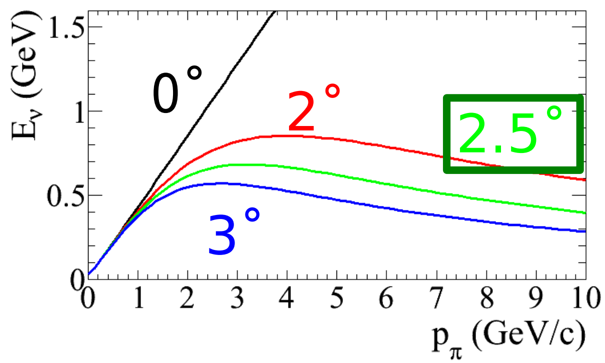
- proton accelerator chain at J-PARC
  - 30 GeV proton beam, 8 bunches, 3 s pulse period
  - power achieved 145kW, designed 750kW
  - position, profile and intensity of the beam monitored
- graphite target, 3 horns focusing positively charged hadrons
- 96 m decay tunnel, beam dump



The ν beam

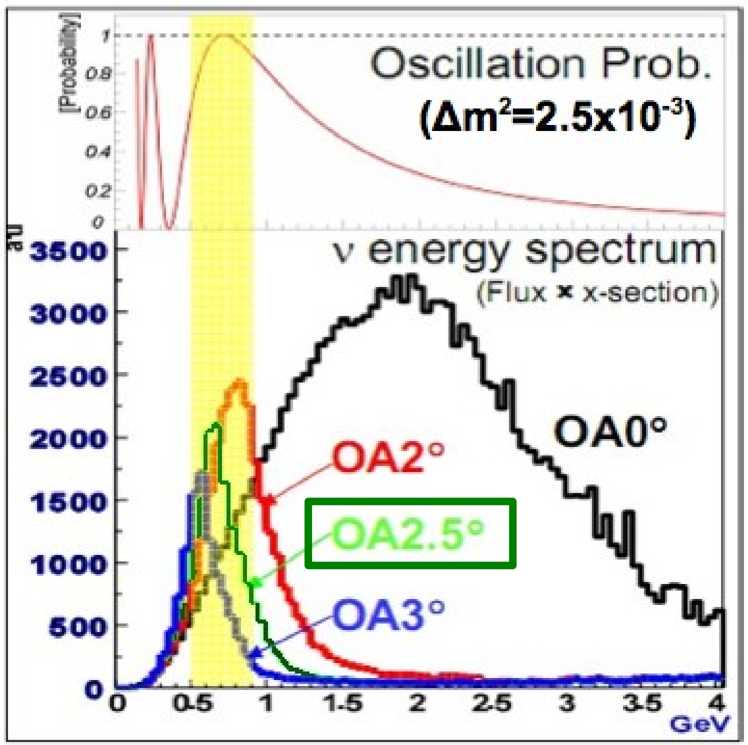
conventional, high intensity, **off-axis** ν_μ beam

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



for angles ≠ 0
the dependence of E_ν
from E_π is reduced

narrow spectrum,
tuned at the first
oscillation maximum

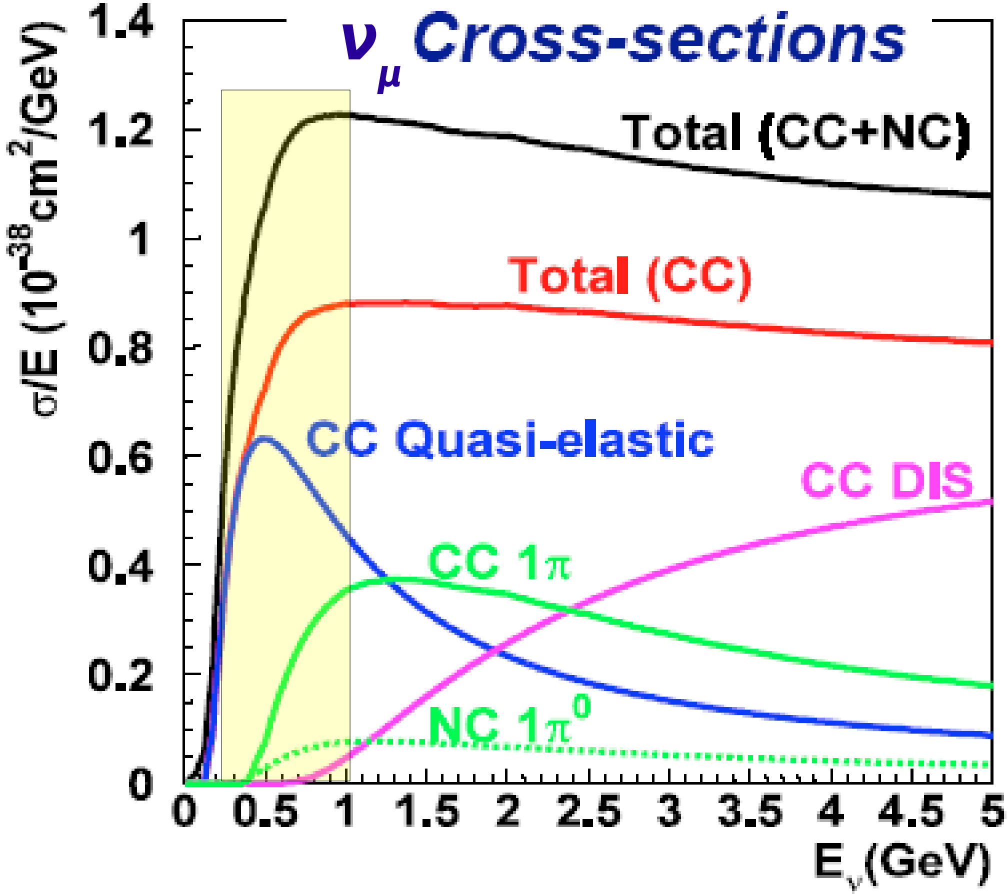


the direction must be precisely controlled
(<1mrad to keep peak energy stable
δE/E ~2% at far detector)

Advantages of the off-axis beam

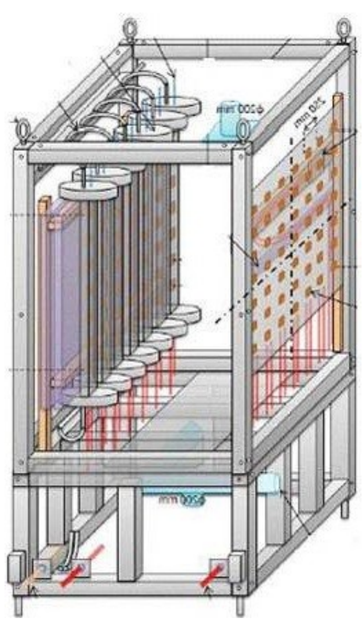
- increase statistics in the interesting region
- high energy tails reduced

  - background from intrinsic ν_e reduced (ν_e at peak ~0.5%)
  - background from π^0 reduced
  - CCQE sample enhanced

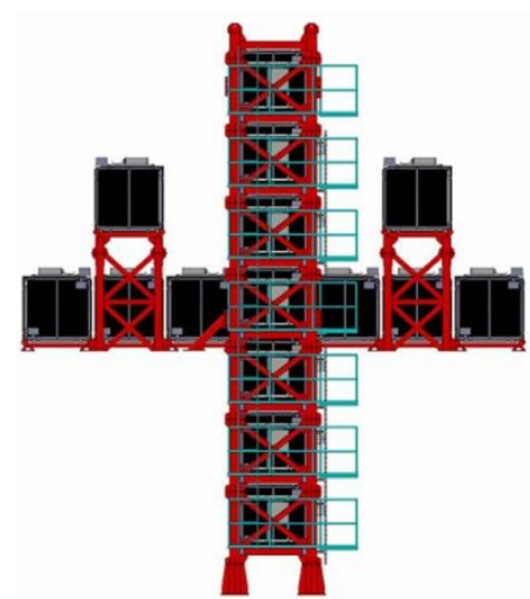


Near detectors – on axis

- Muon monitor
  - measures beam direction and intensity on spill-by-spill basis, with <u>high-energy muons</u> from pion decays, to guarantee the stability
  - ionization chambers and semiconductor arrays

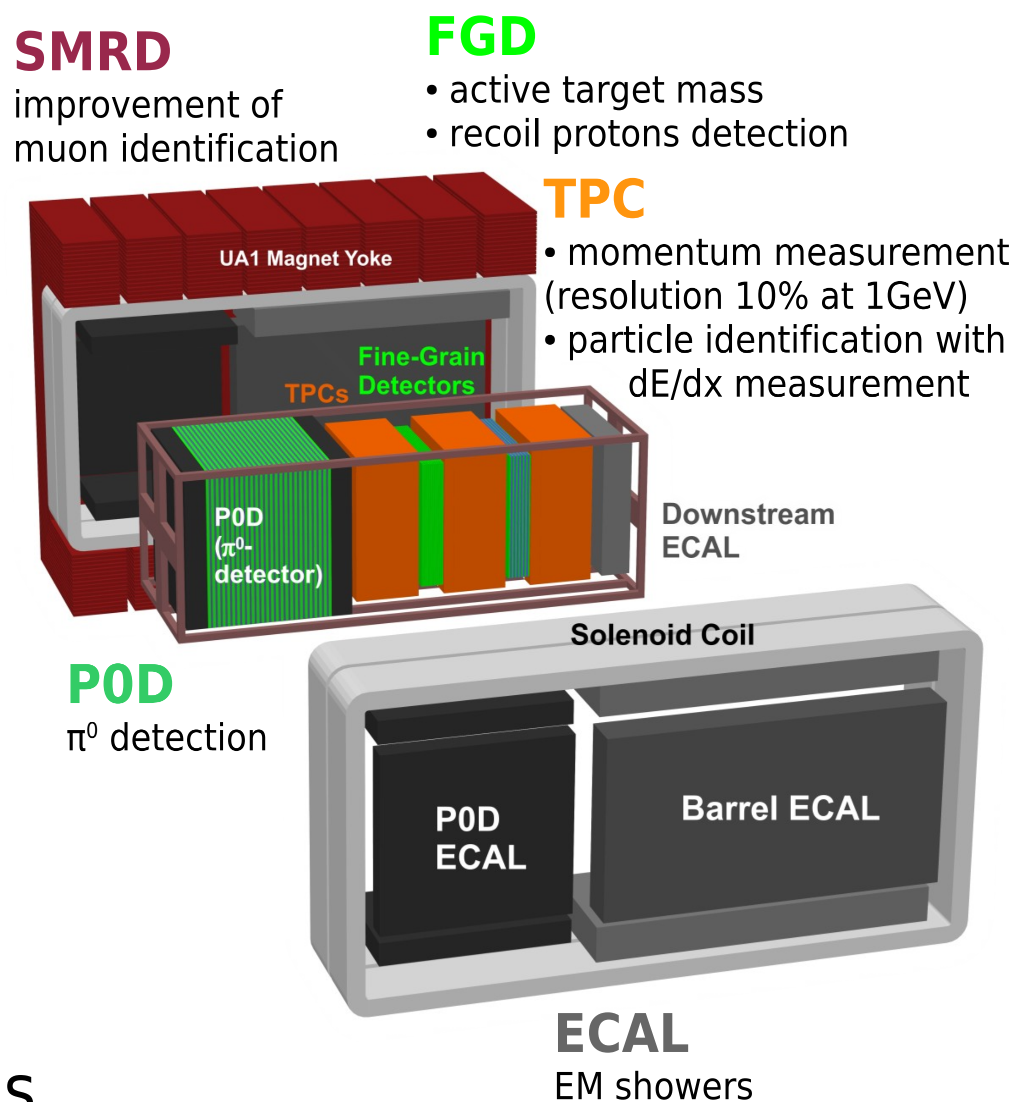


- On-axis Interactive Neutrino GRID (INGRID)
  - monitors the intensity, profile and direction of the beam with <u>ν interactions</u> — but not spectrum!
  - 16 identical cubic modules, iron/scintillator sandwich



Near detector – off axis

- ND280 – multi-purpose detector with magnetic field
  - UA1/NOMAD magnet (magnetic field 0.2 T)
- measures the beam before the oscillation occurs
- reconstructs final states to study neutrino interactions and beam properties
  - measures ν interaction rates and flavour → ν_μ and ν_e spectra
- focused on specific backgrounds



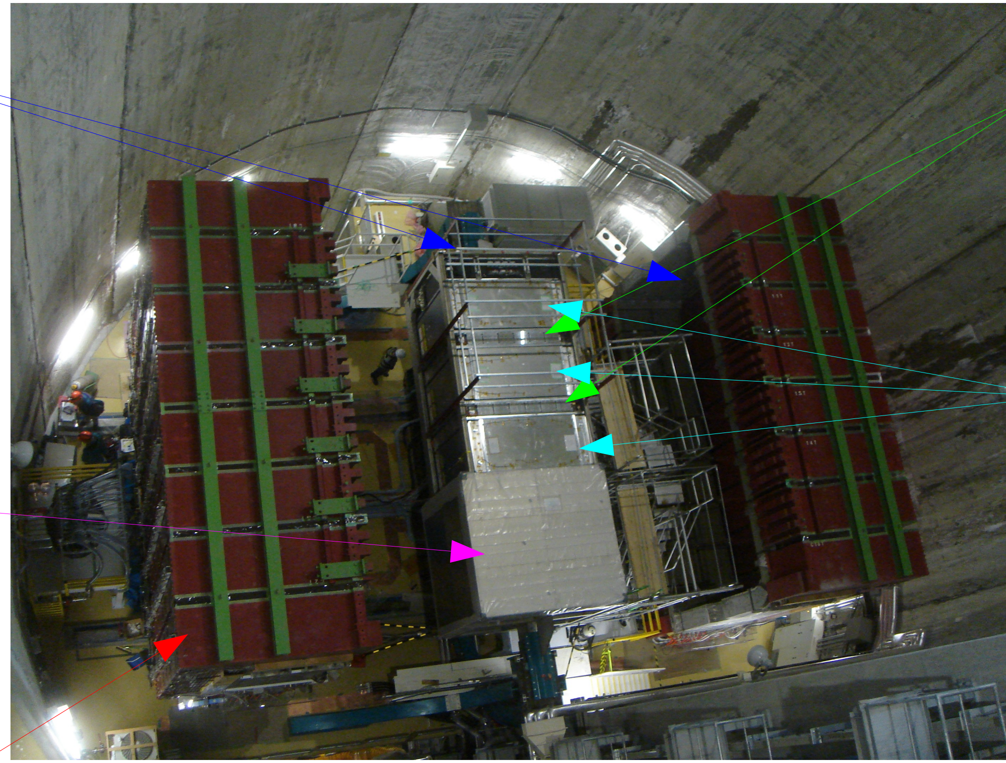
ND280 detector

Tracker

Electromagnetic calorimeters
surround inner detectors (P0D, FGDs, TPCs)
13 modules of plastic scintillator/lead XY planes

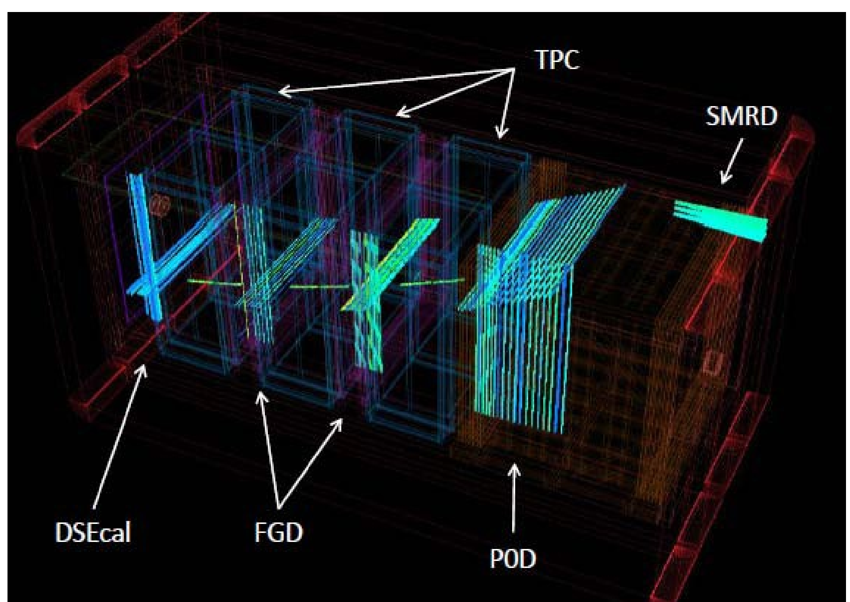
π^0 detector
Scintillator planes interleaved with water and lead/brass layers

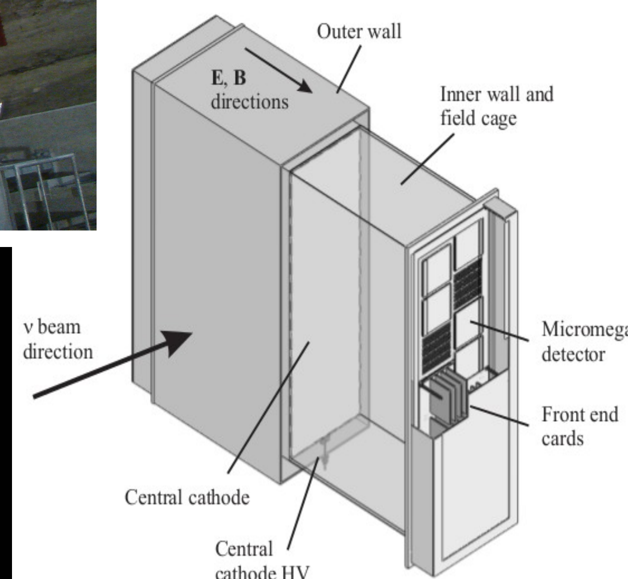
Side Muon Range Detector
Scintillator planes inserted in magnet yoke



2 Fine Grained Detectors
Thin, long scintillator bars, active target (2.2 tons)

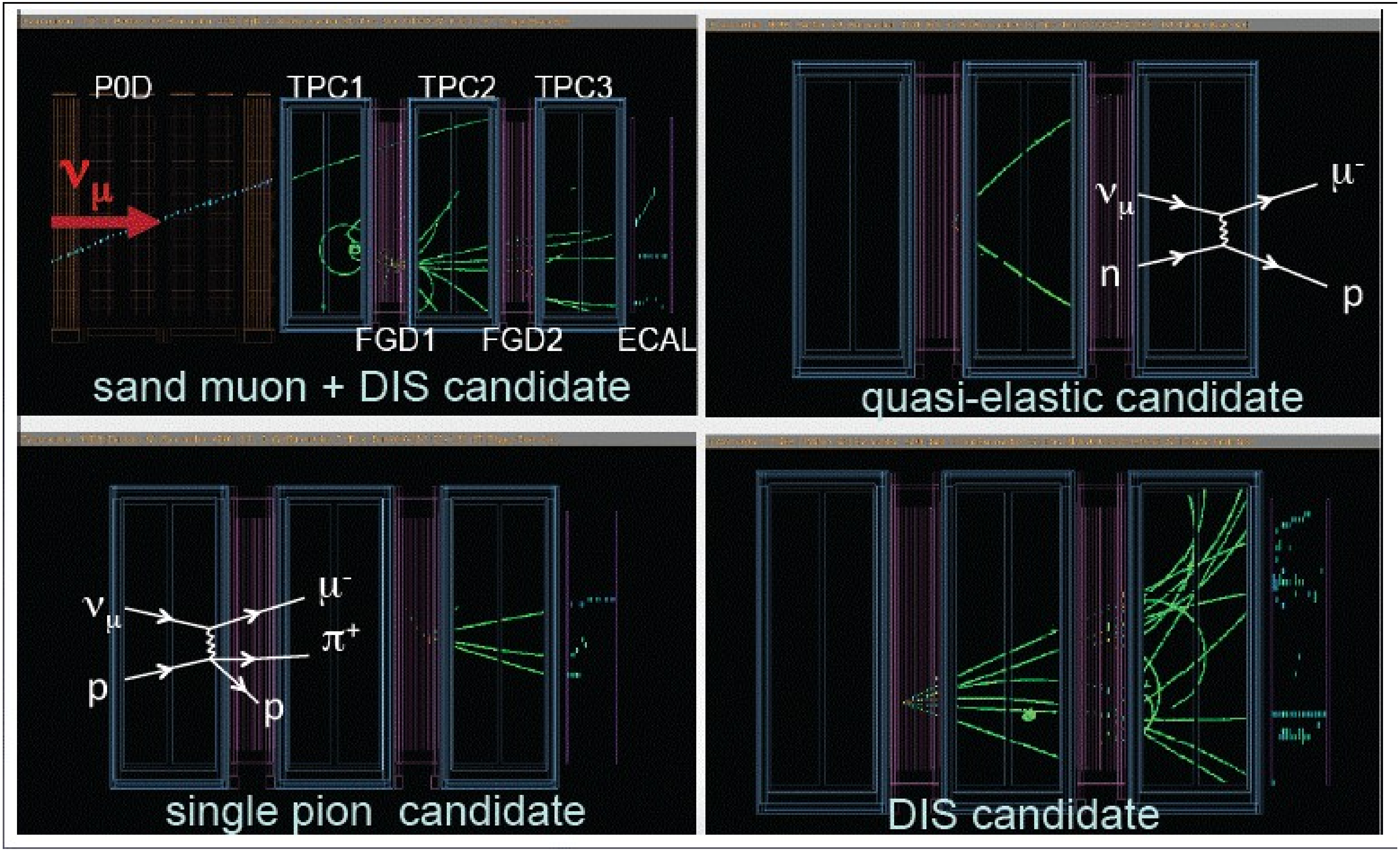
3 Time Projection Chambers





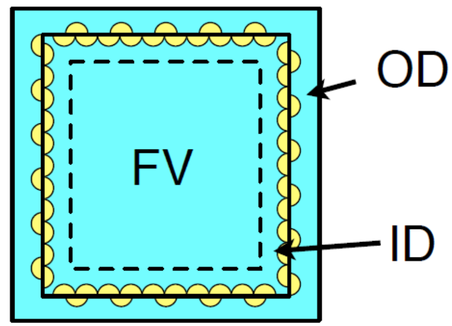
all scintillator detectors use Hamamatsu Multi Pixel Photon Counter for read-out ($1.3x1.3mm^2$, 667 pixels)

Events in ND280

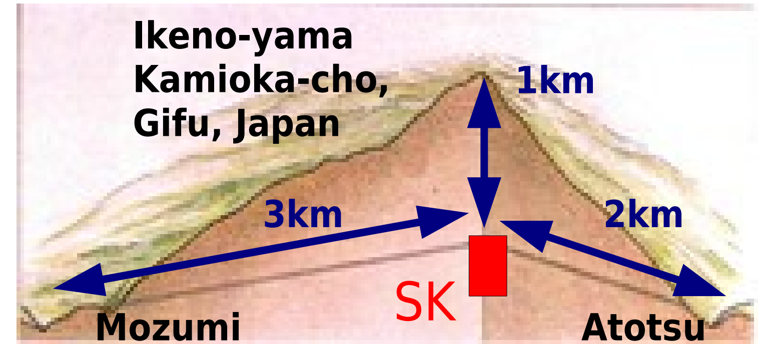


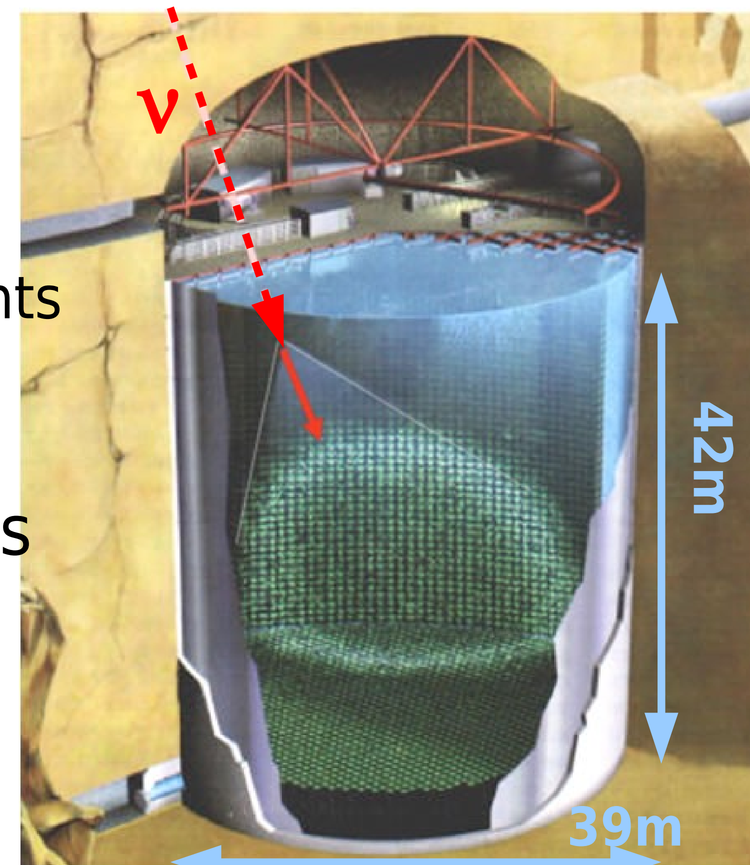
Far detector: Super Kamiokande

- 50 kton water Cherenkov detector
  - 22.5 kton fiducial volume, ultrapure water
- inner and outer detector
  - 11,000 20'' PMT for ID
    - (40% photo coverage)
  - 2,000 outward facing 8'' PMT for OD
    - veto cosmics, radioactivity, exiting events

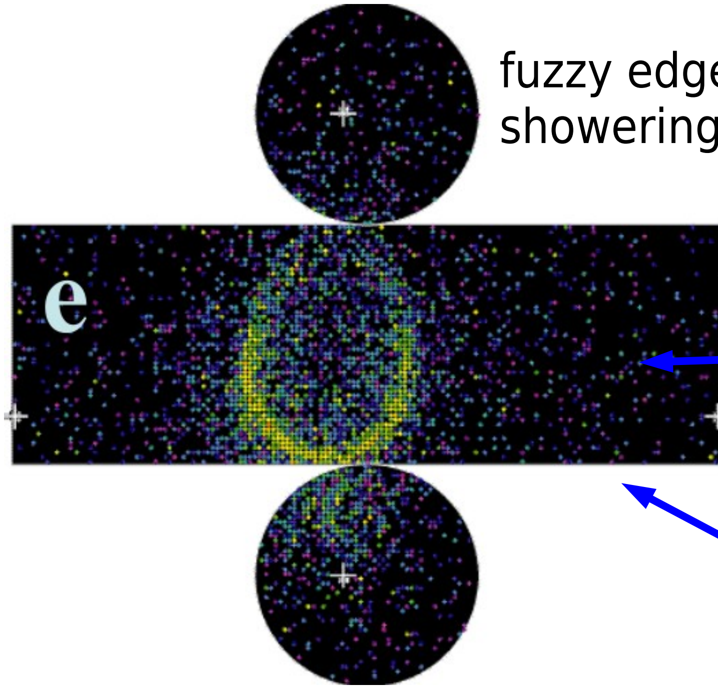


- operated since 1996, well understood,
- since 2006 with new readout electronics
- particle identification capability:
  - muons misidentified as electrons <1%
- ν energy resolution ΔE/E~10% for two-body kinematics



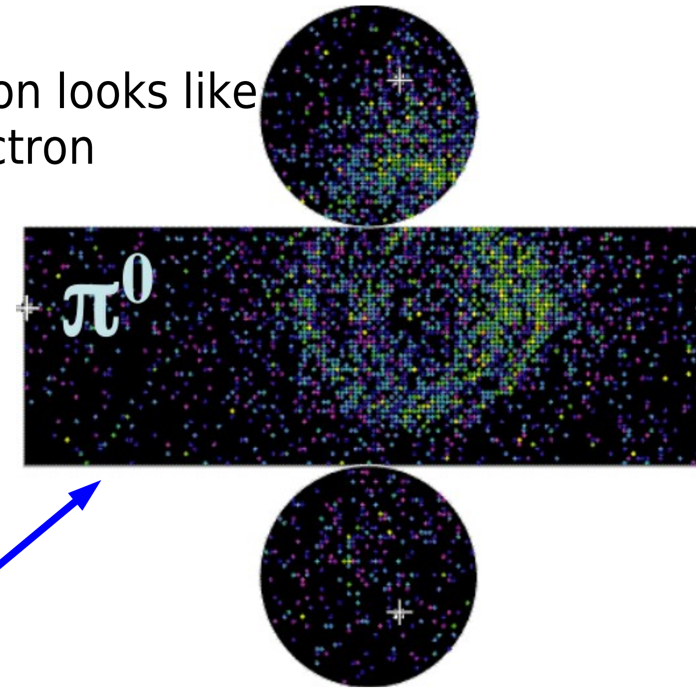


Events in Super Kamiokande



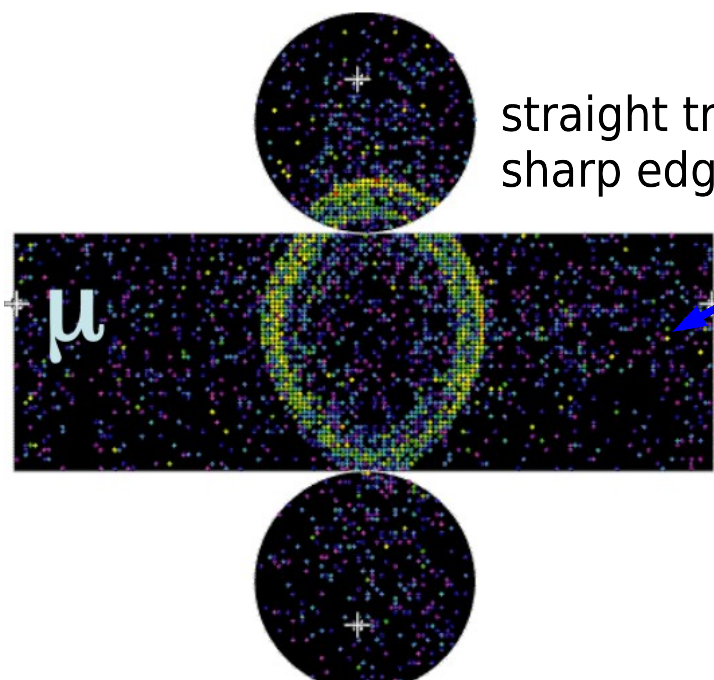
fuzzy edges due to
showering and scattering

γ photon looks like
an electron



oscillation signal

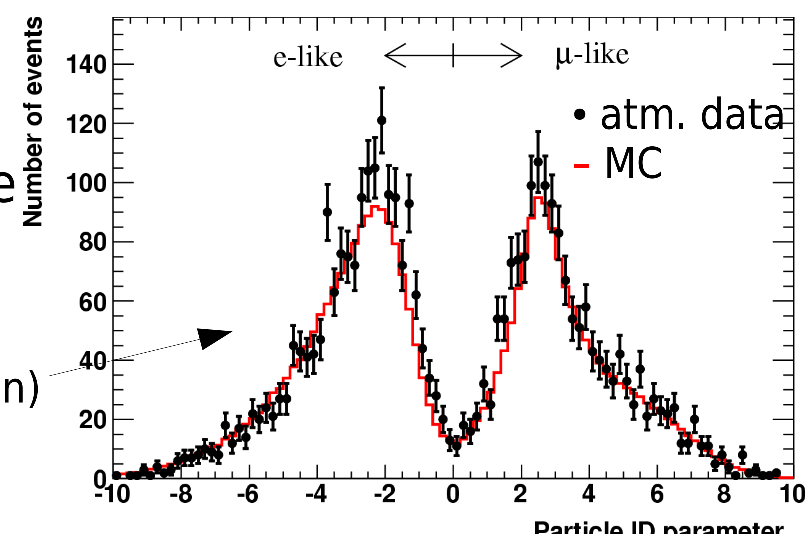
background:
- intrinsic ν_e
- neutral current π^0



straight track
sharp edges

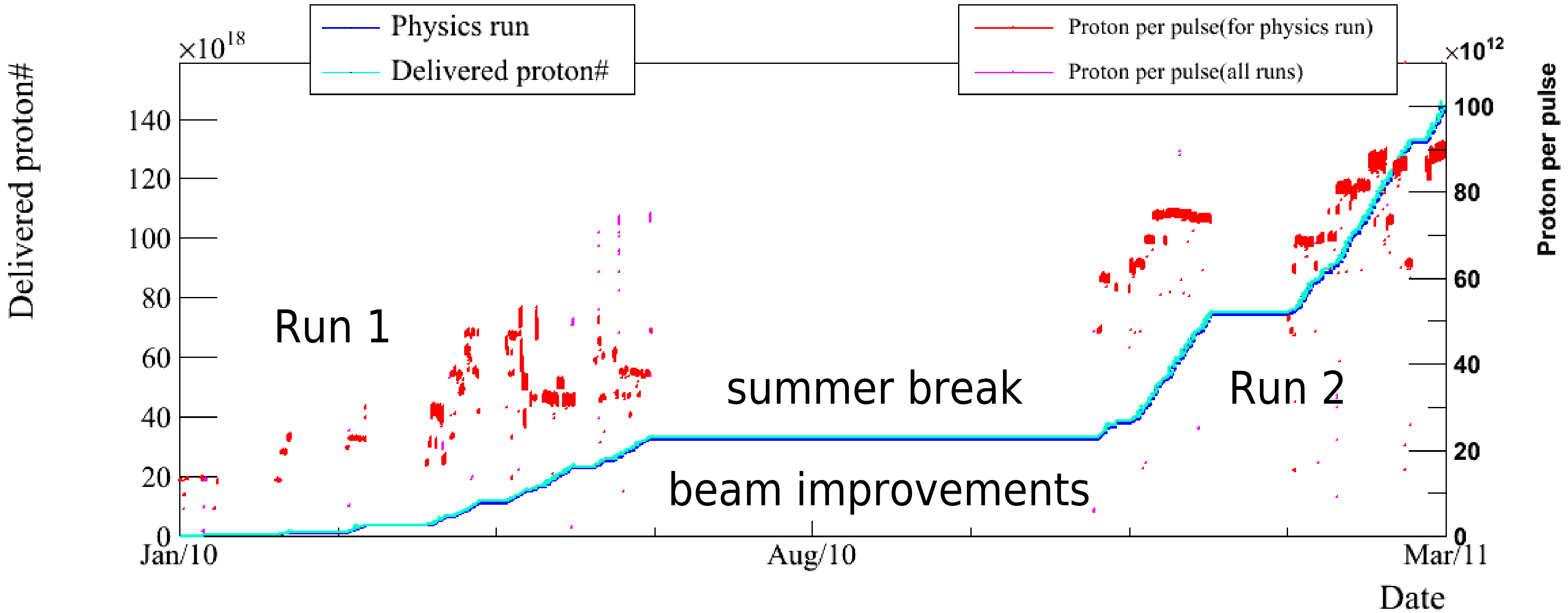
- oscillation signal for ν_μ disappearance
- background for ν_e appearance

(due to μ misidentification)



Collected data

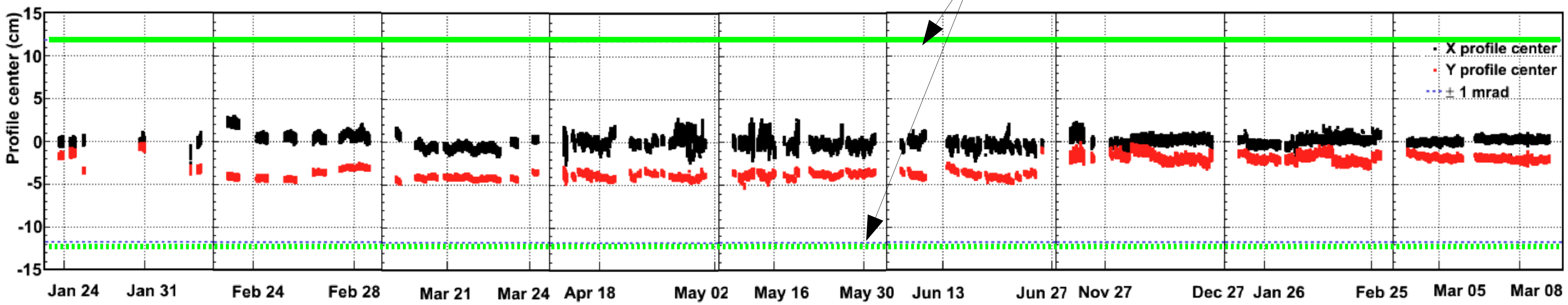
- experiment started to take physics data in January 2010
- two physics run (2010+2011), $1.43 \cdot 10^{20}$ protons on target delivered (2% of final goal)
  - targeting efficiency stable at over 99%
  - beam profile and absolute rate stable and consistent with expectations



Beam stability

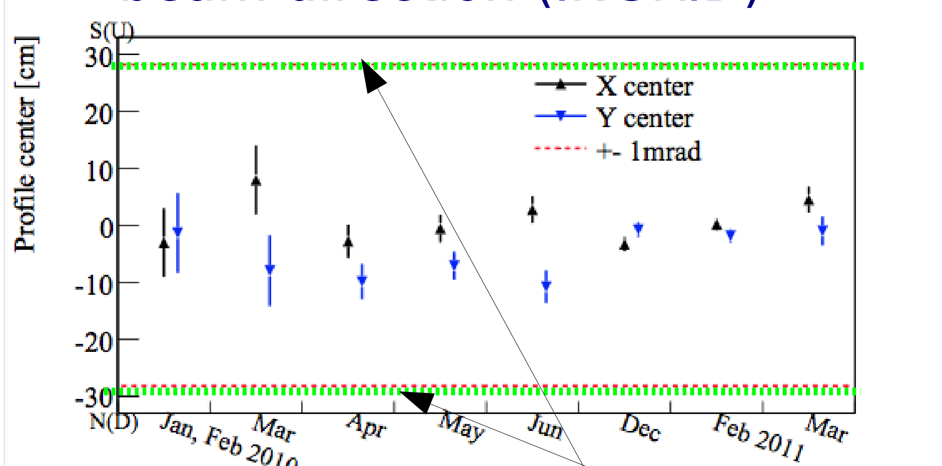
beam direction (muon monitor)

beam direction stability < 1mrad



beam profile center stable within ±0.3 mrad

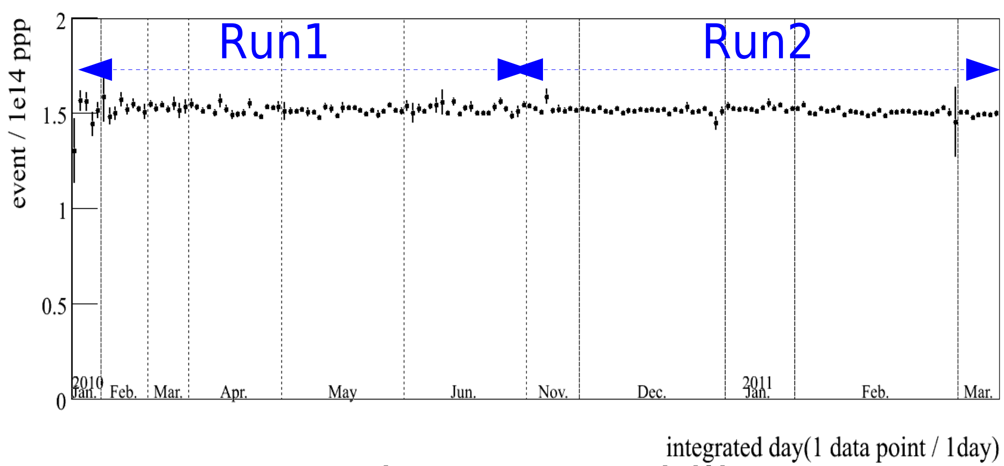
beam direction (INGRID)



beam direction stability < 1mrad

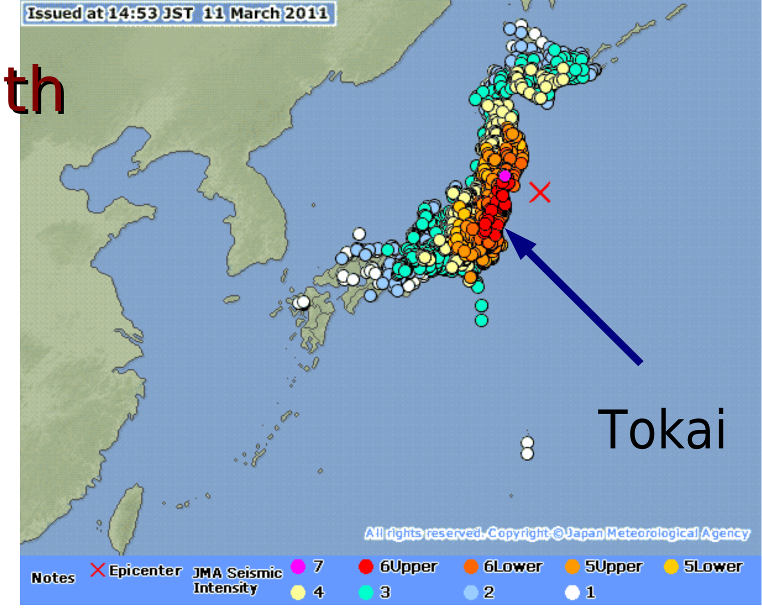
INGRID confirms beam direction within ±0.3 mrad

stability of ν interaction rate normalized by POTs (INGRID)



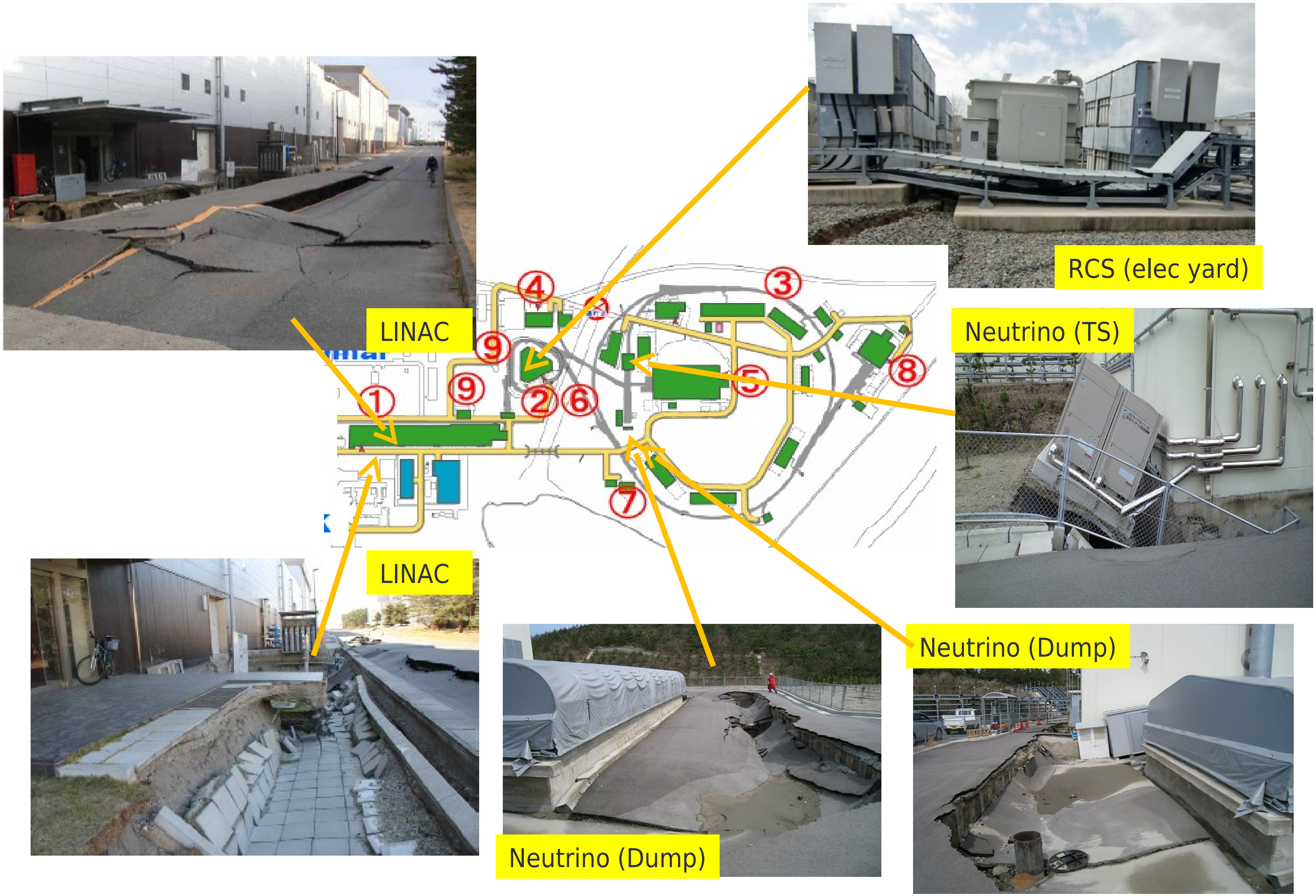
INGRID ν int. rate stability
Run1+2/Run1 < 1%

Earthquake on March 11th



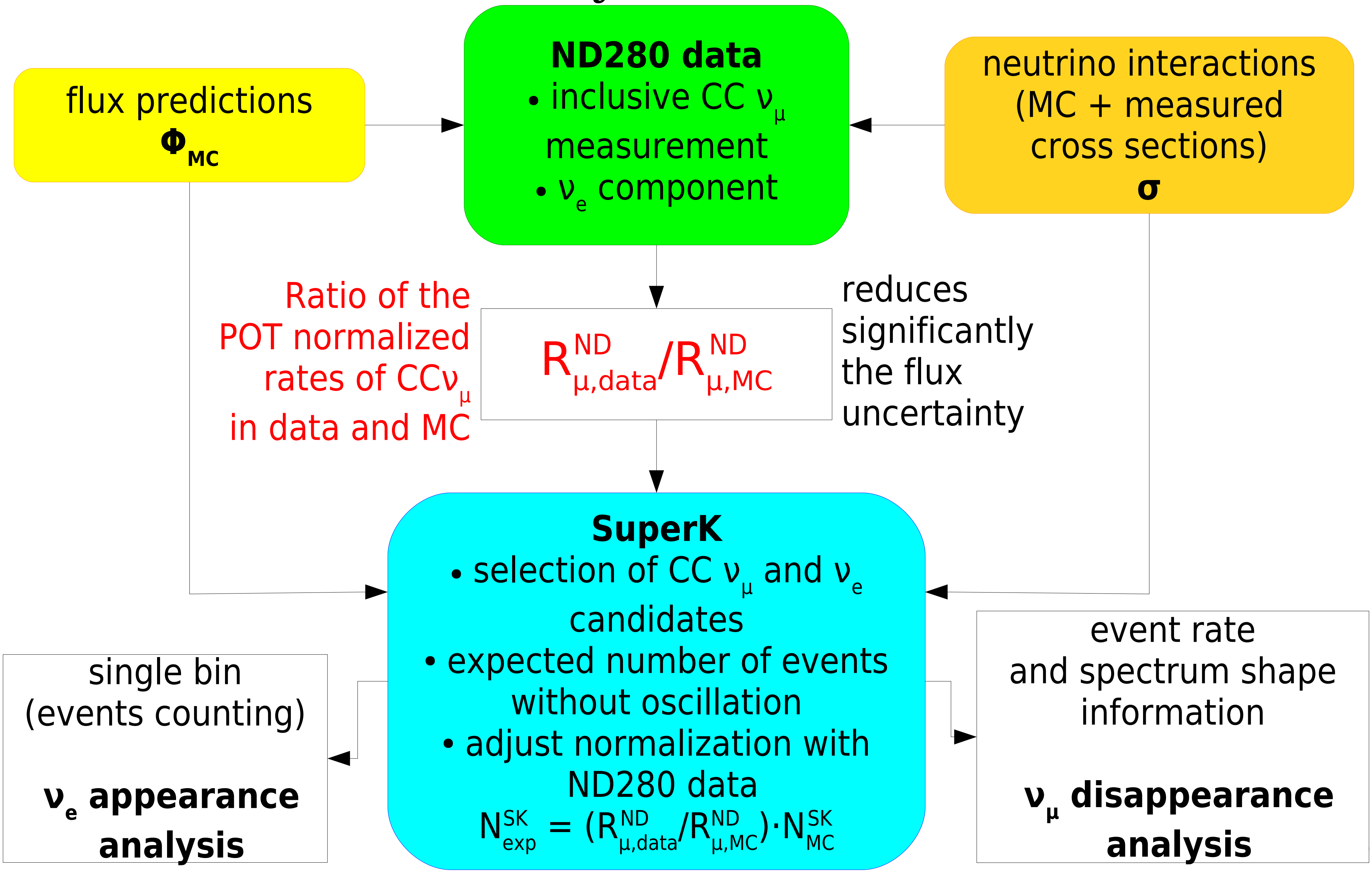
- 9 magnitude
  - at Tokai 6+, avoided tsunami
  - power cut
  - water leaks, drops of ground
  - no <u>serious</u> damages in accelerator, beamline and ND280 area
- Data taking stopped, but the
- analysis continued

Earthquake damages



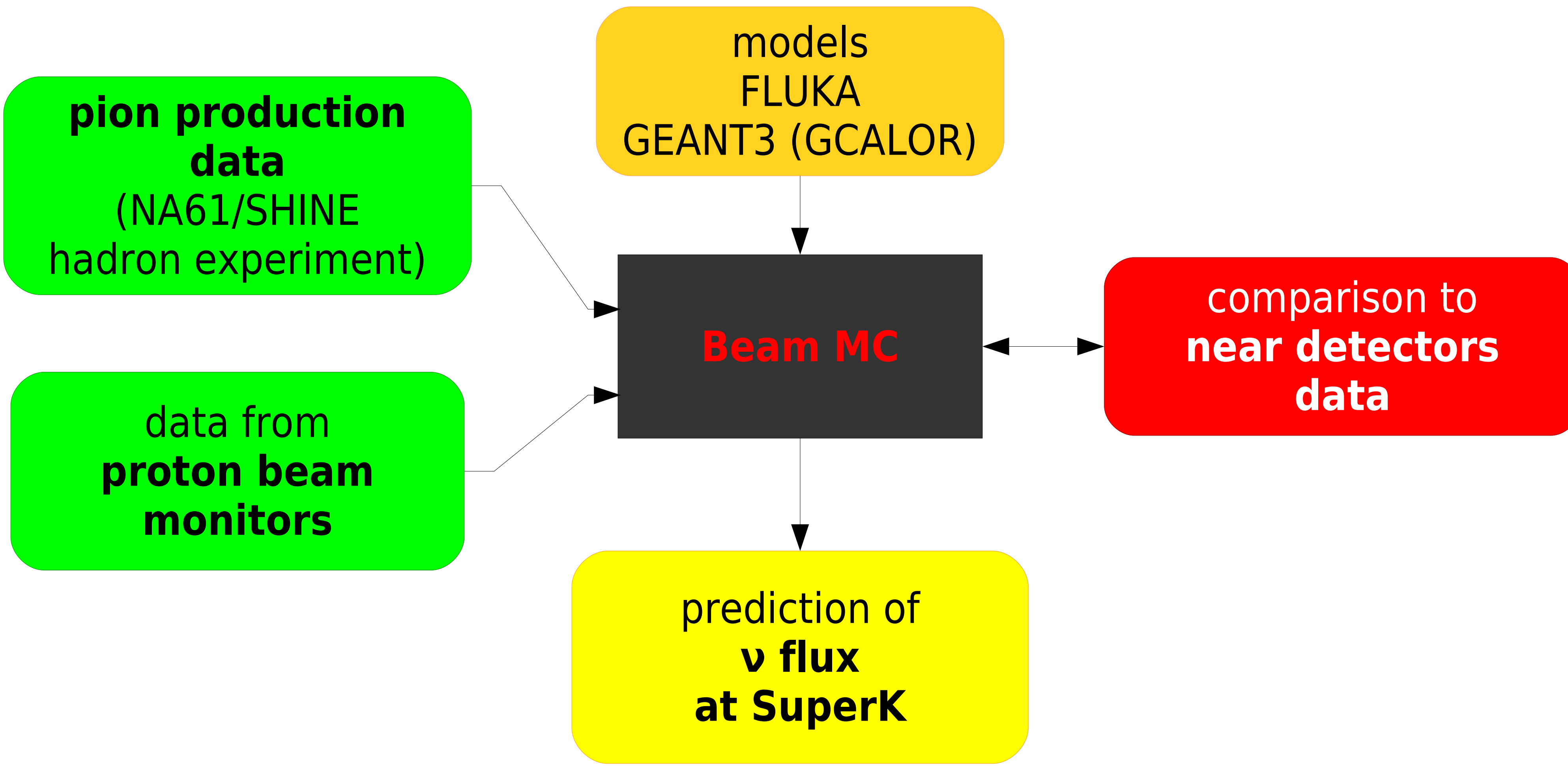
Analysis method

$$N_{MC} = \int \Phi_{MC} \cdot \sigma \cdot \epsilon \, dE$$

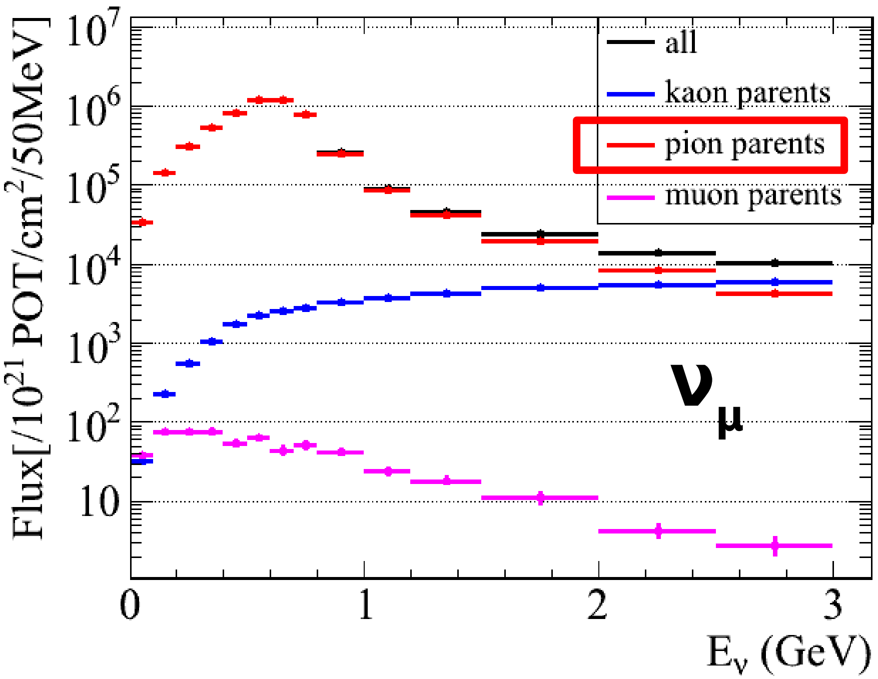


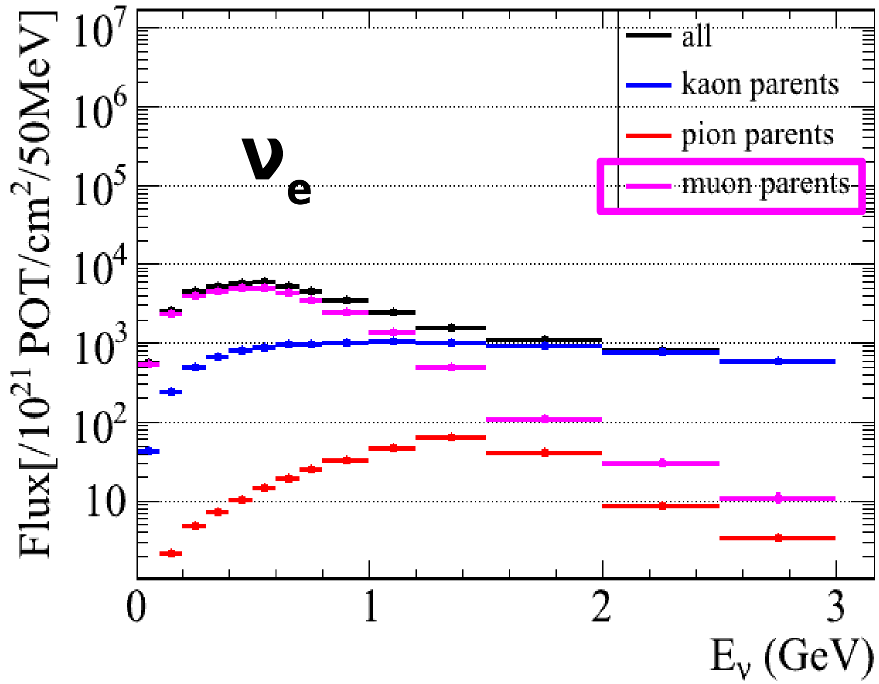
Flux prediction method

- knowledge of the **ν flux** is crucial!
- the flux is computed using the beam Monte Carlo
  - data from near detectors allow to refine the simulation



Predicted fluxes at Far Detector



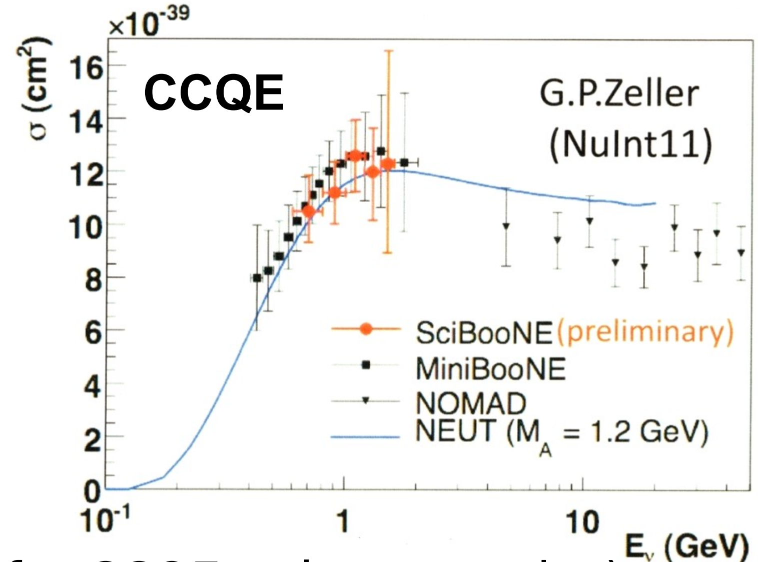


Error source	$R_{ND}^{\mu,\,MC}$	N_{SK}^{MC}	$\frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$	
Pion production	5.7%	6.2%	2.5%	NA61
Kaon production	10.0%	11.1%	7.6%	FLUKA↔ ext. data
Nucleon production	5.9%	6.6%	1.4%	
Production x-section	7.7%	6.9%	0.7%	ext. data
Proton beam position/profile	2.2%	0.0%	2.2%	beam monitors
Beam direction measurement	2.7%	2.0%	0.7%	INGRID&survey
Target alignment	0.3%	0.0%	0.2%	survey
Horn alignment	0.6%	0.5%	0.1%	survey
Horn abs. current	0.5%	0.7%	0.3%	meas.
Total	15.4%	16.1%	8.5%	

normalization with ND280 data significantly reduces the flux uncertainty

Cross sections

- ν cross sections from NEUT generator (and GENIE)
- the uncertainties evaluated from:
  - comparison of models to MiniBooNE, SciBooNE and others
  - comparison between models (i.e. relativistic Fermi gas vs. spectral function for CCQE at low energies)
  - variation of model parameters
  - dominant: final state interactions of pions



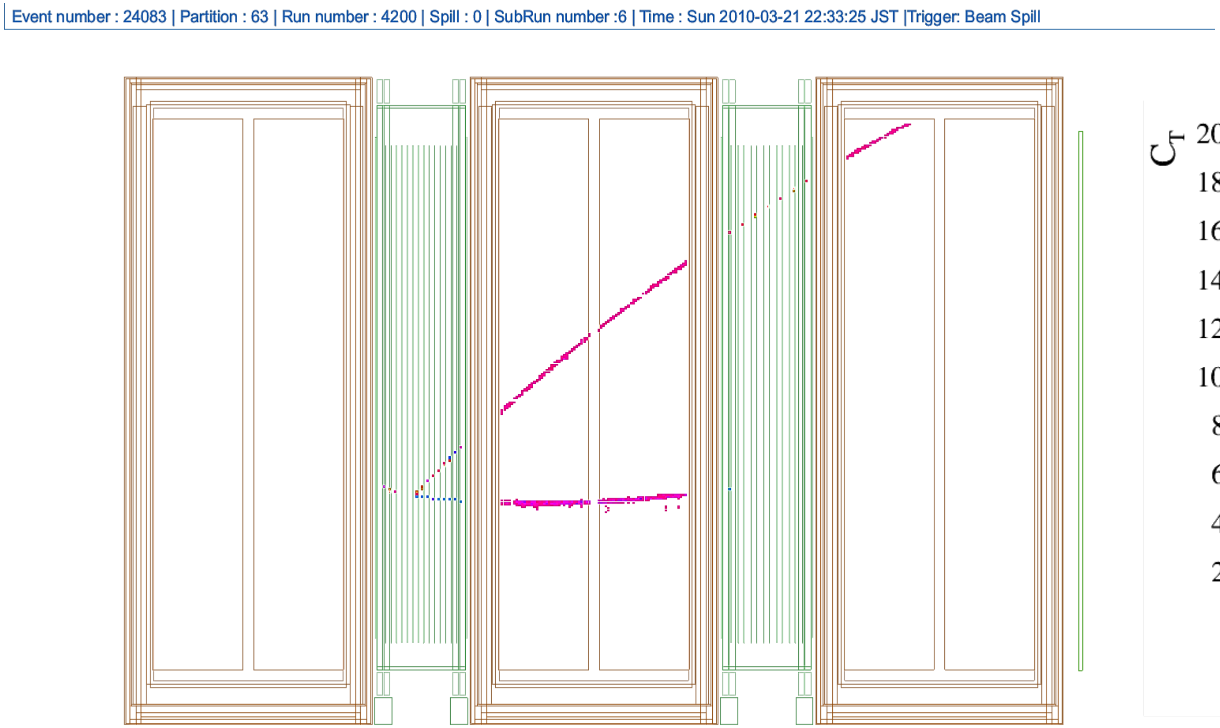
Process	Cross section uncertainty relative to the CCQE total x-section
CCQE	energy dependent ($\sim \pm 7\%$ at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^0	100% (upper limit from [30])
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$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

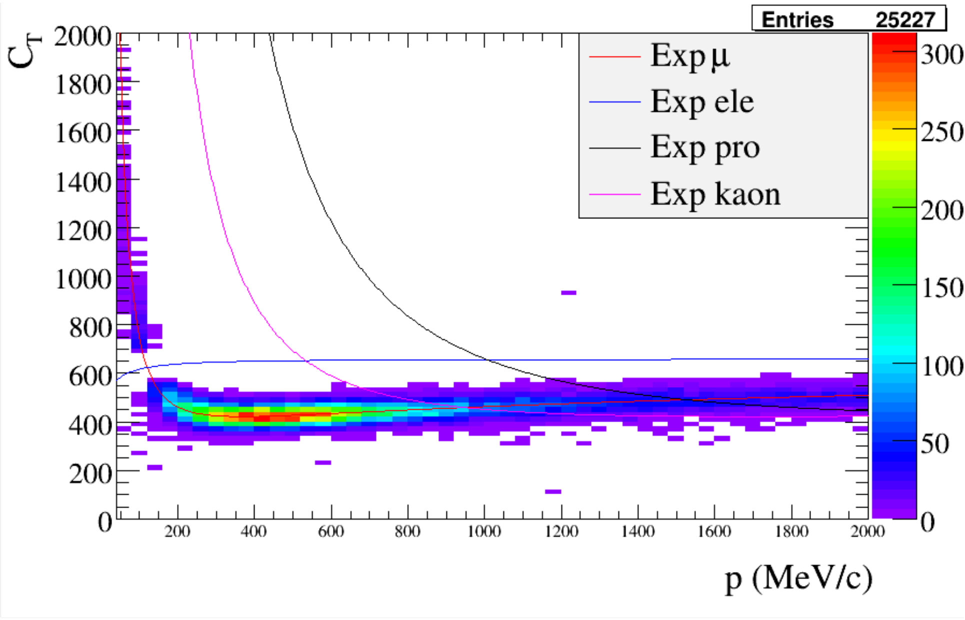
⇒

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%

Near detector analysis

- based on Run1 data only ($2.9 \cdot 10^{19}$ POT)
- FGD+TPC used in the analysis
  - select interactions with vertex in FGD and at least 1 negative track in the downstream TPC
  - track momentum measured in the TPC
  - particle identification based on dE/dx in the TPC



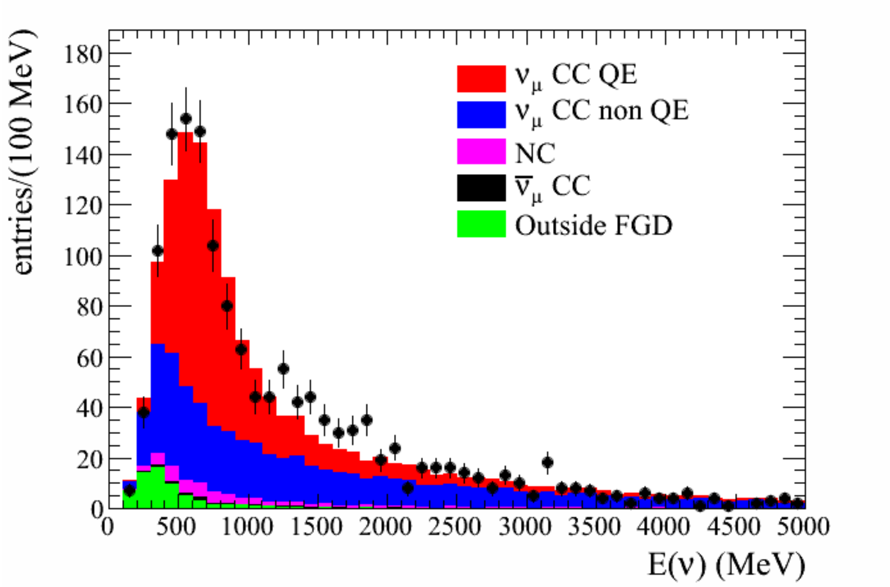


Inclusive CC ν_μ event rate

- selection of negative μ-like tracks (TPC ID)
  - 90% purity and 38% efficiency
  - 1529 events selected
  - dominant systematic error: dE/dx PID, TPC-FGD matching
  - good agreement of MC and data

$$R_{ND}^{\nu_\mu\,DATA} / R_{ND}^{\nu_\mu\,MC} = 1.036 \pm 0.028 (stat.)^{+0.044}_{-0.037} (det.syst.) \pm 0.038 (phys.syst.)$$

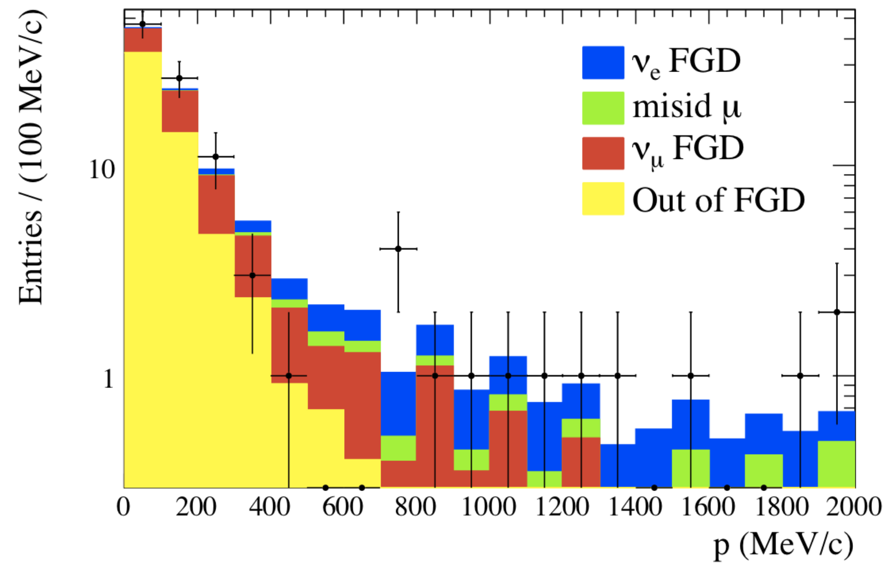
(neutrino interaction model)



Reconstructed neutrino energy distribution assuming CCQE kinematics and using the muon candidate momentum and angle in selected events compared to MC (flux prediction and NEUT).

ν_e beam component

- selection of e-like tracks
  - background from misidentified muons, conversion of photons (coming from outside or from the decay of π^0 produced in neutrino interaction)
  - likelihood fit on electron momentum to measure the number of observed ν_e



Momentum distribution of ν_e candidates with fitted signal and background components

$$R_{\nu_e/\nu_\mu} = (1.0 \pm 0.7(stat.) \pm 0.3(syst.))\,\%$$

$$R^{data}_{\nu_e/\nu_\mu} / R^{MC}_{\nu_e/\nu_\mu} = 0.6 \pm 0.4(stat.) \pm 0.2(syst.)$$

observed ratio consistent with expectations

ν_e appearance analysis

- reminder:
  - CCQE interactions dominate in the T2K peak region
  - signal: single electron-like rings (proton invisible)
  - main background: intrinsic ν_e contamination, NC events with misidentified π^0
- selection criteria fixed with Monte Carlo studies before data were collected (efficiency 66%, background reduction 99% for NC events, 77% for beam ν_e events)
- observed number of events compared to expectations, based on neutrino flux and cross-section predictions
  - null oscillation hypothesis
  - various sets of oscillation parameters

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{23}^2 L}{4 E_\nu} + \text{subleading terms}$$

Number of expected events

- In 3-flavor neutrino oscillation scenario the expected number of events is 1.5±0.3 (syst.)
  - with $|\Delta m^2_{23}| = 2.4\cdot10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0$
  - renormalized with data/MC ratio measured by ND280

	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam total	1.4	1.3
beam ν_e CC	0.8	0.7
all NC	0.6	0.6
$\nu_\mu \rightarrow \nu_e$	0.1 solar term	4.1 solar term + signal
Total	**1.5**	5.4

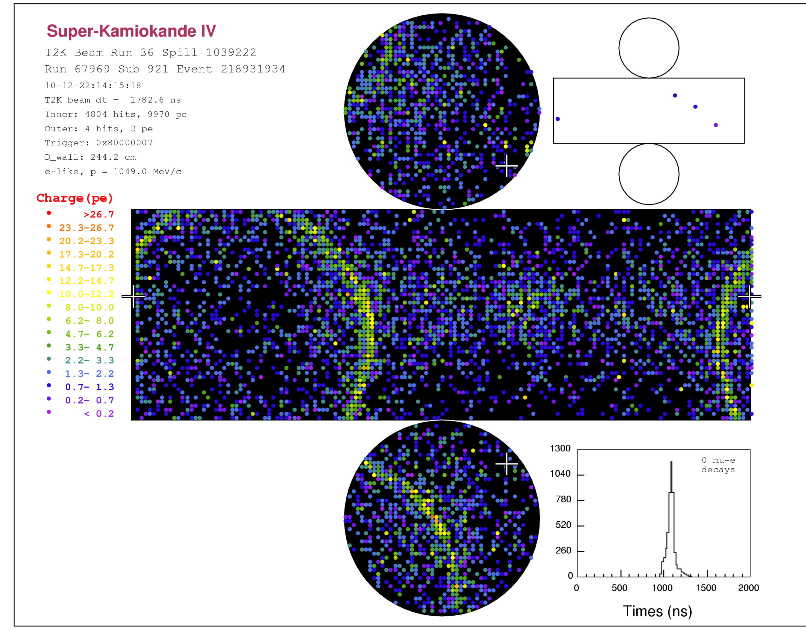
- systematic errors

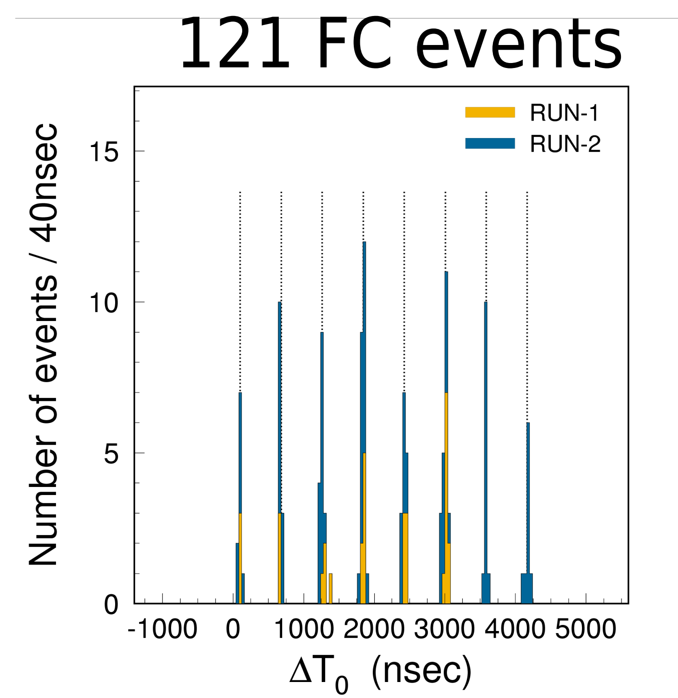
		$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
ν flux	dominated by hadron production	±8.5%	±8.5%
ν cross section	by FSI and NCπ^0 uncertainties	±14.0%	±10.5%
near detector	reconstruction efficiency	+5.6% -5.2%	+5.6% -5.2%
far detector (signal/background)	ring counting (3.9%/8.3%), PID (3.8%/8.0%), π^0 mass cut (5.1%/8.7%), NC1π^0 eff (/3.6%)	±14.7%	±9.4%
near detector statistics		±2.7%	±2.7%
total		+22.8% -22.7%	+17.6% -17.5%

Smaller cross-section and SK uncertainties for signal events

Event selection – common cuts

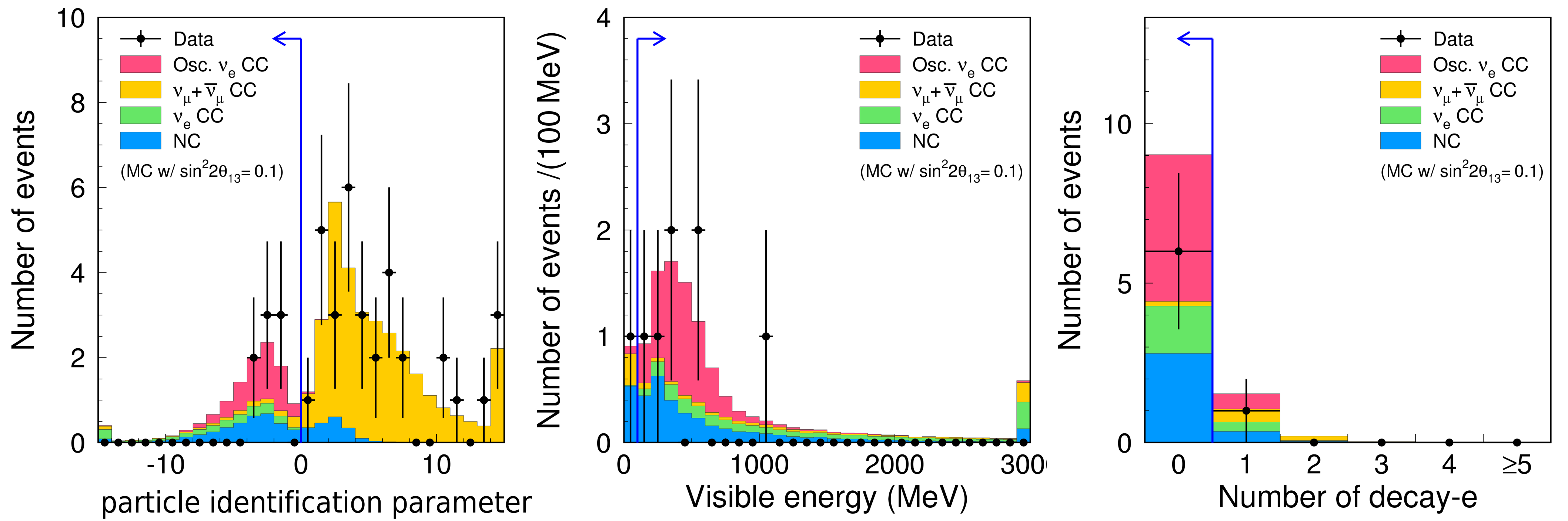
- the first steps are common for ν_μ and ν_e analysis
  - beam timing
    - reduces background from atmospheric neutrinos
  - minimal activity in outer detector
  - fully contained (FC) (121 events)
    - allows to measure the energy of the particle
  - starting in fiducial volume (FCFV)
    - reduces background from cosmic muons and radioactivity
    - difficult to reconstruct the vertex near the wall (→ 88 events)
  - single ring
    - enriched CC QE sample (→ 41 events)





Selection cuts for ν_e analysis (1)

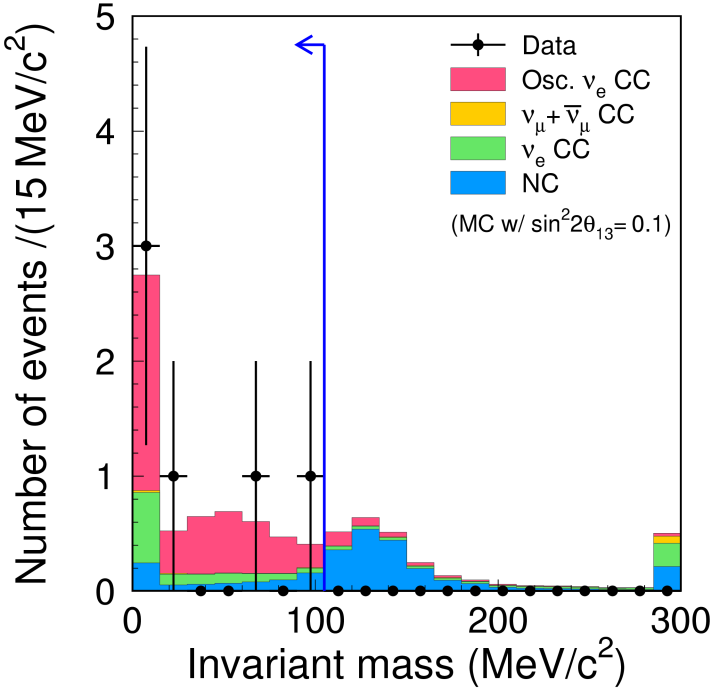
- single ring e-like (→ 8 events)
- E_{vis}>100MeV (→ 7 events)
  rejects NC background and electrons from muon decay
- no delayed electron (→ 6 events)
  rejects invisible (below threshold) muons and pions

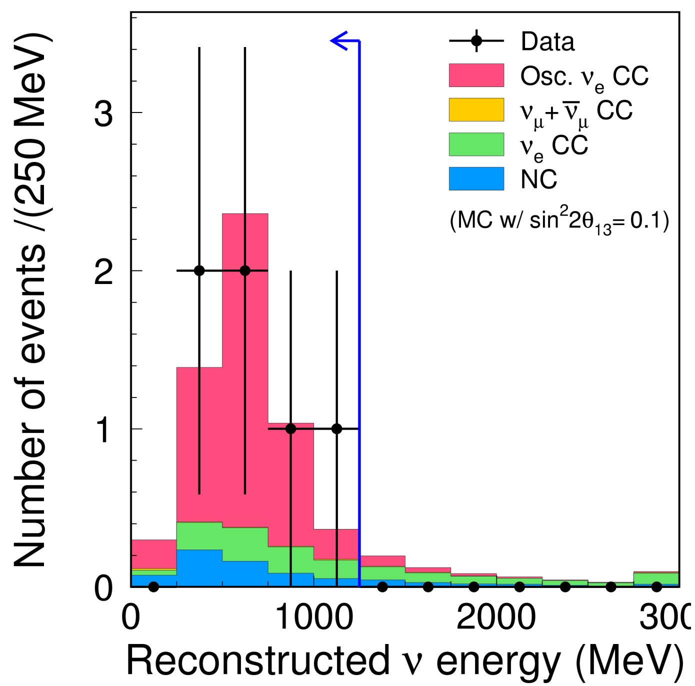


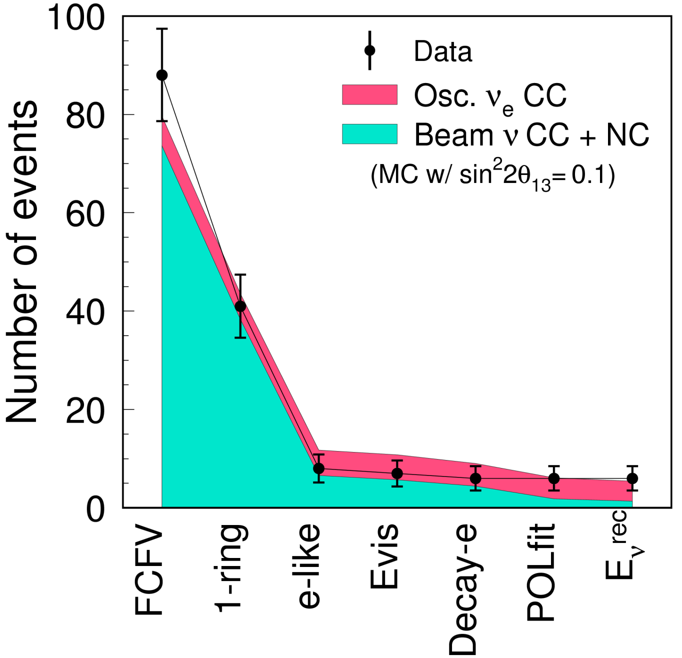
Selection cuts for ν_e analysis (2)

- forced 2[nd] ring and invariant mass <105MeV (→ 6 events)
  rejects NC π^0 background
- reconstructed E_ν<1250MeV (→ 6 events)
  rejects beam ν_e from K decays

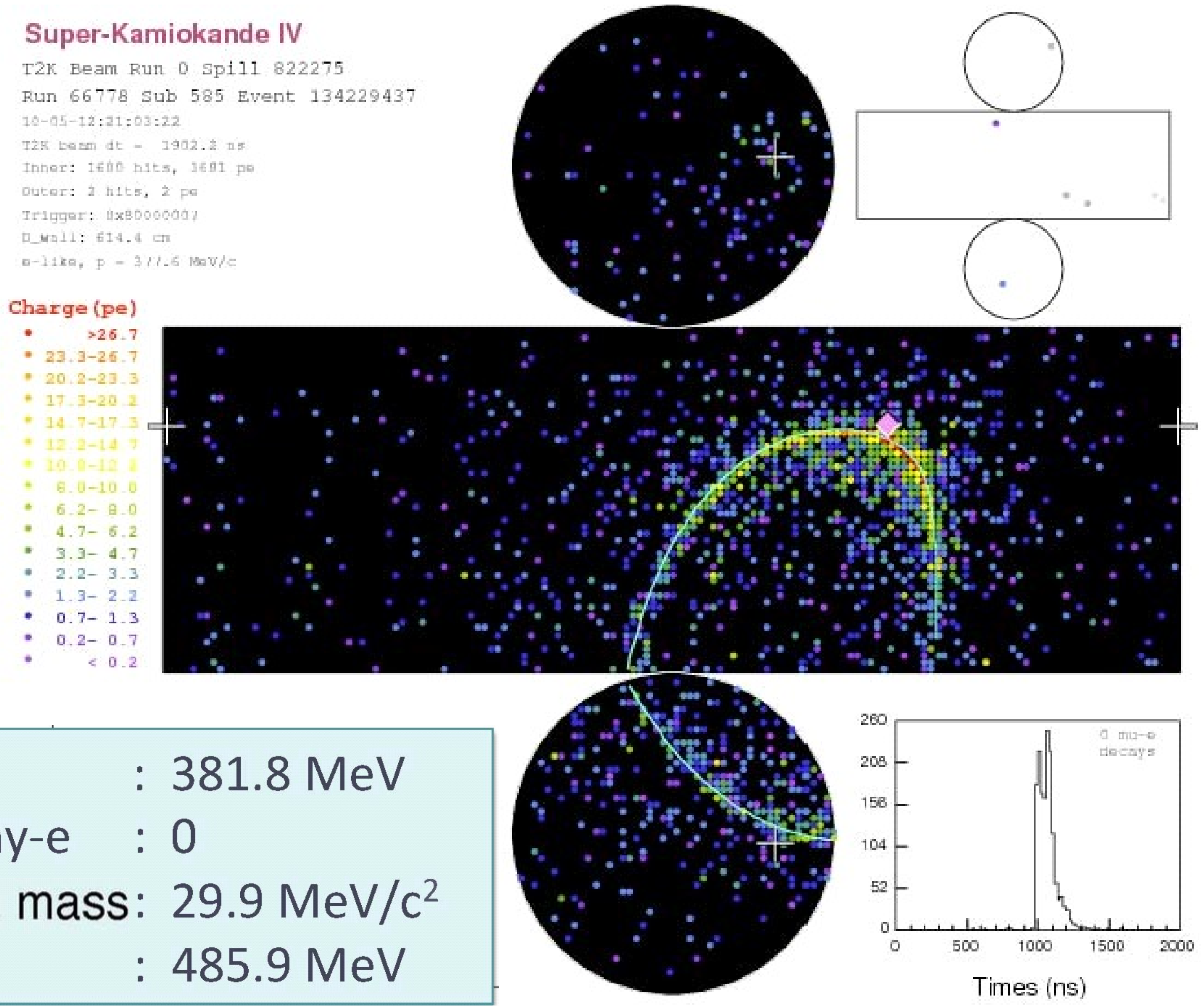
6 ν_e events observed





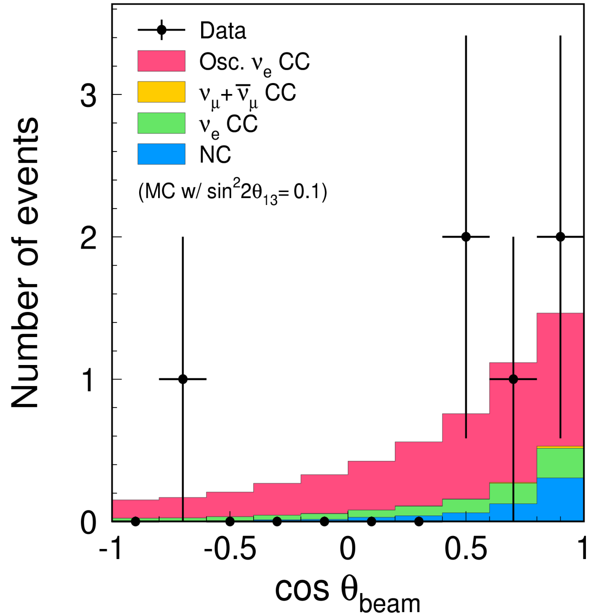


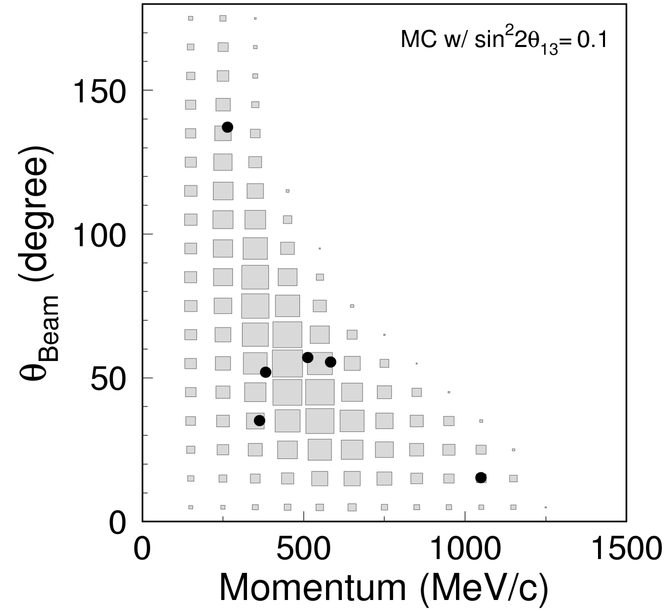
ν_e appearance candidate



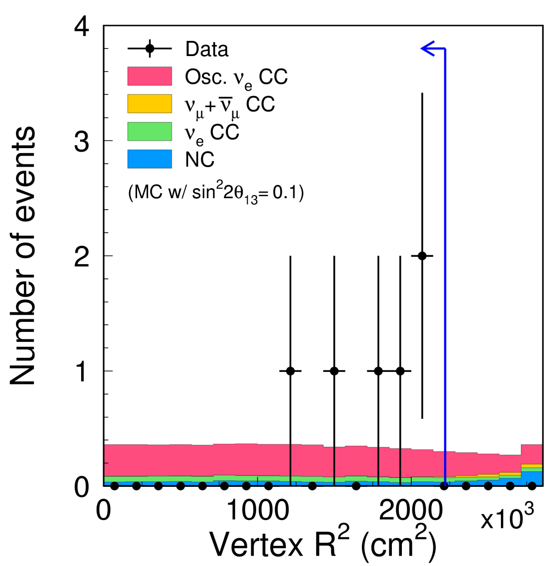
Evis	:	381.8 MeV
Ndecay-e	:	0
2γ Inv. mass	:	29.9 MeV/c^2
E_ν^{rec}	:	485.9 MeV

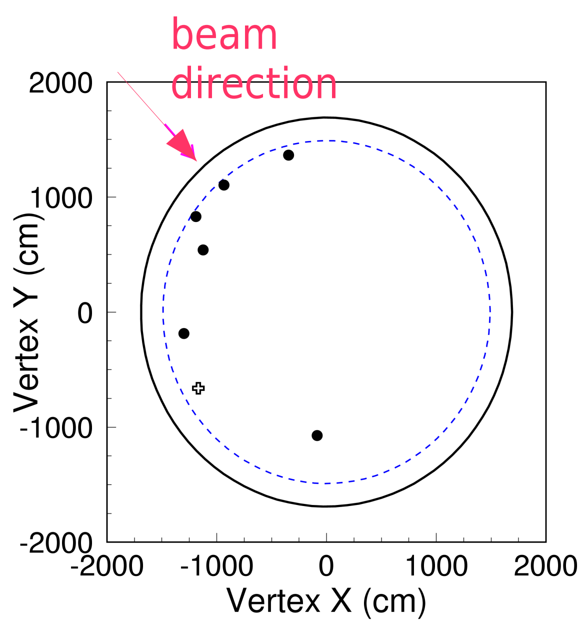
ν_e events distributions

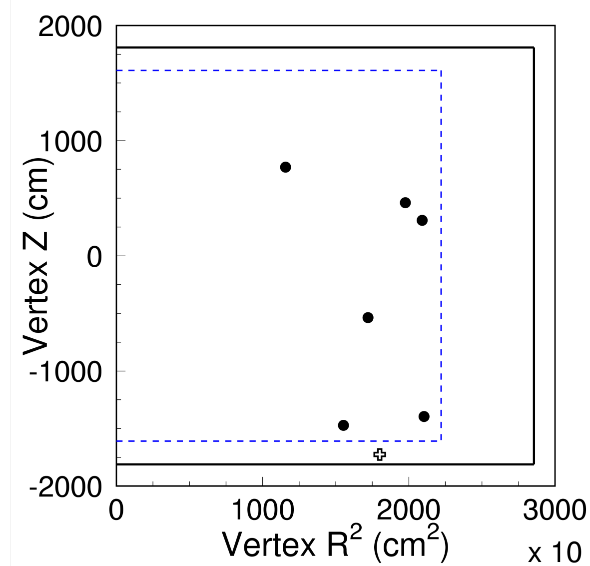




- events clustered at large R (near the edge of the fiducial volume)

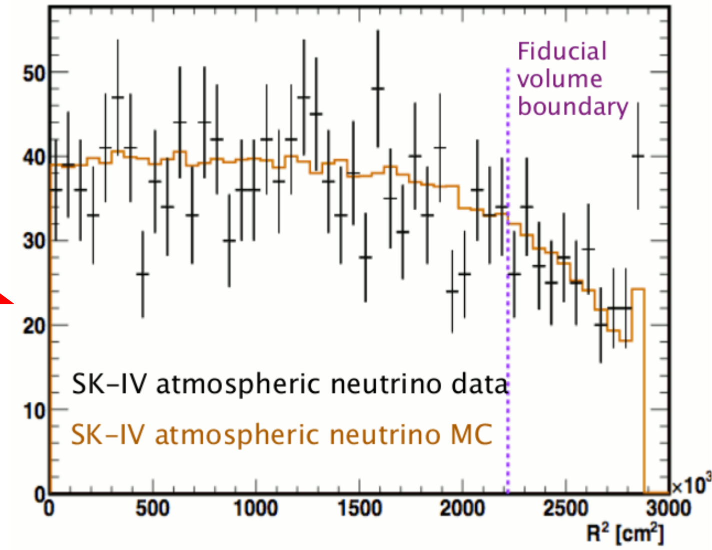






Possible sources

- reconstruction algorithm?
  - checked with the distribution of atmospheric neutrinos (SK IV sub-GeV+T2K-like cuts)
  - good agreement between data and MC
- contamination from outside ID?



- expected beam-induced background with true vertex outside the inner detector
  - MC with events produced up to 550 cm outside the ID wall

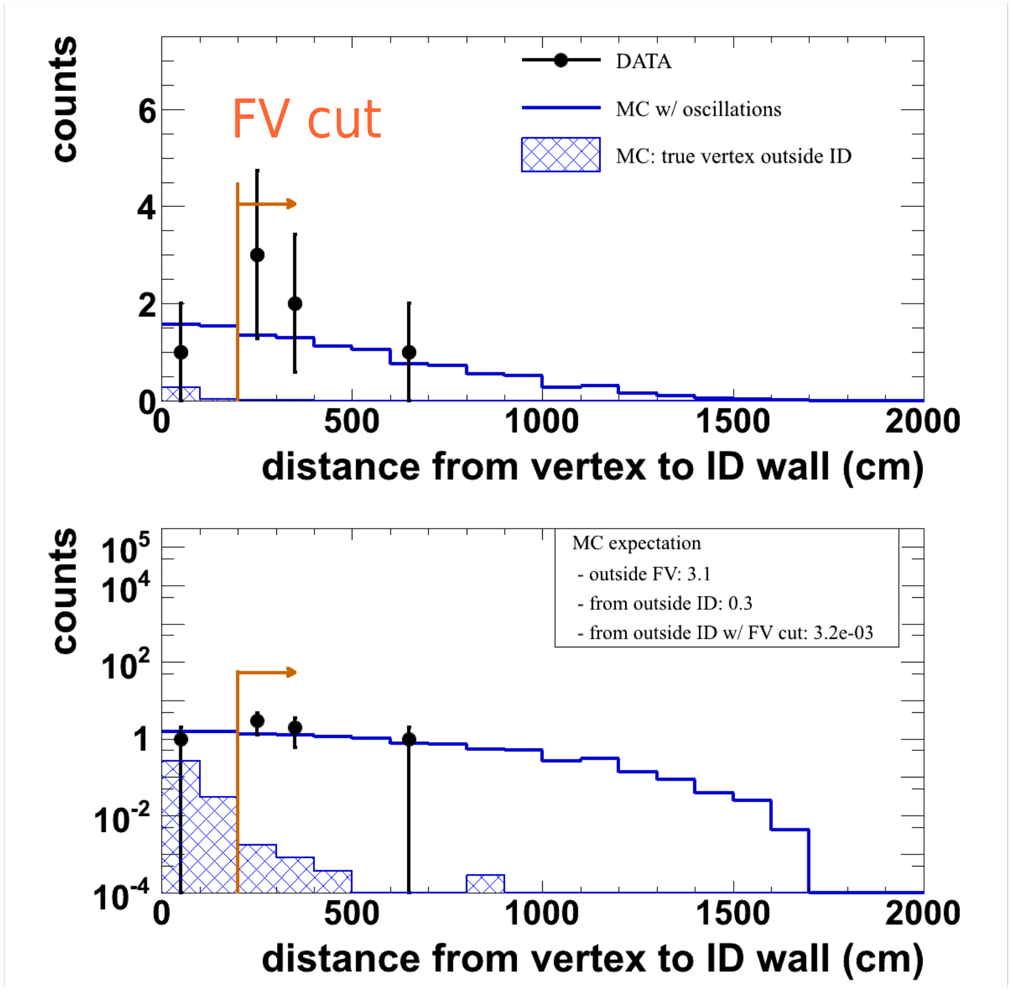
Sample	Expected true vertex outside ID	Source of track, from MC truth* mis-id muon	pi0 photon	neutron	K-long	K-short
Nue Analysis Sample (w/ FV cut)	3.16E-03	9%	78%	11%	0.01%	<0.01%
Nue Analysis Sample (w/o FV cut)	0.30	4%	75%	3%	<0.01%	<0.01%

no significant contribution to FCFV sample expected

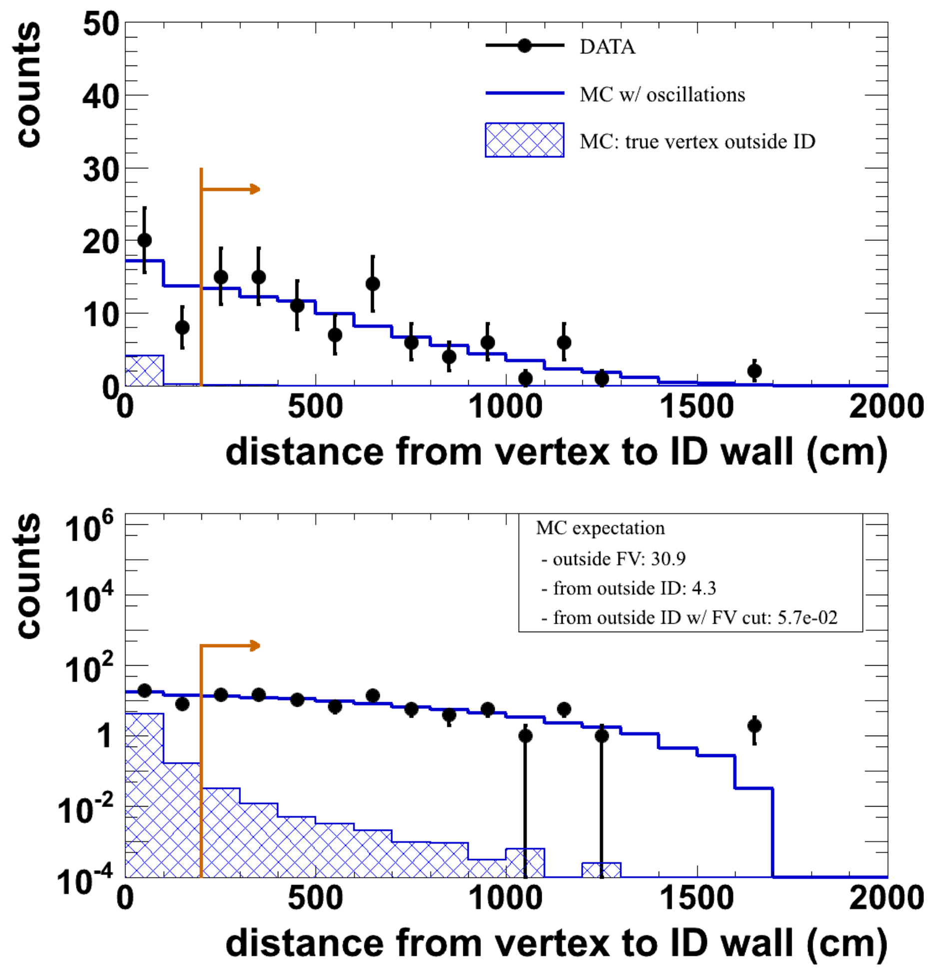
*percentages do not total to 100% because list here is not exhaustive
Expectation assumes $\sin^2\theta_{13} = 0.1$, $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2.

Vertices distributions

ν_e sample



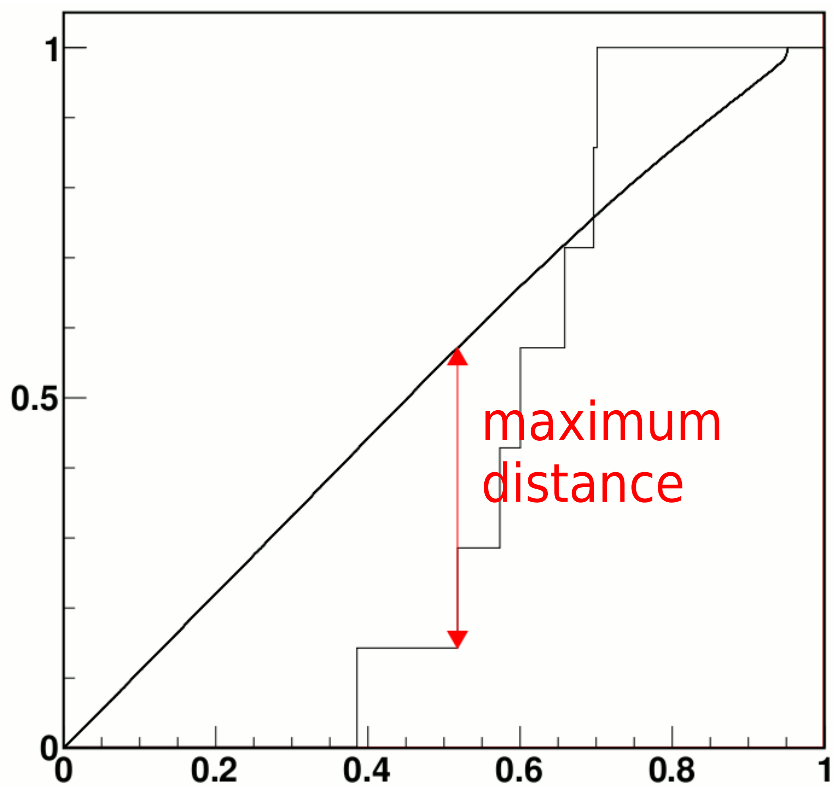
FC sample



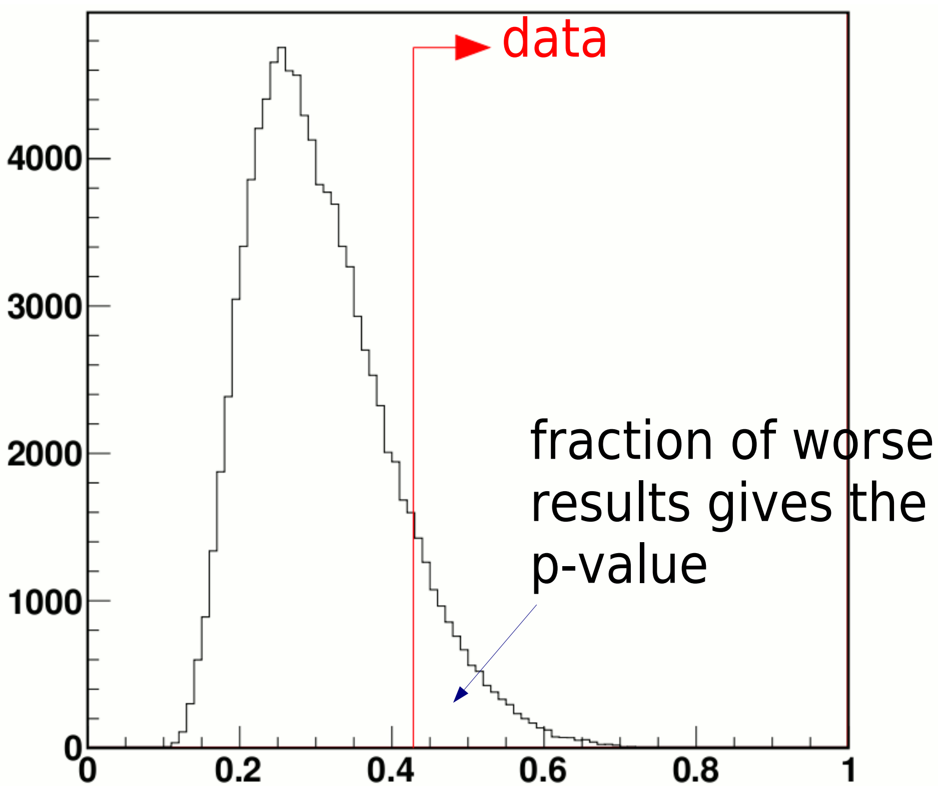
Kolmogorov-Smirnov test

- finding the maximum distance between two normalized distributions
- more reliable at lower statistics than $\chi 2$
- distributions of max. distances obtained from toy MCs, by randomly selecting the same number of events as in data, using T2K MC distribution as p.d.f.

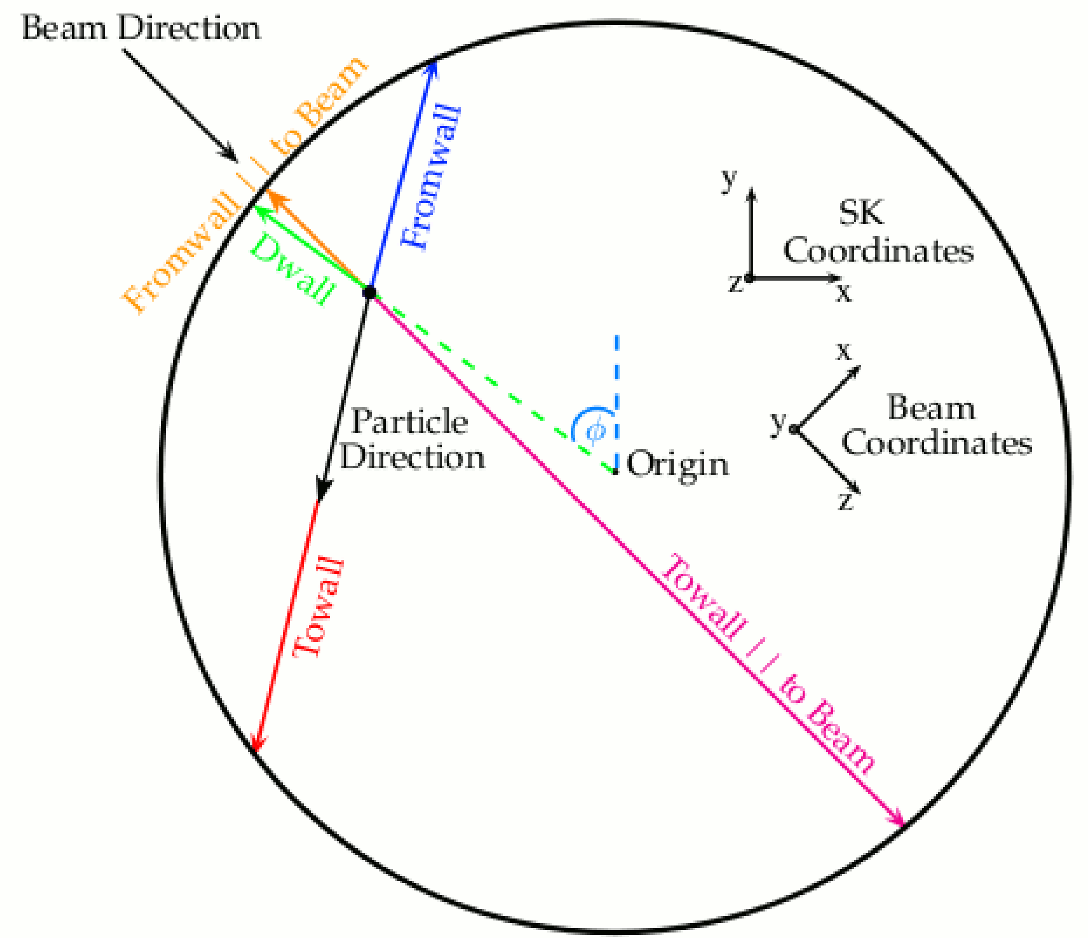
Cumulative distribution of R^2



Toy MC distribution of max. distances



Tested distributions



Probabilities from toy MC

distribution	6 FCFV Events	7 FC Events
Dwall	3.7%	20.6%
Fromwall	0.14%	1.4%
Fromwall || to Beam	1.1%	5.1%
R^2	3.1%	10.9%

ν_e appearance result

- if $\sin^2 2\theta_{13} = 0$, the probability to observe six or more candidate events is 0.7% for an expected background of 1.5±0.3 events (equivalent to 2.5σ significance)
- the data are consistent with

Best fit: **0.11**

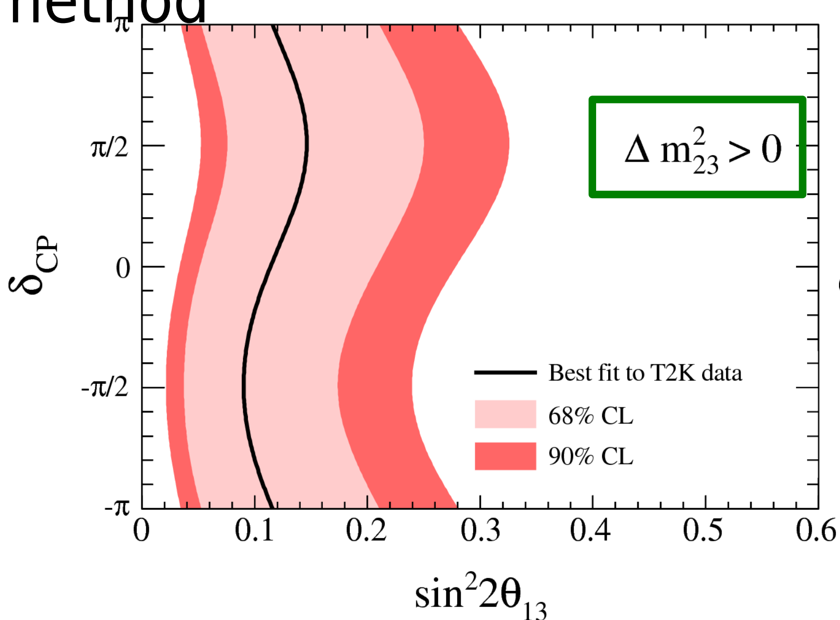
$$\mathbf{0.03\ (0.04) < \sin^2 2\theta_{13} < 0.28\ (0.34)}$$

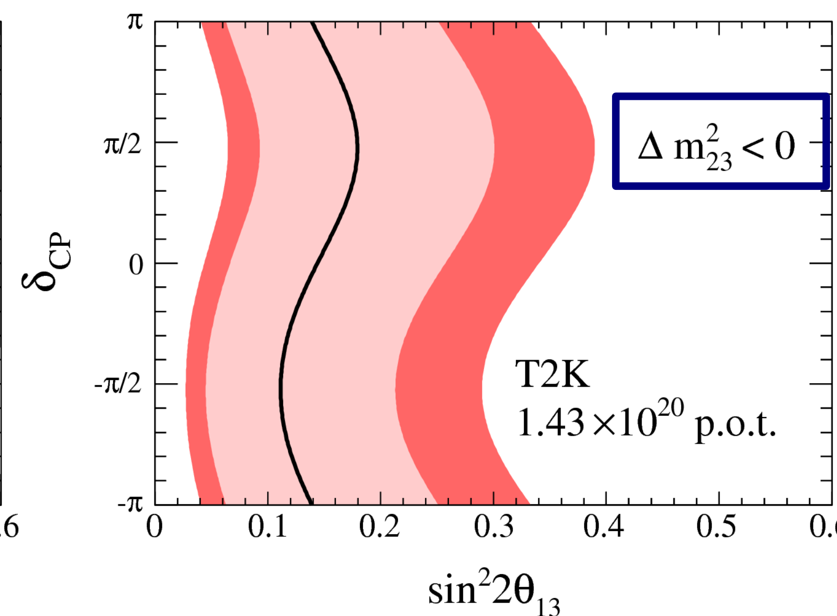
Best fit: **0.14**

for normal (inverted) hierarchy, 90% C.L.

$\sin^2(2\theta_{23}) = 1.0$, $\Delta m^2_{23} = 2.4\times10^{-3}\ \mathrm{eV}^2$, $\delta_{CP} = 0$

- confidence intervals produced using Feldman-Cousins unified method

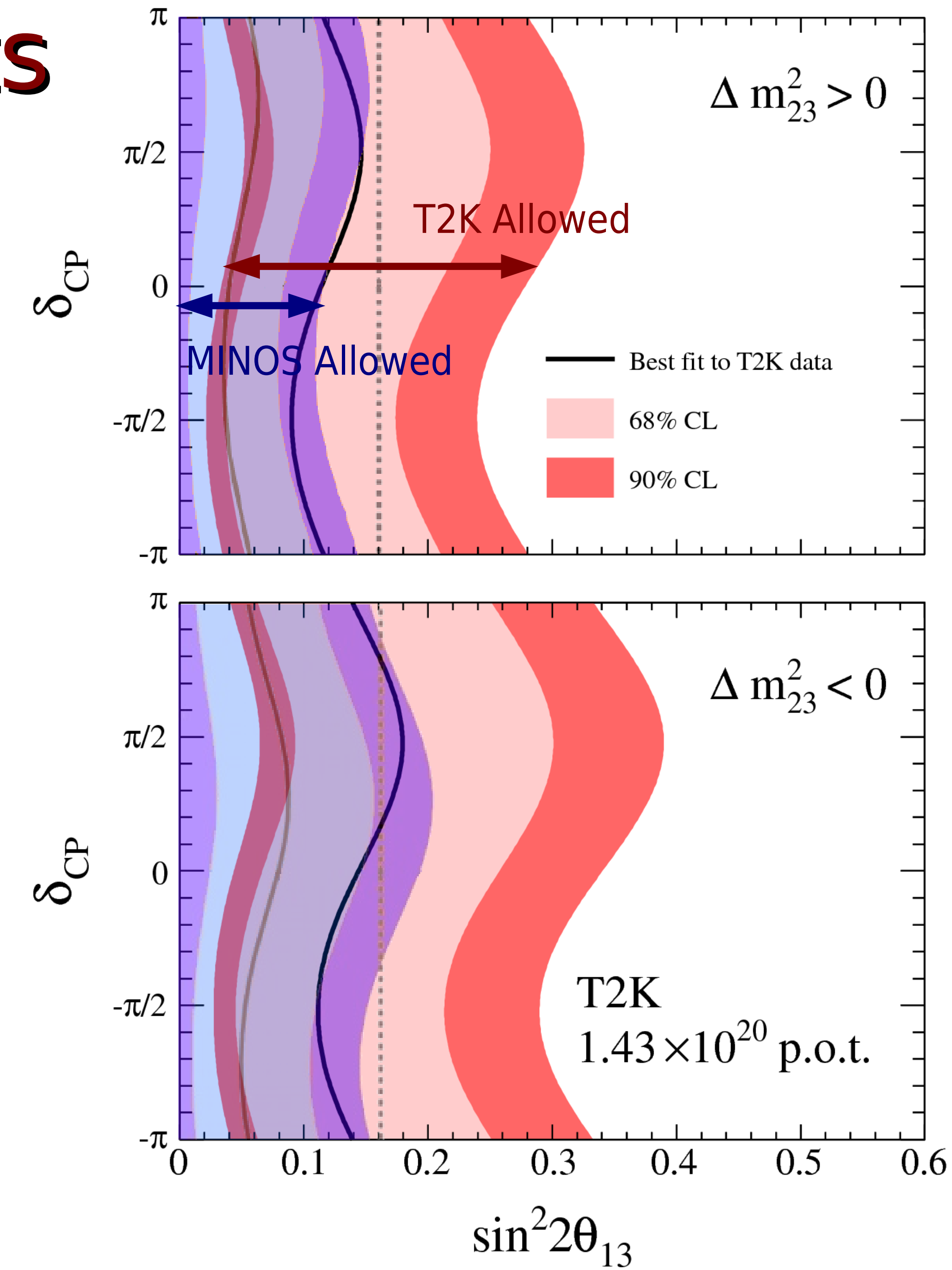




Comparison with MINOS 2011 results

- T2K:
  0.03 (**0.04**) **< $\sin^2 2\theta_{13}$ <** **0.28** (**0.34**)
  best fit **0.11** (**0.14**)

- MINOS 2011:
  - expectation
    49.5 ± 7.0(stat) ± 2.8(syst)
  - observation
    62 candidates
  - limit
    $\sin^2 2\theta_{13}$ < 0.12 (**0.19**)
    at 90% CL



ν_μ disappearance analysis

T2K

fit with 2 flavor model $P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4 E_\nu}$

103.6 events expected without oscillations

Two independent methods to extract oscillation parameters

Method A:
Maximum likelihood with fitting of the systematics parameters:

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

L_{norm} → Poisson distribution of the total number of events

L_{shape} → un-binned spectrum shape

f – parameter representing systematic errors

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

Method B:
Comparison of the observed spectrum with the expected spectrum varying oscillation parameters to minimize:

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

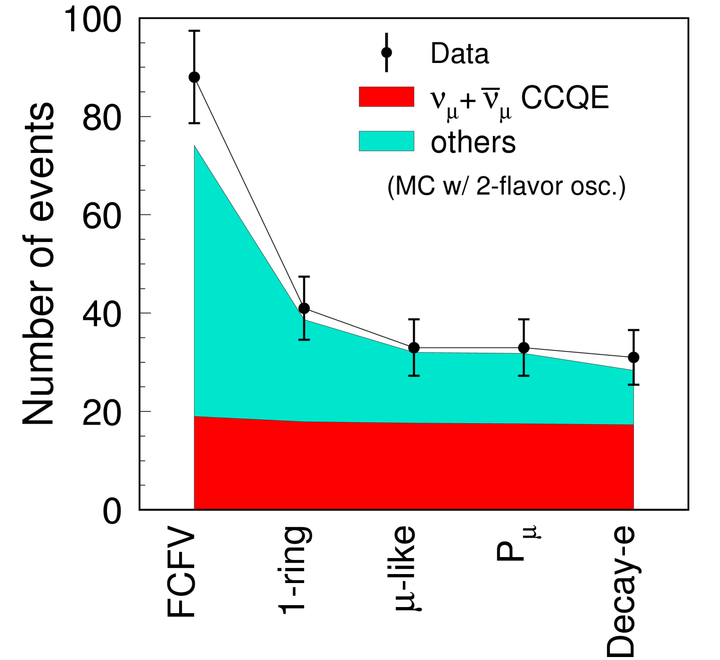
i = bin number in SK energy

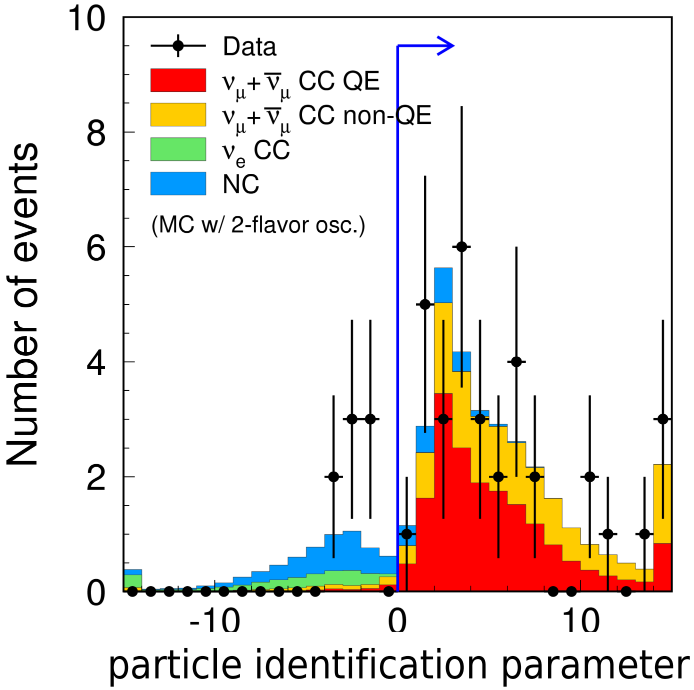
$n_i^{obs(exp)}$ number of observed (expected) events in the i-th bin

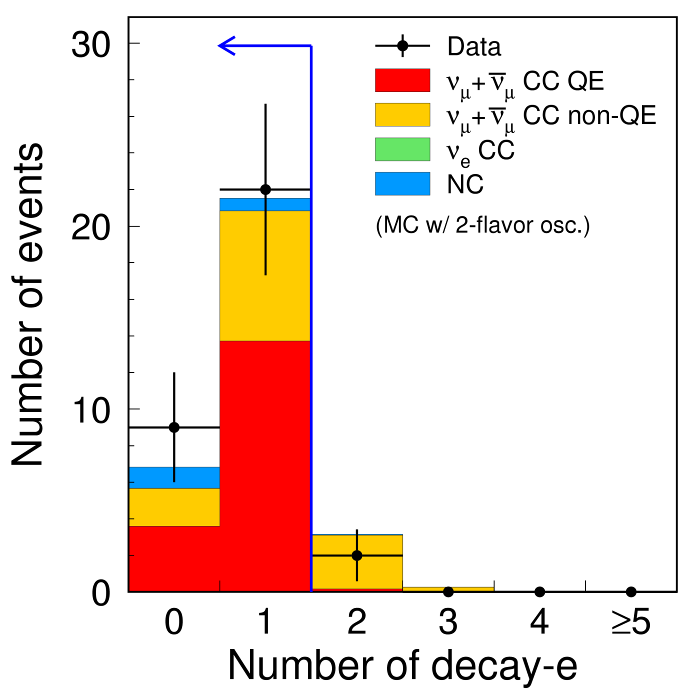
In this method systematic *f* parameters are not fitted

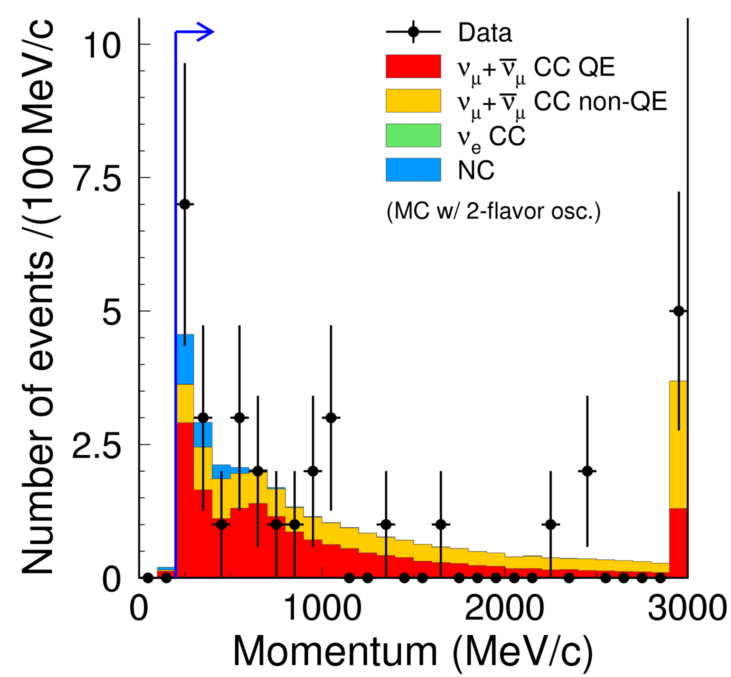
Selection cuts for ν_μ analysis

- Selection cuts
  - common cuts, already presented
  - μ-like ring
  - less than 2 decay electrons
  - momentum > 200MeV/c
  - 31 candidates







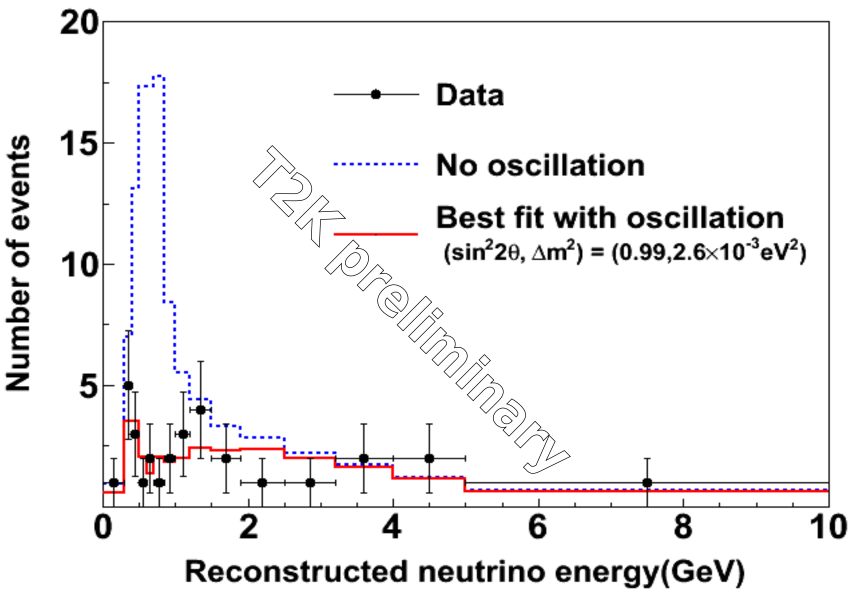


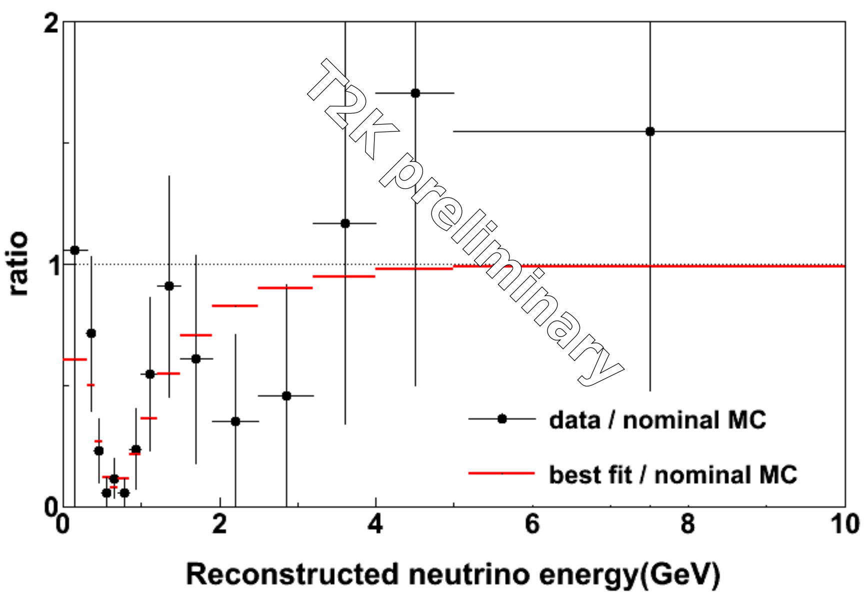
Oscillation pattern

- 103.6 ν_μ expected without oscillations
- 31 ν_μ candidates observed

- null-oscillation hypothesis excluded at 4.5σ level

- ν_μ energy spectrum → the oscillation pattern clearly visible





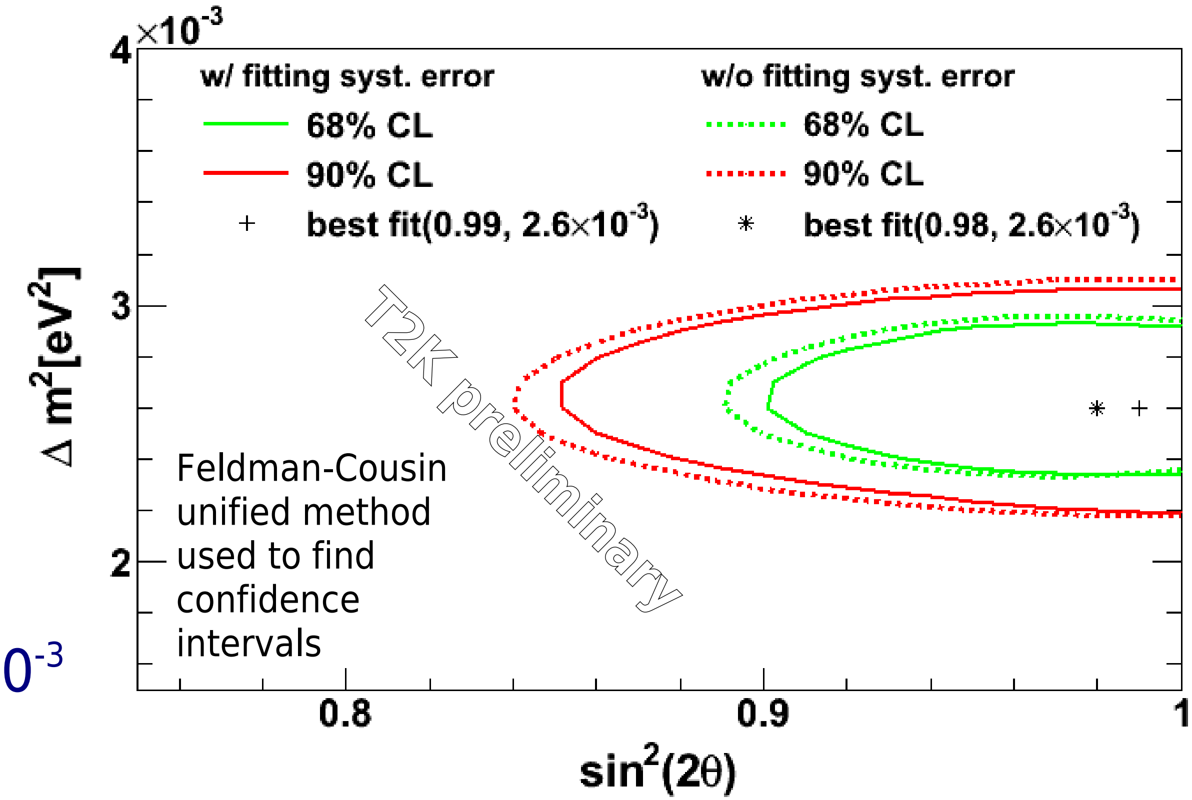
ν_μ disappearance results

method A **(method B)**

$\sin^2 2\theta_{23}$ = 0.99 (0.98),
$\Delta m^2_{23} = 2.6 \cdot 10^{-3} eV^2$

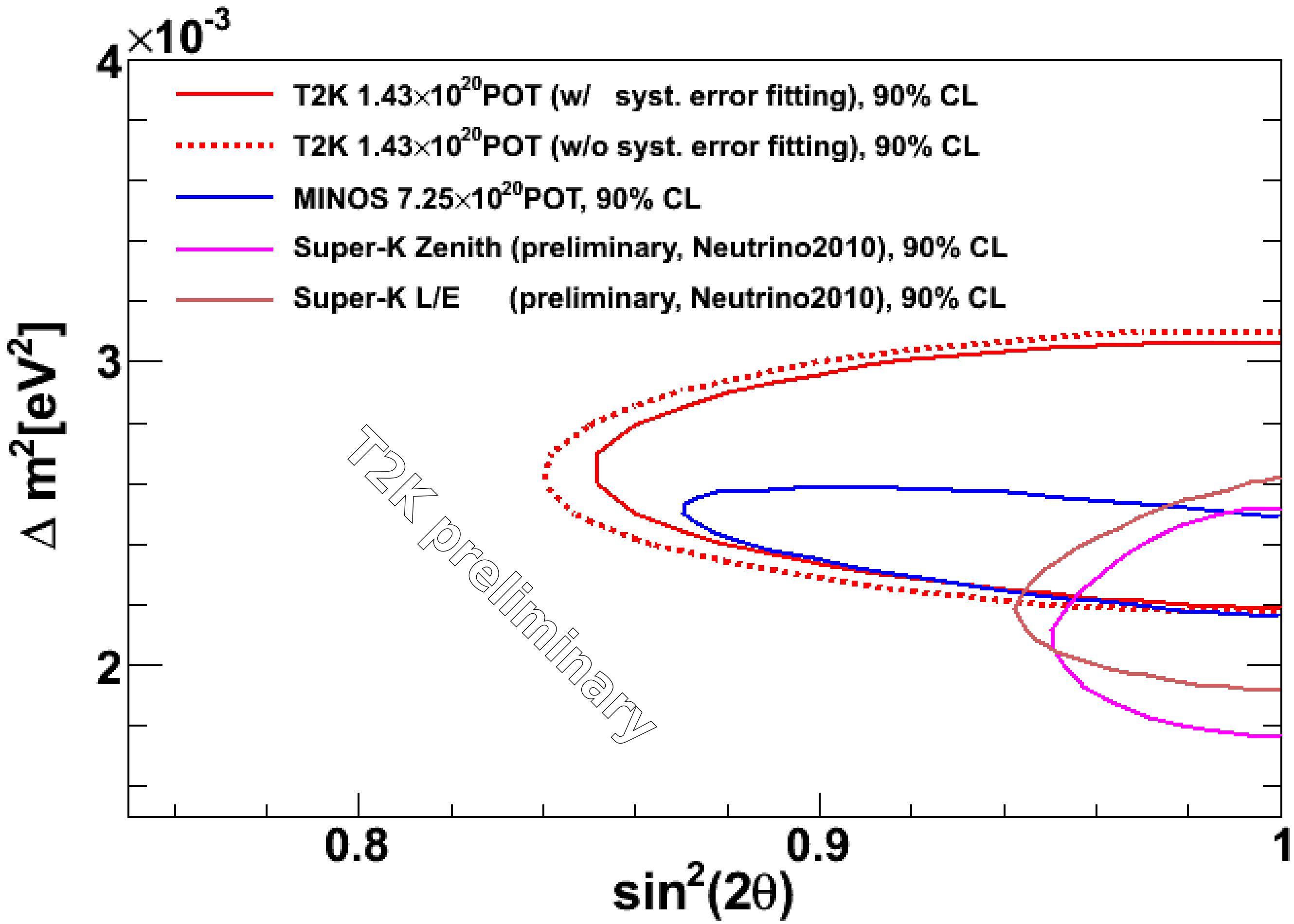
90% C.L:

$\sin^2 2\theta_{23}$ > 0.85 (0.84)
$2.1 \cdot 10^{-3} < |\Delta m^2_{23}|(eV^2) < 3.1 \cdot 10^{-3}$



very good agreement between analyses
main difference is due to the fit to systematics (in method A)

Comparison with other measurements



good agreement with MINOS and SK

Near future

Aim: firmly establish ν_e appearance

more data needed!

- Experiment recovery – in progress
  - activity in J-PARC (accelerator+neutrino facility) by December 2011
  - neutrino facility ready by November
  - beam for physics as soon as possible after re-commisioning of the accelerators

- Analysis improvements
  - new analysis method for ν_e, using the reconstructed energy, are under development
  - ν_μ CCQE events measured in ND280 allow to better constrain the uncertainties of the flux and cross sections

Not so near future

- we aim to accumulate 10^{21} POT in summer 2013
  - confirm the non zero θ_{13}
  - more than 5σ discovery at present best fit for θ_{13}
- then
  - $2 \cdot 10^{21}$ POT – 3σ for $\sin^2 2\theta_{13} > 0.04$, within few years
  - $8 \cdot 10^{21}$ POT – 3σ for $\sin^2 2\theta_{13} > 0.02$, approved goal

- Full dataset of T2K ($8 \cdot 10^{21}$ POT) allows to get sensitivity 20 times better than CHOOZ
- If non-zero θ_{13} will be confirmed (and sufficiently large) the possibilities to study the mass hierarchy and CP violation in lepton sector are open

Summary

- T2K experiment completed two oscillation analyses, based on data collected in 2010 and 2011 (with $1.43\cdot10^{20}$ protons on target)
- **ν_e appearance analysis**
  - indication of $\nu_\mu \to \nu_e$ appearance observed in data (2.5σ)
  - best fit $\sin^2 2\theta_{13}$=0.11 (0.14), 0.03 (0.04)<$\sin^2 2\theta_{13}$<0.28 (0.34) at 90% C.L., for normal (inverted) hierarchy
  - published in PRL 107, 041801 (2011)
- **ν_μ disappearance analysis**
  - null oscillation hypothesis excluded at 4.5σ,
  - $\sin^2 2\theta_{23}>0.85$, $2.1\cdot10^{-3}<|\Delta m^2_{23}|(eV^2)<3.1\cdot10^{-3}$ at 90% C.L.
- experiment is recovering after the earthquake, J-PARC will restart operation in December 2011

T2K collaboration

Canada

- U. Alberta
- U. B. Columbia
- U. Regina
- U. Toronto
- TRIUMF
- U. Victoria
- York U.

France

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

Germany

- U. Aachen

Italy

- INFN, U. Bari
- INFN, U. Napoli
- INFN, U. Padova
- INFN, U. Roma

Japan

- ICRR Kamioka
- ICRR RCCN
- KEK
- Kobe U.
- Kyoto U.
- Miyagi U. Edu.
- Osaka City U.
- U. Tokyo

Poland

- NCBJ, Warsaw
- H.Niewodniczanski, Cracow
- U. Silesia, Katowice
- T. U. Warsaw
- U. Warsaw
- U. Wroclaw

Russia

- INR

S. Korea

- Chonnam N.U.
- Dongshin U.
- Seoul N.U.

Spain

- IFIC, Valencia
- U. A. Barcelona

Switzerland

- ETH Zurich
- U. Bern
- U. Geneva

UK

- Imperial C. L.
- Lancaster U.
- Liverpool U.
- Queen Mary U. L.
- Oxford U.
- Sheffield U.
- STFC/RAL
- STFC/Daresbury
- Warwick U.

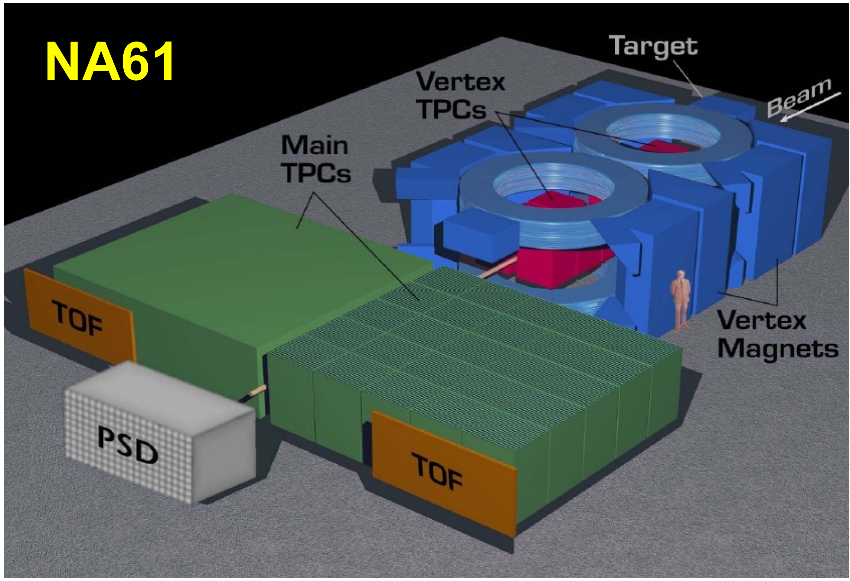
USA

- Boston U.
- B.N.L.
- Colorado S. U.
- U. Colorado
- Duke U.
- U. C. Irvine
- Louisiana S. U.
- U. Pittsburgh
- U. Rochester
- Stony Brook U.
- U. Washington

Near & Far sites: KEK/JAEA ICRR

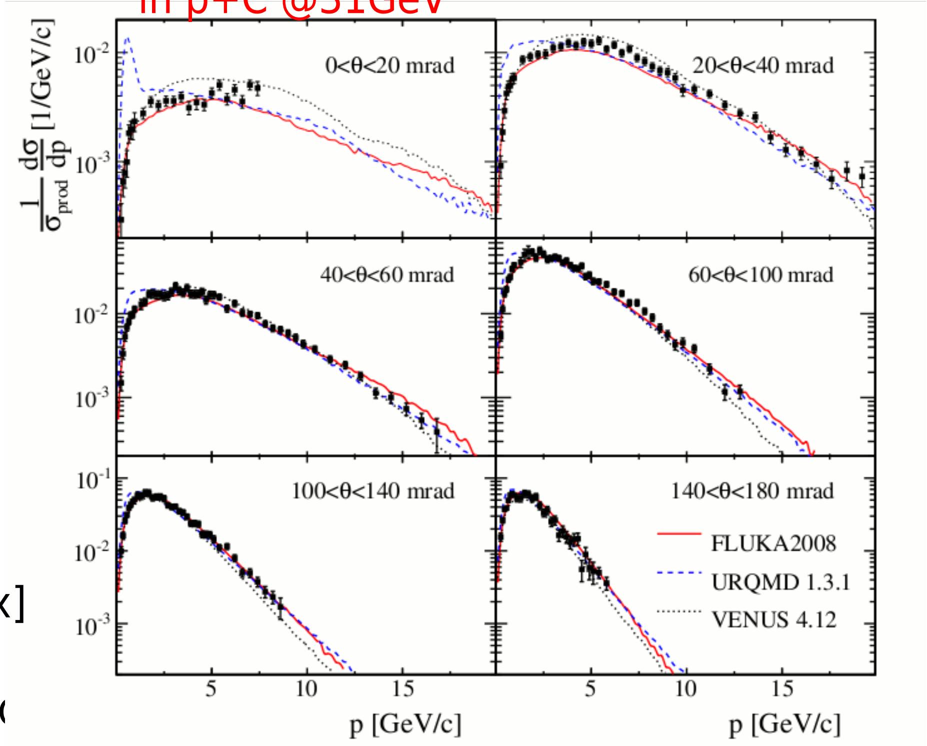
Backup slides

NA61/SHINE



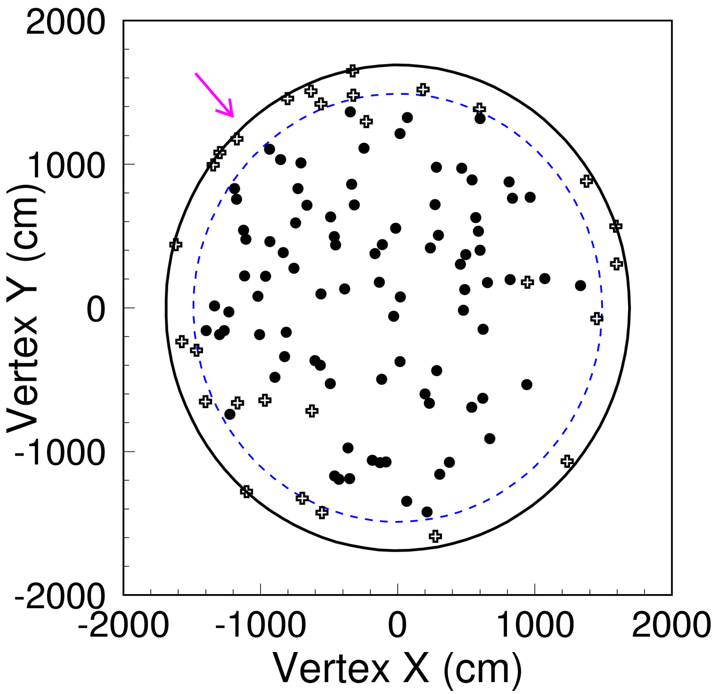
- spectrometer and time of flight detectors
  - TOF and dE/dx allow for particle identification
  - the same beam proton energy and target material as in T2K
  - the pion production data used in the T2K beam simulation
  - 5-10% systematic error on each data point
  - 2.3% normalization error

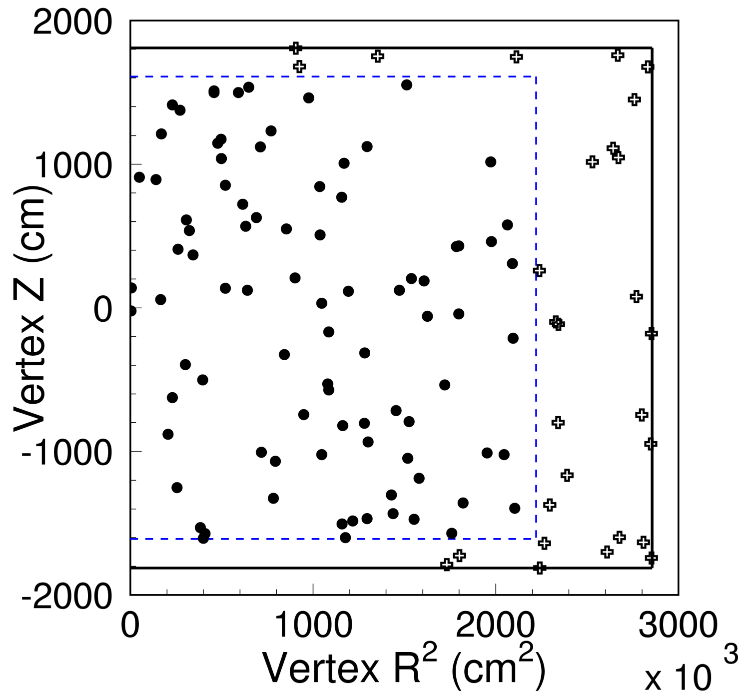
Differential π production multiplicity in p+C @31GeV



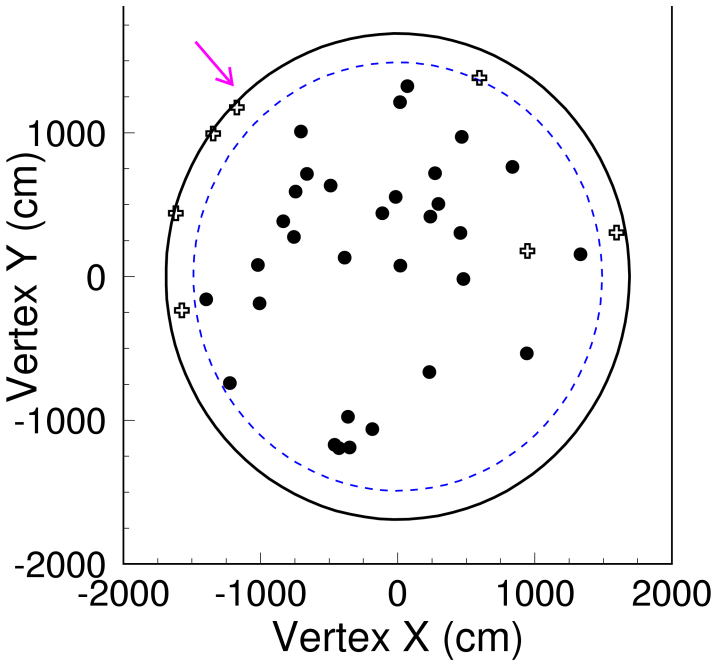
N.Abgrall et al., arXiv:1102.0983 [hep-ex] accepted by Phys.Rev.C (2011)

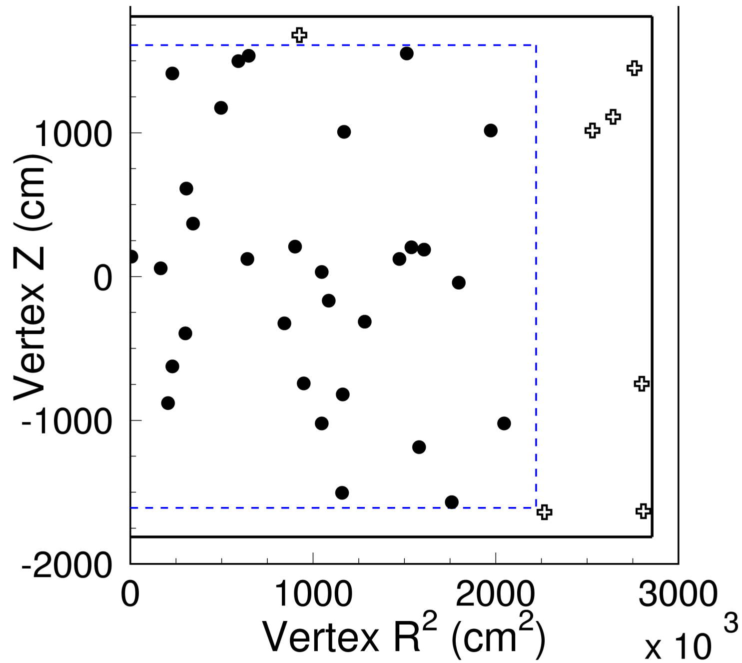
Vertex positions





fully contained sample





ν_μ candidates

ν_e systematics

numbers of expected events

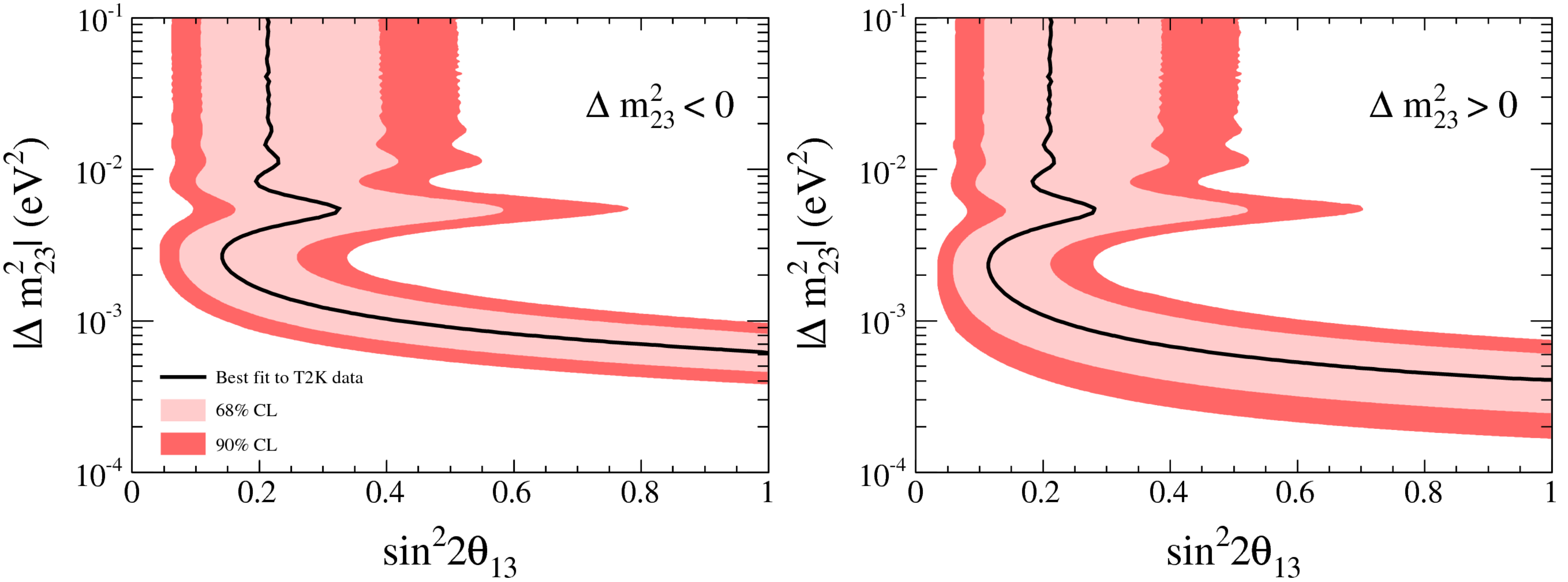
with ND normalization

signal+background

Error source		$\sin^2 2\theta_{13}=0$ N_{ND}	N_{SK}	N_{SK}/N_{ND}	$\sin^2 2\theta_{13}=0.1$ N_{SK}	N_{SK}/N_{ND}
SK Norm.	f^{SKnorm}	± 0.0	± 1.4	± 1.4	± 1.4	± 1.4
SK Energy Scale	f^{Energy}	± 0.0	± 1.1	± 1.1	± 0.6	± 0.6
SK Ring Counting	$f^{N_{ring}}$	± 0.0	± 8.1	± 8.1	± 5.0	± 5.0
SK PID Muon	$f^{PID\mu}$	± 0.0	± 0.9	± 0.9	± 0.3	± 0.3
SK PID Electron	f^{PIDe}	± 0.0	± 7.8	± 7.8	± 4.9	± 4.9
SK POLfit Mass	f^{POLfit}	± 0.0	± 8.5	± 8.5	± 6.0	± 6.0
SK Decay Electron	$f^{N_{dcy}}$	± 0.0	± 0.3	± 0.3	± 0.2	± 0.2
SK π^0 Efficiency	$f^{\pi^0 eff}$					
CC QE shape	$f^{CCQEshape}$					
CC 1π	$f^{CC1\pi}$					
CC Coherentπ	f^{CCcoh}					
CC Other	$f^{CCother}$					
NC $1\pi^0$	$f^{NC1\pi^0}$					
NC Coherentπ	f^{NCcoh}					
NC Other	$f^{NCother}$					
$\sigma(\nu_e)$	$f^{\sigma(\nu_e)}$	< 0.1	± 3.4	± 3.4	± 5.3	± 5.3
FSI	f^{FSI}	± 0.0	± 10.1	± 10.1	± 5.4	± 5.4
Beam Norm.	$f^{\phi}_{SK/ND}$	± 15.4	± 16.1	± 8.5	± 14.9	± 8.5
ND Efficiency	$f^{\epsilon_{ND}}$	$^{+5.6}_{-5.2}$	± 0.0	$^{+5.6}_{-5.2}$	± 0.0	$^{+5.6}_{-5.2}$
Overall Norm.	f^{norm}	± 0.0	± 0.0	± 2.7	± 0.0	± 2.7
Total		± 18.4	± 25.6	$^{+22.8}_{-22.7}$	± 20.2	$^{+17.6}_{-17.5}$

Error source	$\sin^2 2\theta_{13}=0$ N_{ND}	N_{SK}	N_{SK}/N_{ND}	$\sin^2 2\theta_{13}=0.1$ N_{SK}	N_{SK}/N_{ND}
SK Efficiency	± 0.0	± 14.7	± 14.7	± 9.4	± 9.4
Cross section	± 8.3	± 13.5	± 14.0	± 9.8	± 10.5
Beam Flux	± 15.4	± 16.1	± 8.5	± 14.9	± 8.5
ND Efficiency	$^{+5.6}_{-5.2}$	± 0.0	$^{+5.6}_{-5.2}$	± 0.0	$^{+5.6}_{-5.2}$
Overall Norm.	± 0.0	± 0.0	± 2.7	± 0.0	± 2.7
Total	± 18.4	± 25.6	$^{+22.8}_{-22.7}$	± 20.2	$^{+17.6}_{-17.5}$

Confidence intervals



ν_μ systematics

Super K efficiency

cross sections

different E_{vis}

Source of systematic errors	change of N^{SK}_{exp} ($\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$)	change of N^{SK}_{exp} ($\sin^2 2\theta = 1.0, \Delta m^2 = 2.32$)	change of N^{SK}_{exp} (Null Osc.)
f^{SK}_{CCQE0}	+1.0% -1.0%	+1.0% -1.0%	+1.4% -1.4%
f^{SK}_{CCQE1} f^{SK}_{CCQE2} f^{SK}_{CCQE3}	+3.2% -3.2%	+3.2% -3.2%	+3.1% -3.1%
f^{SK}_{CnCQE}	+6.5% -6.5%	+6.5% -6.5%	+3.3% -3.3%
f^{SK}_{NC}	+7.2% -7.2%	+7.0% -7.0%	+2.0% -2.0%
$f^{SK}_{CC\nu_e}$	+0.0% -0.0%	+0.0% -0.0%	+0.0% -0.0%
$f^{SK}_{E-scale}$	+0.0% -0.0%	+0.0% -0.0%	+0.0% -0.0%
f^{ND}	+6.2% -5.9%	+6.2% -5.9%	+6.2% -5.9%
f^{Xsec}_{CCQE}	+2.5% -2.5%	+2.4% -2.4%	+4.1% -4.1%
$f^{Xsec}_{CC1\pi}$	+0.4% -0.5%	+0.5% -0.6%	+2.2% -1.9%
$f^{Xsec}_{CCothers}$	+4.1% -3.6%	+4.1% -3.7%	+5.3% -4.7%
f^{Xsec}_{NC}	+0.9% -0.9%	+0.8% -0.8%	+0.8% -0.8%
$f^{Xsec}_{\nu_e/\nu_\mu}$	+0.0% -0.0%	+0.0% -0.0%	+0.0% -0.0%
f^{FSI}	+6.7% -6.7%	+6.6% -6.6%	+3.2% -3.2%
$f^{Flux}_{SK/ND}$	+4.8% -4.8%	+4.7% -4.7%	+6.9% -6.9%
Total	+15.4% -15.1%	+15.2% -14.9%	+13.2% -12.7%